Measurement of anisotropies in cosmic ray arrival directions with the Alpha Magnetic Spectrometer on the ISS
July 13, 2017
ICRC 2017, Busan, Korea

Iris Gebauer for the AMS collaboration
WHY ANISOTROPY SEARCHES?

AMS has observed a number of unexpected structures in the spectra of positrons, protons, helium and other nuclei. These structures may be connected to new phenomena which could induce some degree of anisotropy in their arrival directions.

Cosmic ray arrival directions are therefore directly related to the understanding of the spectral features observed by AMS.
WHAT DOES AN ISOTROPIC SKY LOOK LIKE?

AMS-02 does not scan the galactic sky uniformly.

ISS global position 1 day

AMS-02 galactic pointing direction 2.5 years

(Galactic coordinates)

On top of that we have:

- Geomagnetic cutoff → high rate of low energy particles at poles → trigger busy
- Position dependent efficiencies
WHAT DOES AN ISOTROPIC SKY LOOK LIKE?

AMS-02 does not scan the galactic sky uniformly.

ISS global position 1 day

AMS-02 proton sky
(>40 GV, Galactic coordinates)

On top of that we have:

- Geomagnetic cutoff → high rate of low energy particles at poles → trigger busy
- Position dependent efficiencies

Opening angle:
~ 40 degs for protons
~ 25 deg for electrons
Reference maps: best guess for an image of an isotropic sky measured by AMS-02 in the respective data taking period. Any deviation from this reference map might be detected as a signal.
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Choices for reference maps:

1) other cosmic ray species (e.g. protons used for positrons)
THE SEARCH FOR ANISOTROPIES WITH AMS-02

A likelihood fit procedure is used to expand the normalized ratio of data and reference map into a dipole.

\[ f(\theta, \varphi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta, \varphi) \]

**Ratio**

(data/reference)

- **North-South:** \( \rho_{NS} = \sqrt{\frac{3}{4\pi}} a_{10} \)
- **Forward-Backward:** \( \rho_{FB} = \sqrt{\frac{3}{4\pi}} a_{11} \)
- **East-West:** \( \rho_{EW} = \sqrt{\frac{3}{4\pi}} a_{1-1} \)

**Dipole amplitude:** \( \delta = \sqrt{\rho_{NS}^2 + \rho_{FB}^2 + \rho_{EW}^2} \)

Analysis is performed for any coordinate system of interest.
POSITRONS OVER ELECTRONS – GALACTIC COORDINATES

Data: 5 years, Mar11 – Mar16

All dipole components are compatible with statistical fluctuations within $1\sigma$.

Analysis is based on 70,000 positrons and 1 mio. electrons between 16 and 350 GeV.

$E_{\text{max}} = 350$ GeV
Isotropic expectation: calculated from MC using *isotropic* signal and reference maps $\rightarrow$ 68.3% CL of $\delta$ distribution is quoted.

95% C.L. limit: calculated from MC using simulated dipoles and isotropic reference maps $\rightarrow$ 95% CL is bayesian, computed from the distribution of true dipole strengths for the dipole strength measured on data.
ISOTROPY OF POSITRON ARRIVAL DIRECTIONS

A search for a possible dipole signal in the arrival directions of positrons was performed, using electrons and protons as a reference for isotropy.

No significant deviation from isotropy is found.
No significant time dependence was observed.

δ_{e+/e-}(>16 GeV) < 2 % at 95% C.L.
δ_{e+/p}(>16 GeV) < 2% at 95% C.L.

Upper limits at ISS orbit 5yrs:

Each analysis was performed by 3 independent groups within AMS.
All analyses are in excellent agreement.
REFERENCE MAPS FOR ANISOTROPY SEARCHES

**Reference maps:** best guess for an image of an isotropic sky measured by AMS-02 in the respective data taking period. Any deviation from this reference map might be detected as a signal.

**Choices for reference maps:**

I) other cosmic ray species (e.g. protons used for positrons)

II) *same* cosmic ray species (at different energy)
Use low energy protons to normalize for exposure and efficiencies → Reference map.

Stay well above geomagnetic cutoff.

Fullspan protons only (same geometry for all rigidities).

**Protons** with energy $>300$ GV in galactic coordinates

Signal map

**Protons** with $40$ GV $< E < 80$ GV in galactic coordinates

Reference map
RELATIVE PROTON ANISOTROPIES – GALACTIC COORDINATES

Data: 5 years, Mar11 - Mar16

\[ R_{\text{max}} = 1.8 \text{ TV} \]

Analysis is based on \( 1.3 \times 10^7 \) protons above 40 GV

Dipole amplitude: \( \delta = \sqrt{\rho_{NS}^2 + \rho_{FB}^2 + \rho_{EW}^2} \)

Preliminary data. Please refer to the AMS forthcoming publication in PRL.
REFERENCE MAPS FOR ANISOTROPY SEARCHES

**Reference maps:** best guess for an image of an isotropic sky measured by AMS-02 in the respective data taking period. Any deviation from this reference map might be detected as a signal.

**Choices for reference maps:**

I) other cosmic ray species (e.g. protons used for positrons)

II) *same* cosmic ray species (at different energy)

III) simulation of an isotropic sky from data

![Image of reference maps](attachment:image.png)

- 40 GV-1.8 TV protons
- 40 GV-1.8 TV IsoSky
- Ratio (proton/IsoSky)
SIMULATION OF AN ISOTROPIC SKY

**Idea:** Project detector's field of view on the galactic sky for the respective measurement time and weight with detector livetime and efficiencies.

**Method:** IG, PoS(ICRC2015)408

See poster by MA Velasco, today 15h room F, CRD052, board #028
SIMULATION OF AN ISOTROPIC SKY

Fri, 13 Jul 2012 17:53:24 GMT

Low

High

Number of expected particles

Position Of ISS
SIMULATION OF AN ISOTROPIC SKY

Fri, 13 Jul 2012 18:13:24 GMT

Low  Number of expected particles  High

Position Of ISS
SIMULATION OF AN ISOTROPIC SKY

Fri, 13 Jul 2012 18:33:24 GMT

Position Of ISS

Number of expected particles

Low

High

Fri, 13 Jul 2012 18:33:24 GMT
SIMULATION OF AN ISOTROPIC SKY

Fri, 13 Jul 2012 18:53:24 GMT

Low

Number of expected particles

High

Position Of ISS

Gate OD Theta deg

Gate OD Phi deg

-150  -100  -50     0     50    100    150
SIMULATION OF AN ISOTROPIC SKY

Fri, 13 Jul 2012 19:13:24 GMT

Low   High
Number of expected particles

Position Of ISS

GTO/D Theta deg

GTO/D Phi/deg

-150   -100   -50   0   50   100   150

-80   -60   -40   -20   0   20   40   60   80
SIMULATION OF AN ISOTROPIC SKY

Fri, 13 Jul 2012 19:33:24 GMT

Low  Number of expected particles  High

Position Of ISS

GTOD Theta/deg

GTOD Phi/deg
SIMULATION OF AN ISOTROPIC SKY

Fri, 13 Jul 2012 19:53:24 GMT

Number of expected particles

Low | High

Position Of ISS

GTOD Theta/deg

GTOD Phi/deg
SIMULATION OF AN ISOTROPIC SKY

Fri, 13 Jul 2012 20:13:24 GMT

Low

High

Number of expected particles

Position Of ISS
SIMULATION OF AN ISOTROPIC SKY

Fri, 13 Jul 2012 20:33:24 GMT

Low  High

Number of expected particles

Position Of ISS

GTOD Theta/deg

GTOD Phi/deg

-150  -100  -50  0  50  100  150
SIMULATION OF AN ISOTROPIC SKY

Fri, 13 Jul 2012 20:53:24 GMT

Low

High

Number of expected particles

Position Of ISS
SIMULATION OF AN ISOTROPIC SKY

Fri, 13 Jul 2012 21:13:24 GMT

Number of expected particles

Low

High

Position Of ISS

GTOD Phi/deg

-150  -100  -50  0  50  100  150

GTOD Theta/deg

-80  -60  -40  -20  0  20  40  60  80
SIMULATION OF AN ISOTROPIC SKY

Fri, 13 Jul 2012 21:33:24 GMT

Number of expected particles

Low       High

Position Of ISS

GTOD Phi/deg

GTOD Theta/deg

-150 -100  -50   0   50  100  150

-80  -60  -40  -20     0     20     40     60     80
SIMULATION OF AN ISOTROPIC SKY

5 year simulated proton sky, 40 GV – 1.8 TV, galactic coordinates
SIMULATION OF AN ISOTROPIC SKY

5 year data proton sky, 40 GV – 1.8 TV, galactic coordinates
SIMULATION OF AN ISOTROPIC SKY
ABSOLUTE PROTON ANISOTROPY – GALACTIC COORDINATES

Data: 5 years, Mar11 - Mar16

Analysis is based on $5.12 \times 10^7$ protons between 18 GV and 1.8 TV

Dipole amplitude: $\delta = \sqrt{\rho_{NS}^2 + \rho_{FB}^2 + \rho_{EW}^2}$

Systematics of efficiency corrections included

See poster by F. Bindel, today 15h room F, CRD046, board #003

Preliminary data. Please refer to the AMS forthcoming publication in PRL.
A search for a possible dipole signal in the arrival directions of protons was performed, using low energy protons and a data-driven simulation of an isotropic sky as a reference for isotropy.

No significant deviation from isotropy is found. No significant time dependence was observed.

Upper limits at ISS orbit 5yrs:

Galactic coordinates

\( \delta_{p/p^*}(>300 \text{ GV}) < 1\% \text{ at } 95\% \text{ C.L.} \)

\( \delta_p(>300 \text{ GV}) < 1\% \text{ at } 95\% \text{ C.L.} \)

Each analysis was performed by 2 independent groups within AMS. Both analyses are in excellent agreement.
SUMMARY

● The near to full sky coverage, long exposure and high particle identification capabilities of AMS allow us to search for full 3D dipole anisotropies in the arrival directions of individual charged cosmic rays. The latter may be directly related to the origin of some of the unexplained features observed by AMS.

● Using data from the first 5 years of AMS data taking a search for anisotropies in the arrival directions of cosmic protons, positrons and also electrons was performed:

   No significant deviation from isotropy was observed, no significant time dependence was observed in any observable and any coordinate system.

● An upper limit on the full 3D absolute proton (positron, electron) anisotropy of 1% (2%, 0.4%) above 300 GV (16 GeV, 16 GeV) was obtained.
AMS will continue to take data until the end of ISS operations. The current limits will decrease with increasing statistics.
ADDITIONAL MATERIAL
SIMULATION OF AN ISOTROPIC SKY

**Idea:** Project field of view on galactic sky for measuring time and weight with detector livetime.

Get a list of particle incoming directions \((\Theta, \varphi)_i\) in detector coordinates from selected data events.

**For every second of data taking:**

1. Draw \(N\) sets of incoming directions \((\Theta, \varphi)_i\) from list. → **geometric acceptance**

2. Calculate galactic arrival direction \(\psi_i\) from incoming direction and detector position at this second. → **project geometric acceptance in galactic sky**

3. Weight events with detector livetime \(T_{\text{Exp}}\) in this second to account for busy trigger and a time and position dependent correction factor \(\varepsilon(t, \bar{x})\).
ISOTROPIC EXPECTATION

- Create **isotropic signal maps** with \( n \) events and **isotropic reference map** with \( n'>>n \) events (*poisson distributed pixel entries, 2.5 mio ratio maps*)
  - Get distribution of dipole strength measured in case of isotropy \( H_0 \)

\[
\delta = \sqrt{\rho_{NS}^2 + \rho_{FB}^2 + \rho_{EW}^2}
\]

Dipole strength is always positive \( >0! \)
  - **Two-sided confidence interval**

For \( n'>>n \) the distribution only depends on the number of signal particles \( n \), independent of coordinate system and reference map.
POSITRONS OVER ELECTRONS – ISOTROPIC EXPECTATION

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

Iris Gebauer
Institut für Experimentelle Kernphysik

July 13th, Anisotropy searches with AMS-02 (contribution CRD-071)
ERROR ON DIPOLE STRENGTH

- Draw dipole components from multivariate correlated Gaussian distribution following the measured dipole components and their correlations

→ calculate delta from drawn dipole components
Reconstructed dipole strength is consistent with the isotropic expectation.
LIMIT CALCULATION

- Create maps with \( n=N_{\text{signal}} \) events and dipole signal
  \((\text{Poisson times signal distributed pixel entries})\)

- Create isotropic reference map with \( n'>>n \) events
  \(\rightarrow\) Fit dipole components

- 95% CL is computed from the distribution of \textit{true dipole strengths} for the dipole strength measured on data
POSITRONS OVER ELECTRONS – LIMIT ON DIPOLE STRENGTH

- Isotropic Expectation
- Measured Dipole Strength
- 95% C.L. Limit

Preliminary data. Please refer to the AMS forthcoming publication in PRL.
SUMMARY

Positron anisotropy (GAL):

$\delta_{e+/e-}(>16 \text{ GeV}) < 1.8\% \text{ at } 95\% \text{ C.L.}$

$\delta_{e+/p}(>16 \text{ GeV}) < 1.7\% \text{ at } 95\% \text{ C.L.}$

$\delta_{e-}(>16 \text{ GeV}) < 0.5\% \text{ at } 95\% \text{ C.L.}$

Electron anisotropy (GAL):

$\delta_{e-/p}(>16 \text{ GeV}) < 0.4\% \text{ at } 95\% \text{ C.L.}$

$\delta_{e-}(>16 \text{ GeV}) < 0.5\% \text{ at } 95\% \text{ C.L.}$

Proton anisotropy (GAL):

$\delta_{p/p^*}(>80 \text{ GV}) < 0.2\% \text{ at } 95\% \text{ C.L.}$

$\delta_{p}(>80 \text{ GV}) < 0.2\% \text{ at } 95\% \text{ C.L.}$

$\delta_{p}(>18 \text{ GV}) < 0.1\% \text{ at } 95\% \text{ C.L.}$

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