Precision Measurement of Positron Fraction by the AMS on the International Space Station

Zuhao LI / IHEP, CAS
On behalf of the AMS Collaboration
ICRC 2017
14, July, 2017

5m x 4m x 3m
7.5 tons
AMS: A TeV precision, multipurpose, magnetic spectrometer

Transition Radiation Detector (TRD)
Identify $e^+$, $e^-$

Silicon Tracker
$Z, P$ or $R=P/Z$

Electromagnetic Calorimeter (ECAL)
$E$ of $e^+$, $e^-$

Time of Flight (TOF)
$Z, E$

Magnet
$\pm Z$

Ring Imaging Cherenkov (RICH)
$Z, E$

Z and $P$, $E$ or $R$ are measured independently by Tracker, ECAL, TOF and RICH
Proton rejection at 90% efficiency

Typically, 1 in 1,000 protons may be misidentified as a positron.

TRD estimator = $-\ln\left(\frac{P_e}{P_e + P_p}\right)$

ISS Data

Measurement with 1 of the 20 TRD Layers

Protons

Electrons

Transition Radiation

20 layers: fleece radiator and proportional tubes

ISS Data
Silicon Tracker

9 planes, 200,000 channels
The coordinate resolution is 10 μm.

Maximum Detectable Rigidity (MDR) for Z=1 particles is 2.0 TV

Test Beam
\[ \sigma = 10 \, \mu m \]
Electromagnetic Calorimeter

Provides a precision, 17 $X_0$, TeV, 3-dimensional measurement of the directions and energies of electrons and positrons, separate $e^\pm$ from protons.

Typically, 1 in 10,000 protons may be misidentified as a positron.

Proton rejection at 90% $e^+$ efficiency.

Test beam result:

\[
\sqrt{\frac{(10.4)^2}{E}} + (1.4)^2
\]

Boosted Decision Tree (BDT):

3D shower shape

ECAL estimator

Proton rejection at 90% $e^+$ efficiency

Typically, 1 in 10,000 protons may be misidentified as a positron.
In 6 years on ISS, AMS has collected over 100 billion cosmic rays. Search for Dark Matter is one of the main physics topic of AMS.

100 billion events collected 08/05/2017
Dark Matter: $\chi$

Collision of Cosmic Rays with the Interstellar Media will produce $e^+, \bar{p}...$

$p, \text{He} + \text{ISM} \rightarrow e^+, \bar{p} + ...$

Dark Matter ($\chi$) annihilations: $\chi + \chi \rightarrow e^+, \bar{p} + ...$

The excess of $e^+, \bar{p}$ from Dark Matter ($\chi$) annihilations can be measured by AMS

1. The energy at which it begins to increase.

2. The rate of increase with energy.

3. The existence of sharp structures.

4. The energy beyond which it ceases to increase.

5. Isotropy.

6. The rate at which it falls beyond the turning point.

Analysis: 2D fit to measure $\text{Ne}^{\pm}$ and $\text{Np}$

After an efficient ECAL selection to remove the majority of protons, 2D reference spectra for the signal and the background are fitted to data in the $[\text{TRD estimator-log}(E/|P|)]$ plane.

This method combines information from
- TRD
- ECAL
- Tracker

It provides better statistical accuracy compared to cut-based analysis.
Fit results:
The TRD Estimator shows clear separation between protons and positrons with a small charge confusion background.

\[\chi^2/d.f. = 0.60\]
**Fit results:**

The ECAL energy and Tracker momentum matching (E/P) quantifies the small charge confusion in the signal region.

![Graph showing fit results](graph.png)

- **Data**
- **Fit**
- **Positrons**
- **Protons**
- **Charge confusion (e⁻ → e⁺)**

$\chi^2$/d.f. = 0.60

**TRD Estimator < 0.75**
Systematic errors

Extensive check for systematic errors on the positron fraction measurement

1. Charge confusion ($e^- \rightarrow e^+$) is the dominating source of systematic uncertainty at high energies.

Two sources: 1) large angle scattering and 2) production of secondary tracks along the path of the primary track. Both are well reproduced by the Monte Carlo. The small difference is taken as a systematic error.
Systematic errors

2. Selection dependence

The measurement is stable over wide variations of the cuts in the ECAL shower Shape, E/p matching, etc. For each energy bin, over 1,000 sets of cuts (trials) were analyzed.
Systematic errors

3) $\sigma_{\text{acc}}$: Acceptance asymmetry
Due to known minute tracker asymmetry (negligible for all energy bin)

4) $\sigma_{\text{mig}}$: Absolute energy scale and bin-to-bin migration negligible above 5 GeV

5) $\sigma_{\text{ref}}$: Reference spectra because definition of the reference spectra is based on pure samples of electrons and protons of finite statistics.

<table>
<thead>
<tr>
<th>Energy [GeV]</th>
<th>N_{e^+}</th>
<th>Fraction</th>
<th>$\sigma_{\text{stat}}$</th>
<th>$\sigma_{\text{acc}}$</th>
<th>$\sigma_{\text{sel}}$</th>
<th>$\sigma_{\text{mig}}$</th>
<th>$\sigma_{\text{ref}}$</th>
<th>$\sigma_{\text{c.c.}}$</th>
<th>$\sigma_{\text{syst}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.73–11.54</td>
<td>9504</td>
<td>0.0532</td>
<td>0.0006</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0002</td>
<td>0.0001</td>
<td>0.0002</td>
<td>0.0003</td>
</tr>
<tr>
<td>50.87–54.98</td>
<td>1041</td>
<td>0.0887</td>
<td>0.0028</td>
<td>0.0002</td>
<td>0.0006</td>
<td>0.0007</td>
<td>0.0001</td>
<td>0.0003</td>
<td>0.0010</td>
</tr>
<tr>
<td>100.0–115.1</td>
<td>524</td>
<td>0.1205</td>
<td>0.0054</td>
<td>0.0002</td>
<td>0.0014</td>
<td>0.0007</td>
<td>0.0004</td>
<td>0.0013</td>
<td>0.0021</td>
</tr>
<tr>
<td>350.0–500.0</td>
<td>72</td>
<td>0.1471</td>
<td>0.0278</td>
<td>0.0003</td>
<td>0.0064</td>
<td>0.0007</td>
<td>0.0022</td>
<td>0.0182</td>
<td>0.0194</td>
</tr>
</tbody>
</table>

PRL113,121101(2014)
6.8 million $e^\pm$ events
Selected from 25 billion events collected during the first 18 months of operations: May 19, 2011 to December 10, 2012
Selected by APS as a highlight of the Year 2013

10.9 million $e^\pm$ events
Selected from the sample of 41 billion events

Two papers had been cited ~1000 times
Positron Fraction

Energy [GeV]

Positron Fraction

AMS-02
PAMELA
Fermi
AMS-01
HEAT
TS93
CAPRICE94

PRL113, 121101(2014)
Positron fraction begin to increase at 7.8 GeV
The positron fraction rise slope decreases with energy, the maximum is reached at $275 \pm 32\text{GeV}$.

Zero crossing $275 \pm 32 \text{ GeV}$
Examples of Theoretical Models for positrons

From Dark Matter
1) J. Kopp, Phys. Rev. D 88, 076013 (2013);
4) M. Ibe, S. Iwamoto, T. Moroi and N. Yokozaki, JHEP 1308 (2013) 029
7) L. Bergstrom, T. Bringmann, I. Cholis, D. Hooper and C. Weniger, PRL 111 (2013) 171101
11) Y. Zhao and K.M. Zurek, JHEP 1407 (2014) 017

……

From Astrophysical Sources
7) E. Amato, Int.J.Mod.Phys.Conf.Ser. 28 (2014) 1460160
10) M. DiMauro, F. Donato, N. Fornengo, R. Lineros and A. Vittino, JCAP 1404 (2014) 006

……

From Secondary Production

……
Models to explain the AMS Positron Fraction Measurements

Some models are constrained by complementary measurement of AMS.

Examples 1: Modified propagation of cosmic rays

R. Cowsik et al., Ap. J. 786 (2014) 124, (pink band) explaining that the AMS positron fraction (gray circles) above 10 GV is due to propagation effects.

However, this requires a specific energy dependence of the B/C ratio.
Models explain the AMS Positron Fraction Measurements

Some models are constrained by complementary measurement of AMS.

Examples 2: Supernova Remnants

Subir Sarkar: AMS days@CERN, April 2015:
Not able to fit simultaneously the positron and B/C.
Models to explain the Positron Fraction Measurements

Examples: Pulsars

M. DiMauro, F. Donato, N. Fornengo, R. Lineros, A. Vittino, JCAP 1404 (2014) 006

The rate of falls predicted by pulsars model and dark matter model are different.
Models to explain the Positron Fraction Measurements

Examples: Dark Matter model with intermediate state


The accuracy of the measurement in the last bin is limited by statistics. To understand the origin of the positron excess, we need more data.
Comparison of the latest results of positron fraction measurement with a Dark Matter model

- AMS 2016
  17 million events

Preliminary Data. Please refer to the AMS forthcoming publication in PRL.

$M_\chi = 1$ TeV

To collect data up to 2024, we should be able to understand the origin of the positron excess.

AMS 2024

Pulsars

$M_{\chi} = 1 \text{ TeV}$

Collision of Cosmic Rays with the ISM

E (GeV)

Positron fraction

$10^{-2}$

$10^{-1}$

$10^2$
The latest data collected by AMS in the first 6 years of data taking is being analyzed, the new data will provide more information of the positron fraction.

Comprehensive measurements of AMS provide more insight on the origin of the unexpected e\(^+\) excess.

In the foreseeable decades, AMS is a unique experiment which could measure cosmic ray positron to 1 TeV.

By collecting data through 2024, we should be able to determine the origin of the positron excess.
backups
Event selection

- DAQ:
  - livetime >50% (no SAA)
  - Geomagnetic cutoff: E>1.2 max cutoff

- TRACKER:
  - Track quality
  - geometrical match with ECAL shower

- TRD:
  - at least 15 hits

- TOF:
  - downgoing particle,
  - \( \beta > 0.8, \ 0.8 < Z < 1.4 \)

- ECAL:
  - shower axis within the fiducial ECAL volume
  - electromagnetic shape of the shower
Reject charge confused events

Charge confusion estimator $\Lambda_{CC}$ to reject charge confused events ($e^- \rightarrow e^+$)

- $[\text{MC } e^- \text{ 500-700GeV}]$

![Graph showing probability distribution against $\Lambda_{CC}$]
2D fit to measure $Ne^\pm$ and $Np$

- The number of positrons and electrons are determined from a template fit in TRD - Charge Confusion Estimator 2D phase space
- The $e^+$ and proton template are obtained from high purity $e^-$, proton data
- Charge confusion studied using $e^-$ test beam and MC
Example of fit

- The number of positrons and electrons are determined from a template fit in TRD - Charge Confusion Estimator 2D phase space
- The e+ and proton template are obtained from high purity e-, proton data
- Charge confusion studied using e- test beam and MC
Anisotropy

Astrophysical point sources like pulsars will imprint a higher level of anisotropy on the arrival directions of energetic positrons than a smooth dark matter halo.

\[ \delta = 3 \sqrt{\frac{C_1}{4\pi}} \]

\( C_1 \) is the dipole moment

The fluctuations of the positron ratio \( e^+/e^- \) are isotropic \( 16 < E \text{ [GeV]} < 350 \).

Data taking to 2024 will allow to explore anisotropies of 1%
Alternative Models to explain the AMS Positron Flux and Positron Fraction Measurements

- Modified Propagation of Cosmic Rays
- Supernova Remnants
- Pulsars

Examples:

The AMS Antiproton-to-Proton ratio

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

Presented by Weiwei XU