The phenomenological cornucopia of SU(3) exotica

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EFT for exotic color-charged states

- The Standard Model (SM) is under increasing pressure
  - *Old*: hierarchy problem, unification, dark matter
  - *Newer*: $(g-2)_\mu$, ℓ flavor universality, W boson mass [1] (!!)
- Some of these can be explained by models containing additional states charged under SM color gauge group $\mathrm{SU}(3)_\mathrm{c}$
- Models with new color-charged states are numerous as standalone scenarios [2] and embedded in complete(ish) frameworks [3]
- Community increasingly leans on **effective field theories** (EFTs) to parametrize new physics without committing to a particular (UV-complete?) framework
- Comprehensive efforts — *e.g.*, SMEFT — should be accompanied by EFTs involving external light states
- We begin [4] with **sextets** transforming in the **6** of $\mathrm{SU}(3)_\mathrm{c}$

Why start with sextets?

- Unlike in SU(2), a low-dimensional irreducible representation lies between fundamental and adjoint of SU(3)
- Sextets can couple to color-charged SM fields in structures unfamiliar to triplets and octets, enabling *e.g.* (spoilers)
  - $\Phi \to q_I q_J$
  - $\Psi \to q_I g$ [not renormalizable]
- Expect copious pair production at hadron colliders (almost as much as octets [5, 6]) but exotic signatures — see [7, 8] and this talk — help sextets evade standard searches
- Some recent press: CMS-EXO-21-010 [9] might see some excess events in search for pairs of dijet resonances... CMS uses sextet **diquark** as benchmark model for resonant search
- We want to find all the (sizable) interactions of sextets with SM

$\mathrm{SU}(3)_{\mathrm{C}}$ SINGLETS BY ITERATION

- Some group theory review: direct-product reps of SU(3) can be reduced to irreducible reps; for example [10, 11],

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

  Then $\exists$ *e.g.* an invariant combination (singlet) in $\mathbf{3} \otimes \mathbf{3} \otimes \bar{\mathbf{6}}$
- Observation: If $\mathbf{r}_1 \otimes \cdots \otimes \mathbf{r}_n \otimes \mathbf{p}$ and $\mathbf{q}_1 \otimes \cdots \otimes \mathbf{q}_m \otimes \mathbf{p}$ contain singlets, then so does $\mathbf{r}_1 \otimes \cdots \otimes \mathbf{r}_n \otimes \bar{\mathbf{q}}_1 \otimes \cdots \otimes \bar{\mathbf{q}}_m$
- Example: $\mathbf{6} \otimes \bar{\mathbf{3}} = \mathbf{3} \oplus \ldots$ and $\mathbf{8} \otimes \mathbf{3} = \mathbf{3} \oplus \ldots \Longrightarrow \mathbf{3} \otimes \mathbf{3} \otimes \bar{\mathbf{6}} \otimes \mathbf{8}$ contains a singlet
- Iterate to build all possible color structures containing sextets

Ensuring Lorentz invariance

	Examples	Bilinears	Notes
$(\bar{\chi}\chi')$	$(\bar{q}q')$ $(\bar{\mathbf{3}}\otimes\mathbf{3})$, $(\bar{\Psi}\Psi)$ $(\bar{\mathbf{6}}\otimes\mathbf{6})$, $(\bar{q}\ell)$ $(\bar{\mathbf{3}}\otimes\mathbf{1})$	$\bar{X}_{\mathrm{L}} H \Gamma \chi'_{\mathrm{R}}$	
		$\bar{X}_{\mathrm{L}} \Omega\, \gamma^{\mu} X'_{\mathrm{L}}$	only if half of four-fermion operator with second γ_{μ}
		$\bar{\chi}_{\mathrm{R}} \gamma^{\mu} \chi'_{\mathrm{R}}$	
$(\chi\chi')$	(qq') $(\mathbf{3}\otimes\mathbf{3})$, $(\Psi\Psi)$ $(\mathbf{6}\otimes\mathbf{6})$, $(q\ell)$ $(\mathbf{3}\otimes\mathbf{1})$	$\overline{\chi^{\mathrm{c}}_{\mathrm{R}}} \Gamma \chi'_{\mathrm{R}}$	$\Gamma = \sigma^{\mu\nu}$ non-vanishing only if $\chi' \neq \chi$
		$\overline{X^{\mathrm{c}}_{\mathrm{L}}} \Omega\, \Gamma X'_{\mathrm{L}}$	
		$\overline{X^{\mathrm{c}}_{\mathrm{L}}} H \gamma^{\mu} \chi'_{\mathrm{R}}$	needs second γ_{μ} again

Operator	Notes
$\Gamma \in \{\mathbf{1}, \sigma^{\mu\nu}\}$	$\sigma^{\mu\nu}$ must be accompanied by $\sigma_{\mu\nu}$ or a field-strength tensor $F_{\mu\nu}$, $F_{\mu\nu} \in \{B_{\mu\nu}, t^{A}_{\mathbf{2}} W^{A}_{\mu\nu}, G^{a}_{\mu\nu}\}$
$\Omega \in \{HH^{\dagger}, \mathrm{i}\tau^{2}\}$	

THE CATALOG, SCHEMATICALLY

	Scalar sextet Φ only		*Dirac* sextet Ψ only		≥ 1 of each	
SU(3)$_c$ invariant	d_{min}	Structure	d_{min}	Structure	d_{min}	Structure
$\mathbf{3} \otimes \mathbf{3} \otimes \bar{\mathbf{6}}$	4	$(qq')\Phi^\dagger$	6	$(qq')(\bar{\Psi}\ell)$		
	6	$(qq')\|H\|^2\Phi^\dagger$		$(\bar{\Psi}q)(q\ell)$		
				$(\bar{\Psi}q)(\bar{\ell}q)$		
$\mathbf{3} \otimes \mathbf{6} \otimes \mathbf{8}$	6	$(q\ell)\Phi G$	5	$(q\Psi)G$		
		$(\bar{\ell}q)\Phi G$	7	$(q\Psi)\|H\|^2 G$		
$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{6} \otimes \mathbf{6}$	5	$(qq')\Phi\Phi$	6	$(qq')(\Psi\Psi)$	7	$(qq')(\Psi\ell)\Phi$
	7	$(qq')\Phi\|H\|^2\Phi$		$(q\Psi)(q'\Psi)$		$(q\ell)(q'\Psi)\Phi$
$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} \otimes \mathbf{6}$	7	$(qq')(q''q''')\Phi$				

Filling in the details

- To build a section of the catalog: pick a sextet and an invariant, then cycle through the Lorentz-invariant structures and fix Y

$\mathbf{3} \otimes \mathbf{6} \otimes \mathbf{8}$	Singlet (Lorentz + $\mathcal{G}_{\text{SM}}$)			L	Y
	Generic	Specific	Coupling		
Scalar Φ_s	$(q\ell)\Phi G$	$J^{s\,ia}\, \Phi_s\, (\overline{q^{\text{c}}_{\text{R}Ii}}\, \sigma^{\mu\nu} \ell_{\text{R}X})\, G_{\mu\nu\, a}$	$\frac{1}{\Lambda_\Phi^2}\, \lambda_I^X$	-1	$\{\frac{1}{3}, \frac{4}{3}\}$
	$(\bar{\ell} q)\Phi G$	$J^{s\,ia}\, \Phi_s\, (\bar{L}_{\text{L}X} H \sigma^{\mu\nu} q_{\text{R}Ii})\, G_{\mu\nu\, a}$	$\frac{1}{\Lambda_\Phi^3}\, \lambda_I^X$	1	$\{-\frac{5}{3}, -\frac{2}{3}\}$
Dirac Ψ_s	$(q\Psi)G$	$J^{s\,ia}\, (\overline{q^{\text{c}}_{\text{R}Ii}}\, \sigma^{\mu\nu} \Psi_s)\, G_{\mu\nu\, a}$	$\frac{1}{\Lambda_\Psi}\, \kappa_I$	0	$\{-\frac{2}{3}, \frac{1}{3}\}$
		$J^{s\,ia}\, (\overline{q^{\text{c}}_{\text{R}Ii}}\, \Psi_s)\, B^{\mu\nu} G_{\mu\nu\, a}$	$\frac{1}{\Lambda_\Psi^3}\, \kappa_I$		
	$(q\Psi)\lvert H\rvert^2 G$	$J^{s\,ia}\, (\overline{q^{\text{c}}_{\text{R}Ii}}\, \sigma^{\mu\nu} \Psi_s)\, \lvert H\rvert^2\, G_{\mu\nu\, a}$			

Sextet collider phenomenology

- Consider a particular scenario with

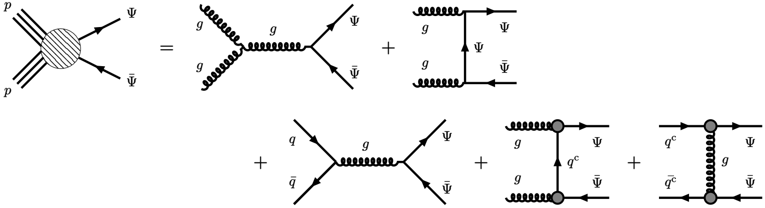
$$\Psi_q \sim (\mathbf{6}, \mathbf{1}, Y_q) \quad \text{and} \quad \Phi_q \sim (\mathbf{6}, \mathbf{1}, Y_q)\ [+\, L_{\Phi_q} = -1]$$

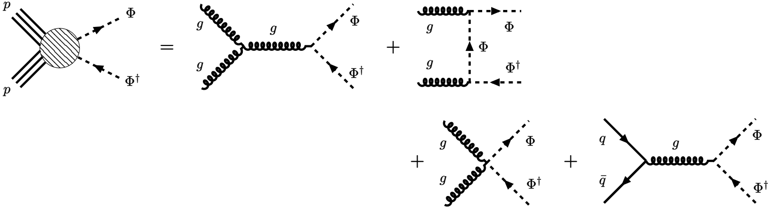
- Leading operators from our catalog for these sextets:

$$\mathcal{L} \supset \frac{1}{\Lambda_{\Psi_q}} [\kappa_q^I\, J^{s\,ia}\, (\overline{q^{\text{c}}_{\text{R}Ii}}\, \sigma^{\mu\nu} \Psi_{qs})\, G_{\mu\nu\,a} + \text{H.c.}] + \frac{1}{\Lambda^3_{\Psi_{qB}}} [\kappa_{qB}^I\, J^{s\,ia}\, (\overline{q^{\text{c}}_{\text{R}Ii}}\, \Psi_{qs})\, B^{\mu\nu} G_{\mu\nu\,a} + \text{H.c.}] + \frac{1}{\Lambda^2_{\Phi_q}} [\lambda_q^{XI}\, J^{s\,ia}\, \Phi_{qs}\, (\overline{q^{\text{c}}_{\text{R}Ii}}\, \sigma^{\mu\nu} \ell_{\text{R}X})\, G_{\mu\nu\,a} + \text{H.c.}]$$

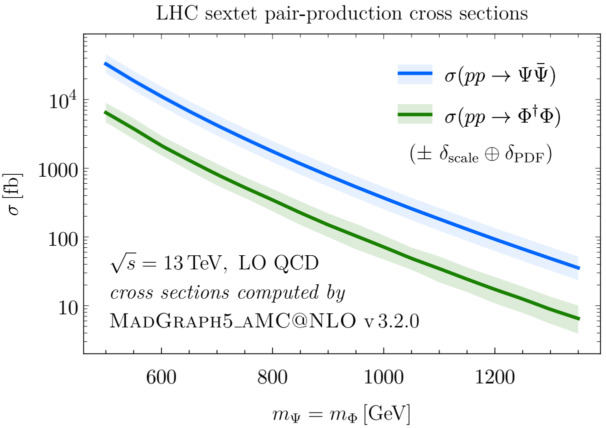
- Let us explore some cross sections and signatures

Color-sextet pair production



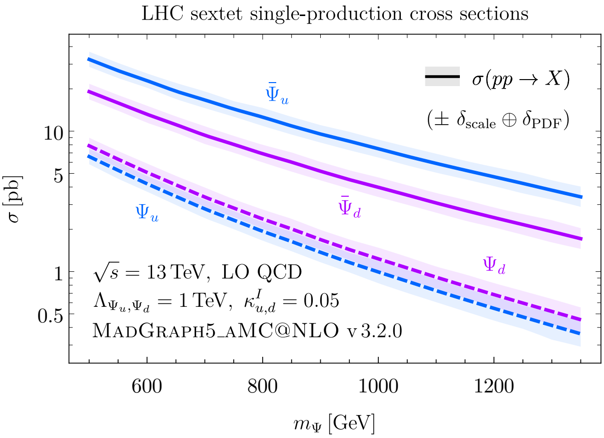


Color-sextet pair production



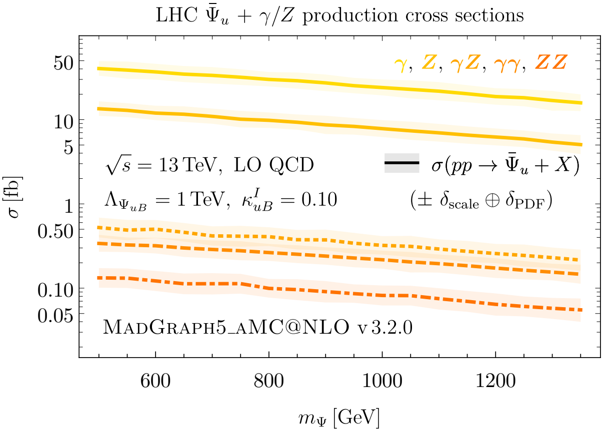
Single fermion production

$$\frac{1}{\Lambda_{\Psi_q}}\,\kappa_q^I\,J^{s\,ia}\,(\overline{q^{\mathrm{c}}_{\mathrm{R}}}{}_{Ii}\,\sigma^{\mu\nu}\,\Psi_{qs})\,G_{\mu\nu\,a}$$



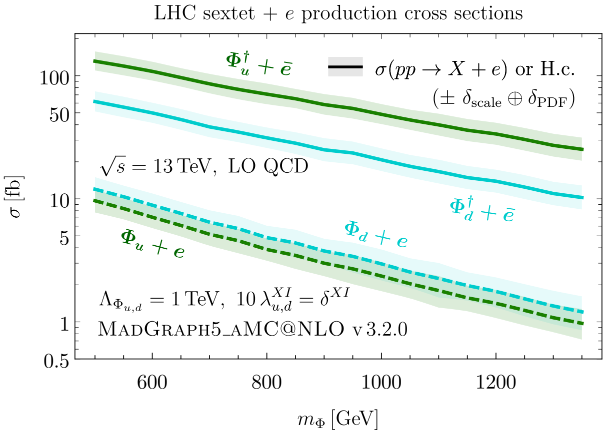
Fermion + EW boson production

$$\frac{1}{\Lambda^3_{\Psi_{qB}}}\,\kappa^I_{qB}\,J^{s\,ia}\,(\overline{q^{\rm c}_{{\rm R}Ii}}\,\Psi_{qs})\,B^{\mu\nu}G_{\mu\nu\,a}$$



Scalar + lepton production

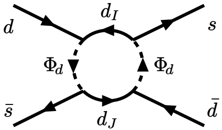
$$\frac{1}{\Lambda^2_{\Phi_q}}\,\lambda_q^{XI}\,J^{s\,ia}\,\Phi_{qs}\,(\overline{q^{c}_{\mathrm{R}Ii}}\,\sigma^{\mu\nu}\,\ell_{\mathrm{R}X})\,G_{\mu\nu\,a}$$



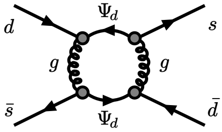
Constraining an example model

- Return to the fermion model $\propto (\overline{q^{\mathrm{c}}_{\mathrm{R}}} \sigma^{\mu\nu} \Psi_q) G_{\mu\nu} + \mathrm{H.c.}$
- Dimension-five $\Psi \to \bar{q} g$ may generate sizable dijet signal
- But what about flavor-changing neutral currents?
  Consider K^0-$\bar{K}^0$ mixing, hence $q = d$:

$$\lambda^{IJ} K_s{}^{ij} \Phi_q^{\dagger s} (\overline{q^{\mathrm{c}}_{\mathrm{R}Ii}} q_{\mathrm{R}Jj})$$

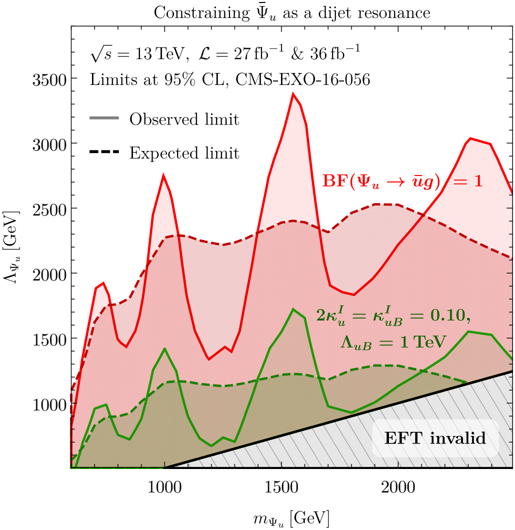


$$\frac{1}{\Lambda_{\Psi_q}} \kappa_q^I J^{s\,ia} (\overline{q^{\mathrm{c}}_{\mathrm{R}Ii}} \sigma^{\mu\nu} \Psi_{qs}) G_{\mu\nu\,a}$$



- Limits as strong as $|\lambda_{11}\lambda_{22}^*| \leq \mathcal{O}(10^{-6}) \times (m_\Phi/\mathrm{TeV})^2$ for dimension-four operators [12, 13], but note Λ suppression in EFT

Can we estimate the cutoff scale?



Outlook

Growing collection of experimental anomalies
+ No smoking gun for any specific framework

Effective descriptions of new physics

- $SU(3)_c$ color sextets have received attention but deserve more
- We have cataloged dimension-five and -six operators consisting of SM fields + color-sextet scalars Φ and/or Dirac fermions Ψ
- Also provided some example phenomenology for Φ and Ψ
- Many obvious extensions: embed in larger models/suggest UV completions? Move on to other color representations?

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Thank you for your attention

I am happy to answer questions if we have time

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Bonus material

SU(3) Clebsch-Gordan coefficients

- Implementing our models requires coefficients $J^{s\,ia}$ forming gauge-invariant contractions of $\mathbf{3} \otimes \mathbf{6} \otimes \mathbf{8}$
- Define coefficients to satisfy [6]

$$\bar{J}_{s\,ai} = [J^{s\,ia}]^\dagger \quad \text{and} \quad \mathrm{tr}\, J_s \bar{J}^{\,t} = \delta_s{}^t$$

and compute according to $[t^a_{\mathbf{6}}]_s{}^t = -\{J^{s\,ib}\,\bar{J}_{t\,cj}\,[t^a_{\mathbf{3}\otimes\mathbf{8}}]_{ib}{}^{jc}\}^*$ with

$$t^a_{\mathbf{r}_1\otimes\mathbf{r}_2} = t^a_{\mathbf{r}_1} \otimes \mathbf{1}_{\mathbf{r}_2} + \mathbf{1}_{\mathbf{r}_1} \otimes t^a_{\mathbf{r}_2}$$

- Fun fact: coefficients of different invariants are related; *e.g.*,

$$J^{s\,ia} = -\mathrm{i}\sqrt{2}\,L^{ijk}[t^a_{\mathbf{3}}]_j{}^l\,\bar{K}^s{}_{lk}$$

with $\{L^{ijk},\, K_s{}^{ij}\}$ the coefficients for $\{\mathbf{3}\otimes\mathbf{3}\otimes\mathbf{3},\, \mathbf{3}\otimes\mathbf{3}\otimes\bar{\mathbf{6}}\}$

CMS-EXO-16-056 SUMMARY

- Search for dijet resonances using $\mathcal{L} = 36\,\mathrm{fb}^{-1}$ [14]
- ≥ 1 vertex reconstructed using anti-k_T with $R = 0.4$
- Two regimes: $m_{jj}^{\mathrm{low}} \in [0.6, 1.6]$ TeV, $m_{jj}^{\mathrm{high}} \in (1.6, 8.0]$ TeV
- Low-mass trigger $H_\mathrm{T} > 250\,\mathrm{GeV}$, high-mass $H_\mathrm{T} > 800$ or $900\,\mathrm{GeV}$
- No excess found over SM expectation (narrow/wide shapes generated by PYTHIA)
- Model-independent limits on $\sigma \times \mathrm{BF} \times \mathcal{A}$ provided for resonances decaying to qq, qg, gg
- $\sim 1\,\mathrm{pb}$ resonance cross sections excluded for $m_{jj} \sim 1\,\mathrm{TeV}$
- Worth examining: newer ATLAS dijet-resonance search, ATLAS-EXOT-2019-03 [15], using full $\mathcal{L} = 139\,\mathrm{fb}^{-1}$ dataset, and CMS-EXO-21-010 (dijet pairs) [9], which might see an excess

Top secret: UV completion for $\Psi \to \bar{q} g$

- Straightforward to UV complete many of our effective operators
- Consider once more the operator $\propto (\overline{q^{\mathrm{c}}_{\mathrm{R}}}\sigma^{\mu\nu}\Psi_q)\,G_{\mu\nu}$
- This operator is generated by two loops of quarks + color-triplet scalar $\tilde{q}$ (a "squark") with the gauge-invariant interactions

$$\mathcal{L} \supset \kappa^{IJ}\, \mathsf{K}_s{}^{ij}\, \tilde{q}_{Ii}\,(\bar{\Psi}^s_q\, q_{\mathrm{R}Jj}) + \lambda^{IJK}\, \mathsf{L}^{ijk}\, \tilde{q}_{Ii}\,(\overline{q^{\mathrm{c}}_{\mathrm{R}Kk}}\, q_{\mathrm{R}Jj}) + \mathrm{H.c.}$$