Branon Dark Matter

and the γ–ray signal from the galactic center

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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)**

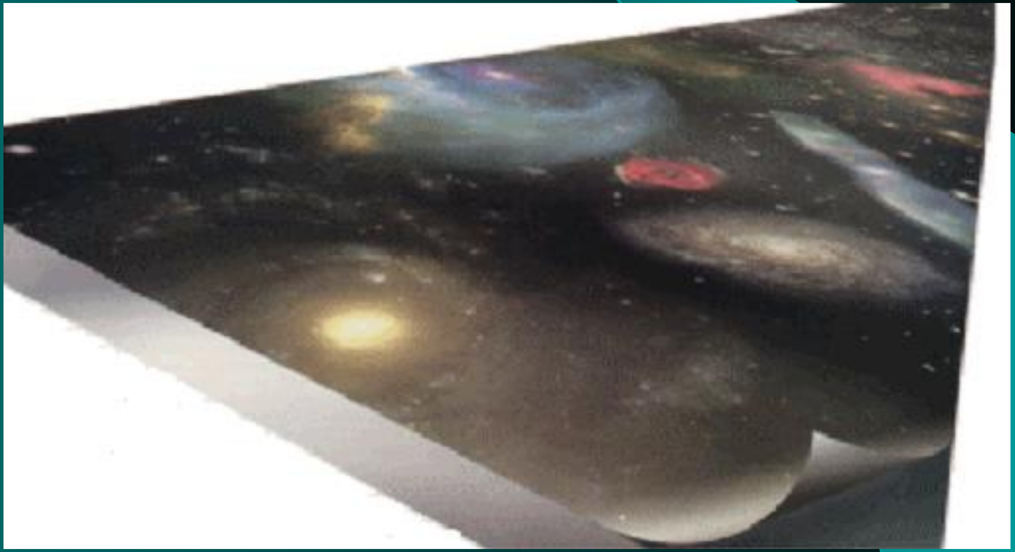
ADD Model (Arkani-Hamed, Dimopoulos and Dvali, 1998)

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:

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

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 confi**
  - 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 w
given by :

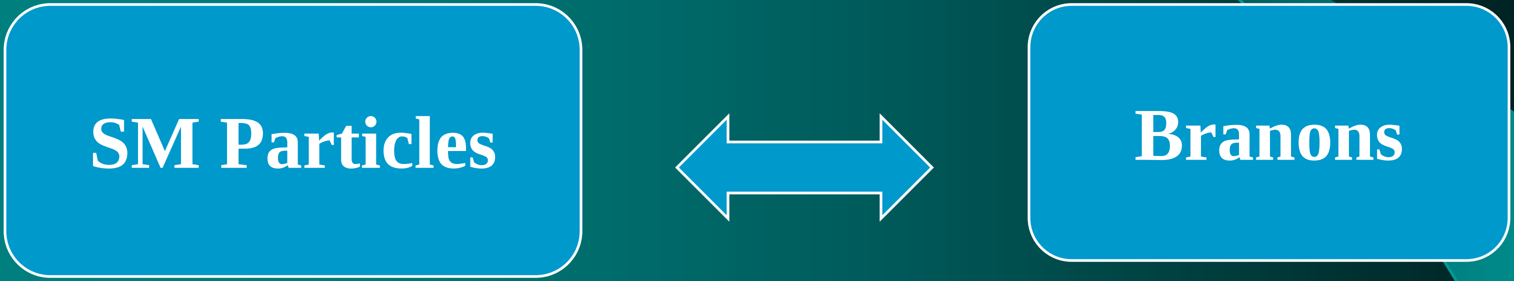
$$= g \cdot e^{\;\;\frac{}{2}\left(\frac{}{R}\right)^2 \frac{M_F^2}{f^4}}$$

(Bando, Kugo, Noguchi and Yoshioka)

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

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.



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

Description through an
EFFECTIVE LAGRANGIAN

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

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

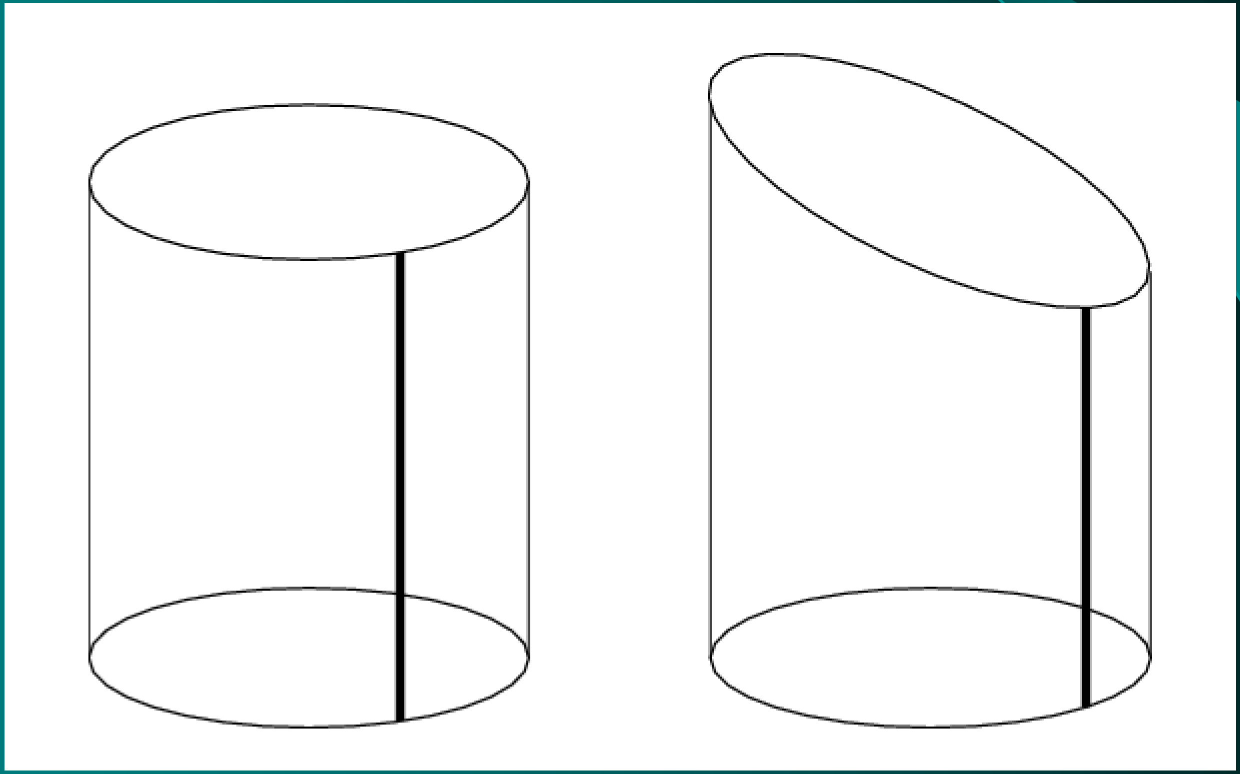
$$\kappa^2 = 16\pi / M_P^2$$

$$\xi_a \left\{ \right.$$

Killing vectors corresponding to translations on the extra space.

LOWER DIMENSIONAL EXAMPLE

Brane with trivial topology. The branon is massless on the left geometry but massive in the second, where the translational invariance is broken explicitly.



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 equiva extra space, if it is homog

Formally very similar to chiral lagrangians in QCD

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

BRANON MASSES

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

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

This fact is related to non factorizable metrics.

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

SM INTERACTIONS

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

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

$$2\ \ M_{\alpha\beta}\pi^\alpha\pi^\beta$$

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

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.

Z AND *W* DECAYS

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

1.- Z invisible width:

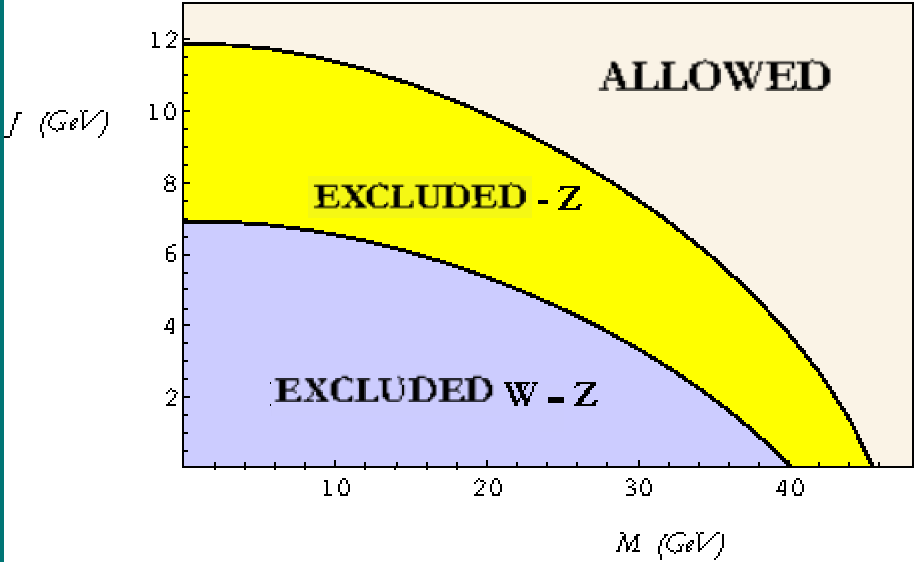
$\Delta\Gamma_Z^{inv.} < 2.0$ MeV (LEP I)

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

2.- W total width:

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

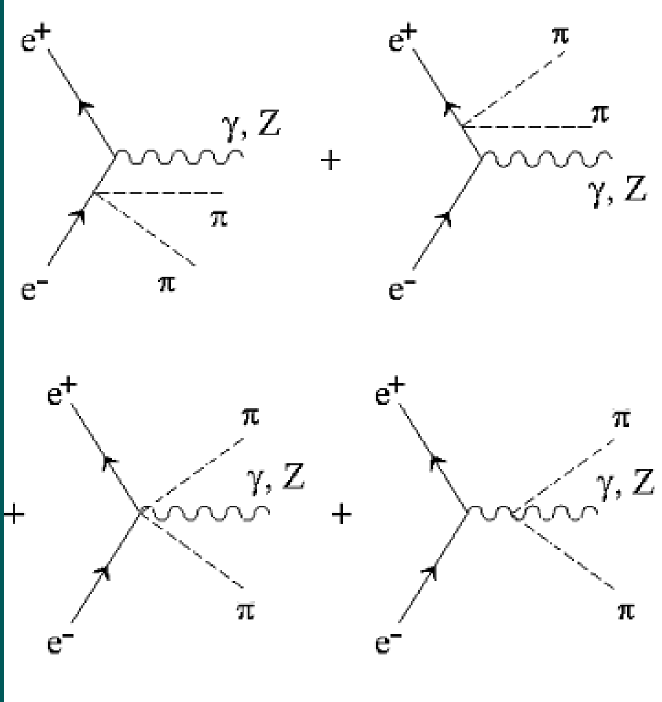
$$\begin{aligned} \Gamma_W^b\!: \; W^- &\longrightarrow l^-(p_1)\bar{\nu}(p_2)\pi(k_1)\pi(k_2) \\ W &\longrightarrow q(p_1)\bar{q}(p_2)\pi(k_1)\pi(k_2) \end{aligned}$$



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

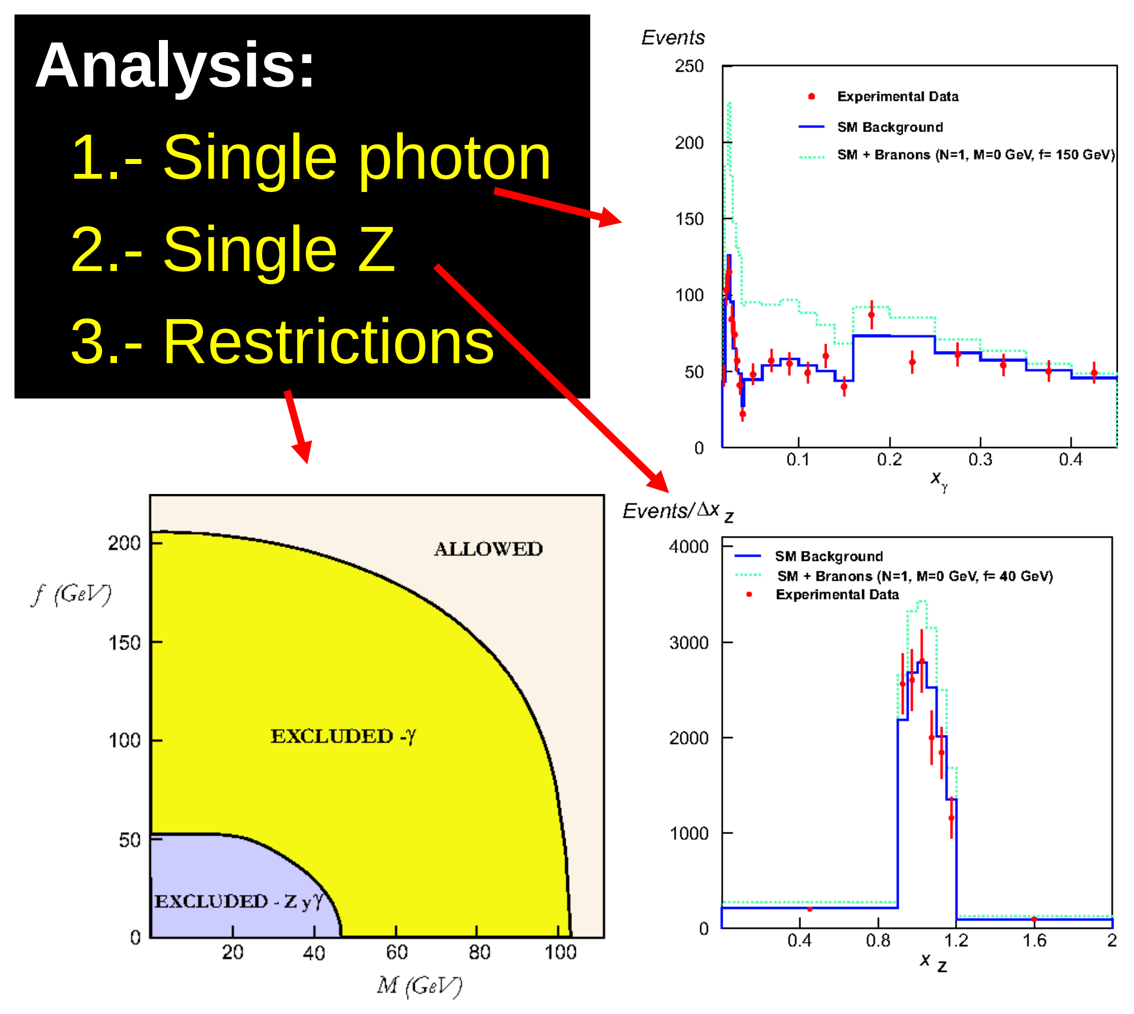


$$\frac{d\sigma_A}{dx\,d\cos\theta} = \frac{|h|^2}{4\pi}\frac{s(c_V^2+c_A^2)(s(1-x)-4\boxed{M^2})^2\boxed{N}}{61440\boxed{f^8}\pi^2}\sqrt{1-\frac{4\boxed{M^2}}{s(1-x)}}$$
$$\left[x(3-3x+2x^2)-x^3\sin^2\theta+\frac{2(1-x)(1+(1-x)^2)}{x\sin^2\theta}\right]$$

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 ($\mathcal{L}$) difference:

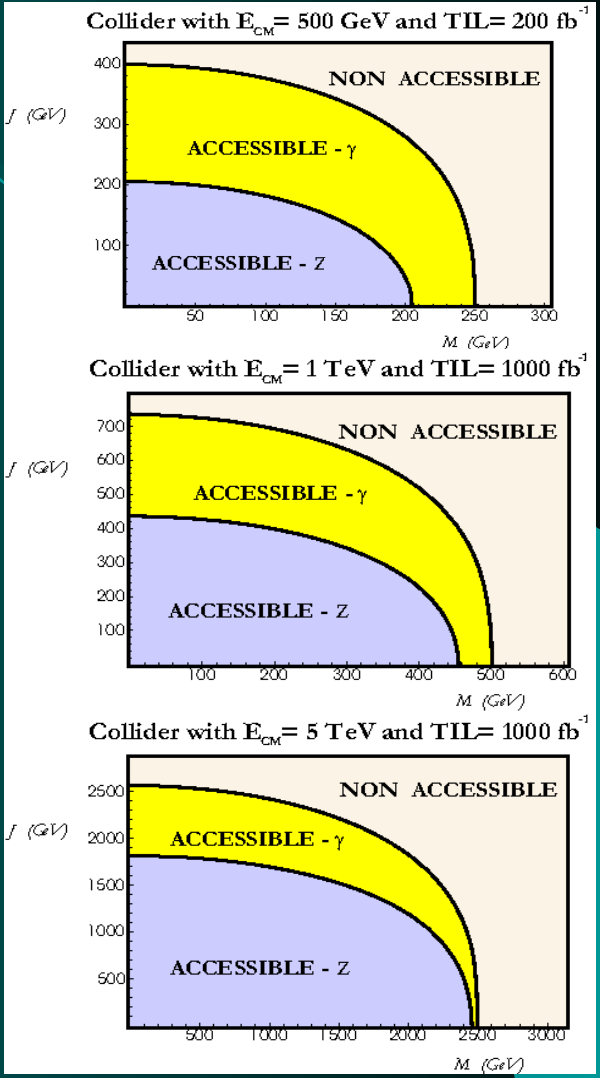
$$\sigma^{i}_{TII} = \sqrt{\frac{\mathcal{L}_{TII}}{\mathcal{L}_{TI}}}\,\sigma^{i}_{TI}$$

1.- Medium time.

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

2.- Long time

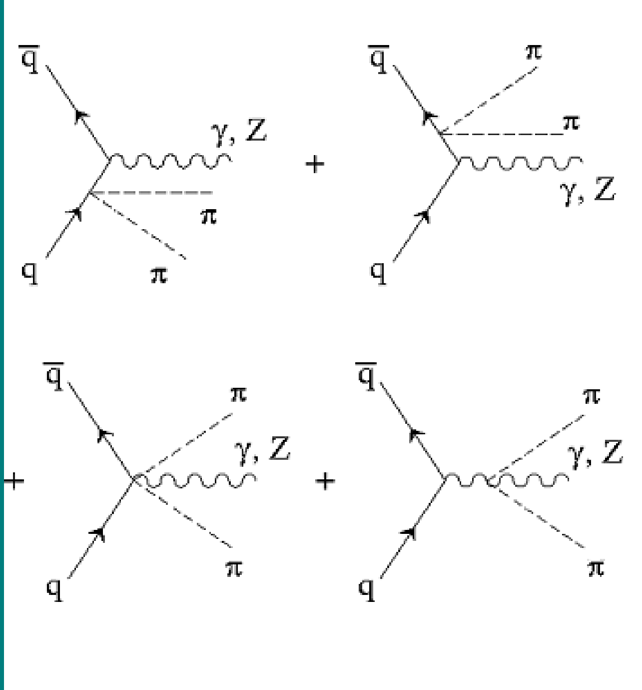
- 2.- CLIC
- 2.a. E_{CM} = 5 TeV



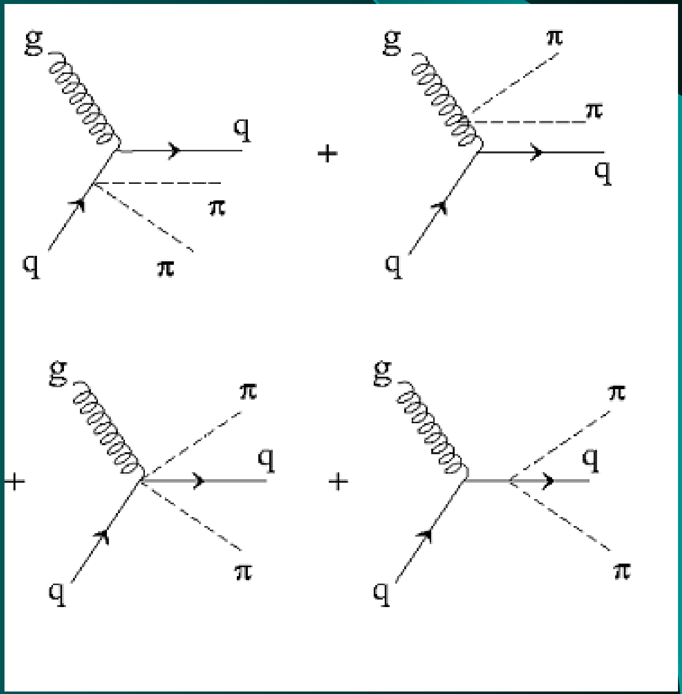
HADRONIC COLLIDERS

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

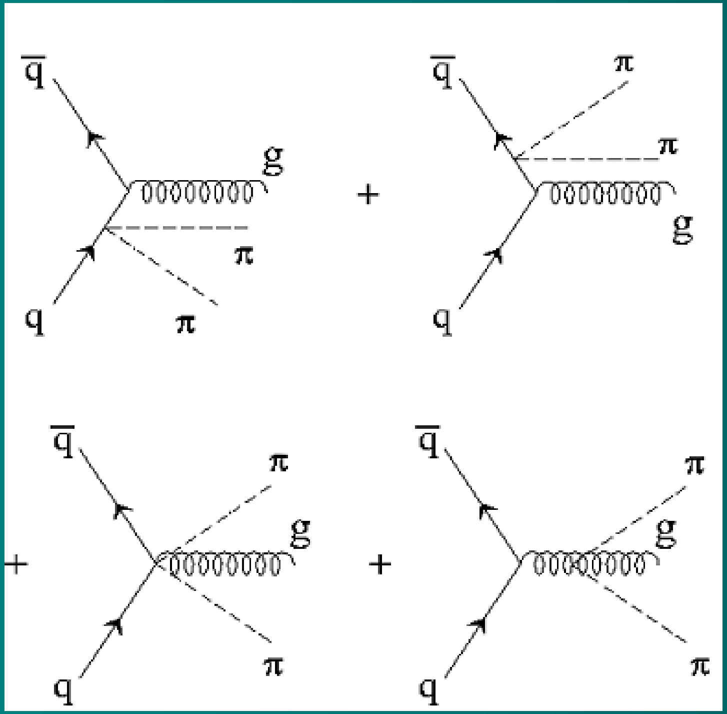


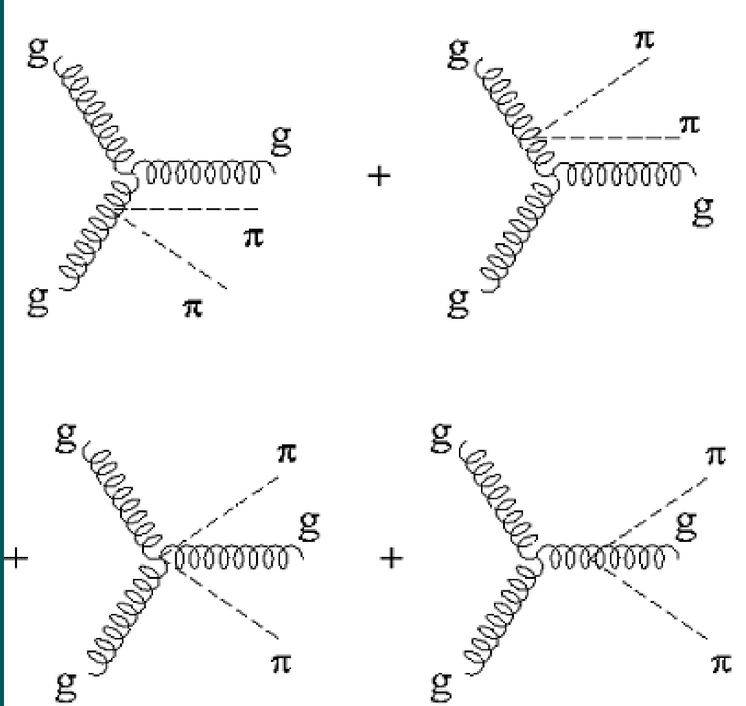
One quark production



GLUON PRODUCTION

Gluon production





TEVATRON RESULTS

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

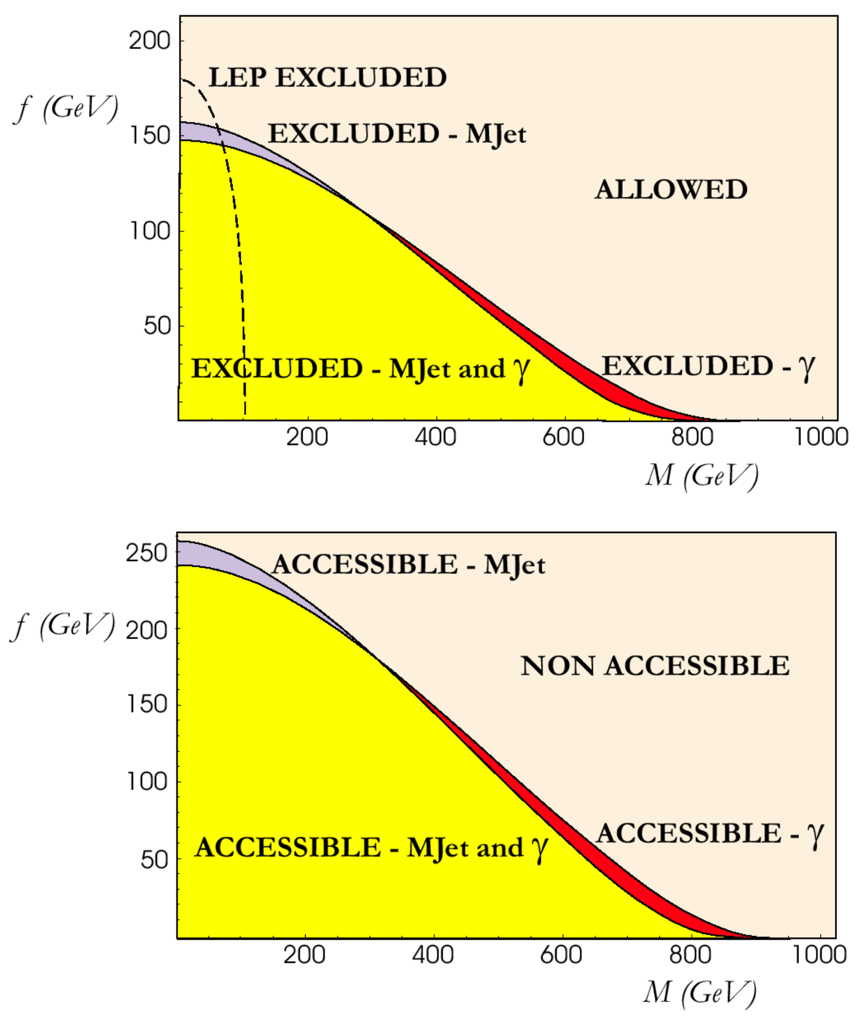
1st Run: E_{MC}= 1.8 TeV

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

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

2nd Run: E_{MC}= 1.96 TeV

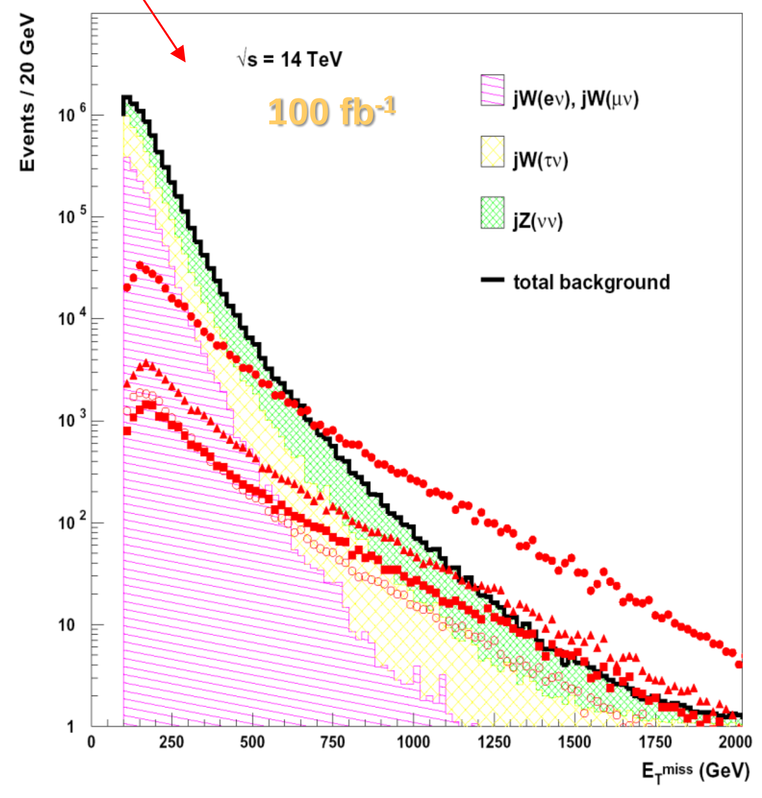
$\mathcal{L}$ = 1000 pb^{-1}



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

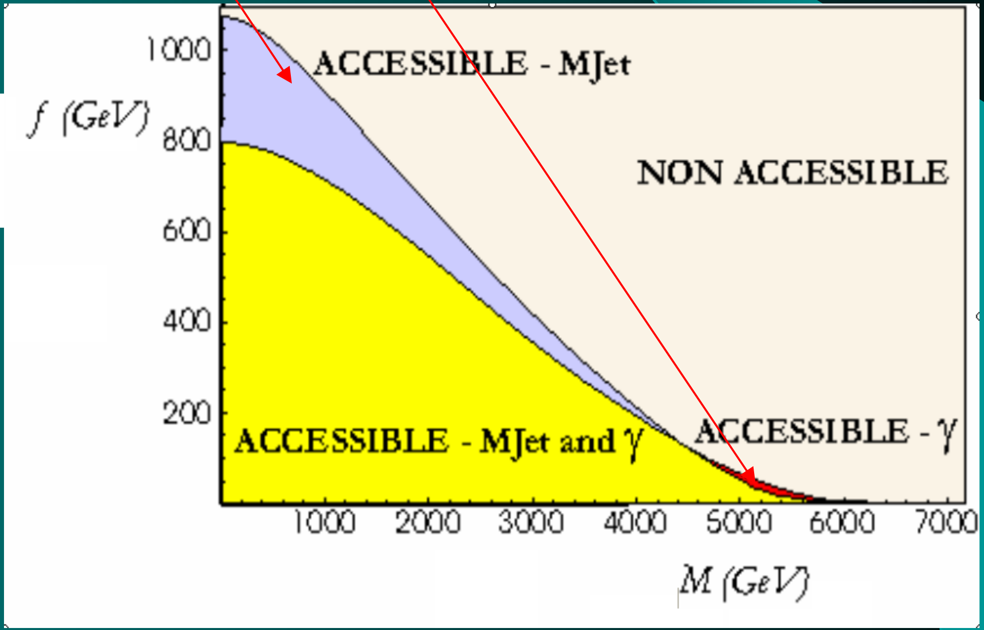
1.- Signals

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

2.- Backgrounds

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

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



Sensitivity:

$E_{CM} = 14$ TeV

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

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:

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

Thermal equilibrium density:

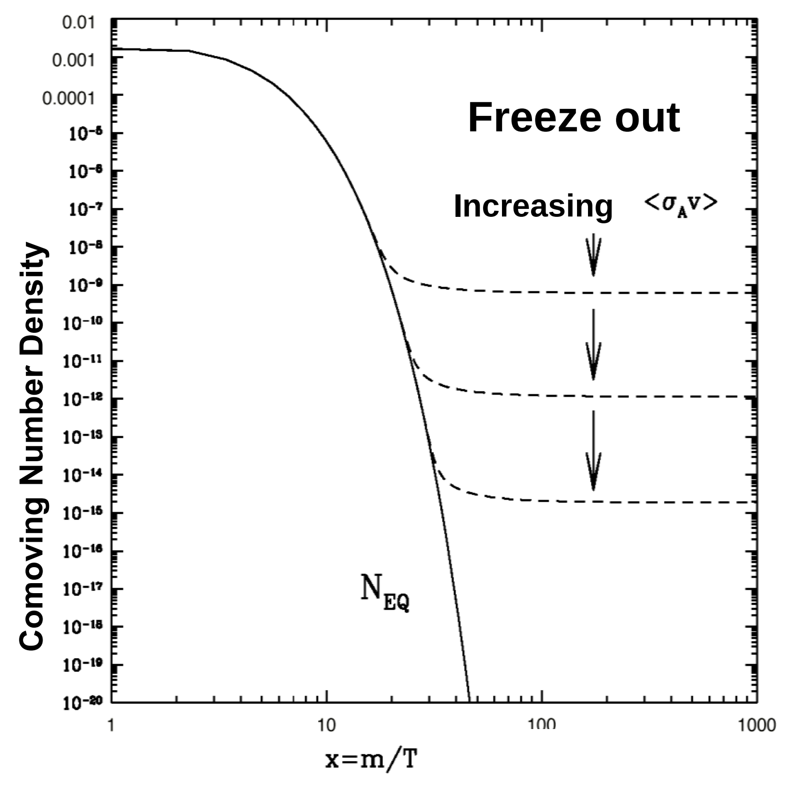
$$n_{Br}^{eq} = g/(2\pi)^3 \int f(p)\, d^3p$$

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

Cold DM relic density: →

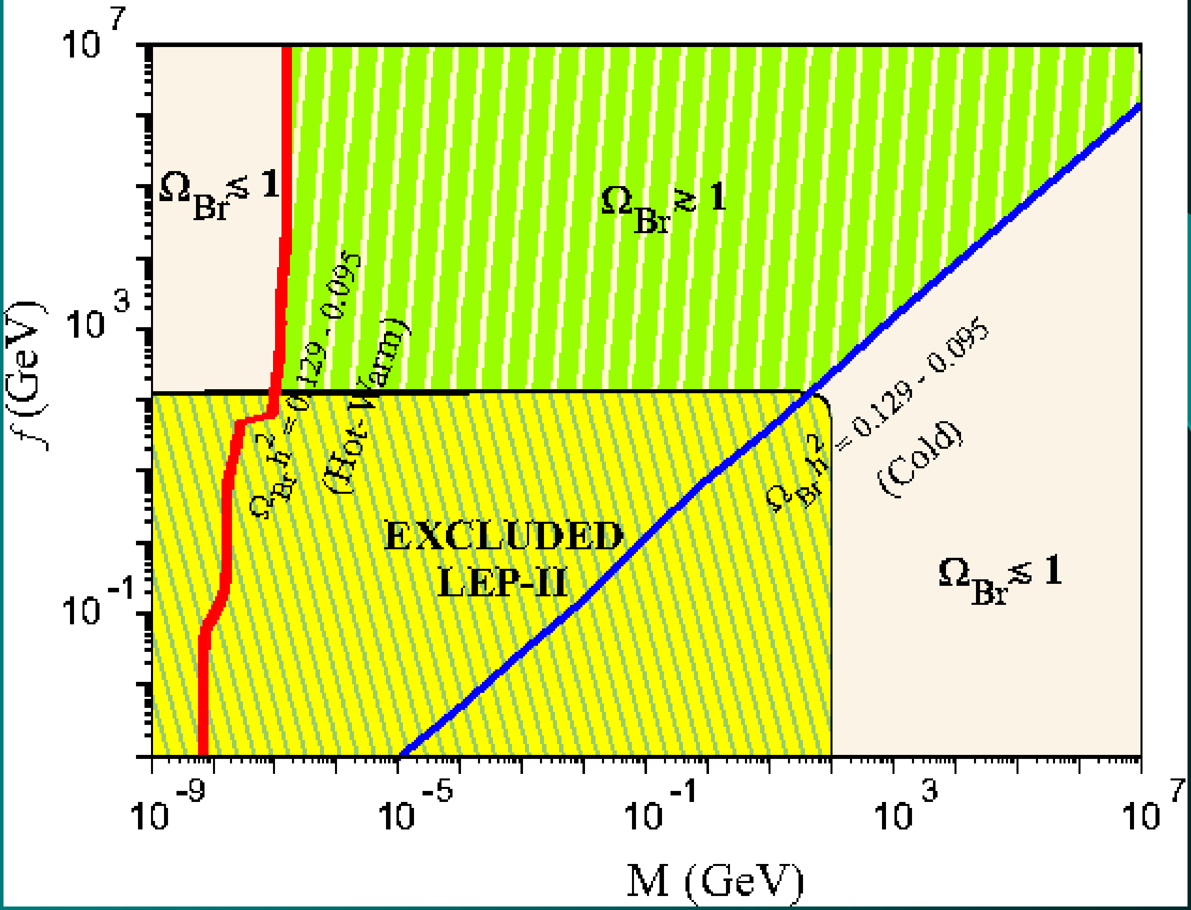
$$\Omega_{Br}\, h^2 \propto m_{Br} / \langle \sigma_A v_{Br} \rangle$$

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



BRANON ABUNDANCE

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



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.

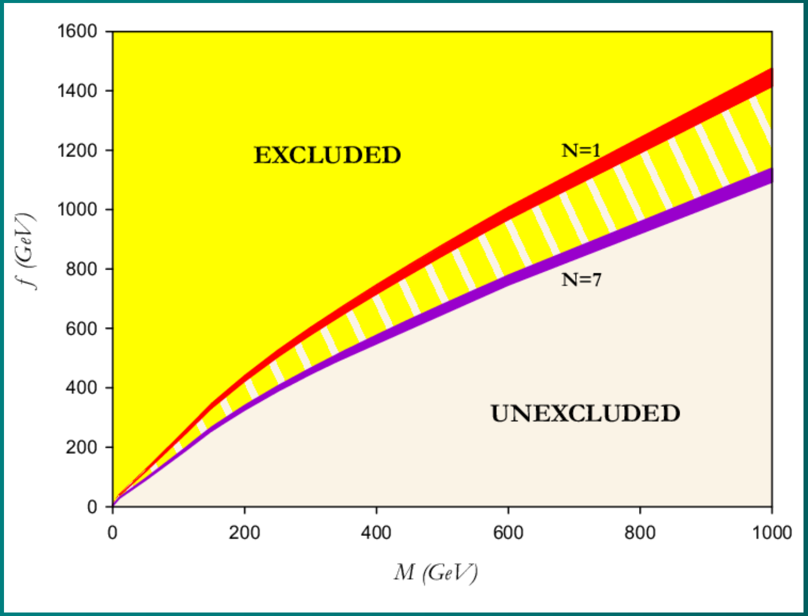
3.- Astrophysical Observations → 3.a. Supernova SN1987A

TOTAL DARK MATTER DENSITY

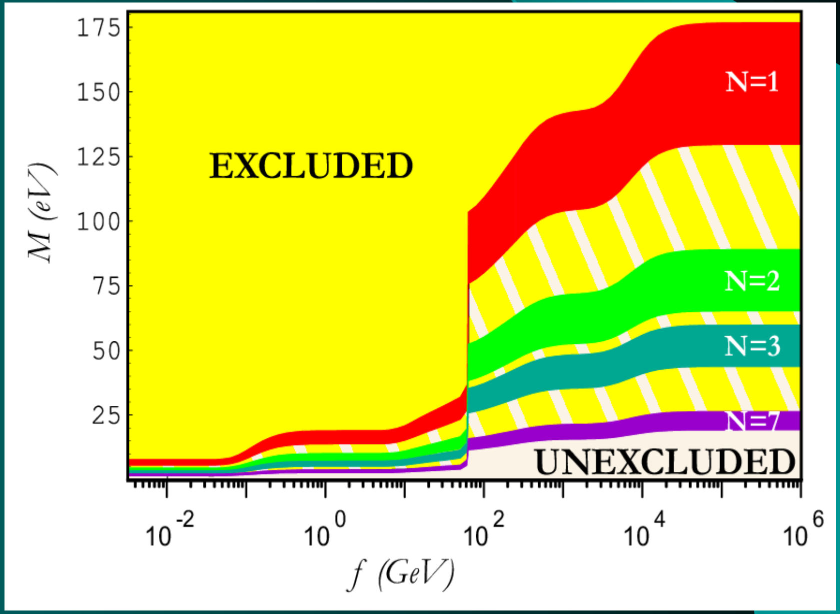
The observational bounds to the total non baryonic dark matter density coming from *WMAP* are:

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

Branon as Cold Relic



Branon as Hot Relic

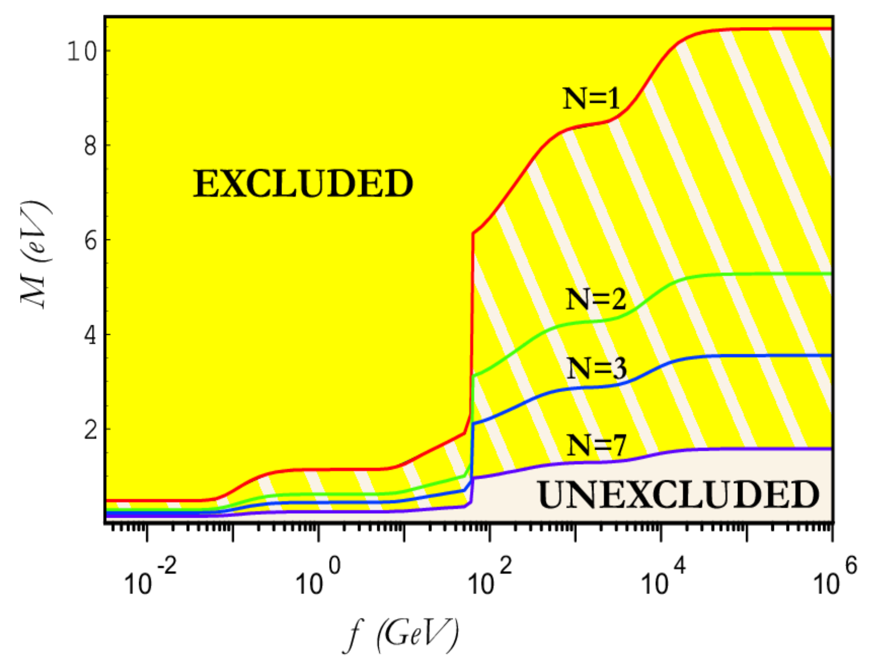


HOT DARK MATTER DENSITY

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.



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:

$$N_\nu = 3 + \Delta N_\nu$$

BBN RESTRICTIONS

Restrictions for the number of branons *N* :

1.- If branons decouple after nucleosynthesis:

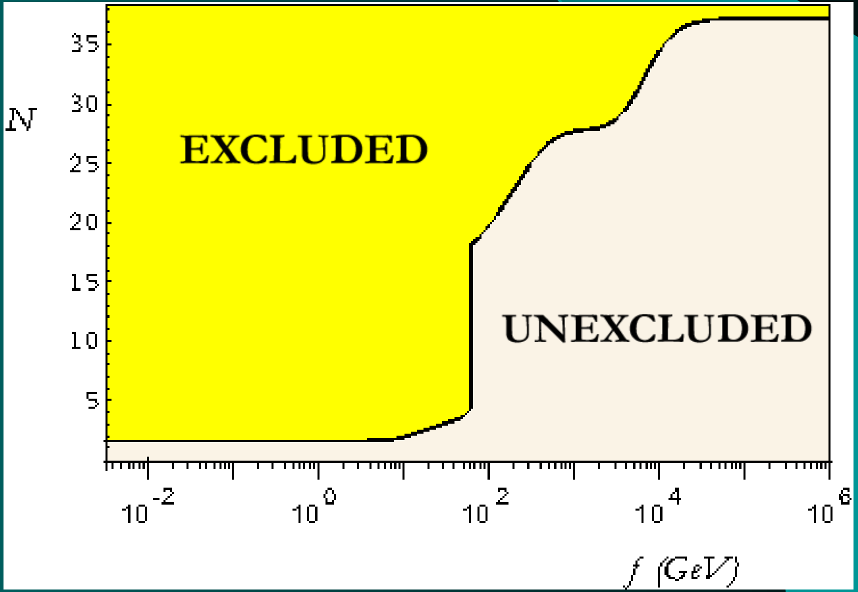
$$N \leq \frac{7}{4}\Delta N_\nu$$

2.- If branons decouple before nucleosynthesis:

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

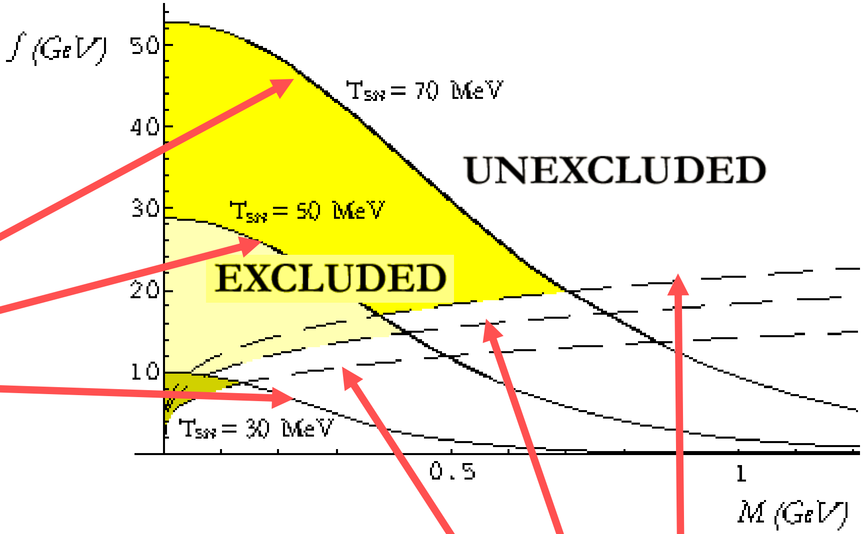
For example, a conservative bound for the number of effective neutrinos is:

$$\Delta N_\nu = 1$$



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:

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

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

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

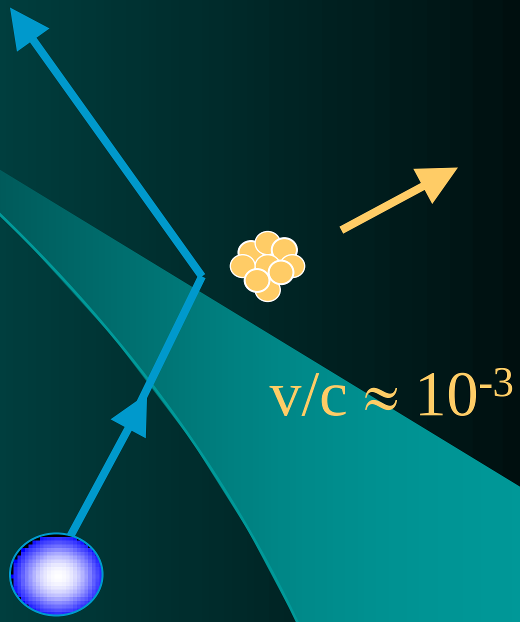
$$R \sim \mathcal{O}(10)\ \mathrm{Km}$$

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.

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

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

$$m \simeq 939 \text{ MeV}$$

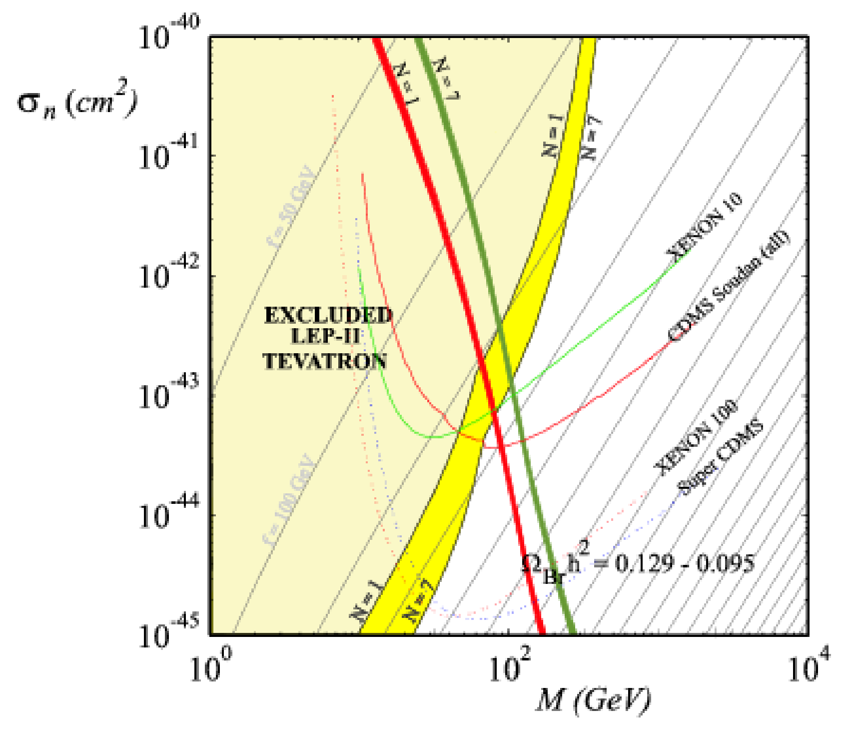
v is the relative velocity

For the branon case:

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

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.



For the branon case:

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

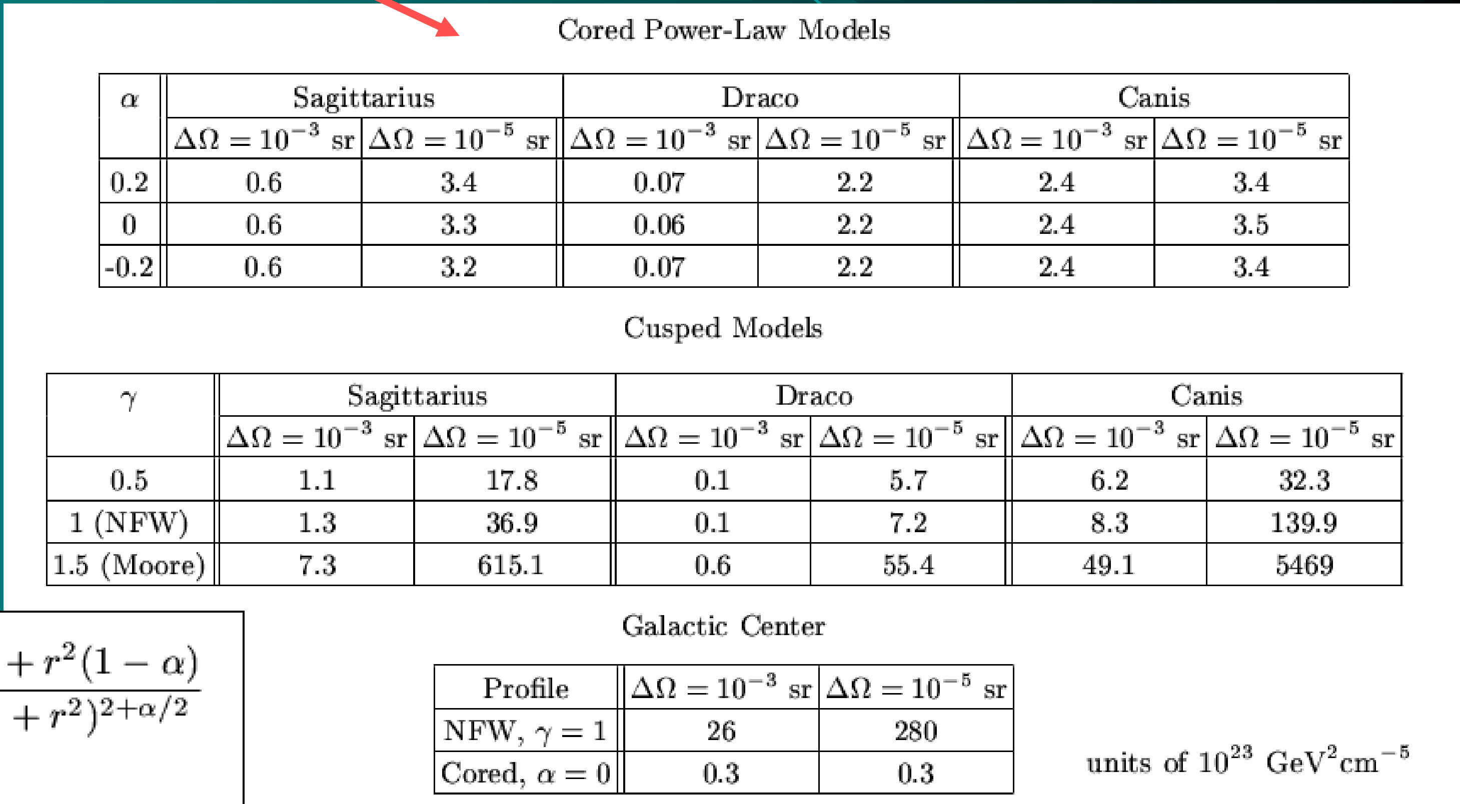
Lilian Prado

INDIRECT SEARCHES

$$\Phi_\gamma(\psi) = \boxed{\frac{N_\gamma\langle\sigma v\rangle}{4\pi m^2}} \times \boxed{\frac{1}{\Delta\Omega}\int_{\Delta\Omega} \mathrm{d}\Omega \int_{\mathrm{los}} \rho^2[r(s)]\ \mathrm{d}s}$$

2.- Astrophysical dependence

1.- Particle model dependence



Cored Power-Law Models

α	Sagittarius		Draco		Canis	
	$\Delta\Omega = 10^{-3}$ sr	$\Delta\Omega = 10^{-5}$ sr	$\Delta\Omega = 10^{-3}$ sr	$\Delta\Omega = 10^{-5}$ sr	$\Delta\Omega = 10^{-3}$ sr	$\Delta\Omega = 10^{-5}$ sr
0.2	0.6	3.4	0.07	2.2	2.4	3.4
0	0.6	3.3	0.06	2.2	2.4	3.5
-0.2	0.6	3.2	0.07	2.2	2.4	3.4

Cusped Models

γ	Sagittarius		Draco		Canis	
	$\Delta\Omega = 10^{-3}$ sr	$\Delta\Omega = 10^{-5}$ sr	$\Delta\Omega = 10^{-3}$ sr	$\Delta\Omega = 10^{-5}$ sr	$\Delta\Omega = 10^{-3}$ sr	$\Delta\Omega = 10^{-5}$ sr
0.5	1.1	17.8	0.1	5.7	6.2	32.3
1 (NFW)	1.3	36.9	0.1	7.2	8.3	139.9
1.5 (Moore)	7.3	615.1	0.6	55.4	49.1	5469

Galactic Center

Profile	$\Delta\Omega = 10^{-3}$ sr	$\Delta\Omega = 10^{-5}$ sr
NFW, $\gamma = 1$	26	280
Cored, $\alpha = 0$	0.3	0.3

units of 10^{23} GeV^{2}cm^{-5}

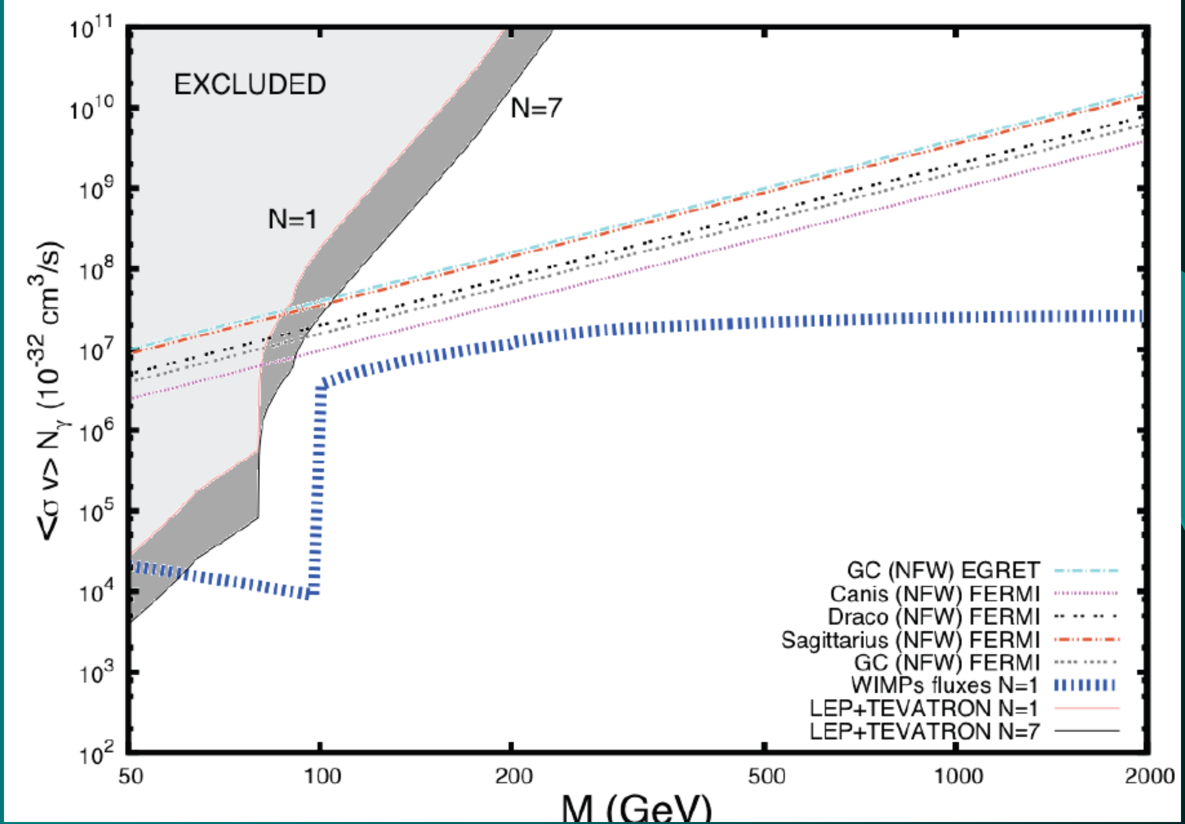
$$\rho_{\mathrm{pow}}(r) \equiv \frac{v_a^2 r_c^\alpha}{4\pi G}\frac{3r_c^2 + r^2(1-\alpha)}{(r_c^2 + r^2)^{2+\alpha/2}}$$

$$\rho_{\mathrm{cusp}}(r) \equiv \frac{A}{r^\gamma (r + r_s)^{3-\gamma}}$$

(Evans, Ferrer, and Sarkar)

GAMMA RAY ANALYSIS

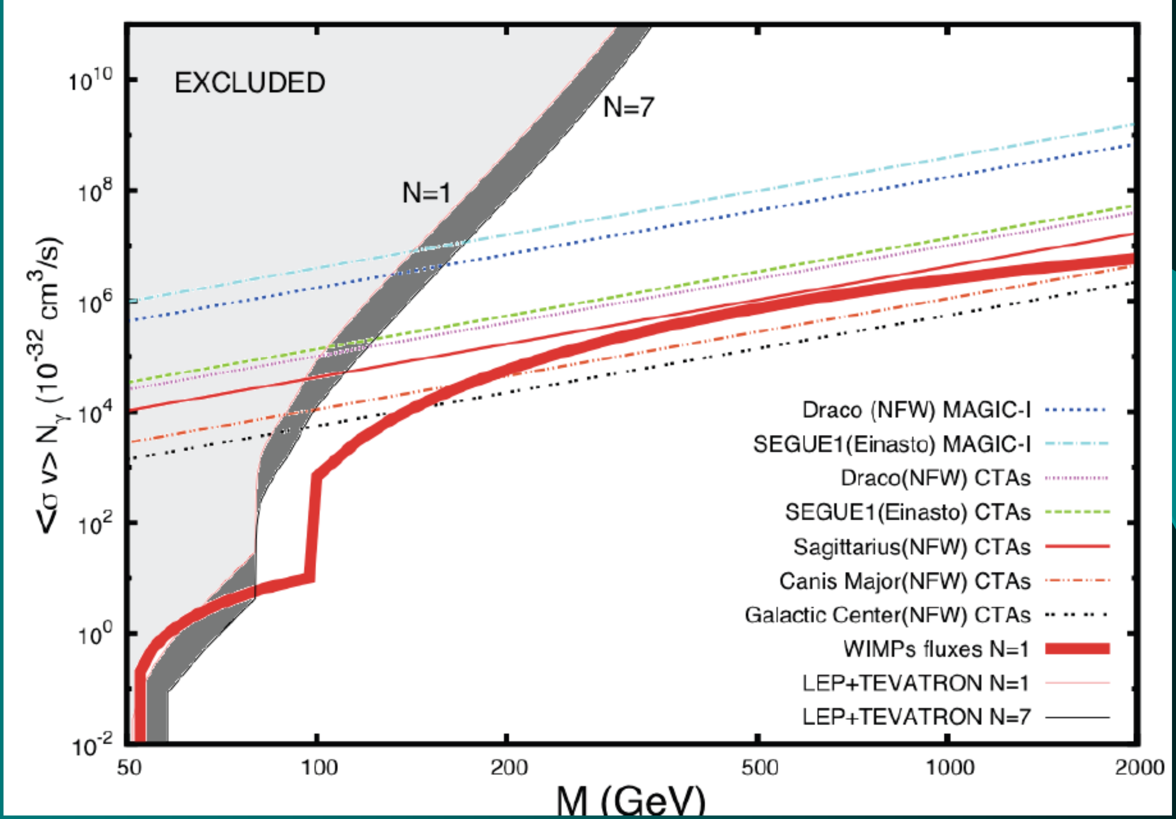
For the branon case:



(Cembranos, de la Cruz-Dombriz, Gammaldi and Maroto)

GAMMA RAY ANALYSIS

For the branon case:



(Cembranos, de la Cruz-Dombriz, Gammaldi and Maroto)

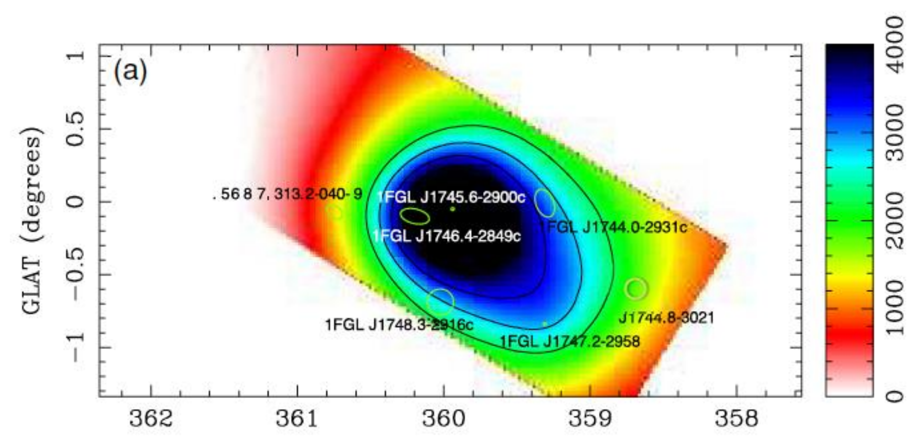
GALACTIC CENTER SIGNAL

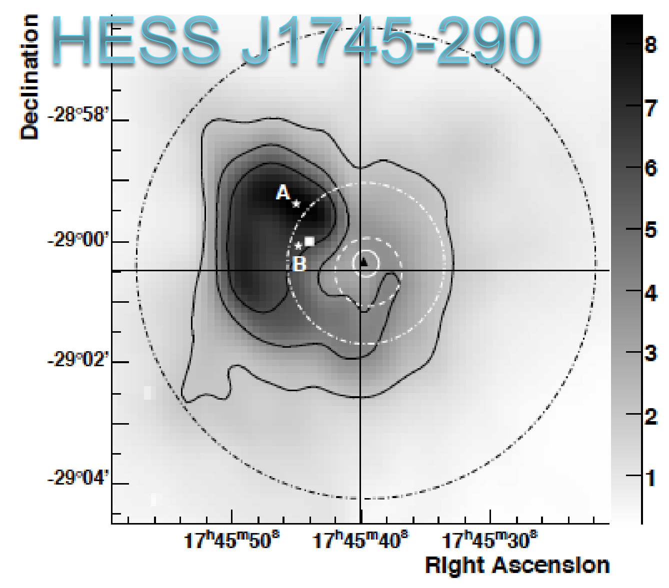
Observed by CANGAROO, VERITAS, MAGIC, HESS and Fermi-LAT.

Multiplies sources observed but not always spatially well identified (Radio flux, Sgr A* black hole, SNR Sgr A East, pulsar candidate, gamma emission).

Variability in Radio and X flux but not in gamma flux

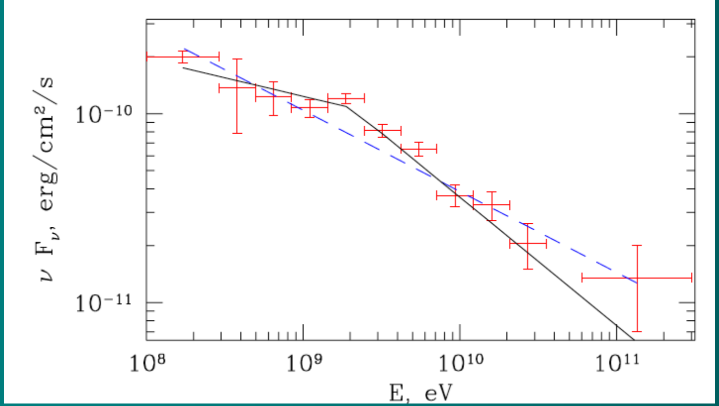
1FGL J1745.6-2900





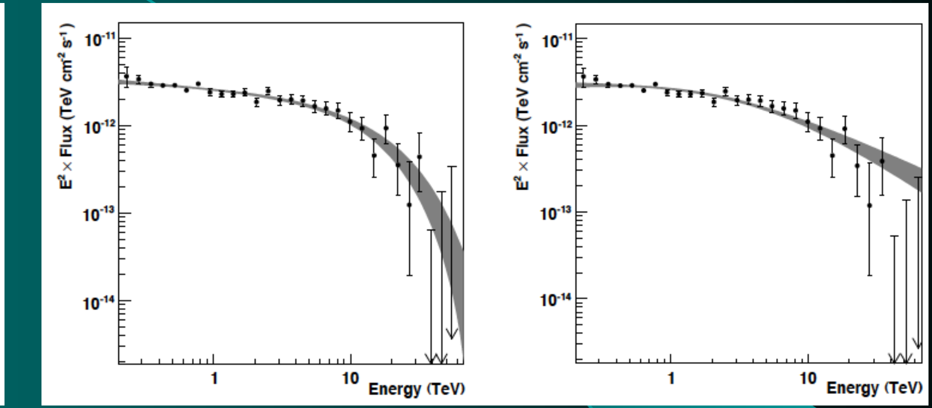
GALACTIC CENTER SIGNAL

Fermi-LAT: Background



1FGL J1745.6-2900

HESS: Signal



HESS J1745-290

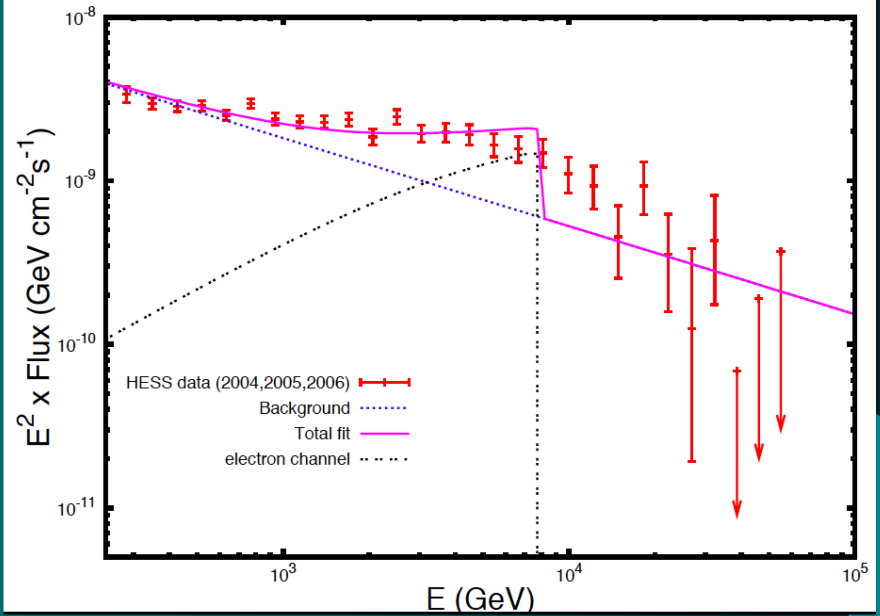
$$\frac{d\Phi_{Tot}}{dE} = \frac{d\Phi_{Bg}}{dE} + \frac{d\Phi_{DM}}{dE}$$

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

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

DM + BG ORIGIN

Viviana Gammaldi,
Antonio Maroto,
J. Cembarnos



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e^+e^-	8.11 ± 0.02	7.80 ± 0.70	2.74 ± 0.51	2.54 ± 0.06	2.23	35.8	120 ± 21
$\mu^+\mu^-$	8.12 ± 0.03	20.8 ± 1.82	2.75 ± 0.51	2.54 ± 0.06	2.18	34.6	853 ± 149
$\tau^+\tau^-$	12.6 ± 1.3	7.88 ± 0.71	3.13 ± 0.61	2.58 ± 0.06	1.61	20.9	295 ± 81
$u\bar{u}$	35.0 ± 5.1	5.61 ± 0.76	5.93 ± 4.67	2.89 ± 0.28	0.79	1.2	1153 ± 459
dd	45.2 ± 4.8	4.80 ± 0.50	7.78 ± 7.19	3.00 ± 0.33	0.74	0.0	1409 ± 419
$s\bar{s}$	55.0 ± 0.9	4.98 ± 0.30	6.87 ± 5.35	2.93 ± 0.27	0.90	3.9	2245 ± 280
$c\bar{c}$	38.5 ± 7.0	6.17 ± 1.01	16.3 ± 31.9	3.27 ± 0.71	1.45	17.0	1688 ± 826
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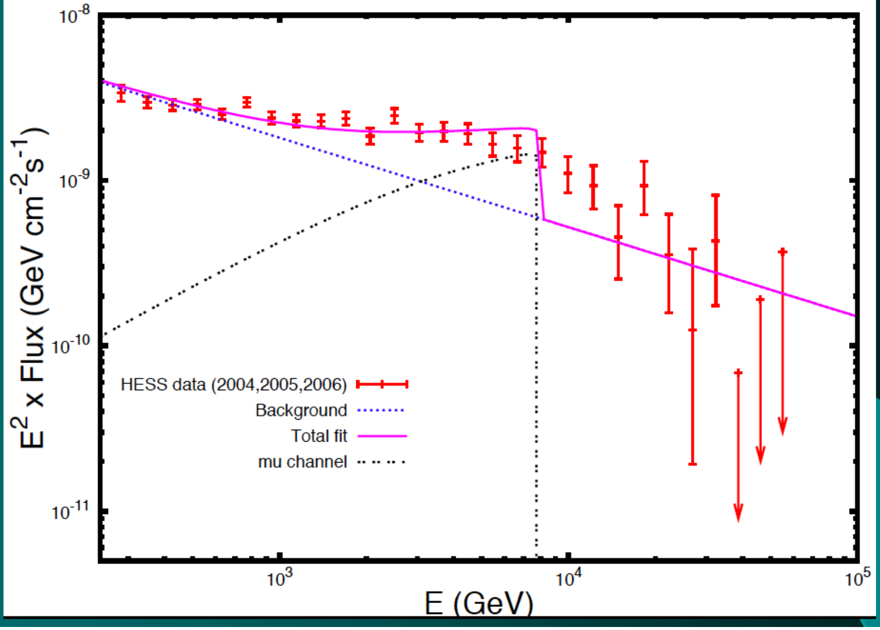

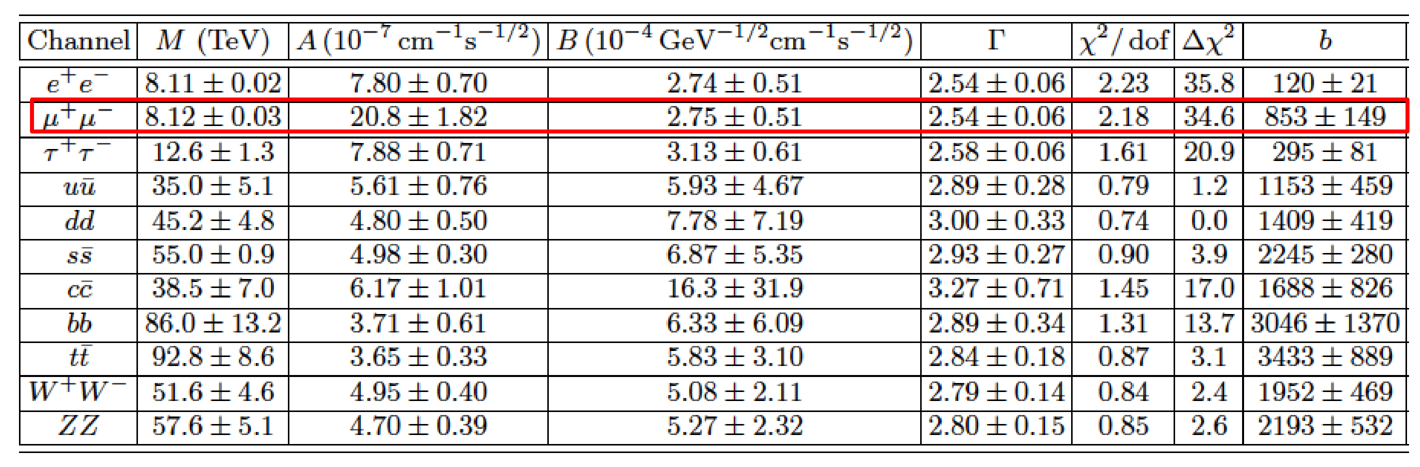

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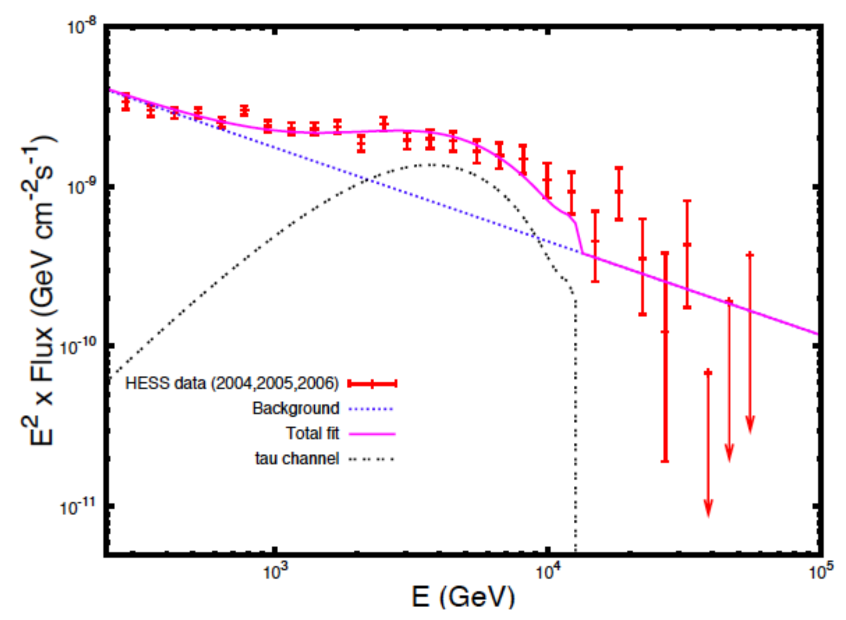

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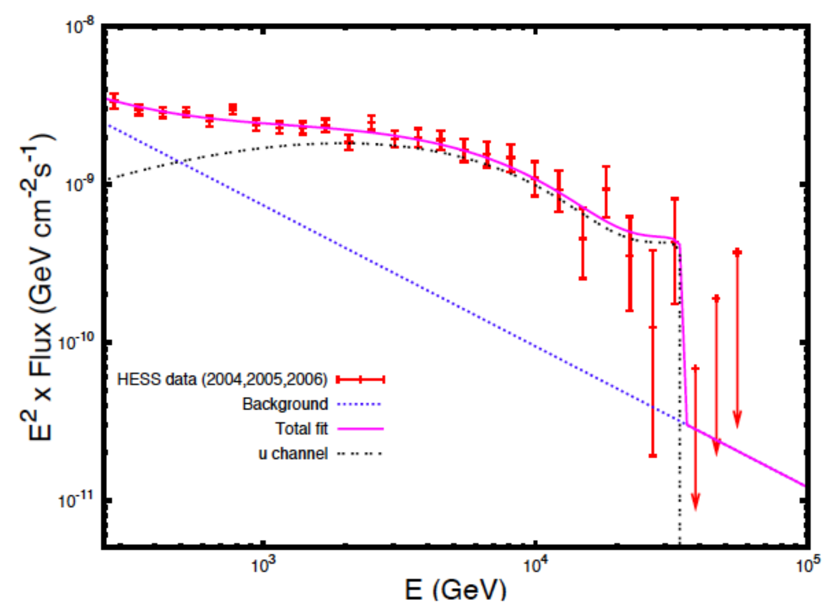

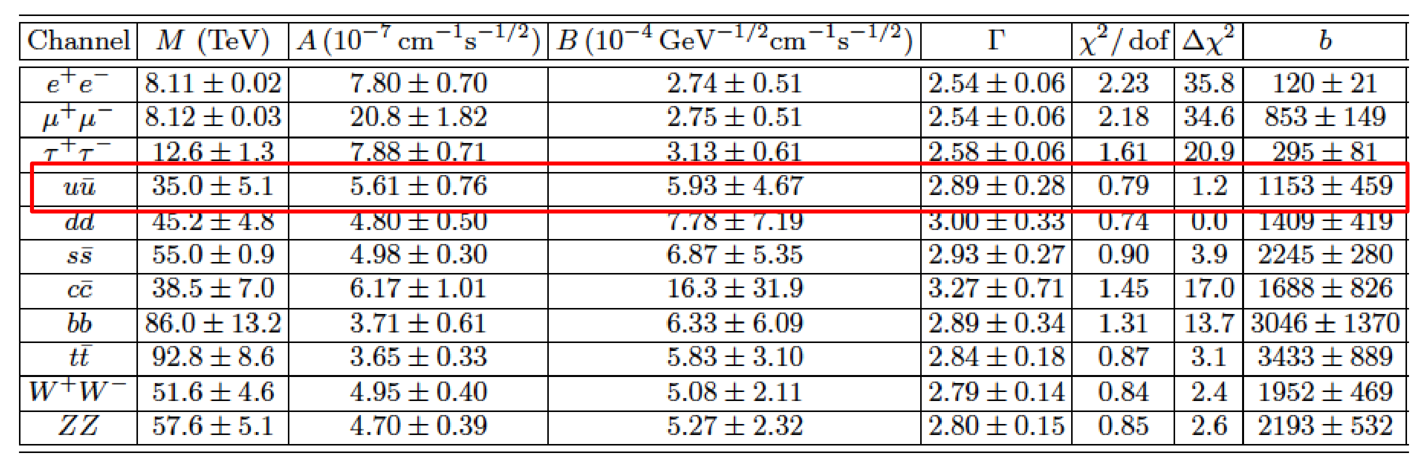

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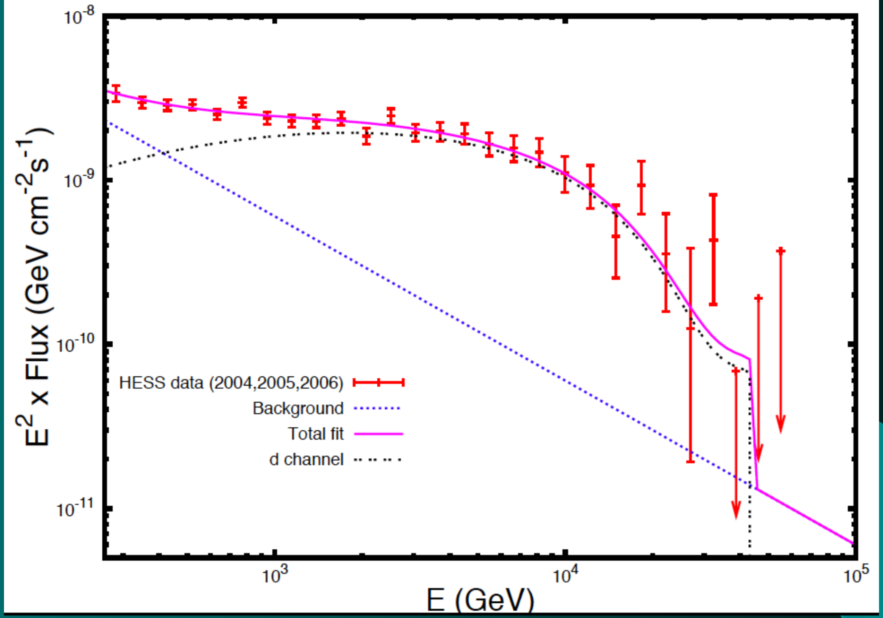

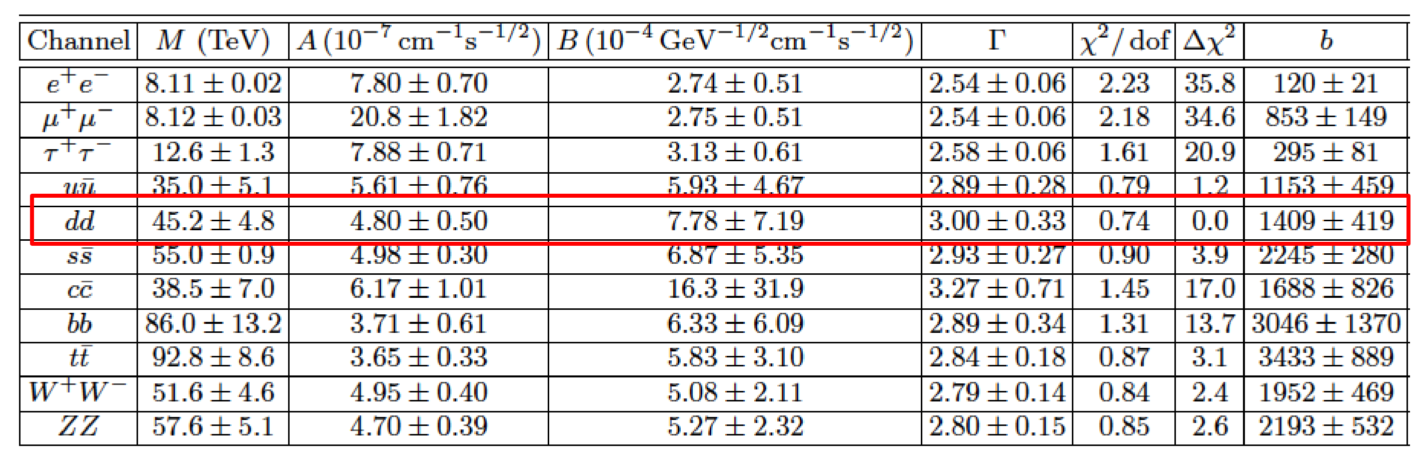

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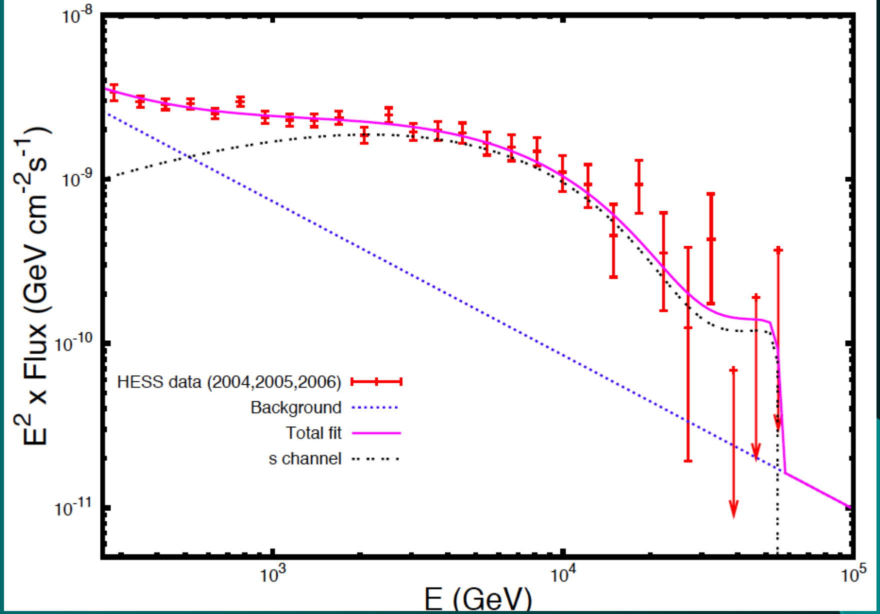

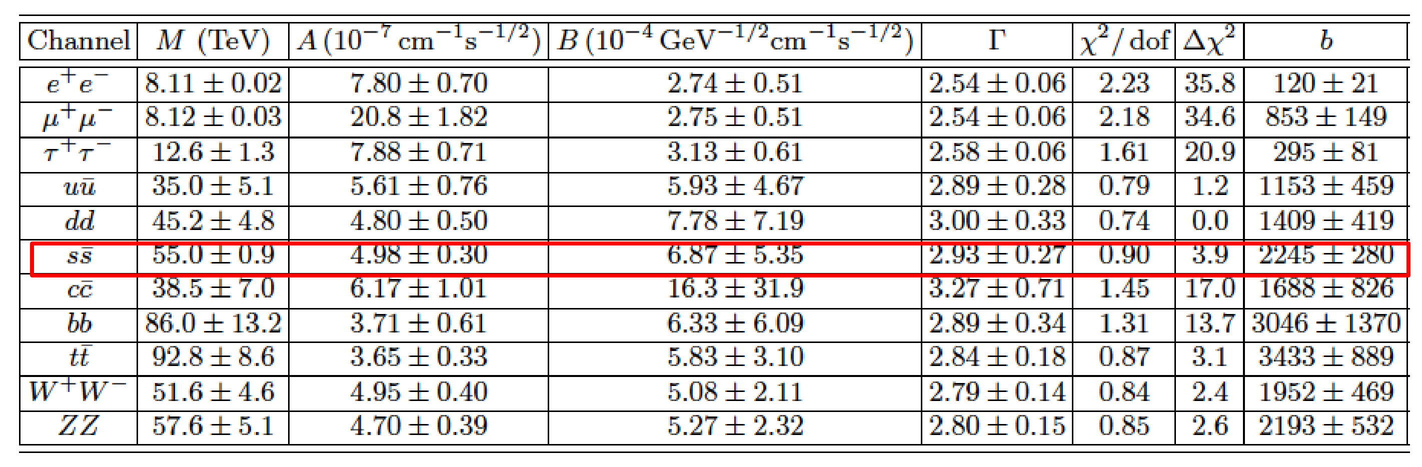

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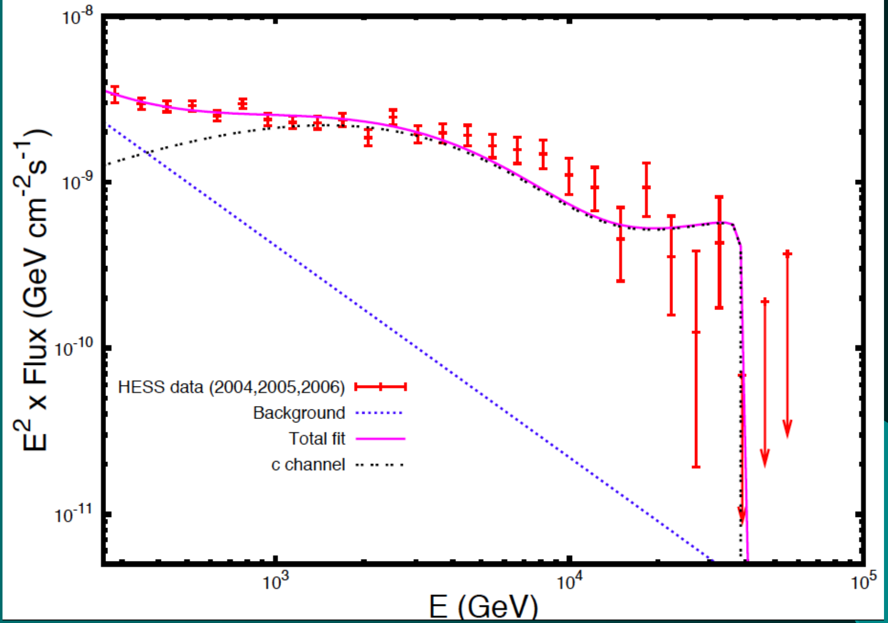

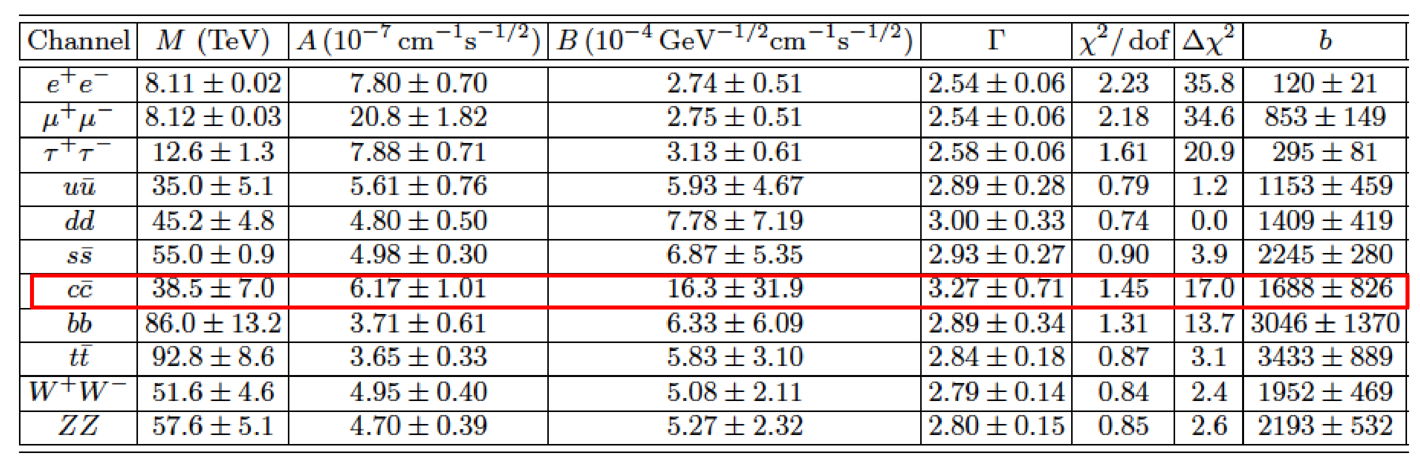

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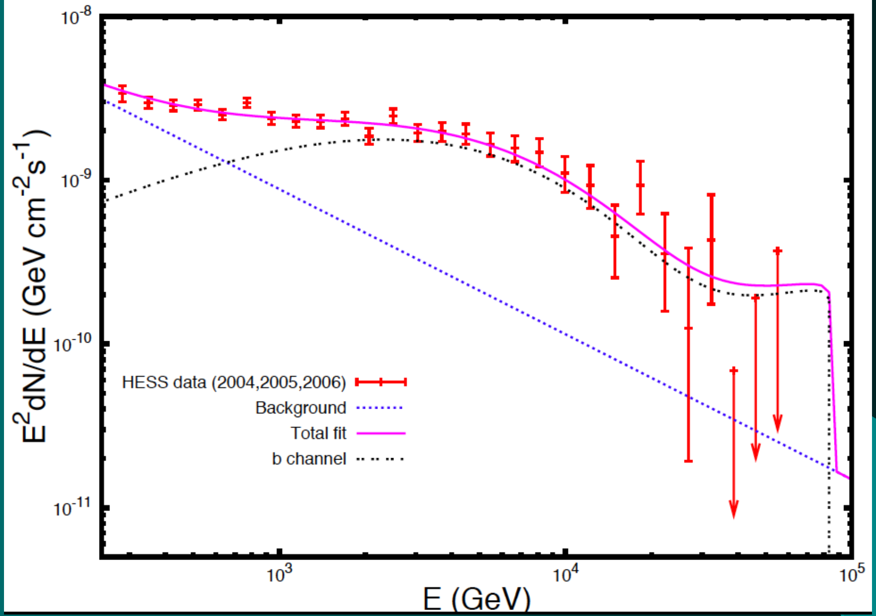

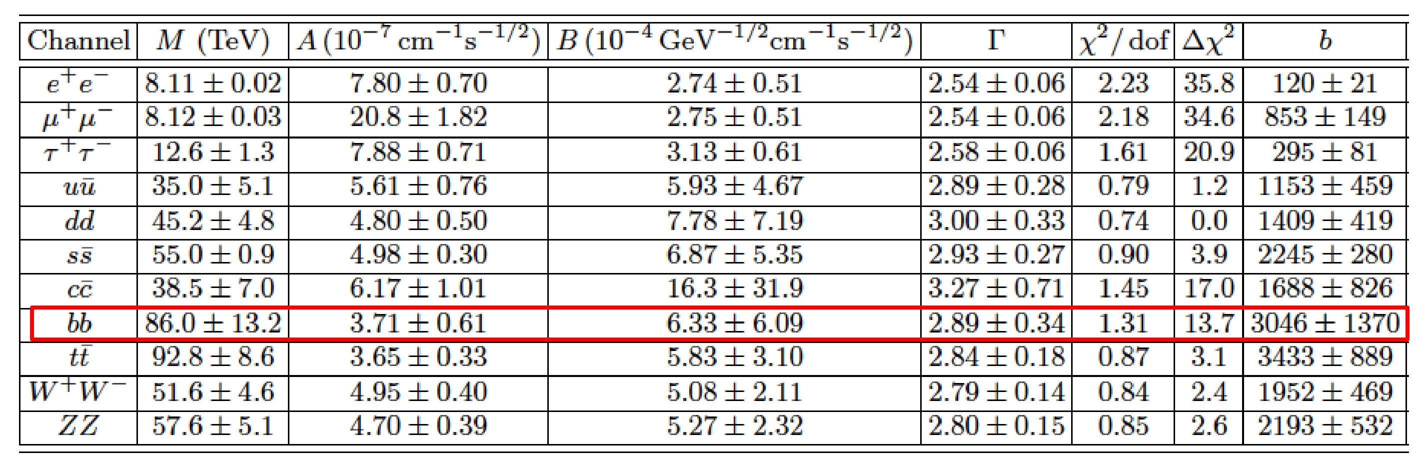

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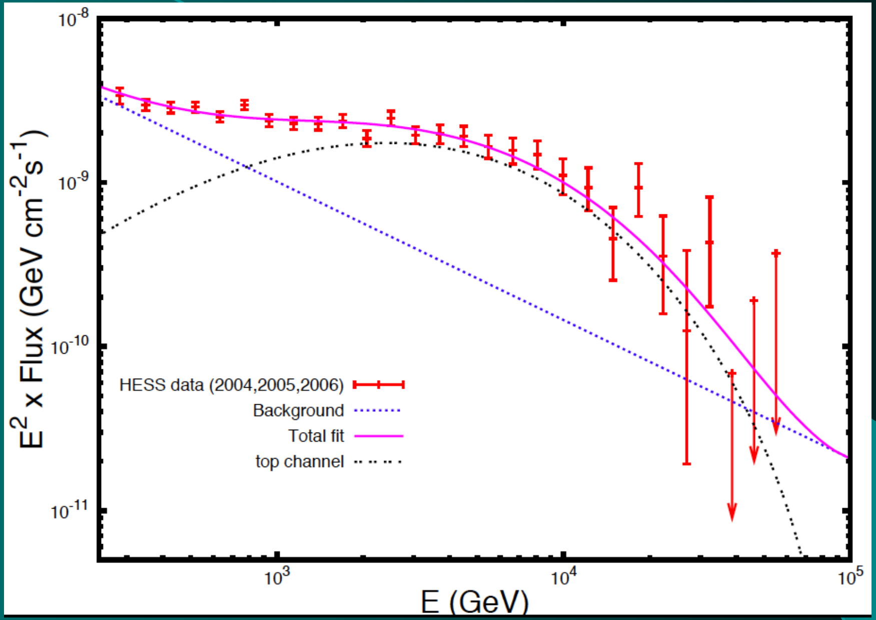

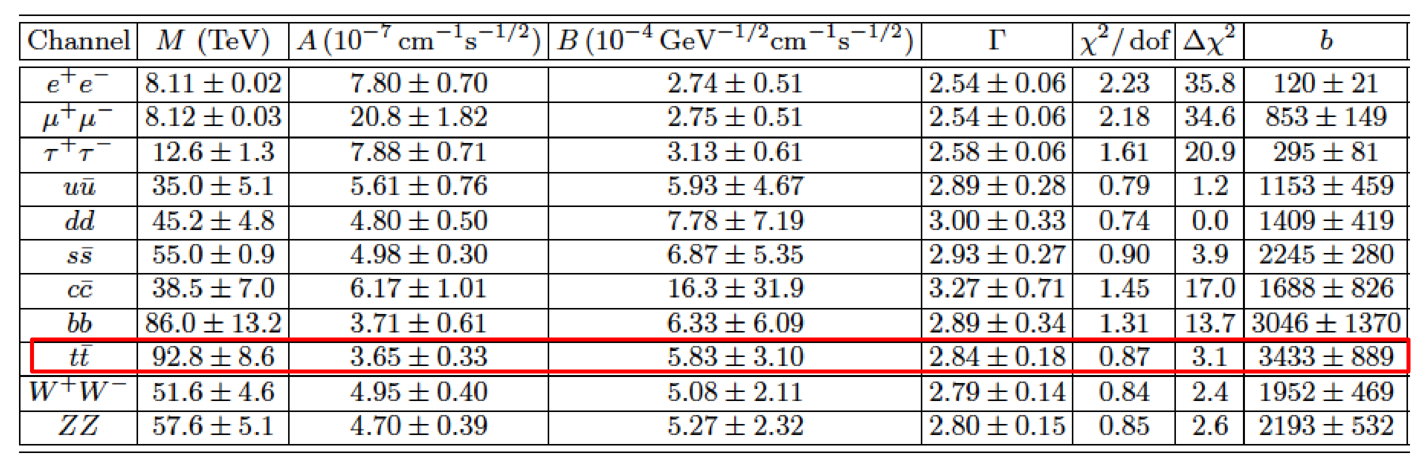

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$\tau^+\tau^-$	12.6 ± 1.3	7.88 ± 0.71	3.13 ± 0.61	2.58 ± 0.06	1.61	20.9	295 ± 81
$u\bar{u}$	35.0 ± 5.1	5.61 ± 0.76	5.93 ± 4.67	2.89 ± 0.28	0.79	1.2	1153 ± 459
dd	45.2 ± 4.8	4.80 ± 0.50	7.78 ± 7.19	3.00 ± 0.33	0.74	0.0	1409 ± 419
$s\bar{s}$	55.0 ± 0.9	4.98 ± 0.30	6.87 ± 5.35	2.93 ± 0.27	0.90	3.9	2245 ± 280
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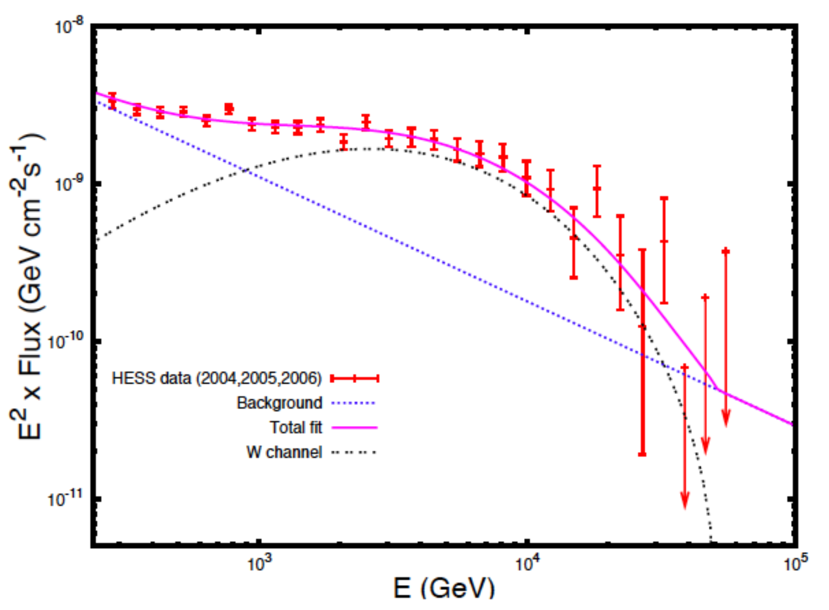
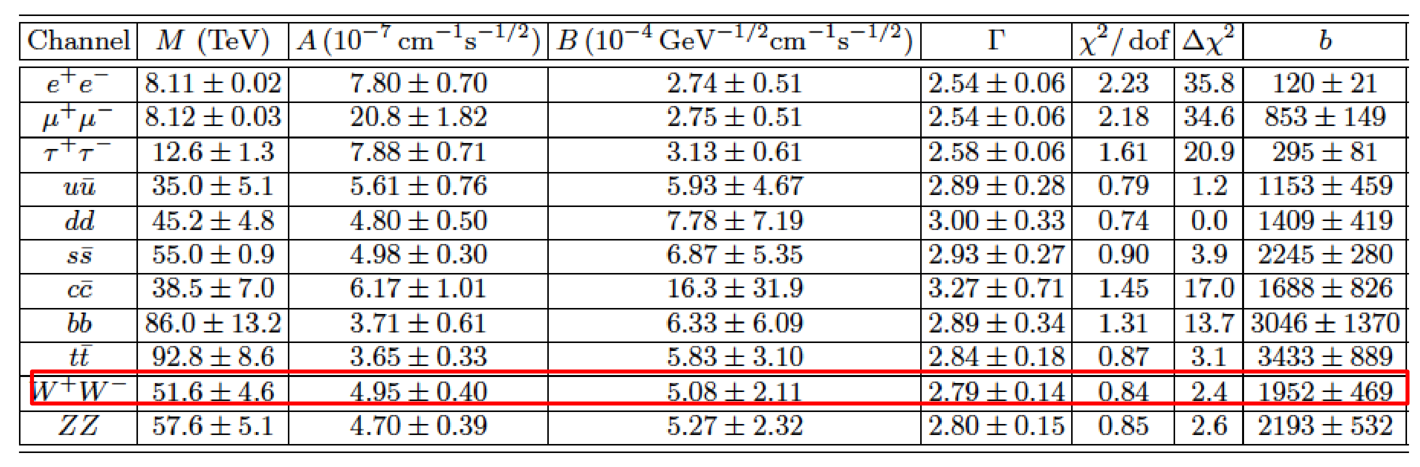
$t\bar{t}$	92.8 ± 8.6	3.65 ± 0.33	5.83 ± 3.10	2.84 ± 0.18	0.87	3.1	3433 ± 889
W^+W^-	51.6 ± 4.6	4.95 ± 0.40	5.08 ± 2.11	2.79 ± 0.14	0.84	2.4	1952 ± 469
ZZ	57.6 ± 5.1	4.70 ± 0.39	5.27 ± 2.32	2.80 ± 0.15	0.85	2.6	2193 ± 532

DM + BG ORIGIN

Viviana Gammaldi,
Antonio Maroto,
J. Cembarnos





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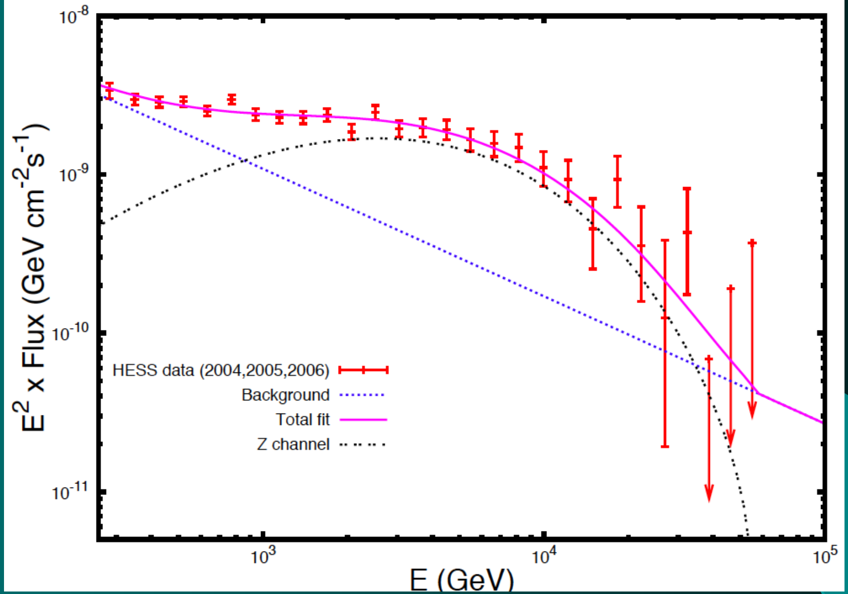

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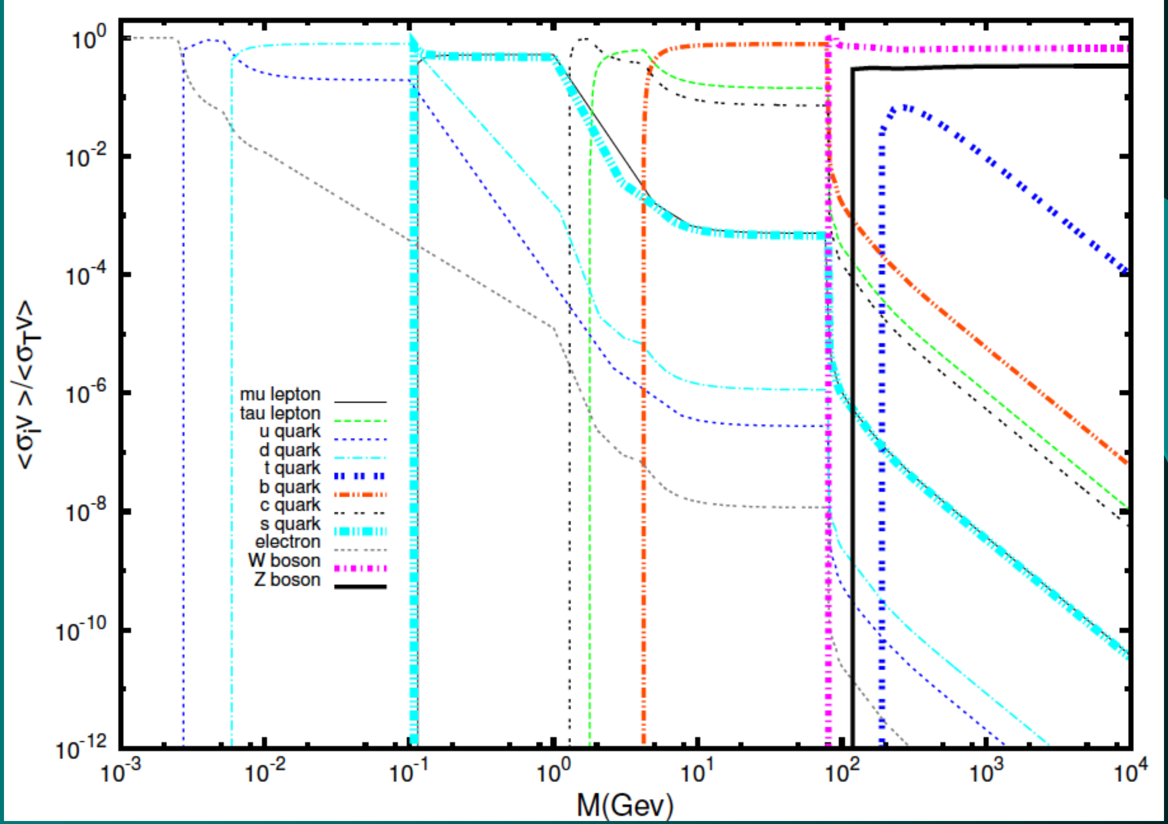
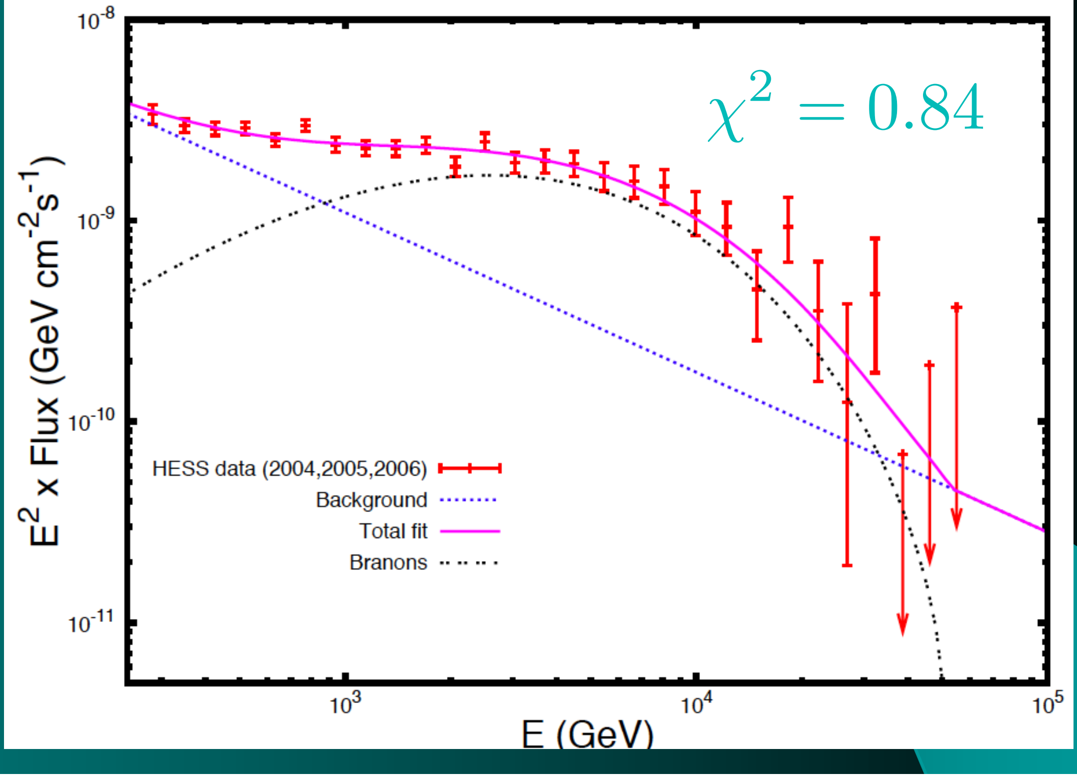
BRANONS

Heavy branons decay fundamentally in WW and ZZ channels:



BRANON DM MODEL

Viviana Gammaldi,
Antonio Maroto,
J. Cembarnos



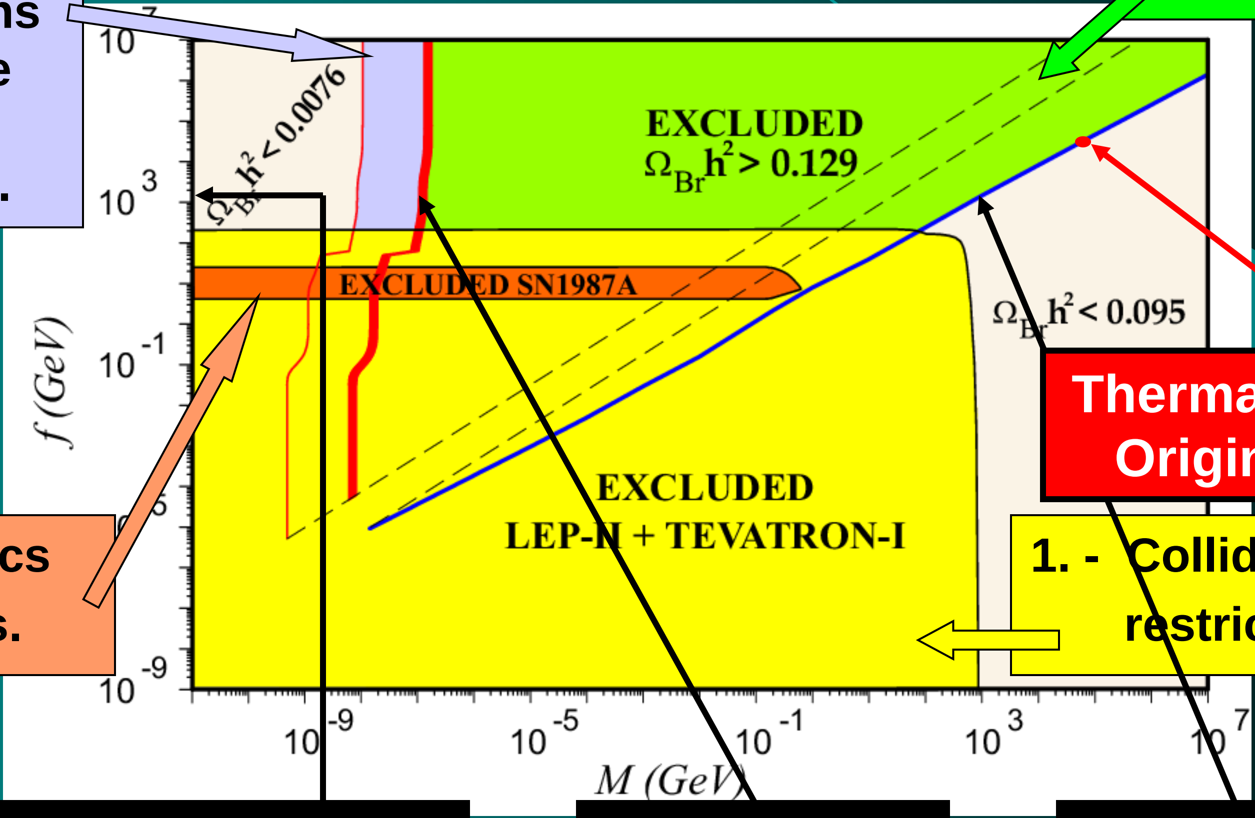
Branons	M (TeV)	C (10^{-2} GeV cm^{-1}s$^{-1/2}$)	B (10^{-4} GeV$^{-1/2}$cm^{-1}s$^{-1/2}$)	Γ	χ^2/ dof	$\Delta\chi^2$	b
W+Z	53.5 ± 4.8	1.57 ± 0.13	5.16 ± 2.19	2.80 ± 0.15	0.84	2.4	5414 ± 1320

$$\langle \sigma v \rangle = (1.14 \pm 0.18) \cdot 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}$$

$$f = 28.7 \pm 2.5\, TeV$$

GENERAL SITUATION

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



3. - Restrictions due to the power spectrum.

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

Thermal Branons Origin of GC γ

4. - Astrophysics restrictions.

1. - Collider restrictions.

C.- Branons as Non Thermal Relic

B.- Branons as Warm DM

A.- Branons as WIMPs

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 ma tic mom

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

LHC PROSPECTS

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

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

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

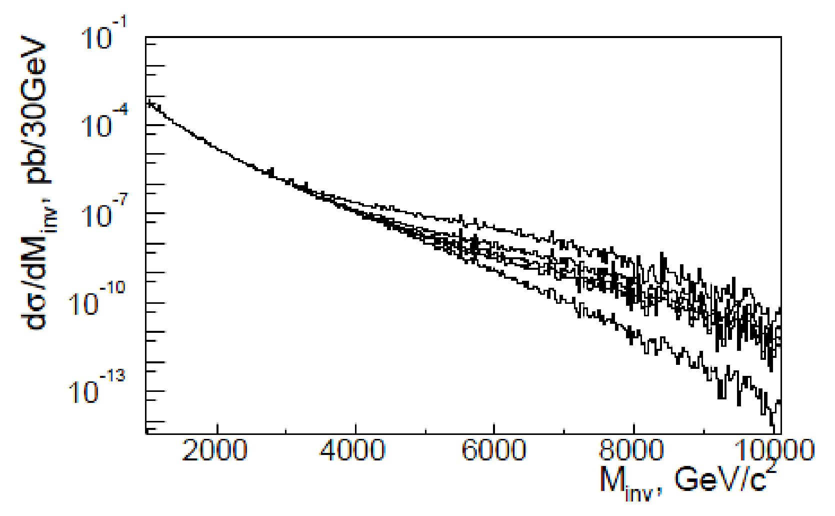
Dimuon is accepted for

$|\eta| \leq 2.4 \qquad p_T \geq 20\ \mathrm{GeV}$

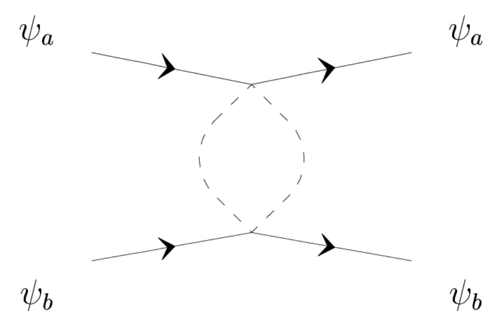
Estimated sensitivity and resolution:

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

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



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.

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 .

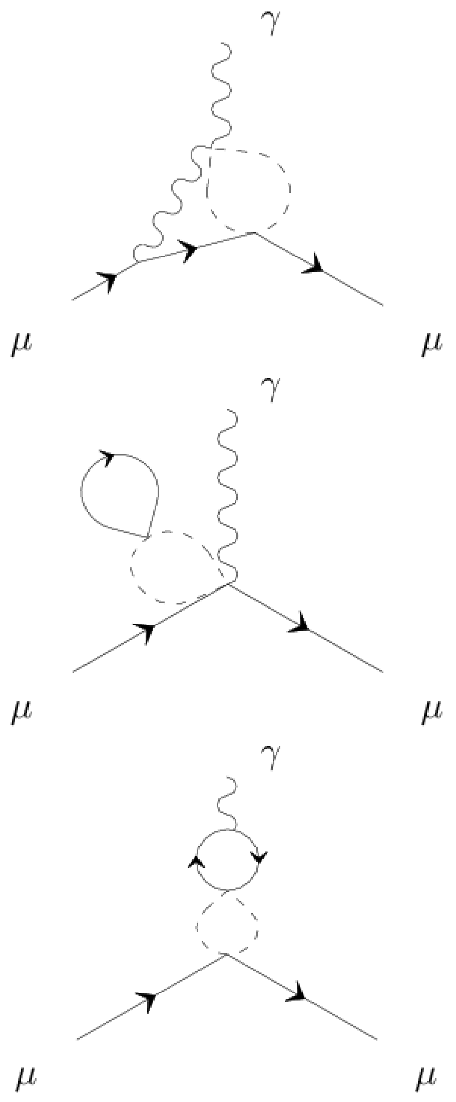
The E821 Collaboration at BAGS has found a 2.6 σ deviation with the SM:

$$\delta a_\mu \equiv a_\mu(exp) - a_\mu(SM) = 23.5\ (9.0) \times 10^{-10}$$

(Passera, Höcker)

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

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

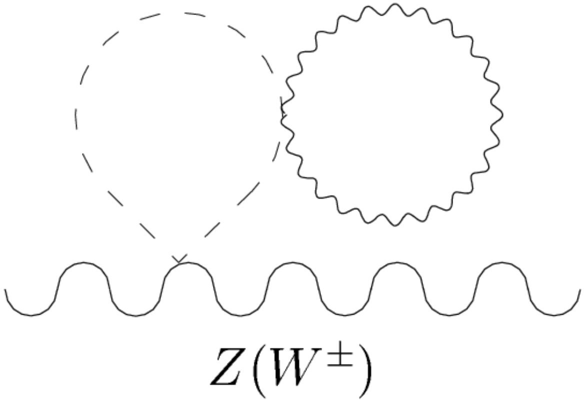


EW PRECISION OBSERVABLES

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: $\bar{\epsilon} \equiv \frac{\delta M_W^2}{M_W^2} - \frac{\delta M_Z^2}{M_Z^2}$

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



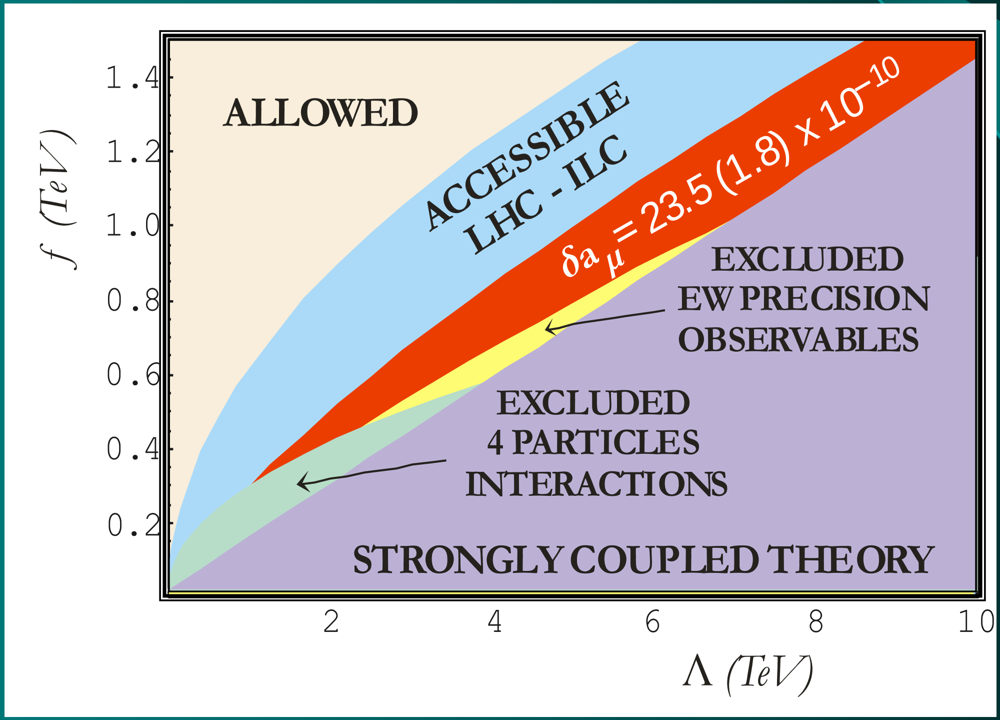
LEP and SLD result: $\bar{\epsilon} = 12.7\ (1.6) \times 10^{-3}$

(Altarelli, LEP EW Working Group)

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

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):



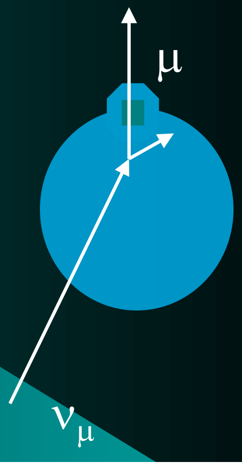
INDIRECT SEARCHES

***WIMPs* annihilate**

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

high energy neutrinos.

Antares, Amanda, IceCube, ...

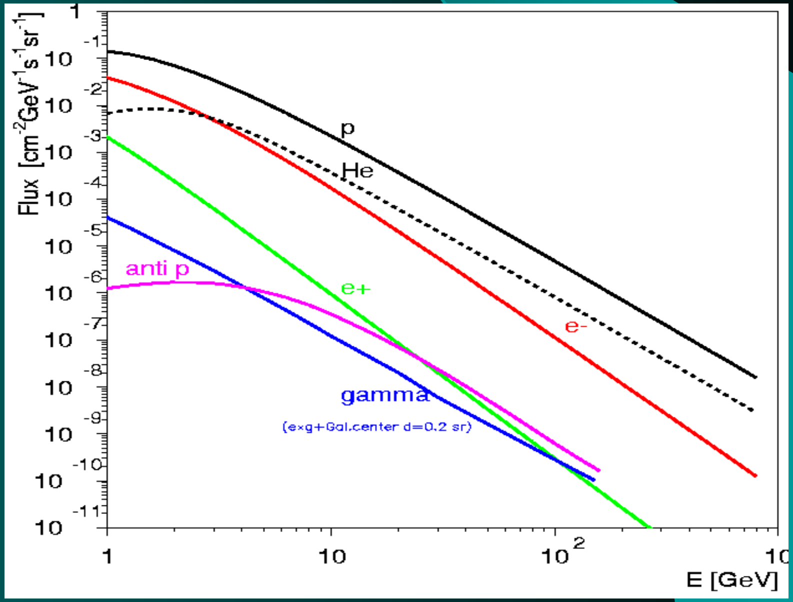


2.- In the halo: γ, e+, p-, D ...

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.



AMS-02 PROSPECTS

Cosmic Rays : p, D, He, C, …,e+, e-, γ, …

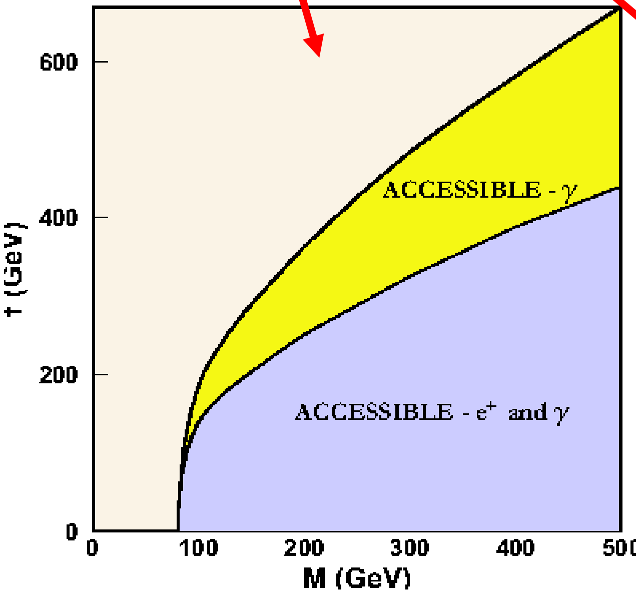
Will Collect ~10^{10} CRs in Near-Earth Orbit from few GeV to few TeV.

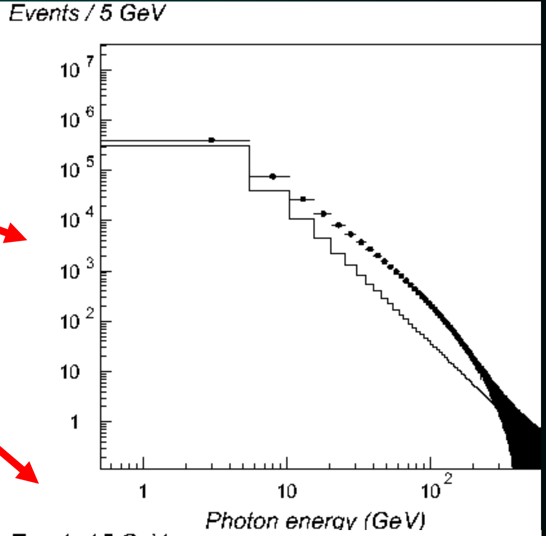
AMS estimations:

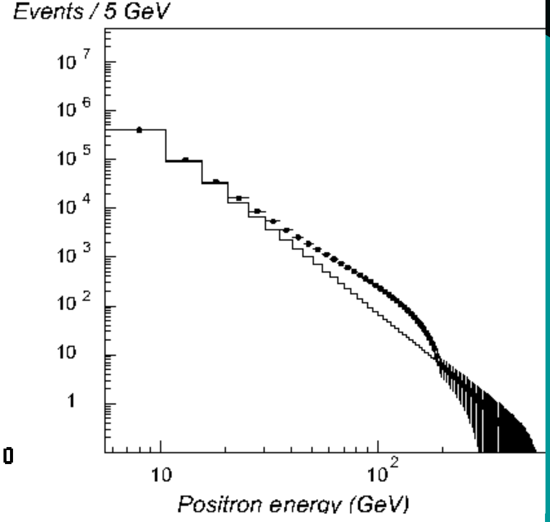
1.- Positrons

2.- Photons

3.- Sensitivity

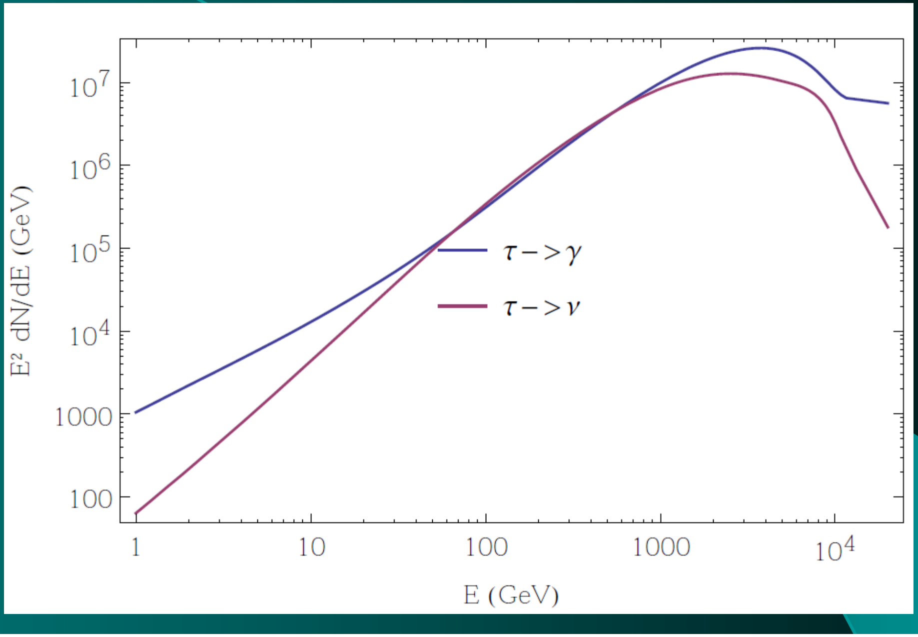


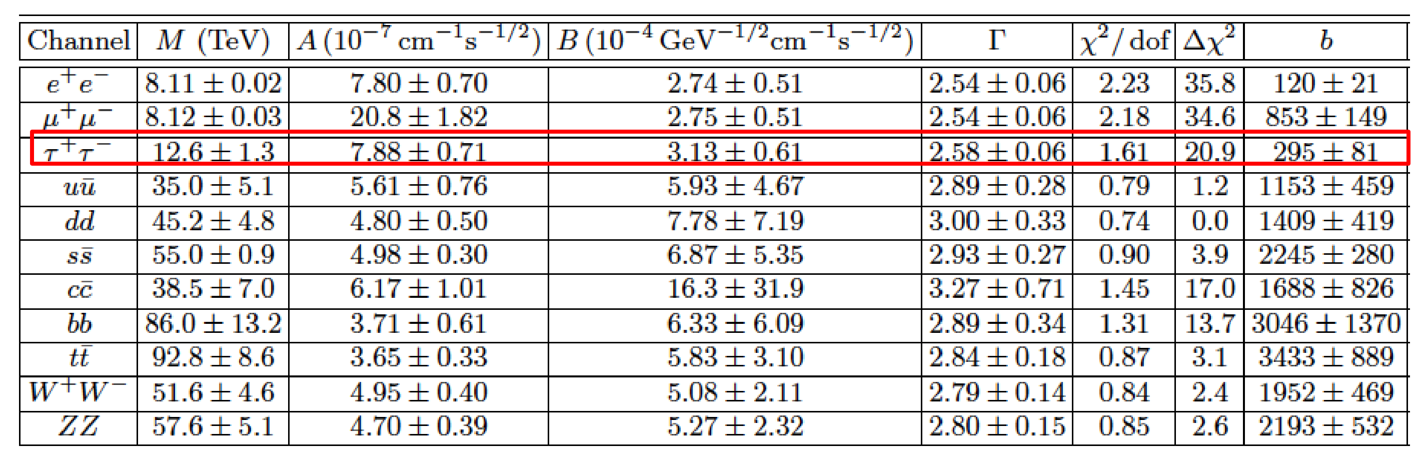




γ vs ν spectrum

Viviana Gammaldi





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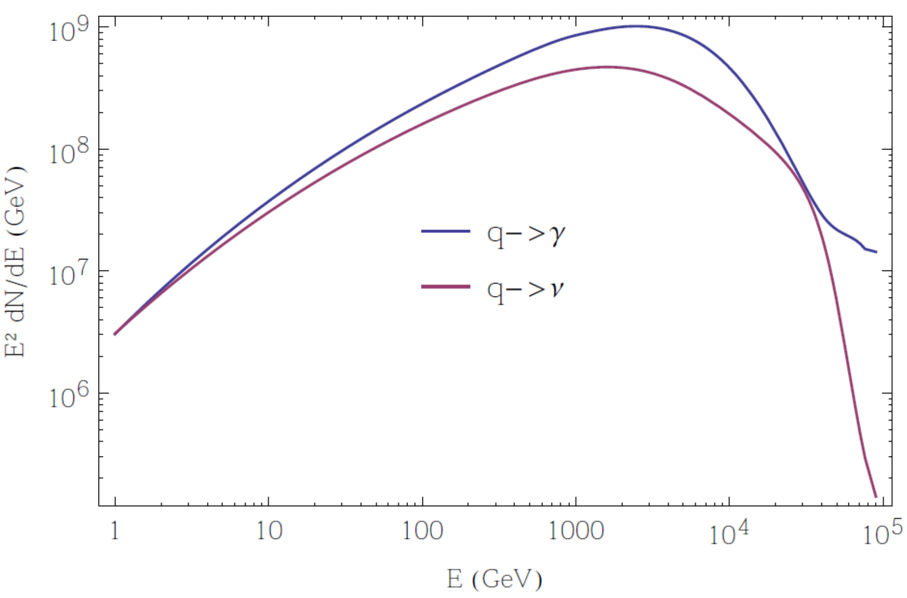
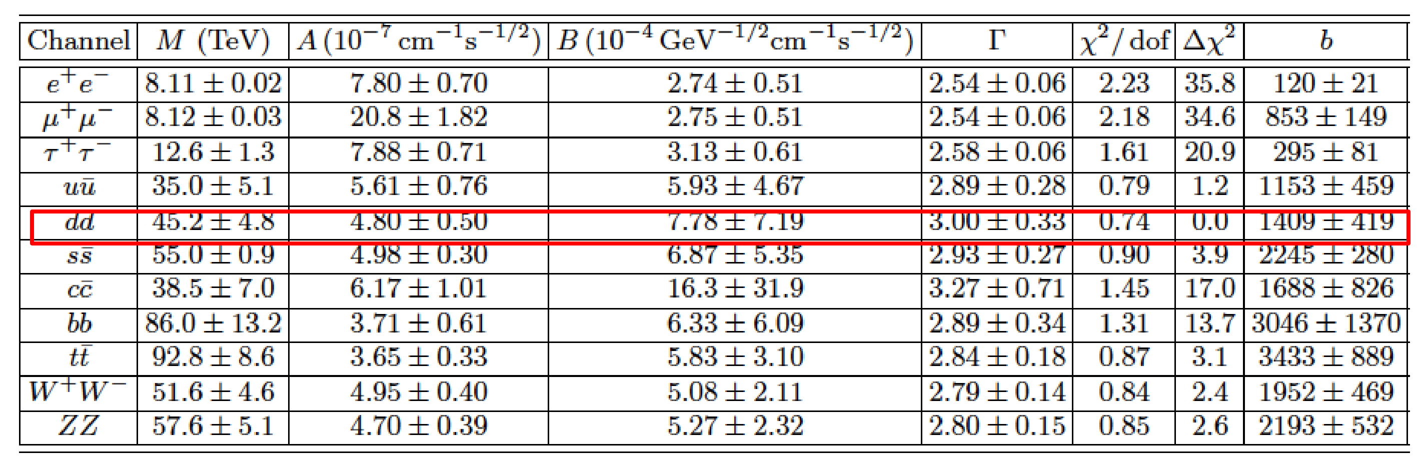


Viviana Gammaldi



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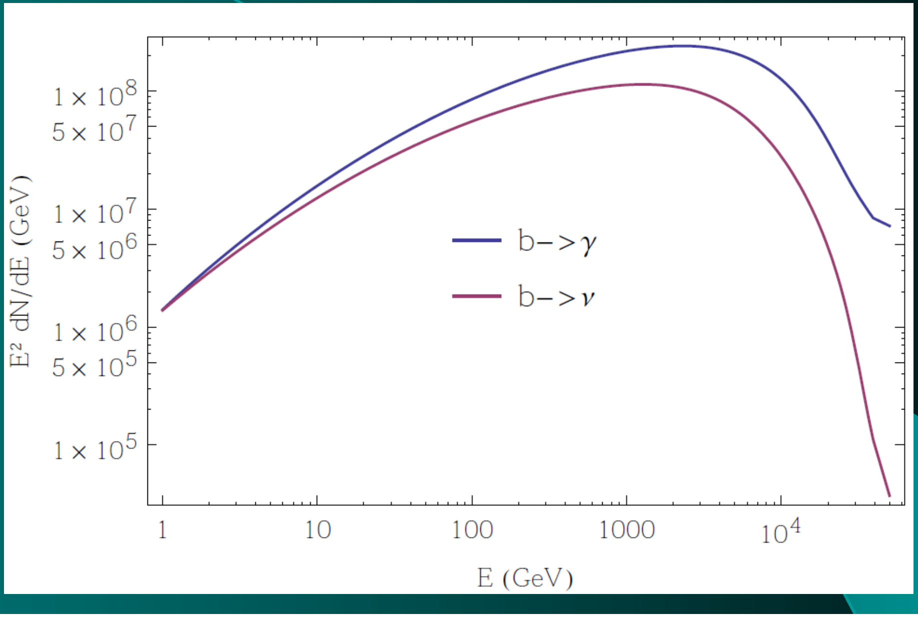

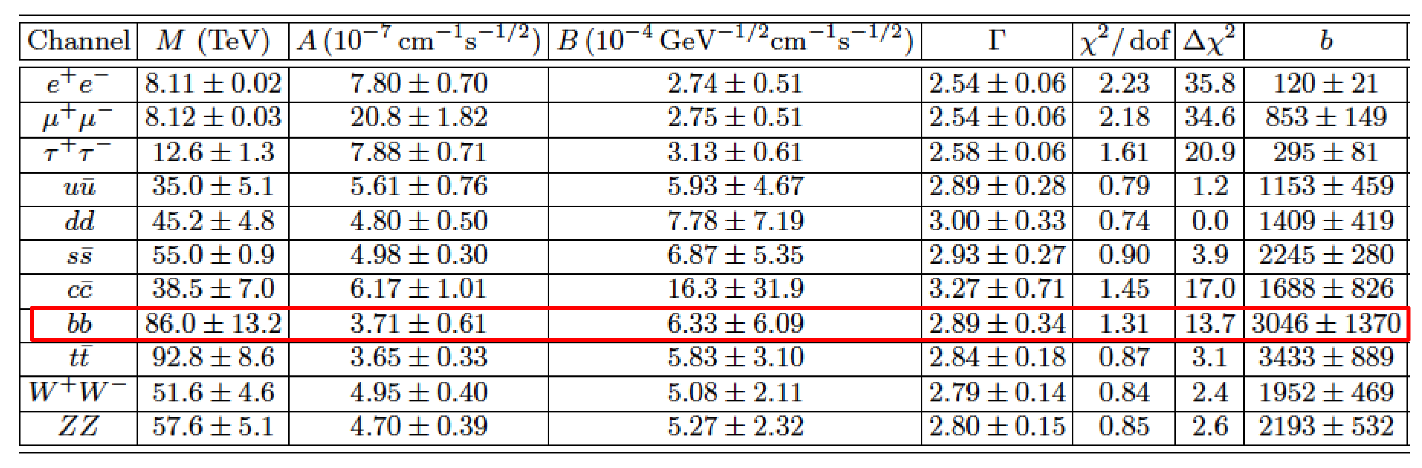

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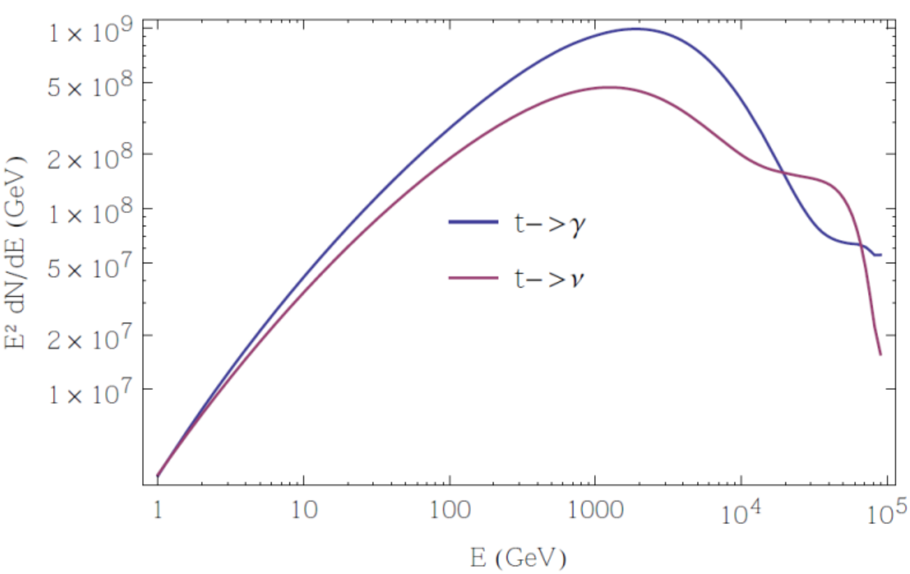
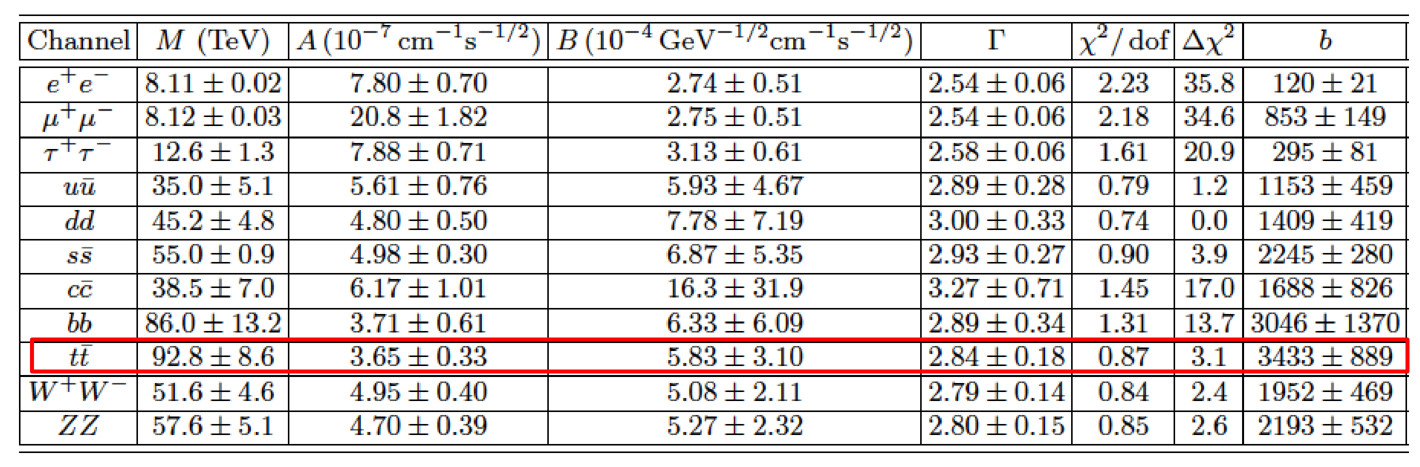
W^+W^-	51.6 ± 4.6	4.95 ± 0.40	5.08 ± 2.11	2.79 ± 0.14	0.84	2.4	1952 ± 469
ZZ	57.6 ± 5.1	4.70 ± 0.39	5.27 ± 2.32	2.80 ± 0.15	0.85	2.6	2193 ± 532

γ vs ν spectrum

Viviana Gammaldi





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^-	8.11 ± 0.02	7.80 ± 0.70	2.74 ± 0.51	2.54 ± 0.06	2.23	35.8	120 ± 21
$\mu^+\mu^-$	8.12 ± 0.03	20.8 ± 1.82	2.75 ± 0.51	2.54 ± 0.06	2.18	34.6	853 ± 149
$\tau^+\tau^-$	12.6 ± 1.3	7.88 ± 0.71	3.13 ± 0.61	2.58 ± 0.06	1.61	20.9	295 ± 81
$u\bar{u}$	35.0 ± 5.1	5.61 ± 0.76	5.93 ± 4.67	2.89 ± 0.28	0.79	1.2	1153 ± 459
dd	45.2 ± 4.8	4.80 ± 0.50	7.78 ± 7.19	3.00 ± 0.33	0.74	0.0	1409 ± 419
$s\bar{s}$	55.0 ± 0.9	4.98 ± 0.30	6.87 ± 5.35	2.93 ± 0.27	0.90	3.9	2245 ± 280
$c\bar{c}$	38.5 ± 7.0	6.17 ± 1.01	16.3 ± 31.9	3.27 ± 0.71	1.45	17.0	1688 ± 826
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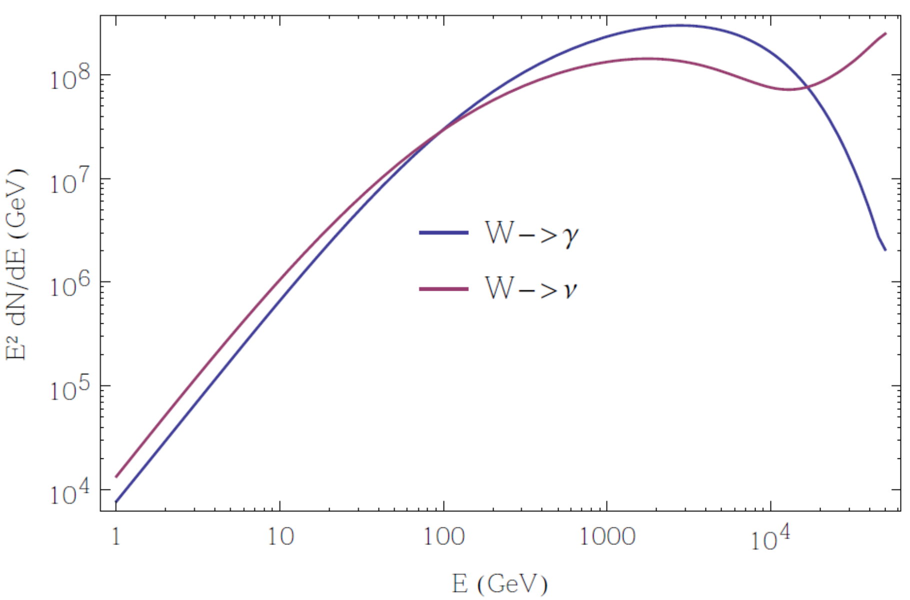
Viviana Gammaldi



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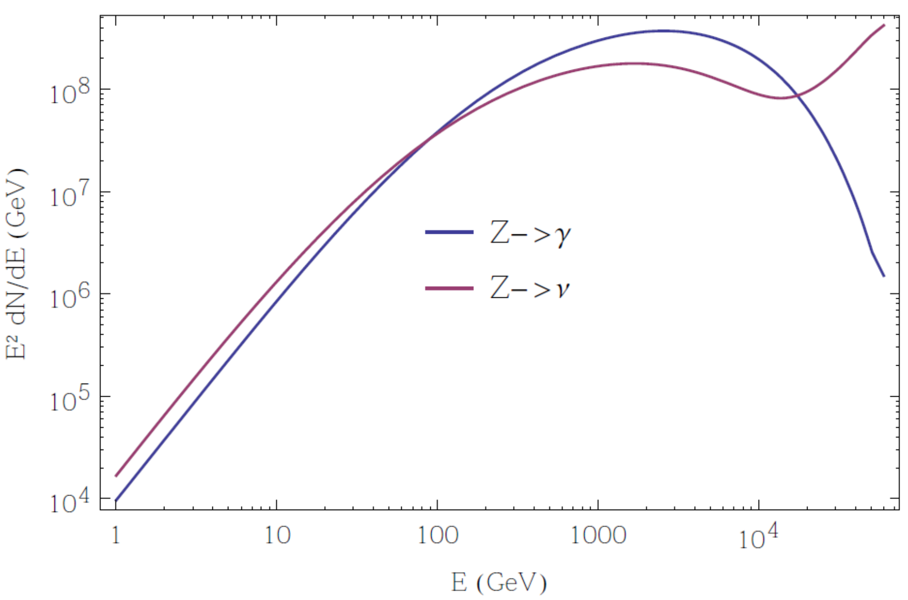
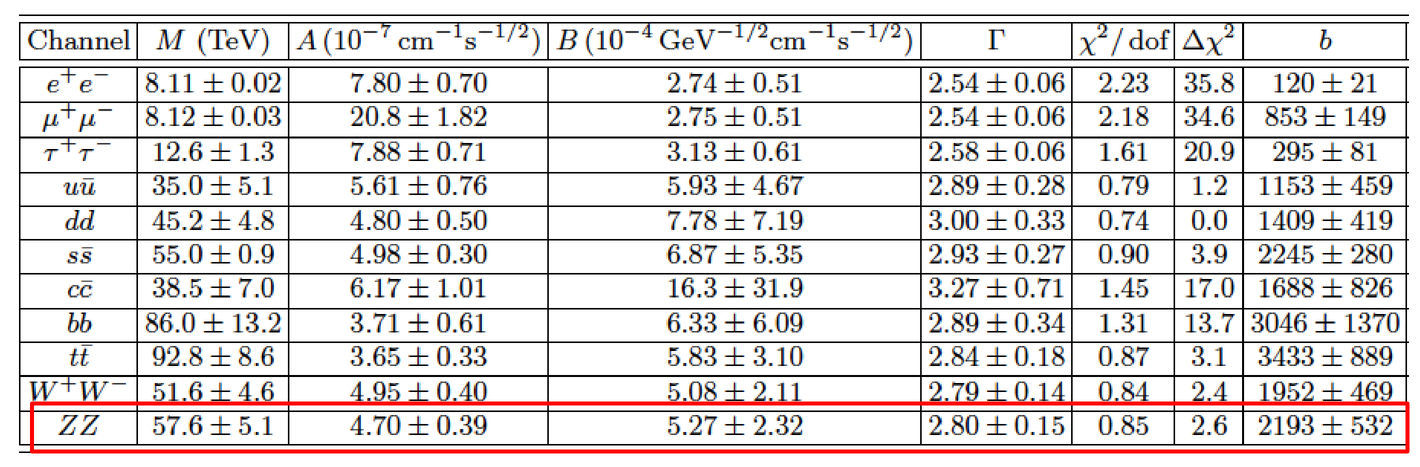
γ vs ν spectrum

Viviana Gammaldi





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ZZ	57.6 ± 5.1	4.70 ± 0.39	5.27 ± 2.32	2.80 ± 0.15	0.85	2.6	2193 ± 532

CONCLUSIONS

1.- 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.

4.- Branons are motivated dark matter candidates in a large range of masses and interactions.

- 4.a. In particular, they can have masses over 10 TeV and provide the right thermal DM abundance.
- 4.b. It is interesting for a DM interpretation of the galactic center gamma ray flux observed by H.E.S.S.

BACKGROUND SLIDES

H.E.S.S. GC SIGNAL

$$\frac{dN}{dE} = \Phi_0 \times \left(\frac{E}{1\mathrm{TeV}}\right)^{-\Gamma}$$

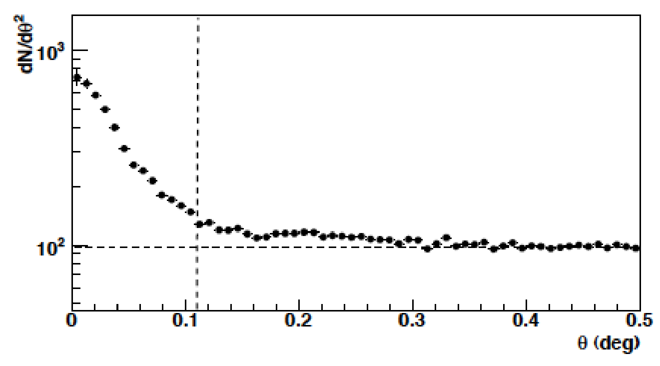
$$\chi^2 = 2.37$$

$$\frac{dN}{dE} = \Phi_0 \times \left(\frac{E}{1\mathrm{TeV}}\right)^{-\Gamma} \times e^{-\left(\frac{E}{E_{\mathrm{cut}}}\right)}$$

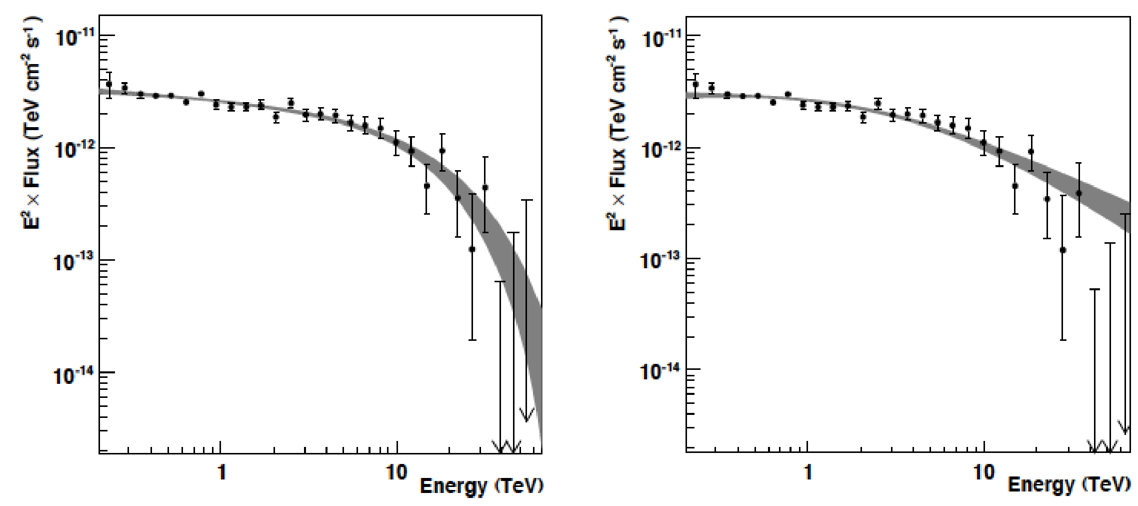
$$\chi^2 = 0.88$$

$$\frac{dN}{dE} = \Phi_0 \times \left(\frac{E}{1\mathrm{TeV}}\right)^{-\Gamma_1} \times \frac{1}{\left(1+\left(\frac{E}{E_{\mathrm{break}}}\right)^{(\Gamma_2-\Gamma_1)}\right)}$$

$$\chi^2 = 1.05$$



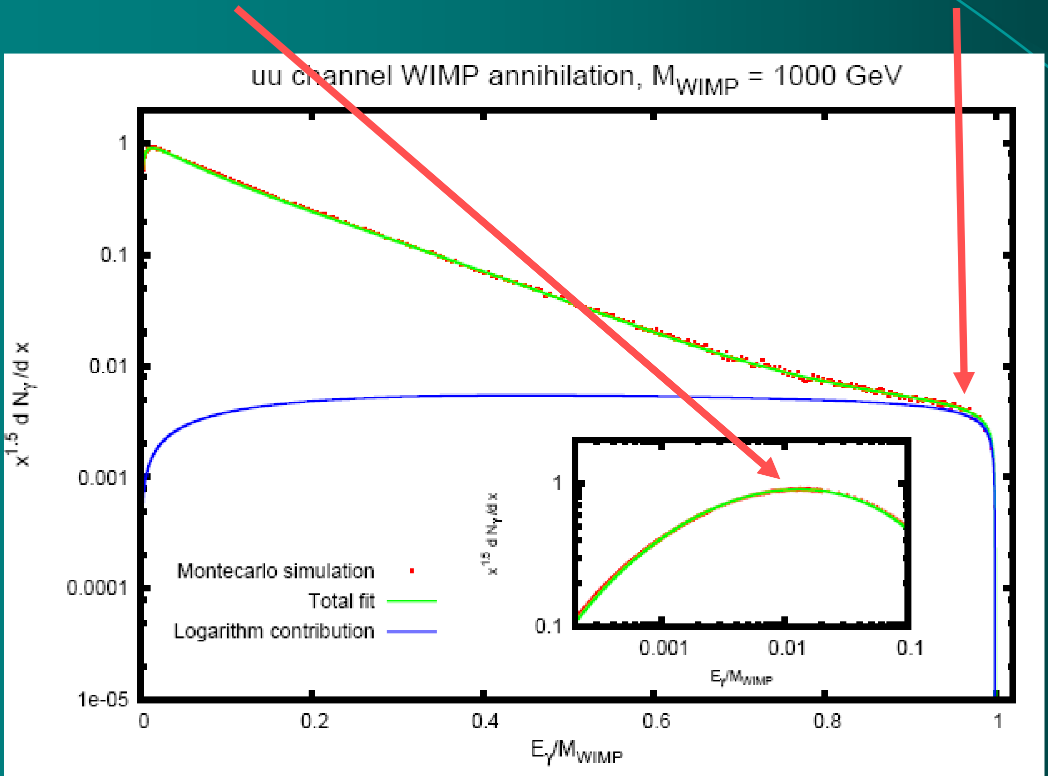
$\Theta < 0.1°$



GAMMA RAY SPECTRA

Two different strategies for a continuous spectrum:

1.- Maximum fit   **2.- Weizsacker-Williams radiation**



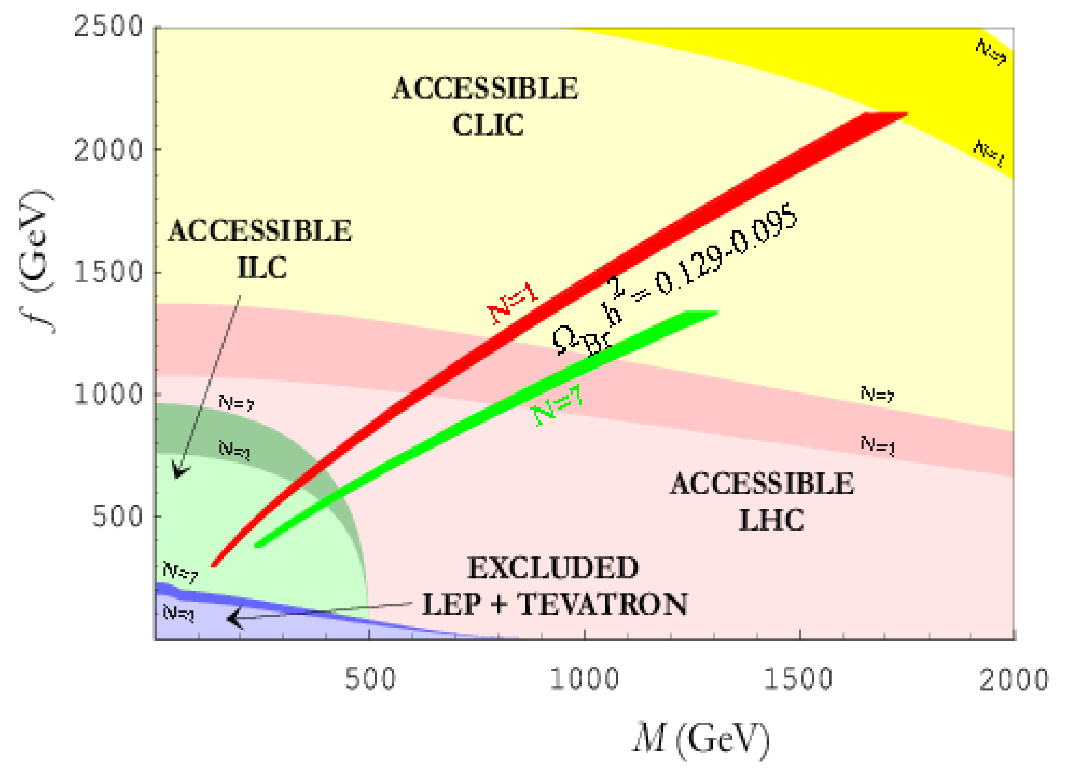
(de la Cruz-Dombriz, Cembranos, Dobado, and Maroto)

$$\pi(p_1)\pi(p_2) \longrightarrow e^+(k_1)e^+(k_2)\gamma_\mu(q)$$

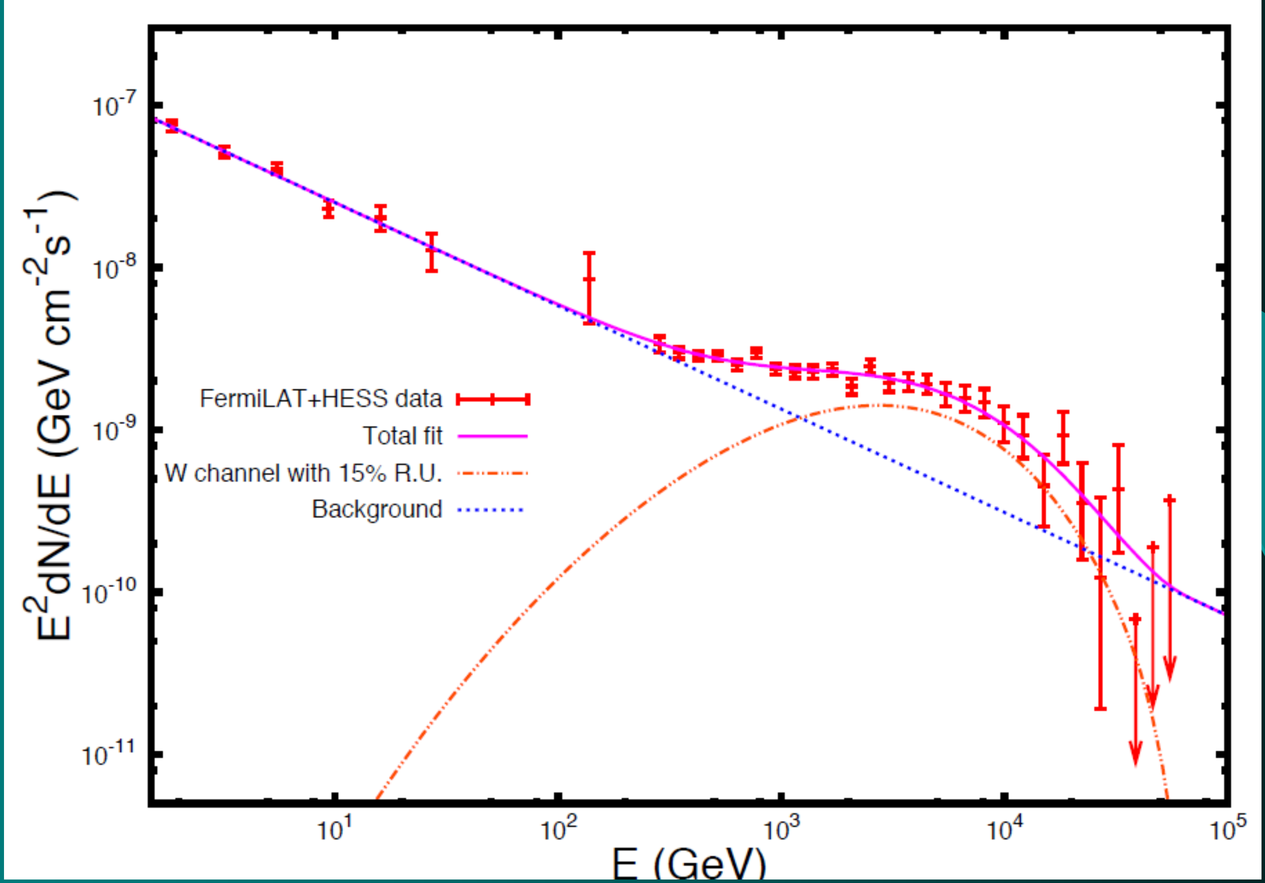
$$x = E_\gamma/M$$

$$\langle \frac{d\sigma_\gamma}{dx} v \rangle = \frac{\alpha M^6 x[1-\frac{m_e^2}{M^2(1-x)}]^{1/2}}{90 f^8 \pi^2 N} \left\{ x^2[9(1-x)+4x^2] + 3(1-x)[1+(1-x)^2]\ln\frac{M^2(1-x)}{m_e^2} \right\}$$

BACKGROUND


2500
2000
1500
1000
500
f (GeV)
500
1000
1500
2000
M (GeV)
ACCESSIBLE CLIC
ACCESSIBLE ILC
ACCESSIBLE LHC
EXCLUDED LEP + TEVATRON
$\Omega_{Br} h^2 = 0.129\text{-}0.095$
N=1
N=7
N=7
N=1
N=7
N=1
N=7
N=1
N=7
N=1

BACKGROUND



10-7
10-8
10-9
10-10
10-11
E²dN/dE (GeV cm⁻²s⁻¹)
10¹
10²
10³
10⁴
10⁵
E (GeV)
FermiLAT+HESS data
Total fit
W channel with 15% R.U.
Background