PROPAGATION OF COSMIC RAY POSITRONS
AND DARK MATTER SEARCHES

Mathieu Boudaud
LAPTh - Annecy, France

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Cosmic Ray Alpine Collaboration
M.B., E. F. Bueno, S. Caroff, Y. Génolini, V. Poulin, V. Poireau, A. Putze,
P. Salati and M. Vecchi
The AMS-02 collaboration data (PRL.113.121102) confirm the **positron anomaly**: the high energy part of the positron spectrum cannot be explained by the astrophysical secondary component.
Introduction

The high energy data can be explained adding a dark matter component for the positron flux coming from WIMP particle annihilation.

\[ m_\chi = 27 \text{ TeV} \]

\[ \chi \chi \rightarrow \bar{b}b \]

\[ \langle \sigma v \rangle = 10^{-21} \text{ cm}^3 \text{ s}^{-1} \]

\[ \chi_{dof}^2 = 0.65 \]

Boudaud et al. 2015

\[ \lambda X \rightarrow b\bar{b} \]

\[ \chi^2 / (\text{dof}) = 0.65 \]

\[ \sigma_{\text{tot}} = 1 \times 10^{-21} \text{ cm}^3 \text{ s}^{-1} \]

\[ m_{\chi\text{best}} = 27 \text{ TeV} \]
The high energy data can be explained adding a dark matter component for the positron flux coming from WIMP particle annihilation.

\[ m_\chi = 27 \text{ TeV} \]

\[ \langle \sigma v \rangle = 10^{-21} \text{ cm}^3 \text{s}^{-1} \]

\[ \chi^2_{dof} = 0.65 \]

This scenario is in tension with the antiprotons data…

\[ \chi \chi \rightarrow \bar{b} \bar{b} \]
Introduction

The high energy data can be explained adding a dark matter component for the positron flux coming from WIMP particle annihilation.

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\[ \chi^2_{dof} = 0.65 \]

...and in tension with the gamma rays data.

Lopez et al. 2016

Boudaud et al. 2015
The high energy data can be explained by the presence of one single pulsar in the vicinity of the solar system.

<table>
<thead>
<tr>
<th>Name</th>
<th>Age [kyr]</th>
<th>Distance [kpc]</th>
<th>$fW_0 [10^{54} \text{ GeV}]$</th>
<th>$\gamma$</th>
<th>$\chi^2$</th>
<th>$\chi^2_{\text{ dof}}$</th>
<th>$p$</th>
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<td>J1745−3040</td>
<td>546</td>
<td>0.20</td>
<td>(2.95 ± 0.07) · 10^{-3}</td>
<td>1.45 ± 0.02</td>
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<td>1.4</td>
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<td>1.70 ± 0.02</td>
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<td>1.52</td>
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<td>J1825−0935</td>
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</table>

Demonstrating that the positron fraction data can be explained by a **unique pulsar** contribution provides with a **valid alternative** to the DM explanation of the positron anomaly.

*Boudaud et al. 2015*
All these conclusions are derived from the high energy data points ($E \geq 10$ GeV).

**Why?**

Until now, we can not predict the positron flux below 10 GeV with the classic semi-analytical method. The low energy effects of cosmic propagation are neglected for the calculation of the positron flux.
I - The propagation of cosmic rays in the Galaxy and the semi-analytical method
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The two-zone model

\[ 1 < L < 15 \text{ kpc} \]

\[ K(E) = K_0 \beta \left( \frac{R}{1 \text{ GV}} \right)^\delta \]

\[ \vec{V}_C = V_C \text{ sign}(z) \vec{e}_z \]

\[ K_{EE}(E) = \frac{2}{9} V_A^2 \frac{E^2 \beta^4}{K(E)} \]

\[ \psi(E, t, \vec{x}) \equiv \frac{d^4N}{d^3x \, dE} \]

Cosmic rays transport equation

\[ \partial_t \psi - K(E) \Delta \psi + \partial_z [V_C \text{ sign}(z) \psi] + \partial_E [b(E, \vec{x}) \psi - K_{EE}(E, \vec{x}) \partial_E \psi] = Q(E, t, \vec{x}) \]

\[ Q(E, t, \vec{x}) = Q^{\text{source}}(E, t, \vec{x}) - Q^{\text{sink}}(E, \vec{x}) \]
The two-zone model

Cosmic rays nuclei

The energy losses processes take place only in the Galactic disk.

\[
\psi(E, t, \vec{x}) \equiv \frac{d^4 N}{d^3 x \, dE}
\]

Cosmic rays transport equation

\[
\partial_t \psi - K(E) \Delta \psi + \partial_z \left[ V_C \, \text{sign}(z) \, \psi \right] + 2h \, \delta(z) \, \partial_E \left[ b(E) \, \psi - K_{EE}(E) \, \partial_E \psi \right] = Q(E, t, \vec{x})
\]

The transport equation can be solved in a semi-analytical way using the Bessel formalism.

*Maurin et al. 2001*
I - The propagation of cosmic ray in the Galaxy and the semi-analytical method

The two-zone model

\[ 1 < L < 15 \text{ kpc} \]

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Maurin et al. 2001
Donato et al. 2003

<table>
<thead>
<tr>
<th>Case</th>
<th>( \delta )</th>
<th>( K_0 ) [kpc(^2)/Myr]</th>
<th>( L ) [kpc]</th>
<th>( V_C ) [km/s]</th>
<th>( V_\alpha ) [km/s]</th>
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<tr>
<td>MIN</td>
<td>0.85</td>
<td>0.0016</td>
<td>1</td>
<td>13.5</td>
<td>22.4</td>
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<tr>
<td>MED</td>
<td>0.70</td>
<td>0.0112</td>
<td>4</td>
<td>12</td>
<td>52.9</td>
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<tr>
<td>MAX</td>
<td>0.46</td>
<td>0.0765</td>
<td>15</td>
<td>5</td>
<td>117.6</td>
</tr>
</tbody>
</table>
The two-zone model

Cosmic rays electrons and positrons
The energy losses processes take place in all the magnetic halo. We cannot use the same method as for nuclei.

For $E \gtrsim 10$ GeV the main processes electrons and positrons undergo are:

- Diffusion
- Energy losses from IC scattering and synchrotron emission
I - The propagation of cosmic ray in the Galaxy and the semi-analytical method

The two-zone model

Cosmic rays electrons and positrons
The energy losses processes take place in all the magnetic halo. We cannot use the same method as for nuclei.

The high-energy ($E \gtrsim 10$ GeV) approximation:

$$\partial_t \psi - K(E) \Delta \psi + \partial_z \left[ V_C \text{sign}(z) \psi \right] + \partial_E \left[ b(E, \bar{x}) \psi - K_{EE}(E, \bar{x}) \partial_E \psi \right] = Q(E, t, \bar{x})$$

High energy electrons transport equation

$$\partial_t \psi - K(E) \Delta \psi + \partial_E \left[ b(E) \psi \right] = Q(E, t, \bar{x})$$
The astrophysical component of secondary positrons

\[ Q^{\Pi}(E, \vec{x}) = 4\pi \sum_{i=p,\alpha} \sum_{j=H,He} n_j \int_{E_0}^{+\infty} dE_i \phi_i(E_i, \vec{x}) \frac{d\sigma}{dE_i}(E_j \rightarrow E) \quad \begin{cases} \text{i = projectile} \\ j = \text{target} \end{cases} \]

• Measured spectra of primary cosmic ray proton and helium at the Earth.

AMS-02 data: PRL.114.171103, PRL.115.211101

See Manuela Vecchi’s talk @ TeVPa 2016

• Positron production cross-section from pp interactions.

Kamae et al. (2006)
I - The propagation of cosmic ray in the Galaxy and the semi-analytical method

The astrophysical component of secondary positrons

\[ Q^\Pi(E, \vec{x}) = 4\pi \sum_{i=p,\alpha} \sum_{j=H,He} n_j \int_{E_0}^{+\infty} dE_i \phi_i(E_i, \vec{x}) \frac{d\sigma}{dE_i}(E_j \to E) \]

\begin{align*}
&\left\{ \begin{array}{l}
p + \Delta^+ \\
\Delta^+ \to n + \pi^+ \\
\pi^+ \to \nu_\mu + \mu^+ \\
\mu^+ \to \bar{\nu}_\mu + \nu_e + e^+
\end{array} \right. \\
\left\{ \begin{array}{l}
p + p \\
P + \pi^+ \\
\pi^+ \to \nu_\mu + \mu^+ \\
\mu^+ \to \bar{\nu}_\mu + \nu_e + e^+
\end{array} \right. \\
\left\{ \begin{array}{l}
x + \pi^+ \\
\pi^+ \to \nu_\mu + \mu^+ \\
\mu^+ \to \bar{\nu}_\mu + \nu_e + e^+
\end{array} \right. \\
\left\{ \begin{array}{l}
x + K^+ \\
\nu_\mu + \mu^+ \\
\mu^+ \to \bar{\nu}_\mu + \nu_e + e^+
\end{array} \right. \\
\left\{ \begin{array}{l}
x + K^+ \\
\pi^0 + \pi^+ \\
\pi^+ \to \nu_\mu + \mu^+ \\
\mu^+ \to \bar{\nu}_\mu + \nu_e + e^+
\end{array} \right. \\
\left\{ \begin{array}{l}
x + K^+ \\
K^+ \to \pi^0 + \pi^+ \\
\pi^+ \to \nu_\mu + \mu^+ \\
\mu^+ \to \bar{\nu}_\mu + \nu_e + e^+
\end{array} \right.
\end{align*}
I - The propagation of cosmic ray in the Galaxy and the semi-analytical method

The astrophysical component of secondary positrons

\[ Q_{\Pi}^{\Pi}(E, \vec{x}) = 4\pi \sum_{i=p, \alpha} \sum_{j=H, He} n_j \int_{E_0}^{+\infty} dE_i \phi_i(E_i, \vec{x}) \frac{d\sigma}{dE_i}(E_j \rightarrow E) \]

\[ \left\{ \begin{array}{l}
  i = \text{projectile} \\
  j = \text{target}
\end{array} \right. \]

\[
\begin{align*}
p + \Delta^+ & \rightarrow n + \pi^+ \\
\Delta^+ & \rightarrow \nu_\mu + \mu^+ \\
\pi^+ & \rightarrow \bar{\nu}_\mu + \nu_e + e^+ \\
X + \pi^+ & \rightarrow \nu_\mu + \mu^+ \\
\mu^+ & \rightarrow \bar{\nu}_\mu + \nu_e + e^+ \\
X + K^+ & \rightarrow \nu_\mu + \mu^+ \\
\mu^+ & \rightarrow \bar{\nu}_\mu + \nu_e + e^+ \\
K^+ & \rightarrow \pi^0 + \pi^+ \\
\pi^+ & \rightarrow \nu_\mu + \mu^+ \\
\mu^+ & \rightarrow \bar{\nu}_\mu + \nu_e + e^+ 
\end{align*}
\]
II - Full treatment of positron propagation using the pinching method of high energy losses
We cannot solve analytically the transport equation when energy losses processes take place in different places.
II - Full treatment of positron propagation using the pinching method of high energy losses

Cosmic rays transport equation (steady state)

\[-K(E)\Delta \psi + \partial_z [V_C \text{sign}(z) \psi] + \partial_E [b(E, \bar{x}) \psi - K_{EE}(E, \bar{x}) \partial_E \psi] = Q(E, \bar{x})\]

\[b_{\text{disc}} = b_{\text{adia}} + b_{\text{ioni}} + b_{\text{brem}} + b_{\text{coul}}\]

\[b_{\text{halo}} = b_{\text{IC}} + b_{\text{sync}}\]

\[-K(E)\Delta \psi + \partial_z [V_C \text{sign}(z) \psi] + 2h \delta(z) \partial_E \left\{b_{\text{disc}}(E) + b_{\text{eff, halo}}(E)\right\} \psi - K_{EE}(E) \partial_E \psi = Q\]
II - Full treatment of positron propagation using the pinching method of high energy losses

\[-K(E)\Delta\psi + \partial_z [V_C \text{sign}(z)\psi] + 2h \delta(z) \partial_E \left\{ \left[ b_{\text{disc}}(E) + b^{\text{eff}}_{\text{halo}}(E) \right] \psi - K_{EE}(E) \partial_E \psi \right\} = Q\]

\[b_{\text{halo}} = b_{IC} + b_{\text{sync}} \quad \Rightarrow \quad b^{\text{eff}}_{\text{halo}}(E, r) = \bar{\xi}(E, r) b_{\text{halo}}(E)\]

The pinching factor for secondary positrons.

From now we are able to compute the positron flux including all propagation effects!
II - Full treatment of positron propagation using the pinching method of high energy losses

The astrophysical component of secondary positrons.

High energy approximation
II - Full treatment of positron propagation using the pinching method of high energy losses

The astrophysical component of secondary positrons.

Full calculation

\[ E^3 \phi_{e^+} \propto [s^{-1} \text{cm}^{-2} \text{sr}^{-1} \text{GeV}^2] \]

\[ \phi_F = 724 \text{MV} \]

AMS-02

Preliminary

MED

Propagation uncertainty

Positron Energy E [GeV]
II - Full treatment of positron propagation using the pinching method of high energy losses

The astrophysical component of secondary positrons.

The high energy approximation is no longer valid to derive conclusions from the AMS-02 data!
II - Full treatment of positron propagation using the pinching method of high energy losses

The astrophysical component of secondary positrons.

Full calculation

$E^3 \Phi_{e^+}^H \left[ \text{s}^{-1} \text{cm}^{-2} \text{sr}^{-1} \text{GeV}^{-2} \right]$

AMS-02

Preliminary

$\phi_F = 724 \text{MV}$

- MED
- Propagation uncertainty

Positron Energy $E$ [GeV]
III - The positron secondary component and the AMS-02 data: consequences for the propagation parameters
The low energy positrons can be used in order to shrink the space of propagation parameters. \textit{Lavalle et al. 2014}

We exclude all the sets of propagation parameters compatible with the B/C that overshoot the AMS-02 positron data more than 3 $\sigma$ CL.

The low energy part of the spectrum is affected by the solar modulation. To be conservative we maximise the solar effect with $\phi_F = \phi_F^0 + 3 \sigma$, $\phi_F^0 = 724$ GV \textit{Ghelfi et al. 2015}
The low energy part of the spectrum is affected by the solar modulation effect. To be conservative we maximise the solar effect with $\phi_F = \phi_F^0 + 3\sigma$.

We exclude all the sets of propagation parameters compatible with the B/C that overshoot the AMS-02 positron data more than $3\sigma$ CL.

The AMS-02 positron prefer the MAX-type sets of propagation parameters.
The astrophysical component of secondary positrons compatible at $3 \sigma$ CL with the AMS-02 data.

We need an additional component of positrons in order to explain the AMS-02 data.
IV - The dark matter scenario and the positron AMS-02 data

Does the dark matter scenario still viable to explain the AMS-02 data?
IV - The dark matter scenario and the positron AMS-02 data

\[ \chi \chi \longrightarrow B_b \bar{b}b + B_W W^+W^- + B_{\tau} \tau^+\tau^- + B_{\mu} \mu^+\mu^- + B_e e^+e^- \]

\[ Q^{\text{DM}}_{e^+}(E, \bar{x}) = \left( \frac{\rho(\bar{x})}{m_\chi} \right)^2 \times \frac{1}{2} \sum_i \langle \sigma v \rangle B_i \frac{dN_i(E)}{dE} \]

\( \rho(\bar{x}) \): DM density profile

Navarro Frenk White

\( \frac{dN_i}{dE} \): e+ spectrum at source

MicrOMEGAs
IV - The dark matter scenario and the positron AMS-02 data

We scan over:

- the DM mass range \( m_\chi \in [100 \text{ GeV}, 1 \text{ TeV}] \)
- all the sets of propagation parameters left
- the Fisk potential range \( \phi_F \in [647, 830] \text{ MV} \) (3 \( \sigma \) CL)

we fit the dark matter parameters (\( \langle \sigma v \rangle, B_b, B_W, B_\tau, B_\mu, B_e \)) on the AMS-02 data.

The AMS-02 positron data can not be explained by the dark matter scenario!
Conclusions and outlook

• We provide a new method to deal with the propagation of low energy positrons. We are now able to predict the positron flux over all the AMS-02 energy range.

• The positron data favour the MAX-type sets of propagation parameters with a large halo size (L > 10 kpc). This conclusion was already pointed out by the antiprotons data. See Pierre Salati’s talk @ TeVPa 2016

• We compute the astrophysical component of secondary positrons. The positron excess appears from 1 GeV.

• The dark matter scenario is no longer viable to explain the positron excess.

Thank you for your attention!
Conclusions and outlook

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I - The propagation of cosmic ray in the Galaxy and the semi-analytical method

II - Full treatment of positron propagation using the pinching method of high energy losses

III - The positron secondary component and the AMS-02 data: consequences for the propagation parameters

IV - The positron dark matter scenario and the AMS-02 data
II - Full treatment of positron propagation using the pinching method of high energy losses

\[-K(E)\Delta \psi + \partial_z [V_C \text{sign}(z) \psi] + 2\hbar \delta(z) \partial_E \left\{ \left[ b_{\text{disc}}(E) + b_{\text{halo}}^{\text{eff}}(E) \right] \psi - K_{EE}(E) \partial_E \psi \right\} = Q\]

\[b_{\text{halo}} = b_{\text{IC}} + b_{\text{sync}} \quad \Rightarrow \quad b_{\text{halo}}^{\text{eff}}(E, r) = \bar{\xi}(E, r) b_{\text{halo}}(E)\]

\[\bar{\xi}(E, r) = \frac{1}{\psi(E, r, 0)} \sum_{i=1}^{+\infty} J_0(\alpha_i \frac{r}{R}) \bar{\xi}_i(E) P_i(E, 0)\]

\[\bar{\xi}_i(E) = \frac{+\infty}{\int_E dE} \left[ J_i(E_S) + 4k_i^2 \int_{E}^{E_S} dE' \frac{K(E')}{b(E')} B_i(E', E_S) \right] \frac{+\infty}{\int_E dE} B_i(E, E_S)\]
II - Full treatment of positron propagation using the pinching method of high energy losses

\[-K(E)\Delta \psi + \partial_z [V_C \text{sign}(z) \psi] + 2h \delta(z) \partial_E \left\{ b_{\text{disc}}(E) + b_{\text{halo}}^{\text{eff}}(E) \right\} \psi - K_{EE}(E) \partial_E \psi \right\} = Q \]

\[b_{\text{halo}} = b_{\text{IC}} + b_{\text{sync}} \quad \Rightarrow \quad b_{\text{halo}}^{\text{eff}}(E, r) = \bar{\xi}(E, r) b_{\text{halo}}(E)\]

The error we commit pinching the halo energy losses is smaller than 0.1%.

From now we are able to compute the positron flux including all propagation effects!
We scan over:

- the mass range $m_\chi \in [100 \text{ GeV}, 1 \text{ TeV}]
- all the set of propagation parameters left
- the Fisk potential range $\phi_F \in [647, 830] \text{ MV} \ (3 \sigma \text{ CL})$

we fit the dark matter parameters ($\langle \sigma v \rangle$, $B_b$, $B_W$, $B_\tau$, $B_\mu$, $B_e$) on the AMS-02 data.

Best fit:

$m_\chi = 264 \text{ GeV}$

$\langle \sigma v \rangle = 8 \times 10^{-24} \text{ cm}^3 \text{ s}^{-1}$

$B_b = 92\%$

$B_\mu = 3\%$

$B_e = 5\%$

$p = 0.4\%$