In 8 years, 140 billion charged particles have been measured by AMS

M.Graziani/Karsruhe Institute of Technology
THE PHYSICS OF AMS-02: COSMIC RAYS

AMS-02 range: GV-TV
On the Origins of Cosmic Positrons

Supernovae

Interstellar Medium

Protons (~90%)
Helium (~8%)
electrons (~1%) ...

Positrons from Collisions
Institute for Experimental Particle Physics

Maura Graziani

Interstellar Medium

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Supernovae

Pulsars

On the Origins of Cosmic Positrons

Positrons from Collisions

Positrons from Pulsars

Interstellar Medium
On the Origins of Cosmic Positrons

Supernovae

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Protons (~90%)
Helium (~8%)
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Positrons from Collisions

Pulsars

Positrons from Pulsars

Dark Matter

Positrons from Dark Matter

Electrons
Particles and nuclei are measured by their charge ($Z$), energy ($E$), momentum ($P$) or Rigidity $R = P/Z$.

TRD: Identify $e^+$, $e^-$, $Z$

Silicon Tracker: $Z$, $P$

ECAL: $E$ of $e^+$, $e^-$

Magnet: $\pm Z$

TOF: $Z$, $E$

RICH: $Z$, $E$

Z and P are measured independently by the Tracker, RICH, TOF and ECAL.
Transition Radiation Detector (TRD)

One of 20 layers

radiator

heavy particle

electron

Signal wire

Straw Tube

Xe/CO₂

5th June, WIN 2019, Bari

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Proton rejection at 90% $e^+$ efficiency

Rigidity (GV)

$\epsilon_e$

70%

80%

90%
Electromagnetic Calorimeter

provides a $17 \times X_0$, TeV, 3-dimensional measurement of $e^+$, $e^-$, and gamma ray:

1. the directions to ± 1 degree
2. the energy resolution of 2%
3. Distinguishes electrons and positrons from protons, helium, …by a factor of 10,000

50,000 fibers, $\phi = 1$ mm distributed uniformly inside 600 Kg of lead

![Calorimeter Image]

![Fiber Arrangement Image]

![Graph Image]
AMS is a unique magnetic spectrometer in space

In 8 years, the detectors have performed flawlessly.

AMS is able to pick out 1 positron from 1,000,000 protons;
unambiguously separate positrons from electrons up to a trillion eV;
and accurately measure all cosmic rays to trillions of eV.
AMS was installed on the ISS in May 2011 and it will continue through the lifetime of ISS.

- 28.1 × 10^6 electrons
- 1.9 × 10^6 positrons
Electron and Positron spectra before AMS
Electron and Positron spectra after AMS

Energy [GeV]

$E^3 \Phi_{e^\pm}$ [GeV$^2$ m$^{-2}$ sr$^{-1}$ s$^{-1}$]

Electrons

28.1 million electrons

Positrons x10

1.9 million positrons

28th May, CRATER 2018

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Towards Understanding the Origin of Cosmic-Ray Positrons

AMS-02
1.9 million positrons

Energy [GeV]
AMS-02 positron flux at high energies

\[ E^3 \Phi_{e^+} \text{[GeV}^2 \text{m}^{-2} \text{sr}^{-1} \text{s}^{-1}] \]

Energy [GeV]

- AMS-02
- PAMELA
- Fermi-LAT
- MASS
- CAPRICE
- AMS-01
- HEAT

5th June, WIN 2019, Bari

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Institute for Experimental Particle Physics
The Spectral Index of the Positron Flux as a function of energy

\[ \Phi = CE^\gamma \]

\[ \gamma = \frac{d[\log(\Phi_e)]}{d[\log(E)]} \]

The spectral index has complex energy dependence with a significant decrease towards higher energies.
Fits of the data to

\[ \Phi_{e^+}(E) = \begin{cases} \mathcal{C}E^\gamma, & E \leq E_0; \\ \mathcal{C}E^\gamma (E/E_0)^{\Delta \gamma}, & E > E_0. \end{cases} \]

(a) An excess above

\[ E_0 = 25.2 \pm 1.8 \text{ GeV} \]

(b) A sharp drop-off at

\[ E_0 = 284^{+91}_{-64} \text{ GeV} \]
The positron flux is the sum of low-energy $e^+$ from collisions plus a new source of high-energy $e^+$

$$\Phi_{e^+}(E) = \frac{E^2}{\bar{E}^2} \left[ C_d (\bar{E}/E_1)^{\gamma_d} + C_s (\bar{E}/E_2)^{\gamma_s} \exp(-\bar{E}/E_s) \right]$$
Origins of Cosmic Positrons

The low energy positron data can be explained by the collision of cosmic rays.

\[ \Phi_{e^+}(E) = \frac{E^2}{E^2} \left[ C_d \left( \frac{E}{E_1} \right)^{\gamma_d} + C_s \left( \frac{E}{E_2} \right)^{\gamma_s} \exp \left( - \frac{E}{E_s} \right) \right] \]

- Positron data – (Source)

Models of the collisions of cosmic rays
Origins of Cosmic Positrons

At high energies $e^+$ come from dark matter or new astrophysical sources

$$\Phi_{e^+}(E) = \frac{E^2}{\bar{E}^2} [C_d (\bar{E}/E_1)^{\gamma_d} + C_s (\bar{E}/E_2)^{\gamma_s} \exp(-\bar{E}/E_s)]$$

- Positron data – (Collisions)

New Source

$E^3 \Phi_{e^+}$ [GeV$^2$ m$^{-2}$ sr$^{-1}$ s$^{-1}$]

Energy [GeV]
Origins of Cosmic Positrons

\[
\Phi_{e^+}(E) = \frac{E^2}{\bar{E}^2} \left[ C_d (\bar{E}/E_1)^{\gamma_d} + C_s (\bar{E}/E_2)^{\gamma_s} \exp(-\bar{E}/E_s) \right]
\]

A finite energy cutoff of the source term \( E_s = 810^{+310}_{-180} \) GeV, is established with a significance more than 4\( \sigma \).

\( E_s = 810 \) GeV

\( 1/E_s = 0 \) or \( E_s = \infty \) excluded at 4.07\( \sigma \)
Consistency check:

Positron flux with proton rejection increased by x3
Towards Understanding the Origin of Cosmic-Ray Electrons

AMS
28.1 million electrons
AMS-02 electron flux at high energies
Comparison of the behavior of the cosmic ray electrons and positrons

\[ \gamma = \frac{d[\log(\Phi)]}{d[\log(E)]} \]

- **Electrons**: Blue line and dots
- **Positrons**: Green line and dots

*Note: The graph shows the spectral index \( \gamma \) as a function of energy [GeV], with data points indicating the behavior of electrons and positrons. The spectral indices are nearly energy-independent in the shown range.*
Fits of the data to

$$\Phi_{e^-}(E) = \begin{cases} CE^\gamma, & E \leq E_0; \\ CE^\gamma (E/E_0)^{\Delta\gamma}, & E > E_0. \end{cases}$$

A significant excess above

$$E_0 = 42^{+5.4}_{-5.2} \text{ GeV}$$

$$\Delta \gamma = 0.094 \pm 0.014$$

7σ effect
The electron flux is the sum of two power law

\[
\Phi_{e^-}(E) = \frac{E^2}{\bar{E}^2} \left[ 1 + \left( \frac{E}{E_t} \right)^{\Delta\gamma_t} \right]^{-1} \left[ C_a \left( \frac{E}{E_a} \right)^{\gamma_a} + C_b \left( \frac{E}{E_b} \right)^{\gamma_b} \right]
\]

Solar & low-energy

Electron Spectrum

- Fit with Eq. (5) and 68% C.L. band
- Power law a
- Power law b

Electrons have neither source nor cutoff.
Origins of Cosmic Electrons

At low energies positrons come from cosmic ray collisions, electrons do not.

\[
\Phi_{e^-}(E) = \frac{E^2}{E^2} \left[ 1 + \left( \frac{E}{E_t} \right)^{\Delta \gamma t} \right]^{-1} \left[ C_a \left( \frac{E}{E_a} \right)^{\gamma a} + C_b \left( \frac{E}{E_b} \right)^{\gamma b} \right]
\]

- Electron data – (power law \(b\))

Solar & low-energy

Electrons power law \(a\)

Positrons from collisions
Origins of Cosmic Electrons

The positron source term has a cutoff, whereas electrons have neither source term nor the cutoff.

\[ \Phi_{e^-}(E) = \frac{E^2}{E^2} \left[ 1 + \left( \frac{E}{E_t} \right)^{\Delta y_t} \right]^{-1} \left[ C_a \left( \frac{E}{E_a} \right)^{Y_a} + C_b \left( \frac{E}{E_b} \right)^{Y_b} \right] \]

Solar & low-energy

- Electron data – (power law \(a\))

Electrons power law \(b\)

Positrons from source

Energy [GeV] 10^2 10^3

\(\Phi_{e^-} \) [GeV^2 m^-2 s^-1 sr^-1]
Origins of Cosmic Electrons

The cosmic ray electrons originate from different sources than high energy positrons.

![Graph showing the energy distribution of cosmic electrons and positrons with fits and data points.](image)
Conclusions

- the measurement of the \textbf{e}^{-} flux from 0.5 GeV to 1.4 TeV based on $28.1 \times 10^6$ events and of the \textbf{e}^{+} flux from 0.4 to 1 TeV based on $1.9 \times 10^6$ event have been presented.

- The positron flux:
  - significant \textbf{excess} starting from $\sim 25.2$ GeV and a sharp \textbf{dropoff} above 284 GeV
  - is well described by the sum of a \textbf{diffuse term} associated with the secondary positrons production and a new source term of positrons, which dominates at high energies
  - shows a finite \textbf{energy cutoff} of the source term of $E \sim 810$ GeV (significance $> 4\sigma$)

- The electron flux:
  - significant \textbf{excess} starting from $\sim 42$ GeV but the nature of this excess is different from the positron flux excess above $\sim 25.2$ GeV.
  - is well described by the sum of two \textbf{power law} components.
  - The electron flux does not have an \textbf{energy cutoff} below 1.9 TeV.

- In the entire energy range the \textbf{electron and positron spectra have distinctly different magnitudes and energy dependences.}
  - most high energy electrons originate from different sources than high energy positrons.
Back up
The Positron Flux through 2024

Extend the measurements to 2 TeV and double the current statistics to determine the sharpness of the drop off.

By 2024, AMS will have a definitive result on the dark matter origin of positrons

\[ \Phi_{e^+} E^3 \text{[m}^2\text{s}^{-1}\text{sr}^{-1}\text{s}^{-1}] \]

Energy [GeV]

Collision of Cosmic Rays

Dark Matter

\( \chi + \chi \rightarrow e^+ + \ldots \)
Positron excess also can be expressed in terms of the positron fraction, which explores the same physics.

- 1.9 million positrons

\[ \text{Positron fraction} = \frac{e^+}{(e^+ + e^-)} \]

Collision of Cosmic Rays

Dark Matter + Collision of Cosmic Rays

New Propagation Models explaining the AMS e+ data

Explaining the AMS positron fraction (gray circles) is due to propagation effects.

This requires a specific energy dependence of the B/C ratio

The observed features of the AMS e+ data cannot be explained by standard propagation models.
AMS Combined positron + electron flux

$\Phi_{e^+e^-} \propto E^{3}$

$\text{m}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^2$

Energy [GeV]

$E^3$ $\Phi_{e^+e^-}$ [m$^{-2}$ s$^{-1}$ sr$^{-1}$ GeV$^2$]
HAWC rules out that the AMS positron excess is from nearby pulsars

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