Vector Pair Production: The Onshell Way

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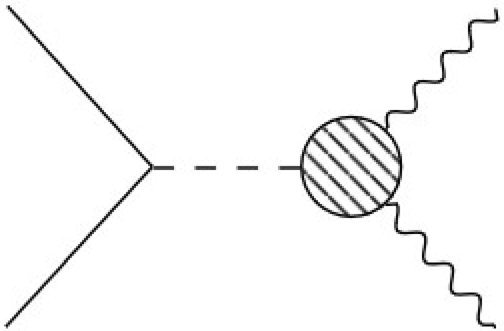
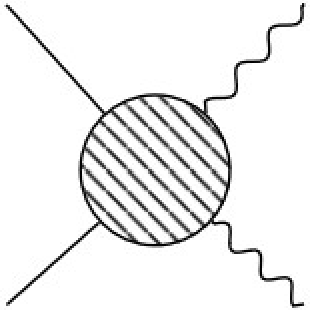
In collaboration with Hongkai Liu (BNL)

BSM Odyssey,
Cargese 2025 Intl.
Summer School



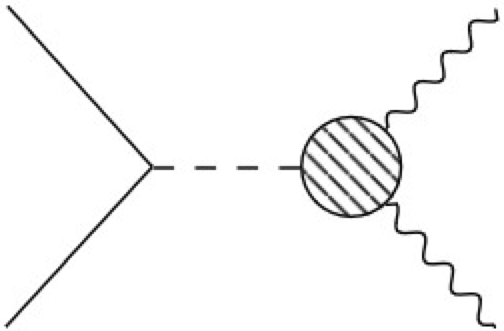
Factorize-able Terms

- Can be constructed from lower point amplitudes.



Contact Terms

- Input for construction of higher-point amplitudes
- Parameterize NP contributions in the EFT.



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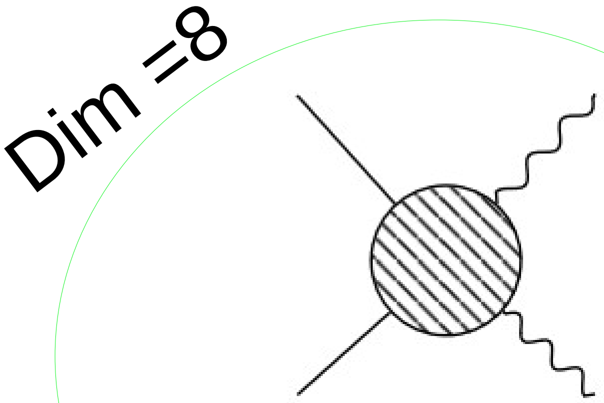

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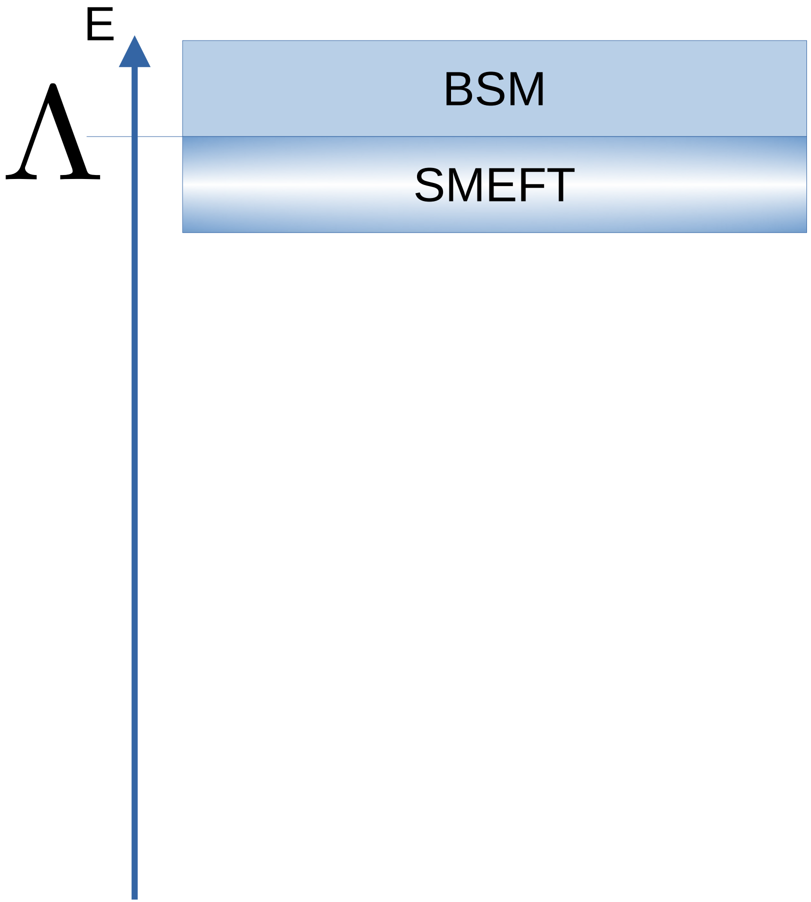
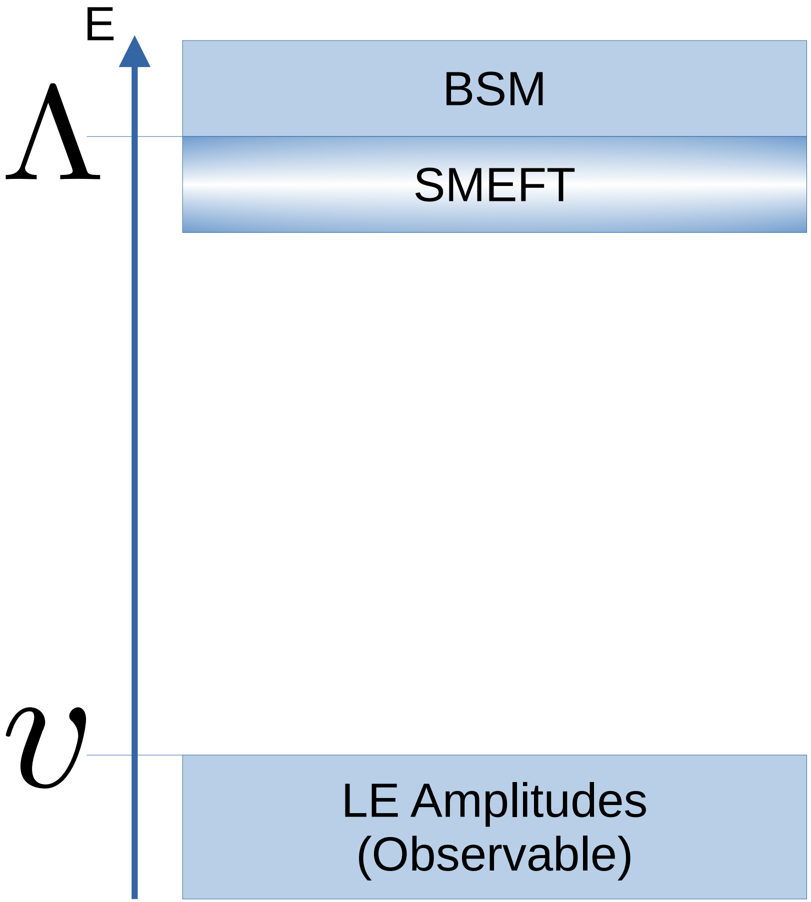

E
Λ
BSM
SMEFT


E
Λ
BSM
SMEFT
v
LE Amplitudes
(Observable)

E

Λ

BSM

SMEFT

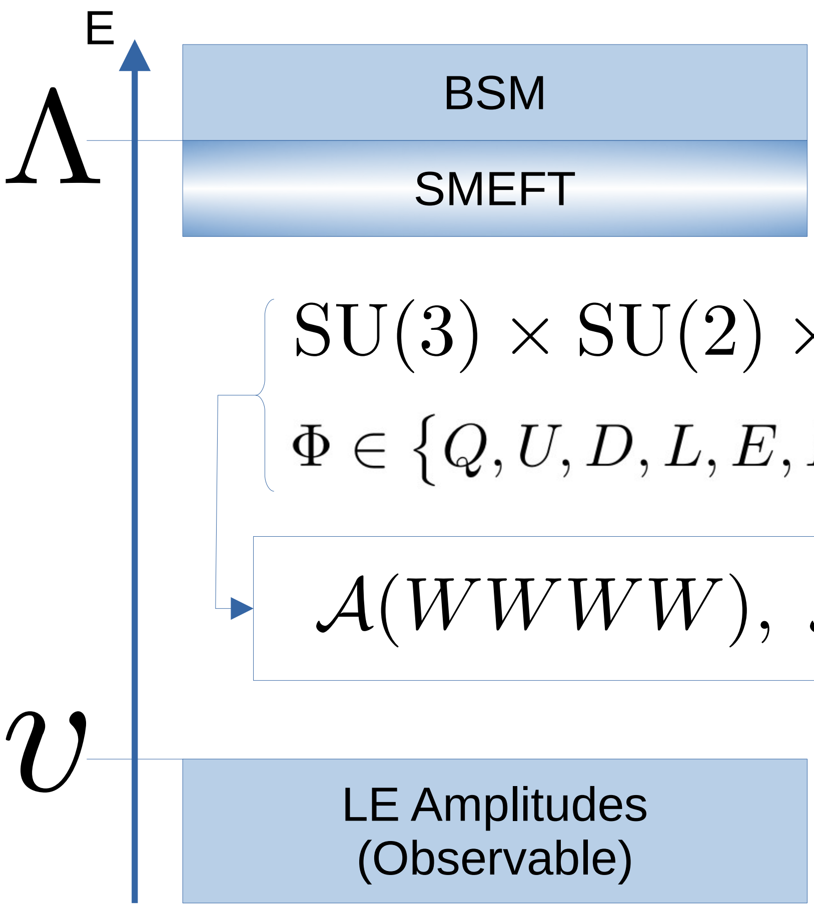
$$\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$$

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

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

v

LE Amplitudes
(Observable)



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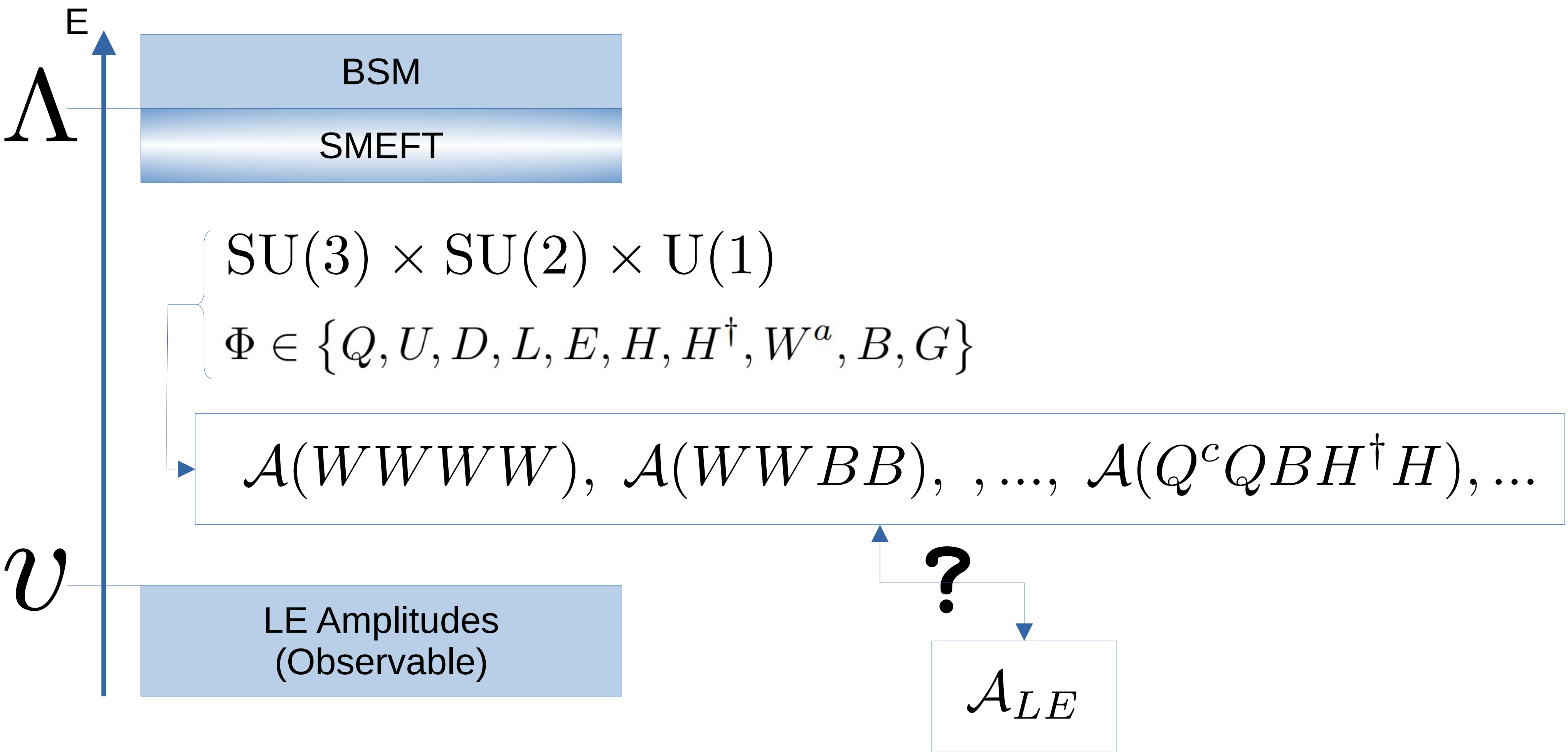
$$\mathcal{A}_{LE}$$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?
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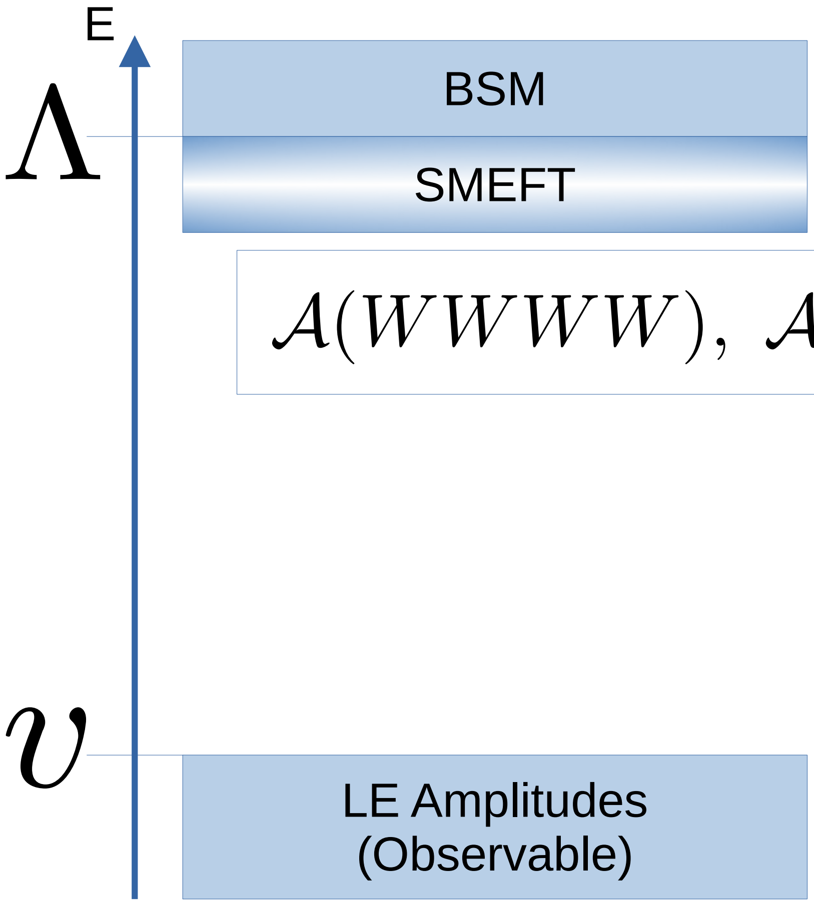


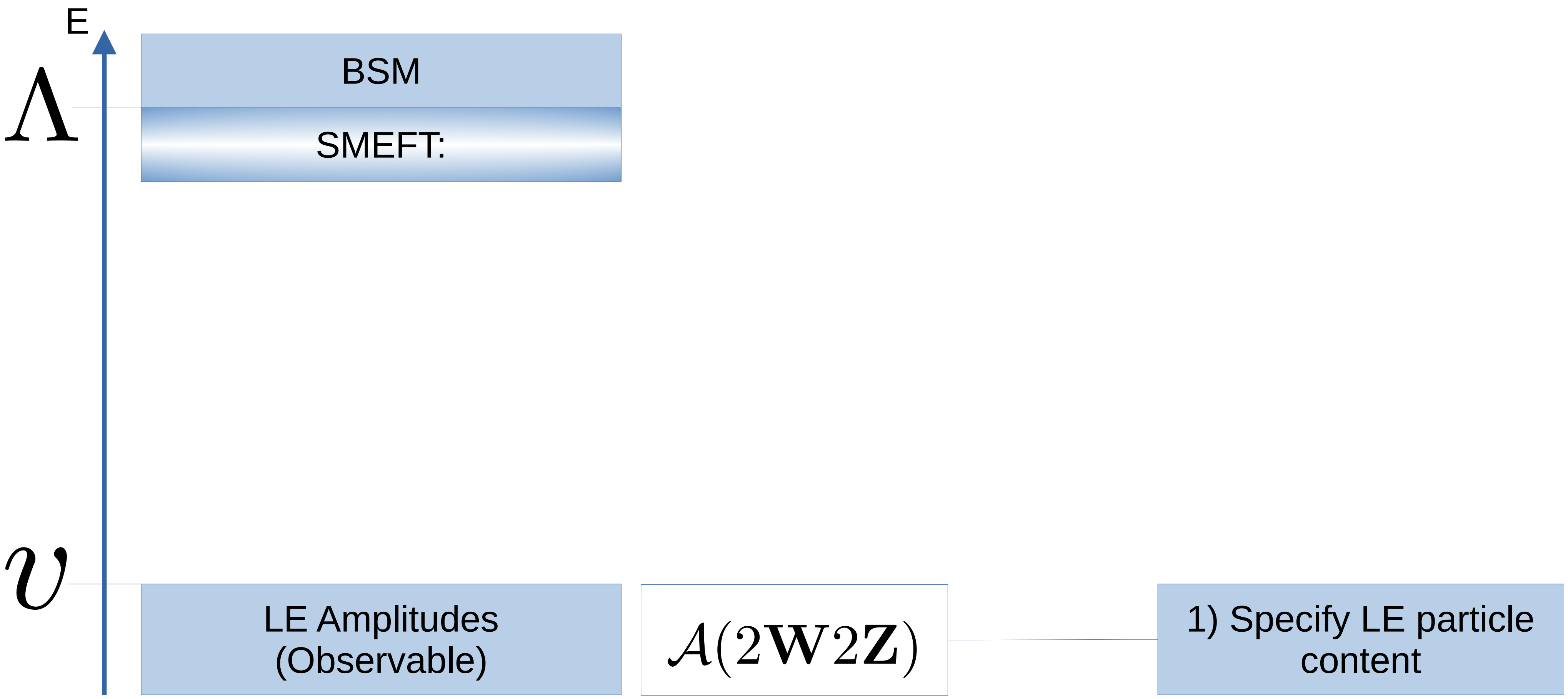
U(1) Covariant

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

Little Group!!

$$\mathcal{A}_{LE}$$

SU(2) Covariant


E
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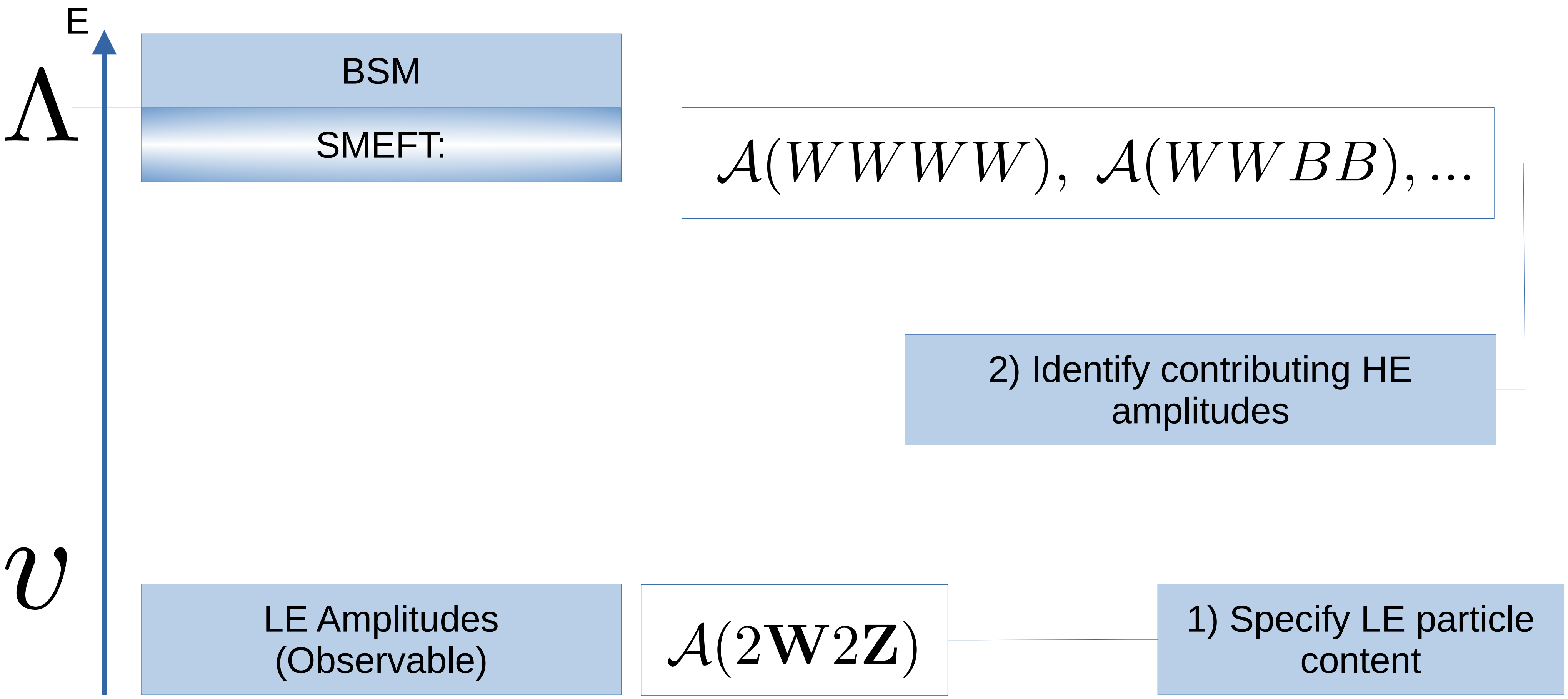
SMEFT:
v
LE Amplitudes
(Observable)
$\mathcal{A}(2\mathbf{W}2\mathbf{Z})$
1) Specify LE particle
content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$\mathcal{A}(WWWWW), \mathcal{A}(WWBB), \ldots$
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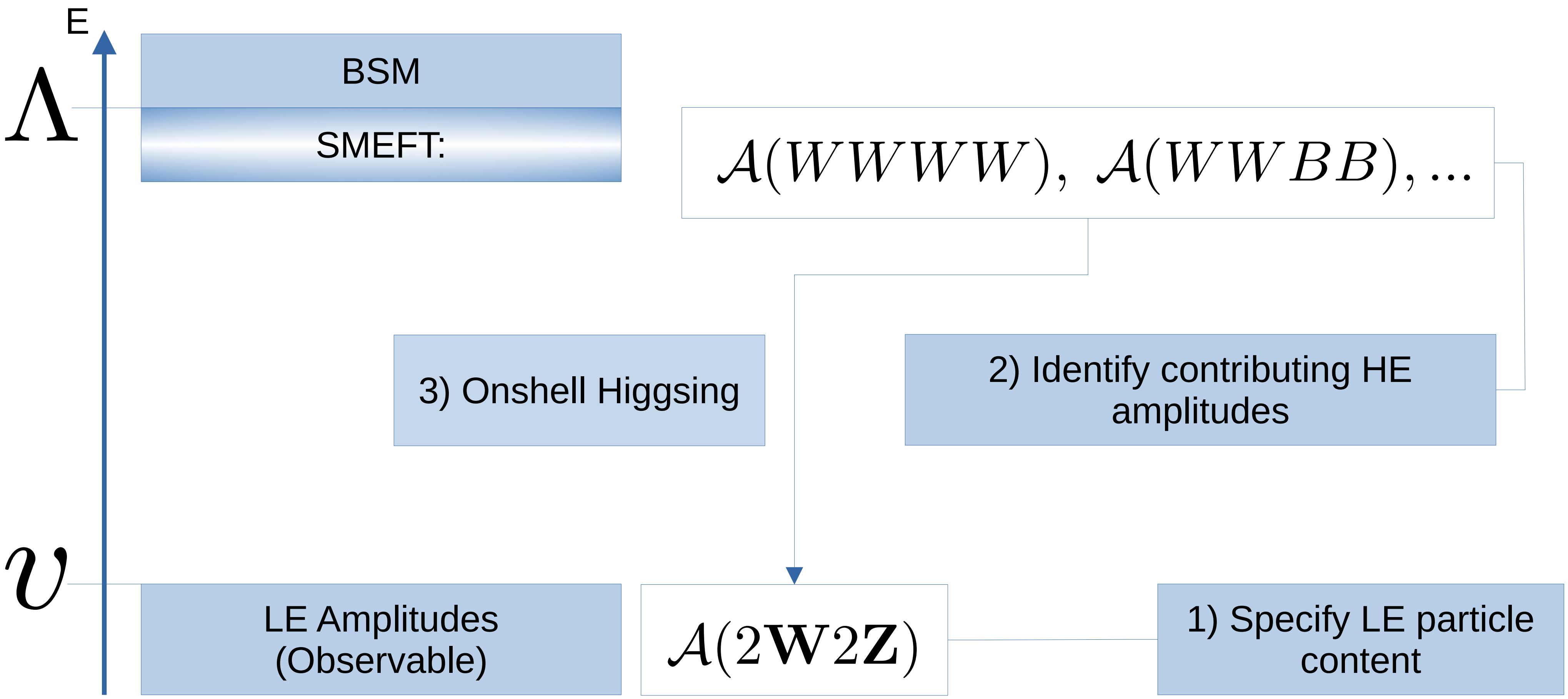
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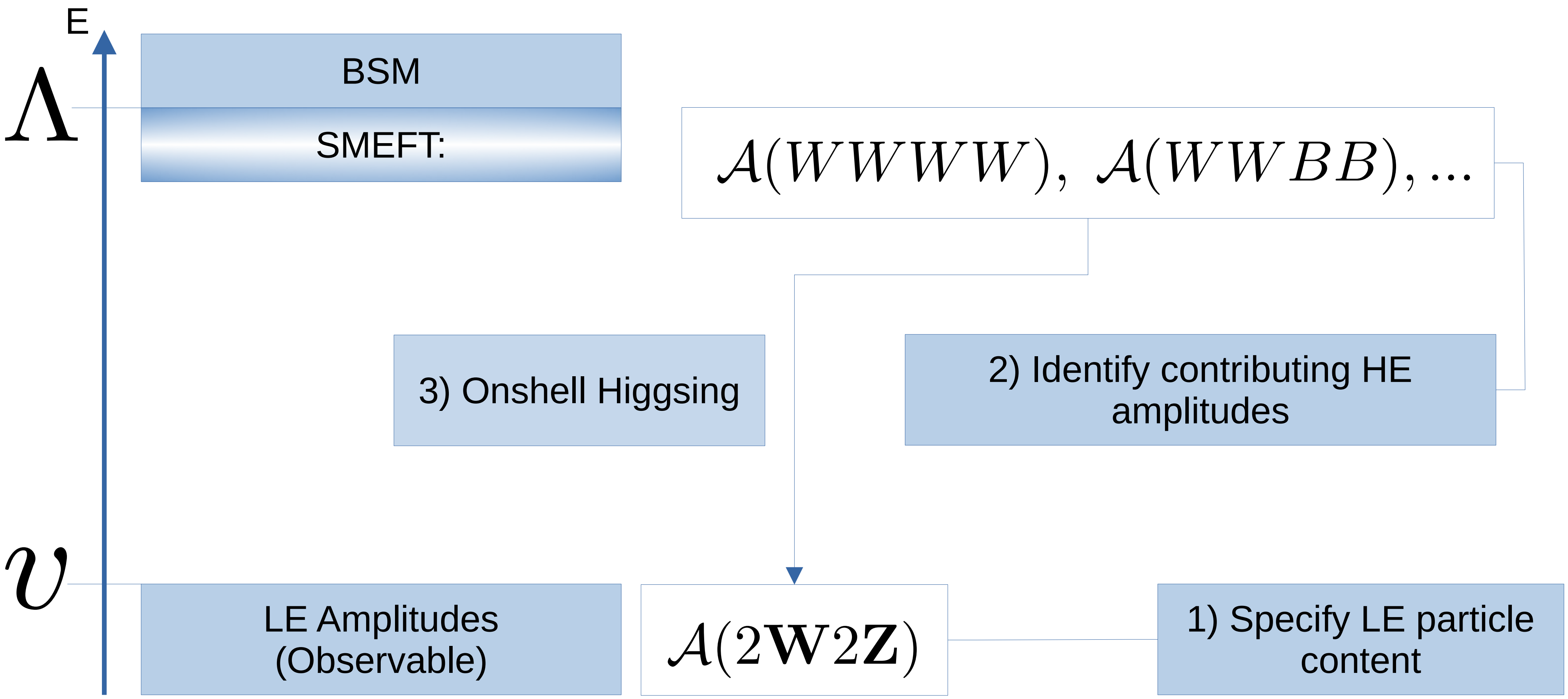
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LE Amplitudes (Observable)
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1) Specify LE particle content

- 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
- Comparison to HEFT

Thanks for Listening!

Backups

The Standard Model EFT (SMEFT)

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

$$SU(3)_C \times SU(2)_L \times U(1)_Y \; + \; \Phi \in \{Q, U, D, L, E, H, H^\dagger, W^a, B, G\}$$

Effective Field Theories

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

Constructing higher dim operators is a significant challenge due to:
- IBP
- EOMS
- Field Redefinitions

The Standard Model EFT (SMEFT)

e.g. for the SM Effective Field Theory (SMEFT):
Dim 6 operators, 1 fermion gen: 59
Dim 8 operators, 1 fermion gen: 889
Dim 8 operators, 3 fermion gen: >40000

Amplitude Structure

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

Amplitude Structure

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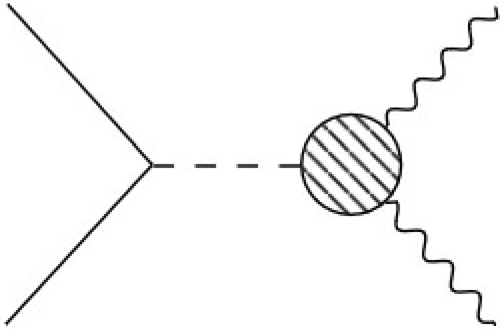
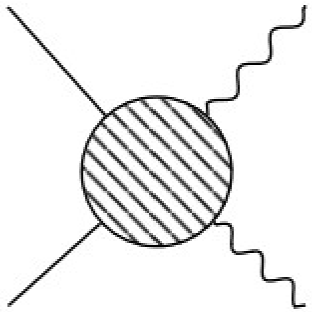


Factorizeable

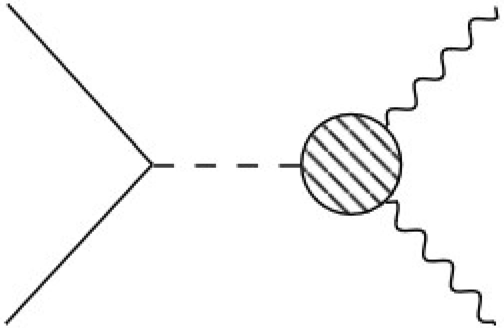
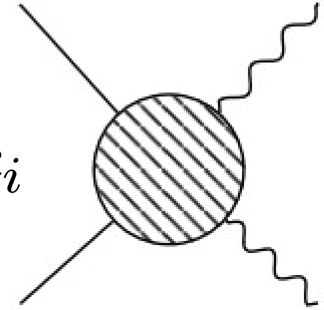
Amplitude Structure

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



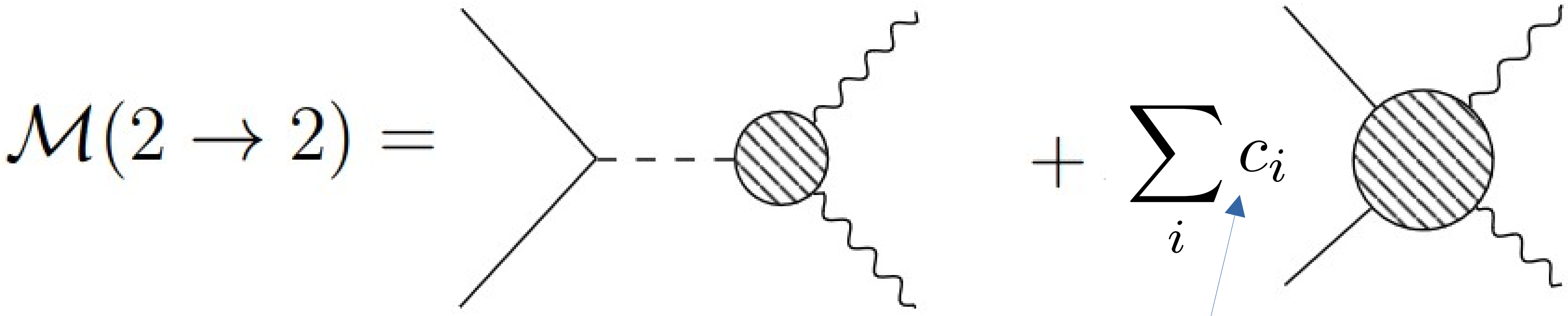
Contact Terms:
4-pt and higher

Amplitude Structure

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

Each independent contact-term comes with a coefficient

Amplitude Structure

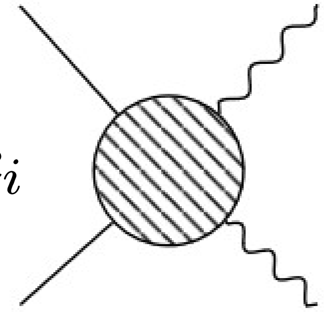


Combining all possible contact term contributions gives the most general EFT amplitude.

Contact with SMEFT

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

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



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

Shadmi, Weiss '18

Contact with SMEFT

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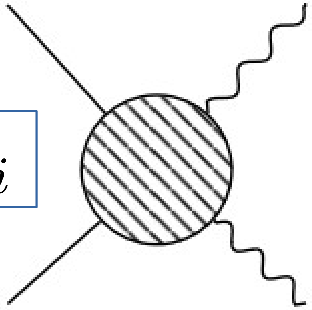

Wilson Coefficients: Parameterization of New Physics effects

Contact with SMEFT

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

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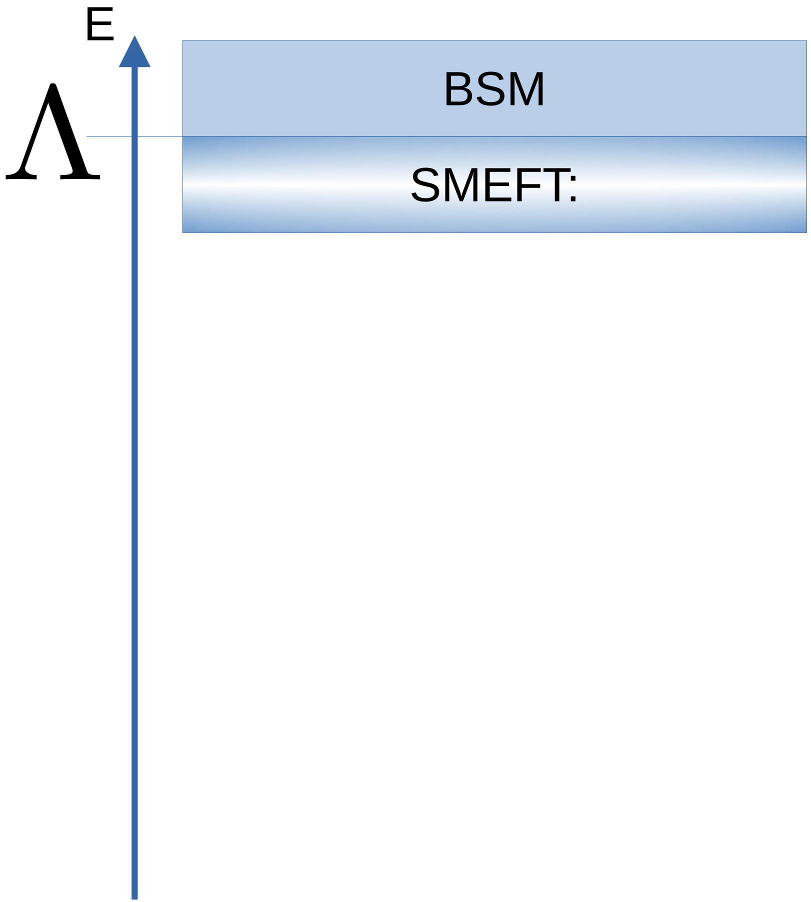
$$\dim[\mathcal{O}] = 8$$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Λ
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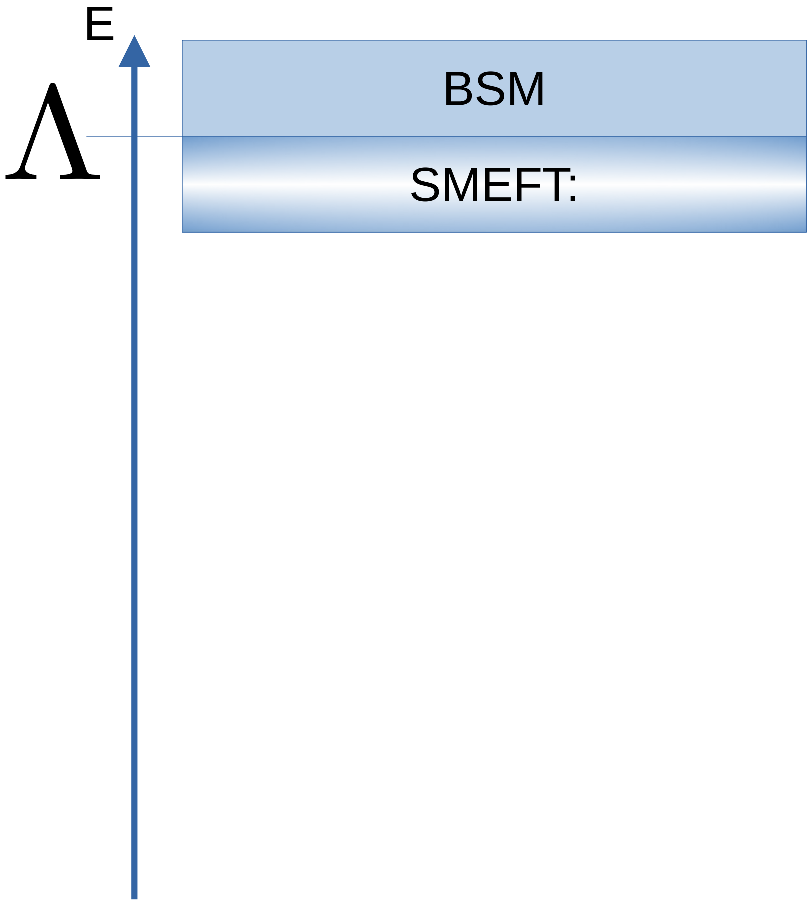
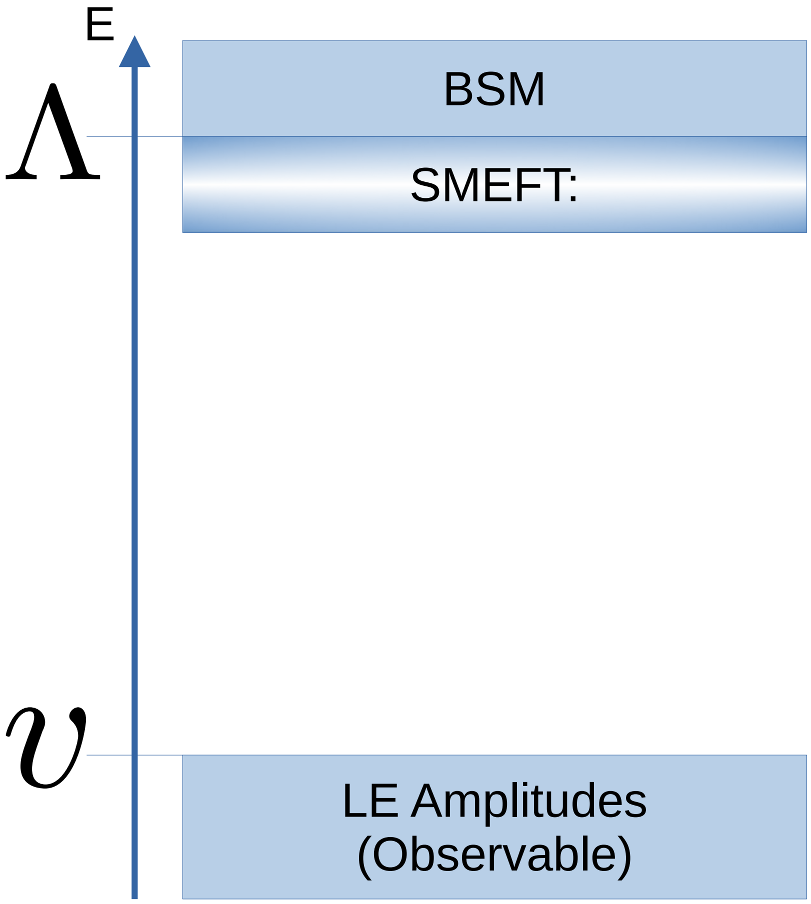


$$\mathcal{A}_{\text{SMEFT}} : \quad SU(3) \times SU(2) \times U(1)$$



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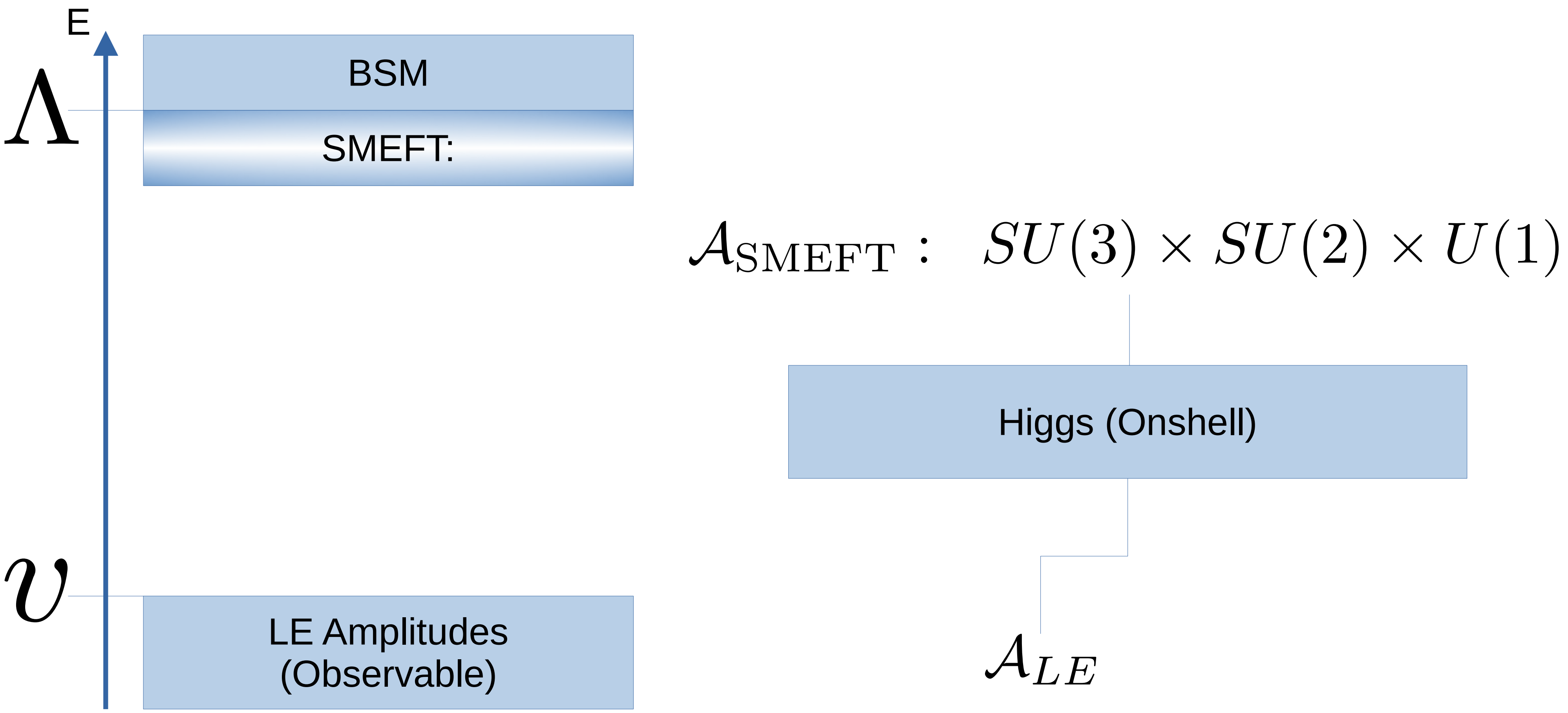

Goals: Construction of SMEFT Amplitudes

Onshell Methods: Spinor Variables

The Little Group

States in QFT

$$|p, \sigma\rangle = U(L(p;k))\,|k, \sigma\rangle$$

The Little Group

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$$|p,\sigma\rangle = U(L(p;k))\,|k,\sigma\rangle$$

$$p = Lk$$

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Reference Momentum

The Little Group

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Λ — Generic Lorentz Transf

$$|p,\sigma\rangle \to U(\Lambda)\,|p,\sigma\rangle = D_{\sigma\sigma'}(W(\Lambda,p;k))\,|\Lambda p,\sigma'\rangle$$

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Representation of the "Little Group," leaves

From the Lorentz invariance of the S matrix:

$$\mathcal{M}(p_a, \sigma_a) = \delta^{(D)}(p_1^\mu, ..., p_n^\mu) M(p_a, \sigma_a)$$

$$M(p_a, \sigma_a) \underset{\Lambda}{\rightarrow} \prod_a (D_{\sigma_a, \sigma'_a}(W)) M(\Lambda p_a, \sigma'_a)$$

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Amplitudes transform with representations of the LG!

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Amplitudes transform with representations of the LG!

Admit construction as symmetric tensors

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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- Basic building blocks are 2-component spinors

Spinors! → $|p]^{\alpha}\ , \quad \langle p|^{\dot{\beta}}$

Massless Spinors

- LG = U(1)
- Bra-kets represent *helicity weights*:
  - Square = +1
  - Angle = -1

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

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Spinors!

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

Massless Spinors

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

Massive Spinors:

- LG = SU(2)
- Each spinor gets an SU(2) index $I \in \{1, 2\}$

Arkani-Hamed, Huang, Huang ‘21

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Spinors!

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

For Massless Spinors

- Contracting the spinor indices defines spinor bra-kets
- These are LG covariant objects!

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

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

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Spinors!

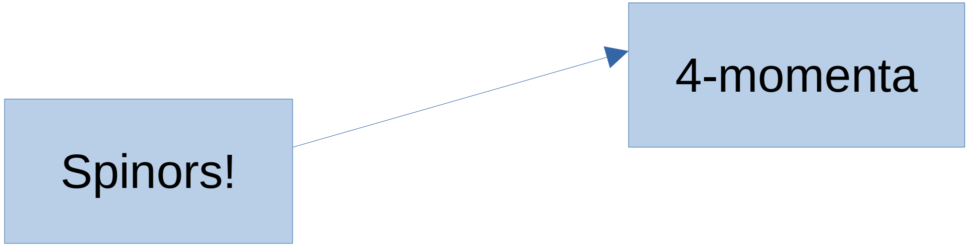
$$\left|p^I\right], \quad \langle p_I| \equiv |\mathbf{p}], \quad \langle\mathbf{p}|$$

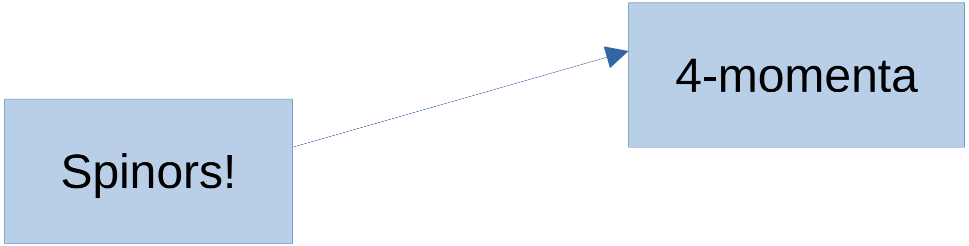
For Massive Spinors

- Amplitudes are represented by *symmetric* tensors
- SU(2) indices must be symmetrized → Bold notation

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

Onshell Methods: Amplitude Construction


4-momenta
Spinors!



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

4-momenta

Spinors!

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

Massless: rank(1)

Spinors!

4-momenta

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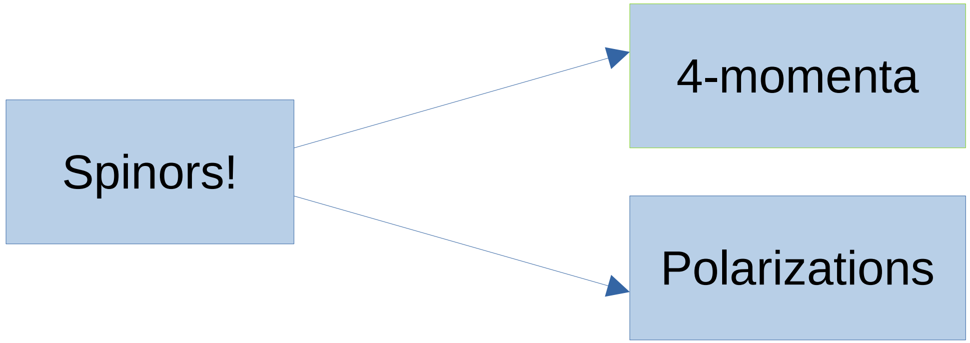
$$|p]^\alpha \langle p|^{\dot\beta}$$

Massless: rank(1)

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

Massive: rank(2)



Spinors!
4-momenta
Polarizations

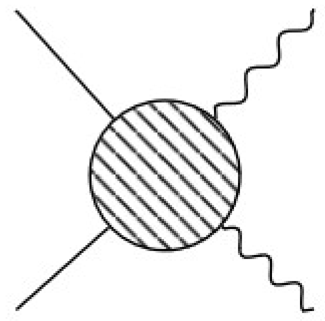
Massless Fermions:

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

4-momenta

Spinors!

Polarizations



Massless Vectors

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

Spinors!

4-momenta

Polarizations

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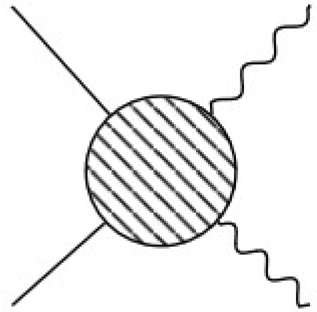


Massive Vectors

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

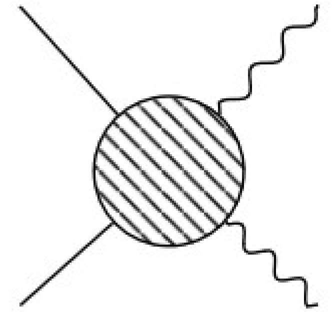
Spinors!

4-momenta

Polarizations

Massive Fermions:

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



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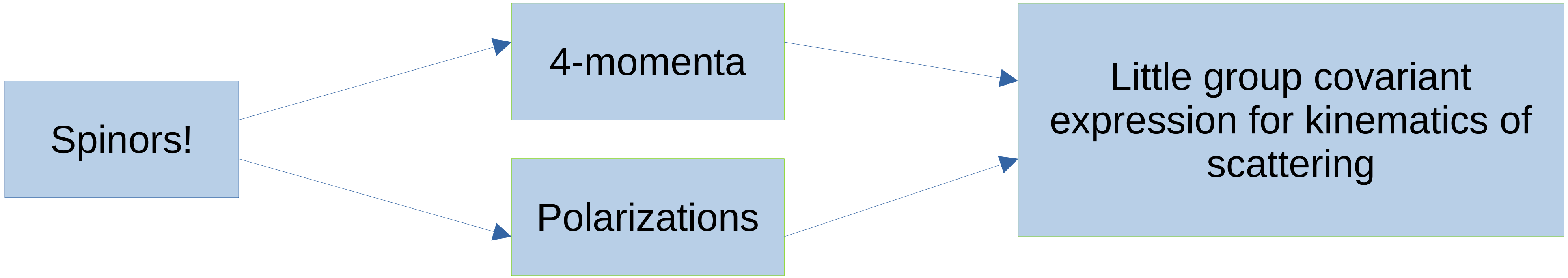
Arkani-Hamed, Huang, Huang ‘21


Spinors!
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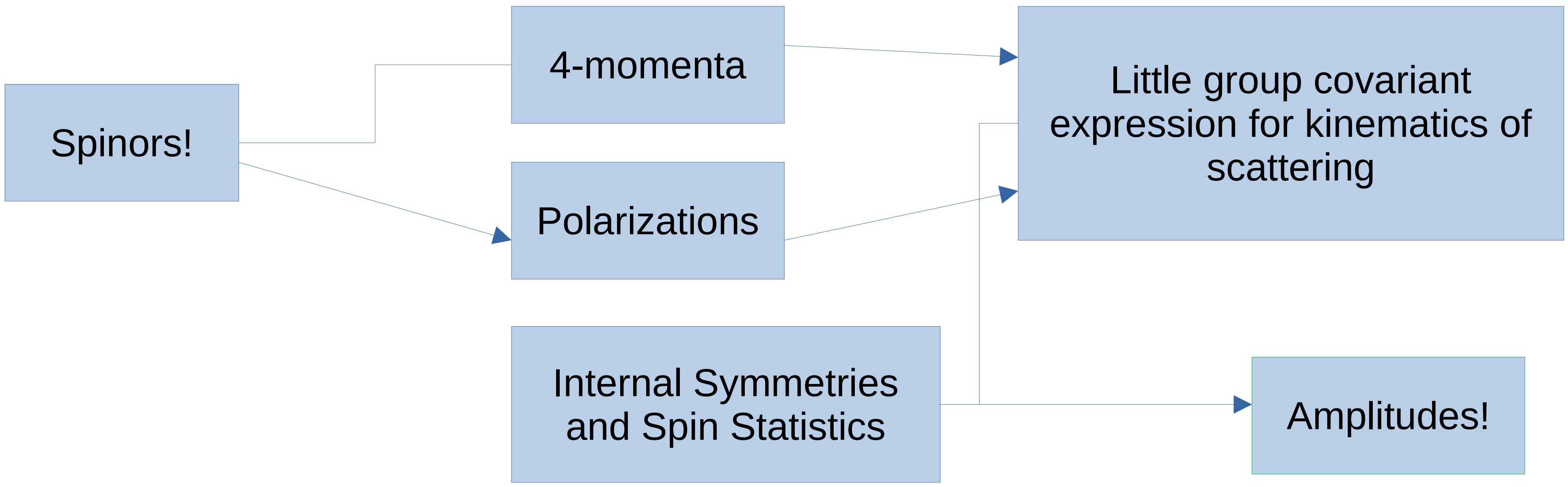
Little group covariant expression for kinematics of scattering



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

Example: $W^a_+(1)W^b_+(2)W^c_+(3)W^d_+(4)$

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← SMEFT amplitudes are for the HE fields

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$$|p] \times 2, \;\; p \in \{1,2,3,4\}$$

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1) Kinematic Terms

$$|p] \times 2, \;\; p \in \{1,2,3,4\}$$

Contract spinors →

$$[12]^2\,[34]^2$$

$$[13]^2\,[24]^2$$

$$[14]^2\,[23]^2$$

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Terms like:

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Are linearly dependent on the three listed terms

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2) Group Theory Terms

$$\delta^{ab}\delta^{dc}, \;\; \delta^{ac}\delta^{bd}, \;\; \delta^{ad}\delta^{bc}$$

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Four identical particles, **symmetrize** over 1a,2b,3c,4d:

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2) Group Theory Terms

$$\delta^{ab}\delta^{dc},\ \delta^{ac}\delta^{bd},\ \delta^{ad}\delta^{bc}$$

Four identical particles, **symmetrize** over 1a,2b,3c,4d:

$$[12]^2\,[34]^2\,\delta^{ab}\delta^{cd} + \text{Permutations}(1a, 2b, 3c, 4d)$$

$$([13]^2\,[24]^2 + [14]^2\,[23]^2)\delta^{ab}\delta^{cd} + \text{Permutations}(1a, 2b, 3c, 4d)$$

Example: $W_+^a(1)W_+^b(2)W_+^c(3)W_+^d(4)$

SMEFT amplitudes are for the HE fields

1) Kinematic Terms

$$[12]^2\,[34]^2 \quad [13]^2\,[24]^2 \quad [14]^2\,[23]^2$$

2) Group Theory Terms

$$\delta^{ab}\delta^{dc}, \;\; \delta^{ac}\delta^{bd}, \;\; \delta^{ad}\delta^{bc}$$

Four identical particles, **symmetrize** over 1a,2b,3c,4d:

Each term gets an *independent* coefficient

$$c_1\,[12]^2\,[34]^2\,\delta^{ab}\delta^{cd} + \text{Permutations}(1a, 2b, 3c, 4d)$$

$$c_2([13]^2\,[24]^2 + [14]^2\,[23]^2)\delta^{ab}\delta^{cd} + \text{Permutations}(1a, 2b, 3c, 4d)$$

C,C,P

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

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

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

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

Or come with hermitian conjugates, e.g.:

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

$$\Rightarrow c_3 = c_2^*$$

C,C,P

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

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

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

C,C,P

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

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Complex Conjugation

C,C,P

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

Complex Conjugation

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

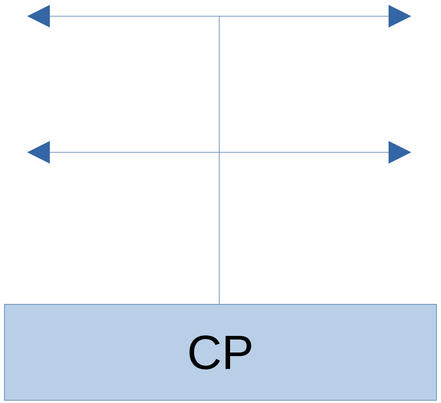
4 complex coefficient → 2 complex coefficients. This counting applies to all amplitudes.

C,C,P

These amplitudes are also related by CP transformations (not a CP eigenbasis):

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

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



C,C,P

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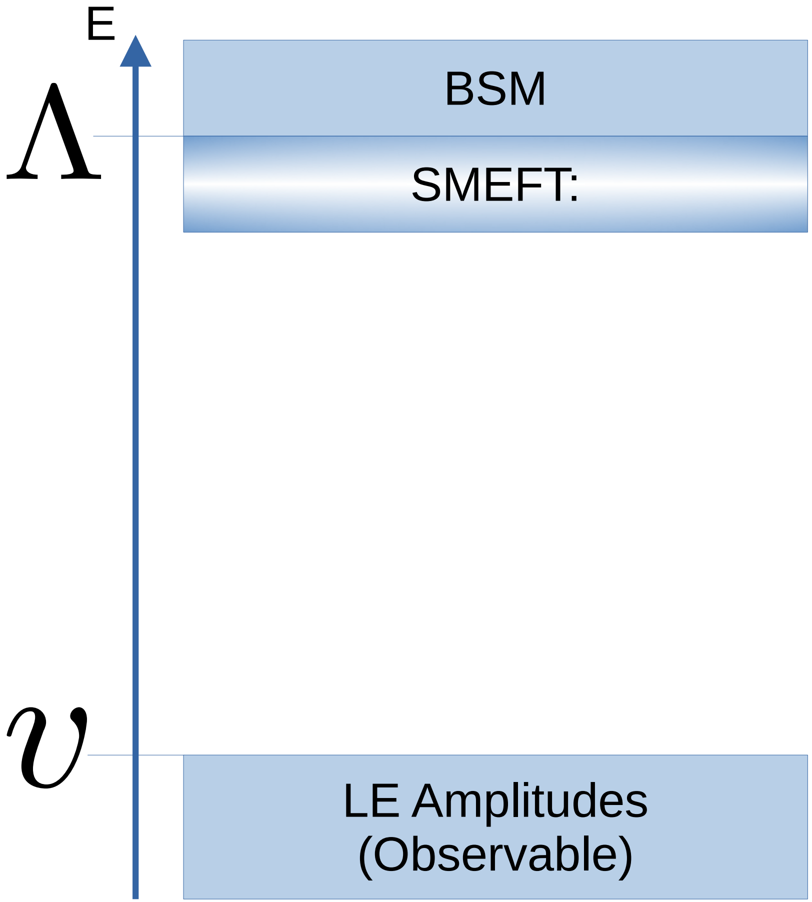
CP

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

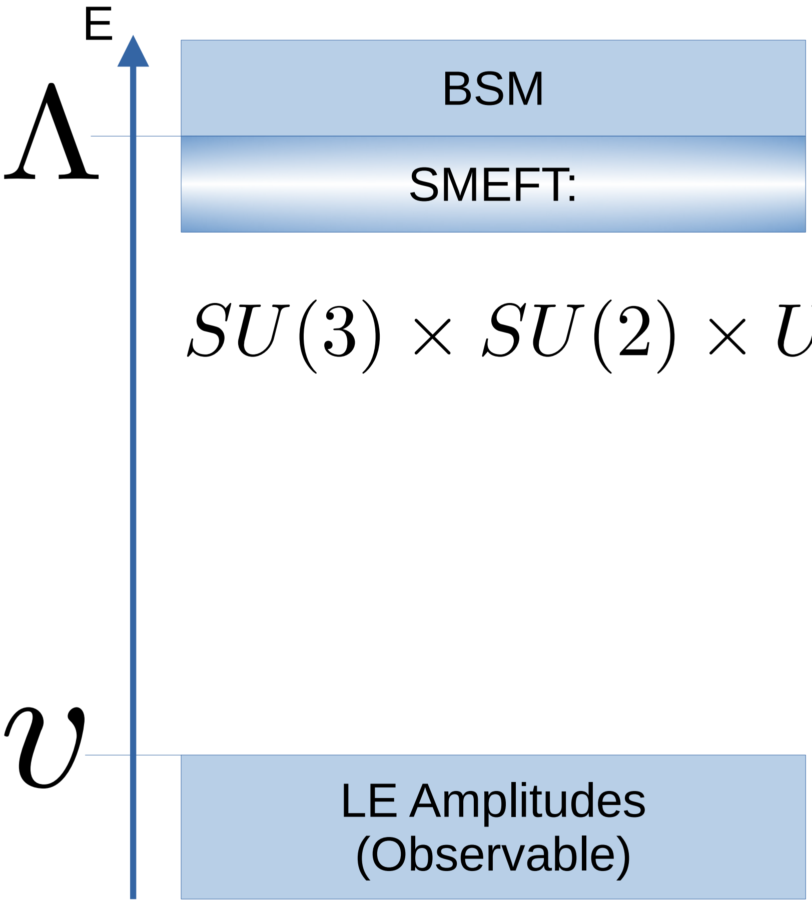
Demanding CP invariance: 2 complex coefficients → two real coefficients

Construction of LE (Massive) SMEFT Amplitudes



Construct set of HE contact terms:

Construction of SMEFT Amplitudes: Massless Amplitudes (HE)



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

Construct set of HE contact terms:

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

E

Λ

BSM

SMEFT:

Construct set of HE contact terms:

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

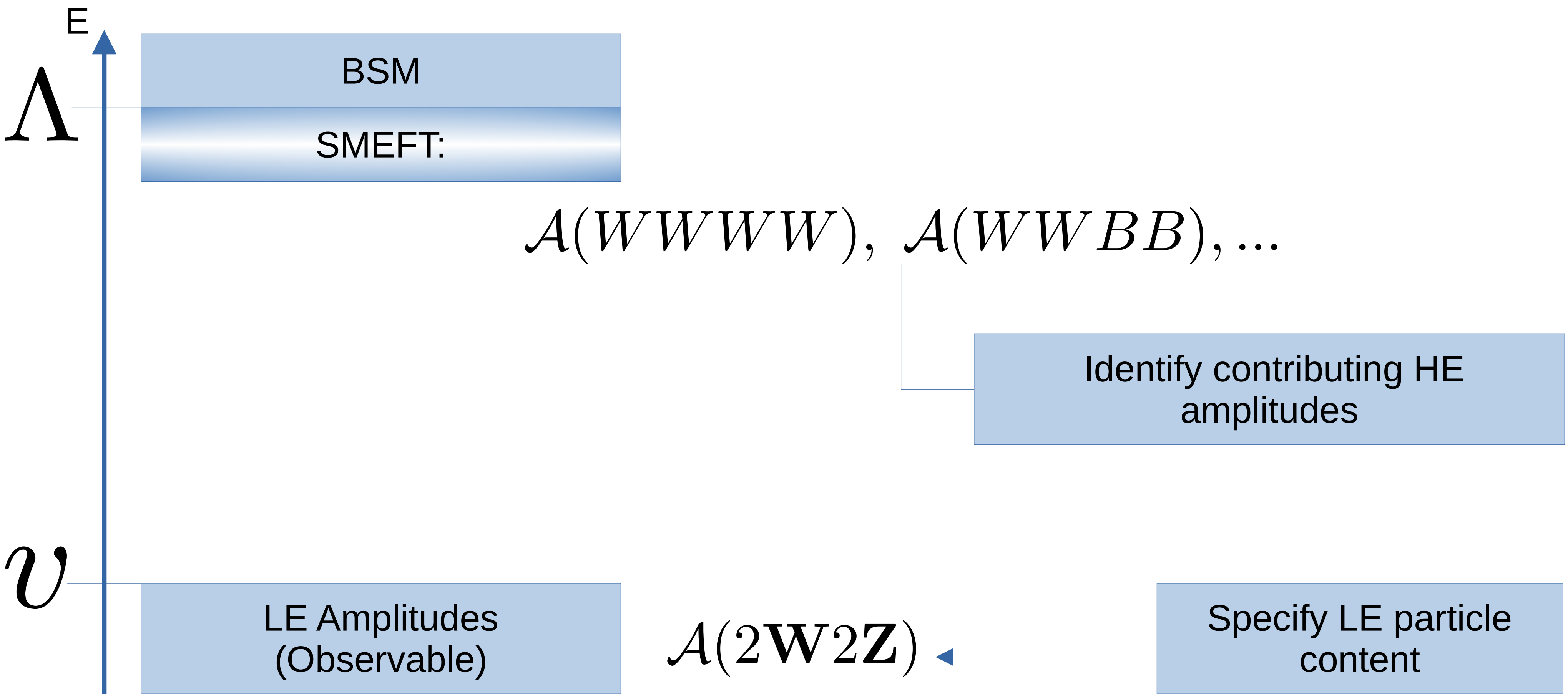
$$\Phi \in \{Q, U, D, L, E, H, H^\dagger, W^a, B, G\}$$

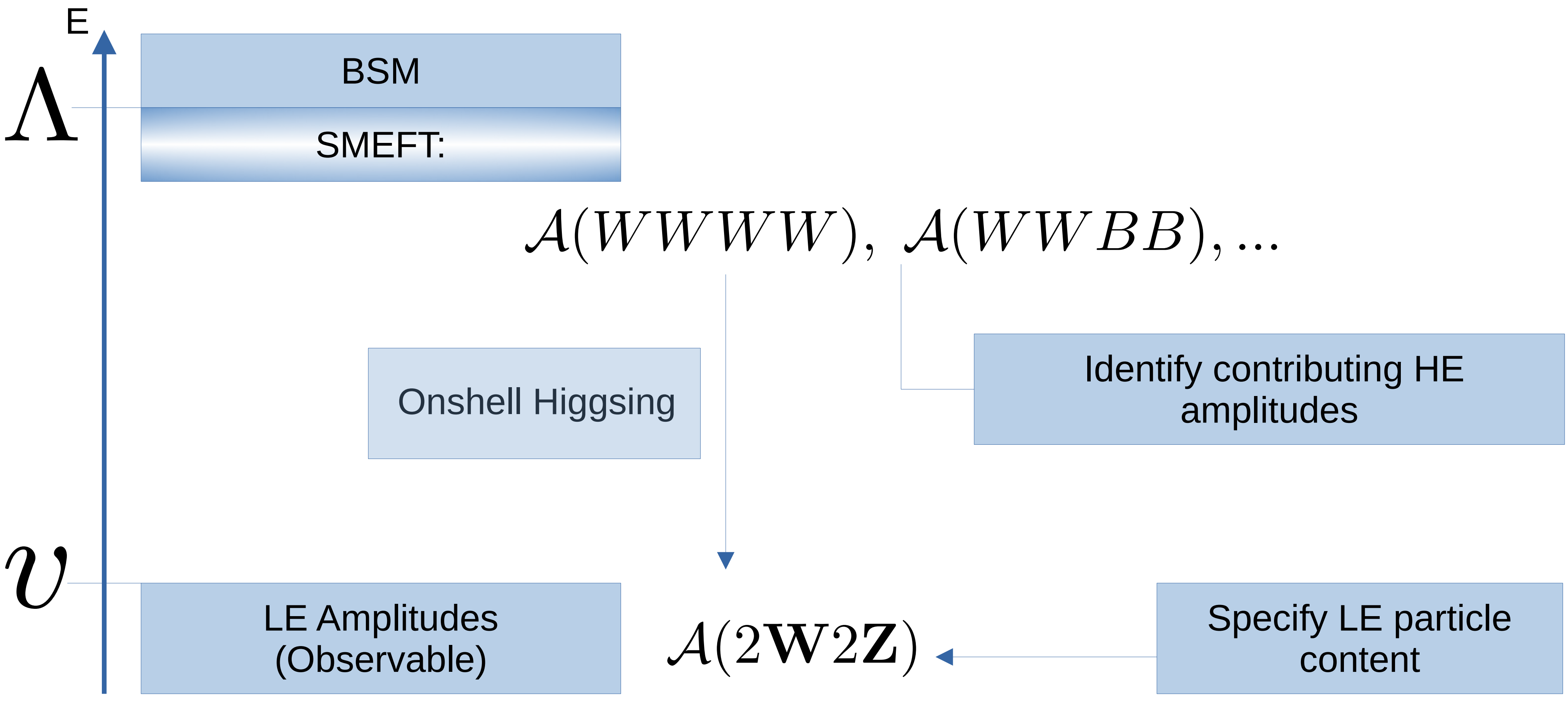
$$\mathcal{A}(WWWWW),\ \mathcal{A}(WWBB),\ ,\ldots,\ \mathcal{A}(Q^c Q B H^\dagger H), \ldots$$

v

LE Amplitudes
(Observable)

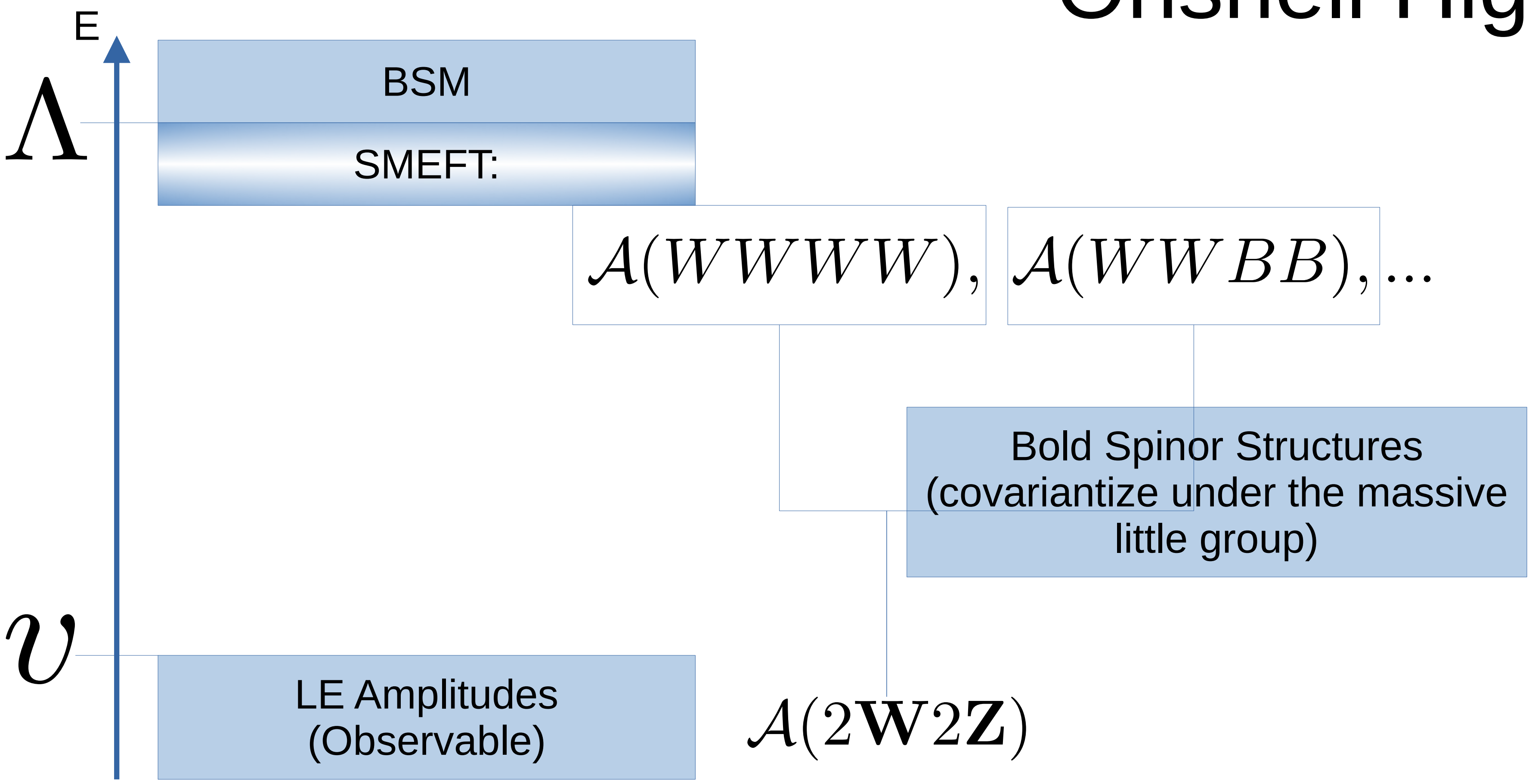

E
Λ
BSM
SMEFT:
v
LE Amplitudes
(Observable)
$\mathcal{A}(2\mathbf{W}2\mathbf{Z})$
Specify LE particle
content


E
Λ
v
BSM
SMEFT:
$\mathcal{A}(WWWWW),\ \mathcal{A}(WWWBB),\ldots$
Identify contributing HE amplitudes
LE Amplitudes (Observable)
$\mathcal{A}(2\mathbf{W}2\mathbf{Z})$
Specify LE particle content



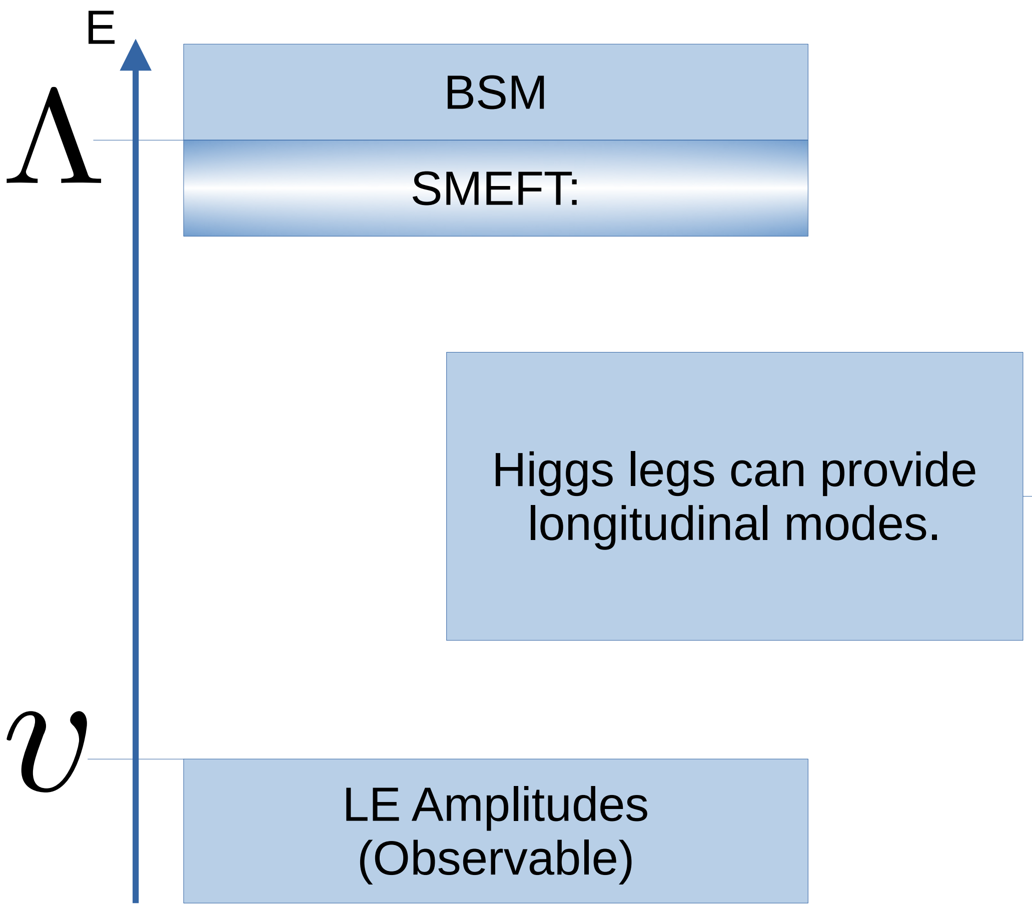
Construction of SMEFT Amplitudes: LE (Massive) Amplitudes

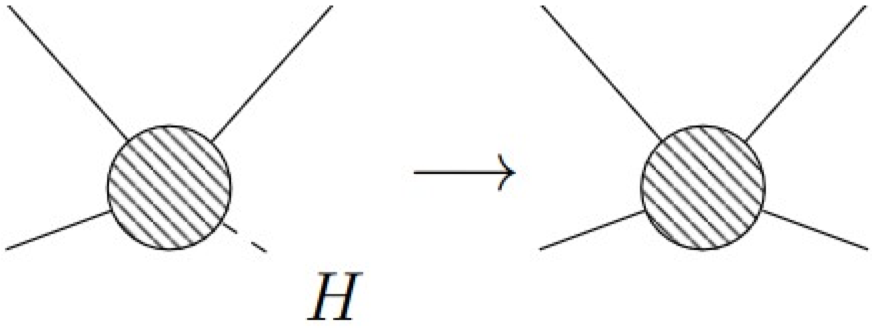
Onshell Higgsing



Balkin, Durieux, Kitahara, Shadmi, Weiss '21

Onshell Higgsing





$$H \to V_L$$

Balkin, Durieux, Kitahara, Shadmi, Weiss ‘21

Onshell Higgsing

E

Λ

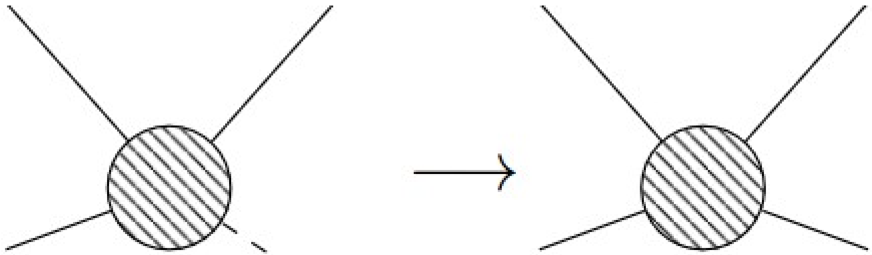
BSM

SMEFT:

Higgs legs can provide longitudinal modes.

v

LE Amplitudes
(Observable)



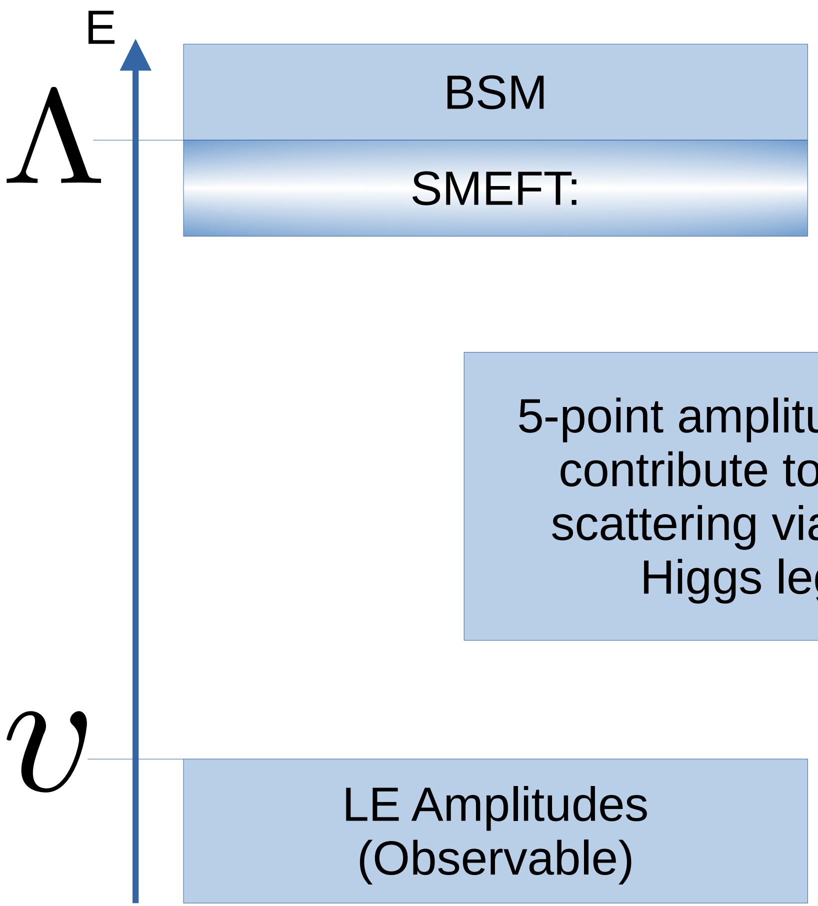
H

$$H \to V_L$$

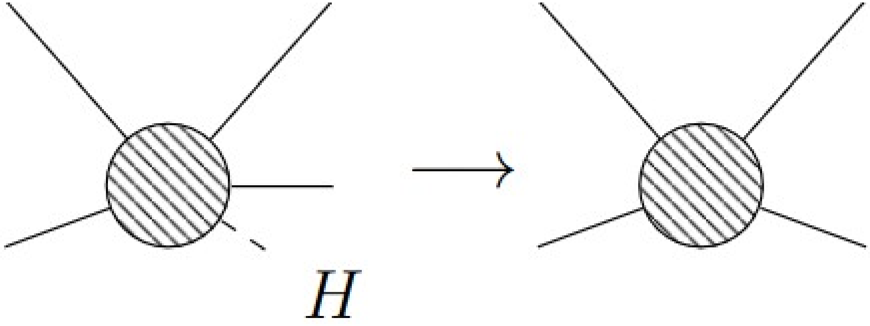
$$|p_H]\,\langle p_H| \to |\mathbf{p_H}]\,\langle \mathbf{p_H}|$$

Balkin, Durieux, Kitahara, Shadmi, Weiss ‘21

Onshell Higgsing



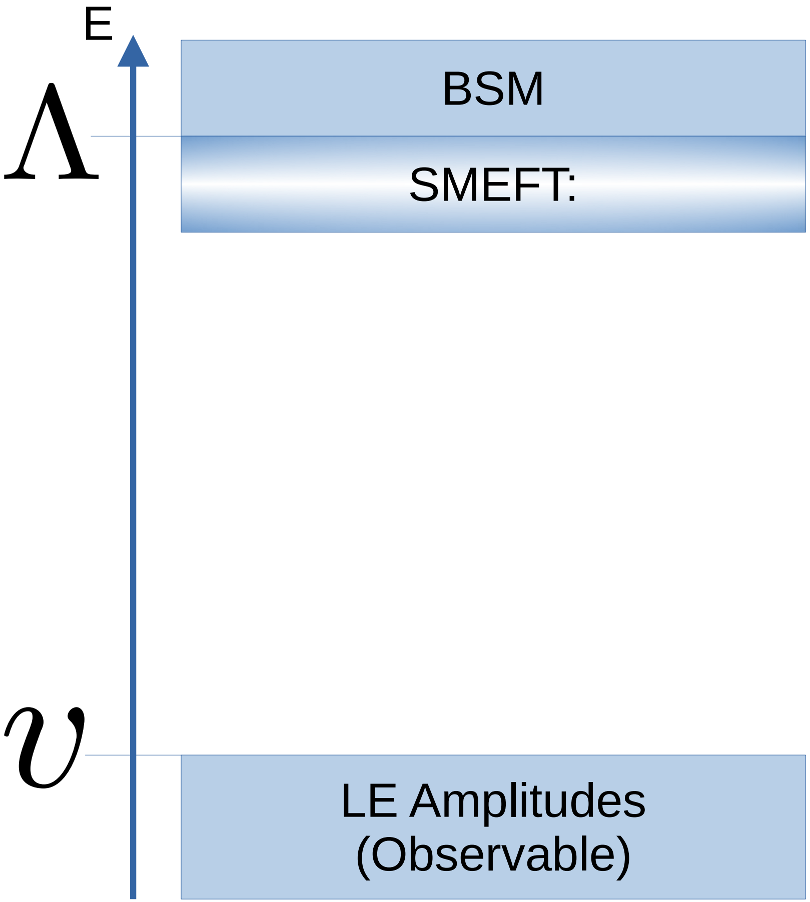
5-point amplitudes can contribute to 2-to2 scattering via extra Higgs legs



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

$$p_h \to 0$$

Balkin, Durieux, Kitahara, Shadmi, Weiss ‘21

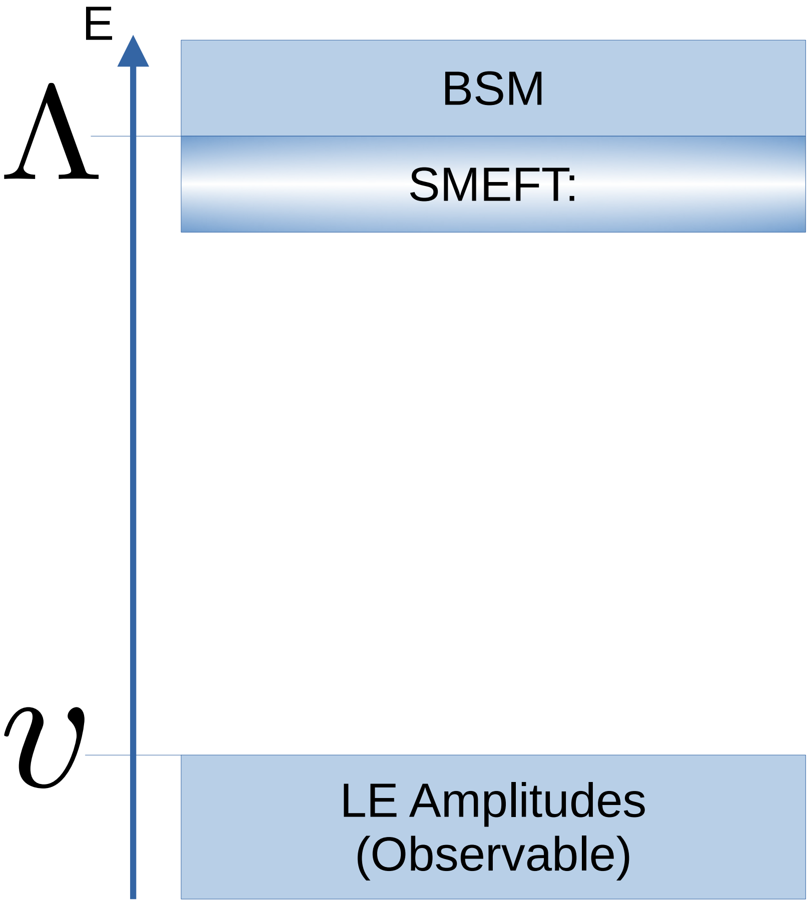


$$\mathcal{A}(Q^c Q B H^\dagger H)$$

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

Higgs legs can provide longitudinal modes.

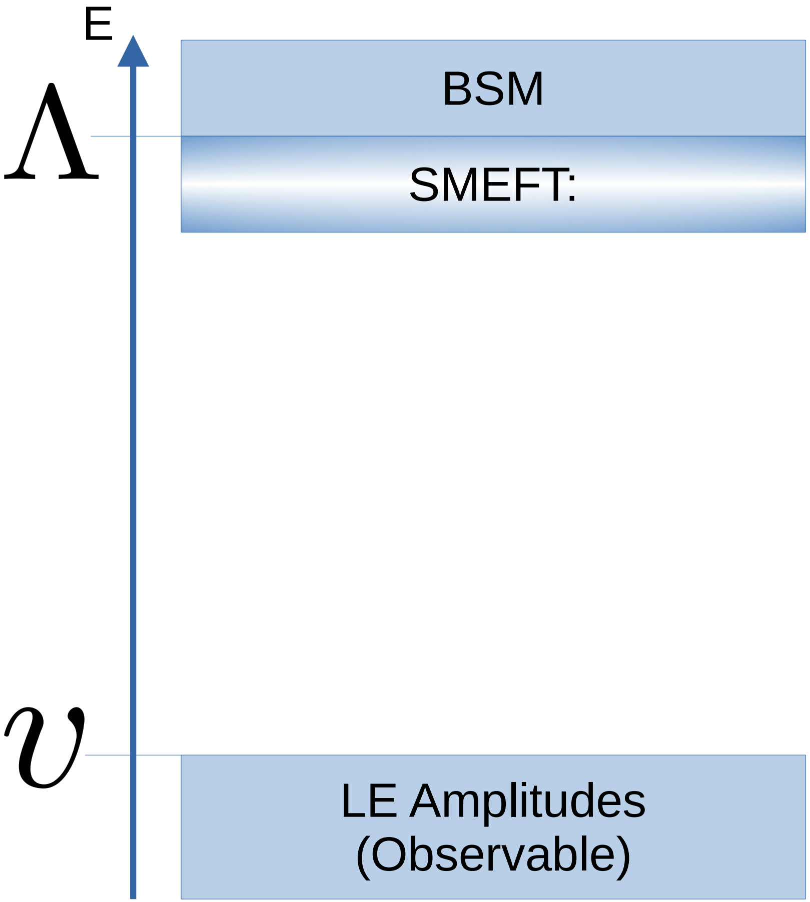
$$\mathcal{A}(u^c d 2\mathbf{Z})$$



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

Transverse Z from B field

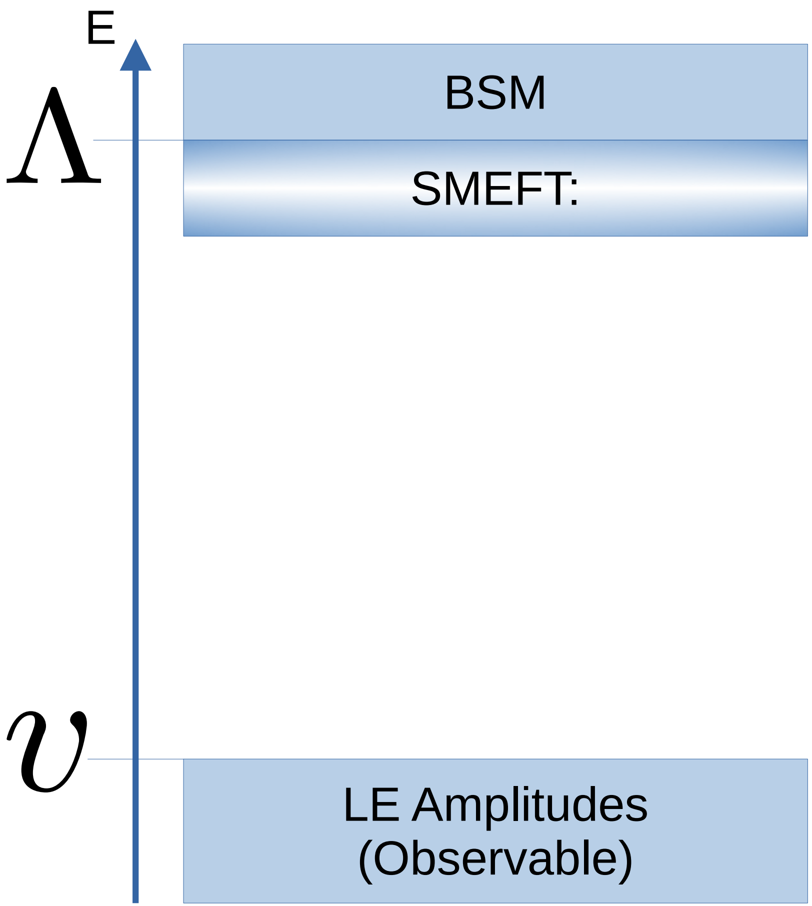
$$\mathcal{A}(u^c d 2\mathbf{Z})$$



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

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

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



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

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

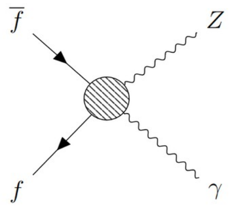
$$\mathcal{A}(u^c d 2\mathbf{Z}) \cdot v$$

Results

Results

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

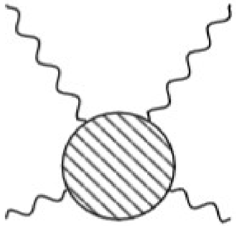
- Selection rules on kinematic configurations of observable amplitudes



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

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

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



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

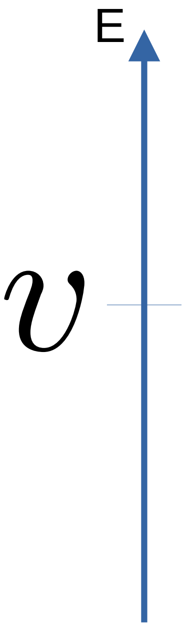
- SU(2) Symmetry Breaking pattern in the amplitudes, e.g:

Structure	$\bar{u}uW^+W^-$	$\bar{d}dW^+W^-$
$[13][\mathbf{34}]\langle\mathbf{4}2\rangle$	$\frac{v}{\sqrt{2}}(c_2^{Q^cQW_+2H} + c_3^{Q^cQW_+2H})$	$-\frac{v}{\sqrt{2}}c_2^{Q^cQW_+2H}$

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

- 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.