Unitarization for Vector Boson Scattering at the LHC

G. Perez, M. Sekulla and D. Zeppenfeld. Institute for Theoretical Physics, KIT.

The Standard Model as an Effective Field Theory

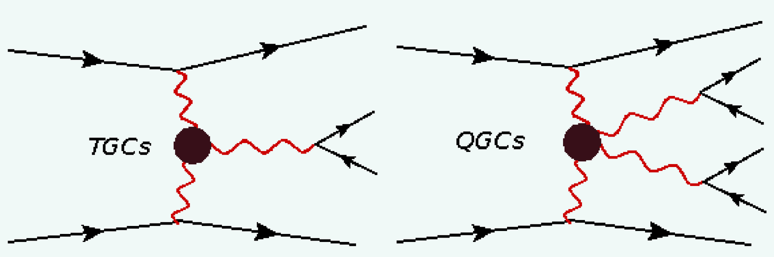
Effective Field Theory parameterizes new physics (NP) using the SM information available: working with a *bottom up* description, physics above the SM could be expanded in terms of a cut-off energy (Λ), where the NP is expected to be,

$$\mathcal{L}_{\mathrm{EFT}} = \underbrace{\mathcal{L}_{\mathrm{SM}}}_{\text{dim-4}} + \underbrace{\sum_{i} \frac{c_i}{\Lambda^2}\mathcal{O}_{i}}_{\text{dim-6}} + \underbrace{\sum_{j} \frac{f_{S,j}}{\Lambda^4}\mathcal{O}_{S,j} + \sum_{k} \frac{f_{T,k}}{\Lambda^4}\mathcal{O}_{T,k} + \sum_{l} \frac{f_{M,l}}{\Lambda^4}\mathcal{O}_{M,l}}_{\text{dim-8}}.$$

General Anomalous Quartic Couplings: Dim-8 Operators

Deviations from the SM can be parameterized by:

- **Dim-6 operators**
  TGCs and QGCs
- **Dim-8 operators**
  QGCs



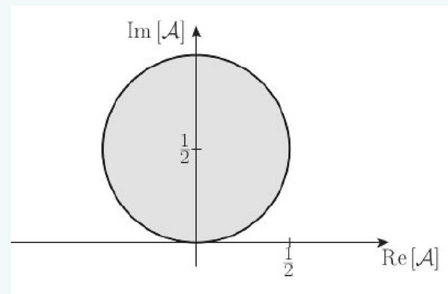
Dim-6 Anomalous Couplings are related to guarantee gauge invariance: deviations cannot be treated separately and TGCs are strongly constrained; thus, an independent parameterization of QGCs requires **dim-8 operators.**

The dim-8 operators are characterized by their field content:

- Covariant derivatives acting on the Higgs doublet, $\mathcal{O}_{S,j}$, $\quad \mathcal{O}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$ $\rightarrow$ **Longitudinal scattering**.
- Field strength tensors, $\mathcal{O}_{T,j}$, $\quad \mathcal{O}_{T,0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right]$ $\rightarrow$ **Transverse scattering**.
- Or a mixture of both, $\mathcal{O}_{M,j}$, $\quad \mathcal{O}_{M,0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$ $\rightarrow$ **Mixed polarization**.

Unitarity Problem

Unitarity bounds are derived from on-shell 2$\rightarrow$2 scattering:

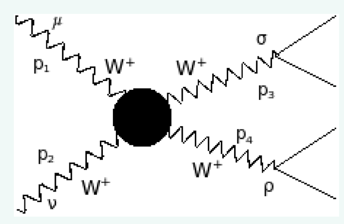


The Argand Circle

Using **partial wave decomposition** to rewrite the scattering amplitude and the **optical theorem**:

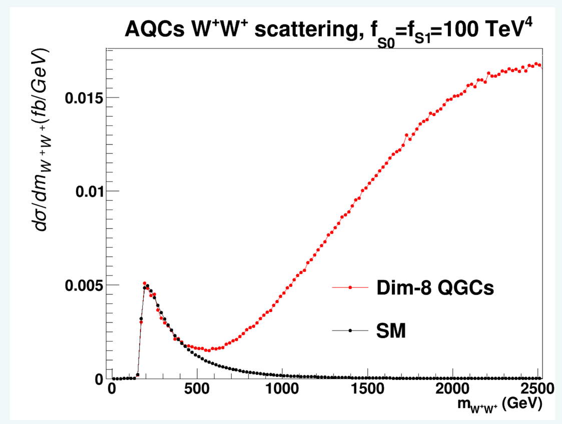
$$\left|\mathcal{A}_j - \tfrac{i}{2}\right| \leq \tfrac{1}{2} \;\Rightarrow\; Re(\mathcal{A}_j) < \tfrac{1}{2}$$

The Scattering amplitudes are not allowed to grow proportional to energy, or the cross section becomes unphysical.



$$\mathcal{A}_{S,0} \propto \frac{f_{S,0}}{\Lambda^4}\,\epsilon_1\cdot\epsilon_2\,\epsilon_3^*\cdot\epsilon_4^* \;\Rightarrow\; \mathcal{A}_{S,0} \propto \frac{s^2}{4}$$

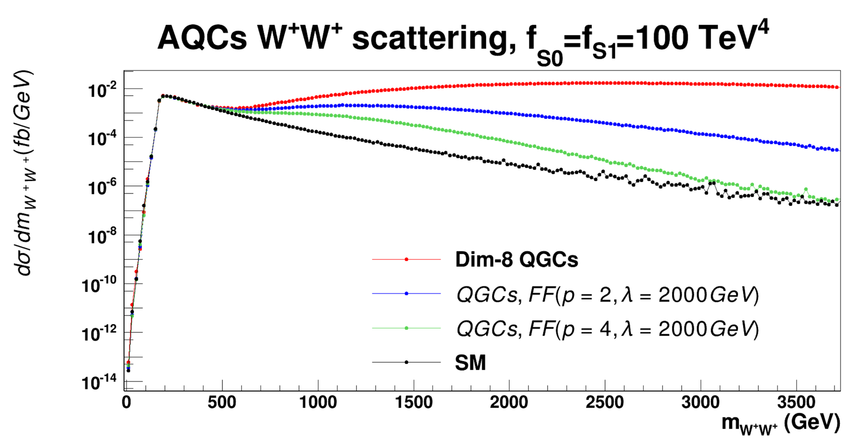
A unitarization scheme needed to obtain a valid prediction in this region.



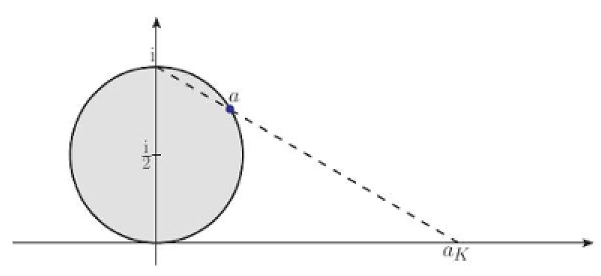
Restoring Unitarity

- **Form Factor Unitarization**

In VBFNLO [1] , a function $\mathcal{F}(s)$ is multiplied to the couplings, so it suppresses the high energy tail of amplitudes arising from the operators and thus ensures unitarity.



- **On-Shell K-Matrix Unitarization**



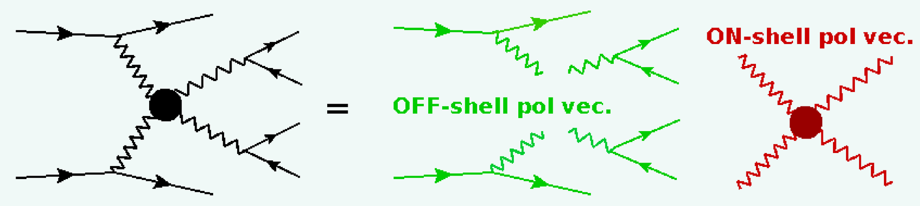
$$a_k = \frac{a}{1-\mathrm{i}\;a}$$

Real scattering amplitudes are projected onto the Argand circle to restore unitarity, using the Cayley transform of the S-matrix (the K-matrix[2]).

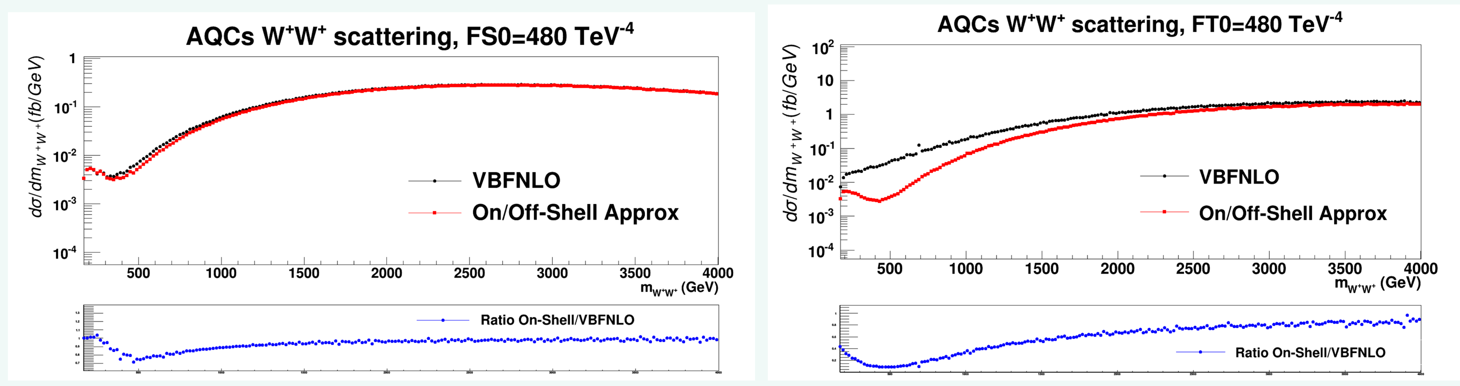
VBS at the LHC

- **On/Off-Shell Approximation**

Using the properties of the polarization vectors, the scattering amplitude can be rewrite as,



to restore unitarity for the on-shell part, in an off-shell process.



The on/off-shell approach fails when transverse polarized particles are involved.

- **Analytic Solution**

Using the partial wave decomposition for off-shell amplitudes,

$$A_{QC}(\lambda_1,\lambda_2,\lambda_3,\lambda_4) = 16\pi\sum_{j=0}^{2}(2j+1)\,d^j_{\lambda1-\lambda2,\lambda3-\lambda4}(\theta)\,a^j(\lambda_1,\lambda_2,\lambda_3,\lambda_4)$$

we can determine unitarized amplitudes, calculating the analytic K-matrix.

REFERENCES

(1) J. Baglio et al., *VBFNLO: A parton level Monte Carlo for processes with electroweak bosons* [arxiv:1404.3940]

(2) W. Killian, T. Ohl, J. Reuter and M. Sekulla, *High-Energy Vector Boson Scattering after the Higgs Discovery.* [arxiv:1408.6207]