SM/BSM interference pattern

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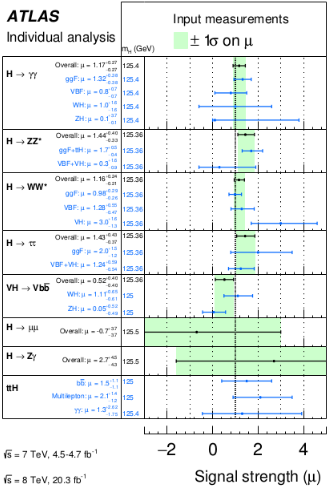
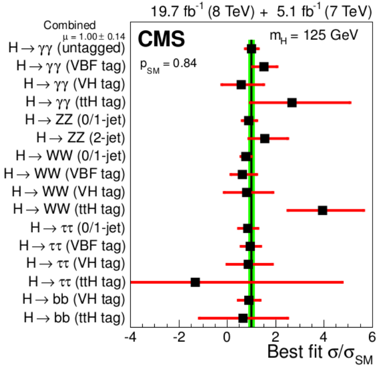
ICTP

arXiv:1607.05236 A.A, R.Contino, C.Machado, F.Riva

~~Current~~ constraints on the Higgs interactions

13 TeV constraints are already comparable/stronger in some of the channels!





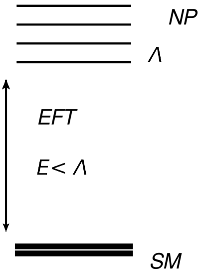
- No significant deviations in the Higgs couplings.
- However current measurements constrain mostly inclusive rates, constraints on differential distributions are still weak.

- What LHC searches are more sensitive to the modifications of the SM interactions?
- What searches can be more easily interpreted as a constraints on BSM?

EFT: parametrizing the new physics effects

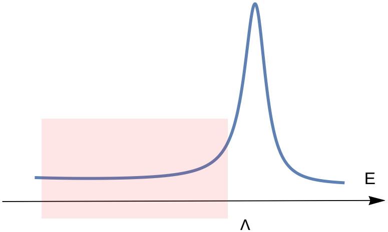
EFT provides a consistent framework for the parametrization of the new physics effects.

- If new physics states are heavier than the SM statesand the typical mass scale of the process $\Lambda > E$.
- We can integrate these states out and parametrize their effects in terms of the higher dimensional operators.
- The effects of new physics will appear as a corrections in the $\left(\frac{E}{\Lambda}\right)$ series.



Range of validity

- EFT expansion is valid only below the mass of the new heavy resonance
- We are testing the deviations from the SM in the tails of the Breight -Wigner resonances.
- EFT analysis becomes important if the new resonances are too heavy to be directly produced at the collider.



- If we assume the lepton number conservation

$$\mathcal{L} = \mathcal{L}^{\mathrm{SM}} + \mathcal{L}^6 + \mathcal{L}^8 + \cdots , \quad \mathcal{L}^D = \sum_i c_i^{(D)} \mathcal{O}_i^{(D)}$$

$$c_i^{(D)} \sim \frac{1}{\Lambda^{D-4}}$$

- Dominant effects come from the dimension six operators!

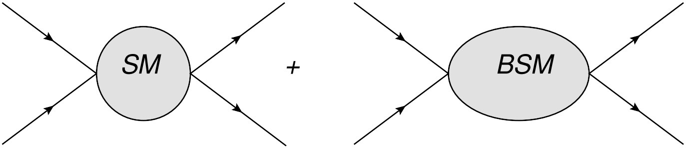
$$\sigma \sim \mathrm{SM}^2 + \frac{SM \times BSM_6}{\Lambda^2} + \frac{BSM_6^2}{\Lambda^4} + \frac{SM \times BSM_8}{\Lambda^4} + \ldots$$

- leading term in $\frac{1}{\Lambda^2}$ comes from the interference between SM and BSM!

What are the properties of the interference term?

$$\boxed{\frac{\mathbf{SM \times BSM_6}}{\mathbf{\Lambda^2}}}$$

Energy dependence of $2 \to 2$ scattering



- From dimensional analysis

$$A_{2\to 2} \sim A_{SM} + A_{BSM_6}\left(\frac{m^2}{\Lambda^2} + \frac{\mathbf{E^2}}{\mathbf{\Lambda^2}}\right)$$

- Large energy E region is most sensitive to BSM effects, however we need to be careful to make sure the EFT expansion remains valid.

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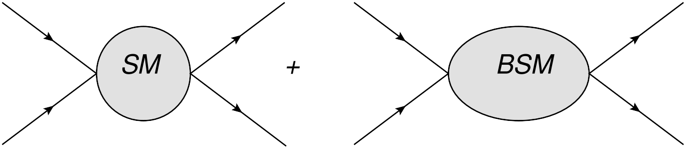

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For simplicity let us start with the massless theory i.e. $E \gg m_W, m_t$

$2 \to 2$ scattering at tree level: the best basis

- There are many basis for dimension six operators, which one is more convenient for understanding the properties of $2 \to 2$ scattering?
- It is easier to calculate the contact diagram, so it is better to reduce the number of the bivalent and trivalent operators to minimum.
- So we need something like Warsaw basis with the following operators:
  $\mathbf{F^3}, \mathbf{F^2}\phi^\mathbf{2}, \mathbf{F}\psi^\mathbf{2}\phi, \psi^\mathbf{4}, \psi^\mathbf{2}\bar{\psi}^\mathbf{2}, \psi\bar{\psi}\phi^\mathbf{2}\mathbf{D}, \phi^\mathbf{4}\mathbf{D^2}, \psi^\mathbf{2}\phi^\mathbf{3}, \phi^\mathbf{6}$
- $F \equiv F_{\mu\nu}, D \equiv D_\mu$

Selection rules for $2 \to 2$ scattering in SM

- Amplitudes of the massless gauge theory follow the helicity selection rules (MHV)

$$
\begin{aligned}
A(V^+V^+V^+V^+) = A(V^+V^+V^+V^-) = \ & A(V^+V^+\psi^+\psi^-) \\
= A(V^+V^+\phi\phi) = A(V^+\psi^+\psi^+\phi) = 0.&
\end{aligned}
$$

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It is very important to trace the helicity of the BSM amplitudes! very transparent in the helicity-spinor formalism!

Helicity counting rules

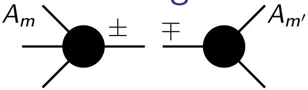
- fermions: Weyl spinors $\psi_\alpha, \bar{\psi}^{\dot{\alpha}}$ transforming as (1/2,0) and (0,1/2) under Lorentz group
- gauge field (1/2,1/2):

$$F_{\mu\nu}\sigma^{\mu}_{\alpha\dot{\alpha}}\sigma^{\nu}_{\beta\dot{\beta}} \equiv F_{\alpha\beta}\bar{\epsilon}_{\dot{\alpha}\dot{\beta}} + \bar{F}_{\dot{\alpha}\dot{\beta}}\epsilon_{\alpha\beta}$$

  where $F, \bar{F}$ are self-dual and anti-self dual parts transforming as (1,0) and (0,1). $F(\bar{F})$ project helicity $+1(-1)$ states.
- Calculation of the helicity of the amplitudes from the 4-valent operators becomes trivial:

  $$\boxed{h(\phi^2 F^2) = 2h(\phi) + 2h(F) = 2}$$

Helicity of the non-contact diagrams



- Helicity of the total amplitude will be

$$h(A_n) = h(A_m) + h(A_{m'})$$

- True if there is a pole in the factorization channel, i.e. we have a definite helicity state propagating on the virtual line.
- in SM always true, in EFT the pole of the propagator can be cancelled by the derivatives in the new vertex:
  $\boxed{\Box\phi/p^2 \sim \phi \Rightarrow \text{no pole}}$
- To avoid cancellations between the derivatives in the vertex and the poles it is better to redefine operators to have as less derivatives as possible.

It is better to use basis where the operators have less number of derivatives and more fields.

Classifying the dimension six operators (Cheung, Shen)

- Define for an arbitrary amplitude holomorphic and anti-holomorphic weights:

$$w(A) = n(A) - h(A), \quad \bar{w}(A) = n(A) + h(A)$$

- We can define the weight of the operator in the following way

$$w(\mathcal{O}) = \min_A \{w(A)\}\,, \quad \bar{w}(\mathcal{O}) = \min_A \{\bar{w}(A)\}$$

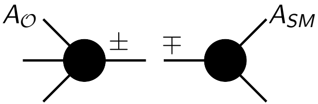
- **note that this definition can be applied in any basis of dim 6 operators.**

Properties of holomorphic weights $(w, \bar{w})$ (Cheung, Shen)

- we need to find

$$w(\mathcal{O}) = \min_A \{w(A)\}\,, \quad \bar{w}(\mathcal{O}) = \min_A \{\bar{w}(A)\}$$

- note that weights are monotonically growing functions of n



$$\Delta w = \Delta n + \Delta h = 1 + h(A_{SM}) \gtrsim 0$$
$$\Delta \bar{w} = \Delta n - \Delta h = 1 - h(A_{SM}) \gtrsim 0$$

- **the weight of the operator is defined by the diagram with less number of legs!**

The weights of the dimension six operators

$\mathcal{O}_i$	n_{min}	h_{min}	$(w,\bar{w})$	c_i
F^3	3	3	(0,6)	g_*/Λ^2
$F^2\phi^2$, $F\psi^2\phi$, ψ^4	4	2	(2,6)	g_*^2/Λ^2
$\psi^2\bar{\psi}^2$, $\psi\bar{\psi}\phi^2 D$, $\phi^4 D^2$	4	0	(4,4)	g_*^2/Λ^2
$\psi^2\phi^3$	5	1	(4,6)	g_*^3/Λ^2
ϕ^6	6	0	(6,6)	g_*^4/Λ^2

The helicity of the amplitude generated by the operator $\mathcal{O}$ will be constrained

$$\boxed{\bar{w}(\mathcal{O}) - n \leq h(A_n^{\mathcal{O}}) \leq n - w(\mathcal{O})\,.}$$

BSM noninterference for $2 \to 2$ processes

A_4	$\lvert h(A_4^{\rm SM})\rvert$	$\lvert h(A_4^{\rm BSM})\rvert$
$VVVV$	0	4,2
$VV\phi\phi$	0	2
$VV\psi\psi$	0	2
$V\psi\psi\phi$	0	2
$\psi\psi\psi\psi$	2,0	2,0
$\psi\psi\phi\phi$	0	0
$\phi\phi\phi\phi$	0	0

no interference for V^4, $V^2\phi^2$, $V^2\psi^2$, $V\psi\psi\phi$ **processes!!**

Higher order processes

$$h^{\mathcal{O}}_{min} \leq h(A^{\mathcal{O}}_{n \geq n_{min}}) \leq h^{\mathcal{O}}_{max}$$

with h even (odd) for n even (odd)

$\mathcal{O}_i$	$h^{\mathcal{O}}_{min}$	$h^{\mathcal{O}}_{max}$
F^3	$6-n$	n
$F^2\phi^2$, $F\psi^2\phi$, ψ^4	$6-n$	$n-2$
$\psi^2\bar{\psi}^2$, $\psi\bar{\psi}\phi^2 D$, $\phi^4 D^2$	$4-n$	$n-4$
$\psi^2\phi^3$	$6-n$	$n-4$
ϕ^6	$6-n$	$n-6$

For $n \gtrsim 5$ BSM amplitudes start to interfere with SM

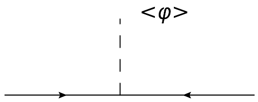
Mass effects

- If we have to deal with electroweak processes mass is $m \neq 0$!
- Let us consider high energy regime $E \gg m$, then the interference must be controlled by the small expansion parameters:

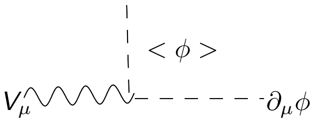
$$\varepsilon_V \equiv \frac{m_V}{E}\,, \qquad \varepsilon_\psi \equiv \frac{m_\psi}{E}$$

- Can we systematically find the interference pattern as a series of ϵ_v and ϵ_ψ?

Classifying the finite mass effects



- insertion of the Higgs vev flips the fermion helicity $\Delta h = 1$, and every helicity flip will cost $\sim \epsilon_\psi$.



- Insertion of the one scalar vev can transform the transverse component to longitudinal and vice versa $\Delta h = 1 \sim \epsilon_V$

The amplitude structure for massless fermions

Channel	SM	BSM_6/E^2
$++++$	ε_V^4	ε_V^0
$+++-$	ε_V^2	ε_V^0
$++--$	ε_V^0	ε_V^2
$+\frac{1}{2}\ -\frac{1}{2}\ +\ +$	ε_V^2	ε_V^0
$+\frac{1}{2}\ -\frac{1}{2}\ +\ -$	ε_V^0	ε_V^2
$+\frac{1}{2}\ -\frac{1}{2}\ 0\ +$	ε_V^1	ε_V^1
$+\frac{1}{2}\ -\frac{1}{2}\ 0\ 0$	ε_V^0	ε_V^0

Channel	SM	BSM_6/E^2
$0+++$	ε_V^3	ε_V^1
$0++-$	ε_V^1	ε_V^1
$0\ 0++$	ε_V^2	ε_V^0
$0\ 0+-$	ε_V^0	ε_V^2
$0\ 0\ 0+$	ε_V^1	ε_V^1
$0\ 0\ 0\ 0$	ε_V^0	ε_V^0

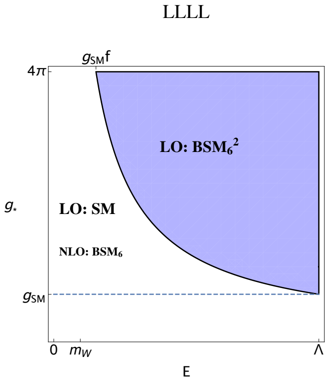
Phenomelogical implications

- The contribution of the dimension six operators is often suppressed.
- What is a region where ignoring dim 8 operators is consistent?When the square of the dimension six operator becomes important?
- We need to assume some power counting to estimate the size of the operators.
- For example if the new theory has one scale Λ and one new coupling g_*.

  $$c^{(D)} \sim \frac{g_*^{n-2}}{\Lambda^{D-4}}$$

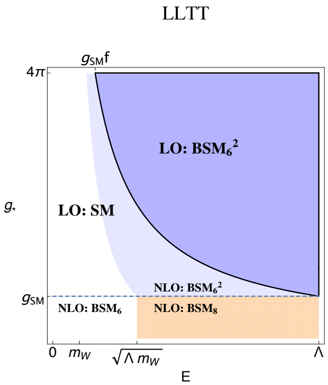
  where n is a number of fields in the operator.

Phenomenology applications $V_L V_L \to V_L V_L$



$$\sigma_L \sim \frac{g_{SM}^4}{E^2}\left[1 + \underbrace{\frac{g_*^2}{g_{SM}^2}\frac{E^2}{\Lambda^2}}_{BSM_6 \times SM} + \underbrace{\frac{g_*^4}{g_{SM}^4}\frac{E^4}{\Lambda^4}}_{BSM_6{}^2} + \underbrace{\frac{g_*^2}{g_{SM}^2}\frac{E^4}{\Lambda^4}}_{BSM_8 \times SM} + \ldots\right]$$

Phenomenology applications $V_L V_L \to V_T V_T$



$$\sigma_{LT} \sim \frac{g_{SM}^4}{E^2}\left[1 + \overbrace{\frac{g_*^2}{g_{SM}^2}\frac{m_W^2}{\Lambda^2}}^{\text{BSM}_6\times\text{SM}} + \overbrace{\frac{g_*^4}{g_{SM}^4}\frac{E^4}{\Lambda^4}}^{\text{BSM}_6{}^2} + \overbrace{\frac{g_*^2}{g_{SM}^2}\frac{E^4}{\Lambda^4}}^{\text{BSM}_8\times\text{SM}} + \dots\right]$$

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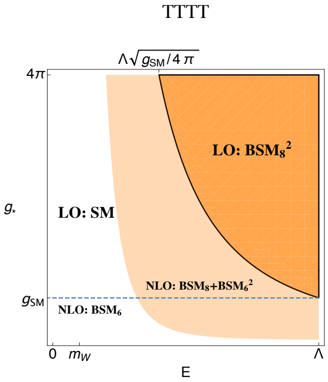
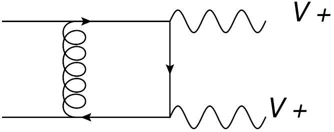


$$\sigma_T \sim \frac{g_{SM}^4}{E^2}\left[1 + \overbrace{\frac{g_*}{g_{SM}}\frac{m_W^2}{\Lambda^2}}^{BSM_6\times SM} + \overbrace{\frac{g_*^2}{g_{SM}^2}\frac{E^4}{\Lambda^4}}^{BSM_6{}^2} + \overbrace{\frac{g_*^2}{g_{SM}^2}\frac{E^4}{\Lambda^4}}^{BSM_8\times SM} + \overbrace{\frac{g_*^4}{g_{SM}^4}\frac{E^8}{\Lambda^8}}^{BSM_8{}^2} + \dots\right].$$

NLO is important (work in progress with J.Elias-Miro, Y.Reyimuaji,E.Venturini)

- Non-interference pattern is not true at NLO, $A(V^2\psi^2) \neq 0$!



- NLO corrections (from MCFM) can qualitatively change the results

$$\sigma_{LO} = 54. - 1.7^{\pm 0.3} c_{3w} + 15. c_{3w}^2 fb$$
$$\sigma_{NLO} = 83. + 7.3^{\pm 0.6} c_{3w} + 15. c_{3w}^2 fb$$

not a simple K factor!

$2 \to 3$ processes (work in progress with J.Elias-Miro, Y.Reyimuaji,E.Venturini)

- in QCD, due to the non-interference of the $2 \to 2$ scattering it is better to look at the $2 \to 3$ processes to test the operator O_{3g} (*Shadmi,Dixon, 94*)

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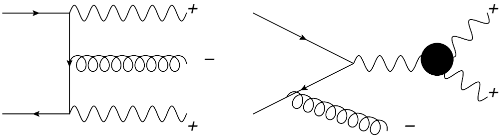
- We can do the same thing for the electroweak O_{3W} with an extra hard QCD jet $A(V(+)V(+)g(-)\psi^2) \neq 0$ there will be still an interference!



Summary

- There is an interesting pattern of interference/noninterference between dimension six operators and the SM for $2 \to 2$ processes.
- Spinor-helicity techniques are very useful in understanding it, since we are interested in the high energy regime.
- Non-interference restricts the region of the applicability of the EFT studies.
- NLO corrections can qualitatively modify bounds on the dimension six operators.
- $2 \to 3$ processes can be very important.

From Contino's talk

Notice: Dominance of quadratic term (over linear ones) is per se neither sufficient nor necessary a condition for the EFT to be valid

✗ Not sufficient — Ex: TGC at LEP2

$$\frac{\delta\sigma}{\sigma} \sim \frac{c_{3W}}{g} E^2 \sim \frac{g^2}{16\pi^2} \frac{E^2}{\Lambda^2}$$

large / small

✗ Not necessary — Ex: $V_L V_L$ scattering

$$O_6 = (H\partial H)^2 \qquad c^{(6)} \sim \frac{g_*^2}{\Lambda^2}$$

$$\sigma(LL \to LL) \sim \frac{g_{SM}^4}{E^2}\Big[1 + \underbrace{\frac{g_*^2}{g_{SM}^2}\frac{E^2}{\Lambda^2}}_{\mathrm{BSM}_6\times\mathrm{SM}} + \underbrace{\frac{g_*^4}{g_{SM}^4}\frac{E^4}{\Lambda^4}}_{\mathrm{BSM}_6{}^2} + \dots\Big]$$