Transverse Modes and Higgs Bosons in Vector-Boson Scattering

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EFT for LHC production processes (such as VBS)

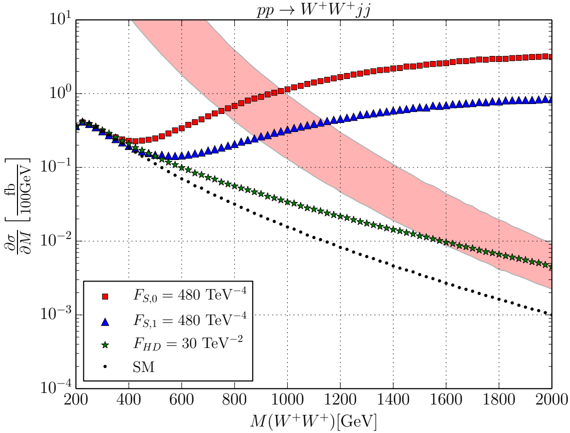
- EFT: Low-energy Taylor expansion of scattering amplitudes, generated by gauge-invariant Lagrangian
- High-energy limit (UV completion) unknown
  but parameterized by operator coefficients
- PDFs ($p \to q \to W$) enforce power suppression for high-energy tails,
  therefore amplitudes probed up to few TeV
  (not up to 14 TeV)

Issues with EFT for LHC production processes

- Power suppression applies to SM and $D = 6$ EFT amplitudes, but not to $D = 8$ EFT (and beyond)
- $D = 8$ operators are required to describe new quartic interactions that are independent from trilinear interactions
  (example: strongly interacting resonances enter at tree-level)
- OTOH, unitarity limits UV amplitude to a constant.
  A constant amplitude is subject to high-energy power suppression.

  $\Rightarrow$ contradiction: $D \geq 8$ EFT does not qualify as a useful universal description of production processes at the LHC.

How this looks like (extreme case)



Solution and Scope

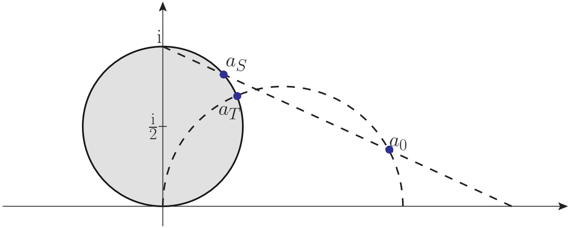
Without knowning an UV completion,
simply project the EFT result onto the unitarity circle

⇒ some arbitrariness in the projection, but still:

- Consistent with perturbation theory in the range where it applies:
  1. QCD and EW perturbation theory
  2. EFT expansion
- Consistent with unitarity where PT doesn't apply, and therefore
  - ⇒ power suppression works, thus UV modelling arbitrariness are minor corrections, again.
- Systematic improvement straightforward: more parameters, analyticity relations, etc.

Projection schemes, in a nutshell

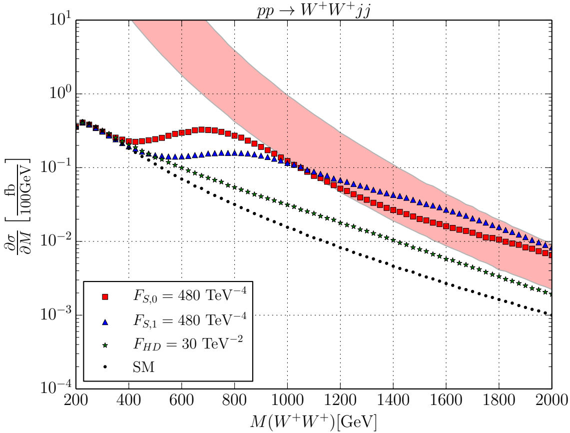
Graphically (single scalar amplitude)



Explicitly (general scattering matrix)

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

Applied to longitudinal VBS, $D = 8$ only, extreme case:



$\rightarrow$ WK, T. Ohl, J. Reuter, M. Sekulla, `arXiv:1408.6207` (PRD91)

New results: Because Goldstone modes are not alone

The role of the Higgs

H is in a common doublet with W/Z Goldstone modes (longitudinal)

$\Rightarrow$ same methods apply (universal up to Higgs potential)

$\Rightarrow$ similar results regarding $D = 8$ EFT interactions

Transverse polarization

W_T and Z_T may also be affected by BSM corrections

$\Rightarrow$ EFT method + T-matrix projection applicable

$\Rightarrow$ Technically more involved

$\rightarrow$ S. Brass, C. Fleper, WK, J. Reuter, M. Sekulla, arXiv:1807.02512

The EFT side of the problem (1)

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

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

The EFT side of the problem (2)

$$\mathcal{L}_{M,0} = -g^2 F_{M_0} \mathrm{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\mu \mathbf{H})\right] \mathrm{tr}\left[\mathbf{W}_{\nu\rho}\mathbf{W}^{\nu\rho}\right],$$

$$\mathcal{L}_{M,1} = -g^2 F_{M_1} \mathrm{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\rho \mathbf{H})\right] \mathrm{tr}\left[\mathbf{W}_{\nu\rho}\mathbf{W}^{\nu\mu}\right],$$

$$\mathcal{L}_{M,2} = -g'^2 F_{M_2} \mathrm{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\mu \mathbf{H})\right] \mathrm{tr}\left[\mathbf{B}_{\nu\rho}\mathbf{B}^{\nu\rho}\right],$$

$$\mathcal{L}_{M,3} = -g'^2 F_{M_3} \mathrm{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger (\mathbf{D}^\rho \mathbf{H})\right] \mathrm{tr}\left[\mathbf{B}_{\nu\rho}\mathbf{B}^{\nu\mu}\right],$$

$$\mathcal{L}_{M,4} = -gg' F_{M_4} \mathrm{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger \mathbf{W}_{\nu\rho} (\mathbf{D}^\mu \mathbf{H}) \mathbf{B}^{\nu\rho}\right],$$

$$\mathcal{L}_{M,5} = -gg' F_{M_5} \mathrm{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger \mathbf{W}_{\nu\rho} (\mathbf{D}^\rho \mathbf{H}) \mathbf{B}^{\nu\mu}\right],$$

$$\mathcal{L}_{M,7} = -g^2 F_{M_7} \mathrm{tr}\left[(\mathbf{D}_\mu \mathbf{H})^\dagger \mathbf{W}_{\nu\rho} \mathbf{W}^{\nu\mu} (\mathbf{D}^\rho \mathbf{H})\right] ;$$

The EFT side of the problem (3)

$$\mathcal{L}_{T_0} = g^4 F_{T_0} \mathrm{tr}\left[\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}\right] \mathrm{tr}\left[\mathbf{W}_{\alpha\beta}\mathbf{W}^{\alpha\beta}\right],$$

$$\mathcal{L}_{T_1} = g^4 F_{T_1} \mathrm{tr}\left[\mathbf{W}_{\alpha\nu}\mathbf{W}^{\mu\beta}\right] \mathrm{tr}\left[\mathbf{W}_{\mu\beta}\mathbf{W}^{\alpha\nu}\right],$$

$$\mathcal{L}_{T_2} = g^4 F_{T_2} \mathrm{tr}\left[\mathbf{W}_{\alpha\mu}\mathbf{W}^{\mu\beta}\right] \mathrm{tr}\left[\mathbf{W}_{\beta\nu}\mathbf{W}^{\nu\alpha}\right],$$

$$\mathcal{L}_{T_5} = g^2 g'^2 F_{T_5} \mathrm{tr}\left[\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}\right] \mathrm{tr}\left[\mathbf{B}_{\alpha\beta}\mathbf{B}^{\alpha\beta}\right],$$

$$\mathcal{L}_{T_6} = g^2 g'^2 F_{T_6} \mathrm{tr}\left[\mathbf{W}_{\alpha\nu}\mathbf{W}^{\mu\beta}\right] \mathrm{tr}\left[\mathbf{B}_{\mu\beta}\mathbf{B}^{\alpha\nu}\right],$$

$$\mathcal{L}_{T_7} = g^2 g'^2 F_{T_7} \mathrm{tr}\left[\mathbf{W}_{\alpha\mu}\mathbf{W}^{\mu\beta}\right] \mathrm{tr}\left[\mathbf{B}_{\beta\nu}\mathbf{B}^{\nu\alpha}\right],$$

$$\mathcal{L}_{T_8} = g'^4 F_{T_8} \mathrm{tr}\left[\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu}\right] \mathrm{tr}\left[\mathbf{B}_{\alpha\beta}\mathbf{B}^{\alpha\beta}\right],$$

$$\mathcal{L}_{T_9} = g'^4 F_{T_9} \mathrm{tr}\left[\mathbf{B}_{\alpha\mu}\mathbf{B}^{\mu\beta}\right] \mathrm{tr}\left[\mathbf{B}_{\beta\nu}\mathbf{B}^{\nu\alpha}\right].$$

Calculation

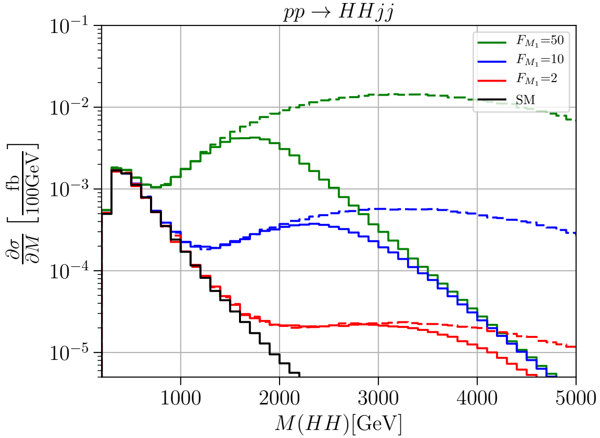
Simplification

- Keep $SU(2)_C$: 2S, 3M, 3T operators
- On-shell treatment of unitarity projection (but off-shell evaluation)
- Analytic calculation: one operator at a time

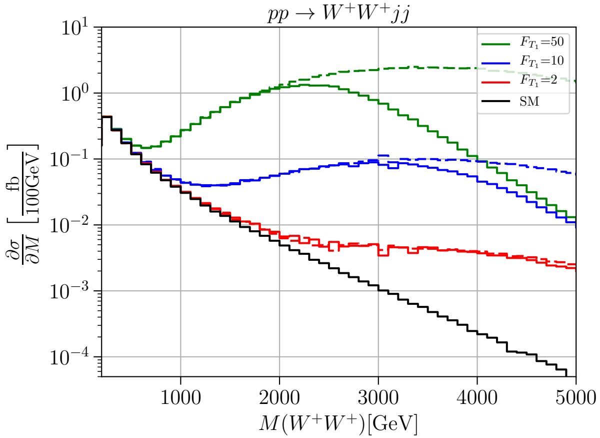
Method

- Diagonalize Wigner decomposition analytically $\Rightarrow$ master amplitudes
- Unitary projection for diagonal amplitude
- Re-insertion in form of momentum-dependent Feynman rules
- Sample implementation in WHIZARD

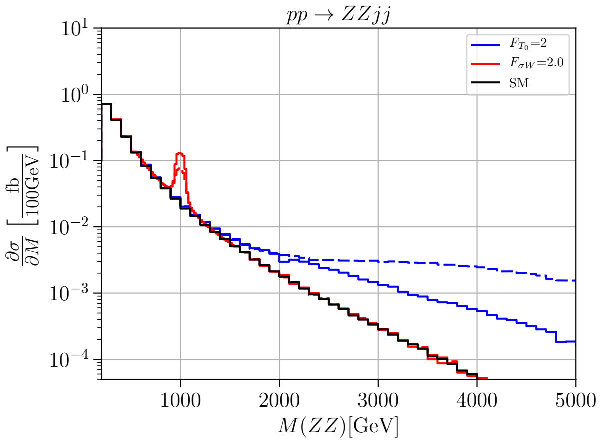
Results: Higgs coupled to W_T



Results: W_T coupled to W_T



Results: Strongly coupled scalar resonance



→ WK, T. Ohl, J. Reuter, M. Sekulla, `arXiv:1511.0002` (PRD93)

→ S. Brass, C. Fleper, WK, J. Reuter, M. Sekulla, `arXiv:1807.02512`

Application to LHC analyses

- Provide viable phenomenological models for VBS distributions (EFT, resonances, coupled channels, invisible, . . .)
- Connect UV-complete models to EFT w/ realistic simulation
  (embedded via effective Feynman rules in MC generator)
- Enable sensitivity analyses without ad-hoc phase-space restrictions

- Follow-up: Dieter's talk (relaxing some simplifications)
- Parameter space concerns: Cen's talk