ALPs, the on-shell way

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ALPs = Axion-like particles

- Exact/Approximate shift-symmetry:

$$\phi(x) \to \phi(x) + \text{cnst} \qquad \Rightarrow \qquad \text{Physical amplitudes}$$

- Relies on Lagrangian formulation!

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- Exact/Approximate shift-symmetry:

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- Relies on Lagrangian formulation!

- Invert the reasoning:

$$\text{Properties of amplitudes} \qquad \overset{?}{\Rightarrow} \qquad \phi(x) \to \phi(x) + \text{cnst}$$

On-shell methods

- No fields and Lagrangians, only amplitudes.
- Example for ALP and 2 fermions:

$$\mathcal{A}[\phi\psi_1\bar{\psi}_2] = g_L \, \langle \mathbf{12} \rangle \; + \; g_R \, [\mathbf{12}]$$

Coefficients

Can depend on kinematical invariants

Kinematical structures

Fixed by little-group covariance

Some of the progess in on-shell methods:

[Parke, Taylor, '86]
[Bern et al, '95]
[Britto, Cachazo, Feng, '05]
[Britto et al, '05]
[Zwiebel, '12]
[Elvang, Huang, '13]
[Dixon, '13]
[Plefka, Henn, '14]
[Cheung et al, '14]
[Wilhelm, '15]
[Arkani-Hamed, Huang, Huang, '17]
[Durieux et al, '19]
[Falkowski, Isabella, Machado, '20]
[Batarella et al, '20]
[Elias Miró et al, '20]
[Jiang et al, '20]
[Balkin et al, '21]
[Alves, Bertuzzo, GMS, '21]
[Bonnefoy et al, '21]
[Travaglini et al, '22]
[GMS, '22]
[Machado, Renner, Sutherland, '22]
[Angelis, '22]
......

A set of conditions

- Soft factorization condition:

$$\mathcal{A}_{n+1}[\phi] \xrightarrow{p_\phi \to 0} \mathcal{A}_n \times \mathcal{S} \;\; \text{is regular} \qquad \Rightarrow \qquad \text{ALP 3-point interactions}$$

- Soft contact condition:

$$\lim_{p_\phi \to 0} \mathcal{A}_{\text{contact}} = 0 \qquad \Rightarrow \qquad \text{Higher-order interactions}$$

- ALP-Higgs obstruction:

$$\lim_{p_\phi, p_H \to 0} \mathcal{A}[\phi\ H \cdots] = \lim_{p_\phi \to 0} \lim_{\text{high-energy}} \frac{1}{v} \mathcal{A}[\phi \cdots] \qquad \Rightarrow \qquad \text{Connection to SM particle content}$$

Summary

- Determined set of on-shell and physical conditions to recover shift-symmetry;

- Pheno application of higher-order interactions and more on the poster!

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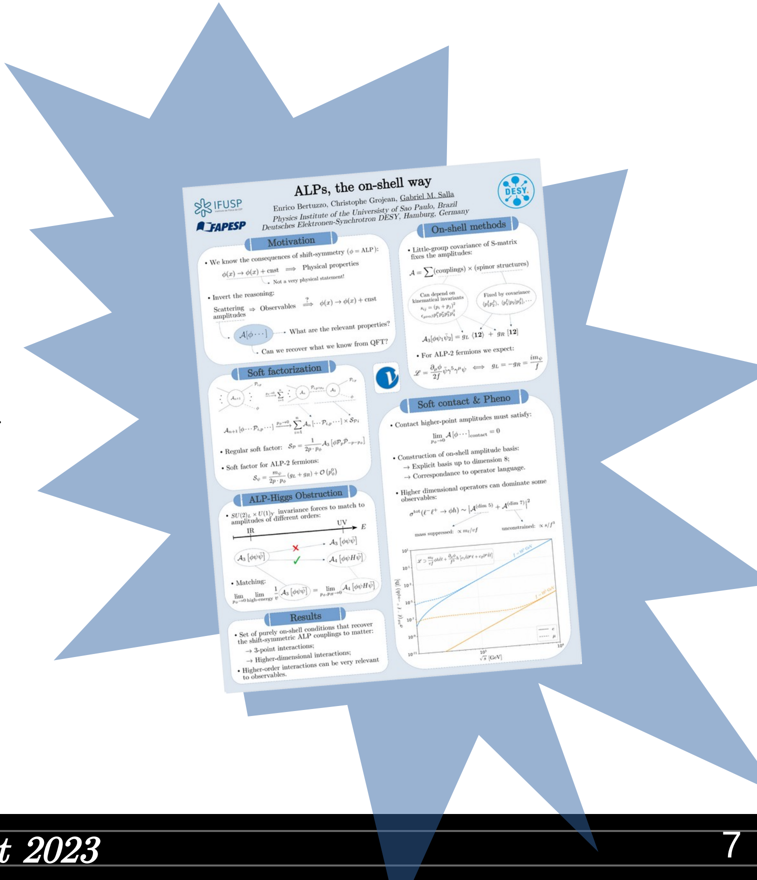
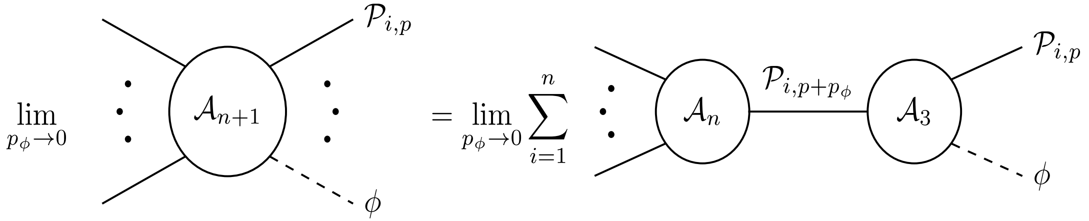
Thank you!



Backup

Soft factorization condition

- Soft limit of ALP in generic amplitude:



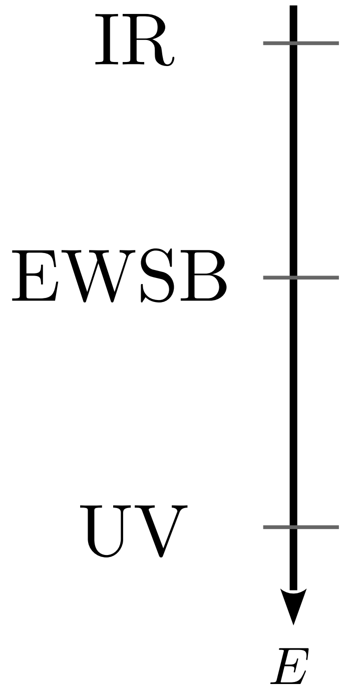
$$\lim_{p_\phi \to 0} \mathcal{A}_{n+1}\Big[\phi \cdots \mathcal{P}_{i,p}^{I_1,\cdots I_{2s}} \cdots\Big] = \lim_{p_\phi \to 0} \sum_{i=1}^{n} \mathcal{A}_n\Big[\cdots \mathcal{P}_{i,p}^{K_1,\cdots K_{2s}} \cdots\Big] \times (\mathcal{S}_{\mathcal{P}_i})^{I_1,\cdots,I_{2s}}_{K_1,\cdots K_{2s}}$$

- Soft factor imposed to be regular:

$$(\mathcal{S}_{\mathcal{P}_i})^{I_1,\cdots,I_{2s}}_{K_1,\cdots K_{2s}} = \frac{\epsilon_{K_1 J_1} \cdots \epsilon_{K_{2s} J_{2s}}}{2p \cdot p_\phi} \mathcal{A}_3\Big[\phi \mathcal{P}_{i,p}^{I_1,\cdots,I_{2s}} \bar{\mathcal{P}}_{i,-p-p_\phi}^{J_1,\ldots,J_{2s}}\Big]$$

ALP-Higgs obstruction

- Soft limit of ALP in generic amplitude:



$$\mathcal{A}\left[\phi\psi_1\bar{\psi}_2\right] \sim m_\psi\langle\mathbf{12}\rangle \sim \langle\mathbf{1}|p_\phi|\mathbf{2}]$$

Dimension mismatch
$\rightarrow$ Insertion of v

Direct matching
$(\pm,\mp)$

$$\mathcal{A}\left[\phi H\psi_L\bar{\psi}_R\right] \sim \langle 12\rangle$$

$$\mathcal{A}\left[\phi\psi_L\bar{\psi}_L\right] \sim \langle 1|p_\phi|2] = 0$$

Determination of higer-order interactions

Dimension 6

Particle content	$\mathcal{A}\times f^2$	$\mathcal{O}\times f^2$
$\phi^2 H\bar{H}$	$p_{\phi_1}\cdot p_{\phi_2}$	$(\partial_\mu\phi)(\partial^\mu\phi)\vert H\vert^2$

Dimension 7

Particle content	$\mathcal{A}\times f^3$	$\mathcal{O}\times f^3$
$\phi\psi_1\bar{\psi}_2 H$	$(p_\phi\cdot p_1)\,\langle 12\rangle$	$(\partial_\mu\phi)\bar{\psi}H(D^\mu\psi)$
	$(p_\phi\cdot p_2)\,\langle 12\rangle$	$(\partial_\mu\phi)(D^\mu\bar{\psi})H\psi$
$\phi\psi_1\bar{\psi}_2 V_3$	$\langle 13\rangle\,\langle 3\vert p_\phi\vert 2]\,,\langle 23\rangle\,\langle 3\vert p_\phi\vert 1]$	$(\partial^\mu\phi)\bar{\psi}\gamma^\nu\psi V_{\mu\nu}$
		$(\partial^\mu\phi)\bar{\psi}\gamma^\nu\psi\tilde{V}_{\mu\nu}$
		$(\partial^\mu\phi)\bar{\psi}\gamma^\nu T^A\psi V^A_{\mu\nu}$
		$(\partial^\mu\phi)\bar{\psi}\gamma^\nu T^A\psi\tilde{V}^A_{\mu\nu}$
$\phi H_1\bar{H}_2 V_3$	$\langle 3\vert\,p_\phi(p_1-p_2)\,\vert 3\rangle$	$(\partial_\mu\phi)(H^\dagger i\overleftrightarrow{D}_\nu H)V^{\mu\nu}$
		$(\partial_\mu\phi)(H^\dagger i\overleftrightarrow{D}_\nu H)\tilde{V}^{\mu\nu}$
		$(\partial_\mu\phi)(H^\dagger i\overleftrightarrow{D}_\nu^A H)V^{A,\mu\nu}$
		$(\partial_\mu\phi)(H^\dagger i\overleftrightarrow{D}_\nu^A H)\tilde{V}^{A,\mu\nu}$
$\phi H\bar{H}\psi_1\bar{\psi}_2$	$\langle 1\vert p_\phi\vert 2]$	$(\partial_\mu\phi)(\bar{\psi}\gamma^\mu\psi)\vert H\vert^2$
		$(\partial_\mu\phi)(\bar{\psi}\gamma^\mu T^A\psi)(H^\dagger T^A H)$
$\phi H_1\bar{H}_2 H_3\bar{H}_4$	$p_\phi\cdot(p_1-p_2)$ + symm.	$(\partial^\mu\phi)(H^\dagger i\overleftrightarrow{D}_\mu H)\vert H\vert^2$

Dimension 8

Particle content	$\mathcal{A}\times f^4$	$\mathcal{O}\times f^4$
ϕ^4	$(p_{\phi_1}\cdot p_{\phi_2})(p_{\phi_3}\cdot p_{\phi_4})$ + symm.	$(\partial_\mu\phi\,\partial^\mu\phi)^2$
$\phi^2 H_1\bar{H}_2$	$(p_{\phi_1}\cdot p_{\phi_2})^2$	$(\partial_\mu\partial_\nu\phi\,\partial^\mu\partial^\nu\phi)\vert H\vert^2$
	$(p_{\phi_1}\cdot p_1)\,(p_{\phi_2}\cdot p_2)$ + symm.	$(\partial^\mu\phi\,\partial^\nu\phi)(D_\mu H^\dagger D_\nu H)$
$\phi^2 V_1 V_2$	$(p_{\phi_1}\cdot p_{\phi_2})\,\langle 12\rangle^2$	$(\partial_\alpha\phi\,\partial^\alpha\phi)V_{\mu\nu}V^{\mu\nu}$
		$(\partial_\alpha\phi\,\partial^\alpha\phi)V_{\mu\nu}\tilde{V}^{\mu\nu}$
		$(\partial_\alpha\phi\,\partial^\alpha\phi)V^A_{\mu\nu}V^{A,\mu\nu}$
		$(\partial_\alpha\phi\,\partial^\alpha\phi)V^A_{\mu\nu}\tilde{V}^{A,\mu\nu}$
	$\langle 1\vert p_{\phi_1}\vert 2]\,\langle 1\vert p_{\phi_2}\vert 2]$	$(\partial^\mu\phi\,\partial_\nu\phi)V_{\mu\alpha}V^{\alpha\nu}$
		$(\partial^\mu\phi\,\partial_\nu\phi)V^A_{\mu\alpha}V^{A,\alpha\nu}$
$\phi^2\psi_1\bar{\psi}_2$	$(p_{\phi_1}\cdot p_1)\,\langle 1\vert p_{\phi_2}\vert 2]$ + symm.	$(\partial_\mu\phi\,\partial_\nu\phi)(\bar{\psi}\gamma^\mu D^\nu\psi)$
$\phi^2\psi_1\bar{\psi}_2 H$	$(p_{\phi_1}\cdot p_{\phi_2})\,\langle 12\rangle$	$(\partial_\mu\phi\,\partial^\mu\phi)\bar{\psi}H\psi$
$\phi^2 H^4$	$p_{\phi_1}\cdot p_{\phi_2}$	$(\partial_\mu\phi\,\partial^\mu\phi)\vert H\vert^4$

Phenomenological application

- Process $\ell^-\ell^+ \to \phi h$ for (not so) high energies

- Cross-section dominated by higher-order interactions

$$\mathscr{L} \supset \frac{C^{(1)}_{\phi\ell^2 D^2 H}}{f^3}\partial_\mu\phi D^\mu \bar{L} H \ell_R + \frac{C^{(1)}_{\phi\ell^2 D^2 H}}{f^3}\partial_\mu\phi \bar{L} H D^\mu \ell_R + h.c.$$

$$\frac{\mathrm{d}\sigma^{\text{tot}}(\ell^-\ell^+ \to \phi h)}{\mathrm{d}\cos\theta} \simeq \frac{1}{512\pi f^6}\Big[(u^2+t^2)\left(|C^{(1)}_{\phi\ell^2 HD^2}|^2 + |C^{(2)}_{\phi\ell^2 HD^2}|^2\right) + 4tu\mathrm{Re}\left(C^{(1)}_{\phi\ell^2 HD^2} C^{(2)*}_{\phi\ell^2 HD^2}\right)\Big],$$