Validity of EFT for VBS

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Presented at:

VBSCAN meeting after MBI 2017, KIT, Karlsruhe (Germany)

arXiv:1707.04580 [hep-ph], EPJC **77** (2017) no.7, EPJC **77** no.4 (2017) 205
PRL **114** (2015) 221803; PRD **91** (2015) 075017; JHEP **1407** (2014) 149;
JHEP **1402** (2014) 121; and J. Phys. G: Nucl. Part. Phys. **41** (2014)
025002

Theoretical Study of the TeV scale

- From Top to Bottom: construct a full theory (renormalizable and UV complete), and describe the TeV scale in terms of the parameters of the BSM Lagrangian. For instance: MSSM has ~ 100 free parameters.
  - Advantage: a full model. Renormalizability.
  - Problems: no hints about the UV completion chosen by nature.
  - Examples: MSSM (~ 100 free parameters), non-MSSM SUSY, Technicolor, KK,...
- From Bottom to Top: construct an Effective Field Theory (EFT), based on the symmetries and available degrees of freedom at low energy.
  - Advantage: we do not rely on a specific UV completion.
  - Disadvantage: valid only at certain energy scale. Non-renormalizable in the classical QFT sense, but in the ChPT one.
  - The usual EFT approach breaks when the low energy EFT reaches the unitarity bound, becoming non-perturbative.
  - For phenomenology, EFTs with the BSM physics (resonances) as explicit degrees of freedom are used.

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Non-linear Electroweak Chiral Lagrangian

Non-linear EFT[1] for VV scattering at NLO level, minimally coupled to hh,

$$\mathcal{L} = \frac{v^2}{4} g(h/f)\,\mathrm{Tr}[(D_\mu U)^\dagger D^\mu U] + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h),$$

where

$$g(h/v) = 1 + 2a\frac{h}{v} + b\left(\frac{h}{v}\right)^2 + \ldots$$

$$V(h) = V_0 + \frac{M_h^2}{2}h^2 + \sum_{n=3}^{\infty} \lambda_n h^n$$

$$D_\mu U = \partial_\mu U + i\hat{W}_\mu U - iU\hat{B}_\mu .$$

M_h and λ_n are subleading in chiral counting.

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We need the parameterization of the $U(\omega^a) \in SU(2)_L \times SU(2)_R / SU(2)_C$ coset. In either case, whatever the non–linear term is,

$$U(x) = \mathbb{1} + i\frac{\tau^a \omega^a(x)}{v} + \mathcal{O}\left(\omega^2\right).$$

Two choices have been used:

Spherical parameterization

$$U(x) = \mathbb{1}\sqrt{1 - \frac{\omega^2(x)}{v^2}} + i\frac{\tau^a \omega^a(x)}{v}$$

Exponential parameterization (here, a cross-check for EWSBS+$\gamma\gamma$)

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Since we are considering scattering processes within the EWSBS, the covariant derivate reduces to

$$D_\mu U = \partial_\mu U.$$

Define

$$V_\mu \equiv (D_\mu U)U^\dagger.$$

The next counterterms are needed for the NLO computation of the VV scattering, minimally coupled to hh

$$\begin{aligned}\mathcal{L}_4 = a_4[\mathrm{Tr}(V_\mu V_\nu)][\mathrm{Tr}(V^\mu V^\nu)] + a_5[\mathrm{Tr}(V_\mu V^\mu)][\mathrm{Tr}(V_\nu V^\nu)] \\ + \frac{d}{v^2}(\partial_\mu h \partial^\mu h)\,\mathrm{Tr}[(D_\nu U)^\dagger D^\nu U] + \frac{e}{v^2}(\partial_\mu h \partial^\nu h)\,\mathrm{Tr}[(D^\mu U)^\dagger D_\nu U] \\ + \frac{g}{v^4}(\partial_\mu h \partial^\mu h)(\partial_\nu h \partial^\nu h).\end{aligned}$$

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Validity of EFTs

- We are interested in the collider phenomenology of Vector Bosons Scattering since it is very sensitive to new physics in the EW sector in the LHC.
- The NLO-computed EFT groves with the CM energy like $A \sim s^2$. Hence, it will eventually reach the unitarity bound, becoming non-perturbative. 2 options available:
  - The common one: limit the validity range of the EFT to the perturbative region. I.e., until the unitarity bound is reached (see the talk of Matthias, *Unitarity limits for EFT parameters*). Consider the EFT as a useful parameterization of slight deviations from the SM in the range under the TeV scale.
  - Take advantage of the analytical properties of the S-Matrix (encoded inside dispersion relations and unitarization procedures) to study the non-perturbative region (TeV scale) of the theory. A decomposition in partial waves required. Going back from partial waves to scattering amplitude can be tricky, because of contributions from higher order spherical harmonics.

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Unitarity for partial waves

- Unit. cond. for $S - matrix$: $SS^\dagger = \mathbb{1}$,
- plus analytical properties of matrix elements,
- plus time reversal invariance,

Unitarity condition for partial waves

$$\mathrm{Im}\, A_{IJ,p_i\to k_1}(s) = \sum_{\{a,b\}} \sqrt{1-\frac{4m_q^2}{s}}[A_{IJ,p_i\to q_{i,ab}}(s)][A_{IJ,q_{i,ab}\to k_i}(s)]^*$$

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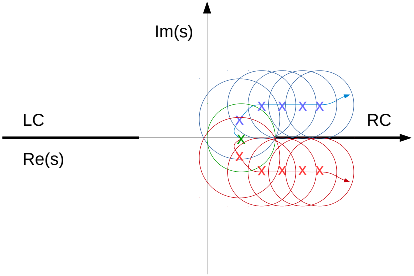

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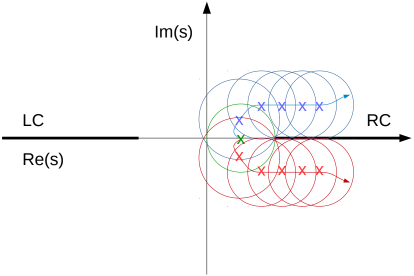

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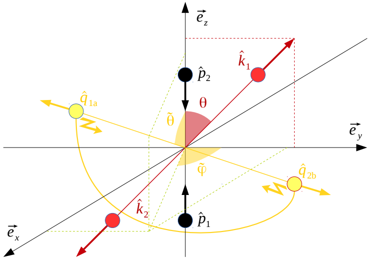

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EWSBS partial waves

The form of the partial wave is

$$A_{IJ}(s) = A_{IJ}^{(0)} + A_{IJ}^{(1)} + \mathcal{O}\left[(s/v^2)^3\right].$$

Which will be decomposed as

$$A_{IJ}^{(0)} = Ks$$

$$A_{IJ}^{(1)} = \left(B(\mu) + D\log\frac{s}{\mu^2} + E\log\frac{-s}{\mu^2}\right)s^2.$$

As $A_{IJ}(s)$ must be scale independent,

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$$A_{IJ}^{(1)} = \left(B(\mu) + D\log\frac{s}{\mu^2} + E\log\frac{-s}{\mu^2}\right) s^2.$$

As $A_{IJ}(s)$ must be scale independent,

$$B(\mu) = B(\mu_0) + (D+E)\log\frac{\mu^2}{\mu_0^2}$$
$$= B_0 + p_4 a_4(\mu) + p_5 a_5(\mu).$$

Unitarization procedures for elastic processes

$$A^{IAM}(s) = \frac{[A^{(0)}(s)]^2}{A^{(0)}(s) - A^{(1)}(s)},$$

$$A^{N/D}(s) = \frac{A^{(0)}(s) + A_L(s)}{1 - \frac{A_R(s)}{A^{(0)}(s)} + \frac{1}{2}g(s)A_L(-s)},$$

$$A^{IK}(s) = \frac{A^{(0)}(s) + A_L(s)}{1 - \frac{A_R(s)}{A^{(0)}(s)} + g(s)A_L(s)},$$

$$A_0^K(s) = \frac{A_0(s)}{1 - iA_0(s)},$$

where

$$g(s) = \frac{1}{\pi}\left(\frac{B(\mu)}{D+E} + \log\frac{-s}{\mu^2}\right)$$

$$A_L(s) = \pi g(-s) D s^2$$

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Usability channel of unitarization procedures

IJ	00	02	11	20	22
Method of choice	Any	N/D IK	IAM	Any	N/D IK

- The IAM method cannot be used when $A^{(0)} = 0$, because it would give a vanishing value.
- The N/D and the IK methods cannot be used if $D + E = 0$, because in this case computing $A_L(s)$ and $A_R(s)$ is not possible.
- The naive K-matrix method,

$$A_0^K(s) = \frac{A_0(s)}{1 - iA_0(s)},$$

fails because it is not analytical in the first Riemann sheet and, consequently, it is not a proper partial wave compatible with microcausality.

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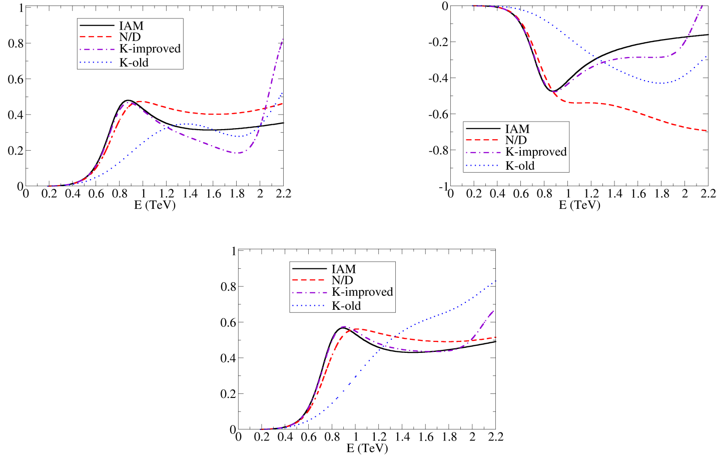
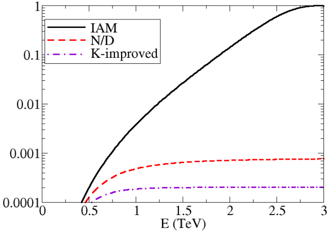
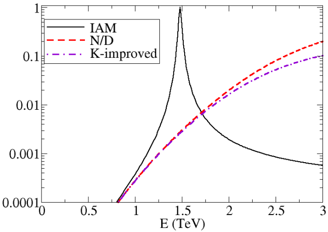
Scalar-isoscalar channels



From left to right and top to bottom, elastic $\omega\omega$, elastic hh, and cross channel $\omega\omega \to hh$, for $a = 0.88$, $b = 3$, $\mu = 3\,\mathrm{TeV}$ and all NLO parameters set to 0.
PRL **114** (2015) 221803, PRD **91** (2015) 075017.

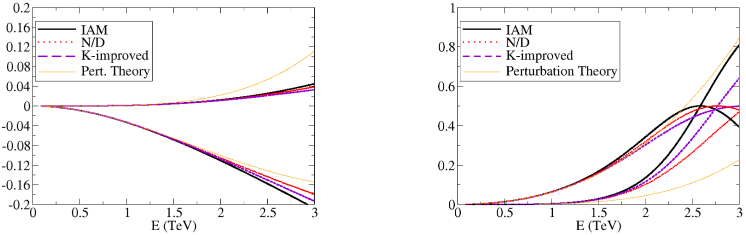




From our ref[2]. We have taken $a = 0.88$ and $b = 1.5$, but while for the left plot all the NLO parameters vanish, for the right plot we have taken $a_4 = 0.003$, known to yield an IAM resonance according to the Barcelona group[3].

[2] PRD **91** (2015) 075017
[3] PRD **90** (2014) 015035

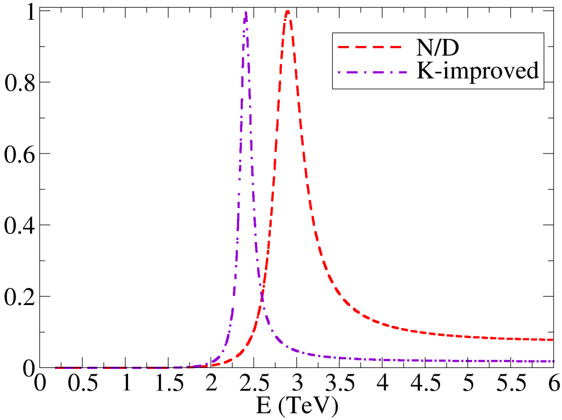
Scalar-isotensor channels ($IJ = 20$)



From our ref[4]. From left to right, $a = 0.88$, $a = 1.15$. We have taken $b = a^2$ and the NLO parameters set to zero. Both real and imaginary part shown. Real ones correspond to bottom lines at left and upper at low E at right.

[4] PRD **91** (2015) 075017

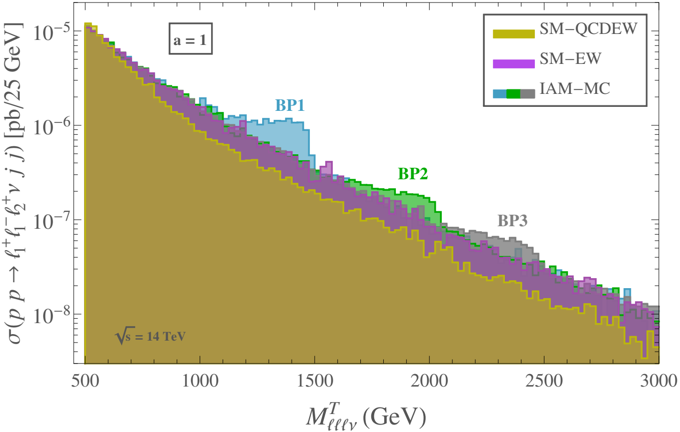
Isotensor-scalar channels ($IJ = 02$)



$a = 0.88$, $b = a^2$, $a_4 = -2a_5 = 3/(192\pi)$, all the other NLO param. set to zero.
PRD **91** (2015) 075017.

New MadGraph model, Isovector Resonance: leptonic final state

arXiv:1707.04580 [hep-ph]



$a = 1$; $a_4 \cdot 10^4 = 3.5$ (BP1), 1 (BP2), 0.5 (BP3);

Conclusions

- Studied $2 \to 2$ VBF processes within the EWSBS, including coupled channels (hh).
- An extensive analysis of the validity of unitarization methods.
- We provide a MadGraph v5 model for the unitarized ChPT, without relying on the naive K-matrix.
- Prospects for the Benchmark Points at the LHC (14 TeV, $WZ \to WZ$ process, arXiv:1707.04580 [hep-ph]):

	$\mathcal{L} = 300\,\mathrm{fb}^{-1}$			$\mathcal{L} = 1000\,\mathrm{fb}^{-1}$			$\mathcal{L} = 3000\,\mathrm{fb}^{-1}$		
	N_l^{IAM}	N_l^{SM}	σ_l^{stat}	N_l^{IAM}	N_l^{SM}	σ_l^{stat}	N_l^{IAM}	N_l^{SM}	σ_l^{stat}
BP1	2	1	0.6	6	4	1.1	19	13	1.8
BP2	0.6	0.4	-	1	1	0	4	3	0.1
BP3	0.1	0.1	-	0.4	0.3	-	1	1	0
BP1'	6	2	2.3	19	8	4.2	57	23	7.2
BP2'	2	0.9	1	6	3	1.8	19	9	3.7
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