Dark Matter from Disformal Theories of Gravity: Branon Phenomenology

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MultiDark
Multimessenger Approach for Dark Matter Detection

Work done in collaboration with
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L. Díaz-Cruz, A. Dobado,
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DISFORMAL SCALAR FIELDS

Scalar field with coupling:

$$\bar{g}_{\mu\nu} = \mathcal{A}(\phi, (\partial\phi)^2) g_{\mu\nu} - \frac{\mathcal{B}(\phi, (\partial\phi)^2)}{m^4} \partial_\mu \phi \partial_\nu \phi$$

Bekenstein, PRD 48 (1993) 341

They arise in many different theories:

1. Brane-world models

Cembranos, Dobado, Maroto, PRL 90 (2003) 241301

Alcaraz, Cembranos, Dobado, Maroto, PRD 67 (2003) 075010

2. Massive gravity

Rham, Gabadadze, PRD 82 (2010) 04020, 1007.0443

Gabadadze, Rham, Tolley, PRL 231101 (2011) 1011.1232

CONTENTS

EXTRA DIMENSIONS

The main motivations for considering extra dimensions have a theoretical origin.

In the last years the most part of the development in theoretical physics required the introduction of extra dimensions (ED):

1.- Modern Kaluza-Klein (KK) Theories
2.- Supersymmetry (SUSY) and Supergravity (SUGRA)
3.- Superstrings
4.- M-Theory

Introduction of new ideas related to non-perturbative effects : BRANES

BRANE WORLDS (BW)

Detectable extra dimensions.
Posible new physics at the TeV scale

New scenarios where resolving the hierarchy problem: **Brane Worlds (BW)**

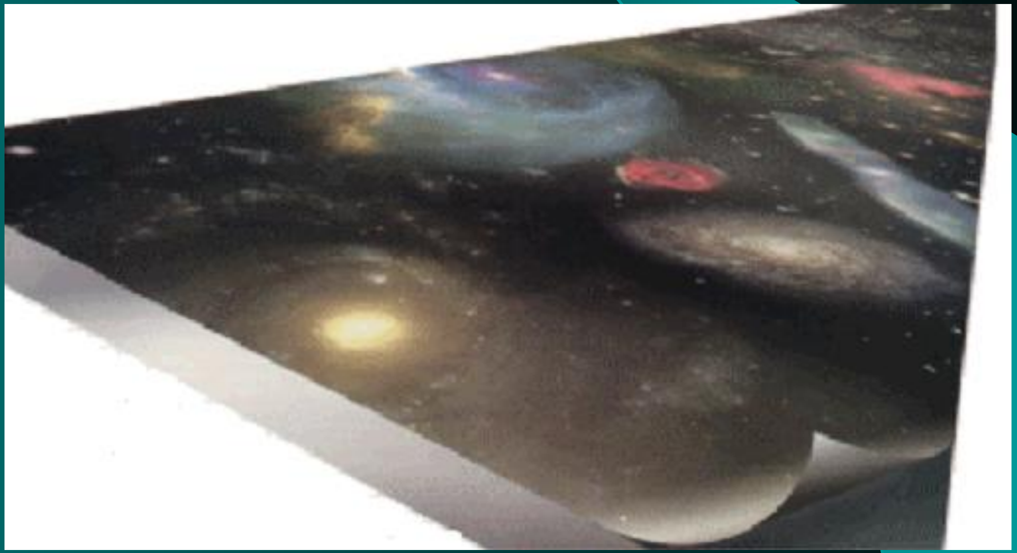
ADD Model (Arkani-Hamed, Dimopoulos and Dvali, 1998)

RS Models (Randall and Sundrum, 1999) ...

THE RESTRICTED UNIVERSE

The main idea is that our universe is restricted to a 3-brane embedded in a higher *D* dimensional space, with $D = 4+\delta$, being the δ extra dimensions compactified..

In this picture the Standard Model (SM) particles are confined to the 3-brane but gravitons can propagate along the whole bulk space.



ADD HIERARCHY

The fundamental scale of gravity is M_F , which could be of the order of the electroweak scale in order to solve the hierarchy problem:

$$M_F \simeq 1\,\mathrm{TeV} \Longleftarrow M_P^2 = V_\delta\, M_F^{2+\delta}$$

The hierarchy between the Planck and electroweak scale is generated by the large volume of the extra dimensions

The typical size *R*, of the extra dimensions ranges from a fraction of *mm* for $\delta = 2$ to about *10 F* for $\delta = 7$.

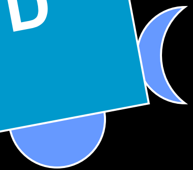
BRANE WORLD SIGNALS

1.- New Gravitation:

Newton law deviations

KK gravit

Black



New physics at the M_F scale

M_F : Fundamental gravitation scale in D dimensions ($M_P^2 = V_\delta M_F^{D-2}$)

2.- The brane as a new dynamical object:

Branons = Brane fluctuations

Topological brane conf

St

Bra apped States

New physics at the f scale

f : Brane tension scale

($\tau = f^4$)

BRANE FLUCTUATIONS

Rigid objects do not exist in relativistic theories.

Consequences of the brane oscillations:

1.- Branons: New fields which represent the position of the brane in the bulk space.

These fields are the (pseudo-)Goldstone bosons corresponding to the spontaneous symmetry breaking of the translation invariance produced by the presence of the brane.

2.- KK coupling suppression : The re
produces an effective
brane wit ... given by :

$$g_k = g \cdot e^{-\frac{1}{2}\left(\frac{k}{R}\right)^2 \frac{M_F^2}{f^4}}$$

$f << M_F$: The KK modes decouple from the SM particles (on the brane)

(Bando, Kugo, Noguchi and Yoshioka)

BRANONS AND THE SM PARTICLES

The conclusion is that for flexible branes ($f \ll M_F$), the only relevant degrees of freedom at low energies in the ADD scenario are the SM particles and the branons.

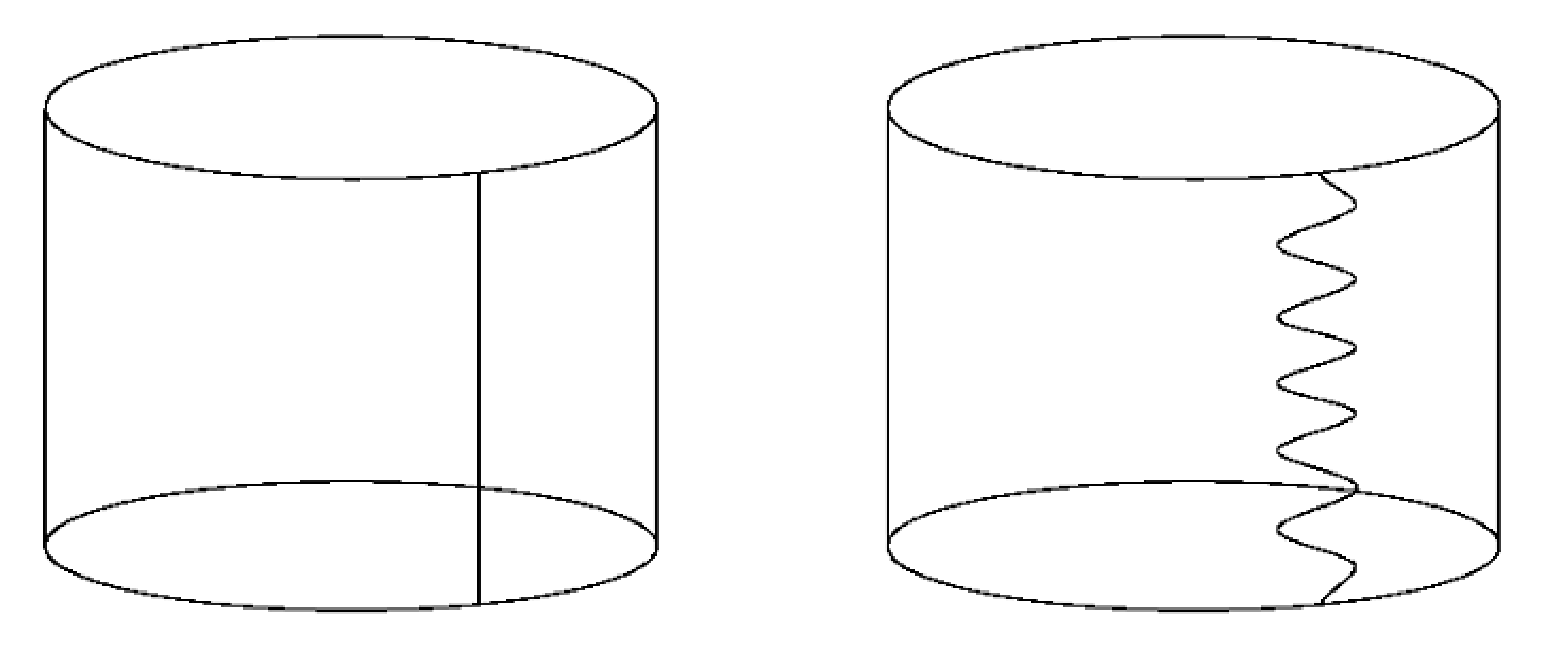
SM Particles ⟷ **Branons**

Branons, as Goldstone or pseudo-Goldstone bosons, are expected to be weakly interacting at low energies (compared with f).

Description through an EFFECTIVE LAGRANGIAN

LOWER DIMENSIONAL EXAMPLE

Brane with trivial topology. The ground state of the brane is represented on the left. On the right we plot an excited state.



BRANON FIELD

Bulk Metric:

Brane coordinates

$$G_{MN} = \begin{pmatrix} \tilde{g}_{\mu\nu}(x) & 0 \\ 0 & -\tilde{g}'_{mn}(y) \end{pmatrix}$$

Extra dimensional coordinates

Induced Metric:

$$g_{\mu\nu} = \partial_\mu Y^M \partial_\nu Y^N G_{MN} = \tilde{g}_{\mu\nu} - \partial_\mu Y^m \partial_\nu Y^n \tilde{g}'_{mn}$$

Branon fields

$$Y^m(x) = Y^m(Y_0, \pi^\alpha(x)) = Y_0^m + \frac{1}{\kappa f^2}\xi_\alpha^m(Y_0)\pi^\alpha(x) + \mathcal{O}(\pi^2)$$

$$\kappa^2 = 16\pi/M_P^2$$

ξ_a } Killing vectors corresponding to translations on the extra space.

BRANON NLSM

At low energies the dominant term in the brane action is the Nambu-Goto term:

$$S_B = -f^4 \int_{M_4} d^4x \sqrt{g}$$

Expanding in branon fields, the dominant term at low energies is a Non-Linear Sigma Model for branons defined on the coset space (or equival… extra space, if it is homog…

Formally very similar to chiral lagrangians in QCD

$$S_B^{(2)} = \ldots \frac{1}{2}\int_{M_4} d^4x \sqrt{\tilde{g}}\,\tilde{g}^{\mu\nu} h_{\alpha\beta}(\pi)\,\partial_\mu \pi^\alpha \partial_\nu \pi^\beta$$

BRANON MASSES

The branons acquire mass in a more general case, when the translational isometries of the extra space are only approximated.

$$G_{MN} = \left(\begin{array}{cc} \tilde{g}_{\mu\nu}(x,y) & 0 \\ 0 & -\tilde{g}'_{mn}(y) \end{array} \right)$$

This fact is related to non factorizable metrics.

$$\sqrt{g} = 1 - \frac{1}{2f^4}\eta^{\mu\nu}\delta_{\alpha\beta}\partial_\mu\pi^\alpha\partial_\nu\pi^\beta + \frac{1}{2f^4}M^{(2)}_{\alpha\beta}\pi^\alpha\pi^\beta + \ \dots$$

SM INTERACTIONS

The interaction of the branons with the SM particles is given by:

$$S_B = \int_{M_4} d^4x\sqrt{g}[-f^4 + \mathcal{L}_{SM}(\ldots$$

$$\ldots - M^2_{\alpha\beta}\pi^\alpha\pi^\beta\eta_{\mu\nu})T^{\mu\nu}_{SM}(\eta_{\mu\nu})\Big] + \mathcal{O}(\pi^3).$$

N: Number of branons.
M: Branon mass.
f: Brane tension scale.

As in the case of the gravitons, the branons couple to the SM through:

$$T^{\mu\nu}_{SM} = -\left(\tilde{g}^{\mu\nu}\mathcal{L}_{SM} + 2\frac{\delta\mathcal{L}_{SM}}{\delta\tilde{g}_{\mu\nu}}\right)\Bigg|_{\tilde{g}_{\mu\nu}=\eta_{\mu\nu}}$$

(Sundrum, Creminelli and Strumia)

PARTICLE COLLIDERS

1.- Electroweak bosons widths modifications.

- 2.a. Invisible Z width.
- 2.b. W decay.

2.- Direct searches in e^+e^- colliders.

- 2.a. Single photon channel.
- 2.b. Single Z channel.
- 2.c. Prospects for future LC.

3.- Direct searches in hadronic colliders.

- 3.a. Single photon channel.
- 3.b. Mono jet channel.
- 3.c. Prospects for future hadronic colliders.

Alcaraz, Cembranos, Dobado, Maroto, PRD 67 (2003) 075010

Z AND *W* DECAYS

Restrictions from LEP-I (plot for *N* = 1):

1.- Z invisible width:

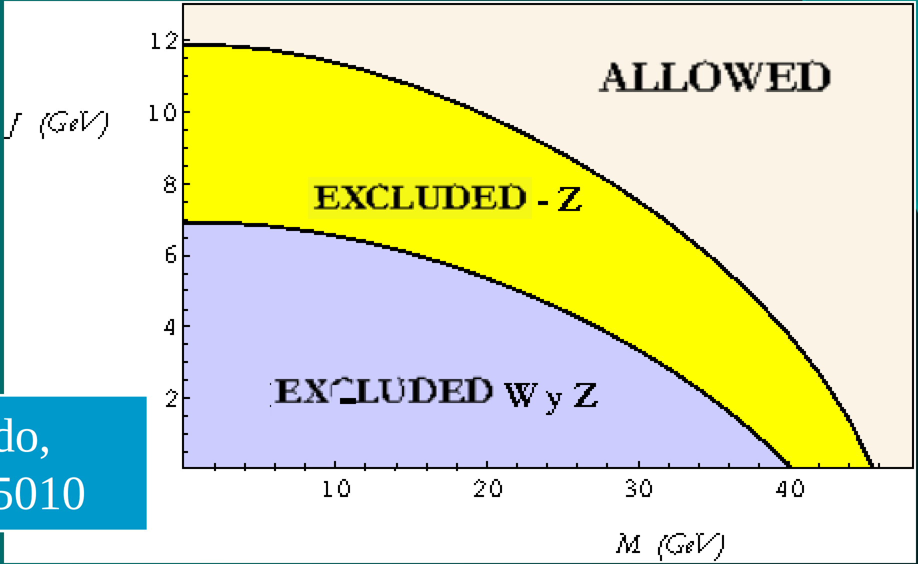
$\Delta\Gamma_Z^{inv.} < 2.0$ MeV (LEP I)

$$\Gamma_Z^b:\ Z \longrightarrow \bar{\nu}(p_1)\nu(p_2)\pi(k_1)\pi(k_2)$$

2.- W total width:

$\Delta\Gamma_W^{total} < 240$ MeV (LEP I)

$$\Gamma_W^b:\ W^- \longrightarrow l^-(p_1)\bar{\nu}(p_2)\pi(k_1)\pi(k_2)$$
$$W \longrightarrow q(p_1)\bar{q}(p_2)\pi(k_1)\pi(k_2)$$



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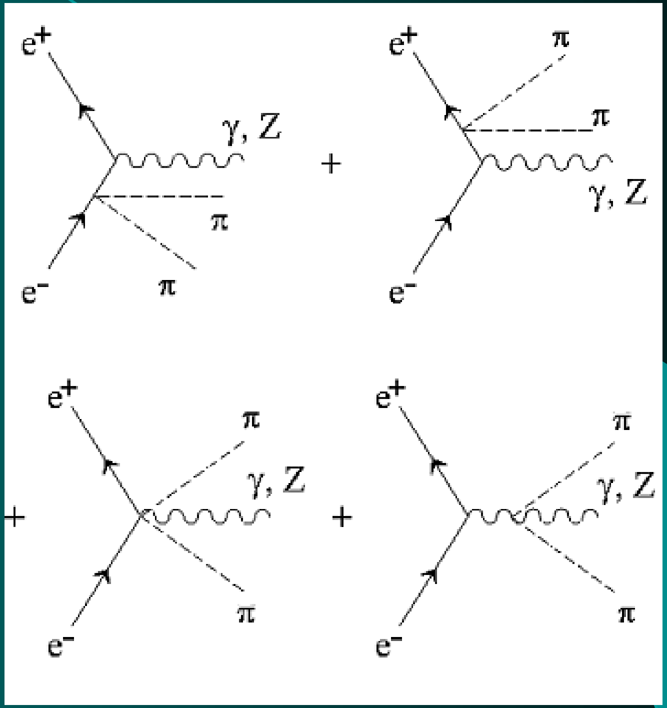
SINGLE γ AND Z CHANNELS

A more important experimental signal is associated to the single photon channel (or single Z channel) plus missing energy.

γ or Z production



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$$\frac{d\sigma_A}{dx\,d\cos\theta} = \frac{|h|^2}{4\pi}\frac{s(c_V^2+c_A^2)(s(1-x)-4\boxed{M^2})^2\boxed{N}}{61440\boxed{f^8}\pi^2}\sqrt{1-\frac{4\boxed{M^2}}{s(1-x)}}\left[x(3-3x+2x^2)-x^3\sin^2\theta+\frac{2(1-x)(1+(1-x)^2)}{x\sin^2\theta}\right]$$

L3 DATA ANALYSIS

L3 is a collaboration with more than 50 institutions from all the world.

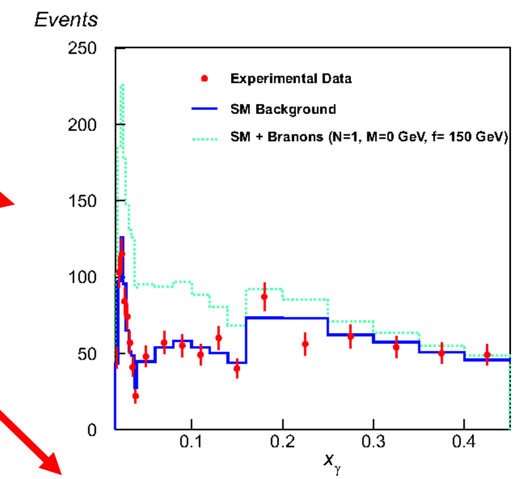
L3 was a detector working with the produced particles in the electron-positron collisions in the LEP ring (CERN).

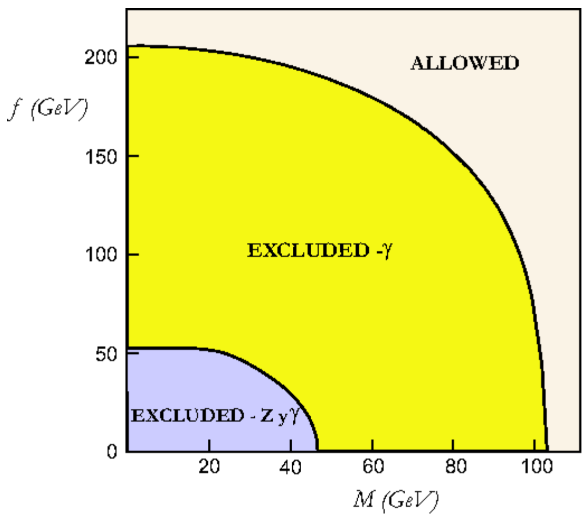
Analysis:

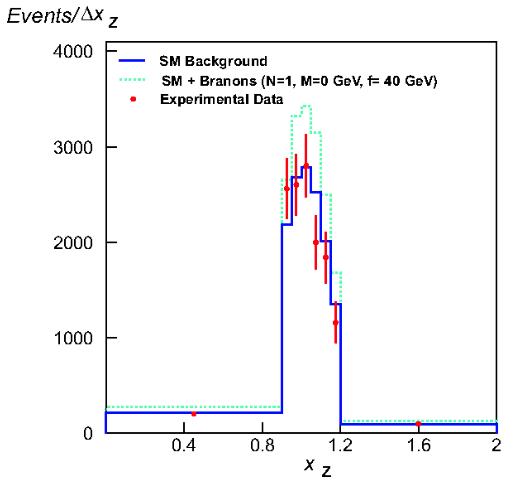
1.- Single photon

2.- Single Z

3.- Restrictions







LC PROSPECTS

To estimate the future linear colliders sensitivity, we have take into account the statistics improuve due to the total integrated luminosity ($\mathfrak{L}$) difference:

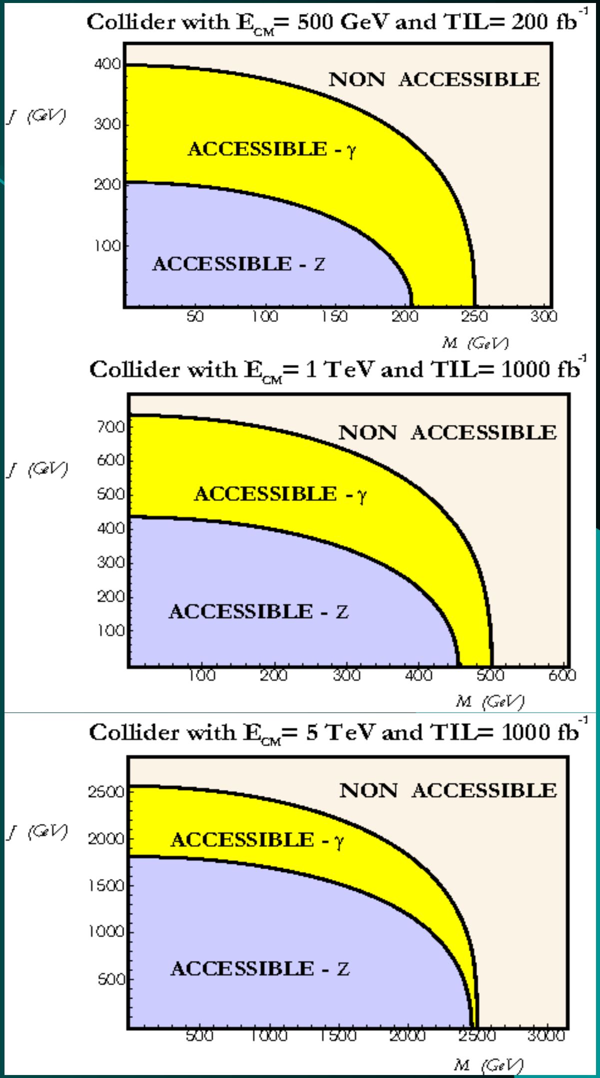
$$\sigma^i_{TII} = \sqrt{\frac{\mathcal{L}_{TII}}{\mathcal{L}_{TI}}}\,\sigma^i_{TI}$$

1.- Medium time.

- 1.- ILC
- 1.a. E_{CM} = 500 GeV
- 1.b. E_{CM} = 1 TeV

2.- Long time

- 2.- CLIC
- 2.a. E_{CM} = 5 TeV



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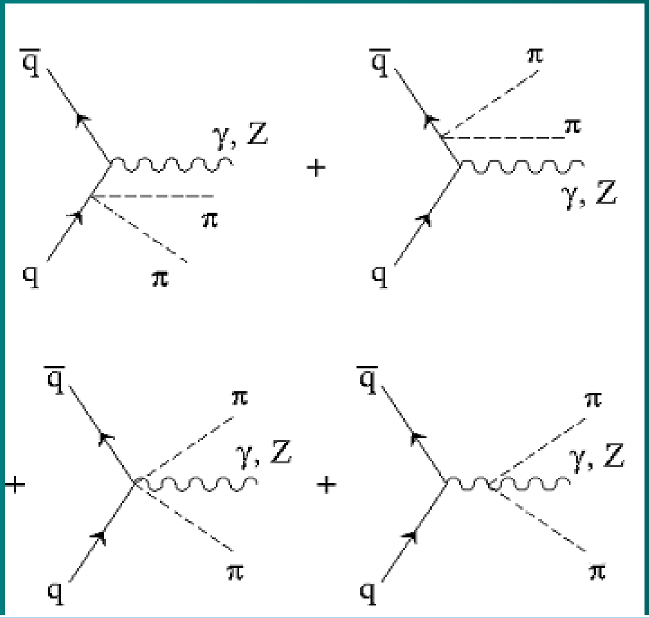
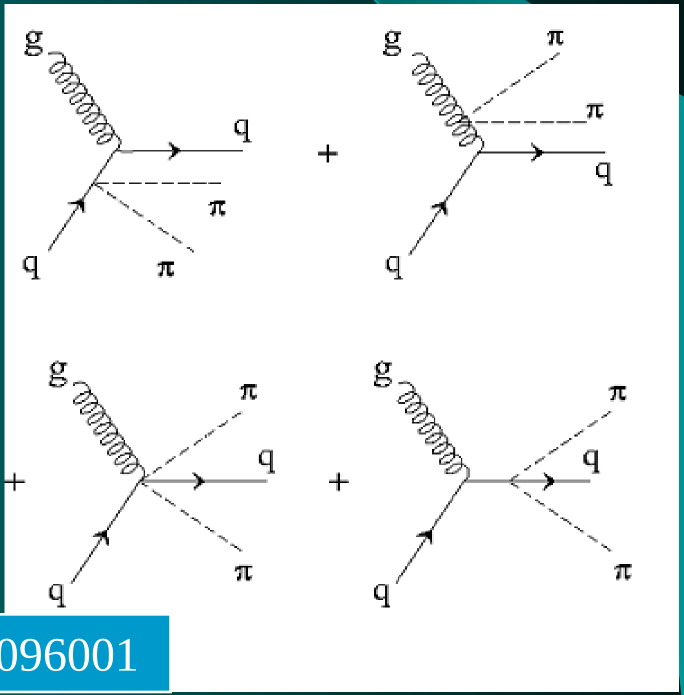
HADRONIC COLLIDERS

The main experimental signals come from the single photon channel (or electroweak boson) and the monojet production plus missing energy and transversal momentum.

One γ or Z production



One quark production



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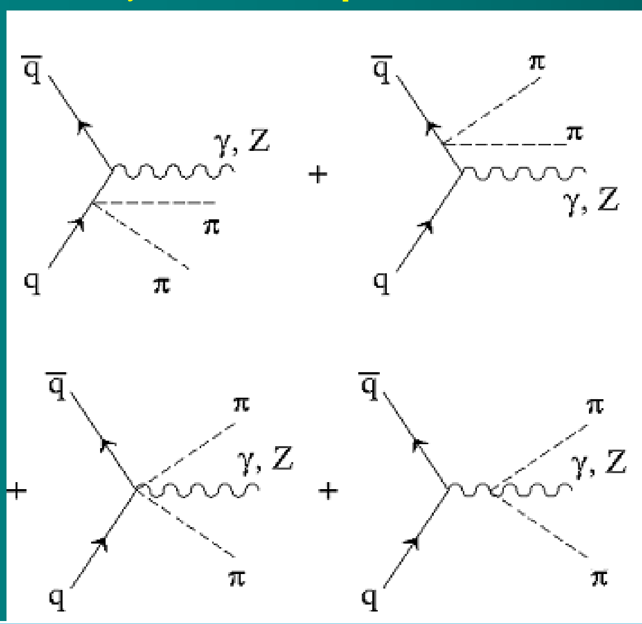

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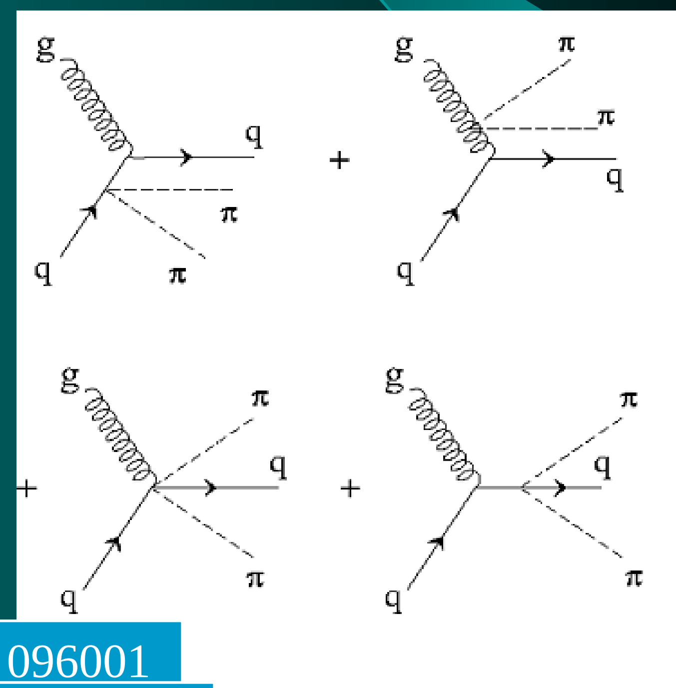

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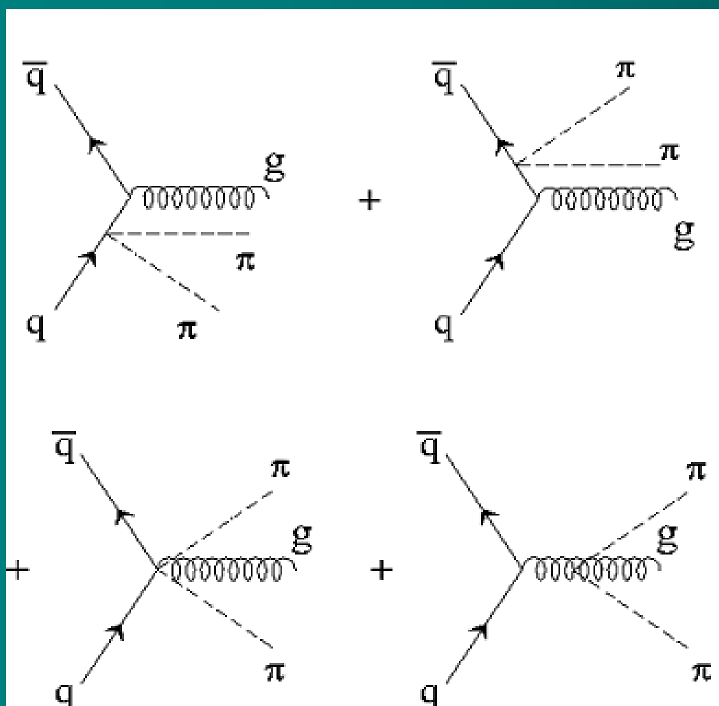
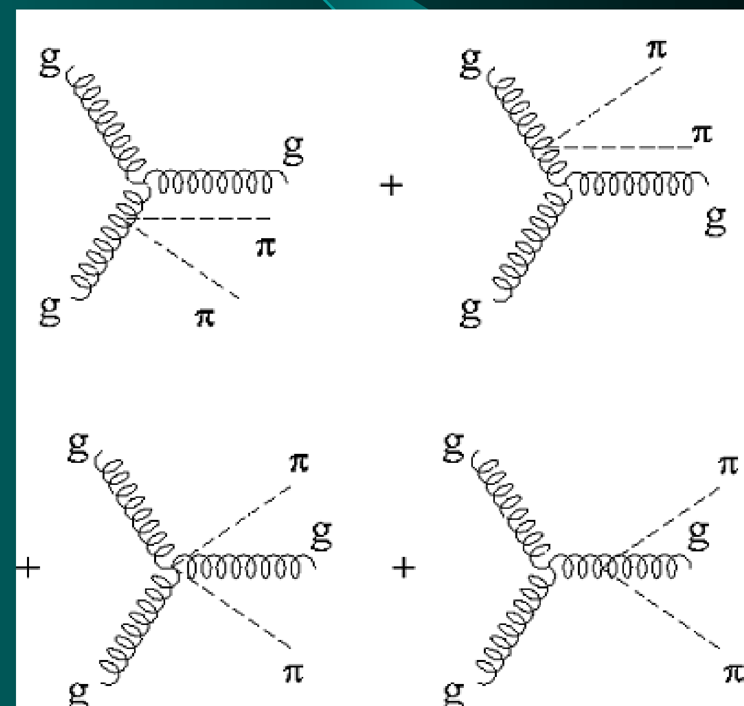
GLUON PRODUCTION

Gluon production





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TEVATRON RESULTS

Tevatron is a collider proton-antiproton placed in the *Fermi National Laboratory Accelerator* (Chicago)

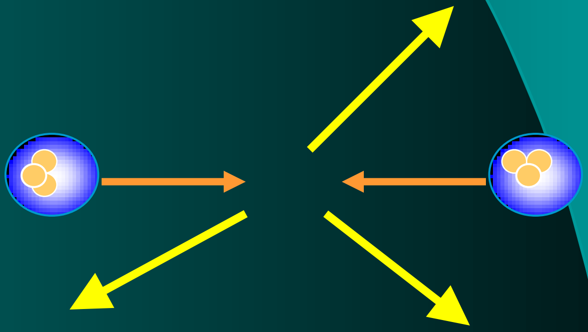
1^{st} Run: E_{CM}= 1.8 TeV

$\mathcal{L}$ = 78.8 pb^{-1} (D0)

$\mathcal{L}$ = 87.4 pb^{-1} (CDF)

2^{nd} Run: E_{CM}= 1.96 TeV

$\mathcal{L}$ = 1000 pb^{-1}



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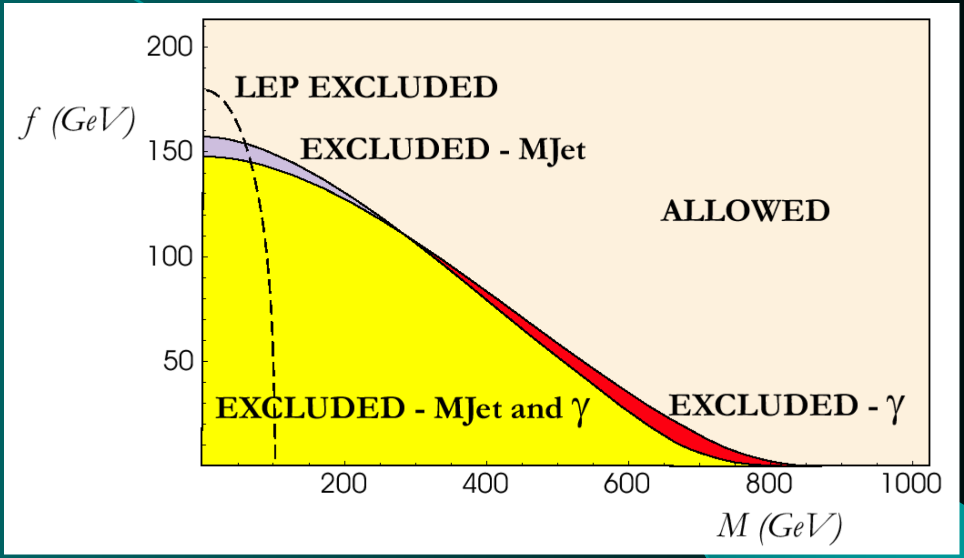

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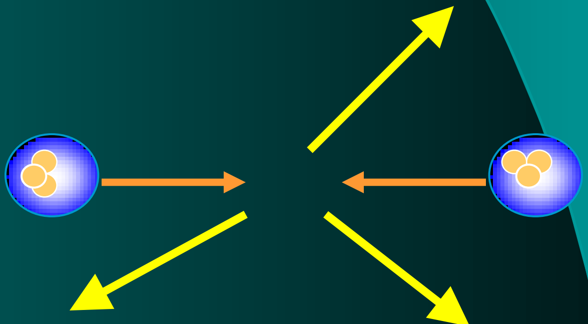

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LHC SENSITIVITY

1.- Signals

$$\left.\begin{array}{l} \bar{q}q \to gG^{(k)}, \gamma G^{(k)} \\ qg \to qG^{(k)} \\ gg \to gG^{(k)} \end{array}\right\} \text{jets} + \not{E}_T, \ \gamma + \not{E}_T$$

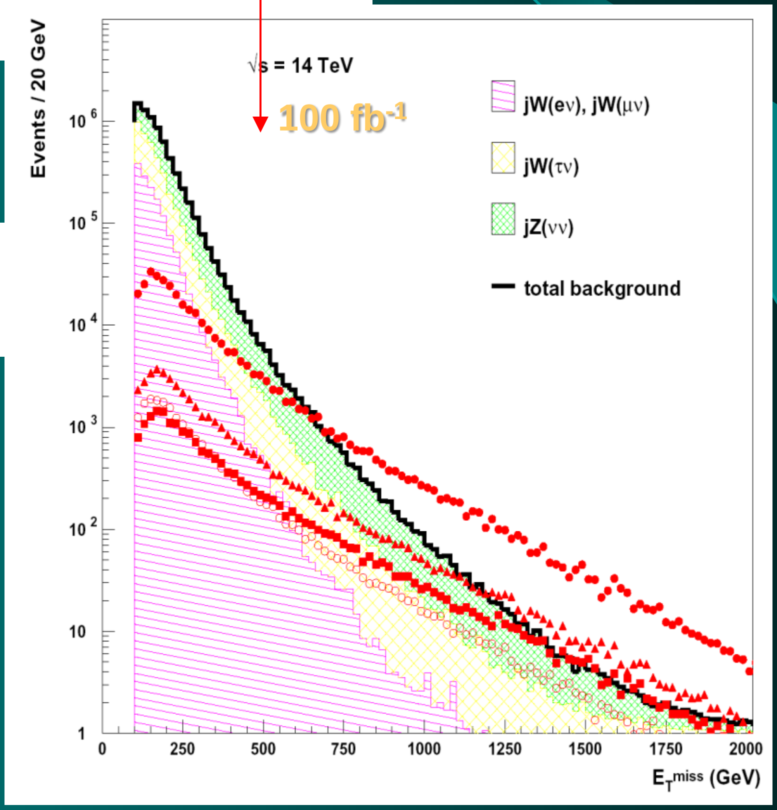
2.- Backgrounds

$$\text{jets} + (Z \to \nu\nu)$$
$$\text{jets} + (W \to (\ell)\nu)$$

Sensitivity:

E_{CM}= 14 TeV

$\mathcal{L}$ = 10^5 pb^{-1}



LHC PROSPECTS

1.- Signals

$$\left.\begin{array}{l} \bar{q}q \rightarrow gG^{(k)}, \gamma G^{(k)} \\ qg \rightarrow qG^{(k)} \\ gg \rightarrow gG^{(k)} \end{array}\right\} \text{jets} + \not{E}_T,\ \gamma + \not{E}_T$$

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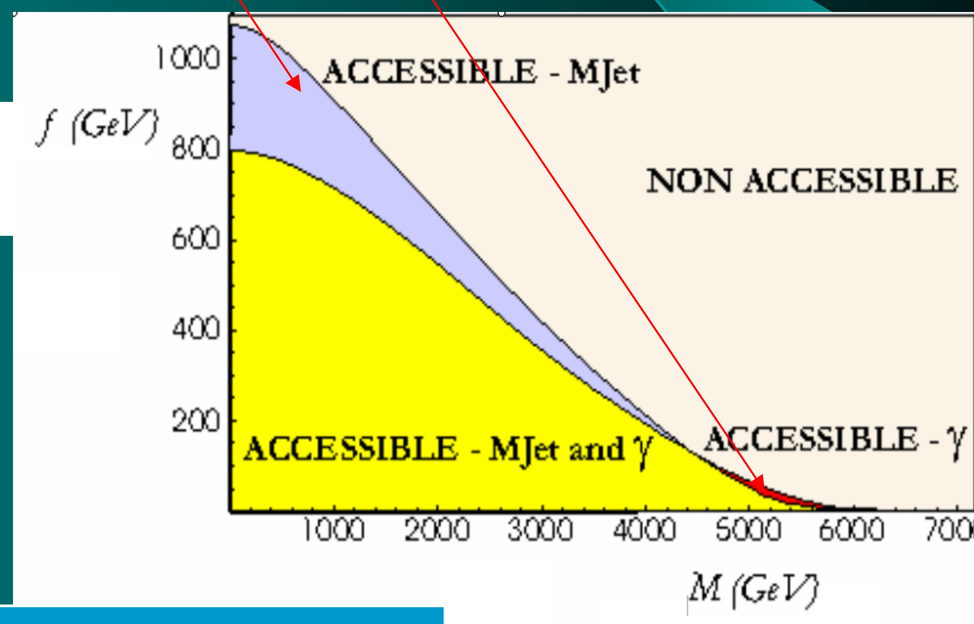

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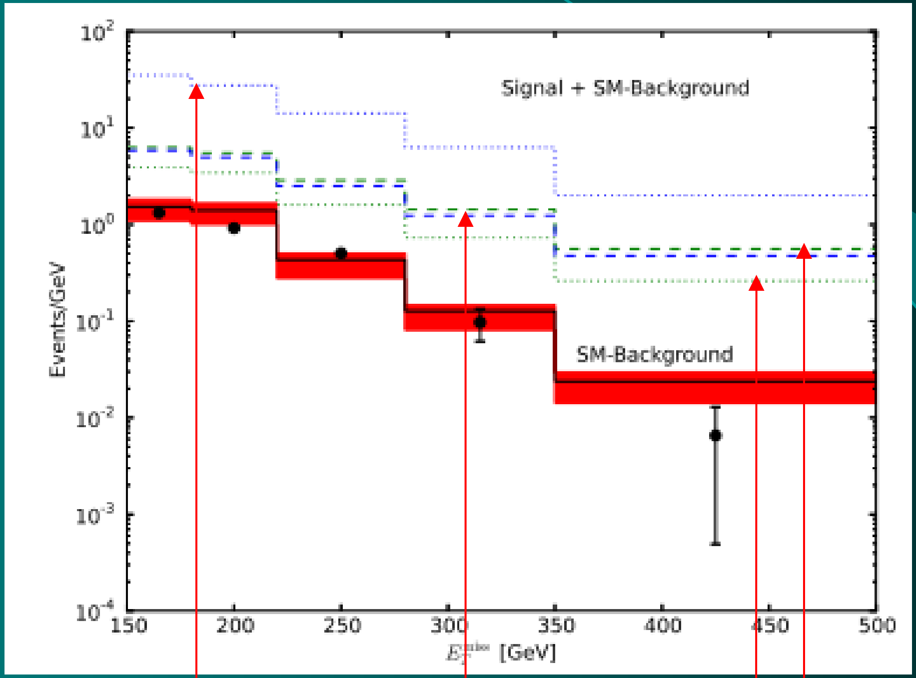
LHC CONSTRAINTS

Signals vs. background



LHC (ATLAS):

E_{CM}= 7 TeV,

$\mathcal{L}$ = 4.6 fb^{-1}

ADD KK-gravitons: (M_D= 1 TeV, N=2); (M_D= 1.5 TeV, N=6)

Branons: (f= 60 GeV, M=2 TeV, N=1) ; (f= 200 GeV, M=1 TeV, N=1)

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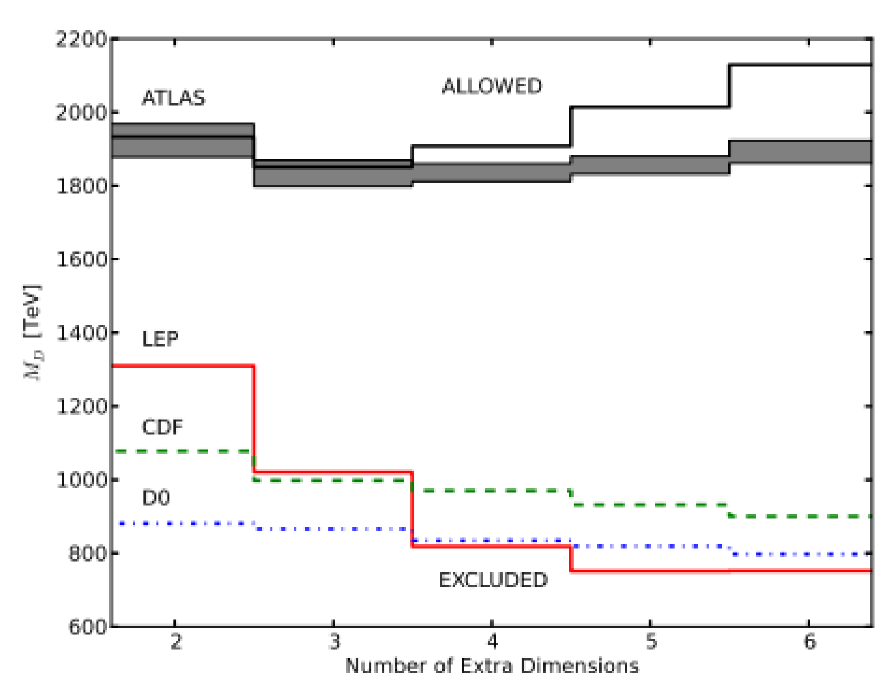
LHC CONSTRAINTS

ADD constraints:



LHC (ATLAS): E_{CM}= 7 TeV, $\mathcal{L}$ = 4.6 fb^{-1}

Tevatron: E_{CM}= 1.96 TeV, $\mathcal{L}$ = 200 pb^{-1}

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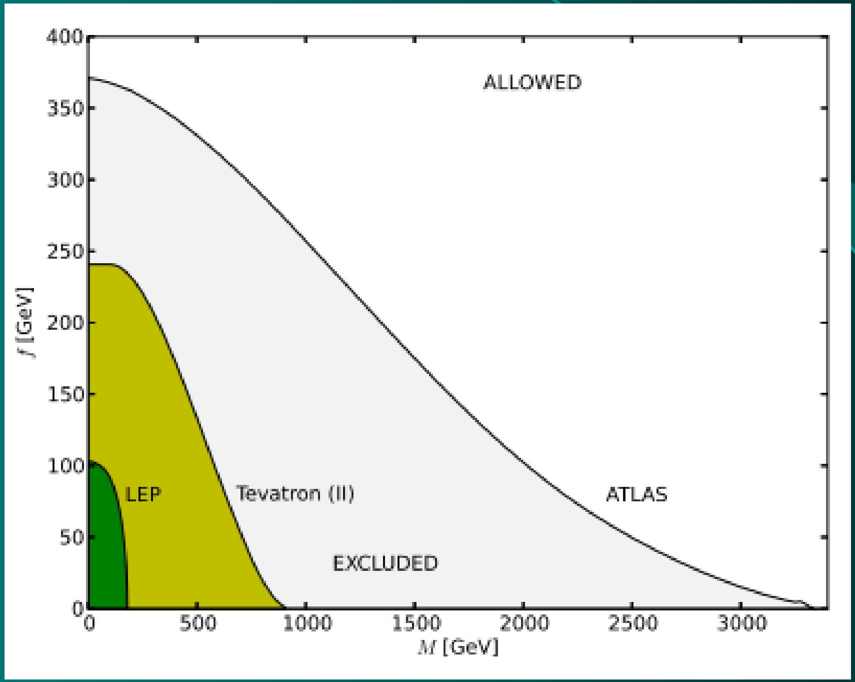
LHC CONSTRAINTS

Branon constraints:



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BRANONS IN COSMOLOGY

Branons are generically stable, weakly interactive and massive.

Weakly Interactive Massive Particles: WIMPs.

1.- Branons: Dark Matter (DM) candidates.

2.- Searches of branons as Dark Matter.

2.a.- Direct detection experiments.

2.b.- Indirect detection experiments.

3.- Cosmological and astrophysical restrictions.

RELIC DENSITY

The evolution of the number density follow the Boltzmann equation:

$$dn_{Br}/dt = -3Hn_{Br} - \langle \sigma_A v \rangle[(n_{Br})^2 - (n_{Br}^{eq})^2]$$

Thermal equilibrium density:

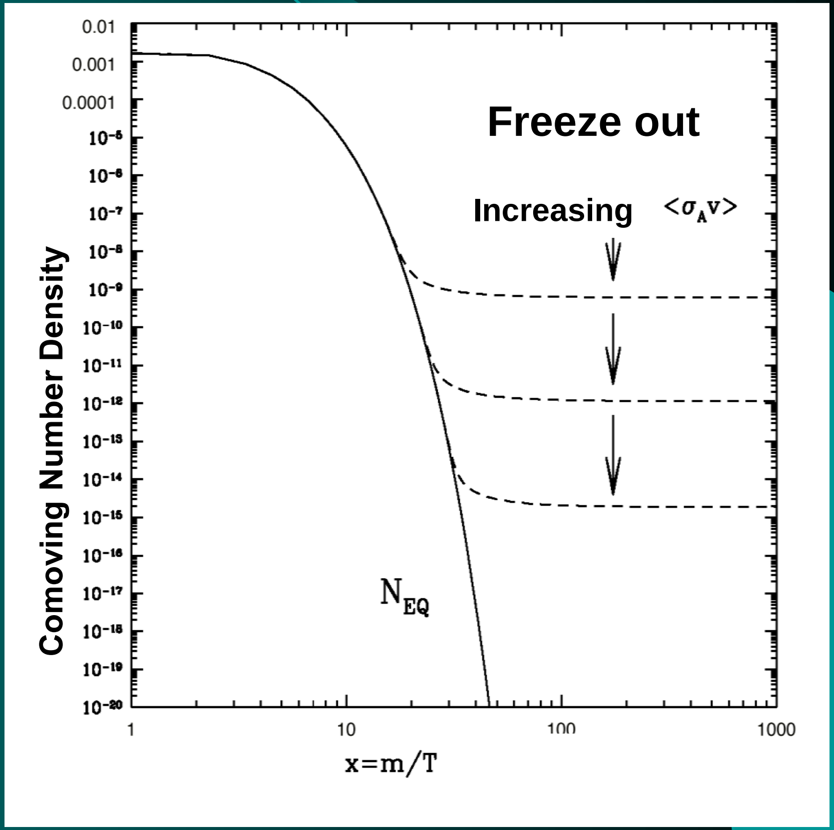
$$n_{Br}^{eq} = g/(2\pi)^3 \int f(p)\, d^3p$$

When $\Gamma = \langle\sigma_A v\rangle\, n_{Br} < H$, the DM is frozen out.

Cold DM relic density:

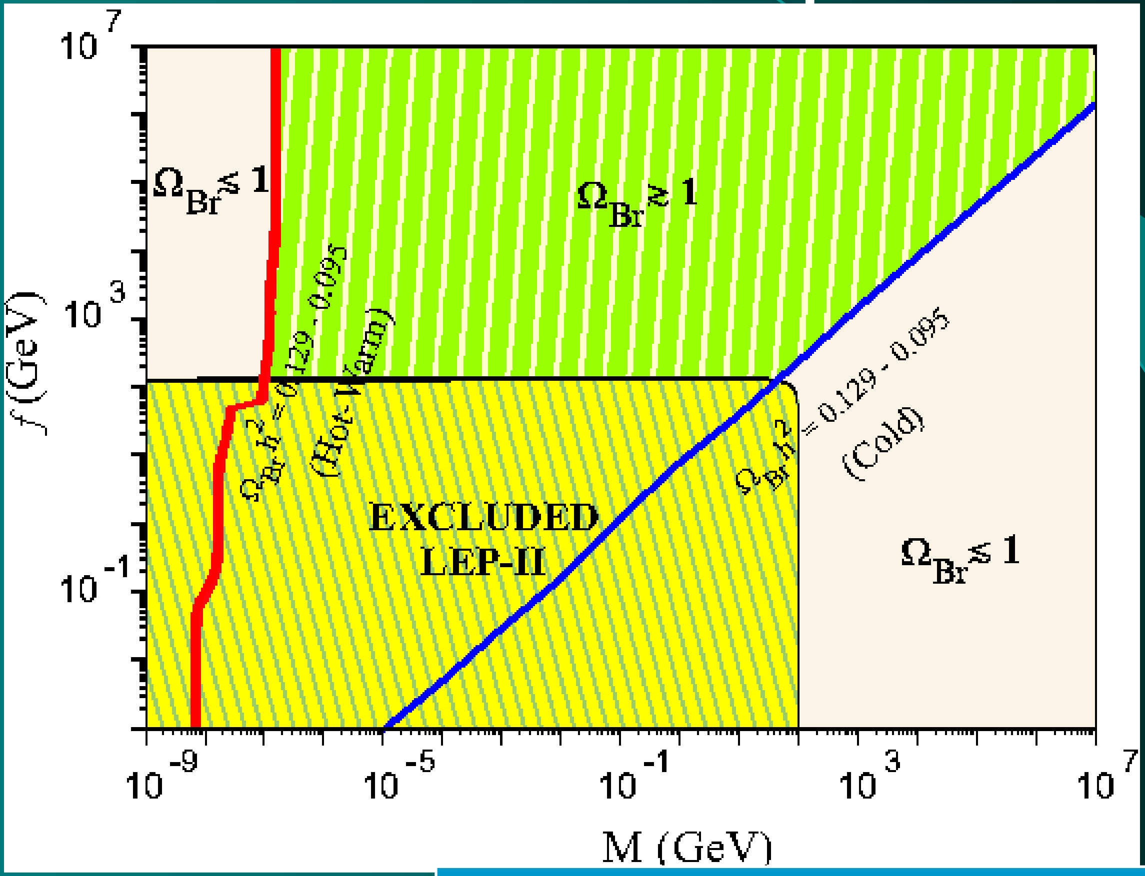
$$\Omega_{Br}\, h^2 \propto m_{Br} / \langle \sigma_A v_{Br} \rangle$$

$$T_{FO} \sim m_{Br} / 20$$



BRANON ABUNDANCE

We have taken into account the total annihilation cross section of branons to SM particles.



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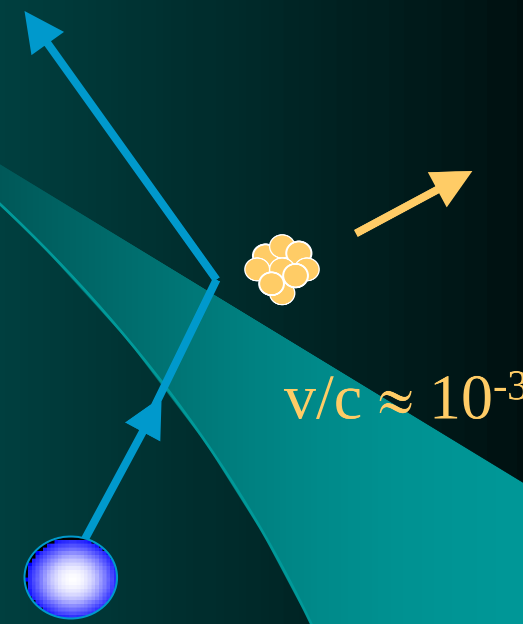
DIRECT SEARCHES

***WIMPs* elastically scatter off nuclei**

nuclear recoils

Measure recoil energy spectrum



Direct interaction of the DM halo with the detector. Typical nucleus recoil energy: E_R~1-100 keV.

The rate of the *WIMP* interactions depends on the local DM density and relative *WIMP* velocity.

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DIRECT RESULTS

The appropriate quantity to compare with the experimental results is not the elastic branon-nucleus cross section σ, but the differential cross section per nucleon at zero momentum transfer: σ_n.

$$\frac{d\sigma}{d|q|^2} = \frac{\sigma_n A^2 F^2(|q|)}{4v^2\mu^2}$$

$F(|q|)$ is a nuclear form factor normalization $F(0) = 1$

A is the mass number of the nucleus

$\mu = Mm/(M+m)$

$m \simeq 939$ MeV

v is the relative velocity

For the branon case:

$$\sigma_n = \frac{9M^2m^2\mu^2}{64\pi f^8}$$

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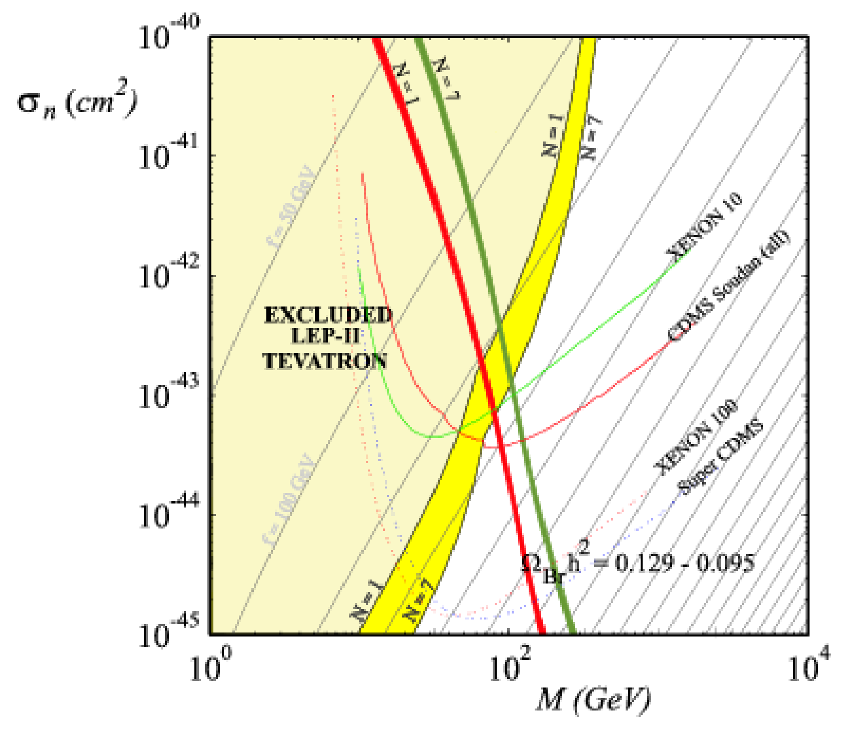

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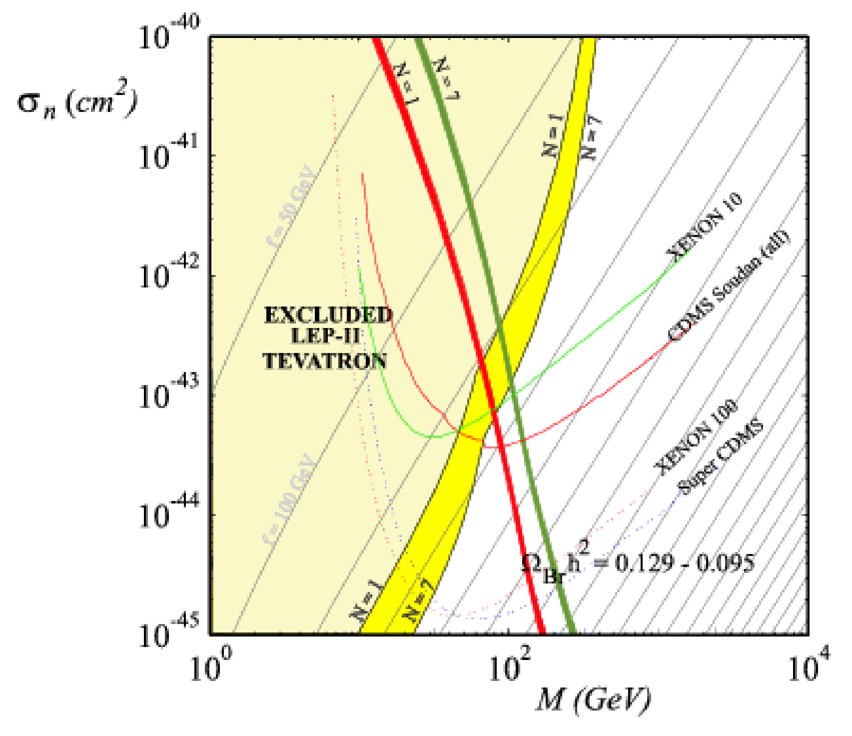

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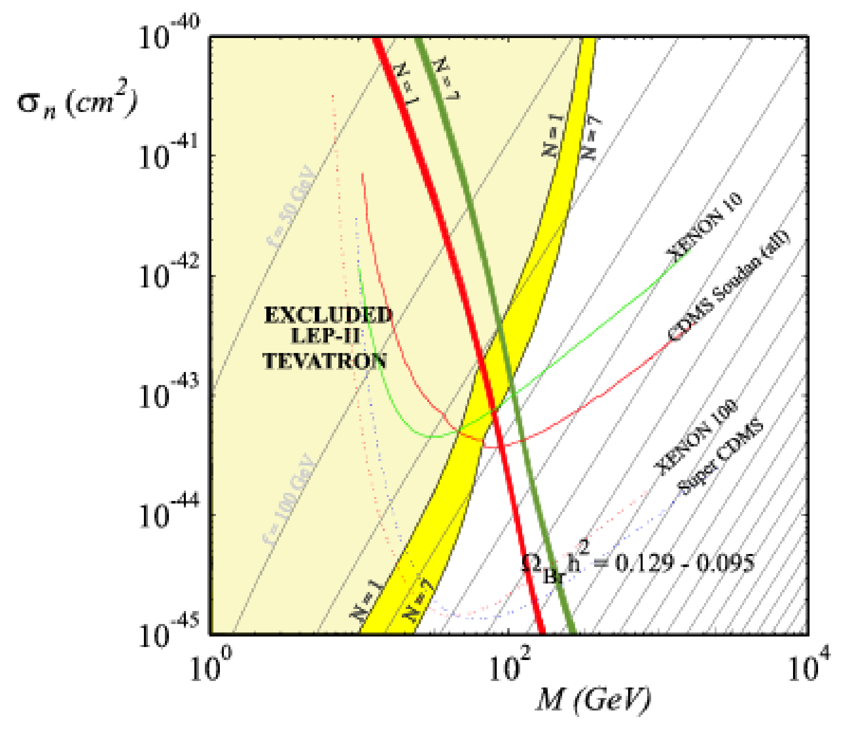
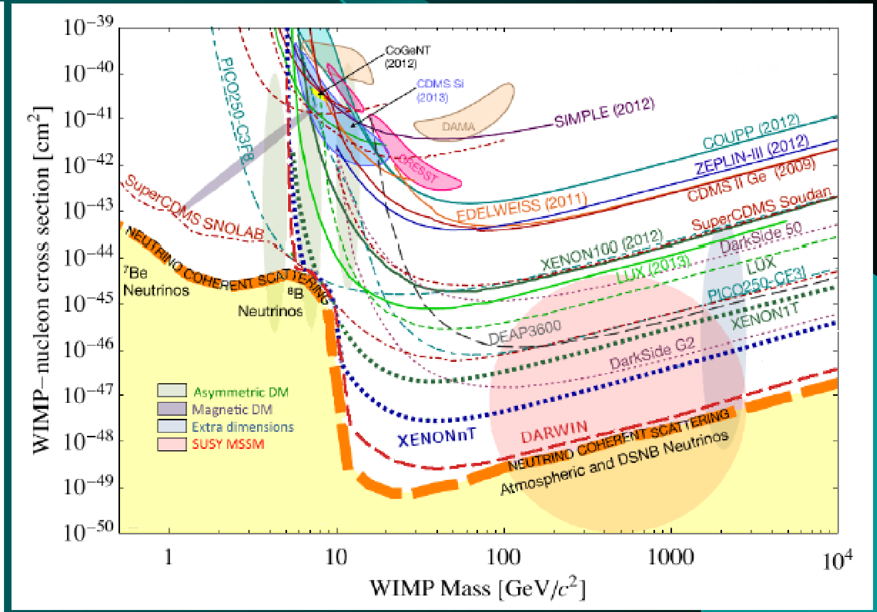
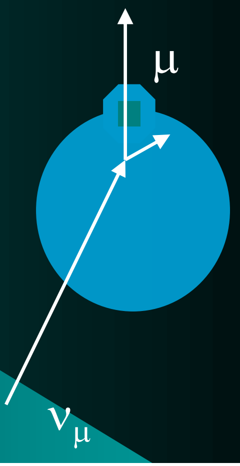




Cembranos, Dobado, Maroto, PRL 90 (2003) 241301

INDIRECT SEARCHES



WIMPs **annihilate**

1.- In the center of the Sun, and the Earth core: high energy neutrinos.

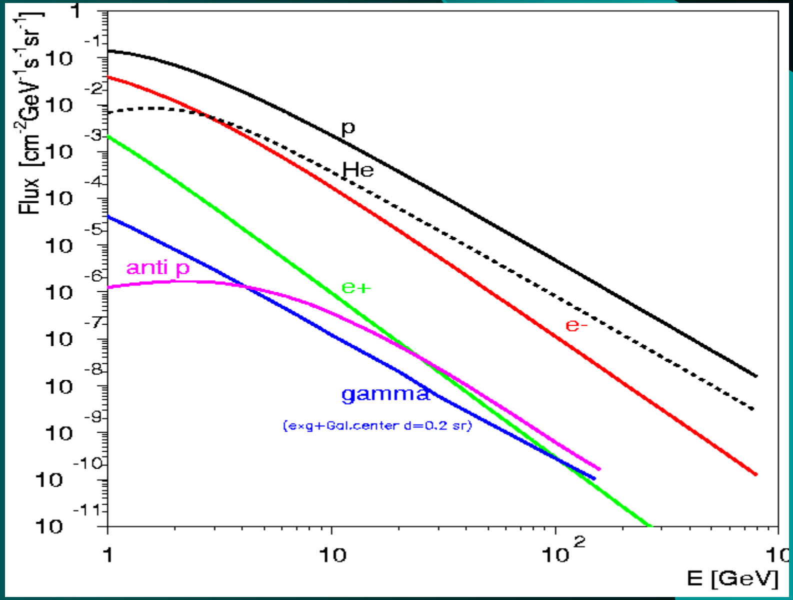
Antares, Amanda, IceCube, ...

2.- In the halo: γ, e+, p-, D ...

2.a.- Halo profiles from simulations and rotation curves.

2.b.- Green´s functions from propagation model.

2.c.- Average cross section from the effective theory.



Indirect search of dark matter

WIMPs may annihilate into SM particles, whose subsequent decay and hadronization generate gamma ray photons.

- Differential γ-rays fluxes from galactic sources

$$\frac{\mathrm{d}\,\Phi_\gamma^{DM}}{\mathrm{d}\,E_\gamma} = \underbrace{\frac{1}{4\pi M^2}\sum_i \langle\sigma_i v\rangle \frac{\mathrm{d}\,N_\gamma^i}{\mathrm{d}\,E_\gamma}}_{\text{Particle model dependent}} \times \underbrace{\frac{1}{\Delta\Omega}\int_{\Delta\Omega}\mathrm{d}\Omega\int_{l.o.s.}\rho^2[r(s)]\mathrm{d}s}_{\text{Astrophysical factor}}$$

Particle model dependent part

$$\frac{d\,\Phi_\gamma^{DM}}{d\,E_\gamma} = \frac{1}{4\pi M^2} \boxed{\sum_i \langle\sigma_i v\rangle \frac{d\,N_\gamma^i}{d\,E_\gamma}} \times \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_{l.o.s.} \rho^2[r(s)]ds$$

➢ Differential flux of photon:

- Simulated by PYTHIA 6.418 Monte Carlo event generator
- Energy bins for the variable x $=E_\gamma/M_{WIMP}$ in the interval [0, 1]

➢ The thermal annihilation cross section accounts for the DM model

Gamma Ray Fitting Functions

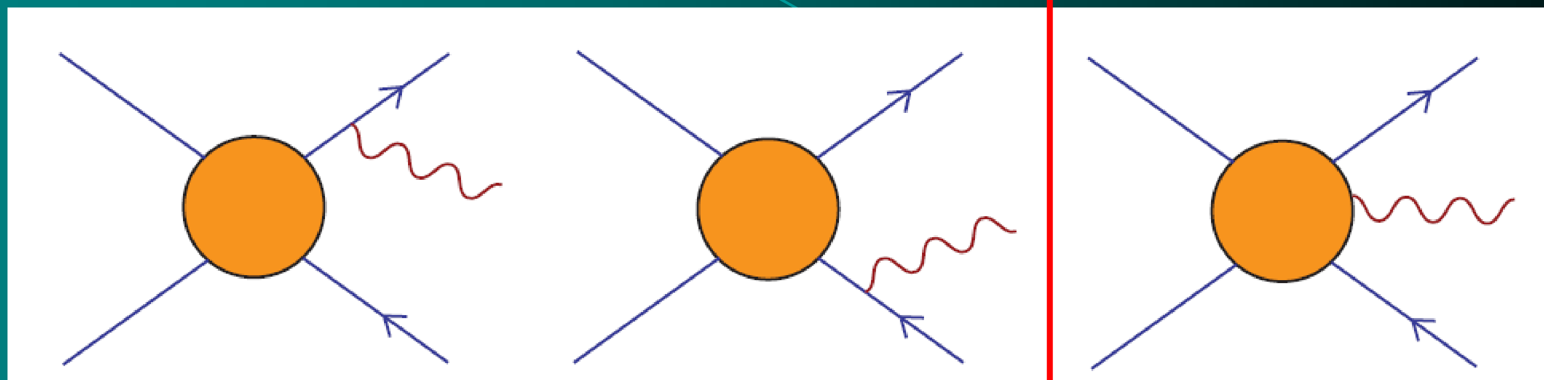
- Gamma-ray spectra do not depend on DM model or DM model except for small particular tuned regions of the parameter space:

- Fitting functions for particle-antiparticle channels.

JARC, Cruz-Dombriz, Dobado, Lineros and Maroto, Phys. Rev. D 83, 083507 (2011) arXiv: 1009.4939

(PYTHIA 6.418, Fortran)

Internal Bremsstrahlung



Bringmann, Bergström and Edsjö **JHEP 0801:049,2008**.

✓ bremsstrahlung contributions **I** and **II** are included in the performed simulations.

✓ Model dependent contribution **III** is negligible except for very particular region of models with degenerate spectrum

Cannoni, Gómez, Sánchez-Conde, Prada & Panella **PRD 81 : 107303, 2010.**

Gamma Ray Fitting Functions

I. Leptons and quarks (except *top* quark)

$$x^{1.5}\frac{\mathrm{d}N_\gamma}{\mathrm{d}x} = a_1\mathrm{exp}\left(-b_1 x^{n_1} - b_2 x^{n_2} - \frac{c_1}{x^{d_1}} + \frac{c_2}{x^{d_2}}\right) + q\, x^{1.5}\ln\left[p(1-x)\right]\frac{x^2-2x+2}{x}$$

II. *W* and *Z* gauge bosons

$$x^{1.5}\frac{\mathrm{d}N_\gamma}{\mathrm{d}x} = a_1\exp\left(-b_1\, x^{n_1} - \frac{c_1}{x^{d_1}}\right)\left\{\frac{\ln[p(j-x)]}{\ln p}\right\}^q$$

$$x \equiv E_\gamma/M$$

III. Top quark

$$x^{1.5}\frac{\mathrm{d}N_\gamma}{\mathrm{d}x} = a_1\exp\left(-b_1\, x^{n_1} - \frac{c_1}{x^{d_1}} - \frac{c_2}{x^{d_2}}\right)\left\{\frac{\ln[p(1-x^l)]}{\ln p}\right\}^q$$

JARC, Cruz-Dombriz, Dobado, Lineros and Maroto, Phys. Rev. D 83, 083507 (2011) arXiv: 1009.4939

IFAE UAB Universitat Autònoma de Barcelona

Gamma Ray Fitting Functions

✓ MATHEMATICA **[AdICD et *al*., 2010]**

MultiDark
Multimessenger Approach for Dark Matter Detection

http://teorica.fis.ucm.es/PaginaWeb/downloads.html

✓ ROOT-based **[D. Nieto et *al*., 2011]**

DAMASCO (DArk Matter Analytical Spectral COde)

http://cta.gae.ucm.es/gae/damasco

MAGIC
Major Atmospheric Gamma Imaging Cerenkov Telescopes

JARC, Cruz-Dombriz, Dobado, Lineros and Maroto, Phys. Rev. D 83, 083507 (2011) arXiv: 1009.4939

(PYTHIA 6.418, Fortran)

Thermal Cross Section

For cold relics, the earlier the decoupling occurs, the larger the relic abundance, and the decoupling occurs earlier as we decrease the cross section (x=M/T):

$$\langle \sigma_A v \rangle = \sum_{n=0}^{\infty} c_n x^{-n} \approx c_0$$

c_0(M, m, f) contains the parameter of the model:

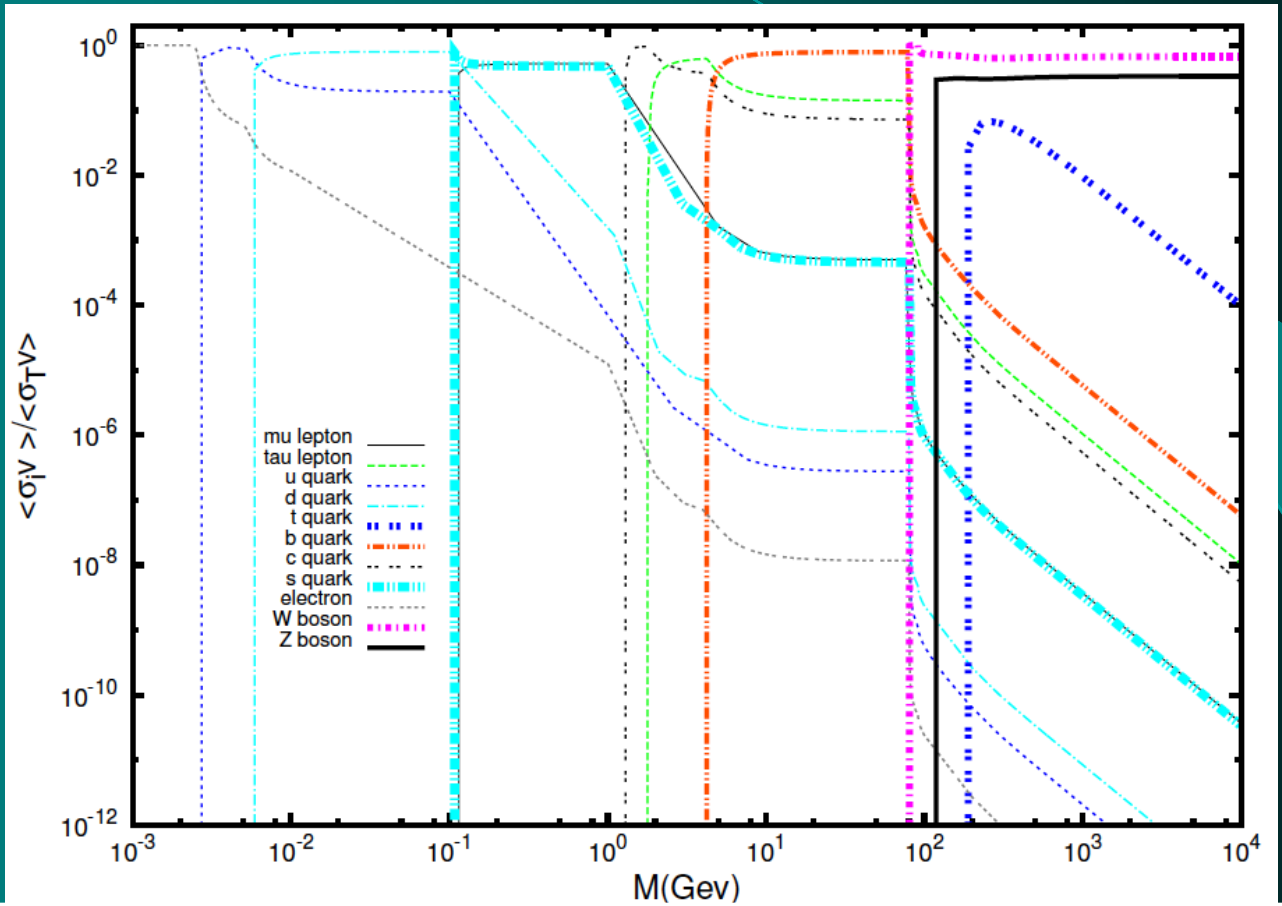
Dirac fermions:

$$c_0 = \frac{1}{16\pi^2 f^8} M^2 m_\psi^2 (M^2 - m_\psi^2) \sqrt{1 - \frac{m_\psi^2}{M^2}}$$

Massive gauge fields:

$$c_0 = \frac{M^2 \sqrt{1 - \frac{{m_Z}^2}{M^2}} \left(4\, M^4 - 4\, M^2\, {m_Z}^2 + 3\, {m_Z}^4\right)}{64\, f^8\, \pi^2}$$

Branon Branching Ratio



Cembranos, Cruz-Dombriz, Gammaldi, Maroto, Phys. Rev. D 85, 043505 (2012) arXiv: 1111.4448

Astrophysical factor

$$\frac{\mathrm{d}\,\Phi_\gamma^{DM}}{\mathrm{d}\,E_\gamma} = \frac{1}{4\pi M^2}\sum_i \langle\sigma_i v\rangle \frac{\mathrm{d}\,N_\gamma^i}{\mathrm{d}\,E_\gamma} \times \boxed{\frac{1}{\Delta\Omega}\int_{\Delta\Omega}\mathrm{d}\Omega\int_{l.o.s.}\rho^2[r(s)]\mathrm{d}s}$$

- ρ density distribution of DM, depending of the assumed profile
- r(s) contains the parameter of the integration along the l.o.s (distance of the source from the observer)
- ΔΩ solid angle, depending of the detector

Cembranos, Cruz-Dombriz, Gammaldi, Maroto, Phys. Rev. D 85, 043505 (2012) arXiv: 1111.4448

Integrated γ-rays flux

$$\boxed{\Phi_\gamma^{DM}} = \frac{1}{4\pi M^2} \langle \sigma_A v \rangle N_\gamma \times \; < J >_{\Delta\Omega}$$

$$\frac{\Phi_\gamma \sqrt{\Delta\Omega A_{eff} t}}{\sqrt{\Phi_\gamma + \Phi_{Bg}}} \geq 5,2$$

Minimum detectable flux:

- φ_γ annihilation flux
- φ_{Bg} background flux
- $\Delta\Omega$ solid angle
- A_{eff} effective area of the instrument
- t exposition time

Cembranos, Cruz-Dombriz, Gammaldi, Maroto, Phys. Rev. D 85, 043505 (2012) arXiv: 1111.4448

Experiments and sources

Ground-based: MAGIC-I and CTA

Primary background: hadronic

$$\frac{dN_{bg}}{dE_{bg}} \approx \epsilon \times 10^{-5} GeV^{-1} cm^{-2} s^{-1} sr^{-1} \times \left(\frac{100GeV}{E_{bg}}\right)^{2.7}$$

- Draco, Sagittarius, Canis Major dSphs (NFW profile)
- Galactic Center (NFW profile)
- SEGUE 1 (Einasto profile)

Satellites: FERMI and EGRET

Primary background: diffuse γ -ray flux from astrophysical sources

- Draco, Sagittarius, Canis Major dSphs (NFW profile)
- Galactic Center (NFW profile)

Cembranos, Cruz-Dombriz, Gammaldi, Maroto, Phys. Rev. D 85, 043505 (2012)

Draco dSph				
Experiment	EGRET	FERMI	MAGIC-I*	CTA
A_{Eff}	$10^3(*)$ 1.5×10^3	10^4	5×10^8	10^{10}
$\Delta\Omega$	10^{-3}	$9\times10^{-5}(*)$ 10^{-5}	10^{-5}	10^{-5}
t_{exp}	1 yr		40 h	50 h
Φ_{Bg}	$3.3\times10^{-7}(*)$ 6.7×10^{-7}		$1.9\times10^{-7}(**)$	$\sim10^{-7}(**)$
$\Phi_\gamma^{(5)}$	$1.04\times10^{-6}(*)$ 9.15×10^{-7}	$1.14\times10^{-6}(*)$ 8.55×10^{-6}	1.00×10^{-7}	1.25×10^{-8}
$\Phi_\gamma^{(2)}$	$2.78\times10^{-7}(*)$ 2.84×10^{-7}	$2.97\times10^{-7}(*)$ 1.75×10^{-6}	3.54×10^{-8}	4.83×10^{-9}
$\langle J\rangle_{\Delta\Omega}$	0.1	7.2		
$N_\gamma^{(5)}\langle\sigma v\rangle/M^2$	$1.31\times10^5(*)$ 1.15×10^5	$1.98\times10^3(*)$ 1.49×10^4	1.75×10^2	21.8
$N_\gamma^{(2)}\langle\sigma v\rangle/M^2$	$3.49\times10^4(*)$ 3.57×10^4	$5.19\times10^2(*)$ 3.06×10^3	61.8	8.42

Cembranos, Cruz-Dombriz, Gammaldi, Maroto, Phys. Rev. D 85, 043505 (2012) arXiv: 1111.4448

Sagittarius dSph			
Experiment	EGRET	FERMI	CTA
A_{Eff}	1.5×10^3	10^4	10^{10}
$\Delta\Omega$	10^{-3}	$\sim 10^{-5}$	10^{-5}
t_{exp}	1 yr		100 h
Φ_{Bg}	3.18×10^{-6}		$2.7 \times 10^{-4}(**)$
$\Phi_\gamma^{(5)}$	1.59×10^{-6}	1.04×10^{-5}	1.25×10^{-6}
$\Phi_\gamma^{(2)}$	5.62×10^{-7}	2.74×10^{-6}	4.83×10^{-9}
$\langle J \rangle_{\Delta\Omega}$	1.3	36.9	
$N_\gamma^{(5)} \langle \sigma v \rangle / M^2$	1.53×10^4	3.53×10^3	4.25
$N_\gamma^{(2)} \langle \sigma v \rangle / M^2$	5.44×10^3	9.33×10^2	1.64

Cembranos, Cruz-Dombriz, Gammaldi, Maroto, Phys. Rev. D 85, 043505 (2012) arXiv: 1111.4448

Canis Major dSph			
Experiment	EGRET	FERMI	CTA
A_{Eff}	1.5×10^3	10^4	10^{10}
$\Delta\Omega$	10^{-3}	$\sim 10^{-5}$	10^{-5}
t_{exp}	1 yr		100 h
Φ_{Bg}	3.87×10^{-6}		2.7×10^{-4}(**)
$\Phi_\gamma^{(5)}$	1.71×10^{-6}	1.08×10^{-5}	1.25×10^{-8}
$\Phi_\gamma^{(2)}$	6.15×10^{-7}	2.94×10^{-6}	4.82×10^{-9}
$\langle J \rangle_{\Delta\Omega}$	8.3	139.9	
$N_\gamma^{(5)} \langle \sigma v \rangle / M^2$	2.60×10^3	9.68×10^2	1.12
$N_\gamma^{(2)} \langle \sigma v \rangle / M^2$	9.32×10^2	2.64×10^2	0.43

Cembranos, Cruz-Dombriz, Gammaldi, Maroto, Phys. Rev. D 85, 043505 (2012) arXiv: 1111.4448

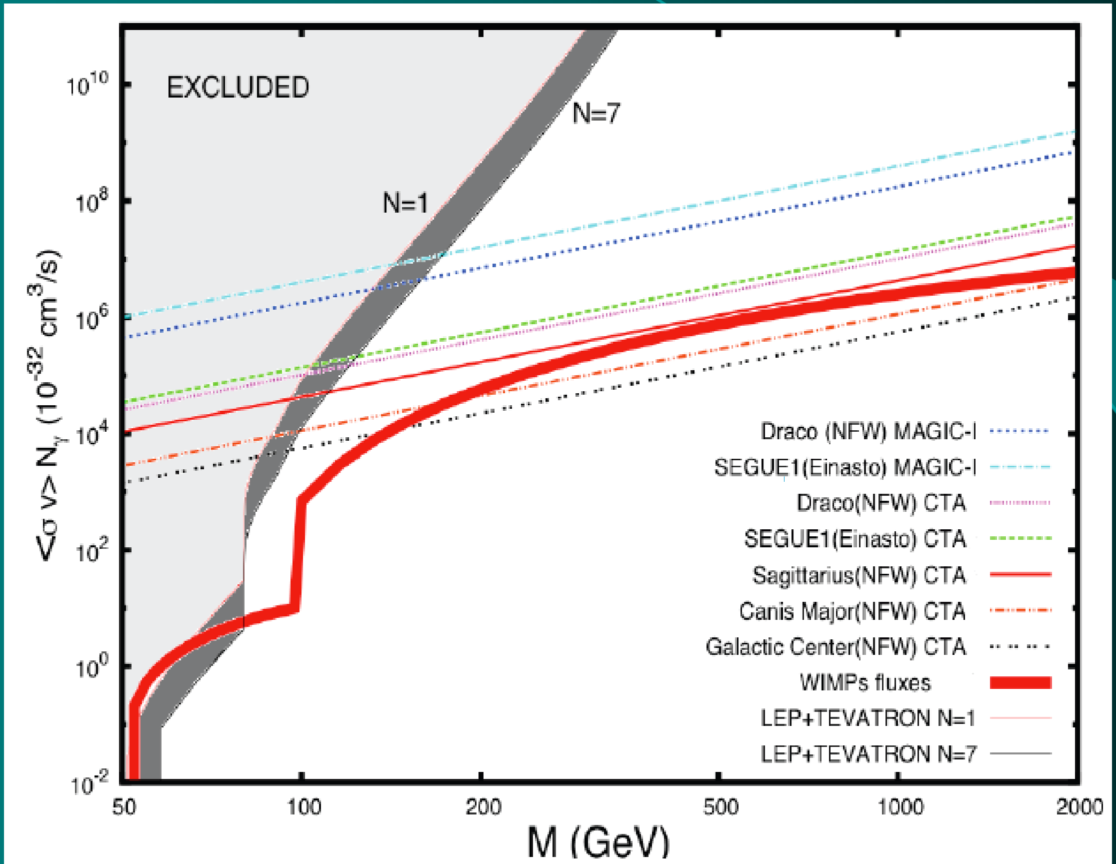
SEGUE 1		
Experiment	MAGIC-I	CTA
A_{Eff}	$\sim 10^8$	10^{10}
$\Delta\Omega$	10^{-5}	10^{-5}
t_{exp}	29.4 h	50 h
Φ_{Bg}	1.9×10^{-7}(**)	10^{-7}
$\Phi_\gamma^{(5)}$	3.61×10^{-7}	1.25×10^{-8}
$\Phi_\gamma^{(2)}$	1.06×10^{-7}	4.83×10^{-9}
$\langle J \rangle_{\Delta\Omega}$	11.4	
$N_\gamma^{(5)} \langle \sigma v \rangle / M^2$	3.97×10^2	13.8
$N_\gamma^{(2)} \langle \sigma v \rangle / M^2$	1.16×10^2	5.32

Cembranos, Cruz-Dombriz, Gammaldi, Maroto, Phys. Rev. D 85, 043505 (2012) arXiv: 1111.4448

Galactic Center			
Experiment	EGRET	FERMI	CTA
A_{Eff}	1.5×10^3	10^4	10^{10}
$\Delta\Omega$	10^{-3}	$\sim 10^{-5}$	10^{-5}
t_{exp}	1 yr		100 h
Φ_{Bg}	1.2×10^{-4}		2.7×10^{-4}(**)
$\Phi_\gamma^{(5)}$	8.23×10^{-6}	3.51×10^{-5}	1.25×10^{-8}
$\Phi_\gamma^{(2)}$	3.23×10^{-6}	1.30×10^{-5}	4.82×10^{-9}
$\langle J \rangle_{\Delta\Omega}$	26	280	
$N_\gamma^{(5)} \langle \sigma v \rangle / M^2$	3.98×10^3	1.57×10^3	0.56
$N_\gamma^{(2)} \langle \sigma v \rangle / M^2$	1.56×10^3	5.83×10^2	0.21

Cembranos, Cruz-Dombriz, Gammaldi, Maroto, Phys. Rev. D 85, 043505 (2012) arXiv: 1111.4448

Exclusion limits for ACTs E>50GeV



Cembranos, Cruz-Dombriz, Gammaldi, Maroto, Phys. Rev. D 85, 043505 (2012) arXiv: 1111.4448

Galactic Center

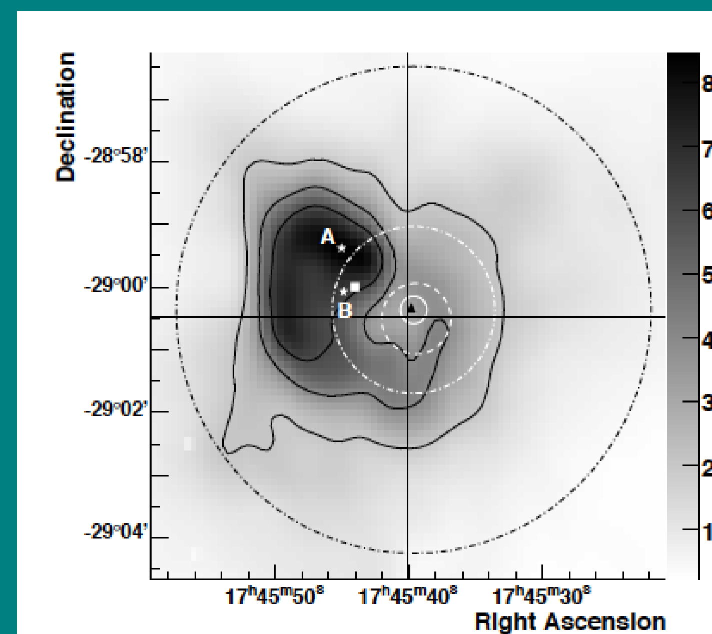
- Possible DM distribution close to the Earth but embedded in a very complex region due to the presence of multiplies sources.

- Multiplies sources observed (Radio flux, Sgr A* black hole, SNR Sgr A East, pulsar candidate, gamma emission).

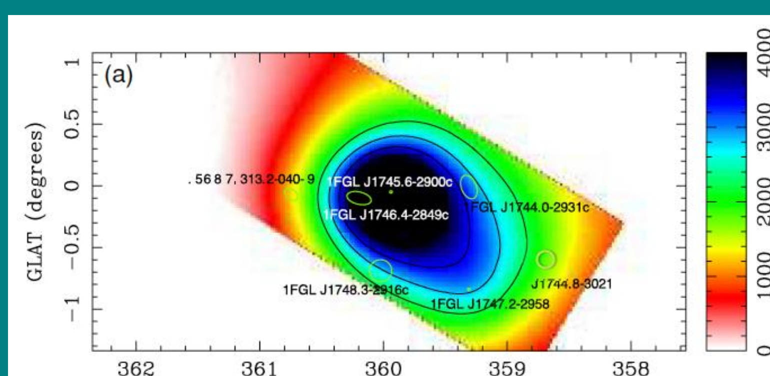
- Variability in Radio and X,

but not in gamma flux

HESS J1745-290



1FGL J1745.6-2900c

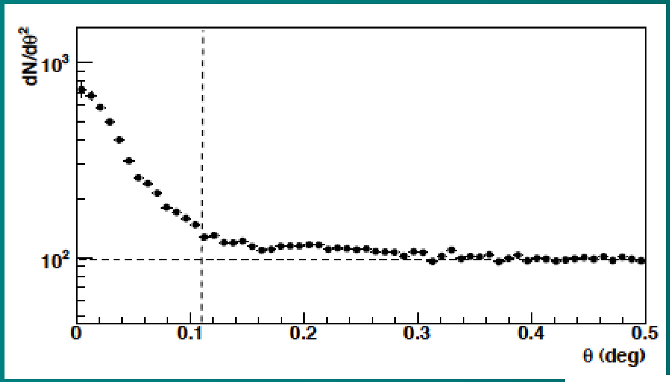


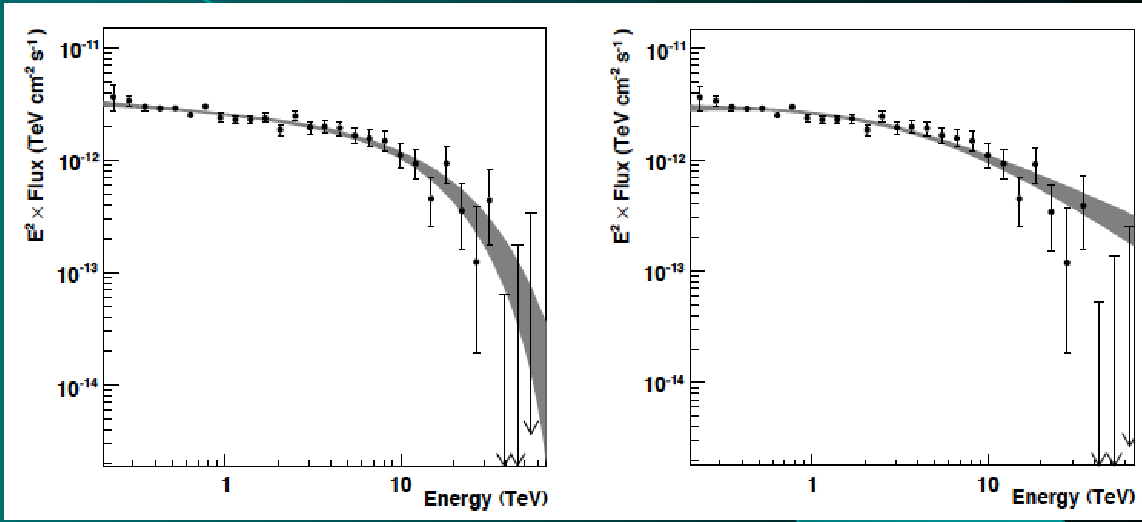
HESS data

By HESS:

270 GeV-70 TeV

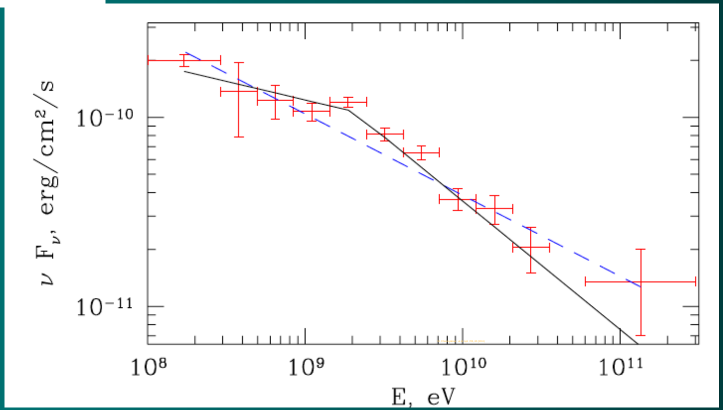
$\Theta < 0.1^o$





By Fermi-LAT:

100 MeV-300 GeV



$$E > E_{br}$$

$$\chi^2/d.o.f. = 0.81$$

$$\Gamma = 2.68 \pm 0.05$$

Gamma Rays from the Galactic Center

Background component: $$\frac{d\Phi_{Bg}}{dE} = B^2 \cdot \left(\frac{E}{\mathrm{GeV}}\right)^{-\Gamma}$$

$$\boxed{\frac{d\Phi_{Tot}}{dE} = \frac{d\Phi_{Bg}}{dE} + \frac{d\Phi_{DM}}{dE}}$$

4 free parameters:

$$B, \Gamma, A, M$$

DM contribution: $$\frac{\mathrm{d}\,\Phi_{\mathrm{DM}}}{\mathrm{d}\,E} = \sum_i \frac{\langle \sigma_i v \rangle}{2} \frac{\mathrm{d}\,N_i}{\mathrm{d}\,E} \times \frac{\overbrace{\Delta\Omega \,\langle J_{(2)} \rangle_{\Delta\Omega}}^{A}}{4\pi M^2}$$

Cembranos, Gammaldi, Maroto arXiv [1204.0655v1], PRD 86, 103506 (2012), JCAP 1304 (2013) 051

Gamma Rays from the Galactic Center

Channel	M (TeV)	$A\,(10^{-7}\,\mathrm{cm}^{-1}\mathrm{s}^{-1/2})$	$B\,(10^{-4}\,\mathrm{GeV}^{-1/2}\mathrm{cm}^{-1}\mathrm{s}^{-1/2})$	Γ	$\chi^2/\,\mathrm{dof}$	$\Delta\chi^2$	b
e^+e^-	7.51 ± 0.11	8.12 ± 0.73	2.78 ± 0.79	2.55 ± 0.06	2.09	32.6	111 ± 20
$\mu^+\mu^-$	7.89 ± 0.21	21.2 ± 1.92	2.81 ± 0.53	2.55 ± 0.06	2.04	31.4	837 ± 158
$\tau^+\tau^-$	12.4 ± 1.3	7.78 ± 0.69	3.17 ± 0.62	2.59 ± 0.06	1.59	20.6	278 ± 76
$u\bar{u}$	27.9 ± 1.8	6.51 ± 0.46	9.52 ± 9.47	3.08 ± 0.35	0.78	1.2	987 ± 189
$d\bar{d}$	42.0 ± 4.4	4.88 ± 0.48	8.26 ± 7.86	3.03 ± 0.34	0.73	0.0	1257 ± 361
$s\bar{s}$	53.9 ± 6.2	4.85 ± 0.57	6.59 ± 5.43	2.92 ± 0.29	0.90	4.1	2045 ± 672
$c\bar{c}$	31.4 ± 6.0	6.90 ± 1.06	53.0 ± 157	3.70 ± 1.07	1.78	25.0	1404 ± 689
$b\bar{b}$	82.0 ± 12.8	3.69 ± 0.61	6.27 ± 6.07	2.88 ± 0.35	1.32	14.2	2739 ± 1246
$t\bar{t}$	87.7 ± 8.2	3.68 ± 0.34	6.07 ± 3.34	2.86 ± 0.19	0.88	3.6	3116 ± 820
W^+W^-	48.8 ± 4.3	4.98 ± 0.40	5.18 ± 2.23	2.80 ± 0.15	0.84	2.6	1767 ± 419
ZZ	54.5 ± 4.9	4.73 ± 0.40	5.38 ± 2.45	2.81 ± 0.16	0.85	2.9	1988 ± 491

$$A^2 = \frac{\langle \sigma v \rangle \, \Delta\Omega \, \langle J_{(2)} \rangle_{\Delta\Omega}}{8\pi M^2}$$

$$\langle \sigma v \rangle = 3 \cdot 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}$$

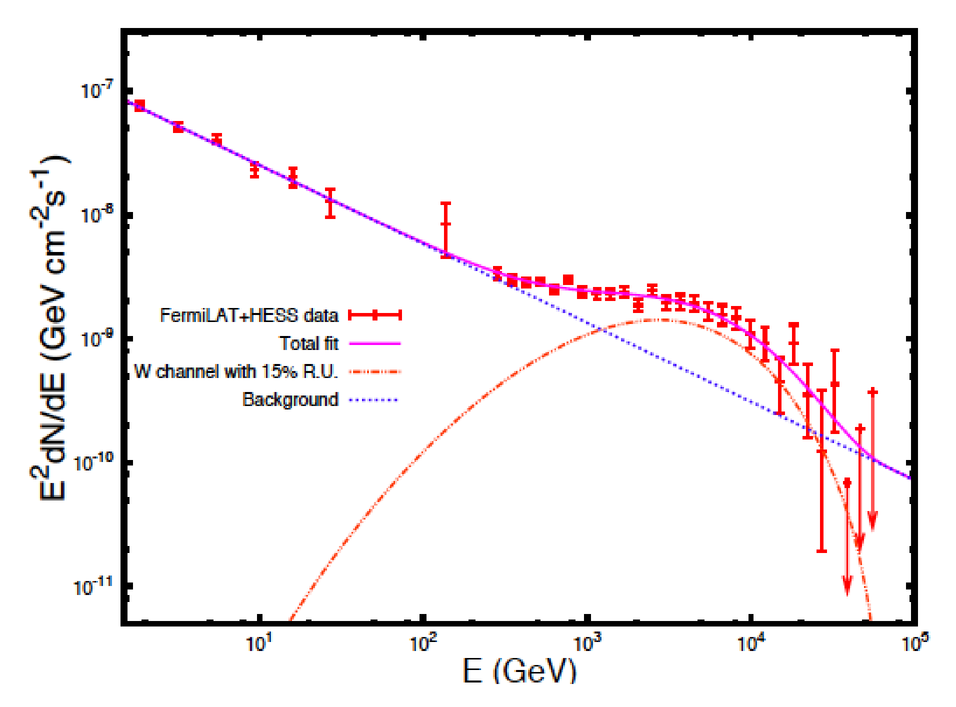
$$\Delta\Omega \simeq 10^{-5}$$

$$b \equiv \langle J_{(2)} \rangle / \langle J_{(2)}^{\mathrm{NFW}} \rangle$$

$$\langle J_{(2)}^{\mathrm{NFW}} \rangle \simeq 280 \cdot 10^{23}\ \mathrm{GeV}^2\mathrm{cm}^{-5}$$

Cembranos, Gammaldi, Maroto arXiv [1204.0655v1], PRD 86, 103506 (2012), JCAP 1304 (2013) 051

Gamma Rays from the Galactic Center



Cembranos, Gammaldi, Maroto arXiv [1204.0655v1], PRD 86, 103506 (2012), JCAP 1304 (2013) 051

M_{DM}>10 TeV

Boost factor =<J>/<J>$_{NFW}$≈ 10^3

Bg. compatible with Fermi-LAT

(Fermi-LAT Data)	W^+W^-
M	51.7 ± 5.2
A	4.44 ± 0.34
B	3.29 ± 1.03
Γ	2.63 ± 0.02
$\chi^2/$ dof	0.75

Indirect Searches: Cosmic rays

Cosmic-ray fluxes at the Earth from DM annihilating or decay in Galactic sources depend by the Standard Model (SM) secondary particle of interest.

Gamma rays:

$$\frac{d\Phi_\gamma}{dE} = \sum_{a=1}^{2} \sum_{i}^{\text{channels}} \frac{\zeta_i^{(a)}}{a} \cdot \frac{dN_i^{(\gamma)}}{dE} \cdot \frac{\Delta\Omega \left\langle J_{(a)} \right\rangle_{\Delta\Omega}}{4\pi M^a}$$

Neutrinos:

$$\frac{d\Phi_{\nu_f}}{dE} = \sum_{p=1}^{3} \sum_{a=1}^{2} \sum_{i}^{\text{channels}} P_{fp} \cdot \frac{\zeta_i^{(a,\nu_p)}}{a} \frac{dN_i^{(\nu_p)}}{dE} \cdot \frac{\Delta\Omega \left\langle J_{(a)} \right\rangle_{\Delta\Omega}}{4\pi M^a}$$

Antiprotons:

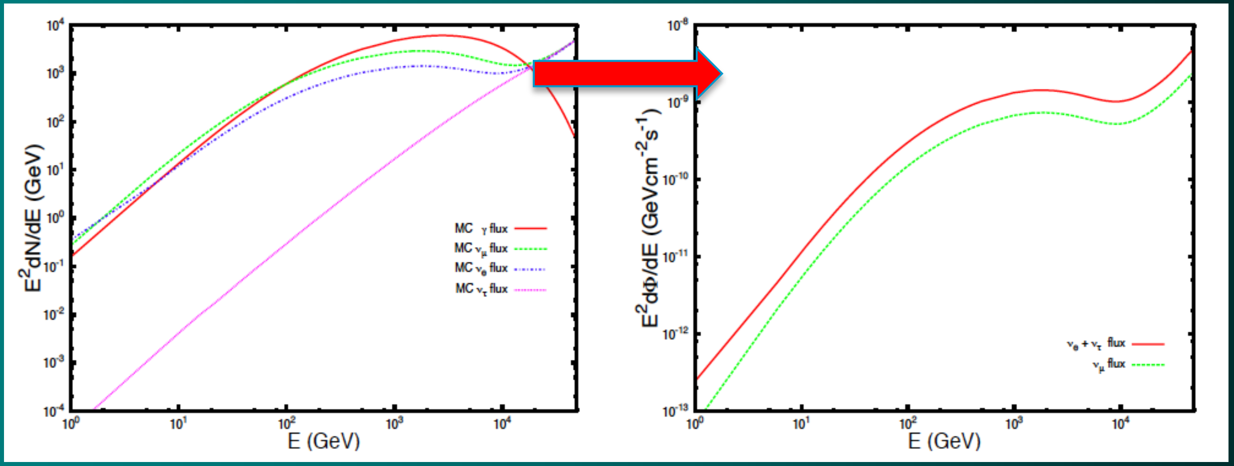
$$\frac{\mathrm{d}\Phi_{\bar{p}}}{\mathrm{d}E_{\bar{p}}} = \sum_{a=1}^{2} \sum_{i}^{\text{channels}} \frac{\zeta_i^{(a)}}{a} \frac{\mathrm{d}N_i^{(\bar{p})}}{\mathrm{d}E_{\bar{p}}} \cdot \frac{v_{\bar{p}}}{4\pi} \left(\frac{\rho_\odot}{M}\right)^a R_{(a)}(E_{\bar{p}})$$

Neutrinos from the Galactic Center

$$\frac{d\Phi_{\nu_f}}{dE} = \sum_{p=1}^{3}\sum_{a=1}^{2}\sum_{i}^{\text{channels}} P_{fp} \cdot \frac{\zeta_i^{(a,\nu_p)}}{a}\frac{dN_i^{(\nu_p)}}{dE} \cdot \frac{\Delta\Omega \left\langle J_{(a)} \right\rangle_{\Delta\Omega}}{4\pi M^a}$$

W^+W^- boson channel parameters from gamma-rays fit:

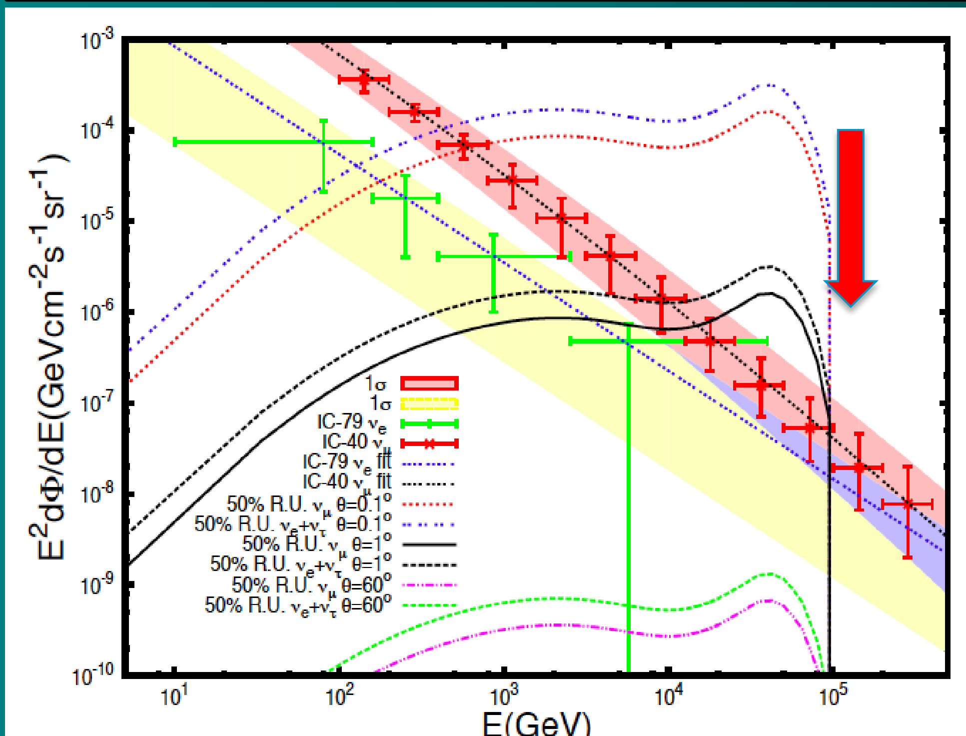
$M_{DM} \approx 50$ TeV



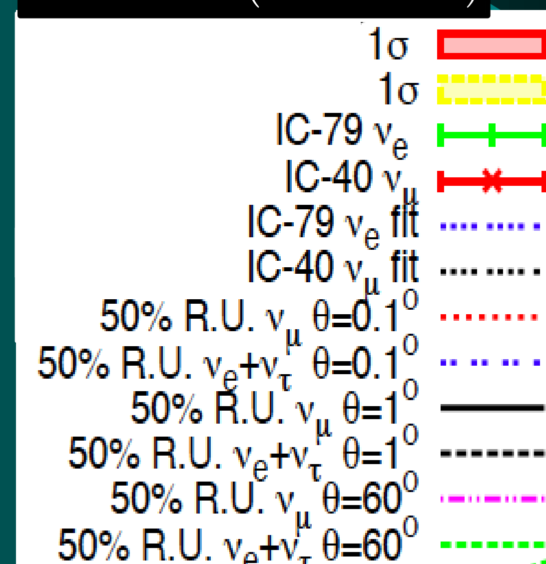
Cembranos, Gammaldi, Maroto, , PRD 90 (2014) 4, 043004 arXiv [1403.6018]

Neutrinos from the Galactic Center

$$\frac{d\Phi_{\nu_f}}{dE} = \sum_{p=1}^{3}\sum_{a=1}^{2}\sum_{i}^{\text{channels}} P_{fp}\cdot\frac{\zeta_i^{(a,\nu_p)}}{a}\frac{dN_i^{(\nu_p)}}{dE}\cdot\frac{\boxed{\Delta\Omega}\,\langle J_{(a)}\rangle_{\Delta\Omega}}{4\pi M^a}$$



$$\Delta\Omega = 2\pi(1-\cos\theta)$$



Cembranos, Gammaldi, Maroto, , PRD 90 (2014) 4, 043004 arXiv [1403.6018]

Neutrinos from the Galactic Center

Effective Area and Resolution Angle depend on:

- Energy range;
- Neutrino flavor and background;
- Position of the source with respect to the detector (Northern or Southern sky);
- Number of strings in the configuration of observation.

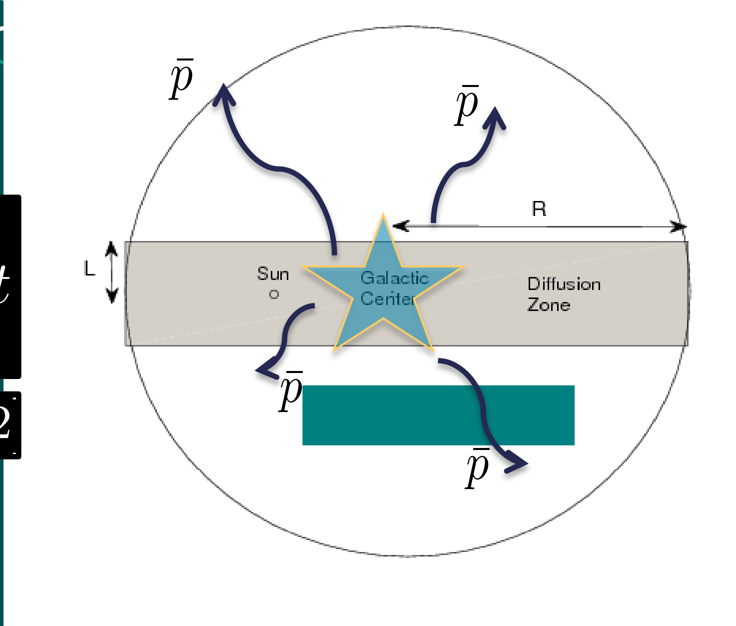
$$\chi_{\nu_i} = \frac{\Phi_{\nu_i}\sqrt{A_{\rm eff}\, t_{\rm exp}\, \Delta\Omega}}{\sqrt{\Phi_{\nu_i} + \Phi_{\nu_i}^{\rm Atm}}} = 5\,(3,\ 2)$$

$$N_{\nu_f}^{t_{exp}} = \int_{E_{\rm min}^{\nu}}^{\infty} dE_\nu\ \frac{d\Phi_{\nu_f}}{dE} \times A_{\rm eff}\, t_{\rm exp}$$

Cembranos, Gammaldi, Maroto, , PRD 90 (2014) 4, 043004 arXiv [1403.6018]

Antiprotons from the Galactic Center

The antiprotons spatial production and propagation is described by :



$$R^{\delta}(E_{\bar{p}}) = \frac{2}{R^2}\sum_{m=1}^{\infty}\frac{J_0\left(\zeta_1\frac{r_\odot}{R}\right)}{A_m J_1^2(\zeta_m)} \times Const$$

$$A_m(E_{\bar{p}}) = 2h\Gamma_{inel} + V_c + K(E_{\bar{p}})\, S_m \coth[S_m L/2]$$

$$K(E_{\bar{p}}) = K_0\beta(p/GeV)^{\delta}$$

Model	δ	K_0 [kpc^2/Myr]	V_c [km/s]	L [kpc]
MIN	0.85	0.0016	13.5	1
MED	0.70	0.0112	12	4
MAX	0.46	0.0765	5	15

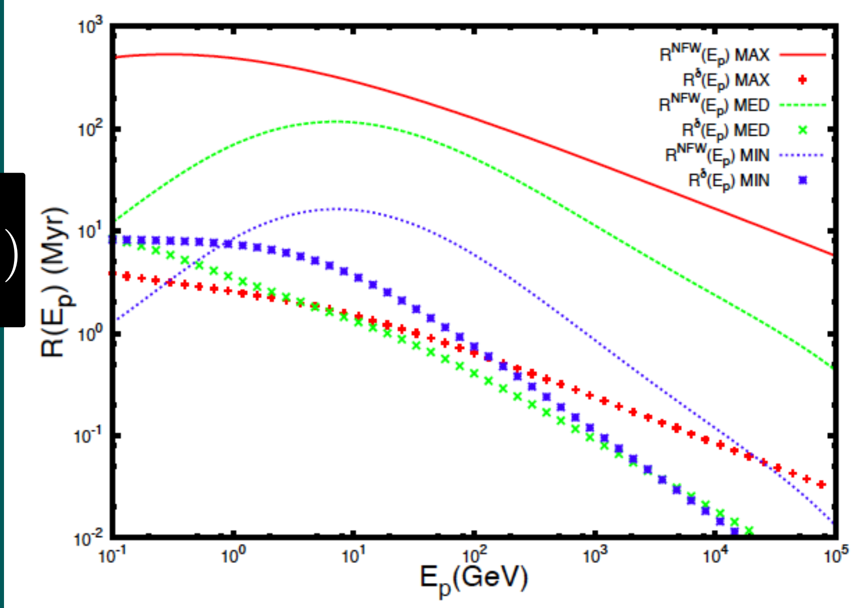
Where the new constant volume needs to be determined.

Cembranos, Gammaldi, Maroto, JCAP 1503 (2015) 03, 041 arXiv: 1410.6689

Antiprotons from the Galactic Center

To determine the new constant, we refer to the astrophysical factor for “not charged” particles:

$$\langle J_a \rangle = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} \mathrm{d}\Omega \int_0^{l_{max}(\Psi)} \rho^a[r(l)]dl(\Psi)$$

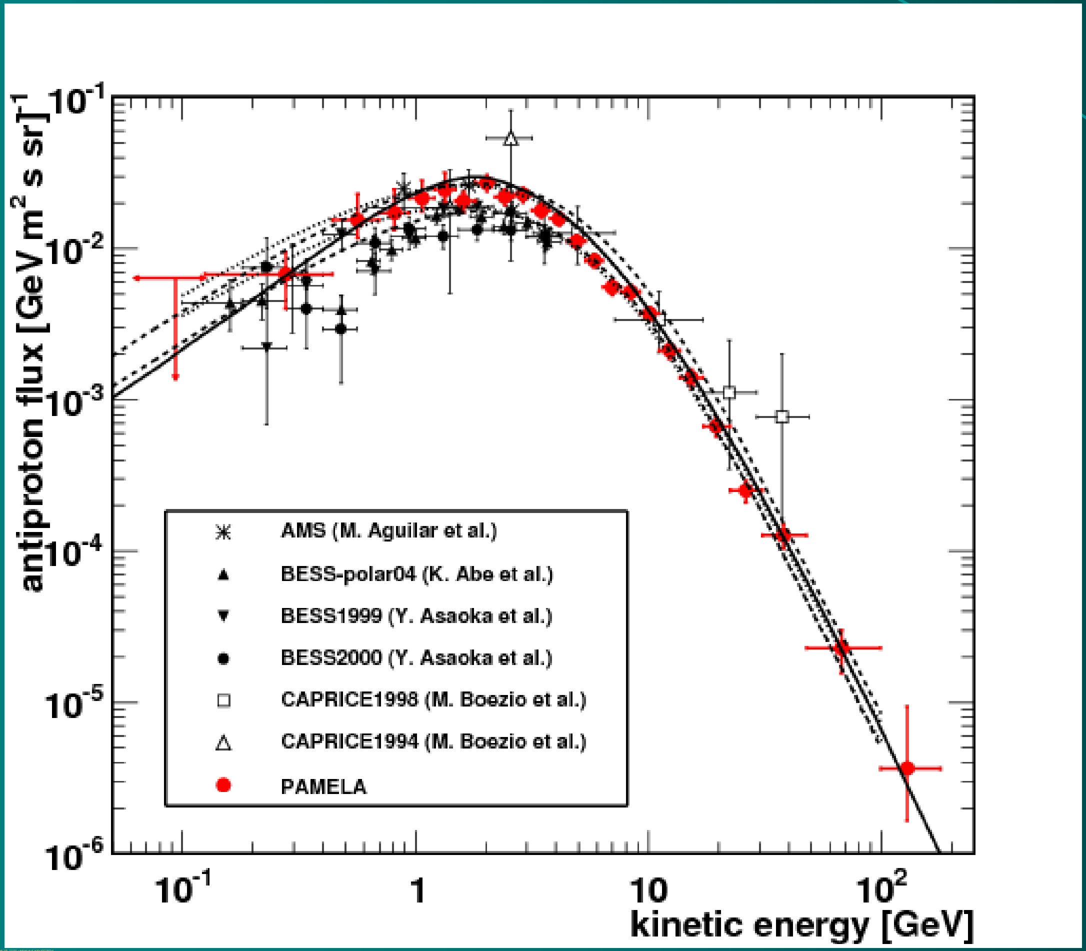


$$\left(\frac{\rho(r,0)}{\rho_\odot}\right)^2 \simeq C_2 \times \delta^{(3)}(\vec{r})$$

$$C_2 = Const \times 2\pi = \langle J \rangle^{NFW}_{\Delta\Omega}\,\Delta\Omega_{HESS}\left(\frac{D_\odot}{\rho_\odot}\right)^2 \approx \quad 2.13 \times 10^{60} m^3 \mathrm{sr}$$

Cembranos, Gammaldi, Maroto, JCAP 1503 (2015) 03, 041 arXiv: 1410.6689

Pamela Antiproton Data



- Compatible with antiproton *secondary* emission
- Any new primary source needs to be compatible with such antiproton flux.

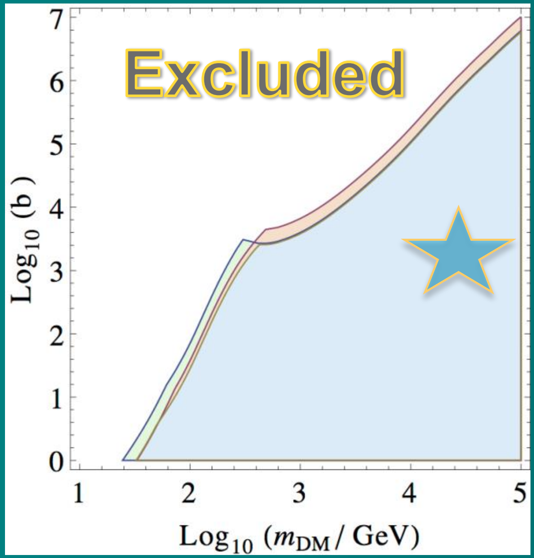
Cembranos, Gammaldi, Maroto, JCAP 1503 (2015) 03, 041 arXiv: 1410.6689

Antiprotons from the Galactic Center

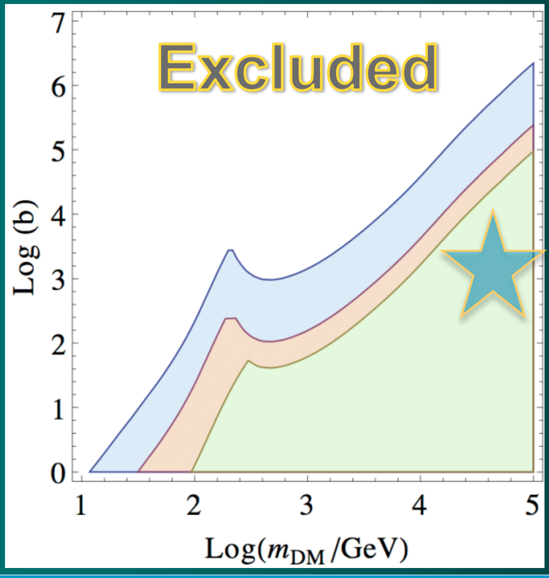
$$\frac{d\Phi_{\bar{p}}}{dE_{\bar{p}}} = \frac{v_{\bar{p}}}{4\pi}\frac{1}{2}\left(\frac{\rho_\odot}{m_{DM}}\right)^2 \sum_j \langle\sigma v\rangle_j \frac{dN^j_{\bar{p}}}{dE_{\bar{p}}}\left(b^j_{NFW} \times R^{NFW}(E_{\bar{p}}) + b^j_\delta \times C_1 \times R^\delta(E_{\bar{p}})\right).$$

MIN	ME	MA

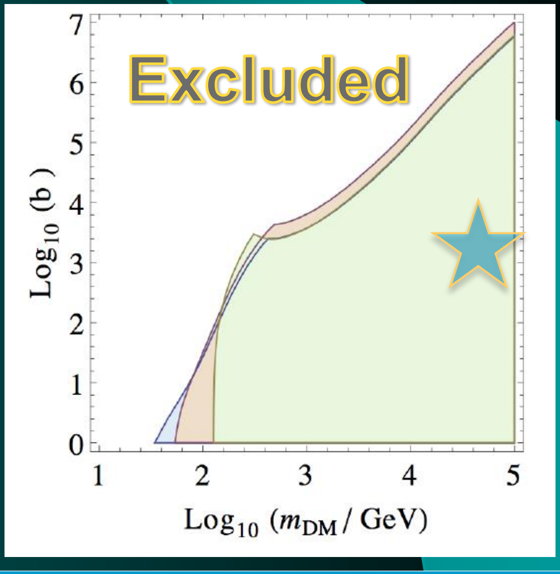
$b^W_{NFW}=0$



$b^W_\delta=0$



$b^W_{NFW}=1$



Cembranos, Gammaldi, Maroto, JCAP 1503 (2015) 03, 041 arXiv: 1410.6689

COSMOLOGICAL RESTRICTIONS

1.- Dark Matter density.

- 1.a. Cold Dark Matter.
- 1.b. Hot Dark Matter.
  - 1.b.I.- Restrictions due to the total dark matter density.
  - 4.b.II-.Restrictions due to the power spectrum.

2.- Nucleosynthesis.

3.- Astrophysical Observations → 3.a. Supernova SN1987A

TOTAL DARK MATTER DENSITY

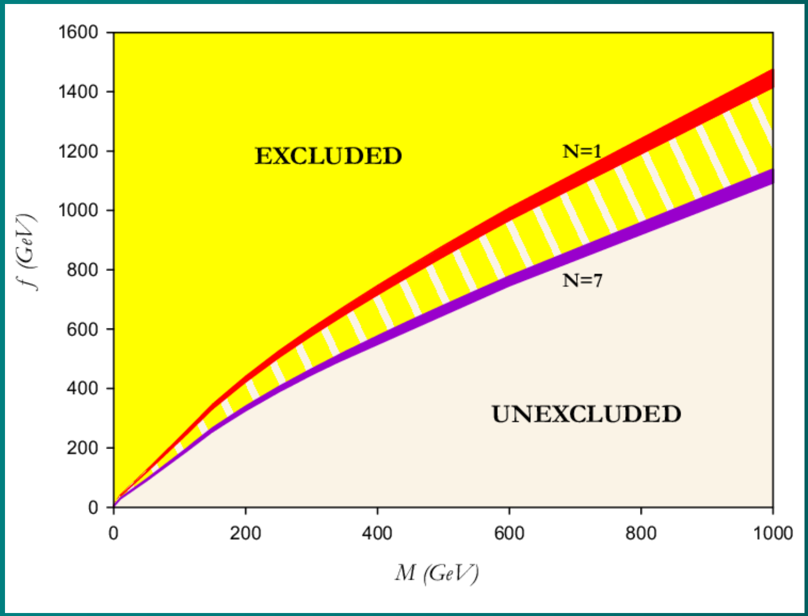
The observational bounds to the total non baryonic dark matter density coming from *WMAP* are:

$$\Omega_{NBDM}\ h^2 = 0.129 - 0.095 \text{ at the } 95\% \text{ C.L.}$$

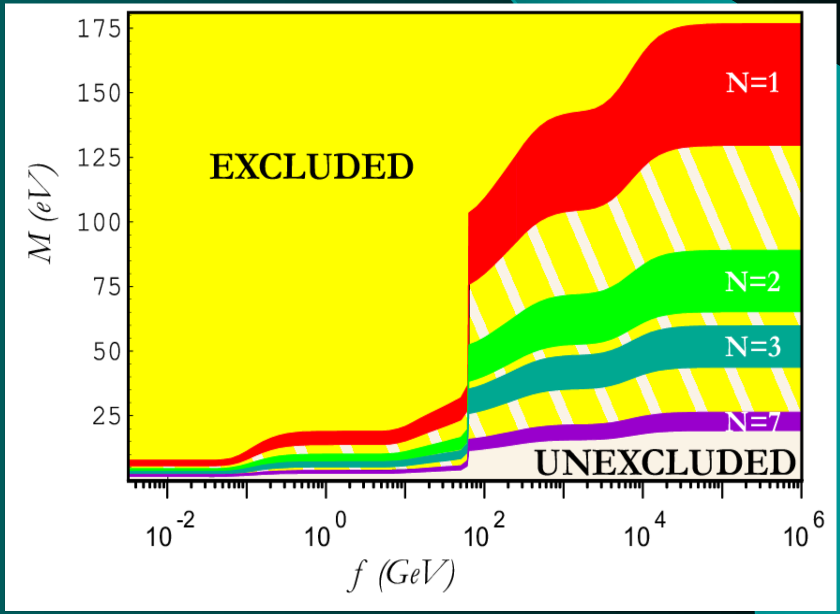
Cembranos, Dobado, Maroto, PRL 90 (2003) 241301

Cembranos, Dobado, Maroto, PRD 68 (2003) 103505

Branon as Cold Relic



Branon as Hot Relic



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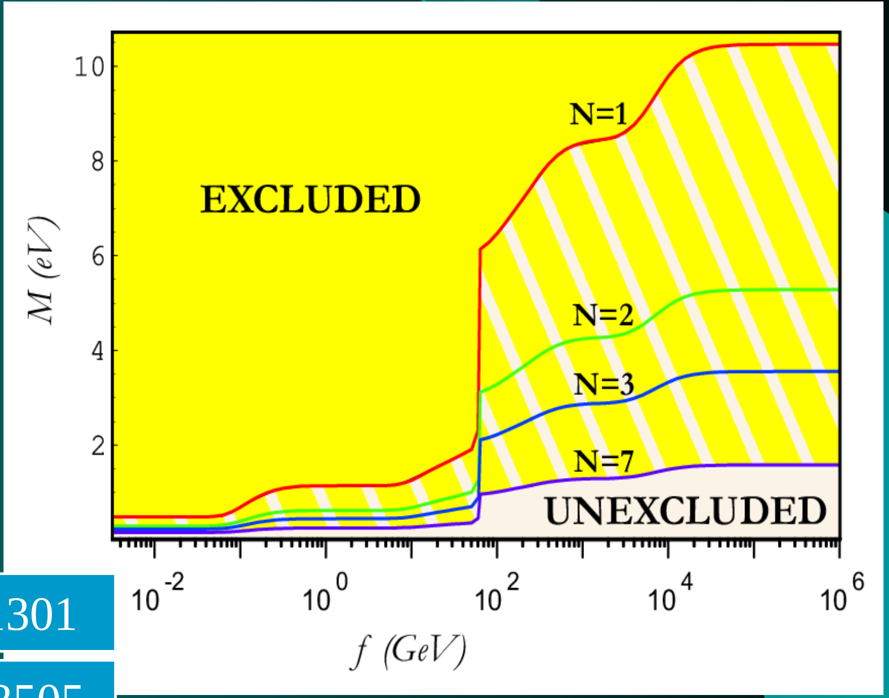
J.A.R. Cembranos

HOT DARK MATTER DENSITY

More constraining limits on the hot dark matter energy density can be derived from a combined analysis of the data from *WMAP, CBI, ACBAR, 2dF* and *Lyman-α*.

$\Omega_{HDM} h^2 < 0.0076$ at the 95% C.L.

Hot dark matter is able to cluster on large scales but free-streaming reduces the power on small scales.



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NUCLEOSYNTHESIS

One of the most successful predictions of the standard cosmological model is the relative abundance of the light elements.

It is very sensitive to the number of relativistic degrees of freedom through the Hubble parameter *H* (rate of the Universe expansion). At a given temperature *T* :

$$g_{eff}(T) = g_{eff}^{SM}(T) + \sum_{\text{nuevos bosones}} g_i \left(\frac{T_i}{T}\right)^4 + \frac{7}{8} \sum_{\text{nuevos fermiones}} g_i \left(\frac{T_i}{T}\right)^4$$

An increase in the number of relativistic degrees of freedom during nucleosynthesis could deviate the predictions from the observations.

Usually, this restriction is parameterized in terms of the effective number of neutrino species: $N_\nu = 3 + \Delta N_\nu$

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BBN RESTRICTIONS

Restrictions for the number of branons *N* :

1.- If branons decouple after nucleosynthesis:

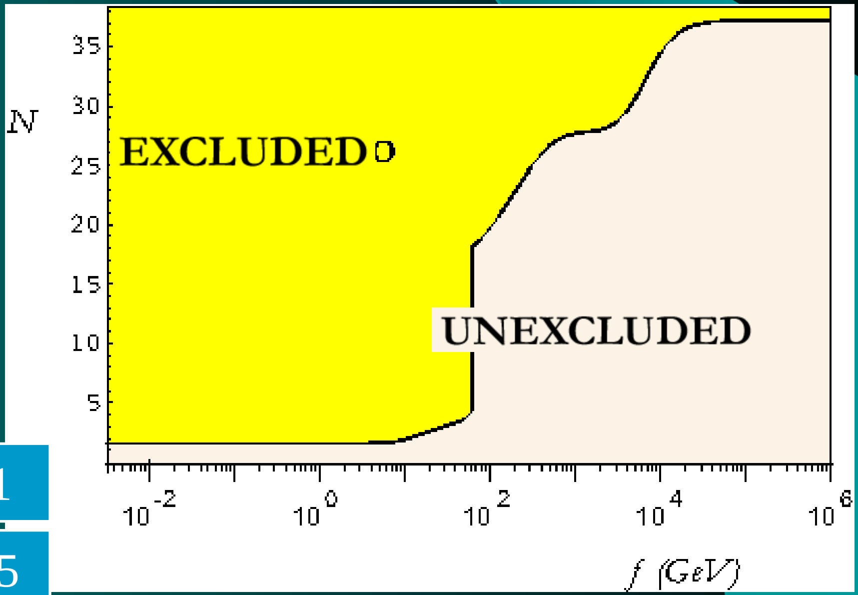
$$N \leq \frac{7}{4}\Delta N_\nu$$

2.- If branons decouple before nucleosynthesis:

$$N \leq \frac{7}{4}\Delta N_\nu \left(\frac{g_{eff}(T_{f,B})}{10.75}\right)^{4/3}$$

For example, a conservative bound for the number of effective neutrinos is:

$$\Delta N_\nu = 1$$



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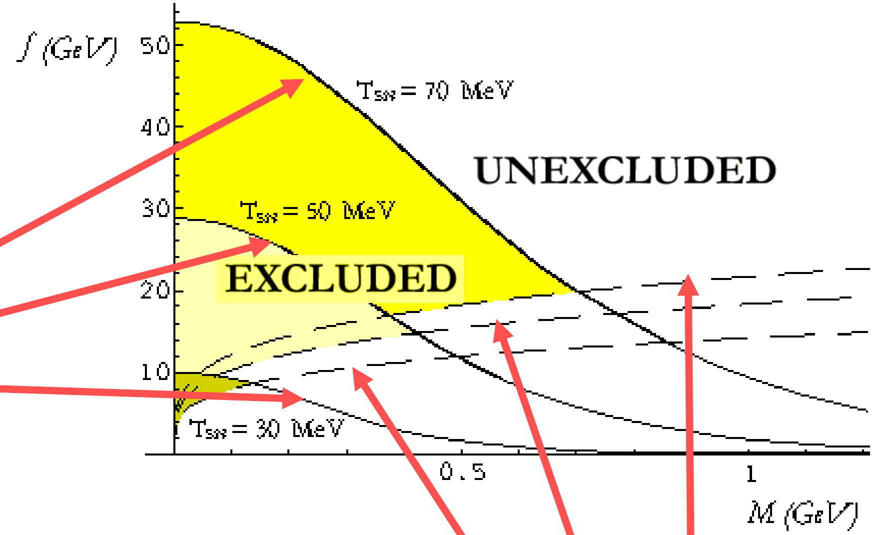
SUPERNOVA SN1987A

Results for different SN1987A temperatures

$$Q \gtrsim 5 \times 10^{-30}\ \mathrm{GeV}^5$$



We estimate such energy by considering the channel corresponding to electron-positron annhilation:

$$Q_{Br}(f,M) \equiv \int \prod_{i=1}^{2} \left\{ \frac{d^3 k_i}{(2\pi)^3 2E_i} 2f_i \right\} (E_1 + E_2) 2s\ \sigma_{e^+e^- \to \pi\pi}(s,f,M)$$

On the other hand, the mean free path should be larger than the star size

$$L \sim (8\pi f^8)/(M^2 T_{SN}^4 n_e)$$

$$R \sim \mathcal{O}(10)\ \mathrm{Km}$$

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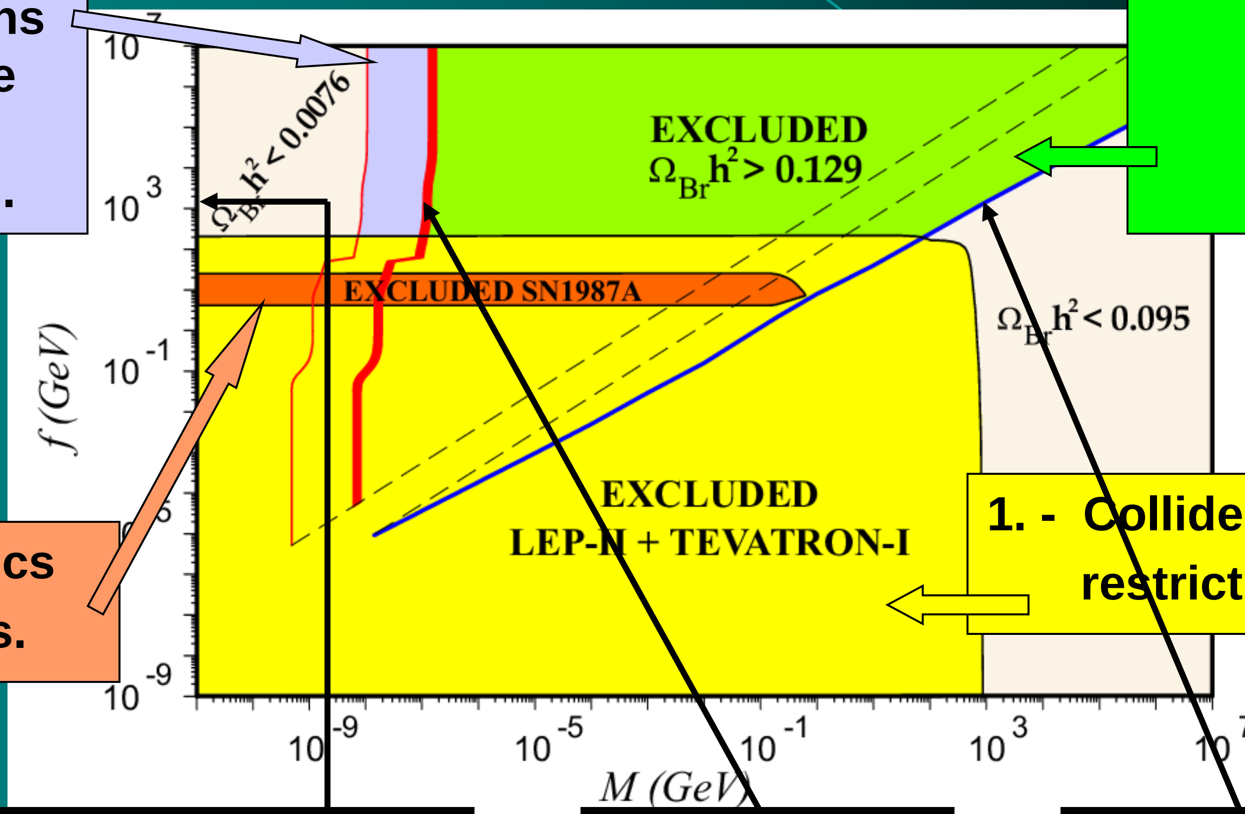
GENERAL SITUATION

General situation of the branon physics and its cosmological interest ($N = 1$):

3. - Restrictions due to the power spectrum.

2.- Restrictions due to the total dark matter density.



1. - Collider restrictions.

4. - Astrophysics restrictions.

C.- Branons as Non Thermal Relic

B.- Branons as Warm DM

A.- Branons as WIMPs

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RADIATIVE CORRECTIONS

Modifications in the standard model phenomenology due to branon radiative corrections:

1.- One loop correction

- 1.a. New effective interactions among four particles.
- 1.b. Force mediated by branons.

2.- Two loop corrections

- 2.a. Electroweak precision observables.
- 2.b. Muon anomalous magn...ic mom...

Cembr... ...s, PRD 73 (2006) 057303

Λ: **Scale associated with new physics.**

ONE LOOP CORRECTION

New phenomenology in particle accelerators:

$$\Gamma_L^{(2)}[\Phi] = \frac{N\Lambda^4}{192\,(4\pi)^2 f^8}\int dx\,\{2T^{\mu\nu}T_{\mu\nu} + T^\mu_\mu T^\nu_\nu\}$$

Lower bounds for the parameter: $f^2/(N^{1/4}\Lambda)$.

Prospects for future experiments:

	$\sqrt{s}$ (TeV)	$\mathcal{L}$ (fb^{-1})	$f^2/(N^{1/4}\Lambda)$
ILC	0.5	500	261
	1.0	200	421
Tevatron	2.0	2	83
	2.0	30	108
LHC	14	10	332
	14	100	383

Cembranos, Dobado, Maroto, PRD 73 (2006) 035008, PRD 73 (2006) 057303

LHC PROSPECTS

Signals: $q\bar{q}, gg \to \gamma\gamma, \ell^+\ell^-, (WW, t\bar{t}...)$

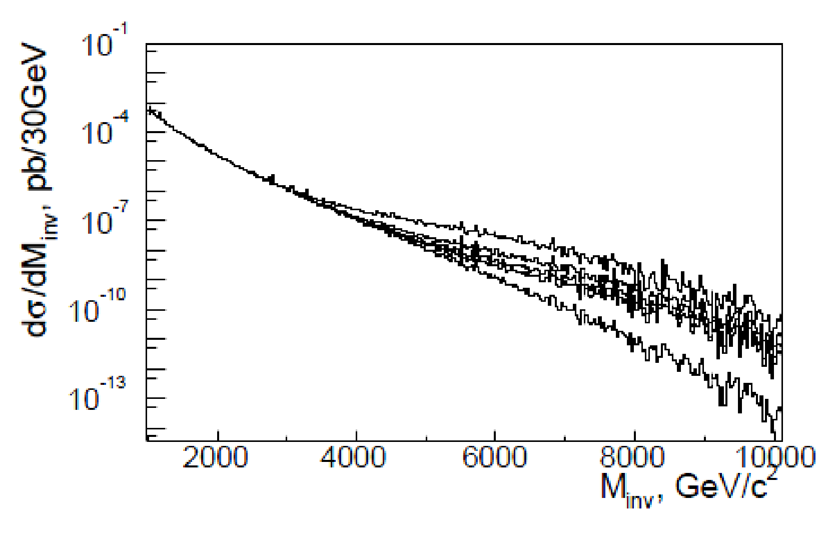
1.- Excess in di-leptons and di-photons mass distribution

2.- Event shape: distribution of gg more central (s-channel)

Example: dimuon channel

Different excesses for

$f^2/(N^{1/4}\Lambda)=$ 50, 100, 150, 200



Dimuon is accepted for

$|\eta| \leq 2.4 \qquad p_T \geq 20$ GeV

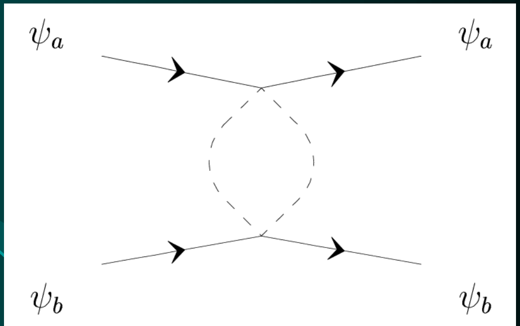
Estimated sensitivity and resolution:

$\varepsilon \approx 83 \div 91\ \%$

$\delta p_T \approx 4\% \sqrt{p_T/TeV}$

FORCE MEDIATED BY BRANONS

The non relativistic force mediated by branons is also an one loop effect.



The result takes form:

$$V_{br}(r) = -N\frac{m_a m_b\, e^{-2\,M\,r}}{240\, f^8 (4\pi)^3\, r^7}\mathcal{P}(M r)$$

with: $\mathcal{P}(x) = 360 + 720\,x + 636\,x^2 + 312\,x^3 + 95\,x^4 + 30\,x^5$

The associated asymptotic limits are respectively:

$$V_{br}(r) = \begin{cases} -N\frac{3 m_a m_b}{2 f^8 (4\pi)^3}\frac{1}{r^7}\left(1 - \frac{7(M r)^2}{30} + \ldots\right) & ;\ 2\,r M << 1 \\ -N\frac{m_a m_b M^5}{8 f^8 (4\pi)^3}\frac{e^{-2\,M\,r}}{r^2}\left(1 + \frac{19}{6 M r} + \ldots\right) & ;\ 2\,r M >> 1 \end{cases}$$

Far from the experimental ranges.

Cembranos, Dobado, Maroto, PRD 73 (2006) 035008, PRD 73 (2006) 057303

MUON ANOMALOUS MOMENT

The BAGS (Brookhaven Alternating Gradient Synchrotron) has reached a relative precision of 0.5 ppm in the determination of a $_\mu$= (g$_\mu$ - 2)/2 .

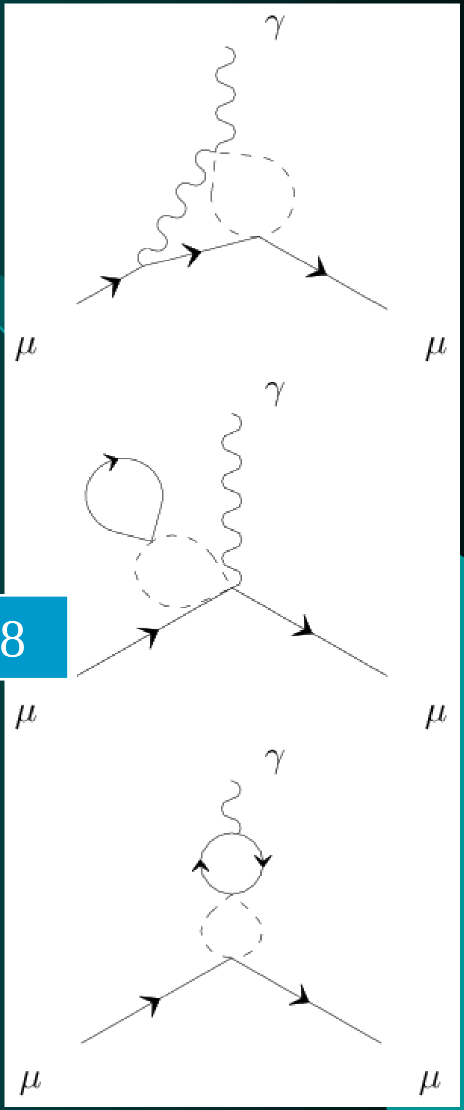
The E821 Collaboration at BAGS has found a 2.6 σ deviation with the SM:

$$\delta a_\mu \equiv a_\mu(exp) - a_\mu(SM) = 24.9\ (8.7) \times 10^{-10}$$

Aoyama, Hayakawa, Kinoshita, Nio, PRL 109 (2012) 111808

The branon contribution to the muon anomalous magnetic moment is a two loop effect.

$$\delta a_\mu \approx \frac{5\, m_\mu^2}{114\,(4\pi)^4}\,\frac{N\Lambda^6}{f^8}$$



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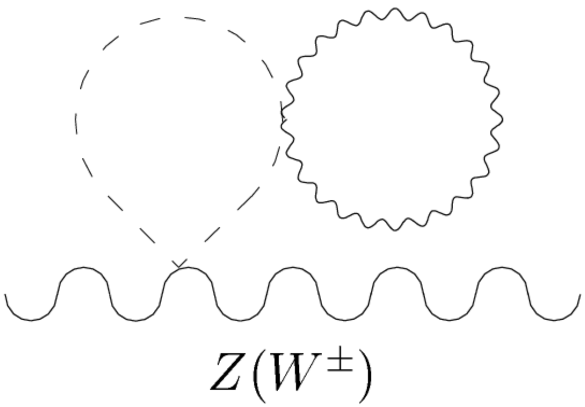
EW PRECISION OBSERVABLES

The results of the electroweak precision tests performed at LEP and SLC form a stringent set of precise constraints to compare with new physics.

We can focus on the parameter: $\bar{\epsilon} \equiv \frac{\delta M_W^2}{M_W^2} - \frac{\delta M_Z^2}{M_Z^2}$

$$\delta\bar{\epsilon} \approx \frac{5\,(M_Z^2 - M_W^2)}{12\,(4\pi)^4}\frac{N\Lambda^6}{f^8}$$



LEP and SLD result: $\bar{\epsilon} = 12.7\ (1.6) \times 10^{-3}$

(Altarelli, LEP EW Working Group)

The branon contribution to the electroweak precision observables is also a two loop effect.

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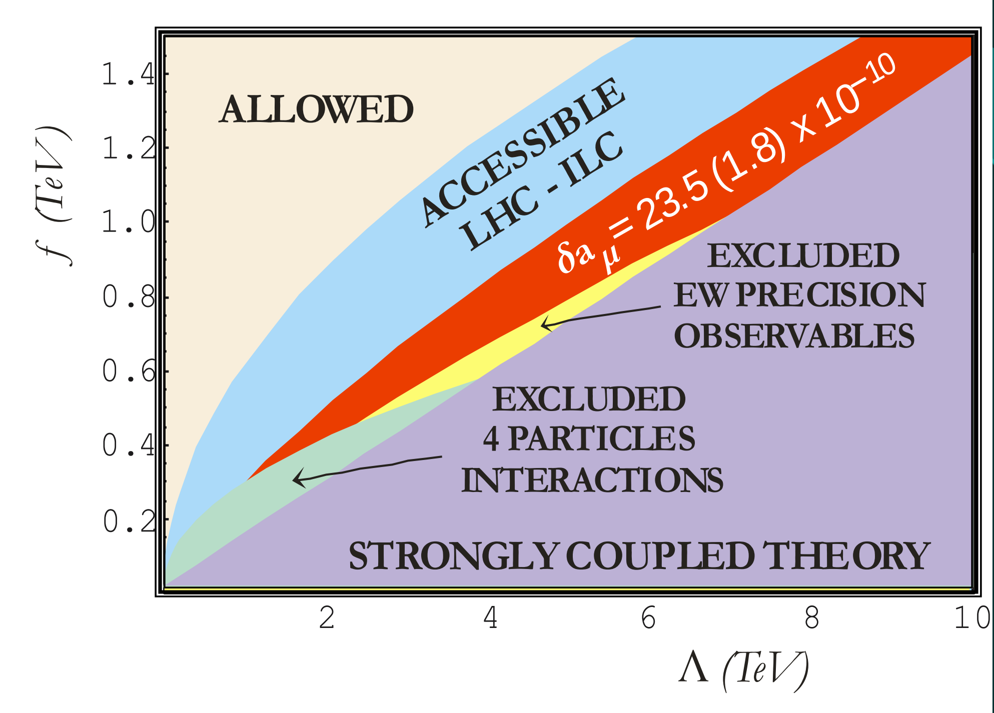
RADIATIVE RESULTS

The branon radiative effects (at 95% C.L.) on the Standard Model phenomenology can be observed in the following general plot (*N* = 1):



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CONCLUSIONS

1.- Disformal scalar fields arise in different theoretical frameworks: brane-worlds, massive gravity,…

2.- The branon signals constitute the first observational evidence for some extra dimensional models:

Flexible Brane Worlds ($f \ll M_F$).

2.- Their phenomenology can be determined in a model independent way in terms of the brane tension scale f, their number *N* and their masses *M*.

3.- This phenomenology is very rich and could be related with a great variety of experimental signals beyond the SM:

3.a. Scattering experiments: Single γ , MonoJet production, bhabha scattering …

3.b. Cosmological observations: Dark Matter candidate …

3.c. Astrophysical Analysis: Direct searches, Indirect searches …

3. d. Precision observables: Electroweak PO, dipole moments,…