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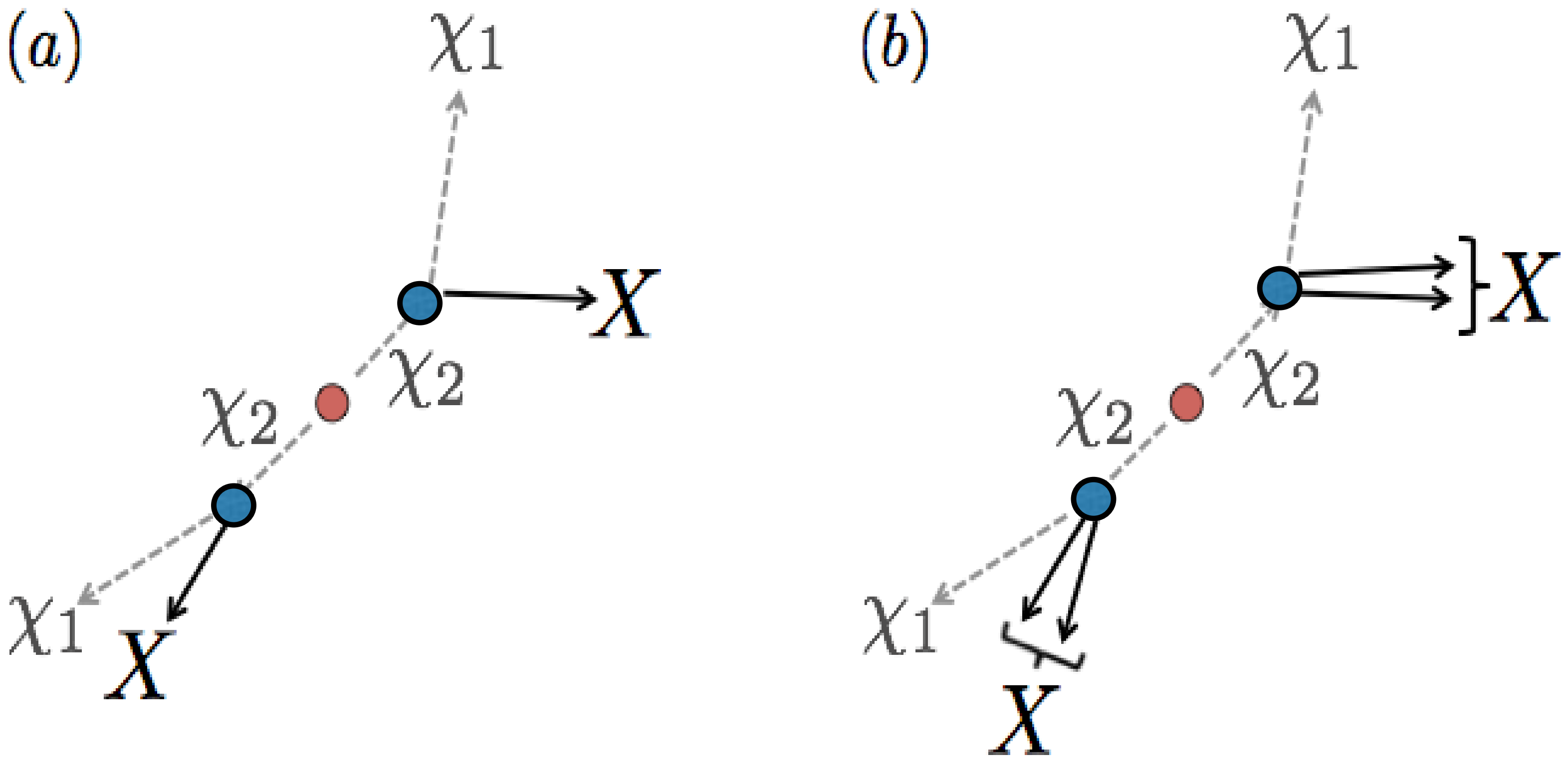
Simplified Models for Displaced Vertices

Oliver Buchmueller, Albert de Roeck, Kristian Hahn, Matthew McCullough, Pedro Schwaller, Kevin Sung, Tien-Tien Yu

arXiv:1704.06515

Searches for long-lived particles at the LHC: Workshop of the LHC LLP Community
April 26, 2017

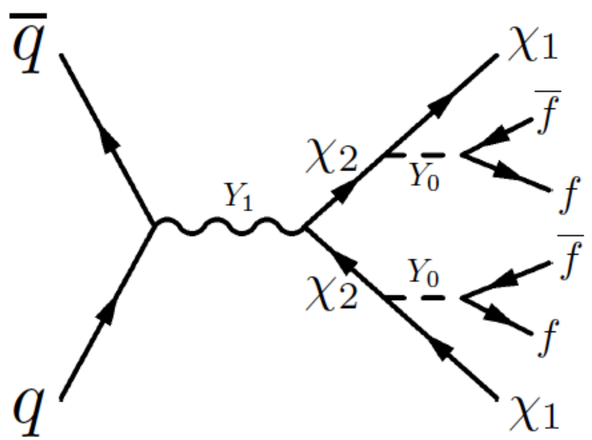
WANTED:
Systematic programme for displaced vertex searches



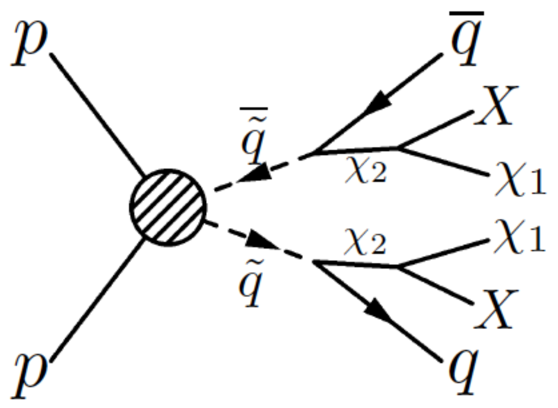
WANTED: Systematic programme for displaced vertex searches

Production through simplified models: DM or SUSY

Example: simplified DM



Example: simplified SUSY

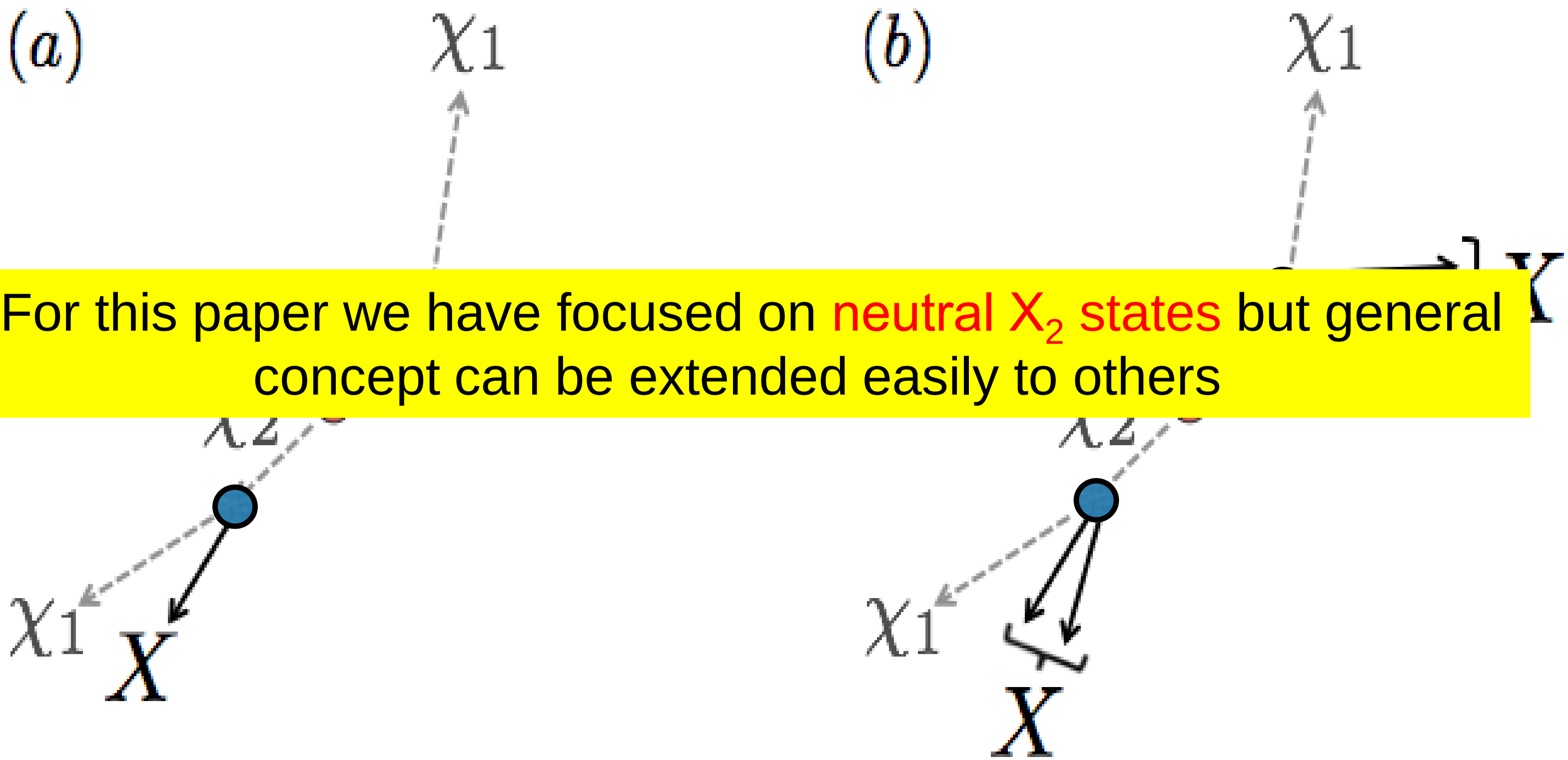


Advantage:

Can revert to a large and well understood portfolio of simplified models that are already in use by the experiments!

http://feynrules.irmp.ucl.ac.be/wiki/DMsimp
https://github.com/ksung25/DisplacedDM

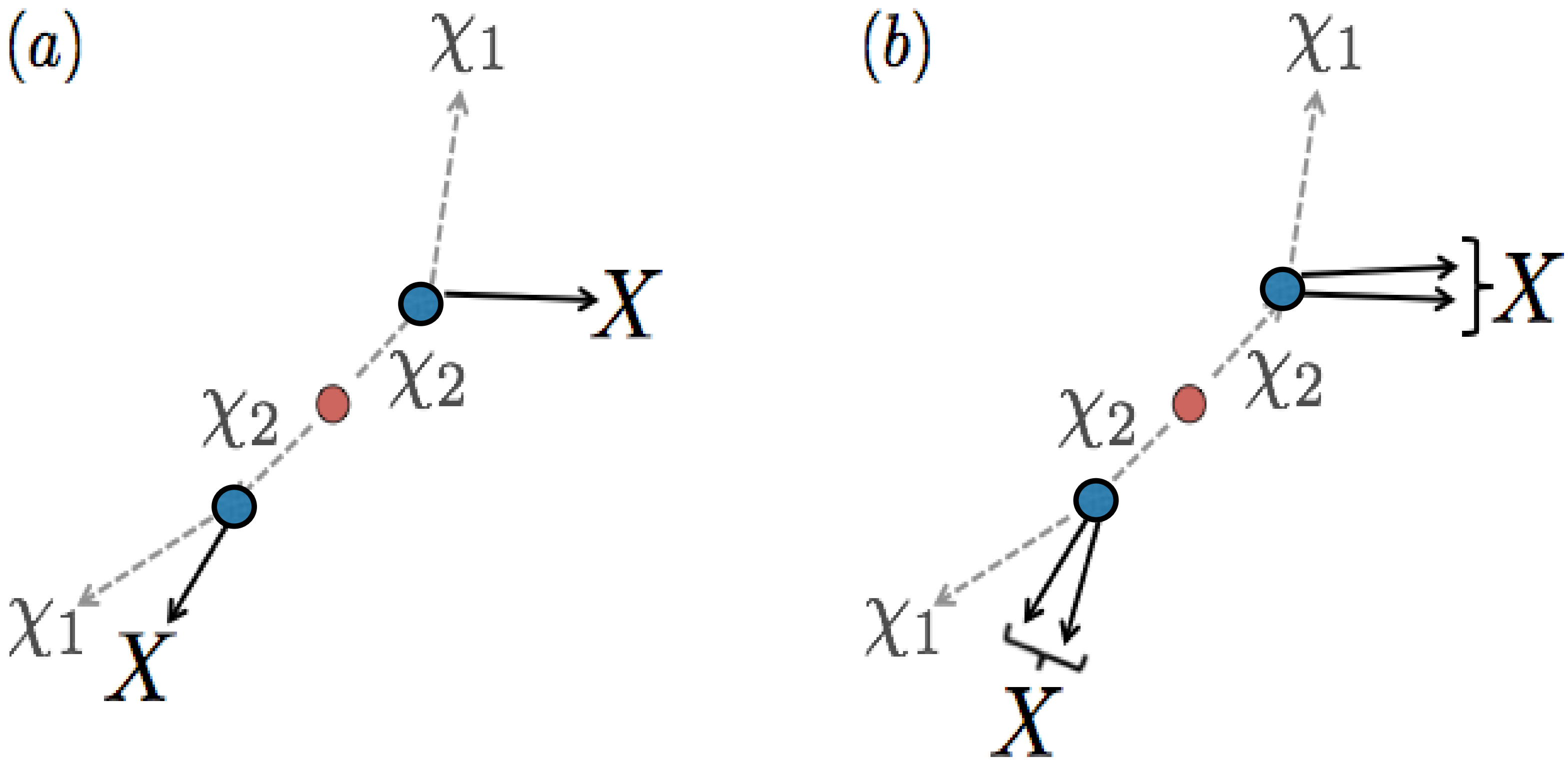
WANTED:
Systematic programme for displaced vertex searches



For this paper we have focused on neutral X_2 states but general concept can be extended easily to others

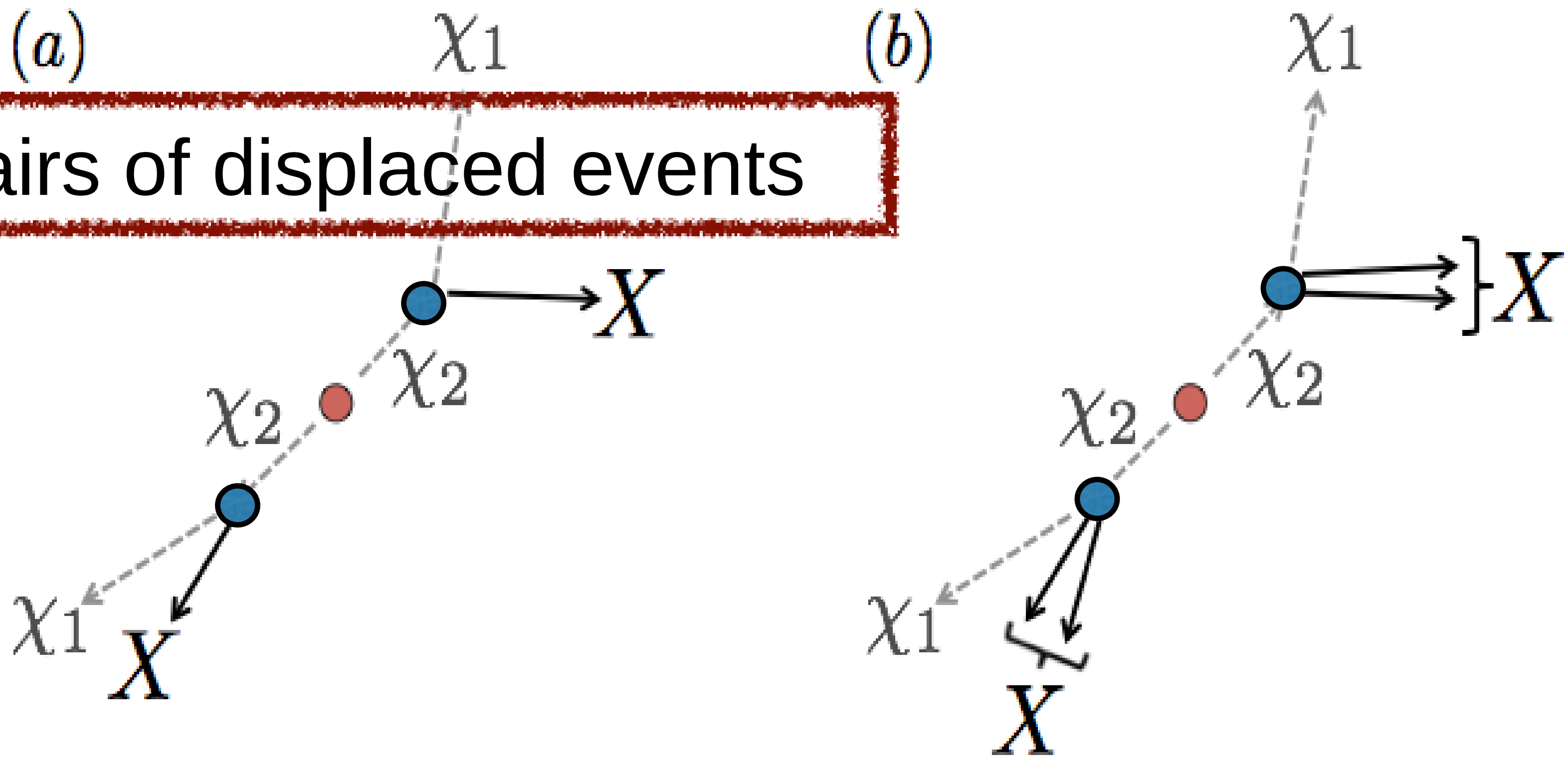
Production through simplified models: DM or SUSY

Experimental Signature

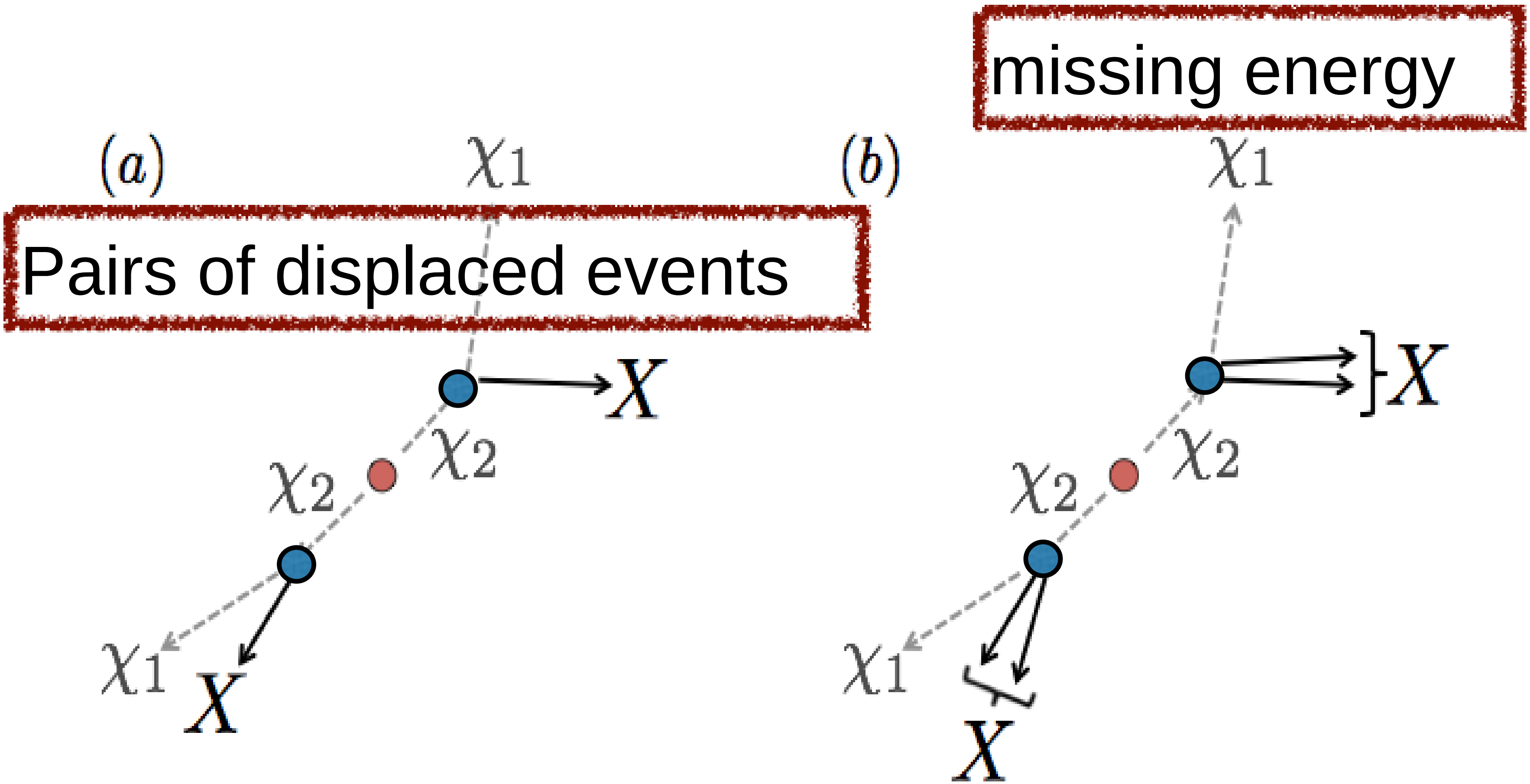


Experimental Signature

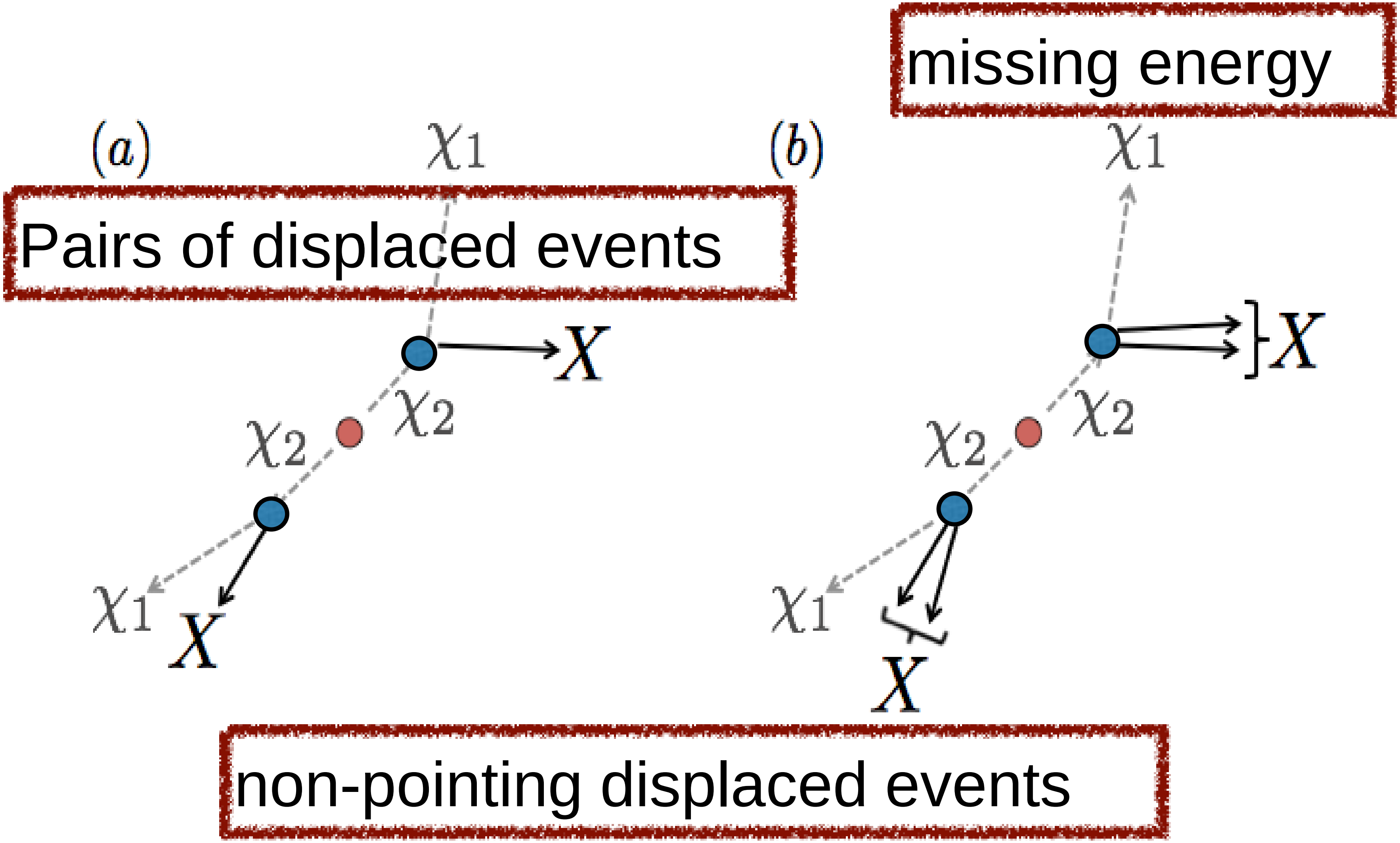
Pairs of displaced events



Experimental Signature

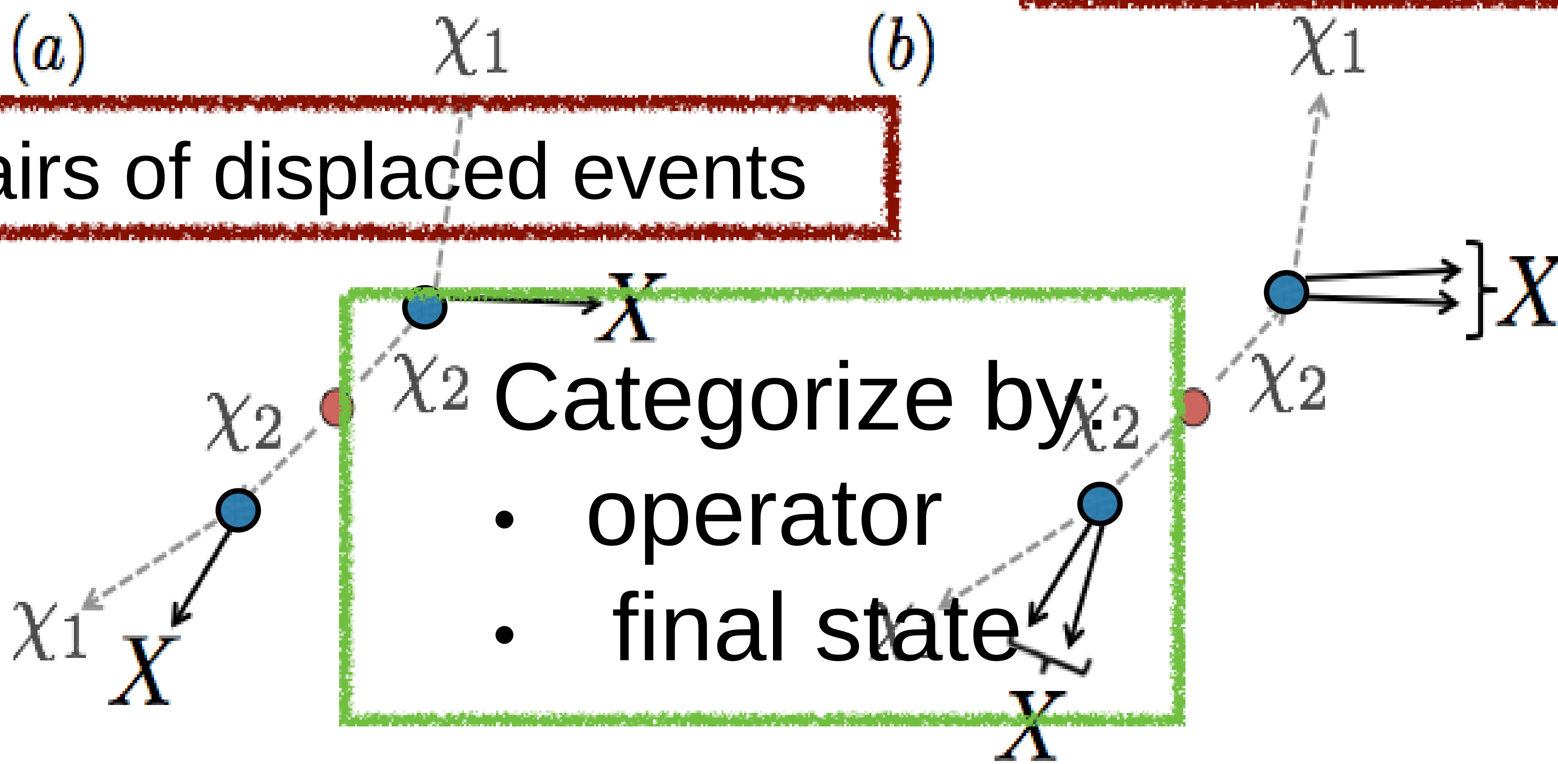


Experimental Signature



Experimental Signature

missing energy



Pairs of displaced events

Categorize by:

- operator
- final state

non-pointing displaced events

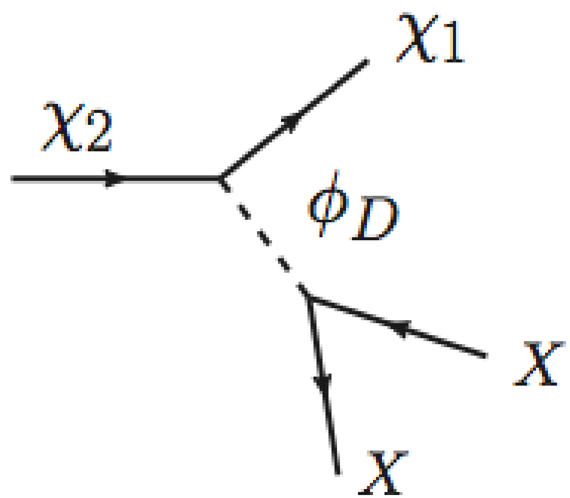
Example Operators

$$\chi_2 \to \chi_1 + X$$

final state X	$\mathcal{O}_F$	$\mathcal{O}_S$
γ/γ^*	$\frac{1}{\Lambda}\overline{\chi}_2\sigma_{\mu\nu}\chi_1 F^{\mu\nu}$	$\frac{1}{\Lambda^2}(\partial_\mu\phi_2\partial_\nu\phi_1)F^{\mu\nu}$
Z	$\frac{1}{\Lambda}\overline{\chi}_2\sigma_{\mu\nu}\chi_1 Z^{\mu\nu}$	$\frac{1}{\Lambda^2}(\partial_\mu\phi_2\partial_\nu\phi_1)Z^{\mu\nu}$
h	$\overline{\chi}_2\chi_1 h$	$\Lambda\phi_2\phi_1 h$
jj	$\frac{1}{\Lambda^3}\overline{\chi}_2\chi_1\mathrm{Tr}[G^{\mu\nu}G_{\mu\nu}]$	$\frac{1}{\Lambda^2}\phi_2\phi_1\mathrm{Tr}[G^{\mu\nu}G_{\mu\nu}]$
$\bar{l}l$	$\frac{1}{\Lambda^2}\bar{l}l\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{l}l$
$\bar{b}b$	$\frac{1}{\Lambda^2}\bar{b}b\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{b}b$
$\bar{t}t$	$\frac{1}{\Lambda^2}\bar{t}t\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{t}t$

*can also have diboson final states

Light Mediator



final state	$\mathcal{O}_{DM} + \mathcal{O}_{SM}$
$\bar{f}f$	$-g_{12} Z'_\mu \bar{\chi}_1 \gamma^\mu \chi_2 - g_q Z'_\mu \bar{l} \gamma^\mu l$ $-g_{12} Z'_\mu \bar{\chi}_1 \gamma^\mu \gamma_5 \chi_2 - g_q Z'_\mu \bar{l} \gamma^\mu \gamma_5 l$ $-g_{12} \phi \bar{\chi}_1 \chi_2 - g_q \phi \bar{l} l$ $-i g_{12} \phi \bar{\chi}_1 \gamma^5 \chi_2 - g_q \phi \bar{l} \gamma^5 l$ $-(g_1 \tilde{l}^* \bar{\chi}_1 l + g_2 \tilde{l}^* \bar{\chi}_2 l + h.c.)$

Parameters

Simplified DM Models		
Variables	DM candidate	Interaction
m_ϕ	Dirac	Vector
m_1	Majorana	Axial-Vector
g_χ	Scalar-real	Scalar
g_ϕ	Scalar-complex	Pseudoscalar
Extension Displaced Signature		
τ , m_2	Decay of $\chi_2 \to \chi_1 X$	

DM simplified models program

proposed extension

or $m_2 - m_1$

Minimal Set of Final States to cover Experimentally

$\not{E}_T$ plus displaced X system					
dMETs	dMET$_{jj}$	dMET$_{e^+e^-}$	dMET$_{\mu^+\mu^-}$	dMET$_{\tau^+\tau^-}$	dMET$_{\gamma}$
X	jet-pair	e-pair	μ-pair	τ-pair	γ

Table 4. Minimal set of dMETs searches for neutral displaced SM particles. To facilitate the trigger acceptance for these topologies, especially for soft X systems, the dMETs can be combined with an ISR signature, such as an additional hard jet or hard γ. A list of basic operators that would give rise to such topologies is shown in Table 2.

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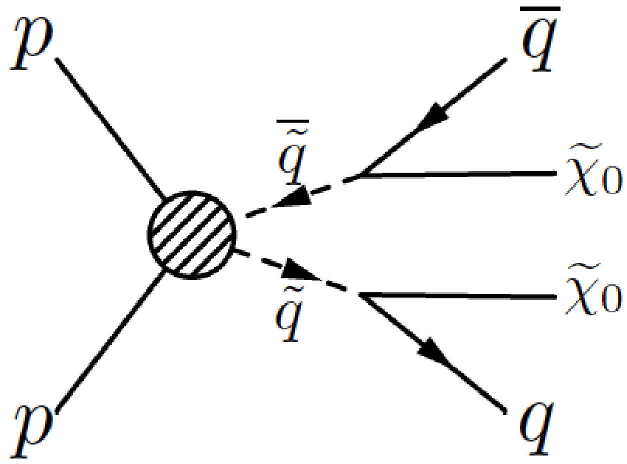
dMETγ: displaced gamma with MET is the only of these signature that is currently covered with a dedicated analysis by experiments.

Simulation in a nutshell

Simulation

1) Chose simplified Model for production



Simulation in a nutshell

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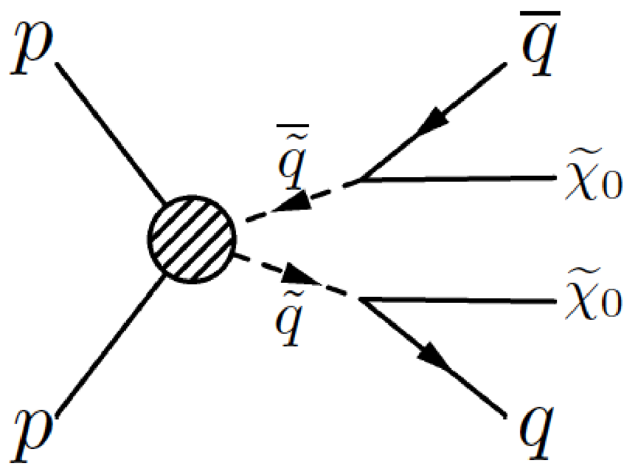
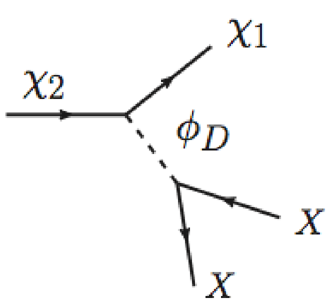


2) Chose ansatz to add long-lived particle and decay:

final state X	$\mathcal{O}_F$	$\mathcal{O}_S$
γ	$\frac{1}{\Lambda}\overline{\chi}_2\sigma_{\mu\nu}\chi_1 F^{\mu\nu}$	$\frac{1}{\Lambda^2}(\phi_2\partial_\mu\partial_\nu\phi_1)F^{\mu\nu}$
Z	$\frac{1}{\Lambda}\overline{\chi}_2\sigma_{\mu\nu}\chi_1 Z^{\mu\nu}$	$\frac{1}{\Lambda^2}(\phi_2\partial_\mu\partial_\nu\phi_1)Z^{\mu\nu}$
h	$\overline{\chi}_2\chi_1 h$	$\Lambda\phi_2\phi_1 h$
jj	$\frac{1}{\Lambda^3}\overline{\chi}_2\chi_1 \mathrm{Tr}[G^{\mu\nu}G_{\mu\nu}]$	$\frac{1}{\Lambda^2}\phi_2\phi_1 \mathrm{Tr}[G^{\mu\nu}G_{\mu\nu}]$
$\bar{l}l$	$\frac{1}{\Lambda^2}\bar{l}l\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{l}l$
$\bar{b}b$	$\frac{1}{\Lambda^2}\bar{b}b\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{b}b$
$\bar{t}t$	$\frac{1}{\Lambda^2}\bar{t}t\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{t}t$

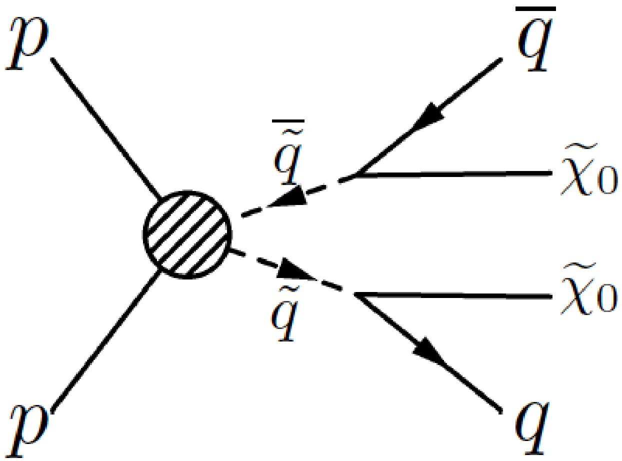
EFT like decay



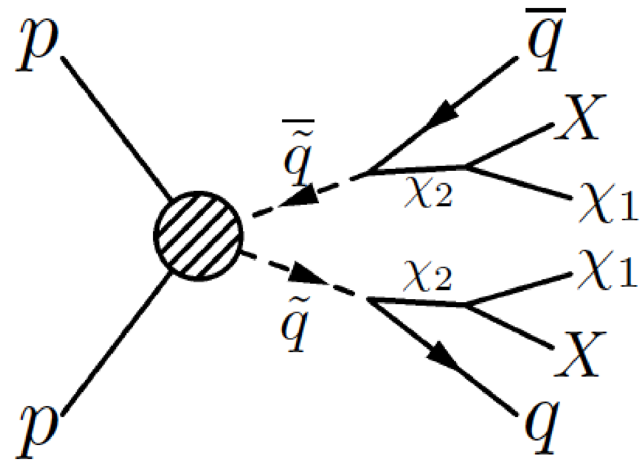
Resolved (light) mediator

Simulation in a nutshell

1) Chose simplified Model for production



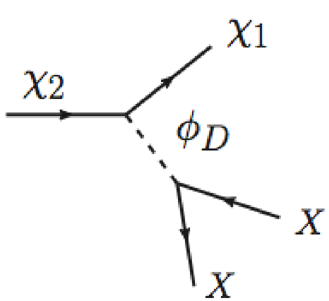
3) Simulate full chain



2) Chose ansatz to add long-lived particle and decay:

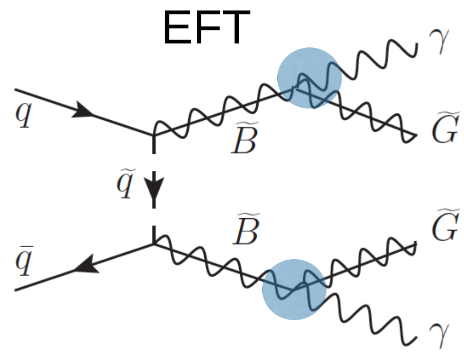
final state X	$\mathcal{O}_F$	$\mathcal{O}_S$
γ	$\frac{1}{\Lambda}\overline{\chi}_2\sigma_{\mu\nu}\chi_1 F^{\mu\nu}$	$\frac{1}{\Lambda^2}(\phi_2\partial_\mu\partial_\nu\phi_1)F^{\mu\nu}$
Z	$\frac{1}{\Lambda}\overline{\chi}_2\sigma_{\mu\nu}\chi_1 Z^{\mu\nu}$	$\frac{1}{\Lambda^2}(\phi_2\partial_\mu\partial_\nu\phi_1)Z^{\mu\nu}$
h	$\overline{\chi}_2\chi_1 h$	$\Lambda\phi_2\phi_1 h$
jj	$\frac{1}{\Lambda^3}\overline{\chi}_2\chi_1 \mathrm{Tr}[G^{\mu\nu}G_{\mu\nu}]$	$\frac{1}{\Lambda^2}\phi_2\phi_1 \mathrm{Tr}[G^{\mu\nu}G_{\mu\nu}]$
$\bar{l}l$	$\frac{1}{\Lambda^2}\bar{l}l\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{l}l$
$\bar{b}b$	$\frac{1}{\Lambda^2}\bar{b}b\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{b}b$
$\bar{t}t$	$\frac{1}{\Lambda^2}\bar{t}t\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{t}t$

EFT like decay



Resolved (light) mediator

Example: EFT like decay for X_2 -> γ X_1



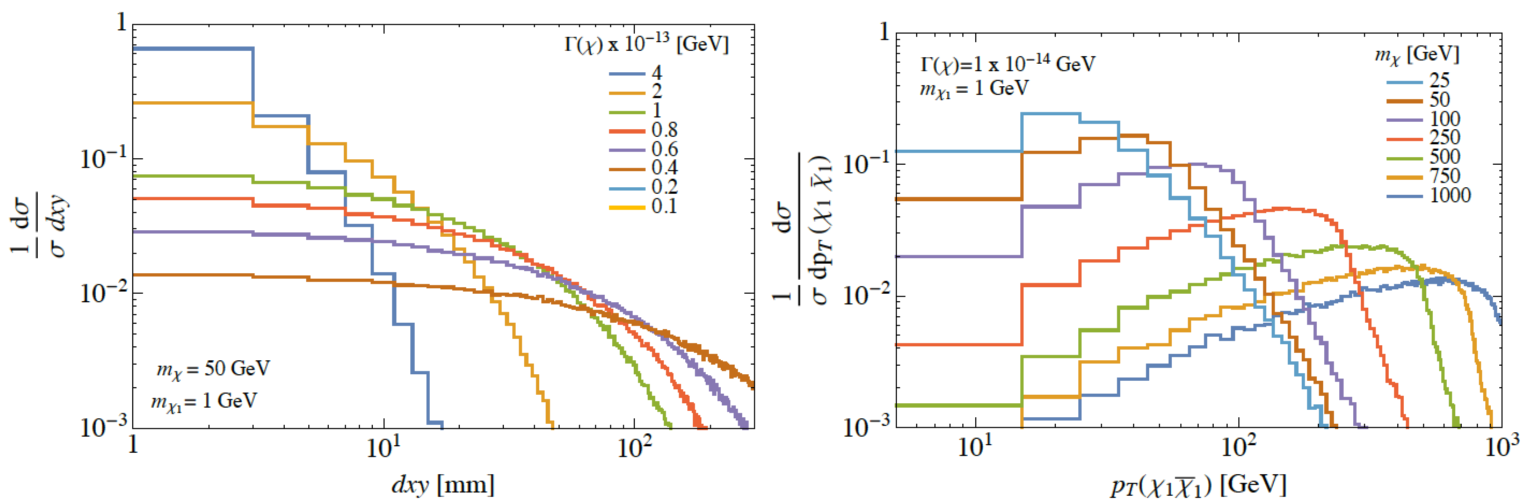
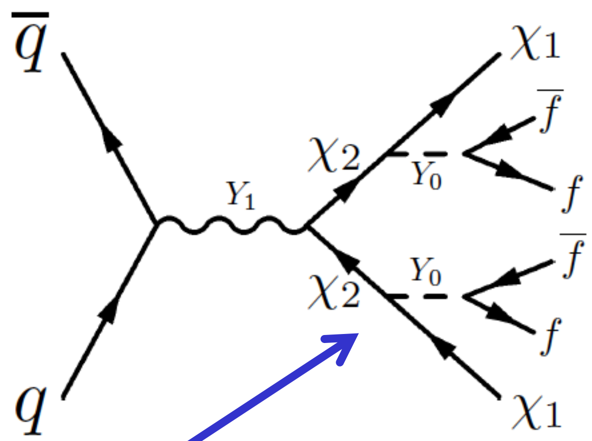
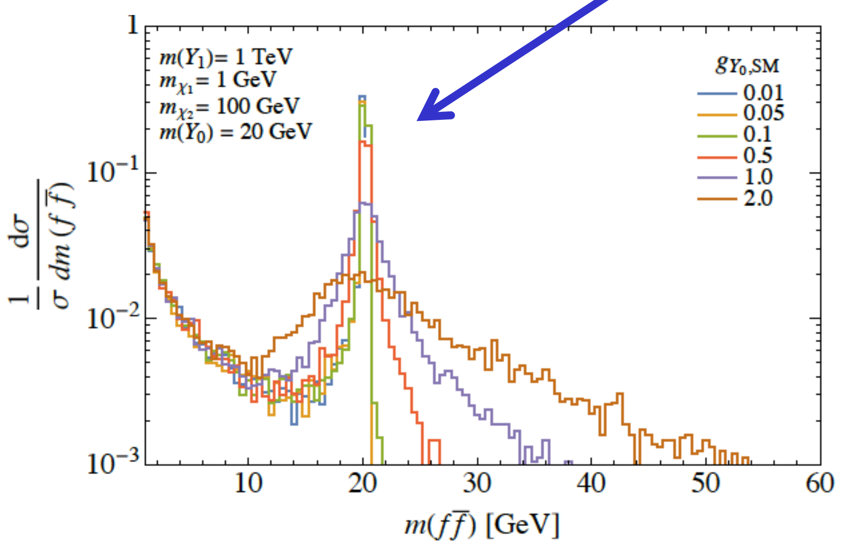
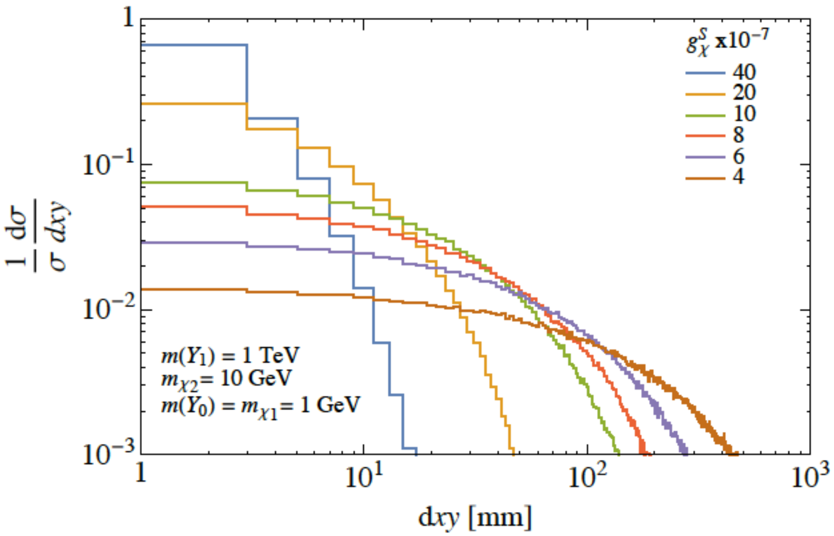


Figure 10. Left: the transverse impact parameter of $\chi_1\gamma$ vertices for a range of χ widths. Right: the transverse momentum of the DM system ($p_T(\chi_1\bar{\chi_1})$) for various χ masses. Other parameters in the GMSB model are fixed as per the panel headings. The distributions in both panels are unit-normalised.

Example: Resolved decay for $X_2 \rightarrow Y_0 X_1 \rightarrow ff X_1$







Simulation

1. **Add the new particle content to the original DM simplified model.**

   For an EFT decay model, this is simply the new, stable DM particle χ_1.

   For the simplified decay model the mediating particle must also be included.

2. **Add new interactions to the original model.**

   These can either be single-parameter EFT operators, or interaction terms involving a mediator.

3. **Configure the relevant particle masses and couplings in the MG5 aMC@NLO param card.dat to achieve displaced decays.**

4. **Generate the pp $\rightarrow \chi\bar{\chi}$ in process MG5 aMC@NLO, which will result in an LHE file that contains the necessary width information in the SLHA header.**

5. **Pass the resulting LHE to Pythia, which will perform the $\chi \rightarrow \chi_1 X$ decay using the SLHA information.**

More details are provided in arXiv:1704.06515

Mapping Simplified Models on complete models/theories

We have also shown in this paper that properties/limits obtained from simplified models can be mapped onto complete models:

Example:

GMSB and Fraternal Twin Higgs model

No time to cover here:

See backup and paper

Summary:arXiv:1704.06515

- We propose a systematic programme to search for long-lived neutral particle signatures through a minimal set of displaced MET searches (dMETs).
- Our approach is to extend the well established simplified models to include displaced vertices. A displaced secondary vertex, characterised by the mass of the long-lived particle and its lifetime, is added for the displaced signature.
- We show how these models can be motivated by, and mapped onto, complete models such as gauge-mediated SUSY breaking and models of neutral naturalness.
- We also outline how this approach can be used to extend other simplified models to incorporate displaced signatures.

Backup Material

EFT

$$\Gamma \sim \frac{1}{\Lambda^{2d}}(m_2 - m_1)^a m_2^{2d+1-a}$$

displaced decay means

$$\Gamma \ll m_2$$

characteristic energy is roughly m2-m1

matrix element is always <<1, so using lowest dimension operator is a good approximation.

$$\Rightarrow \quad \Lambda \gg m_2 - m_1$$

Example operators

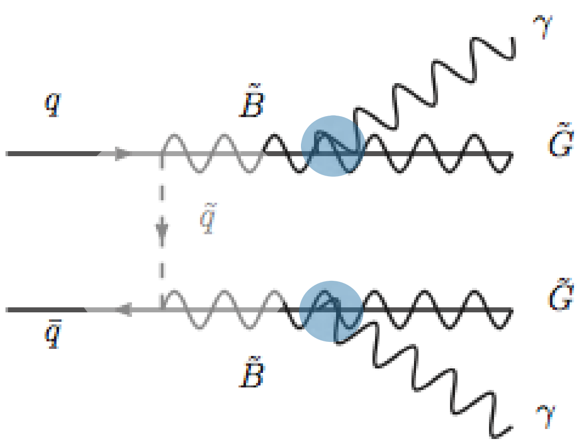
$$\chi_2 \to \chi_1 + X$$

final state X	$\mathcal{O}_F$	$\mathcal{O}_S$
γ	$\frac{1}{\Lambda}\overline{\chi}_2\sigma_{\mu\nu}\chi_1 F^{\mu\nu}$	$\frac{1}{\Lambda^2}(\phi_2\partial_\mu\partial_\nu\phi_1)F^{\mu\nu}$
Z	$\frac{1}{\Lambda}\overline{\chi}_2\sigma_{\mu\nu}\chi_1 Z^{\mu\nu}$	$\frac{1}{\Lambda^2}(\phi_2\partial_\mu\partial_\nu\phi_1)Z^{\mu\nu}$
h	$\overline{\chi}_2\chi_1 h$	$\Lambda\phi_2\phi_1 h$
jj	$\frac{1}{\Lambda^3}\overline{\chi}_2\chi_1 \mathrm{Tr}[G^{\mu\nu}G_{\mu\nu}]$	$\frac{1}{\Lambda^2}\phi_2\phi_1 \mathrm{Tr}[G^{\mu\nu}G_{\mu\nu}]$
$\bar{l}l$	$\frac{1}{\Lambda^2}\bar{l}l\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{l}l$
$\bar{b}b$	$\frac{1}{\Lambda^2}\bar{b}b\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{b}b$
$\bar{t}t$	$\frac{1}{\Lambda^2}\bar{t}t\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{t}t$

GMSB

$$\mathcal{L} = \frac{1}{\Lambda}\tilde{B}\sigma_{\mu\nu}\tilde{G}F^{\mu\nu} + h.c.$$

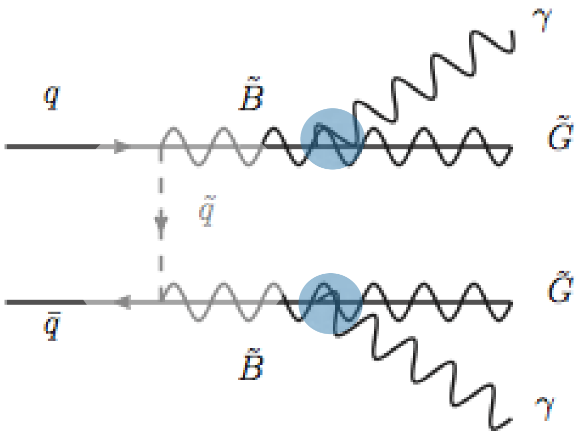
$$\Gamma = \frac{(m_{\tilde{B}}^2 - m_{\tilde{G}}^2)^3}{2\pi\Lambda^2 m_{\tilde{B}}^3}$$



t-channel, scalar

$$\Gamma(\tilde{B} \to \gamma + \tilde{G}) = \frac{\cos^2\theta_W}{16\pi F^2} M_{\tilde{B}}^5$$

GMSB



$$\Gamma = \frac{(m_{\tilde{B}}^2 - m_{\tilde{G}}^2)^3}{2\pi\Lambda^2 m_{\tilde{B}}^3}$$

$$\Gamma(\tilde{B} \to \gamma + \tilde{G}) = \frac{\cos^2\theta_W}{16\pi F^2} M_{\tilde{B}}^5$$

$$M_{\tilde{B}}(t) = \frac{5\alpha_Y(t)}{12\pi} \frac{F}{M} \nearrow \Lambda$$

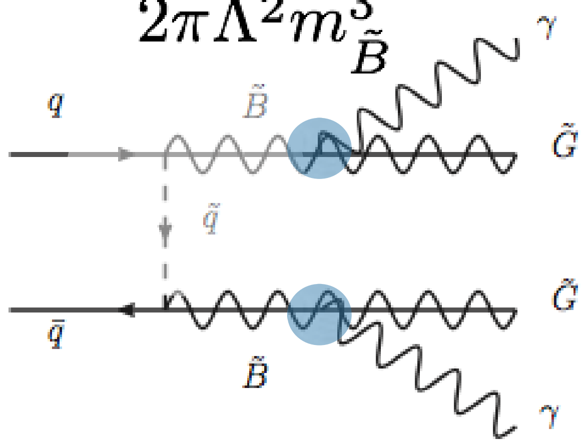
$$m_{\tilde{G}} = \frac{F}{\sqrt{3}M_p}$$

GMSB

$$\mathcal{L} = \frac{1}{\Lambda} \tilde{B} \sigma_{\mu\nu} \tilde{G} F^{\mu\nu} + h.c.$$

$$\mathcal{L} = \frac{1}{F} \frac{M}{4\sqrt{2}} \tilde{B} \sigma_{\mu\nu} \tilde{G} F^{\mu\nu} + h.c.$$

$$\Gamma = \frac{(m_{\tilde{B}}^2 - m_{\tilde{G}}^2)^3}{2\pi \Lambda^2 m_{\tilde{B}}^3}$$

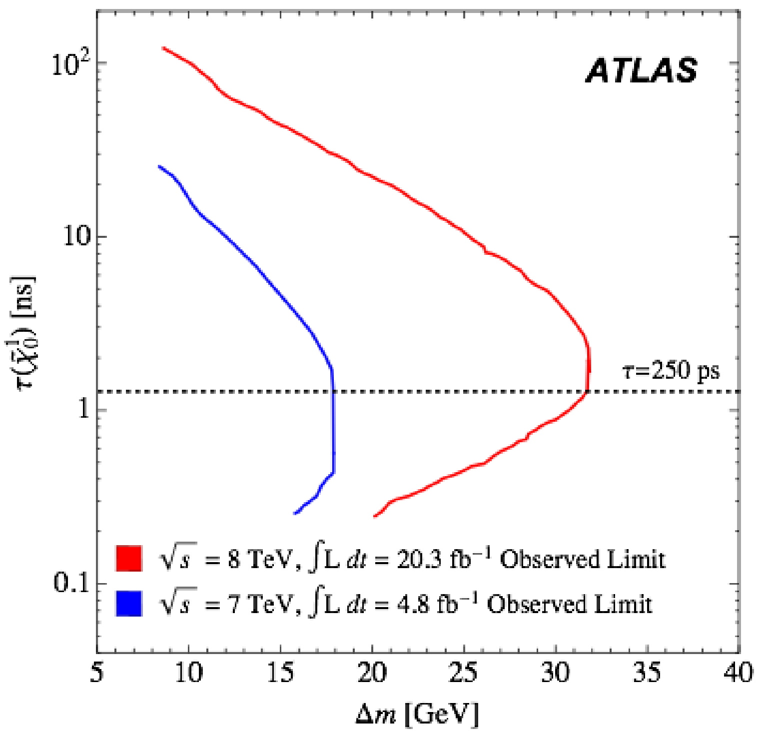


t-channel, scalar

$$\Gamma(\tilde{B} \to \gamma + \tilde{G}) = \frac{\cos^2 \theta_W}{16\pi F^2} M_{\tilde{B}}^5$$

$$2^{++} \to 0^{++} h$$

GMSB



$$\Delta m \equiv \Lambda \left(\frac{5}{12\pi} \alpha_1(t) - \frac{2\Lambda}{\sqrt{3} M_p} \right)$$

$\boxed{\text{SPS8}}$

$$N_{mess} = 1$$
$$M = 2\Lambda$$
$$\tan\beta = 15$$

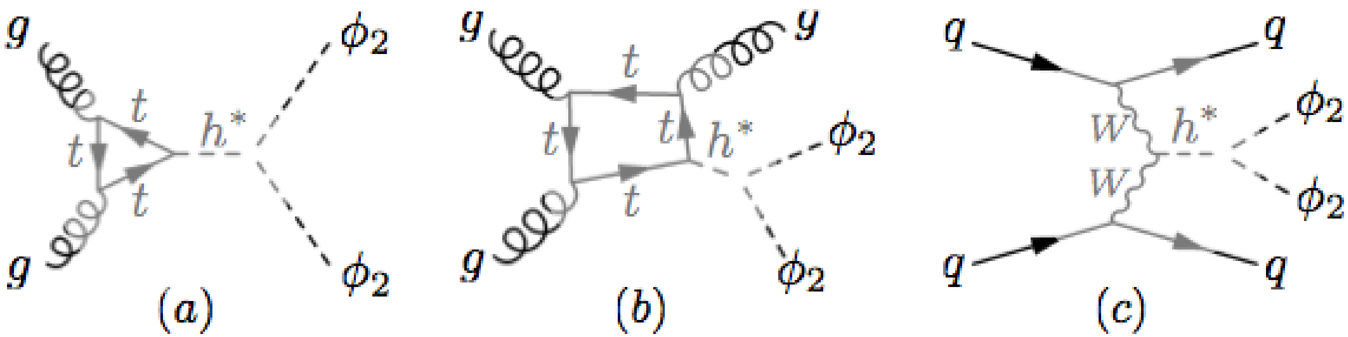
Map of GMSB to simplified models
t-channel, colored scalar mediator
$\tilde{\chi}_0^1$ Dirac fermion
$m_{\tilde{q}} \to m_\phi$
$m_{\tilde{\chi}_0^1} \to m_1$
$\sqrt{4\pi\alpha_1} \to g$
$\tau(\tilde{\chi}_0^1) \to \tau$
$\Delta m = m_{\tilde{\chi}_0^1} - m_{\tilde{G}} \to m_2$

Example operators

$$\chi_2 \to \chi_1 + X$$

final state X	$\mathcal{O}_F$	$\mathcal{O}_S$
γ	$\frac{1}{\Lambda}\overline{\chi}_2\sigma_{\mu\nu}\chi_1 F^{\mu\nu}$	$\frac{1}{\Lambda^2}(\phi_2\partial_\mu\partial_\nu\phi_1)F^{\mu\nu}$
Z	$\frac{1}{\Lambda}\overline{\chi}_2\sigma_{\mu\nu}\chi_1 Z^{\mu\nu}$	$\frac{1}{\Lambda^2}(\phi_2\partial_\mu\partial_\nu\phi_1)Z^{\mu\nu}$
h	$\overline{\chi}_2\chi_1 h$	$\boxed{\Lambda\phi_2\phi_1 h}$
jj	$\frac{1}{\Lambda^3}\overline{\chi}_2\chi_1\mathrm{Tr}[G^{\mu\nu}G_{\mu\nu}]$	$\frac{1}{\Lambda^2}\phi_2\phi_1\mathrm{Tr}[G^{\mu\nu}G_{\mu\nu}]$
$\bar{l}l$	$\frac{1}{\Lambda^2}\bar{l}l\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{l}l$
$\bar{b}b$	$\frac{1}{\Lambda^2}\bar{b}b\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{b}b$
$\bar{t}t$	$\frac{1}{\Lambda^2}\bar{t}t\overline{\chi}_2\chi_1$	$\frac{1}{\Lambda}\phi_2\phi_1\bar{t}t$

Fraternal Twin Higgs*



$$\mathcal{L} \supset -\frac{\alpha_3^T}{6\pi}\frac{v}{f}\frac{h}{f}\mathrm{Tr}\; G^T_{\mu\nu}G^{T\mu\nu}$$

0911.5616

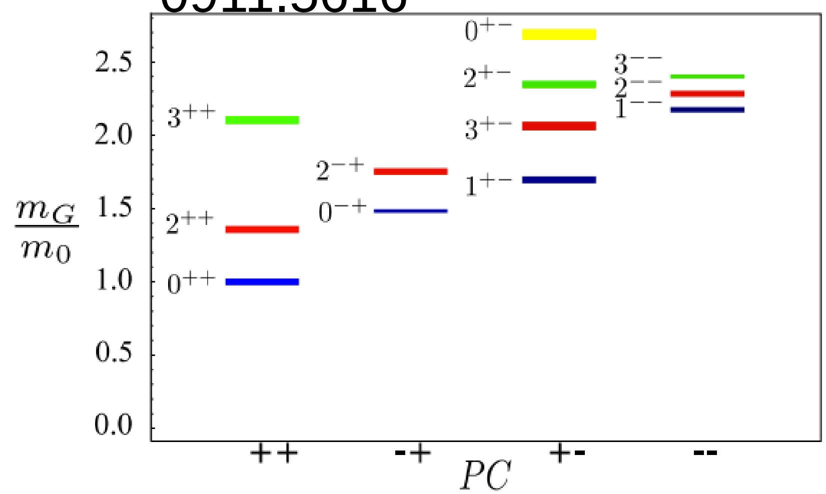
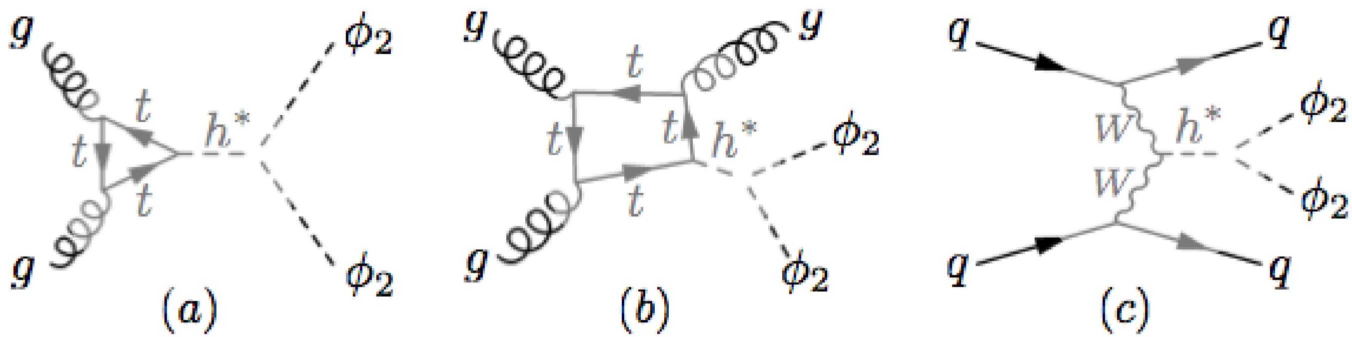
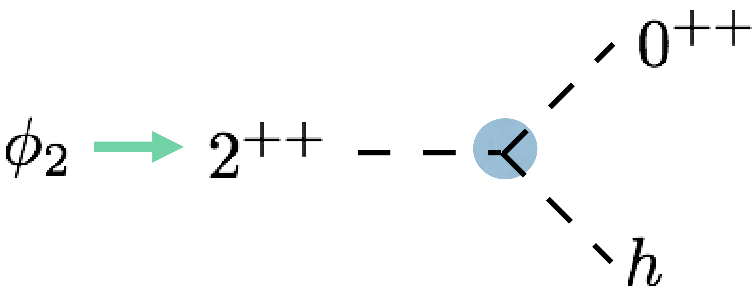


Figure 1: Spectrum of stable glueballs in pure glue $SU(3)$ theory [12]. Masses are shown in units of the lightest v-glueball mass m_0.

*Hidden Valley

Fraternal Twin Higgs





Map of Fraternal Twin to simplified models
s-channel, higgs mediator
ϕ_2 scalar
$m_{G_{2^{++}}} = 1.4 m_0 \to m_\phi$
$m_{G_{0^{++}}} = m_0 \to m_1$
$\frac{\hat{\alpha}_3 v_h}{6\pi f^2} \to g$
$\tau(G_{2^{++}}) \to \tau$
$\Delta m = 0.4 m_0$

decays into twin taus, b, Ws, etc…