(In)visible Z' and Dark Matter

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E. Dudas, Y. Mambrini, S. Pokorski, A.R.
JHEP 0908:014,2009 – arXiv:0904.1745 [hep-ph]

A. Falkowski, Y. Mambrini, A.R. in progress

N. Bernal, A. Goudelis, A.R. in progress

Extensions of Standard Model

We know that the Standard Model is only an effective field theory, there is something more (at least neutrino masses and dark matter).

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Add new space-time structures

ex) Supersymmetry, Extra-dimensions, String Theory,...

Combine the three

The "hidden" sector (heavy matter) communicates with the visible one (the usual Standard Model) through different mechanisms (supersymmetric and/or gravitational interactions, Kaluza-Klein modes, . . .), and the extra gauge-group provides a portal among the others to the new physics.

Example: KKLT framework

The presence of an extra U(1) can help to impose the suitable constraints (moduli stabilization, vanishing cosmological constant, TeV superpartner masses), and provide original spectra and dark matter scenarios.

("D-term induced" uplift [E.Dudas, Y.Mambrini, S. Pokorski, A.R., M. Trapletti, 08-09])

Forget SUSY and extra-dim: Only heavy fermions & Extra U(1)$_X$

Z'-hunter's guide

Hye-Sung Lee http://sites.google.com/site/zprimeguide/,
or

P. Langacker, "The Physics of Heavy Z' Gauge Bosons," Rev. Mod. Phys. **81** (2008) 1199 [arXiv:0801.1345 [hep-ph]].

- Sources of U$(1)'$
- U$(1)'$ Symmetry Breaking at TeV-scale
- Alternative Solutions to the μ-problem
- Challenges in TeV-scale Z' model building
- U$(1)'$ and Proton Decay and also exotic fields
- More Z' Models
- Implications of Z': Gauge boson sector, EWPT sector, CP and FCNC sector, Neutrino sector, Neutralino sector, Sneutrino sector, Baryogenesis sector, Higgs sector, ...

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Hybrid sector

States with SM and U(1)$_X$ quantum numbers. They act as a portal between the two previous sector.

A possibility: Kinetic Mixing

Chun et al., Mambrini, 2010

SU(3) $\times$ SU(2) $\times$ U(1)$_Y$ $\times$ U(1)$_X$

$$\mathcal{L} = \frac{1}{4g_Y^2} F_{Y,\mu\nu} F_Y^{\mu\nu} + \frac{1}{4g_X^2} F_{X,\mu\nu} F_X^{\mu\nu} + \delta F_{Y,\mu\nu} F_X^{\mu\nu} + \dots$$

The coefficient δ can be generated at one-loop by the matter in the hybrid sector.

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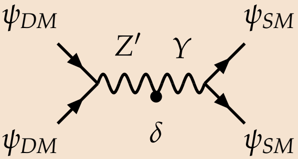
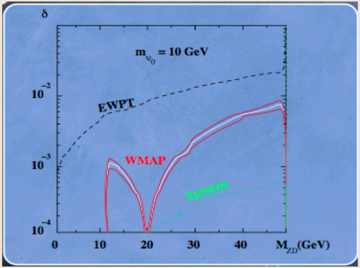
Open a portal on hidden physics

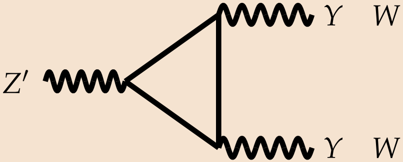
We can have informations for example from the Dark Matter side





A new portal: The trilinear bosonic couplings

Another possibility



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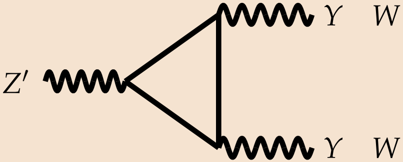

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Z′, and its analysis at LHC (ex: WW-fusion)

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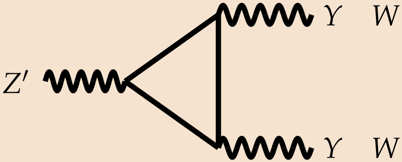

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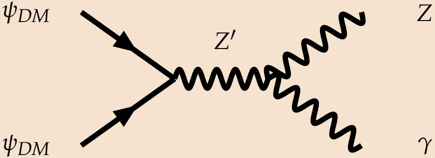
Dark Matter, and its detection through γ-ray lines



Summary

From the very beginning...

Whatever extra we want to introduce, the effective field theory at low energy has to be compatible with experimental constraints (EW precision data).

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They will reflect the symmetries of the UV physics.

Examples of H.-D. operators

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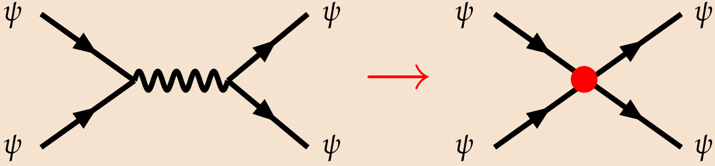
Fermi theory



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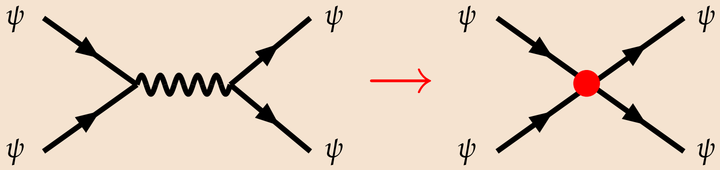

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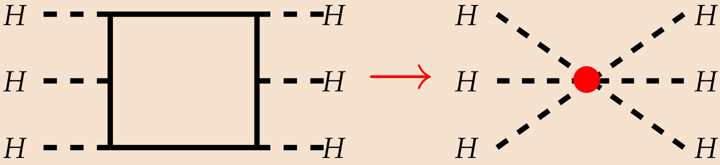
Loop suppressed



$\psi\psi H$ $\qquad$ $\frac{1}{16\pi^2 M_\psi^2} H^6 + \ldots$

4-D. operators

Are there contributions to the 4-dimensional operators coming from heavy particles "integrated out"?

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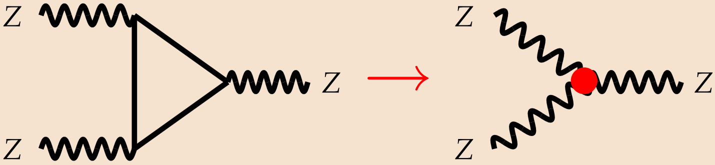
Yes, an example is given by the kinetic mixing

In particular, what about: Triangles?



$\psi\psi Z$ $\longrightarrow$ $(???)\partial ZZZ$

Decoupling

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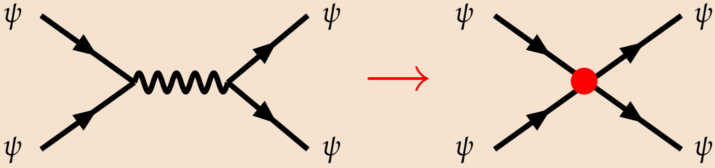
Decoupling "theorem"

T. Appelquist, J. Carazzone, Phys. Rev. D 11 (1975) 2856

The decoupling theorem states that, in the limit of heavy masses $M_\psi \longrightarrow \infty$, the extra terms will have no observable effects. Or, more precisely, those effects from heavy particles are either suppressed by inverse powers of M_ψ, or can be reabsorbed into renormalizations of couplings, masses, or field strength tensors of the theory.

Again..

Fermi theory



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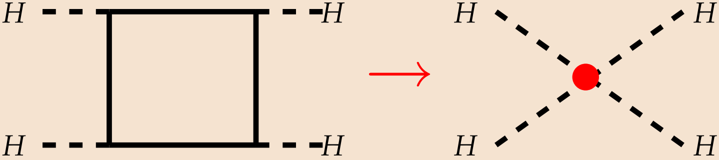

$\lambda H^4 + \psi\psi H$ $\qquad$ $\left(\lambda' + \frac{1}{16\pi^2} f\left(\frac{\Box}{M_\psi^2}\right)\right) H^4$

Anomalies

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Gauge Anomaly

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The only way to restore consistency of a theory is to arrange the exact cancellation of anomalies between various chiral sectors of the theory (ex. in SM between quarks and leptons).

Particles involved in anomaly cancellation may have very different masses (ex: the mass of the top quark in the SM is much higher than the masses of all other fermions).

Anomalies vs. Decoupling

Gauge invariance should pertain in the theory at all energies

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Gauge invariance should pertain in the theory at all energies

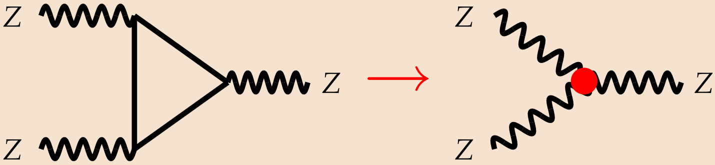
E. D'Hoker, E. Farhi, Nucl. Phys. B248 (1984)

The case of anomaly cancellation presents a notable counterexample to the decoupling theorem:

- anomalous (i.e. gauge-variant) terms in the effective action have topological nature and are therefore scale independent.
- they are not suppressed even at energies much smaller than the masses of the particles producing these terms via loop effects.

Then...

Triangles: integrate out the top



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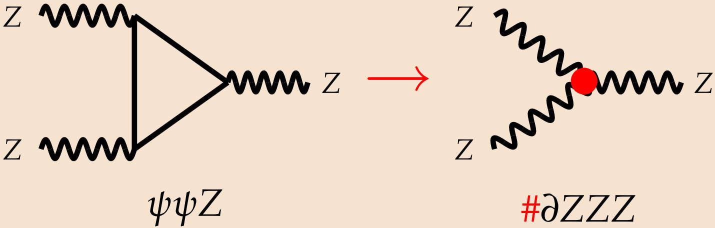

There is an effective operators of the form

$$\sim \frac{1}{H^\dagger H}\, \epsilon^{\mu\nu\rho\sigma}\, D_\mu \theta_H\, \left(H^\dagger D_\nu H - D_\nu H^\dagger H\right) F_{\rho\sigma}$$

which restores the gauge invariance of the total (tree-level + 1-loop) effective lagrangian.

Focusing on extra U(1)

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Standard Z' theories

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- Only gauge and Yukawa interactions are present.

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Anomalous Z' theories

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 can generate (non?)-decoupling effects at low-energy.

Anomalous Z' theories

Anastasopoulos, Bianchi, Dudas, Kiritsis, JHEP 0611 (2006) 057; Coriano et al., …

Effective action (forgetting kinetic mixing for the moment)

$$\mathcal{S} = -\sum_i \int d^4x \frac{1}{4g_i^2} F_{i,\mu\nu} F_i^{\mu\nu} + \frac{1}{2}\int d^4x \sum_i (\partial_\mu a^i - g_i V_i A^i_\mu)^2$$

$$+ \frac{1}{96\pi^2} C^I_{ij}\, \epsilon^{\mu\nu\rho\sigma} \int a^I F^i_{\mu\nu} F^j_{\rho\sigma} + \frac{1}{48\pi^2} E_{ij,k}\, \epsilon^{\mu\nu\rho\sigma} \int A^i_\mu A^j_\nu F^k_{\rho\sigma}\ .$$

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Stueckelberg mixing terms with axions which render the corresponding gauge fields massive.

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Axionic exchanges: nonlocal contributions

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Generalized Chern-Simons terms: "anomalous" three gauge bosons coupling

Stueckelberg mechanism

The Stueckelberg mechanism can be understood as a heavy Higgs mechanism, where an extra Higgs field S takes vev V and then the form:

$$S = (V + s)\exp\,[i\frac{a_X}{V}]$$

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This picture is useful when we think to an heavy fermionic sector taking chiral mass. However, one could discuss about Stueckelberg mechanism in more general framework

(Mambrini's paper).

Anomalous three gauge boson couplings

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Gauge invariance requirement

$$Tr(Q_i Q_j Q_k) + E_{ij,k} + M_i^I C_{jk}^I = 0$$

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Our starting point

Notice that it is possible to have standard (anomaly-free) Z', $Tr(Q_i Q_j Q_k) = 0$, and non-vanishing anomalous three gauge boson couplings at low energy. They have the form

$$d_{ij,k} \, \epsilon^{\mu\nu\rho\sigma} \, (\partial a^i - M_i A^i)_\mu \, (\partial a^j - M_j A^j)_\nu \, F_{\rho\sigma}^k$$

(In)visible Z' and decoupling of heavy fermions

Definition

(In)visible Z': extra $\mathrm{U}(1)$ massive gauge boson, and:

- All SM fields are neutral under Z'
- There is a sector of heavy fermions charged both under the SM and Z', chiral but anomaly-free
- The effects of the heavy fermions are only encoded at low-energy in effective couplings, containing anomalous three gauge boson couplings

Warm up: Two Z' 's case

In this case there is a genuine non-decoupling effect.

It's easy in fact to write down a gauge invariant operator with 2 different covariant derivatives.

The corresponding operator is [with $\theta_i = a_i/(g_i V_i)$]

$$E_{Z'_1 Z'_2, Y}\, \epsilon^{\mu\nu\rho\sigma}\, (\partial\theta_1 - Z'_1)_\mu (\partial\theta_2 - Z'_2)_\nu\, F^Y_{\rho\sigma}$$

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NOTE: I am asking for two extra gauge fields, two extra "Higgs fields", an extra sector of fermions . . . maybe it's not a "simple" extension of the Standard Model.

However: this sector can be "arbitrarily" heavy, but its effects on the low-energy theory remain sizeble.

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Subtlety

Calculations in the limit: Yukawa's $\lambda_i \to \infty$, VEV's V_i finite.

Explicit example for the two Z' 's case

Formula in the limit $\lambda_i \to \infty$, X^i charges of the (h) = heavy spectrum under i group

$$E_{ij,k} \;=\; \frac{1}{4}\sum_h (X^i_L X^j_R - X^i_R X^j_L)^{(h)}(X^k_R + X^k_L)^{(h)}\,,$$

It is then easy to find examples of heavy fermionic sectors generating it (l_a fermions Ψ and l_m fermions χ)

	Y	Z'_1	Z'_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	$z_m - \epsilon_m$

$Tr(Z'_1 Z'_2 Y) = \sum_a l_a \epsilon_a y_a z_a + \sum_m l_m \epsilon_m x_m y_m,\qquad E_{Z'_1 Z'_2, Y} = \frac{1}{2}\left(\sum_a l_a \epsilon_a y_a z_a - \sum_m l_m \epsilon_m x_m y_m\right)$

and then

$Tr(Z'_1 Z'_2 Y) = 0 \qquad \Rightarrow \qquad E_{Z'_1 Z'_2, Y} = \sum_a l_a \epsilon_a y_a z_a \neq 0$

One Z' case

Decoupling

In this case, by symmetry,

$$E_{Z'Z',Y}\, \epsilon^{\mu\nu\rho\sigma}\, (\partial\theta_X - Z')_\mu (\partial\theta_X - Z')_\nu\, F^Y_{\rho\sigma} = 0$$

One Z' case

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Heavy fermions at mass scale Λ

- If they are vector-like, effective operators have to preserve charge conjugation C.
  Furry's theorem $\rightarrow$ Euler-Heisemberg type $(1/\Lambda^4)F^4 + \ldots$
- If they are chiral, effective operators violate C and trilinear coupling are allowed.

One Z' case: CP even operators

- Dimension-four operators :

$$\delta\, F^{Y}_{\mu\nu} F^{X\,\mu\nu} \qquad , \qquad i\eta\, \mathcal{D}_\mu \theta_X H^\dagger D_\mu H + c.c.$$

- Dimension-six operators :

$$\begin{aligned}
\frac{1}{\Lambda^2}\Big\{ & b_1 \mathcal{T}r(F^X F^Y \widetilde{F}^Y) + 2b_2 \mathcal{T}r(F^X F^W \widetilde{F}^W) + b_3 \mathcal{T}r(F^Y F^X \widetilde{F}^X) \\
& + \mathcal{D}^\mu \theta_X \left[i(D^\nu H)^\dagger (c_1 \widetilde{F}^Y_{\mu\nu} + c_2 \widetilde{F}^W_{\mu\nu} + c_3 \widetilde{F}^X_{\mu\nu}) H + c.c. \right] \\
& + \partial^\mu \mathcal{D}_\mu \theta_X \left[d_1 (F^Y \widetilde{F}^Y) + 2 d_2 (F^W \widetilde{F}^W) + d_3 (F^Y \widetilde{F}^X) \right] \\
& + \mathcal{D}_\mu \theta_X \mathcal{D}^\mu \theta_X \left[d_4 (F^Y F^Y) + 2 d_5 (F^W F^W) \right] \Big\} .
\end{aligned}$$

Notation

$\mathcal{D}_\mu \theta_X = (\partial \theta_X - Z')_\mu$ $\qquad$ $D^\nu H$: SM covariant derivative of Higgs

One Z' case: Trilinear couplings

$$
\begin{aligned}
\Gamma^{Z'\gamma Z}_{\mu\nu\rho}(p_3;p_1,p_2) &= -8\,\frac{(d_1-d_2)}{\Lambda^2} g_X \sin\theta_W \cos\theta_W (p_1+p_2)^\mu \epsilon_{\nu\rho\sigma\tau} p_2^\sigma p_1^\tau \\
&\quad -2\,\frac{e\,g_X}{\cos\theta_W \sin\theta_W}\frac{v^2}{\Lambda^2}\left[c_1\cos\theta_W + c_2\sin\theta_W\right]\epsilon_{\mu\nu\rho\sigma}p_1^\sigma \\
\Gamma^{Z'ZZ}_{\mu\nu\rho}(p_3;p_1,p_2) &= -4\,\frac{(d_1\sin^2\theta_W + d_2\cos^2\theta_W)}{\Lambda^2} g_X (p_1+p_2)^\mu \epsilon_{\nu\rho\sigma\tau} p_2^\sigma p_1^\tau \\
&\quad -\frac{e\,g_X}{\cos\theta_W \sin\theta_W}\frac{v^2}{\Lambda^2}\left[c_2\cos\theta_W - c_1\sin\theta_W\right]\epsilon_{\mu\nu\rho\sigma}(p_2^\sigma - p_1^\sigma) \\
\Gamma^{Z'W^+W^-}_{\mu\nu\rho}(p_3;p_1,p_2) &= -4\,\frac{d_2}{\Lambda^2} g_X (p_1+p_2)^\mu \epsilon_{\nu\rho\sigma\tau} p_2^\sigma p_1^\tau \\
&\quad -\frac{e\,g_X}{\cos\theta_W \sin\theta_W}\frac{v^2}{\Lambda^2} c_2 \epsilon_{\mu\nu\rho\sigma}(p_2^\sigma - p_1^\sigma)
\end{aligned}
$$

Coefficients related to structures

$c_i \leftrightarrow (v^2\,\partial)/\Lambda^2;\qquad d_i \leftrightarrow (\partial^3)/\Lambda^2$

Experimental signatures

How is it possible to experimentally detect such theories with extra $\mathrm{U}(1)_X$?

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If SM fermions are charged with respect to the $\mathrm{U}(1)_X$ group, and the mass of the new Z' bosons is around the TeV scale, we should be able to see the corresponding resonance in the forthcoming runs of LHC; ex) $q\bar{q} \to Z' \to f\bar{f}$.
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What happens if the SM fermions are not charged with respect to the $\mathrm{U}(1)_X$ group?

(Kumar, Rajaraman, Wells, arXiv:0707.3488 [hep-ph]
Antoniadis, Boyarsky, Espahbodi, Ruchayskiy, Wells, arXiv:0901.0639 [hep-ph]
→ study of LHC detection)

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

see also Y. Mambrini, JCAP 0912 (2009) 005

Main Idea

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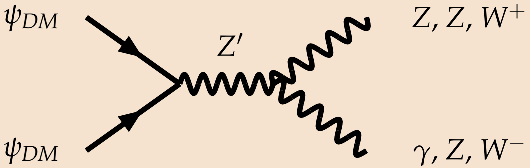

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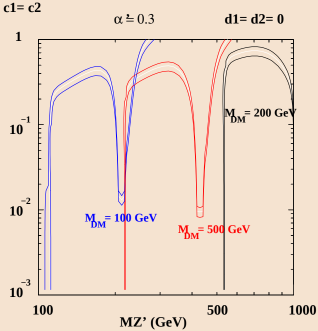

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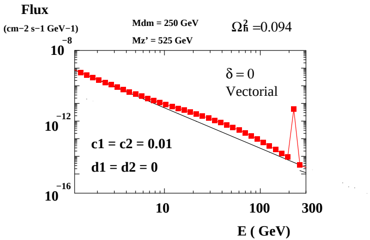
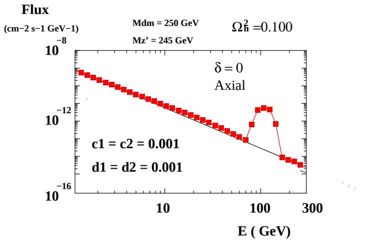
- It gives the correct relic density [implementing it into CompHEP of micrOMEGAs]
- The same diagram produces a mono-chromatic gamma ray

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

  which could be visible in future experiments.
  Crucial point: DM annihilation happens almost at rest.
- There is NO $\gamma\gamma$ final state C. N. Yang, Phys. Rev. **77** (1950) 242.

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

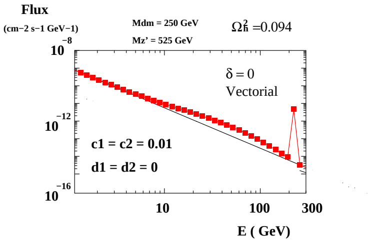


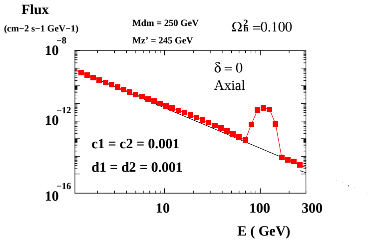


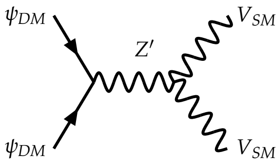
Examples of a gamma-ray differential spectrum (red boxes) for different values of Z' masses at a fixed DM mass $M_{dm} = 250$ GeV and $\Lambda = 1$ TeV, in comparison with the background (black line).

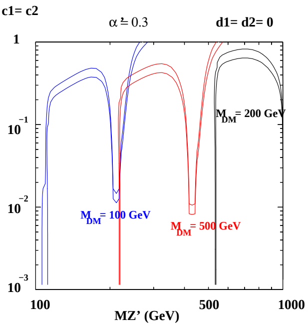
Remember: $c_i \leftrightarrow (v^2\,\partial)/\Lambda^2$; $\quad d_i \leftrightarrow (\partial^3)/\Lambda^2 \sim (M_{DM}^2\,\partial)/\Lambda^2$

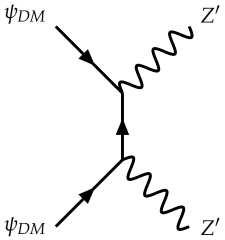
(In)visible Z' as mediator of dark matter annihilation











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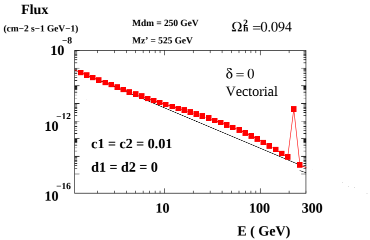
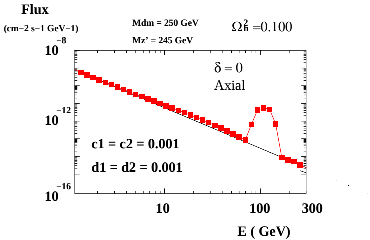
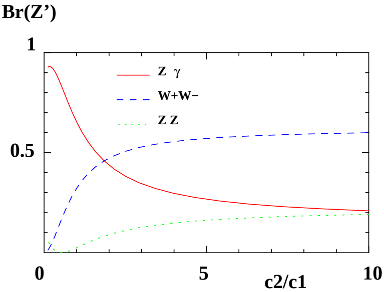




Branching ratio for $M_{DM} = 200$ GeV, $M_{Z'} = 215$ GeV and $d_1 = d_2 = 0$



Dark Matter detection

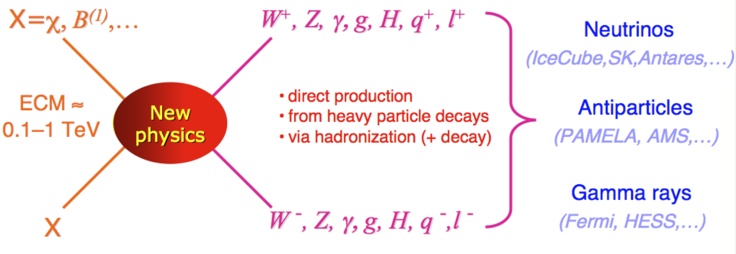
Usual strategies:

Serpico's talk at Planck09

Experiment	*Source*	*Interaction*	*Channel*
Direct	Local (crossing Earth surface)	WIMP-nucleus scattering	Phonons
Indirect	Earth, Sun, Galaxy, Cosmos	WIMP decay/ annihilation	γ,ν, Antimatter
Collider	Controlled production	WIMP pair production	$\not{E}$

Dark Matter detection

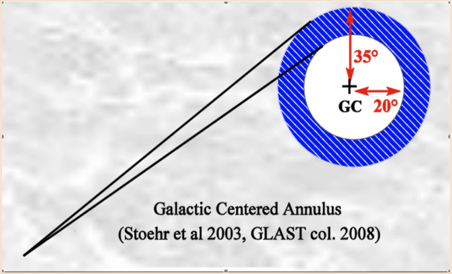
Indirect detection



Target	Advantage	Challenges
Spectral line $E \approx m_X$ anywhere	Smoking gun	Loop process, suppressed, Experimental E-resolution

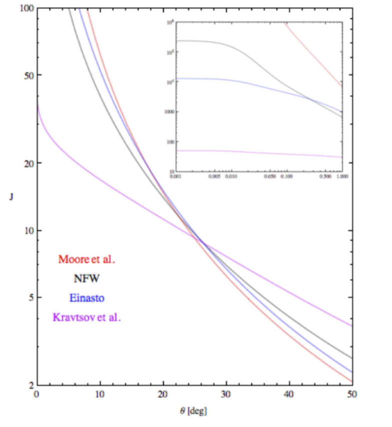
Indirect detection: Observability

Observed region



- Signal to noise ratio increased 12 times with respect to the Galactic Center
- Almost independent of the Galactic Profile

Indirect detection: Observability



Indirect detection: Observability

Parameters

Assuming coefficients of order 1 (natural charges) in front of the different operators, there are essentially three free mass parameters for: dark matter, extra gauge boson, heavy fermions.

In particular we are interested in the region 100 GeV - few TeV.

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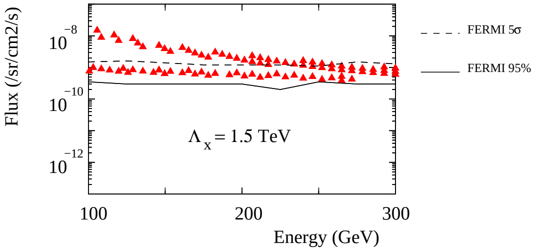
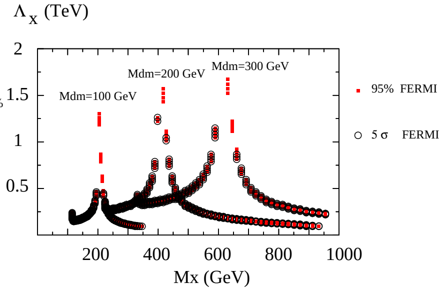
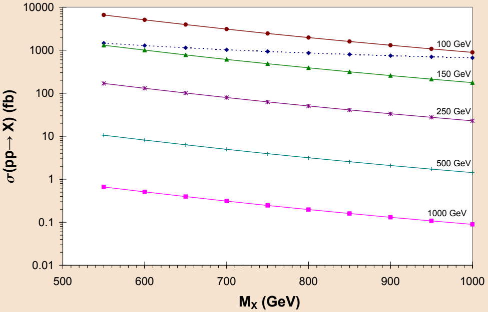




Indirect detection: Observability

To compare with colliders analysis:

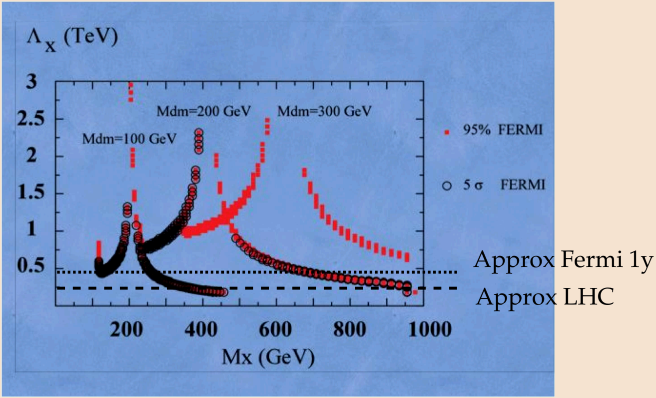


At $\sqrt{s_{pp}} = 14$ TeV LHC as a function of the mass of the extra gauge boson, for different heavy sector scales. The dashed line corresponds to the cross-section required for detection at LHC in the $WW \to X \to ZZ \to 4l$ decay channel.

Kumar, Rajaraman, Wells, Phys. Rev. D **77** (2008) 066011

Indirect detection: Observability

Or looking at the same picture as before:



Kinetic Mixing

Actually the first non-trivial operator one can write is the kinetic mixing between Z' and Y

$$\delta \, F^{Z'}_{\mu\nu} F^{Y\,\mu\nu}$$

The possibilities given by this term have been already studied in many papers (see for example Arkani-Hamed et al. JHEP 0812:104,2008).

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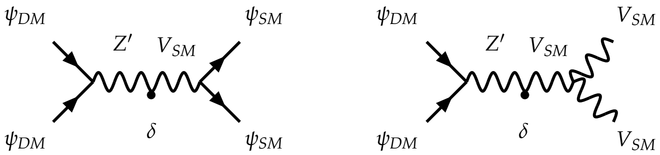
In our case, it can interplay in two ways:

- If δ is small, it just rotates mass states with respect to the gauge ones ($\rightarrow$ Milli-charged dark matter)
- If it is dominant over $Z'\,Z\,\gamma$ coupling, it will tend to lower its effects (namely the gamma line)



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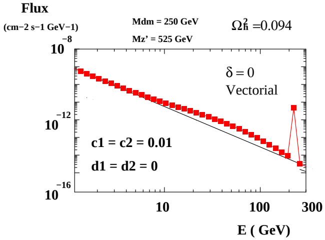

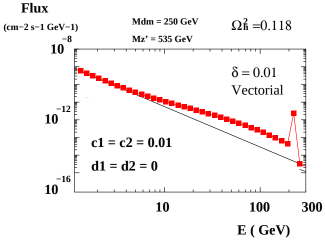

Flux spectrum profile changes when the kinetic mixing term δ is turned on, keeping the good value for relic density.

Kinetic Mixing

Constraints from direct detection

If the kinetic mixing is turned on, the dark matter annihilates effectively in Z-boson, which can interact with nucleons

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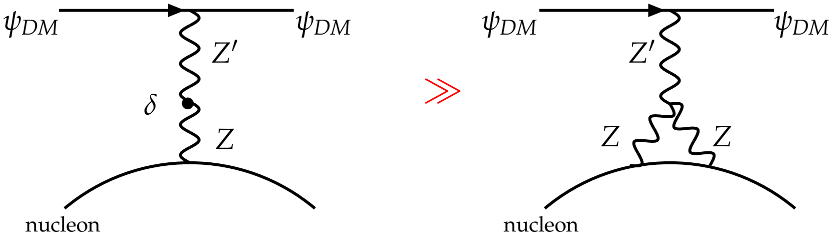
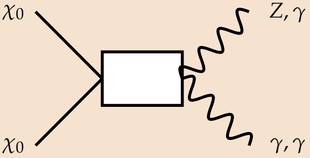


The γ-ray line is still there

For this kind of models, XENON imposes $\delta < 0.01$

Other possibilities

SUSY/KK



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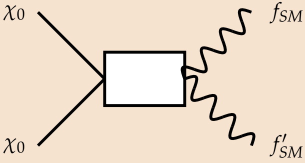

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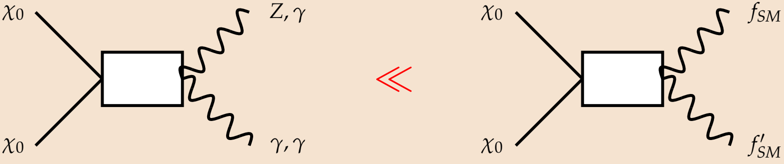
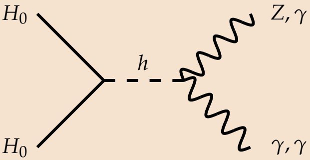
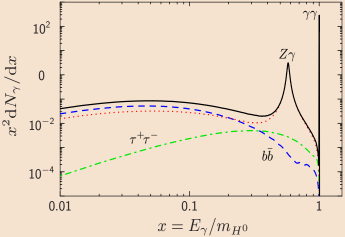


Inert Higgs

Gustafsson et al, Phys. Rev. Lett. 99, 041301 (2007)



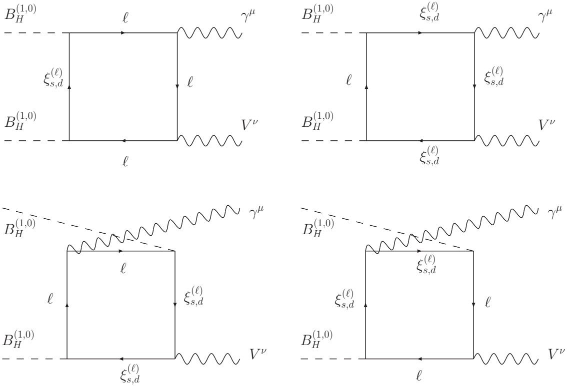


WIMP Forest: The Chiral Square

Bertone et al., Phys. Rev. D 80 (2009) 023512

6dim-model.

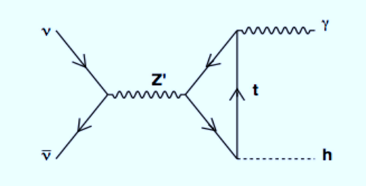
Scenario characterized by three lines ($V = \gamma, Z, KK - exc.$). The two lines at and around the dark matter (LKP), and a line at much lower energies that is clearly distinguishable from the other ones.



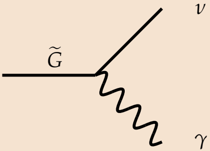
Or again:

Higgs in space! Jackson et al. JCAP 1004 (2010) 004

Like us, but also a line:



Decaying dark matter Bertone et al. JCAP 0711 (2007) 003



From Yann Mambrini's talk

Here the summary of some different known possibilities concerning γ-ray lines from dark matter.

Masse	Direct detection	Indirect detection	LHC
SUSY/KK	Yes	No line	Yes
Chiral Square	Yes	3 lines	?
Inert HiggsModel	Yes	2 lines	Yes
Milli-charged	Yes	No line	Yes
(In)visible X	No	1 line	No

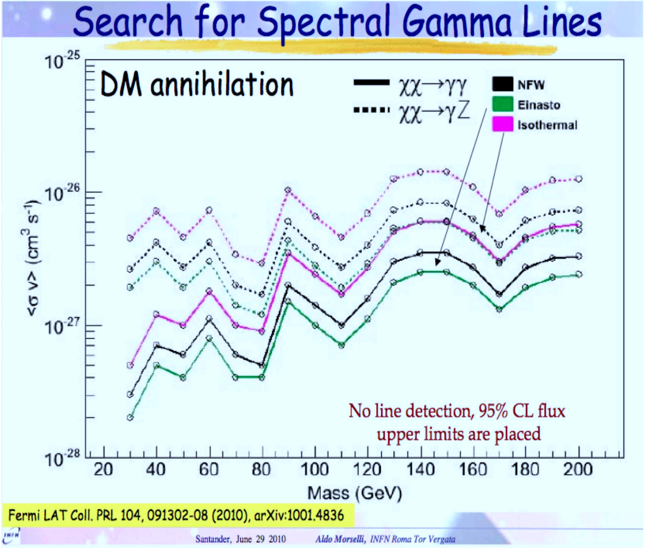
What do experimental data say?

FERMI results (after 1 year data taking) in the region 30-200 GeV

The limits on $\langle\sigma v\rangle_{\gamma\gamma}$ ($\langle\sigma v\rangle_{\gamma Z}$) shown in Table I are about one or more orders of magnitude weaker than the cross-sections expected for a typical thermal WIMP. However, there are several models in the literature that predict larger cross-sections and are constrained by these results. A WIMP produced non-thermally may have a much larger annihilation cross-section than a thermally produced WIMP and still produce the required DM relic density. An example is the "Wino LSP" model [19] that explains the recent positron measurement by PAMELA [37], and predicts $\langle\sigma v\rangle_{\gamma Z} \simeq 1.4 \times 10^{-26}$ cm^3 s^{-1} at $E_\gamma \sim 170$ GeV. Our results disfavor this model by about a factor of $\sim 2-5$, depending on the dark matter halo profile (see Table I). Other models that are partially

Fermi LAT Collaboration, arXiv:1001.4836 [astro-ph.HE]

What do experimental data say?

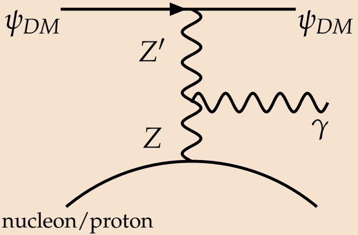


Conclusions & Outlook

- Three gauge boson "anomalous" vertices can connect an otherwise invisible Z' to SM.
- The diagram generating the correct relic density also generates one visible gamma-ray line.
- There is no $\gamma\gamma$ final state, differently from SUSY neutralino and inert Higgs scalars (but sensitivity ...).
- It would be interesting to analyze more generally the non-decoupling effects of heavy chiral fermions : for two Z' is there a violation of the decoupling "theorem" ?
  [N.Bernal, A.Goudelis, A.R.]

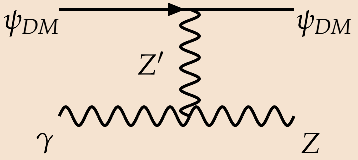
Conclusions & Outlook

New possible funny effects: A.Falkowski, Y.Mambrini, A.R.



Direct Detection + γ-ray?

Scattering with proton (in clouds) + γ-ray?



Scattering with photons with Z-production?