LEX-EFT
Light Exotics Effective Field Theory

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General Methods for Model Agnostic Collider Phenomenology

Some Examples

- Machine Learning-Anomaly Detection
- SMEFT- EFT for SM operators, new physics offshell

On Shell General EFT for Light Exotics LEX-EFT

Given a set of new states indexed by quantum numbers corresponding to symmetries, write all interactions with SM up to given dimension

LEX Operators

SM fields

$$\frac{1}{\Lambda^d}\,\lambda\,(\Phi_1\Phi_2\ldots)(\psi_1\psi_2\ldots)$$

BSM fields

Effective cut off

operator dimension = d+4

- LEX-EFT offers a complete list of all possible interactions between light exotics and the Standard Model up to the desired order in effective cut-off (mass dimension). It is thus a guide for bSM precision and collider searches, it allows for the analysis of new event topologies, and it offers a comprehensive map of event kinematics without the burden of specifying UV-complete models.

- A complete LEX-EFT catalog would subsume other classes of exotic bSM models including supersymmetry, exotic Higgs models, and dark matter EFTs. Such a complete catalog may illuminate new interactions in these theories and thus new phenomenological channels for study.

- The LEX-EFT catalog would also bring to theoretical consideration bSM states that have not received model-building attention. It would thus cast a wider net over all of theory space. As we imagine the LEX-EFT approach would be closely followed up by a simplified model building approach, this would spark new theoretical innovation.

Advantages of On-shell EFT

Picture of New Event Topology and Kinematics

Accurate cross section prediction up tp validity limit of EFT

Charge Flow Clebsch-Gordon Coefficients for Charge Contraction-

Different ways to contract charges of same fields-different operators
May lead to naturally large couplings/cross sections
Have effects of validity to EFT

Complementarity to Off-Shell EFT

Operator Correlation: Symmetries lead to operator correlation between op
once LEX states integrated out, maps to SMEFT for heavy LEX states

Implications for Precision Measurements

Charge Flow: Constructing Singlets

Construct Charge Singlet Operators Under All gauge and global symmetry groups

SM :SU(3), SU(2), U(1) , BSM: U(1)', SU(2)$_{R,}$ etc.
Global:SU(N) flavor etc.

Fields are in representations $\mathbf{r}_i$ of a group

$$\frac{1}{\Lambda^d}\lambda\,(\Phi_1\Phi_2\ldots)(\psi_1\psi_2\ldots)$$

$\mathbf{r}_1$ $\mathbf{r}_2$

$$\mathbf{r}_1\otimes\mathbf{r}_2\otimes\ldots.=1$$

singlet

Use iterative tensor products to construct new singlets

Iterative Construction of Singlets

Method for constructing group theory invariants from basic 2 field tensor product relations

$$\mathbf{r}_1 \otimes \mathbf{r}_2 = \mathbf{q}_1 \oplus \mathbf{q}_2 \oplus \ldots .$$

example from SU(3)

$$\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8}$$

quark

gluon

anti-quark

Higgs, photon, etc

$$\mathbf{3} \otimes \bar{\mathbf{3}} \otimes \mathbf{8}$$

Example constructing invariant with new sextet

$$\mathbf{3} \otimes \mathbf{3} = \bar{\mathbf{3}}_{\mathrm{a}} \oplus \mathbf{6}_{\mathrm{s}},$$
$$\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8},$$
$$\mathbf{6} \otimes \mathbf{3} = \mathbf{8} \oplus \mathbf{10},$$
$$\mathbf{6} \otimes \bar{\mathbf{3}} = \mathbf{3} \oplus \mathbf{15},$$
$$\mathbf{6} \otimes \mathbf{6} = \bar{\mathbf{6}}_{\mathrm{s}} \oplus \mathbf{15}_{\mathrm{a}} \oplus \mathbf{15}'_{\mathrm{s}},$$
$$\mathbf{6} \otimes \bar{\mathbf{6}} = \mathbf{1} \oplus \mathbf{8} \oplus \mathbf{27},$$
$$\mathbf{8} \otimes \mathbf{3} = \mathbf{3} \oplus \bar{\mathbf{6}} \oplus \mathbf{15},$$
$$\mathbf{8} \otimes \bar{\mathbf{6}} = \mathbf{3} \oplus \bar{\mathbf{6}} \oplus \mathbf{15} \oplus \mathbf{24},$$
$$\mathbf{8} \otimes \mathbf{8} = \mathbf{1}_{\mathrm{s}} \oplus \mathbf{8}_{\mathrm{s}} \oplus \mathbf{8}_{\mathrm{a}} \oplus \mathbf{10}_{\mathrm{a}} \oplus \overline{\mathbf{10}}_{\mathrm{a}} \oplus \mathbf{27}_{\mathrm{s}}$$

By iterating tensor products
We construct new invariant

$$\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{8} = \mathbf{6} \otimes \mathbf{3}$$

$$\mathbf{3} \otimes \bar{\mathbf{3}} \otimes \bar{\mathbf{3}} \otimes \bar{\mathbf{6}}$$

With coefficient

$$[t_3^a]_j{}^i \, \bar{J}_{s\,ak}$$

Fundamentals contacted into 8

6-3-8 contraction

Example SU(3) invariant

$$\mathbf{3} \otimes \mathbf{3} \otimes \bar{\mathbf{6}} \otimes \mathbf{8}$$

quark   quark   LEX sextet   gluon

Clebsch-Gordon coeff.

Lorentz

$$\mathcal{L}_{\Phi qqg} \supset \frac{1}{\Lambda^2}\,\lambda^{IJ}_{qq}\,\Pi_s{}^{a\,ij}\,\varphi^{\dagger s}\,(\overline{q^c_{\mathrm{R}}}_{Ii}\,\sigma^{\mu\nu}\,q_{\mathrm{R}Jj})\,G_{\mu\nu\,a} + \mathrm{H.c}$$

LEX sextet   quark   gluon

Fields may be contracted in several different ways, corresponding to linearly independent operators...

there may be multiple coeff icients for a given set of fields

Effect on EFT Validity from Unitarity

Consider the 2 to 2 process

$$qg \to \varphi q^{c}$$

With the perturbative unitarity bound

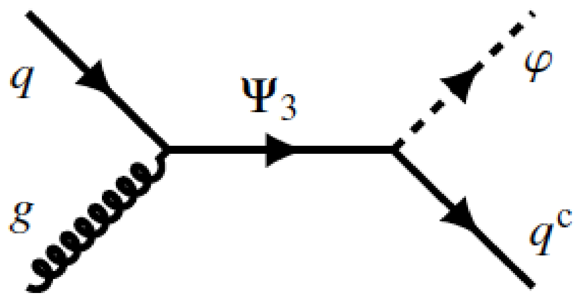
$$\Lambda \geq (\Pi_{s}{}^{a\,ij}\bar{\Pi}^{s}{}_{a\,ij})^{1/4}\left(\frac{\lambda_{qq}^{IJ}}{2\pi}\right)^{1/2}(\hat{s}-m_{\varphi}^{2})^{1/2}$$

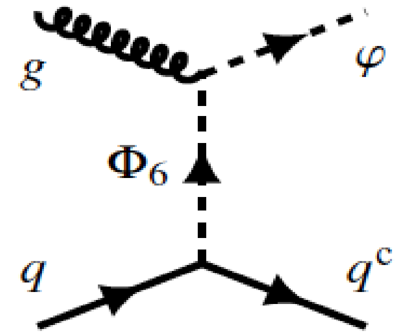
Given two linearly independent operators, the validity limit on cut-offs between two sextet coefficients varies by a factor of

$$\left(\frac{[\Pi_{\mathbf{6}}]_{s}{}^{a\,ij}[\bar{\Pi}_{\mathbf{6}}]^{s}{}_{a\,ij}}{[\Pi_{\mathrm{loop}}]_{s}{}^{a\,ij}[\bar{\Pi}_{\mathrm{loop}}]^{s}{}_{a\,ij}}\right)^{1/4}=9^{1/4}\approx 1.73$$

Production cross sections differ by a factor of 9

$\mathbf{3} \otimes \mathbf{3} \otimes \bar{\mathbf{6}} \otimes \mathbf{8}$





$\mathbf{3} \otimes \bar{\mathbf{3}} \otimes \mathbf{8}$ and $\mathbf{3} \otimes \mathbf{3} \otimes \bar{\mathbf{6}}$

$\mathbf{6} \otimes \bar{\mathbf{6}} \otimes \mathbf{8}$ and $\mathbf{3} \otimes \mathbf{3} \otimes \bar{\mathbf{6}}$.

$$[\Pi_{\mathbf{3}}]_s{}^{a\,ij} = K_s{}^{ik}[t^a_{\mathbf{3}}]_k{}^j$$

$$[\Pi_{\mathbf{6}}]_s{}^{a\,ij} = K_r{}^{ij}[t^a_{\mathbf{6}}]_s{}^r$$

$$\sigma(qg \to \varphi q^c)$$

$$K_s{}^{ik}[t^a_{\mathbf{3}}]_k{}^j[t^a_{\mathbf{3}}]_j{}^{k'}\bar{K}^s{}_{ik'} = 8$$

$$K_r{}^{ij}[t^a_{\mathbf{6}}]_s{}^r[t^a_{\mathbf{6}}]_{r'}{}^s\bar{K}^{r'}{}_{ij} = 20$$

Kinematics

Consider the LEX spin 0 CP-even color sextet

Field	$SU(3)_c \times SU(2)_L \times U(1)_Y$	B	L
$\boldsymbol{\Phi}$	$(\mathbf{6}, \mathbf{1}, \frac{1}{3})$	0	-1

Consider the LEX spin 0 CP-even color sextet

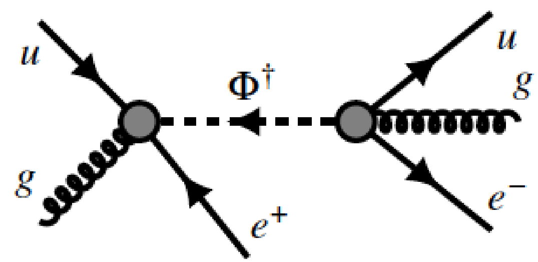
with interaction term

$$\mathcal{L}_{\Phi\ell^-} \supset \frac{1}{\Lambda^2}\,\lambda^{IX}_{u\ell}\,J^{s\,ia}\,\Phi_s\,(\overline{u^{c}_{R}}_{Ii}\,\sigma^{\mu\nu}\,\ell_{RX})\,G_{\mu\nu\,a}$$

lepton-quark-gluon-sextet

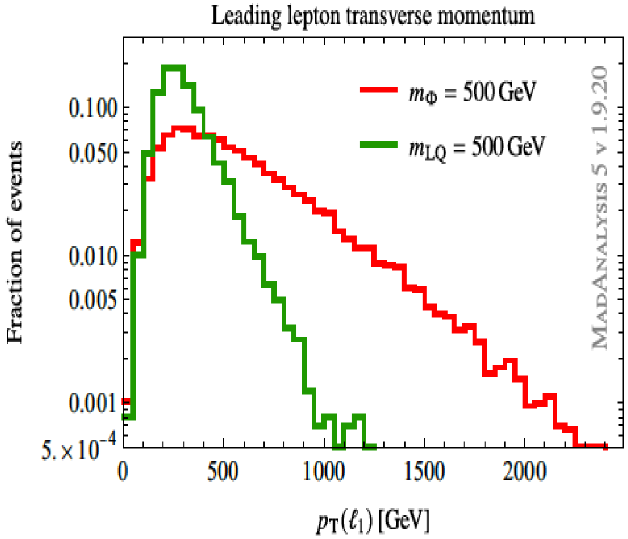
qg fusion gives sextet+hard lepton

The collider production process is



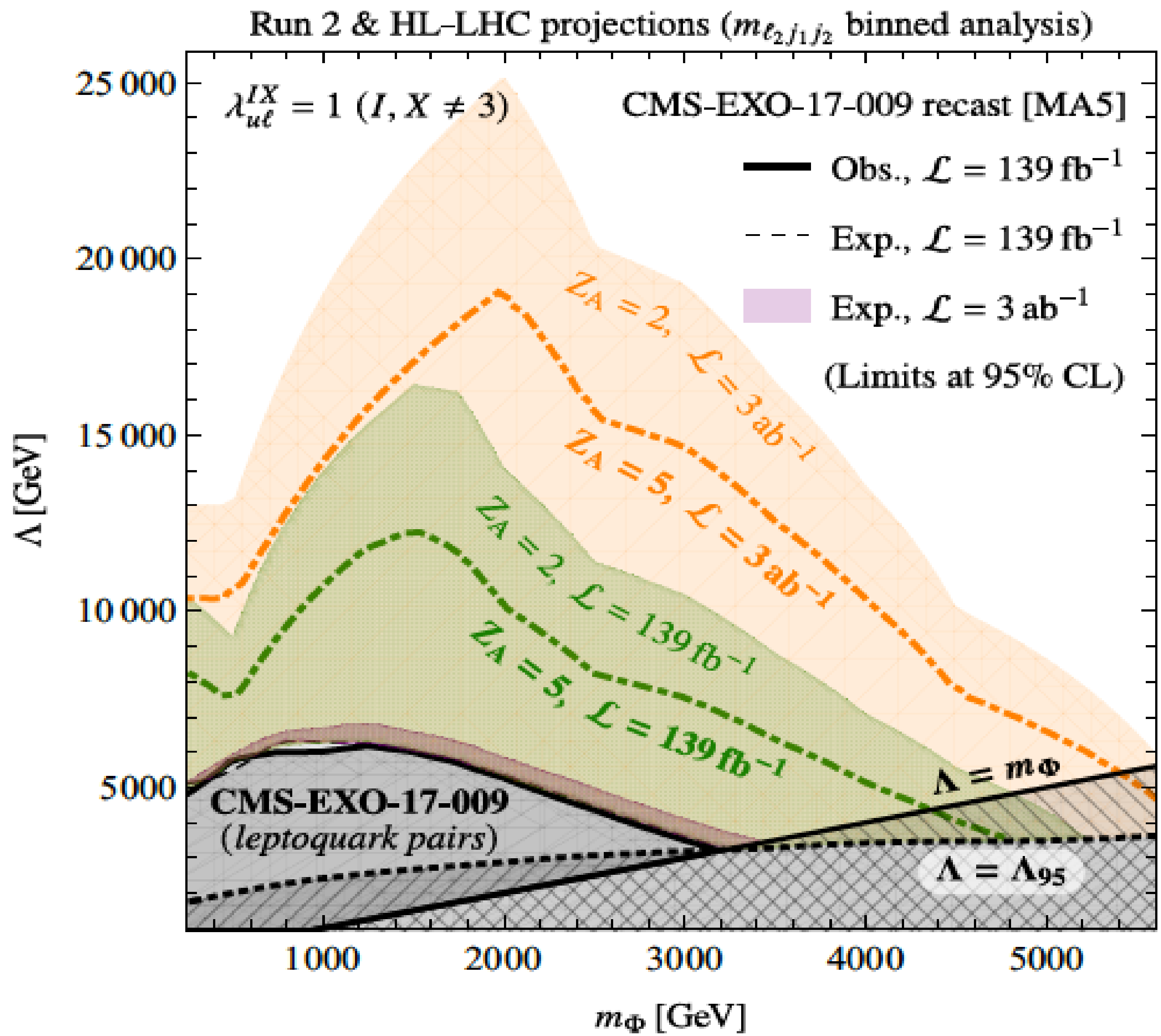
With final state $j\,j\,\ell^+\ell^-$

Distinctive kinematics distinguishes these events from other BSM searches, eg lepto-quarks with similar final state

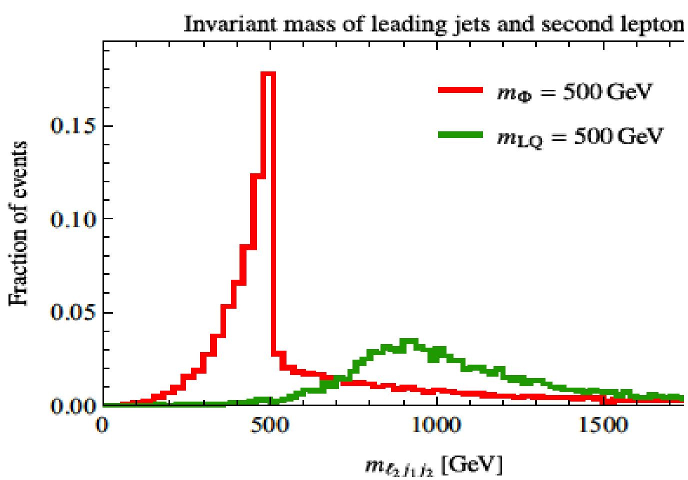


Leading lepton transverse momentum
Fraction of events
m_Φ = 500 GeV
m_{LQ} = 500 GeV
MadAnalysis 5 v 1.9.20
$p_T(\ell_1)$ [GeV]

V



Run 2 & HL–LHC projections ($m_{\ell_2 j_1 j_2}$ binned analysis)
$\lambda^{IX}_{u\ell} = 1$ $(I, X \neq 3)$
CMS-EXO-17-009 recast [MA5]
Obs., $\mathcal{L} = 139$ fb^{-1}
Exp., $\mathcal{L} = 139$ fb^{-1}
Exp., $\mathcal{L} = 3$ ab^{-1}
(Limits at 95% CL)
$Z_A = 2$, $\mathcal{L} = 3$ ab^{-1}
$Z_A = 5$, $\mathcal{L} = 3$ ab^{-1}
$Z_A = 2$, $\mathcal{L} = 139$ fb^{-1}
$Z_A = 5$, $\mathcal{L} = 139$ fb^{-1}
CMS-EXO-17-009
(leptoquark pairs)
$\Lambda = m_\Phi$
$\Lambda = \Lambda_{95}$
Λ [GeV]
m_Φ [GeV]



Invariant mass of leading jets and second lepton
Fraction of events
m_Φ = 500 GeV
m_{LQ} = 500 GeV
$m_{\ell_2 j_1 j_2}$ [GeV]

Two approaches to Operator Catalogs

- **Field based**, pick an example LEX state with specific quantum numbers and write all possible operators up to desired mas dimension e.g. dim 6

- **Portal based**, pick a SM portal and write all possible LEX states that can couple through that portal (eg Higgs portal, lepton portal)

Example Catalog: Di-Boson Portal

Catalog all CP even spin zero scalars that couple to pairs of SM vector bosons

Gives phenomenology of single exotic states produced associated production, gluon fusion, and vbf channels

Complete catalog contains surprising phenomenology, including states with higher dimensional representations of SU(3) and SU(2)

Exotic Octets coupling to SU(2) tensor and Gluon

$(\mathbf{8}, \mathbf{2}, \frac{1}{2})$ $\quad \mathcal{L} \supset \frac{1}{\Lambda^2} H^{\dagger i} (\sigma^a)_i{}^j \phi_j^A W^{a\mu\nu} G_{\mu\nu}^A$

$(\mathbf{8}, \mathbf{3}, 0)$ $\quad \mathcal{L} \supset \frac{1}{\Lambda} \phi^{Aa} W^{a\mu\nu} G_{\mu\nu}^A.$

$(\mathbf{8}, \mathbf{1}, 0)$ $\quad \mathcal{L} \supset \frac{1}{\Lambda^3} (H^\dagger \sigma^a H) \phi^A W^{a\mu\nu} G_{\mu\nu}^A.$

$(\mathbf{8}, \mathbf{4}, -\frac{1}{2})$ $\quad \phi_{ijk} H^k W^{ij\mu\nu} G_{\mu\nu}$

$(\mathbf{8}, \mathbf{5}, 0)$ $\quad \phi_{ijkl} H^{\dagger i} H^j W^{kl\mu\nu} G_{\mu\nu}$

W-Gluon resonance

Dimension	$SU(3)_c \times SU(2)_L \times U(1)_Y$	Operators
$5\left[\times\frac{1}{\Lambda}\right]$	$(\mathbf{1},\mathbf{5},0)$	$\phi_{ijkl}\, W^{ij\mu\nu} W^{kl}_{\mu\nu}$
	$(\mathbf{10},\mathbf{1},0)$	$\varepsilon^{KLM}\,\phi_{IJK}\, G^{I\mu\nu}_{L} G^{J}_{M\mu\nu}$
	$(\mathbf{27},\mathbf{1},0)$	$\phi^{KL}_{IJ}\, G^{I\mu\nu}_{K} G^{J}_{L\mu\nu}$
$6\left[\times\frac{1}{\Lambda^2}\right]$	$(\mathbf{1},\mathbf{4},-\frac{1}{2})$	$\phi_{ijk}\, H^k\, W^{ij\mu\nu} B_{\mu\nu}$
	$(\mathbf{8},\mathbf{4},-\frac{1}{2})$	$\phi_{ijk}\, H^k\, W^{ij\mu\nu} G_{\mu\nu}$
	$(\mathbf{1},\mathbf{4},-\frac{1}{2})$	$\phi_{ijk}\, H_l\, W^{ij\mu\nu} W^{kl}_{\mu\nu}$
	$(\mathbf{1},\mathbf{6},-\frac{1}{2})$	$\phi_{ijklm}\, H^m\, W^{ij\mu\nu} W^{kl}_{\mu\nu}$
$7\left[\times\frac{1}{\Lambda^3}\right]$	$(\mathbf{1},\mathbf{5},0)$	$\phi_{ijkl}\, H^{\dagger i} H^j\, W^{kl\mu\nu} B_{\mu\nu}$
	$(\mathbf{8},\mathbf{5},0)$	$\phi_{ijkl}\, H^{\dagger i} H^j\, W^{kl\mu\nu} G_{\mu\nu}$
	$(\mathbf{1},\mathbf{7},0)$	$\phi_{ijklmn}\, H^{\dagger m} H^n\, W^{ij\mu\nu} W^{kl}_{\mu\nu}$
	$(\mathbf{10},\mathbf{3},0)$	$\varepsilon^{KLM}\,[H^{\dagger i}\phi_{IJKij}H^j]\, G^{I\mu\nu}_{L} G^{J}_{M\mu\nu}$
	$(\mathbf{27},\mathbf{3},0)$	$[H^{\dagger i}\phi^{KL}_{IJij}H^j]\, G^{I\mu\nu}_{K} G^{J}_{L\mu\nu}$

Collider Processes

$$\mathcal{L} \supset \frac{1}{\Lambda}\,\phi_{ijkl}\,W^{\mu\nu ij}W^{kl}_{\mu\nu}$$

Yields associated production process

$$pp \to \Phi^{++}W^{-}$$

Through the same operator

$$\Phi^{++} \to W^{+}W^{+}$$

Tri-boson process

$$pp \to \phi^{++}W^{-} \to (W^{+}W^{+})\,W^{-}$$

Future Directions

- Many catalogs to build *e.g. high reps of SU(2)*
- Explore existing catalogs, *e.g. di-boson portal, color sextet scalars*
- Search for classes of outstanding collider signatures
- Build UV completions

We now argue from induction. To build three-field invariants involving a LEX field, we need only consider the m possible bilinear tensor products of the LEX state with other representations allowed in the theory, $[\mathbf{r}_{\text{LEX}} \otimes \mathbf{r}_i]_{\mathbf{r}'_j}$, to obtain the finite list of irreducible representations $\mathbf{r}'$ in the direct product. If any single field in the theory is in the conjugate representation $\bar{\mathbf{r}}'_j$, then we can directly contract indices to form an invariant:

$$[\mathbf{r}_{\text{LEX}} \otimes \mathbf{r}_i]_{\mathbf{r}'_j} \otimes \bar{\mathbf{r}}'_j$$

With a list in hand of all m possible bilinear products $\mathbf{r}_{\text{LEX}} \otimes \mathbf{r}_i$ in representations $\mathbf{r}'_j$, we can proceed to construct the four-field invariants. We find the direct products of the allowed representations $\mathbf{r}_k \otimes \mathbf{r}_l$ that are in a given conjugate representation $\bar{\mathbf{r}}'_j$ and contract these fields according to

$$[\mathbf{r}_{\text{LEX}} \otimes \mathbf{r}_i]_{\mathbf{r}'_j} \otimes [\mathbf{r}_k \otimes \mathbf{r}_l]_{\bar{\mathbf{r}}'_j}$$

to obtain singlets. To proceed to five fields, we now consider all possible trilinear products of the form $\mathbf{r}_{\text{LEX}} \otimes \mathbf{r}_i \otimes \mathbf{r}_j$. We note we have already found by exhaustion the representations of bilinear products of the first two fields in the previous step. In that step, the bilinears were in representations $\mathbf{r}'_j$ such that $\mathbf{r}_{\text{LEX}} \otimes \mathbf{r}_i \supset \mathbf{r}'_j$. We can thus iterate the bilinear tensor products $\mathbf{r}'_j \otimes \mathbf{r}_j \supset \mathbf{r}'_k$ to find the representations $\mathbf{r}'_k$ of all trilinear products. We then find the remaining bilinear representations $\mathbf{r}_k \otimes \mathbf{r}_l$ that are in the conjugate representation $\bar{\mathbf{r}}'_k$ and contract *these* fields to form the five-field invariant. This process can be repeated indefinitely and will ultimately produce all possible terms — we only need to know the list of bilinear tensor products that involve relevant SM/LEX fields and the intermediate representations $\mathbf{r}'_j$, $\mathbf{r}'_k$, and so on.