(In)visible Z’ and Dark Matter

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CONTINOUS INTEREST IN ADDITIONAL U(1) SYMMETRIES

(spontaneously broken by a vev of S)

RECENTLY: IN THE CONTEXT OF HIDDEN SECTORS AND/OR DARK MATTER CANDIDATES

G. BELANGER ET AL.,JCAP 0801,009 (2008); N.ARKANI-HAMED ET AL., PHYS.REV. D 79 (2009) 015014 and JHEP 0812 (2008) 104; C.CHEUNG et al., hep-ph/0902.3246; S.Cassel, D.Ghilencea and G.Ross, hep-ph/0903.1118;
D.Feldman, Z.Liu and P.Nath, Phys.Rev.D79(2009),063509;
J.Kumar, A.Rajaraman and J.Wells, Phys.Rev.D77(2008)066011;
I.Antoniadis, A.Boyarski, S.Espahbodi, O.Ruchayskiy and J.Wells, Hep-ph/0901.0639;
…..

Various versions and various constraints (e.g. from electroweak data) have been discussed

- SM FERMIONS AND SM HIGGS DOUBLET CHARGED UNDER ADDITIONAL U(1)
  a) SM + U(1)
  b) SM + U(1) + NEW FERMIONS, POSSIBLY CHIRAL
(CHARGED UNDER BOTH)

CHIRAL ANOMALY CANCELLATION CONSTRAINTS,
IN PARTICULAR MIXED (SM, U(1)) ANOMALIES

„INVISIBLE" Z' -- SM FERMIONS ARE NOT CHARGED UNDER ADDITIONAL U(1)'s

NO TREE LEVEL PROCESS $qq \rightarrow X \rightarrow ff$

X- the extra gauge boson(s)

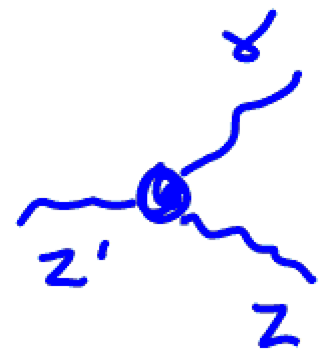
COUPLING OF THE SM TO THE HIDDEN SECTOR CAN THEN BE GENERATED AT THE LOOP LEVEL, BY HEAVY FERMION EXCHANGE

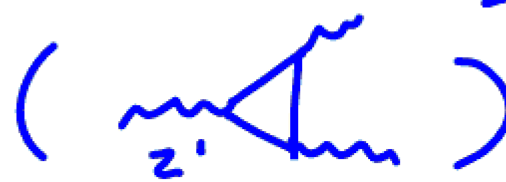
Kinetic mixing operator

$$\delta\, F_X^{\mu\nu} F^Y_{\mu\nu}$$

Generalized Chern-Simons (GCS) term

$$\epsilon^{\mu\nu\rho\sigma} Z'_\mu B_\nu F^Y_{\rho\sigma}$$





A SETUP: additional U(1)'s, „higgsed” and realized non-linearly at electroweak scale;
a set of heavy fermions, chiral with respect to U(1) but vector-like under SM gauge group;
they get their masses from Yukawa couplings to the Higgs boson S, used to break U(1).

$$M_X = g_X V \qquad V > v$$

$$M_h = \lambda V \qquad \lambda >> g_X$$

FERMIONS ARE HEAVIER THAN Z' AND WE ARE INTERESTED IN THE EFFECTIVE THEORY IN THE RANGE BETWEEN Z AND Z', AFTER INTEGRATING OUT HEAVY FERMIONS

CHIRAL ANOMALIES, INCLUDING MIXED ANOMALIES WITH THE SM, CANCEL OUT IN THE HEAVY FERMION SECTOR ITSELF

BUT THE TRIANGLE DIAGRAMS WITH HEAVY FERMIONS GIVE
EFFECTIVE Z'VV VERTICES IN THE LOW ENERGY THEORY

A scenario: heavy fermion masses are symmetric with respect to the SM (heavy fermions are vector-like wrt SM); the operator $\varepsilon^{\mu\nu\rho\sigma} Z'_\mu B_\nu F^Y_{\rho\sigma}$ should be invariant under non-linearly realized Z' symmetry and under linearly realized SM:

dim 6 $$\frac{i}{M_n^2} \varepsilon^{\mu\nu\rho\sigma} \mathcal{D}_\mu \theta_x \left(H^\dagger \mathcal{D}_\nu H - h.c.\right) F^Y_{\rho\sigma}$$

where

$$\mathcal{D}_\mu = \partial_\mu \theta_x - g_X Z'_\mu$$

θ_x - Stueckelberg axion

$\mathcal{D}_\mu$ - Stueckelberg gauge invariant combination

D_μ - covariant derivative

M_n - heavy fermion mass, coming from the Higgs mechanism breaking Z' gauge symmetry

After electroweak breaking we get

$$\frac{v^2}{M_h^2}\,\varepsilon^{\mu\nu\rho\sigma} Z'_\mu B_\nu F^Y_{\rho\sigma}$$

With two extra $U(1)'$s :

$$\varepsilon^{\mu\nu\rho\sigma} \mathcal{D}_\mu \theta_x \mathcal{D}_\nu \theta'_x F^Y_{\rho\sigma}$$

dim 4

Can be generated by a heavy chiral but anomaly-free spectrum

A digression: difference between one and two (or more) U(1)'s

WITH ONE Z', the coefficient of dim 4 gauge invariant operator
vanishes for anomaly
free fermionic sector in the triangle;

(the gauge invariant dim 4 operator is a sum of the axionic coupling and the CS term)

The heavy sector is by itself anomaly free

$$\sum_h \left(X_L^i X_L^j X_L^k - X_R^i X_R^j X_R^k \right)^{(h)} = 0$$

We parametrize $S_i = (V_i + s_i)\, e^{i a_i / V_i}$

The gauge transformations

$$\delta A_\mu^i = \partial_\mu \alpha^i \qquad \delta a_i = V_i \alpha^i$$

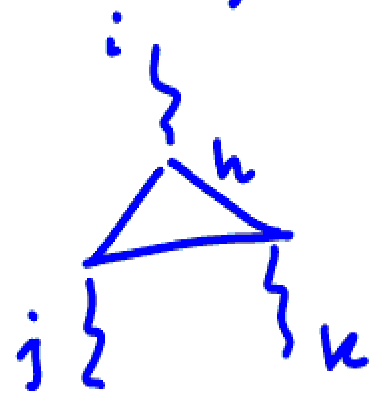
ANOMALY IS MASS INDEPENDENT;

THE NEW EFFECTS COME FROM MASS INSERTIONS ON THE FERMIONIC LINES IN THE TRIANGLE

(WE WANT TO INTEGRATE OUT HEAVY FERMIONS)

Anastasopoulos, Bianchi, Dudas, Kiritsis

Performing a diagrammatic computation of triangle diagrams



and expanding in powers of external momenta $k/M^{(h)}$, we can define the effective action

$$S = -\sum_i \int \frac{1}{4} F_{i,\mu\nu} F_i^{\mu\nu}$$

$$+ \frac{1}{2} \int \sum_i \left(\partial_\mu a^i - g_i V_i A_\mu^i \right)^2$$

Stueckelberg field

$$+ \frac{1}{96\pi^2} C^i_{ij} \, \varepsilon^{\mu\nu\rho\sigma} \int a^i F^i_{\mu\nu} F^j_{\rho\sigma}$$

axion coupling

$$+ \frac{1}{48\pi^2} E_{ij,k} \, \varepsilon^{\mu\nu\rho\sigma} \int A^i_\mu A^j_\nu F^k_{\rho\sigma}$$

generalized Chern-Simons term

where $E_{ij,k} + E_{jk,i} + E_{ki,j} = 0$

Explicitly, in the decoupling limit $M^{(h)} \to \infty$, with V_i - fixed

$$E_{ij,k} = \frac{1}{4} \sum_h \left(X_L^i X_R^j - X_R^i X_L^j \right)^{(h)} \times \left(X_R^k + X_L^k \right)^{(h)}$$

$$C_{ij}^I = \frac{1}{4 g_I V_I} \sum_{h_I} \varepsilon^{(h_I)I} \left[2 \left(X_L^i X_L^j + X_R^i X_R^j \right) + X_L^i X_R^j + X_R^i X_L^j \right]^{(h_I)}$$

Gauge invariance of the effective S gives

$$C^{i}_{jk}\, g_i V_i - E_{ij,k} - E_{ik,j} = 0$$

$$C^{i}_{jk}\, g_i V_i + C^{j}_{ki}\, g_j V_j + C^{k}_{ij}\, g_k V_k = 0$$

Therefore

$$E_{ij,k} = \frac{1}{3}\left(g_i V_i C^{i}_{jk} - g_j V_j C^{j}_{ik}\right)$$

Example : one Z'

We are interested in the XYY GCS term, where $X \equiv Z'$, Y - hypercharge

	Y	X
ψ_L^a	y_a	x_a
ψ_R^a	y_a	$x_a - \epsilon_a$

$$l_a = \dim R_a$$

Mixed anomaly

$$\mathrm{Tr}(Y^2 X) = \sum_a \ell_a y_a^2 \epsilon_a$$

GCS :

$$E_{XY,Y} = \frac{1}{2} \sum_a \ell_a y_a^2 \epsilon_a$$

axion coupling

$$C_{YY} = \frac{3}{2gV} \sum \ell_a y_a^2 \epsilon_a$$

$$\mathrm{Tr}(Y^2 X) = 0 \Rightarrow E = C = 0$$

Example: two Z'

	Y	X_1	X_2
ψ^a_L	y_a	x_a	z_a
ψ^a_R	y_a	$x_a - \epsilon_a$	z_a
χ^m_L	y_m	x_m	z_m
χ^m_R	y_m	x_m	$z_m - \epsilon_m$

The effective action S' can be rewritten as (using the previous relations, following from its gauge invariance)

$$\frac{1}{48\pi} d_{ijk} \, \varepsilon^{\mu\nu\rho\sigma} (\partial a^i - g^i V^i A^i)_\mu \times$$

$$\times (\partial a^j - g^j V^j A^j)_\nu F^k_{\rho\sigma}$$

INVISIBLE Z' AND DARK MATTER

An effective model with

$\left.\begin{array}{l}\psi_L^{DM} \\ \psi_R^{DM}\end{array}\right\}$ charged under a spontaneously broken extra $U(1)_X$, with charges X_L^{DM}, X_R^{DM}

and vector-like under SM;

SM fermions are neutral under $U(1)_X$;
the only way Z' can contribute to the low-energy physics is through effective interactions

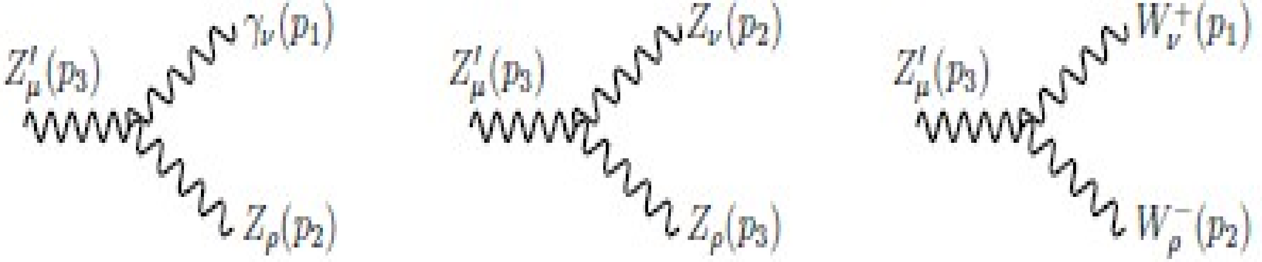


Figure 1: Three vertices of interest generated by (9).

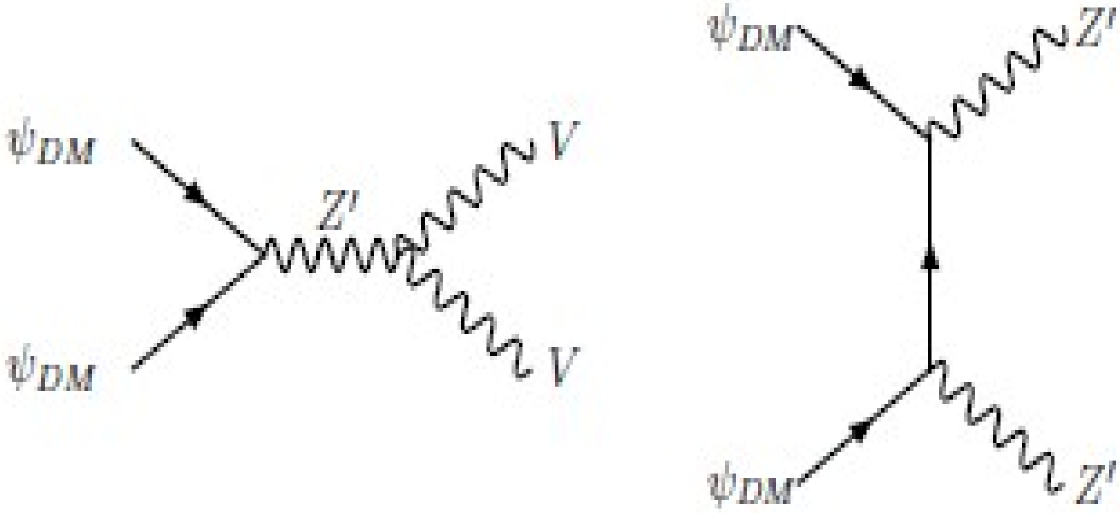


Figure 2: Feynman diagrams contributing to the dark matter annihilation.

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{\psi}_L^{DM} D_\mu^{(X)} \psi_L^{DM} + \psi_L \to \psi_R$$

$$- \left(\bar{\psi}_L^{DM} M_{DM} \psi_R^{DM} + h.c. \right) +$$

$$+ \frac{1}{2} \left(\partial_\mu a - M_{Z'} Z'_\mu \right)^2 - \frac{1}{4} F^X_{\mu\nu} F^{X\mu\nu}$$

$$+ \mathcal{L}_1 (Z'_\mu) + \mathcal{L}_2 (B_\mu, W^a_\mu) + \mathcal{L}_{mix}(Z', B_\mu, W^a_\mu)$$

$$\delta A_X = \partial^\mu \alpha \qquad \delta a_X = \alpha g_X V$$

Higgs $\quad S = (V + s) \exp(i \, a_X / v)$

$X^{DM}_{L,R}$ charges

$X^{DM}_L = X^{DM}_L$ vector-like

$X^{DM}_L = X^{DM}_R \pm 1$ chiral

$\lambda_{DM} S \bar{\Psi}^{DM}_L \Psi^{DM}_R$

$\lambda_{DM} S^+ \bar{\Psi}^{DM}_L \Psi^{DM}_R$

$$\theta_x \equiv \frac{a_x}{V} \quad , \quad \mathcal{D}_\mu \theta_x \equiv \partial_\mu \theta_x - g_x Z'$$

$$\tilde{F} \equiv \epsilon^{\mu\nu\rho\sigma} F^{\rho\sigma}$$

$$(FG) \equiv \mathrm{Tr}\left[F_{\mu\nu} G^{\mu\nu}\right]$$

$$\mathrm{Tr}\,(EFG) \equiv \mathrm{Tr}\left[E_\mu{}^\lambda F_{\lambda\nu} G^{\nu\mu}\right]$$

S carries charge $+1$ under $U(1)_x$

dim 6

$$\frac{1}{M^2}\Big\{ b_1 \,\mathrm{Tr}\,(F^X F^Y \tilde{F}^Y) + b_2 \,\mathrm{Tr}\,(F^X F^W \tilde{F}^W) + b_3 \,\mathrm{Tr}(F^Y F^X \tilde{F}^X)$$

$$+ \mathcal{D}^\mu \vartheta_x \big[i (\mathcal{D}^\nu H)^\dagger (c_1 \tilde{F}^Y_{\mu\nu} + c_2 \tilde{F}^W_{\mu\nu} + c_3 \tilde{F}^X_{\mu\nu}) H$$

$$+ \text{c.c} \big]$$

$$+ \partial^\mu \mathcal{D}_\mu \vartheta_x \big[d_1 (F^Y \tilde{F}^Y) + 2 d_2 (F^W \tilde{F}^W) + d_3 (F^Y \tilde{F}^X) \big] + \mathcal{D}_\mu \vartheta_x \mathcal{D}^\mu \vartheta_x [\quad]$$

We are interested in the couplings reproducing

$$\varepsilon^{\mu\nu\rho\sigma} \mathcal{D}_\mu \theta_x \mathcal{D}_\nu \theta_H F^Y_{\rho\sigma}$$

$$\theta_H = {}^a H/v$$

(after electroweak breaking)

to get $\quad \varepsilon^{\mu\nu\rho\sigma} Z'_\mu B_\nu F^Y_{\rho\sigma}$;

indeed, we get $\dfrac{v^2}{M_H^2} \varepsilon^{\mu\nu\rho\sigma} Z'_\mu B_\nu F^Y_{\rho\sigma}$

$$\Gamma^{Z' \gamma Z}_{\mu\nu\rho}(p_3, p_1, p_2) =$$

$$= -g \frac{(d_1 - d_2)}{M_Z^2} g_X \sin\theta_W \cos\theta_W \,*$$

$$* \underline{(p_1 + p_2)^\mu} \varepsilon_{\nu\rho\sigma\tau} p_2^\sigma p_1^\tau$$

$$- 2 \frac{e g_X}{\cos\theta_W \sin\theta_W} \frac{v^2}{M^2} \left[c_1 \cos\theta_W + c_2 \sin\theta_W \right] *$$

$$* \epsilon_{\mu\nu\rho\sigma} p_1^\sigma$$

Similarly for $\Gamma^{Z'ZZ}$, $\Gamma^{Z'W^+W^-}$

$$\Gamma_{\psi_{DM}\psi_{DM}Z'} = i\frac{g'}{4}\gamma^\mu\left(V_{DM} - A_{DM}\gamma_5\right)$$

Pure vectorial coupling: d_i do not contribute because of the vector current conservation; for axial $\partial j_A \sim M_{DM}$

$$\psi^{DM}\psi^{DM} \rightarrow Z' \rightarrow \gamma\gamma$$

$$E_\gamma = M_{DM}\left[1 - \left(\frac{M_Z}{2M_{DM}}\right)^2\right]$$

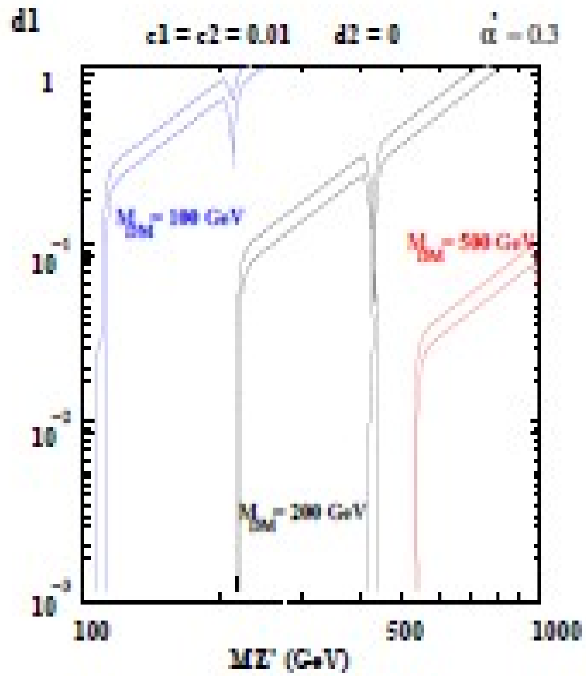


Figure 4: Scan on the mass of Z' (in logarithmic scale) versus the coupling d_1 for $d_2 = 0$ and $M = 1$ TeV. We also defined $\alpha' = g_X^2/4\pi$. Colored lines represent the WMAP limits on the dark matter relic density for different values of the dark matter mass. Notice that the results are invariant under the rescaling $M \to \alpha M$, $(c_i, b_i) \to (\alpha^2 c_i, \alpha^2 d_i)$.

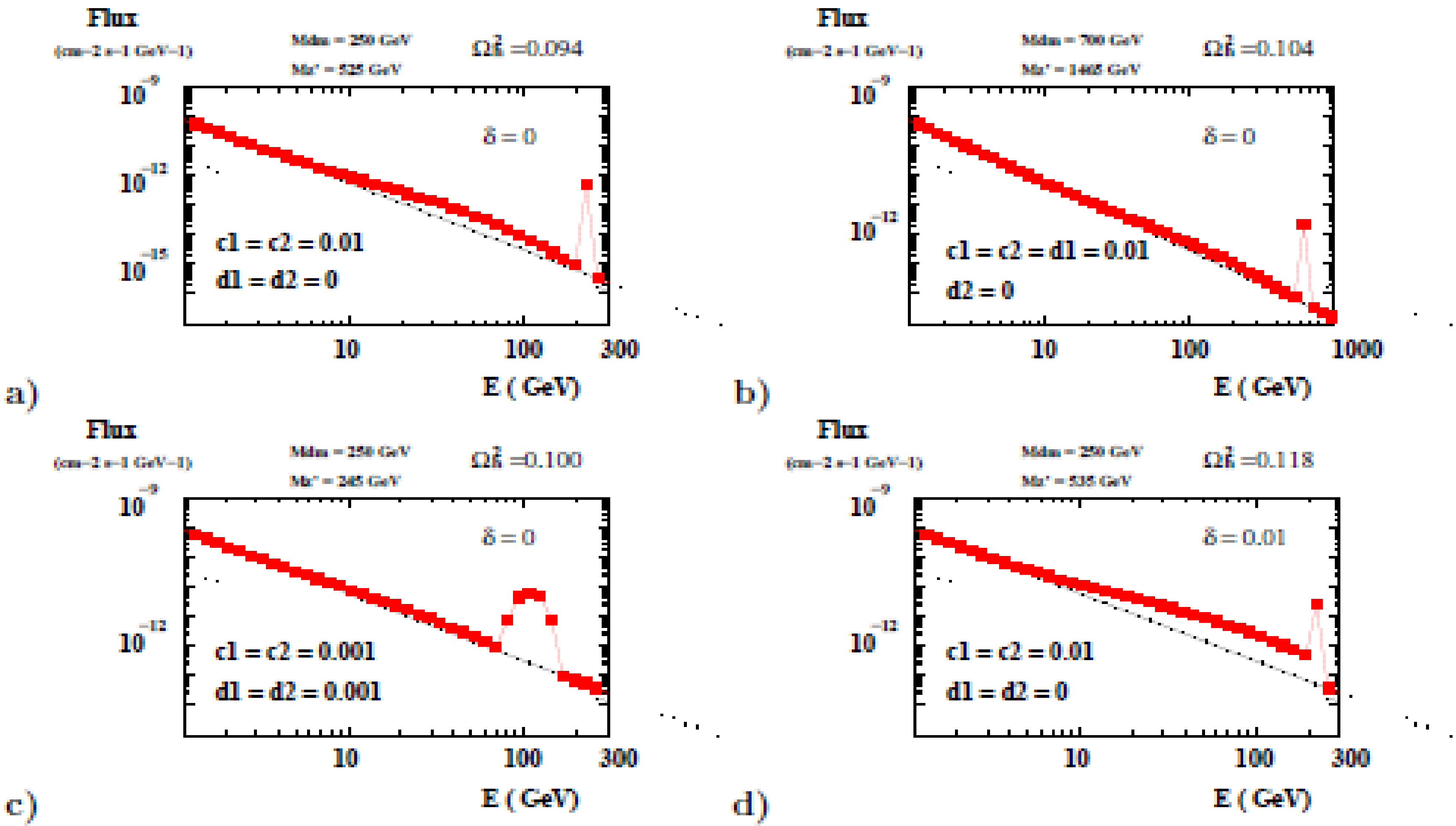


Figure 5: Typical example of a gamma-ray differential spectrum for different masses of dark matter and Z' and $Z - Z'$ mixing angle, compared with the background (black line [19]). All fluxes are calculated for a classical NFW halo profile and $M = 1$ TeV.

SUMMARY

Heavy fermions, chiral under additional U(1) and vector-like with respect to the SM, generate effective operators that mixSM with Z’ via a Z’VV effective vetices, even if they cancel among themselves all gauge anomalies.

The lightest fermion charged under Z’ is stable and could be a darkmatter candidate. Its annihilations could produce a visible gamma-ray line (no signal is expected from a direct detection experiments).

$\mathcal{L}_{mix}\,(Z', B, W)$:

dim 4 : $\delta\, F^{Y}_{\mu\nu} F^{X\,\mu\nu}$, $i\eta\, \bar{\theta}_{\mu}\theta_X\, H^{+} D_{\mu} H + h.c$

kinetic mixing

mass mixing

$Z - Z'$

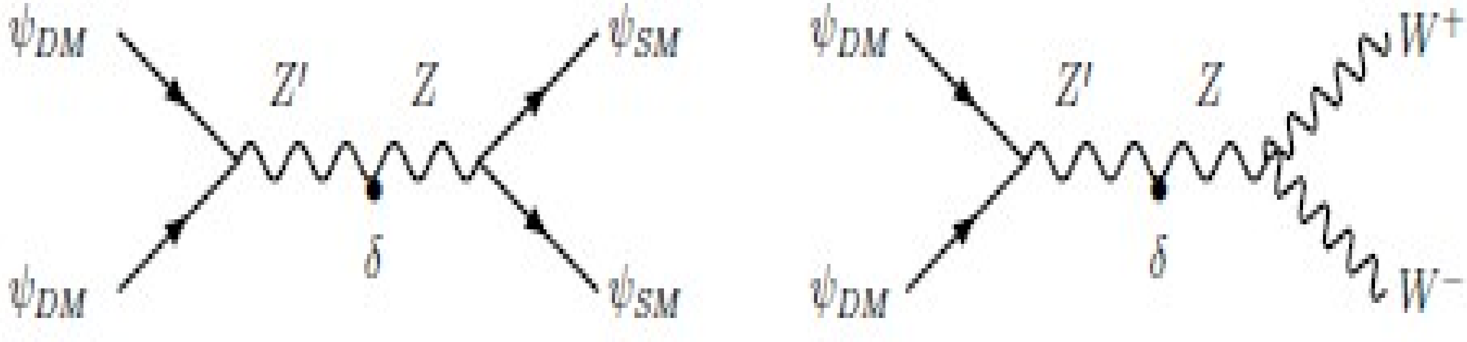


Figure 3: Rôle of the mixing parameter δ.

Several spontaneously broken $U(1)$'s

$\psi^{n}_{L,R}$ – chiral fermions, with masses given by Yukawa couplings and $U(1)_i$ charges $X^{(n)i}_{L,R}$

S_i – Higgs fields, with charge 1 under $U(1)_i$, and zero otherwise

$$L_h = \bar{\psi}_L^{(h)} \left(i\gamma^\mu \partial_\mu + g^i X_L^{(h)i} \gamma^\mu A_\mu^i \right) \psi_L^{(h)}$$

$$+ \bar{\psi}_R^{(h)} \left(i\gamma^\mu \partial_\mu + g^i X_R^{(h)i} \gamma^\mu A_\mu^i \right) \psi_R^{(h)}$$

$$- \left(\bar{\psi}_L^{(h)} M^{(h)} \psi_R^{(h)} + h.c. \right)$$

$$M_{ab}^{(h)} = \lambda_{ab}^{h} S_i \qquad \langle S_i \rangle = V_i$$

or $$M_{ab}^{(h)} = \lambda_{ab}^{h} \bar{S}_i$$

$$X_L^{(h_i)i} - X_R^{(h_i)i} = \pm 1 \equiv \varepsilon^{(h_i)i}$$

We are interested in $E_{x_1 x_2 , Y}$

and $C^{1}_{x_2 Y}$, $C^{2}_{x_1 Y}$

$$\mathrm{Tr}(X_1 X_2 Y) = \sum_a l_a \epsilon_a y_a z_a + \sum_m l_m \epsilon_m x_m y_m$$

$$E_{x_1 x_2 , Y} = \frac{1}{2}\left(\sum_a l_a \epsilon_a y_a z_a - \sum_m l_m \epsilon_m x_m y_m\right)$$

$$C^{x_1}_{x_2 Y} = \frac{3}{2 g_1 V_1} \sum_a l_a \epsilon_a y_a z_a \, , \quad C^{x_2}_{x_1 Y} \simeq \sum_m l_m \epsilon_a x_m y_m$$

Imposing $\mathrm{Tr}(X_1 X_2 Y) = 0$ we get the effective action

$$d_{X_1 X_2, Y}\, \varepsilon^{\mu\nu\rho\sigma} (\partial a_1 - g_1 V_1 A_1)_\mu (\partial a_2 - g_2 V_2 A_2)_\nu F^Y_{\rho\sigma}$$

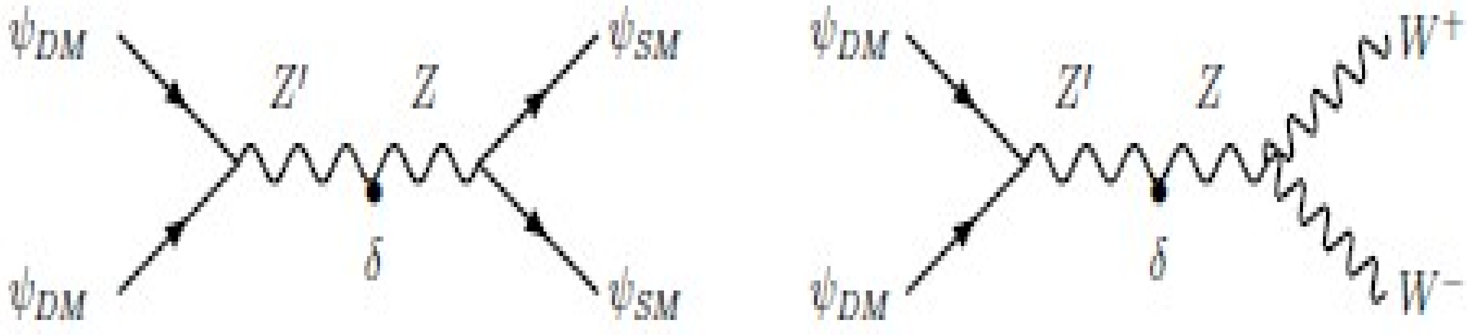
$$d_{X_1 X_2, Y} = \frac{1}{g_1 g_2 V_1 V_2} E_{X_1 X_2, Y}$$

The fermions are charged (vector-like) under the SM group, and chiral with respect to $U(1)$'s

Let's suppose $\lambda^{h}_{ab} \gg g_i$

We consider the limit M_V fixed, $M^{(h)} \to \infty$

We are interested in the (in)visible Z', where SM fermions are neutral under the massive $U(1)$'s



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