# EFT Lagrangian Morphing

## Modelling physics distributions in the framework of an Effective Field Theory (EFT)

2<sup>nd</sup> Pan-European Advanced School on Statistics in High Energy Physics

30th March 2021

Rahul Balasubramanian, Carsten Burgard, Wouter Verkerke









## Outline

### **Effective field theory**

- Motivation for EFT approach at the Large Hadron Collider
- ✦ Effective Lagrangian
- Observable dependence on EFT parameters

## **Effective Lagrangian Morphing**

- Morphing physics distributions within EFT
- Interface between data and theory

### Implementation within ROOT

- Modelling EFT observables with RooLagrangianMorphFunc
- Examples based on 2 and 3 EFT parameters





## **Effective field theory**

- ◆ Introduction to Effective Field Theories, Manohar, Les Houches Lect. Notes 108(2020)
- + The Standard Model as an effective field theory, Brivio, Trott, Physics Reports, Volume 793, 2019

## **Effective Lagrangian Morphing**

- collaboration, <u>ATL-PHYS-PUB-2015-047</u>
- Effective Lagrangian Morphing, Balasubramanian, Burgard, Verkerke, <u>arXiv:2202.13612</u>

## Morphing within ROOT

← <u>RooFit tutorials</u>

• A morphing technique for signal modelling in a multidimensional space of coupling parameters, The ATLAS



## Outline

### **Effective field theory**

- Motivation for EFT approach at the Large Hadron Collider
- ✦ Effective Lagrangian
- Observable dependence on EFT parameters

### **Effective Lagrangian Morphing**

- Morphing physics distributions within EFT
- Interface between data and theory

### Implementation within ROOT

- Modelling EFT observables with RooLagrangianMorphFunc
- Examples based on 2 and 3 EFT parameters





## Effective field theory

- Effective theories appear everywhere in physics !
- + Based on the principle of separation of scale, physics at a given energy scales decouples from physics at another scale except for a few parameters <u>Ex</u>: Fermi theory sufficient to describe  $\beta$  decays, no description of electroweak Interactions required !



2<sup>nd</sup> Pan-European Advanced School on Statistics in High Energy Physics



## Two types of EFT

### <u>Top-down</u>

 Theory at higher-energy scale known, known can simplify the picture to describe phenomena at lower energy scales.

low <u>ex.</u> energy EFT top quark ( $M_t = 173$  GeV) is much of known theory heavier for QCD processes where the interactions are at the O(few) GeV scale

### Bottom-up

 Valid theory valid theory known unknown at a current energy scale, however no description of physics at higher scales. Current theory can be viewed as a low-energy effective approximation low energy of a more fundamental theory EFT <u>ex.</u> Fermi theory is the low energy approximation of the Standard Model known



- The Standard Model (SM) is a remarkably successful theory
- It is being studied extensively at the LHC and other experiments around the world
- No direct evidence for new members of the family
- However lacks explanation for many phenomena ! dark matter, matter-antimatter asymmetry, etc..





# Standard Model - highly predictive !

- The Standard Model predictions agree well with measurements at the LHC
- The energy scale probed by these measurements typically around vev (246 GeV)
- Important to measure differential distributions to separate out regions with higher energy reach !



cross-sections

## Direct searches for new particles

- Direct searches probe • resonant production or non-resonant effects direct production of new particles
- Usually based on a particular models with unique signature(s)
- Mass reach saturated at I-I0TeV

Status: May 2020 Mode ADD GKK ADD non-ADD QBH ADD BH I ADD BH RS1 G<sub>KK</sub> Bulk RS ( Bulk RS ( Bulk RS g 2UED / R SSM Z' -SSM Z' Leptophol Leptophol SSM W' SSM W HVT W' HVT V' -HVT V' -HVT W' LRSM W LRSM W CI qqqq CIℓℓqq CI tttt Axial-vect Colored s  $VV_{\chi\chi}$  EF Scalar res Scalar LQ Scalar LQ Scalar LQ Scalar LQ VLQ TT VLQ BB VLQ  $T_{5/3}$ VLQ  $Y \rightarrow$ VLQ  $B \rightarrow$ VLQ QQ Excited qu Excited qu Excited qu Excited le Excited le Type III Se LRSM Ma Higgs trip Higgs trip Multi-char Magnetic

article

with

odels

### **ATLAS Exotics Searches\* - 95% CL Upper Exclusion Limits**

el	$\ell$ , $\gamma$	Jets†	$\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}$	∫£ dt[fb	<sup>-1</sup> ]	Limit		
$+ g/q$ resonant $\gamma\gamma$ h high $\sum p_T$ nultijet $\rightarrow \gamma\gamma$ $S_{KK} \rightarrow WW/ZZ$ $S_{KK} \rightarrow WV \rightarrow \ell \nu q q$ $Y_{KK} \rightarrow tt$ PP	$\begin{array}{c} 0 \ e, \mu \\ 2 \ \gamma \\ - \\ \geq 1 \ e, \mu \\ - \\ 2 \ \gamma \\ \\ multi-channe \\ 1 \ e, \mu \\ 1 \ e, \mu \\ 1 \ e, \mu \end{array}$	1 - 4j -2j $\ge 2j$ $\ge 3j$ -2j/1J $\ge 1 b, \ge 1J/2$ $\ge 2 b, \ge 3$	Yes – – – – Yes 2j Yes j Yes	36.1 36.7 37.0 3.2 3.6 36.7 36.1 139 36.1 36.1	M <sub>D</sub> M <sub>S</sub> M <sub>th</sub> M <sub>th</sub> M <sub>th</sub> G <sub>KK</sub> mass         G <sub>KK</sub> mass         G <sub>KK</sub> mass         G <sub>KK</sub> mass         KK mass         KK mass	4.1 TeV 2.3 TeV 2.0 TeV 3.8 TeV 1.8 TeV	7.7 TeV 8.6 TeV 8.9 TeV 8.2 TeV 9.55 TeV	$\begin{array}{l} n = 2 \\ n = 3 \; \text{HLZ NLO} \\ n = 6 \\ n = 6, \; M_D = 3 \; \text{TeV, rot BH} \\ n = 6, \; M_D = 3 \; \text{TeV, rot BH} \\ k/\overline{M}_{Pl} = 0.1 \\ k/\overline{M}_{Pl} = 1.0 \\ k/\overline{M}_{Pl} = 1.0 \\ \Gamma/m = 15\% \\ \text{Tier (1,1), } \mathcal{B}(A^{(1,1)} \to tt) = 1 \end{array}$
	$\begin{array}{c} 2 \ e, \mu \\ 2 \ \tau \\ - \\ 0 \ e, \mu \\ 1 \ e, \mu \\ 1 \ \tau \\ B \ 1 \ e, \mu \\ B \ 0 \ e, \mu \\ multi-channe \\ 0 \ e, \mu \\ multi-channe \\ 2 \ \mu \end{array}$	$\begin{array}{c} - \\ - \\ 2 b \\ \geq 1 b, \geq 2 , \\ - \\ 2 j / 1 J \\ 2 J \\ el \\ \geq 1 b, \geq 2 , \\ el \\ 1 J \end{array}$	– – J Yes Yes Yes – J	139 36.1 36.1 139 36.1 139 36.1 139 36.1 139 36.1 80	Z' mass Z' mass Z' mass Z' mass W' mass W' mass W' mass V' mass V' mass V' mass W' mass W' mass WR mass	5.1 2.42 TeV 2.1 TeV 4.1 TeV 6 3.7 TeV 4.3 TeV 3.8 TeV 2.93 TeV 3.2 TeV 3.2 TeV 3.25 TeV 5.0	TeV 1.0 TeV 7	$\Gamma/m = 1.2\%$ $g_V = 3$ $g_V = 3$ $g_V = 3$ $g_V = 3$ $m(N_R) = 0.5 \text{ TeV}, g_L = g_R$
or mediator (Dirac DM calar mediator (Dirac I	$ \begin{array}{c} - \\ 2 \ e, \mu \\ \geq 1 \ e, \mu \\ \end{array} $ $ \begin{array}{c} 0 \ e, \mu \\ 0 \ e, \mu \\ \end{array} $	2j - $\geq 1 b, \geq 1 j$ 1 - 4 j 1 - 4 j	– Yes Yes Yes	37.0 139 36.1 36.1 36.1	Λ       Λ       Λ       Μmed       mmed	2.57 TeV 1.55 TeV 1.67 TeV		$\begin{array}{c} \mathbf{1.8 \ TeV}  \eta_{LL}^{-} \\ \hline \mathbf{21.8 \ TeV}  \eta_{LL}^{-} \\ \hline \mathbf{35.8 \ TeV}  \eta_{LL}^{-} \\  C_{4t}  = 4\pi \\ g_q = 0.25, \ g_{\chi} = 1.0, \ m(\chi) = 1 \ \text{GeV} \\ g = 1.0, \ m(\chi) = 1 \ \text{GeV} \end{array}$
T (Dirac DM) son. $\phi \rightarrow t\chi$ (Dirac DM) $2^{nd}$ gen $3^{rd}$ gen $3^{rd}$ gen	$ \begin{array}{c} 0 \ e, \mu \\ 0 \ -1 \ e, \mu \\ \hline 1,2 \ e \\ 1,2 \ \mu \\ 2 \ \tau \\ 0 \ -1 \ e, \mu \end{array} $	$ \begin{array}{c} 1 \text{ J, } \leq 1 \text{ j} \\ 1 \text{ b, } 0-1 \text{ J} \\ \geq 2 \text{ j} \\ \geq 2 \text{ j} \\ 2 \text{ b} \\ 2 \text{ b} \\ \end{array} $	Yes Yes Yes Yes - Yes	3.2 36.1 36.1 36.1 36.1 36.1 36.1	M <sub>∗</sub> m <sub>φ</sub> LQ mass LQ mass LQ <sup>4</sup> mass LQ <sup>4</sup> mass	700 GeV 3.4 TeV 1.4 TeV 1.56 TeV 1.03 TeV 970 GeV		$m(\chi) < 150 \text{ GeV}$ $y = 0.4, \lambda = 0.2, m(\chi) = 10 \text{ GeV}$ $\beta = 1$ $\beta (LQ_3^u \rightarrow b\tau) = 1$ $\mathcal{B}(LQ_3^d \rightarrow t\tau) = 0$
$ \rightarrow Ht/Zt/Wb + X  \rightarrow Wt/Zb + X  T_{5/3} T_{5/3} \rightarrow Wt + X  + Wb + X  Hb + X  \rightarrow WqWq $	multi-channe multi-channe $2(SS)/\geq 3 e, \mu$ $1 e, \mu$ $0 e, \mu, 2 \gamma$ $1 e, \mu$	el el $\mu \ge 1  ext{ b, } \ge 1  ext{ j}$ $\ge 1  ext{ b, } \ge 1  ext{ j}$ $\ge 1  ext{ b, } \ge 1  ext{ j}$ $\ge 4  ext{ j}$	Yes Yes Yes Yes	36.1 36.1 36.1 36.1 79.8 20.3	T mass B mass T <sub>5/3</sub> mass Y mass B mass Q mass	1.37 TeV 1.34 TeV 1.64 TeV 1.85 TeV 1.21 TeV 690 GeV		SU(2) doublet SU(2) doublet $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) = 1$ $\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$ $\kappa_B = 0.5$
uark $q^* \rightarrow qg$ uark $q^* \rightarrow q\gamma$ uark $b^* \rightarrow bg$ pton $\ell^*$ pton $\nu^*$	- 1 γ - 3 e, μ 3 e, μ, τ	2 j 1 j 1 b, 1 j - -		139 36.7 36.1 20.3 20.3	q* mass q* mass b* mass ℓ* mass ν* mass	5.3 2.6 TeV 3.0 TeV 1.6 TeV	6.7 TeV TeV	only $u^*$ and $d^*$ , $\Lambda = m(q^*)$ only $u^*$ and $d^*$ , $\Lambda = m(q^*)$ $\Lambda = 3.0 \text{ TeV}$ $\Lambda = 1.6 \text{ TeV}$
jorana $v$ et $H^{\pm\pm} \rightarrow \ell \ell$ et $H^{\pm\pm} \rightarrow \ell \tau$ ged particles monopoles	$1 e, \mu$ $2 \mu$ $2,3,4 e, \mu$ (SS $3 e, \mu, \tau$ - - - - - - - -	≥ 2 J 2 j S) - - - - -	Yes - - - - - - - - - - - - - -	79.8 36.1 20.3 36.1 34.4	Nº mass         N <sub>R</sub> mass         H <sup>±±</sup> mass         H <sup>±</sup> mass	3.2 TeV 870 GeV 00 GeV 1.22 TeV 2.37 TeV		$m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ DY production DY production, $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell \tau) = 1$ DY production, $ q  = 5e$ DY production, $ g  = 1g_D$ , spin 1/2
$\gamma s = \delta \text{ iev}$	artial data	full d	ata		10 <sup>-1</sup>	1	1(	) Mass scale [TeV

\*Only a selection of the available mass limits on new states or phenomena is shown

*†Small-radius (large-radius) jets are denoted by the letter j (J).* 

### excluded masses for individual models

Rahul Balasubramanian

9

ATLA

 $\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$ 

<b>45</b> F	Pre	limi	nary ToV
Refe	o, ere	enc	e
17 17 16 15 17 18 20 18 18	711.0 707.0 703.0 506.0 512.0 707.0 308.0 308.0 904.1 303.0	93301 9127 92265 92586 94147 92380 4636 0823 9678	
19 17 18 20 19 18 20 19 18 17 CERN 18 19	903.0 709.0 305.0 905.0 906.0 906.0 712.0 712.0 -EP- 307.1	6248 7242 9299 5138 5609 66992 4636 8589 6518 2020 0473 2679	-073
17 CERN 18	703.0 -EP- 311.0	9127 2020- 2305	-066
17 17 16 18	711.0 711.0 608.0 812.0	3301 3301 2372 9743	
19 19 19 19	902.0 902.0 902.0 902.0	0377 0377 8103 8103	
18 18 18 ATLAS-0 15	308.0 308.0 307.1 312.0 CON	2343 2343 1883 7343 F-201 4261	8-024
19 17 18 14 14	910.0 709.1 305.0 411.2 411.2	8447 0440 9299 2921 2921	
ATLAS-0 18 17 1 1 18 18	CON 309.1 710.0 411.2 312.0 905.1	F-201 1105 9748 2921 93673 0130	8-020



## Looking for direct signatures



2<sup>nd</sup> Pan-European Advanced School on Statistics in High Energy Physics



## Looking for indirect signatures

### Effective interaction at low energy



### SMEFT allows to probe BSM physics at energies much higher than direct energy reach

### 2<sup>nd</sup> Pan-European Advanced School on Statistics in High Energy Physics



# EFT Lagrangian

### EFT Lagrangian written out as an expansion in terms of $1/\Lambda$ where $\Lambda \gg$ E, vev +

$$\mathscr{L} = \mathscr{L}_{SM} + \frac{1}{\Lambda} \mathscr{L}^{(d=5)} + \frac{1}{\Lambda^2} \mathscr{L}^{(d=6)} + \dots + \frac{1}{\Lambda^{D-4}} \mathscr{L}^{(d=D)} + \dotsb$$

 $\star \mathscr{L}_{SM}$  contains no information of  $\Lambda$ , accessible by higher order terms which are given as sum of all possible operators  $\{\mathcal{O}_i^d\}$  where,

$$\mathscr{L}^{(d)} =$$

- $\bullet$  { $c_i$ } are wilson coefficients are correspond to free parameters of the model
- $\mathcal{O}_i$  all possible terms with known fields that respect allowed symmetries → Lorentz invariance, Gauge symmetry
- $\{\mathcal{O}_i\}$  acts as a basis to describe all allowed deformation to the Standard Model +



$$\mathcal{O}_{Hq}^{(3)} = (H^{\dagger} i \overleftrightarrow{D}_{\mu} H) (\bar{u}_{\mu}$$



## **Observables in EFT**

- We want to model the dependence of observable distribution on the parameters of the model  $\{C_i\}, e_{X,BSM}$ 10<sup>4</sup>
- Distribution predictions can be generated at choice of parameters values using monte-carlo simulations
- However expensive to construct a fine grid of simulations, grid simulations scales exponential with number exponentially with number of parameters involved
  - $\rightarrow$  Prohibitive !
- Crucial to construgt like like thood fonction terms of EFT4 parameters,

### L(data $\overrightarrow{c}$ , Nuisance parameters)



[See Glen Cowan's talk on likelihood based combinations]



## From Lagrangian to observables

- Given the Lagrangian, can write down transition amplitude for process as sum of amplitudes,
- + Let's consider a one operator at d=6 case,



2<sup>nd</sup> Pan-European Advanced School on Statistics in High Energy Physics



## Outline

### **Effective field theory**

- Motivation for EFT approach at the Large Hadron Collider
- ✦ Effective Lagrangian
- Observable dependence on EFT parameters

## **Effective Lagrangian Morphing**

- Morphing physics distributions within EFT
- Interface between data and theory

### **Implementation within ROOT**

- Modelling EFT observables with RooLagrangianMorphFunc
- Examples based on 2 and 3 EFT parameters

# Describing physics observables within EFT



## Mapping distributions to operators

### Distributions map to contributions of all the different operators,

$$|A_{SMEFT}(c)|^{2} = |\mathcal{O}_{SM}|^{2} + 2 \cdot \frac{c}{\Lambda^{2}} \Re(\mathcal{O}_{SM}^{*}\mathcal{O}_{EFT}) + \frac{c^{2}}{\Lambda^{4}} |\mathcal{O}_{EFT}|^{2}$$

+ For one operator, templates generated at three values of the grid should suffice to span the whole parameter space,

$$\begin{aligned} \sigma(c=0) &\propto |\mathcal{O}_{SM}|^2 \\ \sigma(c=1) &\propto |\mathcal{O}_{SM}|^2 + 2 \cdot \frac{c}{\Lambda^2} \Re(\mathcal{O}_{SM}^* \mathcal{O}_{EFT}) + \frac{c^2}{\Lambda^4} |\mathcal{O}_{EFT}|^2 \\ \sigma(c=-1) &\propto |\mathcal{O}_{SM}|^2 - 2 \cdot \frac{c}{\Lambda^2} \Re(\mathcal{O}_{SM}^* \mathcal{O}_{EFT}) + \frac{c^2}{\Lambda^4} |\mathcal{O}_{EFT}|^2 \end{aligned}$$



## Distribution in the full parameter space

- ♦ In this example we saw a one parameter case, however this principle can be extended to arbitrary number of parameters which can be sampled at any set of independent points in the parameter space
- Morphing  $\rightarrow$  procedure to turn a collection of probability models for individual points in parameter space to a continuous description

+ Three samples can be used to generate the continuous description, can fix  $\Lambda = 1$  TeV for reference,

{L(data | c=0, NPs), L(data | c=-1, NPs), L(data | c=+1, NPs)}  $\rightarrow$  L(data | c, NPs)





**Parameter Card** 

Weight Matrix

have well defined weight matrix



2<sup>nd</sup> Pan-European Advanced School on Statistics in High Energy Phros LagrangianMorphFunc



**Morphing Matrix** 

+ The morphing principle is based on linear algebra, very robust ! Only relies on independent sample to

Rahul Balasubramanian



## interface between data and theory - unfolded distributions

Three possible approaches for the interface between data and theory for experimentalist

### I. Publishing theory-level distributions

1) **Full unfolding (very complicated)**  $\rightarrow$ 



- Unfolding is a numerically very difficult problem that requires 'regularization' to make deconvolution step numerically stable
- Many algorithms on the market with variable sensitivity to assumptions, biases, etc.
- Unfolded physics distributions are extremely time and resource intensive for collaborations to produce!



[See Carsten Burgard' talk on unfolding]



## interface between data and theory - template cross-sections

### II. Publishing template distribution close to reconstruction level

2) **Template cross-sections (med. hard)**  $\rightarrow$  SM(EFT) param. (med. hard)



- Avoid unfolding by publishing template cross-sections in regions close to analysis reconstruction region +
- Typically perform for Higgs cross-sections, may not necessarily extend for all use cases
- + Additional work involved in mapping each measurement  $\sigma$  to the expression in  $c_i$







## interface between data and theory - template cross-sections

### II. Publishing template distribution close to reconstruction level

2) **Template cross-sections (med. hard)**  $\rightarrow$  SM(EFT) param. (med. hard)



- Avoid unfolding by publishing template cross-sections in regions close to analysis reconstruction region +
- Typically perform for Higgs cross-sections, may not necessarily extend for all use cases
- + Additional work involved in mapping each measurement  $\sigma$  to the expression in  $c_i$







# interface between data and theory - direct SMEFT modelling

### II. Publishing template distribution close to reconstruction level

3) **Template morphing** with SM(EFT) parametrization (medium)



- Publishing directly results on the parameters of the effective lagrangian
- The lagrangian provides a natural description to measure physics parameter across different process !
- Full power of EFT lies in global combinations !

Measurement

 $\rightarrow$ 



## Outline

### **Effective field theory**

- Motivation for EFT approach at the Large Hadron Collider
- ✦ Effective Lagrangian
- Observable dependence on EFT parameters

### **Effective Lagrangian Morphing**

- Morphing physics distributions within EFT
- Interface between data and theory

### **Implementation within ROOT**

- Modelling EFT observables with RooLagrangianMorphFunc
- Examples based on 2 and 3 EFT parameters

Describing model within RooFit



## Statistical Models with RooFit

- of arbitrary complexity
- Design principle : Mathematical functions map directly to C++ classes ◆

Mathematical concept



 $\bullet$  RooFit : statistical modelling toolkit based on C++ to create and perform inference on statistical models

RooFit class

RooRealVar

RooAbsReal

RooAbsPdf

RooArgSet

RooRealIntegral

RooAbsData



## Data Modelling

 Modelling composite objects based on clear connection between mathematical functions and class objects

Math	gauss (x, m, -
RooFit diagram	S RooGaussian          Image: Constraint of the second state of the second st
RooFit code	<ol> <li>RooRealVar x("x", "x", -</li> <li>RooRealVar m("m", "mean</li> <li>RooRealVar s("s", "sigm</li> <li>RooFormulaVar sqrts("s</li> <li>RooGaussian g("g", "gau</li> </ol>



## Modular design performs well with complex models



2<sup>nd</sup> Pan-European Advanced School on Statistics in High Energy Physics

Reading/writing of full model takes ~4 seconds ROOT file with workspace is ~6 Mb





### ◆ Rootagrangian MorphFunc: Rootats implementing the high artigian morphing



Computational dependency graph for an example object of RooLagrangianMorphFunc





## One parameter use case



SMEFT becoming the standard interpretation framework for measurements at the LHC to look for indirect signs of physics beyond the Standard Model

The morphing technique provide a powerful way to model the EFT distributions in combined likelihoods, now available with ROOT release v6.26.00

SMEFT is global, provides an unifying framework to interpret measurements consistently across different sectors and experiments

Jhanks for your attention !



### Rahul Balasubramanian





