Vector-Pair Production
The Amplitude Way

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TECHNION
Israel Institute of Technology

DPF-PHENO 2024

PHYSICS
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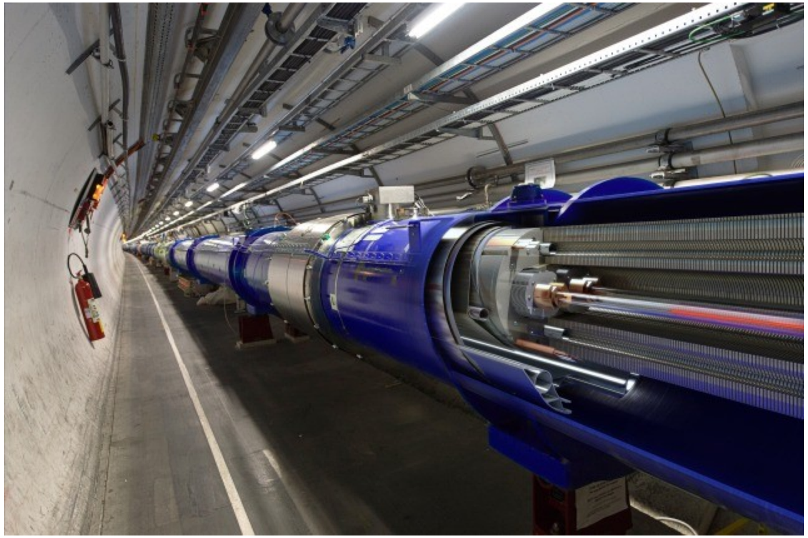
Motivation

- The coming years will see precision measurements of electroweak physics at the LHC



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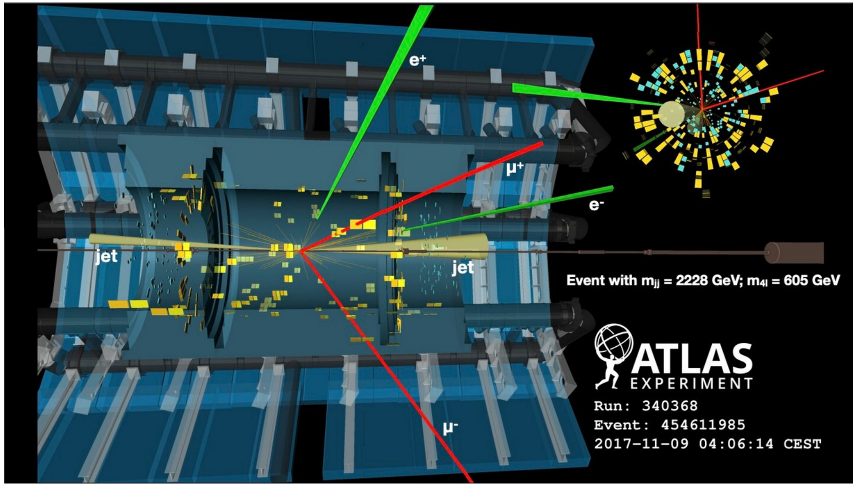

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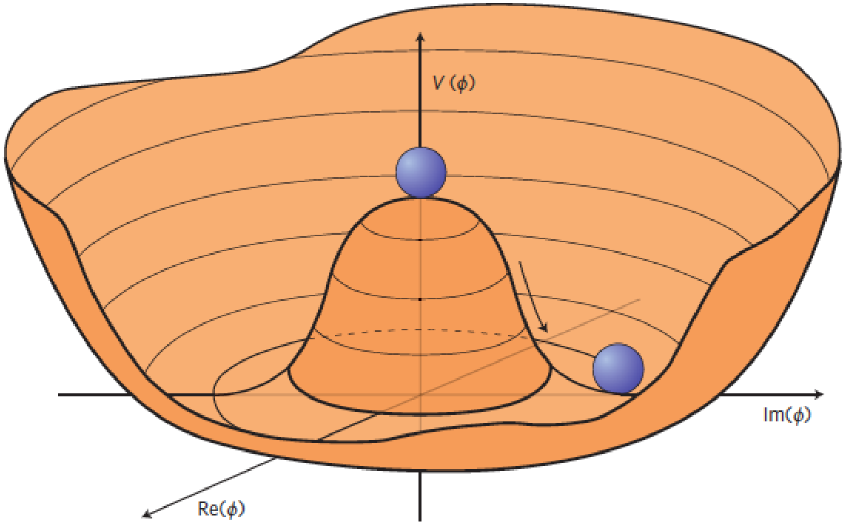
- How do we parameterize these interactions in a model independent way without knowledge of UV physics?
- What do we learn about EWSB?



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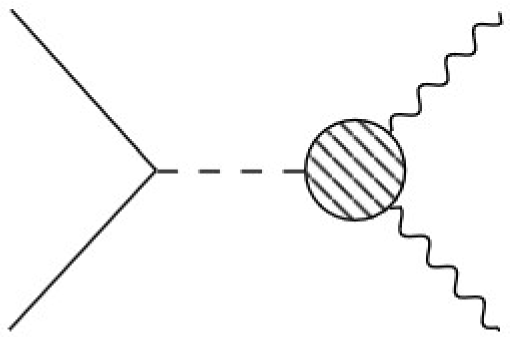
- What do we learn about EWSB?

- Lagrangian formulated EFTs have high number of operators which are difficult to enumerate due to redundancies (EOMs, IBP, Field redef...)

The Goal:

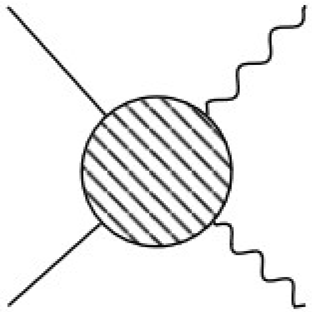
Compute **contact term** contributions to **VV production** at **dimension-8** in the **SMEFT** directly at the **amplitude level**.

Amplitude Structure



Factorizeable

Amplitude Structure

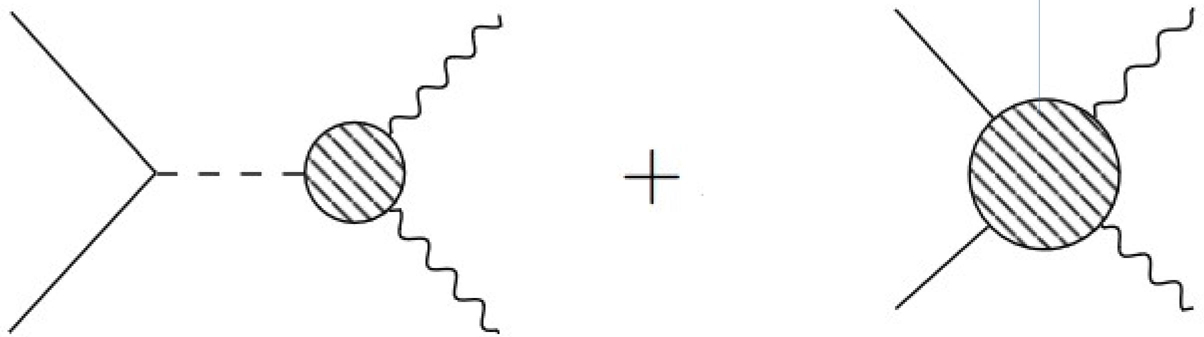


Contact Terms:
4-pt and higher

Amplitude Structure

Sum of higher dim contact terms

$$\mathcal{M}(2 \to 2) =$$



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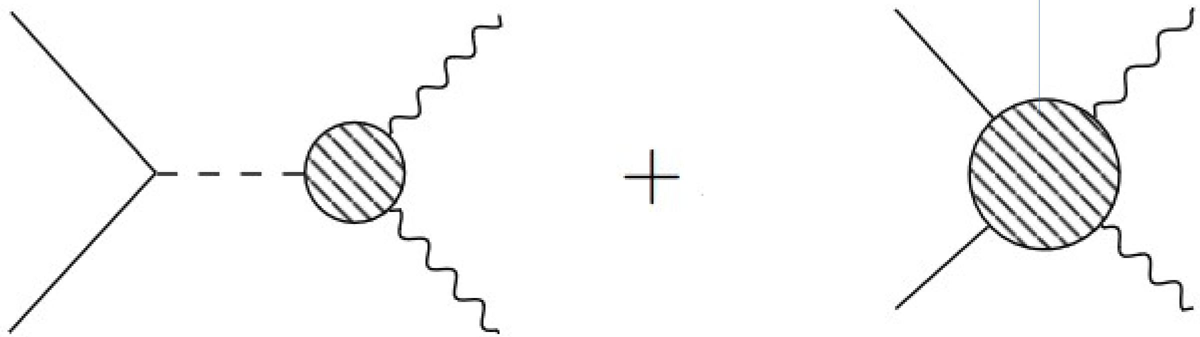
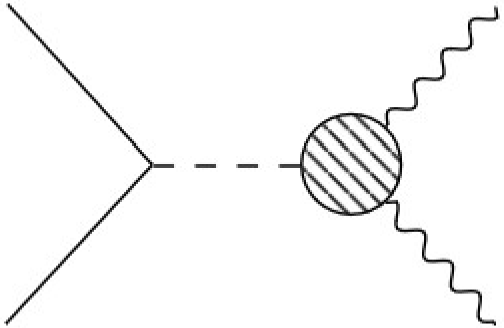
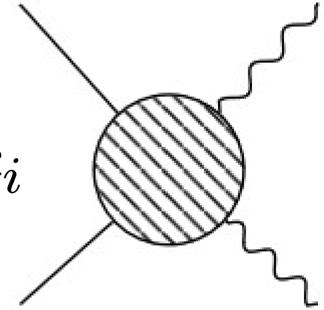


Combining all possible contact term contributions gives the most general EFT amplitude.

Amplitude Structure

$\mathcal{M}(2 \to 2) =$  $+ \sum_i c_i$ 

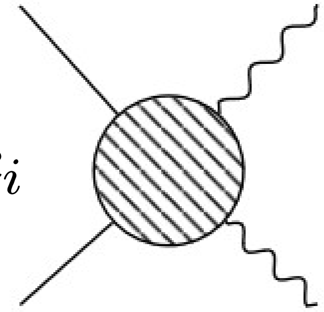
Each independent contact-term comes with a coefficient

Amplitude Structure

Standard **M**odel **EFT**

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \sum_{d>4} c_i \Lambda^{4-d} \mathcal{O}^i$$

$$\sum_i c_i$$



There is a one-to-one correspondence between the massless EFT amplitudes and SMEFT Lagrangian operators

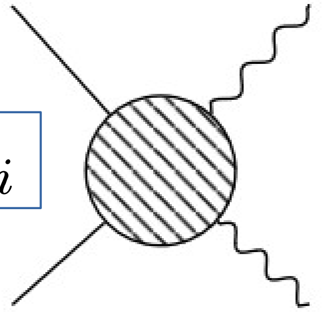
Shadmi, Weiss '18

The SMEFT

Standard Model EFT

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \sum_{d>4} c_i \Lambda^{4-d} \mathcal{O}^i$$

$$\sum_i c_i$$



Wilson Coefficients: Parameterization of New Physics effects

The SMEFT

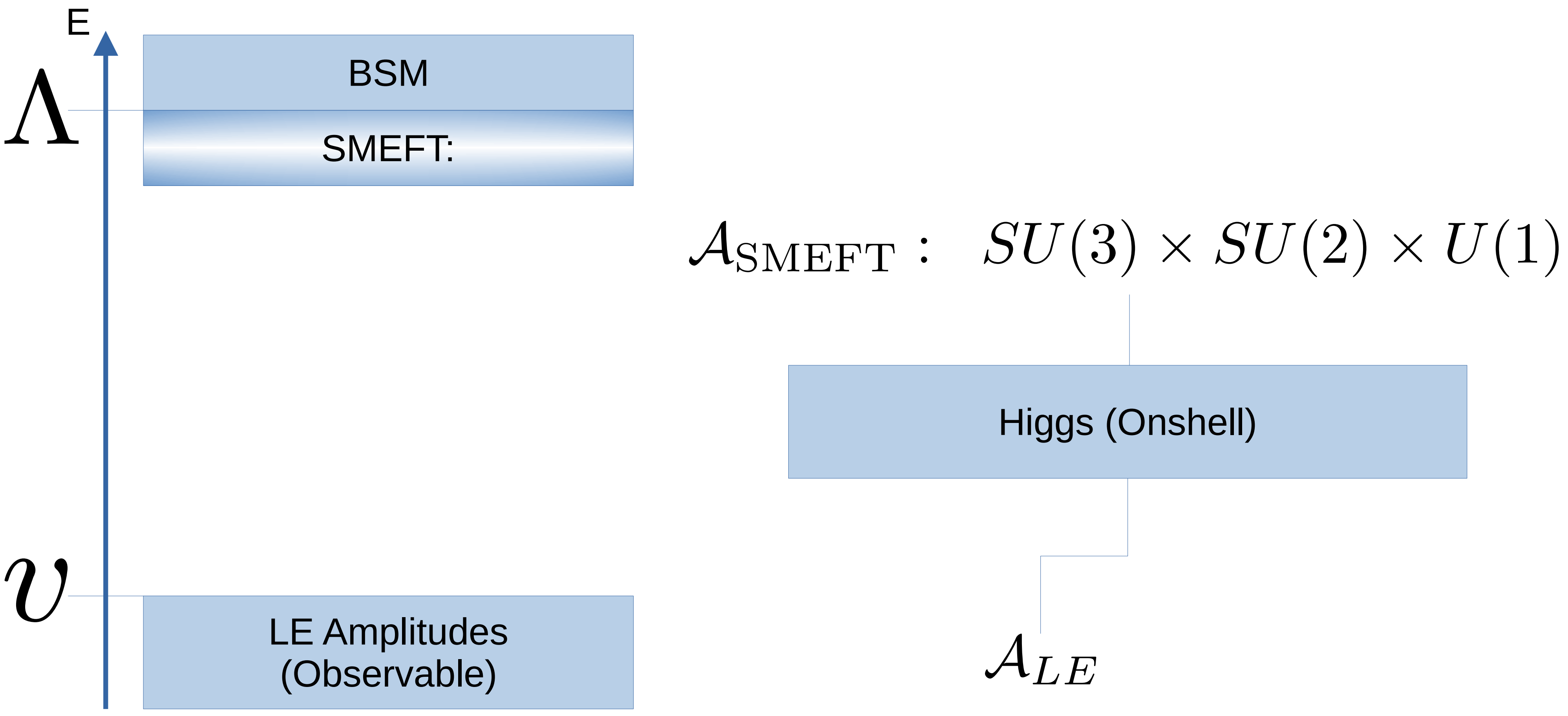
Standard **M**odel **EFT**

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \sum_{d>4} c_i \Lambda^{4-d} \mathcal{O}^i$$

$$\dim [\mathcal{O}] = 8$$

The Goal:

Compute **contact term** contributions to **2-to-2 scattering** processes with **vector-boson final states** at **dimension-8** in the **SMEFT** at the **amplitude level**.



Goals: Construction of SMEFT Amplitudes

Onshell Methods: Spinor Variables

- The Lorentz Group: $SO(3,1) \cong SU(2) \times SU(2)$

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- Basic building blocks are 2-component spinors

Spinors!

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Spinors!

$$p^\mu \to p^{\alpha\dot{\beta}} \equiv p^\mu \sigma_\mu^{\alpha\dot{\beta}}$$

$$|p]^\alpha \langle p|^{\dot{\beta}}$$

Massless: rank(1)

$$|p^I] \langle p_I| \equiv |\mathbf{p}] \langle \mathbf{p}|$$

Massive: rank(2)

- The Lorentz Group: $SO(3,1) \cong SU(2) \times SU(2)$
- Basic building blocks are 2-component spinors

Spinors!

$$|p]^{\alpha} \ \langle p|^{\dot{\beta}}$$

Massless: rank(1)

Massless Case: *helicity weights:*

square = +1

angle = -1

- The Lorentz Group: $SO(3,1) \cong SU(2) \times SU(2)$
- Basic building blocks are 2-component spinors

Spinors!

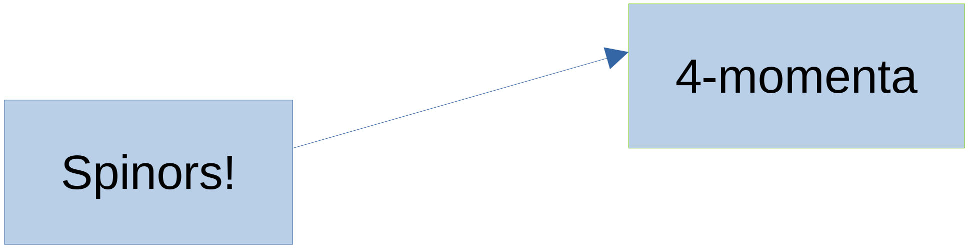
Arkani-Hamed, Huang, Huang '21

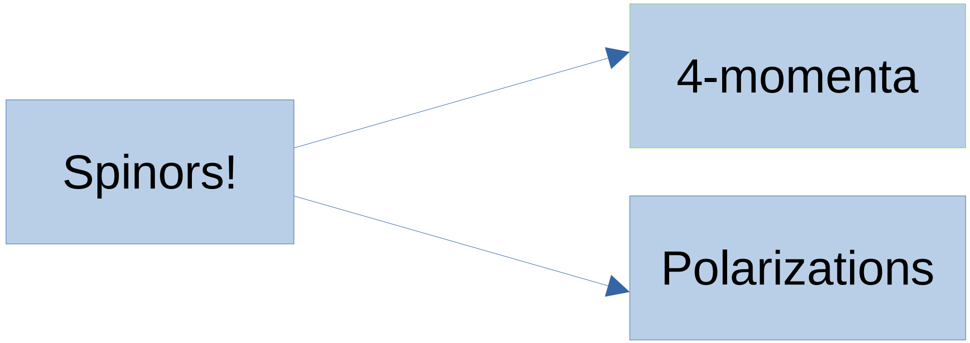
Massive little-group index: $I \in \{1, 2\}$

$$|p^I] \langle p_I| \equiv |\mathbf{p}] \langle \mathbf{p}|$$

Massive: rank(2)

Onshell Methods: Amplitude Construction


4-momenta
Spinors!


Spinors!
4-momenta
Polarizations

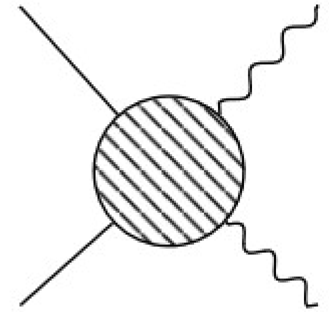
Massless Fermions:

$|p]$ or $|p\rangle$

Spinors!

4-momenta

Polarizations



Massless Vectors

$|p]\,|p]$ or $|p\rangle\,|p\rangle$

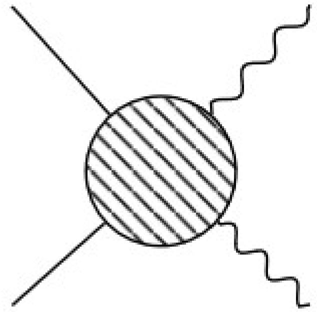
Spinors!

4-momenta

Polarizations

Massive Fermions:

$$|p^I] \text{ or } |p^I\rangle$$



Massive Vectors

$$|p]^{\{I}|p]^{J\}} \text{ or } |p\rangle^{\{I}|p\rangle^{J\}}$$

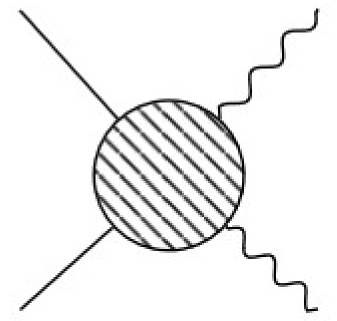
Spinors!

4-momenta

Polarizations

Massive Fermions:

$$|p^I] \text{ or } |p^I\rangle \to |\mathbf{p})$$

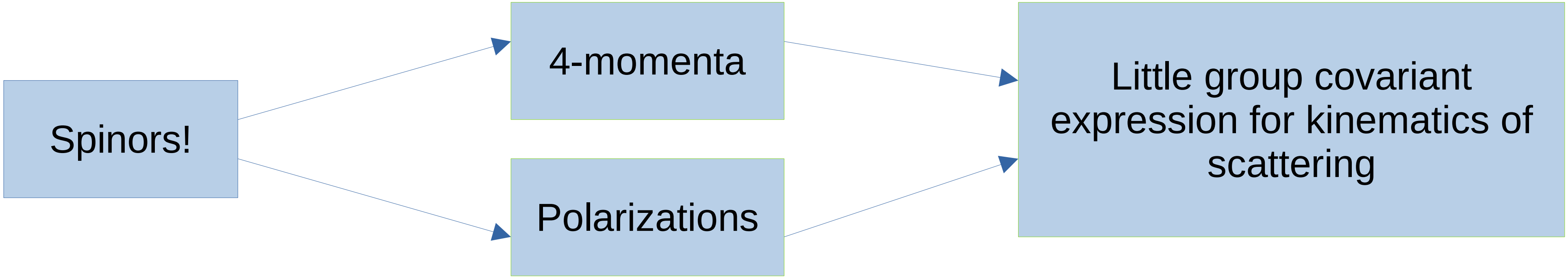


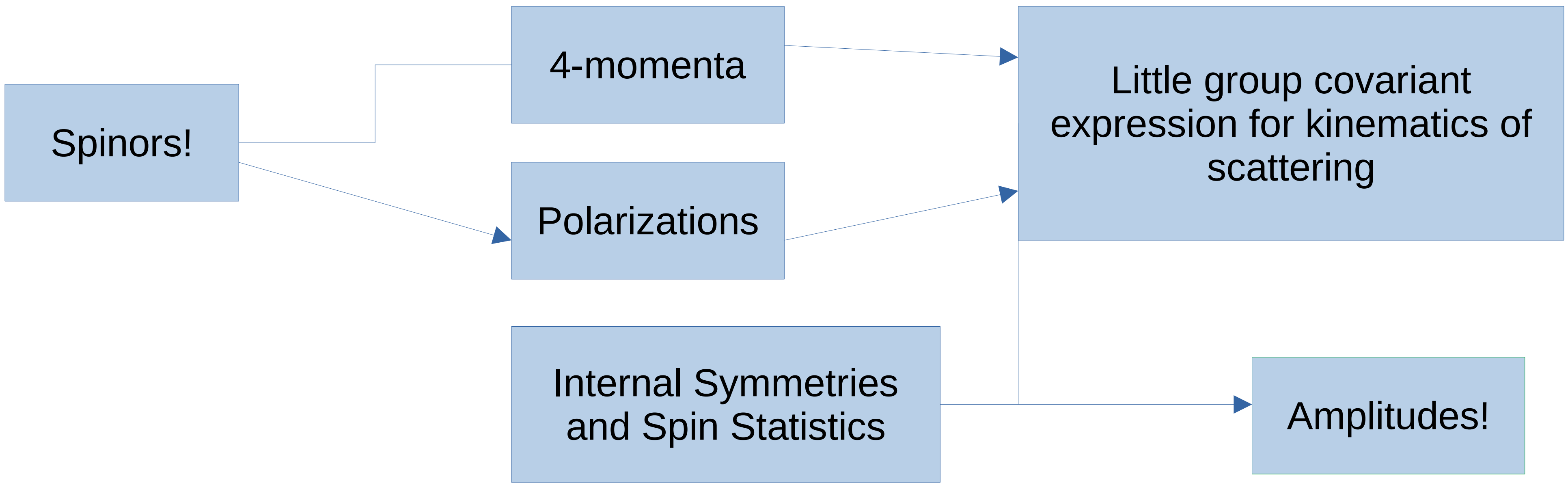
Bold spinors imply LG index symmetrization

Massive Vectors

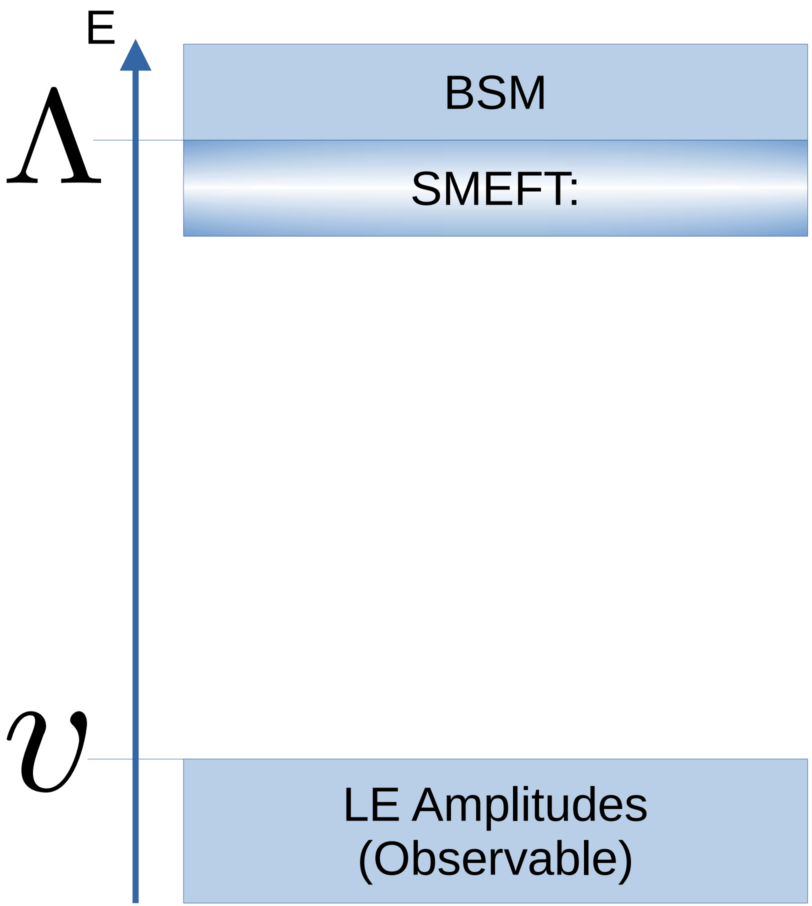
$$|p]^{\{I}|p]^{J\}} \text{ or } |p\rangle^{\{I}|p\rangle^{J\}} \to |\mathbf{p})|\mathbf{p})$$

Arkani-Hamed, Huang, Huang ‘21


Spinors!
4-momenta
Polarizations
Little group covariant expression for kinematics of scattering


Spinors!
4-momenta
Polarizations
Little group covariant expression for kinematics of scattering
Internal Symmetries and Spin Statistics
Amplitudes!

Construction of LE (Massive) SMEFT Amplitudes



Construct set of HE contact terms:

Construction of SMEFT Amplitudes: Massless Amplitudes (HE)

E

Λ

BSM

SMEFT:

$$SU(3) \times SU(2) \times U(1)$$

Construct set of HE contact terms:

$$\Phi \in \{Q, U, D, L, E, H, H^\dagger, W^a, B, G\}$$

v

LE Amplitudes
(Observable)

E

Λ

BSM

SMEFT:

Construct set of HE contact terms:

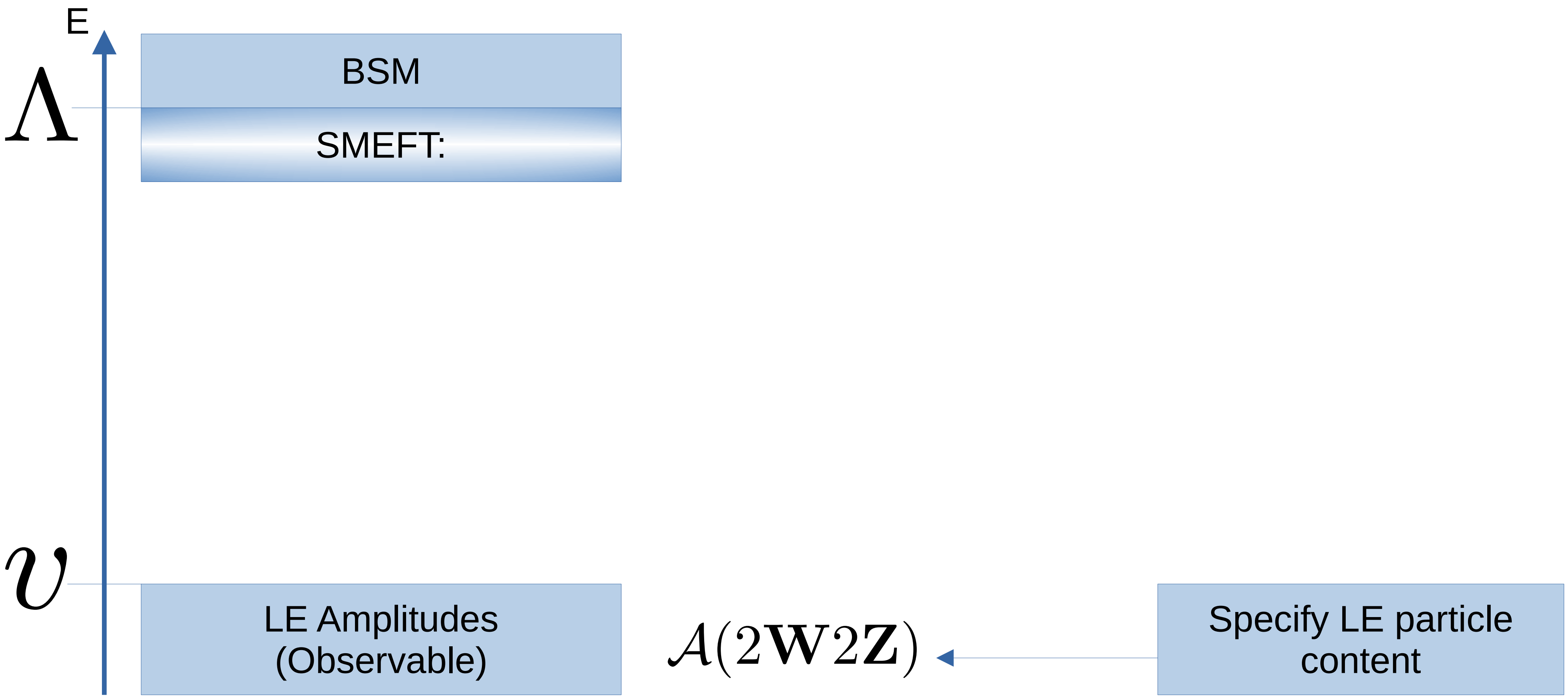
$$SU(3) \times SU(2) \times U(1)$$

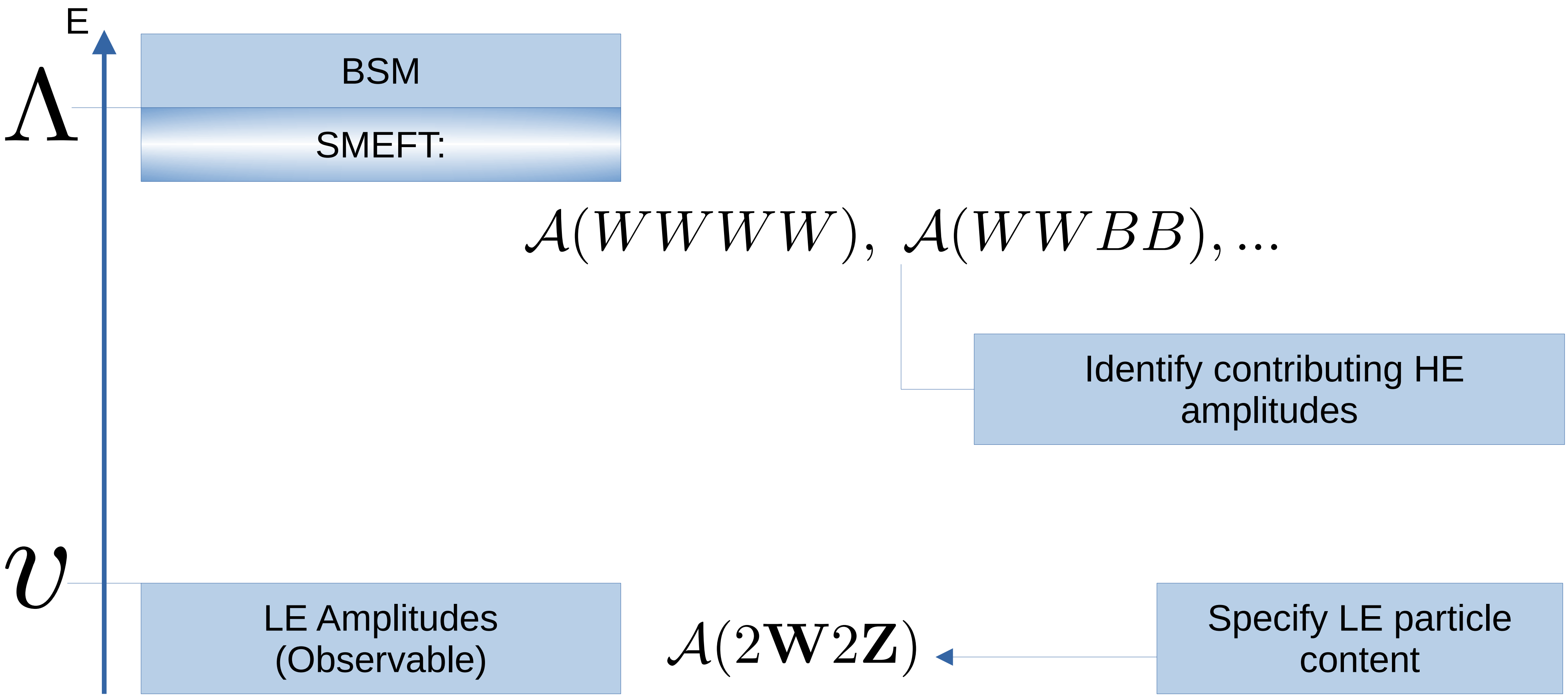
$$\Phi \in \{Q, U, D, L, E, H, H^\dagger, W^a, B, G\}$$

$$\mathcal{A}(WWWWW),\ \mathcal{A}(WWBB),\ ,\ldots,\ \mathcal{A}(Q^cQBH^\dagger H),\ldots$$

v

LE Amplitudes
(Observable)


E
Λ
BSM
SMEFT:
v
LE Amplitudes
(Observable)
$\mathcal{A}(2\mathbf{W}2\mathbf{Z})$
Specify LE particle
content


E
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Identify contributing HE amplitudes
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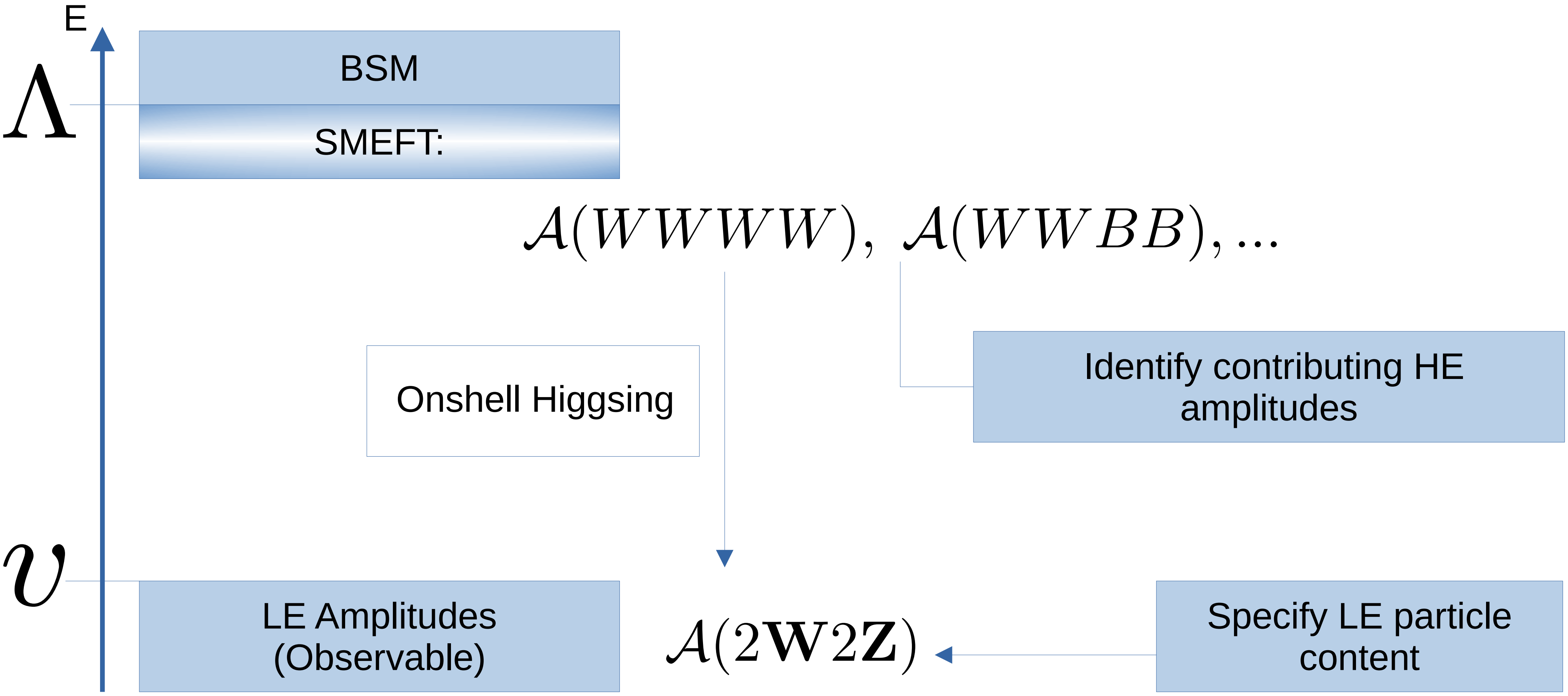
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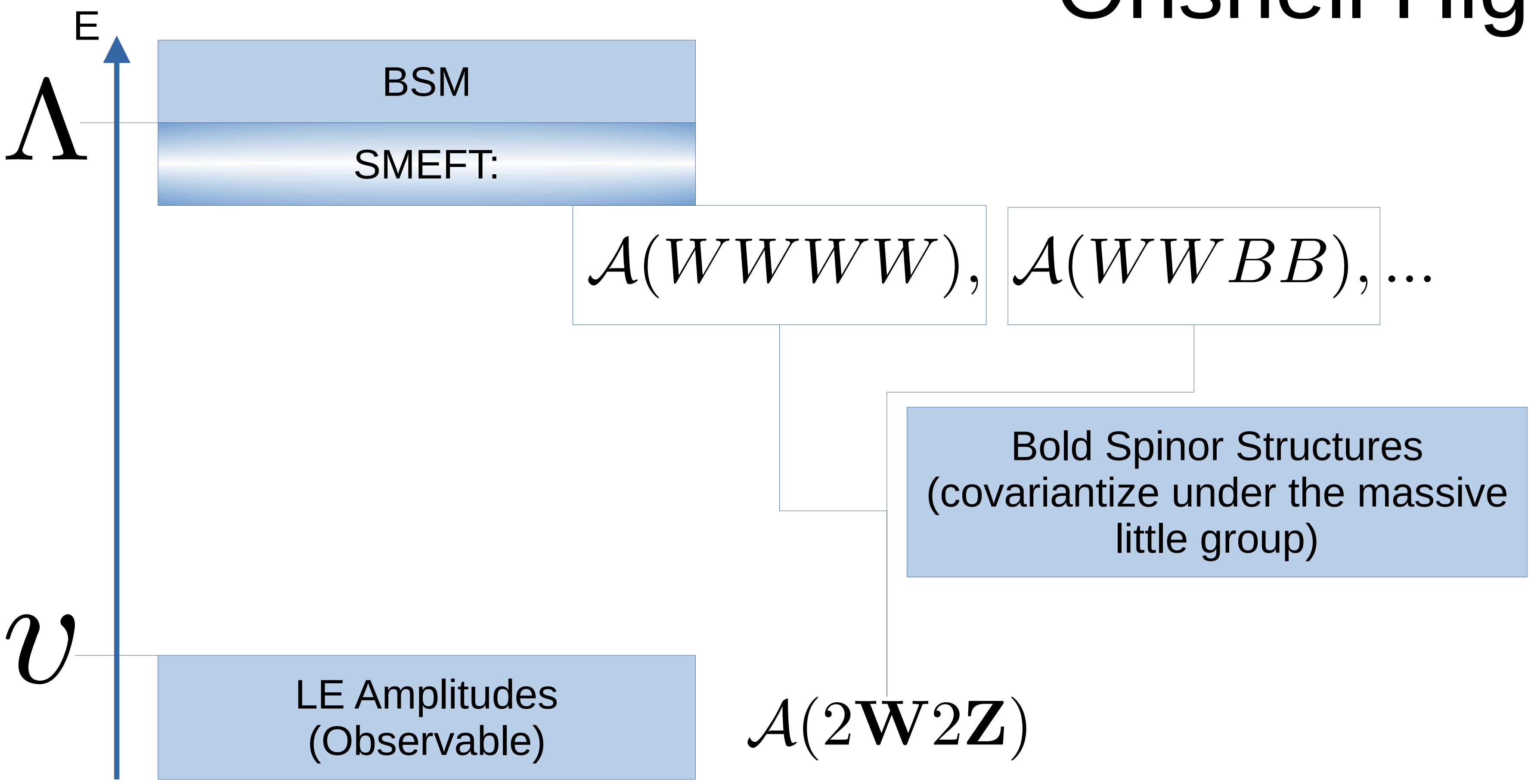
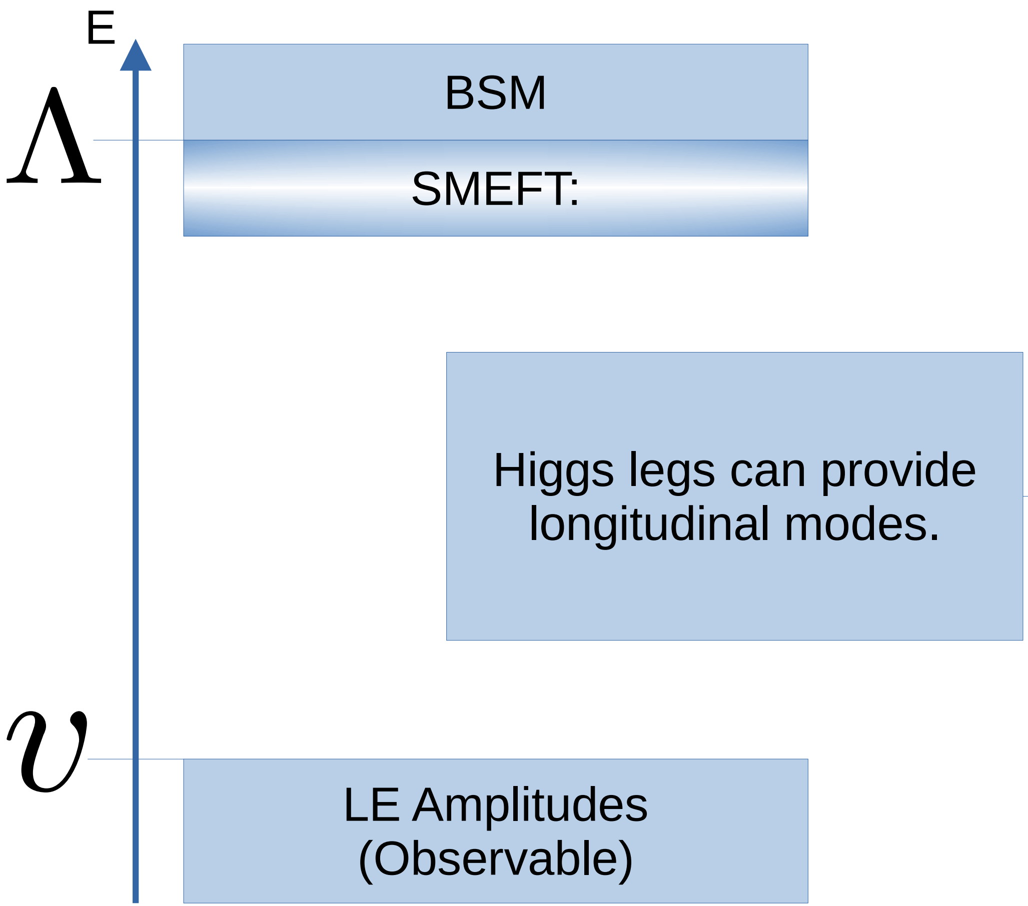
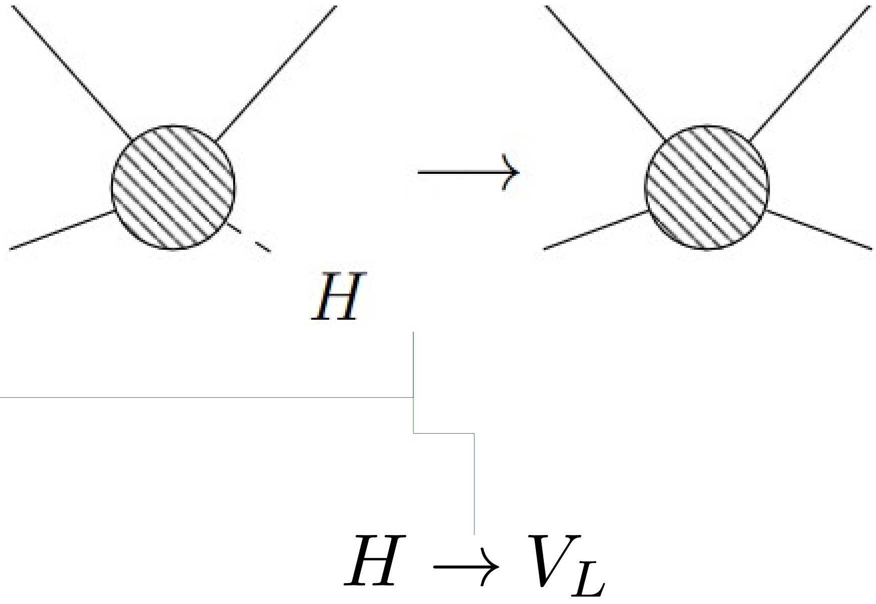


Balkin, Durieux, Kitahara, Shadmi, Weiss '21

Onshell Higgsing





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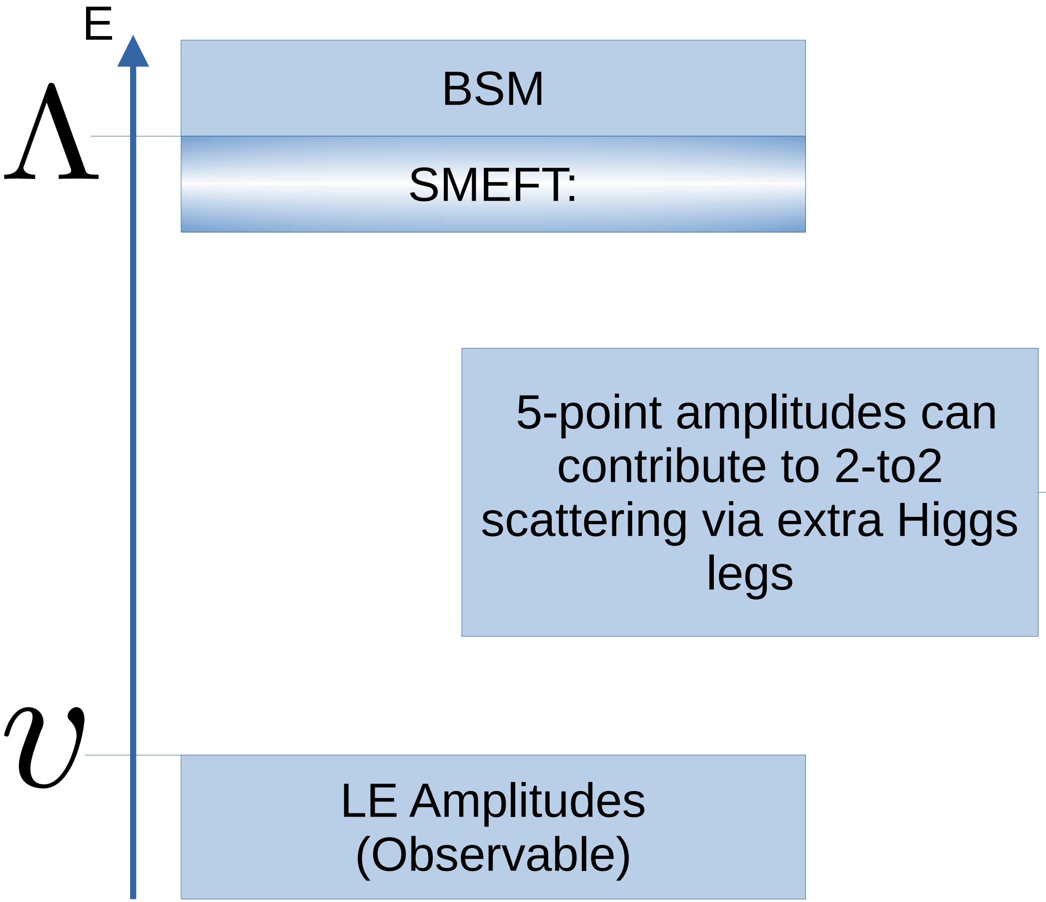
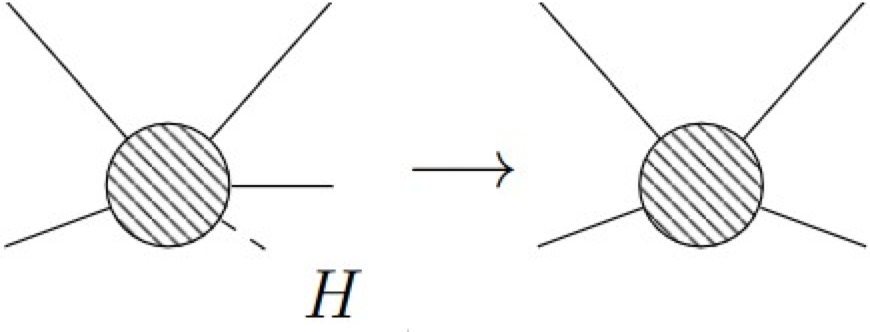
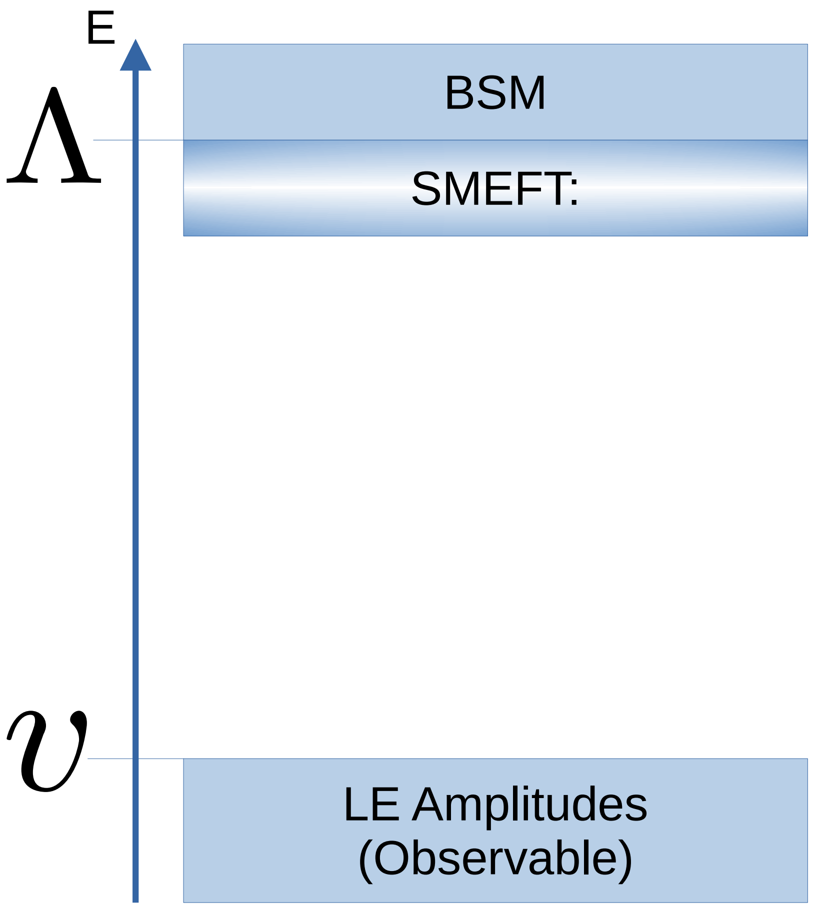




$$H \to \frac{1}{\sqrt{2}}(h+v)$$

$$p_h \to 0$$

Balkin, Durieux, Kitahara, Shadmi, Weiss ‘21

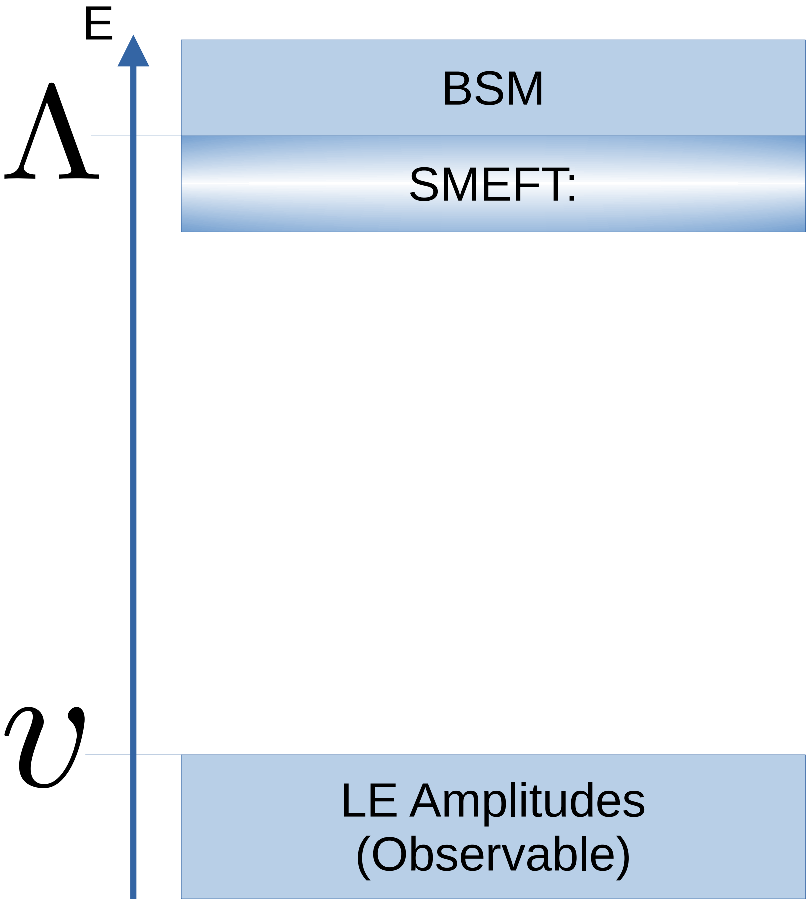


$$\mathcal{A}(Q^c Q B H^\dagger H)$$

5-point amplitudes can contribute to 2-to2 scattering via extra Higgs legs

Higgs legs can provide longitudinal modes.

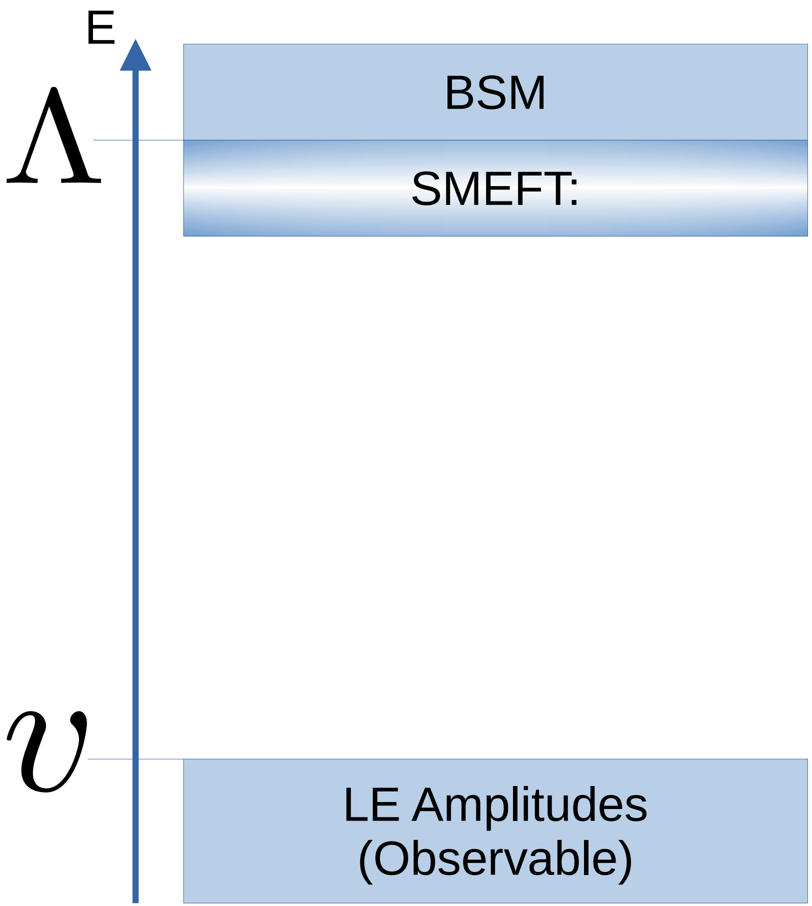
$$\mathcal{A}(u^c d 2\mathbf{Z}) \cdot v$$



$$\mathcal{A}(Q^c Q B H^\dagger H)$$

One of the two Higgs legs maps to the longitudinal mode of the Z

$$\mathcal{A}(u^c d 2\mathbf{Z}) \cdot v$$



$$\mathcal{A}(Q^c Q B H^\dagger H)$$

The remaining Higgs leg is "soft," incurs power of the VeV

$$\mathcal{A}(u^c d 2\mathbf{Z}) \cdot v$$

Results

Results

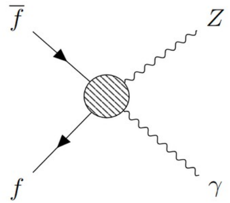
- Full parameterization of LE (massive) VVVV and ffVV contact term amplitudes generated by dim-8 SMEFT

Results

- Full parameterization of LE (massive) VVVV and ffVV contact term amplitudes generated by dim-8 SMEFT
- Leading order (no dim=6 contributions for these amplitudes)

Liu, Ma, Shadmi, Waterbury ‘23

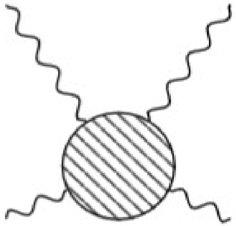
- Selection rules on kinematic configurations of observable amplitudes



$\mathcal{A}(\bar{f}f \to Z\gamma)$

$$[\mathbf{3}4]^2\left([2\mathbf{3}1\rangle - [241\rangle\right)$$

$$[\mathbf{12}]^2\,[\mathbf{34}]\,\langle\mathbf{34}\rangle$$



$\mathcal{A}(WW \to WW)$

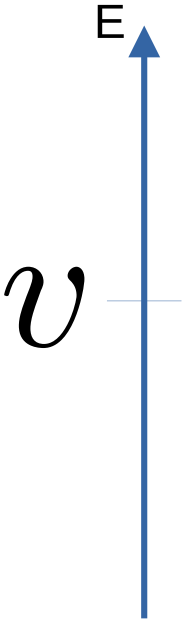
- SU(2) Symmetry Breaking pattern in the amplitudes, e.g:

Structure	$\bar{u}uW^+W^-$	$\bar{d}dW^+W^-$
$[\mathbf{13}][\mathbf{34}]\langle\mathbf{42}\rangle$	$\frac{v}{\sqrt{2}}(c_2^{Q^cQW_+2H} + c_3^{Q^cQW_+2H})$	$-\frac{v}{\sqrt{2}}c_2^{Q^cQW_+2H}$

$$\mathrm{Q} \equiv \begin{pmatrix} u \\ d \end{pmatrix}$$

- Distinguish the SMEFT from bottom-up amplitude construction (HEFT):

Shadmi, Weiss ‘18
Durieux, Kitahara, Shadmi, Weiss ‘19
Liu, Ma, Shadmi, Waterbury ‘23



LE Amplitudes (HEFT)

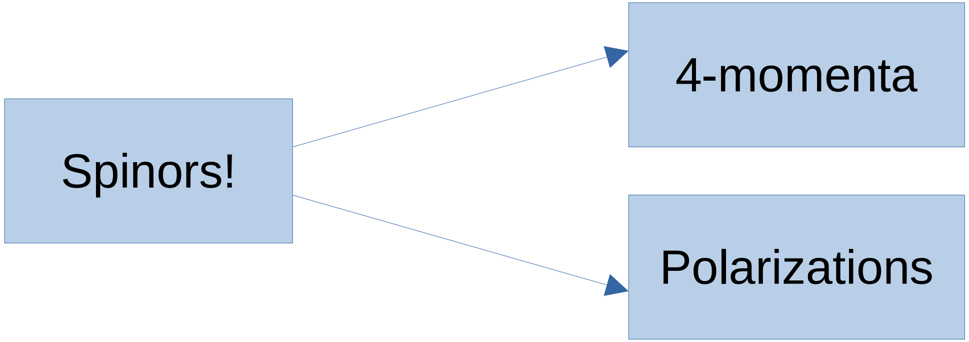
$$SU(3) \times U(1)_{EM}, \text{physical particles} \; \rightarrow \mathcal{A}_{LE}$$

Summary

- Derived LE dim=8 SMEFT amplitudes using onshell Higgsing:
  - Model independent parameterization of low energy observables
  - Complete basis for specific processes: no redundancies!
  - Identification of theoretically interesting observables for study at colliders.

Backup Slides

Massless Onshell Amplitude Construction

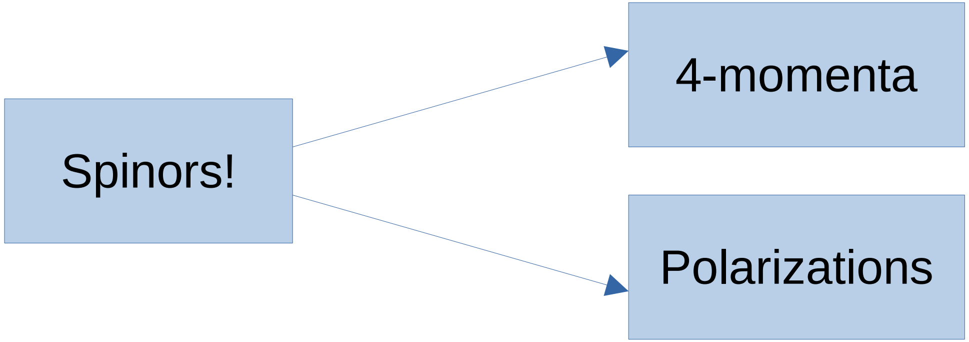


$$[p_1 p_2] \equiv [p_1|^{\alpha}\,|p_2]_{\alpha}$$

$$\langle p_1 p_2\rangle \equiv \langle p_1|^{\dot\beta}\,|p_2\rangle_{\dot\beta}$$

Contraction of spinors gives little-group covariant expressions

Massless Onshell Amplitude Construction



$$[\mathbf{p}q]\,[\mathbf{p}r] \equiv \begin{cases} [p_1^I q]\,[p_1^J r] & I = J \\ [p_1^I q]\,[p_1^J r] + [p_1^J q]\,[p_1^I r] & I \neq J \end{cases}$$

For Vectors, symmetrization
over massive little-group indices

Arkani-Hamed, Huang, Huang (2021)

Onshell Methods

In the Lagrangian formalism, operators must be hermitian, e.g.:

$$\mathcal{O}_1 \equiv c_1 \overline{u} \gamma^\nu u H^\dagger \overrightarrow{D}^\mu H B_{\mu\nu}$$

$$c_1 = c_1^* \Rightarrow c_1 \in \mathbb{R}$$

Or come with hermitian conjugates, e.g.:

$$\mathcal{O}_2 \equiv c_2 \overline{u} \gamma^\nu d \tilde{H}^\dagger \overrightarrow{D}^\mu H B_{\mu\nu} + c_3 \overline{d} \gamma^\nu u H^\dagger \overrightarrow{D}^\mu \tilde{H} B_{\mu\nu}$$

$$c_3 = c_2^* \Rightarrow c_2 \in \mathbb{C}$$

Onshell Methods

This hermiticity is not built into amplitude construction, so must be imposed:

$$c_1\,[23]\,[3(4-5)1\rangle \quad \longleftrightarrow \quad c_2\,\langle 23\rangle\,\langle 3(4-5)2]$$

$$c_3\,[13]\,[3(4-5)2\rangle \quad \longleftrightarrow \quad c_4\,\langle 13\rangle\,\langle 3(4-5)2]$$

Complex Conjugation

$$\Rightarrow c_2 = c_1^*, \quad c_4 = c_3^*$$

4 complex coefficient → 2 complex coefficients. This counting applies to all amplitudes.

Onshell Methods

These amplitudes are also related by CP transformations:

$$c_1\,[23]\,[3(4-5)1\rangle \quad \longleftrightarrow \quad c_2\,\langle 23\rangle\,\langle 3(4-5)2]$$

$$c_3\,[13]\,[3(4-5)2\rangle \quad \longleftrightarrow \quad c_4\,\langle 13\rangle\,\langle 3(4-5)2]$$

CP

$$\Rightarrow c_2 = c_1\,, \quad c_4 = c_3$$

Demanding CP invariance: 2 complex coefficients → two real coefficients