CALET's Sensitivity to Dark Matter and Astrophysical Sources

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Introduction

- Possible (standard?) explanation by nearby astrophysical accelerator (pulsar) emitting equal amount of electrons and positrons with an exponentially cut-off power law spectrum

- Investigated Question: What limits can be set on Dark Matter Annihilation on top of this nearby pulsar source using CALET data together with AMS-02 positron fraction

- Precise measurement by AMS-02 updated in 2014 with better statistics

- CALET total flux data will be complementary information
Parametrization

\[ \Phi_e = \text{total flux of electron+positron} \quad \Phi_{e^+} = \text{positron only flux} \]

\[ \Phi_e(E) = 2\Phi_{DM}(E) \cdot BF + C_e E^{\gamma_e} \left( 2 \frac{C_s}{C_e} E^{\gamma_s-\gamma_e} \cdot \exp \left( \frac{-E}{E_{\text{cuts}}} \right) + \left( \frac{C_{e^+}}{C_e} \cdot E^{\gamma_{e^+-\gamma_e} + 1} \right) \cdot \exp \left( \frac{-E}{E_{\text{cutd}}} \right) \right) \]

- Power law diffuse background flux with different index for total and secondary positron flux and exponential cutoff from propagation
- Power law spectrum of local accelerator (pulsar) with exponential cutoff and with same coefficient and index for electron and positron flux
- Dark Matter Flux \( \Phi_{DM} \) calculated with DarkSUSY for annihilation x-section \( <\sigma v> = 3 \times 10^{-26} \text{ cm}^3\text{s}^{-1} \)
Single Power Law Fit

- Only small influence of $E_{\text{cuts}}$ on $\chi^2$ above 600 GeV → several values from 600 GeV to 1400 GeV simulated and predicted limits calculated for each case

- Power law difference $\gamma_{e^+} - \gamma_e$ not fixed by fit → simulated and studied limits for $[ -0.3, -0.4, -0.5, -0.6, -0.7 ]$

- Distinct background cases for using AMS positron fraction with AMS total flux (AMS/AMS-Fit) and Fermi total flux (AMS/Fermi-Fit)
Comparison with DRAGON

- Confirmation that the parametrization is in agreement with numerical simulation results for reasonable input parameters
- Background and extra source (Geminga/Monogem) simulated with numerical propagation simulation code DRAGON
- Good agreement (mostly < 10%) for $\gamma_{e^+} - \gamma_e = -\delta = -0.4$
What is DRAGON?

- Numerical cosmic ray propagation simulation similar to GALPROP
- CR source (SNR) distribution follows galaxy's spiral arm structure → nearby sources reduced → exponential cut-off from energy loss
- Non-equidistant grid (0.5 kpc, reduced in steps to 0.01 kpc near source and Solar system)
Adapting DRAGON Results to Parametrization Best Fit

• First background parameters optimized:
  - diffusion coefficient exponent ($\delta$) and normalization ($D$)
    ($\delta = 0.4$, $D = 6.20 \times 10^{28}$ cm$^2$/s @ 4 GeV from 0.3 – 0.7 for $\delta$ and 2.7 – 7.2 for $D$ in steps of 0.5)
  - primary electron normalization
  - proton / secondary electron&positron normalization
    (allowed range: 2% from normalization to PAMELA result)

• Then nearby source parameters optimized:
  - injection power law index (from -1.0 to -2.5 in steps of 0.1 → -2.3 for Monogem, -2.1 for Geminga)
  - source cut-off energy (1 TeV, 3 TeV, 10 TeV → 3 TeV for Monogem, 10 TeV for Geminga)
  - normalization factor
Sensitivity with Binned Analysis

- Assumption that a nearby pulsar (single power law extra source) is the reason for the excess

- Starting from the best single power law fit, the Dark Matter term is added and the boost factor increased while repeating the fit each time to adapt other parameters, until 95%CL exclusion limit reached

- Boost factor limit translated into effective annihilation cross-section by multiplication with $\langle \sigma v \rangle = 3 \times 10^{-26}$ cm$^3$s$^{-1}$

- For each background case (combination of positron fraction and total flux measurement) 100 samples of CALET data were simulated

- Binned analysis of the 100 CALET samples + AMS-02 data

- sensitivity = average value of final boost factor
Limits for 100% $\mu$-channel of AMS-AMS and AMS-Fermi case and change with $E_{\text{cut}}$ and $\gamma_{e^+} - \gamma_e$
Main points shown on this plot

- no large dependence of predicted limits on $\gamma_{e^+} - \gamma_e$.
- small difference if choosing AMS/Fermi background case instead of AMS/AMS
- DM mass dependence depends somewhat on the value of $E_{\text{cut}}$ chosen for the background case, but difference small
- predicted limits clearly exclude explanation of the positron excess by Dark Matter annihilation only
- they are better than extragalactic gamma limits
Overview of Expected Limits for Selected Dark Matter Candidates
Main points shown on this plot

- limits on all DM candidates get better with CALET
- half an order of magnitude for “hard” annihilation spectrum DM candidates (LKP, pure $e^+e^-$)
Conclusion for DM Sensitivity

- **If** CALET measures a smooth power law (with exponential cut-off) spectrum, we can set more stringent limits on Dark Matter annihilation.

  - **Reasons:**
    - Better statistics than AMS-02 also at low energy – mismatch between positron fraction and total flux causes bad
    - High energy data: Important mostly for hard annihilation channels where drop-off contributes to
Alternative to Single Power Law: Multiple nearby sources - PWN

- ATNF - catalogue: position, age, total energy of all discovered pulsars
- Relevant pulsars:
  - Distance < 2 kpc
  - Age < 1e6 yr
  \[\rightarrow 40\text{ pulsars}\]
- Can CALET distinguish multiple pulsars from a single power law source explaining the positron excess?
Prediction for flux from the pulsars in the ATNF catalog which matches PAMELA data under these assumptions:

- Power law index $\gamma = 1.5$
- Injection Cut-off $E_{\text{cut}} = 10$ TeV
- Efficiency $\eta = 0.065$
- Injection instantly at time of pulsar creation
- Total Energy of each pulsar calculated from current spin down luminosity $P_{\text{now}}$ taking into account braking index $k$: $E_0 = \tau_0 P_{\text{now}} (1 + (t/\tau_0))^{(k+1)/(k-1)}$
CR Injection by Pulsar Wind Nebula

- Pulsar Wind Nebula traps particles accelerated by pulsar
- Pulsar has high momentum and leaves SNR after $\sim T = ?*10$ kyr
- Pulsar spin down exponentially with assumed constant $\tau_0 = 1$ kyr
- Total energy in PWN is calculated as the pulsar’s output integrated over $T >> \tau_0$: $E_{PWN} = E_0 \left( T / (T + \tau_0) \right) = \sim E_0$
- PWN dissolves after $<< 100$ kyr → exponential decay and particle injection with $T = 10$ kyr assumed: $P = (E_{PWN} / T) e^{- (T / t)}$
Calculation of PWN Spectrum

- Spectra of 40 PWN simulated with DRAGON for all these parameters:
  
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWN Lifetime</td>
<td>10 / 20 / 40 kyr</td>
</tr>
<tr>
<td>Injection Index</td>
<td>1.0 / 1.3 / 1.5 / 1.7 / 2.0</td>
</tr>
<tr>
<td>Cut-off Energy</td>
<td>0.7 / 1.0 / 1.4 / 2.0 / 3.0 / 5.0 / 7.0 / 10 TeV</td>
</tr>
</tbody>
</table>

- Combined to composite spectrum by random walk to find case which fits AMS data.
- Discrete parameters + efficiency factor from [0.1 .. 1] randomly determined for each PWN.
- Additional global scale factor applied to all pulsars in fitting to AMS data → one order of magnitude variation
- Product is the fraction of the pulsars total energy converted into electron+positron cosmic rays
Multiple Nearby Sources (PWN) 
(combined spectrum example case)
χ2 Distribution of Fitting Single Power Law to Multi-PWN CALET Signal (example case)
χ² Distribution of Fitting Single Power Law to Multi-PWN CALET Signal (100 cases x 500 samples)
Conclusion

- **If** CALET measures a smooth power law (with exponential cut-off) spectrum, we can set more stringent limits on Dark Matter annihilation.
- **If not**, and PWN are responsible for structures in the TEV region, we will be able to recognise this and possibly adapt the background model (apart from hopefully learning about PWN and nearby SNR properties – to be studied in the near future)
BACKUP SLIDES
Statistical error of limits

Natural scale of $\langle \sigma v \rangle$ matching thermal relic density
Final fits for muon channel 1TeV
Final fits for $e^+e^-$ channel 1 TeV