Exploring GUT origins of SMEFT operators

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Workshop on Grand Unified Theories: Phenomenology and Cosmology

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Outline

1 Effective Field Theory

2 UV Origins of Effective Operators

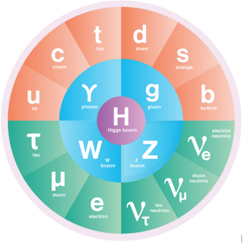
3 Construction of J-Basis

4 GUT Origins of the Resonant States

5 Summary

Standard Model Effective Field Theory

The Standard Model of particle physics is SO successful in describing all data coming from both low-energy experiments and high-energy colliders,

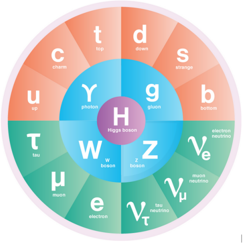


Standard Model Effective Field Theory

The Standard Model of particle physics is SO successful in describing all data coming from both low-energy experiments and high-energy colliders,

that we are compelled to study the potentially small and subtle indirect signatures of New Physics.

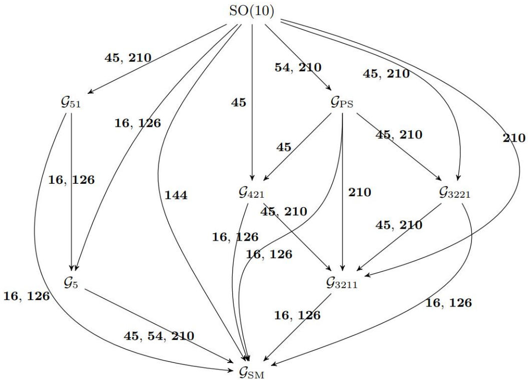
- Dark Matter
- Hierarchy problem
- Neutrino Mass
- Strong CP
- many more ...



Standard Model Effective Field Theory

Grand Unified Theory (GUT) is one of the most interesting UV models

$$\mathcal{G}_{\mathrm{GUT}} \to \mathcal{G}_{\mathrm{SM}} = SU(3)_c \times SU(2)_L \times U(1)_Y$$



[M. Pernow (2021)]

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$$\mathcal{G}_{\rm GUT} \to \mathcal{G}_{\rm SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$$

One of the characteristic features is proton decay $p \to \pi^0 e^+$

- Baryon number violation (BNV)
- Rare event (Super-K, etc.)
- Large log correction

The most suitable way to describe is by BNV effective operators in SMEFT

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{d>4} \sum_i \frac{c_{d,i}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Effective Operators at High Orders

An increasing number of effective operators at high orders:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i=1}^{2} \frac{c_{5,i}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_{i=1}^{84} \frac{c_{6,i}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_{i=1}^{30} \frac{c_{7,i}}{\Lambda^3}\mathcal{O}_i^{(7)} + \sum_{i=1}^{993} \frac{c_{8,i}}{\Lambda^4}\mathcal{O}_i^{(8)}$$

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An increasing number of effective operators at high orders:

$$\mathcal{L}_{\text{SMEFT}}^{n_f=3} = \mathcal{L}_{\text{SM}} + \sum_{i=1}^{12} \frac{c_{5,i}}{\Lambda} \mathcal{O}_i^{(5)} + \sum_{i=1}^{3045} \frac{c_{6,i}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_{i=1}^{1542} \frac{c_{7,i}}{\Lambda^3} \mathcal{O}_i^{(7)} + \sum_{i=1}^{44807} \frac{c_{8,i}}{\Lambda^4} \mathcal{O}_i^{(8)}$$

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- LO contributions to some observables ($\Delta B \neq 0$ or $\Delta L \neq 0$)

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How are they related to UV complete theories?

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1. Effective Field Theory
2. **UV Origins of Effective Operators**
3. Construction of J-Basis
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Tree-Level Matching

The usual way to find UV origins of effective operators are via matching

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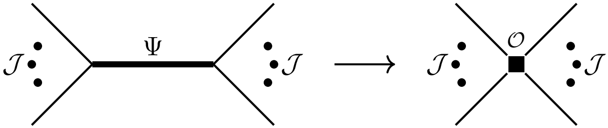
$$\mathcal{A}_{\rm EFT}(\mu) = \mathcal{A}_{\rm UV}^{\rm tree}(\mu) + \mathcal{A}_{\rm UV}^{\rm loop}(\mu)$$

To leading order, we are mostly interested in tree-level matching

$$\mathcal{L}_{\rm UV} \supset \Psi_{\rm heavy} \cdot \mathcal{J}_{\rm light} \quad \longrightarrow \quad \frac{1}{m_\Psi^2} \mathcal{J}_{\rm light} \cdot \mathcal{J}_{\rm light}$$



- How to exhaust all the possible Ψ's for a given low energy observable $\mathcal{O}$?
- How to analyse the operator basis dependence?

The Bottom-Up Approach

- The term "bottom-up" sometimes refers to a model-independent manner.

$$\boxed{\begin{array}{l}\text{the most generic } \mathcal{L}_{\rm UV} \text{ with} \\ \text{all possible } \Psi \text{ and couplings}\end{array}} \xrightarrow{\text{match}} \boxed{\text{low energy operators } \mathcal{O}}$$

However, not until **all the terms** in $\mathcal{L}_{\rm UV}$ are examined
can one finish investigating a certain operator $\mathcal{O}$!

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- Our "bottom-up" approach:

all possible contributing Ψ and couplings	$\overset{?}{\longleftarrow}$	given $\mathcal{O}$

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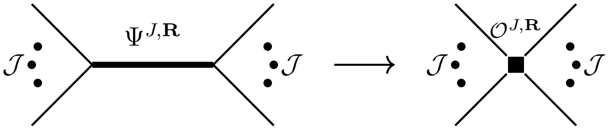

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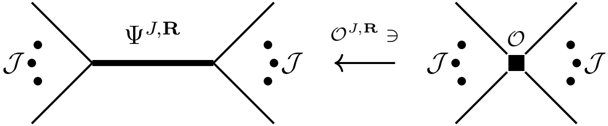

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Current-Current Interaction

The bipartite J-basis operators can be constructed by merely gluing two current operators $\mathcal{J}$ together $\mathcal{O}^{J,\mathbf{R}} \sim \mathcal{J}_1^{J,\mathbf{R}} \cdot \mathcal{J}_2^{J,\mathbf{R}}$

- The quantum number of an operator $\mathcal{J}$ is determined by the tensor structure of its uncontracted indices

$$\mathcal{J}^{0,0} = H^\dagger H \,, \qquad \mathcal{J}^{0,1} = H^\dagger \tau^I H \,,$$
$$\mathcal{J}^{1,0} = H^\dagger i \overleftrightarrow{D}^\mu H \,, \qquad \mathcal{J}^{1,1} = H^\dagger i \tau^I \overleftrightarrow{D}^\mu H \,.$$

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- The J-basis of H^4D^2

$$\mathcal{O}^{0,0} = (H^\dagger H)D^2(H^\dagger H) \,, \qquad \mathcal{O}^{0,1} = (H^\dagger \tau^I H)D^2(H^\dagger \tau^I H) \,,$$
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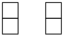
- From covariant derivative expansion:

$$\mathcal{J}_1 \cdot \frac{\mathcal{P}^{J,\mathbf{R}}}{M^2 - D^2} \cdot \mathcal{J}_2 = \frac{1}{M^2} \mathcal{J}_1^{J,\mathbf{R}} \cdot \mathcal{J}_2^{J,\mathbf{R}} + \frac{1}{M^4} \mathcal{J}_1^{J,\mathbf{R}} \cdot D^2 \mathcal{J}_2^{J,\mathbf{R}} + \dots$$

where $\mathcal{P}^{J,\mathbf{R}}$ are projectors onto the representation space of $(J, \mathbf{R})$.

Expansion of J-Basis Operators

Example of H^4D^2 operators in SMEFT, for channel $H_1^\dagger, H_2 \to H_3^\dagger, H_4$:

J	$\mathbf{R}$	J-basis	$\mathcal{K}^{\mathrm{jp}}$	P-basis	$\mathrm{Sym}_{H,H^\dagger}$
0	$\mathbf{1}$	$(H_1^\dagger H_2)D^2(H_3^\dagger H_4)$	$1 \quad 0 \quad 1 \quad 0$	$Q_{\varphi\Box}$	
	$\mathbf{3}$	$(H_1^\dagger \tau^I H_2)D^2(H_3^\dagger \tau^I H_4)$	$-1 \quad 4 \quad -1 \quad 4$	$Q_{\varphi D}$	
1	$\mathbf{1}$	$(H_1^\dagger i\overleftrightarrow{D}_\mu H_2)(H_3^\dagger i\overleftrightarrow{D}^\mu H_4)$	$-1 \quad -4 \quad -1 \quad 4$	$Q'_{\varphi\Box}$	
	$\mathbf{3}$	$(H_1^\dagger i\tau^I \overleftrightarrow{D}_\mu H_2)(H_3^\dagger i\tau^I \overleftrightarrow{D}^\mu H_4)$	$-3 \quad 0 \quad 5 \quad -8$	$Q'_{\varphi D}$	

Combination of effective operators from certain UV resonance:

$$\mathcal{O}^{0,\mathbf{1}} \sim Q_{\varphi\Box} \qquad \mathcal{O}^{0,\mathbf{3}} \sim -Q_{\varphi\Box} + 4Q_{\varphi D}$$

$$\mathcal{O}^{1,\mathbf{1}} \sim -Q_{\varphi\Box} + 4Q_{\varphi D} \qquad \mathcal{O}^{1,\mathbf{3}} \sim -3Q_{\varphi\Box}$$

High Spin Ambiguity

Off-shell longitudinal polarizations of high spin resonances produce ambiguity

$$\text{If } \mathcal{P}^{J=1}_{\mu\nu}(k) = g_{\mu\nu} - \frac{k_\mu k_\nu}{M^2} , \quad \text{then } \mathcal{P}^{J=1}_{\mu\nu} k^\nu = (1 - \frac{k^2}{M^2}) k_\mu \neq 0 .$$

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The UV couplings $(D^\mu \mathcal{O}) V_\mu$ induce the spin-0 low energy effective operator

$$(D^\mu \mathcal{O}) \frac{\mathcal{P}^{J=1}_{\mu\nu}}{M^2 - D^2} (D^\nu \mathcal{O}) = \frac{1}{M^2} \underbrace{(D\mathcal{O})^2}_{J=0} + \dots$$

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Choose the "unitary gauge" by Equation of Motion in the "UV" theory

$$(D^\mu \mathcal{O}) V_\mu \simeq -\mathcal{O}(D^\mu V_\mu) \xlongequal{\text{EOM}} -\frac{1}{M^2} \mathcal{O} D^2 \mathcal{O} \subset \mathcal{L}_{\text{UV}}\ .$$

Consequently, V only couples to conserved currents in the "UV" theory

$$\mathcal{L}_{\text{UV}} \supset V_\mu \mathcal{J}^\mu\ ,\quad \text{where}\ \ D_\mu \mathcal{J}^\mu \simeq 0\ ,\quad \text{like}\ \mathcal{J}^\mu = H^\dagger i \overleftrightarrow{D}^\mu H.$$

On-Shell Construction of J-Basis

Obstacles to systematic construction of J-basis:

- Multi-particle current, multi-partite J-basis?
- Systematic expansion on J-basis?
- High spin resonances?

On-shell amplitude / effective operator correspondence

$$\mathcal{O} \sim \sum_{\Psi} \int \mathrm{d}x \, \langle \Psi | \mathcal{O}(x) | 0 \rangle \equiv \sum_{\Psi} \mathcal{M}^{(\Psi)}(|i\rangle, |i])$$

Find eigenfunctions $\mathcal{M}^{J,\mathbf{R}}$ of Casimir operators:

Poincaré group:	$\mathbf{W}^2 \mathcal{M}^{J,\mathbf{R}} = -P^2 J(J+1) \mathcal{M}^{J,\mathbf{R}}$,
Gauge group:	$\mathbf{C}(T^A) \mathcal{M}^{J,\mathbf{R}} = C(\mathbf{R}) \mathcal{M}^{J,\mathbf{R}}$.

On-Shell Construction of J-Basis

Representation on the space of spinor functions: [2001.04481]

$$\mathbf{J}_{\mu\nu} = i\sum_{i\in\mathcal{I}}\left[\sigma_{\mu\nu}^{\alpha\beta}\left(\lambda_{i\alpha}\frac{\partial}{\partial\lambda_i^{\beta}} + \lambda_{i\beta}\frac{\partial}{\partial\lambda_i^{\alpha}}\right) + \bar{\sigma}_{\mu\nu}^{\dot{\alpha}\dot{\beta}}\left(\tilde{\lambda}_{i\dot{\alpha}}\frac{\partial}{\partial\tilde{\lambda}_i^{\dot{\beta}}} + \tilde{\lambda}_{i\dot{\beta}}\frac{\partial}{\partial\tilde{\lambda}_i^{\dot{\alpha}}}\right)\right]$$

$$\mathbf{W}^2 \equiv \left(\frac{1}{2}\epsilon^{\mu\nu\rho\sigma}\mathbf{P}_{\nu}\mathbf{J}_{\rho\sigma}\right)^2 = \frac{1}{2}\mathbf{P}^2\mathbf{J}^2 + \mathbf{P}_{\mu}\mathbf{J}^{\mu\nu}\mathbf{J}_{\nu\rho}\mathbf{P}^{\rho}$$

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- Multi-particle current, multi-partite J-basis?

$$[\mathbf{W}^2_{\mathcal{I}_1}, \mathbf{W}^2_{\mathcal{I}_2}] = 0 \text{ when } \ \mathcal{I}_1 \cap \mathcal{I}_2 = \emptyset$$

Common eigenfunctions $\mathcal{M}^{J_1, J_2}$ correspond to multi-partite J-basis operators.

On-Shell Construction of J-Basis

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- Systematic expansion of J-basis? [2005.00008, 2201.04639 (package:ABC4EFT)]

On-Shell reduction algorithm: $\mathcal{M} = \sum_i c_i \mathcal{M}_i^{\mathrm{y}}$.

1. Easy to find the basis transformation $\mathcal{K}^{\mathrm{pj}}$.
2. Also good for finding representation matrix $\mathbf{W}^2\mathcal{M}_i^{(\mathrm{y})} = -P^2\mathcal{W}_i^{\ j}\mathcal{M}_j^{(\mathrm{y})}$.

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- High spin resonances

$$\int \mathrm{d}x \, \langle p, \epsilon | D^\mu V_\mu | 0 \rangle = p_\mu \epsilon^\mu = 0$$

The unwanted couplings do not contribute to on-shell amplitudes!

$\Rightarrow$ UV resonance / J-basis correspondence

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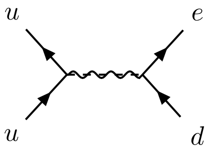
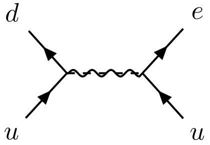
Baryon Number Violating Operators

- $Q_{duu} = \epsilon_{abc}(d_p^a u_r^b)(u_s^c e_t) = Q_{duu}^{\boxed{r}\boxed{s}} \oplus Q_{duu}^{\substack{\boxed{r}\\ \boxed{s}}}$



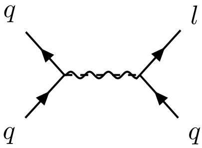
$$\Rightarrow \begin{cases} V(\mathbf{3},\mathbf{1})_{-\frac{4}{3}} & Q_{duu}^{\boxed{r}\boxed{s}} \\ S(\mathbf{3},\mathbf{1})_{-\frac{4}{3}} & Q_{duu}^{\substack{\boxed{r}\\ \boxed{s}}} \end{cases}$$



$$\Rightarrow \begin{cases} V(\mathbf{3},\mathbf{1})_{-\frac{1}{3}} & Q_{duu}^{\boxed{r}\boxed{s}} + \frac{3}{2} Q_{duu}^{\substack{\boxed{r}\\ \boxed{s}}} \\ S(\mathbf{3},\mathbf{1})_{-\frac{1}{3}} & Q_{duu}^{\boxed{r}\boxed{s}} - \frac{1}{2} Q_{duu}^{\substack{\boxed{r}\\ \boxed{s}}} \end{cases}$$

Baryon Number Violating Operators

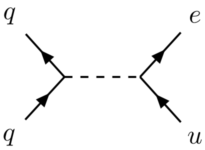
- $Q_{qqq} = \epsilon_{abc}\epsilon_{jn}\epsilon_{km}(q_p^{aj}q_r^{bk})(q_s^{cm}l_t^n) = Q_{qqq}^{\ytableaushort{prs}} \oplus Q_{qqq}^{\ytableaushort{pr,s}} \oplus Q_{qqq}^{\ytableaushort{p,r,s}}$



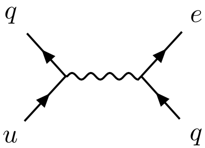
$$\Rightarrow \begin{cases} V(\mathbf{3},\mathbf{3})_{-\frac{1}{3}} & -2Q_{qqq}^{\ytableaushort{prs}} + Q_{qqq}^{\ytableaushort{pr,s}} + Q_{qqq}^{\ytableaushort{ps,r}} \\ S(\mathbf{3},\mathbf{3})_{-\frac{1}{3}} & -2Q_{qqq}^{\ytableaushort{p,r,s}} - Q_{qqq}^{\ytableaushort{pr,s}} + Q_{qqq}^{\ytableaushort{ps,r}} \\ V(\mathbf{3},\mathbf{1})_{-\frac{1}{3}} & -2Q_{qqq}^{\ytableaushort{p,r,s}} + Q_{qqq}^{\ytableaushort{pr,s}} - Q_{qqq}^{\ytableaushort{ps,r}} \\ S(\mathbf{3},\mathbf{1})_{-\frac{1}{3}} & 2Q_{qqq}^{\ytableaushort{prs}} + Q_{qqq}^{\ytableaushort{pr,s}} + Q_{qqq}^{\ytableaushort{ps,r}} \end{cases}$$

Baryon Number Violating Operators

- $Q_{qqu} = \epsilon_{abc}\epsilon_{jk}(q_p^{aj} q_r^{bk})(u_s^c e_t)$



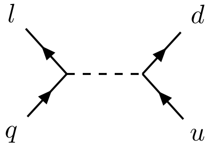
$\Rightarrow \quad S(\mathbf{3},\mathbf{1})_{-\frac{1}{3}} \quad Q_{qqu}$



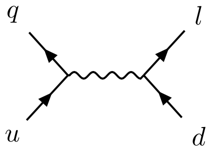
$\Rightarrow \quad V(\mathbf{3},\mathbf{2})_{-\frac{5}{6}} \quad Q_{qqu}$

Baryon Number Violating Operators

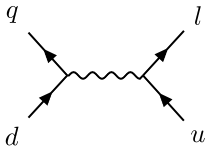
- $Q_{duq} = \epsilon_{abc}\epsilon_{jk}(d_p^a u_r^b)(q_s^{cj} l_t^k)$



$\Rightarrow \quad S(\mathbf{3},\mathbf{1})_{-\frac{1}{3}} \quad Q_{duq}$



$\Rightarrow \quad V(\mathbf{3},\mathbf{2})_{-\frac{5}{6}} \quad Q_{duq}$



$\Rightarrow \quad V(\mathbf{3},\mathbf{2})_{\frac{1}{6}} \quad Q_{duq}$

BNV Resonances States

- Dimension 6: $Q_{duu}, Q_{qqq}, Q_{qqu}, Q_{duq}$

$$V(\mathbf{3},\mathbf{1})_{-\frac{4}{3}}, V(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}, V(\mathbf{3},\mathbf{3})_{-\frac{1}{3}}, V(\mathbf{3},\mathbf{2})_{-\frac{5}{6}}, V(\mathbf{3},\mathbf{2})_{\frac{1}{6}}, S(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$$

$SO(10)$	$\to$	$\mathcal{G}_{51}$	$\to$	$\mathcal{G}_{\rm SM}$
$\mathbf{45}_V$	$\to$	$\mathbf{24}_0$	$\to$	$(\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$
$\mathbf{45}_V$	$\to$	$\mathbf{10}_{-4}$	$\to$	$(\mathbf{3},\mathbf{2})_{\frac{1}{6}}$
$\mathbf{16}_S$	$\to$	$\mathbf{5}_3$	$\to$	$(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$

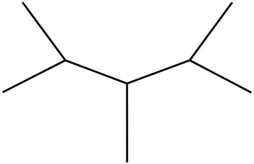
$SO(10)$	$\to$	$\mathcal{G}_{422}$	$\to$	$\mathcal{G}_{\rm SM}$
$\mathbf{45}_V$	$\to$	$(\mathbf{6},\mathbf{2},\mathbf{2})$	$\to$	$(\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$
$\mathbf{45}_V$	$\to$	$(\mathbf{6},\mathbf{2},\mathbf{2})$	$\to$	$(\mathbf{3},\mathbf{2})_{\frac{1}{6}}$
$\mathbf{16}_S$	$\to$	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	$\to$	$(\bar{\mathbf{3}},\mathbf{1})_{\frac{1}{3}}$

BNV Resonances States

- Dimension 6: $Q_{duu}, Q_{qqq}, Q_{qqu}, Q_{duq}$

$$V(\mathbf{3},\mathbf{1})_{-\frac{4}{3}}, V(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}, V(\mathbf{3},\mathbf{3})_{-\frac{1}{3}}, V(\mathbf{3},\mathbf{2})_{-\frac{5}{6}}, V(\mathbf{3},\mathbf{2})_{\frac{1}{6}}, S(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$$

- Dimension 7: $Q_{ldudH}, Q_{ldqqH}, \ldots \ (p \to K^+\bar{\nu})$



$$\{S(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}, S(\bar{\mathbf{3}},\mathbf{2})_{-\frac{1}{6}}\}$$

$$\{F(\mathbf{1},\mathbf{1})_0, V(\mathbf{3},\mathbf{2})_{\frac{1}{6}}\}$$

$$\vdots$$

Outline

1. Effective Field Theory
2. UV Origins of Effective Operators
3. Construction of J-Basis
4. GUT Origins of the Resonant States
5. Summary

Summary

- We establish a genuine bottom-up approach to UV origins of effective operators.
- On-shell correspondence and Casimir operators are the key tools.
- Convenient for looking for UV theories (such as GUT) that generate a particular low energy observable.
- As an example, we show how GUT origins of the BNV operators are explored.
- The methodology can be easily applied to any higher dimensional processes.

Thank you for your attention!