(De-)constructing operators within the EFT paradigm:

(Building a dictionary for new physics)

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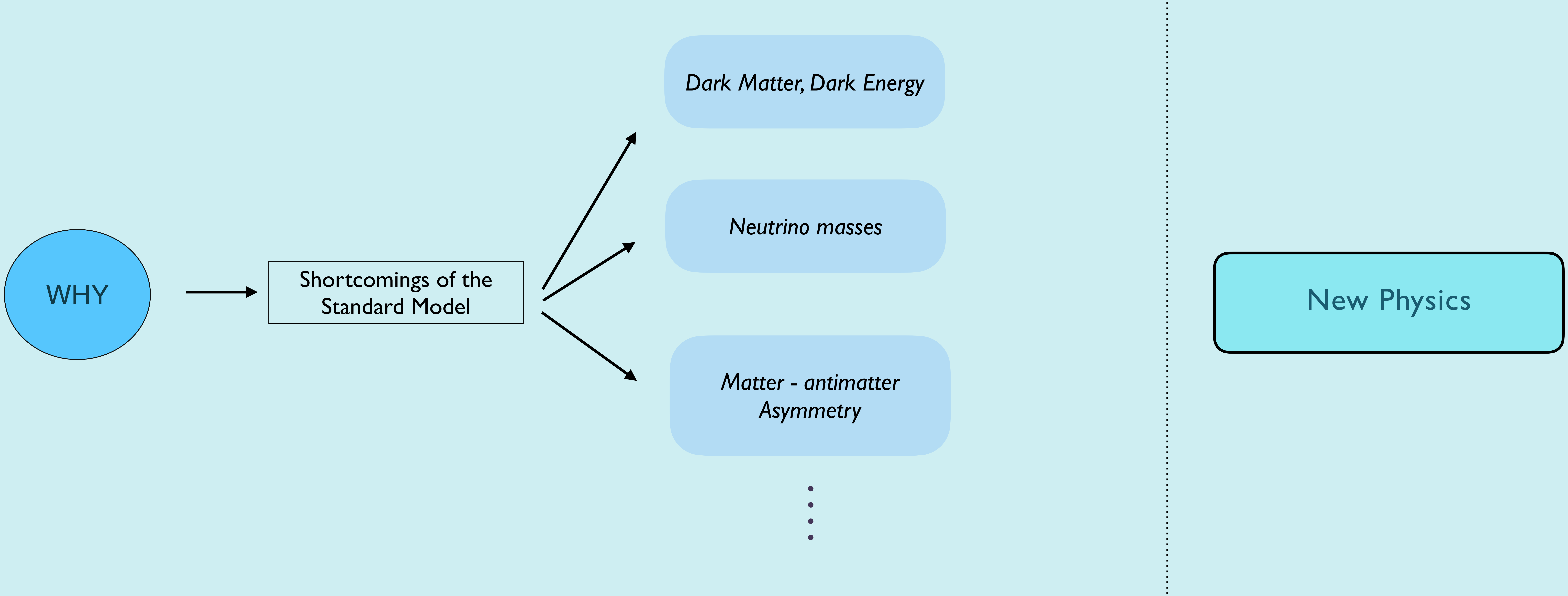
Overview

- Introduction: stepping beyond the SM
- The EFT paradigm: a bridge between the unknown and the observed
- Model building through invariant polynomials - The Hilbert Series program
    - The building blocks
    - Automating the cumbersome
- EFT Diagrammatica: Re-thinking Model Discrimination
    - Assumptions (*abiding by a notion of minimalism*)
    - The building blocks
    - Implementation for SMEFT
- Challenges

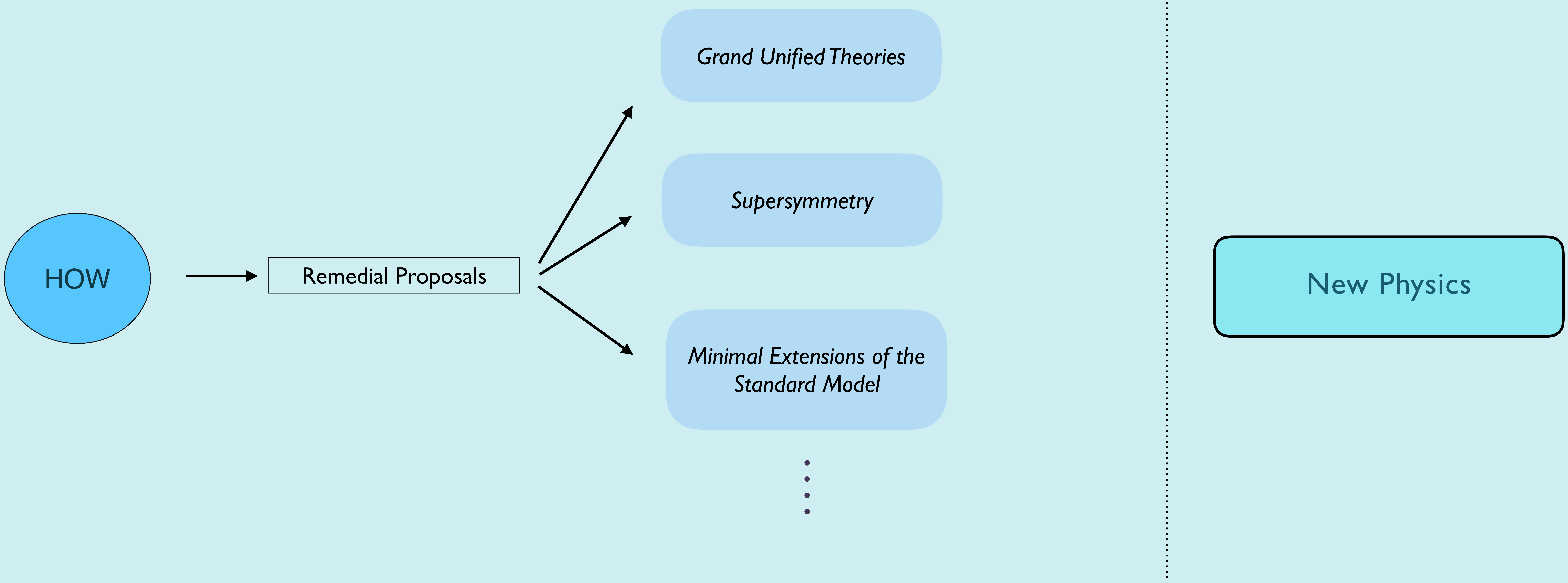
Stepping *beyond* the SM

New Physics

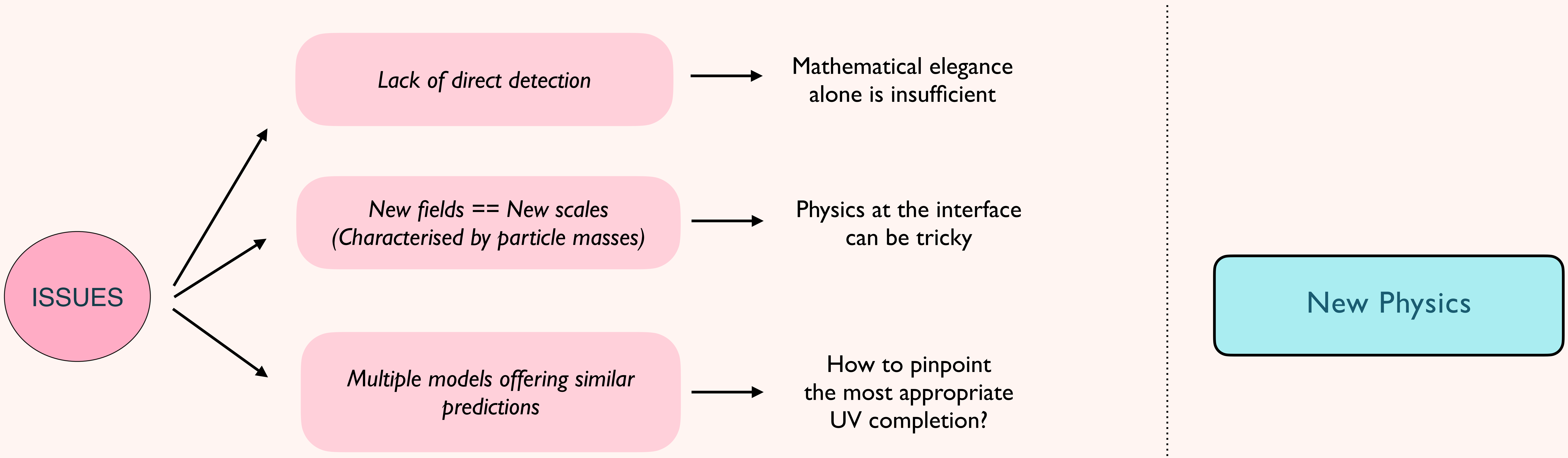
Stepping *beyond* the SM



Stepping *beyond* the SM



Stepping *beyond* the SM



⇓

The aim

Formulation of a framework well - equipped to handle multi-scale theories, while also providing the platform to conduct comparative analyses between multiple Beyond Standard Model (BSM) proposals.

Stepping *beyond* the SM

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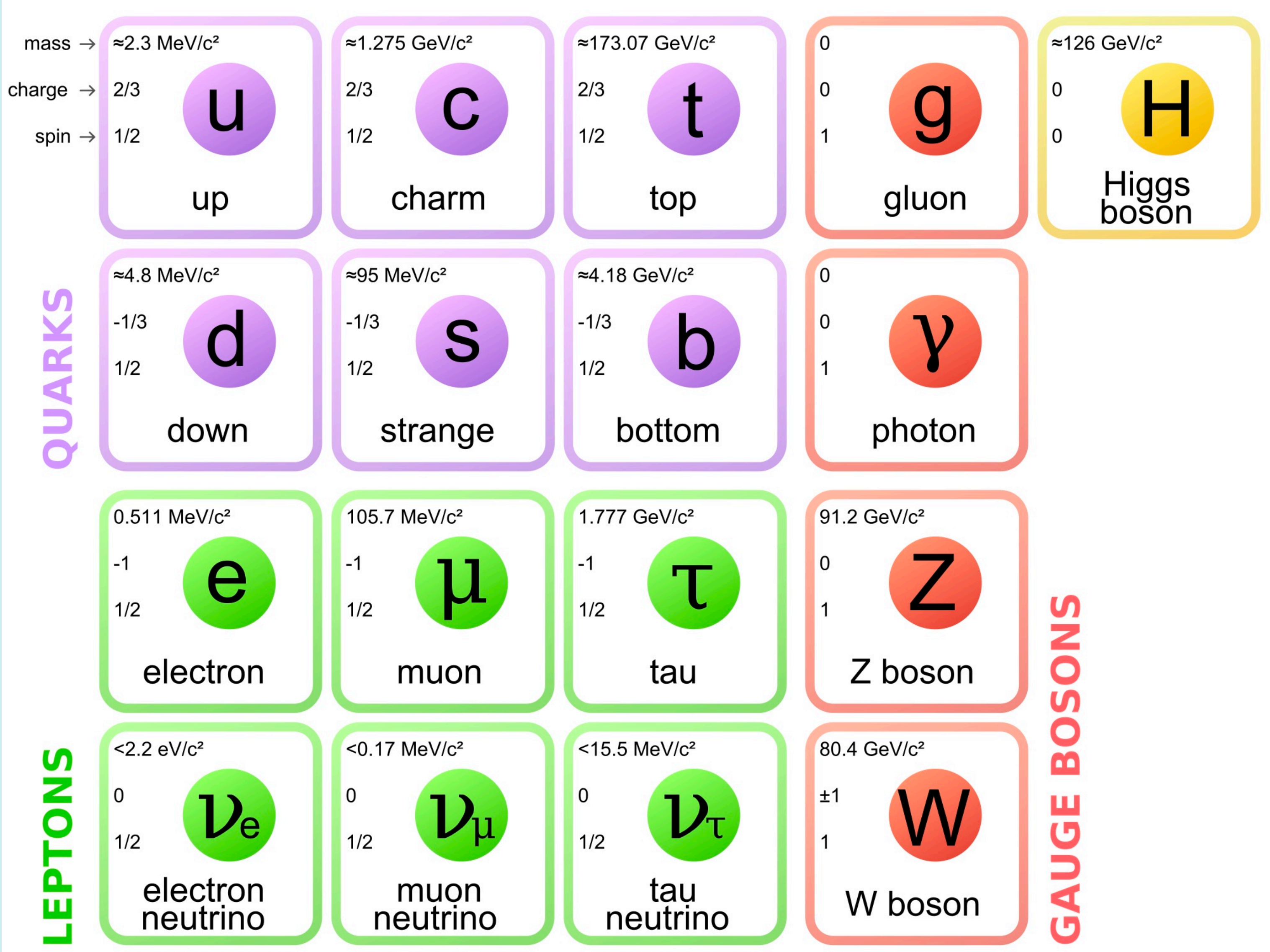
Formulation of a framework well - equipped to handle multi-scale theories, while also providing the platform to conduct comparative analyses between multiple Beyond Standard Model (BSM) proposals.

Effective Field Theory

- *Only valid between two fixed energy scales*
- *Same predictions as the "full" high scale theory*
- *Dynamics encapsulated within higher order interactions*

The EFT paradigm



The Standard Model (SM) of Elementary Particles

→

SM + EFT = SMEFT

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{n=5}^{\infty} \sum_{i=1}^{N} \frac{1}{\Lambda^{(n-4)}} \mathcal{C}_i \, \mathcal{O}_i$$

SMEFT Lagrangian

High energy scale

Wilson Coefficients

Effective Operators

The EFT paradigm

$$\mathcal{L}_{\rm SM} + \sum_{n=5}^{\infty} \sum_{i=1}^{N} \frac{1}{\Lambda^{(n-4)}} \mathcal{C}_i \, \mathcal{O}_i$$

Describes the interactions between all known particles and the agents of fundamental forces

Kinetic terms → Describe the propagation of fields

Potential terms → Describe the interactions among fields

The EFT paradigm

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How do we know which terms must be present in the Lagrangian ?

The EFT paradigm

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How do we know which terms must be present in the Lagrangian ?

↓

Observations (Resonances, Decay patterns)

↓

How nature works must be reflected in the Lagrangian

The EFT paradigm

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How do we know which terms must be present in the Lagrangian ?

A first principle theoretical prescription

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High energy scale

Mass of the lightest "heavy field"
beyond the low energy Lagrangian

$\mathcal{L}_{\rm low}$	Λ
4 - Fermi theory	m_W
NREFTs (HQET, NRQCD)	m_Q

The EFT paradigm

$$\mathcal{L}_{\text{SM}} + \sum_{n=5}^{\infty} \sum_{i=1}^{N} \frac{1}{\Lambda^{(n-4)}} \mathcal{C}_i \, \mathcal{O}_i$$

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$\mathcal{L}_{\text{EFT}}$ is valid between two scales Λ_1, Λ_2 with $\Lambda_1 < \Lambda_2$

SMEFT → v_h (246 GeV)

SMEFT → Λ (Unknown / Model dependent)

The EFT paradigm

$$\mathcal{L}_{\mathrm{SM}} + \sum_{n=5}^{\infty} \sum_{i=1}^{N} \frac{1}{\Lambda^{(n-4)}} \mathcal{C}_i \, \mathcal{O}_i$$

Effective Operators

Wilson Coefficients

The EFT paradigm

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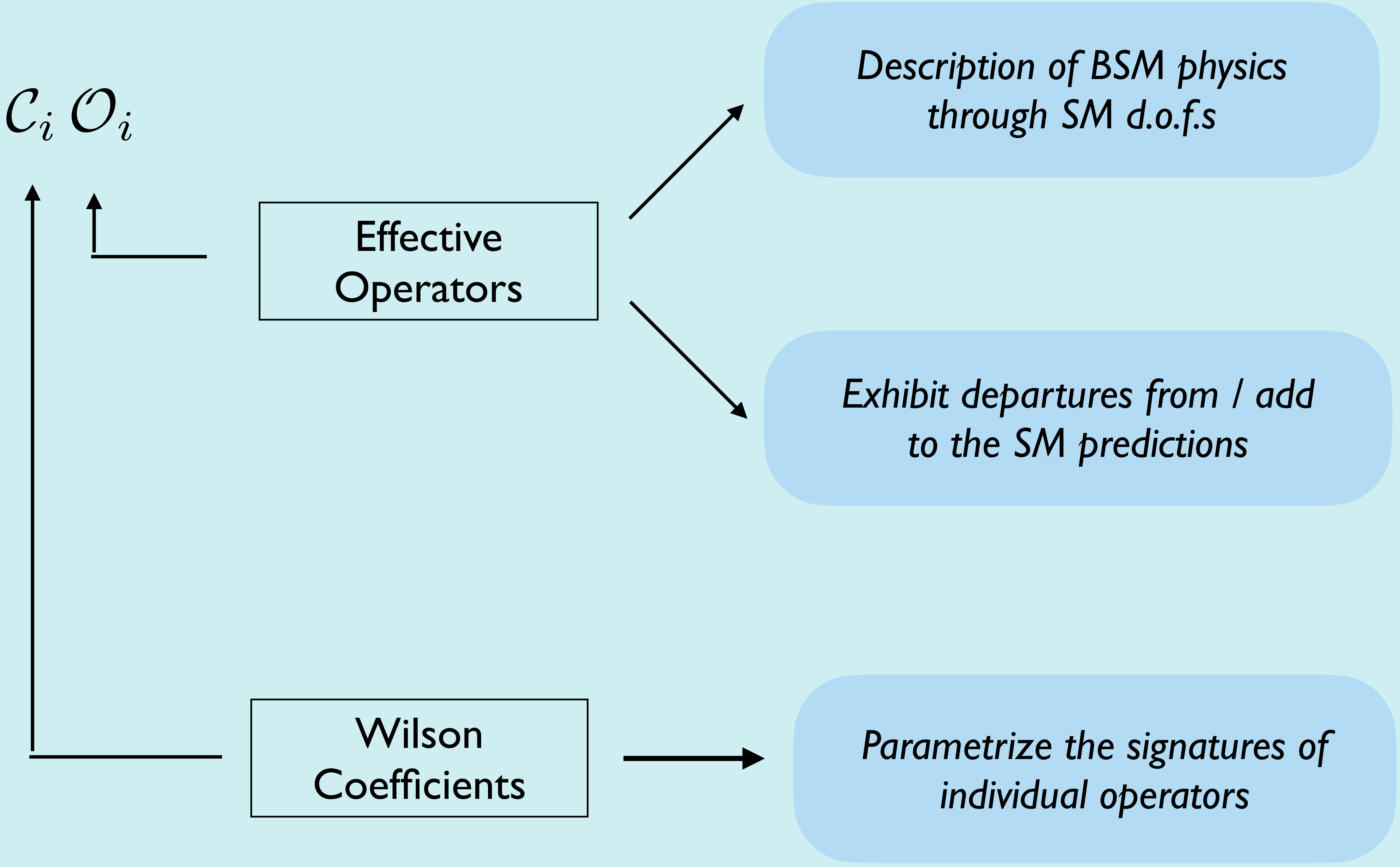

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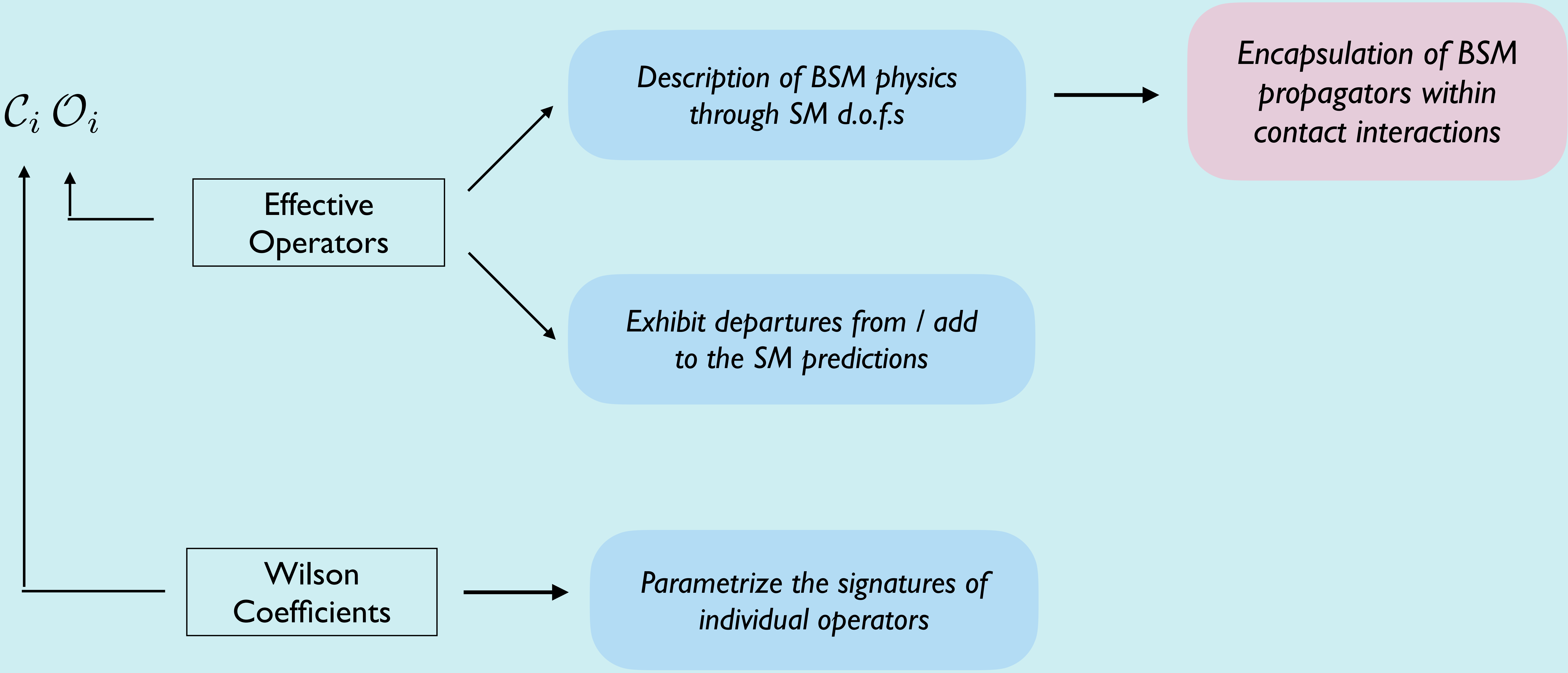

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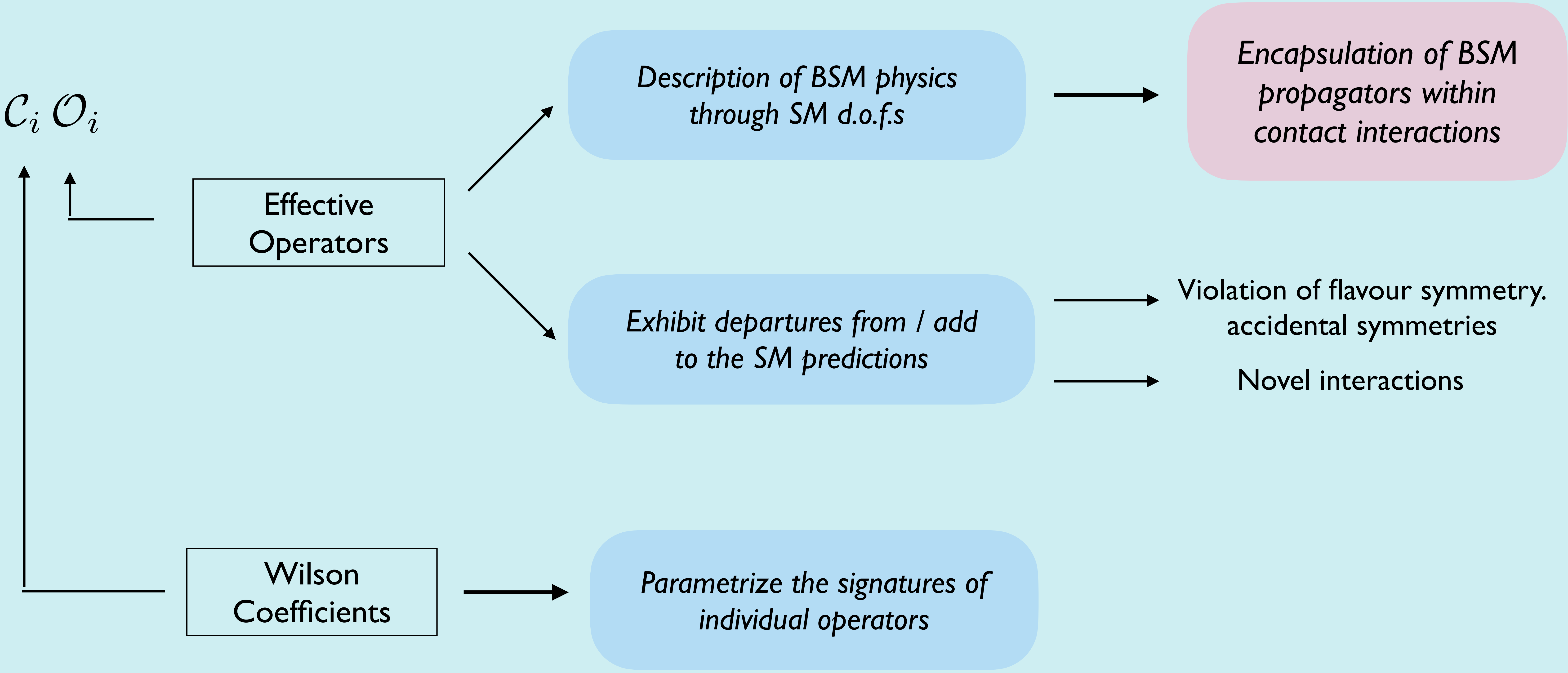


The EFT paradigm

$$\mathcal{L}_{\rm SM} + \sum_{n=5}^{\infty} \sum_{i=1}^{N} \frac{1}{\Lambda^{(n-4)}} \mathcal{C}_i \, \mathcal{O}_i$$

Effective Operators ($\mathcal{O}_i$)

Wilson Coefficients ($\mathcal{C}_i$)

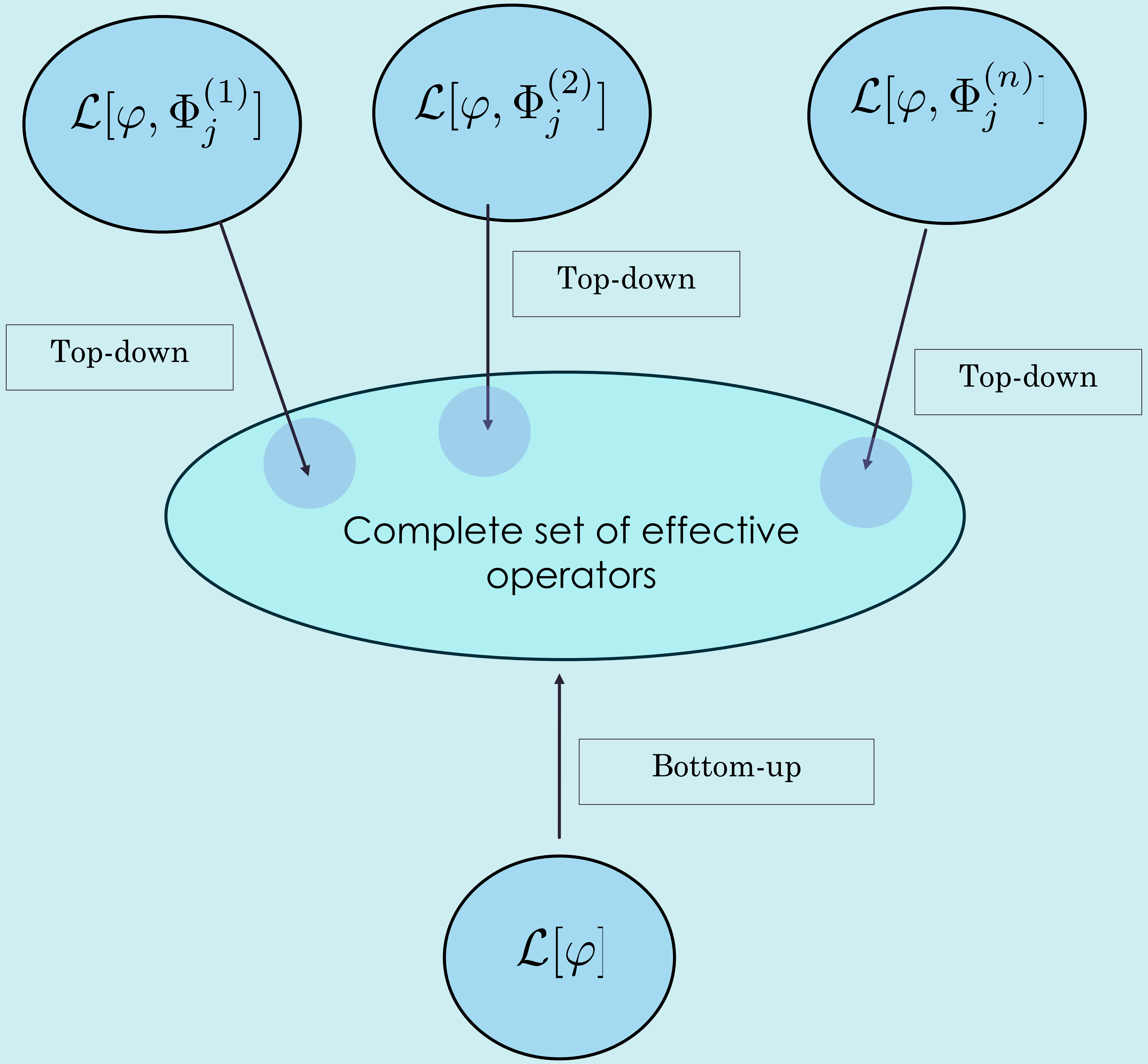
Model Independent	Model Dependent
In principle, an exhaustive set of operators must be taken into account.	Specific subsets are relevant for specific BSM scenarios.
Exact origin of the operators remains unknown.	Interrelations exist between effective operators and BSM interactions.
WCs - free parameters	WCs - functions of BSM parameters

The EFT paradigm

$$\mathcal{L}_{\text{SM}} + \sum_{n=5}^{\infty} \sum_{i=1}^{N} \frac{1}{\Lambda^{(n-4)}} \mathcal{C}_i \, \mathcal{O}_i$$

Effective Operators

Wilson Coefficients



The EFT paradigm

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Effective Operators

Operator basis

Mass Dimension (>5)

The EFT paradigm

$$\mathcal{L}_{\mathrm{SM}} + \sum_{n=5}^{\infty} \sum_{i=1}^{N} \frac{1}{\Lambda^{(n-4)}} \mathcal{C}_i \, \mathcal{O}_i$$

Effective Operators

Operator basis

Mass Dimension (>5) → $\left[\mathcal{S} = \int d^4x \, \mathcal{L} \right]$ is dimensionless

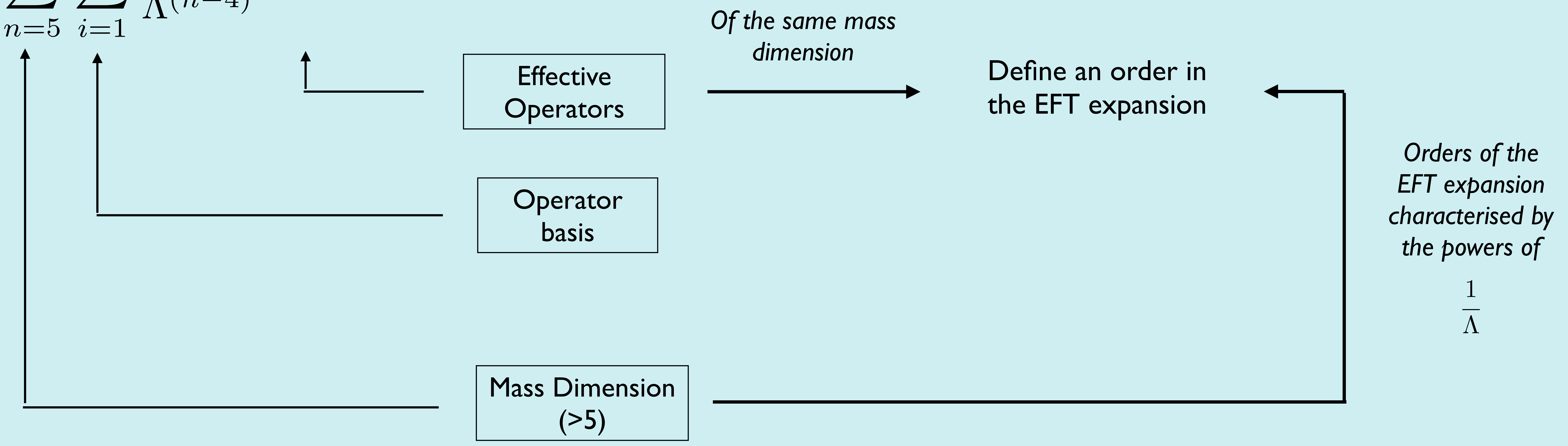
$$\Downarrow$$

$$[\phi] \equiv 1, \quad [\psi] \equiv 3/2, \quad [A^a_\mu] \equiv 1, \quad [\mathcal{D}_\mu] \equiv 1$$

(scalars) (spinors) (vector bosons) (derivatives)

The EFT paradigm

$$\mathcal{L}_{\rm SM} + \sum_{n=5}^{\infty} \sum_{i=1}^{N} \frac{1}{\Lambda^{(n-4)}} \mathcal{C}_i \, \mathcal{O}_i$$



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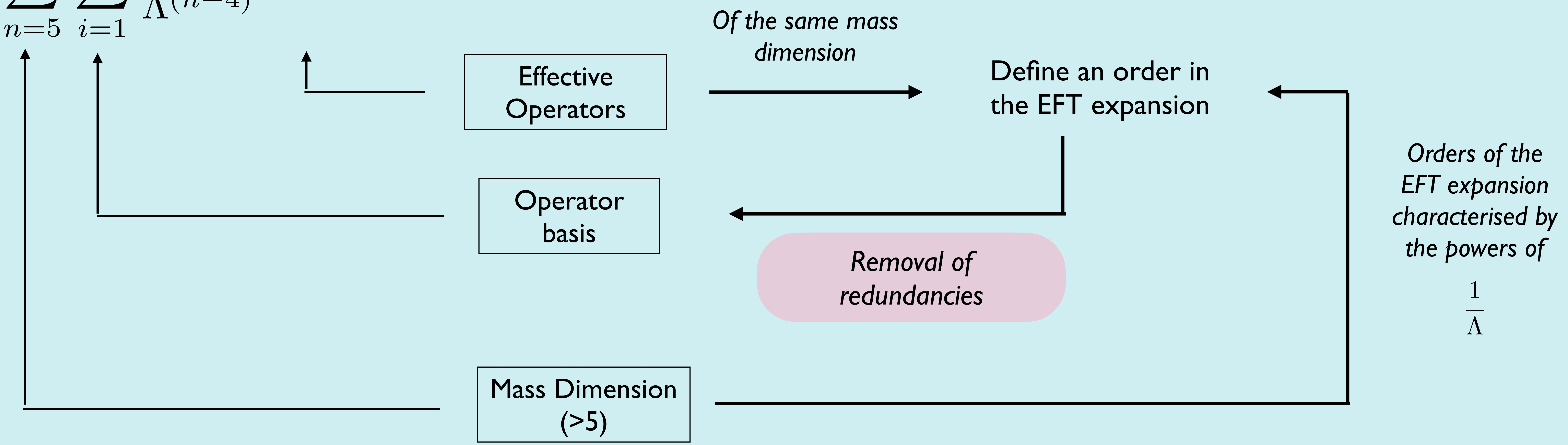

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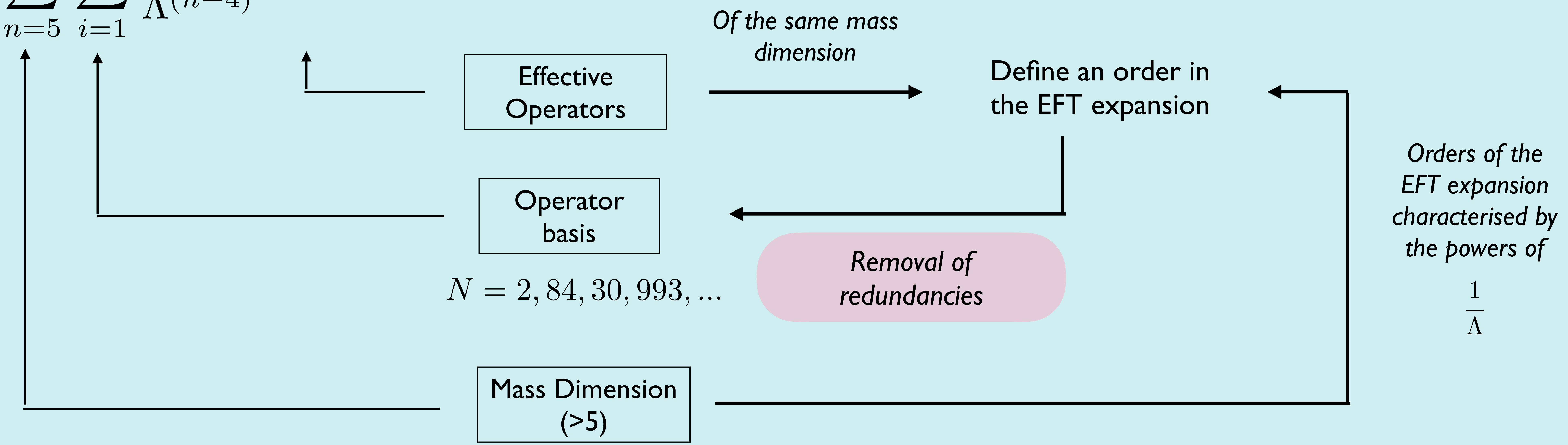


Questions encountered thus far…

How do we know which terms must be present in the Lagrangian ?

Encapsulation of BSM propagators within contact interactions.

How do we assemble the interactions / construct operators for SM, BSM, SMEFT, WET(LEFT), BSMEFT etc. at different orders of EFT ?

Removal of redundancies

Which of these interactions / operators can be included in a complete and independent set ?

Model building and cataloguing

Symmetry

Model building and cataloguing

Symmetry

field transformation under a local (gauge) symmetry described by a Lie group

$$\phi \to U(x)\,\phi, \quad U(x) \in \mathcal{G}$$

gauge invariance necessitates the introduction of a covariant derivative

$$\mathcal{D}_\mu \equiv \partial_\mu - igA^a_\mu\,T^a$$

A^a_μ *- gauge fields*

T^a *- symmetry generators*

the requirement of a "covariant" transformation

$$\mathcal{D}_\mu\phi \to U(x)\,(\mathcal{D}_\mu\phi)$$

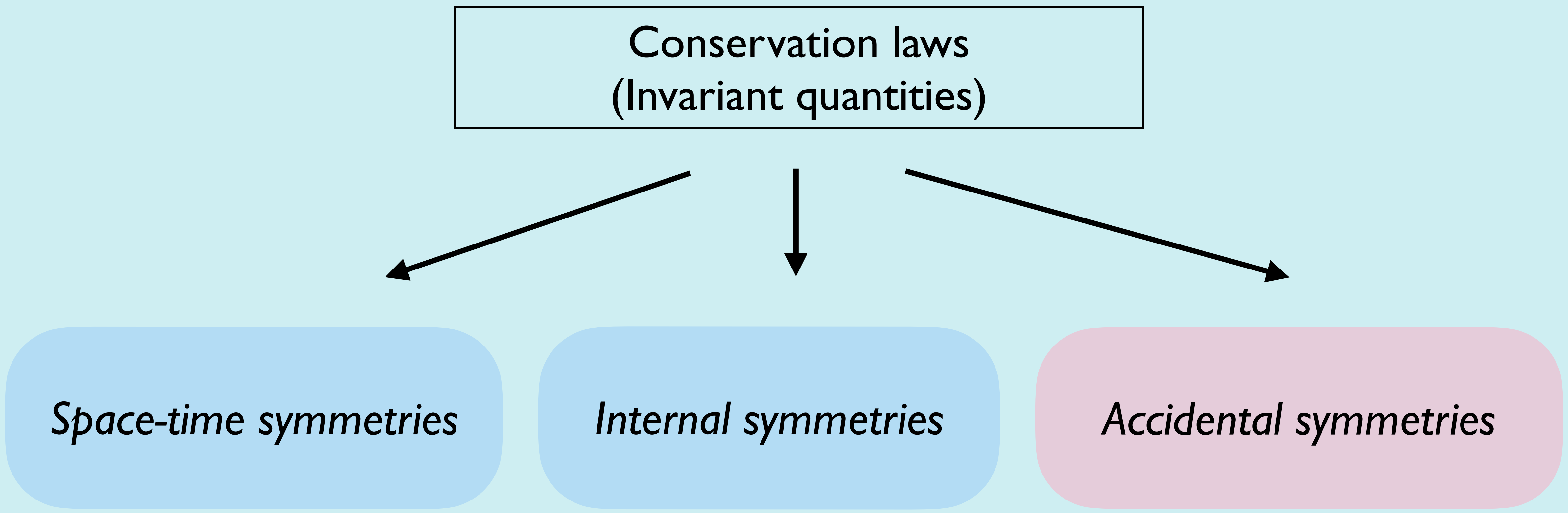
↓

defines the transformation law of the gauge fields

$$A^a_\mu\,T^a \equiv A_\mu \to U\,A_\mu\,U^{-1} + i\,U\,\partial_\mu\,U^{-1}$$

Model building and cataloguing

Symmetry



Model building and cataloguing

Symmetry

Conservation laws
(Invariant quantities)

Space-time symmetries

Internal symmetries

Accidental symmetries

Described by the Poincare group in 3+1 dimensions

for SM and SM-like proposals

Fields $\in$ representations of

$$SO(3,1) \quad \text{or} \quad SU(2) \times SU(2)$$

Model building and cataloguing

Symmetry

Conservation laws
(Invariant quantities)

Space-time symmetries

Internal symmetries

Accidental symmetries

Well-defined patterns followed
by a collection of fields

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

(For the Standard Model)

Model building and cataloguing

Symmetry

Conservation laws
(Invariant quantities)

Space-time symmetries

Internal symmetries

Accidental symmetries

A hierarchy of such symmetries along with sequences of symmetry breaking can unveil chapters in cosmic history

$$SU(4)_C \otimes SU(2)_L \otimes SU(2)_R$$
$$\downarrow$$
$$SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$
$$\downarrow$$
$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$
$$\downarrow$$
$$SU(3)_C \otimes U(1)_{\rm em}$$

Model building and cataloguing

Symmetry

Conservation laws
(Invariant quantities)

Space-time symmetries

Internal symmetries

Accidental symmetries

Baryon and Lepton number conservation in SM

(Need not be preserved in BSM extensions)

Model building and cataloguing

Symmetry

Conservation laws
(Invariant quantities)

Space-time symmetries | *Internal symmetries* | *Accidental symmetries*

The fields of SM and their transformation properties (codified in terms of quantum numbers):

$$q_{L\left(3,2,\frac{1}{6}\right)}$$
$$u_{R\left(3,1,\frac{2}{3}\right)}$$
$$d_{R\left(3,1,-\frac{1}{3}\right)}$$
$$l_{L\left(1,2,-\frac{1}{2}\right)}$$
$$e_{R(1,1,-1)}$$

spin-1/2

$$B_{\mu\,(1,1,0)}$$
$$W^{I}_{\mu\,(1,3,0)}$$
$$G^{A}_{\mu\,(8,1,0)}$$

spin-1

$$H_{\left(1,2,\frac{1}{2}\right)}$$

spin-0

$$I = 1, 2, 3$$
$$A = 1, .., 8.$$
$$\mu = 0, 1, 2, 3$$

Spin assigned based on the transformation property of the field under the Lorentz group *SO(3,1)*

Model building and cataloguing

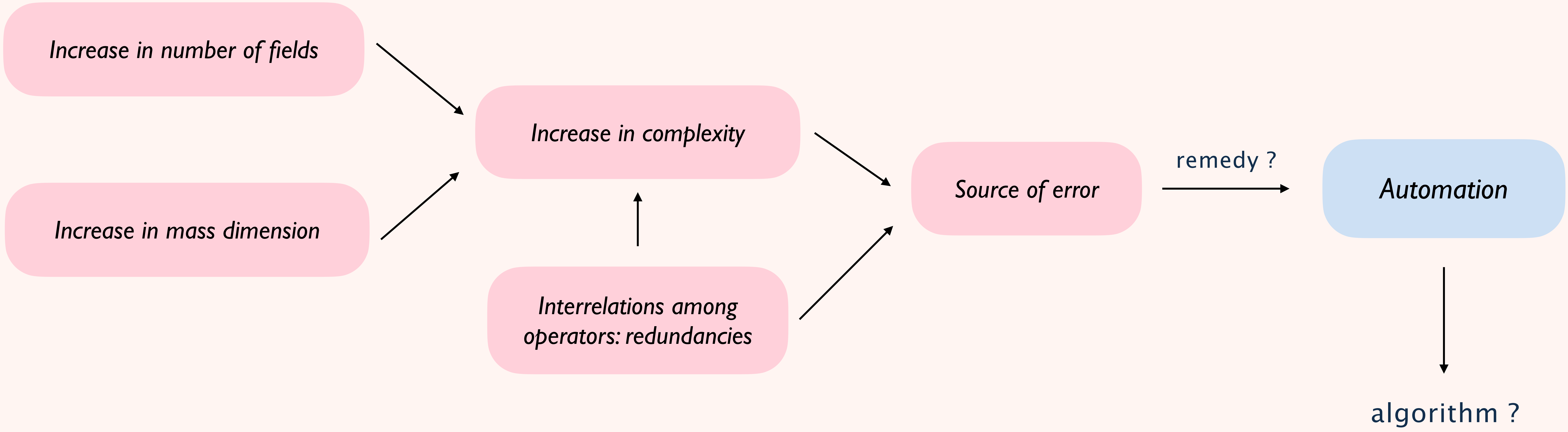
Symmetry

$\Downarrow$

Building + Cataloguing

Space-time symmetries	*Internal symmetries*	*Accidental symmetries*
$\{(\partial_\mu\phi)(\partial^\mu\phi),\ (\bar\psi\gamma^\mu\mathcal{D}_\mu\psi),\ \mathrm{Tr}(F^{\mu\nu}F_{\mu\nu})\}$ →	✓ →	✓
$\{\phi,\ \phi^2,\ \phi^3,\ \phi^4,\ \phi^5\}$ →	$\{\phi^2,\ \phi^4\}$ →	✓
$\{\bar\psi_L\,\psi_R,\ \bar\psi_L\,\psi_R\,\phi,\ \bar\psi_L\,\sigma^{\mu\nu}\psi_R\,F_{\mu\nu}\}$ →	$\{\bar\psi_L\,\psi_R\,\phi\}$ →	✓
$\{\psi_L^2\,\phi^2,\ \psi_{L,R}^4,\ \psi_L^2\,\psi_R^2\}$ →	✓ →	$\{\psi_{L,R}^4,\ \psi_L^2\,\psi_R^2\}$ specific operators, e.g., $l_L\,q_L^3$ can be further filtered out

Challenges associated with model building



Hilbert Series: a prescription for constructing invariants

Complex scalar fields with U(1) symmetry – a toy example

Transformation property: $\phi \to e^{i\theta}\,\phi, \quad \phi^* \to e^{-i\theta}\,\phi^*$

Possible invariants: $(\phi^*\phi)^n$

Number of invariants for each $n = 1$

$$\mathsf{h} = \sum_{n=1}^{\infty} c_n\,(\phi^*\phi)^n = 1 + (\phi^*\phi) + (\phi^*\phi)^2 + (\phi^*\phi)^3 + \ldots$$

An infinite series containing all possible invariants

$$\mathsf{h} = \frac{1}{2\pi}\int_0^{2\pi} \frac{d\theta}{(1-\phi\,e^{i\theta})(1-\phi^*\,e^{-i\theta})} = \frac{1}{2\pi i}\oint_{|z|=1} \frac{dz}{z}\,\frac{1}{(1-\phi\,z)(1-\frac{\phi^*}{z})}$$

$$\left[(1-\phi\,z)\left(1-\frac{\phi^*}{z}\right)\right]^{-1} = \exp\left[-\log(1-\phi\,z) - \log\left(1-\frac{\phi^*}{z}\right)\right] = \exp\left[\sum_{r=1}^{\infty}\frac{(\phi z)^r}{r} + \sum_{r=1}^{\infty}\left(\frac{\phi^*}{z}\right)^r\frac{1}{r}\right]$$

$$\Downarrow$$

$$\underbrace{\mathsf{h}(\phi,\phi^*)}_{\text{Hilbert Series}} = \oint_{|z|=1} \underbrace{\frac{dz}{z}}_{\text{Haar measure}}\ \underbrace{\exp\left[\sum_{r=1}^{\infty}\frac{(\phi z)^r}{r} + \sum_{r=1}^{\infty}\left(\frac{\phi^*}{z}\right)^r\frac{1}{r}\right]}_{\text{Plethystic exponential}}$$

Hilbert Series: a prescription for constructing invariants

Complex scalar fields with U(1) symmetry – a toy example

Integration measure → Haar measure

Generating function → Plethystic exponential

$$\underbrace{\mathsf{h}\,(\phi,\phi^*)}_{\text{Hilbert Series}} = \oint_{|z|=1} \underbrace{\frac{dz}{z}}_{\text{Haar measure}} \underbrace{\exp\left[\sum_{r=1}^{\infty}\frac{(\phi z)^r}{r} + \sum_{r=1}^{\infty}\left(\frac{\phi^*}{z}\right)^r\frac{1}{r}\right]}_{\text{Plethystic exponential}}$$

z and $\frac{1}{z}$

"Characters" corresponding to +1, -1 charges of U(1)

General case

$$\mathrm{PE}\,[\varphi,\mathcal{R}] = \exp\left(\sum_{r=1}^{\infty}\frac{\varphi^r\,\chi_{\mathcal{R}}(z_j^r)}{r}\right)$$

for a spurion φ transforming under representation $\mathcal{R}$ of a Lie group

z_j – variables parametrizing the character $\quad j$ – rank of the group

L. Lehman, A. Martin (2015), arxiv: 1503.07537

Underlying principle

$$f(z_j) = \sum_i c_i\,\chi_i(z_j), \quad \int d\mu\,\chi_i(z)\,\chi_j^*(z) = \delta_{ij}$$

characters of compact Lie groups form an orthonormal set of basis functions on z_j

Building blocks

For SU(N)

$$\chi^{(M(\epsilon))}_{r_1,r_2,\ldots,r_{N-1}} = \frac{|\epsilon^{r_1},\epsilon^{r_2},\ldots,\epsilon^{r_{N-1}},1|}{|\epsilon^{N-1},\epsilon^{N-2},\ldots,\epsilon,1|}$$

(character formula)

$M(\epsilon) = \mathrm{diag}(\epsilon_1,\epsilon_2,\ldots,\epsilon_N)$ denotes a particular representation of $SU(N)$

$r_1, r_2, \ldots, r_{N-1} \in \mathbb{Z}$, such that $r_1 > r_2 > \cdots r_{N-1} > 0$,

obtained from the Dynkin labels of the representation.

Cartan subalgebra

$$\underbrace{|\epsilon^{r_1},\epsilon^{r_2},\ldots,\epsilon^{r_{N-1}},1|}_{numerator} = \begin{vmatrix} \epsilon_1^{r_1} & \epsilon_1^{r_2} & \ldots & \epsilon_1^{r_{N-1}} & 1 \\ \epsilon_2^{r_1} & \epsilon_2^{r_2} & \ldots & \epsilon_2^{r_{N-1}} & 1 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \epsilon_N^{r_1} & \epsilon_N^{r_2} & \ldots & \epsilon_N^{r_{N-1}} & 1 \end{vmatrix}$$

$$\int_{SU(N)} d\mu_{SU(N)} = \frac{1}{(2\pi i)^{N-1} N!} \oint_{|z_l|=1} \prod_{l=1}^{N-1} \frac{dz_l}{z_l} \Delta(\epsilon)\Delta(\epsilon^{-1}).$$

(formula for Haar measure)

Vandermonde determinant

$$\underbrace{|\epsilon^{N-1},\epsilon^{N-2},\ldots,\epsilon,1|}_{denominator} = \begin{vmatrix} \epsilon_1^{N-1} & \epsilon_1^{N-2} & \ldots & \epsilon_1^2 & \epsilon_1 & 1 \\ \epsilon_2^{N-1} & \epsilon_2^{N-2} & \ldots & \epsilon_2^2 & \epsilon_2 & 1 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ \epsilon_N^{N-1} & \epsilon_N^{N-2} & \ldots & \epsilon_N^2 & \epsilon_N & 1 \end{vmatrix} = \prod_{1\le a<b\le N} (\epsilon_a - \epsilon_b)$$

Vandermonde determinant

$$\prod_{a=1}^{N} \epsilon_a = 1, \quad |\epsilon_a| = 1.$$

related to co-ordinates of the maximal torus

Building blocks

Characters and Haar measures w.r.t. spacetime symmetry

Note: — The derivative is a singlet under the internal symmetry groups and only transforms under the Lorentz group.

Issues:

➢ Inclusion of derivatives brings into picture redundancies due to Equations of motion (EOM) of the fields and Integration by parts (IBP) relations between different operators with identical composition.

➢ SO(3,1) is a non-compact group on account of the Minkowskian metric and the Haar measure is only defined for connected, compact groups.

↓ remedy ?

we first shift to the Euclidean group SO(4) (more appropriately, the conformal group SO(4,2)) and we express it as the tensor product $SU(2)_L$ x $SU(2)_R$

↓

Subtraction of EOM and IBP redundancies is automatically implemented when conformal characters are taken into account

(Once again, by exploiting character orthonormality)

Building blocks

Characters under the conformal group for fields with spin-0, ½ and 1.

$$\chi^{(4)}_{[1;(0,0)]}(\mathcal{D},\alpha,\beta) = \mathcal{D}\, P^{(4)}(\mathcal{D},\alpha,\beta) \times \left[1-\mathcal{D}^2\right]$$

$$\chi^{(4)}_{[\frac{3}{2};(\frac{1}{2},0)]}(\mathcal{D},\alpha,\beta) = \mathcal{D}^{\frac{3}{2}}\, P^{(4)}(\mathcal{D},\alpha,\beta) \times \left[\left(\alpha+\frac{1}{\alpha}\right) - \mathcal{D}\left(\beta+\frac{1}{\beta}\right)\right]$$

$$\chi^{(4)}_{[\frac{3}{2};(0,\frac{1}{2})]}(\mathcal{D},\alpha,\beta) = \mathcal{D}^{\frac{3}{2}}\, P^{(4)}(\mathcal{D},\alpha,\beta) \times \left[\left(\beta+\frac{1}{\beta}\right) - \mathcal{D}\left(\alpha+\frac{1}{\alpha}\right)\right]$$

$$\chi^{(4)}_{[2;(1,0)]}(\mathcal{D},\alpha,\beta) = \mathcal{D}^2\, P^{(4)}(\mathcal{D},\alpha,\beta) \times \left[\left(\alpha^2+1+\frac{1}{\alpha^2}\right) - \mathcal{D}\left(\alpha+\frac{1}{\alpha}\right)\left(\beta+\frac{1}{\beta}\right) + \mathcal{D}^2\right]$$

$$\chi^{(4)}_{[2;(0,1)]}(\mathcal{D},\alpha,\beta) = \mathcal{D}^2\, P^{(4)}(\mathcal{D},\alpha,\beta) \times \left[\left(\beta^2+1+\frac{1}{\beta^2}\right) - \mathcal{D}\left(\alpha+\frac{1}{\alpha}\right)\left(\beta+\frac{1}{\beta}\right) + \mathcal{D}^2\right]$$

$$P^{(4)}(\mathcal{D},\alpha,\beta) = \left[(1-\mathcal{D}\,\alpha\,\beta)\left(1-\frac{\mathcal{D}}{\alpha\,\beta}\right)\left(1-\frac{\mathcal{D}\,\alpha}{\beta}\right)\left(1-\frac{\mathcal{D}\,\beta}{\alpha}\right)\right]^{-1}$$

Full Hilbert Series

$$\mathcal{H} = \int \frac{1}{P^{(4)}(\mathcal{D},\alpha,\beta)} \times d\mu_{SU(2)\times SU(2)}(\alpha,\beta) \times d\mu_{SU(3)}(z_1,z_2) \times d\mu_{SU(2)}(y) \times d\mu_{U(1)}(x) \times \mathrm{PE}[\psi,\phi,X]$$

$$\mathrm{PE}[\psi,\phi,X] = \mathrm{PE}[\psi,\mathcal{R}] \times \mathrm{PE}[\phi,\mathcal{R}] \times \mathrm{PE}[X,\mathcal{R}]$$

B. Henning, X. Lu, T. Melia, H. Murayama (2015), arxiv: 1512.03433 - For SMEFT
B. Henning, X. Lu, T. Melia, H. Murayama (2017), arxiv: 1706.08520 - For explicit details on conformal characters

Automation

GrIP - acronym for Group Invariant Polynomials

↓ Mathematica package available from

https://TeamGrIP.github.io/GrIP/

Automation

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U Banerjee, J Chakrabortty, **S Prakash**, SU Rahaman (2020), arxiv: 2004.12830

Functionality

User friendly interface:

- *Model info (symmetry information, field content) read through an input file*
- *Commands entered through a notebook file*
- *Results displayed on the same notebook file*

- *Familiarity with characters, Haar measures and Hilbert series is not required*

Additional capabilities:

- *Filters based on the degree of baryon and lepton number violation*
- *Number of fermion flavour can be modified*

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```
ModelName="StandardModel"
```

User Input : Symmetry Groups

```
SymmetryGroupClass = {
Group[1] = {"GroupName" ->  "SU3",
            "N" ->  3
},
Group[2] = {"GroupName" ->  "SU2",
            "N" ->  2
},
Group[3] = {"GroupName" -> "U1",
            "N" ->  1
}
};
```

User Input : Fields and their properties

```
FieldClass={
Field[1]={
        "FieldName"-> H,
        "Self-Conjugate"-> False,
        "Lorentz Behaviour"-> "SCALAR",
        "Chirality"-> "NA",
        "Baryon Number"-> 0,
        "Lepton Number"-> 0,
        "SU3Rep"-> "1",
        "SU2Rep"-> "2",
        "U1Rep"-> 1/2},
Field[2]={
        "FieldName"-> Q,
        "Self-Conjugate"-> False,
        "Lorentz Behaviour"-> "FERMION",
        "Chirality"-> "l",
        "Baryon Number"-> 1/3,
        "Lepton Number"-> 0,
        "SU3Rep"-> "3",
        "SU2Rep"-> "2",
        "U1Rep"-> 1/6},
```

Automation

GrIP - acronym for Group Invariant Polynomials

↓ Mathematica package available from

https://TeamGrIP.github.io/GrIP/

```
DisplayHSOutput["MassDim" → 4, "OnlyMassDimOutput" → True, "ΔB" → "NA", "ΔL" → "NA", "Flavours" → Nf];
```

```
DisplayBLviolatingOperators["HighestMassDim" -> 15, "ΔB" → 1, "ΔL" -> -1, "Flavours" -> Nf];
```

First instance of ΔB = 1 and ΔL = -1 occurs at mass dimension 6,

Operators:

$$\frac{1}{3} L\,Nf^2\,Q^3 + \frac{2}{3} L\,Nf^4\,Q^3 + dL\,Nf^4\,Q\,u + \frac{1}{2} el\,Nf^3\,Q^2\,u + \frac{1}{2} el\,Nf^4\,Q^2\,u + del\,Nf^4\,u^2$$

Functionality

User friendly interface:

- *Model info (symmetry information, field content) read through an input file*
- *Commands entered through a notebook file*
- *Results displayed on the same notebook file*

- *Familiarity with characters, Haar measures and Hilbert series is not required*

```
DisplayUserInputTable
```

FieldName	Self-Conjugate	Lorentz Behaviour	Chirality	Baryon Number	Lepton Number	SU3Rep	SU2Rep	U1Rep
H	False	SCALAR	NA	0	0	1	2	$\frac{1}{2}$
Q	False	FERMION	l	$\frac{1}{3}$	0	3	2	$\frac{1}{6}$
u	False	FERMION	r	$\frac{1}{3}$	0	3	1	$\frac{2}{3}$
d	False	FERMION	r	$\frac{1}{3}$	0	3	1	$-\frac{1}{3}$
L	False	FERMION	l	0	-1	1	2	$-\frac{1}{2}$
el	False	FERMION	r	0	-1	1	1	-1
Bl	False	VECTOR	l	0	0	1	1	0
Wl	False	VECTOR	l	0	0	1	3	0
Gl	False	VECTOR	l	0	0	8	1	0

Additional capabilities:

- *Filters based on the degree of baryon and lepton number violation*
- *Number of fermion flavour can be modified*

Automation

GrIP - acronym for Group Invariant Polynomials

↓ Mathematica package available from

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Additional capabilities:

- *Filters based on the degree of baryon and lepton number violation*
- *Number of fermion flavour can be modified*

Limitations

- *Only works for spin - 0, 1, 1/2 fields in 3+1 space time dimensions.*
- *Only reports operators in a complete and independent basis, no provisions for Green's basis*
- *Results are reported in "raw" form*

$$
\begin{aligned}
\phi^6 &\to (H^\dagger)^3 H^3 \\
\phi^4 \mathcal{D}^2 &\to 2\,(H^\dagger)^2 H^2 \mathcal{D}^2 \\
X^3 &\to G_L^3 + G_R^3 + W_L^3 + W_R^3 \\
\psi^2\phi^3 &\to l^\dagger e\, H^2 H^\dagger + q^\dagger d\, H^2 H^\dagger + q^\dagger u\, H\, (H^\dagger)^2 \\
\phi^2 X^2 &\to H^\dagger H\, G_L^2 + H^\dagger H\, G_R^2 + H^\dagger H\, W_L^2 + H^\dagger H\, W_R^2 + \\
&\quad H^\dagger H\, B_L^2 + H^\dagger H\, B_R^2 + H^\dagger H\, B_L W_L + H^\dagger H\, B_R W_R \\
\psi^2\phi^2\mathcal{D} &\to e^\dagger e\, H^\dagger H\, \mathcal{D} + 2 l^\dagger l\, H^\dagger H\, \mathcal{D} + u^\dagger u\, H^\dagger H\, \mathcal{D} + d^\dagger d\, H^\dagger H\, \mathcal{D} + \\
&\quad 2\, q^\dagger q\, H^\dagger H\, \mathcal{D} + u^\dagger d\, H^2 \mathcal{D} \\
\psi^2 \phi X &\to l^\dagger e\, H\, B_R + l^\dagger e\, H\, W_R + q^\dagger d\, H\, B_R + q^\dagger d\, H\, W_R + q^\dagger d\, H\, G_R + \\
&\quad q^\dagger u\, H^\dagger\, B_R + q^\dagger u\, H^\dagger\, W_R + q^\dagger u\, H^\dagger\, G_R \\
\psi^4 &\to 2\,(q^\dagger)^2 q^2 + 2\, q^\dagger q\, l^\dagger l + (l^\dagger)^2 l^2 + (e^\dagger)^2 e^2 + (u^\dagger)^2 u^2 + (d^\dagger)^2 d^2 + \\
&\quad e^\dagger e\, u^\dagger u + e^\dagger e\, d^\dagger d + 2\, u^\dagger u\, d^\dagger d + l^\dagger l\, e^\dagger e + l^\dagger l\, u^\dagger u + l^\dagger l\, d^\dagger d + \\
&\quad q^\dagger q\, e^\dagger e + 2\, q^\dagger q\, u^\dagger u + 2\, q^\dagger q\, d^\dagger d + l^\dagger e\, d^\dagger q + 2\, l^\dagger e\, q^\dagger u + 2\,(q^\dagger)^2 u\, d + \\
&\quad l\, q^3 + q^2 e\, u + d\, e\, u^2 + l\, u\, q\, d
\end{aligned}
$$

(Dimension 6 SMEFT operator basis)

SMEFT (d = 6) operator basis

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

B Grzadkowski, M Iskrzynski, M Misiak, J Rosiek (2010), arXiv:1008.4884

SMEFT (d = 6) operator basis continued …

$8:(\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$

$8:(\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

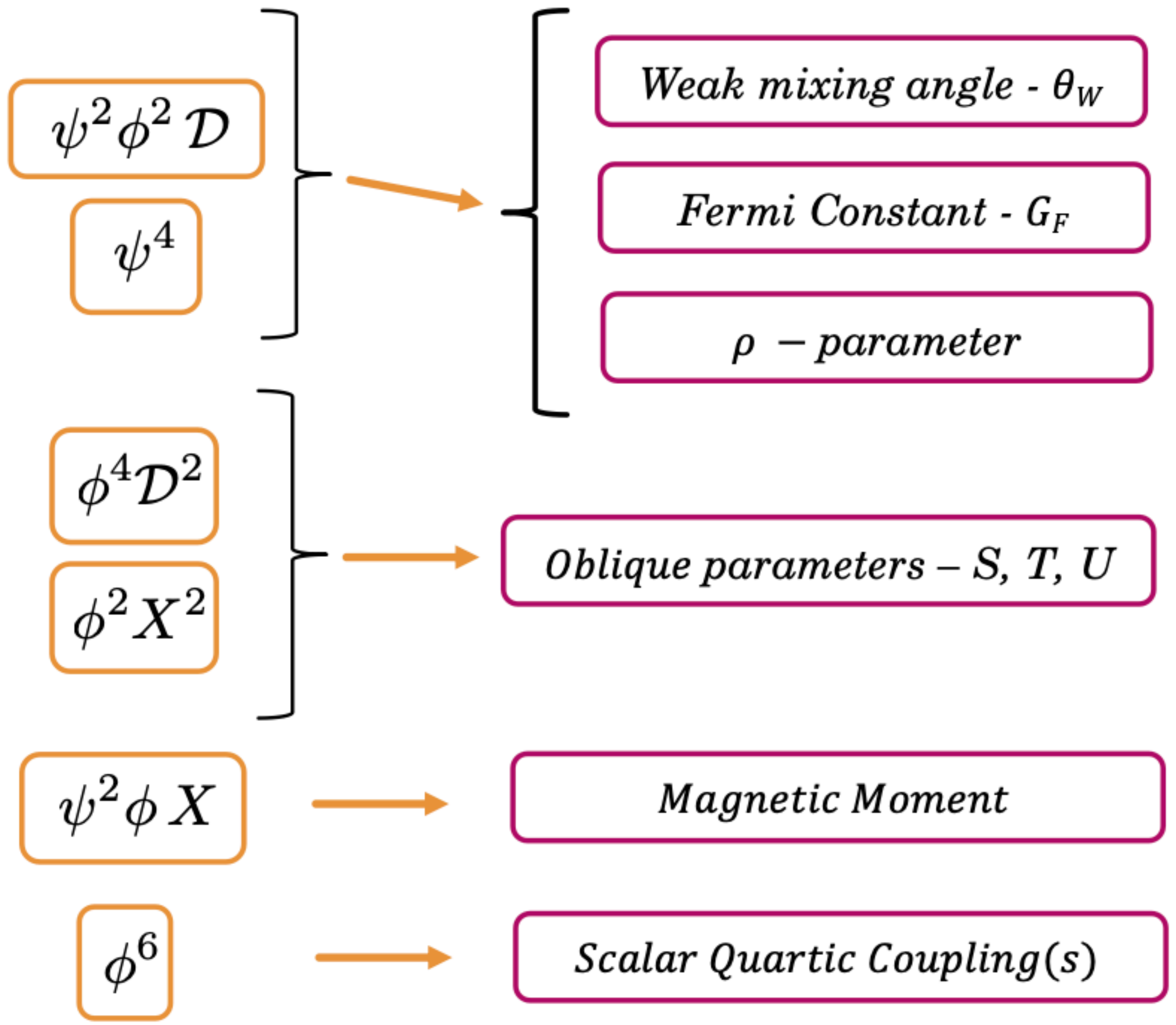
Only B-, L-
Conserving

$8:(\bar{L}R)(\bar{R}L)+\text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8:(\bar{L}R)(\bar{L}R)+\text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$

B Grzadkowski, M Iskrzynski, M Misiak, J Rosiek (2010), arXiv:1008.4884

Operator - observable correspondence



At the level of operator class

W Buchmuller, D Wyler (1986)

EWPO-LO :

$$\{Q_{HD}, Q_{HWB}, Q_{Hq}^{(1)}, Q_{Hq}^{(3)}, Q_{Hl}^{(1)}, Q_{Hl}^{(3)}, Q_{He}, Q_{Hu}, Q_{Hd}, Q_{ll}\}$$

EWPO-NLO-I :

$$\{Q_{HB}, Q_{HW}, Q_{H\Box}\}$$

Higgs Signal Strength (HSS) :

$$\text{EWPO-LO} + \text{EWPO-NLO-I} + \{Q_H, Q_{uH}, Q_{dH}, Q_{eH}, Q_G, Q_{HG}\}$$

At the level of individual operator or groups of operators

SD Bakshi, J Chakrabortty, M Spannowsky (2020), arxiv: 2012.03839

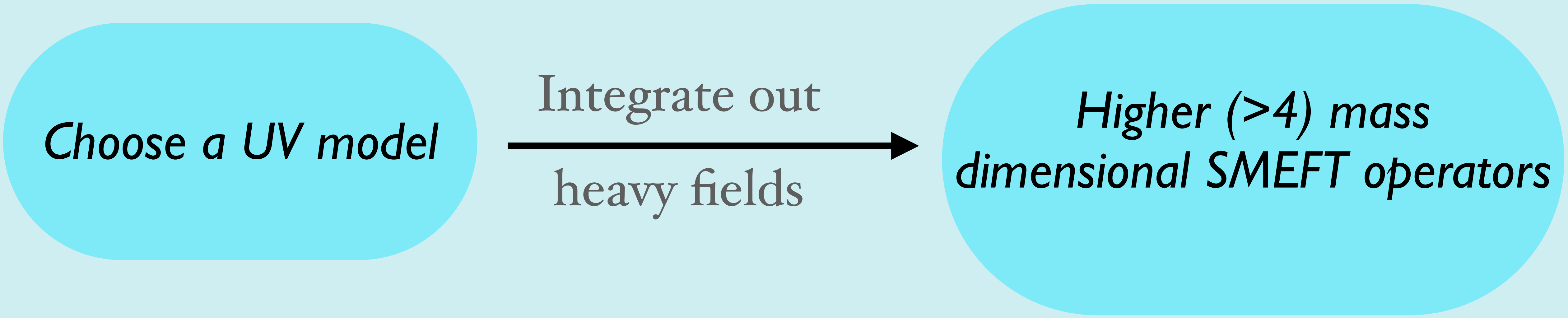
Model discrimination

Popular approach

Choose a UV model

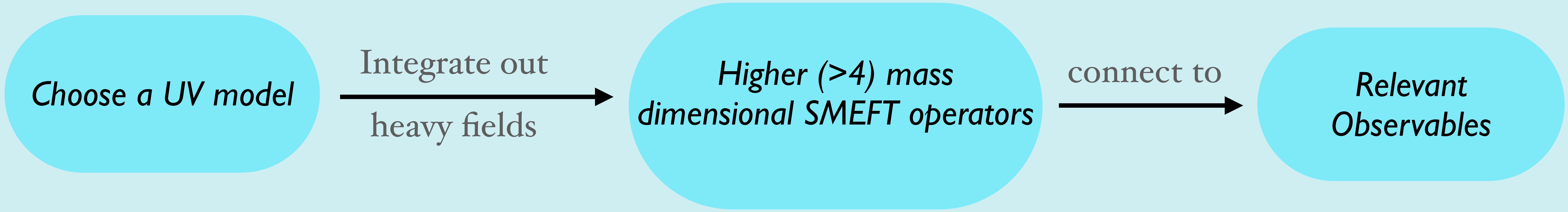
Model discrimination

Popular approach



Model discrimination

Popular approach



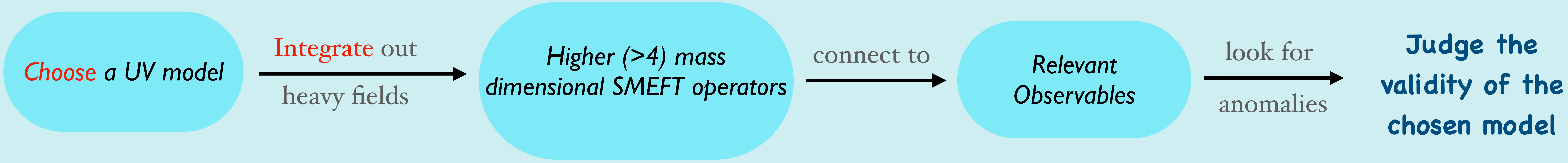
Model discrimination

Popular approach

Choose a UV model → Integrate out heavy fields → *Higher (>4) mass dimensional SMEFT operators* → connect to → *Relevant Observables* → look for anomalies → **Judge the validity of the chosen model**

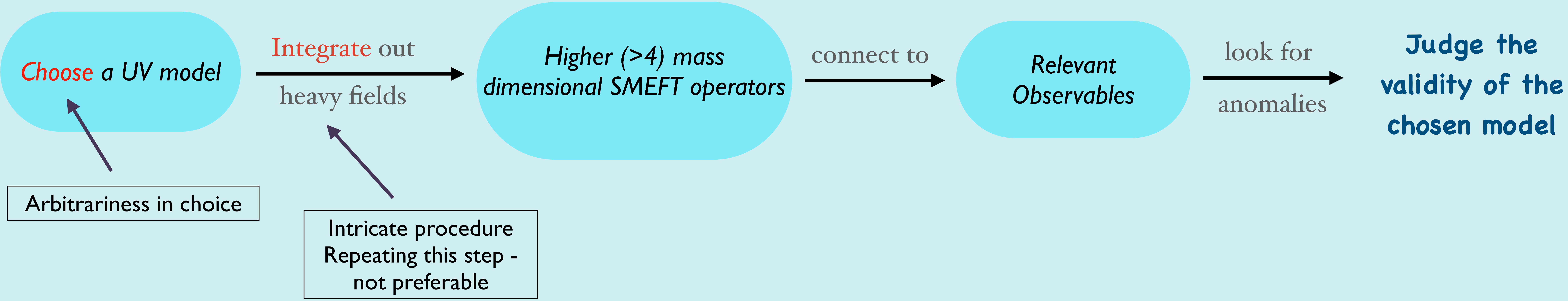
Model discrimination

Popular approach



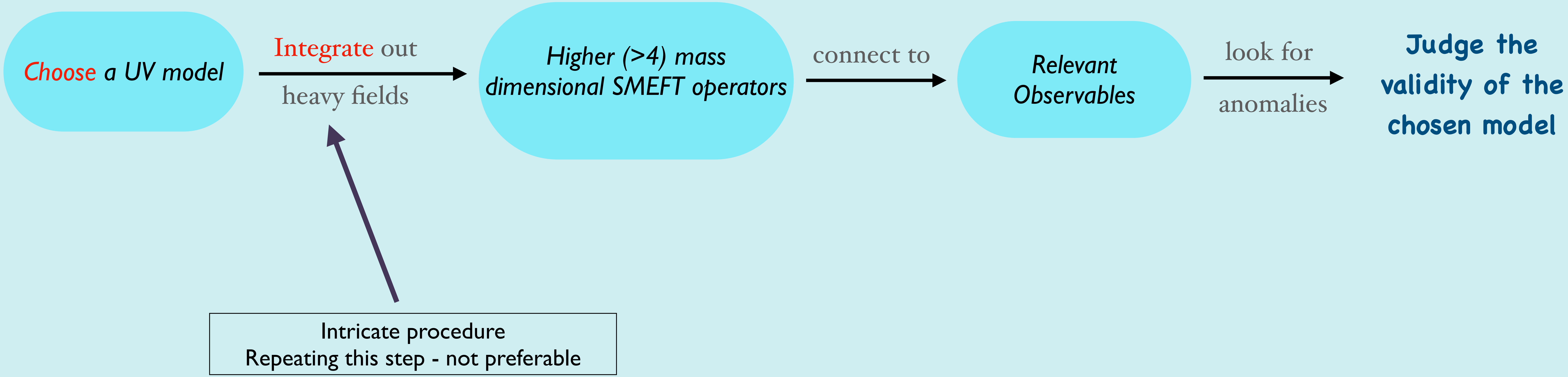
Model discrimination

Popular approach



Model discrimination

Popular approach



Model discrimination

Popular approach

Choose a UV model → (Integrate out heavy fields) → *Higher (>4) mass dimensional SMEFT operators* → (connect to) → *Relevant Observables* → (look for anomalies) → **Judge the validity of the chosen model**

Our proposed approach:

Observable showing anomalous behaviour

Model discrimination

Popular approach

Choose a UV model → (Integrate out heavy fields) → *Higher (>4) mass dimensional SMEFT operators* → (connect to) → *Relevant Observables* → (look for anomalies) → **Judge the validity of the chosen model**

Our proposed approach:

Observable showing anomalous behaviour → (identify) → *Relevant SMEFT operators*

Model discrimination

Popular approach

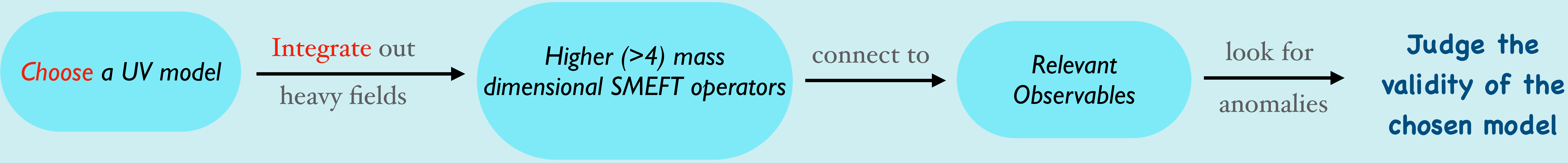
Choose a UV model → Integrate out heavy fields → *Higher (>4) mass dimensional SMEFT operators* → connect to → *Relevant Observables* → look for anomalies → **Judge the validity of the chosen model**

Our proposed approach:

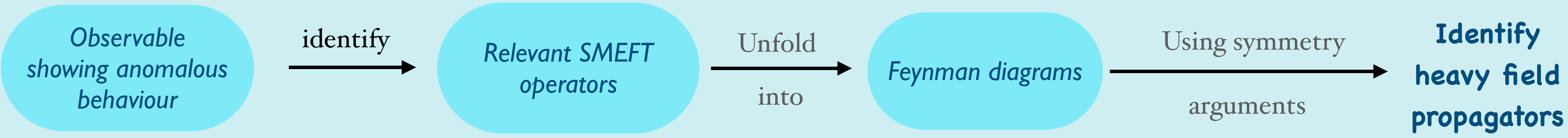
Observable showing anomalous behaviour → identify → *Relevant SMEFT operators* → Unfold into → *Feynman diagrams*

Model discrimination

Popular approach



Our proposed approach:



Model discrimination

Popular approach

Choose a UV model → Integrate out heavy fields → *Higher (>4) mass dimensional SMEFT operators* → connect to → *Relevant Observables* → look for anomalies → **Judge the validity of the chosen model**

Our proposed approach:

Observable showing anomalous behaviour → identify → *Relevant SMEFT operators* → Unfold into → *Feynman diagrams* → Using symmetry arguments → **Identify heavy field propagators**

SD Bakshi, J Chakrabortty, **S Prakash**, SU Rahaman, M Spannowsky (2021), arxiv: 2103.11593

Effective Operators -> Feynman diagrams

The building blocks: *Tree-level diagrams*

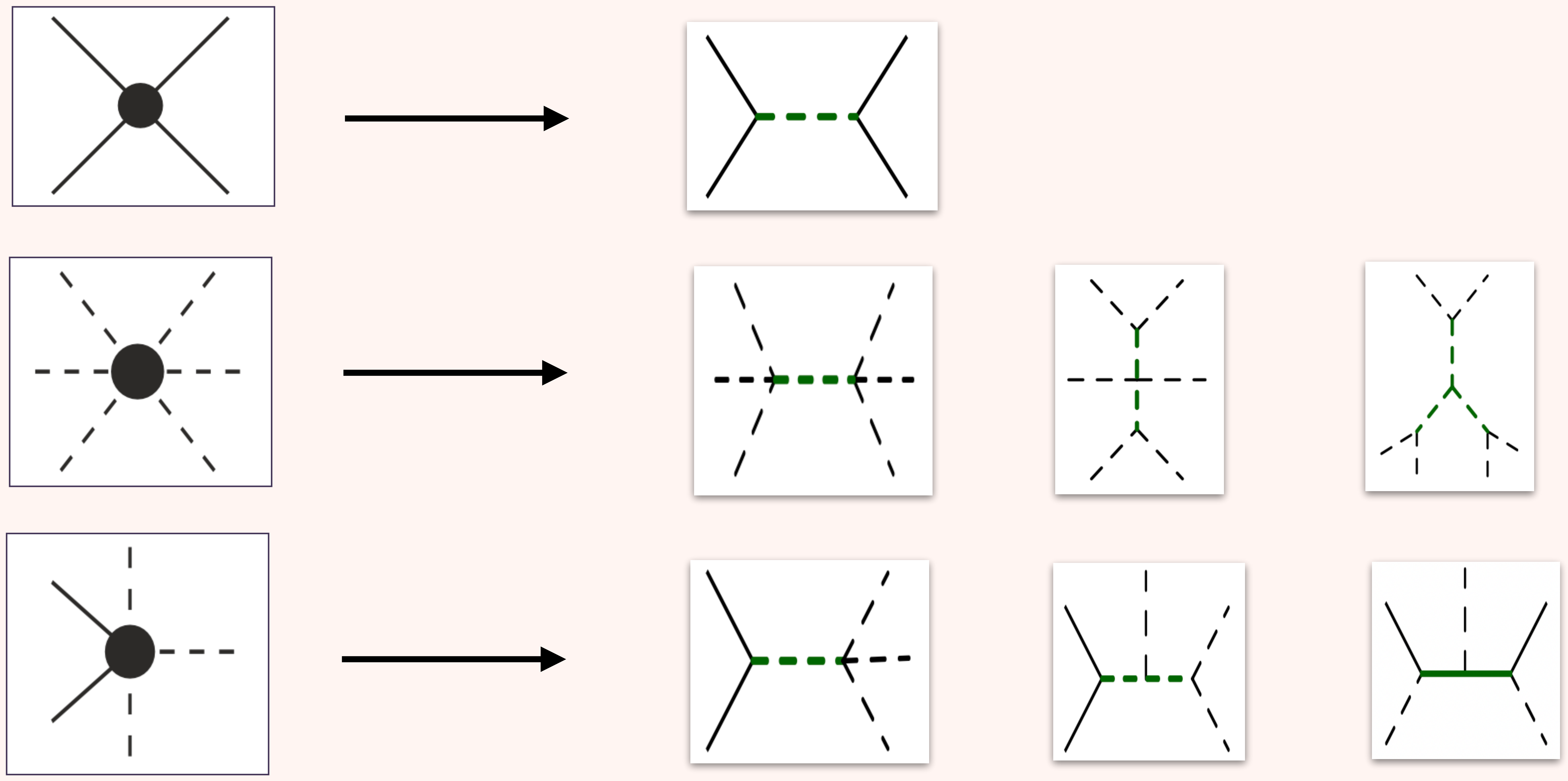
Lorentz invariant unfolding (*simple examples*)

Scalar
Fermion

ψ^4

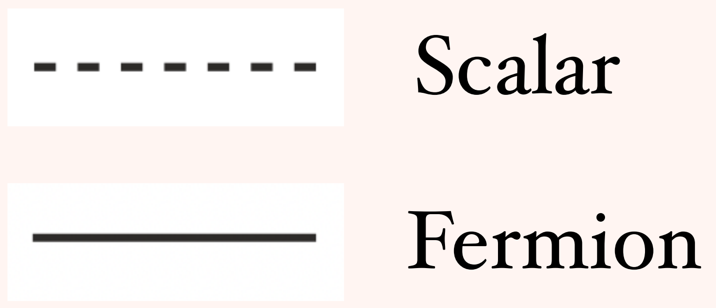
ϕ^6

$\psi^2\phi^3$

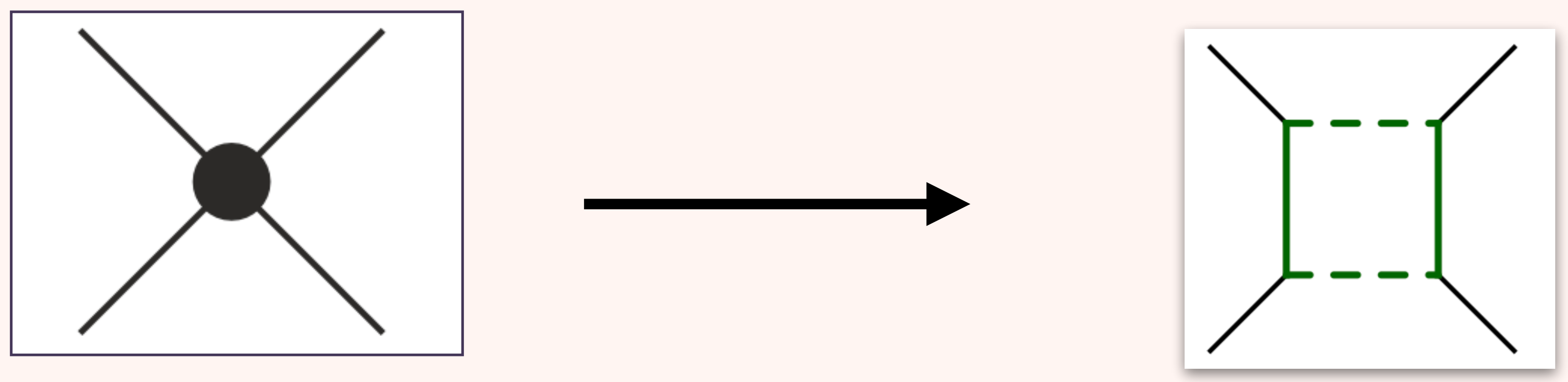


The building blocks: 1-*loop diagrams*

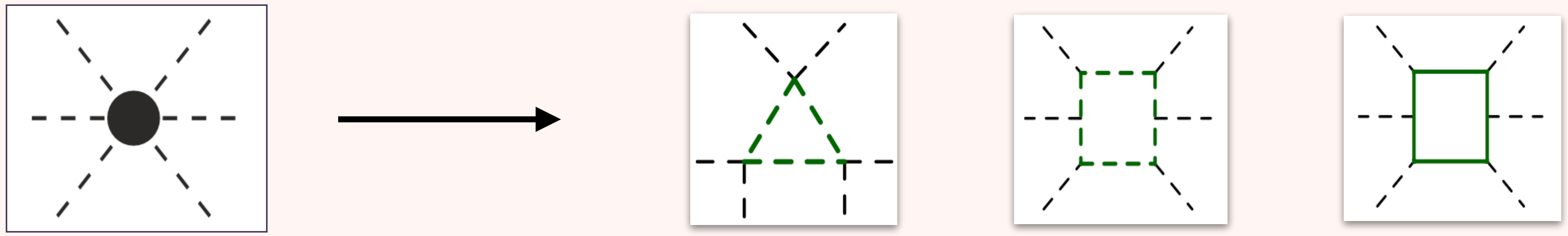
Lorentz invariant unfolding (*simple examples*)



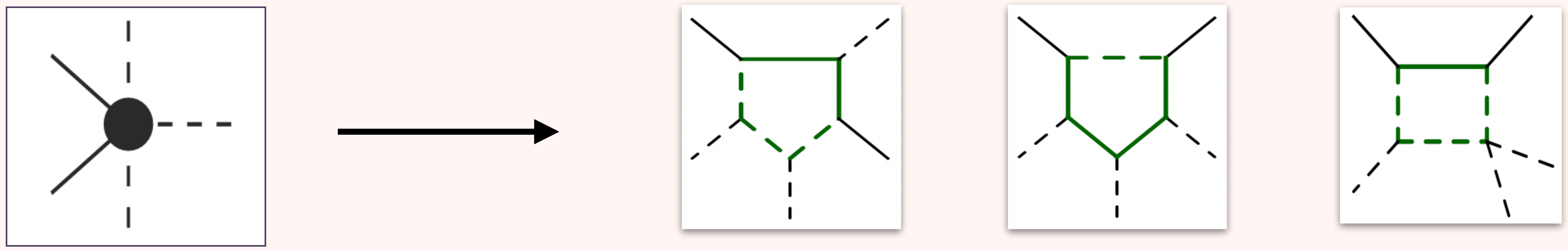
ψ^4



ϕ^6

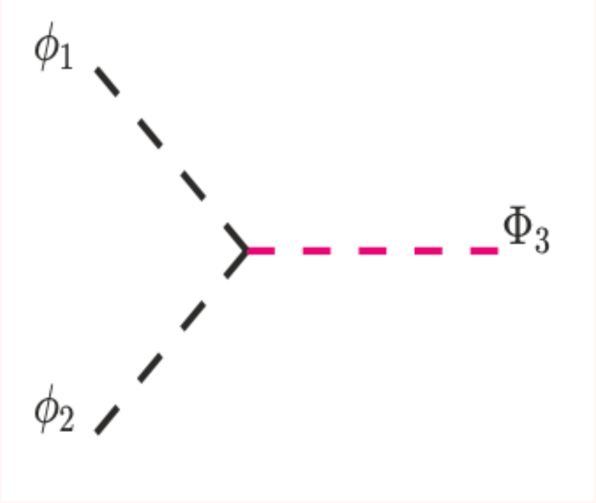


$\psi^2\phi^3$

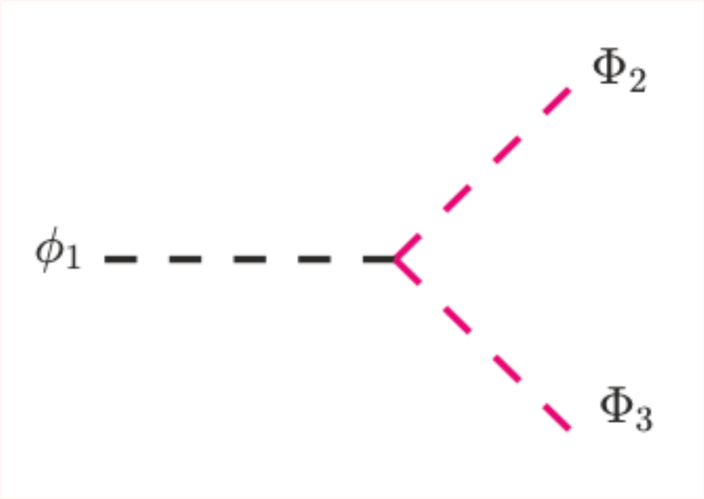


The building blocks: *fixing quantum numbers*

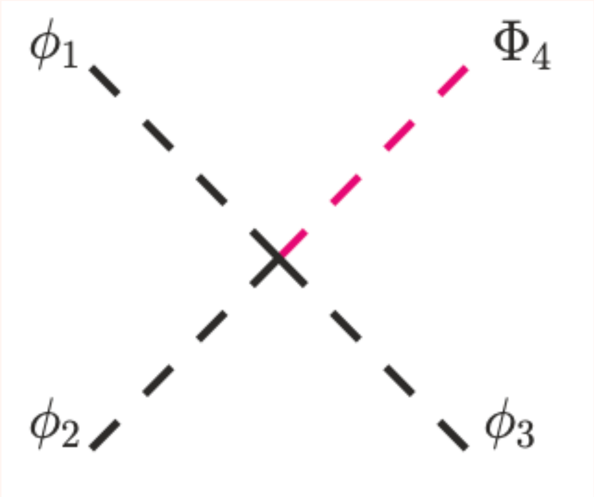
Possible SM - BSM field interactions (scalar sector)



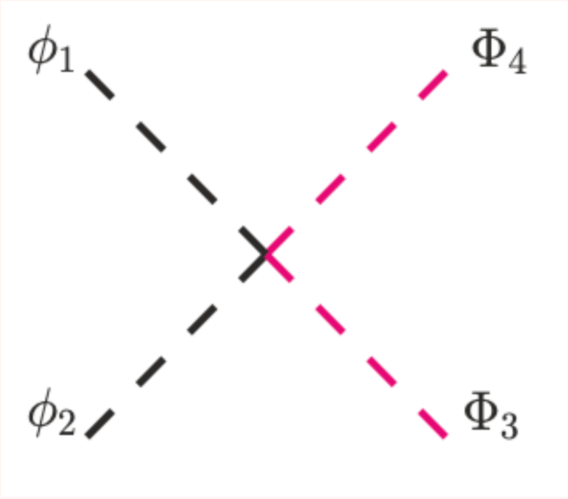
V1



V2



V3

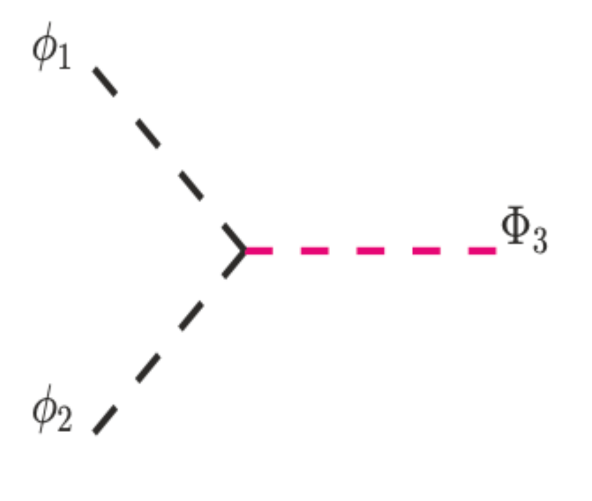


V4

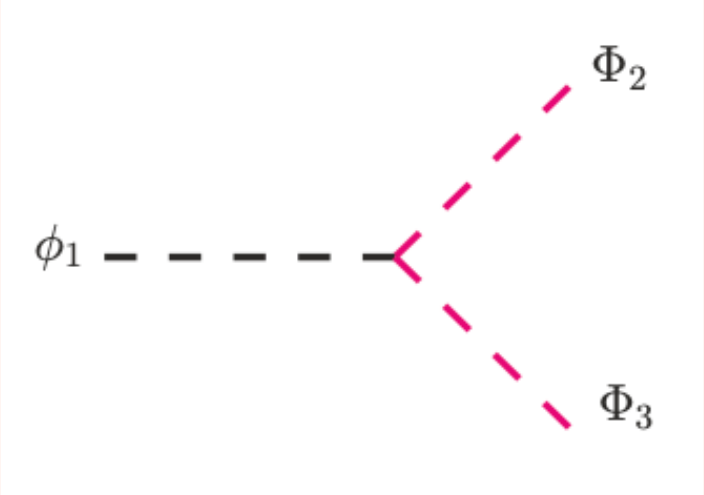
Assumption - all incoming fields at each vertex

The building blocks: *fixing quantum numbers*

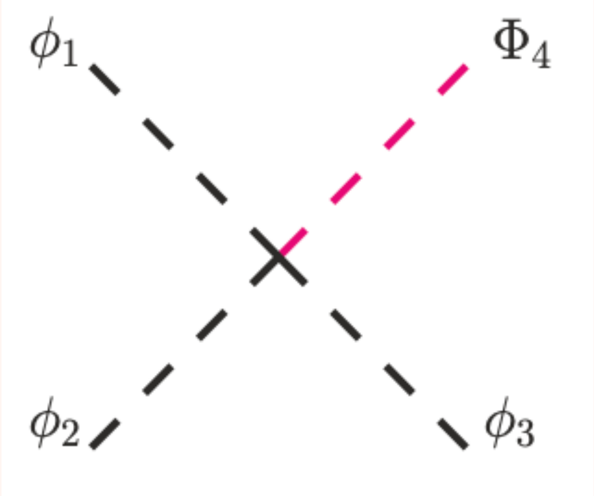
Possible SM - BSM field interactions (scalar sector)



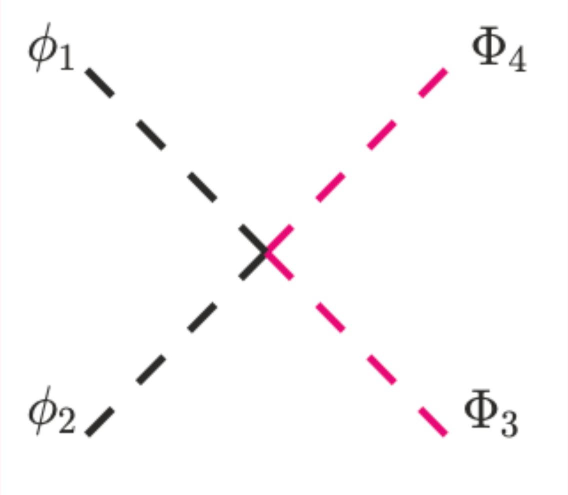
V1



V2



V3



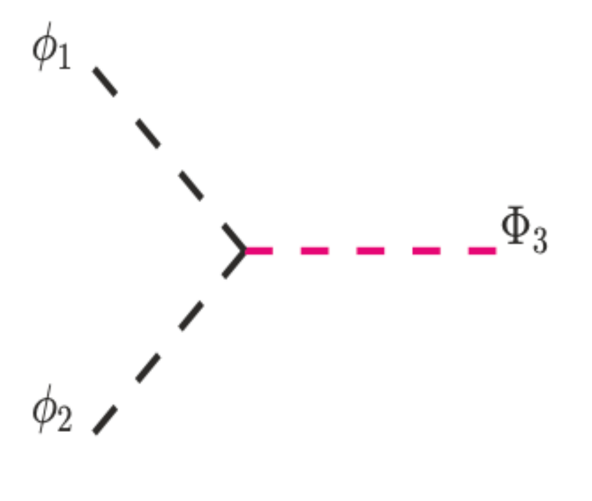
V4

$$(i)\ \phi_1 = \phi_2 = H_{(1,2,\frac{1}{2})} \text{ or } H^\dagger \quad \Rightarrow \quad \Phi_3 \in \{\,(1,3,1),\ (1,1,1)\,\}$$

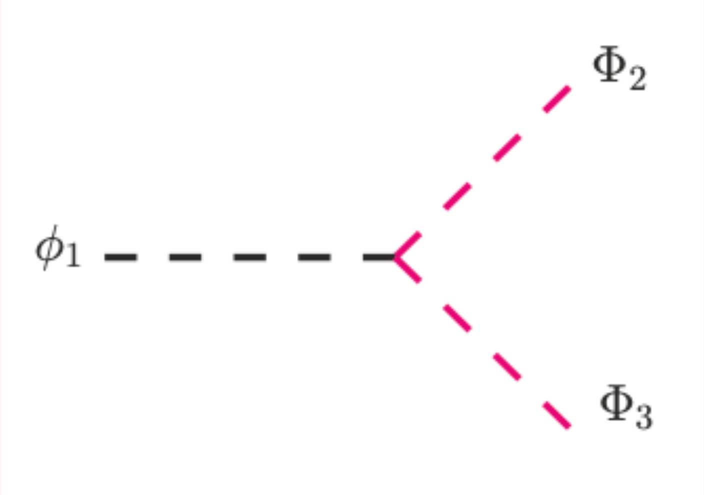
$$(ii)\ \phi_1 = H,\ \phi_2 = H^\dagger \quad \Rightarrow \quad \Phi_3 \in \{\,(1,3,0),\ (1,1,0)\,\}$$

The building blocks: *fixing quantum numbers*

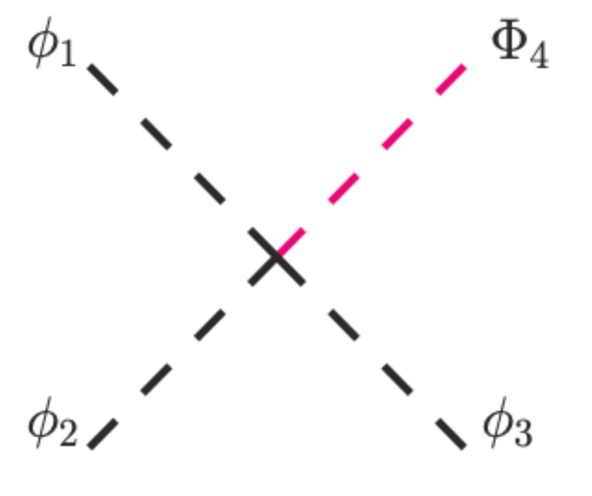
Possible SM - BSM field interactions (scalar sector)



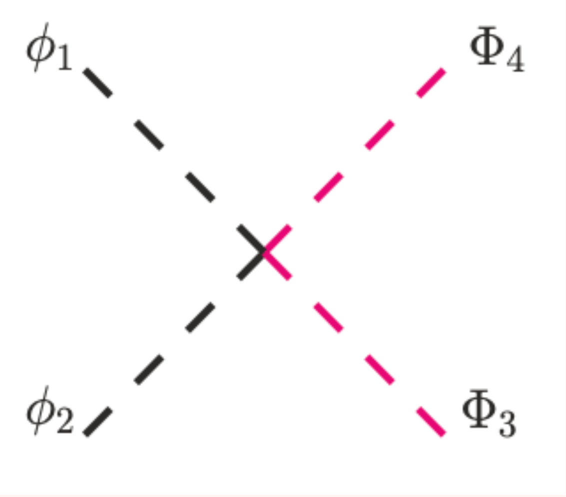
V1



V2



V3



V4

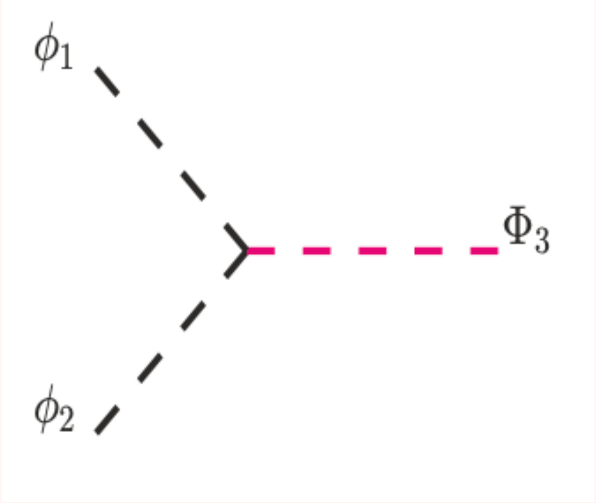
$$\phi_1 = H \text{ or } H^\dagger, \quad \Phi_2 \in (R_{C_2}, R_{L_2}, Y_2), \quad \Phi_3 \in (R_{C_3}, R_{L_3}, Y_3)$$

with

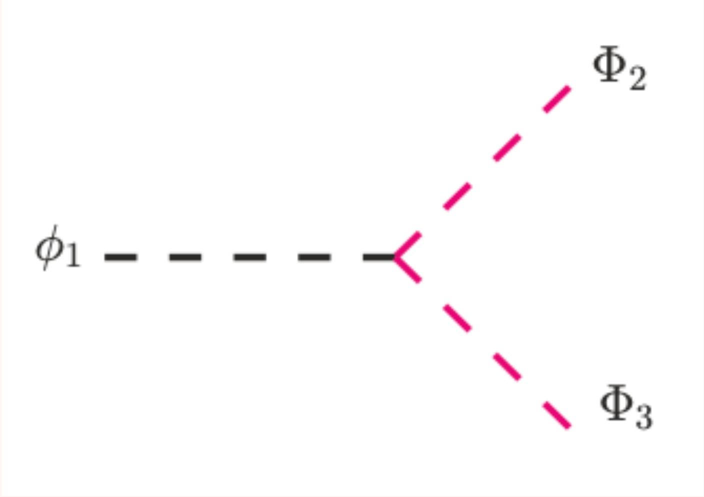
$$R_{C_2} \otimes R_{C_3} = 1, \quad R_{L_2} \otimes R_{L_3} = 2, \quad Y_2 + Y_3 = \mp\frac{1}{2},$$

The building blocks: *fixing quantum numbers*

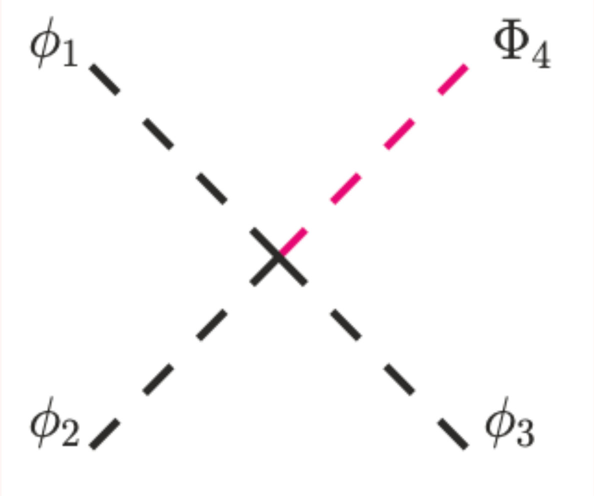
Possible SM - BSM field interactions (scalar sector)



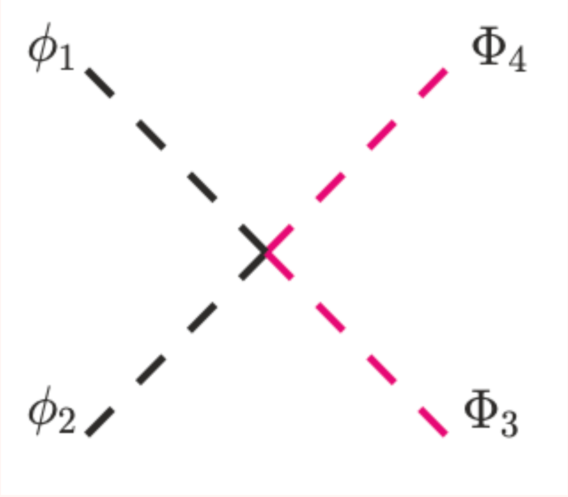
V1



V2



V3



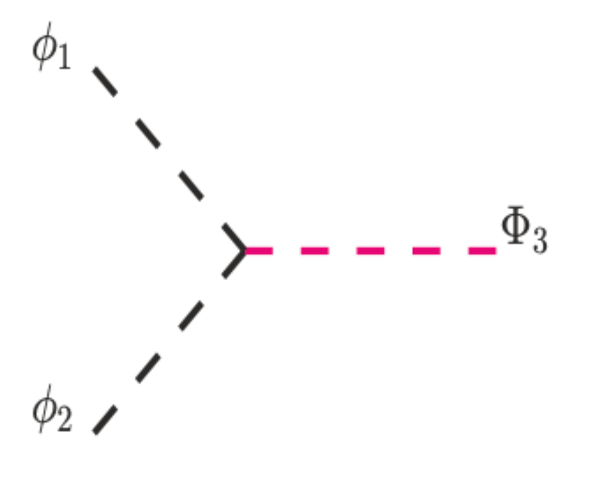
V4

$$(i)\ \phi_1 = \phi_2 = \phi_3 = H \text{ or } H^\dagger \quad \Rightarrow \quad \Phi_4 \in \{\, (1, 4, \mp\frac{3}{2}),\ (1, 2, \mp\frac{3}{2})\,\}$$

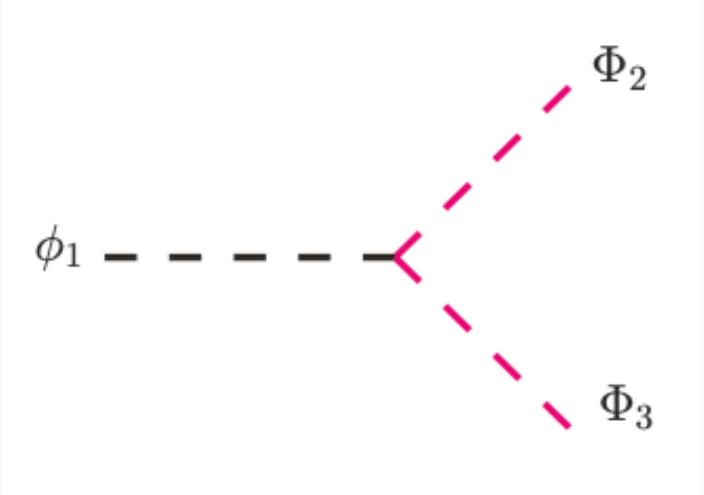
$$(ii)\ \phi_1 = \phi_2 = H,\ \ \phi_3 = H^\dagger \quad \Rightarrow \quad \Phi_4 \in \{\, (1, 4, \mp\frac{1}{2}),\ (1, 2, \mp\frac{1}{2})\,\}$$

The building blocks: *fixing quantum numbers*

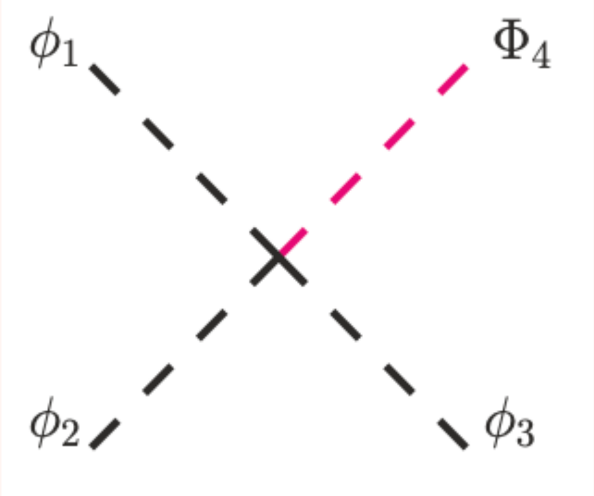
Possible SM - BSM field interactions (scalar sector)



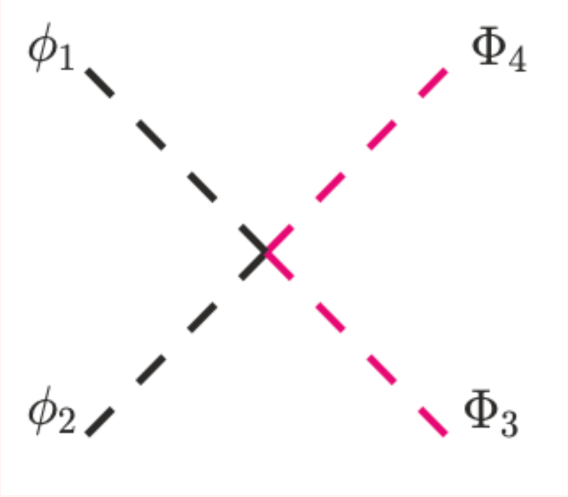
V1



V2



V3



V4

$$(i)\ \phi_1 = H,\ \phi_2 = H^\dagger \quad \Rightarrow \quad \Phi_3 \in (R_C, R_L, Y),\ \ \Phi_4 = \Phi_3^\dagger$$

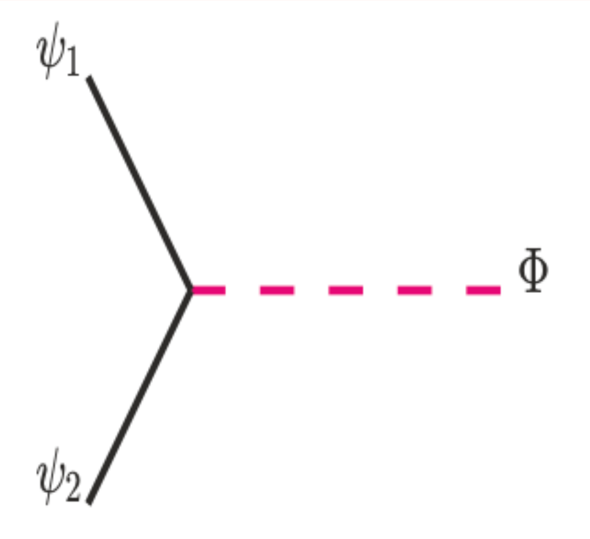
$$(ii)\ \phi_1 = \phi_2 = H \text{ or } H^\dagger \quad \Rightarrow \quad \Phi_3 \in (R_{C_3}, R_{L_3}, Y_3),\ \ \Phi_4 \in (R_{C_4}, R_{L_4}, Y_4),$$

with

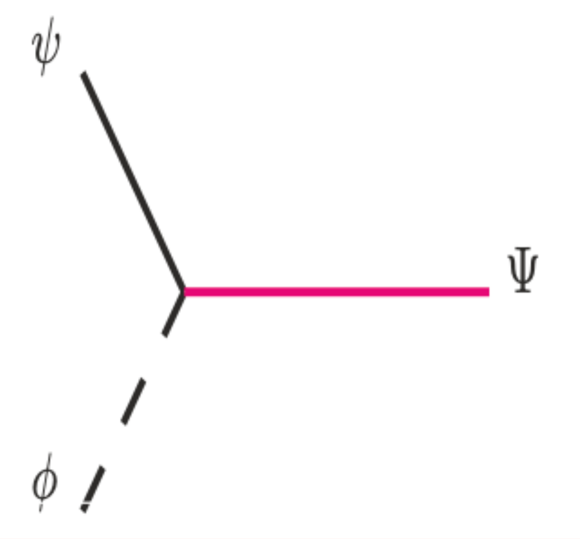
$$R_{C_3} \otimes R_{C_4} = 1,\ \ R_{L_3} \otimes R_{L_4} = 1 \text{ or } 3,\quad Y_3 + Y_4 = \mp 1,$$

The building blocks: *fixing quantum numbers*

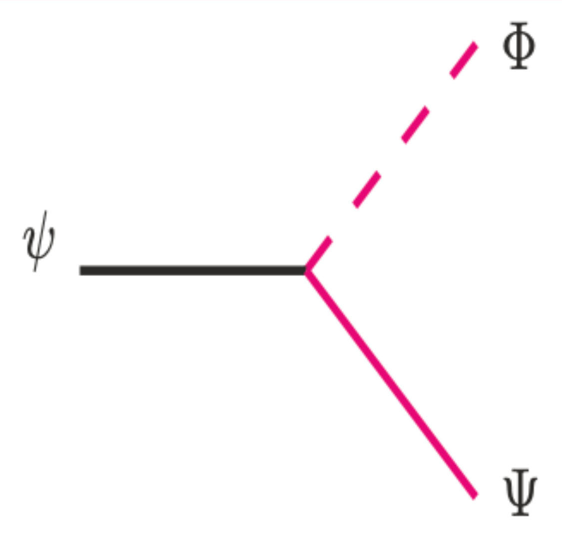
Possible SM - BSM field interactions (Yukawa sector)



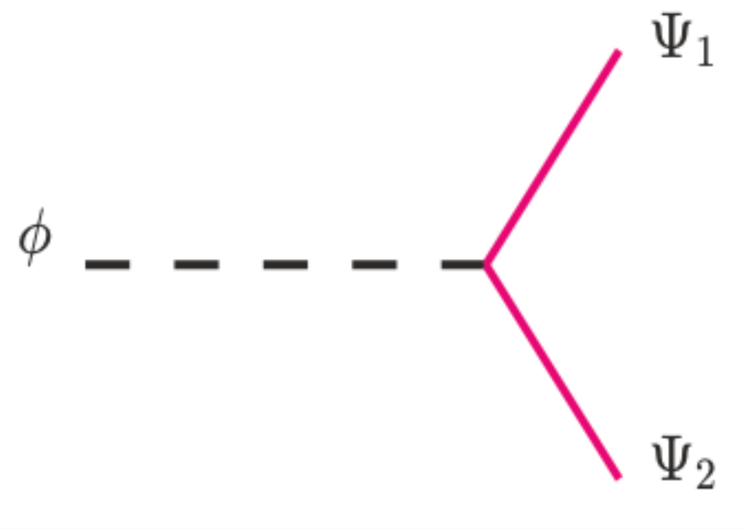
V5



V6



V7

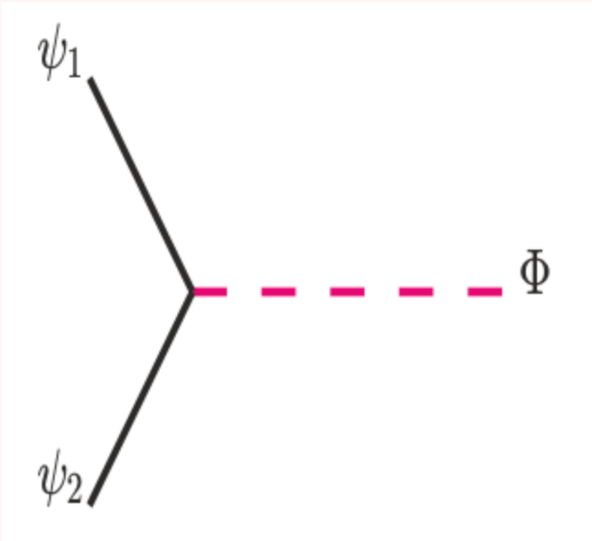


V8

Assumption - all incoming fields at each vertex, arrows not shown explicitly

The building blocks: *fixing quantum numbers*

Possible SM - BSM field interactions (Yukawa sector)



V5

$$(i)\ \psi_1 = \psi_2 = e_{(1,1,-1)} \Rightarrow \Phi \in (1,1,2)$$

$$(ii)\ \psi_1 = \psi_2 = l_{(1,2,-\frac{1}{2})} \Rightarrow \Phi \in (1, 1 \text{ or } 3, 1)$$

$$(iii)\ \psi_1 = \psi_2 = d_{(3,1,-\frac{1}{3})} \Rightarrow \Phi \in (3 \text{ or } \bar{6}, 1, \frac{2}{3})$$

$$(iv)\ \psi_1 = \psi_2 = u_{(3,1,\frac{2}{3})} \Rightarrow \Phi \in (3 \text{ or } \bar{6}, 1, -\frac{4}{3})$$

$$(v)\ \psi_1 = \psi_2 = q_{(3,2,\frac{1}{6})} \Rightarrow \Phi \in (3 \text{ or } \bar{6}, 1 \text{ or } 3, -\frac{1}{3})$$

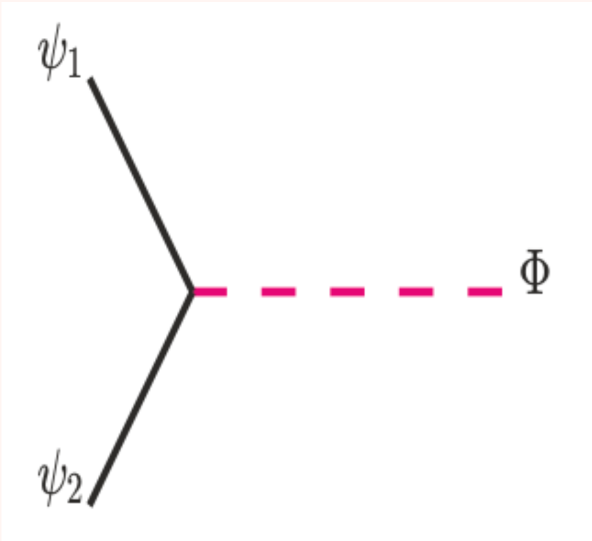
$$(vi)\ (\psi_1, \psi_2) = (\bar{l}, e) \Rightarrow \Phi \in (1, 2, \frac{1}{2})$$

$$(vii)\ (\psi_1, \psi_2) = (\bar{q}, d) \Rightarrow \Phi \in (1 \text{ or } 8, 2, \frac{1}{2})$$

$$(viii)\ (\psi_1, \psi_2) = (\bar{u}, q) \Rightarrow \Phi \in (1 \text{ or } 8, 2, \frac{1}{2})$$

The building blocks: *fixing quantum numbers*

Possible SM - BSM field interactions (Yukawa sector)



V5

$$(ix)\ (\psi_1,\ \psi_2)\ =\ (q,\ l)\quad \Rightarrow\quad \Phi\ \in\ (\bar{3}, 1\ \text{or}\ 3,\ \frac{1}{3})$$

$$(x)\ (\psi_1,\ \psi_2)\ =\ (u,\ d)\quad \Rightarrow\quad \Phi\ \in\ (3\ \text{or}\ \bar{6},\ 1,\ -\frac{1}{3})$$

$$(xi)\ (\psi_1,\ \psi_2)\ =\ (u,\ e)\quad \Rightarrow\quad \Phi\ \in\ (\bar{3},\ 1,\ \frac{1}{3})$$

$$(xii)\ (\psi_1,\ \psi_2)\ =\ (d,\ e)\quad \Rightarrow\quad \Phi\ \in\ (\bar{3},\ 1,\ \frac{4}{3})$$

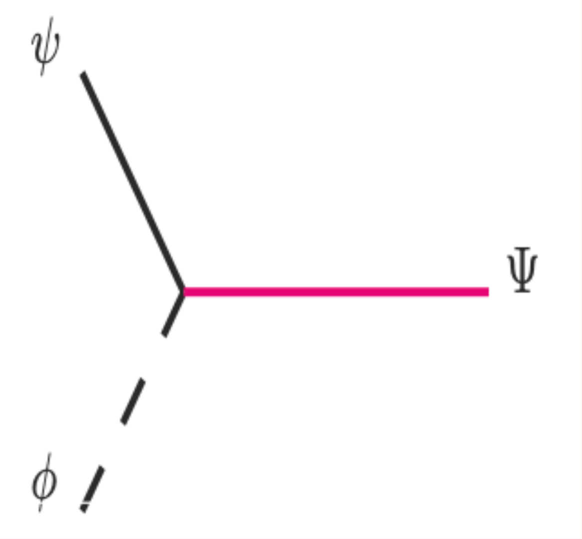
$$(xiii)\ (\psi_1,\ \psi_2)\ =\ (\bar{q},\ e)\quad \Rightarrow\quad \Phi\ \in\ (3,\ 2,\ \frac{7}{6})$$

$$(xiv)\ (\psi_1,\ \psi_2)\ =\ (\bar{l},\ u)\quad \Rightarrow\quad \Phi\ \in\ (\bar{3},\ 2,\ -\frac{7}{6})$$

$$(xv)\ (\psi_1,\ \psi_2)\ =\ (\bar{l},\ d)\quad \Rightarrow\quad \Phi\ \in\ (\bar{3},\ 2,\ -\frac{1}{6})$$

The building blocks: *fixing quantum numbers*

Possible SM - BSM field interactions (Yukawa sector)



V6

$\boxed{\phi = H}$

$(i)\ \psi = l \Rightarrow \Psi \in (1,\ 1 \text{ or } 3,\ 0)$

$(ii)\ \psi = e \Rightarrow \Psi \in (1,\ 2,\ \frac{1}{2})$

$(iii)\ \psi = q \Rightarrow \Psi \in (\bar{3},\ 1 \text{ or } 3,\ -\frac{2}{3})$

$(iv)\ \psi = u \Rightarrow \Psi \in (\bar{3},\ 2,\ -\frac{7}{6})$

$(v)\ \psi = d \Rightarrow \Psi \in (\bar{3},\ 2,\ -\frac{1}{6})$

$\boxed{\phi = H^\dagger}$

$(vi)\ \psi = l \Rightarrow \Psi \in (1,\ 1 \text{ or } 3,\ 1)$

$(vii)\ \psi = e \Rightarrow \Psi \in (1,\ 2,\ \frac{3}{2})$

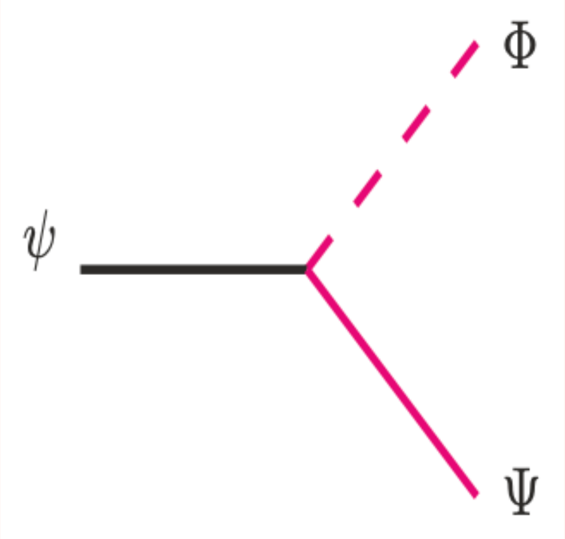
$(viii)\ \psi = q \Rightarrow \Psi \in (\bar{3},\ 1 \text{ or } 3,\ \frac{1}{3})$

$(ix)\ \psi = u \Rightarrow \Psi \in (\bar{3},\ 2,\ -\frac{1}{6})$

$(x)\ \psi = d \Rightarrow \Psi \in (\bar{3},\ 2,\ \frac{5}{6})$

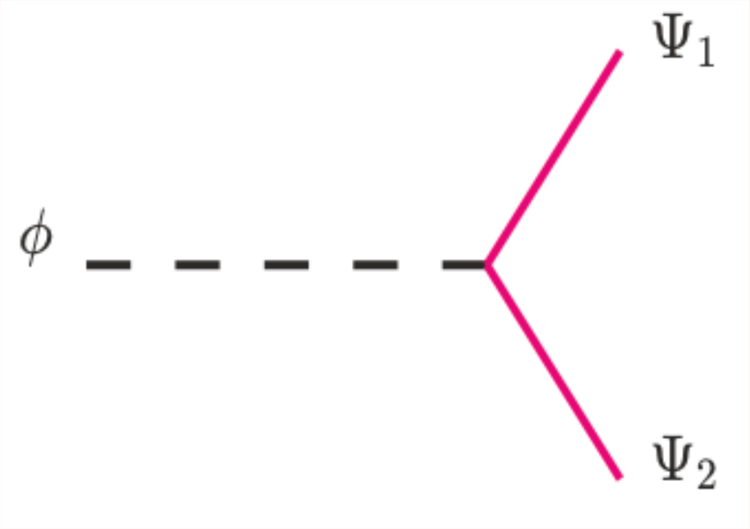
The building blocks: *fixing quantum numbers*

Possible SM - BSM field interactions (Yukawa sector)



V7

$$(i)-(v)\ \psi = f_{SM} \in (R_C, R_L, Y) \Rightarrow \begin{array}{l} \Phi \in (R_{C_1}, R_{L_1}, Y_1) \\ \Psi \in (R_{C_2}, R_{L_2}, Y_2) \end{array} \quad \text{with} \quad \begin{array}{r} R_{C_1} \otimes R_{C_2} = \bar{R}_C \\ R_{L_1} \otimes R_{L_2} = R_L \\ Y_1 + Y_2 = -Y \end{array}$$



V8

$$\phi = H \text{ or } H^\dagger \Rightarrow \begin{array}{l} \Psi_1 \in (R_{C_1}, R_{L_1}, Y_1) \\ \Psi_2 \in (R_{C_2}, R_{L_2}, Y_2) \end{array} \quad \text{with} \quad \begin{array}{r} R_{C_1} \otimes R_{C_2} = 1 \\ R_{L_1} \otimes R_{L_2} = 2 \\ Y_1 + Y_2 = \mp\frac{1}{2} \end{array}$$

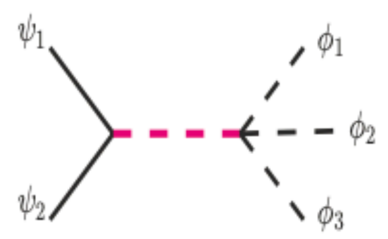
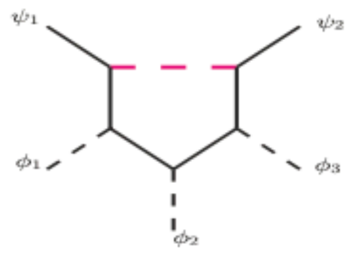
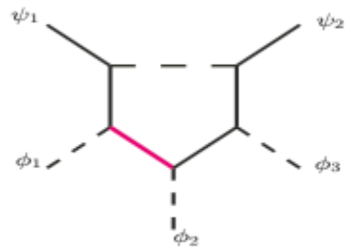
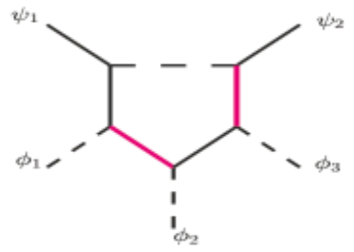
Operator Unfolding

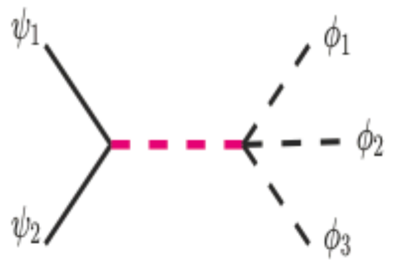
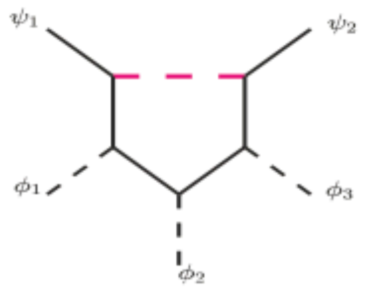
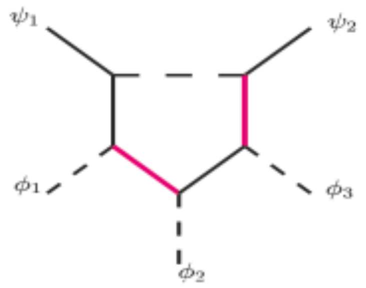
Disclaimer on assumptions and ground rules

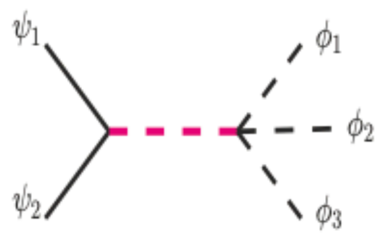
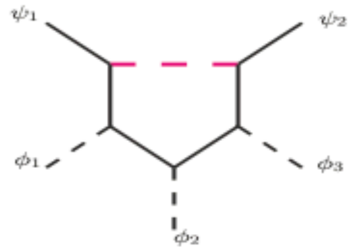
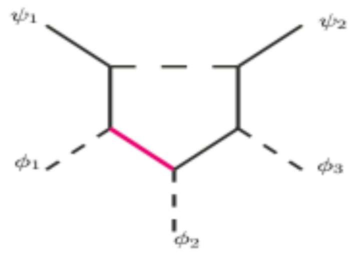
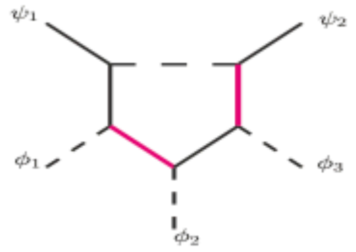
1. SM Gauge group not extended -> No heavy gauge boson propagators considered
2. Types of diagrams considered:
   - For a given operator if a field appears at tree level, we have not drawn a 1-loop diagram for the same heavy field in the context of the same operator.
   - Diagrams with least variety of vertices are preferred.
   - 1-loop diagrams where the entire loop is composed of the same heavy field have been considered
   - For light-heavy mixing in the loop, only a single propagator has been considered.
   - Mixed statistics have been incorporated in the diagrams.
3. The considered diagrams do not form an exhaustive set.

Operator wise catalogue

$\psi^2\phi^3$

$\mathcal{Q}_{dH}$: $(H^\dagger H)(\bar{q}_p d_r H)$		
Heavy fields	**Diagram**	**Vertices**
$\left(1,2,\frac{1}{2}\right)$		V5-(vii), V3-(ii)
$\left(6,1,\frac{1}{3}\right)$, $\left(3,1,-\frac{1}{3}\right)$		V5-(v), V5-(x)
$\left(3,2,\frac{7}{6}\right)$		V6-(iv)
$\left(3,3,-\frac{1}{3}\right)$		V6-(viii)
$\left(3,2,-\frac{5}{6}\right)$		V6-(x)
$\left(3,1,-\frac{2}{3}\right)$, $\left(3,3,-\frac{2}{3}\right)$		V6-(iii)

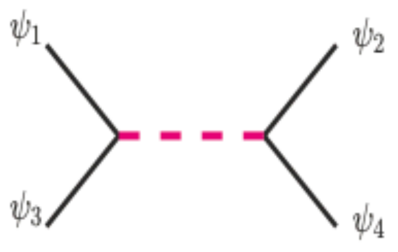
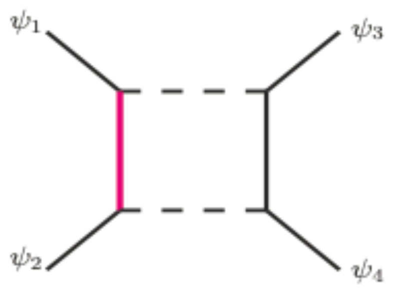
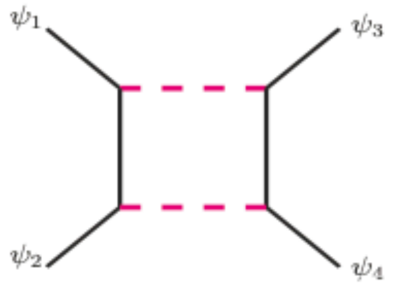
$\mathcal{Q}_{eH}$: $(H^\dagger H)(\bar{l}_p e_r H)$		
Heavy fields	**Diagram**	**Vertices**
$\left(1,2,\frac{1}{2}\right)$		V5-(vi), V3-(ii)
$\left(3,2,\frac{7}{6}\right)$		V5-(xiii), V5-(xiv)
$(1,1,0)$, $(1,3,0)$		V6-(i)

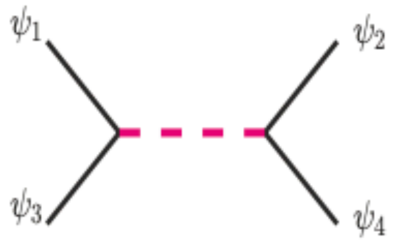
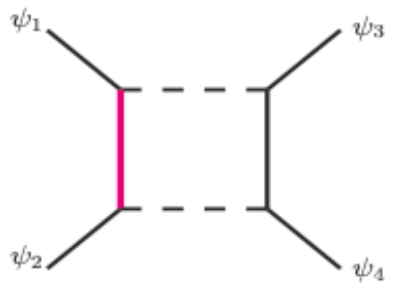
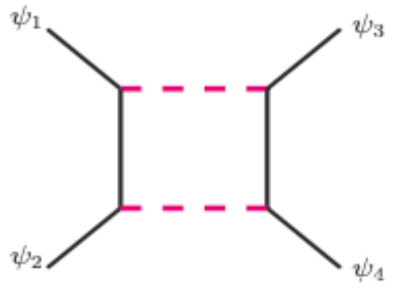
$\mathcal{Q}_{uH}$: $(H^\dagger H)(\bar{q}_p u_r \tilde{H})$		
Heavy fields	**Diagram**	**Vertices**
$\left(1,2,\frac{1}{2}\right)$		V5-(viii), V3-(ii)
$\left(3,2,\frac{7}{6}\right)$		V5-(xiii), V5-(xiv)
$\left(3,1,-\frac{1}{3}\right)$, $\left(6,1,\frac{1}{3}\right)$		V5-(v), V5-(x)
$\left(3,2,-\frac{5}{6}\right)$		V6-(x)
$\left(3,1,-\frac{1}{3}\right)$, $\left(3,3,-\frac{1}{3}\right)$		V6-(viii)

ψ^4

(only a subset)

p, r, s, t - generation indices

$\mathcal{Q}_{qu}^{(1)} : (\bar{q}_p \gamma^\mu q_r)(\bar{u}_s \gamma_\mu u_t)$		
Heavy fields	**Diagram**	**Vertices**
$\left(1, 2, \frac{1}{2}\right)$		V5-(viii)
$\left(3, 1, \frac{2}{3}\right), \left(3, 3, \frac{2}{3}\right)$		V6-(iii)
$\left(3, 1, -\frac{1}{3}\right), \left(3, 3, -\frac{1}{3}\right)$		V6-(viii)
$\left(3, 2, \frac{7}{6}\right)$		V6-(iv)
$\left(3, 2, \frac{1}{6}\right)$		V6-(ix)
$\left(3, 1, -\frac{1}{3}\right)$		V5-(ix), V5-(x)
		V5-(v), V5-(x)
		V5-(ix), V5-(xi)
		V5-(v), V5-(xi)
$\left(6, 1, \frac{1}{3}\right)$		V5-(v), V5-(x)
$\left(3, 2, \frac{7}{6}\right)$		V5-(xiii), V5-(xiv)

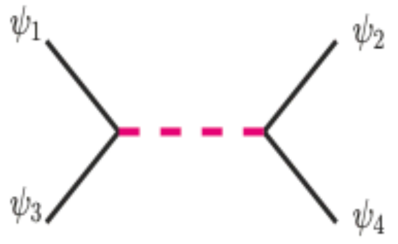
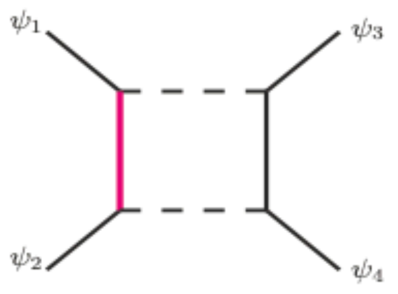
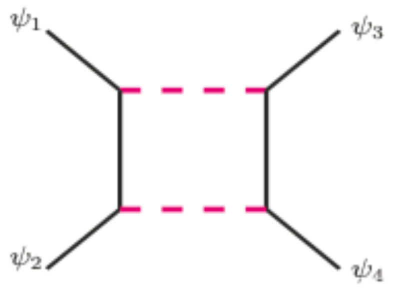
$\mathcal{Q}_{qd}^{(1)} : (\bar{q}_p \gamma^\mu q_r)(\bar{d}_s \gamma_\mu d_t)$		
Heavy fields	**Diagram**	**Vertices**
$\left(1, 2, \frac{1}{2}\right)$		V5-(vii)
$\left(3, 1, \frac{2}{3}\right), \left(3, 3, \frac{2}{3}\right)$		V6-(iii)
$\left(3, 1, -\frac{1}{3}\right), \left(3, 3, -\frac{1}{3}\right)$		V6-(viii)
$\left(3, 2, \frac{1}{6}\right)$		V6-(v)
$\left(3, 2, -\frac{5}{6}\right)$		V6-(x)
$\left(3, 1, -\frac{1}{3}\right)$		V5-(ix), V5-(x)
		V5-(v), V5-(x)
$\left(6, 1, \frac{1}{3}\right)$		V5-(v), V5-(x)

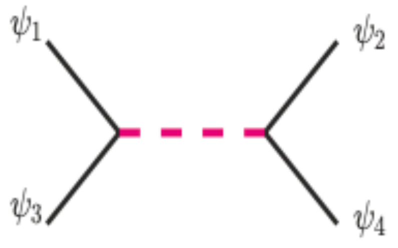
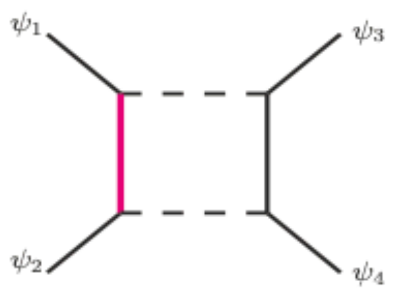
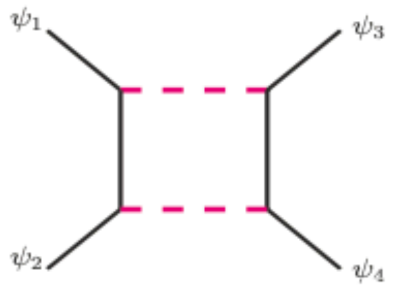
ψ^4

(only a subset)

p, r, s, t - generation indices

Vector - vector interaction → (Fierz relations) → Scalar - scalar interaction

$\mathcal{Q}_{qu}^{(1)} : (\bar{q}_p \gamma^\mu q_r)(\bar{u}_s \gamma_\mu u_t)$		
Heavy fields	**Diagram**	**Vertices**
$\left(1, 2, \frac{1}{2}\right)$		V5-(viii)
$\left(3, 1, \frac{2}{3}\right), \left(3, 3, \frac{2}{3}\right)$		V6-(iii)
$\left(3, 1, -\frac{1}{3}\right), \left(3, 3, -\frac{1}{3}\right)$		V6-(viii)
$\left(3, 2, \frac{7}{6}\right)$		V6-(iv)
$\left(3, 2, \frac{1}{6}\right)$		V6-(ix)
$\left(3, 1, -\frac{1}{3}\right)$		V5-(ix), V5-(x)
		V5-(v), V5-(x)
		V5-(ix), V5-(xi)
		V5-(v), V5-(xi)
$\left(6, 1, \frac{1}{3}\right)$		V5-(v), V5-(x)
$\left(3, 2, \frac{7}{6}\right)$		V5-(xiii), V5-(xiv)

$\mathcal{Q}_{qd}^{(1)} : (\bar{q}_p \gamma^\mu q_r)(\bar{d}_s \gamma_\mu d_t)$		
Heavy fields	**Diagram**	**Vertices**
$\left(1, 2, \frac{1}{2}\right)$		V5-(vii)
$\left(3, 1, \frac{2}{3}\right), \left(3, 3, \frac{2}{3}\right)$		V6-(iii)
$\left(3, 1, -\frac{1}{3}\right), \left(3, 3, -\frac{1}{3}\right)$		V6-(viii)
$\left(3, 2, \frac{1}{6}\right)$		V6-(v)
$\left(3, 2, -\frac{5}{6}\right)$		V6-(x)
$\left(3, 1, -\frac{1}{3}\right)$		V5-(ix), V5-(x)
		V5-(v), V5-(x)
$\left(6, 1, \frac{1}{3}\right)$		V5-(v), V5-(x)

ψ^4

(only a subset)

p, r, s, t - generation indices

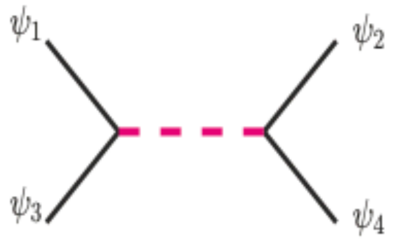
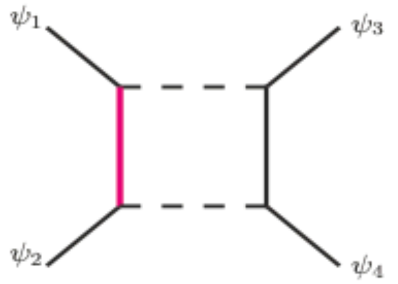
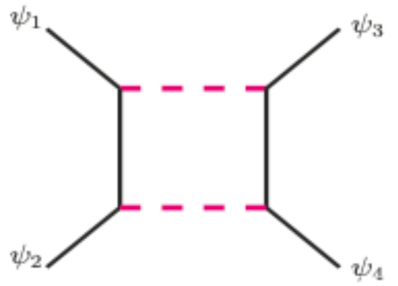
Vector - vector interaction $\xrightarrow[\text{relations}]{\text{Fierz}}$ Scalar - scalar interaction

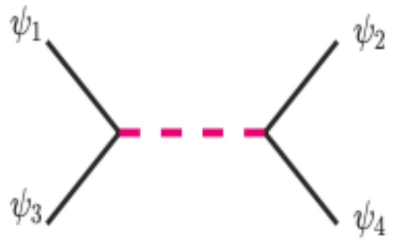
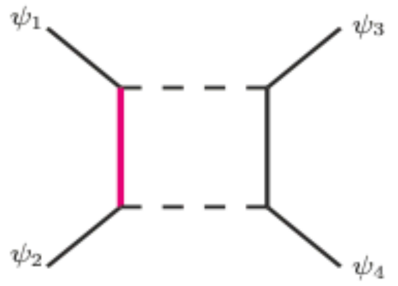
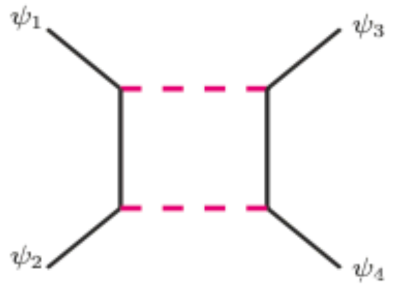
$$(\bar{q}_p\,\gamma^\mu\,q_r)(\bar{u}_s\,\gamma_\mu\,u_t)$$

$$= (\bar{q}^\alpha_p\,\sigma^\mu_{\alpha\dot{\alpha}}\,q^{\dot{\alpha}}_r)\,(\bar{u}_{s,\,\dot{\beta}}\,\bar{\sigma}^{\mu\dot{\beta}\beta}\,u_{t,\,\beta})$$

$$= 2\,(\bar{q}^\alpha_p\,u_{t,\,\beta}\,\bar{u}_{s,\,\dot{\beta}}\,q^{\dot{\alpha}}_r)\,\delta^\beta_\alpha\,\delta^{\dot{\beta}}_{\dot{\alpha}}$$

$$= 2\,(\bar{q}_p\,u_t)\,(\bar{u}_s\,q_r)$$

$\mathcal{Q}^{(1)}_{qu}\,:\,(\bar{q}_p\,\gamma^\mu\,q_r)(\bar{u}_s\,\gamma_\mu\,u_t)$		
Heavy fields	**Diagram**	**Vertices**
$\left(1,2,\frac{1}{2}\right)$		V5-(viii)
$\left(3,1,\frac{2}{3}\right),\left(3,3,\frac{2}{3}\right)$		V6-(iii)
$\left(3,1,-\frac{1}{3}\right),\left(3,3,-\frac{1}{3}\right)$		V6-(viii)
$\left(3,2,\frac{7}{6}\right)$		V6-(iv)
$\left(3,2,\frac{1}{6}\right)$		V6-(ix)
$\left(3,1,-\frac{1}{3}\right)$		V5-(ix), V5-(x)
		V5-(v), V5-(x)
		V5-(ix), V5-(xi)
		V5-(v), V5-(xi)
$\left(6,1,\frac{1}{3}\right)$		V5-(v), V5-(x)
$\left(3,2,\frac{7}{6}\right)$		V5-(xiii), V5-(xiv)

$\mathcal{Q}^{(1)}_{qd}\,:\,(\bar{q}_p\,\gamma^\mu\,q_r)(\bar{d}_s\,\gamma_\mu\,d_t)$		
Heavy fields	**Diagram**	**Vertices**
$\left(1,2,\frac{1}{2}\right)$		V5-(vii)
$\left(3,1,\frac{2}{3}\right),\left(3,3,\frac{2}{3}\right)$		V6-(iii)
$\left(3,1,-\frac{1}{3}\right),\left(3,3,-\frac{1}{3}\right)$		V6-(viii)
$\left(3,2,\frac{1}{6}\right)$		V6-(v)
$\left(3,2,-\frac{5}{6}\right)$		V6-(x)
$\left(3,1,-\frac{1}{3}\right)$		V5-(ix), V5-(x)
		V5-(v), V5-(x)
$\left(6,1,\frac{1}{3}\right)$		V5-(v), V5-(x)

ψ^4

(only a subset)

p, r, s, t - generation indices

Vector - vector interaction $\xrightarrow[\text{relations}]{\text{Fierz}}$ Scalar - scalar interaction

$$(\bar{q}_p\, \gamma^\mu\, q_r)(\bar{u}_s\, \gamma_\mu\, u_t)$$

$$= (\bar{q}_p^{\alpha}\, \sigma^{\mu}_{\alpha\dot{\alpha}}\, q_r^{\dot{\alpha}})\, (\bar{u}_{s,\,\dot{\beta}}\, \bar{\sigma}^{\mu\dot{\beta}\beta}\, u_{t,\,\beta})$$

$$= 2\, (\bar{q}_p^{\alpha}\, u_{t,\,\beta}\, \bar{u}_{s,\,\dot{\beta}}\, q_r^{\dot{\alpha}})\, \delta_{\alpha}^{\beta}\, \delta_{\dot{\alpha}}^{\dot{\beta}}$$

$$= 2\, (\bar{q}_p\, u_t)\, (\bar{u}_s\, q_r)$$

Working in Weyl basis

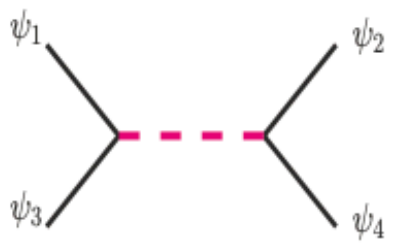
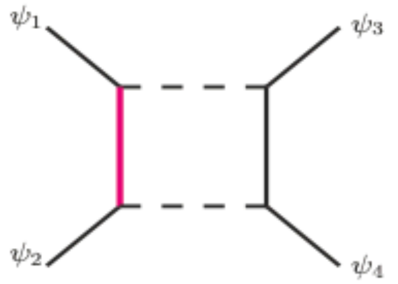
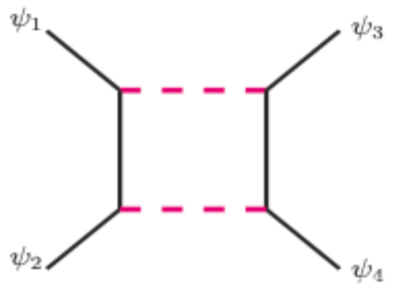
using

$$(\sigma^\mu)_{\alpha\dot{\alpha}}\, (\sigma_\mu)_{\beta\dot{\beta}} = 2\, \varepsilon_{\alpha\beta}\varepsilon_{\dot{\alpha}\dot{\beta}}$$

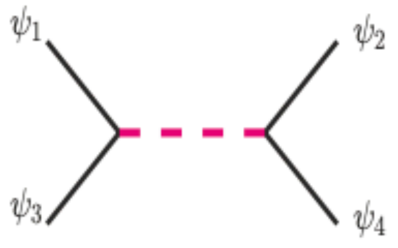
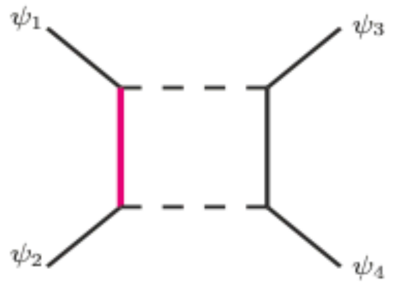
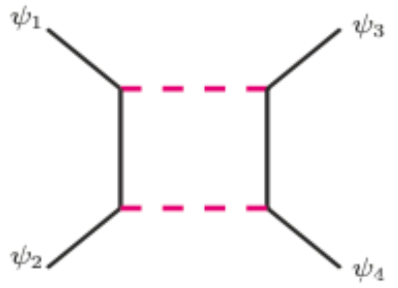
$$(\bar{\sigma}^\mu)^{\dot{\alpha}\alpha} = \varepsilon^{\alpha\beta}\, \varepsilon^{\dot{\alpha}\dot{\beta}}\, (\sigma^\mu)_{\beta\dot{\beta}}$$

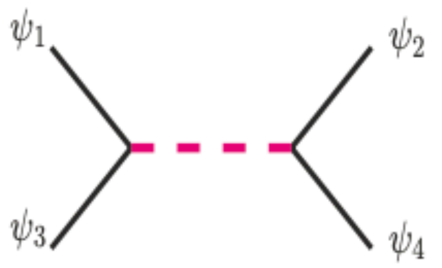
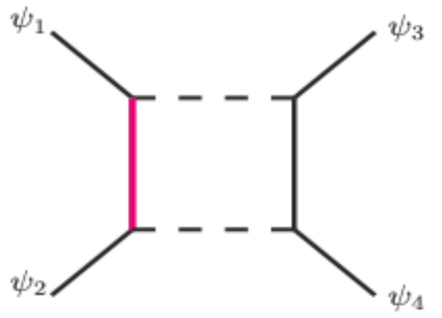
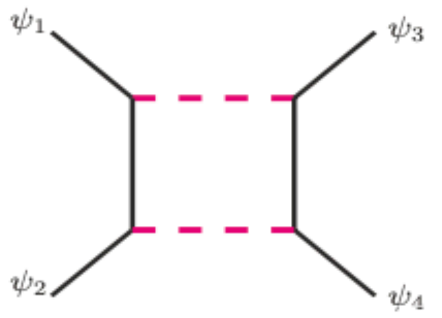
$$\varepsilon_{\alpha\beta}\, \varepsilon^{\beta\lambda} = \delta_{\alpha}^{\lambda}$$

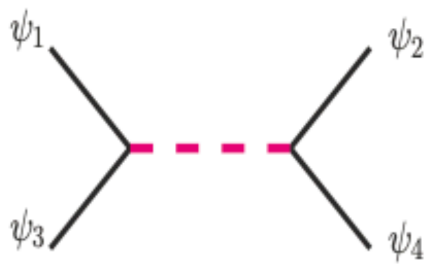
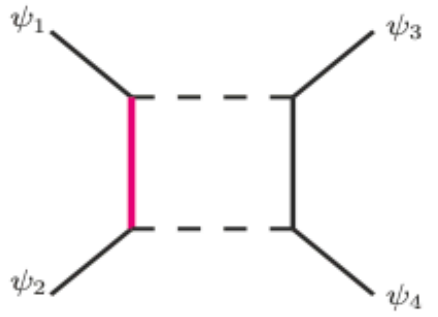
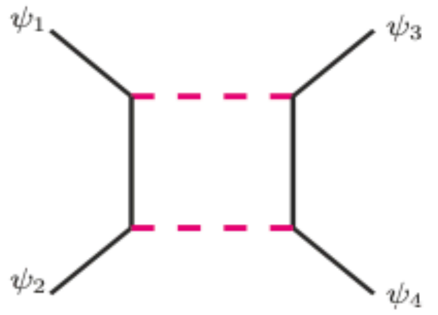
$\mathcal{Q}_{qu}^{(1)} : (\bar{q}_p\, \gamma^\mu\, q_r)(\bar{u}_s\, \gamma_\mu\, u_t)$

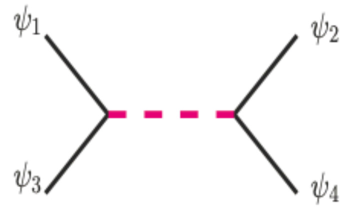
Heavy fields	**Diagram**	**Vertices**
$\left(1, 2, \frac{1}{2}\right)$		V5-(viii)
$\left(3, 1, \frac{2}{3}\right), \left(3, 3, \frac{2}{3}\right)$		V6-(iii)
$\left(3, 1, -\frac{1}{3}\right), \left(3, 3, -\frac{1}{3}\right)$		V6-(viii)
$\left(3, 2, \frac{7}{6}\right)$		V6-(iv)
$\left(3, 2, \frac{1}{6}\right)$		V6-(ix)
$\left(3, 1, -\frac{1}{3}\right)$		V5-(ix), V5-(x)
		V5-(v), V5-(x)
		V5-(ix), V5-(xi)
		V5-(v), V5-(xi)
$\left(6, 1, \frac{1}{3}\right)$		V5-(v), V5-(x)
$\left(3, 2, \frac{7}{6}\right)$		V5-(xiii), V5-(xiv)

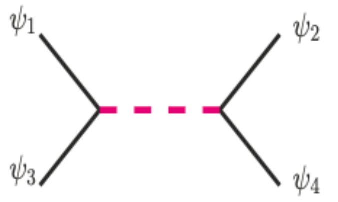
$\mathcal{Q}_{qd}^{(1)} : (\bar{q}_p\, \gamma^\mu\, q_r)(\bar{d}_s\, \gamma_\mu\, d_t)$

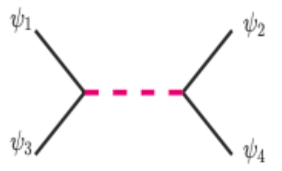
Heavy fields	**Diagram**	**Vertices**
$\left(1, 2, \frac{1}{2}\right)$		V5-(vii)
$\left(3, 1, \frac{2}{3}\right), \left(3, 3, \frac{2}{3}\right)$		V6-(iii)
$\left(3, 1, -\frac{1}{3}\right), \left(3, 3, -\frac{1}{3}\right)$		V6-(viii)
$\left(3, 2, \frac{1}{6}\right)$		V6-(v)
$\left(3, 2, -\frac{5}{6}\right)$		V6-(x)
$\left(3, 1, -\frac{1}{3}\right)$		V5-(ix), V5-(x)
		V5-(v), V5-(x)
$\left(6, 1, \frac{1}{3}\right)$		V5-(v), V5-(x)

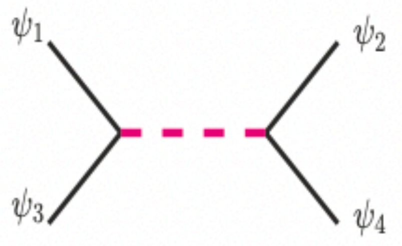
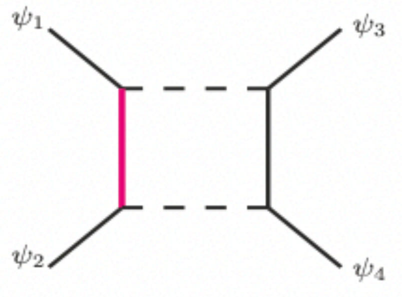
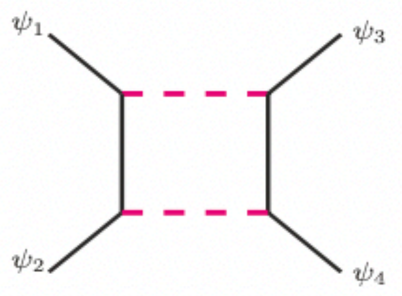
$\mathcal{Q}_{lu}\,:\,(\bar{l}_p\,\gamma^\mu\,l_r)(\bar{u}_s\,\gamma_\mu\,u_t)$		
Heavy fields	**Diagram**	**Vertices**
$\left(3,2,\frac{7}{6}\right)$		V5-(xiv)
$(1,3,0),(1,1,0)$		V6-(i)
$(1,3,1),(1,1,1)$		V6-(vi)
$\left(3,2,\frac{7}{6}\right)$		V6-(iv)
$\left(3,2,\frac{1}{6}\right)$		V6-(ix)
$\left(3,1,-\frac{1}{3}\right)$		V5-(ix), V5-(x)
		V5-(ix), V5-(xi)

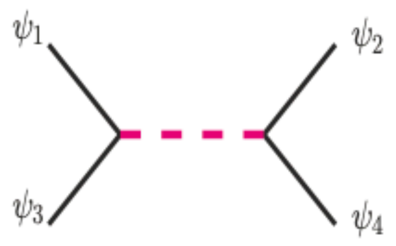
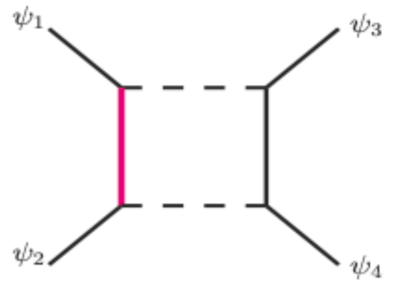
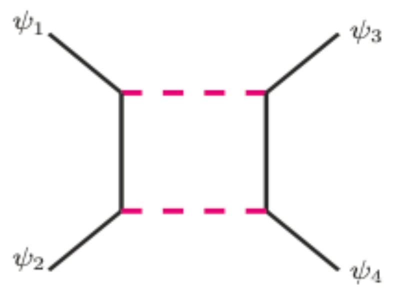
$\mathcal{Q}_{qe}\,:\,(\bar{q}_p\,\gamma^\mu\,q_r)(\bar{e}_s\,\gamma_\mu\,e_t)$		
Heavy fields	**Diagram**	**Vertices**
$\left(3,2,\frac{7}{6}\right)$		V5-(xiv)
$\left(3,1,\frac{2}{3}\right),\left(3,3,\frac{2}{3}\right)$		V6-(iii)
$\left(3,1,-\frac{1}{3}\right),\left(3,3,-\frac{1}{3}\right)$		V6-(viii)
$\left(1,2,\frac{1}{2}\right)$		V6-(ii)
$\left(1,2,\frac{3}{2}\right)$		V6-(vii)
$\left(3,1,-\frac{1}{3}\right)$		V5-(ix), V5-(xi)
		V5-(v), V5-(xi)

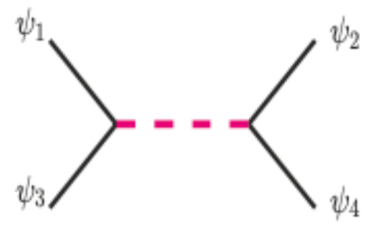
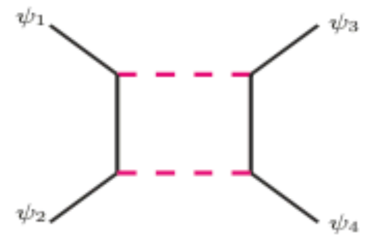
$\mathcal{Q}_{qd}^{(8)}\,:\,(\bar{q}_p\,\gamma^\mu\,T^A\,q_r)(\bar{d}_s\,\gamma_\mu\,T^A\,d_t)$		
Heavy fields	**Diagram**	**Vertices**
$\left(8,2,\frac{1}{2}\right)$		V5-(vii)

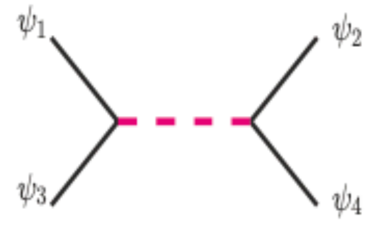
$\mathcal{Q}_{qu}^{(8)}\,:\,(\bar{q}_p\,\gamma^\mu\,T^A\,q_r)(\bar{u}_s\,\gamma_\mu\,T^A\,u_t)$		
Heavy fields	**Diagram**	**Vertices**
$\left(8,2,\frac{1}{2}\right)$		V5-(viii)

$\mathcal{Q}_{quqd}^{(8)}\,:\,(\bar{q}_p^j\,T^A\,u_r)\epsilon_{jk}(\bar{q}_s^k\,T^A\,d_t)$		
Heavy fields	**Diagram**	**Vertices**
$\left(8,2,\frac{1}{2}\right)$		V5-(vii), V5-(viii)

$\mathcal{Q}_{le}$: $(\bar{l}_p\,\gamma^\mu\,l_r)(\bar{e}_s\,\gamma_\mu\,e_t)$		
Heavy fields	**Diagram**	**Vertices**
$\left(1,2,\frac{1}{2}\right)$		V5-(vi)
$(1,3,0),(1,1,0)$		V6-(i)
$(1,3,1),(1,1,1)$		V6-(vi)
$\left(1,2,\frac{1}{2}\right)$		V6-(ii)
$\left(1,2,\frac{3}{2}\right)$		V6-(vii)
$\left(3,2,\frac{7}{6}\right)$		V5-(xiii), V5-(xiv)
$\left(3,1,-\frac{1}{3}\right)$		V5-(ix), V5-(xi)

$\mathcal{Q}_{ld}$: $(\bar{l}_p\,\gamma^\mu\,l_r)(\bar{d}_s\,\gamma_\mu\,d_t)$		
Heavy fields	**Diagram**	**Vertices**
$\left(3,2,\frac{1}{6}\right)$		V5-(xvi)
$(1,3,0),(1,1,0)$		V6-(i)
$(1,3,1),(1,1,1)$		V6-(vi)
$\left(3,2,\frac{1}{6}\right)$		V6-(v)
$\left(3,2,-\frac{5}{6}\right)$		V6-(x)
$\left(3,1,-\frac{1}{3}\right)$		V5-(ix), V5-(x)

$\mathcal{Q}_{ledq}$: $(\bar{l}_p^j\,e_r)(\bar{d}_s\,q_{tj})$		
Heavy fields	**Diagram**	**Vertices**
$\left(1,2,\frac{1}{2}\right)$		V5-(vi), V5-(vii)
$\left(3,1,-\frac{1}{3}\right)$		V5-(v), V5-(ix), V5-(x), V5-(xi)

$\mathcal{Q}_{quqd}^{(1)}$: $(\bar{q}_p^j\,u_r)\epsilon_{jk}(\bar{q}_s^k\,d_t)$		
Heavy fields	**Diagram**	**Vertices**
$\left(1,2,\frac{1}{2}\right)$		V5-(vii), V5-(viii)
$\left(3,1,-\frac{1}{3}\right)$, $\left(\bar{6},1,-\frac{1}{3}\right)$		V5-(v), V5-(x)

Atypical cases

Operator classes containing derivatives

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1. The covariant derivatives cannot be replaced with a gauge boson because electroweak symmetry breaking has not occurred.

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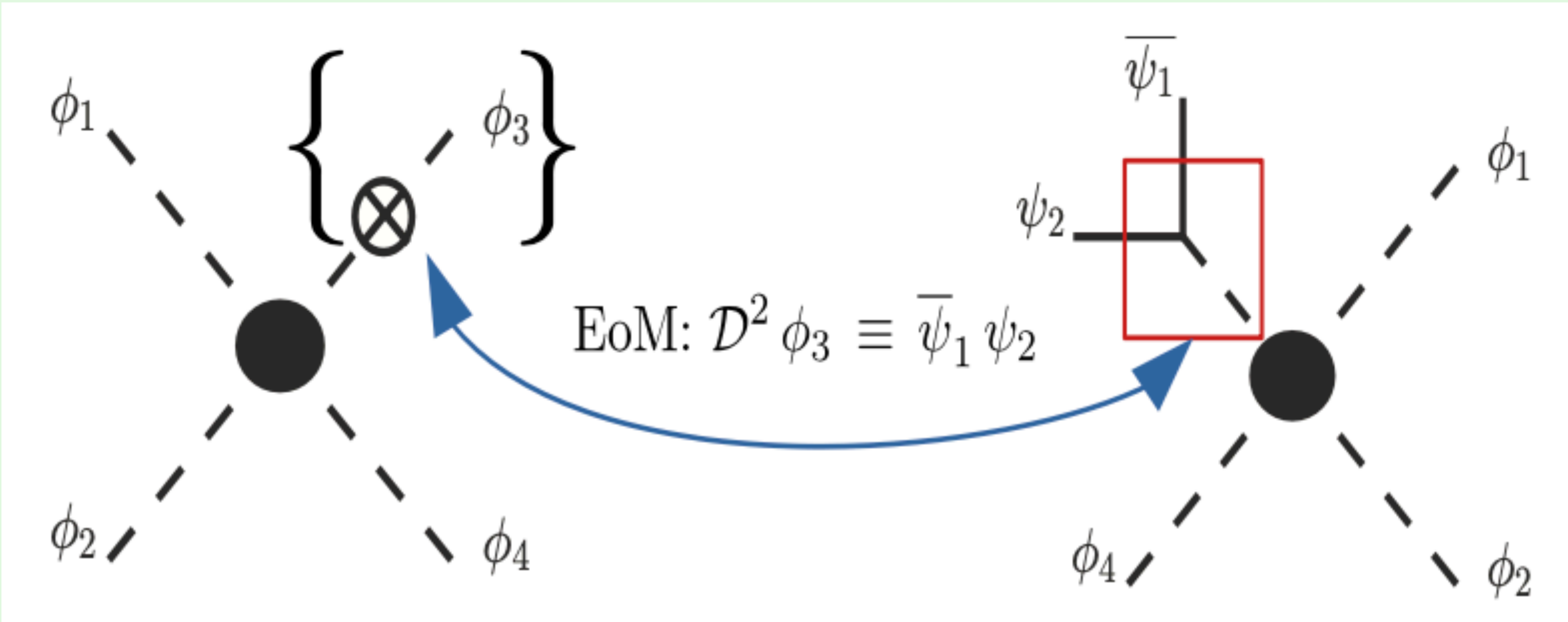

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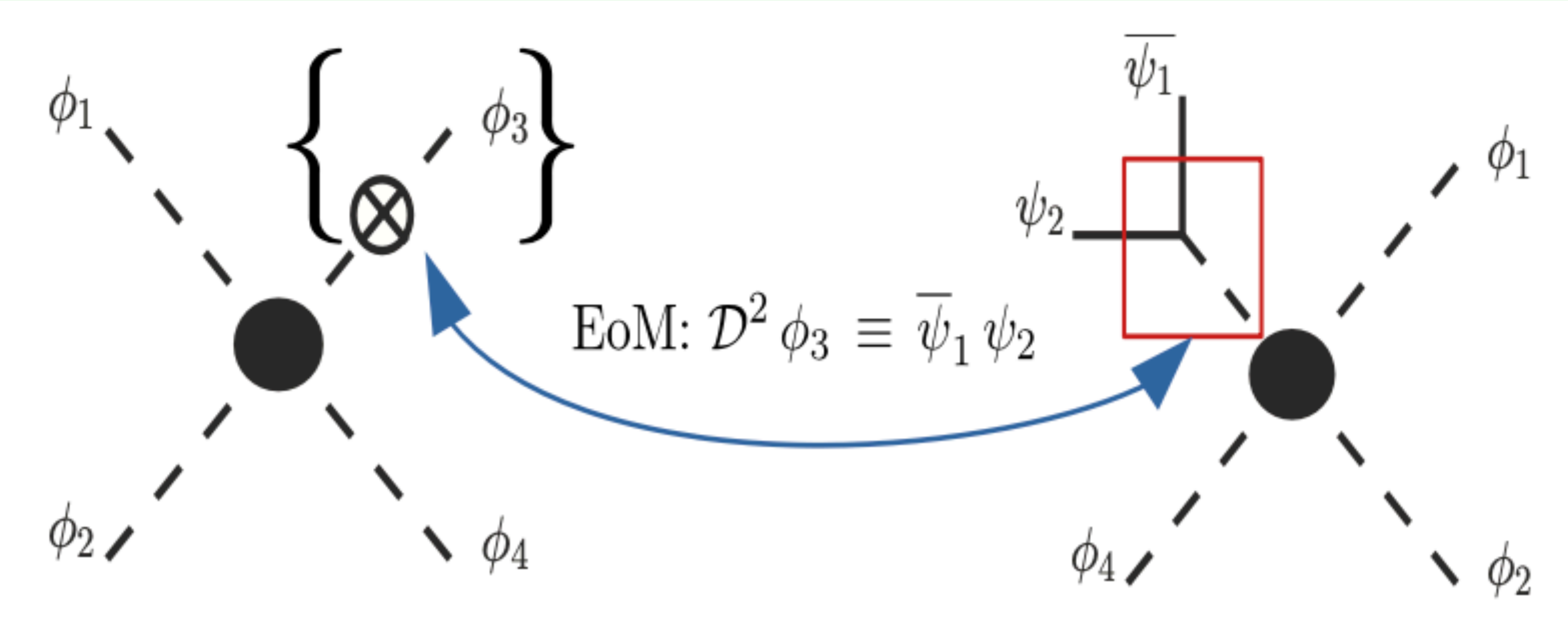
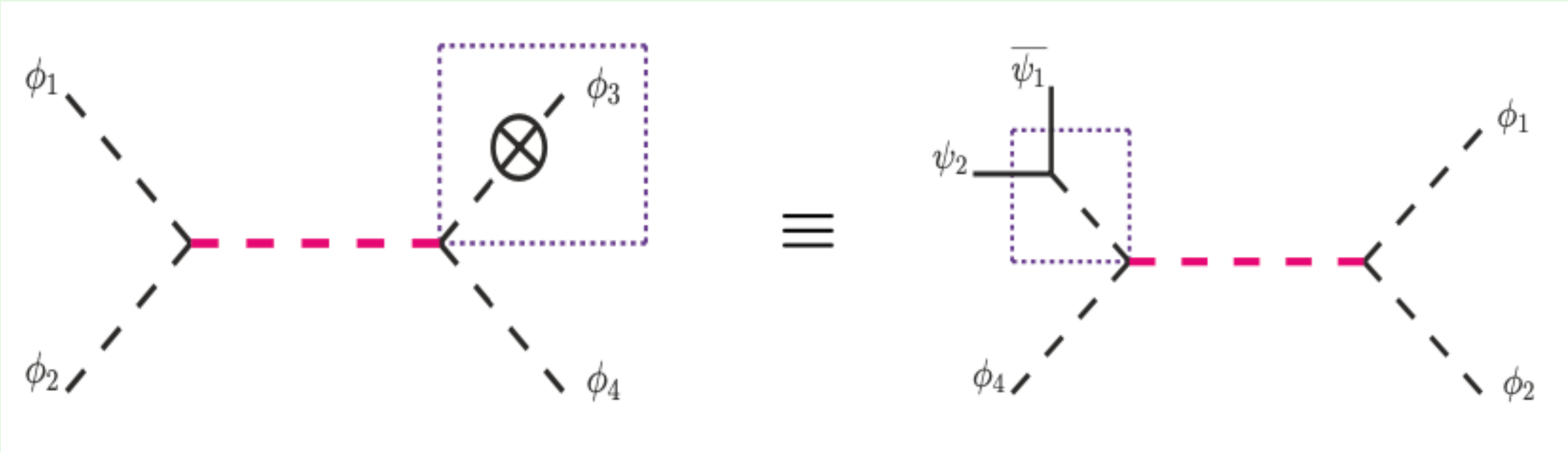




$$\underbrace{(H^\dagger H)(H^\dagger \mathcal{D}^2 H)}_{\text{related to } \mathcal{Q}_{H\Box} \text{ through IBP}} \qquad \underbrace{\mathcal{Q}_{eH},\ \mathcal{Q}_{uH},\ \mathcal{Q}_{dH}}_{\psi^2\phi^3}$$

Atypical cases

Multi-loop diagrams or multiple heavy fields

Atypical cases

Multi-loop diagrams or multiple heavy fields

$\psi^2\phi X$ →

$6 : \psi^2 XH + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I HW^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)HB_{\mu\nu}$
Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\,G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\,W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\,B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)H\,G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I H\,W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\,B_{\mu\nu}$

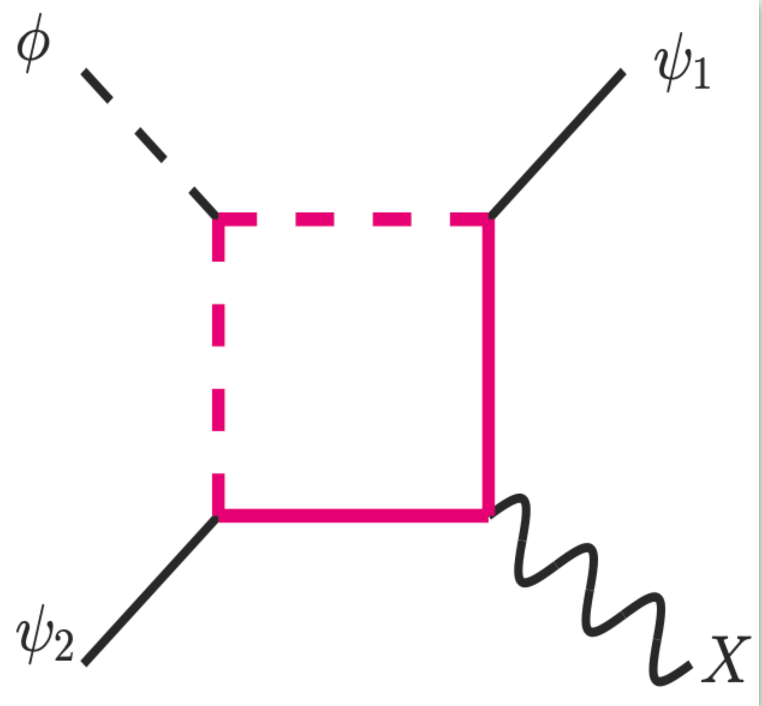
Atypical cases

Multi-loop diagrams or multiple heavy fields

$$\psi^2\phi X \longrightarrow$$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$\longrightarrow$



Atypical cases

Multi-loop diagrams or multiple heavy fields

$$\psi^2 \phi X$$

$6 : \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
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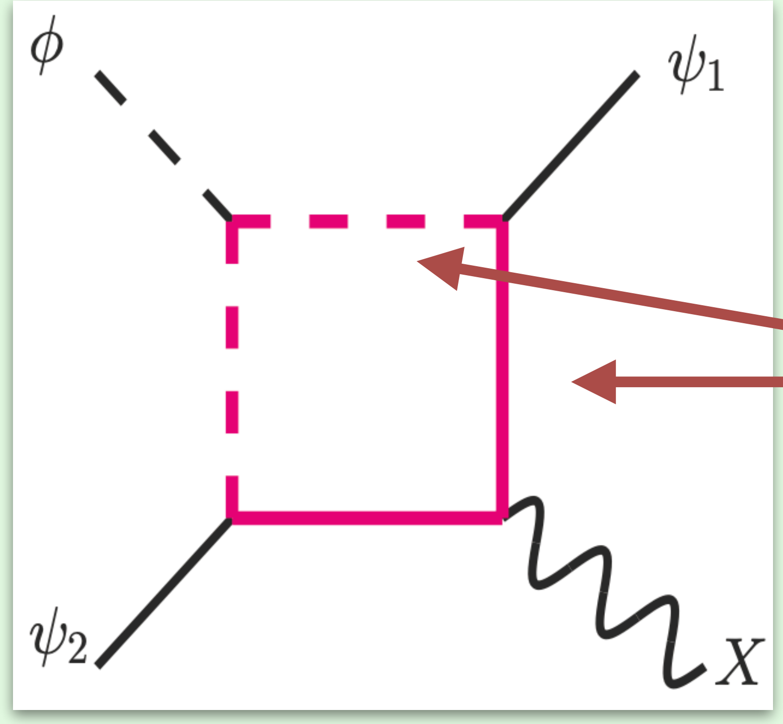
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$



Multiple heavy fields in the loop

Atypical cases

Multi-loop diagrams or multiple heavy fields

$$\psi^2 \phi X \longrightarrow$$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W^I_{\mu\nu}$
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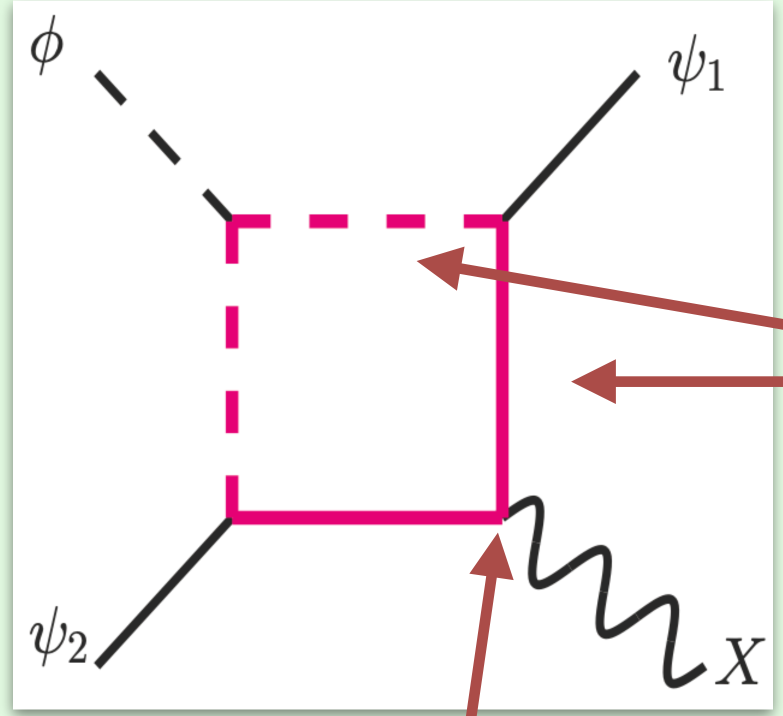

Multiple heavy fields in the loop

Magnetic moment interaction
$(\bar{\psi}_L\, \sigma_{\mu\nu}\, \psi_R\, X^{\mu\nu})$

Atypical cases

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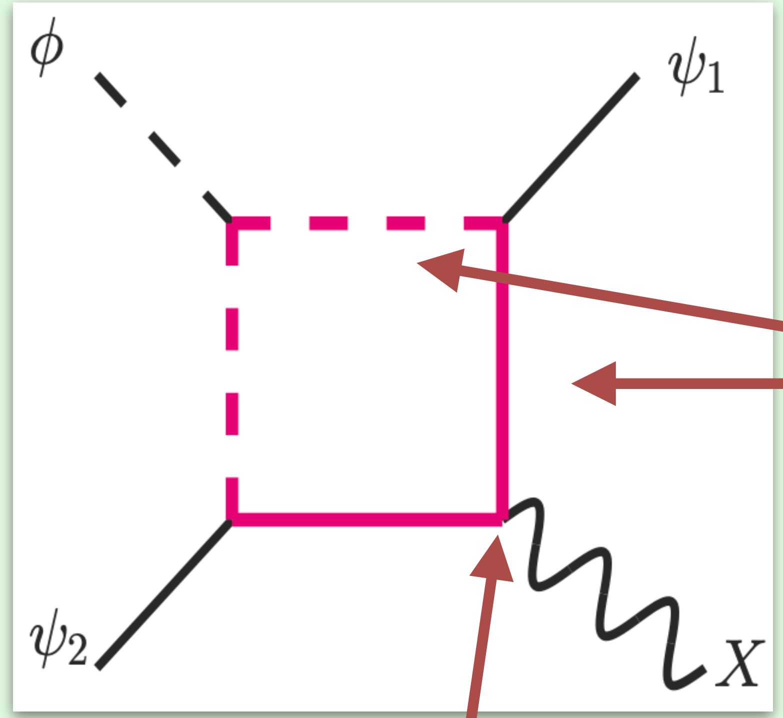

Multiple heavy fields in the loop

Magnetic moment interaction
$(\bar{\psi}_L\, \sigma_{\mu\nu}\, \psi_R\, X^{\mu\nu})$

Mass dimension
> 4

Atypical cases

CP violating operators

Atypical cases

CP violating operators

1 : X^3	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

4 : X^2H^2	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
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Atypical cases

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$$\tilde{X}_{\mu\nu} = \frac{1}{2}\, \varepsilon_{\mu\nu\rho\sigma}\, X^{\rho\sigma}$$

Dual of the Field strength tensor

$$\mathrm{Tr}[\gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma \gamma^5] = -4i\, \varepsilon^{\mu\nu\rho\sigma}$$

signature of CP-violation encoded through relation between γ^5 and $\varepsilon^{\mu\nu\rho\sigma}$

Atypical cases

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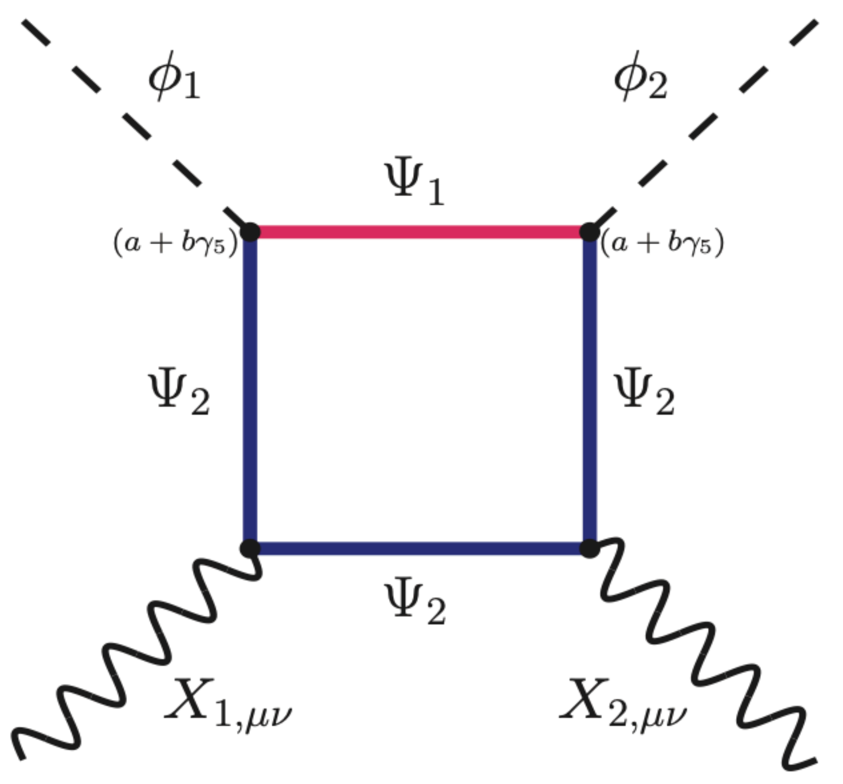

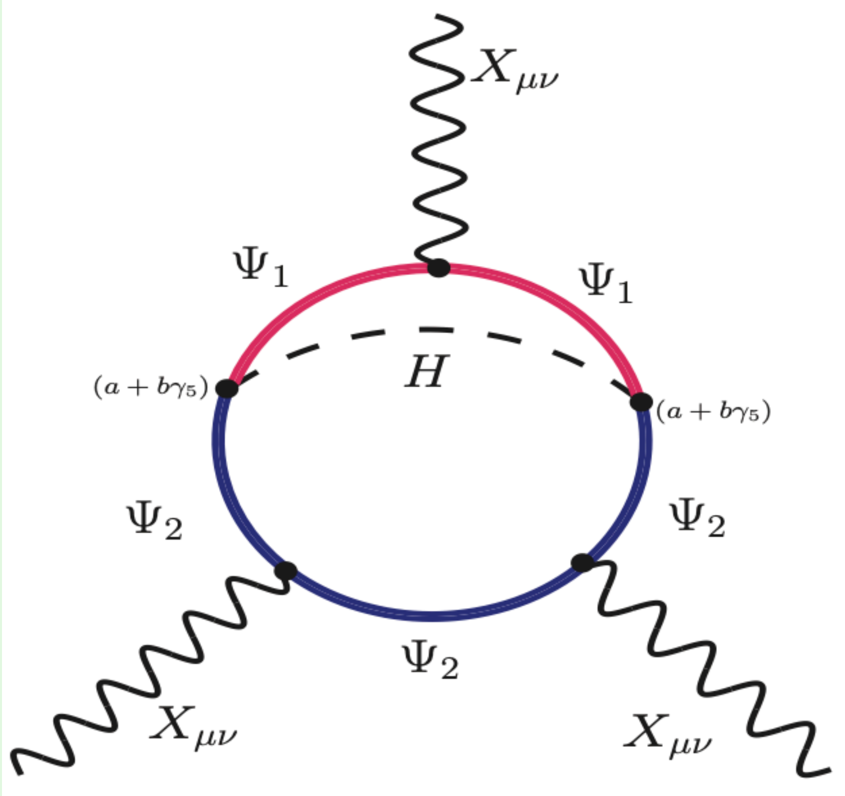

SD Bakshi, J Chakrabortty, C Englert, M Spannowsky, P Stylianou (2020), arxiv: 2009.13394

W Naskar, **S Prakash**, SU Rahaman (2022), arxiv: 2205.00910

Validation of results

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Consider SM extended with a lepto-quark scalar

$$\Theta \;\rightarrow\; (3,\,2,\,\frac{1}{6})$$

Most ubiquitous heavy field representation among our results

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Construct the BSM Lagrangian

(GrIP)

$$\mathcal{L}_\Theta = \mathcal{L}_{SM} + |\mathcal{D}_\mu \Theta|^2 - m_\Theta^2 |\Theta|^2 \quad - \eta_1 (H^\dagger H)(\Theta^\dagger \Theta) - \eta_2 (\Theta^\dagger \tau^I \Theta)(H^\dagger \tau^I H)$$
$$- \lambda_1 (\Theta^\dagger \Theta)^2 - \lambda_2 (\Theta^\dagger \tau^I \Theta)^2 - y_\Theta^{pr} (\epsilon_{ij}\, \Theta^{\alpha i}\, \overline{d}_{p\alpha}\, l_r^j + h.c.).$$

U Banerjee, J Chakrabortty, S Prakash, SU Rahaman (2020), arxiv: 2004.12830

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Integrate out the heavy field

(CoDEx)

$$\mathcal{Q}_{HD}, \mathcal{Q}_{ll}, \mathcal{Q}_{Hu}, \mathcal{Q}_{Hd}, \mathcal{Q}_{He}, \mathcal{Q}_{Hq}^{(1)}, \mathcal{Q}_{Hl}^{(1)}, \mathcal{Q}_{Hl}^{(3)}, \mathcal{Q}_{Hq}^{(3)}, \mathcal{Q}_{HWB}, \mathcal{Q}_{H\Box}, \mathcal{Q}_{HB}, \mathcal{Q}_{HW},$$
$$\mathcal{Q}_{H}, \mathcal{Q}_{G}, \mathcal{Q}_{HG}, \mathcal{Q}_{eH}, \mathcal{Q}_{uH}, \mathcal{Q}_{dH}, \mathcal{Q}_{qq}^{(1)}, \mathcal{Q}_{qq}^{(3)}, \mathcal{Q}_{uu}, \mathcal{Q}_{dd}, \mathcal{Q}_{ud}^{(1)}, \mathcal{Q}_{lq}^{(1)},$$
$$\mathcal{Q}_{ee}, \mathcal{Q}_{eu}, \mathcal{Q}_{ed}, \mathcal{Q}_{le}, \mathcal{Q}_{lu}, \mathcal{Q}_{ld}, \mathcal{Q}_{qe}, \mathcal{Q}_{qu}^{(1)}, \mathcal{Q}_{qd}^{(1)}, \mathcal{Q}_{lq}^{(3)}, \mathcal{Q}_{W}, \mathcal{Q}_{ud}^{(8)}, \mathcal{Q}_{qd}^{(8)}, \mathcal{Q}_{qu}^{(8)}$$

SD Bakshi, J Chakrabortty, SK Patra (2018), arxiv: 1808.04403

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$$\mathcal{Q}_{ee},\mathcal{Q}_{eu},\mathcal{Q}_{ed},\mathcal{Q}_{le},\mathcal{Q}_{lu},\mathcal{Q}_{ld},\mathcal{Q}_{qe},\;\mathcal{Q}_{qu}^{(1)},\mathcal{Q}_{qd}^{(1)},\mathcal{Q}_{lq}^{(3)},\mathcal{Q}_{W},\mathcal{Q}_{ud}^{(8)},\mathcal{Q}_{qd}^{(8)},\mathcal{Q}_{qu}^{(8)}$$

These are the same effective operators which reveal this lepto-quark propagator upon unfolding

Summary

- Limitations of SM -> Motivation for stepping beyond SM
- Effective Field Theories: a capable platform for comparative analyses
  - The vernacular: Operators (Contact interactions); the grammar: Symmetry
- Simplify model comparisons
  - Model choice must not be arbitrary,
  - Repetition of elaborate computation must be avoided
- Diagrammatic unfolding of operators reveals BSM propagators
  - Enables cataloguing of new physics with respect to EFT operators
  - Completes the link between observables <-> operators <-> new physics models

THANK YOU