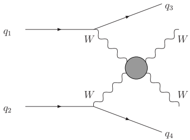
A MadGraph model for VBS based on a unitarized non-linear EChL analysis

Presented by Rafael L. Delgado

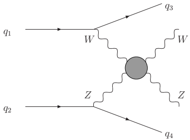
$pp \to W^+W^- j_1 j_2$

by $W^+W^- \to W^+W^-$ scattering



$pp \to WZ j_1 j_2$

by $WZ \to WZ$ scattering



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Linear vs. non–linear: linear representation

- The ω^a and h fit in a left $SU(2)$ doublet.
- The Higgs always appears in the combination $h+v$.
- Typical situation when h is a fundamental field.
- Based in a **cutoff Λ expansion**: $\mathcal{O}(d)/\Lambda^{d-4}$, d and operator of dimension $d = 4, 6, 8, \ldots$.
- The usual approach, based on considering a full basis, allows to make a well-defined biyection between basis and is less model depending, at the price of reaching a high number of operators ($> 10^3$ for dim-8).

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- h is a $SU(2)$ singlet and ω^a are coordinates on a coset:

$$SU(2)_L \times SU(2)_R/SU(2)_V = SU(2) = S^3$$

- ECLh with $F(h)$ insertions.
- **Derivative expansion.**
- Some higher order operators, like a_4 and a_5, that were dim-8 in the linear represenation, can contribute to a lower order in the non–linear one.
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- VBS amplitude rises with energy, eventually leading to violation of unitarity at some new physics state.
- This leads to an *OVERESTIMATED* number of events in VBS due to an unphysical prediction of EFT. That is, amplitudes *cannot* grow uncontrolled.
- Exception, MSM: Higgs exchange exactly cancels this energy rise in VBS, restoring unitarity event at LO.
- Two options:
  - Set up a low-energy cut-off on the theory, due to the validity limits of the EFT itself. This limit, indeed, comes from the UV completion, whose specification would require to pick up a full (renormali. and unitar.) model from the *theory zoo*.
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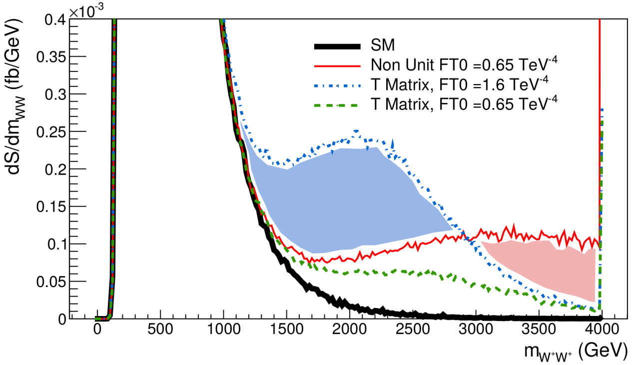

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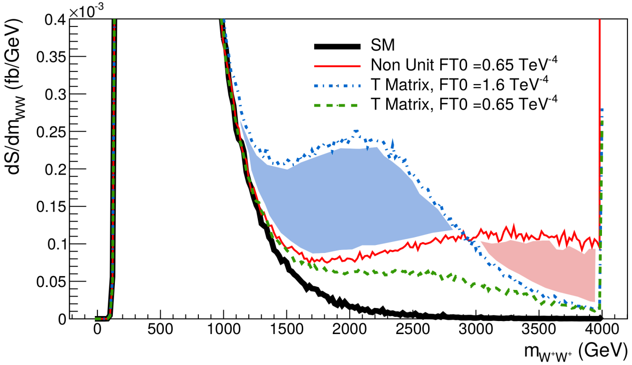

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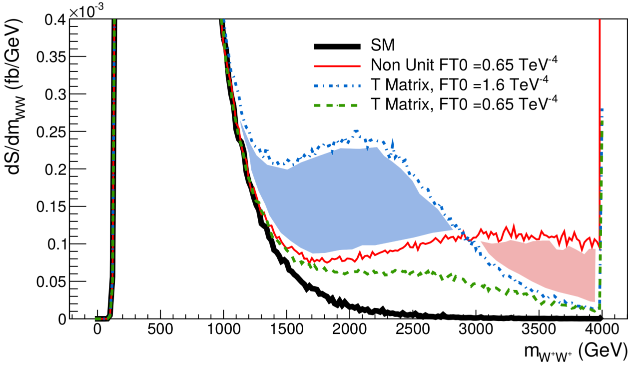

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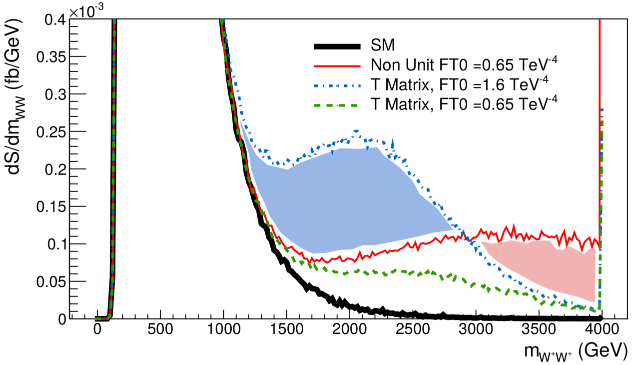

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- *Zoo* of unitarization procedures: IAM, K-matrix, T-matrix, N/D, large-N,...
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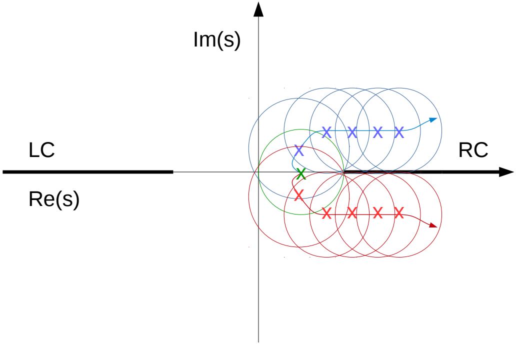

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   e-Print: **arXiv:1803.02846 [hep-ph] | PDF**
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   Marco Bonvini (INFN, Rome), Simone Marzani (Genoa U. & INFN, Genoa). Feb 21, 2018. 7 pp.
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   Peng Sun (Nanjing Normal U. & Michigan State U.), C.P. Yuan (Michigan State U.), Feng Yuan (LBNL, NSD). Feb 8, 2018. 8 pp.
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   Marco Bonetti, Kirill Melnikov (KIT, Karlsruhe), Lorenzo Tancredi (CERN). Jan 31, 2018. 4 pp.
   CERN-TH-2018-011, TTP18-004
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6. **NNLL resummation for the associated production of a top pair with a heavy boson at the LHC**
   Alessandro Broggio (Munich, Tech. U.). Jan 21, 2018. 9 pp.

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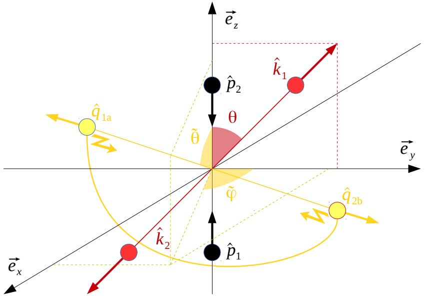

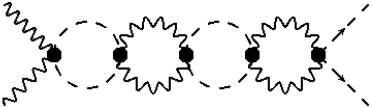

Typical Feynman diagram mixing the $\omega\omega$ and the *hh* channels. [PRL**114**, 221803]

Other Monte-Carlo generators with unitarity

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Our approach: EFTs + Unitarization Procedures

- We are interested in the collider phenomenology of Vector Bosons Scattering ($WZ \to WZ$), since it is very sensitive to new physics in the EW sector in the LHC.
- Bottom to Top approach: we construct an EFT for the EW sector. $SU(2)_L \times SU(2)_R$, EChL copy of ChPT in QCD.
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- 4 considered parameters: a, $b = a^2$, a_4, a_5.
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Effective Lagrangian: considered parameters

$$\mathcal{L}_2 = \frac{v^2}{4}\left[1 + 2a\frac{h}{v} + b\left(\frac{h}{v}\right)^2 + \dots\right] \mathrm{Tr}(D_\mu U^\dagger D_\mu U) + \frac{1}{2}\partial_\mu h \partial^\mu h + \dots$$

$$\mathcal{L}_4 = a_4 [\mathrm{Tr}(V_\mu V_\nu)][\mathrm{Tr}(V^\mu V^\nu)] + a_5 [\mathrm{Tr}(V_\mu V^\mu)][\mathrm{Tr}(V_\nu V^\nu)] + \dots$$

$$V_\mu = (D_\mu U) U^\dagger, \qquad U = \exp\left(\frac{i\omega^a \tau^a}{v}\right)$$

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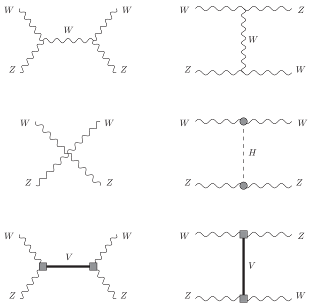
- Degrees of freedom: Gauge Bosons $W^{\pm}$, Z + Higgs-like particle (h).
- 4 considered parameters: a, $b = a^2$, a_4, a_5.
- The NLO-computed EFT grows with the CM energy like $A \sim s^2$. Hence, it will eventually reach the unitarity bound, becoming non-perturbative. Options:
  - Limit the validity range of the EFT to the perturbative region. Consider it 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.

Isovector Resonance [JHEP**1711**, 098]

BP	$M_V(\mathrm{GeV})$	$\Gamma_V(\mathrm{GeV})$	$g_V(M_V^2)$	a	$a_4 \cdot 10^4$	$a_5 \cdot 10^4$
BP1	1476	14	0.033	1	3.5	-3
BP2	2039	21	0.018	1	1	-1
BP3	2472	27	0.013	1	0.5	-0.5
BP1'	1479	42	0.058	0.9	9.5	-6.5
BP2'	1980	97	0.042	0.9	5.5	-2.5
BP3'	2480	183	0.033	0.9	4	-1

These BPs have been selected for vector resonances emerging at mass and width values that are of phenomenological interest for the LHC.
Considered backgrounds: The pure SM-EW background, of order $\mathcal{O}(\alpha_{\mathrm{em}}^2)$.
The mixed SM-QCDEW background, of order $\mathcal{O}(\alpha_{\mathrm{em}}\alpha_s)$.

Channels: $W^+Z \to W^+Z$

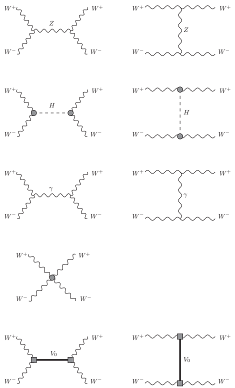


- Our Proca Lagrangian needs $g_v = g_v(z, s)$

$$g_V^2(z) = g_V^2(M_V^2)\frac{M_V^2}{z} \text{ for } s < M_V^2$$
$$g_V^2(z) = g_V^2(M_V^2)\frac{M_V^4}{z^2} \text{ for } s > M_V^2,$$

  $z = s,\ t,\ u$ depending on the channel where V propagates. Fully crossing symmetry leads to a moderate violation of the Froissart bound.
- We are using MadGraph v5 capability of integrating Fortran code inside UFO.
- We encode the Proca processes (those involving the resonace V) as effective vertices inside the UFO.
- The parameters of the Proca Lagrangian are adjusted to the IAM results [dynamic M_V, Γ_V, $g_V(M_V^2)$] via a custom piece of software.
- Currently, $W^+Z \to W^+Z$ tested.
- Leptonic channel studied: $pp \to w^+w^-jj$, $w^\pm \to l^\pm\nu$

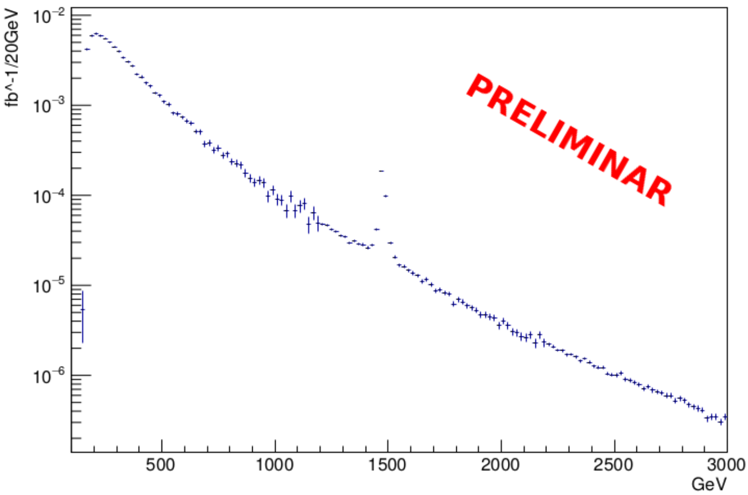
Channels: $W^+W^- \to W^+W^-$



- We are extending our UFO for including $W^+W^- \to W^+W^-$.
- We expect to be able to deal with $WZ \to WZ$, $WW \to ZZ$, $ZZ \to WW$, $W^+W^- \to W^+W^-$, $W^\pm W^\pm \to W^\pm W^\pm$.
- On the longer term, we consider completing the EW model for including $ZZ \to ZZ$.
- The UFO model, actually, works.
- We have been granted 150kh of computer time of C2PAP for testing the new UFO.

Excellence Cluster Universe

M(WZ), MODELS/ww_IAM-a1 BP1



Conclusions

- We are developing a UFO model for MadGraph v5.
- We describe the Vector Boson Scattering processes by means of the Electroweak Chiral Lagrangian and the Inverse Amplitude Method.
- We expect to describe the following processes:

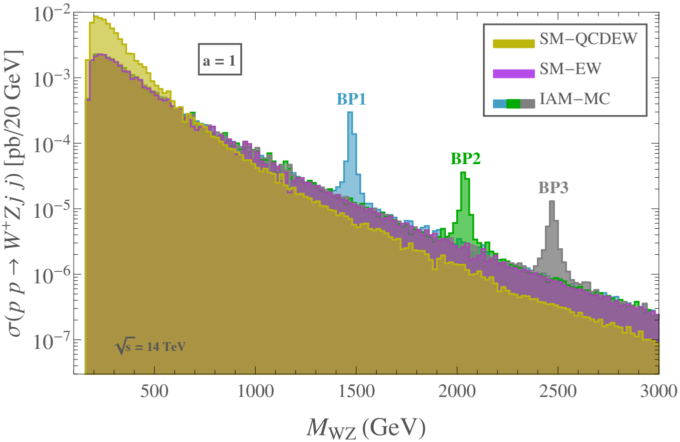
OLD UFO			ON PROGRESS		
$W^\pm Z$	$\rightarrow$	$W^\pm Z$	$W^\pm W^\mp$	$\rightarrow$	$W^\pm W^\mp$
$W^\pm W^\mp$	$\rightarrow$	ZZ	$W^\pm W^\pm$	$\rightarrow$	$W^\pm W^\pm$
ZZ	$\rightarrow$	$W^\pm W^\mp$			

- Making a decision about our goal for $pp \rightarrow w^+ w^- jj \rightarrow w^+ w^- jj$ channel. Suggestions...?
- Several improvements for enhanced usability, so that all parameters of the Proca can be set by stadard MadGraph v5 config files.
- LET'S WAIT FOR IT!!

BACKUP SLIDES

Isovector Resonance: *WZ* in final state

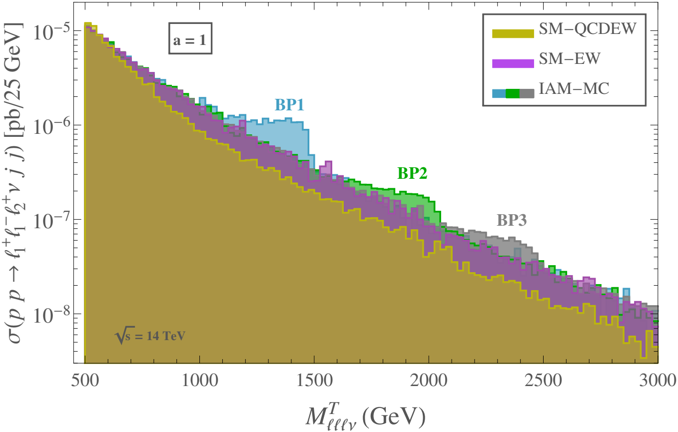
JHEP1711, 098



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

$-a_5 \cdot 10^4 = 3$ (BP1), 1 (BP2), 0.5 (BP3).

Isovector Resonance: leptonic final state
JHEP1711, 098



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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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PRD **91** (2015) 075017

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$$F^{IK}(s) = [1 + G(s) \cdot N_0(s)]^{-1} \cdot N_0(s),$$

where $G(s)$, $F_L(s)$, $F_R(s)$ and $N_0(s)$ are defined as

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

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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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