New Signatures for Color Sextet Scalars- Proposed Searches

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Based on work with L.M. Carpenter and T. Murphy
arXiv: 2209.04456 and 2312.09273

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Introduction & Motivation

There is a wide range of BSM parameter space

Sometimes unwieldy to manage

We use an EFT approach here

$$\mathcal{L}_{\text{int}} \propto \sum_j \frac{c_j}{\Lambda^{n-4}} \mathcal{O}_j$$

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

arXiv: 2110.11359

L.M Carpenter, T. Murphy, T.M.P. Tait

Proposed Operators

Two different color sextet scalar operators

One coupling to charged leptons only, the other to neutrinos or charged leptons

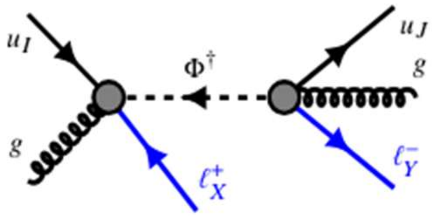
$$\mathcal{L} \supset \frac{1}{\Lambda^2} J^{s\,i\,a}\, \Phi_s\, G_{\mu\nu\,a} \times (\lambda_{\mathrm{L}}^{IX}\, \overline{Q^{\mathrm{c}}_{\mathrm{L}}}_{Ii} \cdot \sigma^{\mu\nu} L_{\mathrm{L}X} + \lambda_{\mathrm{R}}^{IX}\, \overline{u^{\mathrm{c}}_{\mathrm{R}}}_{Ii}\, \sigma^{\mu\nu} \ell_{\mathrm{R}X}) + \mathrm{H.c.}$$

$(SU(3)_c \times SU(2)_L \times U(1)_Y)$: $(6 \times 1 \times 1/3)$

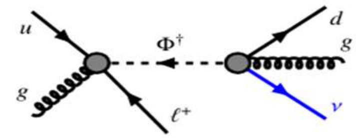
$\lambda = 0$ for $I = 3$, $X = 3$

Signals

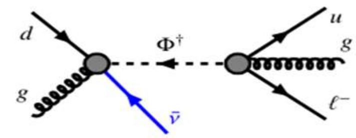
$$\mathcal{L} \supset \frac{1}{\Lambda^2} J^{s\,ia}\,\Phi_s\,G_{\mu\nu\,a} \times (\lambda_L^{IX}\,\overline{Q^c_L}_{Ii}\cdot\sigma^{\mu\nu}L_{LX} + \lambda_R^{IX}\,\overline{u^c_R}_{Ii}\,\sigma^{\mu\nu}\ell_{RX}) + \text{H.c.}$$



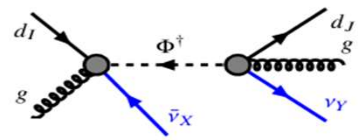
- Single production modes
- Previous studies of sextets have focused on pair production
- Mass resonance + associated lepton/neutrino
- Generated at range of sextet masses between 250-5500 GeV



(a) Diagram for production in association with a lepton followed by decay involving a neutrino.

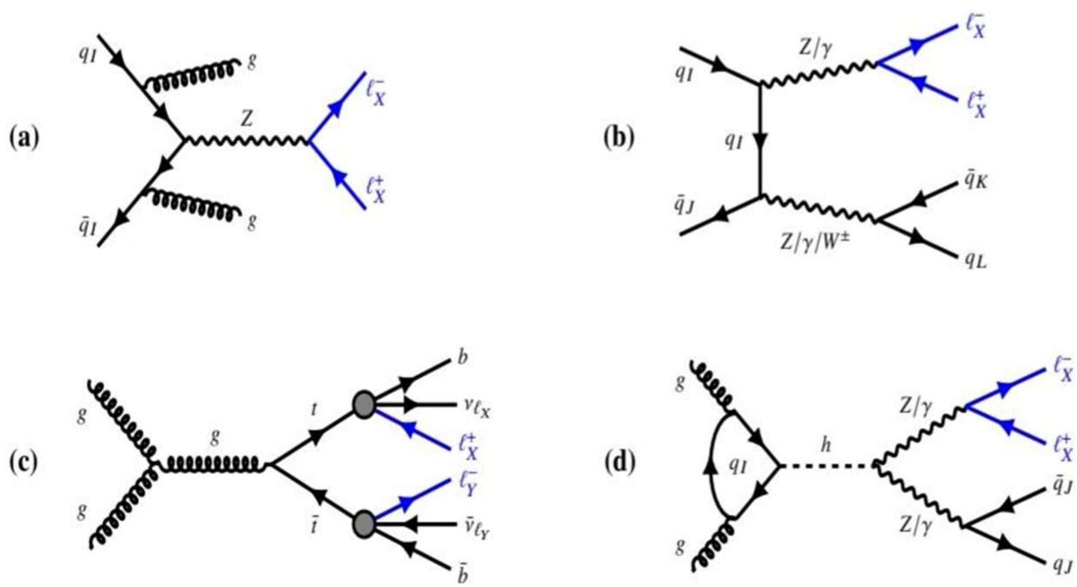


(b) Similar to above for the reverse process with neutrino at the production step.



(c) Diagram for the all-neutrino process.

Backgrounds



Background process
W + jets, $W \to \ell\nu$
Diboson ($WW/WZ/ZZ$)
$t\bar{t}$
$t\bar{t} + Z$
$t\bar{t} + W$
t-channel single top (qt)
tW
tZ ($qt + \nu\bar{\nu}$ incl. non-resonant Z)

Cuts Implemented

Selection criterion	Selection ranges
Jet multiplicity, N_{jet}	$N_{\text{jet}} \geq 2$
Jet kinematics	$p_{\text{T}}(j) > 15\,\text{GeV}$, $\lvert\eta(j)\rvert < 2.5$
	VETO additional jets with $p_{\text{T}} > 500\,\text{GeV}$
Lepton multiplicity	1 opposite-sign (OS) lepton pair
Lepton kinematics	$p_{\text{T}}(\ell_1) > 20\,\text{GeV}$, $p_{\text{T}}(\ell_2) > 15\,\text{GeV}$, $\lvert\eta(\ell)\rvert < 2.5$
	VETO additional leptons with $p_{\text{T}} > 10\,\text{GeV}$
	VETO OSSF lepton pairs with $m_{\ell\ell} \in [81, 101]\,\text{GeV}$
Leading lepton isolation	VETO any jet with $\Delta R(\ell_1, j) < 0.3$
Missing energy, $E_{\text{T}}^{\text{miss}}$	VETO events with $E_{\text{T}}^{\text{miss}} > 25\,\text{GeV}$
Leading jet momentum	$p_{\text{T}}(j_1) > 350\,\text{GeV}$
Leading lepton momentum	$p_{\text{T}}(\ell_1) > 300\,\text{GeV}$

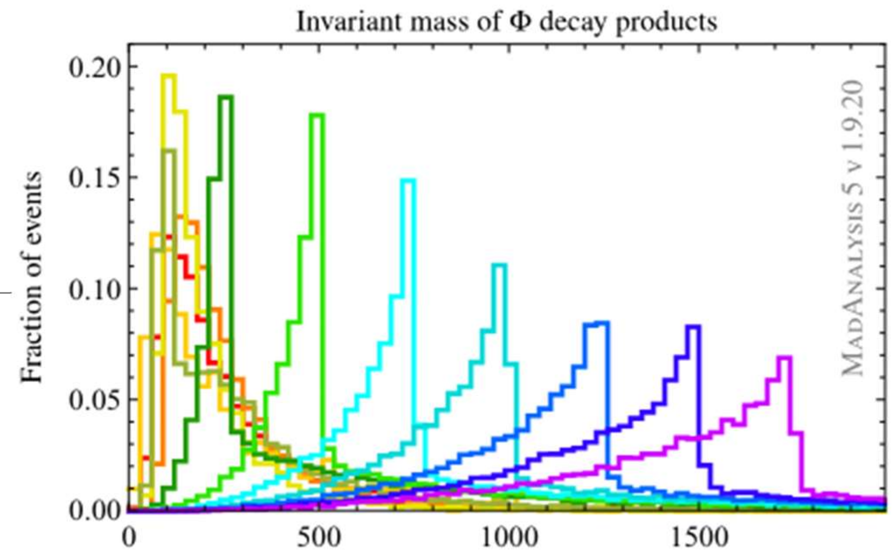
Selection criterion	Selection ranges
Jets, anti-k_t $R = 0.4$	$N_{\text{jet}} \geq 2$
	$p_{\text{T}}(j) > 100\,\text{GeV}$, $\lvert\eta(j)\rvert < 2.5$
Charged leptons	$N_{\ell} = 1$
	$p_{\text{T}}(\ell) > 15\,\text{GeV}$
b-tagged jets	VETO b-jets with $p_{\text{T}} > 15\,\text{GeV}$
Leading jet momenta	$p_{\text{T}}(j_1) > 250\,\text{GeV}$
	$p_{\text{T}}(j_2) > 200\,\text{GeV}$
Lepton momentum	$p_{\text{T}}(\ell) > 250\,\text{GeV}$
Missing energy, $E_{\text{T}}^{\text{miss}}$	Require $E_{\text{T}}^{\text{miss}} > 300\,\text{GeV}$
Jet-$E_{\text{T}}^{\text{miss}}$ separation	$\Delta\phi(j_1, \vec{p}_{\text{T}}^{\text{miss}}) \notin [2\pi/3, 4\pi/3]$

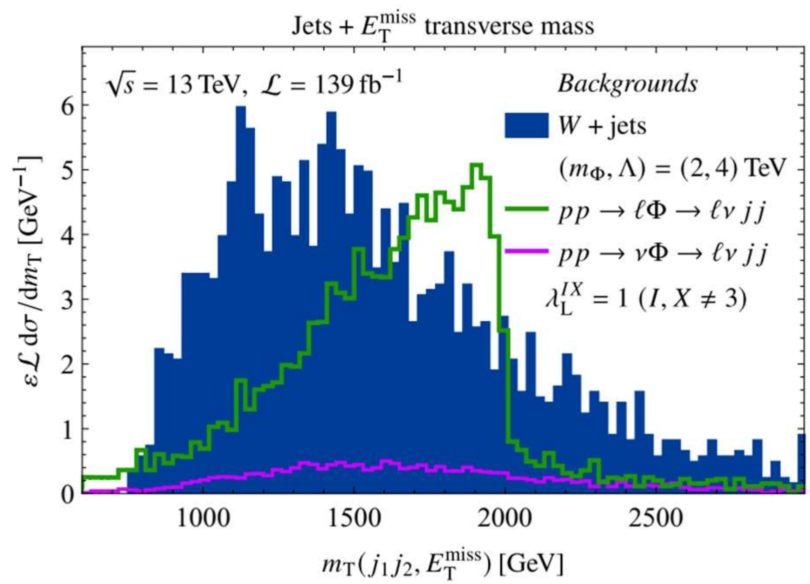
Binned Analysis

Invariant mass/transverse mass cuts

$$Z_A = \left\{2\left[(s+b)\ln\left(1+\frac{s}{b}\right)-s\right]\right\}^{1/2}$$

$$\mathcal{L}(m \mid \mu, b) = \prod_{i=1}^{N_{\text{bin}}} \frac{(\mu s_i + b_i)^{m_i}}{m_i!} e^{-(\mu s_i + b_i)} \times \frac{1}{\sqrt{2\pi}\,\sigma_{b,i}} \exp\left\{-\frac{1}{2}\frac{(b_i - \langle b_i\rangle)^2}{\sigma_{b,i}^2}\right\}$$





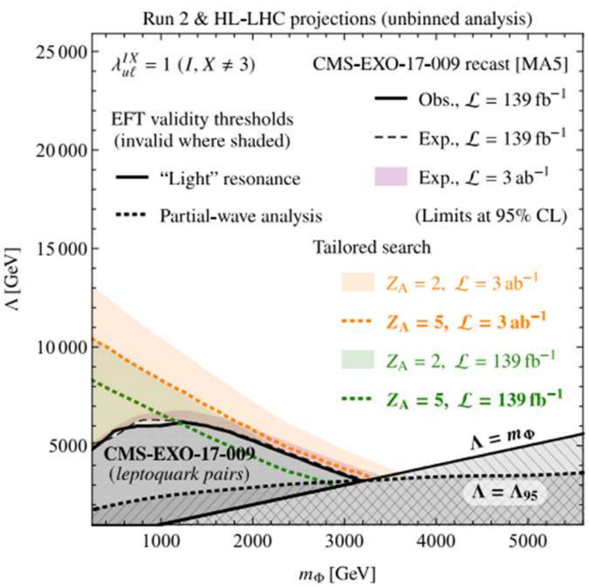
Binned Selections

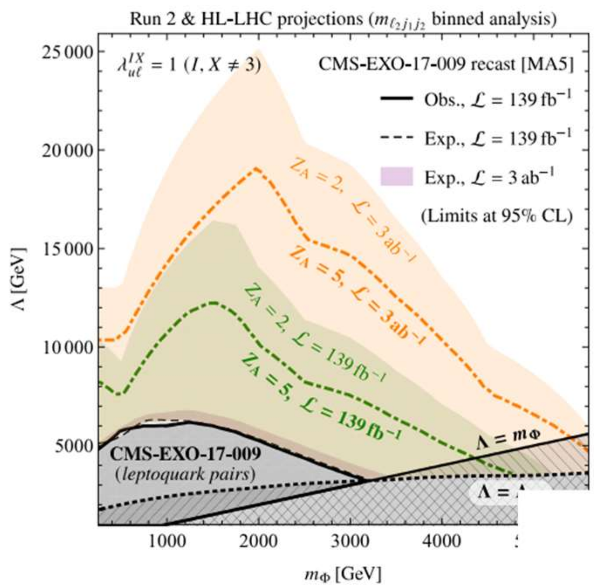
Light signals, $\sqrt{s}$ = 13 TeV, labeled by m_Φ [GeV]

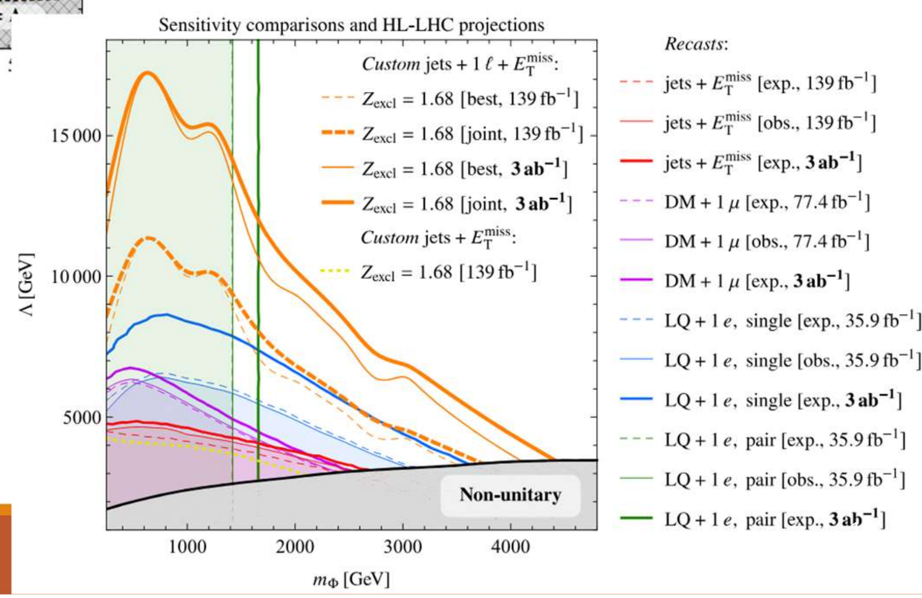
Selection criterion	250	500	750	1000	1250	1500	1750
$N_{\text{jet}} \geq 2$	0.8914	0.9343	0.9501	0.9591	0.9646	0.9373	0.9763
1 OS lepton pair	0.7718	0.8336	0.8558	0.8680	0.8735	0.8780	0.8824
No OSSF pairs from Z	0.7661	0.8303	0.8538	0.8661	0.8720	0.8767	0.8813
$E_{\text{T}}^{\text{miss}} \leq 25$ GeV	0.7349	0.7877	0.7963	0.7986	0.8000	0.7946	0.7932
$p_{\text{T}}(j_1) > 350$ GeV	0.2525	0.3467	0.4568	0.5539	0.6327	0.6795	0.7145
$p_{\text{T}}(\ell_1) > 300$ GeV	0.2392	0.3301	0.4269	0.5124	0.5945	0.6486	0.6907
Best $m_{\ell_2 j_1 j_2}$ [GeV]	200	450	650	900	1200	1400	1700
Final $m_{\ell_2 j_1 j_2}$ cut	0.2331	0.2745	0.3414	0.3486	0.3953	0.3095	0.2075

Process	Lower bound on $m_{\text{T}}(j_1 j_2, E_{\text{T}}^{\text{miss}})$ [TeV] (recall that m_{T} bins are non-overlapping)																		
	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00	3.25	3.50	3.75	4.00	4.25	4.50	4.75
W + jets, $W \to \ell\nu$	58.0	58.0	173.9	116.1	347.8	637.6	289.8	173.9	347.8	347.8	58.0	58.0	58.0	58.0	58.0	58.0	58.0	58.0	58.0
Diboson (1ℓ)	0.77	0.77	0.77	0.77	0.77	0.77	1.54	0.77	0.77	0.77	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38
$pp \to \ell\Phi \to \ell\nu\, jj$	10.6	35.1	101.8	234.5	461.7	684.1	803.4	96.6	47.8	29.0	22.1	17.0	11.1	3.38	3.88	1.46	1.43	0.48	0.99
$pp \to \nu\Phi \to \ell\nu\, jj$	3.04	4.77	17.0	49.9	75.5	75.3	64.4	39.0	25.3	17.1	8.76	5.25	3.08	1.48	1.34	0.80	0.14	0.41	<0.1

LHC Projections







Conclusion

- Identified two new sextet operators with unusual phenomenological signatures
- Examined observable distributions to choose appropriate cuts against the backgrounds
- New proposed search would outperform previously implemented searches at ATLAS and CMS

- Questions?

Clebsh Gordon

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

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