Latest Results from the AMS-02 experiment

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AMS-02 experiment has been installed on the International Space Station on May 19th 2011
AMS-02 collaboration

More than 10 years effort from 500 collaborators from all over the world.
Scientific goals of AMS-02

• Measuring CR spectra up to the iron in GeV to TeV: acceleration and propagation models;

• Indirect search of Dark Matter: $e^+$, antiprotons, antiD, $\gamma$

• Direct search of primordial antimatter and new forms of matter: Anti He, Anti C … strangelets

• Solar activity and modulation: CR spectra over 11 year solar cycle, Forbush decreases, SEPs …

• Contribute to Space Radiation
The AMS-02 detector

Accuracy and Redundancy
Signals from 20 layers are combined in a likelihood estimator which allows an efficient discrimination of proton background.
Time Of Flight (TOF)

Time of Flight and particle velocity ($\beta$)

- Z=2: $\sigma_\beta=2\%$, $\sigma_{\text{Time}}=80\text{ps}$
- Z=6: $\sigma_\beta=1.2\%$, $\sigma_{\text{Time}}=48\text{ps}$

Absolute Charge

Fast trigger generation
Distinction upward/downward going particles
Silicon Tracker

With an effective sensitive area of 6.2 m² the AMS Silicon Tracker is the largest precision tracker ever built for space application.

MDR is about a few TV
Alignment 3 µm, resolution 10 µm
192 read-out units; 200,000 channels;
Ring Imaging CHERENKOV (RICH)

$\Theta \propto V$

Intensity $\propto Z^2$

10,880 photosensors

He Li C O Ca
Electromagnetic Calorimeter (ECAL)

50,000 fibers, $\phi = 1\text{mm}$, distributed uniformly inside 1,200 lb of lead. Provide a precision, 3-dimensional, $17X_0$ measurement of the directions and energies of photons and electrons up to 1 TeV.
AMS-02 electronics on the radiators

650 computers, 300,000 channels
200%-400% redundancy
AMS-02 Journey

May 16: AMS Flight, Space Shuttle Endeavor
May 19: AMS installation completed at 5:15 AM. Data taking started at 9:35 AM.
AMS-02 data

over 4 year of AMS correspond to over 60 billion events

The ISS orbits the Earth at 400 km altitude and 51.6° to the Equator.

Acquisition rate [Hz]

Particle rates vary from 200 to 2000 Hz per orbit
Flight and Ground Operations

AMS

Ku-band High Rate (down):
Events <10Mbit/s
Monitoring: 30 Kbit/s

S-band Low Rate:
Commanding: 1 Kbit/s (up)
No Ku: 10 bits/s (down)

ISS Astronaut with AMS Laptop

Payload Operations Control Centers (POCC) at CERN

AMS Computers at MSFC, AL

White Sands Ground Terminal, NM
AMS-02 in Space is looking for Dark Matter

PAMELA
FERMI ...
AMS
Annihilation

\[ \chi + \chi \rightarrow e^+, \bar{p}, \gamma, \ldots \]

LUX
DARKSIDE
XENON 100
CDMS II

\[ \chi + p \rightarrow \chi + p \] Scattering

Dark Matter 26.8%
Ordinary Matter 4.9%
Dark Energy 68.3%

Production
LHC

\[ \chi + \chi \leftrightarrow p + p \]
In the first 18 months in space, AMS has collected over 25 billion events. 6.8 million are electrons or positrons.
The positron fraction is steadily increasing from 10 to ~250 GeV
No structure in the spectrum
Above 250 GeV the slope decreases by an order of magnitude
The Positron excess could be explained by Dark Matter annihilation or Pulsars.

Dark matter annihilation in light intermediate states

Contribution from nearby young pulsars.
If the excess has a particle physics origin, it should be isotropic.

The fluctuations of the positron ratio $e^+/e^-$ are isotropic.

The relative fluctuations of the positron ratio across the observed sky map show no evident pattern.

$\delta < 0.030$ for $16 < E < 350 \text{GeV}$
AMS-02 positron fraction extended to 0-500 GeV

Energy beyond which it ceases to increase (~275 GeV).
AMS-02 measures cosmic rays: leptons spectra

The spectral indexes of electrons and positrons and their dependence on energy are different.

PRL 113, 221102 (2014).
Electron and positron fluxes at low rigidities are affected by solar modulation. Opposite charge effects in the modulation can be studied.
AMS-02 is capable of measuring all the species of cosmic rays at the percentage level up to the iron and above.
AMS-02 has 7 independent charge measurements

Layer 1 = 6.1
TRD = 6.0
UTOF1 = 9.9
UTOF2 = 5.3
Inner = 4.8
LTOF = 5.2
RICH = 5.0

Tomographic reconstruction of the AMS material using He/p
AMS-02 Proton Flux

Flux $\times E_K^{2.7}$ [m$^{-2}$ sr$^{-1}$ sec$^{-1}$ GeV$^{-1.7}$]

Kinetic Energy ($E_K$) [GeV]
AMS-02 Proton Flux

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

- \( R_0 \) - characteristic transition rigidity
- \( s \) - smoothness

Fit to data above 45 GV:
\[ \chi^2/\text{n.d.f.} = 25/26 \]

\( \Delta \gamma = 0 \)

Important to test for departures from basic features: may provide clues on injection, acceleration, escape, propagation and nearby sources.
Helium flux vs kinetic energy per nucleon
To appear in Phys.Rev.Lett. – Editors’ suggestion
AMS-02 Helium Flux

Helium flux measurement from 2 GV to 3 TV of rigidity
Proton/Helium ratio from 2 GV to 1.8 TV of rigidity

NICOLA TOMASSETTI - LPSC - IN2P3/CNRS GRENOBLE
AMS-02 Boron to Carbon Ratio

B/C is a sensitive observable for the understanding of the propagation of cosmic rays in the Galaxy.
Secondary cosmic ray due to spallation of GCR in the interstellar matter.
In short:

1) **Source** origin for the break: no feature expected in secondaries/primaries

2) **Propagation** origin for the break: should reflect in probes of propagation as B/C (i.e. secondary spectra should show a more pronounced break than primary ones)

3) **Local** models like the “myriad” one may even obtain a softening of sec/primary, since secondaries are ~ sourced by the “unbroken” average spectrum

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**B/C Ratio**

Exposure time of 40 months
7M Carbon, 2M Borons

**Flux \( \times R^{2.7} \)**

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

AMS-02 PAMELA (2014)

B/C preliminary results do not seem to favour 3), surely inconclusive for 1) vs 2)

Qualitative hints for 2) from AMS Lithium?
Dark Matter search: Antiproton/Proton Ratio
Dark Matter search: Antiproton/Proton Ratio

AMS-02 days at CERN (15/04/2015)
Dark Matter search: Antiproton/Proton Ratio

Anomaly?

Based on: M. di Mauro, F. Donato, A. Goudelis and PS, PRD 90, 085017 (2014)
Before harder p and He fluxes at high-E (recently found)
Before newer data on anti-p production cross section NA49 exp. @ CERN
Dark Matter search: Antiproton/Proton Ratio

Realistic comparisons

AMS-02 is opening new scenarios in the physics of cosmic rays
New physics in cosmic rays affects indirect dark matter search
Below a few tens of GeV the spectrum of the cosmic ray spectrum is affected by the solar activity.

AMS, with its large acceptance and fine rigidity resolution, can give an important contribution to solar and heliospheric physics during the next decade.
AMS-02 monthly proton flux at low rigidities decreases with the increase of the solar activity.
Monthly Proton fluxes

Normalized Flux at different rigidities

The short-term behavior at low rigidities is related to the short time scale solar activity, for example Coronal Mass Ejection and Forbush decreases.
Normalized Daily Flux 2012 (GCR + SEPs)

Normalized Flux

Date (2012)

KATIE WHITMAN - UNIVERSITY OF HAWAII
## 15 Confirmed FD Observed by AMS-02
May 5, 2011 – Nov 26, 2013

<table>
<thead>
<tr>
<th>Start Date</th>
<th>Minimum</th>
<th>Recovery</th>
<th>Duration</th>
<th>Max Rigidity</th>
<th>Decrease</th>
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<tr>
<td>2011/06/24</td>
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<td>2 days</td>
<td>4.5 GV</td>
<td>10% ± 1%</td>
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<td>2 days</td>
<td>9 GV</td>
<td>17% ± 1%</td>
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<tr>
<td>2011/09/26</td>
<td>2011/09/27</td>
<td>2011/10/18</td>
<td>22 days</td>
<td>14 GV</td>
<td>20% ± 1%</td>
</tr>
<tr>
<td>2011/10/25</td>
<td>2011/10/25</td>
<td>2011/10/28</td>
<td>3 days</td>
<td>9 GV</td>
<td>10% ± 1%</td>
</tr>
<tr>
<td>2012/01/22</td>
<td>2012/02/01</td>
<td>2012/02/04</td>
<td>12 days</td>
<td>23 GV</td>
<td>23% ± 1%</td>
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<td>2012/02/27</td>
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<td>2012/03/01</td>
<td>3 days</td>
<td>2.7 GV</td>
<td>8% ± 1%</td>
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<td>2012/03/08</td>
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<td>2012/03/22</td>
<td>14 days</td>
<td>21 GV</td>
<td>42% ± 3%</td>
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<tr>
<td>2012/04/06</td>
<td>2012/04/06</td>
<td>2012/04/08</td>
<td>2 days</td>
<td>3 GV</td>
<td>7% ± 1%</td>
</tr>
<tr>
<td>2012/06/17</td>
<td>2012/06/18</td>
<td>2012/06/19</td>
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<td>9 GV</td>
<td>13% ± 2%</td>
</tr>
<tr>
<td>2012/07/15</td>
<td>2012/07/16</td>
<td>2012/07/26</td>
<td>11 days</td>
<td>12 GV</td>
<td>19% ± 1%</td>
</tr>
<tr>
<td>2012/09/04</td>
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<td>2012/09/07</td>
<td>3 days</td>
<td>11 GV</td>
<td>14% ± 1%</td>
</tr>
<tr>
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<td>2 days</td>
<td>5 GV</td>
<td>7% ± 1%</td>
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<tr>
<td>2013/03/17</td>
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<td>2013/03/28</td>
<td>11 days</td>
<td>18 GV</td>
<td>20% ± 1%</td>
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<tr>
<td>2013/04/15</td>
<td>2013/04/15</td>
<td>2013/04/17</td>
<td>2 days</td>
<td>11 GV</td>
<td>9% ± 1%</td>
</tr>
<tr>
<td>2013/06/23</td>
<td>2013/06/28</td>
<td>2013/06/30</td>
<td>7 days</td>
<td>8 GV</td>
<td>12% ± 1%</td>
</tr>
</tbody>
</table>

KATIE WHITMAN - UNIVERSITY OF HAWAII
Solar Events Observed by AMS-02

20 High Energy Solar events above 1GV.

<table>
<thead>
<tr>
<th>AMS-02 Event</th>
<th>Event Date</th>
<th>Flare Class</th>
<th>CME Vel. (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>06/07/11</td>
<td>M2.5</td>
<td>1255</td>
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<tr>
<td>2</td>
<td>08/04/11</td>
<td>M9.3</td>
<td>1315</td>
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<tr>
<td>3</td>
<td>08/09/11</td>
<td>X6.9</td>
<td>1610</td>
</tr>
<tr>
<td>4</td>
<td>01/23/12</td>
<td>M8.7</td>
<td>2175</td>
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<tr>
<td>5</td>
<td>01/27/12</td>
<td>X1.7</td>
<td>2508</td>
</tr>
<tr>
<td>6</td>
<td>03/07/12</td>
<td>X5.4, X1.3</td>
<td>2684, 1825</td>
</tr>
<tr>
<td>7</td>
<td>03/13/12</td>
<td>M-class</td>
<td>1884</td>
</tr>
<tr>
<td>8</td>
<td>05/17/12</td>
<td>M5.1</td>
<td>1582</td>
</tr>
<tr>
<td>9</td>
<td>07/19/12</td>
<td>M7.7</td>
<td>1631</td>
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<td>10</td>
<td>07/23/12</td>
<td>backside</td>
<td>2003</td>
</tr>
<tr>
<td>11</td>
<td>04/11/13</td>
<td>M6.5</td>
<td>861</td>
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<tr>
<td>12</td>
<td>05/22/13</td>
<td>M5.0</td>
<td>1466</td>
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<tr>
<td>13</td>
<td>10/28/13</td>
<td>M5.1, M2.8, M4.4</td>
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<td>11/02/13</td>
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<td>15</td>
<td>12/28/13</td>
<td>backside</td>
<td>1118</td>
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<tr>
<td>16</td>
<td>01/06/14</td>
<td>backside</td>
<td>1118</td>
</tr>
<tr>
<td>17</td>
<td>01/07/14</td>
<td>X1.2</td>
<td>1830</td>
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<tr>
<td>18</td>
<td>02/25/14</td>
<td>X4.9</td>
<td>2147</td>
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<tr>
<td>19</td>
<td>09/01/14</td>
<td>backside</td>
<td>1404</td>
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<tr>
<td>20</td>
<td>09/10/14</td>
<td>X1.6</td>
<td>1267</td>
</tr>
</tbody>
</table>

AMS-02 can measure $P$ and $He$ from solar events at energies not typically accessible from current satellites and with very high statistics.
Solar Energetic Particles can be observed in the geomagnetic polar regions because of geomagnetic cutoff.
AMS-02 is able to perform precise measurements in a short period of time and to collect enough statistics to measure the time evolution of particle excess.

AMS data combined with other instruments at lower energy, will provide a baseline for the modeling of SEP production.
Conclusions

The Space Station is a unique platform for precision physics research for the next decade.

The Sun is the nearest astrophysical laboratory and can provide useful insight on acceleration processes and particles injections.

AMS-02 is a very precise instrument that measures GCR in the GeV to TeV range with percentage uncertainty.

AMS-02 performs high accuracy measurement of GCRs over short periods of time allowing a detailed study of the solar activity and Forbush decrease events for different species of particles.

AMS-02 measured over 20 SEP events in their highest energy range and, thanks to its large acceptance, it is able to performs precise measurements over a few minutes time interval.

AMS-02 provides a new opportunity for the study of the space radiation.
Thank you

More science coming soon! Stay tuned!!!
Challenges

1) The thermal environment constantly changing (90 min orbit)
2) No control of the ISS
3) Radiation

A. The position of the Sun with respect to AMS

B. Visiting Vehicles (Soyuz or Progress)

C. Solar Array Positions
New results from the first 2 years of AMS: Proton flux measurement

\[ F(R) = \frac{N_{\text{obs.}}(R)}{T_{\text{exp.}}(R) A_{\text{eff.}}(R) \varepsilon_{\text{trig.}}(R) \, dR} \]

(For isotropic flux with \( \theta_{\text{zen}} < 20^\circ \))

- \( F \) : Absolute differential flux (m\(^{-2}\)sr\(^{-1}\)s\(^{-1}\)GV\(^{-1}\))
- \( R \) : Measured rigidity (GV)
- \( N_{\text{obs.}} \) : Number of events after proton selection
- \( T_{\text{exp.}} \) : Exposure life time (s)
- \( A_{\text{eff.}} \) : Effective acceptance (m\(^2\) sr)
- \( \varepsilon_{\text{trig.}} \) : Trigger efficiency
- \( dR \) : Rigidity bin (GV)
New results from the first 2 years of AMS: AMS upper limits on dipole anisotropy

Limits on the amplitude of a dipole anisotropy in any axis in galactic coordinates on the positron to electron ratio in the energy range from 16 GeV to 350 GeV:

$$\delta < 0.030 \text{ for } 16 < E < 350\text{GeV}$$

The sensitivity to a dipole anisotropy using the positron to proton ratio is consistent with the one obtained on the positron to electron analysis.
Pulsar interpretation consistent with all data
Tracker and Ecal Performances

Acceptance

Effective Area

Energy Resolution

Angular Resolution
Search for New Matter in the Universe

After many years, the question of the existence of strange quark matter still remains without a definitive answer.

There are six types of Quarks found in accelerators \((u, d, s, c, b, t)\).

All matter on Earth is made out of only two types \((u, d)\) of quarks. "Strangelets" are new types of matter composed of three types of quarks \((u, d, s)\) which should exist in the cosmos.

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Strangelets

Jack Sandweiss (Yale) is leading the AMS search.

Candidate observed with AMS-01 5 June 1998 11:13:16 UTC

Front view

Side view

β

Amplitude => Z, β

Rigidity      = 4.31 ± 0.38 GV
Charge Z      = 2
β₁ = β₂      = 0.462 ± 0.005
Mass          = 16.45±0.15 GeV/c²
Z/A           = 0.114 ± 0.01
Flux (1.5 < E_K < 10 GeV) = 5x10⁻⁵ (m² sr sec)⁻¹

Z/A~0.1
Strangelets

$\Phi_{\text{strangelets}} = 5 \times 10^{-10} \text{(cm}^2\text{s sr)}^{-1}$

AMS-02 (18 Years)

$^{4}\text{He}$

$^{3}\text{He}$

Z=2 Strangelet
AMS collects 7 Gbit/s of scientific data that after online process are reduced to 6 Mbit/s
AMS data parameters

Real Data Summary Per Year Of Operation
• 0.7-1.0 x 10^{10} Raw Data Events Collected
• 15-20 Tb Raw Data Volume
• 60-70 Tb Reconstructed Data Volume

MC Data Summary Per Year Of Operation
• 1.4-2.0 x 10^{10} simulated events will be generated.
• 90-110 TB MC Data Volume
Challenges
A passing heavy nuclei can induce errors or damages in the electronic components

**Radiation:** Total dose (1 KRad/year)
**Reliability:** operational for 20 years.

1083 errors found in the first 26 months

- Bit flip found in program memory by Cyclic Redundancy Check (CRC) which was designed according to the beam test result for the DSP chip. This type of error is checked 4 times per orbit and can be fixed automatically by the on-board main computers.

- Bit flip in DSP memories which cause functional errors. This type of error has a different behavior each time and requires expert intervention.

**Restore nominal condition**
**Redundancy on the Electronics**
Challenges

The thermal environment on ISS is constantly changing:

A. The position of the Sun with respect to AMS

B. Visiting Vehicles (Soyuz or Progress)

C. Solar Array Positions

i) AMS experiences large temperature variations (tens of degrees)
ii) AMS has no control of the Space Station orientation

Constant monitoring of the temperature sensors, improving of the thermal models and developing of safety procedures