AMS-02 latest results & Indirect DM searches

Bruna Bertucci
University and INFN Perugia
Outline
① AMS in a nutshell
② Data analysis
③ Results
④ Conclusions
AMS is a precision, multipurpose magnetic spectrometer operating on the ISS since 2011 to perform accurate measurements of charged cosmic rays in the GeV-TeV energy range:

Its main objectives:
- Search for new physics: anti-matter, dark matter, strange matter
- Shed light on the origin of cosmic rays and their propagation into the galaxy
The quest for Dark Matter

Annihilation

$\chi + \chi \rightarrow p, \bar{p}, e^-, e^+, \gamma$

Production

$\chi + \chi \leftarrow p + p \rightarrow p, \bar{p}, e^-, e^+, \gamma$

Scattering

$\chi + p \rightarrow \chi + p$

$e^-/p \approx O(10^{-2})$

$e^+/p \approx O(10^{-3})$

$\bar{p}/p \approx O(10^{-4})$
The Astrophysical Background:

Origin, propagation and production of CRs and their secondaries in the galaxy
The Astrophysical Background:

Origin, propagation and production of CRs and their secondaries in the galaxy + heliospheric / magnetospheric effects...

\[ p, \text{He,C...}, e^- \]

\[ \text{SNR} \]

\[ \text{Sun} \]

\[ \chi \]

\[ e^-, p, \gamma \]

\[ e^+, \overline{p}, \gamma \]

\[ \overline{\chi} \]

\[ \pi^+ \rightarrow \mu^+ \rightarrow e^\pm \]

\[ p+p \rightarrow p+p \ldots \]

\[ \text{solar modulation} \]

\[ \text{Flux} \]

\[ 20 \text{ GeV/n} \]
The experimental challenge

Hunt rare signals (anti-matter) and provide accurate flux measurements of the CR components to constraint astrophysical models

1) DESIGN: state of the art detectors providing redundant particle measurements
2) TEST: test and calibration on ground
3) OPERATION on ISS: continuous monitoring and calibration
4) DATA ANALYSIS: different independent analyses for internal cross check & reduced systematics.

\[ \pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm \]

\[ p+p \rightarrow p+p… \]
Alpha Magnetic Spectrometer on the ISS: AMS-02

- Launched on May 16, 2011
- Installed on ISS May 19, 2011
- AMS-02 foreseen to operate for the entire ISS lifetime (2024)

5m x 4m x 3m
7.5 tons
$GF \approx 0.5 \, \text{m}^2\text{sr}$
AMS-02: A TeV precision, multipurpose spectrometer

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

Particles and nuclei are defined by their charge ($Z$) and energy ($E$)

Time of Flight (TOF)
$Z, E$

Silicon Tracker
$Z, P$

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

Z, E, R, $\beta$
for the same particle are measured independently by the Tracker, RICH, TOF and ECAL

Magnet (0.15 T)
±$Z$

Ring Imaging Cherenkov (RICH)
$Z, E$
Positron fraction analysis

Protons rejection: $10^3$

Tracker

$\langle \sigma \rangle = 10 \mu m$

Protons rejection: $10^4$

20 million of $e^\pm$ events are selected in the energy range 0.5–700 GeV
TRD Estimator shows clear separation between positrons and protons with a small charge confusion background.

Energy range 206–260 GeV

\[ \chi^2 / \text{d.f.} = 227 / 200 \]
Antiproton analysis

6.5 \cdot 10^{10} \text{ cosmic rays}
3.49 \cdot 10^5 \text{ antiprotons}
2.42 \cdot 10^9 \text{ protons}

1. TRD (transition radiation) to separate $e^{\pm}$ from $p^{\pm}$

Energy range up to 2 TeV

ISS data: 83-100 GeV

2. Tracker measures momentum and separates $+$ from $-$

Charge ($Z$)

Velocity resolution

3. RICH measures velocity, with momentum yields mass

\[ <\sigma> = 10 \text{ \mu m} \]
Selection of the signal at low energies. The $\bar{p}$ signal is well separated from the backgrounds.
Selection of the signal at high energies. Background rejection close to 1 particle in a million.
1. The energy at which it begins to increase.

2. The rate of increase with energy compared with models.

3. The energy beyond which it ceases to increase.

4. Anisotropy

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

Graph: 
- $e^+, e^- \text{ from Collision of Cosmic Rays}$
- Two curves representing $m_\chi = 400 \text{ GeV}$ and $m_\chi = 800 \text{ GeV}$.
1. The energy at which positron fraction begins to increase

Positron fraction reaches minimum at 7.8 GeV
2. The rate of increase with energy. The non-existence of sharp structures.

- 2014 Data
  PRL 113, 121101 (2014)

- 2016 Data
3. The energy beyond which it ceases to increase.

2016 Data

Zero crossing 265 ± 22 GeV

Slope [GeV⁻¹]

-0.002
-0.001
0
0.001
0.002

e± energy [GeV]

Fit c·log(E/E₀)

Data
Additional source of positrons

\[ \Phi_{e^+} = C_{e^+} E^{-\gamma_{e^+}} + C_s E^{-\gamma_s} e^{-E/E_s} \]
\[ \Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_s E^{-\gamma_s} e^{-E/E_s} \]

\[ E_s = 530^{+170}_{-100} \text{ GeV} \quad \chi^2 / n.d.f. = 39/59 \]
What is AMS observing?

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
What is AMS observing?

Something “different” with respect “conventional” models of $e^+$ production by collisions of CR hadrons with the interstellar matter (ISM)
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Something “different” with respect “conventional” models of e$^+$ production by collisions of CR hadrons with the interstellar matter (ISM):

**Astrophysical Sources:**

- Local sources as pulsars (slow fall at high energies, anisotropy..)
- Interactions of CR hadrons in old SNR (but this should affect also other secondary species as anti-protons, B/C)
- purely secondary production in non-conventional models

**Dark matter:**

- The mass of the DM particle could give a sharp cutoff with energy
- Isotropic distribution
- Effects also on anti-p
Secondary production

2.3 million boron nuclei and 8.3 million carbon nuclei

Cowsik (2014)
4. Anisotropy on $e^+$/e$^-$: dipole amplitude

In 2024, AMS will collect above 200,000 positron events in the energy range $16 \text{ GeV} < E < 350 \text{ GeV}$

![Graph showing dipole amplitude over years with predictions for 2024.](image)

**Pulsar Model:**
D. Hooper, P. Blasi & P. D. Serpico, JCAP 0901(2009)
5. The expected rate at which it falls beyond the turning point.

Data by 2024

MC simulation

Pulsars

Maximum
265 ± 22 GeV

Collision of cosmic rays

$M_\chi = 1$ TeV

Other channels…?
e.g. anti-p
AMS results on the $\bar{p}/p$ flux ratio

\begin{itemize}
\item AMS-02
\item PAMELA
\item BESS-polarII
\end{itemize}

$3.49 \times 10^5$ antiprotons
$2.42 \times 10^9$ protons
Elementary particle fluxes measured by AMS
Spectrum of Elementary Particles $e^+$, $\bar{p}$, $p$

have identical energy dependence above 60 GeV

$e^-$ does not
The pbar/p ratio flattens above 60 GeV.

\[ \frac{\Phi_\bar{p}}{\Phi_p} \]

|Rigidity [GV]|
|---|---|
|0 | 10^5 |
|100 | 10^4 |
|200 | 10^3 |
|300 | 10^2 |
|400 | 10^1 |
|500 | 10^0 |

AMS-02
PAMELA
What is AMS observing?

The accuracy of the AMS measurement challenges current knowledge of cosmic background!
XSCRC2017: Cross sections for Cosmic Rays @ CERN

Description: New space borne experiments are ushering us into the era of precision direct measurements in cosmic ray physics. However, a poor knowledge of several particle physics and nuclear physics inputs - such as antiproton production or spallation cross sections - can seriously limit the relevant astroparticle physics information that can actually be extracted from these data, for instance for Galactic propagation parameters or indirect dark matter searches. The goal of the workshop, bringing together different communities, is to review theoretical motivations for the measurements of key processes, current galactic models and recent advances in cosmic ray observations that crucially depend on some of these inputs. The workshop also strongly aims at presenting current efforts and discussing forthcoming perspectives for particle/nuclear measurement campaigns.

Duration: The workshop will start Wednesday, March 29 in the late morning, and will end Friday, March 31 at about 4pm.

Organizing Committee: Bruna Bertucci (Perugia University), F. Donato (Torino University, chair), G. Giudice (CERN), Giovanni Passaleva (INFN, Florence), P. D. Serpico (LAPTH, Annecy, co-chair)

Scientific Advisory Committee: Oscar Adriani (Univ. and INFN, Firenze), Luca Latronico (INFN, Torino), Julie McEnery (Goddard NASA), Nadia Pastrone (INFN, Torino), Pierre Salati (LAPTH, Annecy), Andy Strong (MPE, Munich), Samuel C.C. Ting (MIT, Cern), Guy Wilkinson (Oxford Univ)

Invited Speakers: AMS Collaboration, Compass Collaboration, LHCb Collaboration, Alfredo Ferrari, Nicolao Fornengo, Guðlaugur Jóhannesson, Vladimir Ivanchenko, Tune Karnaæ, David Maurin, Nicola Mazzotta, Igor Moskalenko

Registration: This event is open to new participants.

Register
AMS provides a comprehensive set of measurements to constrain astrophysical background:

Primary Cosmic Rays (p, He, C, O, …)

C, O, …, Fe + ISM → Li, Be, B + X

Secondary Cosmic Rays (Li, Be, B, …)
Cosmic ray composition:
- for $Z > 2$ statistical error is our limit!
Energy reach for less abundant species is just matter of statistics (i.e. time)
H and He fluxes

Flux $\times E_k^{2.7}$ [m$^{-2}$ sr$^{-1}$ s$^{-1}$ (GeV/n)$^{-1.7}$]

Kinetic Energy ($E_k$) [GeV/n]

H and He fluxes

AMS-02 (2011/06-2013/11)
ATIC-2 (2003/01)
BESS (2002/08)
CAPRICE-94 (1994/08)
CAPRICE-98 (1998/05)
CREAM (2004/12-2005/01)
IMAX-92 (1992/07)
JACEE (1979-1995)
PAMELA (2006/07-2008/12)
RUNJOB (1995-1999)

300 M H

50 M He
AMS H and He fluxes

Two power laws $R_\gamma, R_{\gamma+1}$ with a characteristic transition rigidity $R_0$ and a smoothness parameter $s$ well describe H, He measured spectra:

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

\[\Delta \gamma = 0\]

\[
\begin{align*}
\gamma &= -2.849 \pm 0.002 + 0.004/-0.003 \\
s &= 0.024 +0.020/-0.013+0.027/-0.016 \\
\Delta \gamma &= 0.133 + 0.032/-0.021 +0.046/-0.030 \\
R_0 &= 336 +68/-44 + 66/-28 \text{ GV}
\end{align*}
\]

\[\Delta \gamma = 0\]

\[
\begin{align*}
\gamma &= -2.781 \pm 0.005 + 0.005/-0.004 \\
s &= 0.040 +0.032/-0.020+0.021/-0.016 \\
\Delta \gamma &= 0.127 + 0.025/-0.017 +0.035/-0.031 \\
R_0 &= 264 +50/-32 + 33/-32 \text{ GV}
\end{align*}
\]
AMS p/He flux ratio

\[
\frac{\Phi_p}{\Phi_{\text{He}}} = C R^\gamma
\]

Change of slope at \(\sim 45 \text{ GV}\)
What about other primary CRs?

Also for Carbon, Nitrogen and Oxygen the single-power law behaviour is excluded by AMS-02 data: a change of spectral index is observed at \( \approx \) the same rigidity.
Secondary CRs: Boron to Carbon flux ratio

AMS-02 precision challenges current theoretical models

AMS-02 precision challenges current theoretical models

AMS-02

Galprop, Trotta 2011, best fit

(\(\phi = 0.2, 0.5, 0.8\) GV)
More on Secondary CRs:

$^{10}$Be is a natural *clock* to measure the residence time of CR in the galaxy: $^{10}$Be → $^{10}$B + e$^-$ + $\nu$e with half-life of $1.5 \times 10^6$ years

Relativistic time dilation at high energies delays the $^{10}$Be decay and makes the Be/B ratio to increase.

A fit to the Be/B ratio can be used to extract residence time in the galaxy.

Analysis ongoing.
Heliospheric effects: time dependent measurement of ALL particle fluxes to retrieve properties of the LIS
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Conclusions

- AMS is providing simultaneous measurements of different cosmic ray species with O(%) accuracy in an extended energy range.
- New phenomena are being highlighted by these measurements whose nature will be further clarified as more data will be collected by the experiment.
- AMS will match the lifetime of the Space Station: stay tuned!
BACKUP
Tomography of detector materials by means of CR interactions

MLI
Layer 1
TRD
Vacuumcase
TOF
TAS
Magnet

Number of vertices

B.Bertucci
Full Control of fragmentation in the detector: e.g. background from interactions below L1

Carbon Fragmentation to Boron R = 10.6 GV

Measured from Data by fitting the Charge Distribution in L1 with Charge Distribution in L2 obtained by pure nuclear samples selected by charge in the Inner Tracker. Typical systematic error < 0.5%.

Contamination < 3%
Selection efficiency > 96%
Direct measurement of survival probabilities:

Measurement of nuclear cross sections when AMS flies in horizontal attitude

Survival probabilities $L8 \rightarrow L9$ can be evaluated with high statistics in “normal” data taking conditions.
Spectral features & composition

Breaks occur also at “low” energies…
$\frac{\Phi_p}{\Phi_{He}} = C R'$
Anti-proton/proton

the early times (1984)

...around 2000

HEAT ≈ 70 events
CAPRICE ≈ 31 events
Anti-proton/proton : 2010

BESS-POLAR (2004) ≈ 1520 event < 4.2 GeV
PAMELA (2006-2009) ≈ 1500 events
2008-2009: the $e^+/e^-$ puzzle

An excess of cosmic ray electrons at energies of 300–800 GeV

PRL 102, 181101 (2009)

An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

Vol 456 | 20 November 2008 | doi:10.1038/nature07477

Vol 458 | 2 April 2009 | doi:10.1038/nature07942
Electron & Positron measurements before AMS

Electron Spectrum

$E^3$ Flux [GeV$^3$/s sr m$^2$ GeV]]

Positron Spectrum

Energy [GeV]
e^+e^- fluxes

\[ E^3 \times \Phi \text{ (GeV}^2 \text{ m}^2 \text{s}^{-1} \text{sr}^{-1}) \]

\[ \text{Energy (GeV)} \]

**Sources:**
- AMS-02 (2011-2013)
- ATIC01&02 (2001 & 2003)
- BETS04 (2004)
- BETS9798 (1997 & 1998)
- CAPRICE94 (1994)
- Fermi-LAT (2009)
- HEAT94 (1994)
- HEAT95 (1994 & 1995)
e\(^{+}\)+e\(^{-}\) fluxes @ SciNeGhe 2016

Waiting for new results from:

+ AMS
+ CALET
+ DAMPE