What can we learn from cosmic ray antimatter?

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Frankfurt, Feb 2019
Cosmic Rays

The Universe is filled with a gas of high-energy particles.
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Cosmic Rays

Two basic populations:

1. **primary** (p, He, C, O, Fe, e-,...),

2. **secondary** (B, sub-Fe, pbar, e+,...),
Cosmic Rays

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1. **primary** (p, He, C, O, Fe, e-,…), stellar material, accelerated to high energy

2. **secondary** (B, sub-Fe, pbar, e+,…),

Hillas, astro-ph/0607109

Galactic
Cosmic Rays

Two basic populations:

1. **primary** ($p$, He, C, O, Fe, e-,...), stellar material, accelerated to high energy

2. **secondary** (B, sub-Fe, pbar, e+,...), spallation products of primary component
CR antimatter – $\bar{p}$, $e^+$, $\bar{d}$, and $^3\text{He}$ – long thought a smoking gun of exotic high-energy physics like dark matter annihilation
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A host of experiments out there to detect it
CR antimatter – $\bar{p}$, $e^+$, $\bar{d}$, and $^3\text{He}$ – long thought a smoking gun of exotic high-energy physics like dark matter annihilation

AMS02, Dec 2016

**Antiproton-to-proton ratio**

The excess of antiprotons observed by AMS cannot come from pulsars.

It can be explained by Dark Matter collisions or by new astrophysics phenomena.
CR antimatter – \( \bar{\rho}, e^+, \bar{d}, \) and \( ^3\text{He} \) – long thought a smoking gun of exotic high-energy physics like dark matter annihilation.

AMS02, Dec 2016

The AMS results are in excellent agreement with a Dark Matter Model.
Plan
Plan

**Antiprotons**
Confusion in the literature, as to what and how we can calculate.  
=> will try to sort this out

**Positrons**
Common belief: $e^+$ from pulsars or dark matter!
=> *don’t think so.* Will try to sort this out, too

**Anti-He, anti-D**
Thought so scarce that a single event would mark new physics.
=> link to LHC
antimatter is produced in collisions of the bulk of the CRs — protons and He — with interstellar gas.

Need to calculate this background to learn about possible exotic sources.
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Need to calculate this background to learn about possible exotic sources.

**Problem**: we don’t know where CRs come from, nor how long they are trapped in the Galaxy, nor how they eventually escape.

This problem is often under-stated...
About diffusion models

\[ K \sim (E/Z)^\delta \]

NGC 891

Interstellar matter is far from homogeneous.
On ~Myr time scales, it is also far from steady-state
antimatter is produced in collisions of the bulk of the CRs — protons and He — with interstellar gas.

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antimatter is produced in collisions of the bulk of the CRs — protons and He — with interstellar gas.

For stable, relativistic secondary CR nuclei, we have a handle: branching fractions

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\frac{n_a(R)}{n_b(R)} \approx \frac{Q_a(R)}{Q_b(R)}
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\[ \frac{n_a(R)}{n_b(R)} \approx \frac{Q_a(R)}{Q_b(R)} \]
Apply this to antiprotons

\[
n_{\bar{p}}(\mathcal{R}) \approx \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})} Q_{\bar{p}}(\mathcal{R})
\]
Apply this to antiprotons

\[ n_\bar{p}(R) \approx \frac{n_B(R)}{Q_B(R)} Q_\bar{p}(R) \]

\( \sigma(\text{pp} \rightarrow \text{pbar}), 20\% \)
\( \sigma(^{12}\text{C} \rightarrow ^{11}\text{B}), 20\% \)
\( \Phi, (0.2-0.8) \text{ GV} \)
Apply this to antiprotons

\[ n_\bar{p}(R) \approx \frac{n_B(R)}{Q_B(R)} Q_\bar{p}(R) \]

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\( \sigma(^{12}\text{C}\rightarrow^{11}\text{B}), 20\% \)
\( \Phi, (0.2-0.8)\text{ GV} \)

AMS02 2016

Note: neither the over-all CR intensity, nor the target ISM density, needs to be uniform in the propagation region in order for Eq. (1) to apply. Indeed, the ISM exhibits orders of magnitude variations in density across the Galactic gas disc and rarified halo [31].
Antiprotons are probably secondary.

\[ n_{\bar{p}}(\mathcal{R}) \approx \frac{n_{B}(\mathcal{R})}{Q_{B}(\mathcal{R})}Q_{\bar{p}}(\mathcal{R}) \]
What about e+ ?
Towards Understanding the Origin of Cosmic-Ray Positrons

(AMS Collaboration)

Precision measurements of cosmic ray positrons are presented up to 1 TeV based on 1.9 million positrons collected by the Alpha Magnetic Spectrometer on the International Space Station. The positron flux exhibits complex energy dependence. Its distinctive properties are (a) a significant excess starting from $25.2 \pm 1.8$ GeV compared to the lower-energy, power-law trend, (b) a sharp dropoff above $284^{+91}_{-64}$ GeV, (c) in the entire energy range the positron flux is well described by the sum of a term associated with the positrons produced in the collision of cosmic rays, which dominates at low energies, and a new source term of positrons, which dominates at high energies, and (d) a finite energy cutoff of the source term of $E_s = 810^{+310}_{-180}$ GeV is established with a significance of more than 4σ. These experimental data on cosmic ray positrons show that, at high energies, they predominantly originate either from dark matter annihilation or from other astrophysical sources.

DOI: 10.1103/PhysRevLett.122.041102
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FIG. 5: 

The measured $e^+ / \bar{p}$ flux ratio does not exceed and is always comparable – within about a factor of two – to the secondary upper bound. Moreover, the $e^+ / \bar{p}$ ratio saturates the bound over an extended range in rigidity. The most natural interpretation of this result, is that the coincidence of the measured $e^+ / \bar{p}$ ratio with the ratio of the production rates $(pp \rightarrow e^+ + \bar{p}) / (pp \rightarrow \bar{p})$ is not an accident. Taking into account that, as we saw in the previous section, $\bar{p}$ are likely of secondary origin (certainly dominated by secondary production), it is natural to deduce that AMS02 is observing secondary $e^+$ as well.

A compatible but less robust way to represent the secondary $e^+$ upper bound is by computing the zero-loss secondary $e^+$ flux directly from the B/C grammage, as we did for $\bar{p}$ in Fig. 2. Namely, we write

$$n_{e^+} (\mathcal{R}) \lesssim \frac{n_B (\mathcal{R})}{Q_B (\mathcal{R})} Q_{e^+} (\mathcal{R})$$

We stress that, similarly to the $\bar{p}/p$ situation exhibited in Fig. 3, Eq. (9) is much more sensitive to the unknown CR spectra in the spallation regions than is the $e^+ / \bar{p}$ ratio of Fig. 5. Nevertheless, to make contact with common presentations of the data in the literature and to exploit the higher energy $e^+$ data reported by AMS02 [60], we show in Fig. 6 the secondary upper bound on $e^+$ derived Eq. (9).
FIG. 5: $e^+ / \bar{p}$ flux ratio: AMS02 data compared to the secondary upper bound of Eq. (8). The upper bound ($e^+ / \bar{p}$ source ratio) is shown with different assumptions for the proton spectrum in the secondary production regions. Systematic cross section uncertainties in $pp \rightarrow \bar{p}, e^+$, not shown in the plot, are in the ballpark of 10%. Dashed black line shows the result evaluated for the locally measured $J_p$, while blue and green lines show the result for harder and softer proton flux, respectively, as specified in the legend. Taken from [59].

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Secondary upper bound

\[ n_{e^+}(R) \lesssim \frac{n_B(R)}{Q_B(R)} Q_{e^+}(R) \]

**FIG. 5:** $e^+/\bar{p}$ flux ratio: AMS02 data compared to the secondary upper bound of Eq. (8). The upper bound ($e^+/\bar{p}$ source ratio) is shown with different assumptions for the proton spectrum in the secondary production regions. Systematic cross section uncertainties in $pp \to \bar{p}, e^+$, not shown in the plot, are in the ballpark of 10%. Dashed black line shows the result evaluated for the locally measured $J_p$, while blue and green lines show the result for harder and softer proton flux, respectively, as specified in the legend. Taken from [59].

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FIG. 5: \( e^+ / \overline{p} \) flux ratio: AMS02 data compared to the secondary upper bound of Eq. (8). The upper bound (\( e^+ / \overline{p} \) source ratio) is shown with different assumptions for the proton spectrum in the secondary production regions. Systematic cross section uncertainties in \( p p \rightarrow \overline{p}, e^+ \), not shown in the plot, are in the ballpark of 10%. Dashed black line shows the result evaluated for the locally measured \( J_p \), while blue and green lines show the result for harder and softer proton flux, respectively, as specified in the legend. Taken from [59].

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We stress that, similarly to the \( \overline{p} / p \) situation exhibited in Fig. 3, Eq. (9) is much more sensitive to the unknown CR spectra in the spallation regions than is the \( e^+ / \overline{p} \) ratio of Fig. 5. Nevertheless, to make contact with common presentations of the data in the literature and to exploit the higher energy \( e^+ \) data reported by AMS02 [60], we show in Fig. 6 the secondary upper bound on \( e^+ \) derived Eq. (9).
Secondary upper bound

\[ n_{e^+}(\mathcal{R}) \lesssim \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})} Q_{e^+}(\mathcal{R}) \]

**AM02 2013**

![Graph showing the secondary upper bound of Eq. (8). The upper bound (e+/\bar{p} source ratio) is shown with different assumptions for the proton spectrum in the secondary production regions. Systematic cross section uncertainties in pp!\bar{p}, e+, not shown in the plot, are in the ballpark of 10%. Dashed black line shows the result evaluated for the locally measured Jp, while blue and green lines show the result for harder and softer proton flux, respectively, as specified in the legend. Taken from [59].

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AMS02 2019

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e+ are probably secondary.

\[ n_{e^+}(R) \lesssim \frac{n_B(R)}{Q_B(R)} Q_{e^+}(R) \]
Why would dark matter or pulsars inject *this* $e^+$ flux?
Why would dark matter or pulsars inject \textit{this} e$^+$ flux?
Why would dark matter or pulsars inject this e+ flux?

Observational evidence that CR antimatter is secondary, coming from collisions of CRs on ISM.
At $R<100$ GV, $e^+$ flux lies below the bound, suggesting $t_{esc} > t_{cool}$.
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At $R>100$ GV, $e^+$ flux saturates the bound, suggesting $t_{esc} < t_{cool}$
What is the radiative cooling time of CR e+?
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At $R<100$ GV, $e^+$ flux lies below the bound, suggesting $t_{esc} > t_{cool}$

At $R>100$ GV, $e^+$ flux saturates the bound, suggesting $t_{esc} < t_{cool}$
At R\textless{}10 GV, e\(^{+}\) flux lies below the bound, suggesting \(t_{\text{esc}} > 10 \text{ Myr}\)

At R\textgreater{}100 GV, e\(^{+}\) flux saturates the bound, suggesting \(t_{\text{esc}} < t_{\text{cool}}\)

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Popescu (2017)
Porter (2017) R12
Porter (2017) F98

\(B=6 \mu \text{G}\)
\(B=1 \mu \text{G}\)
At $R \sim 10$ GV, e+ flux lies below the bound, suggesting $t_{\text{esc}} > 10$ Myr

At $R \sim 600$ GV, e+ flux saturates the bound, suggesting $t_{\text{esc}} < 0.5$ Myr
It appears likely that some transition in CR propagation takes place around $R \sim 100$ GV.

e+ are not the only CR species for which something like this may be inferred.
It appears likely that some transition in CR propagation takes place around $R \approx 100$ GV.

$e^+$ are not the only CR species for which something like this may be inferred.

Cosmic ray grammage $X_{\text{esc}}$, derived from B/CNO...
anti He3
anti He3

Handful of events?

AMS02, Dec 2016

An anti-Helium candidate:

Momentum = 40.3 ± 2.9 GeV/c
Charge = -2
Mass = 2.96 ± 0.33 GeV/c^2
Velocity = 0.9973 ± 0.0005 c
**anti He3**

Handful of events?

Recently (2018):
AMS report
2 anti-He4 candidates,
And 6 anti-He3 candidates.
anti He3

Handful of events?

Recently (2018):
AMS report
2 anti-He4 candidates,
And 6 anti-He3 candidates.

Not clear if true CR events,
or rare experimental background.

Need to reject freak background
events at a level of ~ 1:100M...

Take it as motivation for theory
examination of astro flux.
The difficult part is to get the cross section right.

Coalescence ansatz:

\[ E_A \frac{dN_A}{d^3p_A} = B_A R(x) \left( E_p \frac{dN_p}{d^3p_p} \right)^A \]

We need \( B_3 \)
The difficult part is to get the cross section right.

Coalescence ansatz:

\[ E_A \frac{dN_A}{d^3p_A} = B_A R(x) \left( E_p \frac{dN_p}{d^3p_p} \right)^A \]

We need \( B_3 \)
For pp we had no $B_3$
For pp we had no $B_3$
For pp we had no $B_3$
For pp we had no $B_3$
For pp we had no $B_3$
For pp we had no $B_3$, but we did have HBT

\[
\frac{B_A}{m^{2(A-1)}} \approx \frac{2J_A + 1}{2^A \sqrt{A}} \left( \frac{m R}{\sqrt{2\pi}} \right)^{3(1-A)}
\]

Scheibl & Heinz, PRC59, 1585 (1999)
KB et al, Phys.Rev. D96 (2017) no.10, 103021
KB & Takimoto, 1901.07088
For pp we had no $B_3$ until Sep 26, 2017

KB et al, Phys.Rev. D96 (2017) no.10, 103021

ALICE, PRC97, 024615 (2018)
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Relevant for cosmic rays: low pt
For pp we had no $B_3$ until Sep 26, 2017

Relevant for cosmic rays: low pt

Production of deuterons, tritons, $^3$He nuclei and their anti-nuclei in pp collisions at $\sqrt{s} = 0.9, 2.76$ and 7 TeV

ALICE, PRC97, 024615 (2018)
Implications of ALICE results for astrophysics:

1 anti-He3 at AMS02, in 5-year exposure: plausible.

6 anti-He3 events: not plausible.
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2 anti-He4?
Implications of ALICE results for astrophysics:

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2 anti-He4?
What can we learn from cosmic ray antimatter?
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Evidence that CR antimatter is secondary: coming from CR collisions with ISM. Certainly no clear hint of BSM.

AMS is in really good company in this respect.
What can we learn from cosmic ray antimatter?

Evidence that CR antimatter is secondary: coming from CR collisions with ISM. Certainly no clear hint of BSM.

But the CR astrophysics is very interesting:

Where do CR come from?
How long are they trapped in the Galaxy?
How do they escape?

When you build a CR experiment, these are the bread-and-butter questions on which you may hope to contribute*.

* Barring, of course, unexpected strokes of luck. These are always possible, but can’t be counted on.
What can we learn from cosmic ray antimatter?

* Barring, of course, unexpected strokes of luck?
Xtra
Production of deuterons, tritons, $^3$He nuclei and their anti-nuclei in pp collisions at $\sqrt{s} = 0.9$, 2.76 and 7 TeV

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Production of deuterons, tritons, $^3$He nuclei and their anti-nuclei in pp collisions at $\sqrt{s} = 0.9, 2.76$ and $7$ TeV

ALICE Collaboration

KB et al, Phys.Rev. D96 (2017) no.10, 103021
antimatter is produced in collisions of the bulk of the CRs -- protons and He -- with interstellar gas

For secondary CR, we have a handle: particle physics branching fractions

\[
\frac{n_a(\mathcal{R})}{n_b(\mathcal{R})} \approx \frac{Q_a(\mathcal{R})}{Q_b(\mathcal{R})}
\]

\[
Q_a(\mathcal{R}) = \sum_P n_P(\mathcal{R}) \frac{\sigma_{P\rightarrow a}(\mathcal{R})}{m} - n_a(\mathcal{R}) \frac{\sigma_a(\mathcal{R})}{m}
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Q_a(R) = \sum_P n_P(R) \frac{\sigma_{P\rightarrow a}(R)}{m} - n_a(R) \frac{\sigma_a(R)}{m}
\]
Recipe for antiproton pie:

\[
\frac{n_a(R)}{n_b(R)} \approx \frac{Q_a(R)}{Q_b(R)} \quad \Rightarrow \quad n_p(R) \approx \frac{n_B(R)}{Q_B(R)} Q_p(R)
\]
Recipe for antiproton pie:

\[
\frac{n_a(\mathcal{R})}{n_b(\mathcal{R})} \approx \frac{Q_a(\mathcal{R})}{Q_b(\mathcal{R})} \quad \Rightarrow \quad n_\bar{p}(\mathcal{R}) \approx \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})} Q_{\bar{p}}(\mathcal{R})
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\frac{n_a(\mathcal{R})}{n_b(\mathcal{R})} \approx \frac{Q_a(\mathcal{R})}{Q_b(\mathcal{R})} \quad \Rightarrow \quad n_{\bar{p}}(\mathcal{R}) \approx \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})} Q_{\bar{p}}(\mathcal{R})
\]

Average column density traversed by CR nuclei during propagation

\[
X_{\text{esc}}(\mathcal{R}) = \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})}
\]
Recipe for antiproton pie:

\[ n_{\bar{p}}(\mathcal{R}) \approx \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})} Q_{\bar{p}}(\mathcal{R}) \]
Recipe for antiproton pie:

\[ n_{\bar{p}}(R) \approx \frac{n_B(R)}{Q_B(R)} Q_{\bar{p}}(R) \]

\[ \sigma_{p\rightarrow \bar{p}}(R) = \frac{2 \int_{R}^{\infty} dR_p J_p(R_p) \left( \frac{d\sigma_{pp\rightarrow \bar{p}X}(R_p,R)}{dR_p} \right)}{J_p(R)} \]
Recipe for antiproton pie:

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Winkler, JCAP 1702 (2017) no.02, 048

KB, Sato, Takimoto, PRD98 (2018) no.6, 063022

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About diffusion models

\[ K \sim (E/Z)^{\delta} \]

NGC 891

To a good approximation, disc+halo homogeneous diffusion models satisfy the criterion of uniform CR composition where spallation happens.

\[
\frac{n_A}{n_B} = \frac{Q_A}{Q_B}
\]
diffusion models fit

\[ X_{\text{esc}}(\mathcal{R}) = \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})} \]

diffusion models fit

\[ X_{\text{esc}}(\mathcal{R}) = \frac{n_B(\mathcal{R})}{Q_B(\mathcal{R})} \]

\[ X_{\text{esc}} = X_{\text{disc}} \frac{L c}{2 D} \frac{2 R}{L} \sum_{k=1}^{\infty} J_0 [v_k (r_s / R)] \frac{\tanh [v_k (L / R)]}{v_k^2 J_1 (v_k)} \]
What’s going on here? (Donato et al PRL102, 071301 (2009))

The excess of antiprotons observed by AMS cannot come from pulsars.

It can be explained by Dark Matter collisions or by new astrophysics phenomena.
What's going on here? (Donato et al PRL102, 071301 (2009))

Antiproton-to-proton ratio

AMS proton flux

New information: The proton flux cannot be described by a single power law $= CR^\gamma$, as has been assumed for decades.

Unexpectedly, we found the spectrum can be described by a double power law with spectral index $\gamma$ below $R_0$ and $\gamma + \Delta \gamma$ above $R_0$. $S$ describes the smoothness of the transition.

$\Phi = C \left( \frac{R}{45 \text{ GV}} \right)^\gamma \left[ 1 + \left( \frac{R}{R_0} \right)^{\Delta \gamma/S} \right]^S$

proton flux assumed for making the pbar/p grey line
What’s going on here? (Donato et al PRL102, 071301 (2009))

**Antiproton-to-proton ratio**

The excess of antiprotons observed cannot come from pulsars.

It can be explained by Dark Matter or by new astrophysics phenomena.

B/C grammage assumed for making the pbar/p grey line.
What’s going on here? (Donato et al PRL102, 071301 (2009))

Antiproton-to-proton ratio

The excess of antiprotons cannot come from collisions of ordinary cosmic rays. It can be explained by Dark Matter or by new astrophysics.

What we get if we use those old proton flux, B/C grammage.
What’s going on here? (Donato et al PRL102, 071301 (2009))

What we get if we use those old proton flux, B/C grammage

Antiproton-to-proton ratio

The excess of antiprotons cannot come from... It can be explained by Dark Matter or by new astrophysics.
Comparing with radioactive nuclei

Time scales:
cooling vs decay
Comparing with radioactive nuclei

Time scales:
cooling vs decay
Comparing with radioactive nuclei

FIG. 5: $e^+ / \bar{p}$ flux ratio: AMS02 data compared to the secondary upper bound of Eq. (8). The upper bound ($e^+ / \bar{p}$ source ratio) is shown with different assumptions for the proton spectrum in the secondary production regions. Systematic cross section uncertainties in $pp \rightarrow \bar{p}, e^+$, not shown in the plot, are in the ballpark of 10%. Dashed black line shows the result evaluated for the locally measured $J_p$, while blue and green lines show the result for harder and softer proton flux, respectively, as specified in the legend. Taken from [55].

AMS02 results hint for a secondary origin for CR $e^+$ [36], however, this result comes with a puzzle. If $e^+$ are secondary, then Fig. 5 suggests that the effect of radiative energy loss in suppressing the $e^+$ flux is never very important, and possibly becomes less significant as we go to higher $e^+$ energy. As we shall see, this behaviour contradicts the expectations within common models of CR propagation.

To appreciate the $e^+$ puzzle, we must go into somewhat more muddy waters of CR astrophysics and consider the interplay of $e^+$ energy losses with the effects of propagation.

For later convenience it proves useful to define the loss suppression factor $f_{e^+}$ via

$$n_{e^+} / n_{\bar{p}} = f_{e^+}(R) Q_{e^+}(R) / Q_{\bar{p}}(R).$$

(9)

In Fig. 6 we show $f_{e^+}$ as derived from Fig. 5. The upper bound means that for secondary $e^+$ we expect $f_{e^+}(R) \leq 1$. The $e^+$ puzzle concerns the observation that $f_{e^+}(R)$ is even much lower than 1 at $R \approx 100 \text{ GV}$. This difference led [56] to conclude that $e^+$ are not affected by radiative losses at all energies; while we believe that the data implies some radiative effect at $R \approx 100 \text{ GV}$. The basic conclusion, putting 30-50% differences aside, is similar: $e^+$ are consistent with secondaries.

---

*Ref. [56] recently joined this understanding. We note, however, that our evaluation of the $Q_{e^+} / Q_{\bar{p}}$ ratio in Fig. 5 is lower than that of [56] by 30-50% at $R \approx 100 \text{ GV}$. This difference led [56] to conclude that $e^+$ are not affected by radiative losses at all energies; while we believe that the data implies some radiative effect at $R \approx 100 \text{ GV}$. The basic conclusion, putting 30-50% differences aside, is similar: $e^+$ are consistent with secondaries.*

For early comprehensive analyses see e.g. [57–59].
Comparing with radioactive nuclei

FIG. 5: e⁺/¯p flux ratio: AMS02 data compared to the secondary upper bound of Eq. (8). The upper bound (e⁺/¯p source ratio) is shown with different assumptions for the proton spectrum in the secondary production regions. Systematic cross section uncertainties in pp → ¯p, e⁺, not shown in the plot, are in the ballpark of 10%. Dashed black line shows the result evaluated for the locally measured Jp, while blue and green lines show the result for harder and softer proton flux, respectively, as specified in the legend. Taken from [55].

AMS02 results hint for a secondary origin for CR e⁺[36]. However, this result comes with a puzzle. If e⁺ are secondary, then Fig. 5 suggests that the effect of radiative energy loss in suppressing the e⁺ flux is never very important, and possibly becomes less significant as we go to higher e⁺ energy. As we shall see, this behaviour contradicts the expectations within common models of CR propagation [12]. To appreciate the e⁺ puzzle, we must go into somewhat more muddy waters of CR astrophysics and consider the interplay of e⁺ energy losses with the effect of propagation.

For later convenience it proves useful to define the loss suppression factor f e⁺ via

\[ \frac{Q_{e^+}}{Q_{\bar{p}}} \sim f_{e^+} (R) \]

(9)

In Fig. 6 we show f e⁺ as derived from Fig. 5. The upper bound means that for secondary e⁺ we expect f e⁺ (R) ≤ 1. The e⁺ puzzle concerns the observation that f e⁺ (R) is even much lower. Ref. [56] recently joined this understanding. We note, however, that our evaluation of the Qe⁺/Q¯p ratio in Fig. 5 is lower than that of [56] by 30-50% at R = 100 GV. This difference led [56] to conclude that e⁺ are not affected by radiative losses at all energies; while we believe that the data implies some radiative effect at R = 100 GV. The basic conclusion, putting 30-50% differences aside, is similar: e⁺ are consistent with secondaries.

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$f(\text{Be}10) \sim 0.4$

$f(\text{e}^+) \sim 0.5$
Stable secondaries with no energy loss

Comment about applicability of the analysis: high energy (relativistic)

Below $R \approx 10\,\text{GV}$, various propagation effects can change energy of particle during trajectory; spallation cross sections are energy dependent; rigidity not transferred in fragmentation;…

Example: solar modulation

We will keep our analysis to $R > 10\,\text{GV}$
AMS02 (2016)
\[ \frac{n_{e^+}}{n_{\bar{p}}} = f_{e^+}(\mathcal{R}) \frac{Q_{e^+}(\mathcal{R})}{Q_{\bar{p}}(\mathcal{R})} \]

A more robust derivation:

Relate \( e^+ \) to \( \bar{p} \)

Rather than directly to \( B/C \)
we expect

In Fig. 6 we show

For later convenience it proves useful to define the loss suppression factor

within common models of CR propagation

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loss in suppressing the

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AMS02 results hint for a secondary origin for CR

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energy losses with the e

ect at

Relate e+ to pbar

Rather than directly to B/C

Secondary upper bound

\[
\frac{n_{e^+}}{n_{\bar{p}}} = f_{e^+}(R) \frac{Q_{e^+}(R)}{Q_{\bar{p}}(R)}
\]

A more robust derivation:

Relate e+ to pbar

Rather than directly to B/C
\[
\frac{n_{e^+}}{n_{\bar{p}}} = f_{e^+}(\mathcal{R}) \frac{Q_{e^+}(\mathcal{R})}{Q_{\bar{p}}(\mathcal{R})}
\]

Secondary upper bound \[ f_{e^+}(\mathcal{R}) \leq 1 \]
AMS02 data supports secondary origin for CR e+.

\[
\frac{n_{e^+}}{n_{p^-}} = f_{e^+}(R) \frac{Q_{e^+}(R)}{Q_{p^-}(R)}
\]

Secondary upper bound

\[f_{e^+}(R) \leq 1\]