Amplitude/Operator Basis from Mathematica

— package ABC4EFT[1]

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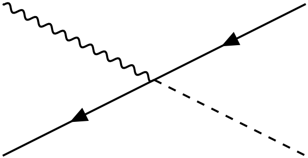

April 30, 2022 @ **PIKIMO 12, University of Notre Dame**

[1] https://abc4eft.hepforge.org/

Basis of Effective Operators

- Operator Redundancies
  - Equation of Motion (EOM):

$$\mathcal{O} \sim \mathcal{O} + \mathcal{O}'_a \frac{\delta S}{\delta \phi_a} \quad \Leftrightarrow \quad \phi_a \to F(\phi_a)$$

  - Integration By Part (IBP):

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  - Operator Identities: Fierz rearrangement, Covariant Derivative Commutator (CDC), Cayley-Hamilton, Gram Determinant ...

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- Weinberg Operator (79') $\to$ Warsaw Basis (10') $\to$ Hilbert Series (15')

$\to$ **Young Tensor Basis (20')** [2005.00008]

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→ **Young Tensor Basis (20')** [2005.00008]

- Conversion among various bases

$$\mathcal{L} = \sum_i C_i \mathcal{O}_i = \sum_i C'_i \mathcal{O}'_i \quad \to \quad f(C_i) = f'(C'_i)$$

Amplitude-Operator Correspondence

- Amplitude from **minimal** form factor: $\mathcal{O} \sim \mathcal{B} \equiv \int \mathrm{d}^4x \, \langle 0|\mathcal{O}(x)|\Psi_i(p_i)\rangle$
  - $\mathcal{O}_1 \sim \mathcal{O}_2 \quad \Leftrightarrow \quad \mathcal{B}_1 = \mathcal{B}_2$
  - $\sum_i p_i = 0$
  - $\mathcal{B}$ is gauge invariant, $D_\mu \sim \partial_\mu \to -ip_\mu$
  - $|\Psi_i\rangle$ defines the **type** of the operator.

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- Remove the "off-shell" pieces: $D^2\phi$, $\not{D}\psi$, $D^\mu F_{\mu\nu} \to 0$, $[D_\mu, D_\nu] \to 0$

$\mathcal{O}$	$F^{\mu\nu}\phi^\dagger i[D_\mu, D_\nu]\phi$	$=$	$F^2\phi^\dagger\phi$
$\|\Psi_i\rangle$	$\|\gamma, \phi^*, \phi\rangle$ ✘		$\|\gamma, \gamma, \phi^*, \phi\rangle$ ✔

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- Use chiral fields $F_{\mathrm{L/R}}$, ψ_α, $\psi^{\dagger\,\dot\alpha}$

$$\underset{(1,0)\oplus(0,1)}{F_{\mu\nu}\sigma^\mu_{\alpha\dot\alpha}\sigma^\nu_{\beta\dot\beta}} = \underset{(1,0)}{F_{\mathrm{L},\alpha\beta}}\tilde\epsilon_{\dot\alpha\dot\beta} + \epsilon_{\alpha\beta}\underset{(0,1)}{F_{\mathrm{R},\dot\alpha\dot\beta}}\ , \qquad \underset{(\frac12,0)\oplus(0,\frac12)}{\Psi} = (\underset{(\frac12,0)}{\psi_\alpha}\ ,\ \underset{(0,\frac12)}{\psi_c^{\dagger\,\dot\alpha}})^\intercal$$

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SMEFT field content: $G_{\mathrm{L,R}}, W_{\mathrm{L,R}}, B_{\mathrm{L,R}}, Q^{(\dagger)}, L^{(\dagger)}, u_c^{(\dagger)}, d_c^{(\dagger)}, e_c^{(\dagger)}, H^{(\dagger)}$

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- Operators with only spinor contractions

$$\mathcal{O} = \epsilon^n \tilde\epsilon^{\tilde n} \prod_{i=1}^{N} D^{w_i}\Psi_i \sim \mathcal{B} = \langle\cdot\rangle^n [\cdot]^{\tilde n}$$

Spinor helicity variables: $p_{i\mu}\sigma^\mu_{\alpha\dot\alpha} = \lambda_{i\alpha}\tilde\lambda_{i\dot\alpha}$

$$\langle ij\rangle \equiv \epsilon^{\alpha\beta}\lambda_{i\alpha}\lambda_{j\beta}\,, \quad [ij] \equiv \tilde\epsilon_{\dot\alpha\dot\beta}\tilde\lambda_i^{\dot\alpha}\tilde\lambda_j^{\dot\beta}$$

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Example

$$(\bar q \gamma^\mu q)(H^\dagger i D_\mu H) \;=\; Q^\alpha Q^{\dagger\dot\alpha} H^\dagger i D_{\alpha\dot\alpha} H \;\sim\; \langle 14\rangle[24]$$

Amplitude Reduction

How to enumerate independent amplitudes?

- Momentum Conservation: $\sum_k \langle ik \rangle [kj] = 0$
- Schouten Identity: $(ij)(kl) + (ik)(lj) + (il)(jk) = 0$

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We need a specific routine of using the above relations: [2007.07899]

1. Eliminate p_1 and most of $p_{2,3}$:

$$\langle i1\rangle[1j] \Rightarrow -\sum_{k=2}^{N}\langle ik\rangle[kj], \quad \langle i2\rangle[21] \Rightarrow -\sum_{k=3}^{N}\langle ik\rangle[k1],$$

$$\langle 23\rangle[31] \Rightarrow -\sum_{k=4}^{N}\langle 2k\rangle[k1], \quad \langle 23\rangle[32] \Rightarrow -\sum_{1<i<j,j>3}^{N}\langle ij\rangle[ji]$$

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1. Eliminate p_1 and most of $p_{2,3}$:
2. Eliminate "disordered" spinor brackets

$$(il)(jk) \Rightarrow -(ij)(kl) - (ik)(lj) \quad \text{when} \quad i < j < k < l$$

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Mathematica Implementation: [2201.04639]

```
In[2]:= << ABC4EFT`

In[3]:= amp = ab[1, 3] × sb[2, 3] × ab[2, 4] × sb[3, 4];
        Print[GetClass[amp, 5], ": ",
         Ampform[amp], "\n=> ", AmpReduce[amp, 5] // Ampform]
```

$D^3\phi^3\psi\bar{\psi}$: [23] [34] ⟨13⟩⟨24⟩

=> −[24] [34] ⟨14⟩⟨24⟩ − [24] [35] ⟨14⟩⟨25⟩ + [23] [45] ⟨14⟩⟨25⟩ − [34] [35] ⟨13⟩⟨45⟩ − [34] [45] ⟨14⟩⟨45⟩

Young Tabluau (Y-)Basis

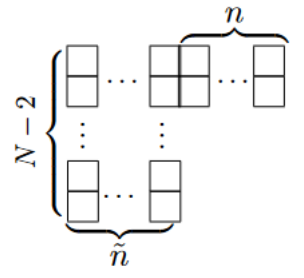
The basis stems from Semi-Standard Young Tableau (SSYT) [1902.06754, 2005.00008]

Mini Game

Fill in the grid on the right with $\tilde{n} - 2h_i$ copies of integer $i \in [1, N]$, with the requirements:

a. Each row consists of non-decreasing integers from left to right.

b. Each column consists of increasing integers from top to bottom.



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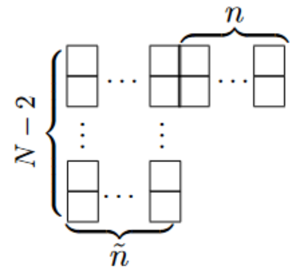

1	1	1	2
2	3	4	4
5	5		

$-[34][24]\langle 14\rangle\langle 24\rangle$

1	1	1	2
2	3	4	5
4	5		

$[35][24]\langle 14\rangle\langle 25\rangle$

1	1	1	2
2	4	4	5
3	5		

$[45][23]\langle 14\rangle\langle 25\rangle$

1	1	1	4
2	2	3	5
4	5		

$-[35][34]\langle 13\rangle\langle 45\rangle$

1	1	1	4
2	2	4	5
3	5		

$[45][34]\langle 14\rangle\langle 45\rangle$

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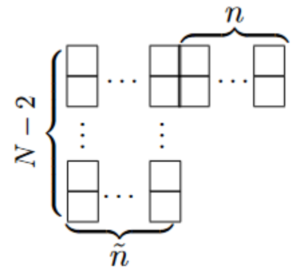
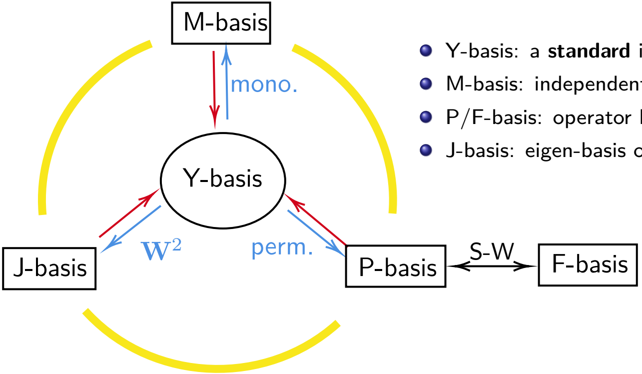


Enumerate all the SSYTs as the amplitude y-basis:

```
In[5]:= ybasis = SSYT[{-1/2, 0, 1/2, 0, 0}, 3];
        FindCor[AmpReduce[amp, 5], ybasis]

Out[6]= {0, -1, 1, 0, 0, 0, 1, 0, 1, -1}
```

Package ABC4EFT



- Y-basis: a **standard** independent basis
- M-basis: independent monomial operators
- P/F-basis: operator basis with flavor sym.
- J-basis: eigen-basis of symmetry algebra.

Example in SMEFT

Define the model:

```
ModelIni[SMEFT];

AddGroup[SMEFT, "U1b"]; (* U(1) Baryon *)
AddGroup[SMEFT, "U1l"]; (* U(1) Lepton *)
AddGroup[SMEFT, "SU3c", GaugeBoson -> "G"]; (* SU(3) color *)
AddGroup[SMEFT, "SU2w", GaugeBoson -> "W"]; (* SU(2) weak *)
AddGroup[SMEFT, "U1y", GaugeBoson -> "B"]; (* U(1) hypercharge *)

nf = 3; (* number of flavors *)
AddField[SMEFT, "Q", -1/2, {"SU3c" -> {1, 0}, "SU2w" -> {1}, "U1y" -> 1/6, "U1b" -> 1/3}, Flavor -> nf];
AddField[SMEFT, "uc", -1/2, {"SU3c" -> {0, 1}, "U1y" -> -2/3, "U1b" -> -1/3}, Flavor -> nf];
AddField[SMEFT, "dc", -1/2, {"SU3c" -> {0, 1}, "U1y" -> 1/3, "U1b" -> -1/3}, Flavor -> nf];
AddField[SMEFT, "L", -1/2, {"SU2w" -> {1}, "U1y" -> -1/2, "U1l" -> 1}, Flavor -> nf];
AddField[SMEFT, "ec", -1/2, {"U1y" -> 1, "U1l" -> -1}, Flavor -> nf];
AddField[SMEFT, "H", 0, {"SU2w" -> {1}, "U1y" -> 1/2}];
```

Example in SMEFT

- The only type of operator in the SMEFT in the Lorentz class $D^3\phi^3\psi\bar{\psi}$ is

```
GetBasisForType[SMEFT, "L" "ec†" "H"^3 "D"^3]
```

$$\langle| \{H \to \{3\}\} \to \{\mathbb{i}\,\epsilon^{ik}\epsilon^{jl} H_j H_k\,(D_\nu D^\mu H_l)\,(L_{p_i}\sigma_\mu\,(D^\nu ec^\dagger{}_r)),\ \epsilon^{ik}\epsilon^{jl} H_j\,(D_\mu H_k)\,(D_\nu H_l)\,(L_{p_i}\sigma_\rho\,(D_\lambda ec^\dagger{}_r))\,\epsilon^{\lambda\mu\nu\rho},\ \mathbb{i}\,\epsilon^{ik}\epsilon^{jl} H_j\,(D_\nu D^\mu H_k)\,(D^\nu H_l)\,(L_{p_i}\sigma_\mu\,ec^\dagger{}_r)\}|\rangle$$

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$\epsilon^{ik}\epsilon^{jl} H_j (D_\mu H_k)(D_\nu H_l)(L_{p_i}\sigma_\rho (D_\lambda ec^\dagger_r))\epsilon^{\lambda\mu\nu\rho},\ i\,\epsilon^{ik}\epsilon^{jl} H_j (D_\nu D^\mu H_k)(D^\nu H_l)(L_{p_i}\sigma_\mu ec^\dagger_r)\} |\rangle$

- The full p-basis contains other symmetries for the H^3:

```
GetBasisForType[SMEFT, "L" "ec†" "H"^3 "D"^3, NfSelect → False]
```

$\langle| \{H \to \{3\}\} \to \{i\, \epsilon^{ik}\epsilon^{jl} H_j H_k (D_\nu D^\mu H_l)(L_{p_i}\sigma_\mu (D^\nu ec^\dagger_r)),$
$\epsilon^{ik}\epsilon^{jl} H_j (D_\mu H_k)(D_\nu H_l)(L_{p_i}\sigma_\rho (D_\lambda ec^\dagger_r))\epsilon^{\lambda\mu\nu\rho},\ i\,\epsilon^{ik}\epsilon^{jl} H_j (D_\nu D^\mu H_k)(D^\nu H_l)(L_{p_i}\sigma_\mu ec^\dagger_r)\},$
$\{H \to \{2, 1\}\} \to \{i\, \epsilon^{ik}\epsilon^{jl} H_j H_k (D_\nu D^\mu H_l)(L_{p_i}\sigma_\mu (D^\nu ec^\dagger_r)),$
$\epsilon^{ik}\epsilon^{jl} H_j (D_\mu H_k)(D_\nu H_l)(L_{p_i}\sigma_\rho (D_\lambda ec^\dagger_r))\epsilon^{\lambda\mu\nu\rho},\ i\,\epsilon^{ik}\epsilon^{jl} H_j (D^\mu H_k)(D_\nu H_l)(L_{p_i}\sigma_\mu (D^\nu ec^\dagger_r)),$
$i\,\epsilon^{ik}\epsilon^{jl} H_j (D_\nu H_k)(D^\mu D^\nu H_l)(L_{p_i}\sigma_\mu ec^\dagger_r),\ i\,\epsilon^{ik}\epsilon^{jl} H_j (D_\nu D^\mu H_k)(D^\nu H_l)(L_{p_i}\sigma_\mu ec^\dagger_r),$
$\epsilon^{ij}\epsilon^{kl} H_j (D_\mu H_k)(D_\nu H_l)(L_{p_i}\sigma_\rho (D_\lambda ec^\dagger_r))\epsilon^{\lambda\mu\nu\rho},\ i\,\epsilon^{ij}\epsilon^{kl} H_j (D_\nu H_k)(D^\mu D^\nu H_l)(L_{p_i}\sigma_\mu ec^\dagger_r)\},$
$\{H \to \{1, 1, 1\}\} \to \{i\, \epsilon^{ik}\epsilon^{jl} H_j H_k (D_\nu D^\mu H_l)(L_{p_i}\sigma_\mu (D^\nu ec^\dagger_r)),$
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- The corresponding amplitudes $\mathcal{B}$:

```
GetBasisForType[SMEFT, "L" "ec†" "H"^3 "D"^3, OutputFormat → "amplitude"]
```

$\langle| \{H \to \{3\}\} \to \{ [45]^2 \epsilon^{i_1 i_3}\epsilon^{i_2 i_4} C_{f_1,f_5} \langle 14\rangle \langle 45\rangle,$
$-[35][45]\epsilon^{i_1 i_3}\epsilon^{i_2 i_4} C_{f_1,f_5} \langle 13\rangle\langle 45\rangle,\ -[34][35]\epsilon^{i_1 i_3}\epsilon^{i_2 i_4} C_{f_1,f_5}\langle 13\rangle\langle 34\rangle\} |\rangle$

Summary

- We developed a systematic way to enumerate independent basis of Lorentz invariant operators as SSYT,
- and the reduction routine to find coordinate of any operator under the y-basis (modulo EOM).
- The package ABC4EFT provides tools for defining models and finding independent operator basis for any given type.
- More functions (e.g. partial waves and j-basis) are explained in the paper for you to explore and have fun!
- Even more functions are being developed (e.g. operator reduction including EOM)!

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Thank you for your attention!