

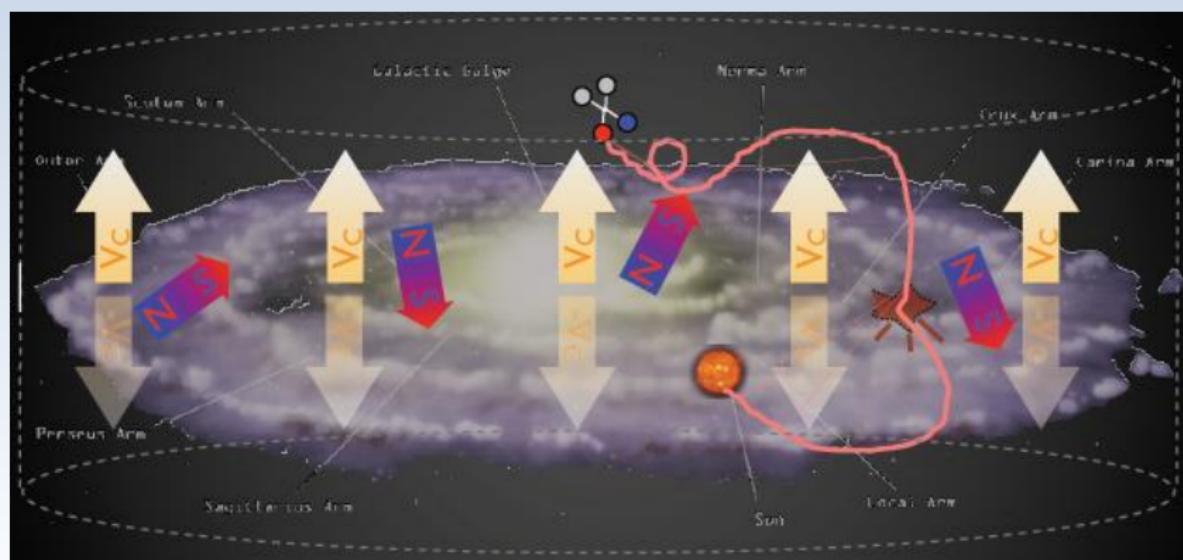
Antiproton constraints on Dark Matter

Gaëlle Giesen

Institut de Physique Théorique (IPhT) - CEA Saclay



DM annihilation or decay in the halo of our Galaxy
⇒ Cosmic Ray propagation (convection, diffusion, etc...)
⇒ Detection at Earth



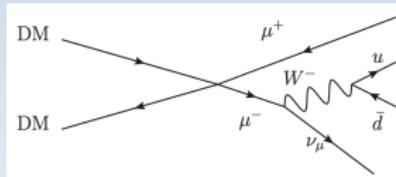
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- For annihilation (decay) into quark or gauge bosons
⇒ hadronization produces antiprotons

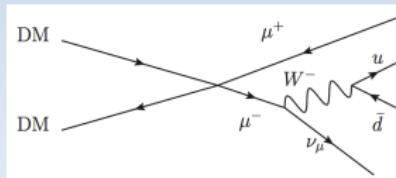
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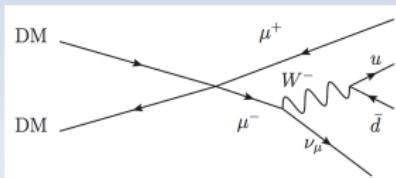
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- Astrophysical background : small uncertainties in the GeV range ⇒ detection of a WIMP signal

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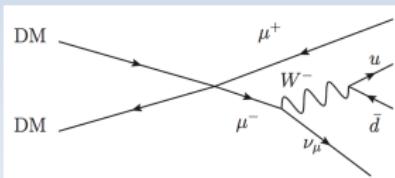
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- Astrophysical background : small uncertainties in the GeV range ⇒ detection of a WIMP signal
- Current PAMELA data already very competitive
- Upcoming AMS-02 data even more precise
⇒ Forecast : sensitivities and reconstruction capabilities

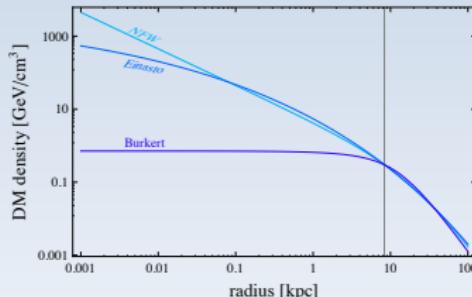
- DM Annihilation/decay channels

$$\begin{array}{ccc} \text{annihilation} & \text{DM} & \text{DM} \\ \text{decay} & & \text{DM} \end{array} \left. \right\} \rightarrow b\bar{b}, t\bar{t}, W^+W^-, ZZ, \mu^+\mu^-, \tau^+\tau^-, \gamma\gamma$$

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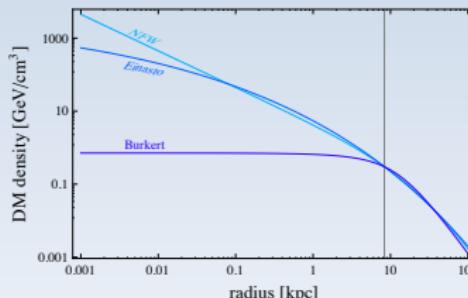
- DM halo profiles



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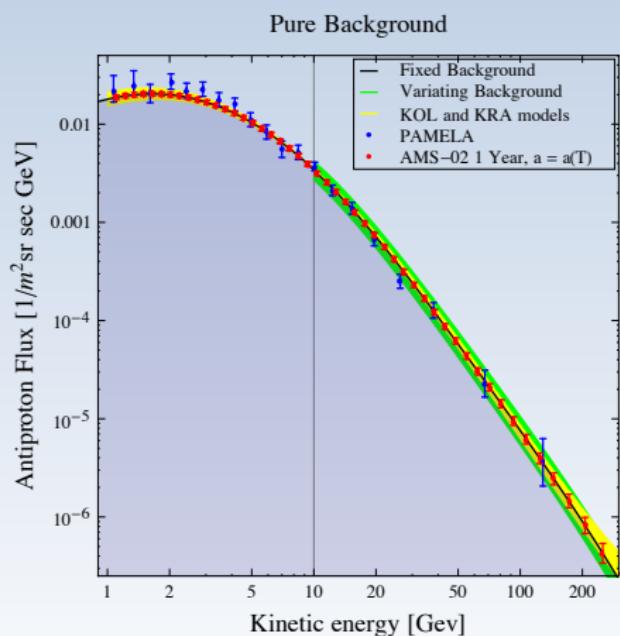
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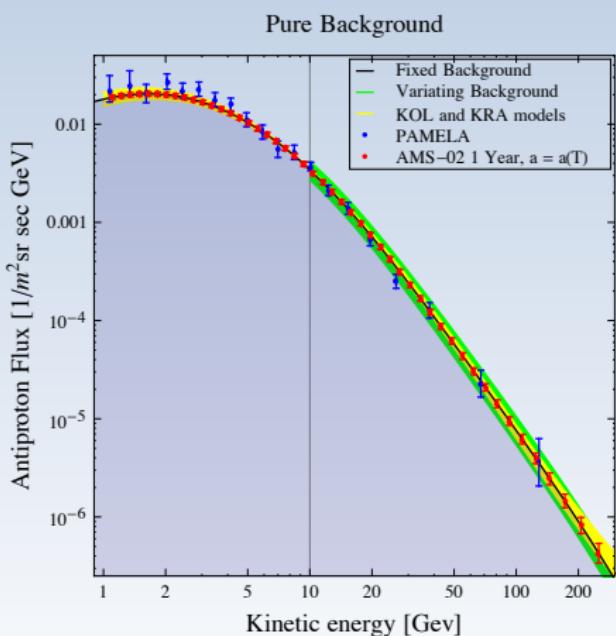
- Antiproton propagation in the galactic halo

Model	δ	\mathcal{K}_0 [kpc²/Myr]	V_{conv} [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

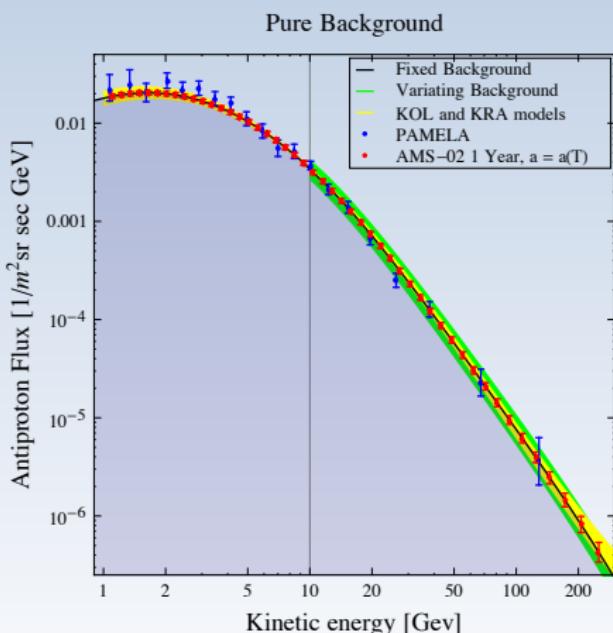


● Fixed Background

$\phi_{\text{fixed}}(T > 10 \text{ GeV})$: power law

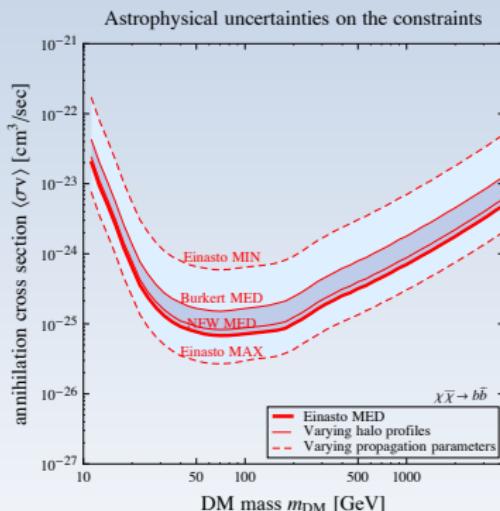
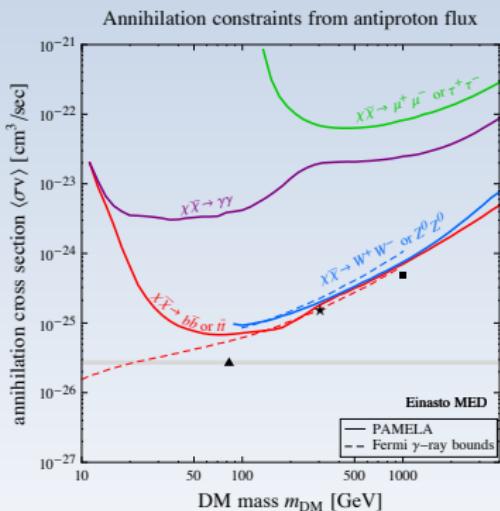


- Fixed Background
 $\phi_{\text{fixed}}(T > 10 \text{ GeV})$: power law
 - Variating background
- $$\phi_{\text{bkg}}(A, p; T) = AT^p \times \phi_{\text{fixed}}(T)$$
- $$A \in [0.9, 1.1] \text{ and } p \in [-0.05, 0.05]$$



- Fixed Background
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 - Variating background
 - Flux with DM signal
- $$\phi_{\text{bkg}}(A, p; T) = AT^p \times \phi_{\text{fixed}}(T)$$
- $$A \in [0.9, 1.1] \text{ and } p \in [-0.05, 0.05]$$
- $$\begin{aligned} \phi_{\text{tot}}(m_{\text{DM}}, \langle \sigma v \rangle; A, p) \\ = \phi_{\text{DM}}(m_{\text{DM}}, \langle \sigma v \rangle) + \phi_{\text{bkg}}(A, p) \end{aligned}$$
- \Rightarrow Marginalization over A and p

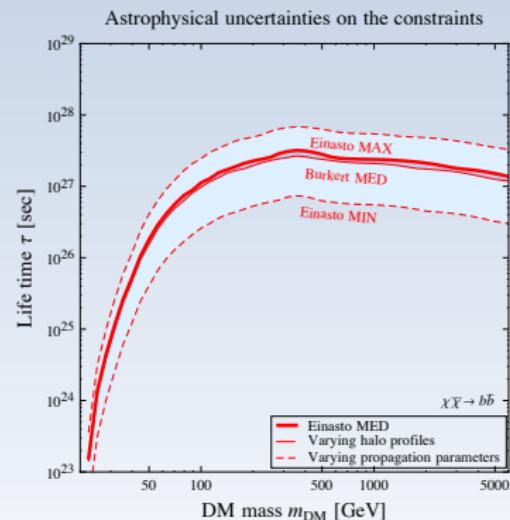
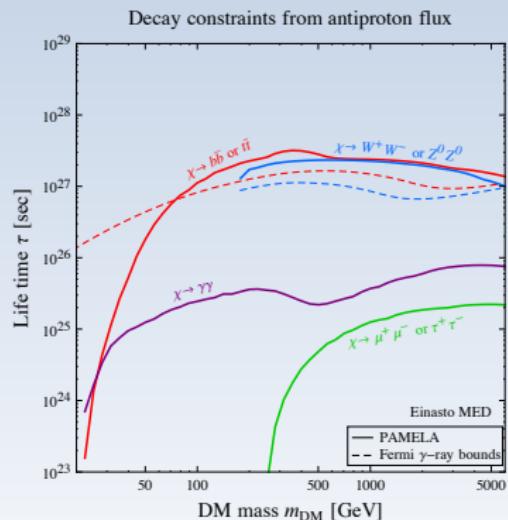
Current Antiproton constraints from PAMELA for annihilating DM



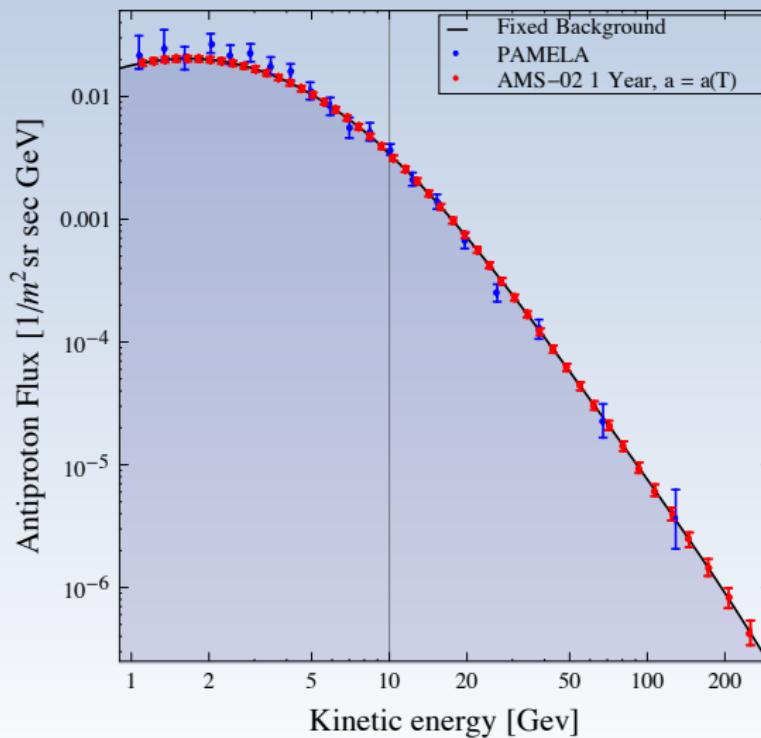
Current constraints

Decaying Dark Matter

Current Antiproton constraints from PAMELA for decaying DM



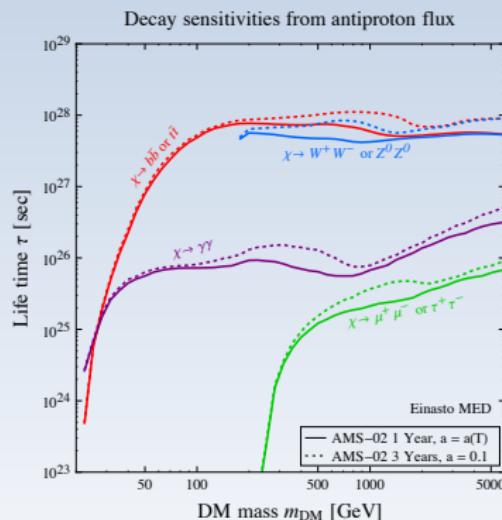
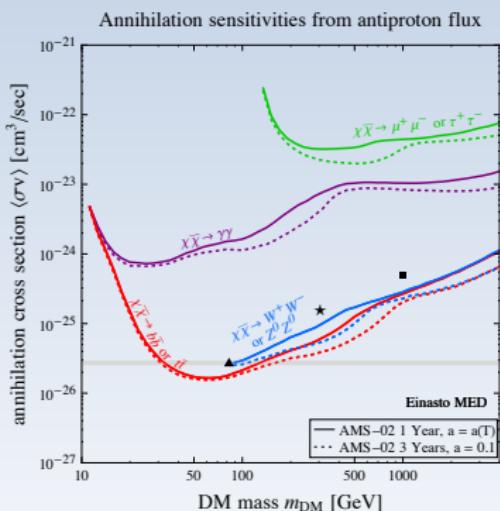
Pure Background



Future Sensitivities

Foreseen constraints

Future sensitivities of AMS-02



Study of three benchmark models :

Annihilation $\chi\chi \rightarrow b\bar{b}$, Einasto profile, MED propagation

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▲ $m_{\text{DM}} = 85 \text{ GeV} \quad \langle \sigma v \rangle = 2.7 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$

Thermal cross-section

DM signal mainly below 10 GeV

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★ $m_{\text{DM}} = 300 \text{ GeV} \quad \langle \sigma v \rangle = 1.5 \times 10^{-25} \text{ cm}^3 \text{ s}^{-1}$

Cross-section at the limit of exclusion

DM signal in the sensitivity of AMS-02

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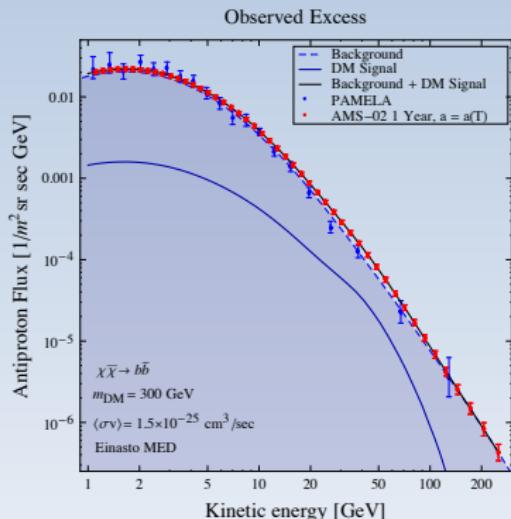
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Cross-section at the limit of exclusion
DM signal in the sensitivity of AMS-02

- $m_{\text{DM}} = 1 \text{ TeV} \quad \langle \sigma v \rangle = 5 \times 10^{-25} \text{ cm}^3 \text{ s}^{-1}$
DM signal at high energies
Data has big uncertainties

Future Sensitivities

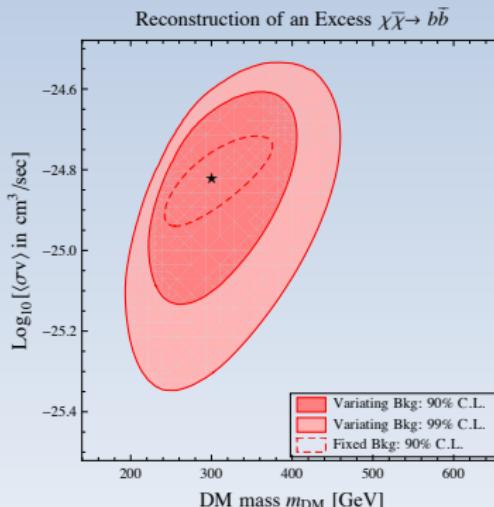
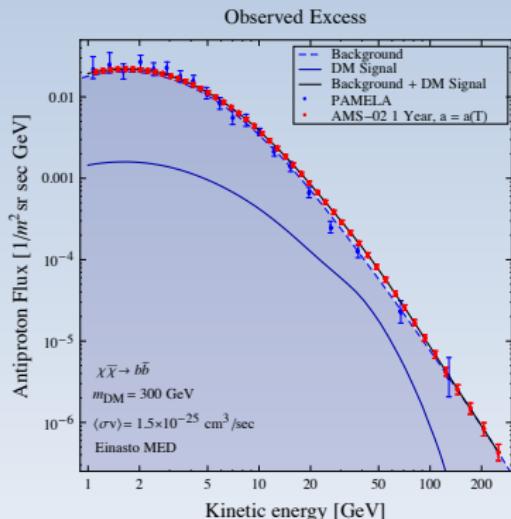
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Antiproton constraints on Dark Matter

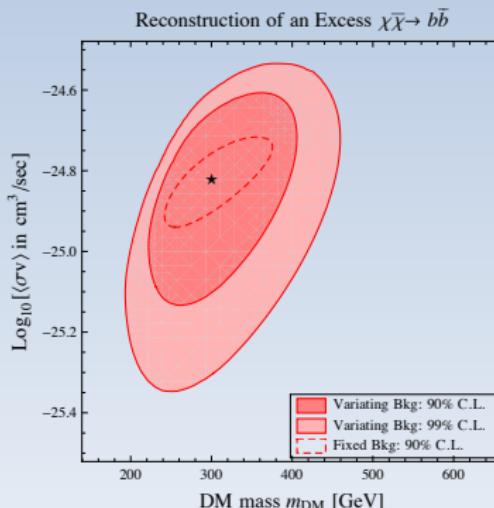
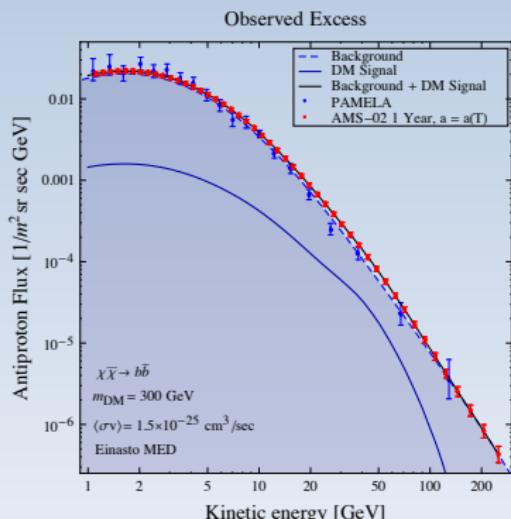
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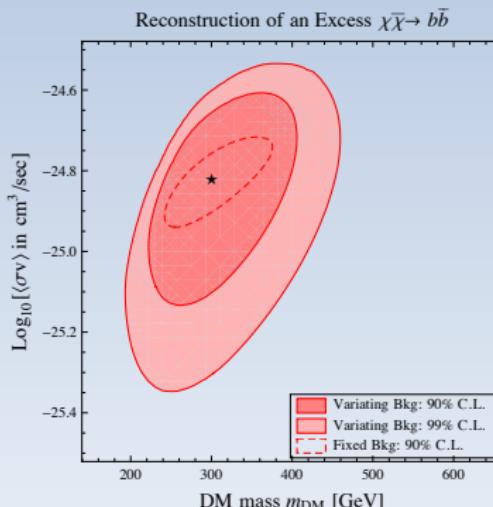
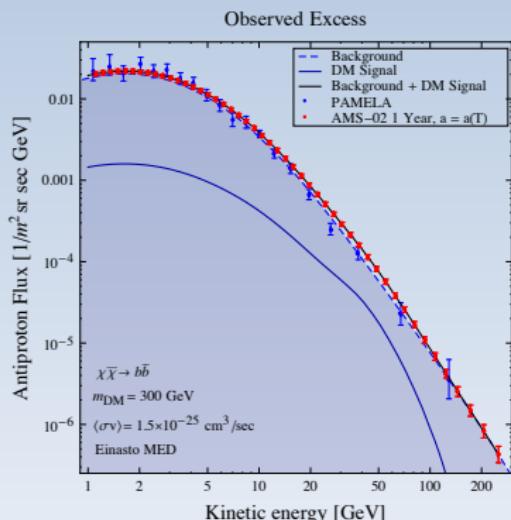
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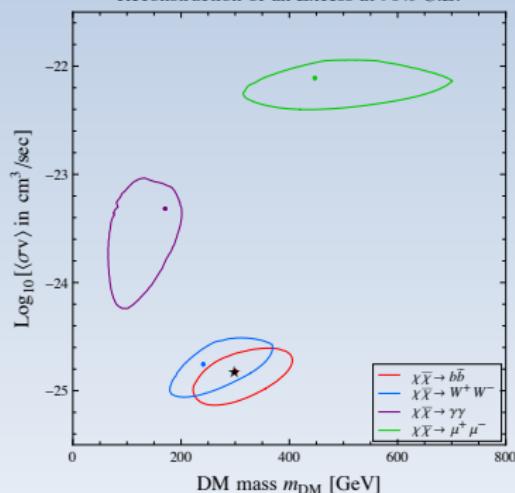


- Fixed background : degeneracy between m^{-2} and $\langle \sigma v \rangle$
- m_{DM} determined with 50% of its value
- $\langle \sigma v \rangle$ determined within an order of magnitude

Future Sensitivities

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Reconstruction of an Excess at 90% C.L.



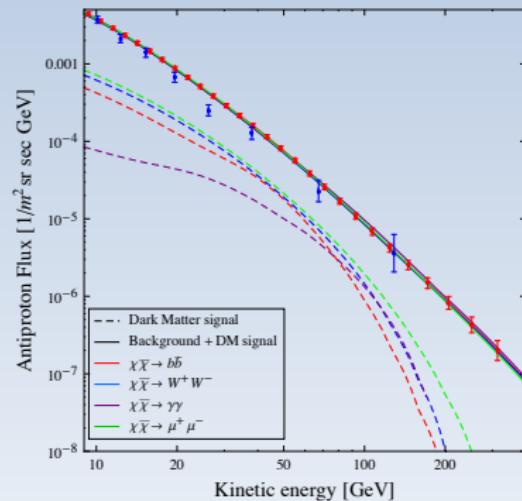
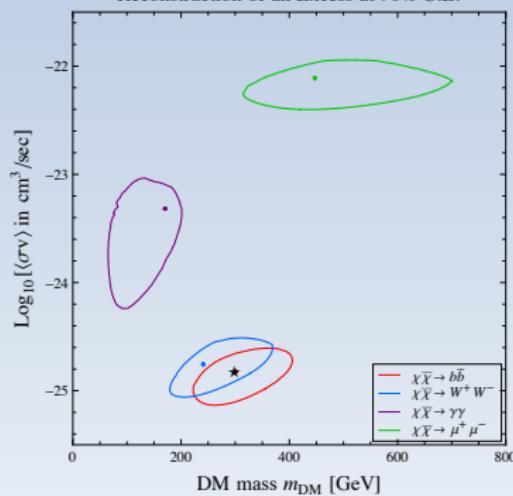
Fixed annihilation channel (true signal : 100% $b\bar{b}$)	mass m_{DM} [GeV]	cross-section $\langle \sigma v \rangle$ [$\text{cm}^3 \text{s}^{-1}$]	$\Delta\chi^2$ with respect to a pure background
$\chi\chi \rightarrow b\bar{b}$	300	1.5×10^{-25}	-21.0
$\chi\chi \rightarrow W^+W^-$	240	1.9×10^{-25}	-19.7
$\chi\chi \rightarrow \gamma\gamma$	169	4.8×10^{-24}	-9.8
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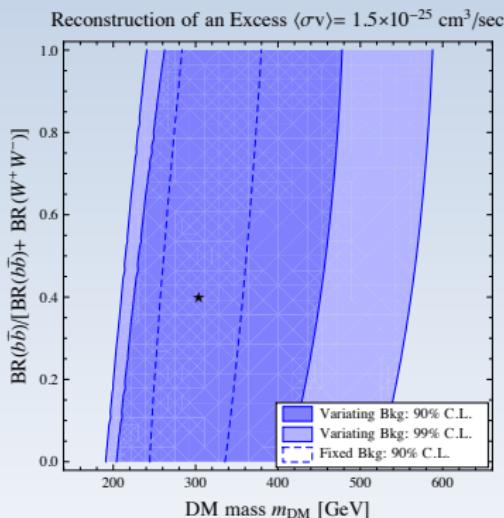


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New annihilation signal : **40% $b\bar{b}$ + 60% W^+W^-**

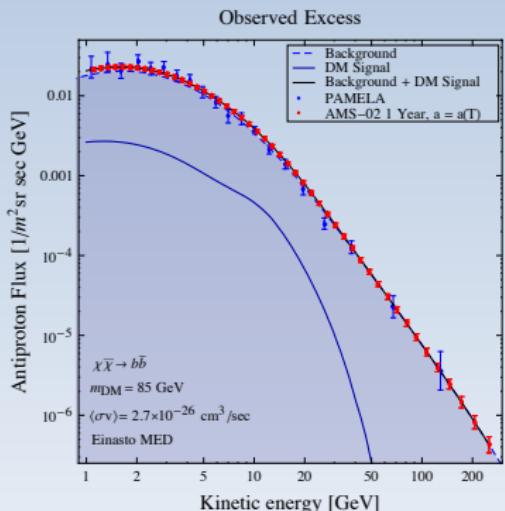


Fixed cross-section $\langle \sigma v \rangle$ [$\text{cm}^3 \text{s}^{-1}$] (true signal : 40% $b\bar{b}$ + 60% W^+W^-)	mass m_{DM} [GeV]	relative branching ratio	$\Delta\chi^2$ with respect to a pure background
1.5×10^{-25}	300	0.4	-13.0

Antiproton constraints on Dark Matter

Future Sensitivities

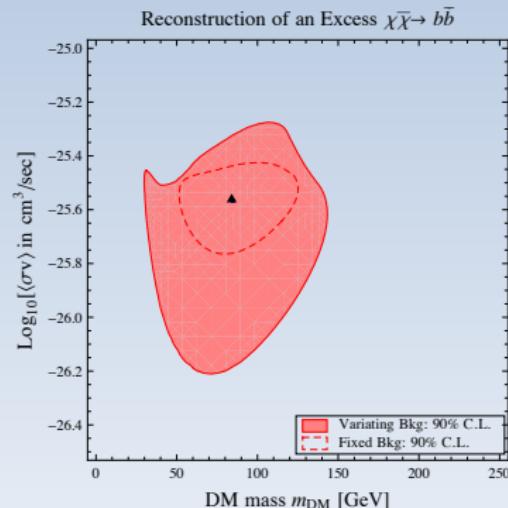
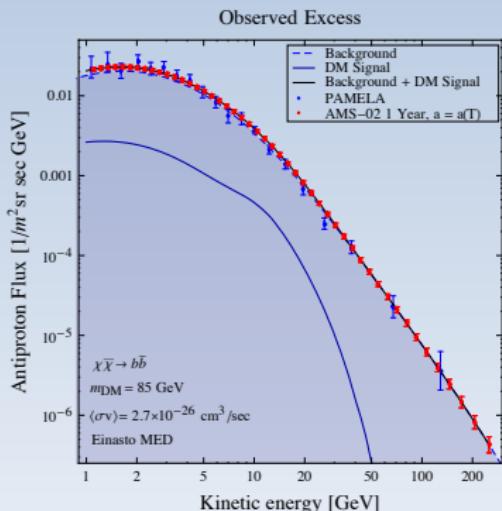
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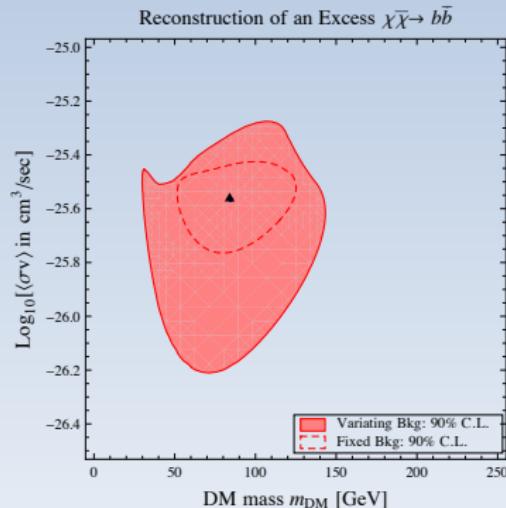
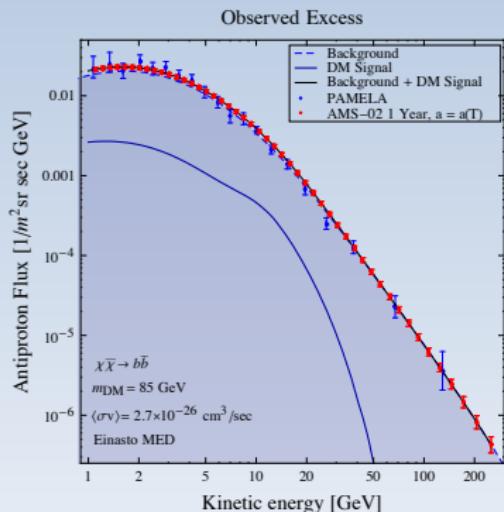
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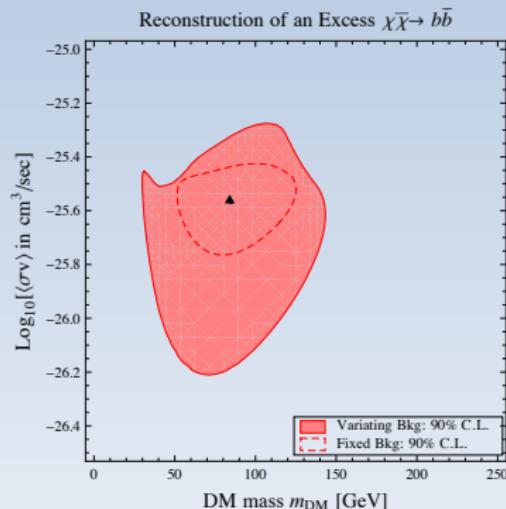
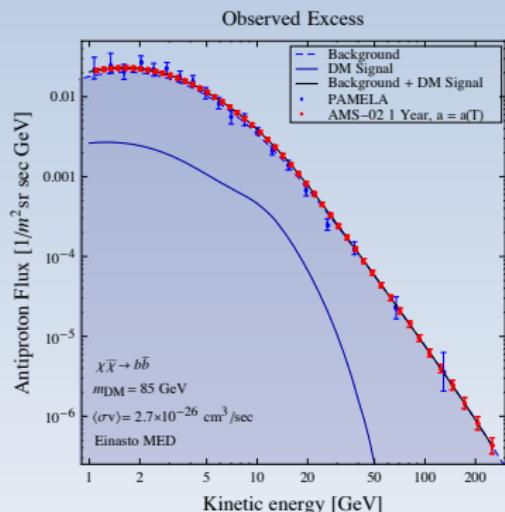
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- Unusual shape, because of the 10 GeV cut

Future Sensitivities

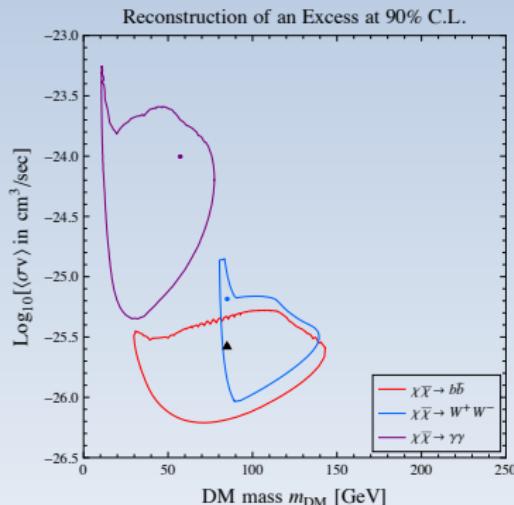
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- Unusual shape, because of the 10 GeV cut
- 99% C.L. contour would extend artificially to low masses
- Points in the 99% C.L. contour prefer a pure background

Future Sensitivities

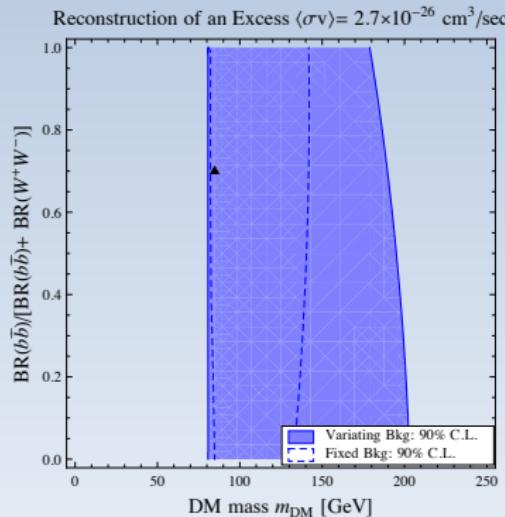
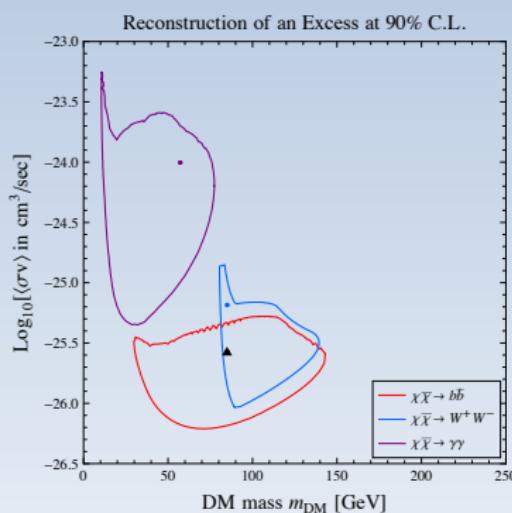
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$\chi\chi \rightarrow b\bar{b}$	84.9	2.7×10^{-26}	-10.5
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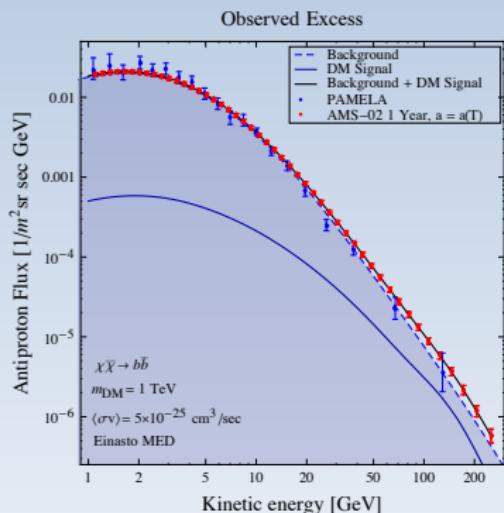


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Fixed cross-section $\langle \sigma v \rangle$ [cm ³ s ⁻¹] (true signal : 70% $b\bar{b}$ + 30% W^+W^-)	mass m_{DM} [GeV]	relative branching ratio	$\Delta\chi^2$ with respect to a pure background
2.7×10^{-26}	84.9	0.7	-5.4

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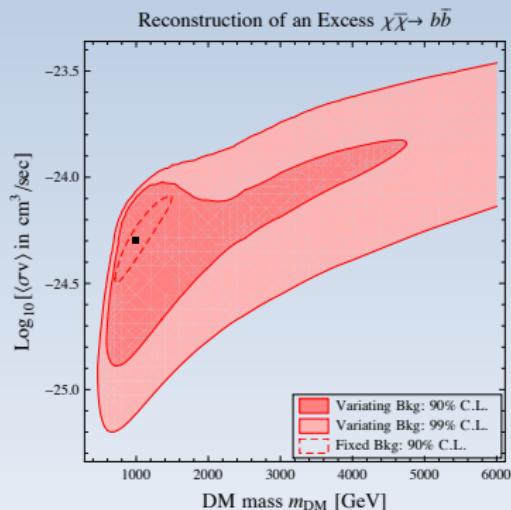
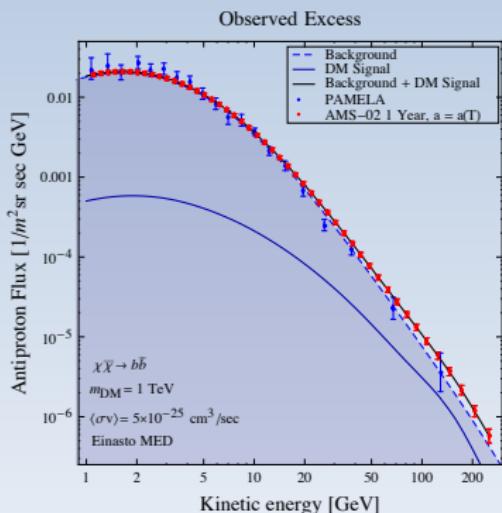
■ $m_{\text{DM}} = 1 \text{ TeV}$ and $\langle \sigma v \rangle = 5 \times 10^{-25} \text{ cm}^3 \text{ s}^{-1}$



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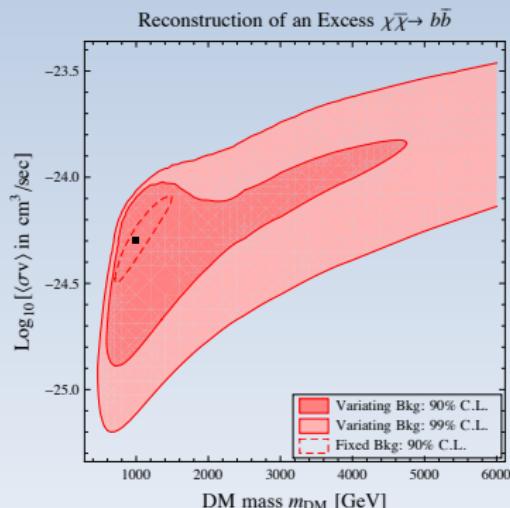
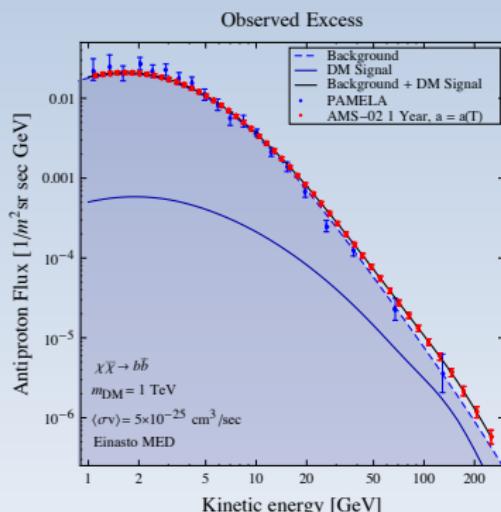
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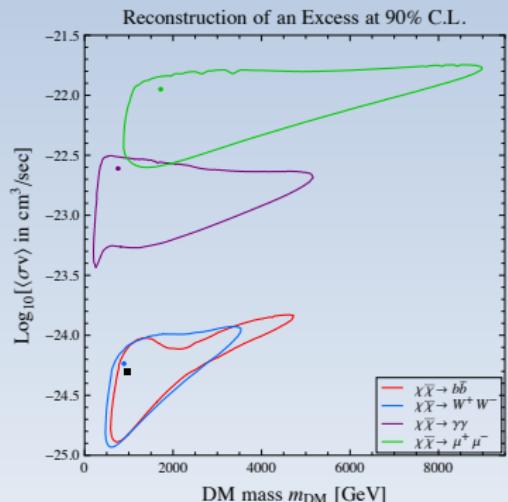
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- 99% C.L. contour extends to high masses
- Any contribution with $m_{\text{DM}} > 1 \text{ TeV}$ can fit the data at 99% C.L. with a cross-section large enough

Future Sensitivities

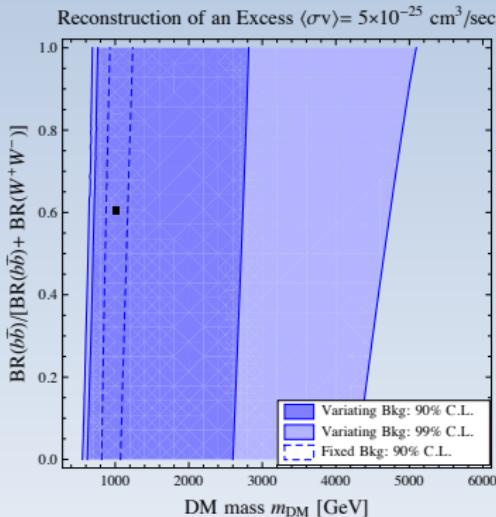
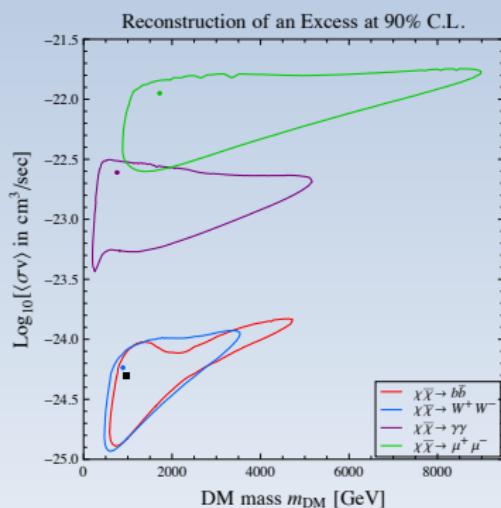
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$\chi\chi \rightarrow b\bar{b}$	999	5×10^{-25}	-15.7
$\chi\chi \rightarrow W^+ W^-$	886	5.8×10^{-24}	-15.1
$\chi\chi \rightarrow \gamma\gamma$	765	2.5×10^{-22}	-14.5
$\chi\chi \rightarrow \mu^+ \mu^-$	1711	1.1×10^{-22}	-14.8

Future Sensitivities

■ $m_{\text{DM}} = 1 \text{ TeV}$ and $\langle \sigma v \rangle = 5 \times 10^{-25} \text{ cm}^3 \text{ s}^{-1}$



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Fixed cross-section $\langle \sigma v \rangle$ [$\text{cm}^3 \text{s}^{-1}$] (true signal : 60% $b\bar{b}$ + 40% $W^+ W^-$)	mass m_{DM} [GeV]	relative branching ratio	$\Delta\chi^2$ with respect to a pure background
5×10^{-25}	999	0.6	-15.3

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- If an excess is measured :
 - Restricting to "traditional" hadronic channels :
 - m_{DM} reconstructed within 50% for $m_{DM} \sim$ few GeV (most favorable case)
 - $\langle\sigma v\rangle$ reconstructed within an order of magnitude
 - If several channels are open, relative branching ratios cannot be determined
 - If "exotic" annihilation channels open, no discrimination

Linear approximation of the rigidity resolution

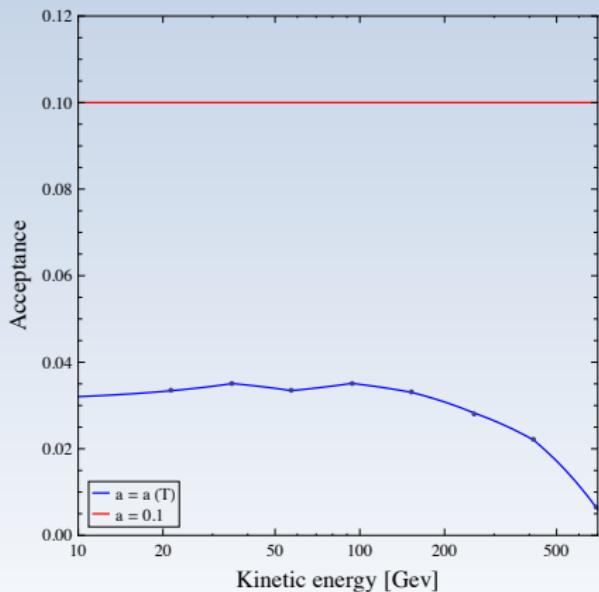
$$r(T) = \frac{\Delta T}{T} = 0.0042 \times T + 0.1$$

The number of collected and reconstructed antiprotons in a bin i centered around a kinetic energy T_i

$$N_i = \epsilon a(T_i) \phi(T_i) \Delta T_i \Delta t$$

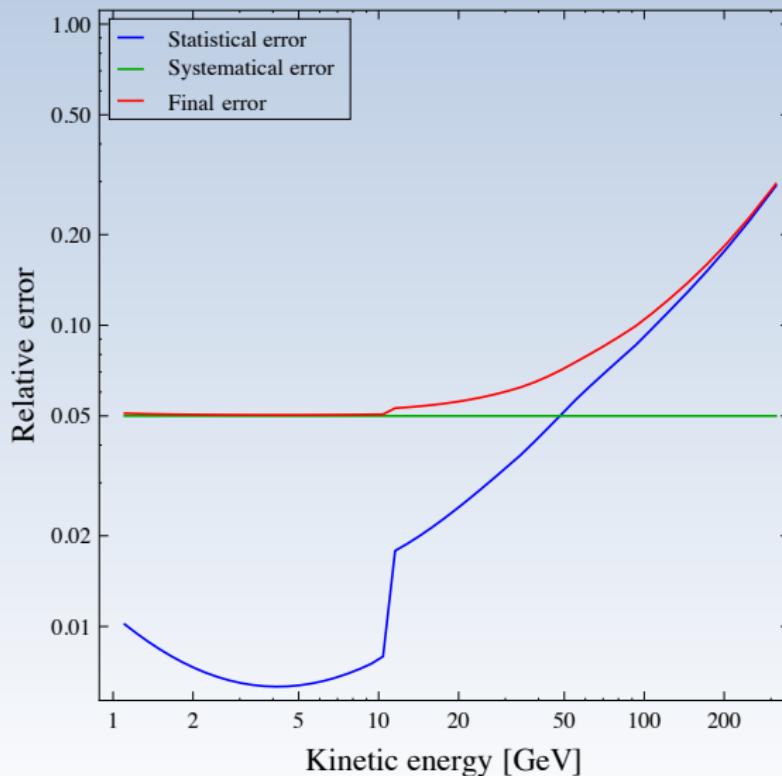
- ϵ the efficiency ($\epsilon = 1$ for protons),
- a the geometrical acceptance of the apparatus,
- ϕ the antiproton flux,
- ΔT the width of the kinetic energy bin and
- Δt the exposure time.

Statistical error : $\Delta N = \sqrt{N} \Rightarrow \Delta \phi_i |_{stat} = \sqrt{\frac{\phi(T_i)}{\epsilon a(T_i) \Delta T_i \Delta t}}$
Systematic errors : $\Delta \phi_i |_{syst} = 0.05 \times \phi_i(T_i)$



Two cases :

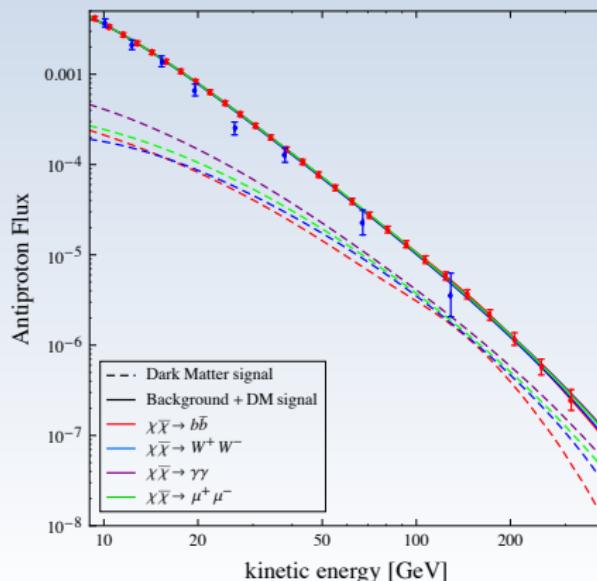
- Realistic
 $\Delta t = 1 \text{ Year}$ and $a = a(T)$,
- Idealistic
 $\Delta t = 3 \text{ Years}$ and $a = 0.1$



Antiproton Fluxes

Real signal : $\chi\bar{\chi} \rightarrow b\bar{b}$, $m_{\text{DM}} = 1 \text{ TeV}$ and $\langle\sigma v\rangle = 5 \times 10^{-25} \text{ cm}^3 \text{s}^{-1}$

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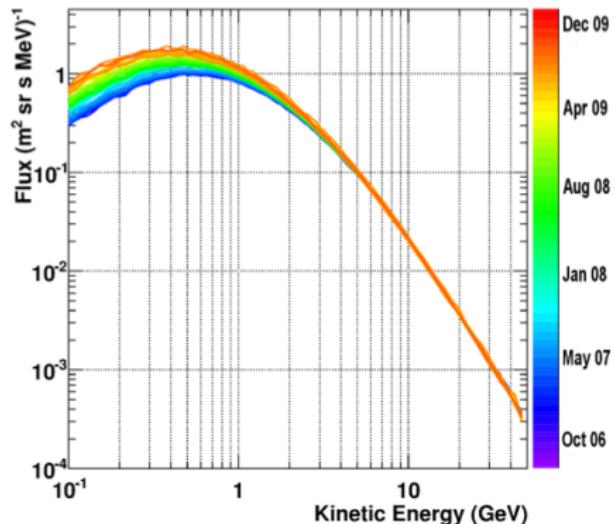


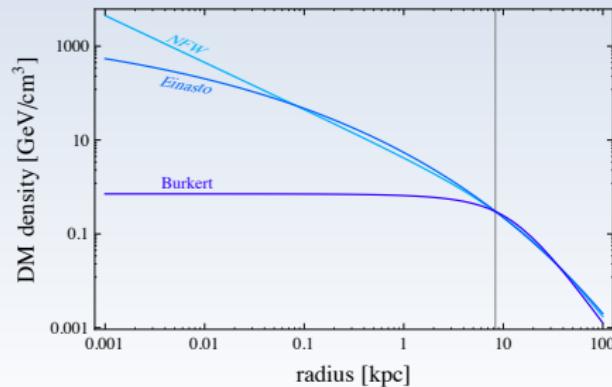
Fig. 4.— The evolution of the proton energy spectrum as particle intensities approached the period of minimum solar activity, from July 2006 (violet), to December 2009 (red). The region between the blue and red curves indicates the spread in proton fluxes during this time.

Dark Matter Halo profiles

$$\rho_{\text{NFW}}(r) = \rho_s \frac{r_s}{r} \left(1 + \frac{r}{r_s}\right)^{-2} \quad r_s = 24.42 \quad \rho_s = 0.184$$

$$\rho_{\text{Ein}}(r) = \rho_s \exp \left\{ -\frac{2}{\alpha} \left[\left(\frac{r}{r_s} \right)^\alpha - 1 \right] \right\} \quad \alpha = 0.17 \quad r_s = 28.44 \quad \rho_s = 0.033$$

$$\rho_{\text{Bur}}(r) = \frac{\rho_s}{(1 + r/r_s)(1 + (r/r_s)^2)} \quad 1r_s = 2.67 \quad \rho_s = 0.712$$



Diffusion equation for the number density of antiprotons per unit energy $f(t, \vec{x}, T)$:

$$\frac{\partial f}{\partial t} - \mathcal{K} \cdot \nabla^2 f + \frac{\partial}{\partial z} (\text{sign}(z) f V_{\text{conv}}) = Q - 2h\delta(z)(\Gamma_{\text{ann}} + \Gamma_{\text{non-ann}})f$$

diffusion term	$\mathcal{K}(T) = \mathcal{K}_0 \beta \left(\frac{p}{\text{GeV}} \right)^\delta$
convective wind	V_{conv}
DM ann/decay source term	Q
annihilation rate of \bar{p} on p	Γ_{ann}
interaction rate of \bar{p}	$\Gamma_{\text{non-ann}}$

Model	δ	\mathcal{K}_0 [kpc ² /Myr]	V_{conv} [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