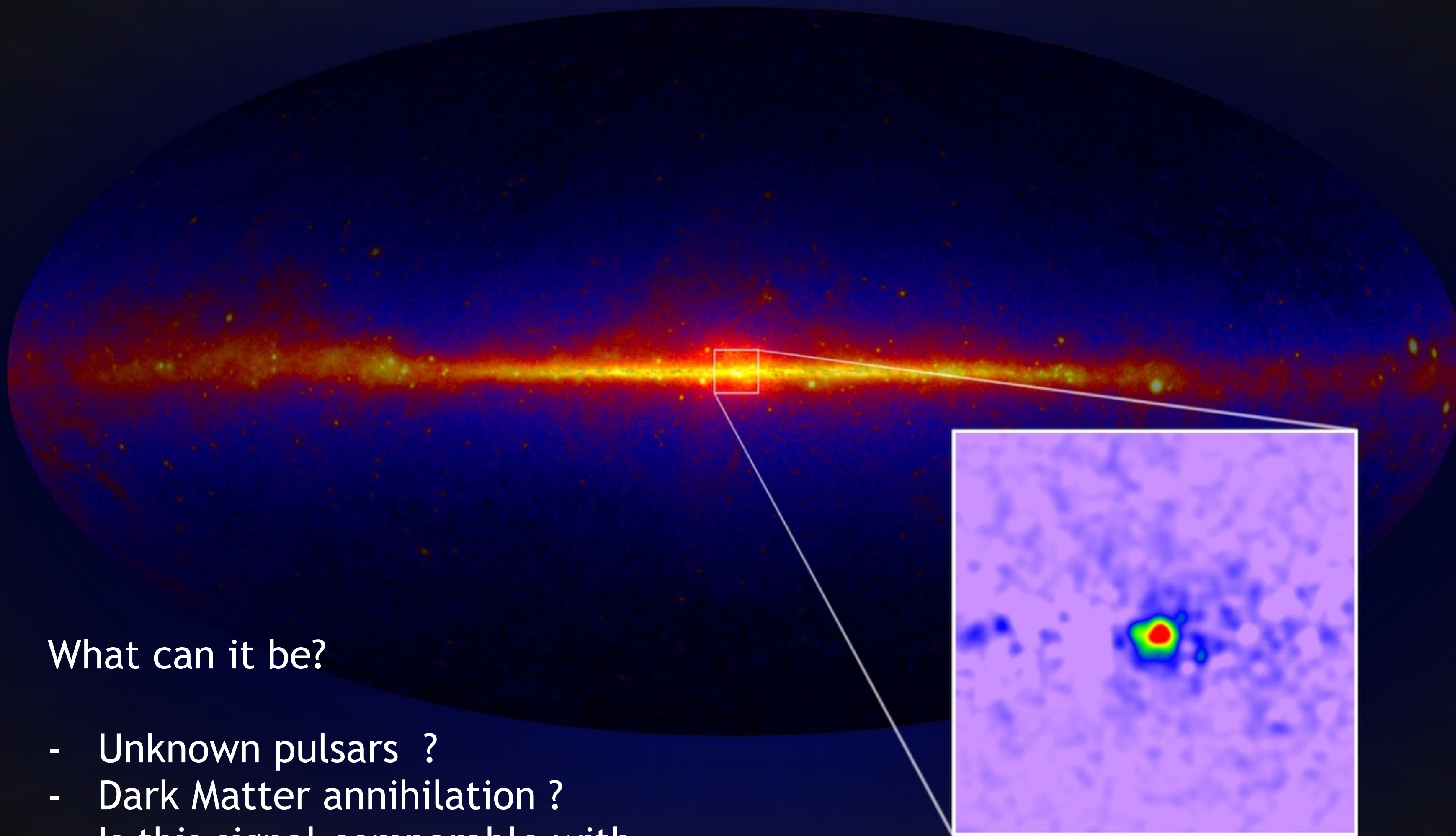
# A description of the Galactic Center excess in the minimal Supersymmetric Standard Modell (MSSM)

EPS HEP conference Vienna 2015

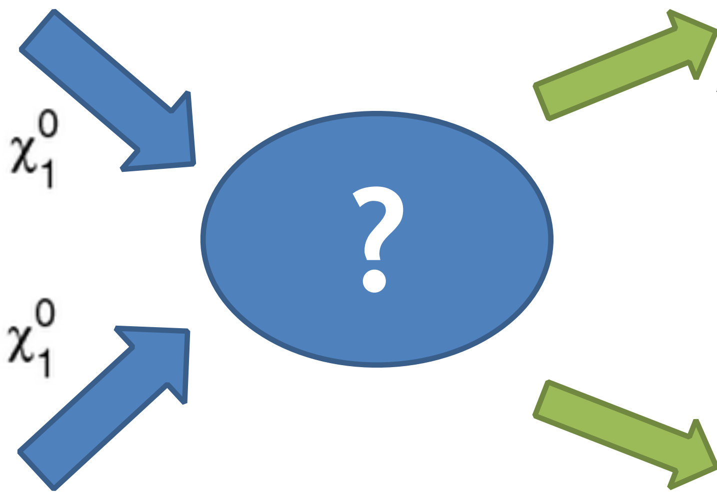
Sascha Caron
(Nikhef and RU Nijmegen)



What can it be?

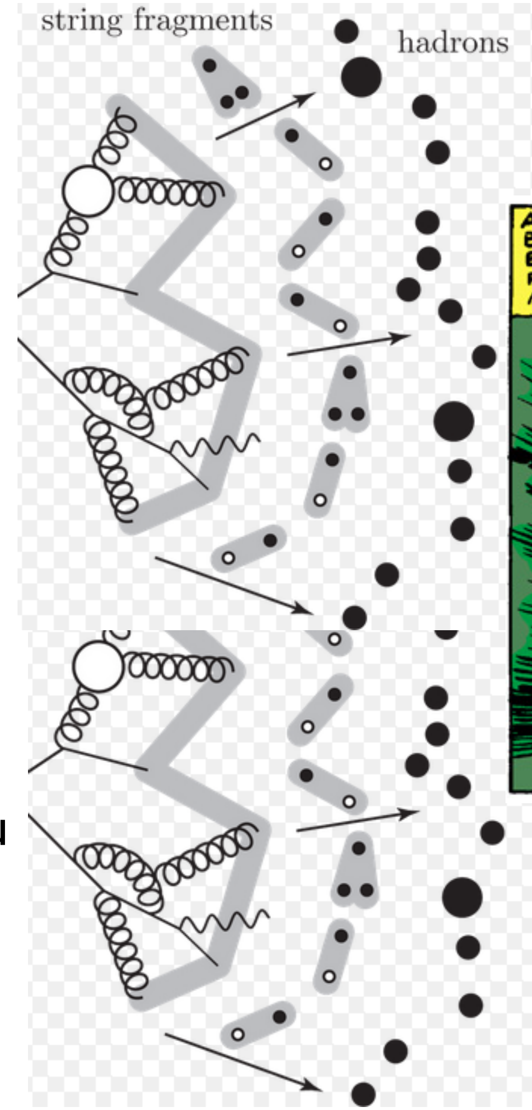
- Unknown pulsars ?
- Dark Matter annihilation ?
- Is this signal comparable with Supersymmetry?
- Something else ?

# DM Signal Modelling



q
tau
?

q
tau
?




Pi0 => gamma gamma


Pi0 => gamma gamma

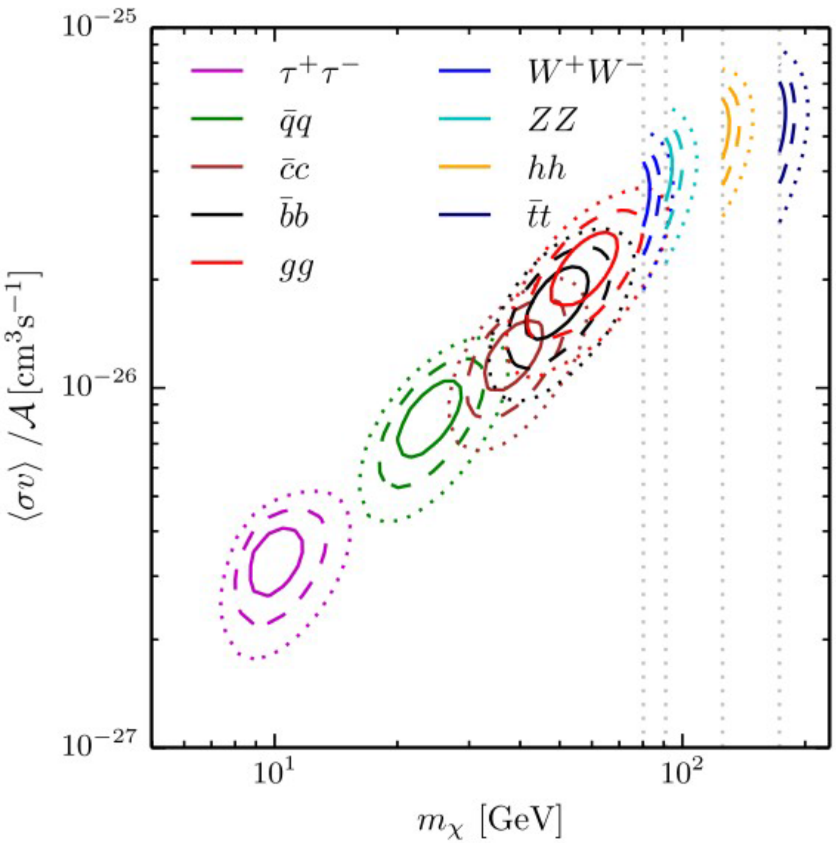
# Model building

- In (earlier days) it seemed to be that the signal could be described by **DM DM => bb or tautau** with a DM mass of **20-40 GeV** => Pythia spectrum nicely in agreement with data
- Such process are **not** possible within ‘minimal SUSY’ models due to limits on staus and sbottoms

*(need to be in nMSSM etc., such DM particles hard to test at LHC since they need to be mixed such that they have escaped detection e.g. at LEP)*

- It seems to be that such processes have also difficulties from recent dwarf limits on DM => gamma rays also;: P. Agrawal, B. Batell, P. J. Fox, and R. Harnik, WIMPs at the Galactic Center, arXiv:1411.2592.

# Model building




| Channel | $\langle \sigma v \rangle$ ($10^{-26}$ cm$^3$ s$^{-1}$) | $m_\chi$ (GeV) | $\chi^2_{\min}$ | $p$-value |
|---|---|---|---|---|
| $\bar{q}q$ | $0.83^{+0.15}_{-0.13}$ | $23.8^{+3.2}_{-2.6}$ | 26.7 | 0.22 |
| $\bar{c}c$ | $1.24^{+0.15}_{-0.15}$ | $38.2^{+4.7}_{-3.9}$ | 23.6 | 0.37 |
| $\bar{b}b$ | $1.75^{+0.28}_{-0.26}$ | $48.7^{+6.4}_{-5.2}$ | 23.9 | 0.35 |
| $\bar{t}t$ | $5.8^{+0.8}_{-0.8}$ | $173.3^{+2.8}_{-0}$ | 43.9 | 0.003 |
| $gg$ | $2.16^{+0.35}_{-0.32}$ | $57.5^{+7.5}_{-6.3}$ | 24.5 | 0.32 |
| $W^+W^-$ | $3.52^{+0.48}_{-0.48}$ | $80.4^{+1.3}_{-0}$ | 36.7 | 0.026 |
| $ZZ$ | $4.12^{+0.55}_{-0.55}$ | $91.2^{+1.53}_{-0}$ | 35.3 | 0.036 |
| $hh$ | $5.33^{+0.68}_{-0.68}$ | $125.7^{+3.1}_{-0}$ | 29.5 | 0.13 |
| $\tau^+\tau^-$ | $0.337^{+0.047}_{-0.048}$ | $9.96^{+1.05}_{-0.91}$ | 33.5 | 0.055 |
| [ $\mu^+\mu^-$ | $1.57^{+0.23}_{-0.23}$ | $5.23^{+0.22}_{-0.27}$ | 43.9 | 0.0036]$_{\text{ICS}}$ |

- Actually a bit more parameter space seems to be allowed

Following slides based on

## A description of the Galactic Center excess in the Minimal Supersymmetric Standard Model

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Abraham Achterberg,[a] Simone Amoroso,[e] Sascha Caron,[a,b] Luc Hendriks,[a] Roberto Ruiz de Austri,[c] Christoph Weniger[d]

arXiv:1502.05703
accepted by JCAP

# Energy Calibration

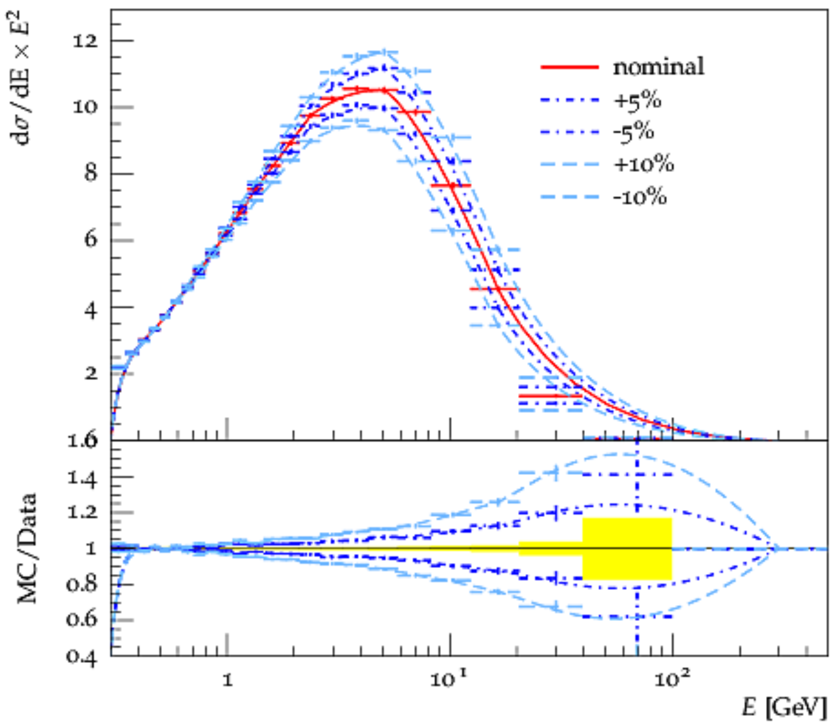
- http://arxiv.org/pdf/1206.1896v2.pdf

- **9% shift measured** in test beams not yet understood
**- 2-5% shift measured** in range 6-13 GeV with

- Fermi-LAT conclusion:
"Based on the full body of information currently available
 we conclude that that the energy scale for the
LAT is correct to +20- 50%
of the energy
resolution of the LAT at a given energy. This corresponds
to an uncertainty of 2-5%
on energy scale over the range 10-100 GeV, and
increases to 4-10%
below 100 MeV and above 300 GeV."

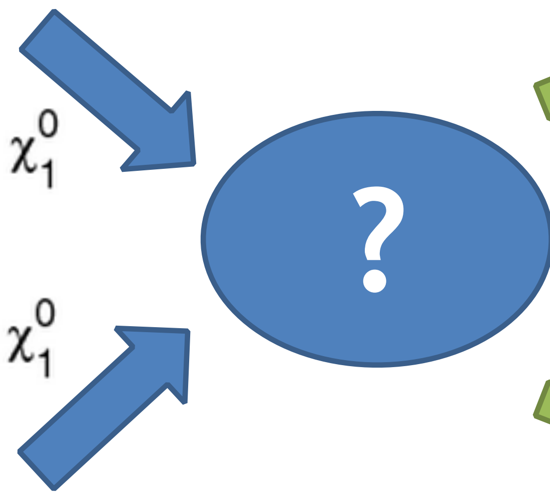
==> So assuming 5% for the unmeasured region at 3-4 GeV seems reasonable.

→ We derived effect on energy spectrum, shape changes by up to 20%




→ Shape uncertainty 3-10%

# DM Signal Modelling




q
tau
?

q
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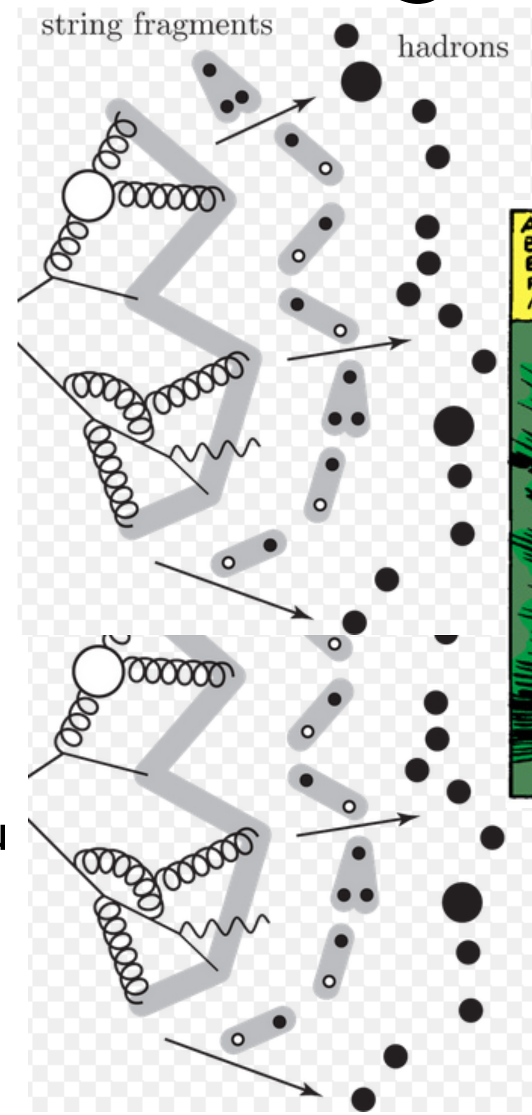
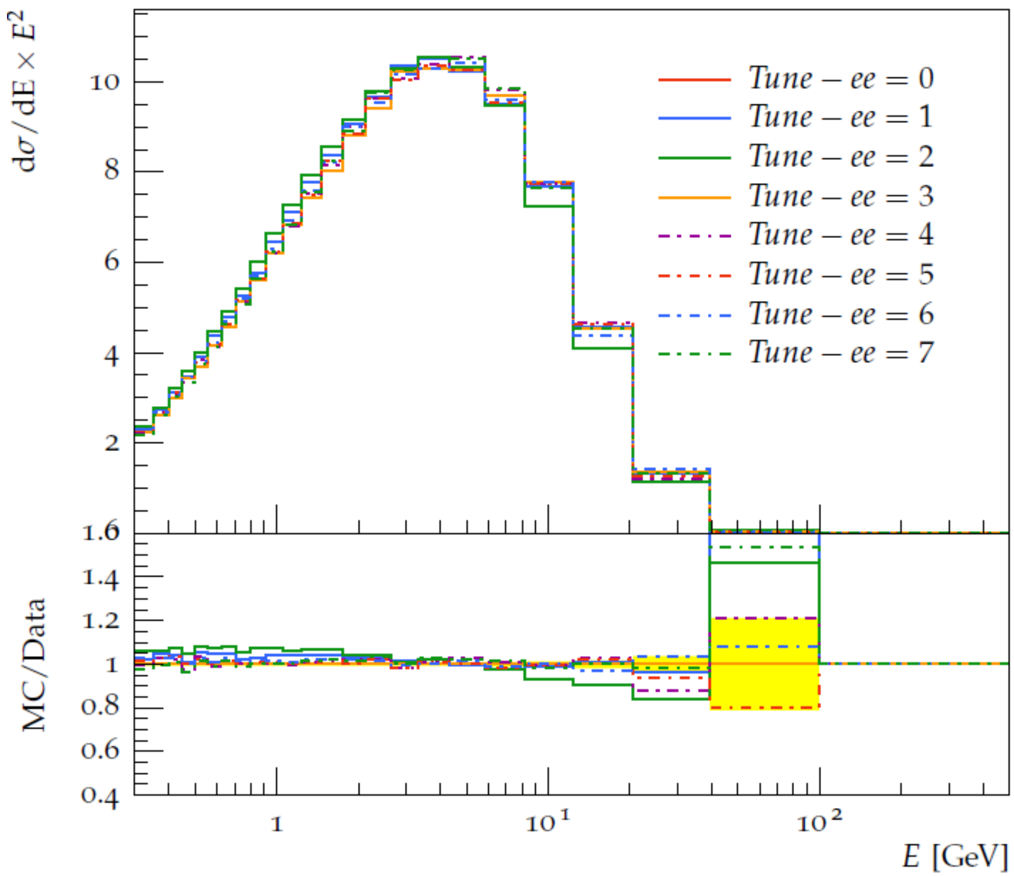
?




Pi0 => gamma gamma


Pi0 => gamma gamma

# Signal Modelling




Minimal modelling again uncertainty 5-10% !

Tunes from here:

http://home.thep.lu.se/~torbjorn/pythia81html/Welcome.html

# Signal Modelling

Adding both effects (MC modelling
and energy scale) in squares yields

a minimal modelling
uncertainty (outside Astronomical uncertainties)
of 8-15%

Changing e.g. only the shape from nominal E to -5% * E
changes p-value for fit from 0.035 to 0.09

# Is there really no minimal Supersymmetry solution ?

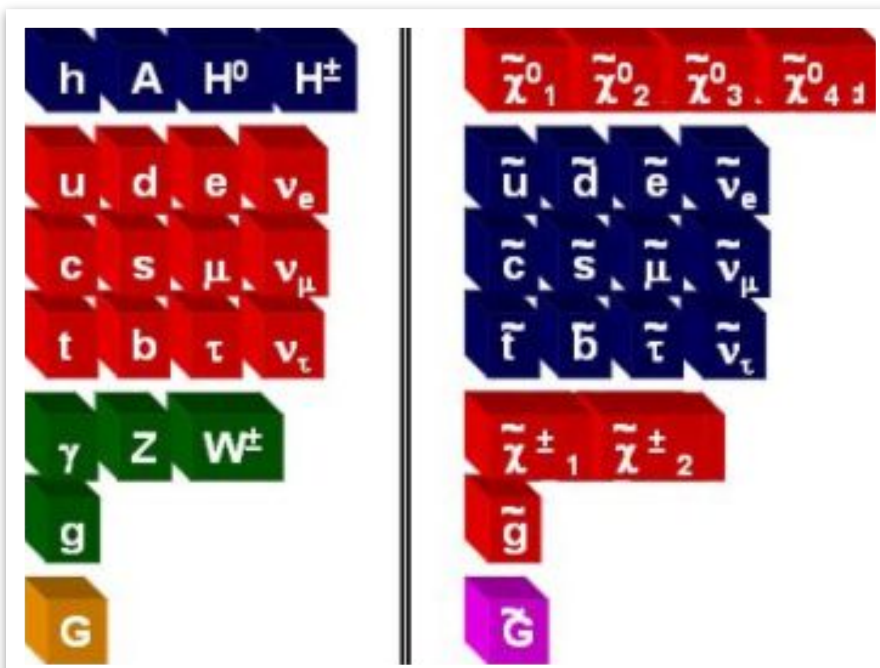
# The Minimal SUSY SM

Remember: This is for almost everybody the most general version you know (105 parameters)….

We are just assuming this:

The MSSM is still the most promising framework for WIMP dark matter.

It is the first to study in my mind.



# Scanning ? How?

- How to search for a solution?

- => Try random sampling
- => Found no solution…

- Tried something more sophisticated… here particle filtering…

# What do we exactly do ?

- Use full machinery of SUSY codes, i.e. Suspect, MicroMegas, DarkSUSY, etc.
- Lightest Neutralino is required to be DM candidate
- LEP limits on the mass of the lightest chargino
- 122 GeV < **mass(Higgs)** < 128 GeV

  (allowing for SUSY code uncertainty of 3 GeV)

- Upper limits from the **LUX** experiment on the spin-independent cross section.
- Upper limits from the **IceCube** experiment with the 79 string configuration on the spin-dependent cross section , assuming that neutralinos annihilate exclusively to W+W- pairs.

# GC chi2 test

We train the particle filter **only** with the chi2 which compares the GC data with the generated GC spectrum

$$\chi^2 = \sum_{i,j} (d_i - m_i)(\Sigma_{ij})^{-1}(d_j - m_j)$$

We adopt here the results from Calore,Cholis,Weniger where the excess emission was studied at latitudes above 2 degree.

[arXiv:1409.0042].

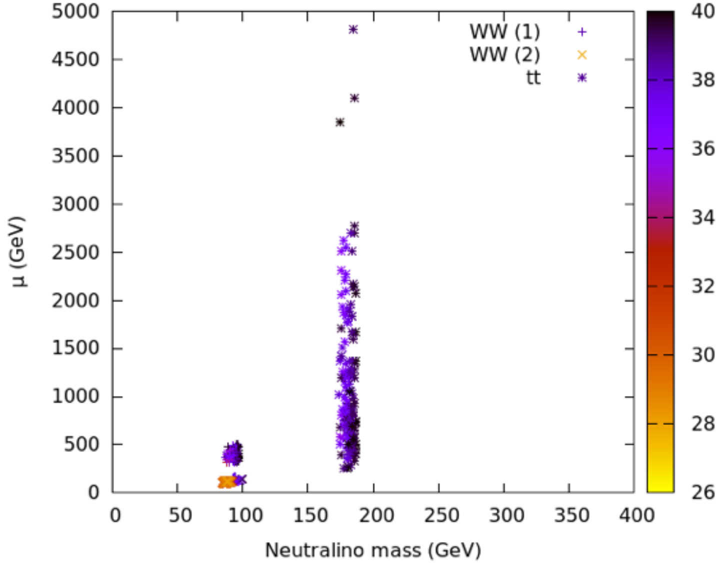
$\Sigma_{ij}$ is the covariance matrix with statistical and systematic uncertainties

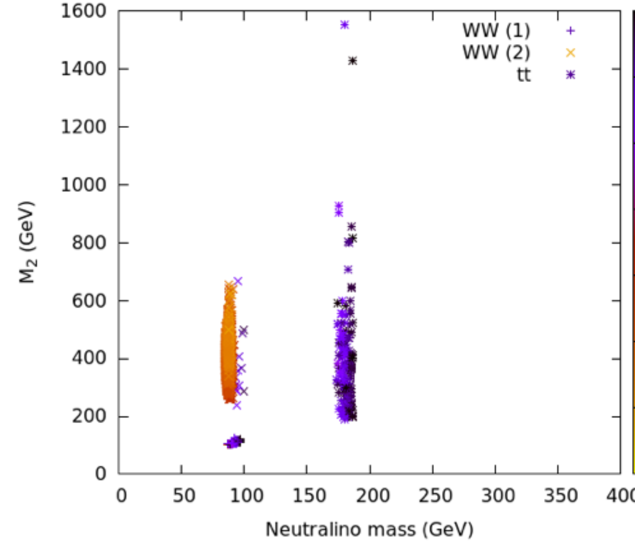
Includes the "highly correlated" Astro uncertainties **+ 10% additional uncertainty for modelling the spectrum (see before)**

*After finding first good fits we constrain the parameter space further to the relevant parameters:*

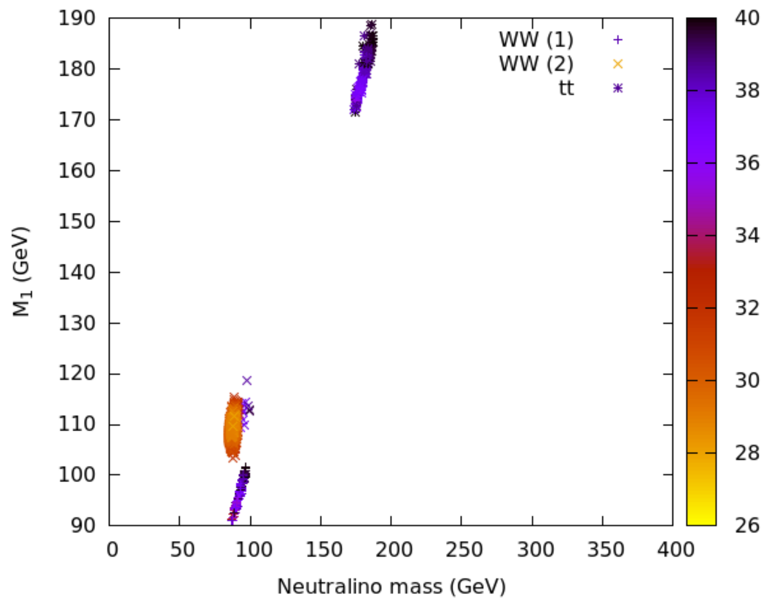
$$M_1, M_2, \mu, \tan\beta, M_A, \tilde{d}_3, \tilde{Q}_3, A_t.$$

# Solutions…

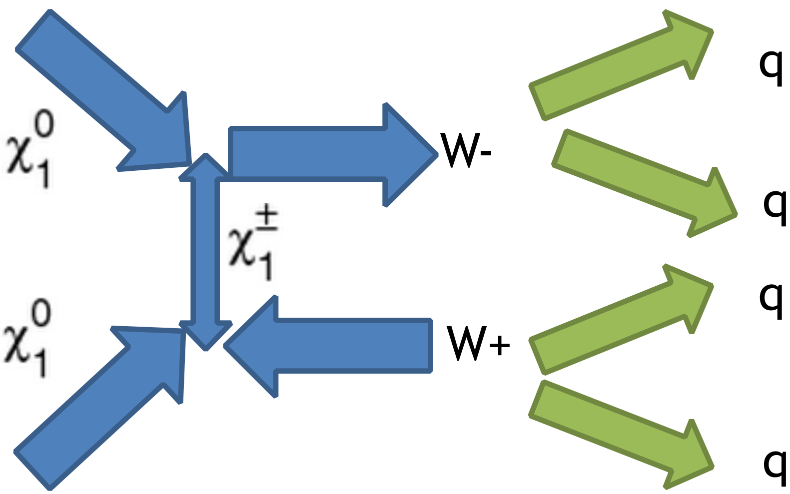


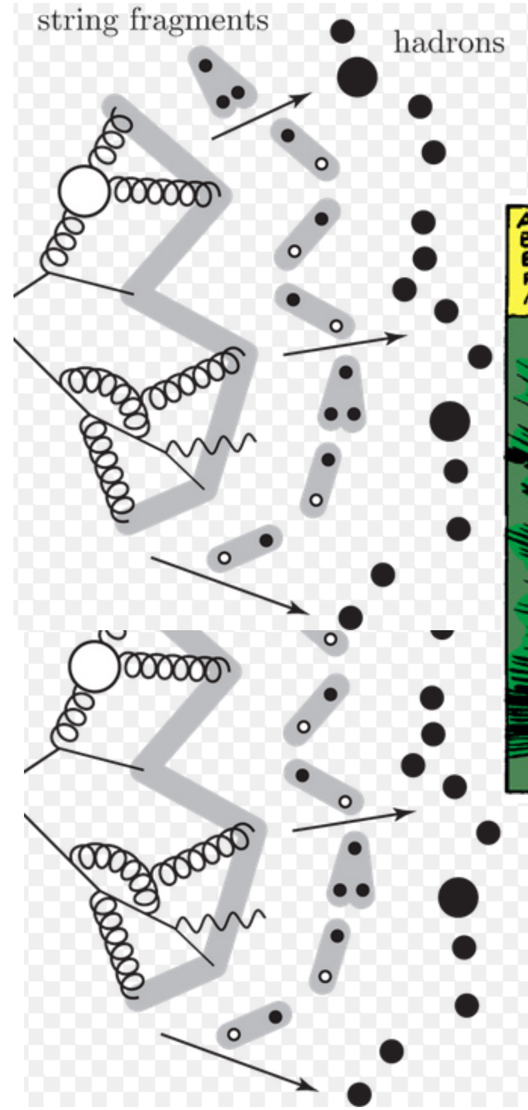




24 degrees of freedom

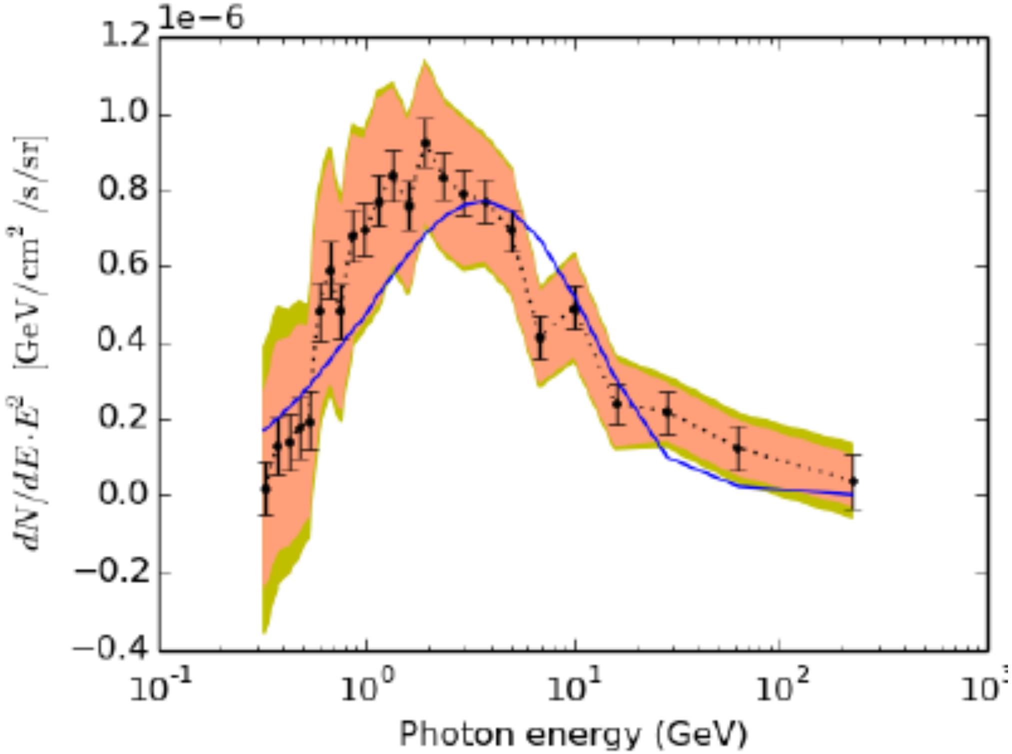


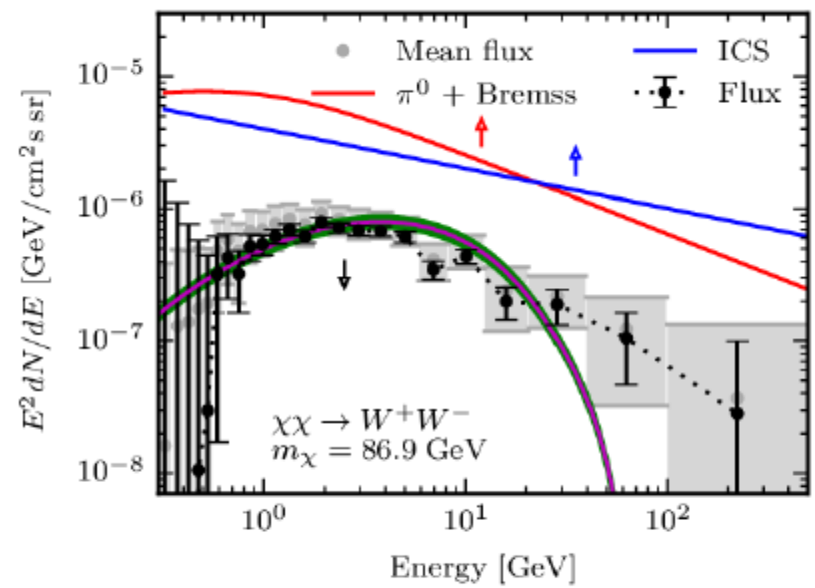
# Signal Modelling




# Signal Modelling




Shown are only Astronomy uncertainties which are highly correlated.

➔ P-value of this fit : **0.3-0.4**

# 3 solutions

**A) Maximum P-value = 0.35:** A Bino-Higgsino neutralino with mass 84-92 GeV as DM annihilating into W+W-

**B) Maximum P-value ≈ 0.13:** A Bino-Wino-Higgsino neutralino with mass 85-100 GeV as DM annihilating into W+W-

**C) Maximum P-value ≈ 0.05**: A (mainly) Bino neutralino with mass about 170-200 GeV as DM annihilating into top pairs

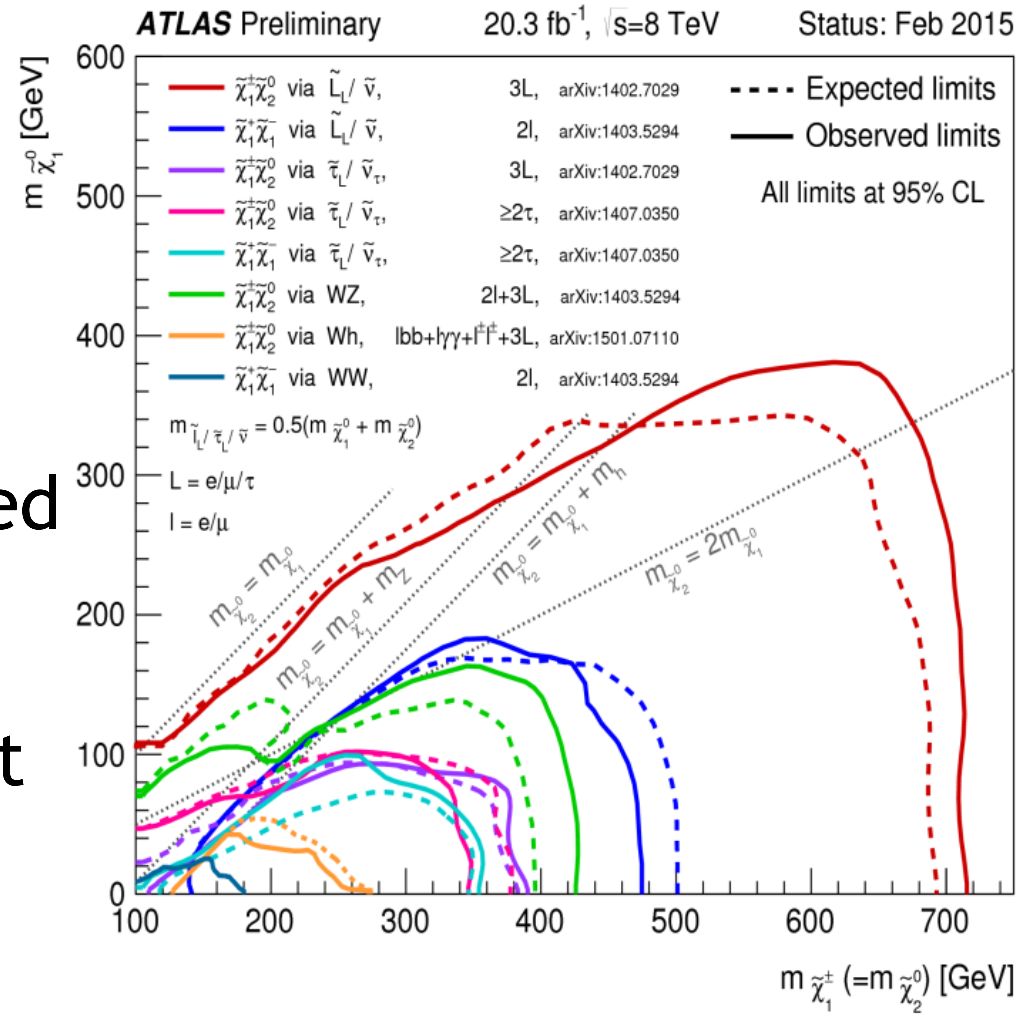
Already excluded by run-1 LHC searches?

# Not excluded so far…

Carefully checked all 3 solutions !

None of them is excluded by LHC

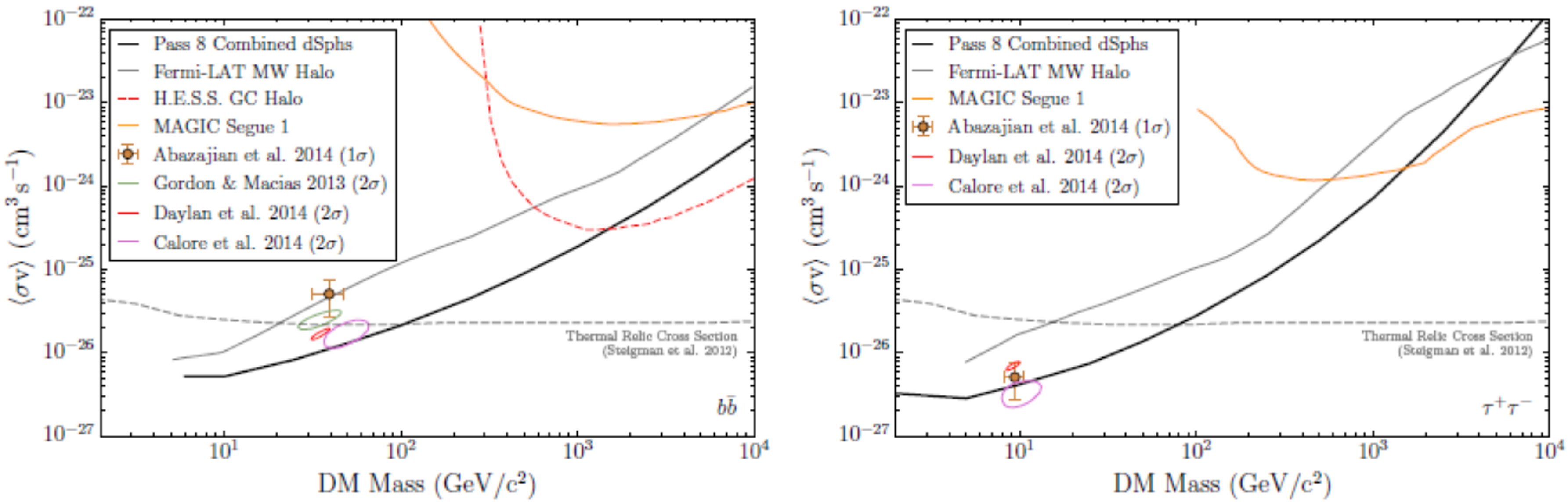
Solutions also consistent with all precision measurements



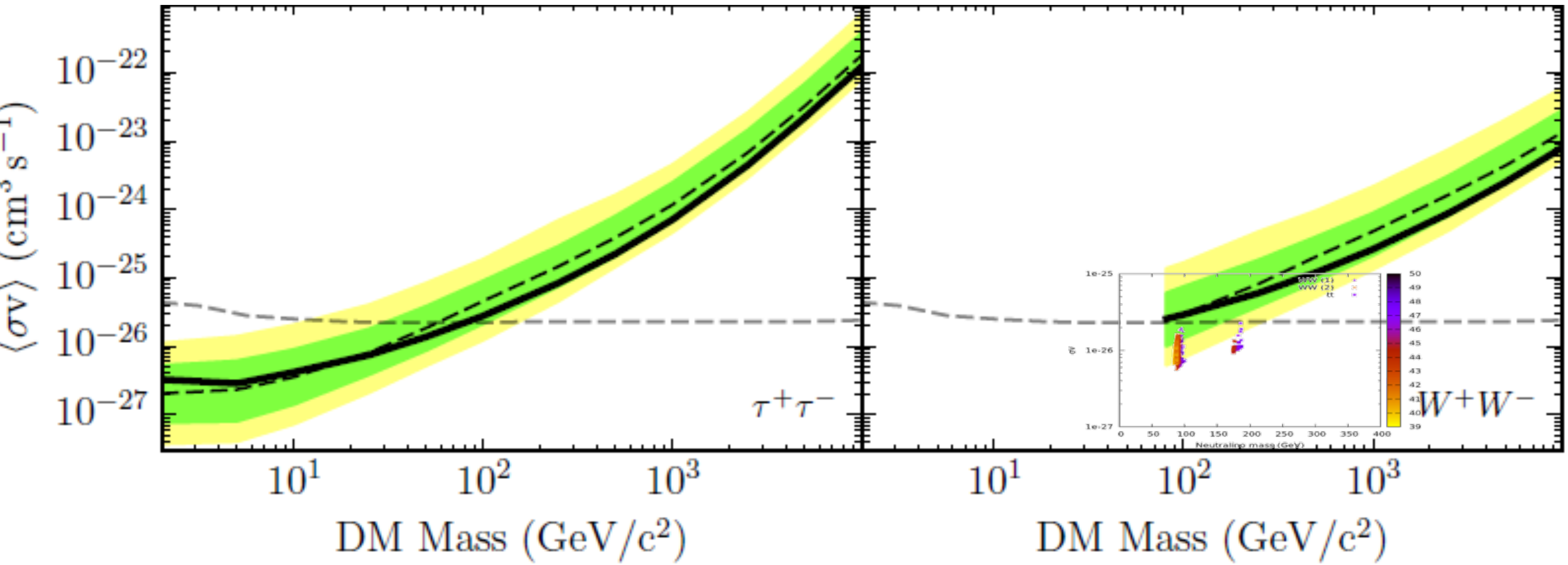
# Let’s look at more properties

# Fermi-LAT vs dwarf galaxies…

## New 6 years limits from 15 dSphs




http://arxiv.org/pdf/1503.02641v1.pdf




. 8. DM annihilation cross-section constraints derived from the combined 15-dSph analysis for various channel

solutions not excluded…

# Relic Density MSSM

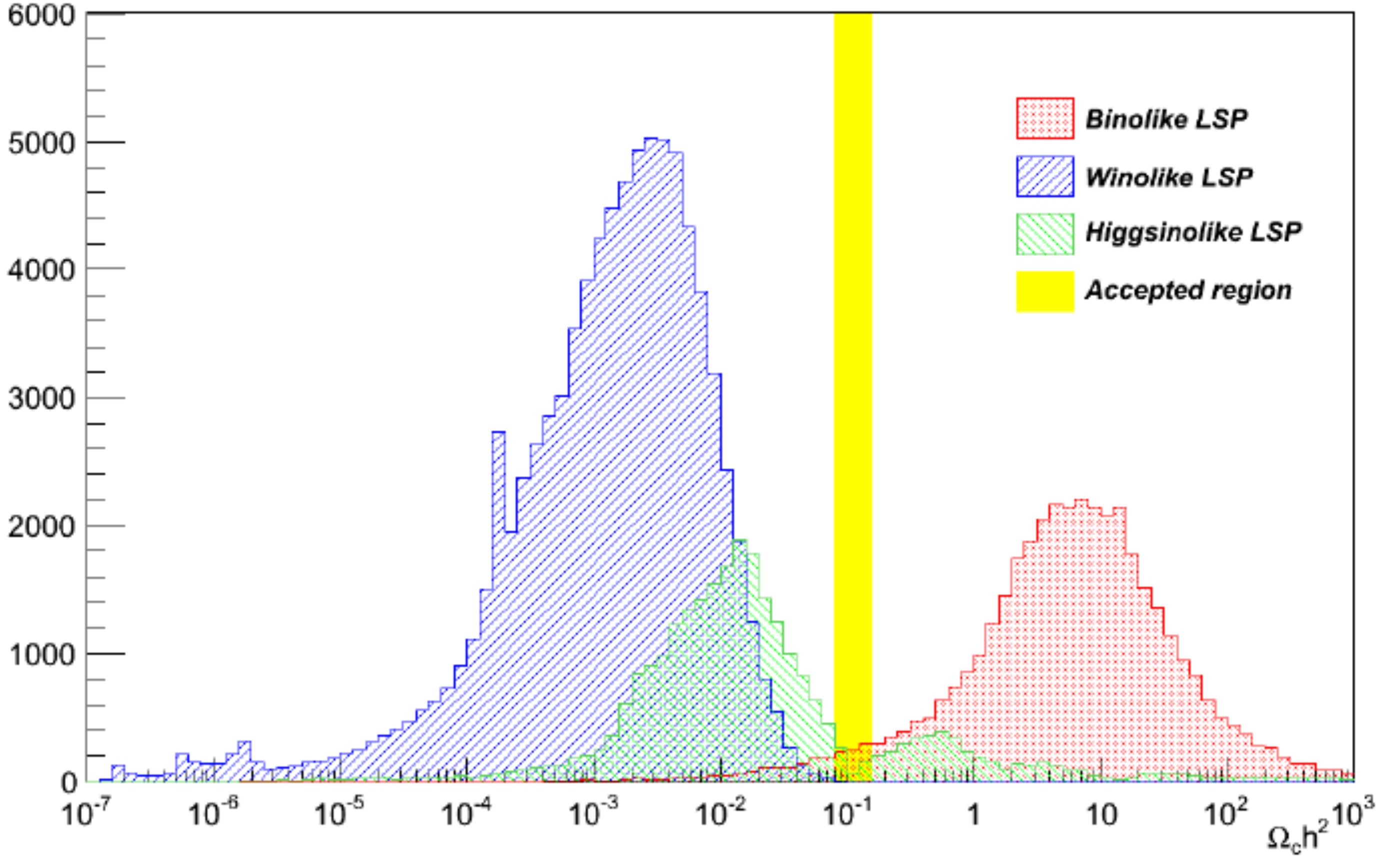
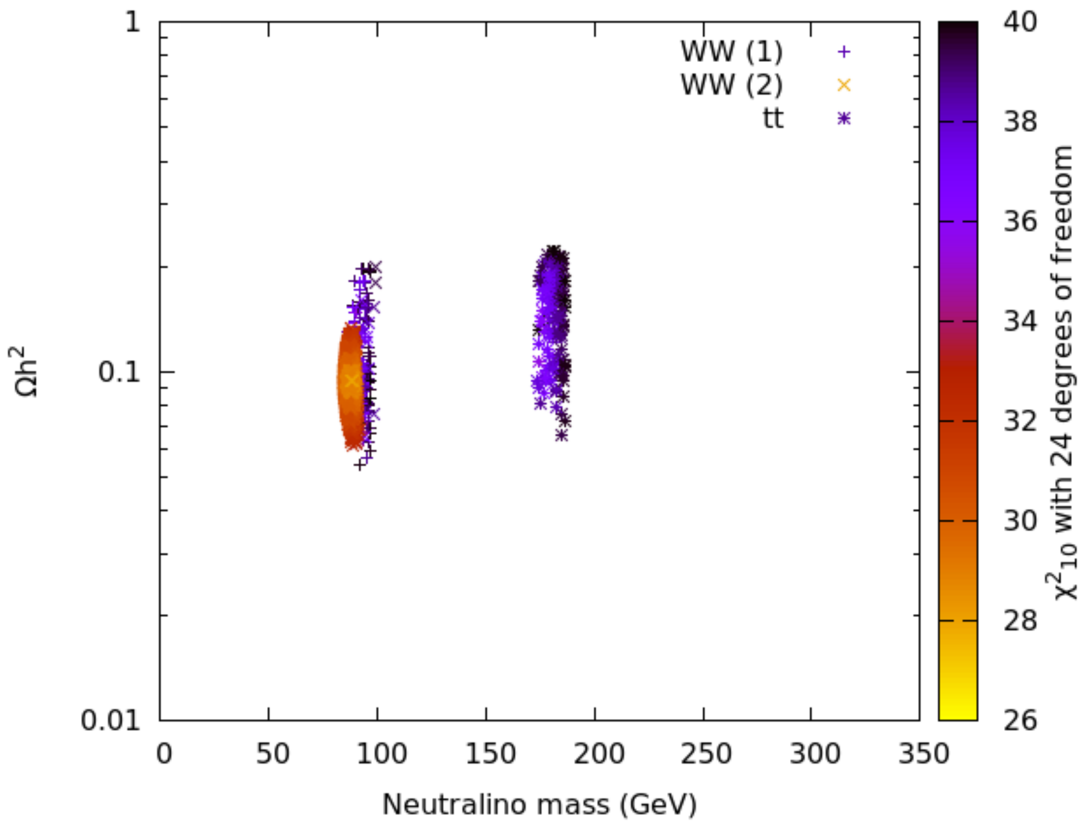



Figure 2: Dark Matter relic density $\Omega_c h^2$ obtained from the 19 parameter pMSSM models compared with the accepted region. The number of models is shown as a function of $\Omega_c h^2$.

# Relic Density best fit points

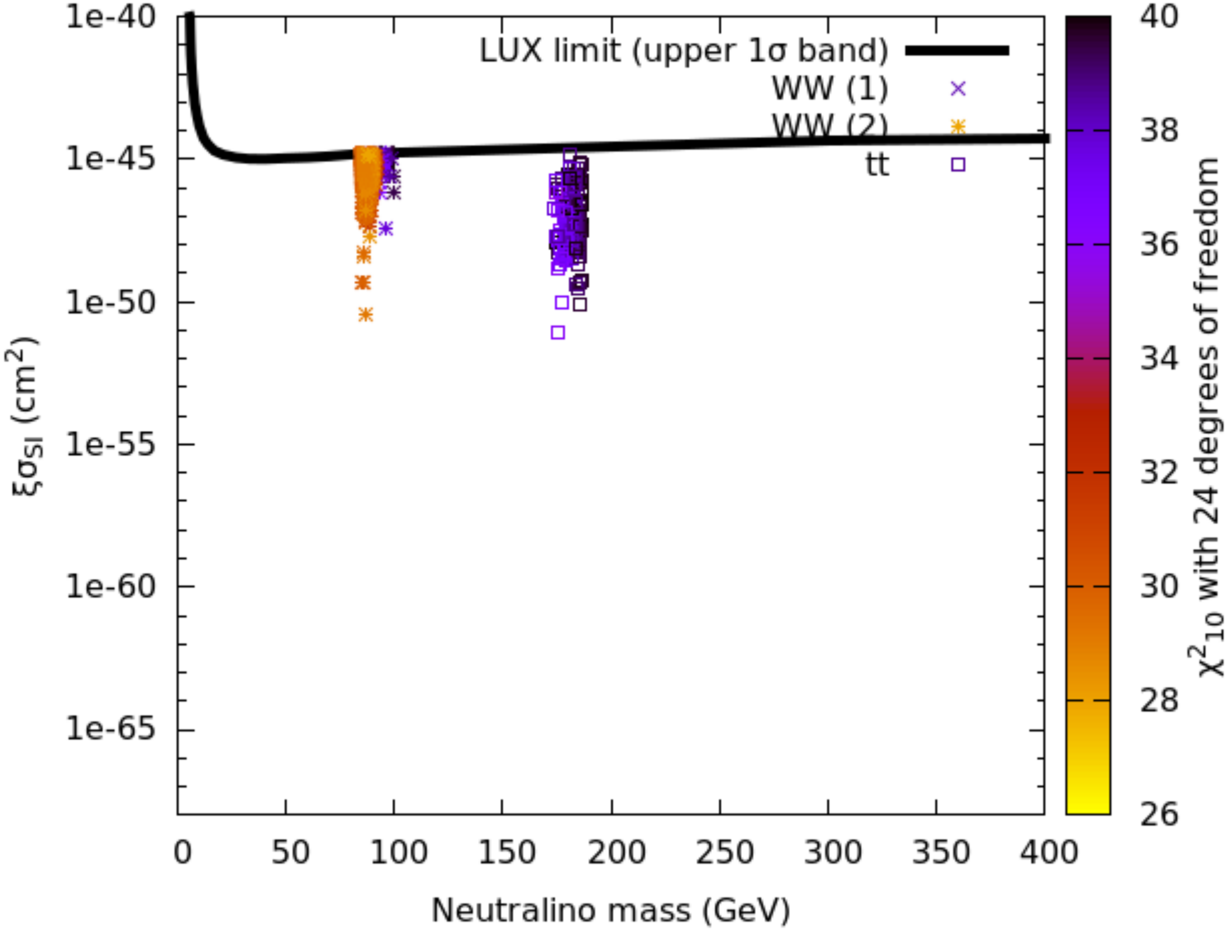



*....Perfect ! (we did not include this in the fit)*

# What can we do now?

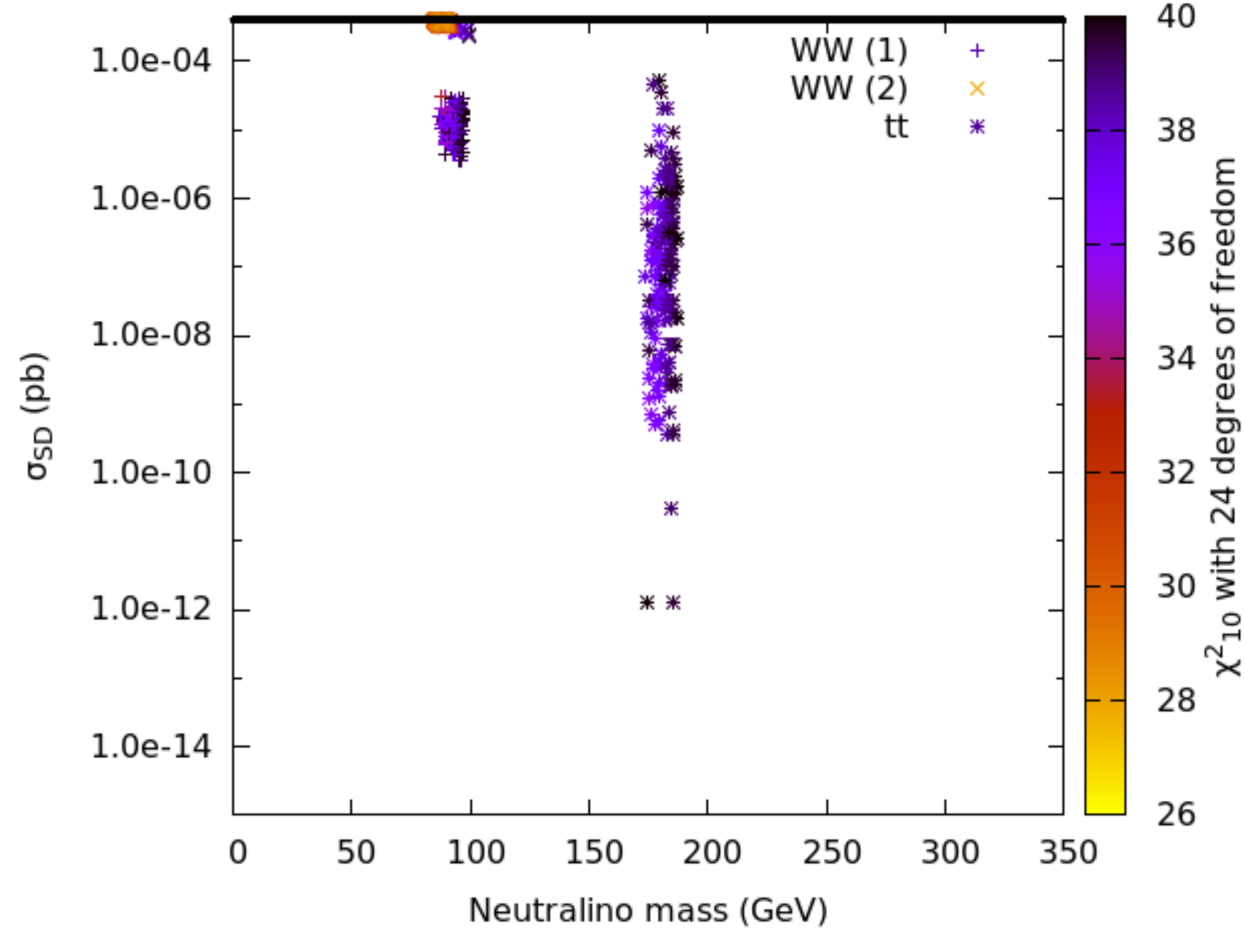
LUX ?

Xenon1T?



# What can we do now?

Best WW Solution will be **tested** with Icecube upgrade



# What can we do now?

- All 3 solutions give precise forecasts for LHC, best to optimize/add:

- Monojets “optimized” for almost compressed chargino/neutralinos
==> Currently a “blind spot”

- Boson(s)+jets+DM stemming
from cascade decays of SUSY particles to heavier (>300 GeV) neutralino/chargino (Wino) and then to the light 85 or 180 GeV neutralino
==> hZ , ZZ, WZ , WW, hh, hW + MET

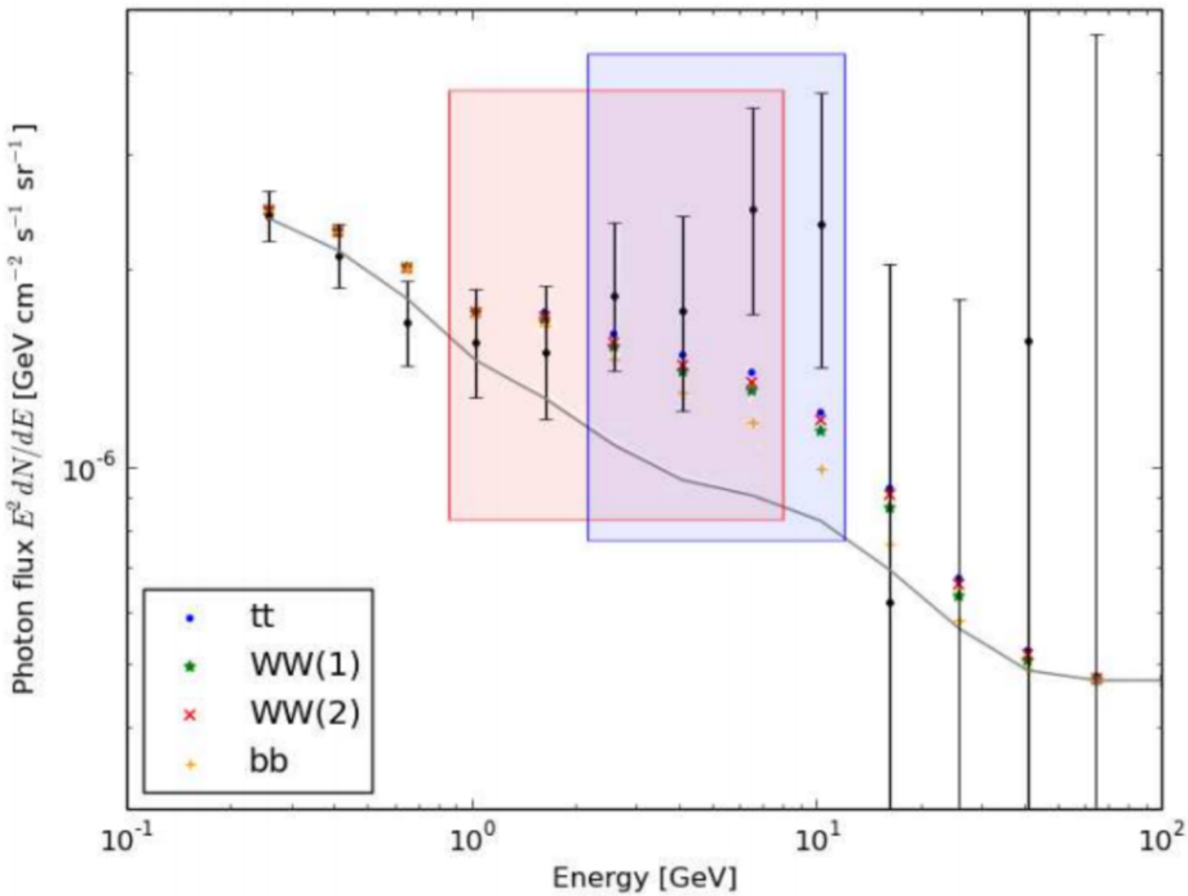
# Further studies

**Comparing Galactic Center MSSM dark matter solutions to the Reticulum II gamma-ray data**

Abraham Achterberg[a], Melissa van Beekveld[a], Wim Beenakker[a,c], Sascha Caron[a,b], and Luc Hendriks[a]

arxiv 1507.04644

- Small excess (2-3 sigma) reported for dwarf galaxy Reticulum-2
- Official Fermi-LAT paper reports p=0.06 including trial factors (for DM mass and shape) with updated dataset (pass8)
- Compare our solutions to data pass7 data from A. Geringer-Sameth, M. G. Walker, S. M. Koushiappas, S. E. Koposov, V. Belokurov, et al., arXiv:1503.02320.




- Blue: “excess” region in data
- Orange: Expected “excess region” for our solutions

# Reticulum 2 comparison

| | Reticulum II data | Observed excess region | Expected excess region |
|---|---|---|---|
| tt | 0.85 | 0.36 | 0.53 |
| WW(1) | 0.79 | 0.27 | 0.36 |
| WW(2) | 0.81 | 0.31 | 0.40 |
| bb | 0.63 | 0.09 | 0.24 |
| background | 0.37 | 0.01 | 0.03 |

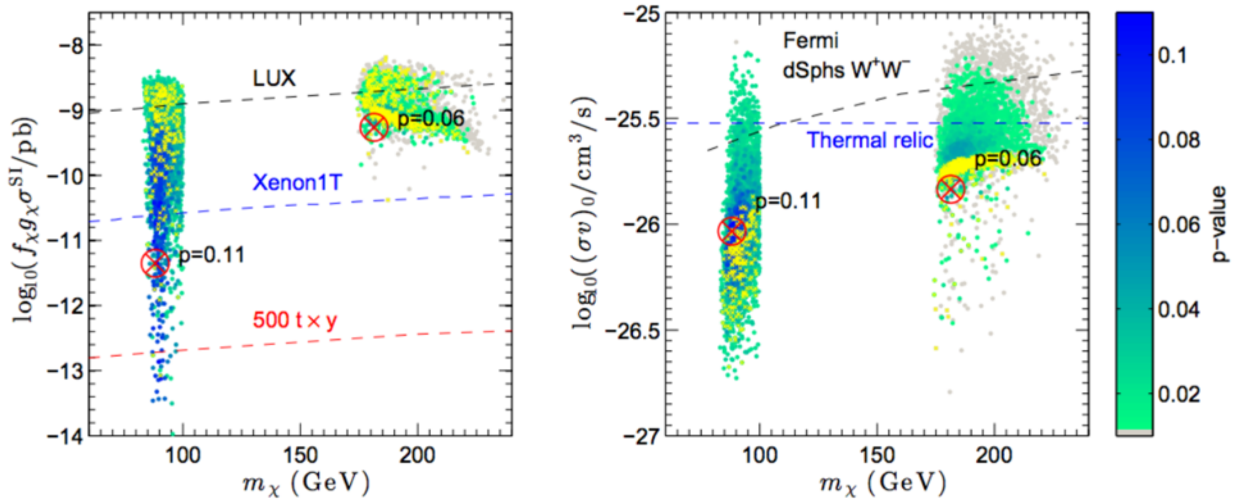
ray excess in Reticulum II. We find here that all these models predict a $J$-factor between $\log_{10}(J(\alpha_{int})) = 20.0$ GeV$^2$cm$^{-5}$ and $\log_{10}(J(\alpha_{int})) = 20.7$ GeV$^2$cm$^{-5}$ (including $1\sigma$ error), which lies within the $1\sigma$ region of $\log_{10}(J(\alpha_{int})) = 19.5^{+1.0}_{-0.6}$ GeV$^2$cm$^{-5}$ for an integration angle of $\alpha_{int} = 0.5°$ as reported by ref. [30]. This deriva-

# Full MSSM19 fit including all world data

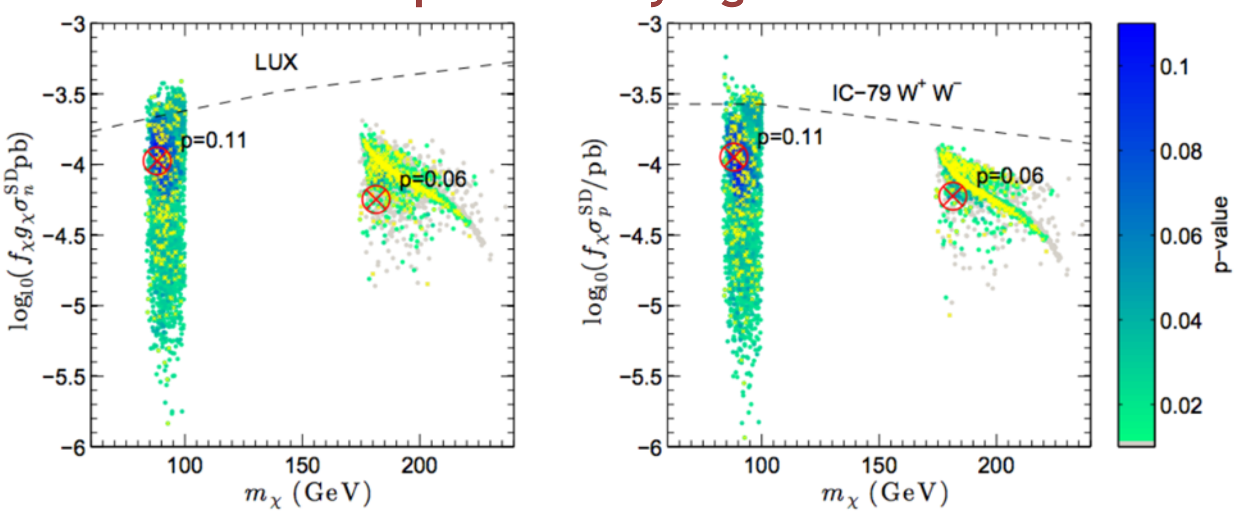
**Global analysis of the pMSSM in light of the Fermi GeV excess: prospects for the LHC Run-II and astroparticle experiments**

Gianfranco Bertone,[a] Francesca Calore,[a] Sascha Caron,[b] Roberto Ruiz,[c] Jong Soo Kim,[d] Roberto Trotta,[e] Christoph Weniger.[a]

on arxiv
in few days




preliminary figures




colour indicates p-value of the fit
yellow means that points have right Omega*h2 within 2 sigma

$$\rho_\chi/\rho_{\mathrm{DM}} = \Omega_\chi/\Omega_{\mathrm{DM}} \equiv f_\chi$$

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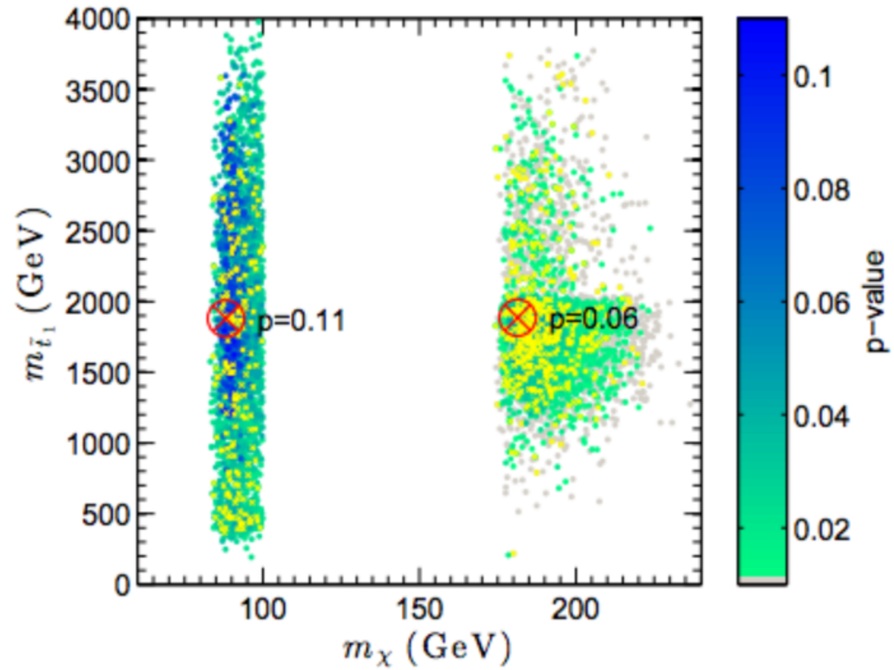
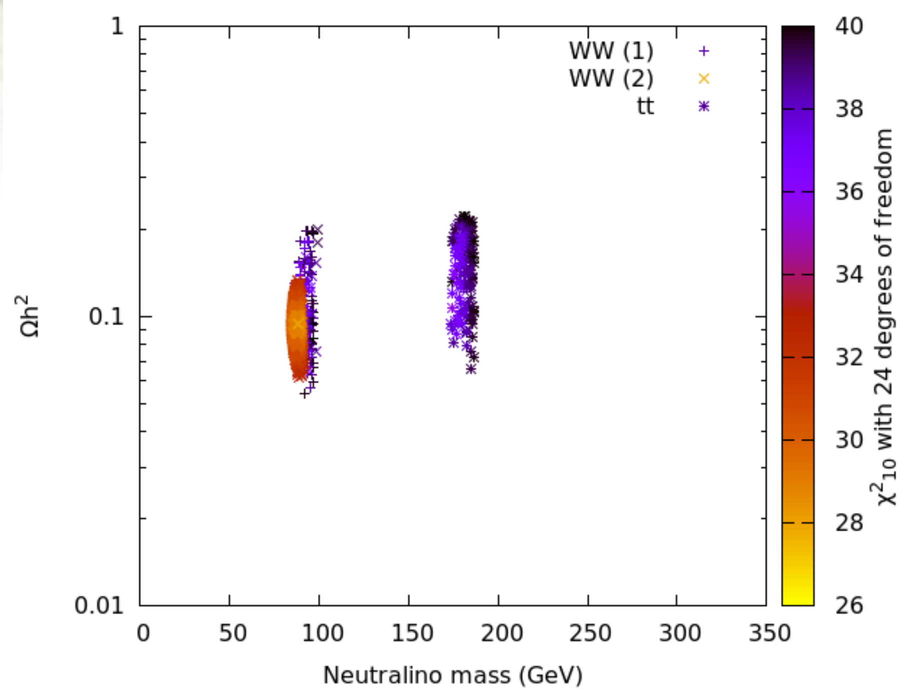



Further solution
with heavy stop masses
and annihilation enhanced
Yukawa coupling
with 180 GeV neutralino


**Summary:**

Is this all
by pure chance?

LHC run-2,
direct detection
and neutrino exp.
can tell us…



# Extra Slides

For massless quarks, the longitudinal component of the energy carried by a hadron formed in the string-breaking process $\mathrm{string} \to \mathrm{hadron} + \mathrm{string}'$ is governed by the Lund symmetric fragmentation function:

$$f(z) \propto \frac{z^{(a_i - a_j)}(1-z)^{a_j}}{z} \exp\left(\frac{-bm_\perp^2}{z}\right) , \tag{3}$$

where $z$ is the energy carried by the newly formed $(ij)$ hadron, expressed as a fraction of the (light-cone) energy of the quark (or antiquark) endpoint, $i$, of the fragmenting string. (The remaining energy fraction, $(1-z)$, goes to the new $\mathrm{string}'$ system, from which another hadron can be split off in the same manner, etc., until all the energy is used up.) The transverse mass of the produced $(ij)$ hadron is defined by $m_\perp^2 = m_{\mathrm{had}}^2 + p_{\perp,\mathrm{had}}^2$, hence heavier hadrons have harder spectra. The proportionality sign in eq. (3) indicates that the function is to be normalized to unity.

# Fermi GC excess: First appearance in 2009

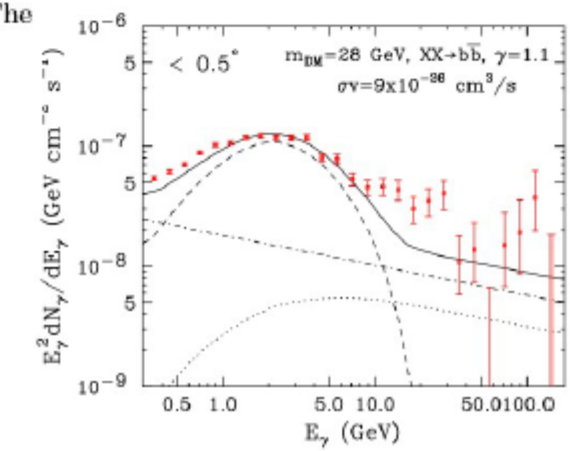
First clear statements about properties of *excess* emission (morphology, spectrum etc, subject to some changes in later analyses):

**Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope**

Lisa Goodenough[1] and Dan Hooper[2,3]

[1] *Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003*
[2] *Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510*
[3] *Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637*

We study the gamma rays observed by the Fermi Gamma Ray Space Telescope from the direction of the Galactic Center and find that their angular distribution and energy spectrum are well described by a dark matter annihilation scenario. In particular, we find a good fit to the data for dark matter particles with a 25-30 GeV mass, an annihilation cross section of $\sim 9 \times 10^{-26}$ cm$^3$/s, and that are distributed with a cusped halo profile, $\rho(r) \propto r^{-1.1}$, within the inner kiloparsec of the




First very cautious comments by the LAT team, without any detailed characterization of the *residual*:

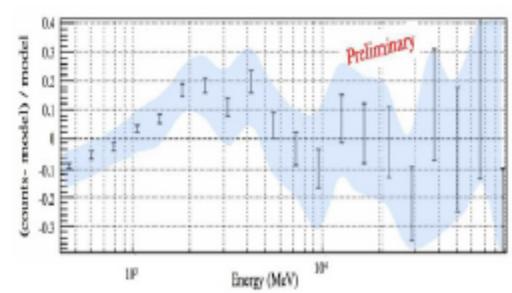
*2009 Fermi Symposium, Washington, D.C., Nov. 2-5*

**Indirect Search for Dark Matter from the center of the Milky Way with the Fermi-Large Area Telescope**

Vincenzo Vitale and Aldo Morselli, for the Fermi/LAT Collaboration
*Istituto Nazionale di Fisica Nucleare, Sez. Roma Tor Vergata, Roma, Italy*

today, can account for the large majority of the detected gamma-ray emission from the Galactic Center. Nevertheless a residual emission is left, not accounted for by the above models.

An improved model of the Galactic diffuse emission and a careful evaluation of new (possibly unresolved) sources (or source populations) will improve the sensitivity for a DM search.






By Ch. Weniger (UvA)

# Signal normalization

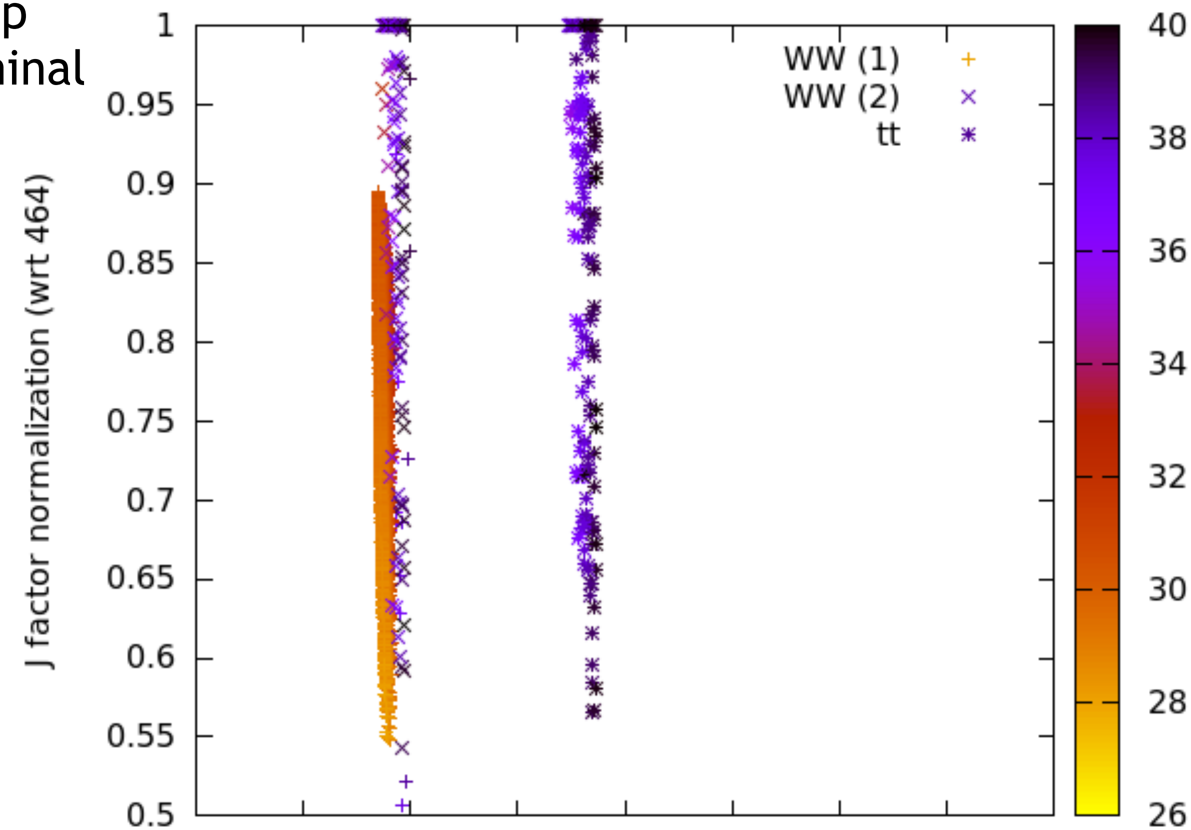
$$\frac{d\Phi_\gamma(E_\gamma)}{dE_\gamma d\Omega} = \frac{\langle \sigma v \rangle}{8\pi m_{\rm DM}^2}\frac{dN_\gamma}{dE}\int ds\, \rho_{\rm DM}^2(r(s\,,\,\theta))$$

NFW profile

DM density^2
has large uncertainties..

Need to be taken into
account

2 sigma up
from nominal



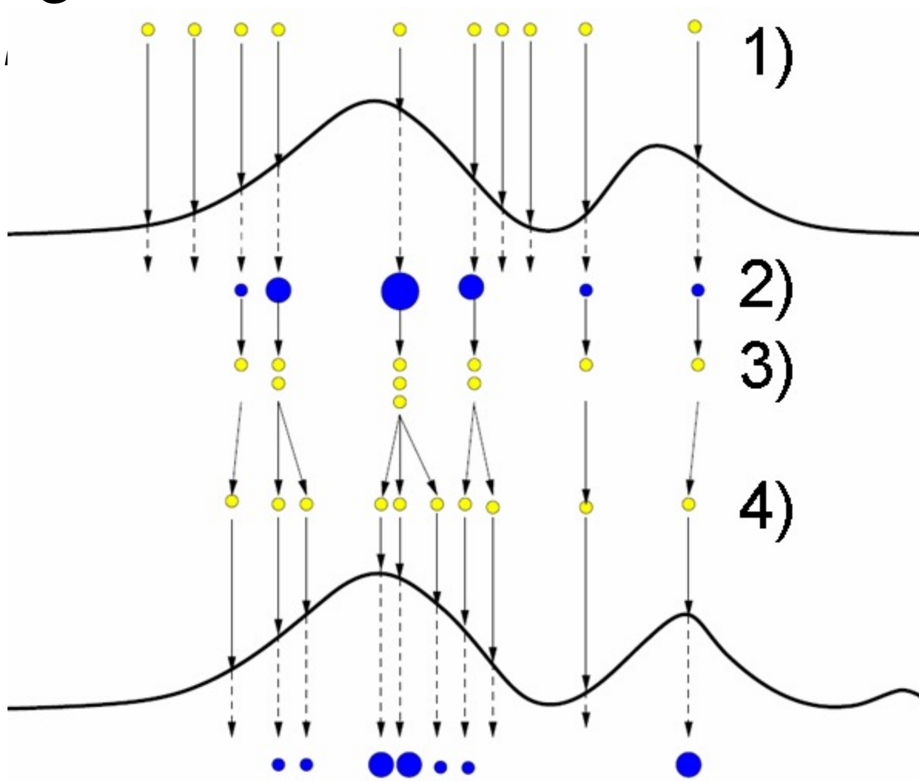

About 1 sigma up

# Iterative Particle Filtering

A filter algorithm (you know the Kalman filter)
Usually used for e.g. "tracking objects" (your new car or drone)
*Idea: importance sampling*
➔ *Generate recursively* ... *ns*

Set of particles
 (parameter points)
to represent the
posterior density.
➔ Particles sampled
 in regions of higher
 likelihood…

➔ Have a look at the MSSM solutions to see how good this actually works…

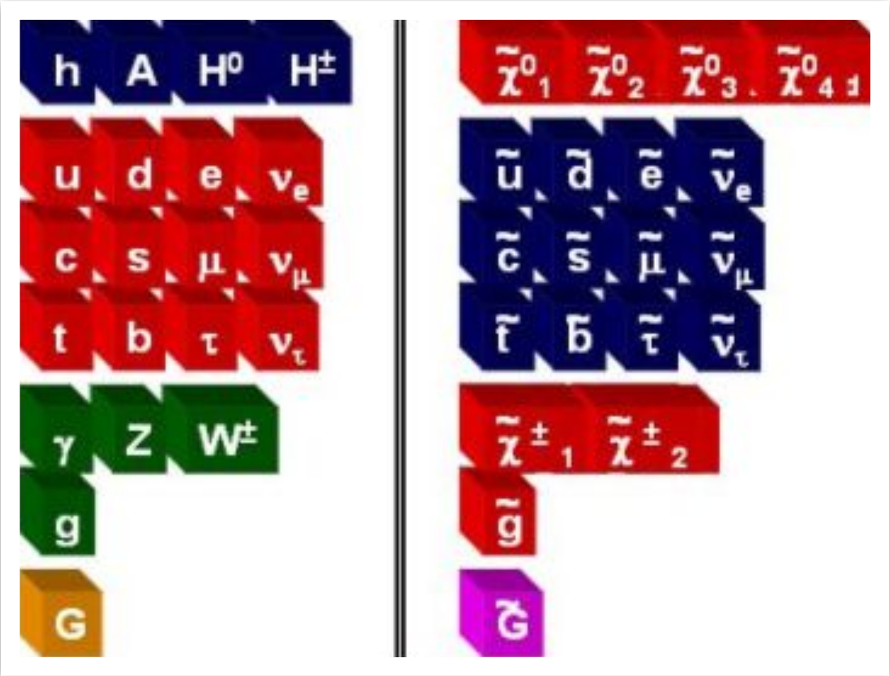


# The Minimal SUSY SM

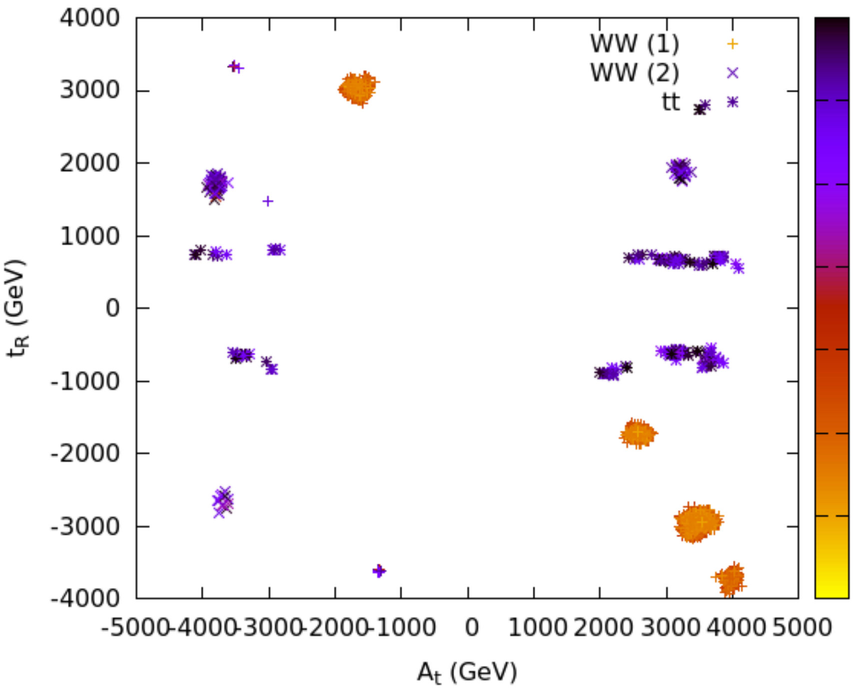
105 parameters can be reduced to 19 which are phenomelogically relevant for DM and direct searches at LHC

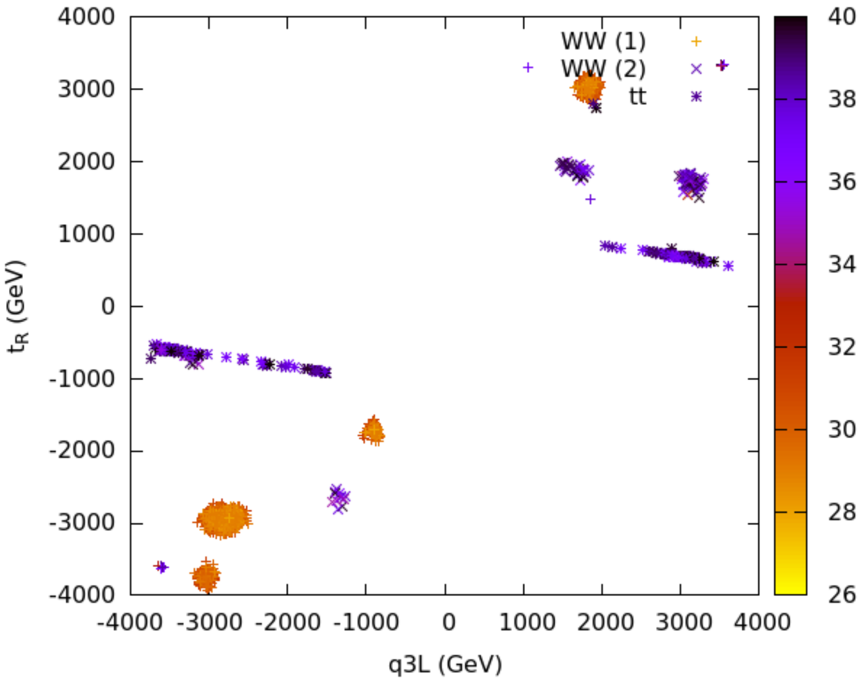
The 19 remaining parameters are 10 sfermion masses,[1] 3 gaugino masses $M_{1,2,3}$, the ratio of the Higgs vacuum expectation values $\tan\beta$, the Higgsino mixing parameter $\mu$, the mass $m_A$ of the CP-odd Higgs-boson $A^0$ and 3 trilinear scalar couplings $A_{b,t,\tau}$.

[1] $\tilde{Q}_1$, $\tilde{Q}_3$, $\tilde{L}_1$, $\tilde{L}_3$, $\tilde{u}_1$, $\tilde{d}_1$, $\tilde{u}_3$, $\tilde{d}_3$, $\tilde{e}_1$ and $\tilde{e}_3$.



# Stop parameters …



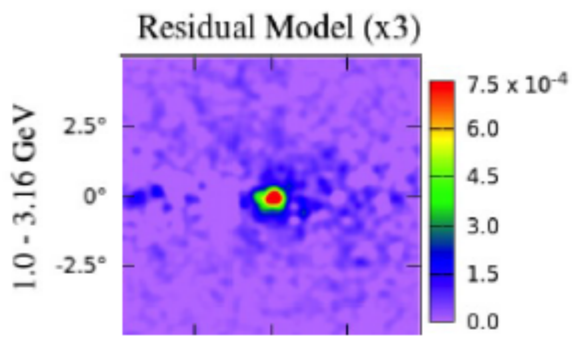



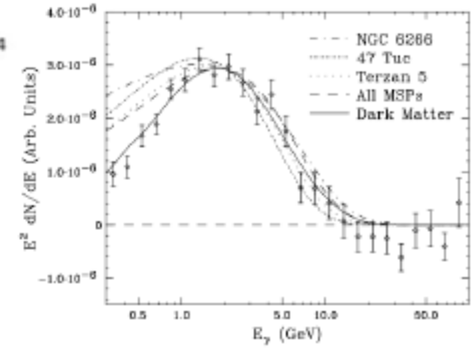

Impressive to find such located solutions… constrained by Higgs mass…
Particle Filter locates regions which are $10^{-20}$ of phase space

# Follow-up studies

## At the Galactic center (roughly 7deg x 7deg)

Goodenough & Hooper 2009
Hooper & Goodenough 2011
Hooper & Linden 2011
Boyarsky+ 2011
Abazajian & Kaplinghat 2012
Gordon & Macias 2013
Macias & Gordon 2014
Abazajian+ 2014
Daylan+2014

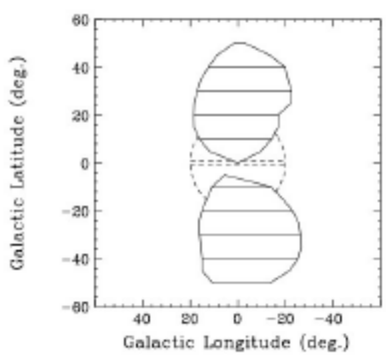


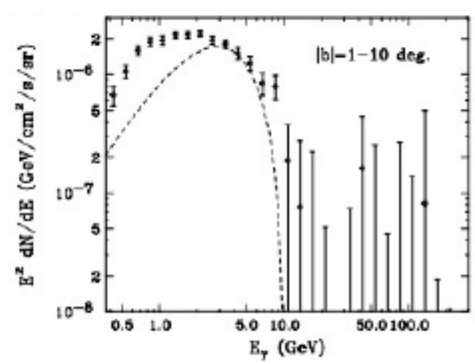




[Daylan+ 2014]

## In the inner Galaxy (roughly |b|>1 deg to tens of deg)

Hooper & Slatyer 2013
Huang+ 2013
Zhou+ 2014
Daylan+ 2014

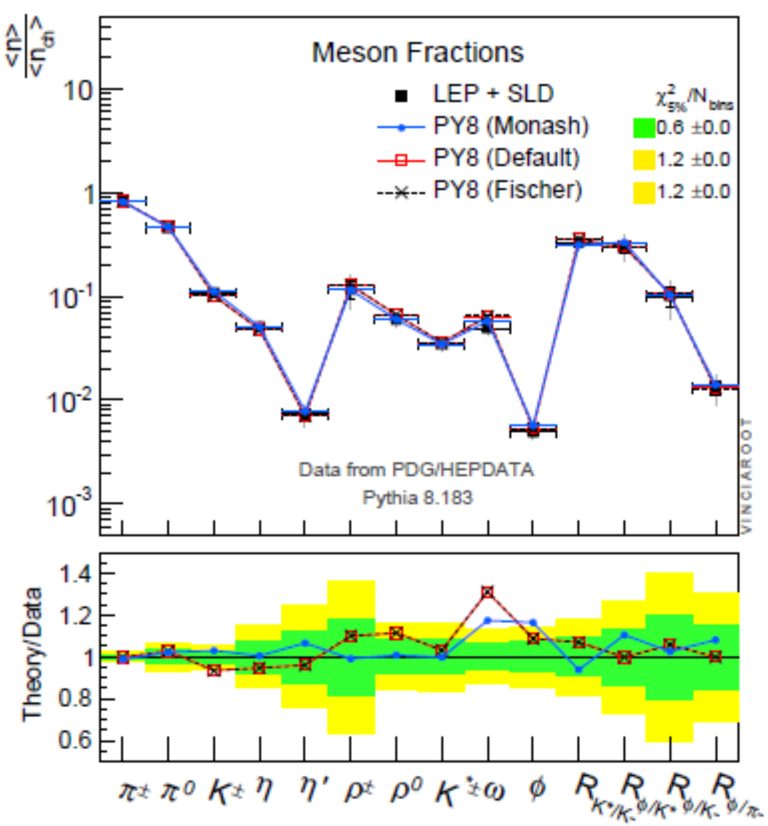


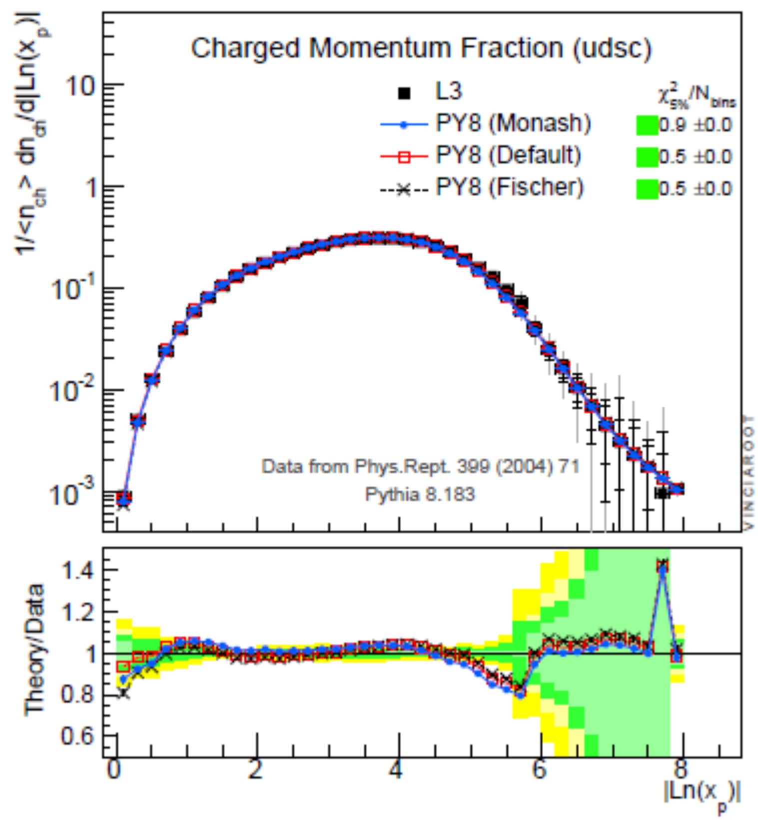




[Hooper & Slatyer 2013]

http://arxiv.org/pdf/1404.5630v1.pdf

# Signal Modelling




- Variation of Pythia8 tunes seems to **underestimate** true uncertainty (pi0 production, charge distribution)

# Phenomenological tasks

**Astronomy:**

➔*Can it be explained by unknown pulsars or other astrophysics source?*

**Particle Physics:**

➔*Is it possible that this is really DM annihilation? Which models work? Can we test these models?*

# Fermi-LAT detector

- Formerly known as GLAST
- Particle physics detector
- Photon Conversion

⇒ Silicon Tracker for pointing resolution

⇒ Calorimeter for energy measurement

*Anticoincidence Detector to remove unwanted charged cosmics*

# Monojets

- Bino Higgsino
  ➔ Should be testable with 50fb-1 at 14 TeV
- Bino Wino Higgsino
  ➔ Difficult…
- Stop pairs…?

➔ Likely we need a new dedicated search for **small (but not too small) compression**, e.g. soft leptons + Monojet to test chargino/neutralino production…

# Boson(s) + jets + DM

- Both WW solutions have quite constrained neutralino/chargino parameters…

Heavy neutralino (3) and 4 will be heavy (but not too heavy) and decay via Z , **Higgs** or W + DM

➔ Also from squark decays we expect a cascade decay leading often to 2 bosons in the final state

# The Minimal SUSY SM

105 parameters can be reduced to 19 which are phenomelogically relevant for DM and direct searches at LHC

*In this scheme, one assumes that: (i) All the soft SUSY-breaking parameters are real, therefore the only source of CP-violation is the CKM matrix.*
*(ii) The matrices of the sfermion masses and the trilinear couplings are diagonal, in order to avoid FCNCs at the tree-level.*
*(iii) First and second sfermion generation universality to avoid severe constraints, for instance, from K 0 mixing.*