A2b: The Higgs Sector in Multi-Boson Processes

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Project A2b: The Physics Question

The SM (and the SM-EFT) provides a robust ansatz for describing the bosons that realize the electro-weak interactions.

Linear $SU(2)_L \times U(1)_Y$ symmetry and the Higgs field:

$$\mathbf{H} = \frac{1}{2}\begin{pmatrix} v + h - \mathrm{i}w^3 & -\mathrm{i}\sqrt{2}w^+ \\ -\mathrm{i}\sqrt{2}w^- & v + h + \mathrm{i}w^3 \end{pmatrix}.$$

(matrix notation makes $SU(2)_L \times SU(2)_R$ explicit)

Robust Ansatz: We can leave this Higgs (the SM) as it is written or extend it, with no immediate contradiction to established facts.

Probes of the Higgs Sector

We may understand the Higgs sector as an unspecified set of new fields and interactions (the set may be empty!)

that is probed by electro-weak bosonic currents.

$$\mathrm{tr}\left[\mathbf{H}^\dagger\mathbf{H}\right]$$
$$\partial_\mu\mathrm{tr}\left[\mathbf{H}^\dagger\mathbf{H}\right]$$
$$\mathrm{tr}\left[\mathbf{D}^\mu\mathbf{H}^\dagger\mathbf{D}_\mu\mathbf{H}\right]$$
$$\mathrm{tr}\left[\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}\right]$$
$$\ldots$$

(Non-singlet currents are subject to EWP contraints, singlet currents evade those.)

Probes of the Higgs Sector at the HL-LHC

- Whatever we are probing here, the effective phenomenology is tied to multi-boson interactions.
- We can't trust further assumptions – there need not be a large scale, there need not be genuine new particles.
- Interaction strengths may be large (in fact, if anything is accessible at all at the HL-LHC, it is very likely rooted in sizable interaction strength!)
- The actual effects at the HL-LHC will nevertheless be small and require sophisticated analyses for unambiguous detection.

Example: effective current-current interaction

$$\mathrm{tr}\left[\mathbf{D}^\mu \mathbf{H}^\dagger \mathbf{D}_\mu \mathbf{H}\right] \mathrm{tr}\left[\mathbf{D}^\nu \mathbf{H}^\dagger \mathbf{D}_\nu \mathbf{H}\right]$$

The SM-EFT Connection

Note:

$$\mathrm{tr}\left[\mathbf{D}^\mu\mathbf{H}^\dagger\mathbf{D}_\mu\mathbf{H}\right]\mathrm{tr}\left[\mathbf{D}^\nu\mathbf{H}^\dagger\mathbf{D}_\nu\mathbf{H}\right]$$

is a dimension-eight operator. Subleading?
However:

$$\partial^\mu\mathrm{tr}\left[\mathbf{H}^\dagger\mathbf{H}\right]\partial_\mu\mathrm{tr}\left[\mathbf{H}^\dagger\mathbf{H}\right]$$

marks a blind direction for hadron-collider measurements.

- SM-EFT power counting is not a useful working hypothesis if we want to maintain an unbiased view on the subject.
- But it clearly allows us to connect to present and future fits of Higgs decays and other SM precision data
- Specific models of the Higgs sector can be evaluated in terms of their SM-EFT coefficients.

Project A2b: The Physics Question

How to make optimal use of HL-LHC data, in our sense of probing the Higgs sector,

by connecting the potential phenomenology of multi-boson interactions

to low-energy data, precision calculations, global fits, constraints from top- and bottom-quark interactions, and model-specific signatures?

Project A2b: Plan

We don't expect to exhaustively cover all aspects in a single CRC project, but we expect to contribute new results in this area, making use of the new opportunities of collaboration within the CRC.

Previous Work

DZ LHC phenomenology and calculations for multi-boson interactions starting from vector-boson fusion topologies, with new physics and with NLO QCD, numerical approach to unitarity modelling, results in tool: VBFNLO

WK Phenomenology for multi-boson interactions in vector-boson scattering topologies, phenomenology of 2H and 3H production at hadron colliders beyond LHC, analytical approach to unitary modelling new phenomena, results in tool: WHIZARD.

++ Unitary approach(es) to modelling new phenomena that mix scalar and vector d.o.f. (transversal) of the Higgs sector.

Constraining New Phenomena

Production Processes at Hadron Colliders (VBS in the SM)

- LO amplitude is constant for $\hat{s} \to \infty$
- PDFs = effective $1/\hat{s}^n$ suppression, where $n \lesssim 4$.

$\Rightarrow$ $\hat{s}$ is virtually unlimited but only threshold is actually probed, $2M \lesssim \sqrt{\hat{s}} \lesssim 1$ TeV

Production Processes at Hadron Colliders (Unitarity Bound)

- LO unitarity bound is constant for $\hat{s} \to \infty$
  (but 1–2 orders of magnitude above SM)
- (all arguments for $\hat{s}$ also hold for p_T distribution)
- This applies to BSM strong interactions (continuum) as well for weak interactions (resonances) and anything else
- PDFs = effective $1/\hat{s}^n$ suppression, where $n \lesssim 4$.

$\Rightarrow$ $\hat{s}$ is virtually unlimited but only threshold is actually probed,
$2M \lesssim \sqrt{\hat{s}} \lesssim$ few TeV

Production Processes at Hadron Colliders (SM-EFT, D6)

- SM-EFT interference $\propto \hat{s}$
- and (SM-EFT)^2 $\propto \hat{s}^2$
- PDFs = effective $1/\hat{s}^n$ suppression, where $n \lesssim 2$.

$\Rightarrow$ range beyond threshold is probed, squared term dominates naive fit (does this make sense?)

SM-EFT at D6: quartic interactions related to trilinear and thus fixed by global D6 fit. Does this make sense?

Production Processes at Hadron Colliders (SM-EFT, D8)

New parameters extend pheno to phenomena where quartic and trilinear interactions are not related

- SM-EFT interference $\propto \hat{s}^2$
- and (SM-EFT)^2 $\propto \hat{s}^4$
- PDFs = no effective $1/\hat{s}^n$ suppression

$\Rightarrow$ full kinematical range is probed, squared term dominates everything

$\Rightarrow$ more "corrections": even worse

Production Processes at Hadron Colliders (SM-EFT, UV Models)

- Between SM and unitarity bound everywhere
- New effects appear at and somewhat beyond threshold
- Actual UV completion (asymptotics) doesn't matter

Constraining New Phenomena

Production Processes at Hadron Colliders (SM-EFT, UV Models, A2b)

- Find reasonable description (simplified models) for phenomena as they are actually probed at the LHC
- Establish the connection to D=6 SM-EFT and global fits
- Explore UV models (such as 2HDM), but be aware that the actual UV completion does not matter (phenomenologically)

Project Topics

- VBS: Relax simplifying conditions, combine the existing approaches, combined handling of D=6 and D=8 SMEFT approximation, more detailed LHC pheno
- Multi-boson production: how exactly related to VBS? Disentangle information from different channels at the LHC? Further final states?
- Unifying the picture: relation between vector-boson and Higgs observables? Practical common scheme for setting up unitary models, inter- and extrapolation? What kind of physics should be implemented in MC tools?

Recruitment

- **Siegen:** 1 PhD position, possible hiring of Postdoc instead (adding in local funding + 1 PhD)
  - Position held by Simon Braß until Sept. 2019 ($\Rightarrow$ DESY)
  - No suitable postdoc candidate found in 1st round Winter 18/19
  - Master student(s)
- **Karlsruhe:**
  - Heiko Schäfer-Siebert working on A2b topics
  - PhD position not yet filled
  - Master student(s)