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(IN)VISIBLE Z', (NON)DECOUPLING AND DARK MATTER

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Outline

- Standard and "anomalous" Z'
- Effective operators
- (In)visible Z' and decoupling of heavy fermions
- (In)visible Z' as mediator of dark matter annihilation

- the monochromatic gamma ray line

- Conclusions

1. Standard and "anomalous" Z'

Simplest extensions of the standard model : additional $U(1)_X$ gauge symmetry, broken around TeV. I will call them Z' theories in what follows.

They are generically of two types :

a) standard (non-anomalous)

- All gauge and gravitational anomalies are canceled by the low-energy spectrum.
- Only gauge and Yukawa interactions are present.

There is a huge literature on such low-energy Z'.

b) ”anomalous”

There are some un-canceled reducible anomalies. They cancel in the underlying theory due to :

- axions with Green-Schwarz type couplings in string theories.
- heavy chiral (wrt Z’) fermions in field theory models, which generate non-decoupling effects at low-energy.

They can also have TeV masses, have distinctive features (some recent papers: Anastasopoulos, Bianchi,E.D., Kiritsis; Haack, Van Proeyen, Zagermann; Kumar, Wells; Anastasopoulos, Fucito,Pradisi et al.; Coriano et al; Antoniadis et al; see talk I. Antoniadis).

- Anomaly cancelation in orientifold models involves several axions.
- Abelian gauge fields $\longrightarrow$ Stueckelberg mixing with axions which render the corresponding, "anomalous" gauge fields, massive.
- They can behave like Z' gauge bosons. However, these massive gauge bosons can and do have anomalous couplings which naively break gauge invariance.
- Important role played by local and gauge non-invariant terms : generalized Chern-Simons terms (GCS).

GCS have a long history : $\mathcal{N} = 2$ SUGRA, brane-Xtra dims. models, Scherk-Schwarz compactifications...

• Relevant terms in the effective action

$$\mathcal{S} \;=\; -\sum_i \frac{1}{4g_i^2} F_{i,\mu\nu} F_i^{\mu\nu} - \frac{1}{2}\sum_I (\partial_\mu a^I - g_i V_i A_\mu^i)^2 \;,$$
$$+\frac{1}{24\pi^2} C_{ij}^I \int a^I F_i \wedge F_j + \frac{1}{48\pi^2} E_{ij,k} \int A_i \wedge A_j \wedge F_k \;,$$

- A_i are abelian gauge fields, a^I are axions with Stueckelberg couplings which render massive (some of) the gauge fields.

Axionic exchanges = nonlocal contributions, whereas the GCS terms are local terms $\rightarrow$
the sum : triangle diagrams, axionic exchange and GCS terms is gauge invariant *and* non vanishing.

It leads to anomalous three gauge boson couplings at low energy.

The coefficients $E_{ij,k}$ satisfy (Andrianopoli,Ferrara, Llledo)

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

and the gauge invariance conditions, in the presence of an anomaly free spectrum, read

$$\begin{aligned} C^i_{jk} g_i V_i - E_{ij,k} - E_{ik,j} &= 0 \ , \\ C^i_{jk} g_i V_i + C^j_{ki} g_j V_j + C^k_{ij} g_k V_k &= 0 \ . \end{aligned} \qquad (1)$$

One can easily find the solution of (1)

$$E_{ij,k} = \frac{1}{3}\left(g_i V_i C^i_{jk} - g_j V_j C^j_{ik}\right) \ . \qquad (2)$$

Notice it is possible to have anomaly-free Z'

$$t_{ijk} \equiv Tr(Q_i Q_j Q_j) = 0$$

and non-vanishing anomalous three gauge boson couplings at low energy. They have the form

$$E_{ij,k}\ (A^i - \frac{1}{g_i V_i} da^i) \wedge (A^j - \frac{1}{g_j V_j} da^j) \wedge F^k \ .$$

2. **Effective operators**

(In)visible Z' is defined by

- it contains anomalous three gauge boson couplings, in particular $Z' \; Z \; \gamma$
- SM fields are neutral under Z'.

• Heavy fermions, charged both under Z' and the SM, with a chiral (but anomaly-free) spectrum can generate non-decoupling effects leading to the one-loop "anomalous" three gauge boson vertices.

Their effects can be encoded in local polynomials, constrained by gauge invariance and CP symmetry.

- One Z' gauge symmetry

Define:

$$\theta_X \equiv \frac{a_X}{V} \quad , \qquad \mathcal{D}_\mu \theta_X \equiv \partial_\mu \theta_X - g_X Z'_\mu \ ,$$
$$\widetilde{F}_{\mu\nu} \equiv \epsilon_{\mu\nu\rho\sigma} F^{\rho\sigma} \quad , \qquad (FG) \equiv \mathrm{Tr}[F_{\mu\nu} G^{\mu\nu}]$$

Gauge invariance and CP select the operators :

- Dimension-four operator :

$$\delta \times \ F^Y_{\mu\nu} F^{X\,\mu\nu}$$

This parameterizes the kinetic mixing between Z' and the hypercharge.

• Dimension-six operators :

$$\mathcal{L}_{mix} \;=\; \frac{1}{M^2}\Big\{\mathcal{D}^\mu\theta_X\left[i(D^\nu H)^\dagger(c_1\widetilde{F}^Y_{\mu\nu}+c_2\widetilde{F}^W_{\mu\nu})H+c.c.\right]$$
$$+\partial^\mu\mathcal{D}_\mu\theta_X\Big[d_1(F^Y\widetilde{F}^Y)+2d_2(F^W\widetilde{F}^W)\Big]\Big\}\;.$$

In the SM broken phase the first line contains :

$$\epsilon^{\mu\nu\rho\sigma}\mathcal{D}_\mu\theta_X\;\mathcal{D}_\nu\theta_H\;F^Y_{\rho\sigma}\;,$$

where $\theta_H = a_H/v$.

Obs : The operators mixing one Z' with SM do decouple. In what follows we consider an energy range

$$0.1\;\leq\;\frac{E}{M}\;\leq\;0.01\;.$$

• Two Z' gauge symmetries . In this case there is a genuine non-decoupling effect; corresponding operator

$$(Z'_1 - \frac{1}{g_1 V_1} da_1) \wedge (Z'_2 - \frac{1}{g_2 V_2} da_2) \wedge F_Y \ .$$

Easy to find heavy fermions generating this operator, see next slides (see also Antoniadis et al, 2009).

3. (In)visible Z' and decoupling of heavy fermions

The axionic and GCs terms can be computed, by adding heavy fermions charged under both SM and $U(1)_i$, with *SM invariant* masses, generated by the $U(1)_i$ Higgs mechanism.

The relevant terms in the effective action of the heavy fermion sector of the theory are

$$\begin{aligned} L_h &= \bar{\psi}_L^{(h)} \left(i\gamma^\mu \partial_\mu + g^i X_L^{(h)i} \gamma^\mu A_\mu^i \right) \psi_L^{(h)} \\ &\quad + \bar{\psi}_R^{(h)} \left(i\gamma^\mu \partial_\mu + g^i X_R^{(h)i} \gamma^\mu A_\mu^i \right) \psi_R^{(h)} \\ &\quad - \left(\bar{\psi}_L^{(h)} M^{(h)} \psi_R^{(h)} + \text{h.c.} \right) \ , \end{aligned}$$

where M^h is the mass matrix of heavy fermions, with matrix elements

$$\begin{aligned} M^{(h)}_{ab} &= \lambda^h_{ab}\ S_i \qquad \text{case (a)} \quad \text{or} \\ M^{(h)}_{ab} &= \lambda^h_{ab}\ \bar{S}_i \qquad \text{case (b)}\ , \end{aligned} \tag{3}$$

where S_i is the Higgs field of charge $+1$ under the gauge group $U(1)_i$ and singlet with respect to the other gauge groups. The Higgses spontaneously break the abelian gauge symmetries via their vevs, $\langle S_i \rangle = V_i$.

• The heavy fermions are *vector-like* wrt SM, but *chiral* wrt $U(1)_i$.

In the decoupling limit

$$M^{(h)}\ ,\ M_{S_i}\ \gg\ M_{Z_i}\quad ,\quad (g_i\ \ll\ \text{Yukawas})$$

with finite Higgs vev's V_i, we obtain

(Anastasopoulos,Bianchi,E.D.,Kiritsis, 06)

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

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

the index h_I refers to the heavy fermionic spectrum coupling to the axion a_I.

Difference compared to d'Hoker-Fahri (DF) operators is that (4) are well-defined in the unbroken SM limit.

Ex: Two Z'

Consider the charge assignments ($\epsilon = \pm 1$)

	Y	X_1	X_2
Ψ_L^a	y_a	x_a	z_a
Ψ_R^a	y_a	$x_a - \epsilon_a$	z_a
χ_L^m	y_m	x_m	z_m
χ_R^m	y_m	x_m	$z_m - \epsilon_m$

We are interested in the GCS term $E_{X_1 X_2, Y}$ and the two axionic couplings $C^1_{X_2 Y}$ and $C^2_{X_1 Y}$. We find

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

$$E_{X_1 X_2 , Y} \ = \frac{1}{2} \left(\sum_a l_a \epsilon_a y_a z_a - \sum_m l_m \epsilon_m x_m y_m \right) \ ,$$

$$C^{X_1}_{X_2 Y} \ = \ \frac{3}{2 g_1 V_1} \ \sum_a l_a \epsilon_a y_a z_a \quad , \quad C^{X_2}_{X_1 Y} \ = \ \frac{3}{2 g_2 V_2} \ \sum_m l_m \epsilon_m x_m y_m$$

By imposing cancelation of the mixed anomaly $Tr\ (X_1 X_2 Y) = 0$, we find that the GCS and the axionic couplings exactly fit into the gauge invariant term

$$E_{X_1 X_2 , Y} \ \epsilon^{\mu\nu\rho\sigma} \ (\frac{1}{g_1 V_1} \partial_\mu a_1 - X_{1,\mu})(\frac{1}{g_2 V_2} \partial_\nu a_2 - X_{2,\nu}) \ F^Y_{\rho\sigma} \ .$$

- Does this violates the Appelquist-Carazzone decoupling theorem ?

3. (In)visible Z' as mediator of dark matter (DM) annihilation

• Main idea :

- The DM is the lightest fermion in the Z' sector.

- it annihilates into $Z\gamma$ and WW via Z' exchange, giving a correct relic density.

- the same diagram produces a mono-chromatic gamma ray

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

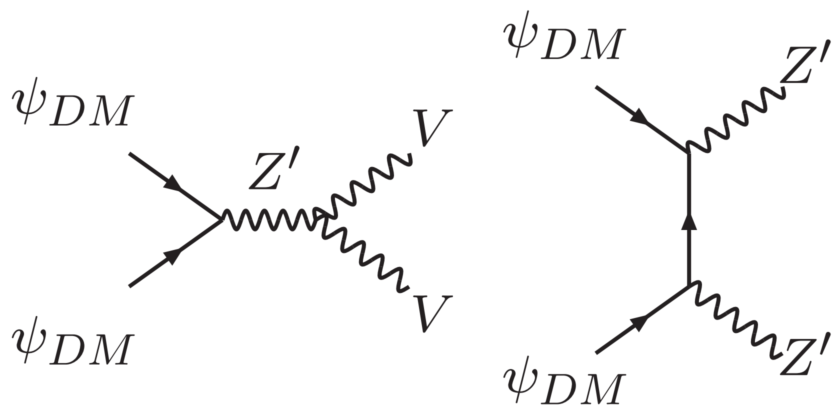
which could be visible in the GLAST/FERMI satelite.

The $Z'VV$ interaction vertices generated by the effective operators are :

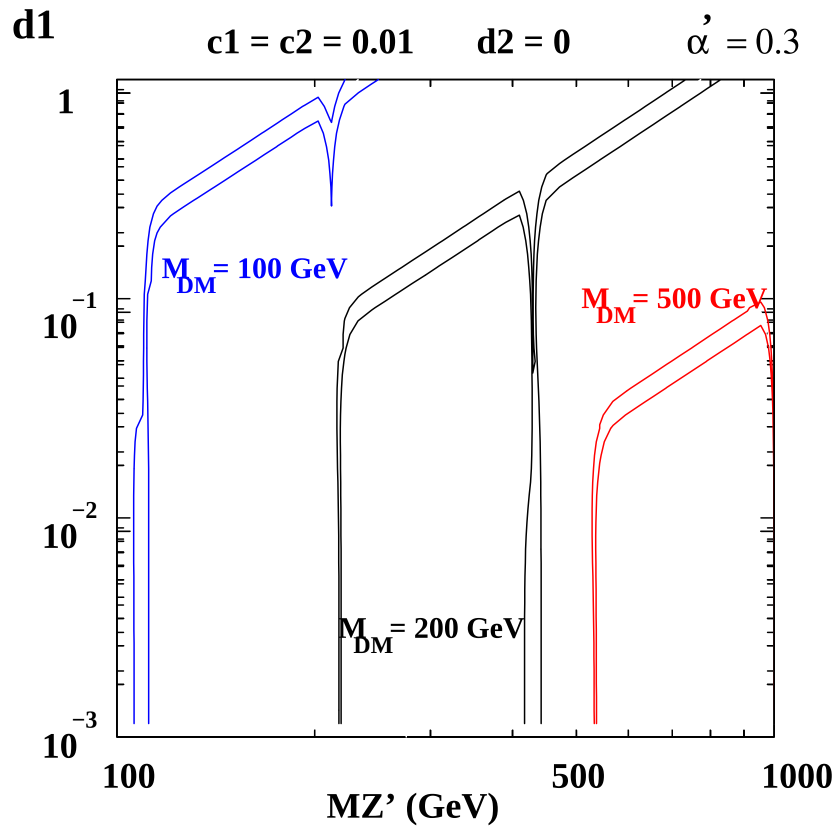
$$\Gamma^{Z'\gamma Z}_{\mu\nu\rho}(p_i) = -8\ \frac{(d_1 - d_2)}{M^2} g_X \sin\theta_W \cos\theta_W (p_1 + p_2)^\mu \epsilon_{\nu\rho\sigma\tau} p_2^\sigma p_1^\tau$$
$$-2\ \frac{e\ g_X}{\cos\theta_W \sin\theta_W} \frac{v^2}{M^2} [c_1 \cos\theta_W + c_2 \sin\theta_W]\, \epsilon_{\mu\nu\rho\sigma} p_1^\sigma\ ,$$

$$\Gamma^{Z'ZZ}_{\mu\nu\rho}(p_i) = -4\ \frac{(d_1 \sin^2\theta_W + d_2 \cos^2\theta_W)}{M^2} g_X (p_1 + p_2)^\mu \epsilon_{\nu\rho\sigma\tau} p_2^\sigma p_1^\tau$$
$$-\ \frac{e\ g_X}{\cos\theta_W \sin\theta_W} \frac{v^2}{M^2} [c_2 \cos\theta_W - c_1 \sin\theta_W]\, \epsilon_{\mu\nu\rho\sigma} (p_2^\sigma - p_1^\sigma)\ ,$$

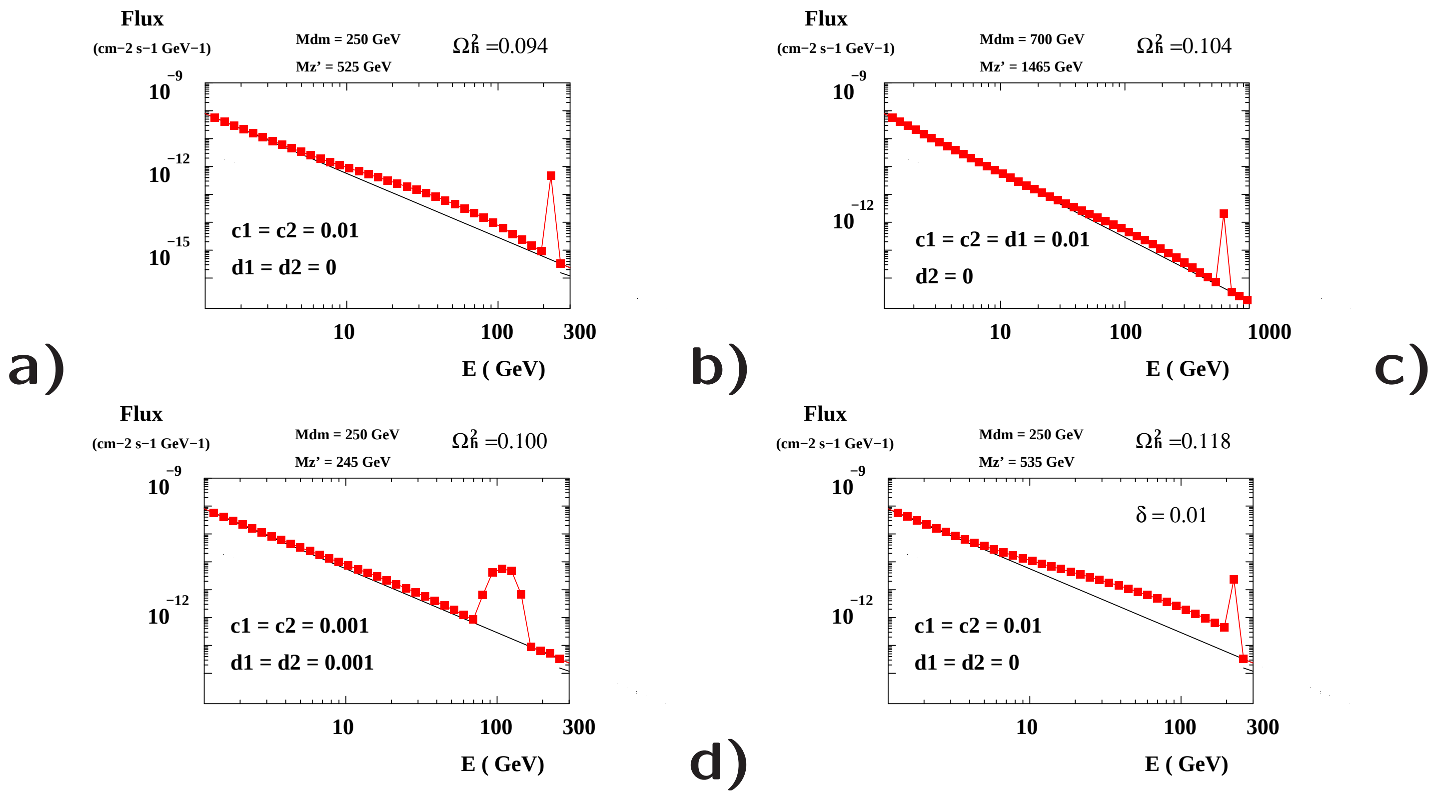
$$\Gamma^{Z'W^+W^-}_{\mu\nu\rho}(p_i) = -4\ \frac{d_2}{M^2} g_X (p_1 + p_2)^\mu \epsilon_{\nu\rho\sigma\tau} p_2^\sigma p_1^\tau$$
$$-\ \frac{e\ g_X}{\cos\theta_W \sin\theta_W} \frac{v^2}{M^2} c_2 \epsilon_{\mu\nu\rho\sigma} (p_2^\sigma - p_1^\sigma)$$



Feynman diagrams contributing to the dark matter annihilation



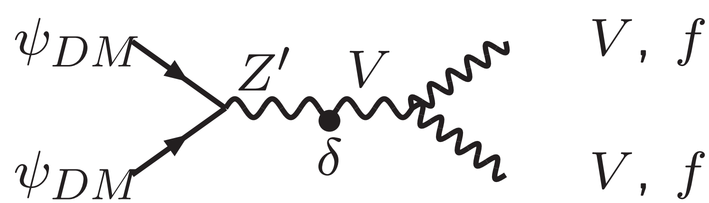
Scan on the mass of Z' (in logarithmic scale) versus the coupling d_1 for $d_2 = 0$ and $M = 1$ TeV. We also defined $\alpha' = g_X^2/4\pi$. Colored lines represent the WMAP limits on the dark matter relic density for different values of the dark matter mass.



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). All fluxes are calculated for a classical NFW halo profile and $M = 1$ TeV.

We neglected the $Z' - Y$ kinetic mixing. If dominant over $Z'Z\gamma$ coupling, tends to erase its effects

• Large literature on SM-hidden sector coupling generated by kinetic mixing : Arkani-Hamed et al, Nath et al, Strassler, Zurek .... It is possible however to suppress kinetic mixing versus $Z'Z\gamma$ coupling. Ex: heavy fermions in complete $SU(5)$ representations.



Including the mixing parameter

Conclusions

• Three gauge boson ''anomalous'' vertices can connect an otherwise invisible Z' to SM.

• We provided explicit examples with heavy fermions generating at low energy these vertices.

• The diagram generating the correct relic density also generates a monochromatic gamma-ray line.

• An (in)visible Z' can be light (GeV) $\longrightarrow$ phenomenology to explore.

• It would be interesting to analyze more generally non-decoupling effects of heavy chiral fermions for LHC.

See you all next year in Paris for String Pheno 2010