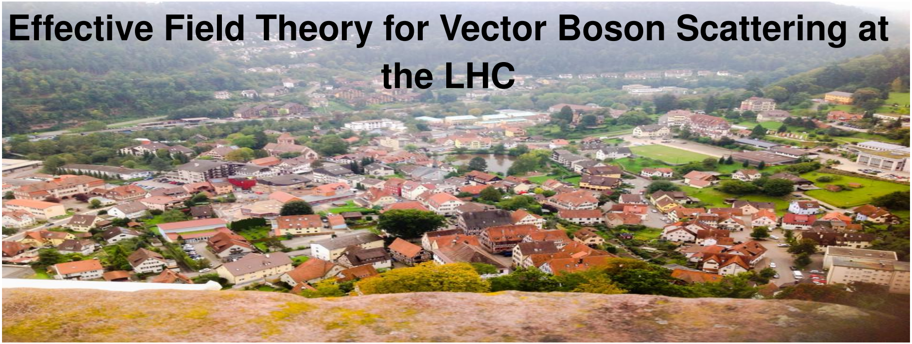
Effective Field Theory for Vector Boson Scattering at the LHC



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Outline

Motivation

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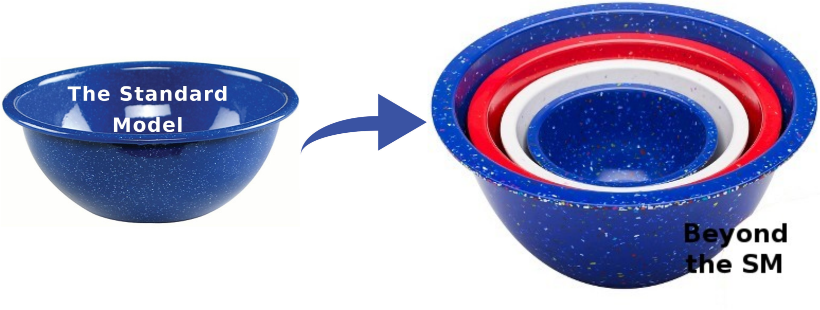

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Bottom-up:
Dimensional expansion for physics above the scales of the SM, expanding in terms of an energy scale (cut-off energy where NP is expected).

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- How to expand the parameters: **Bottom-up description of the SM.**

$$\mathcal{L}_{\rm EFT} = \underset{\sim \Lambda^0}{\mathcal{L}^{(0)}} + \underset{\sim \Lambda^1}{\mathcal{L}^{(1)}} + \underset{\sim \Lambda^2}{\mathcal{L}^{(2)}} + \ldots$$

The Standard Model as an Effective Field Theory

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- The EFT is constructed using the SM fields:

	Gauge Bosons $\mathbf{X}_{\mu\nu}$	Fermions ψ	Scalars ϕ	Derivative $\mathbf{D}_\mu$
	$\mathrm{G}^A_{\mu\nu}$	L^j_L	H^j	$\partial_\mu - i\frac{g}{2} W^a_\mu \sigma^a - ig' B^\mu$
	$\mathrm{W}^J_{\mu\nu}$	e_R		
	$\mathrm{B}_{\mu\nu}$	$\mathrm{Q}^{\alpha j}_L$		
		u^α_R, d^α_R		
Dim	2	$\frac{3}{2}$	1	1

Building Blocks

- The SM includes all the possible dim-4 operators: $\mathcal{L}^{(0)} = \mathcal{L}_{SM}$.

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- The SM includes all the possible dim-4 operators: $\mathcal{L}^{(0)} = \mathcal{L}_{SM}$.
- Symmetries of the SM imposed (Lorentz and gauge invariance are assumed).
- New particles are produced only at the new scale $m \sim \Lambda$: kinematically their production is not allowed before this value.
- Any $\mathcal{L}^{i}$ term should have the same degrees of freedom as the SM.

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- When baryon and lepton numbers are conserved, only operators with even dim can be constructed:

$$\mathcal{L}_{\mathtt{EFT}} = \mathcal{L}_{\mathtt{SM}} + \mathcal{L}_{\mathtt{dim-6}} + \mathcal{L}_{\mathtt{dim-8}} + \ldots$$

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$$\mathcal{L}_{\mathtt{EFT}} = \mathcal{L}_{\mathtt{SM}} + \frac{1}{\Lambda^2}\sum_i \mathsf{c}_i \mathcal{O}_i + \frac{1}{\Lambda^4}\left[\sum_{\mathtt{S}i} \mathsf{c}_{\mathtt{S}i}\mathcal{O}_{\mathtt{S}i} + \frac{1}{\Lambda^4}\sum_{\mathtt{T}i} \mathsf{c}_{\mathtt{T}i}\mathcal{O}_{\mathtt{T}i} + \frac{1}{\Lambda^4}\sum_{\mathtt{M}i} \mathsf{c}_{\mathtt{M}i}\mathcal{O}_{\mathtt{M}i}\right]$$

- Restrictions on the coefficients come from high precision measurements.

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- When baryon and lepton numbers are conserved, only operators with even dim can be constructed:
- Restrictions on the coefficients come from high precision measurements.
- The most stronger constraints come from fermionic interactions, so we concentrate on bosonic searches : electroweak precision tests are sensitive observables to constraint NP.

New Physics from Effective Field Theory

$$\mathcal{L}_{\texttt{EFT}} = \mathcal{L}_{\texttt{SM}} + \frac{1}{\Lambda^2}\sum_i \mathsf{c}_i \mathcal{O}_i + \frac{1}{\Lambda^4}\left[\sum_{\texttt{S}i} \mathsf{c}_{\texttt{S}i}\mathcal{O}_{\texttt{S}i} + \frac{1}{\Lambda^4}\sum_{\texttt{T}i} \mathsf{c}_{\texttt{T}i}\mathcal{O}_{\texttt{T}i} + \frac{1}{\Lambda^4}\sum_{\texttt{M}i} \mathsf{c}_{\texttt{M}i}\mathcal{O}_{\texttt{M}i}\right]$$

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Dim-6 Operators

They affect triple and quartic vector boson couplings (ATGCs & AQGCs, respectively); therefore, the deviations from the SM values cannot be treated separately.

e.g. $\mathcal{O}_{WWW} = \mathtt{Tr}\left[W_{\mu\nu} W^{\nu\rho} W^{\nu}_{\rho}\right]$

$\mathcal{O}_{WWW}$	ZWW	AWW	WWWW
	ZZWW	ZAWW	AAWW

TGCs are strongly constrained
(e.g. by the LEP experiments).

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Dim-8 Operators

- An independent parameterization of QGCs is possible.
- Some NP effects appear as dim-8 operators, e.g. heavy resonances

e.g.
$\mathcal{O}_{\mathtt{S0}} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$

$\mathcal{O}_{T0}$	WWWW	WWZZ
	ZZZZ	

Dim-8 Operators for Vector Boson Scattering

The dim-8 operators can be divided into:

- Operators built from Higgs doublet and covariant derivatives only, $\mathcal{O}_{Si}$. It affects only massive vector bosons (longitudinally polarized particles).

$$\mathcal{O}_{\mathtt{S0}} = \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right] \tag{1}$$

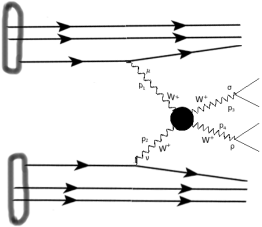
- Operators containing only field strenght tensors, $\mathcal{O}_{Ti}$. Therefore, only transverse polarizations are of importance.

$$\mathcal{O}_{\mathtt{T0}} = \mathtt{Tr}\left[W_{\mu\nu} W^{\mu\nu} \right] \times \mathtt{Tr}\left[W_{\alpha\beta} W^{\alpha\beta} \right] \tag{2}$$

- Operators built from field strength tensors, Higgs doublet and covariant derivatives, $\mathcal{O}_{Mi}$. A mixture between transverse and longitudinal polarization.

$$\mathcal{O}_{\mathtt{M0}} = \mathtt{Tr}\left[W_{\mu\nu} W^{\mu\nu} \right] \times \left[(D_\beta \Phi)^\dagger D_\beta \Phi \right] \tag{3}$$

Example: WW→WW Scattering



$$\mathcal{O}_{S0},\ \mathcal{O}_{S1}$$
$$\mathcal{O}_{T0},\ \mathcal{O}_{T1},\ \mathcal{O}_{T2}$$
$$\mathcal{O}_{M0},\ \mathcal{O}_{M1},\ \mathcal{O}_{M6},\ \mathcal{O}_{M7}$$

$$\mathcal{L} = \mathcal{L}_{\mathtt{SM}} + \frac{c_{\mathtt{S0}}}{\Lambda^4}\mathcal{O}_{\mathtt{S0}}$$

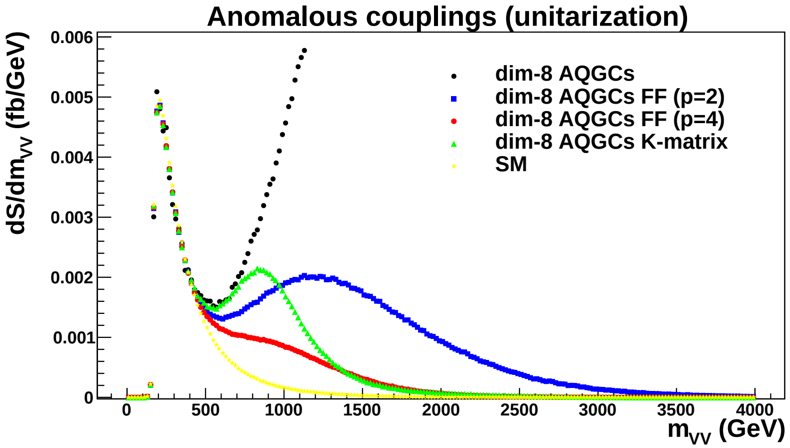
The matrix element can be written as,

$$\mathcal{M} = J^{\mu}_{13}(q_1)J^{\mu}_{24}(q_2)\left(m_{\mu\nu,\mathtt{SM}} + m_{\mu\nu,\mathtt{dim-8}}\right) \tag{4}$$

For this process, the amplitude given by equation (1) is

$$m_{S0} \propto \epsilon(q_1,\lambda_1)\cdot\epsilon(q_2,\lambda_2)\epsilon^*(q_3,\lambda_3)\cdot\epsilon^*(q_4,\lambda_4) \tag{5}$$

When these anomalous couplings are considered, the cross section falls off asymptotically with a slower rate than expected.



The S-Matrix for Vector Boson Scattering

Recall: 2→2 scattering.

The transition amplitude for an initial state $|n\rangle$ to a final state $|m\rangle$ is given by $\langle m|S|n\rangle$, where S is a linear operator, called the S-matrix, and it is unitary.

Properties of the S-matrix

- The S-matrix can be decomposed usefully into two parts, where T describes a non-trivial scattering:

$$S = 1 + i\ T \tag{6}$$

- As S have to be unitary:

$$SS^{\dagger} = 1 \tag{7}$$

therefore,

$$T^{\dagger}T = -i\left(T - T^{\dagger}\right) \tag{8}$$

For two particle scattering: $p_1 \; p_2 \rightarrow p_3 \; p_4$

The T-matrix is related to the scattering amplitude $\mathcal{M}(p_1 p_2 \rightarrow p_3 p_4)$

$$\langle p_3, p_4 | T | p_1, p_2 \rangle = (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4)\mathcal{M} \; . \tag{9}$$

The differential cross section can be written as,

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s} |\mathcal{M}|^2. \tag{10}$$

The equation (7) sets bounds on T, and therefore on the cross sections.

The Unitary problem: Partial Wave Decomposition

Using the partial wave decomposition (simplified version), it is possible to write the scattering amplitude $\mathcal{M}(s, \theta)$ as

$$\mathcal{M}(s, \theta) = 16\pi \sum_j (2j + 1) P_j(cos\ \theta) \mathcal{A}_j \tag{11}$$

where, $\mathcal{A}_j$ is the partial wave and $P_j(cos\ \theta)$ Legendre polynomials.

Using the orthogonal properties of the Legendre polynomials, and the optical theorem, a unitarity bound is set.

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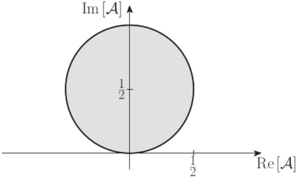

The Argand Circle, with radio $\frac{1}{2}$ and center $\frac{i}{2}$.

$$\mid A_j - \frac{i}{2} \mid \leq \frac{1}{2} \tag{12}$$

$$\Rightarrow \mathtt{Re}(A_j) < \frac{1}{2} \tag{13}$$

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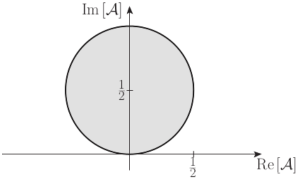

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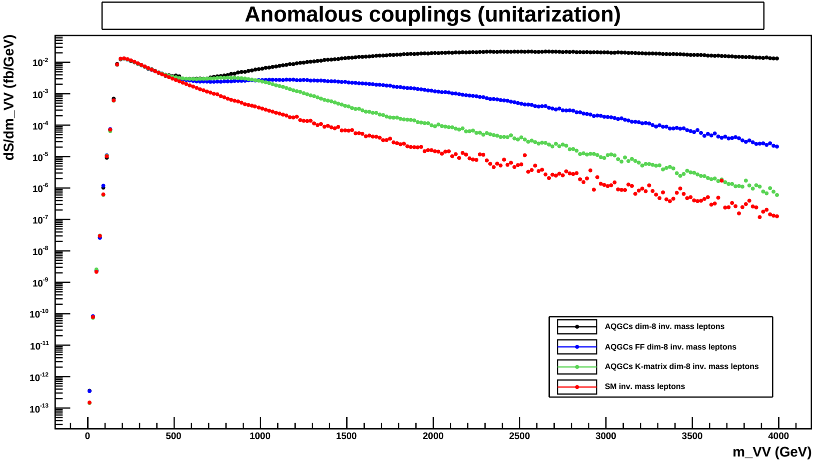
Scattering amplitudes are not allowed to grow proportional with energy, because the σ becomes unphysical (it violates unitarity).



To obtain a valid prediction, which does not violate any fundamental law, a unitarization scheme is needed to reconstruct the amplitudes for the anomalous couplings.

Restoring Unitarity

Unitarity considerations have been used to spot the energy region where underlaying new physics could arise: an *incomplete description of the physics* symptom.

Some unitarization schemes:

Form Factor unitarization

A function $\mathcal{F}(s)$ can be applied to ensure unitarity at high energies: it is multiplied to the couplings, to suppress the tail of the amplitudes arising from the operators.

K-matrix formalism

The real scattering amplitudes are projected onto the Argand circle to restore unitarity, using a Cayley transform of the S-matrix: the K-matrix.

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Unitarity bounds are derived from the partial wave analysis of the on-shell $2 \to 2$ scattering amplitudes, but the LHC processes are off-shell:

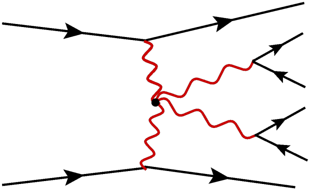
How do we restore unitarity for off-shell processes?

Implementing the Unitarization

VBFNLO - A parton level Monte Carlo for processes with electroweak bosons

J. Baglio et al. [arXiv:1107.4038]

≪A fully flexible parton level Monte Carlo program for the simulation of vector boson fusion, double and triple ector boson production in hadronic collisions at next to leading order in the strong coupling constant. It includes Higgs and vector boson decays with full spin correlations and all off-shell effects.≫



$$\mathcal{M} = J^{\mu}_{13}(q_1) J^{\mu}_{24}(q_2) \left(m_{\mu\nu,\mathtt{SM}} + m_{\mu\nu,\mathtt{dim-8}} \right)$$

The on-shell/off-shell approach

$$m_{\mu\nu,\mathtt{dim-8}} = D^{V_1}_{\mu\alpha}(q_1)\ D^{V_2}_{\nu\beta}(q_2)\ m^{\alpha\beta\gamma\delta}_{AGCs}\left(V_1 V_2 \to V_3 V_4\right) D^{V_3}_{\gamma\xi}(q3) D^{V_4}_{\delta\rho}(q4) j^{\xi}_{56} j^{\rho}_{78} \quad (15)$$

Using the properties of the polarization vectors,

$$\sum\nolimits_{\mathtt{polarizations}} \epsilon^{*\mu}(p_k)\epsilon^{\nu}(p_j) = -g^{\mu\nu} + N(p_k, p_j) p^{\mu}_k p^{\nu}_j$$

So, $D^{V_k}_{\mu\alpha}(q_k) \ = \ d_k \sum_{\lambda} \varepsilon^*_{\lambda,\mu}(q_k)\varepsilon_{\lambda,\alpha}(q_k)$ (with $d_k = \frac{i}{q_k^2 - m^2_{V_k}}$).

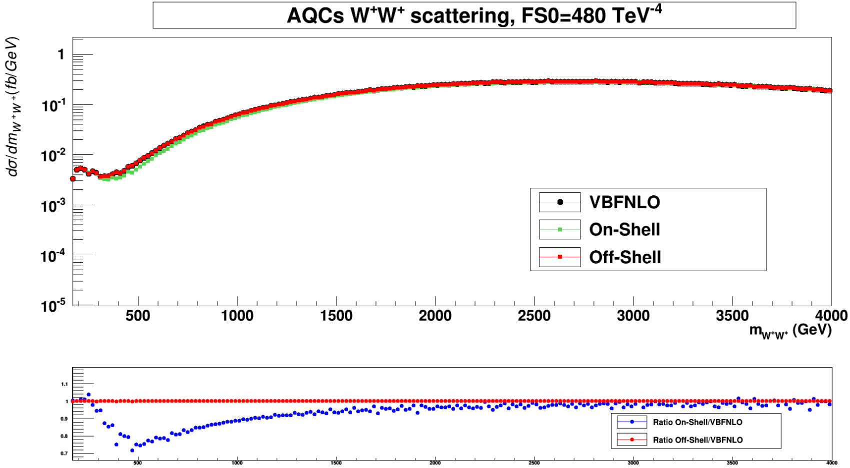
$$\therefore\ m_{\mu\nu} = d_1 d_2 \sum_{\lambda_1,\lambda_2} \varepsilon^*_{\lambda_1,\mu}(q_1)\ \varepsilon^*_{\lambda_2,\nu}(q_2) m_{on/off}\left(\lambda_1, \lambda_2\right) \quad (16)$$

$$m_{on/off}\left(\lambda_1, \lambda_2\right) = \sum_{\lambda_3,\lambda_4} A_{QC}\left(\lambda_1, \lambda_2, \lambda_3, \lambda_4\right) Z_3(\lambda_3) Z_4(\lambda_4) \quad (17)$$

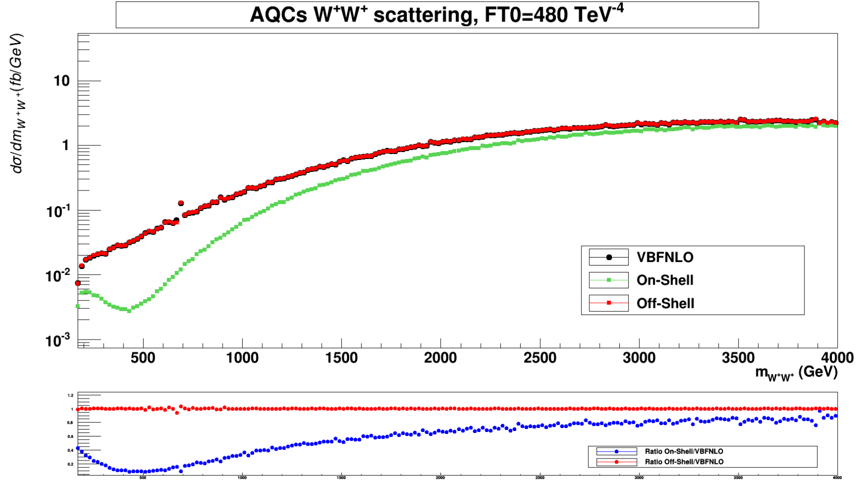
where, $Z_k(\lambda_k) = d_k \varepsilon_{\lambda_k,i}(q_k) j^i$

and

$$A_{QC}\left(\lambda_1, \lambda_2, \lambda_3, \lambda_4\right) \propto \mathtt{f}_{\mathtt{S0}} \varepsilon(q_1, \lambda_1)\cdot \varepsilon(q_2, \lambda_2) \varepsilon^*(q_3, \lambda_3)\cdot \varepsilon^*(q_4, \lambda_4)$$



$$A(\lambda_1,\lambda_2,\lambda_3,\lambda_4) \propto \mathtt{f}_{S0}\left[\varepsilon(q_1,\lambda_1)\cdot\varepsilon(q_2,\lambda_2)\ \varepsilon^*(q_3,\lambda_3)\cdot\varepsilon^*(q_4,\lambda_4)\right]$$



$$
\begin{aligned}
A\,(\lambda_1,\lambda_2,\lambda_3,\lambda_4) \propto \mathtt{f}_{\mathtt{T0}}\ \{\ (&\big[(q_3\cdot\varepsilon(q_2,\lambda_2))\,(q_2\cdot\varepsilon^*(q_3,\lambda_3)) - (\varepsilon^*(q_3,\lambda_3)\cdot\varepsilon(q_2,\lambda_2))\,(q_3\cdot q_2)\big] \\
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\end{aligned}
$$

The analytic K-Matrix

Using the partial wave decomposition, taking into account the helicities of the states

$$A_{QC}\left(\lambda_1, \lambda_2, \lambda_3, \lambda_4\right) = 16\pi \sum_{j=0}^{2} (2j+1) a^j(\lambda_1, \lambda_2, \lambda_3, \lambda_4) d^j_{\alpha\beta}(\theta) \tag{18}$$

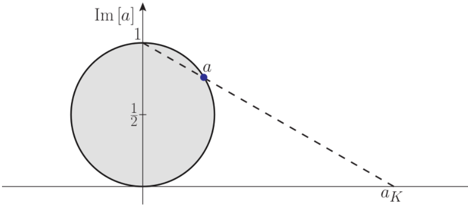
where, $d^j_{\alpha\beta}(\theta)$ are the Wigner d-matrix, and $a^j(\lambda_1, \lambda_2, \lambda_3, \lambda_4)$ the amplitudes to be unitarized.

So, using the bounds given by the Argand Circle, we look for the unitarize amplitudes, using the eigenvalue of the Cayley-transform K-matrix:

$$a_k = \frac{a}{1 + \mathtt{i}a} \tag{19}$$

The unitarize amplitudes are then determined by,

$$a = \frac{a_k}{1 - \mathtt{i}a_k} \tag{20}$$



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- The dim-8 operators within the sensitivity level at the LHC violates unitarity of the S-matrix.
- Unitarity bounds can be calculated using the partial wave decomposition for the amplitudes of the vector boson scattering.
- We use the analytic K-matrix formalism, to project the amplitudes onto the unitarity circle (Argand circle) and restore unitarity. However, this introduce a model dependence.

Thank you

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