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Dark Matter *with* photons

PRD 1009.4936 [hep-th]

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Cercar che giova?
Al buio non si trova.

Cercar che giova?
Al buio non si trova.

Ma per fortuna
è una notte di luna,
e qui la luna
l'abbiamo vicina.

La Bohème,
Giacomo Rossini

SOME QUESTIONS…

- How many photons are produced from particle - antiparticle decay and hadronization processes?

- How are these photons distributed in the accessible energy range?

ON THIS TALK...

I. Overview

- Indirect searches.
- Monte Carlo simulation: PYTHIA.

II. Implementation, results and analysis

- Procedure and statistics.
- PYTHIA software and simulation results.
- **Analytical expressions** for **ALL** annihilation channels.
- Fits to the WIMP mass-dependent parameters.

III. Just one model: Brane-world theories

IV. Conclusions

I. OVERVIEW

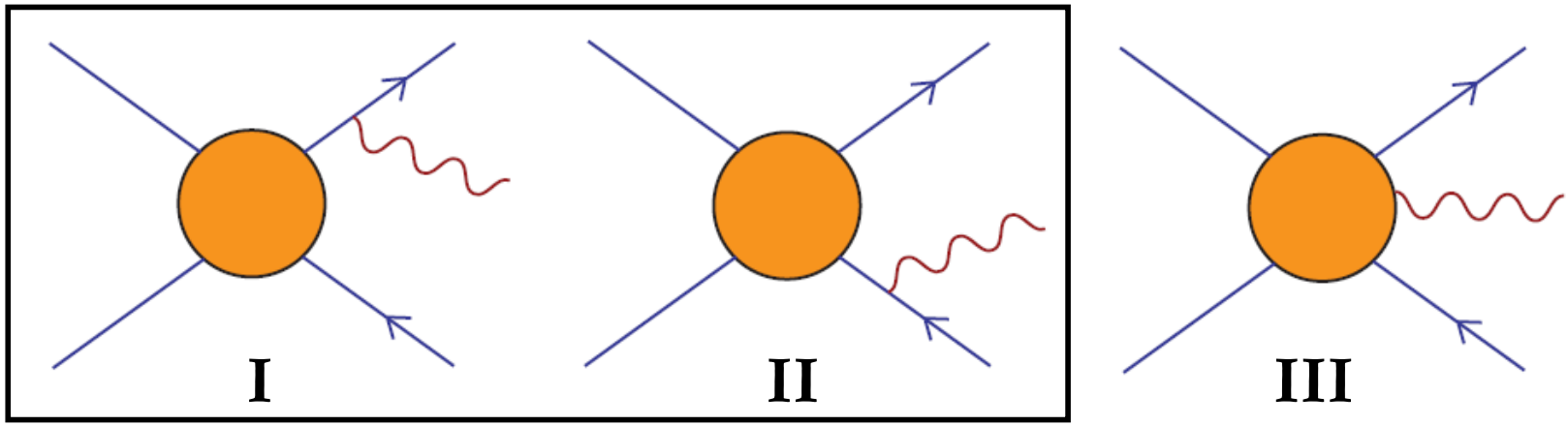
- Gamma rays fluxes from galactic sources

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

Particle model dependent | Dark matter density dependent

- We will focus on differential number of photons $\frac{\mathrm{d}\,N_\gamma^i}{\mathrm{d}\,E_\gamma}$.
- This is an essential piece to interpret photons fluxes as coming from DM annihilation.
- Model dependence comes from annihilation cross section of DM particles.

INTERNAL BREMSSTRAHLUNG…



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

✓ Internal bremsstrahlung contributions **I** and **II** will be included in the performed simulations.

✓ Model dependent contribution **III** is negligible except for models and energies for which lines contribution is dominant over the secondary photons.

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

✓ Dominant contribution of photons at low and intermediate energies photons is produced in decay of outgoing particles.


MONTE CARLO
SIMULATION:
PYTHIA

- Physical process to get gamma rays from WIMPs:

  Firstly: Annihilation of WIMPs (mainly by pairs) in SM particles.

  Secondly: Those unstable SM products decay and/or hadronize.

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$$E_{\rm CM} = 2\,M \quad \text{Center of mass frame}$$

- Simulate $E_{\rm CM}$ ⇔ Simulate different WIMP masses.

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- Package **PYTHIA 6.418** version was used.

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$$E_{\rm CM} = 2\,M \quad \text{Center of mass frame}$$

- Simulate $E_{\rm CM}$ $\Leftrightarrow$ Simulate different WIMP masses.

- Package **PYTHIA 6.418** version was used.

- Energy bins for the variable $x \equiv E_\gamma / M$ in the interval [0, 1]

STATISTICS

✓ What is the number of gamma rays for each simulation?

In $\mathbf{10^7}$ units …

Particle \ Mass (GeV)	100	125	150	200	250	350	500	1000
t	-	-	-	0.70	0.86	0.32	2.81	1.41
W	5.21	-	1.91	6.85	-	7.83	2.91	2.85
Z	0.42	6.01	2.91	14.93	-	14.21	2.81	2.02

Quark \ Mass (GeV)	50	100	200	500	1000	2000	5000	7000	8000
b	11.69	1.91	2.62	2.61	8.81	2.20	3.81	-	1.70
c	2.41	1.99	16.82	2.81	2.81	3.81	12.00	-	3.00
d	1.04	1.96	2.42	2.81	2.81	2.81	2.31	-	-
s	15.30	2.00	1.97	2.81	9.82	2.71	2.71	11.00	1.35
u	2.05	11.86	2.42	2.81	3.82	10.85	5.91	-	2.11

ANALYTICAL EXPRESSIONS TO FIT PYTHIA SIMULATIONS

✓ Now that simulations have been performed, proposed fitting functions:

I. Leptons and quarks (except top quark):

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

- Two increasing and two decreasing exponential factors.
- Logarithm term: Weizsacker-Williams effect.
- Parameter p is usually $(M/\mathrm{m}_{\mathrm{particle}})^2$ free in principle here.
- Some parameters are constant and others mass-dependent.

τ LEPTON RESULTS

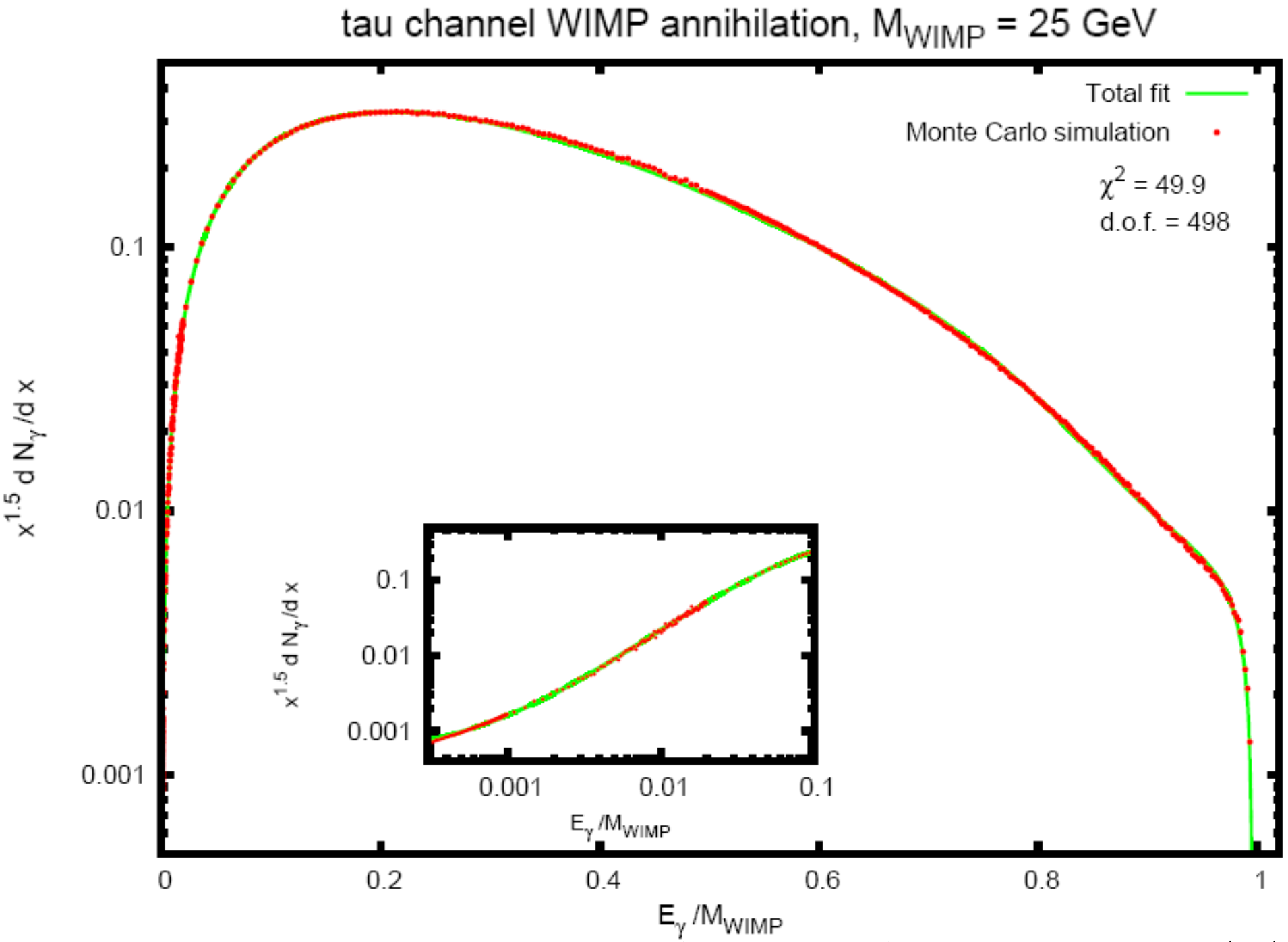
✓ Only **two** parameters are mass-dependent.

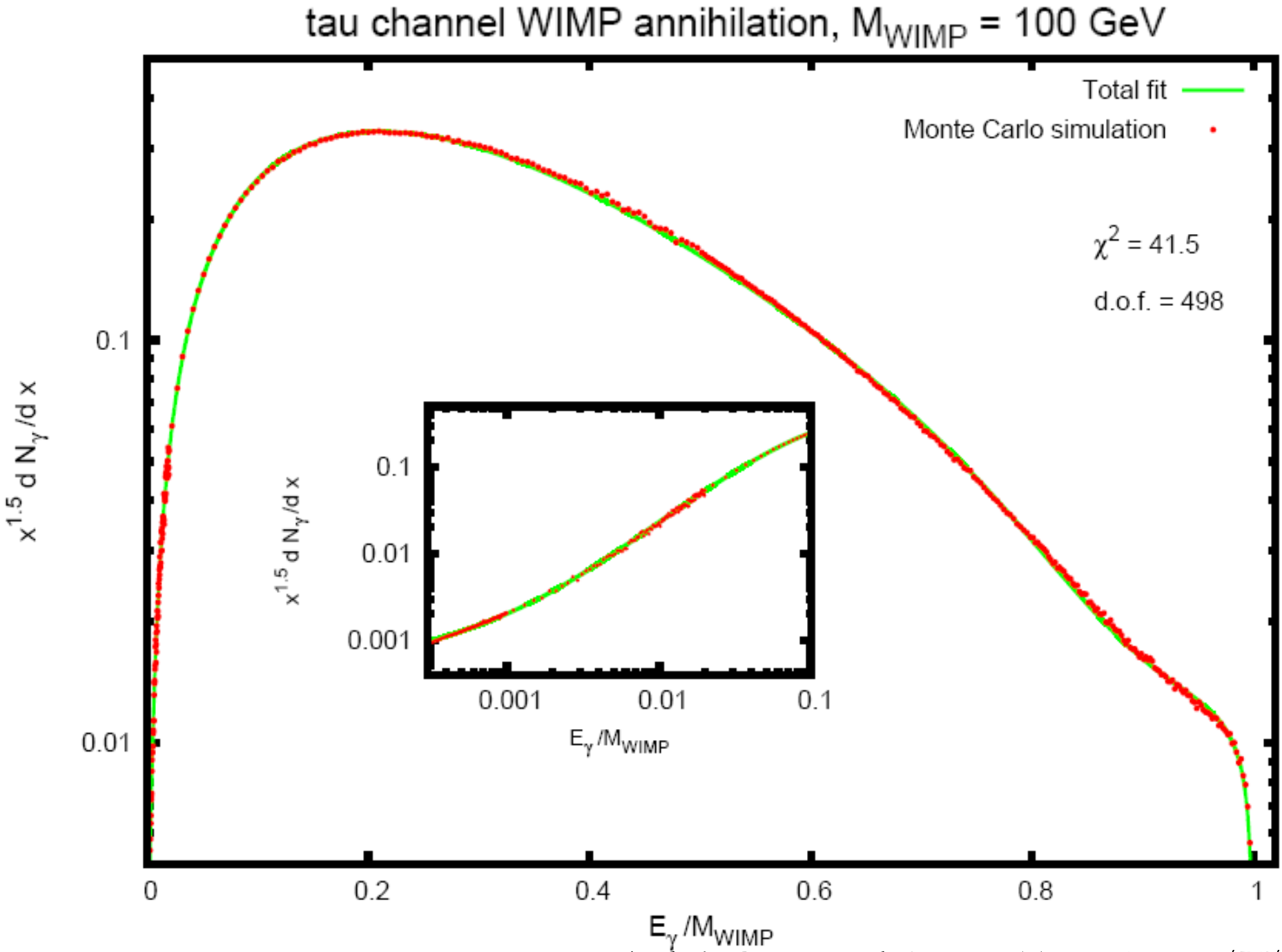
$$a_1 = 14.7,\ b_1 = 5.4,\ b_2 = 5.31,\ n_2 = 1.40$$

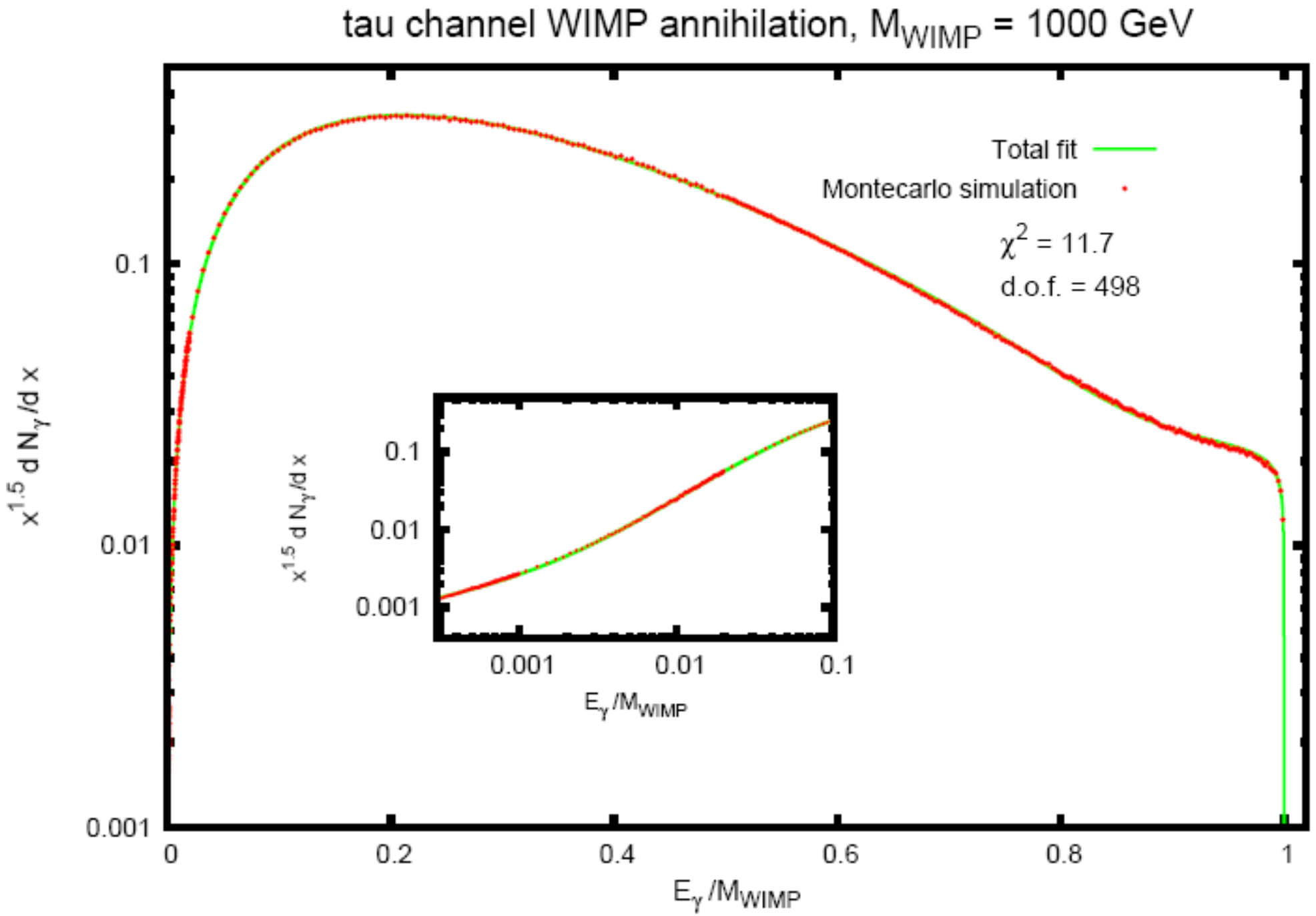
$$c_1 = 2.54\ ,\ d_1 = 0.295\ ,\ c_2 = 0.373$$

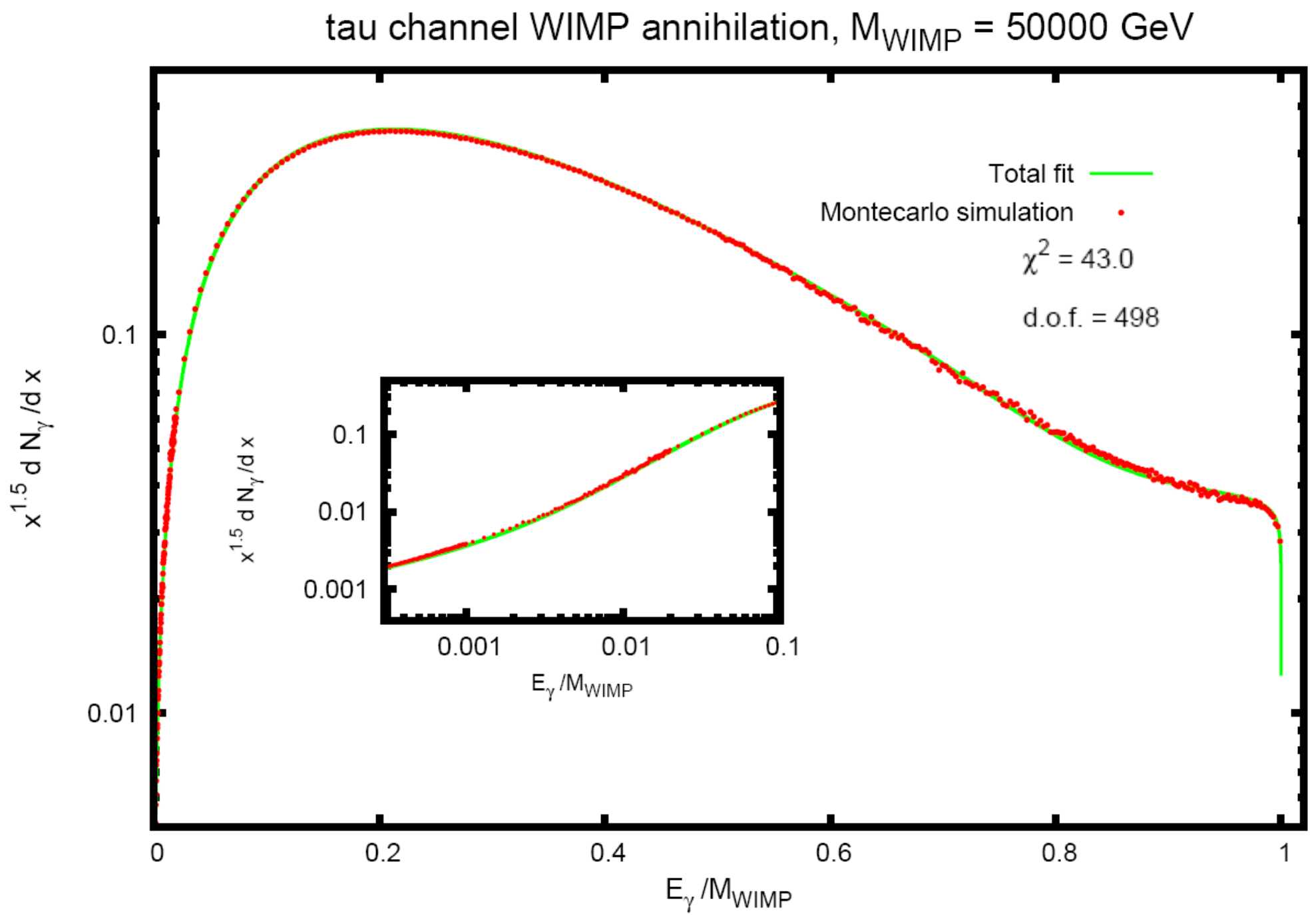
$$d_2 = 0.47 \text{ and } q = 0.0026$$

WIMP mass (GeV)	n_1	p
25	10.1	221
50	10.0	767
100	9.91	2520
200	9.80	8660
500	9.67	$4.01 \cdot 10^4$
1000	9.57	$1.35 \cdot 10^5$
10^4	9.25	$4.80 \cdot 10^6$
$5 \cdot 10^4$	9.14	$5.44 \cdot 10^7$

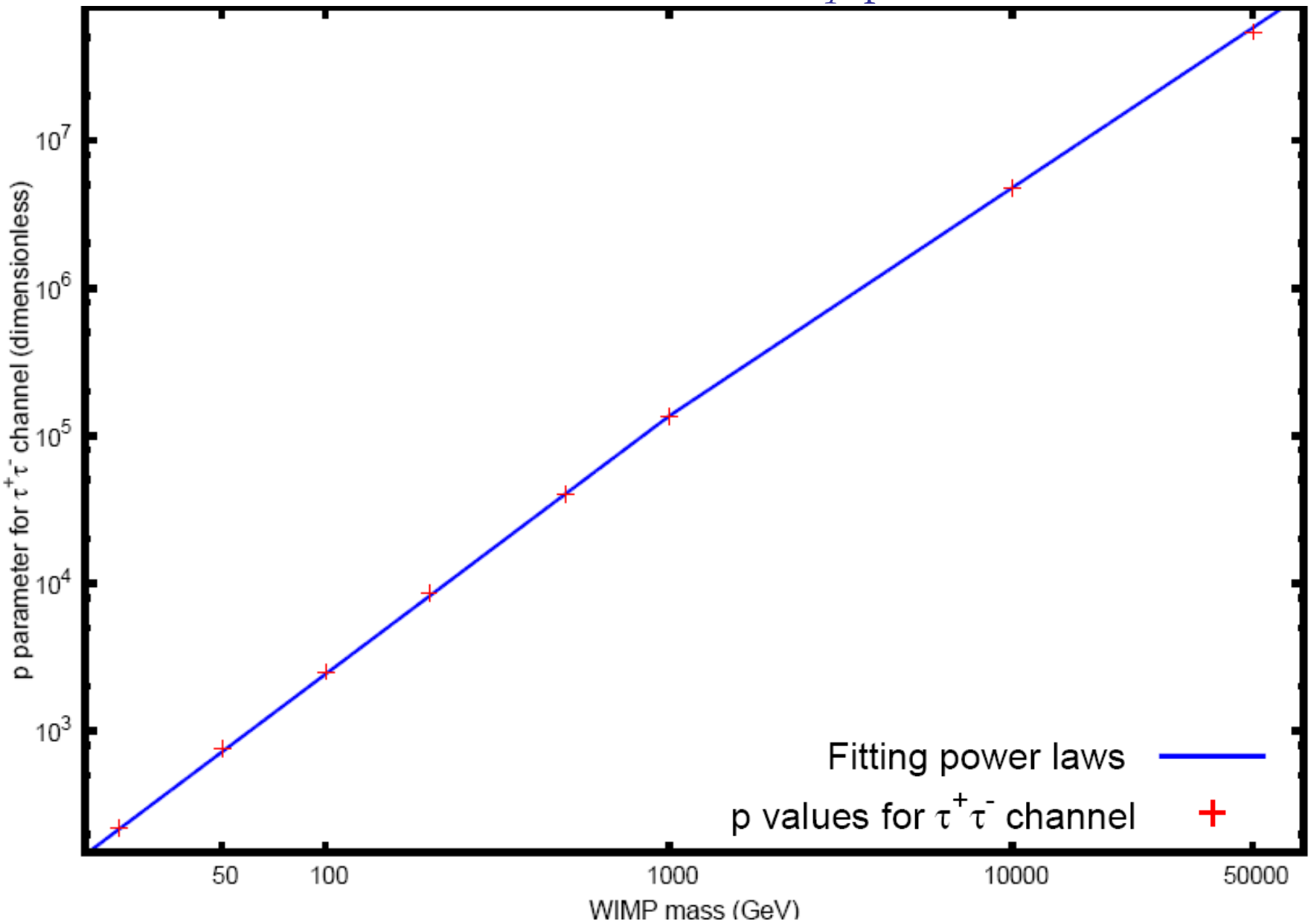

tau channel WIMP annihilation, M_{WIMP} = 25 GeV
Total fit
Monte Carlo simulation
χ^2 = 49.9
d.o.f. = 498
$x^{1.5}$ d N_γ/d x
E_γ /M_{WIMP}
0.1
0.01
0.001
0
0.2
0.4
0.6
0.8
1

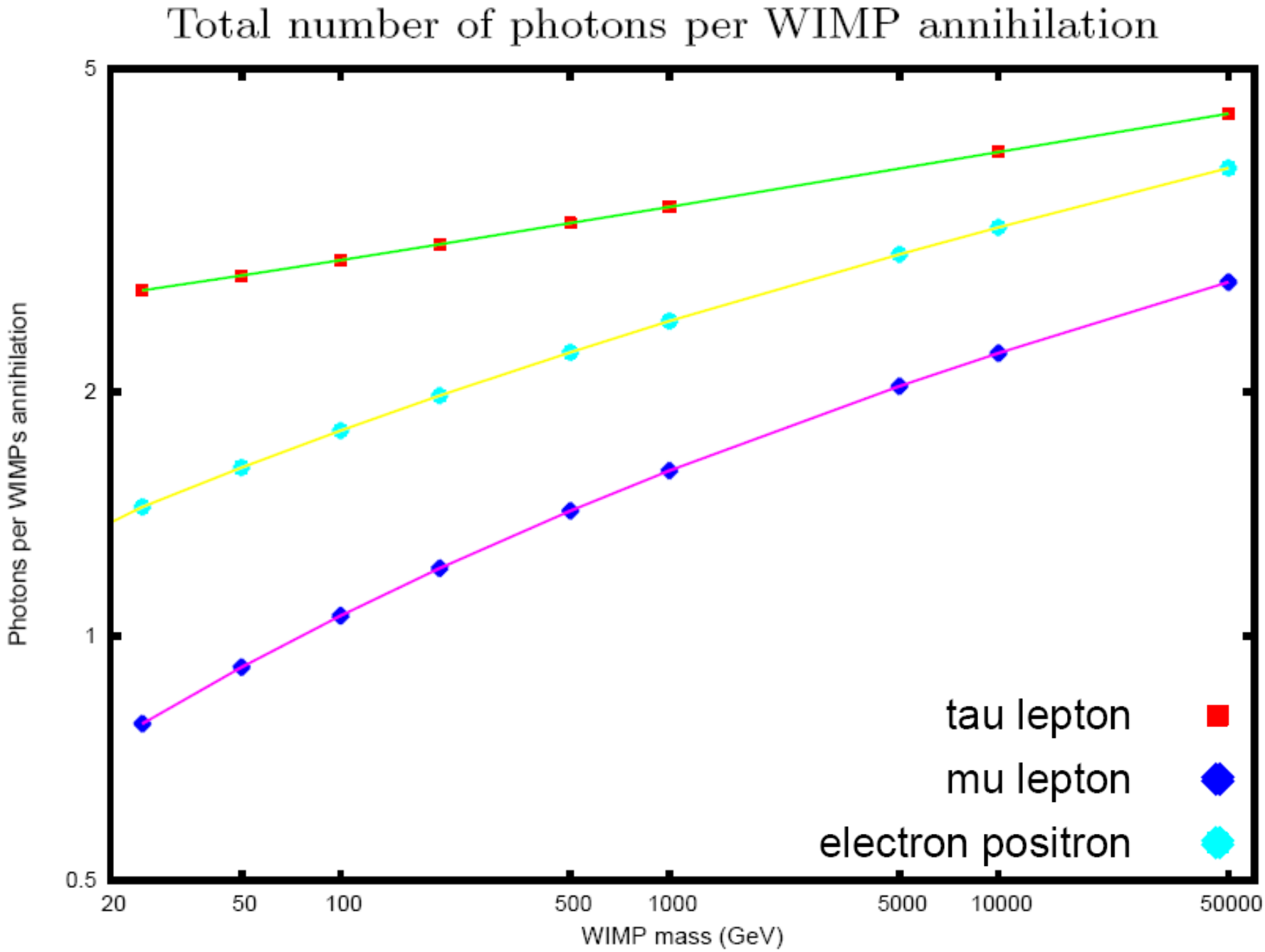

tau channel WIMP annihilation, M_{WIMP} = 100 GeV
Total fit
Monte Carlo simulation
χ^2 = 41.5
d.o.f. = 498
$x^{1.5}$ d N_γ/d x
E_γ /M_{WIMP}
0.1
0.01
0
0.2
0.4
0.6
0.8
1
0.001


tau channel WIMP annihilation, M_{WIMP} = 1000 GeV
Total fit
Montecarlo simulation
χ^2 = 11.7
d.o.f. = 498
$x^{1.5}$ d N_γ/d x
E_γ /M_{WIMP}
0.1
0.01
0.001
0
0.2
0.4
0.6
0.8
1


tau channel WIMP annihilation, M_{WIMP} = 50000 GeV
Total fit
Montecarlo simulation
χ^2 = 43.0
d.o.f. = 498
$x^{1.5}$ d N_γ /d x
E_γ /M_{WIMP}
0.1
0.01
0
0.2
0.4
0.6
0.8
1
0.001

τ channel WIMP annihilation, *p* parameter




Total number of photons per WIMP annihilation
Photons per WIMPs annihilation
5
2
1
0.5
20
50
100
500
1000
5000
10000
50000
WIMP mass (GeV)
tau lepton
mu lepton
electron positron

b QUARK RESULTS

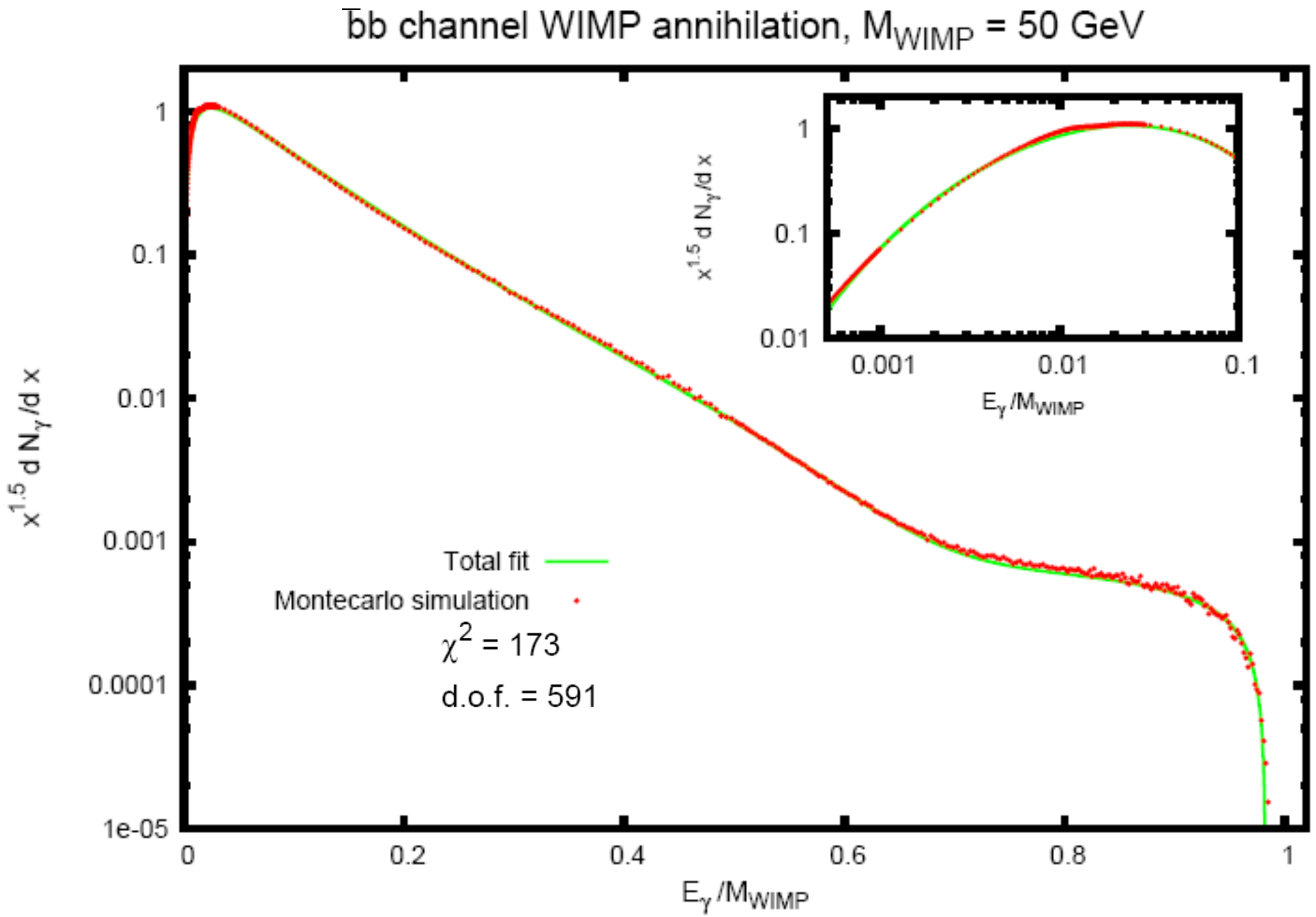
arXiv:1011.2137 [hep-ph] AdlCD et *al*.

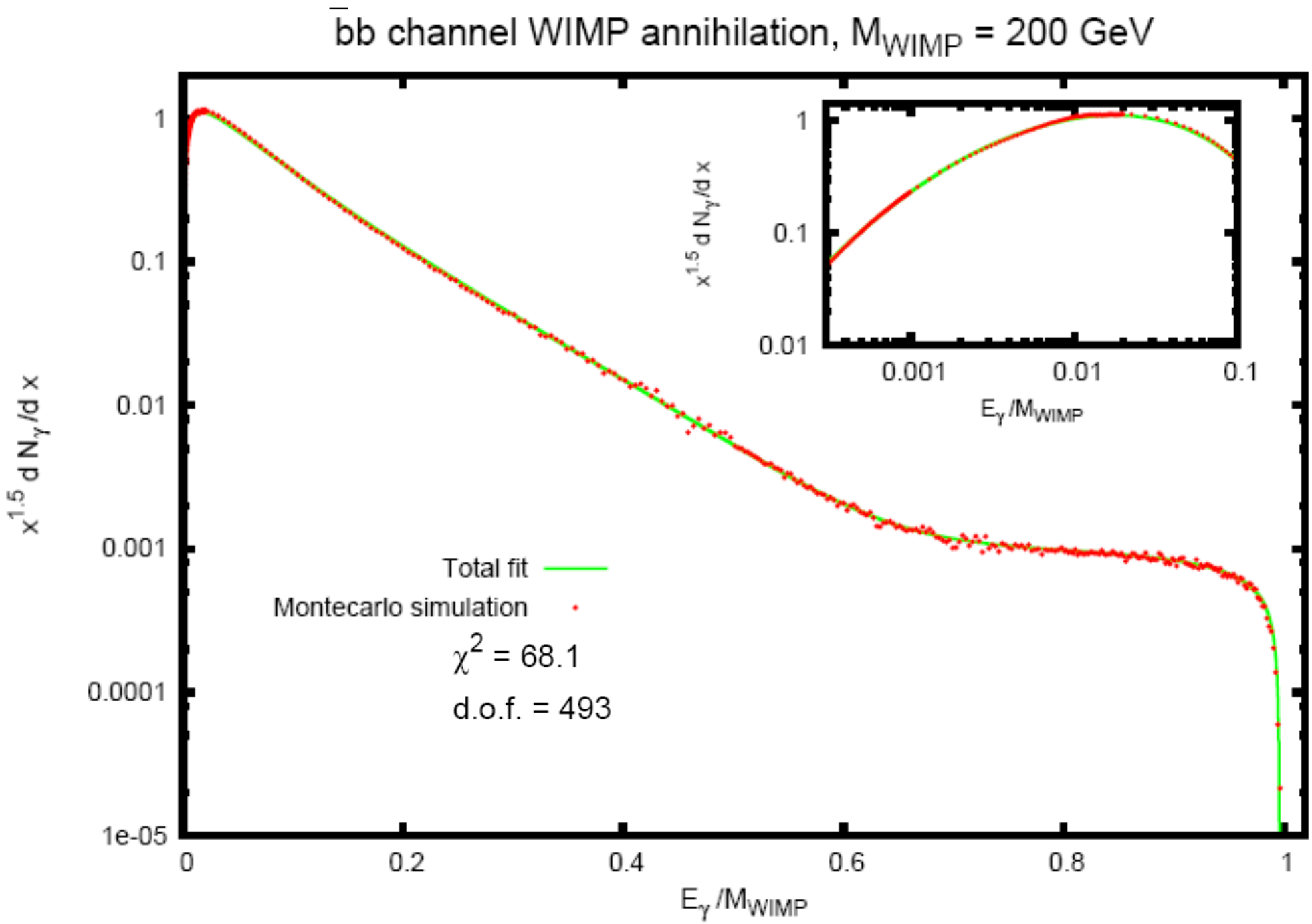
- Five parameters are mass independent:

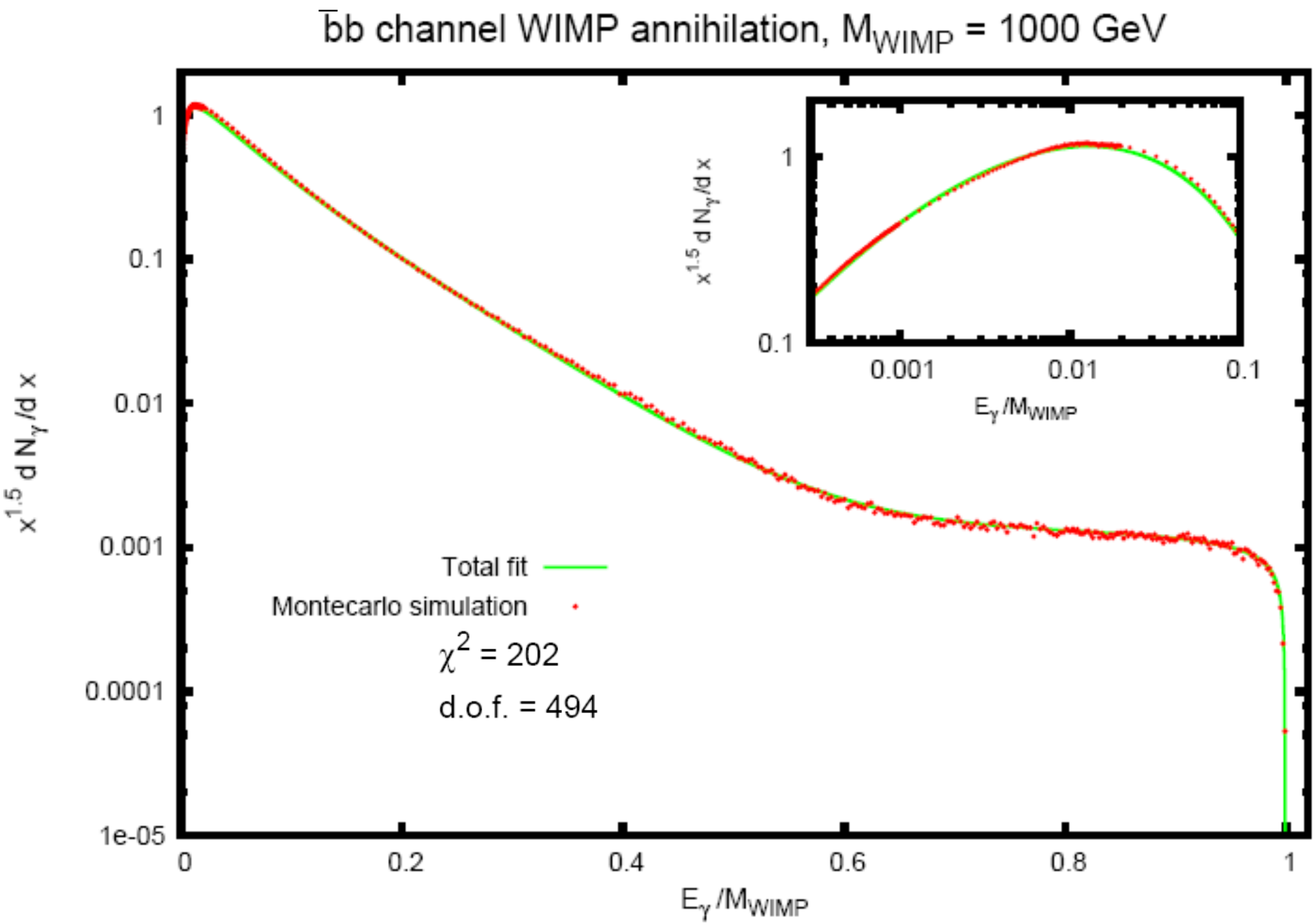
$$a_1 = 10.0,\ b_2 = 11.0,\ c_2 = 0.0151,\ d_2 = 0.55,\ q = 0.00026.$$

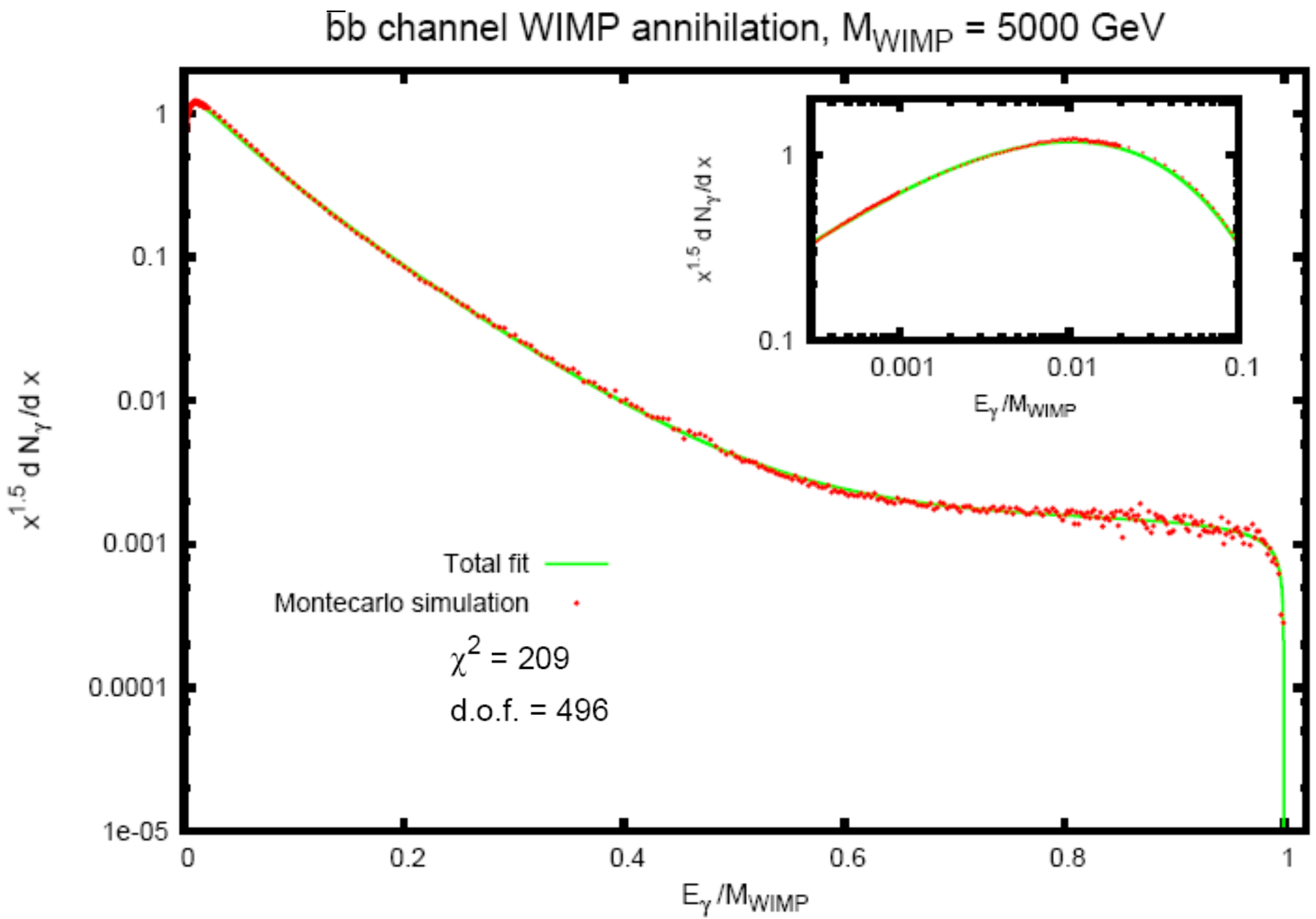
- Six mass-dependent parameters.

WIMP mass (GeV)	b_1	n_1	n_2	c_1	d_1	p
50	19.5	6.48	0.710	0.365	0.393	57.8
100	17.1	5.80	0.695	0.403	0.360	138
200	13.1	5.01	0.680	0.415	0.340	281
500	8.76	4.04	0.660	0.431	0.319	623
1000	6.00	3.36	0.647	0.447	0.305	1030
2000	4.60	2.85	0.640	0.460	0.294	1620
5000	3.00	2.26	0.634	0.479	0.280	2670
8000	2.35	2.00	0.629	0.490	0.274	3790

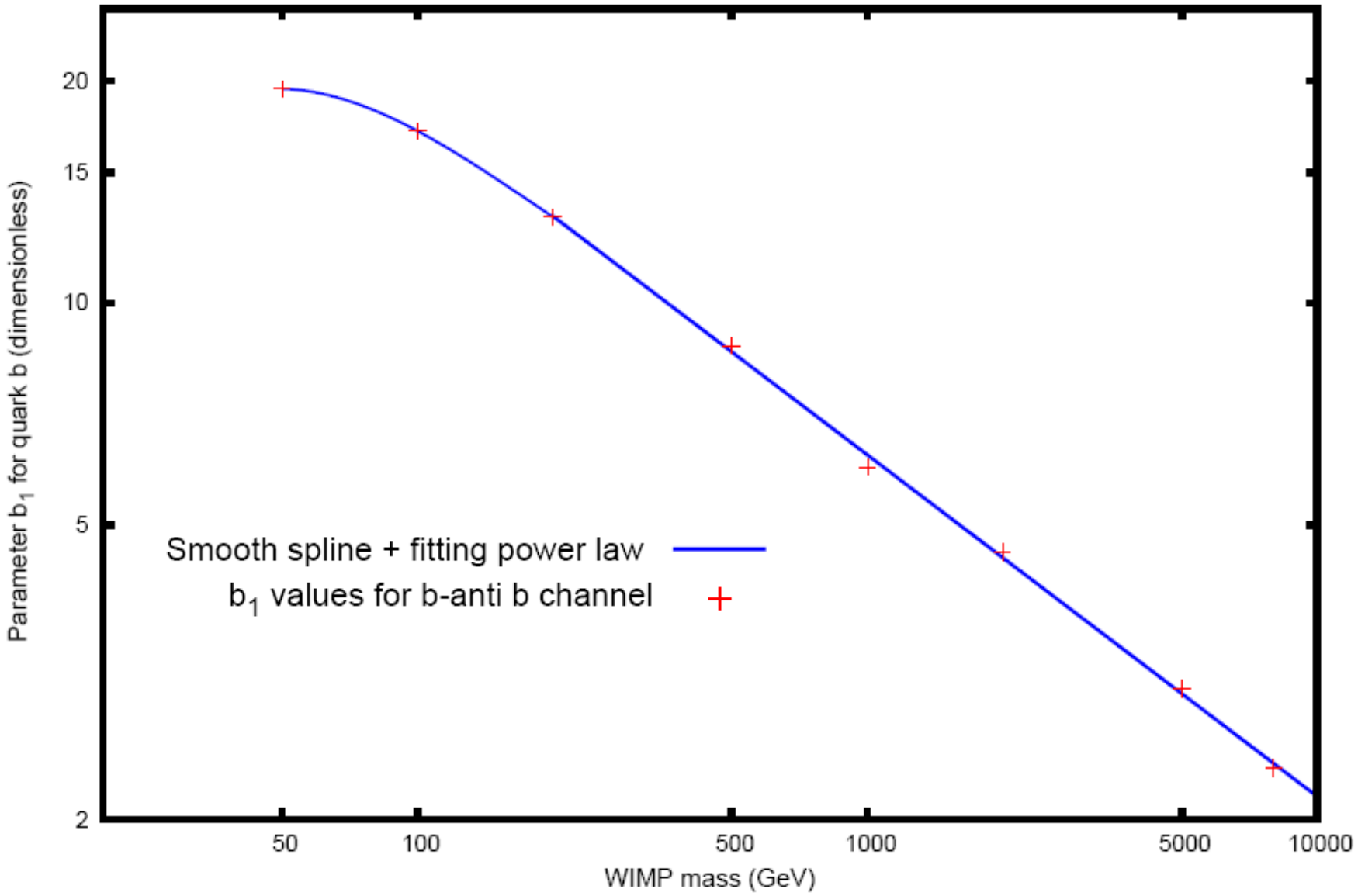

$\bar{b}b$ channel WIMP annihilation, M_{WIMP} = 50 GeV
$x^{1.5}\, d\, N_\gamma / d\, x$
E_γ / M_{WIMP}
Total fit
Montecarlo simulation
χ^2 = 173
d.o.f. = 591
1
0.1
0.01
0.001
0.0001
1e-05
0
0.2
0.4
0.6
0.8
1
0.001
0.01
0.1


$\bar{b}b$ channel WIMP annihilation, M_{WIMP} = 200 GeV
$x^{1.5}\, d\, N_\gamma / d\, x$
E_γ / M_{WIMP}
Total fit
Montecarlo simulation
χ^2 = 68.1
d.o.f. = 493
1
0.1
0.01
0.001
0.0001
1e-05
0
0.2
0.4
0.6
0.8
1
0.001
0.01
0.1


$\bar{b}b$ channel WIMP annihilation, M_{WIMP} = 1000 GeV
$x^{1.5}\, d\, N_\gamma / d\, x$
E_γ / M_{WIMP}
Total fit
Montecarlo simulation
χ^2 = 202
d.o.f. = 494
1
0.1
0.01
0.001
0.0001
1e-05
0
0.2
0.4
0.6
0.8
1
0.001
0.01
0.1


$\bar{b}b$ channel WIMP annihilation, M_{WIMP} = 5000 GeV
$x^{1.5}\, d\, N_\gamma / d\, x$
E_γ / M_{WIMP}
Total fit
Montecarlo simulation
χ^2 = 209
d.o.f. = 496
1
0.1
0.01
0.001
0.0001
1e-05
0
0.2
0.4
0.6
0.8
1
0.001
0.01
0.1

b channel WIMP annihilation, b_1 parameter



✓ In general, parameters follow a linear law at high masses and deviate at low masses.

II. *W* and *Z* gauge bosons:

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

- One increasing and one decreasing exponential factor.
- Logarithm term acquires a multiplicative behavior.
- j parameter allows to cut-off high energy photons.

W GAUGE BOSON RESULTS

arXiv:1012.4473 [hep-ph] AdlCD et *al*.

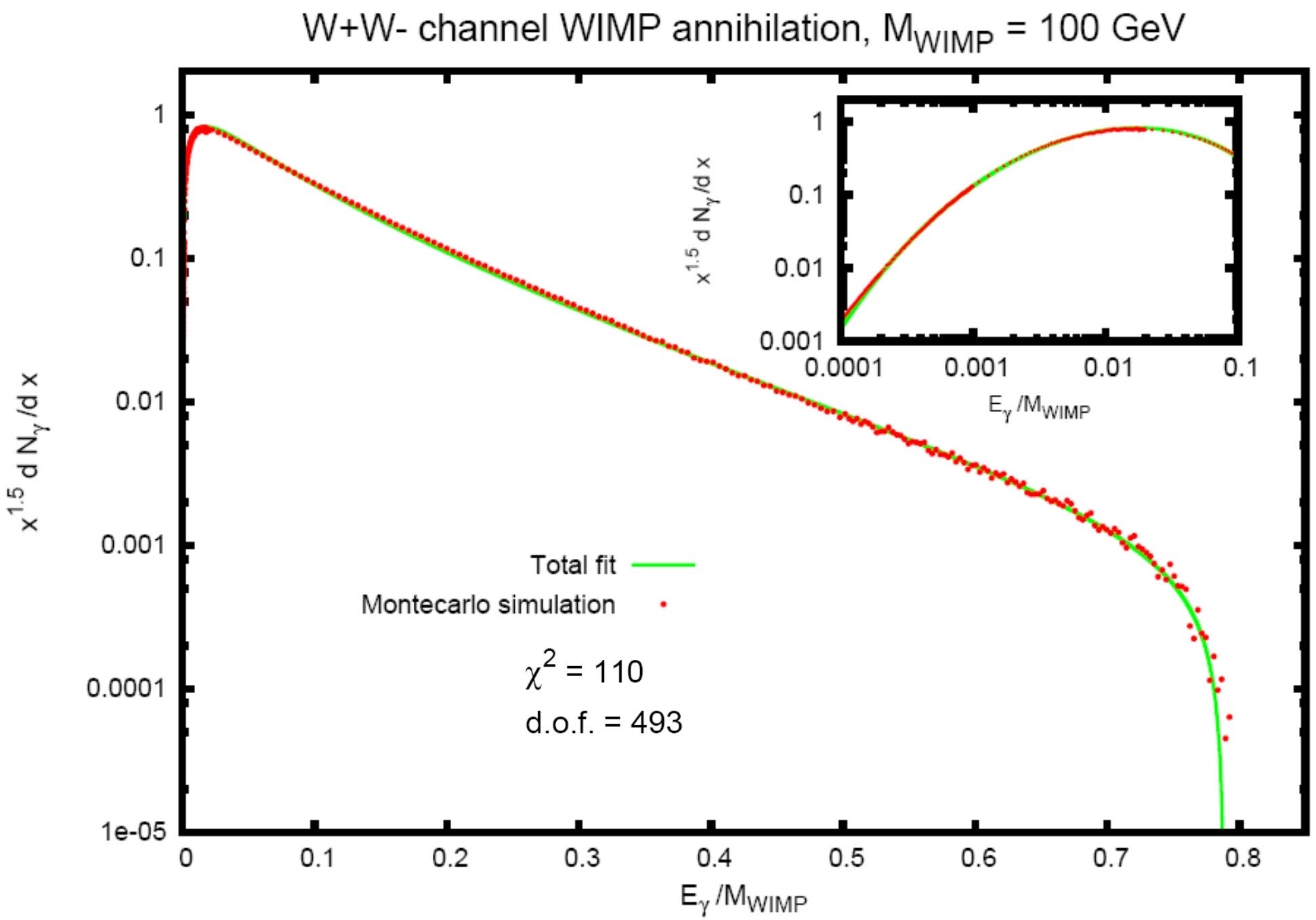
- Three parameters are mass independent.

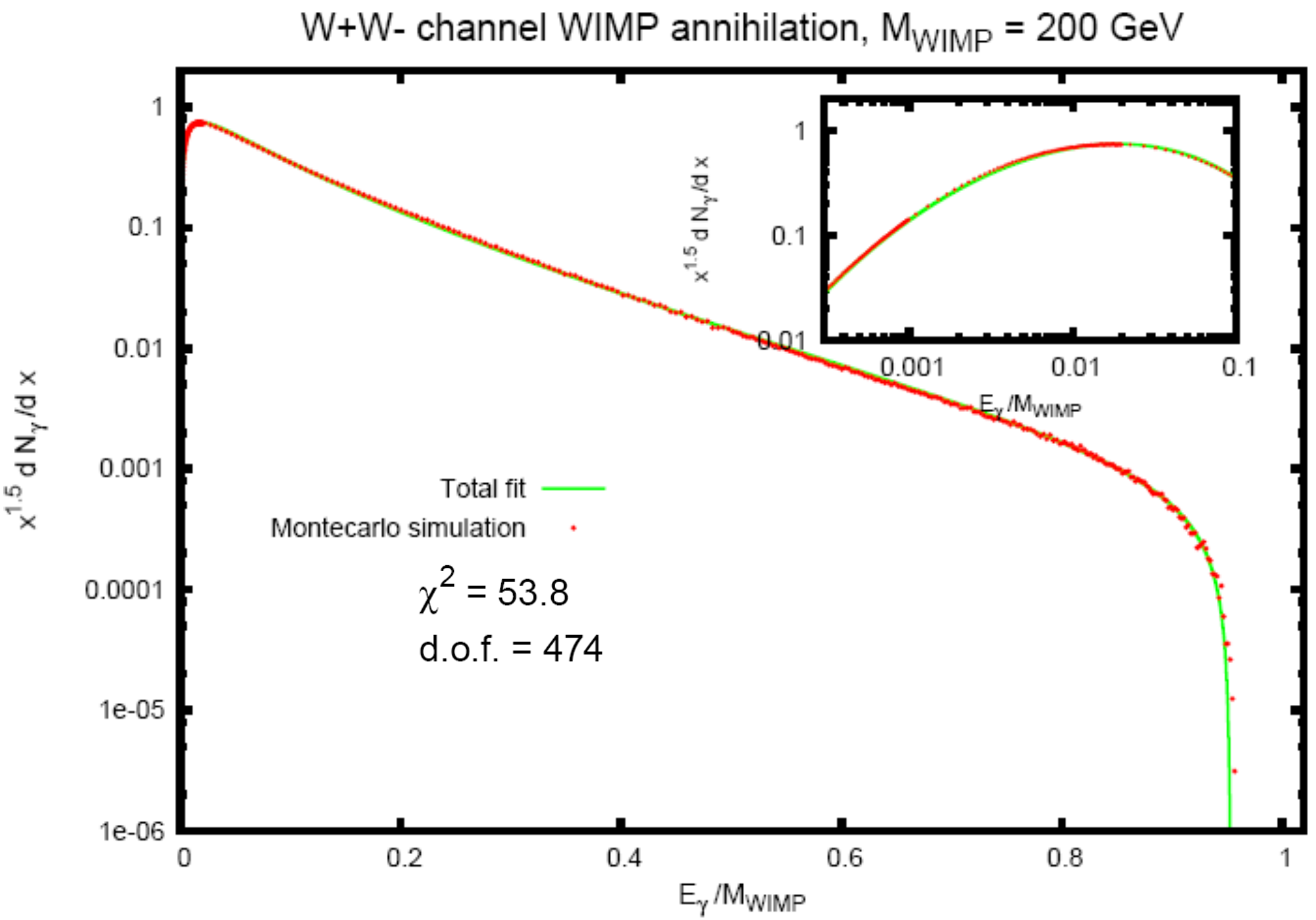
$$a_1 = 25.7 \quad , n_1 = 0.51 \text{ and } q = 3.0$$

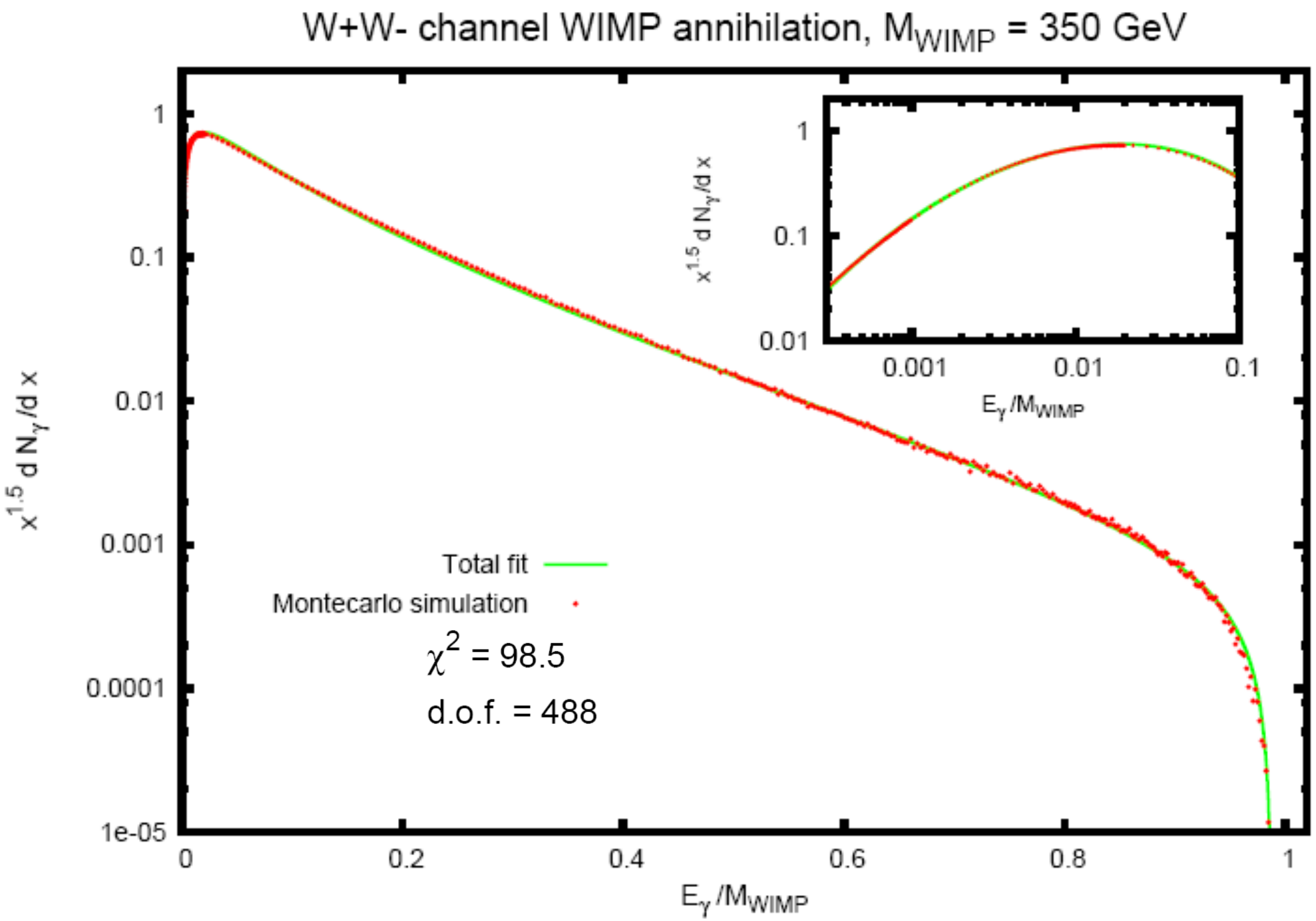
- Five mass-dependent parameters.

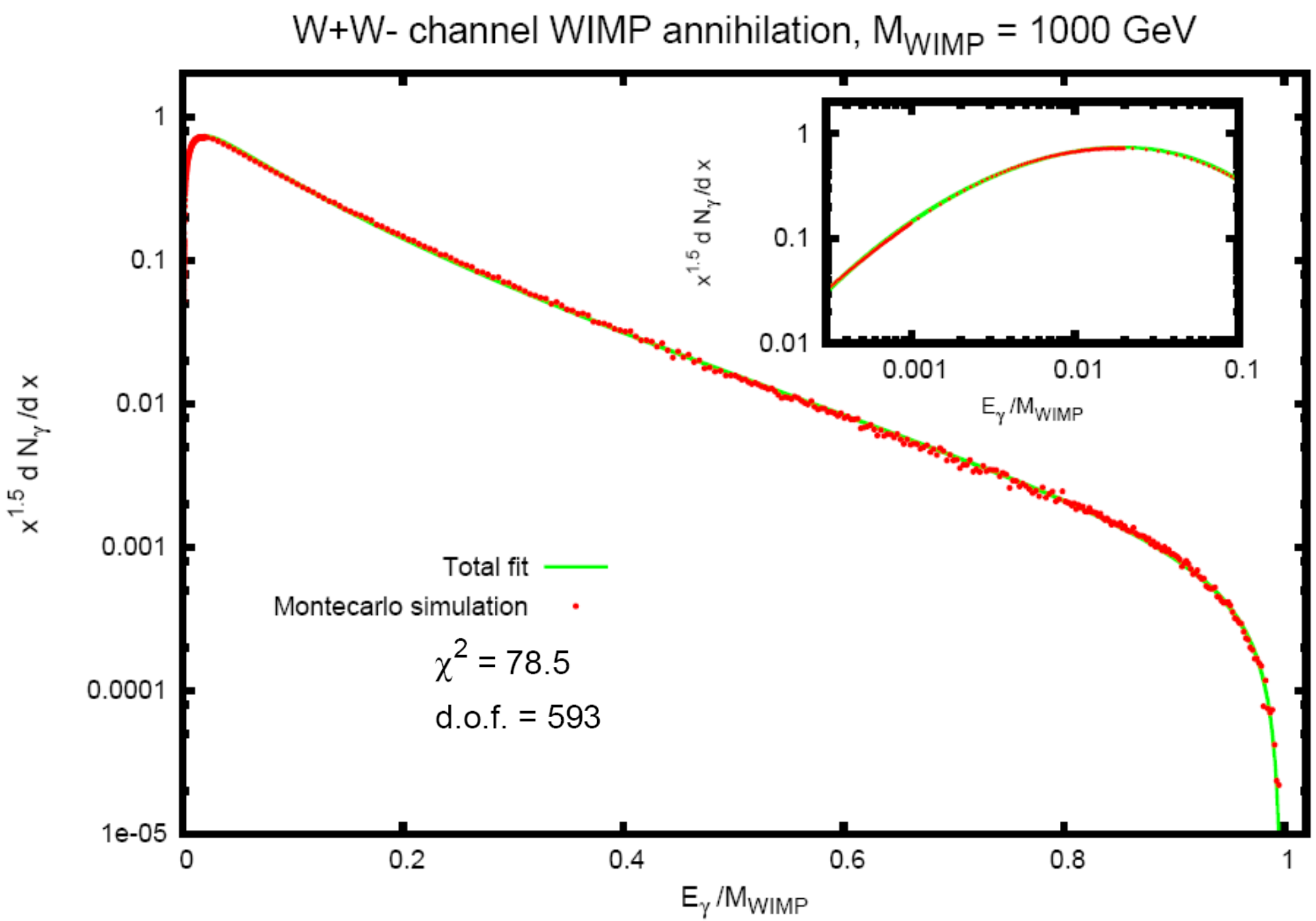
WIMP mass (GeV)	b_1	c_1	d_1	p	j
100	9.48	0.651	0.292	973	0.790
150	8.87	0.808	0.261	783	0.919
200	8.64	0.882	0.250	684	0.955
350	8.56	0.907	0.245	593	0.991
500	8.51	0.917	0.244	560	0.996
1000	8.45	0.931	0.242	535	1.000

- From 1000 GeV onwards, spectra do not change if masses increase.

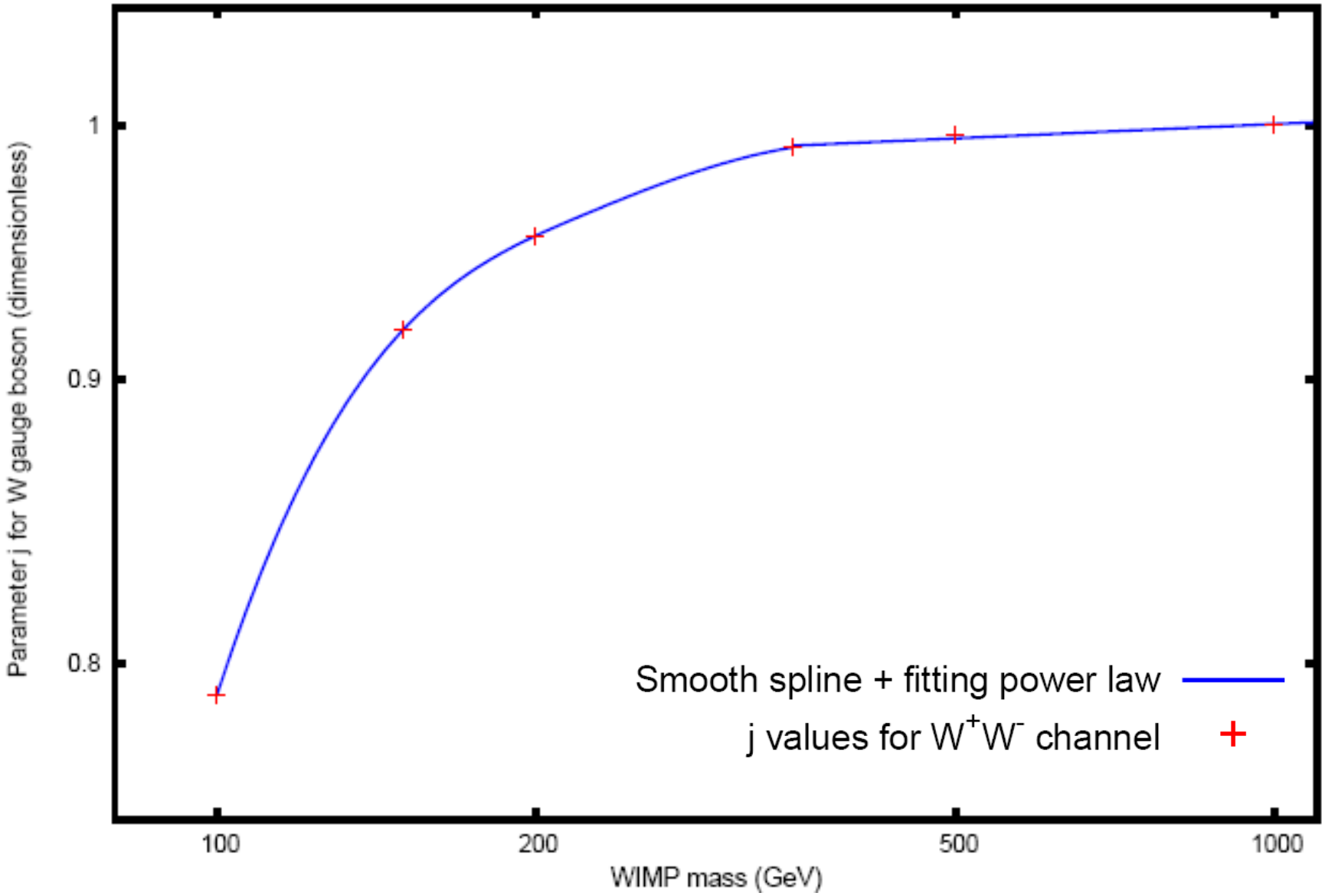

W+W- channel WIMP annihilation, M_{WIMP} = 100 GeV
$x^{1.5}$ d N_γ /d x
E_γ /M_{WIMP}
Total fit
Montecarlo simulation
χ^2 = 110
d.o.f. = 493
1
0.1
0.01
0.001
0.0001
1e-05
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.0001
0.001
0.01
0.1


W+W- channel WIMP annihilation, M_{WIMP} = 200 GeV
$x^{1.5}\, d\, N_\gamma / d\, x$
E_γ / M_{WIMP}
Total fit
Montecarlo simulation
χ^2 = 53.8
d.o.f. = 474
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
0
0.2
0.4
0.6
0.8
1
0.001
0.01
0.1


W+W- channel WIMP annihilation, M_{WIMP} = 350 GeV
$x^{1.5}$ d N_γ/d x
E_γ /M_{WIMP}
Total fit
Montecarlo simulation
χ^2 = 98.5
d.o.f. = 488
1
0.1
0.01
0.001
0.0001
1e-05
0
0.2
0.4
0.6
0.8
1
0.001
0.01
0.1


W+W- channel WIMP annihilation, M_{WIMP} = 1000 GeV
$x^{1.5}\, d\, N_\gamma / d\, x$
E_γ / M_{WIMP}
Total fit
Montecarlo simulation
χ^2 = 78.5
d.o.f. = 593
1
0.1
0.01
0.001
0.0001
1e-05
0
0.2
0.4
0.6
0.8
1
0.001
0.01
0.1

W channel WIMP annihilation, *j* parameter



✓ In general, parameters follow a linear law at high masses and deviate at low masses.

III. Top quark:

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

- One increasing and two decreasing exponential factors.
- Logarithm term also acquires a multiplicative behavior.

NB: Top decay channel is NOT implemented by PYTHIA,
so $t \to W^+ + b$ (BR 98%) was considered.

Prospects: Better simulation for this channel is in progress.

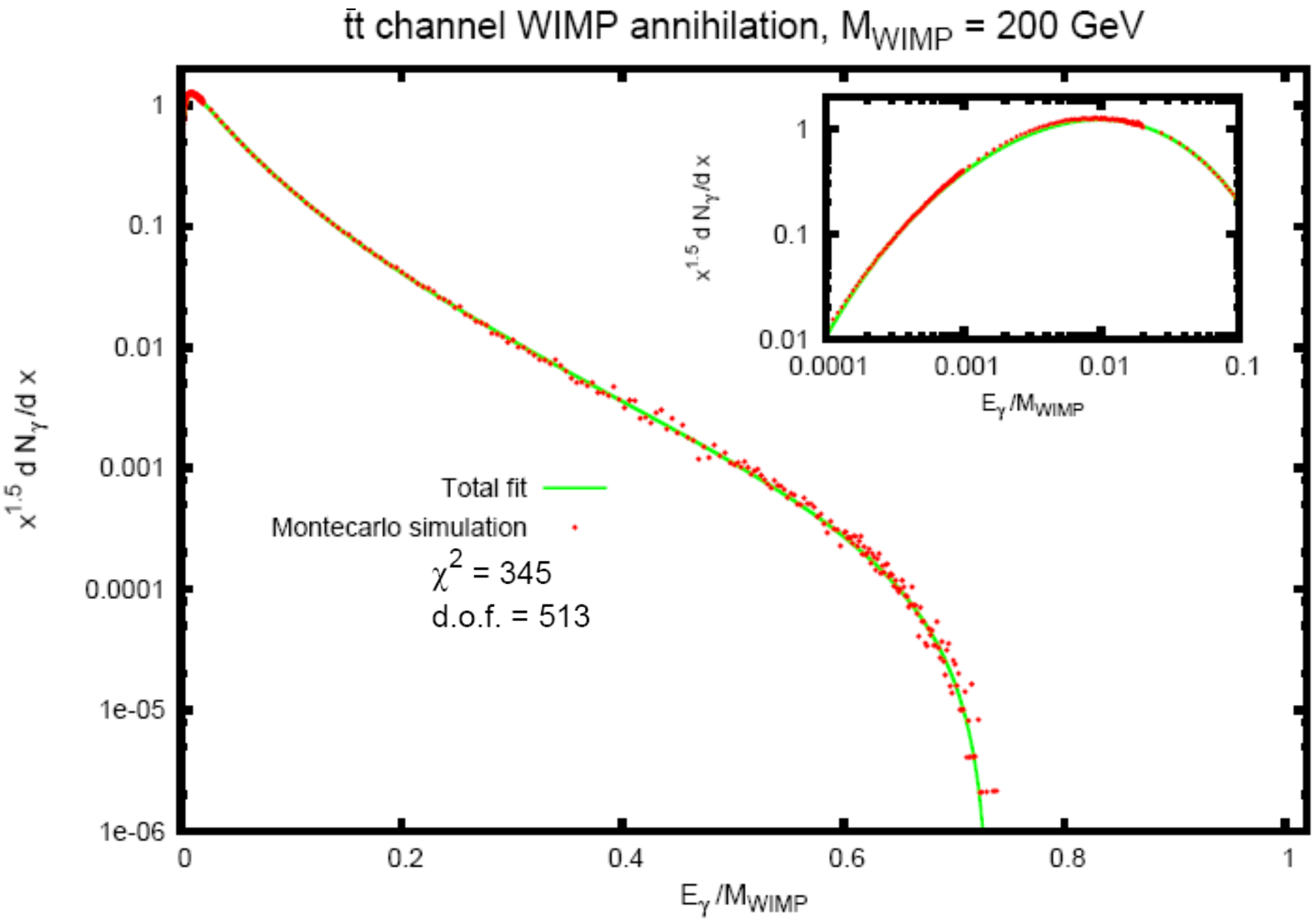
TOP QUARK RESULTS

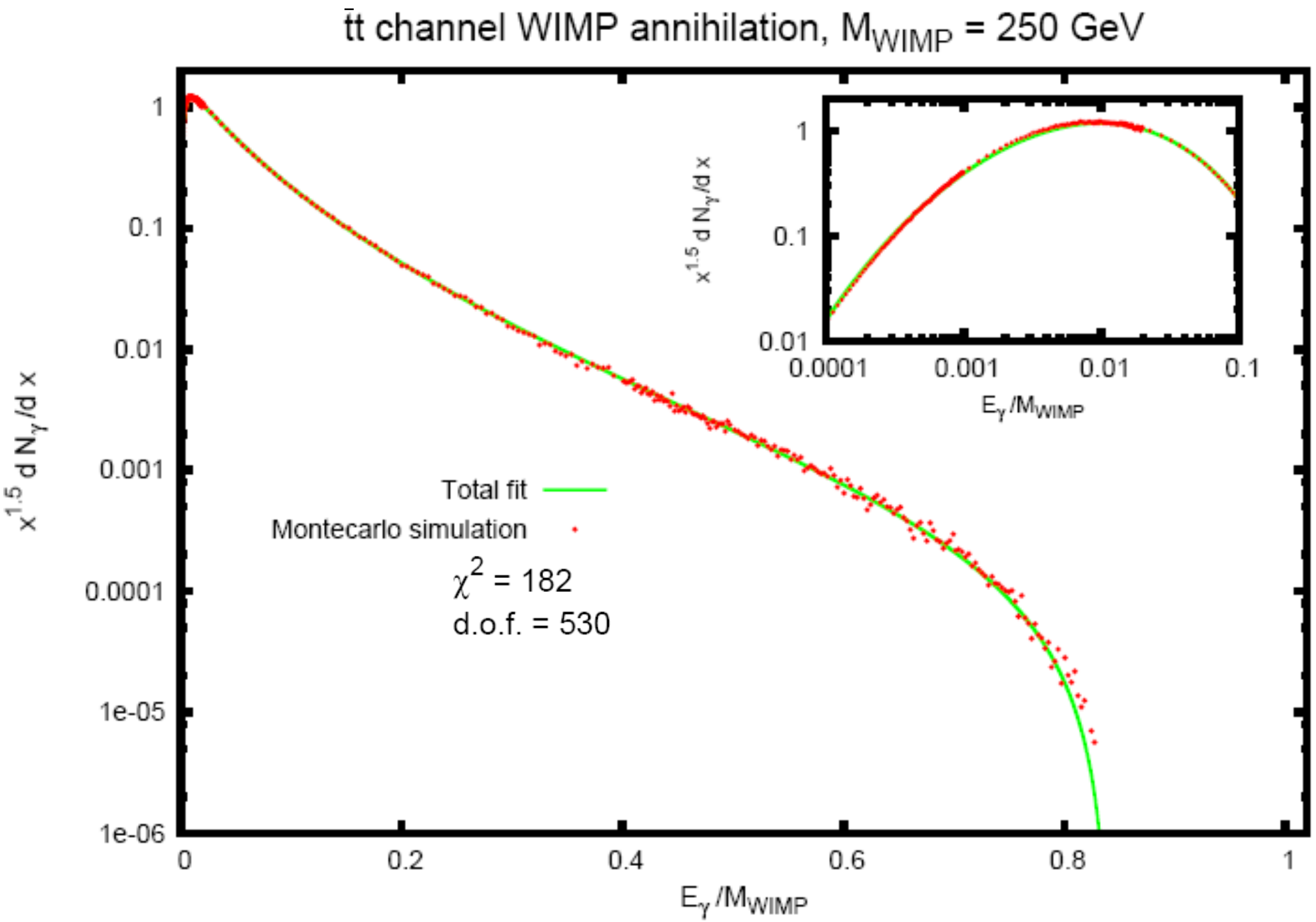
- Four parameters are mass independent.

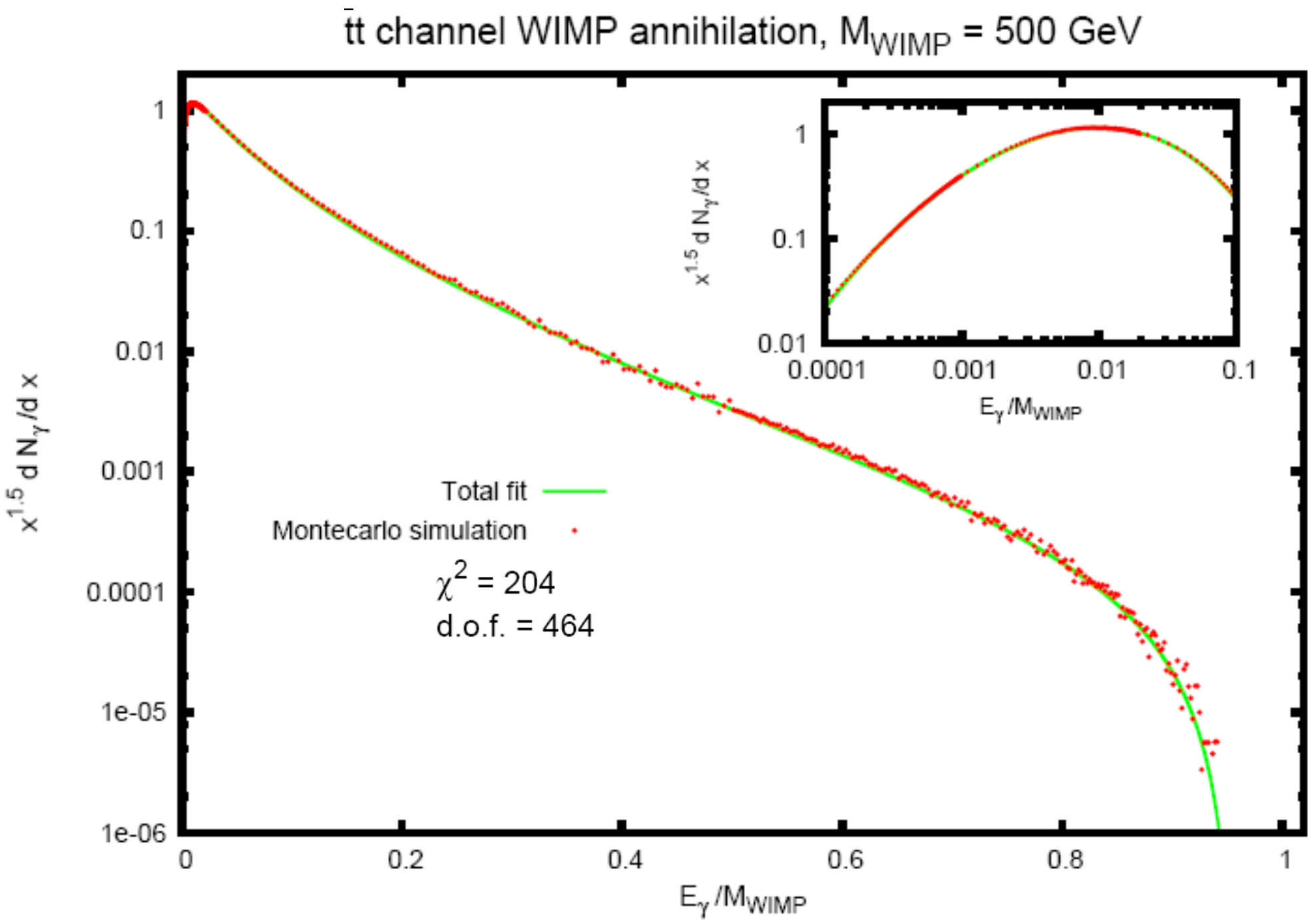
$$a_1 = 290. \ , c_1 = 1.61, d_1 = 0.19 \text{ and } d_2 = 0.8447$$

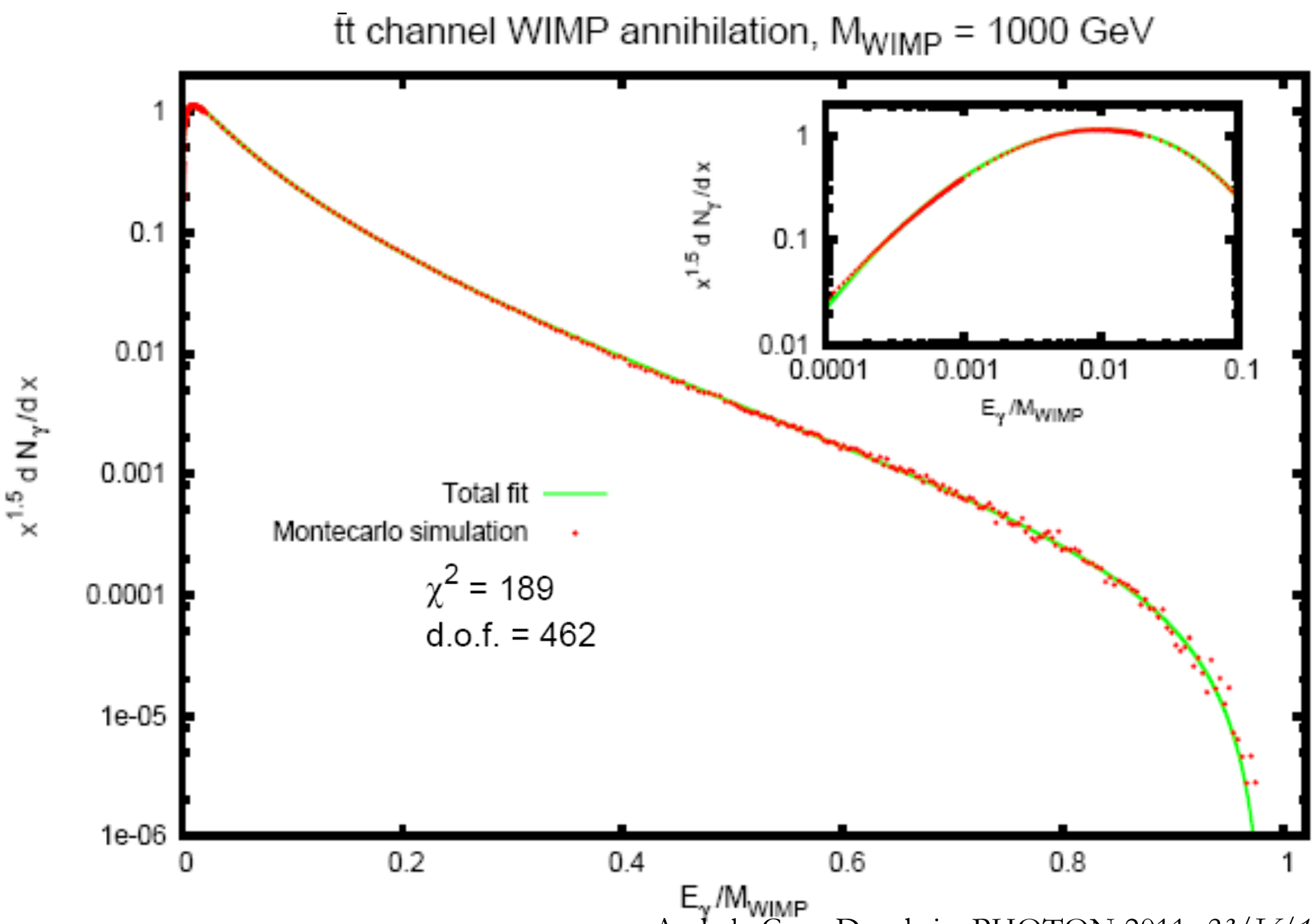
- Six parameters are mass dependent.

WIMP mass (GeV)	b_1	n_1	c_2	p	q	l
200	14.4	0.477	$3.34 \cdot 10^{-4}$	1.34	1.76	4.42
250	13.5	0.457	$1.54 \cdot 10^{-4}$	1.95	1.96	4.14
350	13.0	0.448	$5.99 \cdot 10^{-5}$	3.78	2.32	3.74
500	12.8	0.442	$1.69 \cdot 10^{-5}$	7.40	2.75	3.36
1000	12.4	0.436	$1.80 \cdot 10^{-6}$	30.0	3.85	2.72

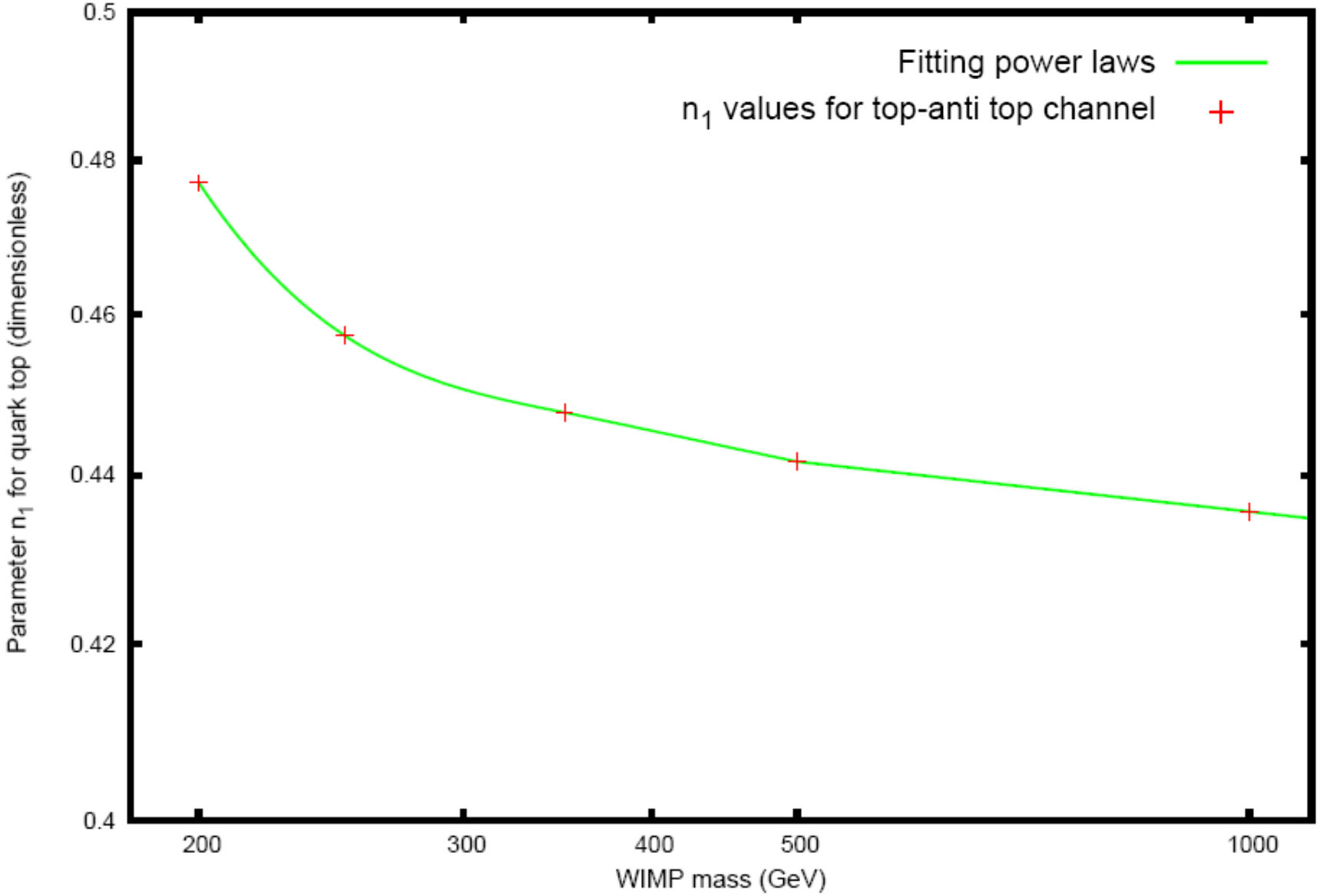

$\bar{t}t$ channel WIMP annihilation, M_{WIMP} = 200 GeV
$x^{1.5}\, d\, N_\gamma / d\, x$
E_γ / M_{WIMP}
Total fit
Montecarlo simulation
χ^2 = 345
d.o.f. = 513
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
0
0.2
0.4
0.6
0.8
1
0.0001
0.001
0.01
0.1


$\bar{t}t$ channel WIMP annihilation, M_{WIMP} = 250 GeV
$x^{1.5}\, d\, N_\gamma / d\, x$
E_γ / M_{WIMP}
Total fit
Montecarlo simulation
χ^2 = 182
d.o.f. = 530
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
0
0.2
0.4
0.6
0.8
1
0.0001
0.001
0.01
0.1

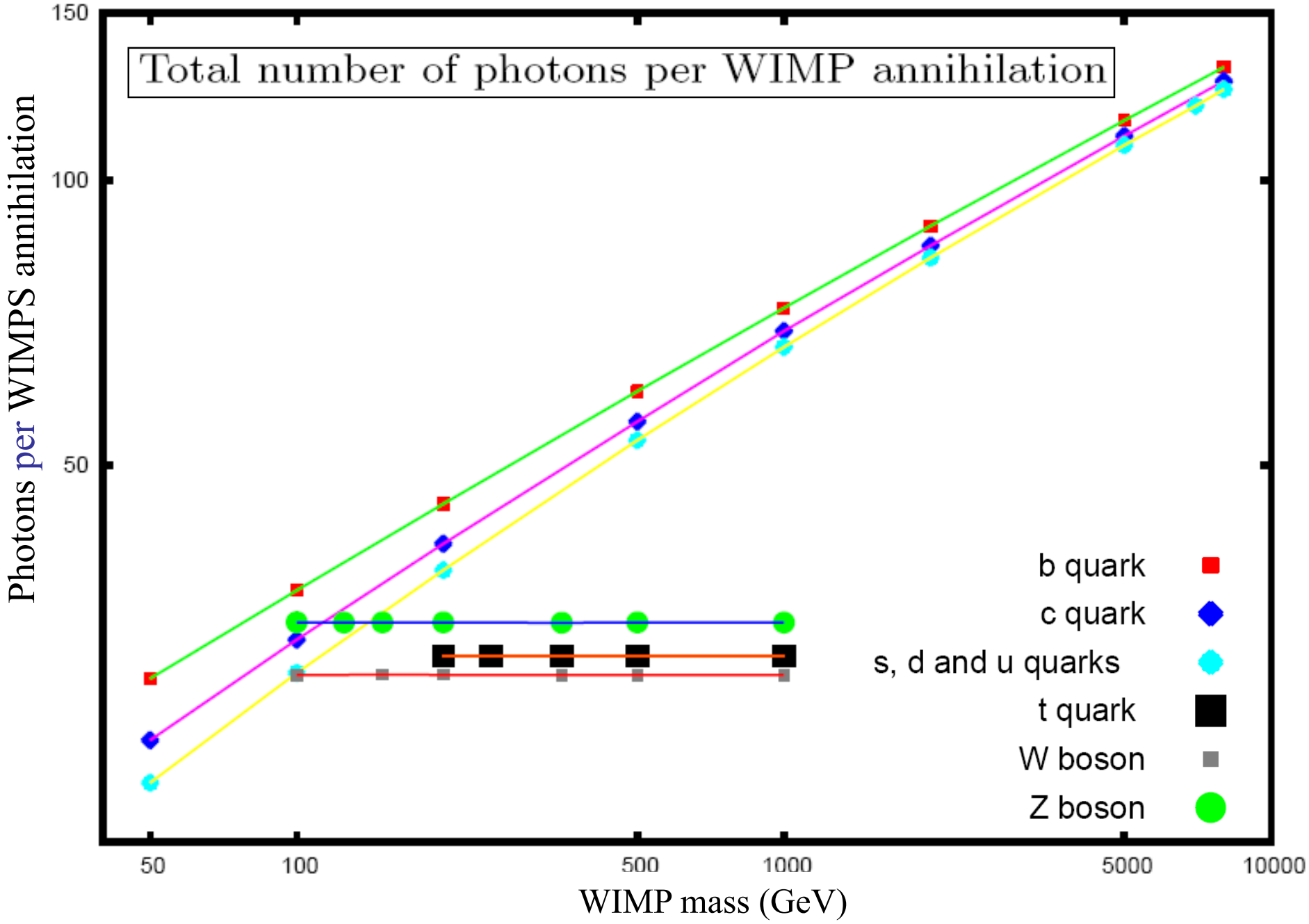

$\bar{t}t$ channel WIMP annihilation, M_{WIMP} = 500 GeV
$x^{1.5}\, d\, N_\gamma / d\, x$
E_γ / M_{WIMP}
Total fit
Montecarlo simulation
χ^2 = 204
d.o.f. = 464
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
0
0.2
0.4
0.6
0.8
1
0.0001
0.001
0.01
0.1


$\bar{t}t$ channel WIMP annihilation, M_{WIMP} = 1000 GeV
$x^{1.5}\, d\, N_\gamma / d\, x$
E_γ / M_{WIMP}
Total fit
Montecarlo simulation
χ^2 = 189
d.o.f. = 462
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
0
0.2
0.4
0.6
0.8
1
0.0001
0.001
0.01
0.1

t channel WIMP annihilation, n_1 parameter



✓ In general, parameters follow a linear law at high masses and deviate at low masses.


Total number of photons per WIMP annihilation
Photons per WIMPS annihilation
150
100
50
50
100
500
1000
5000
10000
WIMP mass (GeV)
b quark
c quark
s, d and u quarks
t quark
W boson
Z boson

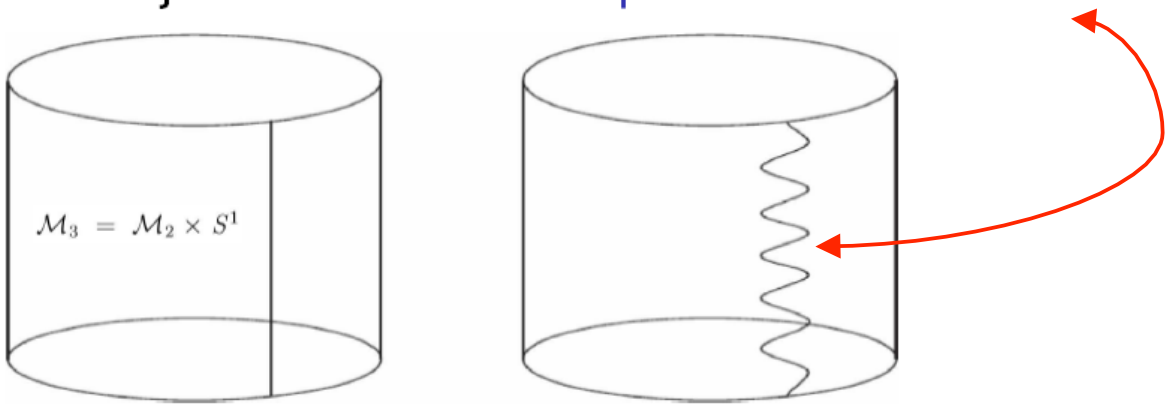
CHANNELS SUMMARY

Channel	Fix parameters	Mass dependent parameters	Fit mass range (GeV)
W^+W^-	3	5	$100 \leq M \leq 10^5$
ZZ	3	5	$100 \leq M \leq 10^5$
$t\bar{t}$	4	6	$200 \leq M \leq 10^5$
$\tau^+\tau^-$	9	2	$25 \leq M \leq 5 \cdot 10^4$
$\mu^+\mu^-$	-	3	$25 \leq M \leq 5 \cdot 10^4$
$u\bar{u}$	4	5	$50 \leq M \leq 8000$
$d\bar{d}$	6	5	$50 \leq M \leq 5000$
$s\bar{s}$	5	4	$50 \leq M \leq 7000$
$c\bar{c}$	4	5	$50 \leq M \leq 8000$
$b\bar{b}$	5	6	$50 \leq M \leq 8000$

III. BRANE-WORLD THEORIES

- Simple model depending on: brane tension f and mass M.

- No rigid relativistic object $\Rightarrow$ the 3-brane present **branons**.



- D dimensional bulk space $\mathcal{M}_D$, assumed $\mathcal{M}_D = \mathcal{M}_4 \times B$.

- Gravity propagates in the total space whereas SM fields are restricted to propagate in the brane.

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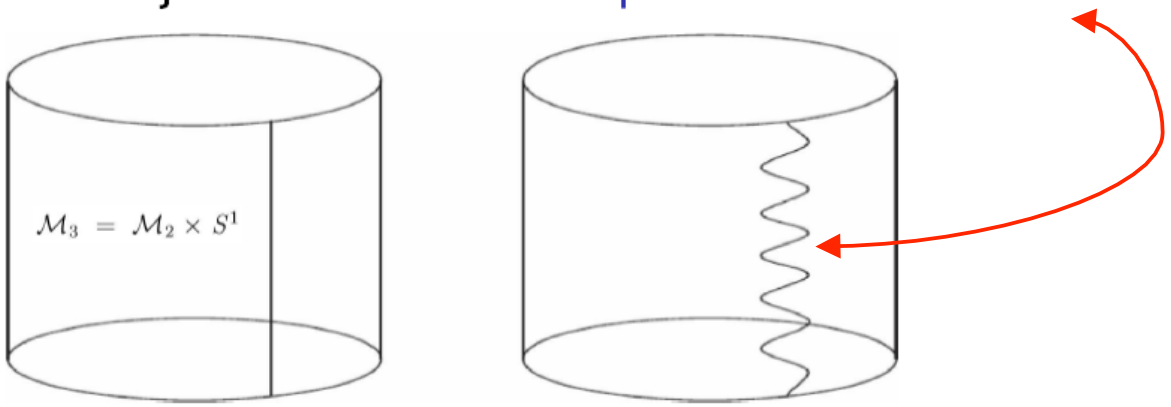

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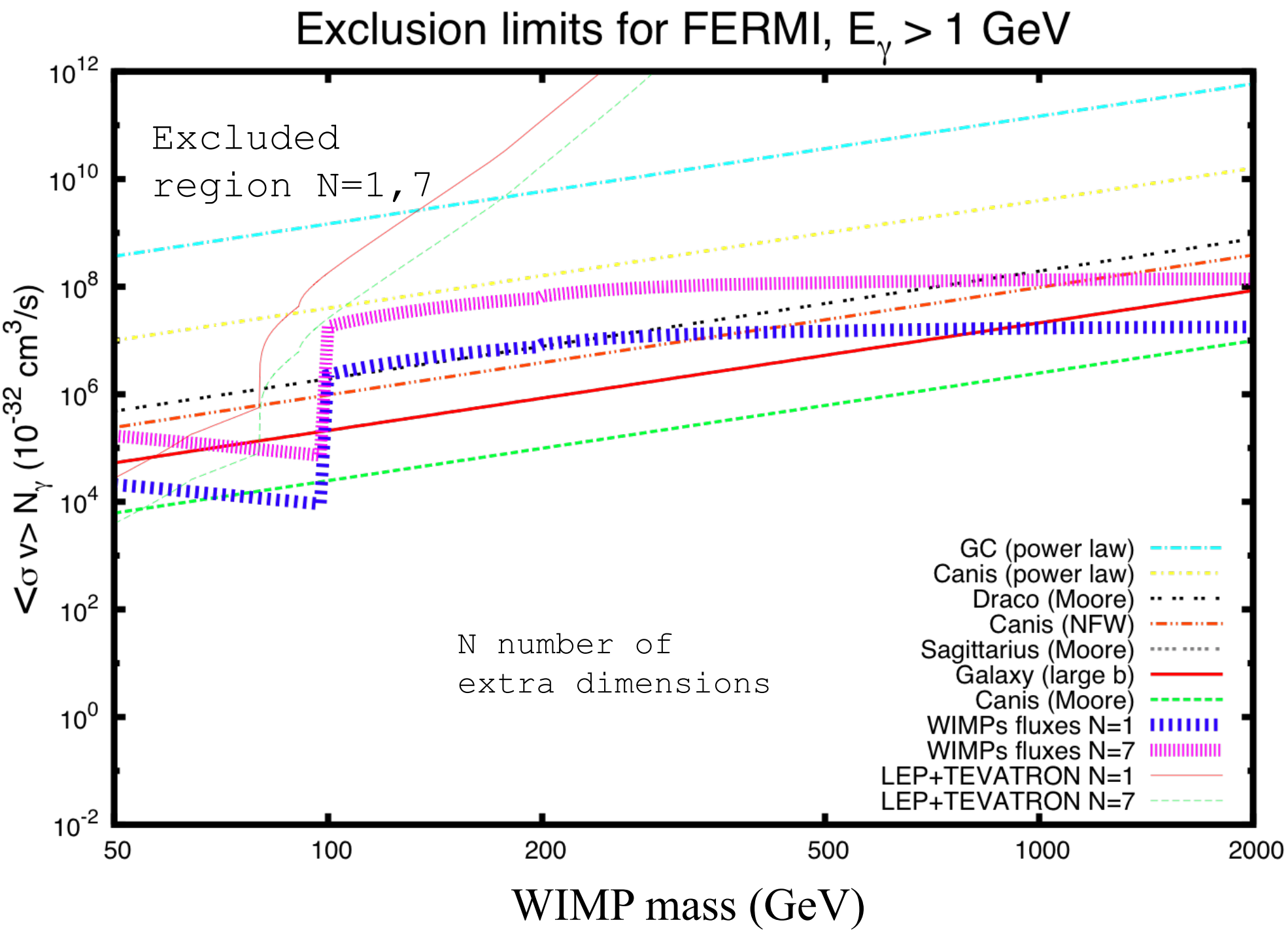
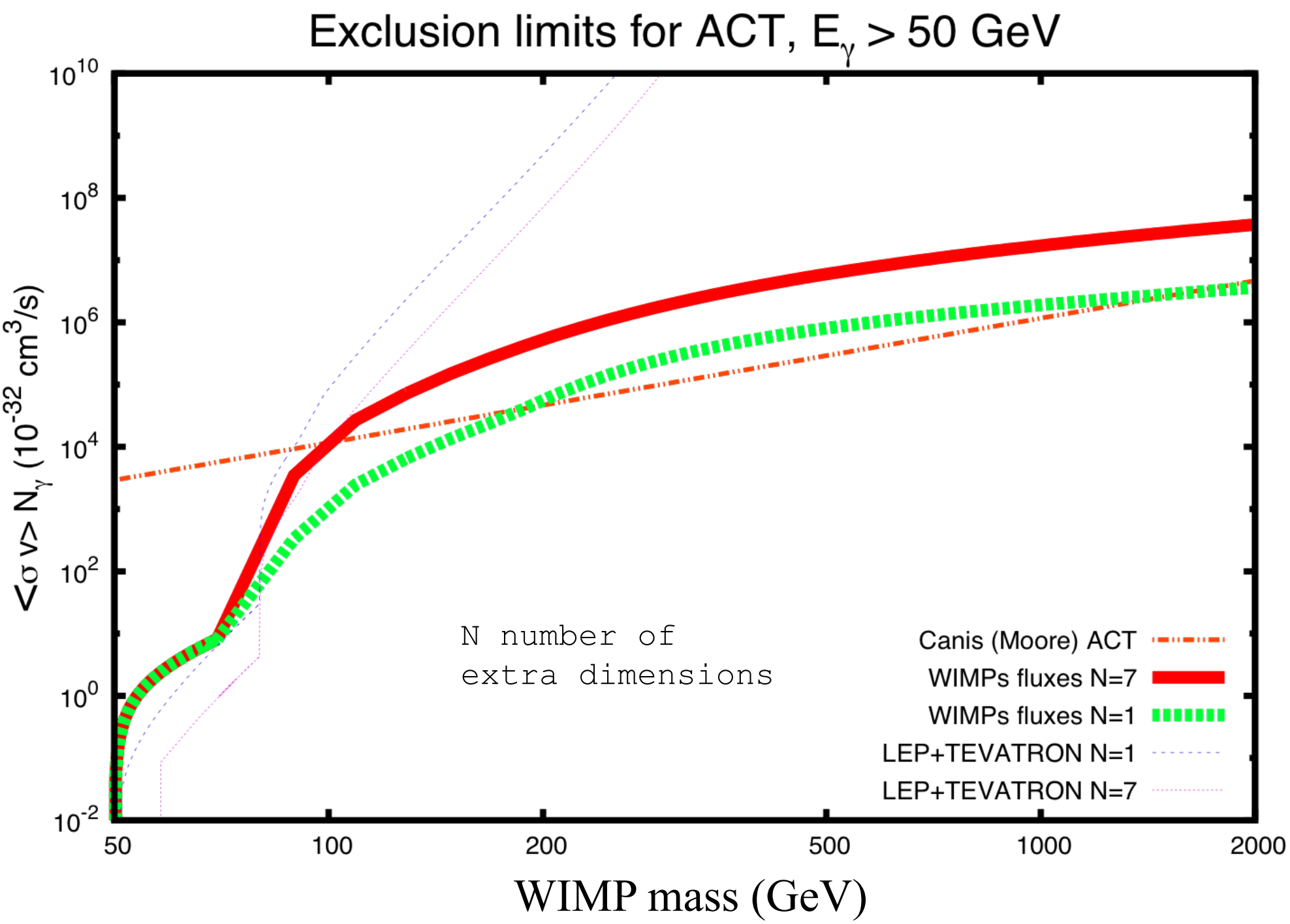
✓ Branons may behave as WIMPs, so our research is applicable.


Exclusion limits for FERMI, $E_\gamma > 1$ GeV
Excluded
region N=1,7
N number of
extra dimensions
$<\sigma v> N_\gamma$ (10^{-32} cm^3/s)
WIMP mass (GeV)
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
50
100
200
500
1000
2000
GC (power law)
Canis (power law)
Draco (Moore)
Canis (NFW)
Sagittarius (Moore)
Galaxy (large b)
Canis (Moore)
WIMPs fluxes N=1
WIMPs fluxes N=7
LEP+TEVATRON N=1
LEP+TEVATRON N=7


Exclusion limits for ACT, $E_\gamma > 50$ GeV
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
$\langle\sigma v\rangle N_\gamma$ (10^{-32} cm^3/s)
50
100
200
500
1000
2000
WIMP mass (GeV)
N number of
extra dimensions
Canis (Moore) ACT
WIMPs fluxes N=7
WIMPs fluxes N=1
LEP+TEVATRON N=1
LEP+TEVATRON N=7

IV. CONCLUSIONS

- Gamma rays spectra for WIMP annihilation into Standard Model particles (*W* and *Z* bosons, quarks and leptons) obtained in a wide range of masses.
- **THREE** fitting formulae for different channels have been proposed: *W* and *Z*, *top* quark and the rest of quarks+leptons.
- SPECTRA energy (MASS) dependence has been studied for each channel.
- Channel relevance in photon production can be established by studying total fluxes for each channel.
- Presented results may be useful if for some WIMP DM candidates, DarkSusy-like packages are not available.
- Fitting functions available at

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

Spanish Relativity Meeting ERE2011

29 August – 2 September 2011,
Universidad Complutense de Madrid, SPAIN

http://teorica.fis.ucm.es/ERE2011/