RECENT RESULTS FROM AMS-02

9 March 2015

Vincent Poireau, LAPP Annecy

OUTLOOK

- Cosmic rays
- The AMS experiment
- Positron fraction measurement
- Electron and positron flux
- Interpretation of the data
  - Dark matter
  - Pulsars

PRL 113, 121101 (2014) PHYSICAL REVIEW LETTERS week ending 19 SEPTEMBER 2014

High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5–500 GeV with the Alpha Magnetic Spectrometer on the International Space Station

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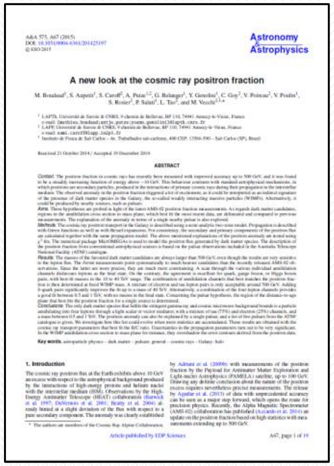
PRL 113, 121102 (2014) PHYSICAL REVIEW LETTERS week ending 19 SEPTEMBER 2014

Electron and Positron Fluxes in Primary Cosmic Rays Measured with the Alpha Magnetic Spectrometer on the International Space Station

PRL 113, 221102 (2014) PHYSICAL REVIEW LETTERS week ending 28 NOVEMBER 2014

Precision Measurement of the $(e^+ + e^-)$ Flux in Primary Cosmic Rays from 0.5 GeV to 1 TeV with the Alpha Magnetic Spectrometer on the International Space Station



A&A 575, A67 (2015)

Astronomy & Astrophysics

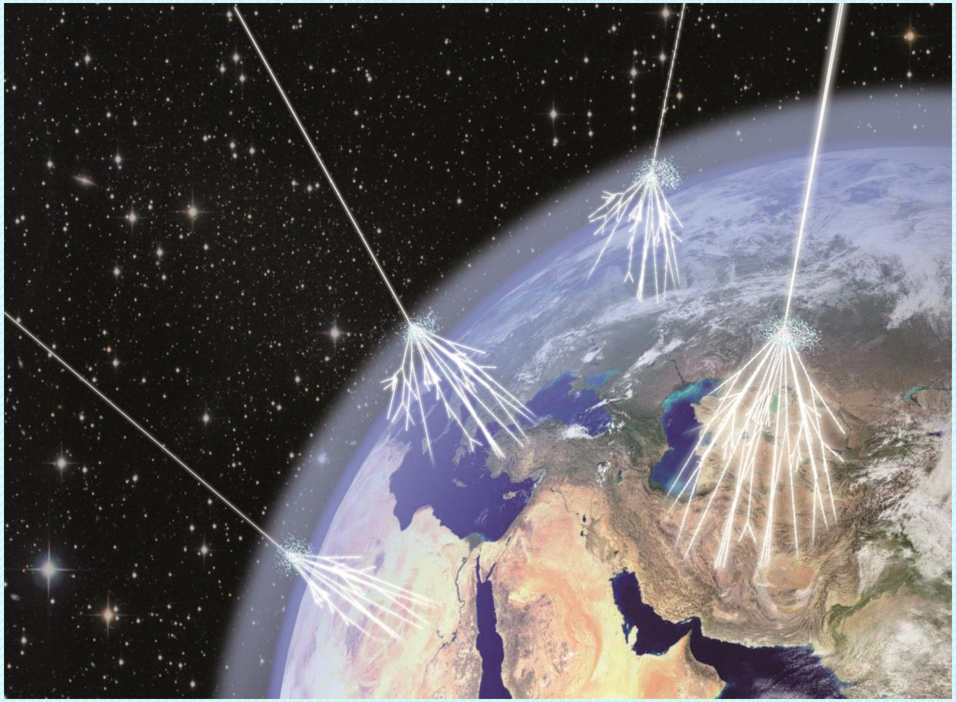
A new look at the cosmic ray positron fraction

ABSTRACT

References :

- Phys. Rev. Lett. 113, 121101 (2014)
- Phys. Rev. Lett. 113, 121102 (2014)
- Phys. Rev. Lett. 113, 221102 (2014)
- A&A 575, A67 (2015)

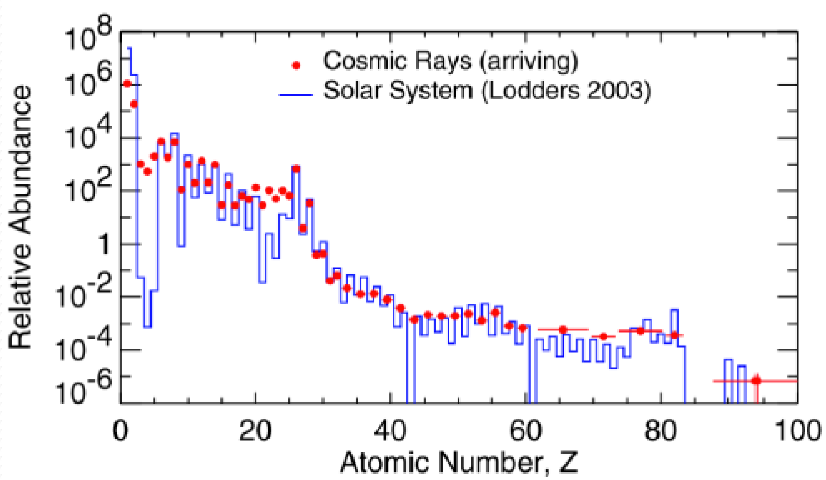
COSMIC RAYS

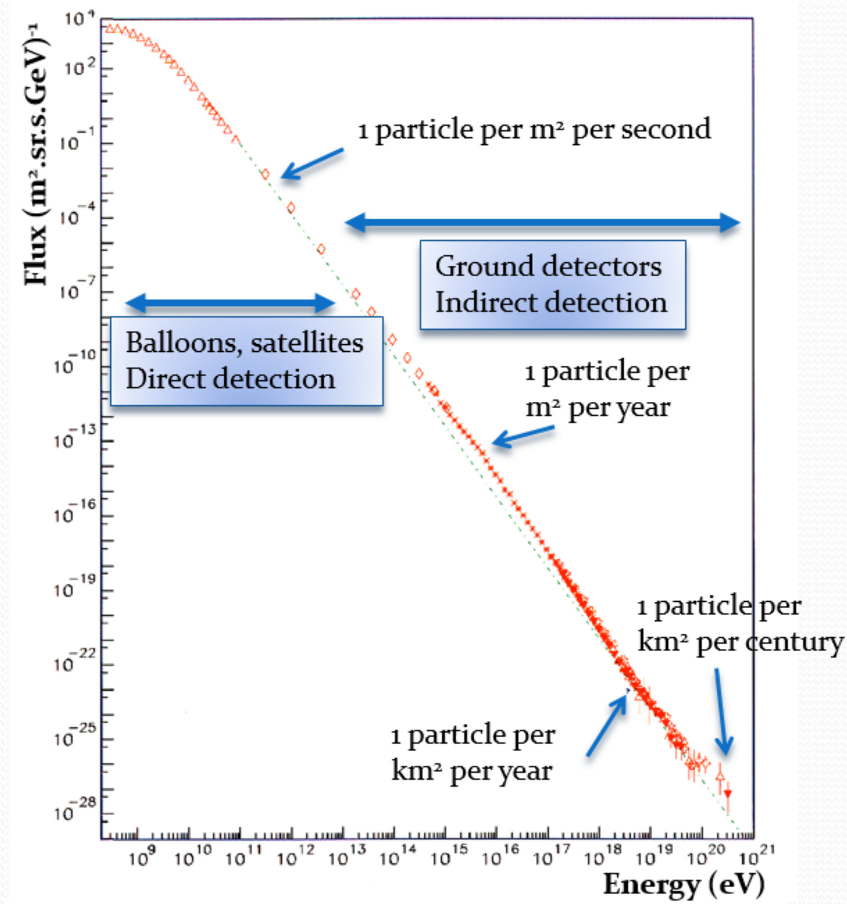


COSMIC RAYS

- Cosmic rays
  - 12 orders in **energy**
    - 100 MeV to 10^{20} eV
  - 30 orders in **flux**
  - Isotropic flux

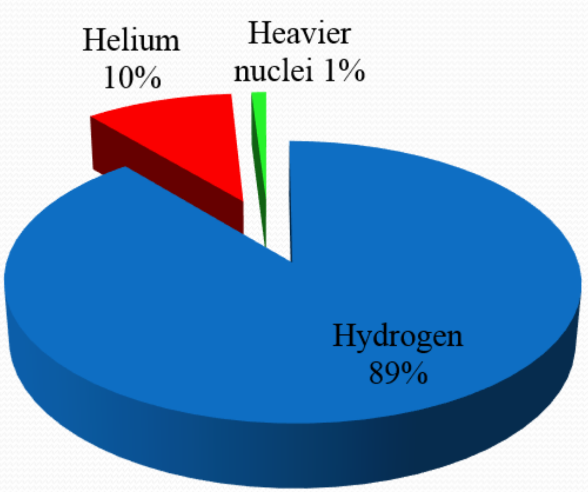
- Abondance of nuclei in the cosmic rays similar to the one from the solar system

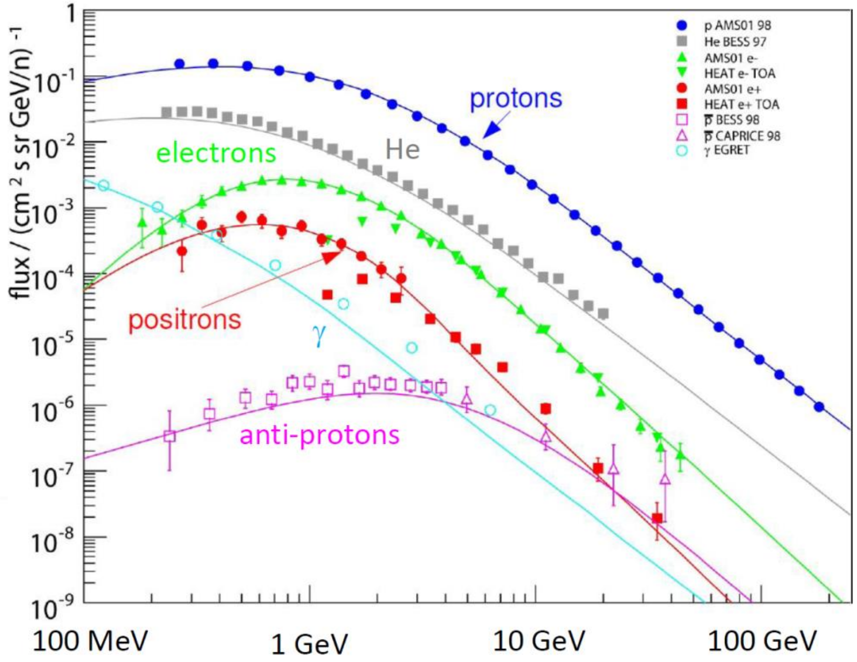




COSMIC RAYS

- Composition
  - **Charged** : electrons, protons, nuclei
  - **Neutral** : photons, neutrinos
- Charged cosmic rays

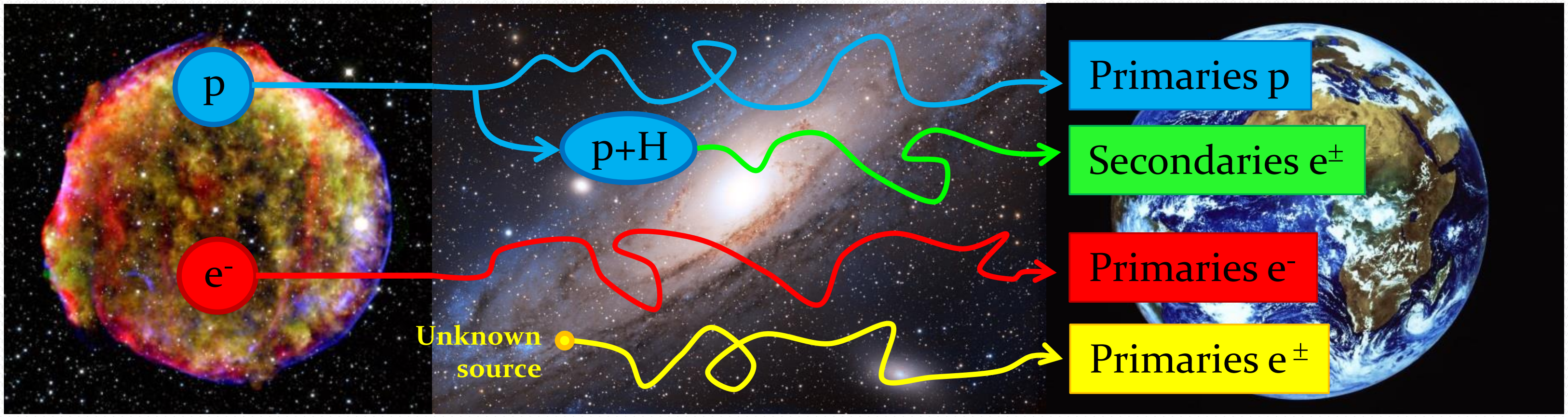




- Power law spectrum $1/E^{\gamma}$, $\gamma = 2.7\text{-}3.5$
  - The measured spectrum results
    - from the **production** and **acceleration** mechanisms ($1/E^{\alpha}$, $\alpha = 2.0\text{-}2.4$)
    - from the **diffusion** ($1/E^{\delta}$, $\delta = 0.3\text{-}0.7$)
  - $\gamma = \alpha + \delta$

COSMIC RAYS

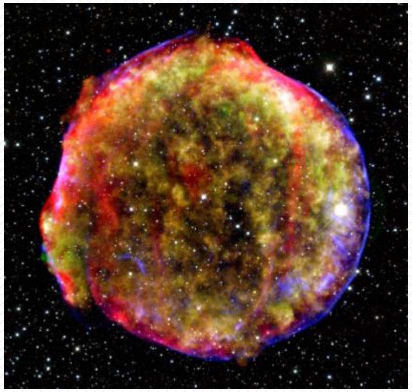
Production and acceleration | Propagation (diffusion) in our Galaxy | Observation



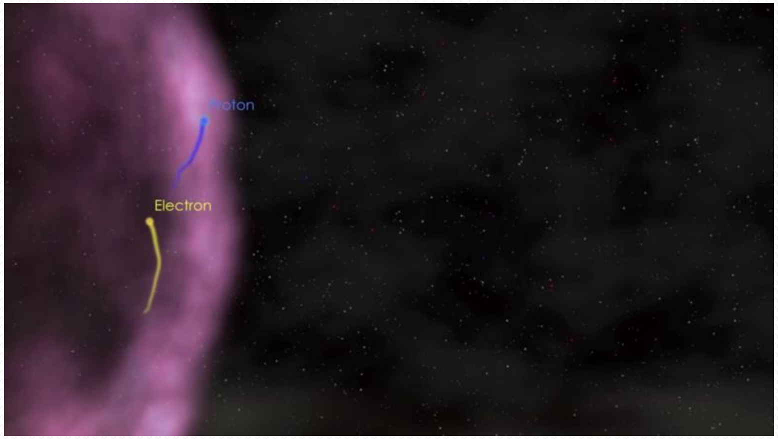
- Primary cosmic rays
  - Produced direcly **in the source**
  - Sources: **supernova remnants, pulsars**, **active galactic nuclei**, **quasars**
  - Primaries include
    - Electrons, protons, helium, carbon, …
- Secondary cosmic rays
  - Originate from the **interaction** of primaries on **interstellar medium**
  - Secondaries include
    - Positrons, antiprotons, bore, …
- Additional sources of electrons and positrons?

ACCELERATION

- In our Galaxy, main source of primary cosmic rays: supernova remnants
  - Very strong magnetic field in the **shell** of supernovas



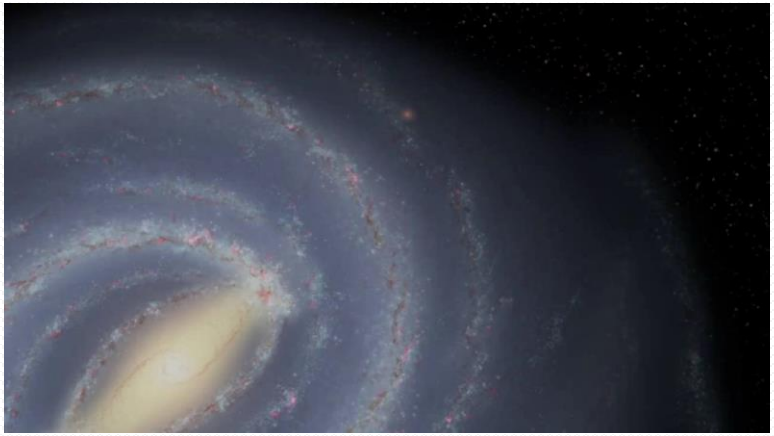
- Acceleration
  - Due to the **shock wave**
  - First order **Fermi mechanism**
  - Naturally produce a **power law** spectrum

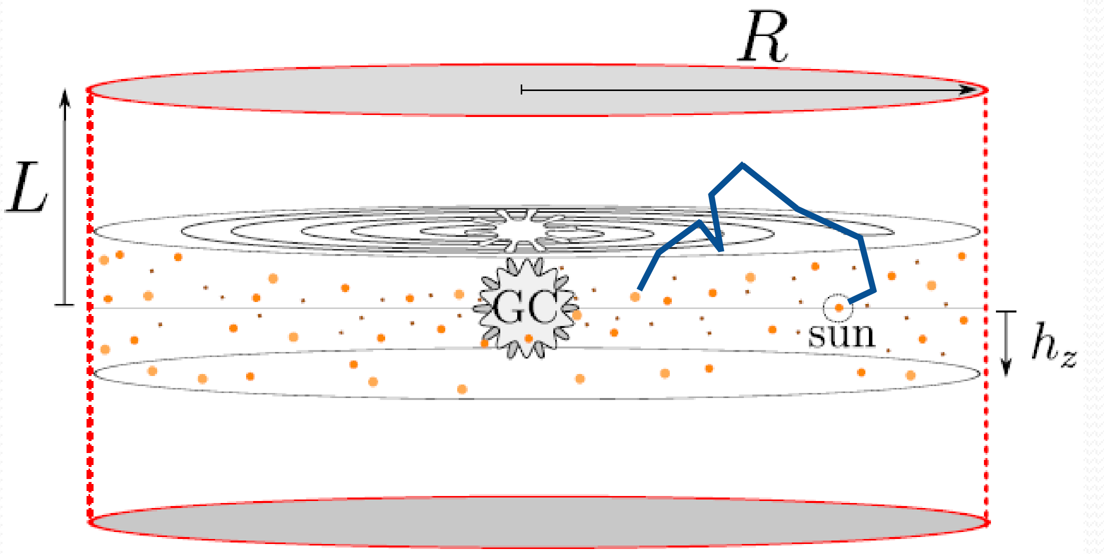


- This process explains why the cosmic ray composition is similar to the one from the solar system

PROPAGATION

- Charged cosmic rays: propagation equivalent to a diffusion in the Galactic medium
  - **Irregular magnetic field** of the diffusive halo = random walk
  - **Diffusion** coefficient $K(E) = K_0 \beta R^{\delta}$ $(R=p/Z)$
    - Free parameters: K_0, δ, L, V_c, V_a
  - Uncertainties on these parameters translated to three parameter sets
    - Min, Med, Max





h_z=200 pc, L=1-15 kpc, R=25 kpc

THE AMS-02 EXPERIMENT

AMS-02

- A particle detector in space
  - Detect **charged** particles and **gamma** rays
  - From **100 MeV** to **a few TeV**

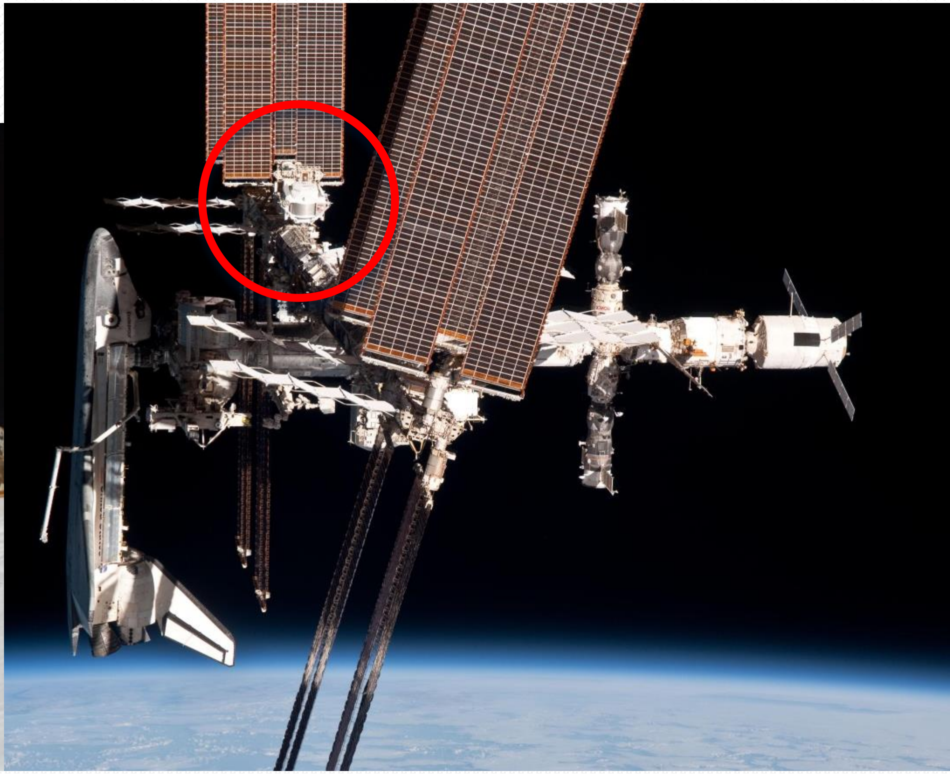
5m x 4m x 3m
7.5 tons

AMS-02

- Launch from Cap Canaveral on the 16th of May 2011
  - **Penultimate** American shuttle!

AMS-02

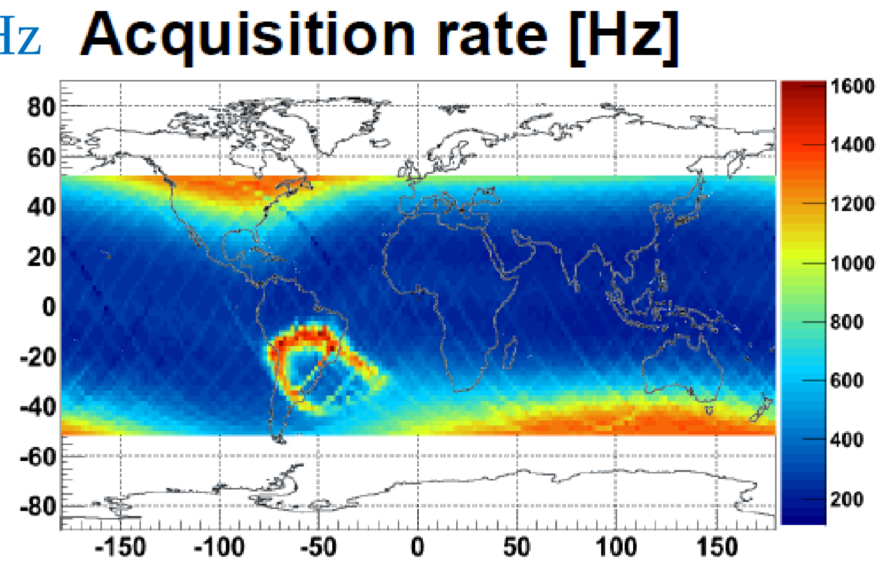
- Installation on the ISS on the 19th of May 2011
  - Orbit at **400 km** altitude
  - One orbit every **90 minutes**



- Detect the cosmic rays before they interact in the atmosphere

FLIGHT OPERATION

- Acquisition rate from 200 to 2000 Hz

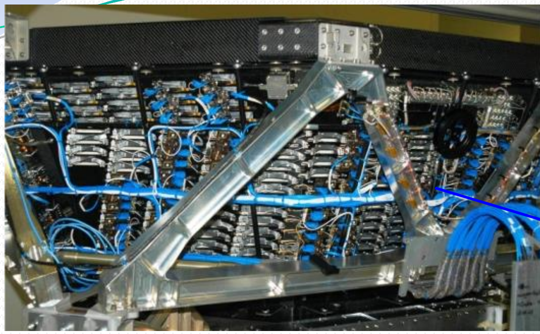


- Continuous operation 7d/7 24h/24
- Acquisition
  - ~**40 millions** events a day
  - ~**100 GB** transferred every day
  - **35 TB** of data every year
  - **200 TB** of reconstructed data every year
- 60 billions of events recorded since May 2011
  - Much more than all the cosmic rays collected **in the last 100 years**
- Will operate at least until 2020
  - Analyses presented here up to **November 2013**

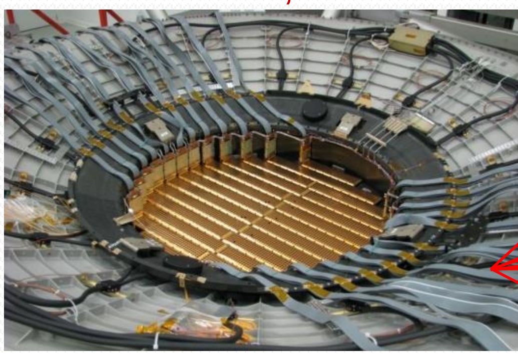
TRANSMISSION

DETECTOR

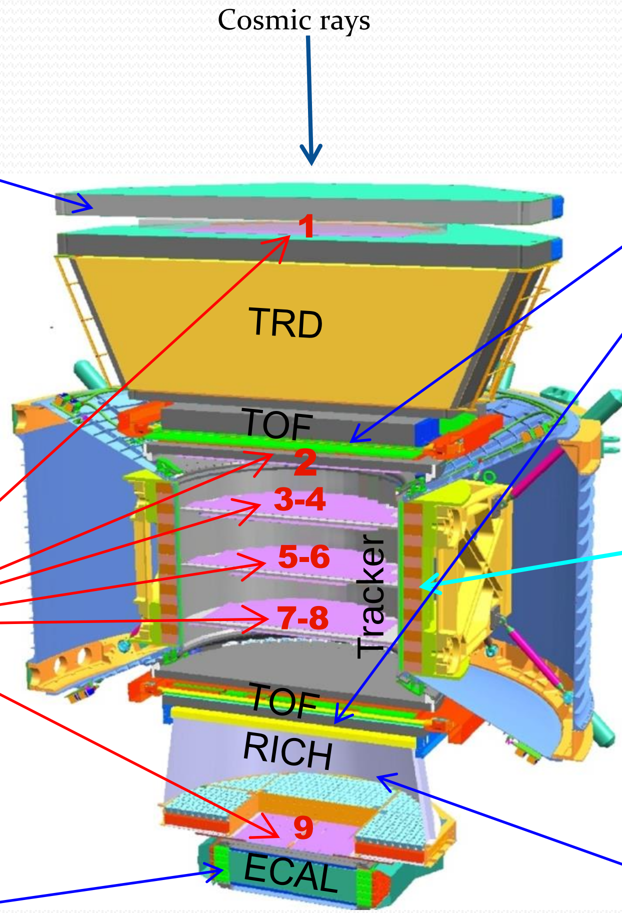
Transition radiation detector
Identifies e^+, e^-



Silicium tracker
Z, P

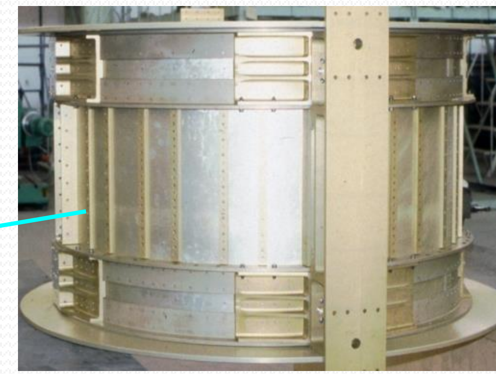


Electromagnetic calorimeter
E of e^+, e^-, γ

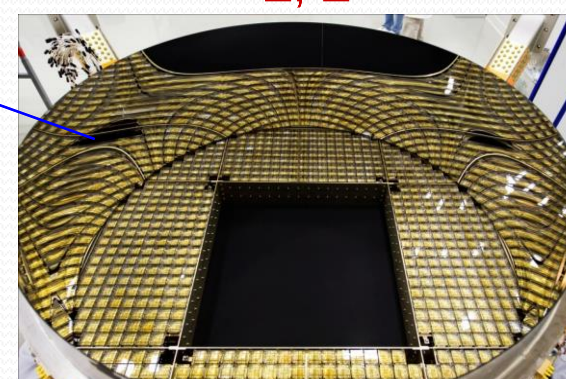


Time of flight
Z, E

Magnet 0,14 T
±Z

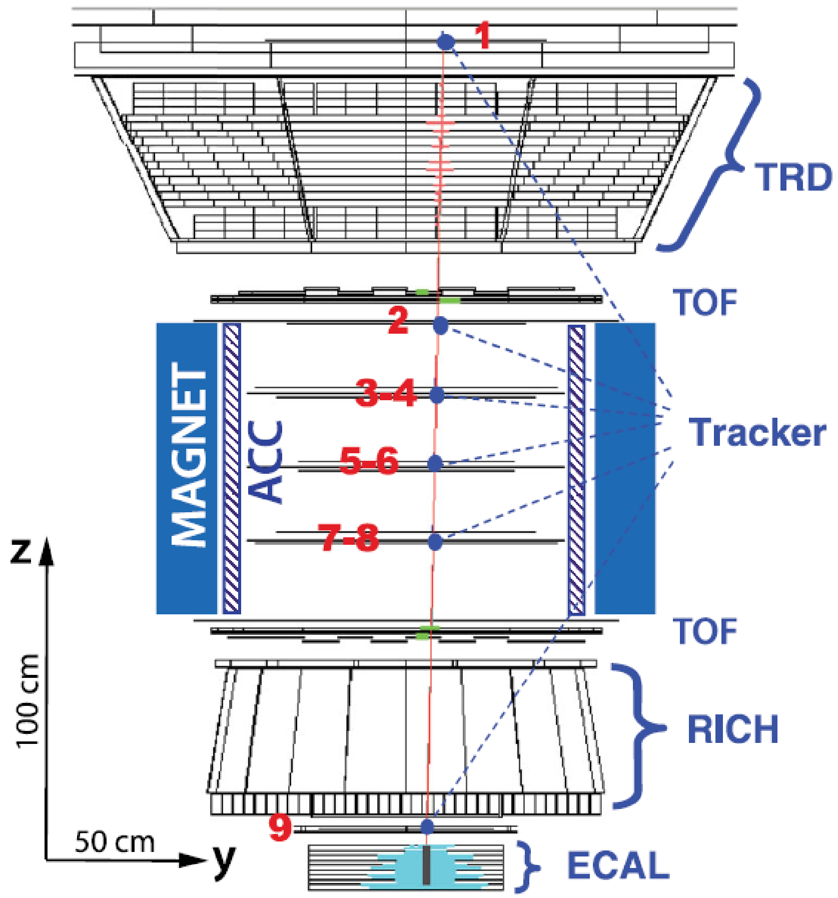


Cherenkov detector
Z, E



DETECTOR

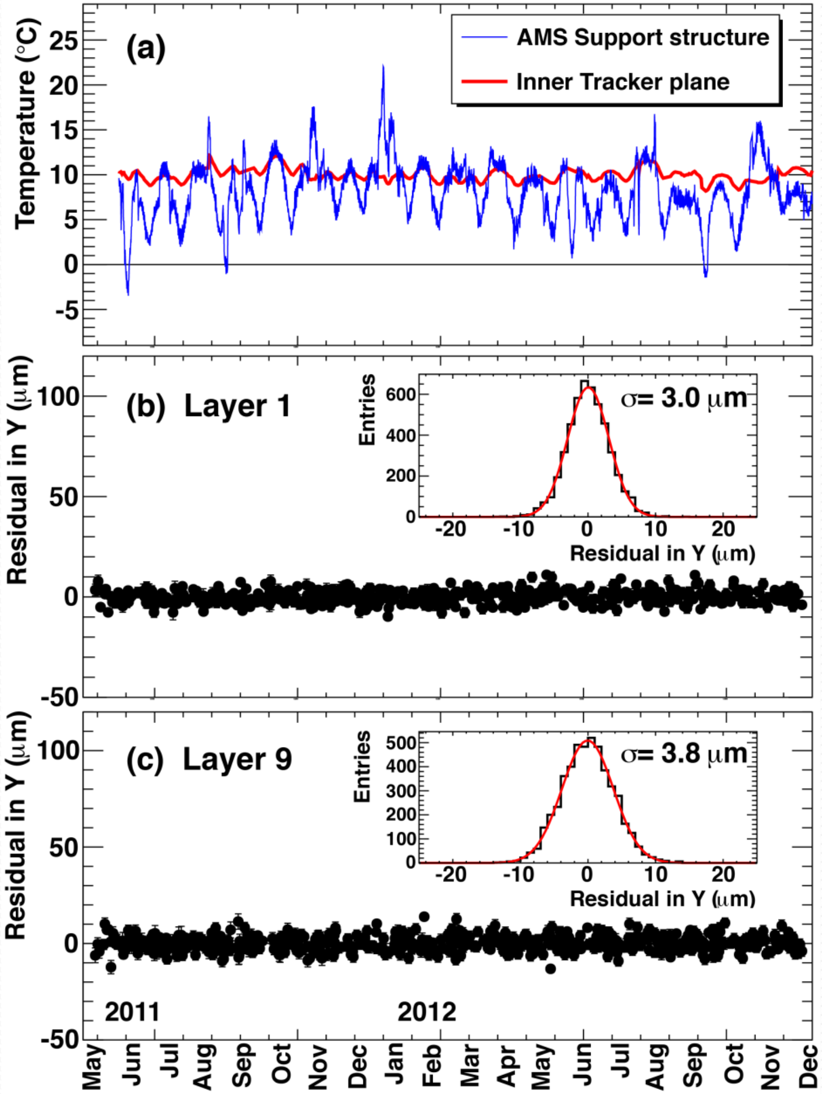
- Rigidity
  - R = p/Z



A 369 GeV positron event

TEMPERATURES

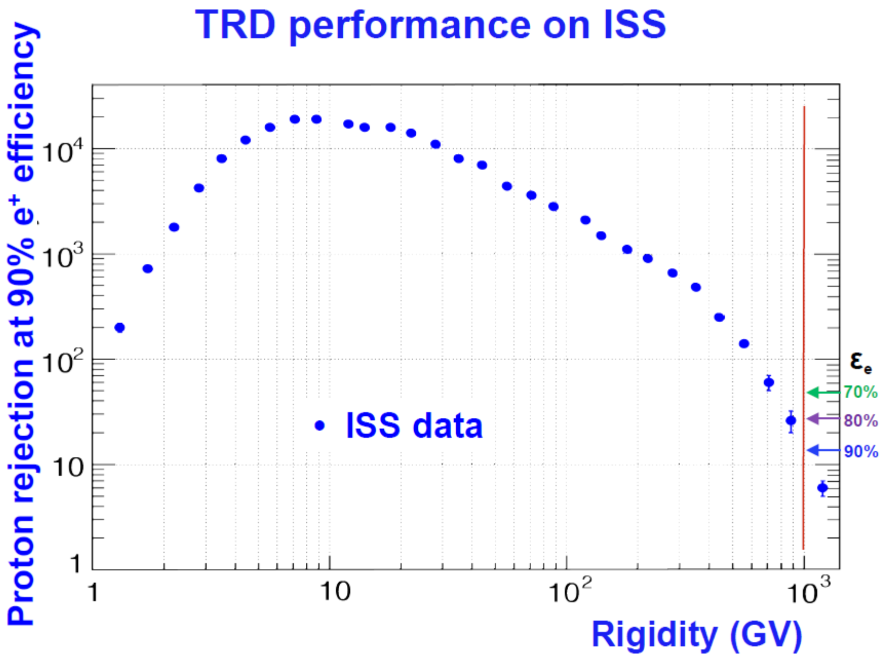
- Temperature variation on external tracker planes
  - Induce shifts of planes of **100 µm**
- Alignment performed with cosmic rays
  - **3-4 µm** precision

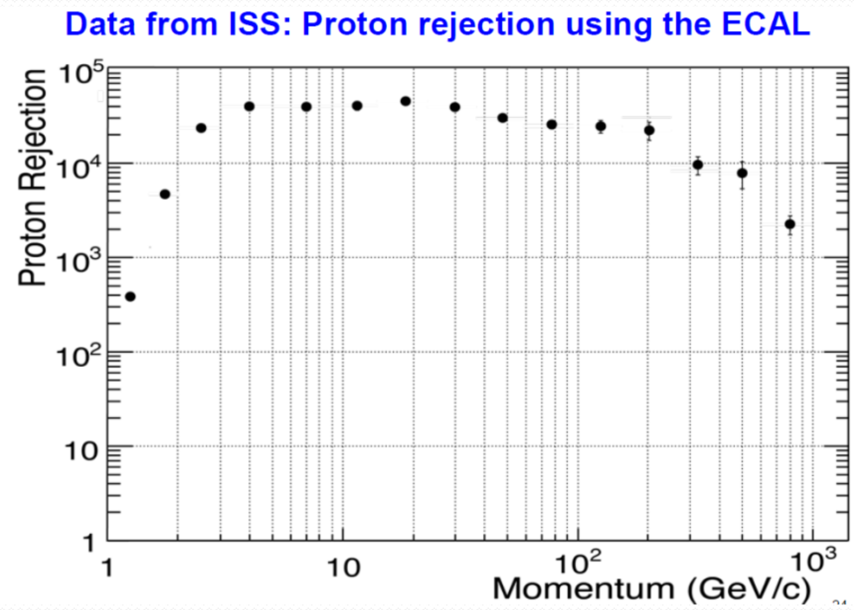


DETECTOR PERFORMANCE

- In this talk, focusing on electrons and positrons
- Reject protons while keeping a good efficiency for e^+/e^-

- TRD and calorimeter performance for rejection

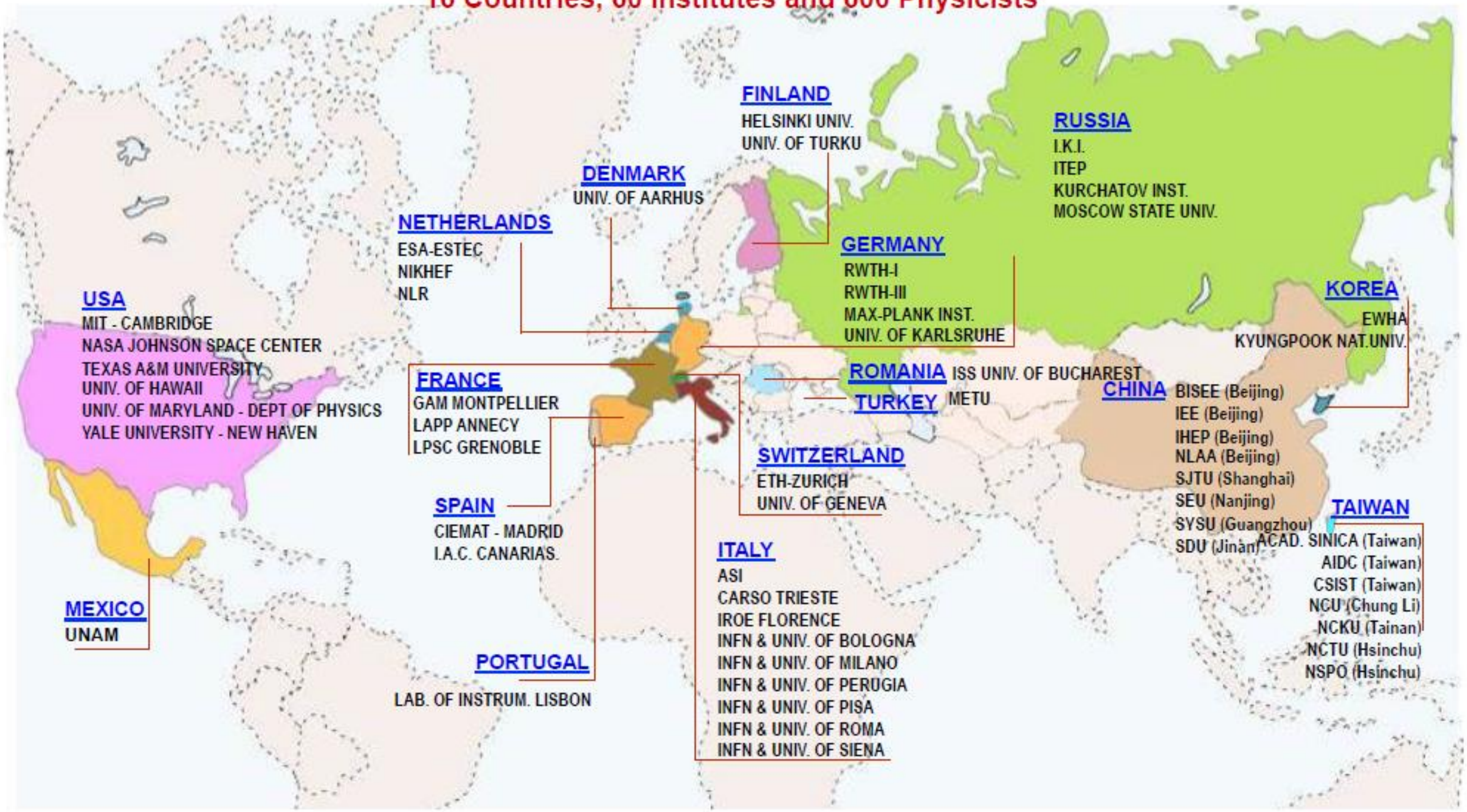




COLLABORATION

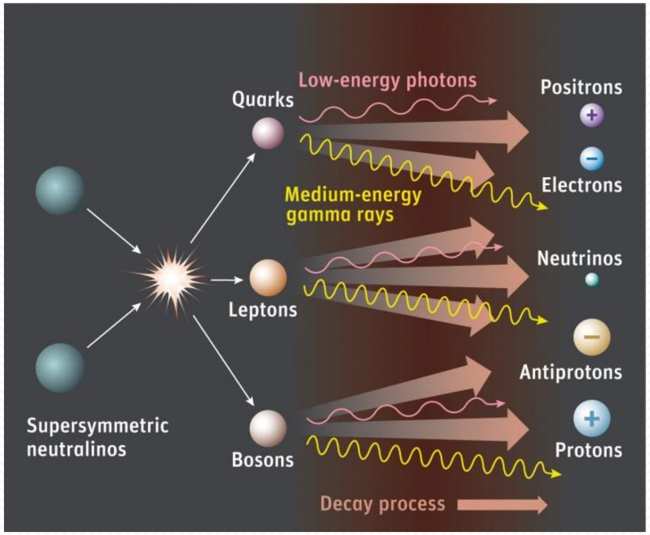
AMS: a U.S. DOE sponsored international collaboration

16 Countries, 60 Institutes and 600 Physicists

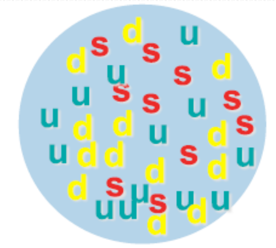


AMS TOPICS

- Measurement of cosmic ray fluxes
  - Understand the cosmic ray **propagation** in our Galaxy



- Indirect search of dark matter
  - **Positrons** and **antiprotons** produced during its annihilation
- Search for primordial antimatter
  - **Anti-helium** relic of the Big-Bang or **anti-carbon** from anti-stars



- Surprises? Strangelets?

POSITRON FRACTION

PRL **113**, 121101 (2014) PHYSICAL REVIEW LETTERS week ending 19 SEPTEMBER 2014

High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5–500 GeV with the Alpha Magnetic Spectrometer on the International Space Station

POSITRON FRACTION

- Positrons : expected only as secondary
- Positron excess with respect to the secondary prediction = source of primary positrons

- Positron fraction $F = \frac{\Phi_{e^+}}{\Phi_{e^+} + \Phi_{e^-}} = \frac{N_{e^+}}{N_{e^+} + N_{e^-}}$
  - Allows to factorize the **acceptance** and efficiencies
  - **Simplify** the computation of systematic uncertainties

- Challenges
  - **100 times** more protons than electrons
  - **2000 times** more protons than positrons

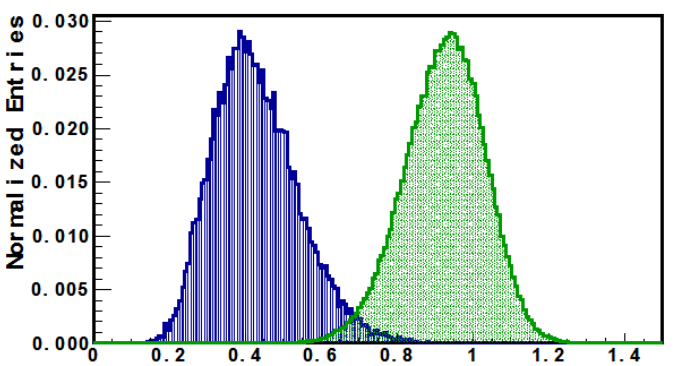
  $\Rightarrow$ Need to divide number of protons by $\mathbf{10^6}$

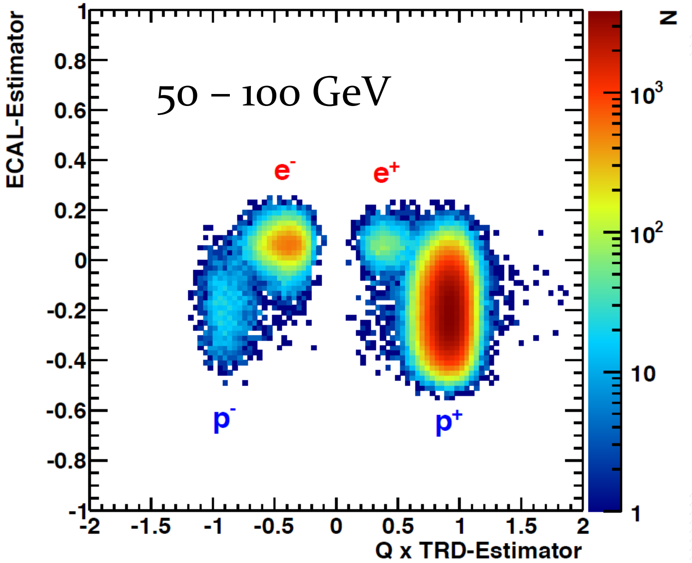
- Analysis based on 10,9 millions of positron and electron events (30 months)

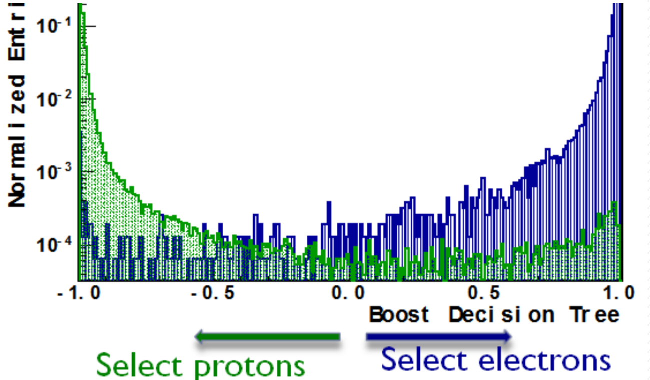
POSITRON FRACTION

- Key detectors for this measurement
  - **TRD**
  - **Tracker**
    - E/p close to 1 for electrons/positrons
  - **Calorimeter**
    - Based on 3D shower shape

- Methodology
  - **Selection** using the calorimeter variable
  - **Count** of e^+ (Z>0) and e^- (Z<0) from a 2D fit on the TRD and tracker variables
  - Count for each **energy range**

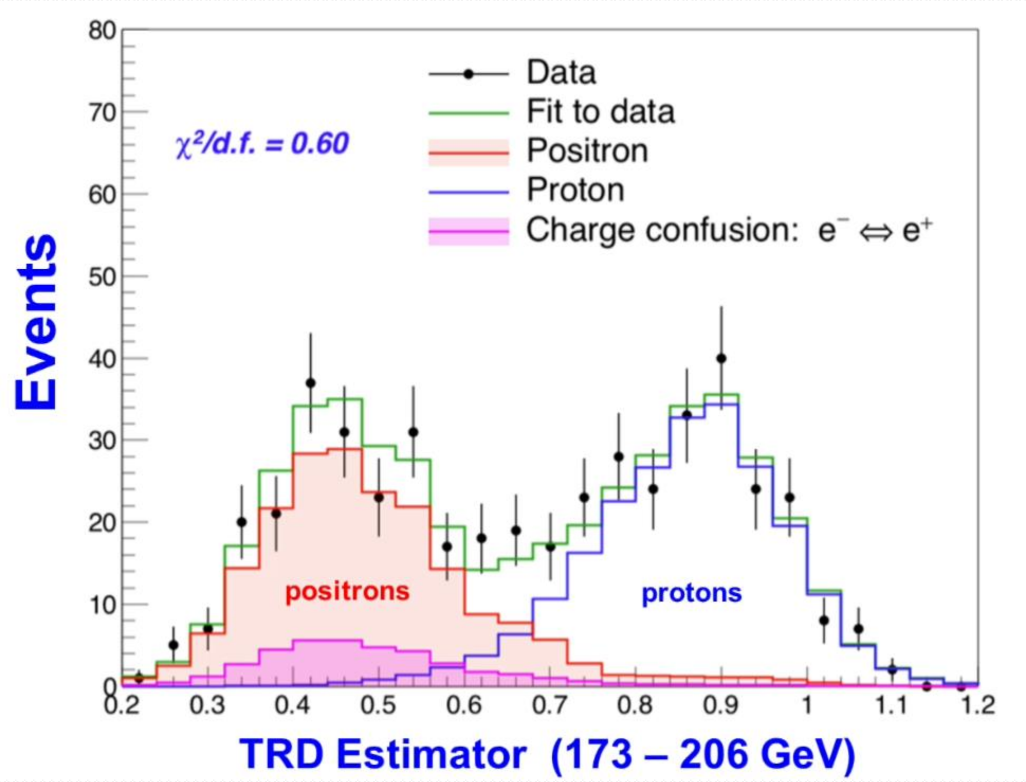






POSITRON FRACTION

- Counts of leptons after the selection
  - **Z > 0** : count of **positrons**

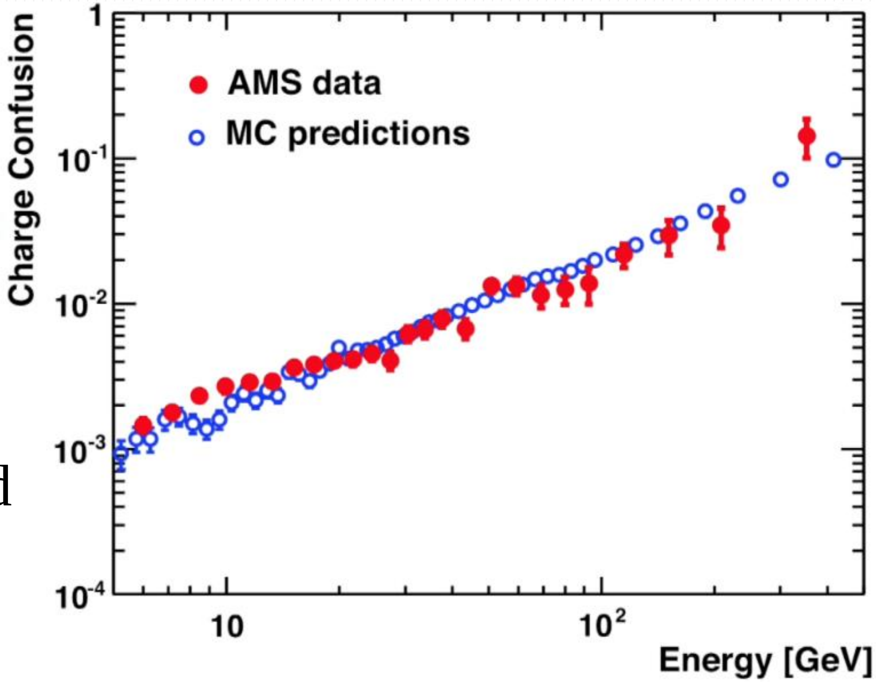


  - **Z < 0** : count of **electrons**

CHARGE CONFUSION

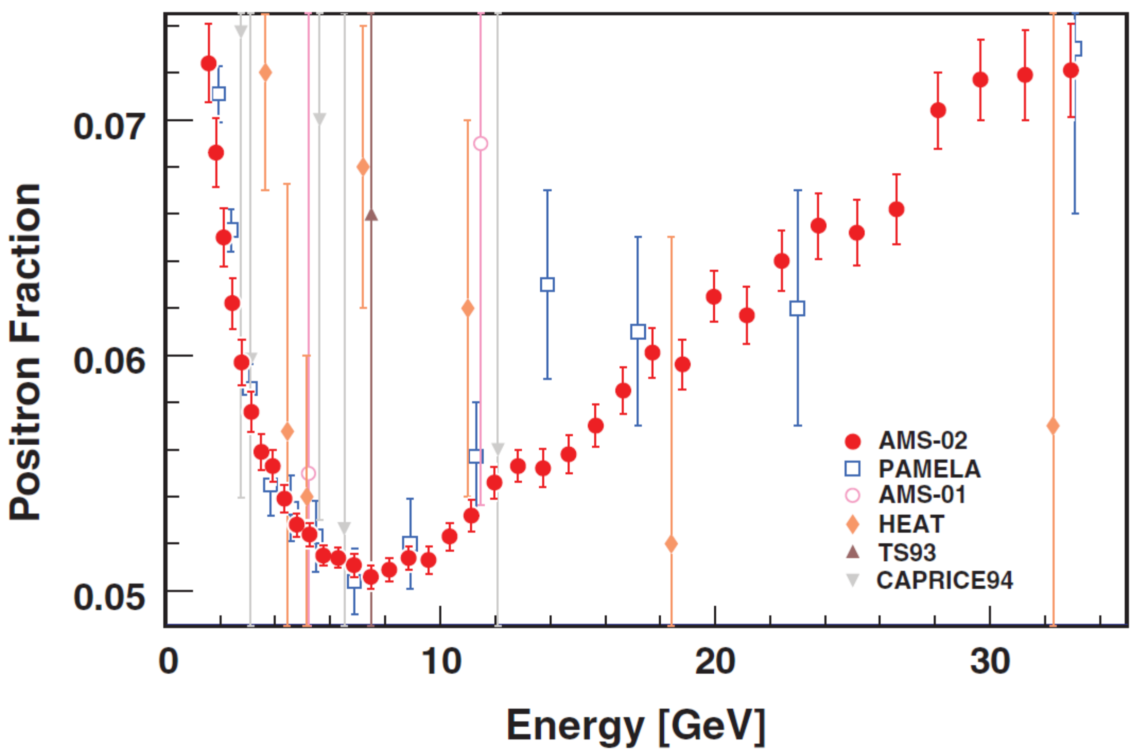
- For some energy range, difficulty to measure the sign of the charge
  $\Rightarrow$ confusion

- Two sources
  - Finite resolution of the tracker and multiple scattering
  - Production of secondary tracks along the path of the primary track



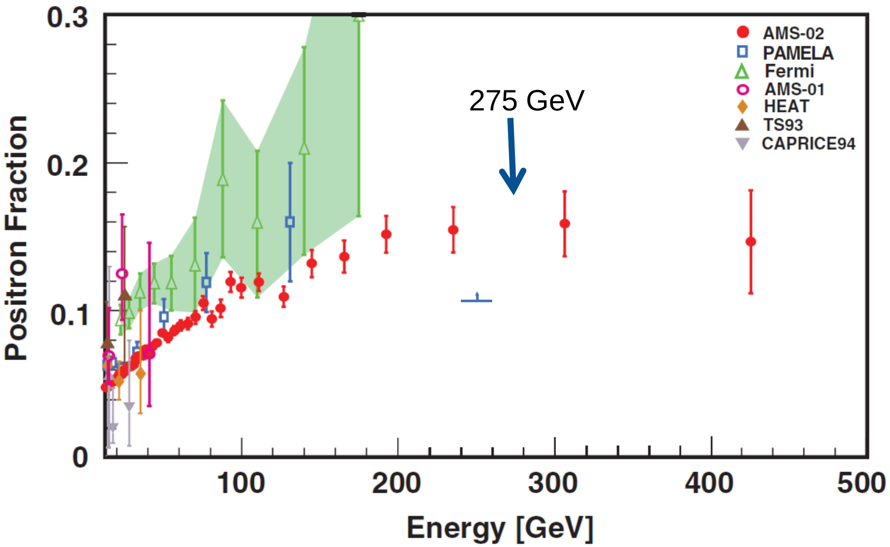
POSITRON FRACTION

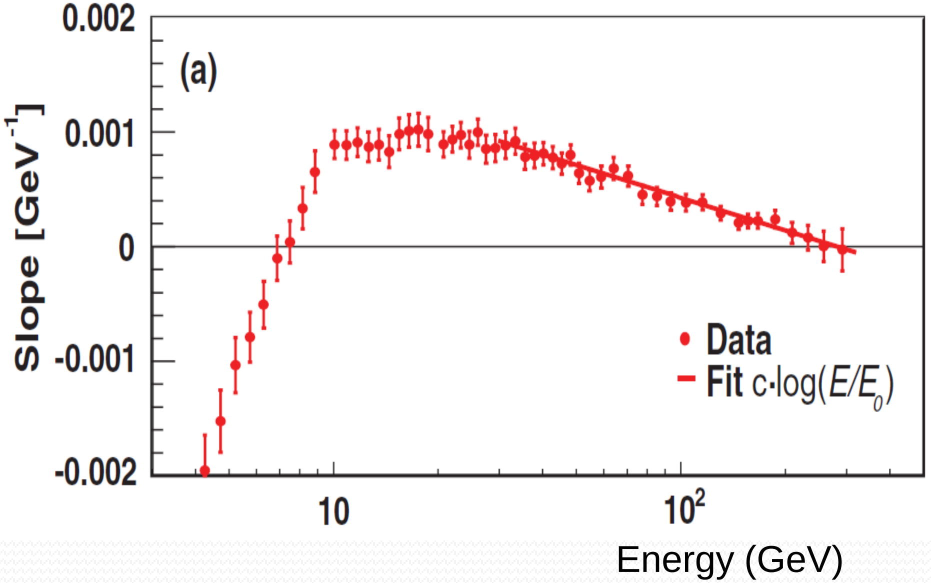
- Result for the positron fraction below 35 GeV
  - Fraction begins to increase **above 10 GeV**
  - **Incompatible** with secondary positrons only
  - A **source of primary positrons** is needed!
    - **Nearby** source since positrons do not propagate more than a **few kpc**



POSITRON FRACTION

- Fraction at high energy





- Precision and energy never reached before
- No sharp structure
- Fit of the slope
  - Cease to increase at **275 ± 32 GeV**
- With the current sensitivity, the flux is isotropic

ELECTRON FLUX
POSITRON FLUX

PRL 113, 121102 (2014) PHYSICAL REVIEW LETTERS week ending 19 SEPTEMBER 2014

Electron and Positron Fluxes in Primary Cosmic Rays Measured with the Alpha Magnetic Spectrometer on the International Space Station

FLUX MEASUREMENT

- Fluxes bring more information for the models than the fraction

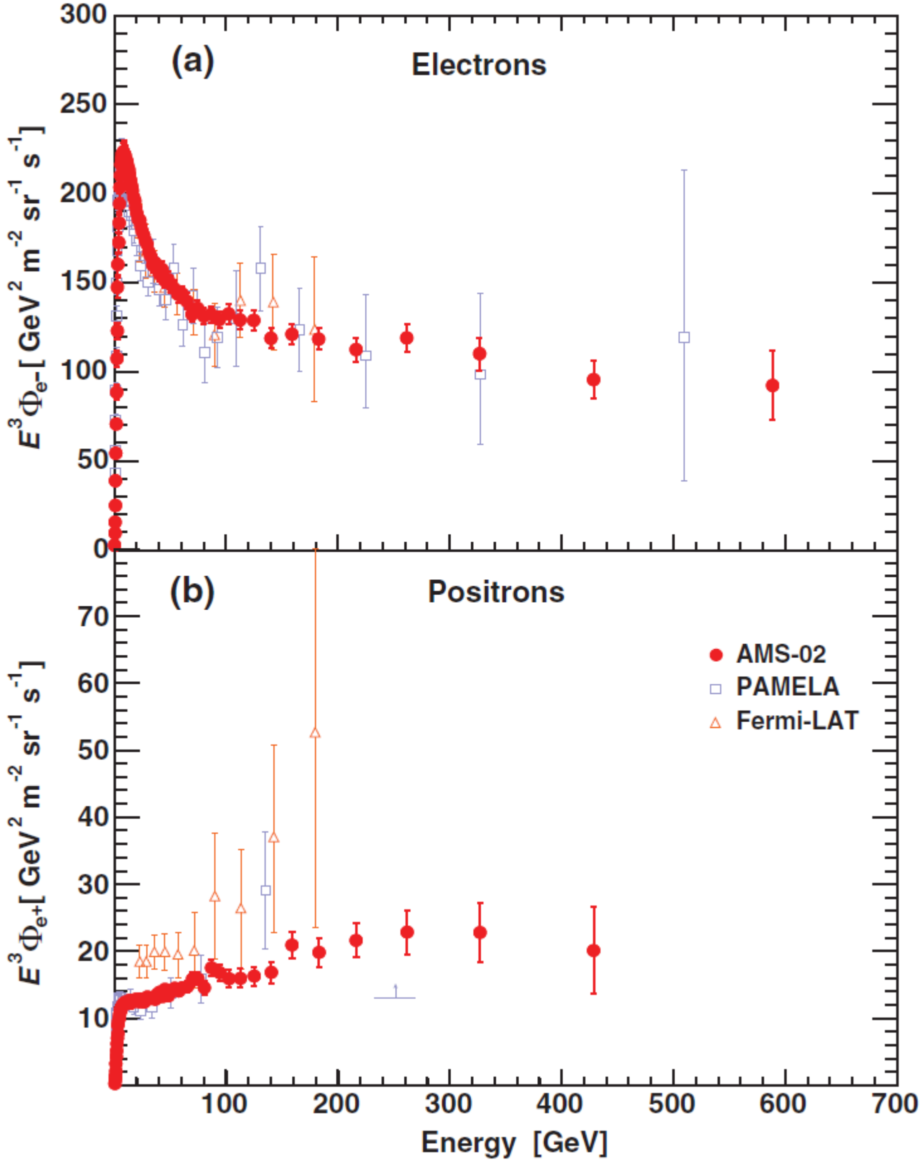
- Obtaining the flux via

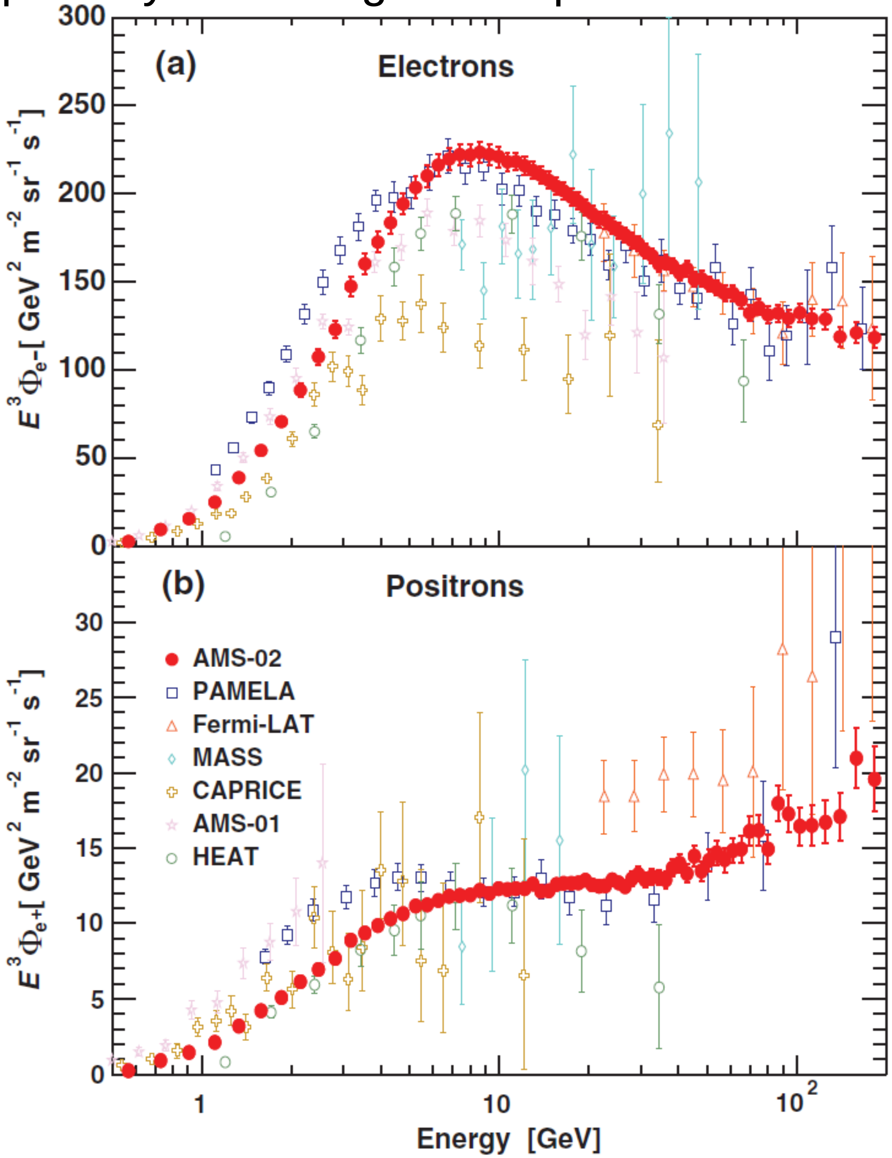
$$\frac{N}{A \times \varepsilon_{Trig.} \times \varepsilon_{sel.} \times T \times dE}$$

  - N **number** of positrons or electrons
  - A **acceptance**
  - ε_{Trig} and ε_{sel} **trigger** and **selection efficiencies**
  - T exposure **time**
  - dE energy **bin size**

FLUX MEASUREMENT

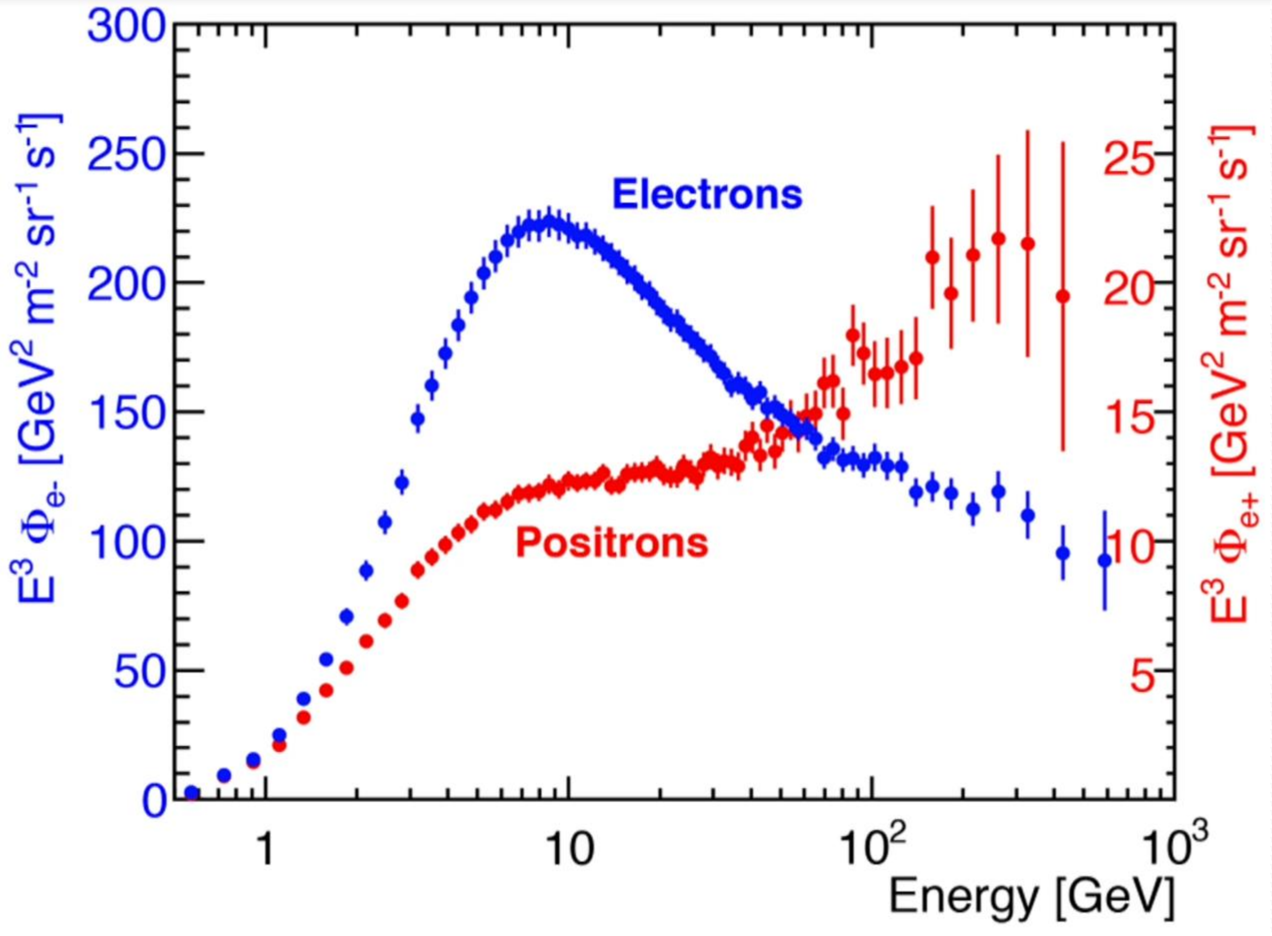
Linear scale Flux multiplied by E^3 Log scale up to 200 GeV





FLUX MEASUREMENT

- The electron and positron fluxes are different in their magnitude and energy dependence

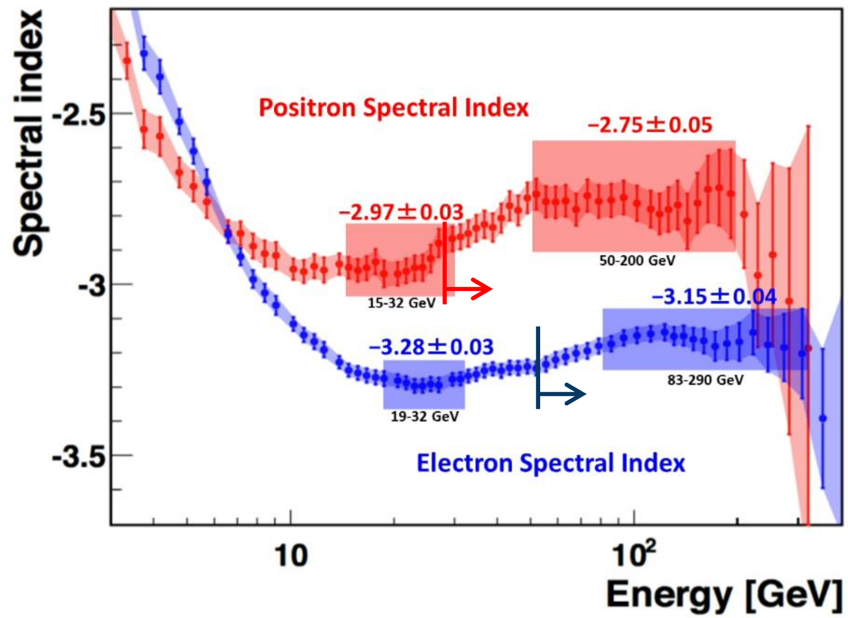


FLUX MEASUREMENT

- Calculation of the spectral indices

$$\Phi_{e^\pm}(E) = C_{e^\pm} E^{\gamma_{e^\pm}} \quad \text{or} \quad \gamma_{e^\pm} = d[\log(\Phi_{e^\pm})]/d[\log(E)]$$

- Observations
  - Both spectra **cannot be described** by single **power laws**
  - The spectral indices of electrons and positrons are **different**
  - **Change of behavior** at ~30 GeV



- Lower energy limit for single power law distribution description
  - **Positrons**: 27.2 GeV
  - **Electrons**: 52.3 GeV

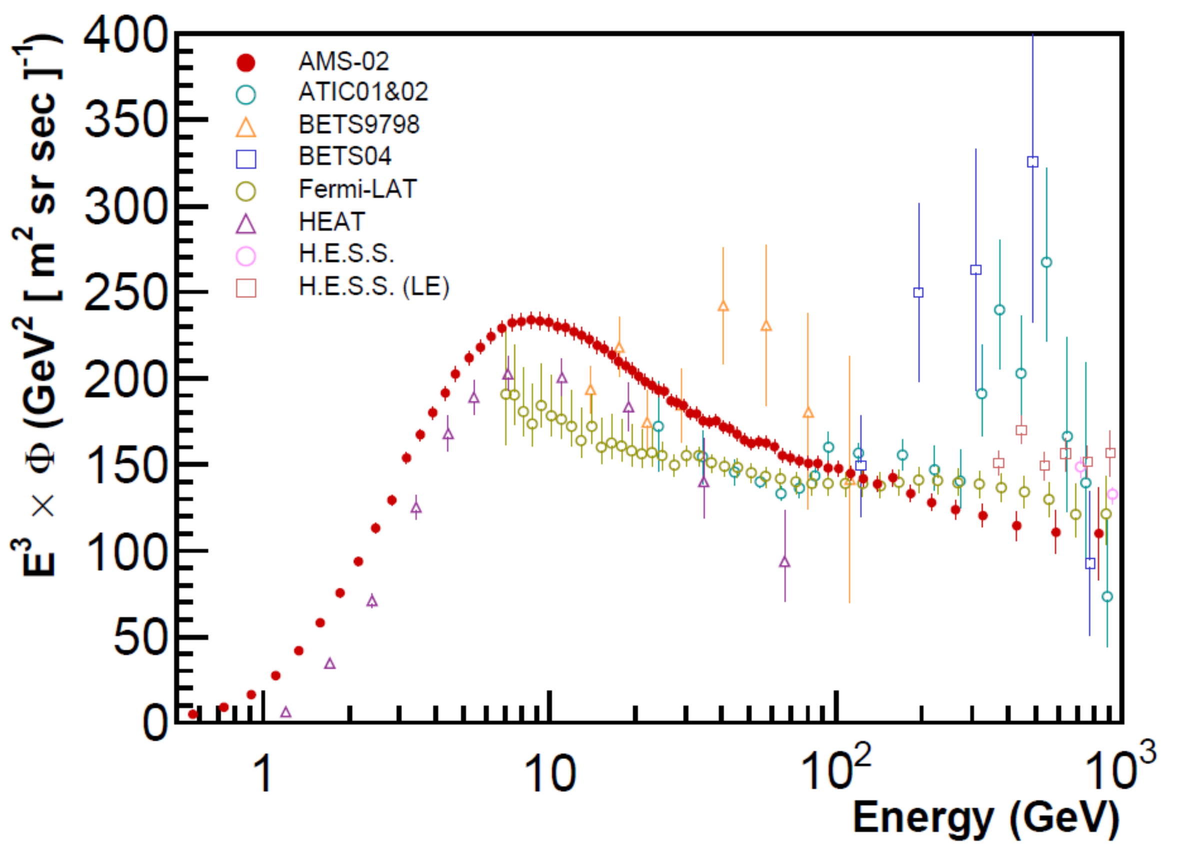
COMBINED $(e^+ + e^-)$ FLUX

PRL **113,** 221102 (2014) PHYSICAL REVIEW LETTERS week ending 28 NOVEMBER 2014

Precision Measurement of the $(e^+ + e^-)$ Flux in Primary Cosmic Rays from 0.5 GeV to 1 TeV with the Alpha Magnetic Spectrometer on the International Space Station

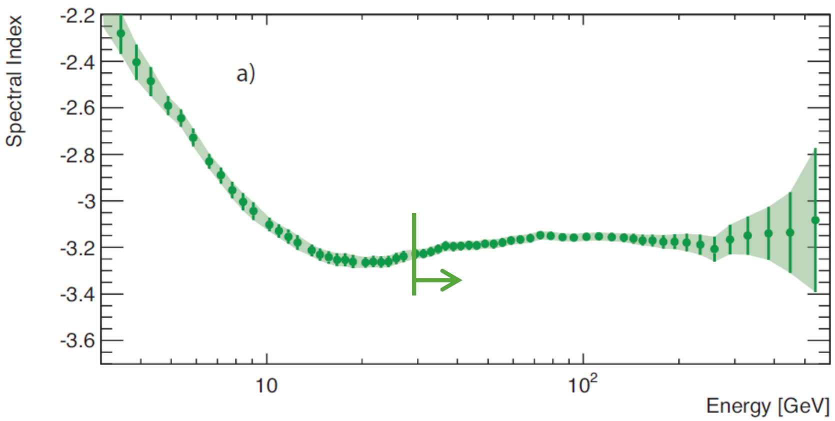
COMBINED FLUX

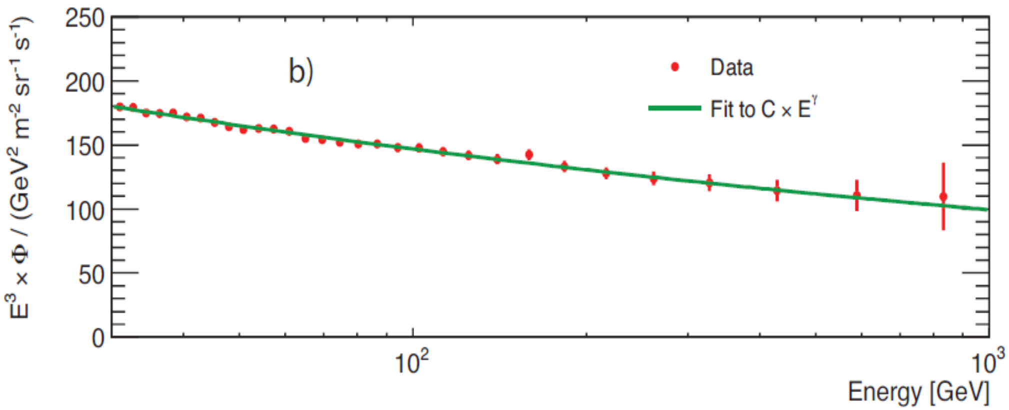
- This measurement
  - Independent from **charge sign** measurement = **no charge confusion**
  - **High selection efficiency** (70% at 1 TeV)



COMBINED FLUX

- Calculation of the spectral index $\phi(e^+ + e^-) = C\,E^{\gamma}$





- The flux is consistent with a single power law above 30 GeV
  - γ = -3.170 ± 0.008 (stat + syst) ± 0.008 (energy scale)

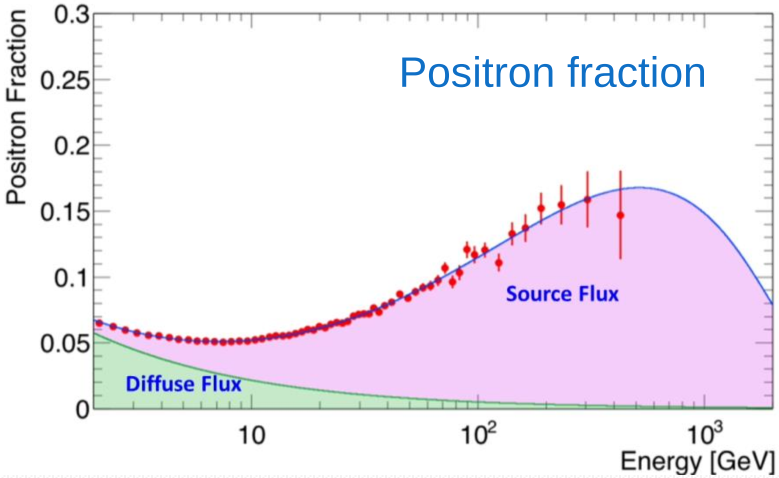
MINIMAL MODEL

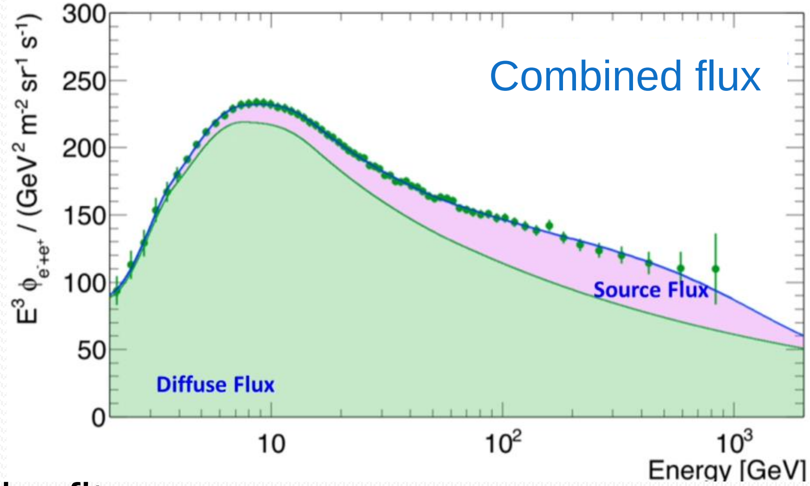
MINIMAL MODEL

- Fit of the AMS data using a minimal model
- Positrons
  - Secondary production $\Phi_{e^+} = C_{e^+} E^{-\gamma_{e^+}} + C_s E^{-\gamma_s} e^{-E/E_s}$
  - + source
- Electrons
  - Primary and secondary production $\Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_s E^{-\gamma_s} e^{-E/E_s}$
  - + same source
- Simultaneous fit to
  - Positron fraction from 2 GeV
  - Combined flux from 2 GeV

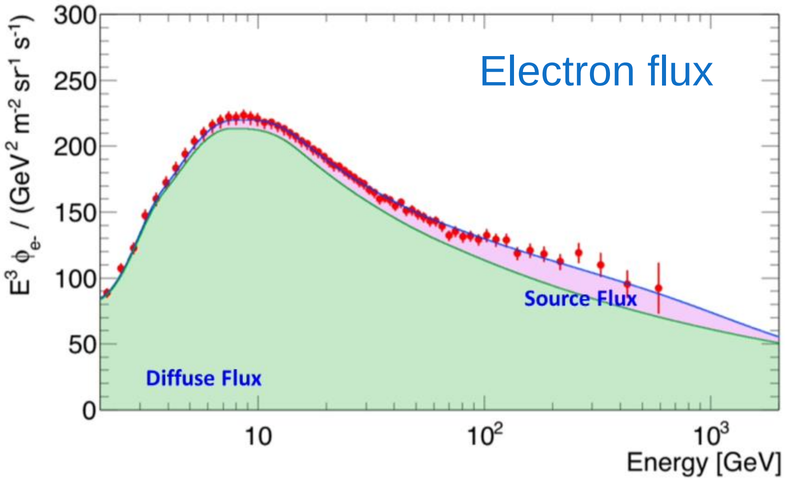
MINIMAL MODEL

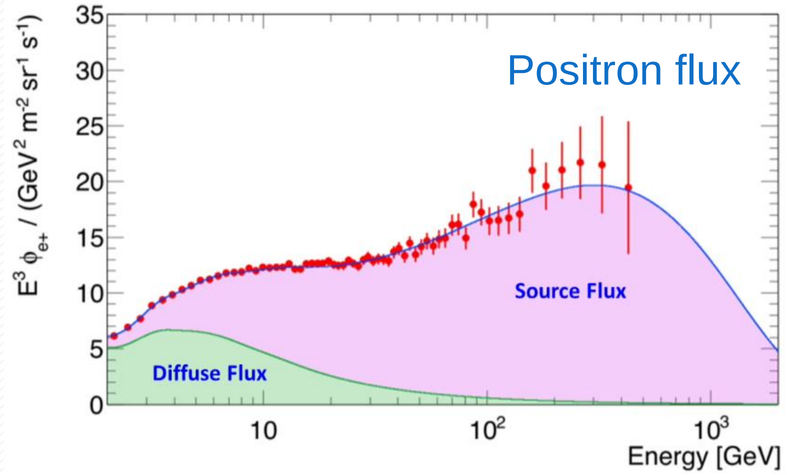
Result from the fits





Prediction from the fits





Fits are satisfactory, which shows that the data can be described by a common e^+/e^- source

INTERPRETATION OF THE DATA

A new look at the cosmic ray positron fraction

M. Boudaud[1], S. Aupetit[1], S. Caroff[2], A. Putze[1,2], G. Belanger[1], Y. Genolini[1], C. Goy[2], V. Poireau[2], V. Poulin[1], S. Rosier[2], P. Salati[1], L. Tao[2], and M. Vecchi[2,3,⋆,⋆⋆]

Cosmic Ray Alpine Collaboration (CRAC)
A&A 575, A67 (2015)

METHOD

- Diffusion equation

$$\frac{\partial \psi}{\partial t} - \nabla \cdot \{K(E)\nabla\psi\} - \frac{\partial}{\partial E}\{b(E)\psi\} = q(\mathbf{x}, t, E) \qquad \psi = dn/dE$$

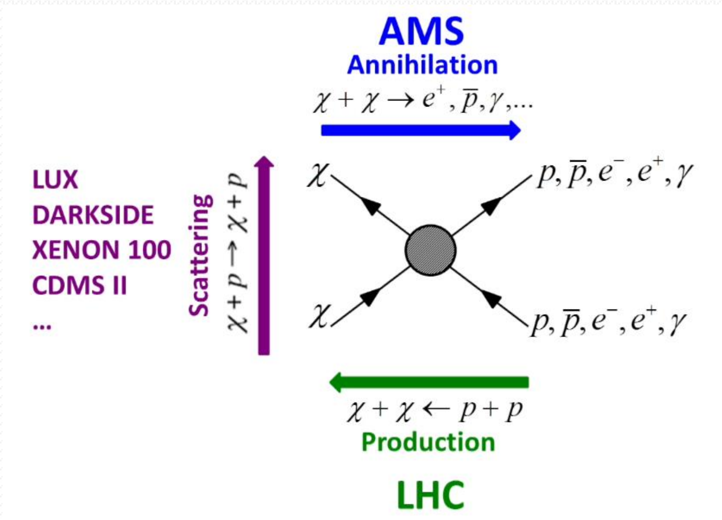
$$K(E) = K_0\,\beta\,(\mathcal{R}/1\ \mathrm{GV})^{\delta} \qquad b(E) = \frac{E_0}{\tau_E}\epsilon^2 \qquad \epsilon = E/E_0$$

- Terms in the diffusion equation
  - **Diffusive** part
  - **Loss of energy** (synchrotron radiation, inverse Compton effect)
  - **Source** term

- Fit the model on the AMS data with a χ^2 method

DARK MATTER

- Dark matter = 26% of the Universe content
  - « **Observation** »: galaxy rotation curves, X-ray emission, gravitional lensing, CMB
  - **Best candidate**: weakly interacting massive particle $\Rightarrow$ **WIMP**



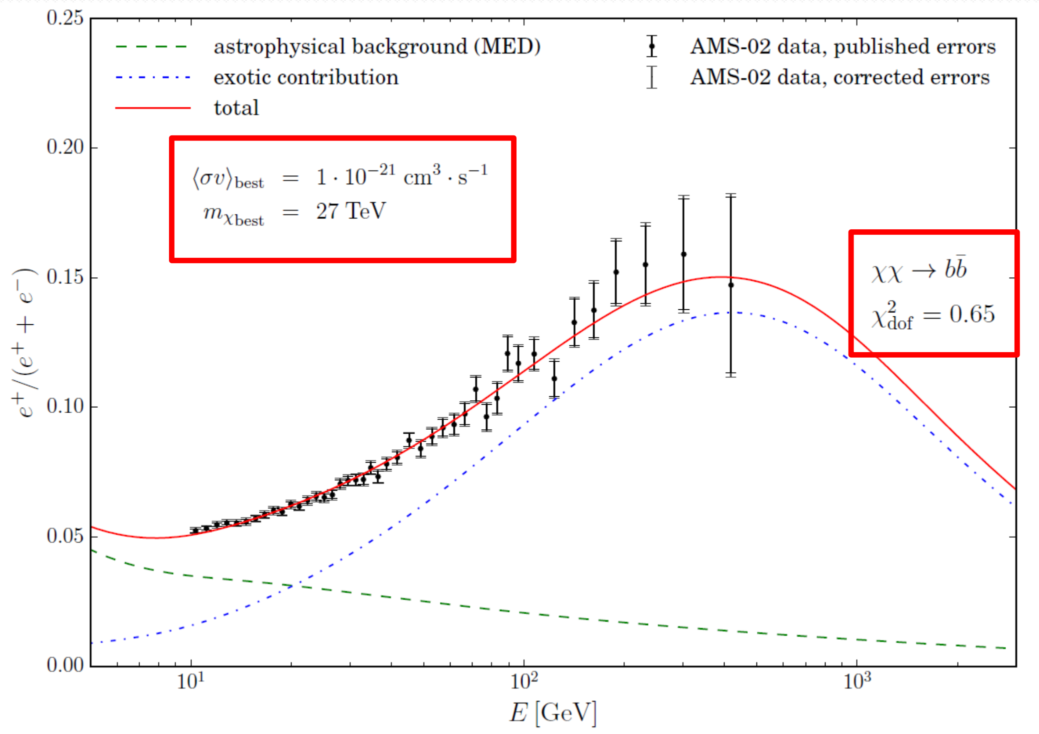
- Annihilation of dark matter in our Galaxy
  - WIMP **annihilation** $\Rightarrow$ **particle-antiparticle** production $\Rightarrow$ positron source
  - **Increase** in the fraction and flux of positrons

- Parameters in the fit (source term)
  - **Fitted parameters**: WIMP mass m_χ, WIMP annihilation cross-section $<\sigma v>$
    - Natural cross-section from relic density: $<\sigma v> \approx 3.10^{-26}$ cm^{3}s^{-1}
  - **Propagation parameters** fixed to the MED model: K_0, δ, L

SINGLE CHANNEL

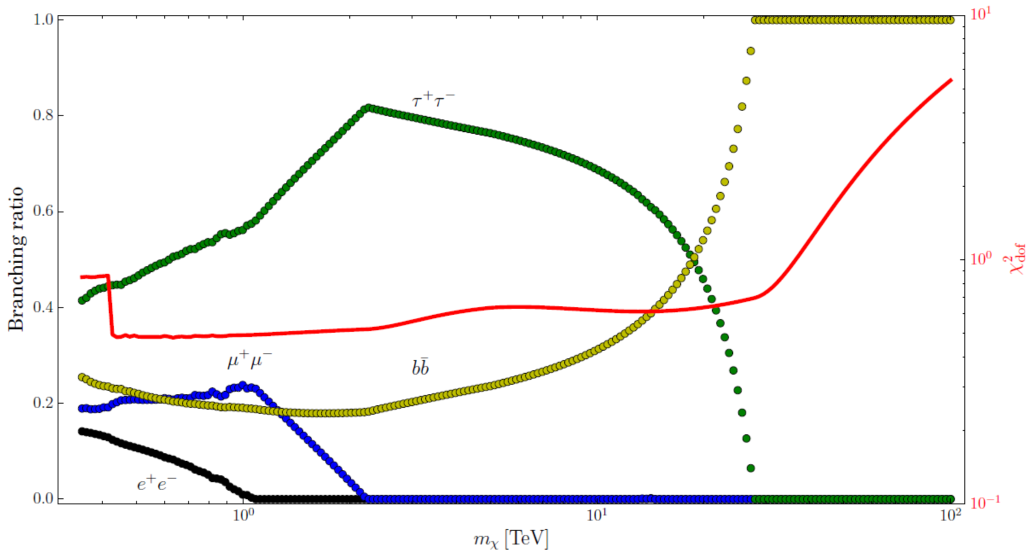
- Fitting the positron fraction using single annihilation channel
  - Working channels: $\chi\chi \to u\bar{u}$, $b\bar{b}$, $t\bar{t}$, $Z\bar{Z}$, WW, HH
    - $m_\chi > 10$ TeV, $<\sigma v> \sim 10^{-21}$ cm^{3}s^{-1}

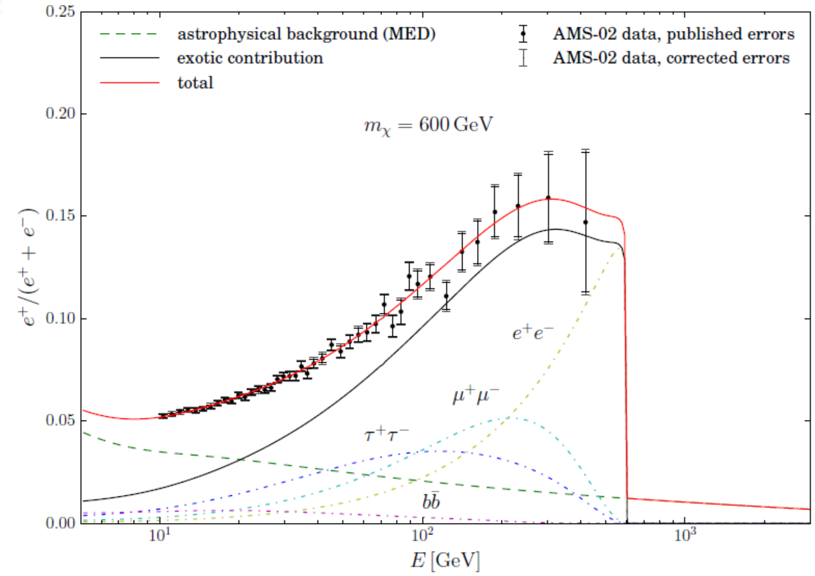
Example:
$\chi\chi \to b\bar{b}$



CHANNEL COMBINATION

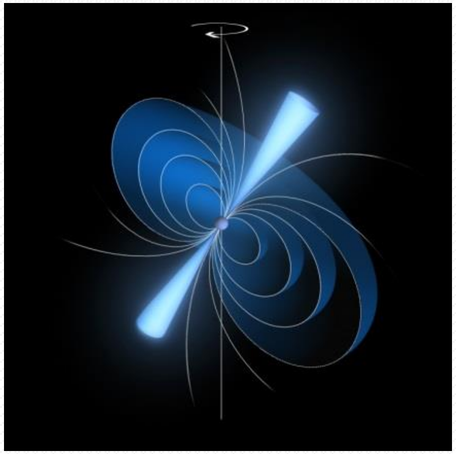
- Given a value of m_χ, fit of the best combination of channels





- Dark matter may explain the fraction, but unnatural annihilation cross-section
  - ×**1000** compared to the one expected from the relic density
- Not likely that AMS has observed an indirect observation of dark matter

PULSARS



- Neutron stars spinning at high rate with a strong magnetic field
- 200 pulsars at less than 2 kpc from Earth
  - Only a **small fraction** able to emit positrons
- Mechanism
  - **Electrons extracted** from the surface by the high fields

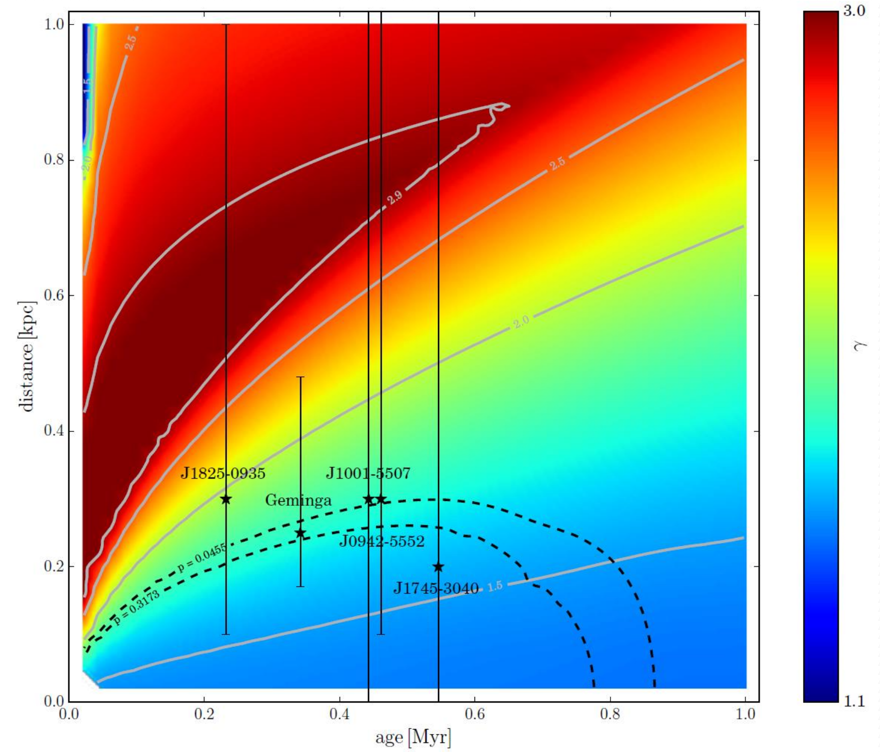
    ⇒ electrons produce **synchrotron photons**

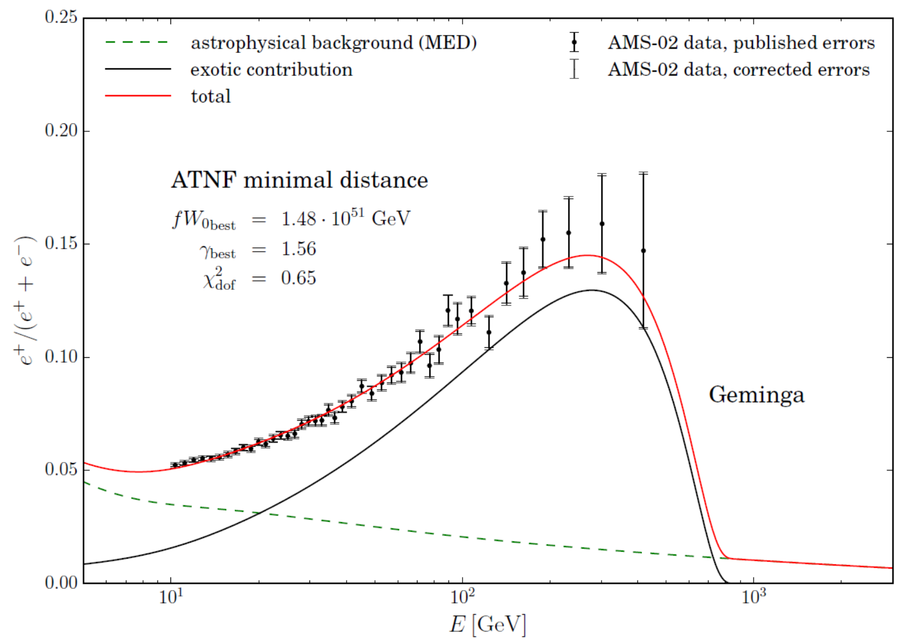
    ⇒ photons produce **e^+-e^- pairs**

    ⇒ Some **escape** from the pulsar
- Precise prediction very difficult
- Parameters in the fit (source term)
  - **Fitted parameters**: spectral index γ, total energy carried by the positrons at the source fW_0
  - **Additional parameters**: age and distance of pulsar

SINGLE PULSAR

- Testing the single pulsar hypothesis

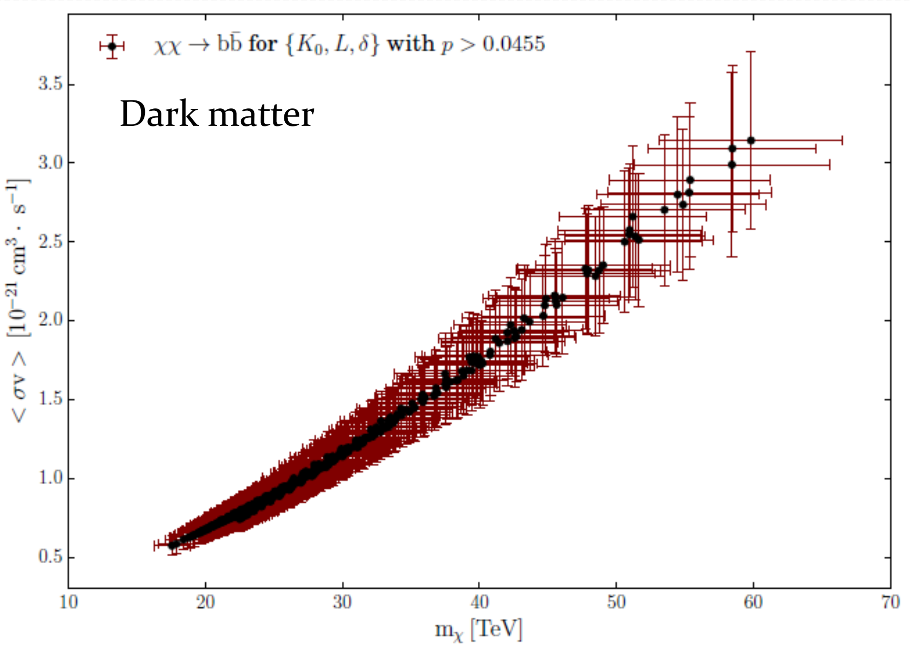


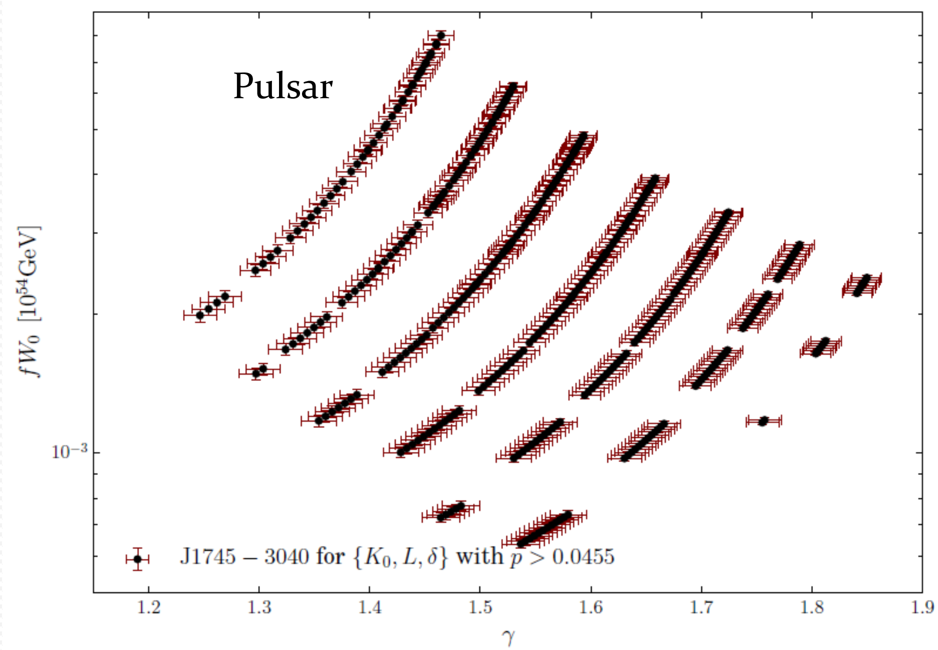


- Five closeby pulsars able to explain the fraction

PROPAGATION UNCERTAINTY

- The uncertainty on the propagation parameters dominates the other uncertainties





- Need cosmic ray measurement to constrain the propagation
  - B/C ratio, isotope ratio, etc.

CONCLUSIONS

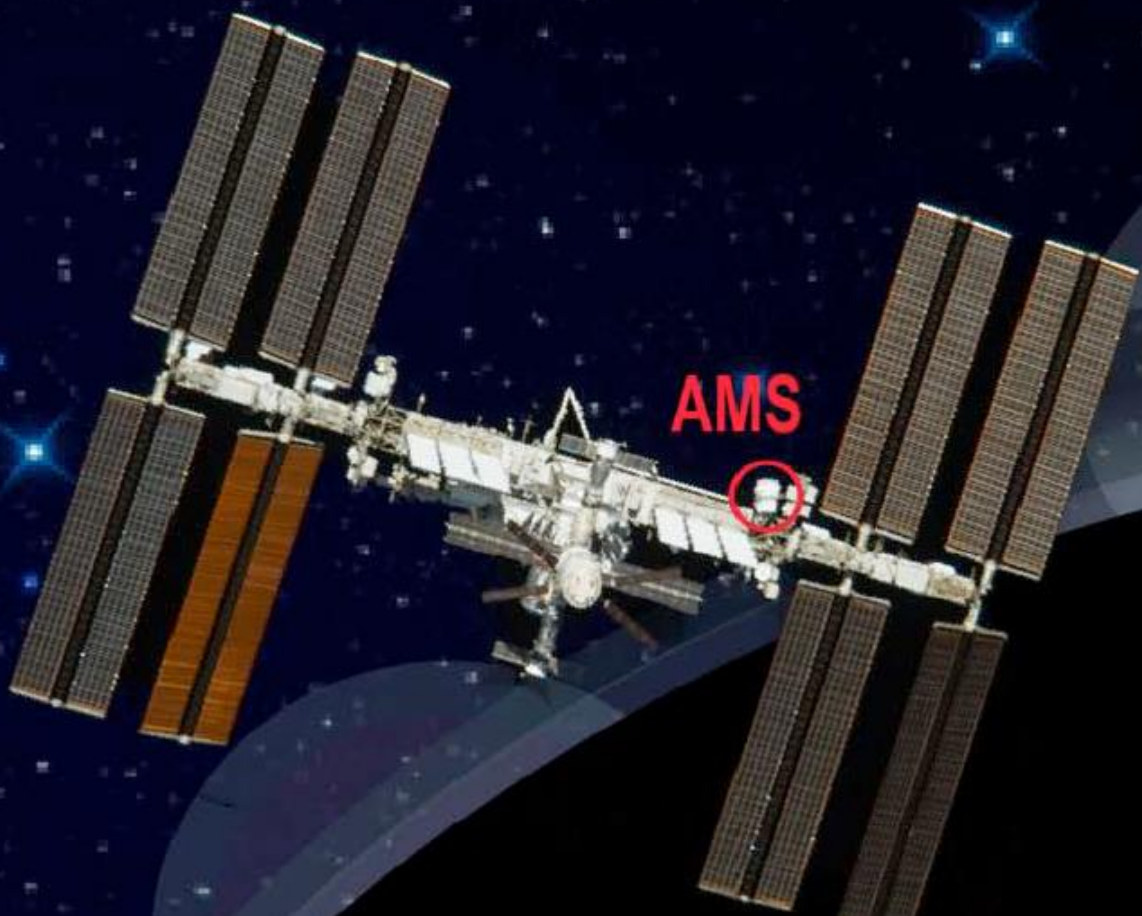
STAY TUNED…

Other measurements yet to be published:

- Proton and helium flux
- Antiproton flux and ratio antiprotons/protons
  - **Excess in antiprotons and positrons** would be an evidence for dark matter
- Anti-nuclei
  - Anti-deuterium, anti-helium
- B/C ratio
  - Constrain the propagation parameters
- Isotopes
  - For example Be^9/Be^{10}
- Study of solar modulation
- …

AMS Days at CERN
The Future of Cosmic Ray Physics and Latest Results

CERN, Main Auditorium,
April 15-17, 2015



Speakers:
Roberto BATTISTON, ASI, Trento
Kfir BLUM, IAS, Princeton
John ELLIS, King's College, London, CERN
Jonathan FENG, UC Irvine
William GERSTENMAIER, NASA
John M. GRUNSFELD, NASA
Francis HALZEN, Wisconsin
Werner HOFMANN, MPI Heidelberg
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Eun-Suk SEO, Maryland
Tracy SLATYER, MIT
Edward C. STONE, Caltech
Michael TURNER, Chicago
Alan A. WATSON, Leeds
Yue-Liang WU, UCAS/ITP, CAS
Fabio ZWIRNER, Padua, CERN
and
presentations on the AMS latest results

Event Webcast at
http://cern.ch

Contact: Ms. Laurence Barrin <laurence.barrin@cern.ch>

OUTLOOK

- The AMS experiment operates since May 2011 and recorded 60 billions of events
- Measurement of the positrons and electrons
  - Measurement of the **fraction**, the **fluxes**, and the **combined flux**
  - A **source** of positrons (and electrons) is needed
  - Fraction does **no longer** exhibit an **increase** with energy
- Interpretation of the data
  - **Dark matter**: unnatural cross-section, large WIMP mass, incompatible with $\bar{p}/p$ data
  - **Pulsars**: may explain the rise of the positrons
  - AMS will extend its **energy range**, and will be able to **discriminate** between the dark matter and pulsar hypotheses
- Many more measurements in the coming months
- AMS is expected to run at least until 2020
  - AMS will bring **many answers**!