Multi-Boson Events in the Light Exotics Effective Field Theory

Linda Carpenter
Ohio State University

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General Methods for Model Agnostic Collider Phenomenology

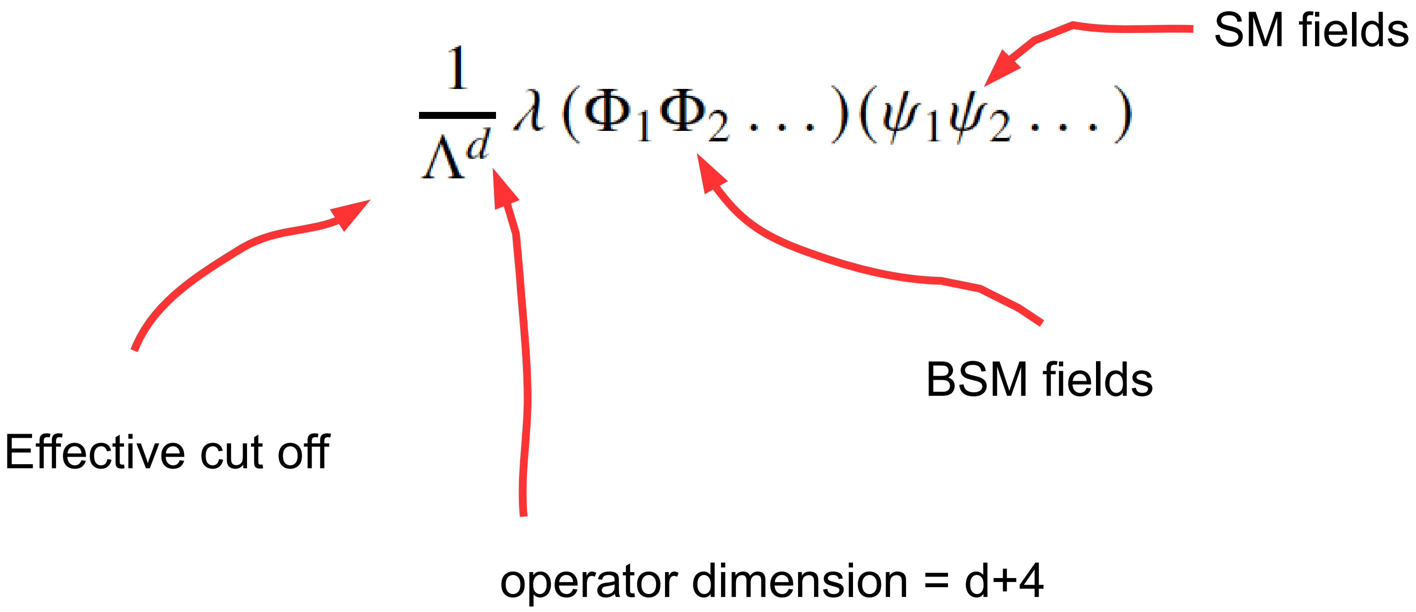
Some Examples

- 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



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

SM fields

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

$$\frac{1}{\Lambda^d}\lambda\,(\underset{\mathbf{r}_1}{\Phi_1}\underset{\mathbf{r}_2}{\Phi_2}\ldots)(\psi_1\psi_2\ldots)$$

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

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

$$\mathbf{3} \otimes \mathbf{3} = \mathbf{\bar{3}}_a \oplus \mathbf{6}_s,$$

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

$$\mathbf{6} \otimes \mathbf{3} = \mathbf{8} \oplus \mathbf{10},$$

$$\mathbf{6} \otimes \mathbf{\bar{3}} = \mathbf{3} \oplus \mathbf{15},$$

$$\mathbf{6} \otimes \mathbf{6} = \mathbf{\bar{6}}_s \oplus \mathbf{15}_a \oplus \mathbf{15}'_s,$$

$$\mathbf{6} \otimes \mathbf{\bar{6}} = \mathbf{1} \oplus \mathbf{8} \oplus \mathbf{27},$$

$$\mathbf{8} \otimes \mathbf{3} = \mathbf{3} \oplus \mathbf{\bar{6}} \oplus \mathbf{15},$$

$$\mathbf{8} \otimes \mathbf{\bar{6}} = \mathbf{3} \oplus \mathbf{\bar{6}} \oplus \mathbf{15} \oplus \mathbf{24},$$

$$\mathbf{8} \otimes \mathbf{8} = \mathbf{1}_s \oplus \mathbf{8}_s \oplus \mathbf{8}_a \oplus \mathbf{10}_a \oplus \mathbf{\overline{10}}_a \oplus \mathbf{27}_s$$

By iterating tensor products
We construct new invariant

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

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

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

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

LEX sextet quark gluon

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

there may be multiple coefficients for a given set of fields

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)

Lower Dim Reps of SU(2)

Dim 5

$(\mathbf{1},\mathbf{1},0)$	$\phi\, B^{\mu\nu} B_{\mu\nu}$
	$\phi\, W^{\mu\nu,a} W^a_{\mu\nu}$
	$\phi\, G^{\mu\nu} G_{\mu\nu}$
	$\phi\,(D^\mu H)^{\dagger i}(D_\mu H)_i$

Dim 7

$\lvert H\rvert^2 \phi\, B^{\mu\nu} B_{\mu\nu}$
$\lvert H\rvert^2 \phi\, W^{\mu\nu,a} W^a_{\mu\nu}$
$\lvert H\rvert^2 \phi\, G^{\mu\nu} G_{\mu\nu}$
$(H^\dagger \sigma^a H)\, \phi\, W^{\mu\nu,a} B_{\mu\nu}$

Dim 6

$(\mathbf{1},\mathbf{2},-\frac{1}{2})$	$H^i (\sigma^a)_i{}^j \phi_j\, W^{\mu\nu,a} B_{\mu\nu}$
	$[H^i \phi_i]\, B^{\mu\nu} B_{\mu\nu}$
	$[H^i \phi_i]\, W^{\mu\nu,a} W^a_{\mu\nu}$
	$[H^i \phi_i]\, G^{\mu\nu} G_{\mu\nu}$
	$[H^i \phi_i]\, D^\mu H_j D_\mu H^{\dagger j}$

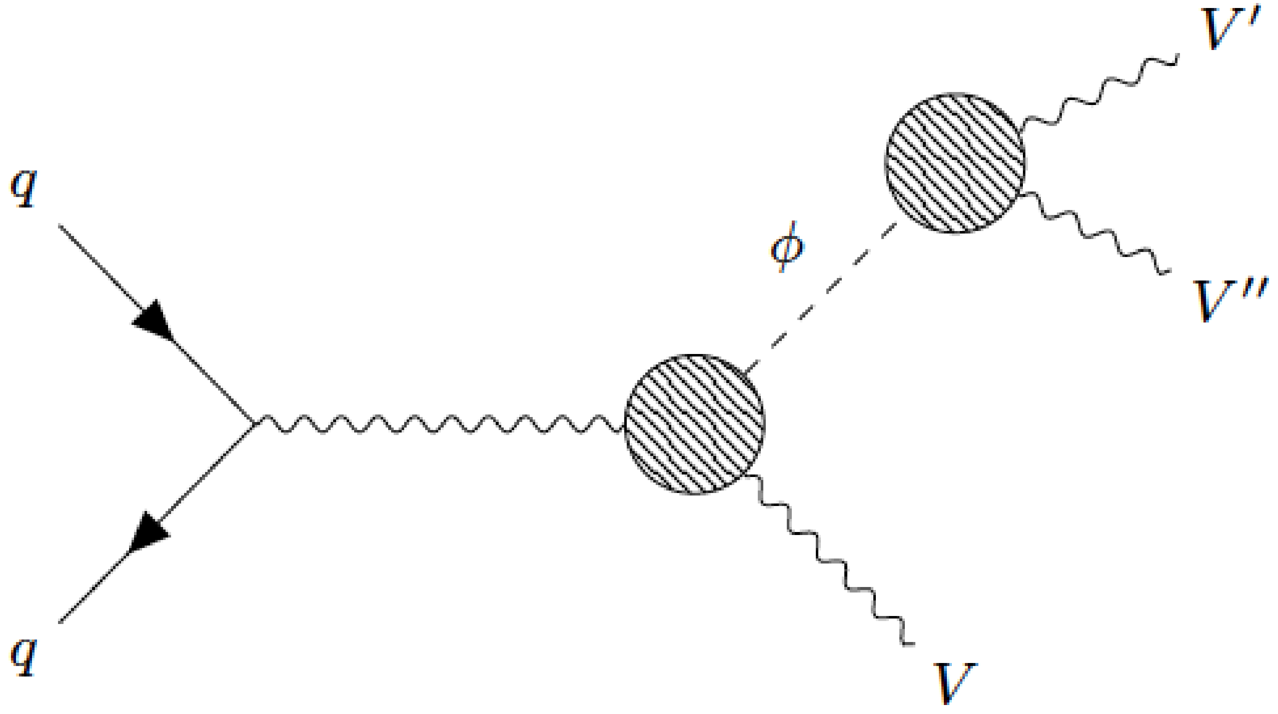
Dim 5

$(\mathbf{1},\mathbf{3},0)$	$\phi^a\, W^{\mu\nu,a} B_{\mu\nu}$
	$\phi_{ij}\,(D^\mu H)^{\dagger i}(D_\mu H)^j$

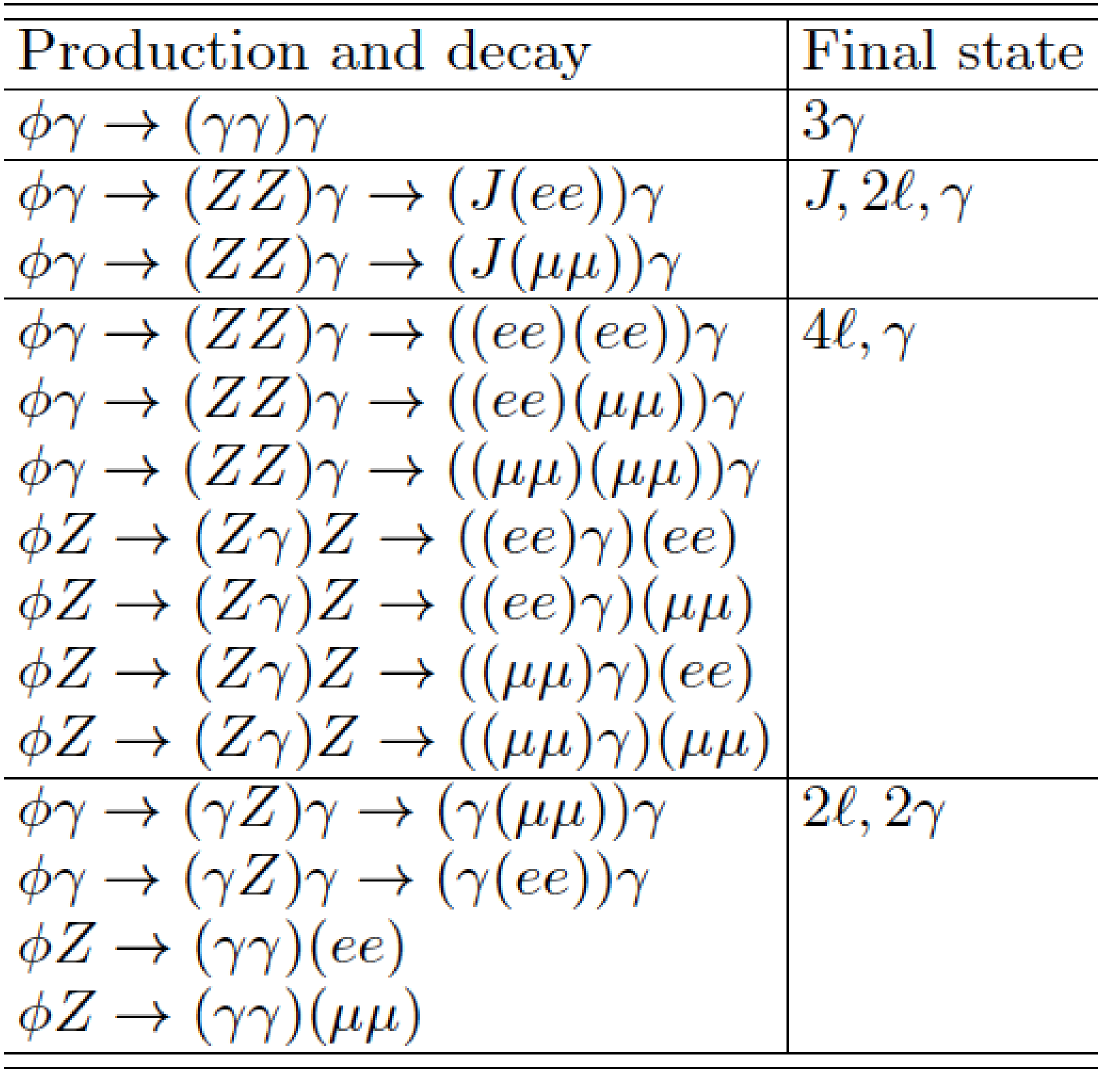
Dim 7

$[H^{\dagger i} \phi^a (\sigma^a)_i{}^j H_j]\, B^{\mu\nu} B_{\mu\nu}$
$[H^{\dagger i} \phi^a (\sigma^a)_i{}^j H_j]\, G^{\mu\nu} G_{\mu\nu}$
$\phi^a\, [H^{\dagger i} (\sigma^a)_i{}^j H_j]\, W^{\mu\nu,b} W^b_{\mu\nu}$
$\phi^a\, [H^{\dagger i} (\sigma^b)_i{}^j H_j]\, W^{\mu\nu,a} W^b_{\mu\nu}$
$\lvert H\rvert^2 \phi^a\, W^{\mu\nu,a} B_{\mu\nu}$
$\varepsilon^{abc}\, \phi^a [H^{\dagger i} (\sigma^b)_i{}^j H_j]\, W^{\mu\nu,c} B_{\mu\nu}$

Associated Production and Decay with EW Gauge Bosons gives Tri-Boson Events

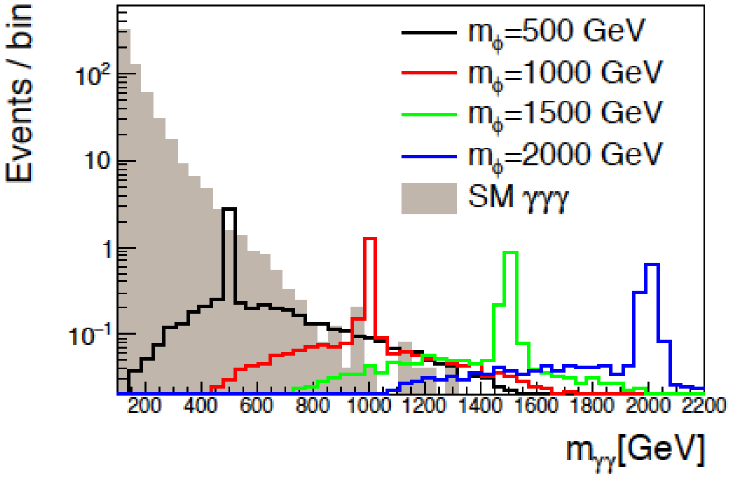


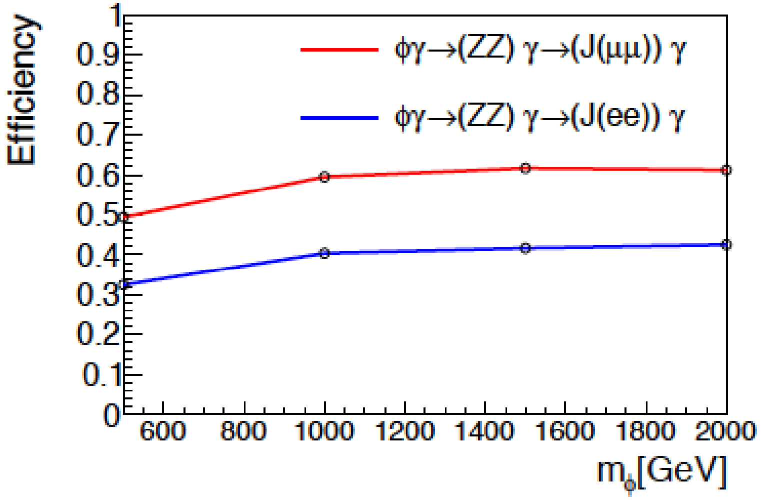
Even limiting to g,Z boson gives many interesting final states

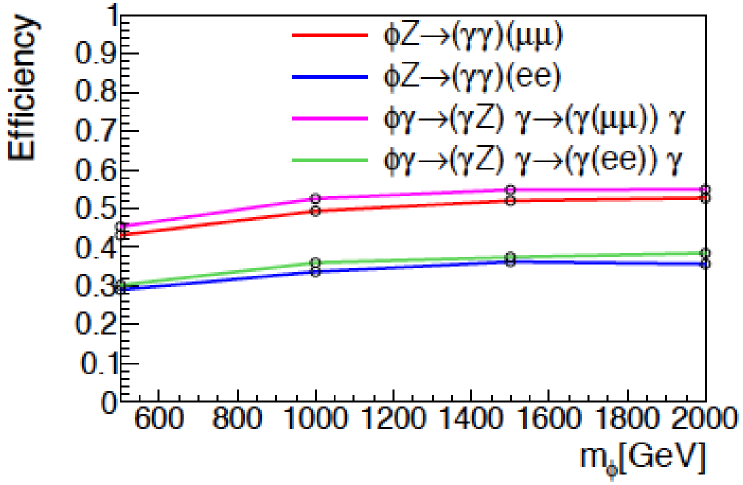


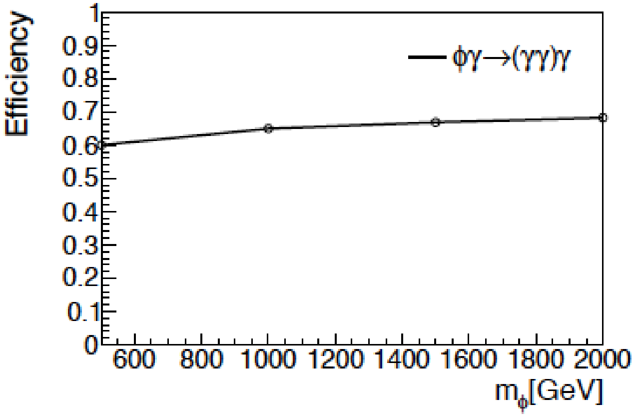
Production and decay	Final state
$\phi\gamma \to (\gamma\gamma)\gamma$	3γ
$\phi\gamma \to (ZZ)\gamma \to (J(ee))\gamma$	$J, 2\ell, \gamma$
$\phi\gamma \to (ZZ)\gamma \to (J(\mu\mu))\gamma$	
$\phi\gamma \to (ZZ)\gamma \to ((ee)(ee))\gamma$	$4\ell, \gamma$
$\phi\gamma \to (ZZ)\gamma \to ((ee)(\mu\mu))\gamma$	
$\phi\gamma \to (ZZ)\gamma \to ((\mu\mu)(\mu\mu))\gamma$	
$\phi Z \to (Z\gamma)Z \to ((ee)\gamma)(ee)$	
$\phi Z \to (Z\gamma)Z \to ((ee)\gamma)(\mu\mu)$	
$\phi Z \to (Z\gamma)Z \to ((\mu\mu)\gamma)(ee)$	
$\phi Z \to (Z\gamma)Z \to ((\mu\mu)\gamma)(\mu\mu)$	
$\phi\gamma \to (\gamma Z)\gamma \to (\gamma(\mu\mu))\gamma$	$2\ell, 2\gamma$
$\phi\gamma \to (\gamma Z)\gamma \to (\gamma(ee))\gamma$	
$\phi Z \to (\gamma\gamma)(ee)$	
$\phi Z \to (\gamma\gamma)(\mu\mu)$	

Above are the most promising signals with fat jets, leptons and or hard photons

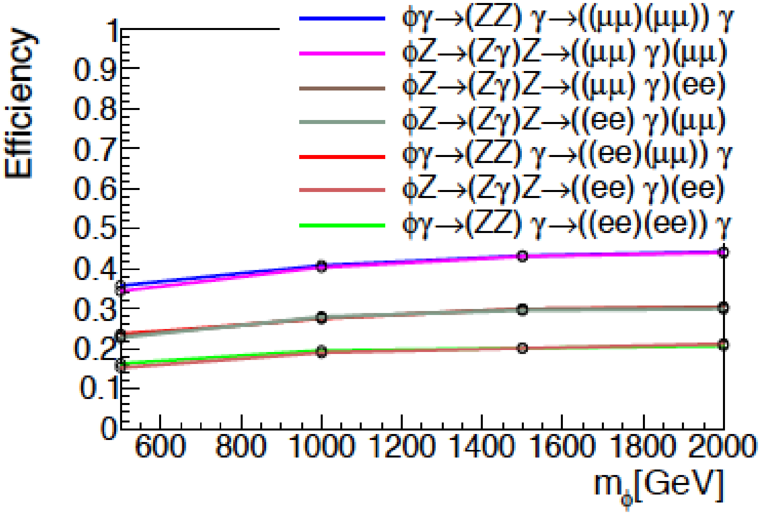

Events / bin
10^2
10
1
10^{-1}
m_ϕ=500 GeV
m_ϕ=1000 GeV
m_ϕ=1500 GeV
m_ϕ=2000 GeV
SM γγγ
200 400 600 800 1000 1200 1400 1600 1800 2000 2200
$m_{\gamma\gamma}$[GeV]

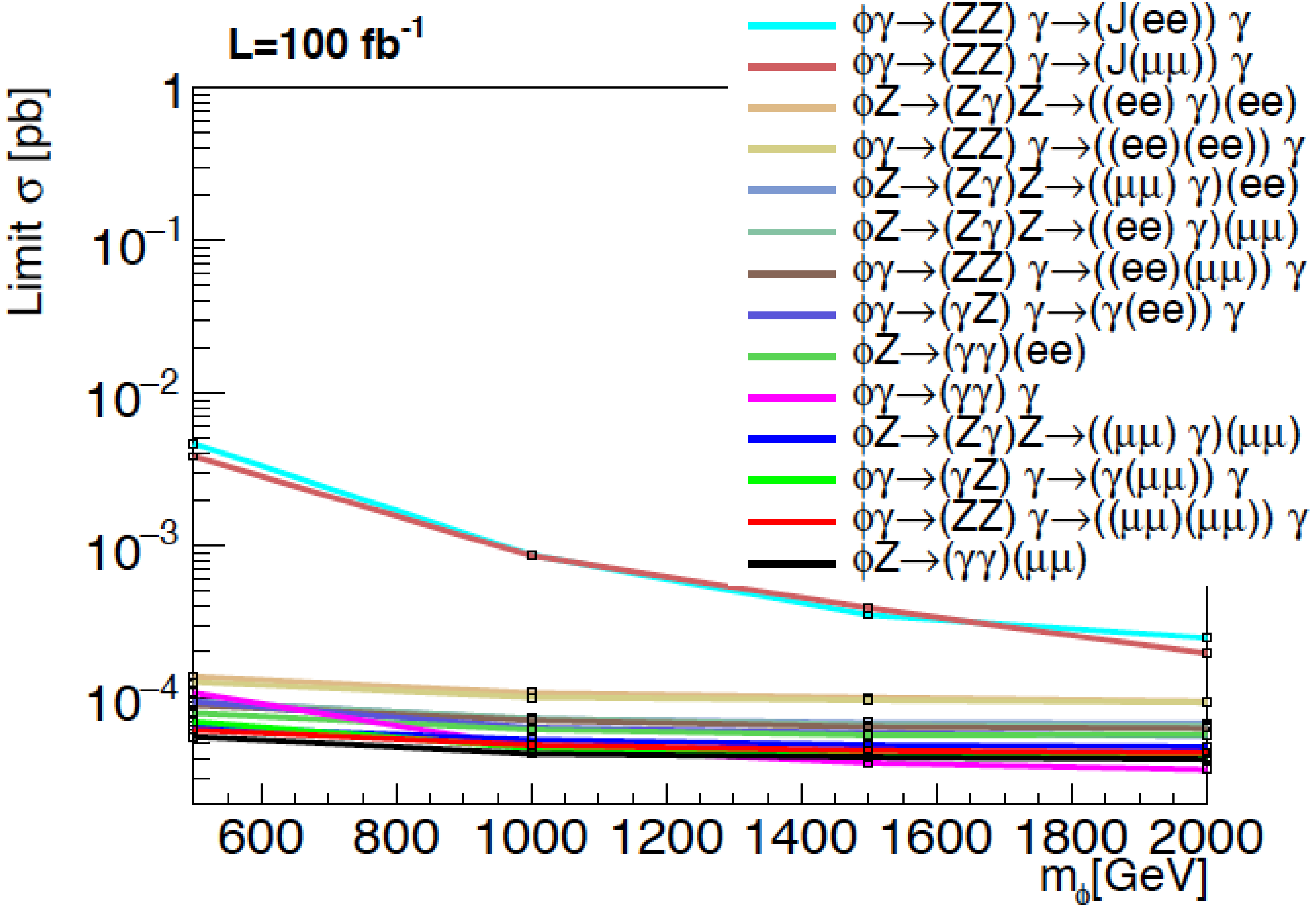

Efficiency
$\phi\gamma\to(ZZ)\,\gamma\to(J(\mu\mu))\,\gamma$
$\phi\gamma\to(ZZ)\,\gamma\to(J(ee))\,\gamma$
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
600 800 1000 1200 1400 1600 1800 2000
m_ϕ[GeV]

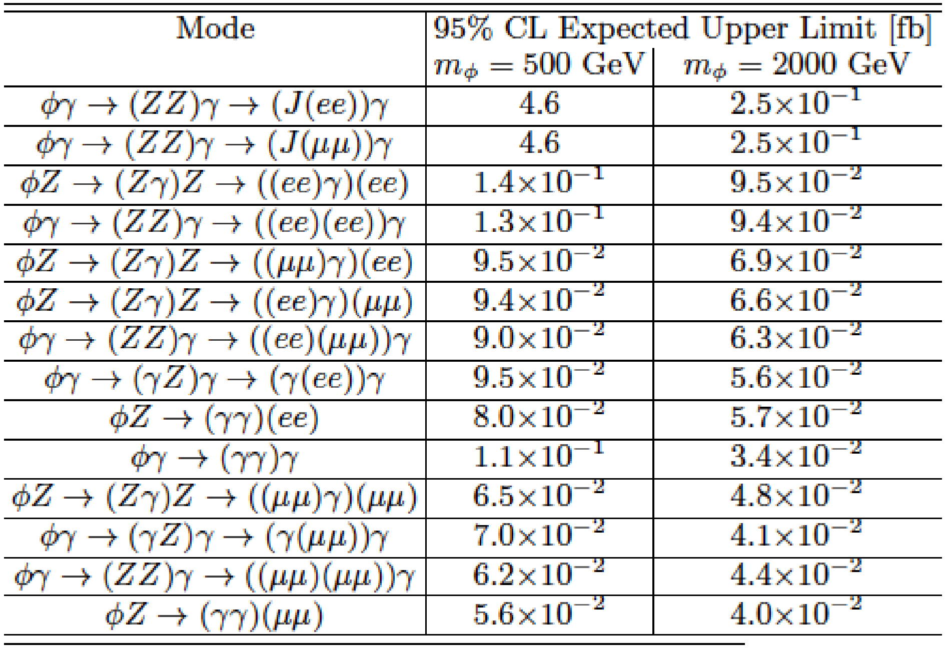

Efficiency
$\phi Z\to(\gamma\gamma)(\mu\mu)$
$\phi Z\to(\gamma\gamma)(ee)$
$\phi\gamma\to(\gamma Z)\,\gamma\to(\gamma(\mu\mu))\,\gamma$
$\phi\gamma\to(\gamma Z)\,\gamma\to(\gamma(ee))\,\gamma$
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
600 800 1000 1200 1400 1600 1800 2000
m_ϕ[GeV]


Efficiency
$\phi\gamma\to(\gamma\gamma)\gamma$
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
600 800 1000 1200 1400 1600 1800 2000
m_ϕ[GeV]

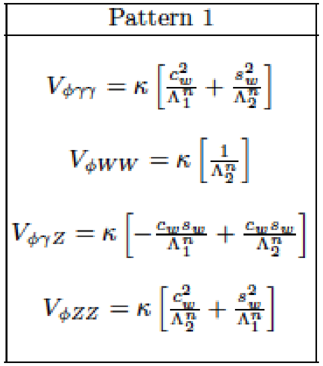
Events / bin


Efficiency
$\phi\gamma\to(ZZ)\,\gamma\to((\mu\mu)(\mu\mu))\,\gamma$
$\phi Z\to(Z\gamma)Z\to((\mu\mu)\,\gamma)(\mu\mu)$
$\phi Z\to(Z\gamma)Z\to((\mu\mu)\,\gamma)(ee)$
$\phi Z\to(Z\gamma)Z\to((ee)\,\gamma)(\mu\mu)$
$\phi\gamma\to(ZZ)\,\gamma\to((ee)(\mu\mu))\,\gamma$
$\phi Z\to(Z\gamma)Z\to((ee)\,\gamma)(ee)$
$\phi\gamma\to(ZZ)\,\gamma\to((ee)(ee))\,\gamma$
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
600 800 1000 1200 1400 1600 1800 2000
m_ϕ[GeV]

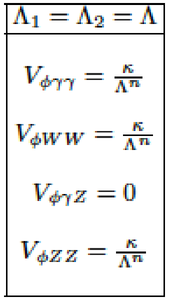

L=100 fb^{-1}
Limit σ [pb]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
600
800
1000
1200
1400
1600
1800
2000
m_ϕ[GeV]
$\phi\gamma \rightarrow (ZZ)\ \gamma \rightarrow (J(ee))\ \gamma$
$\phi\gamma \rightarrow (ZZ)\ \gamma \rightarrow (J(\mu\mu))\ \gamma$
$\phi Z \rightarrow (Z\gamma)Z \rightarrow ((ee)\ \gamma)(ee)$
$\phi\gamma \rightarrow (ZZ)\ \gamma \rightarrow ((ee)(ee))\ \gamma$
$\phi Z \rightarrow (Z\gamma)Z \rightarrow ((\mu\mu)\ \gamma)(ee)$
$\phi Z \rightarrow (Z\gamma)Z \rightarrow ((ee)\ \gamma)(\mu\mu)$
$\phi\gamma \rightarrow (ZZ)\ \gamma \rightarrow ((ee)(\mu\mu))\ \gamma$
$\phi\gamma \rightarrow (\gamma Z)\ \gamma \rightarrow (\gamma(ee))\ \gamma$
$\phi Z \rightarrow (\gamma\gamma)(ee)$
$\phi\gamma \rightarrow (\gamma\gamma)\ \gamma$
$\phi Z \rightarrow (Z\gamma)Z \rightarrow ((\mu\mu)\ \gamma)(\mu\mu)$
$\phi\gamma \rightarrow (\gamma Z)\ \gamma \rightarrow (\gamma(\mu\mu))\ \gamma$
$\phi\gamma \rightarrow (ZZ)\ \gamma \rightarrow ((\mu\mu)(\mu\mu))\ \gamma$
$\phi Z \rightarrow (\gamma\gamma)(\mu\mu)$



Mode	95% CL Expected Upper Limit [fb]	
	$m_\phi = 500$ GeV	$m_\phi = 2000$ GeV
$\phi\gamma \to (ZZ)\gamma \to (J(ee))\gamma$	4.6	$2.5{\times}10^{-1}$
$\phi\gamma \to (ZZ)\gamma \to (J(\mu\mu))\gamma$	4.6	$2.5{\times}10^{-1}$
$\phi Z \to (Z\gamma)Z \to ((ee)\gamma)(ee)$	$1.4{\times}10^{-1}$	$9.5{\times}10^{-2}$
$\phi\gamma \to (ZZ)\gamma \to ((ee)(ee))\gamma$	$1.3{\times}10^{-1}$	$9.4{\times}10^{-2}$
$\phi Z \to (Z\gamma)Z \to ((\mu\mu)\gamma)(ee)$	$9.5{\times}10^{-2}$	$6.9{\times}10^{-2}$
$\phi Z \to (Z\gamma)Z \to ((ee)\gamma)(\mu\mu)$	$9.4{\times}10^{-2}$	$6.6{\times}10^{-2}$
$\phi\gamma \to (ZZ)\gamma \to ((ee)(\mu\mu))\gamma$	$9.0{\times}10^{-2}$	$6.3{\times}10^{-2}$
$\phi\gamma \to (\gamma Z)\gamma \to (\gamma(ee))\gamma$	$9.5{\times}10^{-2}$	$5.6{\times}10^{-2}$
$\phi Z \to (\gamma\gamma)(ee)$	$8.0{\times}10^{-2}$	$5.7{\times}10^{-2}$
$\phi\gamma \to (\gamma\gamma)\gamma$	$1.1{\times}10^{-1}$	$3.4{\times}10^{-2}$
$\phi Z \to (Z\gamma)Z \to ((\mu\mu)\gamma)(\mu\mu)$	$6.5{\times}10^{-2}$	$4.8{\times}10^{-2}$
$\phi\gamma \to (\gamma Z)\gamma \to (\gamma(\mu\mu))\gamma$	$7.0{\times}10^{-2}$	$4.1{\times}10^{-2}$
$\phi\gamma \to (ZZ)\gamma \to ((\mu\mu)(\mu\mu))\gamma$	$6.2{\times}10^{-2}$	$4.4{\times}10^{-2}$
$\phi Z \to (\gamma\gamma)(\mu\mu)$	$5.6{\times}10^{-2}$	$4.0{\times}10^{-2}$

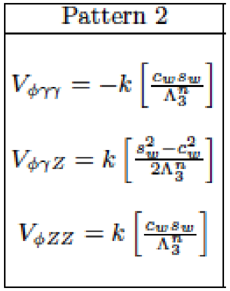


Pattern 1
$V_{\phi\gamma\gamma} = \kappa\left[\frac{c_w^2}{\Lambda_1^n} + \frac{s_w^2}{\Lambda_2^n}\right]$
$V_{\phi WW} = \kappa\left[\frac{1}{\Lambda_2^n}\right]$
$V_{\phi\gamma Z} = \kappa\left[-\frac{c_w s_w}{\Lambda_1^n} + \frac{c_w s_w}{\Lambda_2^n}\right]$
$V_{\phi ZZ} = \kappa\left[\frac{c_w^2}{\Lambda_2^n} + \frac{s_w^2}{\Lambda_1^n}\right]$



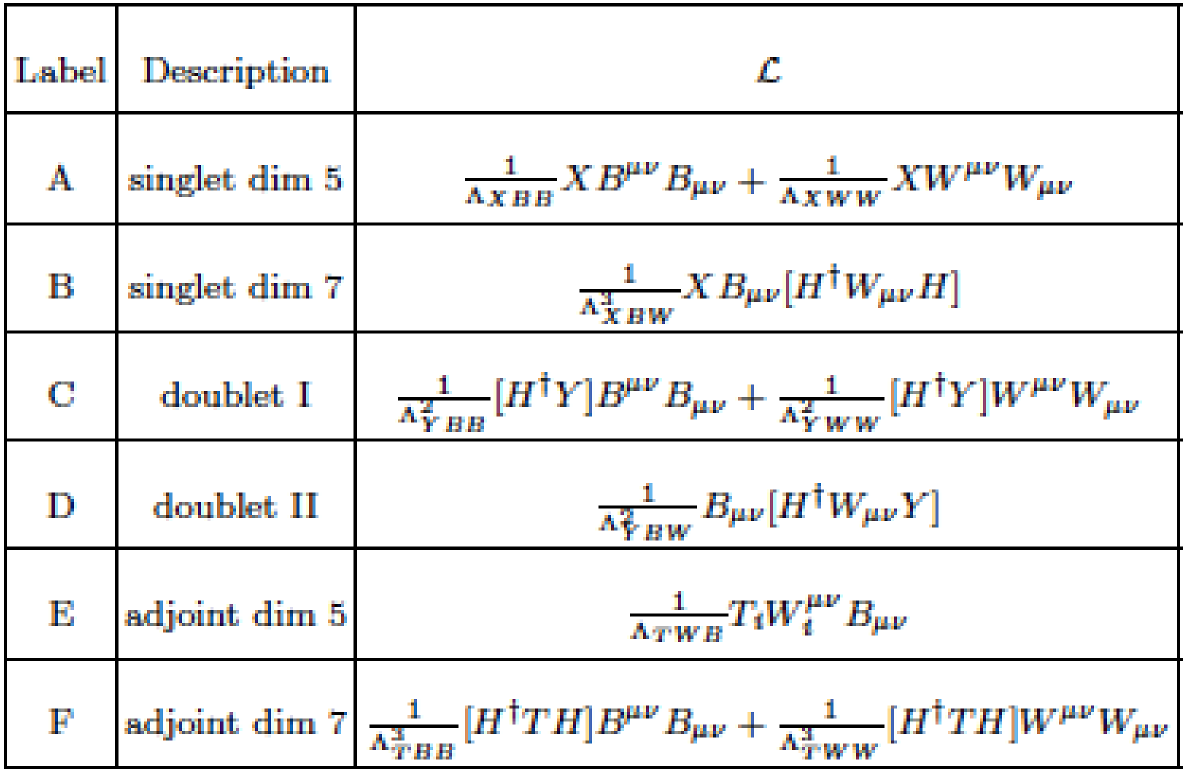
$\Lambda_1 = \Lambda_2 = \Lambda$
$V_{\phi\gamma\gamma} = \frac{\kappa}{\Lambda^n}$
$V_{\phi WW} = \frac{\kappa}{\Lambda^n}$
$V_{\phi\gamma Z} = 0$
$V_{\phi ZZ} = \frac{\kappa}{\Lambda^n}$

Models A,C,F



Pattern 2
$V_{\phi\gamma\gamma} = -k\left[\frac{c_w s_w}{\Lambda_3^n}\right]$
$V_{\phi\gamma Z} = k\left[\frac{s_w^2 - c_w^2}{2\Lambda_3^n}\right]$
$V_{\phi ZZ} = k\left[\frac{c_w s_w}{\Lambda_3^n}\right]$

Models B,D,E



Label	Description	$\mathcal{L}$
A	singlet dim 5	$\frac{1}{\Lambda_{XBB}} X B^{\mu\nu} B_{\mu\nu} + \frac{1}{\Lambda_{XWW}} X W^{\mu\nu} W_{\mu\nu}$
B	singlet dim 7	$\frac{1}{\Lambda_{XBW}^3} X B_{\mu\nu} [H^\dagger W_{\mu\nu} H]$
C	doublet I	$\frac{1}{\Lambda_{YBB}^2} [H^\dagger Y] B^{\mu\nu} B_{\mu\nu} + \frac{1}{\Lambda_{YWW}^2} [H^\dagger Y] W^{\mu\nu} W_{\mu\nu}$
D	doublet II	$\frac{1}{\Lambda_{YBW}^2} B_{\mu\nu} [H^\dagger W_{\mu\nu} Y]$
E	adjoint dim 5	$\frac{1}{\Lambda_{TWB}} T_i W_i^{\mu\nu} B_{\mu\nu}$
F	adjoint dim 7	$\frac{1}{\Lambda_{TBB}^3} [H^\dagger T H] B^{\mu\nu} B_{\mu\nu} + \frac{1}{\Lambda_{TWW}^3} [H^\dagger T H] W^{\mu\nu} W_{\mu\nu}$

Lower Dim Reps of SU(2)

Dim 5

$(\mathbf{1},\mathbf{1},0)$	$\phi\, B^{\mu\nu}B_{\mu\nu}$
	$\phi\, W^{\mu\nu,a}W^a_{\mu\nu}$
	$\phi\, G^{\mu\nu}G_{\mu\nu}$
	$\phi\,(D^\mu H)^{\dagger i}(D_\mu H)_i$

Dim 7

$\lvert H\rvert^2\phi\, B^{\mu\nu}B_{\mu\nu}$
$\lvert H\rvert^2\phi\, W^{\mu\nu,a}W^a_{\mu\nu}$
$\lvert H\rvert^2\phi\, G^{\mu\nu}G_{\mu\nu}$
$(H^\dagger\sigma^a H)\,\phi\, W^{\mu\nu,a}B_{\mu\nu}$

Dim 6

$(\mathbf{1},\mathbf{2},-\frac{1}{2})$	$H^i(\sigma^a)_i{}^j\phi_j\, W^{\mu\nu,a}B_{\mu\nu}$
	$[H^i\phi_i]\, B^{\mu\nu}B_{\mu\nu}$
	$[H^i\phi_i]\, W^{\mu\nu,a}W^a_{\mu\nu}$
	$[H^i\phi_i]\, G^{\mu\nu}G_{\mu\nu}$
	$[H^i\phi_i]\, D^\mu H_j D_\mu H^{\dagger j}$

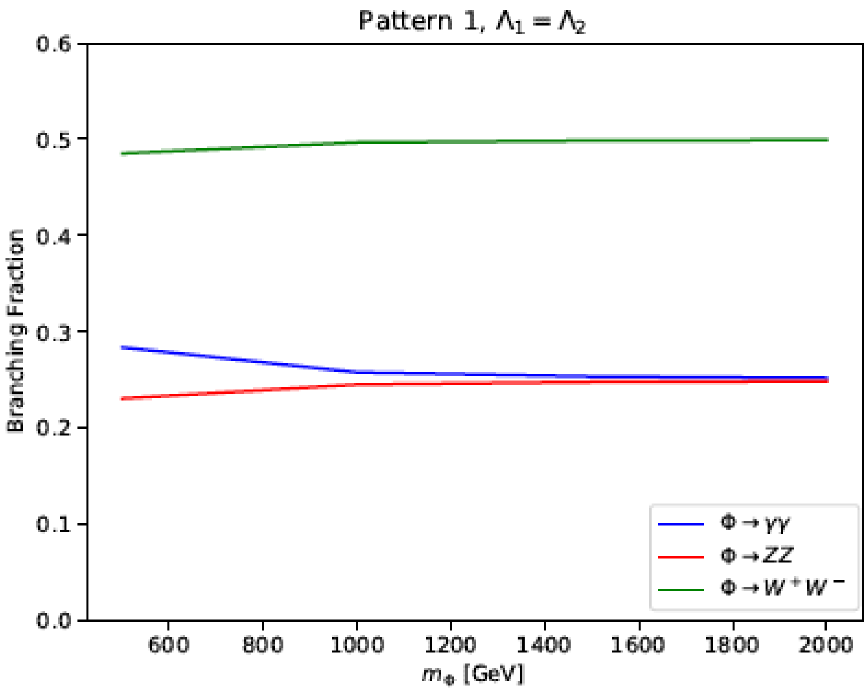
Dim 5

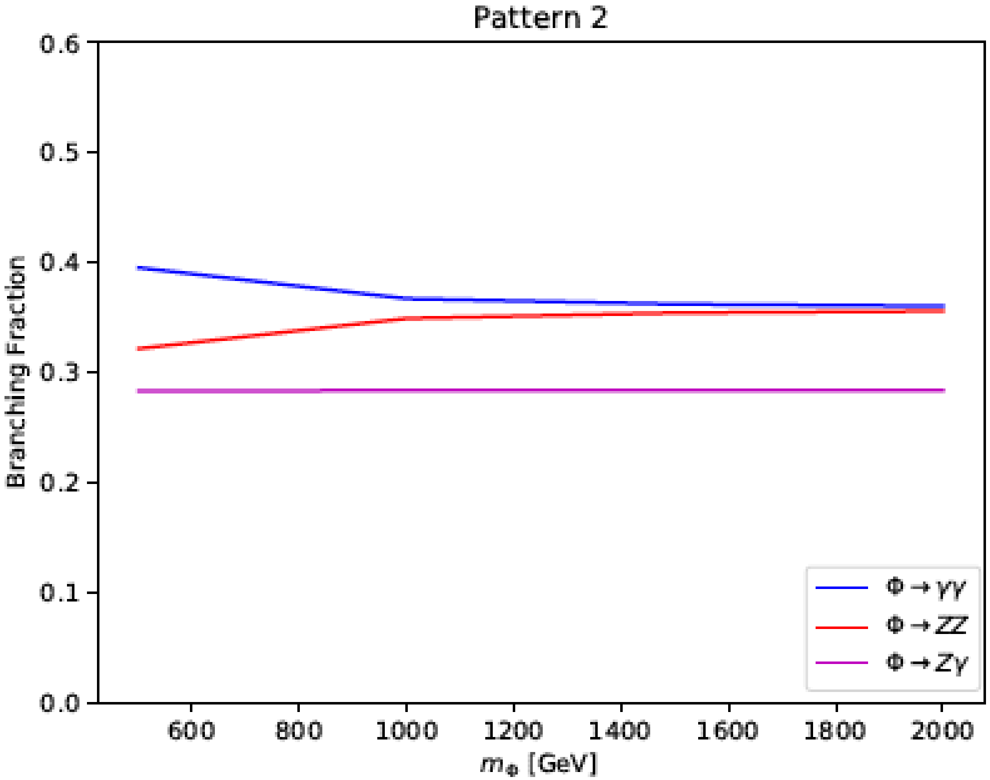
$(\mathbf{1},\mathbf{3},0)$	$\phi^a\, W^{\mu\nu,a}B_{\mu\nu}$
	$\phi_{ij}\,(D^\mu H)^{\dagger i}(D_\mu H)^j$

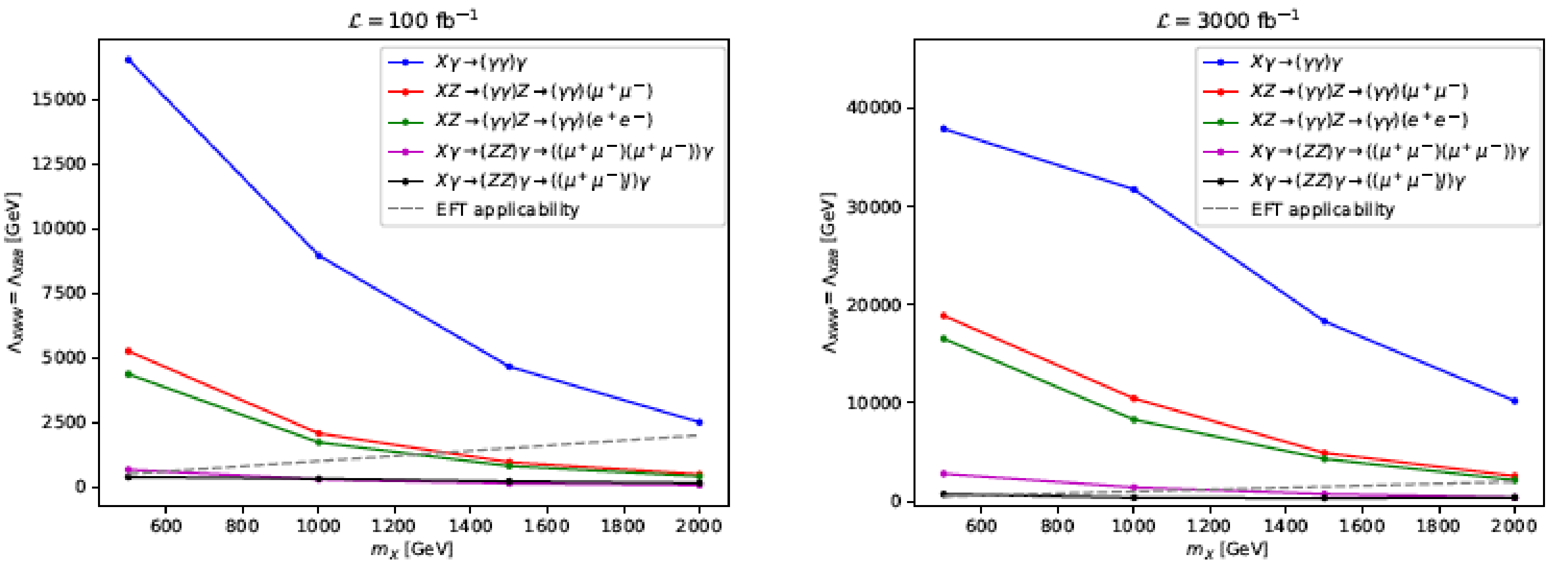
Dim 7

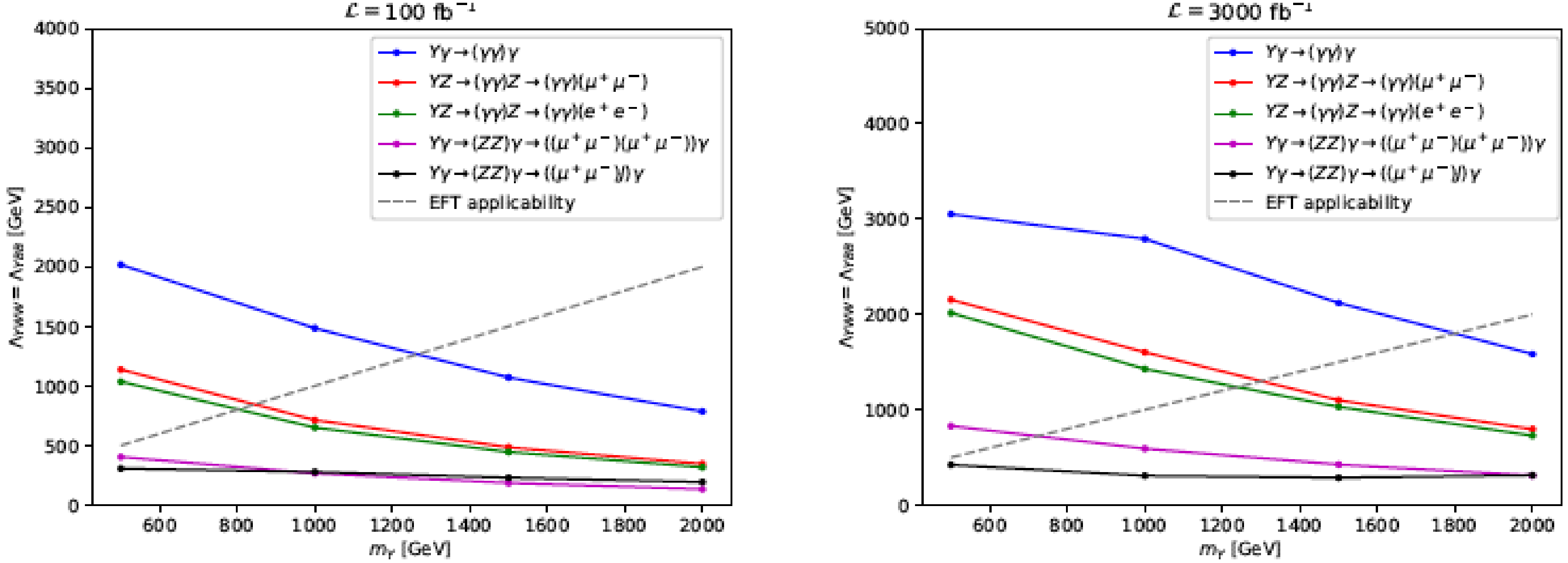
$[H^{\dagger i}\phi^a(\sigma^a)_i{}^j H_j]\, B^{\mu\nu}B_{\mu\nu}$
$[H^{\dagger i}\phi^a(\sigma^a)_i{}^j H_j]\, G^{\mu\nu}G_{\mu\nu}$
$\phi^a\,[H^{\dagger i}(\sigma^a)_i{}^j H_j]\, W^{\mu\nu,b}W^b_{\mu\nu}$
$\phi^a\,[H^{\dagger i}(\sigma^b)_i{}^j H_j]\, W^{\mu\nu,a}W^b_{\mu\nu}$
$\lvert H\rvert^2\phi^a\, W^{\mu\nu,a}B_{\mu\nu}$
$\varepsilon^{abc}\,\phi^a[H^{\dagger i}(\sigma^b)_i{}^j H_j]\, W^{\mu\nu,c}B_{\mu\nu}$

Branching Fraction as a Function of Operator Coefficients



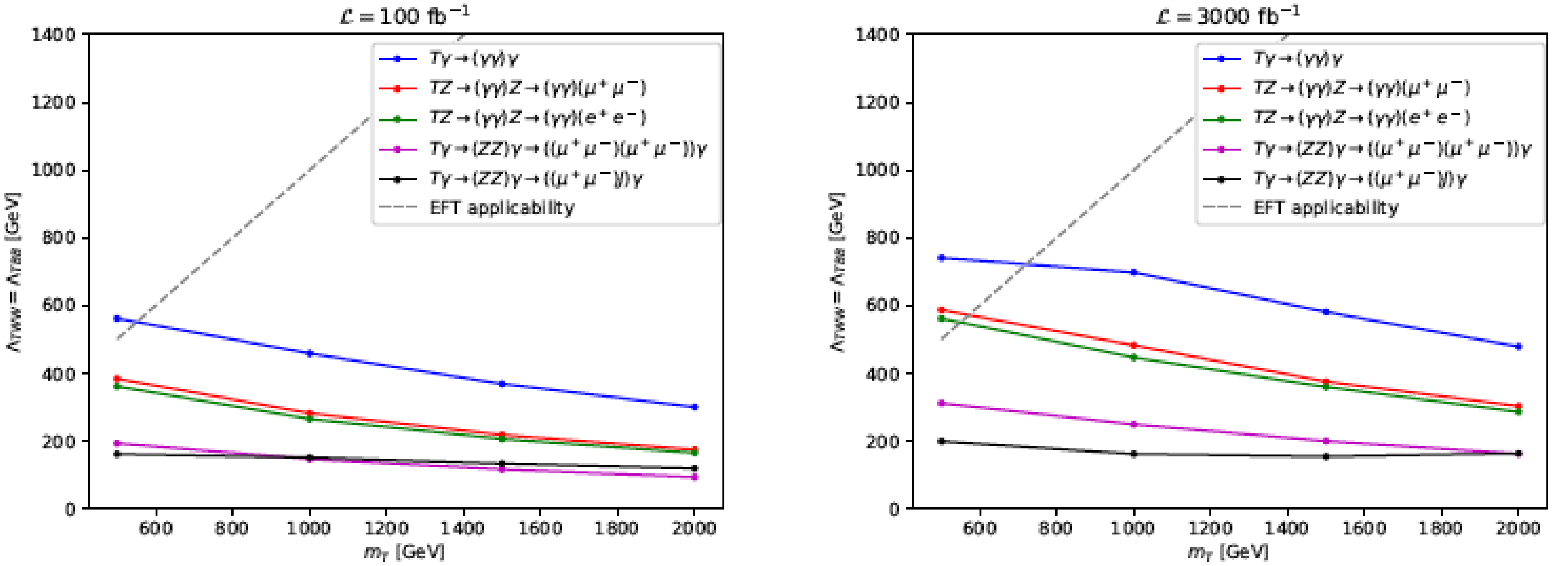






(c) dim 6 doublet model I 100 fb^{-1}

(d) dim 6 doublet model I 3 ab^{-1}



(e) dim 7 adjoint model 100 fb^{-1}

(f) dim 7 adjoint model 3 ab^{-1}

Example Catalog: Di-Boson Portal

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

SU(3) structure

Operators with one gluon, LEX state must be octet of SU(3) LEX states may be SU(2) singlets or have SU(2) structure

Exotic Octets coupling to SU(2) tensor and Gluon

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

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

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

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

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

W-Gluon resonance

$G_{\mu\nu}G^{\mu\nu}$ couplings

We use the tensor product relation

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

$(\mathbf{27}, \mathbf{3}, 0)$ $\qquad [H^{\dagger i} \phi^{KL}_{IJij} H^j]\, G^{I\mu\nu}_K G^J_{L\mu\nu}$

$(\mathbf{10}, \mathbf{3}, 0)$ $\qquad \varepsilon^{KLM} [H^{\dagger i} \phi_{IJKij} H^j]\, G^{I\mu\nu}_L G^J_{M\mu\nu}$

LEX in Higher Dimensional Reps of SU(2)

In SU(2) n dimensional representation maps to algebra of spin J with

$$n = 2J + 1$$

For n=5, J is spin 2 object $J \in \{-2, -1, 0, 1, 2\}$

With tensor products

$$J \otimes L = J + L \oplus J + L - 1 \oplus \cdots \oplus J - L$$

An example product in SU(2)

$\mathbf{3} \otimes \mathbf{3}$ $J = L = 1$ so $J \in \{0, 1, 2\}$

$$\mathbf{3} \otimes \mathbf{3} = \mathbf{1} \oplus \mathbf{3} \oplus \mathbf{5}$$

All possible representations can be constructed by taking successive products of the fundamental These higher-dimensional representations may be denoted as symmetric tensors. Totally symmetric tensors of dimension d and rank r have

$$n = \frac{(d+r-1)!}{r!\,(d-1)!}$$

For SU(2), $d = 2$, so $n = r + 1$

$$\mathbf{5} \text{ of } \mathrm{SU}(2)_{\mathrm{L}} \longrightarrow \qquad \phi_{ijkl}$$

$$\Phi = (\Phi^{++}, \Phi^{+}, \Phi^{0}, \Phi^{-}, \Phi^{--})$$

$$\frac{1}{\Lambda}\phi_{ijkl}W^{ij\mu\nu}W^{kl}_{\mu\nu} = \frac{1}{\Lambda}\Big(\Phi^{++}W^{-\mu\nu}W^{-}_{\mu\nu} + \Phi^{--}W^{+\mu\nu}W^{+}_{\mu\nu} - \sqrt{2}\Phi^{+}W^{-\mu\nu}W^{3}_{\mu\nu} \\ -\sqrt{2}\Phi^{-}W^{+\mu\nu}W^{3}_{\mu\nu} - \sqrt{\frac{2}{3}}\Phi^{0}W^{-\mu\nu}W^{+}_{\mu\nu} + \sqrt{\frac{2}{3}}\Phi^{0}W^{3\mu\nu}W^{3}_{\mu\nu}\Big) \qquad ($$

Adding Higgs insertions

$\mathbf{2}\otimes\mathbf{6}\supset\mathbf{5}$ as with spins $\frac{1}{2}\otimes\frac{5}{2}=1\oplus\underline{2}\oplus 3$

With the product $\mathbf{3}\otimes\mathbf{3}=\mathbf{1}\oplus\mathbf{3}\oplus\mathbf{5}$

We can make the invariant Lagrangian term

$$\mathbf{2}\otimes\mathbf{6}\otimes\mathbf{3}\otimes\mathbf{3}$$

$$\phi_{ijklm}\,H^{i}W^{jk}_{\mu\nu}W^{lm\mu\nu}$$

Dimension	$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$	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 with more EW gauge Bosons

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

Yields associated production process

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

Through the same operator

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

Tri-boson process

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

Derivative Operators

$(\mathbf{1},\mathbf{1},0)$	$D^\mu\phi D^\nu H_i^\dagger H_j\, W^{ij}_{\mu\nu}$	$\phi\,(D^\mu H)^{\dagger i}(D_\mu H)_i$
	$D^\mu\phi D^\nu H_i H^{\dagger i}\, B_{\mu\nu}$	
	$\phi\,\lvert H\rvert^2\lvert D_\mu H\rvert^2$	
	$\phi\,\lvert H^\dagger D_\mu H\rvert^2$	
	$[H^\dagger H\phi]\,(D^\mu H)(D_\mu H^\dagger)$	
$(\mathbf{1},\mathbf{3},0)$	$D^\mu\phi_{ij}D^\nu H^i H^{\dagger j}\, B_{\mu\nu}$	$\phi_{ij}\,(D^\mu H)^{\dagger i}(D_\mu H)^j$
	$D^\mu\phi_{ij}\, H^{\dagger k}D^\nu H_k\, W^{ij}_{\mu\nu}$	
	$[H^{\dagger i}H^j\phi_{ij}]\,\lvert D_\mu H\rvert^2$	
	$\phi_{ij}\,\lvert H\rvert^2 D^\mu H^i D_\mu H^{\dagger j}$	
	$[H^{\dagger i}\phi_{ij}D_\mu H^j][H^{\dagger k}D^\mu H_k]$	
	$H^\dagger\phi^a_A(\sigma^a)_i{}^j H_j(D^\mu H)_k(D_\mu H^\dagger)^k$	
$(\mathbf{1},\mathbf{5},0)$	$[H^{\dagger i}H^{\dagger j}\phi_{ijkl}]\,D^\mu H^k D_\mu H^l$	
	$D^\mu\phi_{ijkl}D^\nu H^{\dagger i}H^j\, W^{kl}_{\mu\nu}$	
$(\mathbf{8},\mathbf{1},0)$	$D^\mu\phi_A D^\nu H_i H^{i\dagger}\, G^A_{\mu\nu}$	
$(\mathbf{8},\mathbf{3},0)$	$D_\mu\phi_{ij\,A}D_\nu H^i H^{j\dagger}\, G^A_{\mu\nu}$	
$(\mathbf{1},\mathbf{4},-\frac{1}{2})$	$[H^i\phi_{ijk}]\,(D^\mu H)^j\,(D_\mu H)^{\dagger k}$	
$(\mathbf{1},\mathbf{2},-\frac{1}{2})$	$[H^i\phi_i]\,D^\mu H_j D_\mu H^{\dagger j}$	

Future Directions

- Test Higgs derivative models for EW gauge bosons, leptonicaly decaying W signals,
- Test associated production in diboson portal with gluon signatures
- Many catalogs to build *e.g. high reps of SU(2)*

- List new classes of outstanding collider signatures
- Build UV completions

Extra Slides

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.

Effect on EFT Validity from Unitarity

Consider the 2 to 2 process

$$qg \rightarrow \varphi q^{\mathrm{c}}$$

With the perturbative unitarity bound

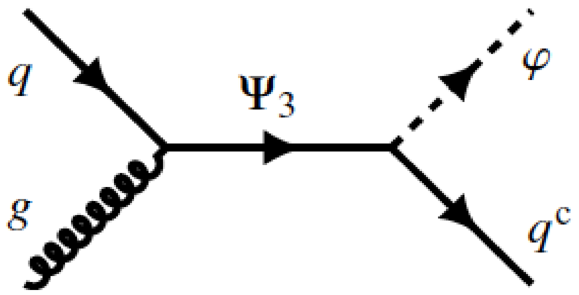
$$\Lambda \geq ({\Pi_s}^{a\,ij} \bar{\Pi}^s{}_{a\,ij})^{1/4} \left(\frac{\lambda_{qq}^{IJ}}{2\pi} \right)^{1/2} (\hat{s} - m_\varphi^2)^{1/2}$$

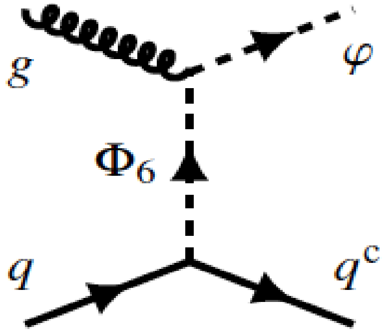
Given two linearly independent operators, the validity limit on cut-offs between two sextet coefficients varies by a factor of

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

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

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

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

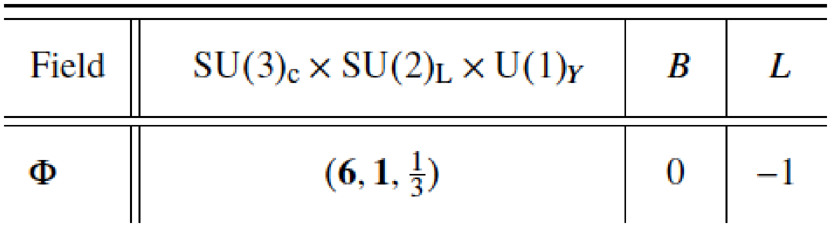
$$\sigma(qg \rightarrow \varphi q^c)$$

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

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

Kinematics

Consider the LEX spin 0 CP-even color sextet



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

Consider the LEX spin 0 CP-even color sextet

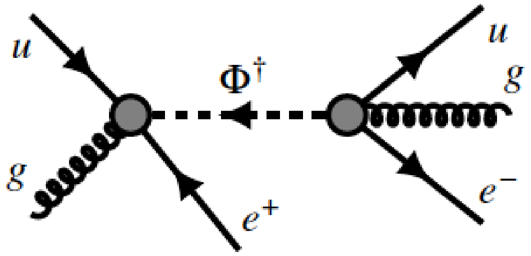
with interaction term

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

lepton-quark-gluon-sextet

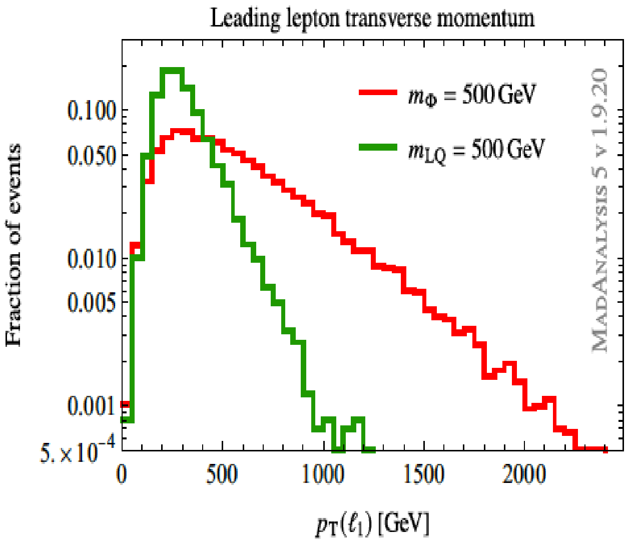
qg fusion gives sextet+hard lepton

The collider production process is

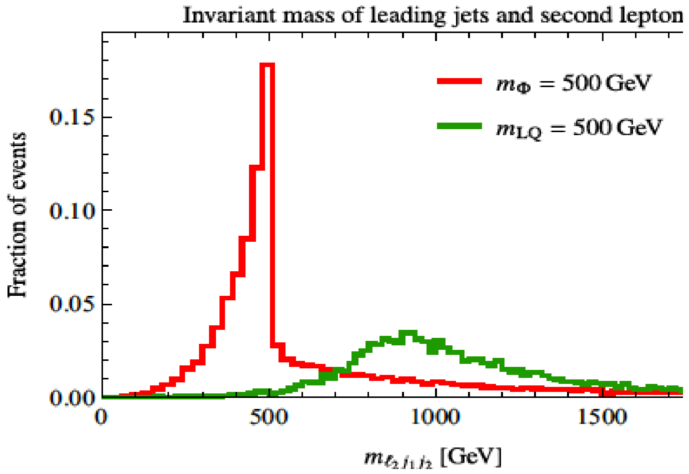


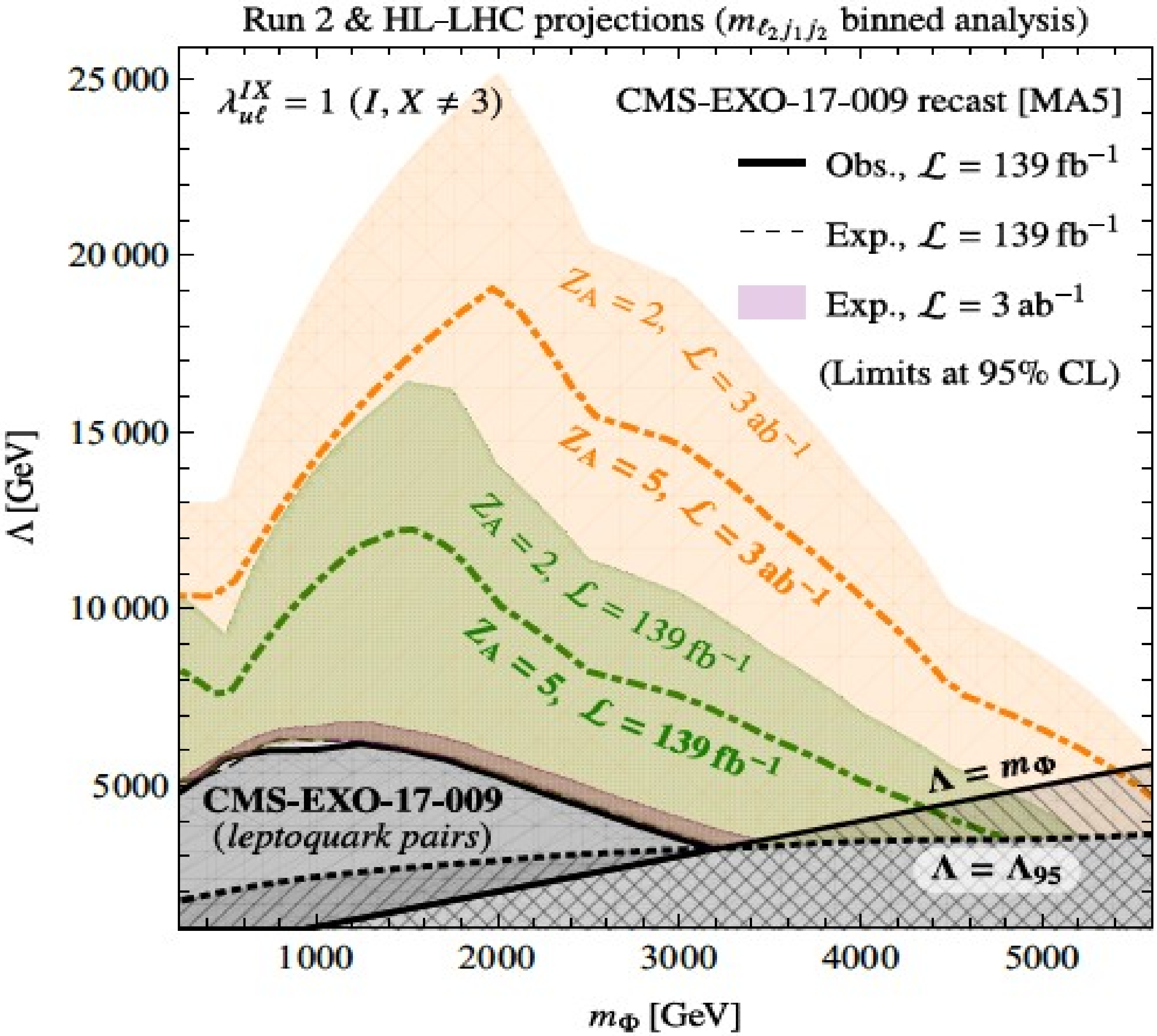
With final state $j\,j\,\ell^+\ell^-$

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


Leading lepton transverse momentum
Fraction of events
0.100
0.050
0.010
0.005
0.001
5.×10^-4
0
500
1000
1500
2000
$p_T(\ell_1)$ [GeV]
m_Φ = 500 GeV
m_{LQ} = 500 GeV
MadAnalysis 5 v 1.9.20

V


Invariant mass of leading jets and second lepton
Fraction of events
0.15
0.10
0.05
0.00
0
500
1000
1500
$m_{\ell_2 j_1 j_2}$ [GeV]
m_Φ = 500 GeV
m_{LQ} = 500 GeV


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}
$\Lambda = m_\Phi$
$\Lambda = \Lambda_{95}$
CMS-EXO-17-009
(leptoquark pairs)
Λ [GeV]
25 000
20 000
15 000
10 000
5000
1000
2000
3000
4000
5000
m_Φ [GeV]