AMS-02 in space

physics results, overview, and challenges

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November 23 – 25 Grenoble, France

The AMS Project

Particle physics detector for high precision CR measurements at TeV energy

Physics goals

- ✓ **Antimatter search** (|Z|>1 anti-nuclei)
- ✓ **Dark Matter** (light anti-matter & γ-rays)
- ✓ Exotic signals from SQM
- ✓ **GCR astrophysics** & γ-rays
- ✓ Heliophysics (long-term modulation & SEP)
- ✓ Magnetospheric physics & space radiation studies

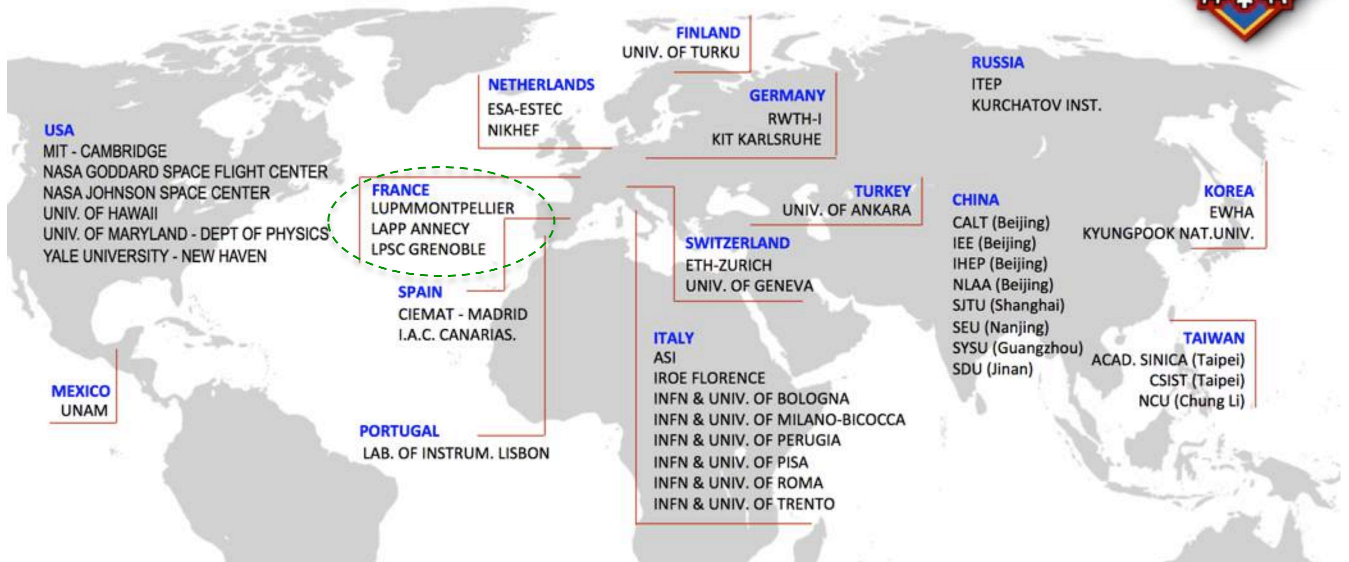
How it will fulfill these goals?

- **Large collaboration: 16 Countries, 60 Institutes and ~500+ Physicists**
- **Same concept (precision & capability) as the large state-of-the-art HEP detectors [but: fitting into the space shuttle & no human intervention after installation]**
- **Operation in space, ISS, at 400km, no backgrounds from atmospheric interactions [extensive multi-step space qualification tests]**
- **Collection power: geometrical factor (≈ 0.5 m2sr) X exposure time (= ISS lifetime) [extensive calibration campaigns on ground]**

The AMS Project

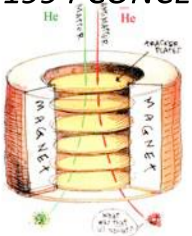
AMS Collaboration

- *16 countries*
- *60 institutes*
- *500+ physicists*
- *20 years*



Project timeline

1994 CONCEPT

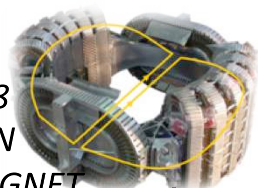


1997 AMS-01 PROTOTYPE

1998: STS-91

2000 @CERN AMS-02 CONSTRUCTION

2008 @CERN SC MAGNET BEAM TEST



2010 TVT @ ESA (NL)

2010 @CERN SC -> PM NEW BEAM TEST

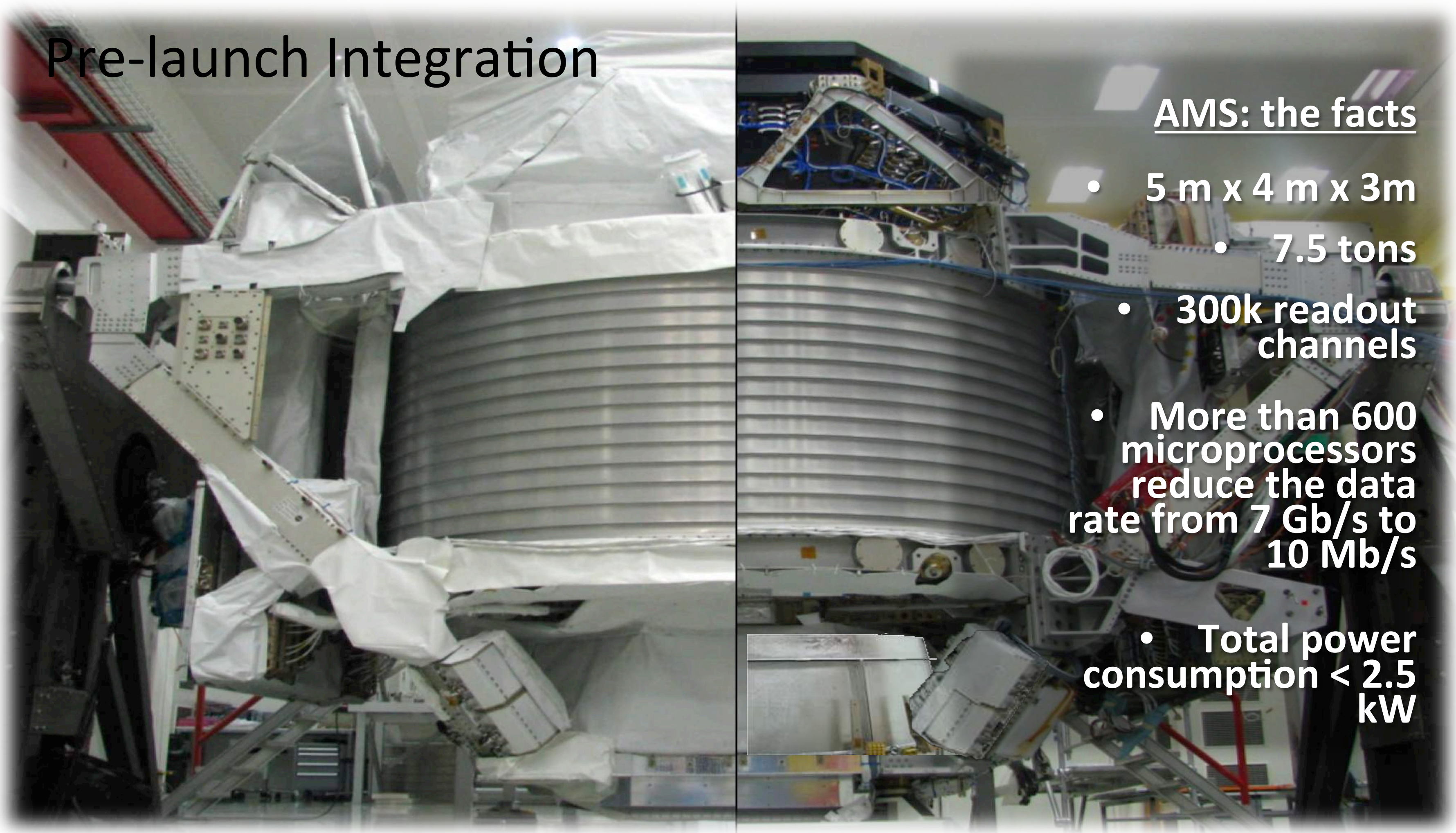
2011 @KSC INTEGRATION & CR-μ RUN

MAY 2011 STS-134 FLIGHT

ON THE ISS

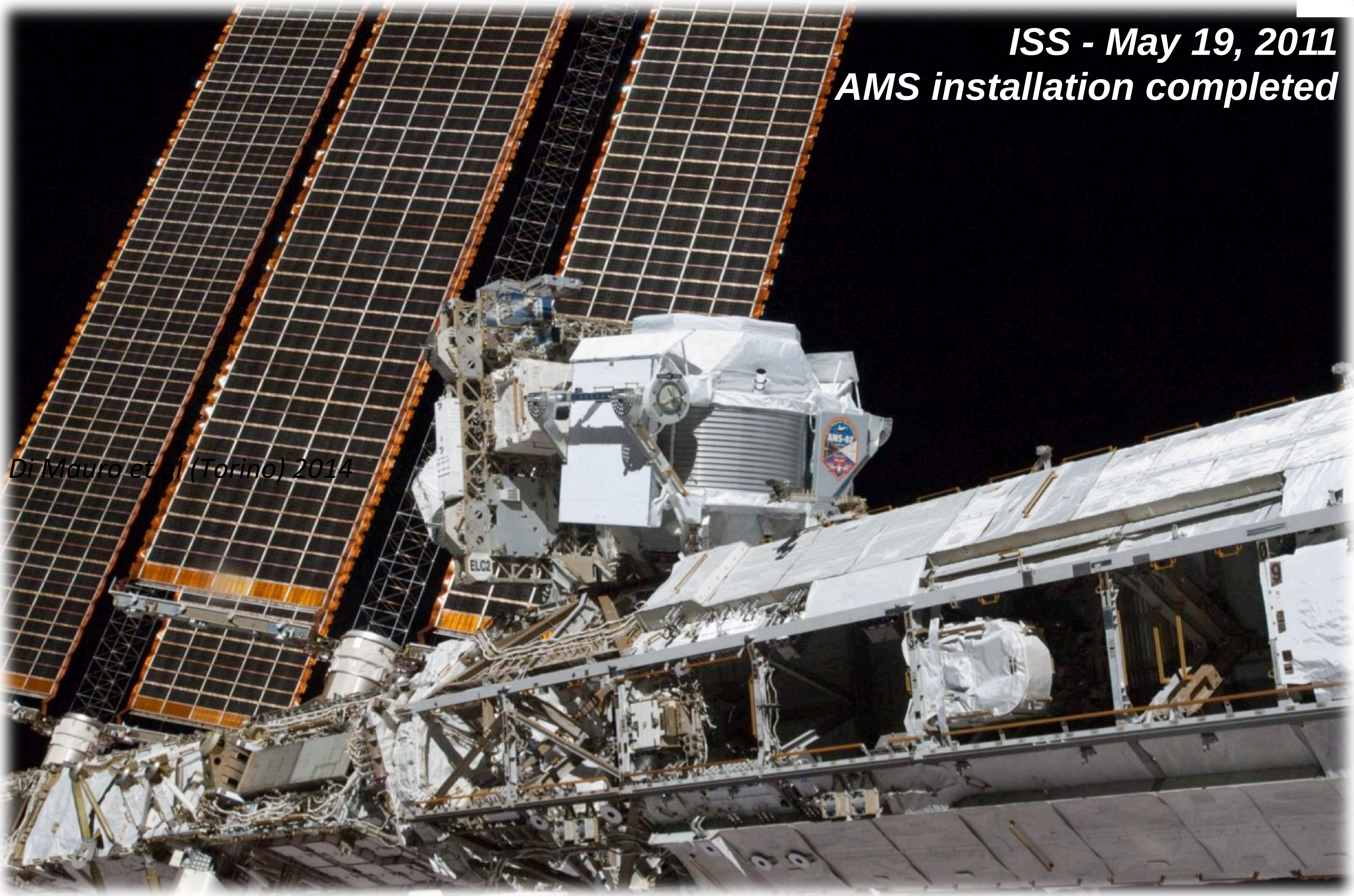
→ Steadily taking data on the ISS since May 19th 2011

1999-2011: contruction and assembly



May 16th 2011: launch!

May 19th 2011: activation!



Full time monitored

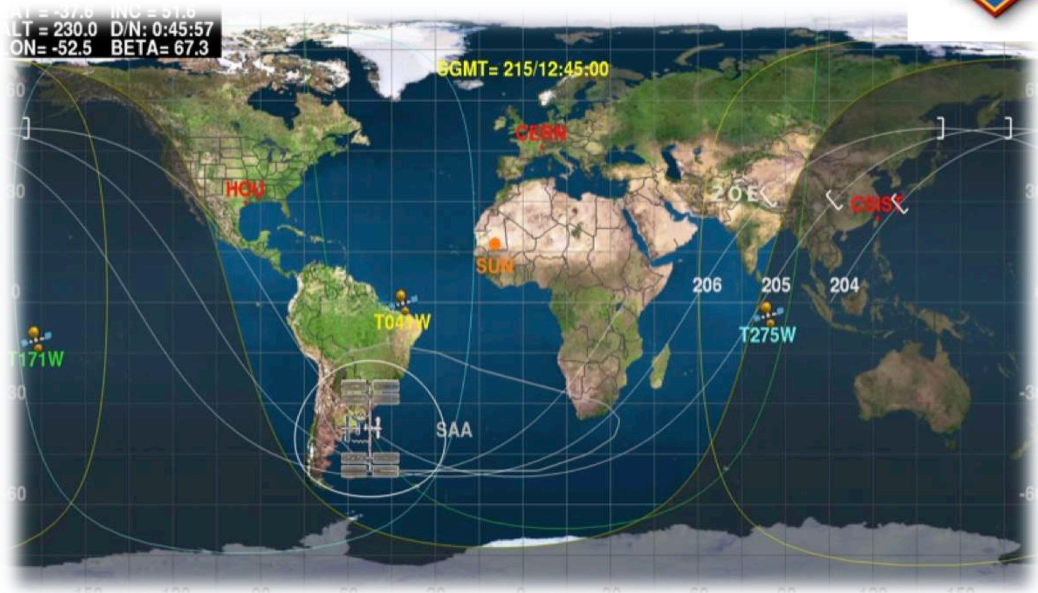
The Payload Operation Control Center (POCC)

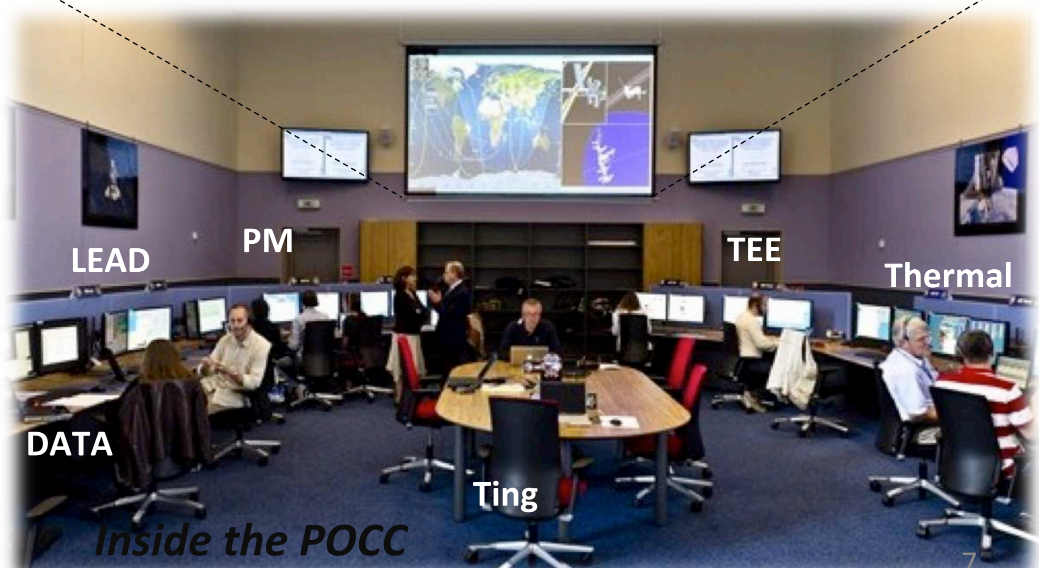
Since the 27th June, 2011, 5:00 am GMT, AMS-02 is controlled 24/7 from the new POCC building at CERN, Prevessin site.

Shifts are organized to monitor the AMS-02 conditions, operations, and the continuous flow of data to ground.

Since July 2012, a second control room (the asia POCC) is running at the CSIST facility in Taiwan.

>80 billion events recorded





Inside the POCC

The AMS physics program

We are aimed at answering two big science questions:

- ✓ *the origin and transport of cosmic rays in the Galaxy*
- ✓ *the particle nature of cosmological dark matter.*

✓ **Leptonic spectra**
- Positron fraction
- Positron and electron fluxes
- All-electron fluxes

→ *Released in 2014*
HE in progress

✓ **Hadronic spectra**
- Proton flux
- Helium flux

→ *New results 2015*

- Nuclei: Li, Be, B, C, N, O…
- Isotopes: H, He, Li, Be, B

→ *In progress*

✓ **Anti-nuclei spectra**
- Antiproton/proton ratio
- Antideuteron and antihelium searchers

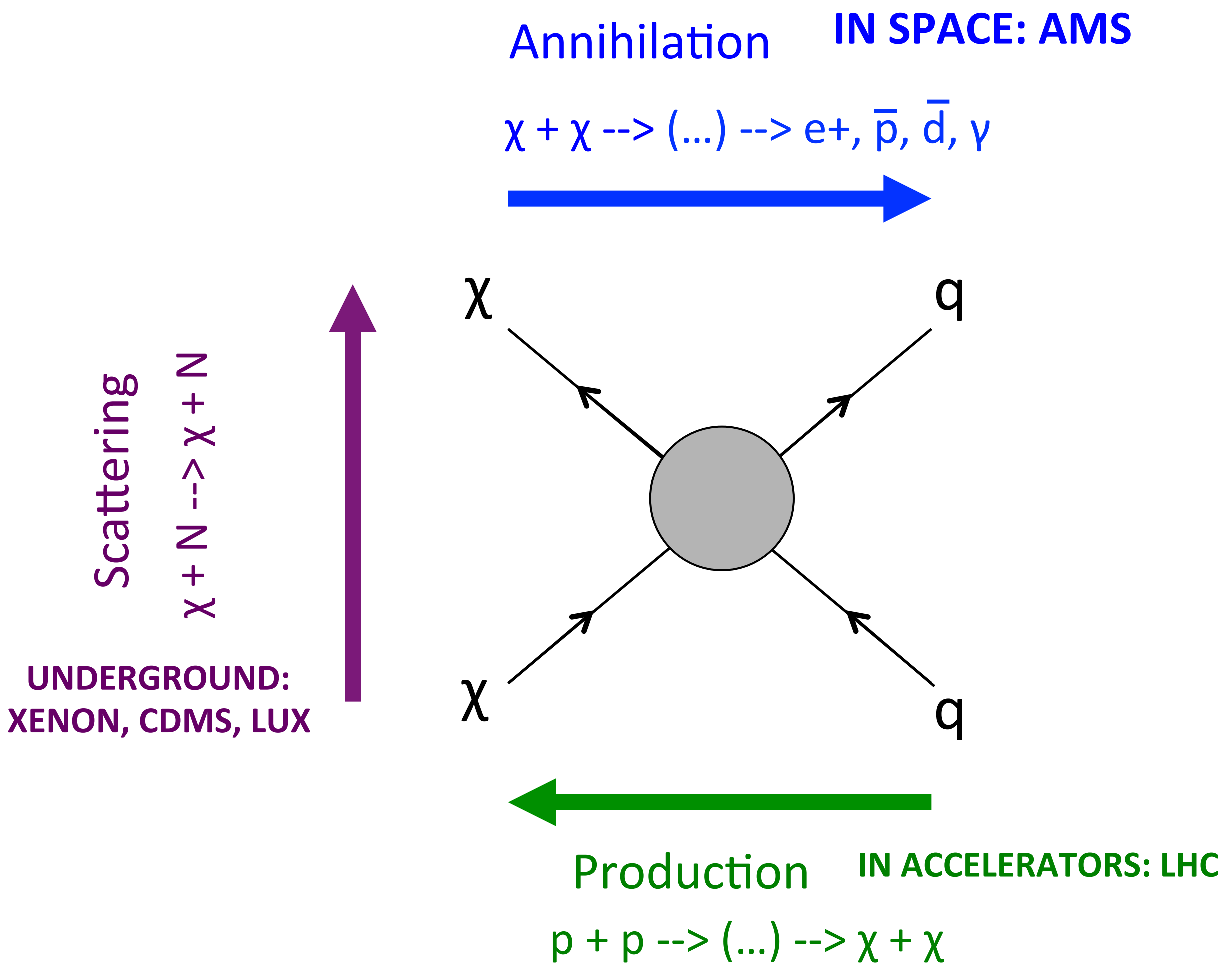
→ *In progress*

✓ **Time variation**

✓ **Flux anisotropy**

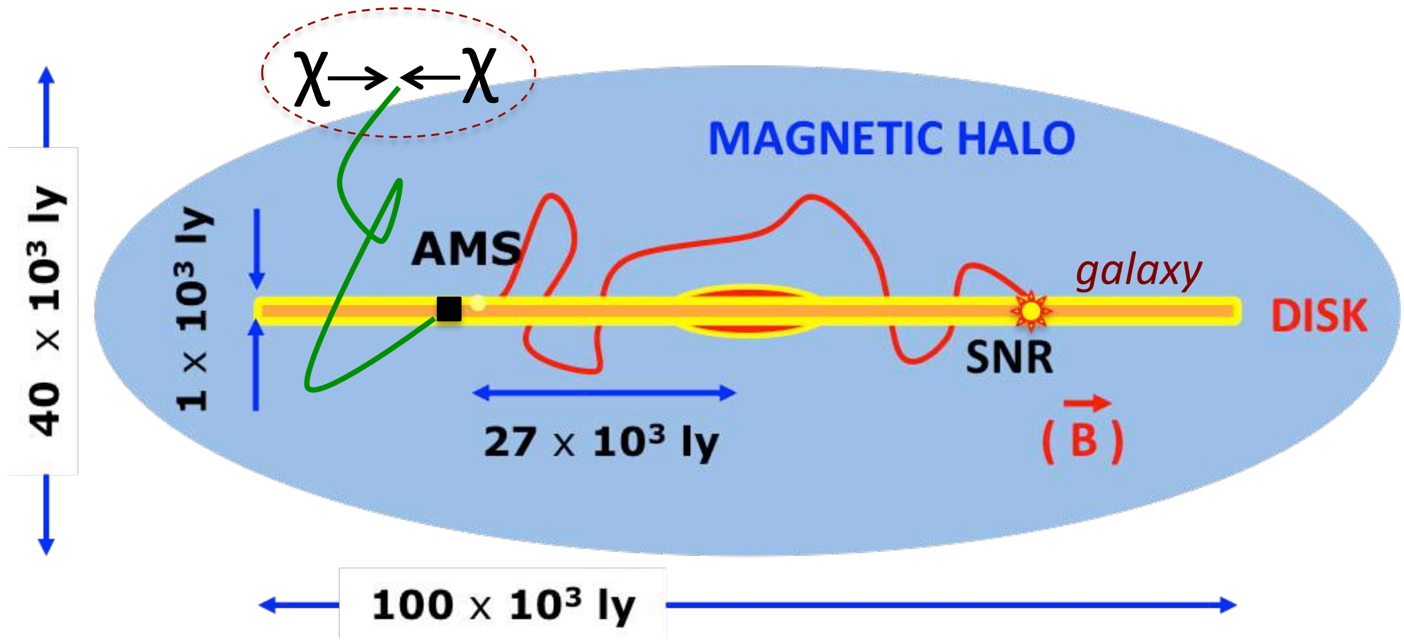
→ *In progress*

Search for dark matter



Dark matter and CR propagation physics

- ✓ *Background* from cosmic-ray sources (SNR) - No anti-matter expected
- ✓ *Background* from p+ISM collisions on disc: from propagation models
- ✓ *Signal* from DM annihilation χ + χ --> (…) --> antimatter



DISC

- *Sources (SNRs)*
- *Intestellar matter (ISM)*

MAGNETIC HALO

- *Turbulent B-field. Zero matter.*
- *Energy dependent CR diffusion*

Dark matter and CR propagation physics

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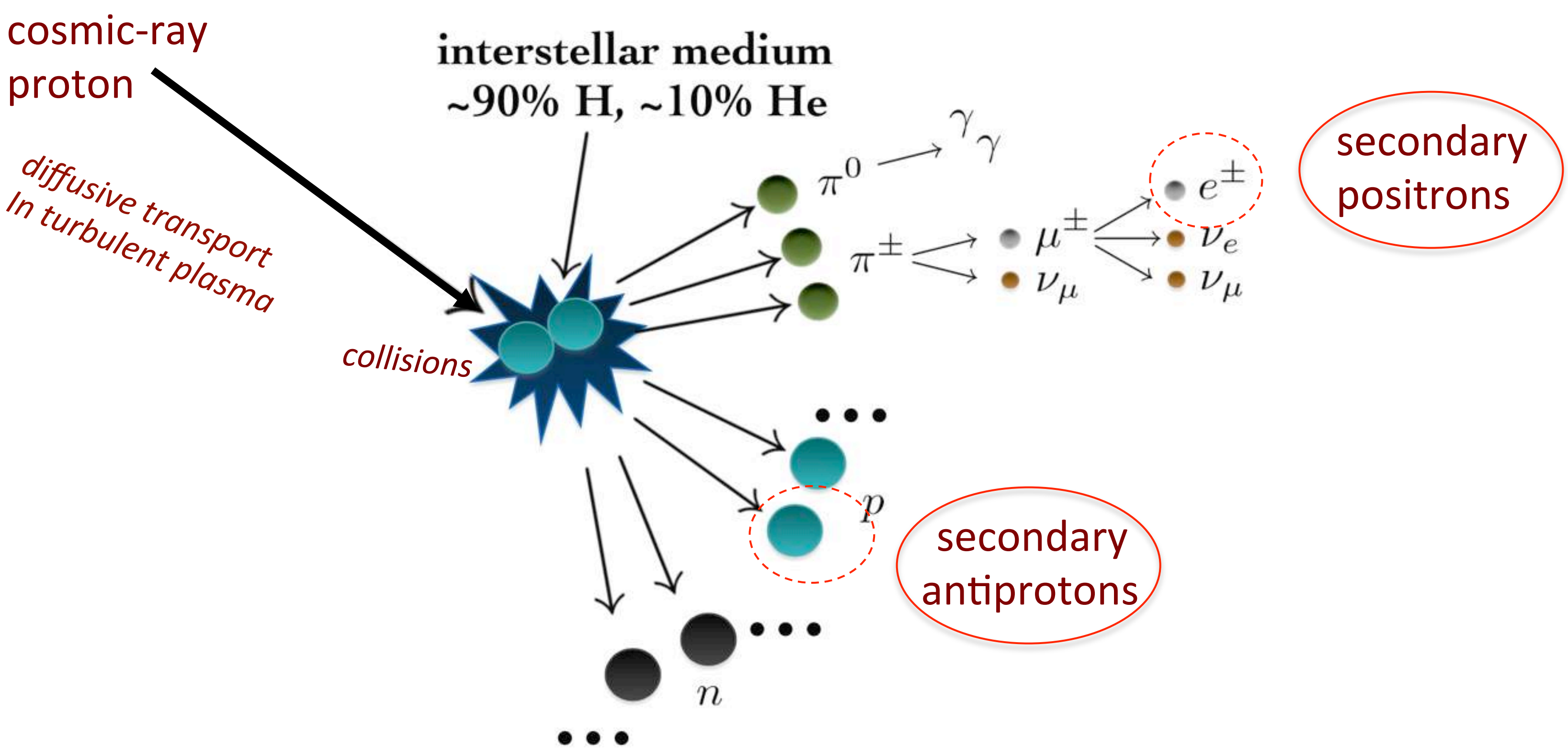

Dark matter and CR propagation physics

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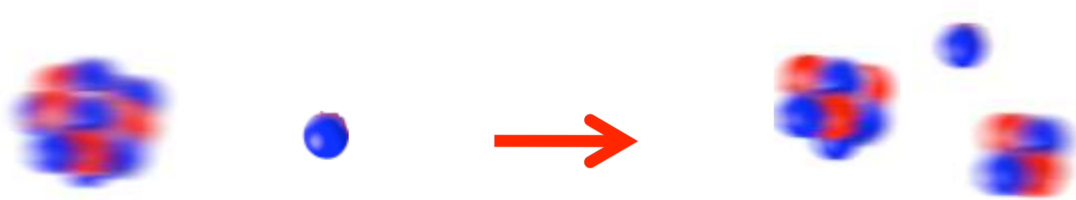
High-energy CNO + gas → LiBeB fragments

primary
C-N-O



high energy CNO

ISM gas

LiBeB

secondary
Li-Be-B

CNO… + ISM → Li, Be, **B**
B, Be + ISM → **Li**, Be
Be +ISM → **Li**

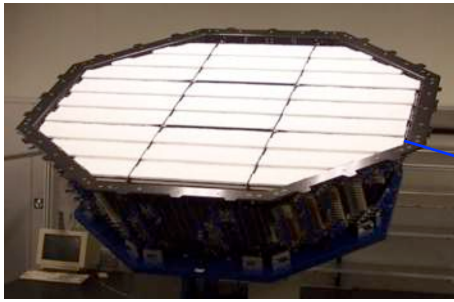
$$\mathrm{B/C} \longleftrightarrow \frac{e^+}{e^+ + e^-}$$

B/C can be used to calibrate the e+ or pbar secondary production

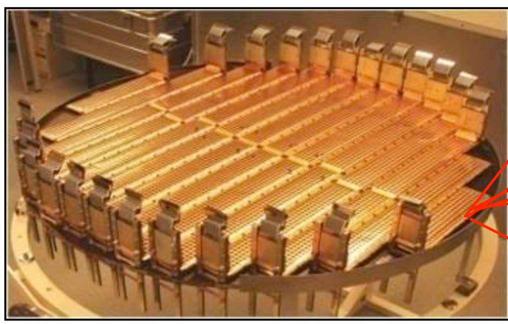
- ✓ *Primary spectra -> acceleration in SNRs*
- ✓ *Secondary/primary ratios -> propagation -> level of secondary antimatter*
- ✓ *Unstable/stable ratios, heavy nuclei, anisotropy…*

The AMS-02 instrument

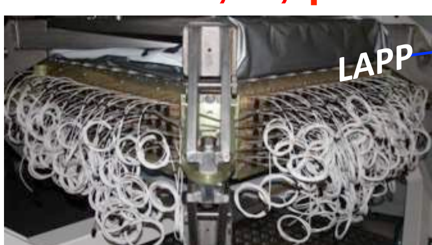
TRD
Identify e+, e-



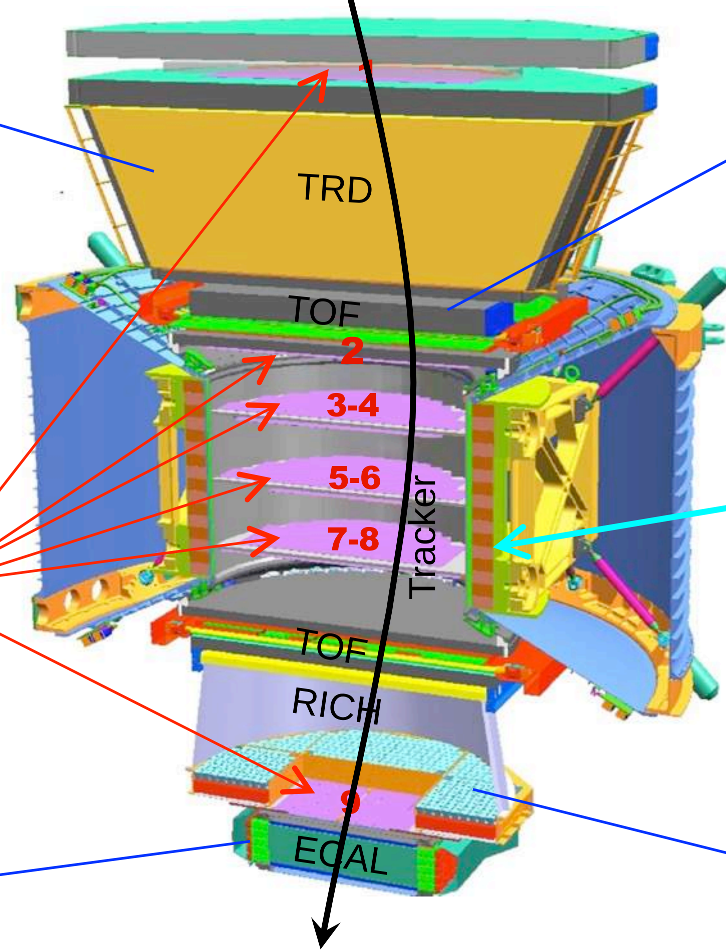
Silicon Tracker
Z, P



ECAL
E of e+, e-, γ



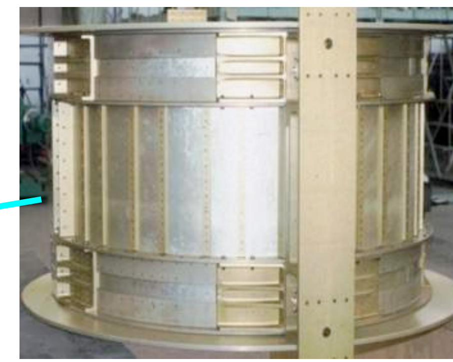
Particles and nuclei are defined by their charge (Z) and energy (E ~ P)



Z, P are measured independently from Tracker, RICH, TOF and ECAL

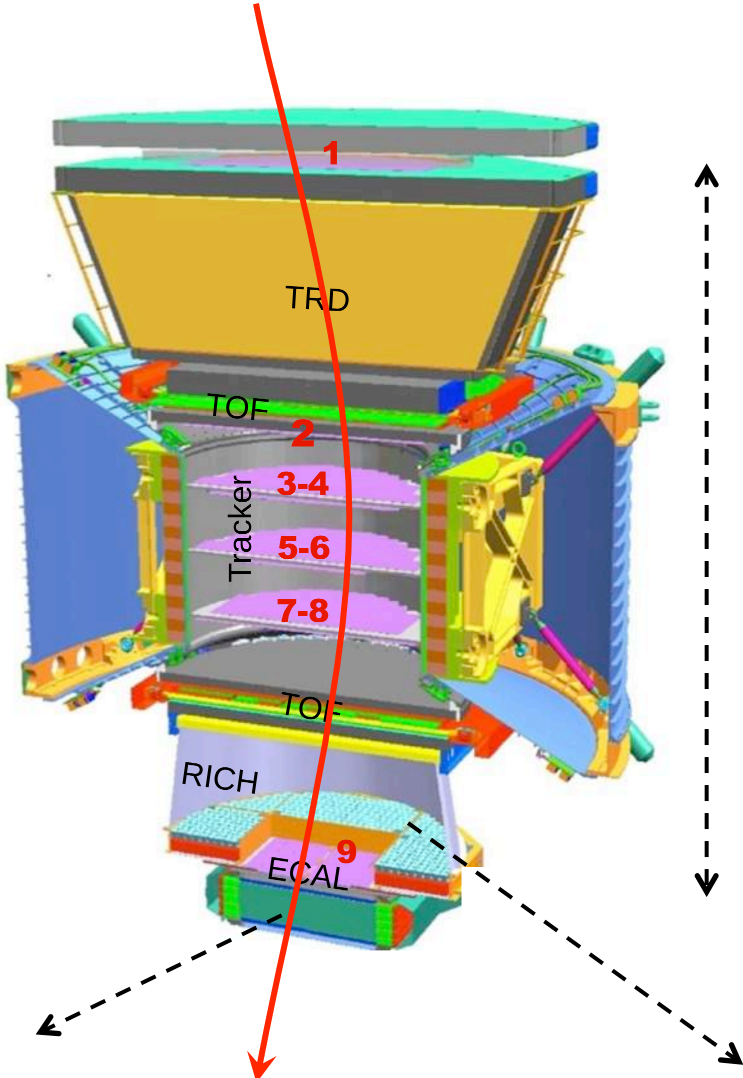
TOF
Z, E

Magnet
±Z



RICH
Z, E

Multiple measurements of energy



Tracker, R = p/Z
MDR ≈ 2TV (p); 3TV (He)

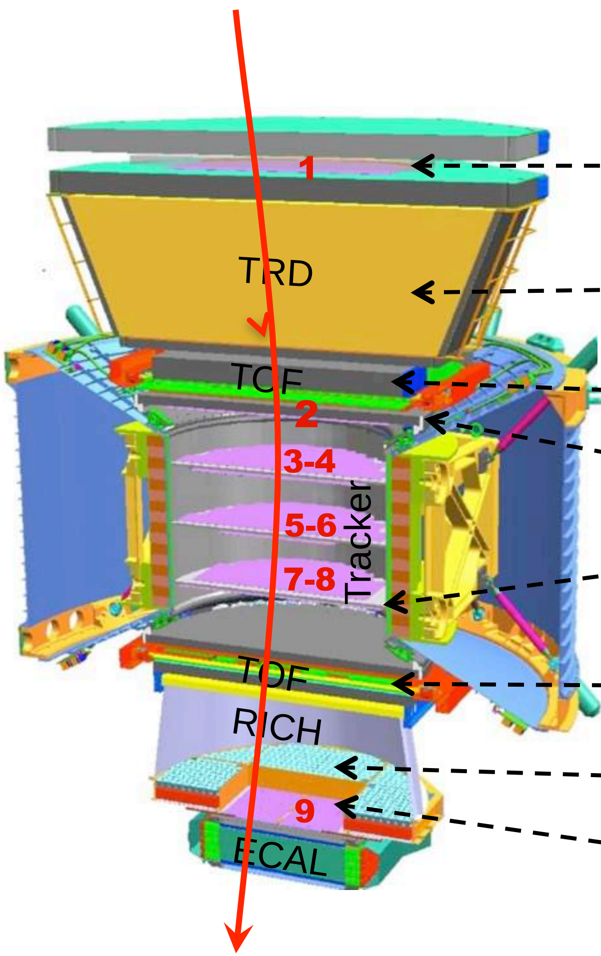
***TOF**, β*
Δβ/β ≈ 1%

ECAL, E
ΔE/E (TeV e±) ~ 2 %
ΔE/E (TeV p) ~ 50 %

***RICH**, β*
Δβ/β ≈ 0.05%

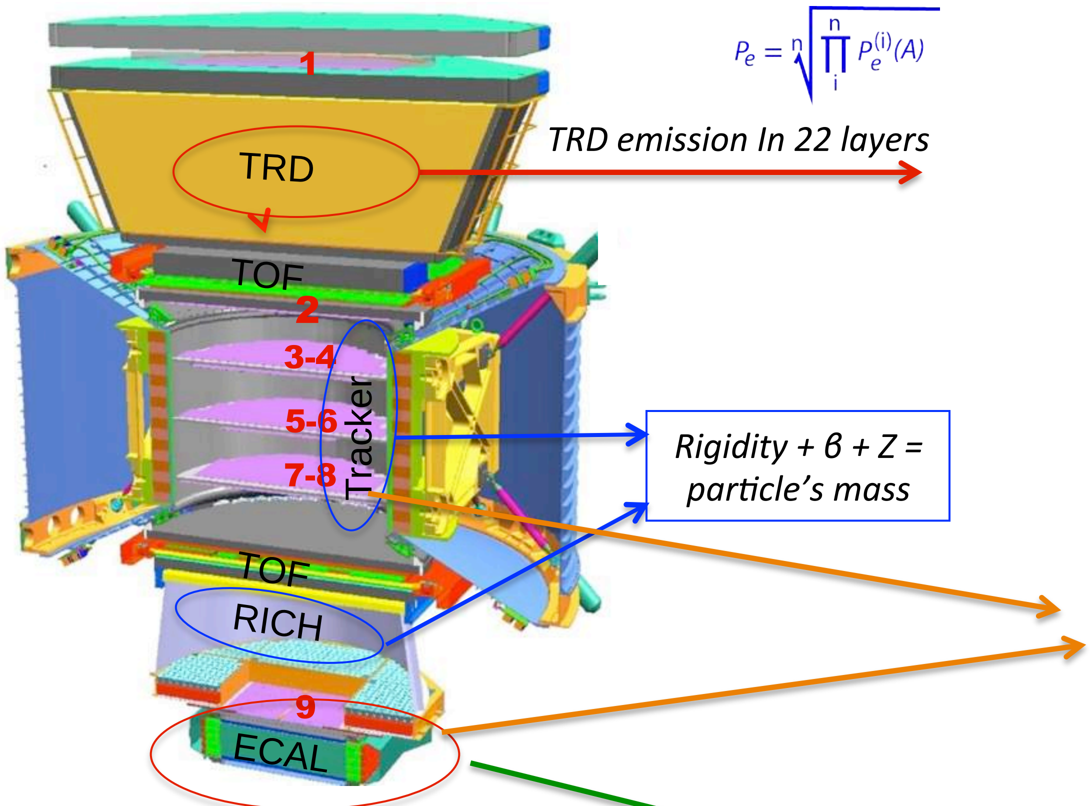
Geomagnetic cutoff, R
ΔR/R ≈ 10% up ~25 GV

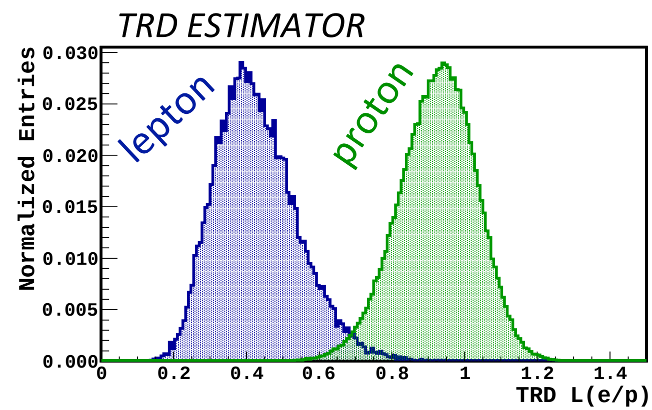
Multiple determination of charge

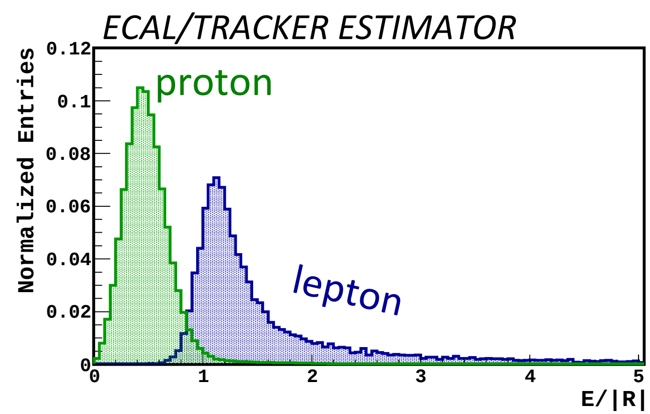


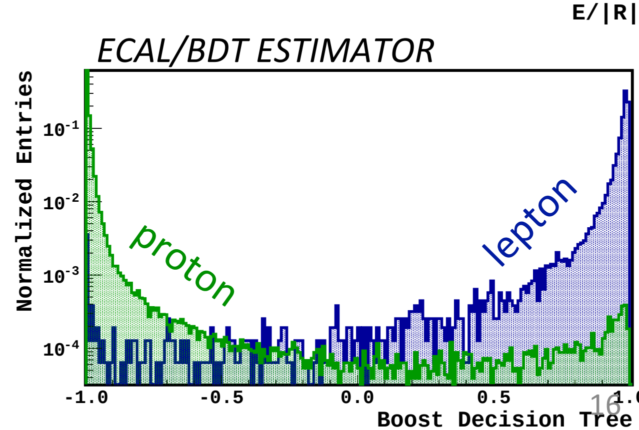
	ΔZ (carbon)
Tracker Plane 1 (L1)	*0.30*
TRD	*0.33*
Upper TOF (1 counter)	*0.16*
Inner Tracker (L2-L8)	*0.12*
Lower TOF (1 counter)	*0.16*
RICH	*0.32*
Tracker Plane 9 (L9)	*0.30*

Multiple lepton/hadron separation

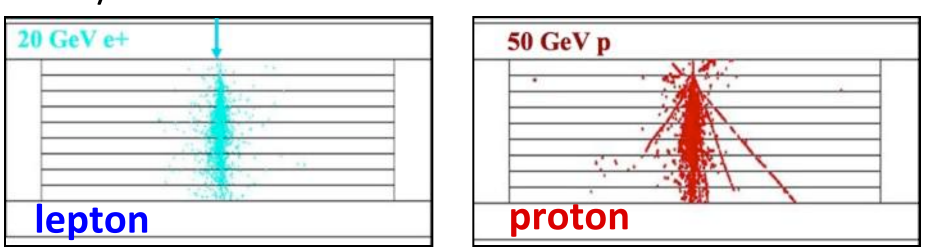




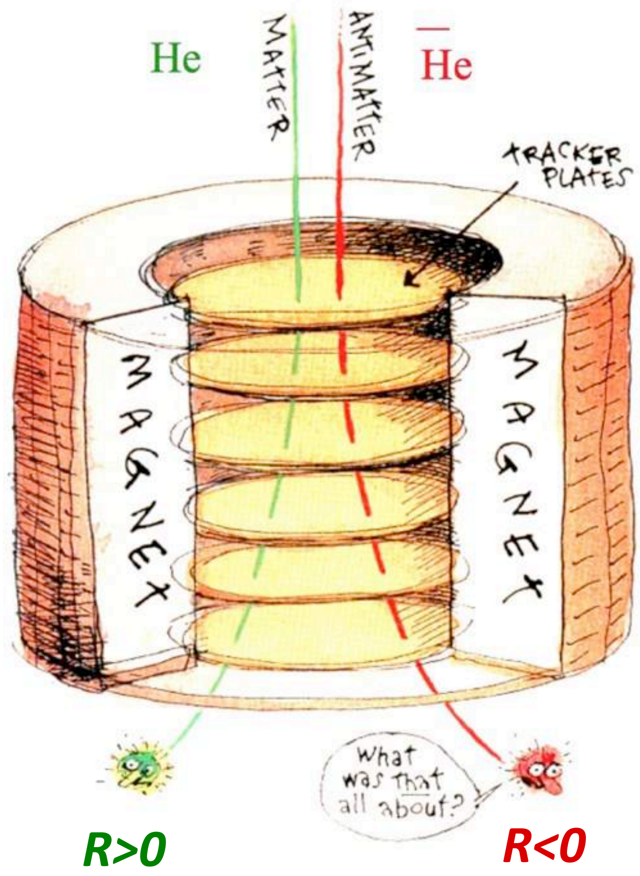




ECAL/BDT DISCRIMINATION ON SHOWER TOPOLOGY



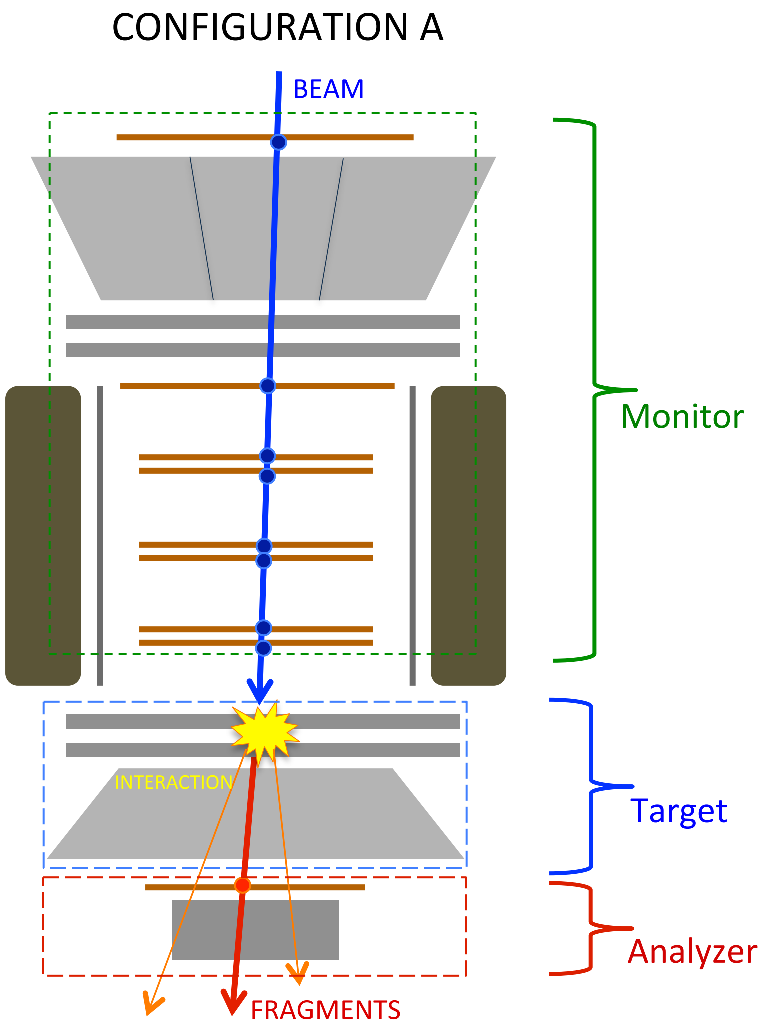
No redundancy for particle sign

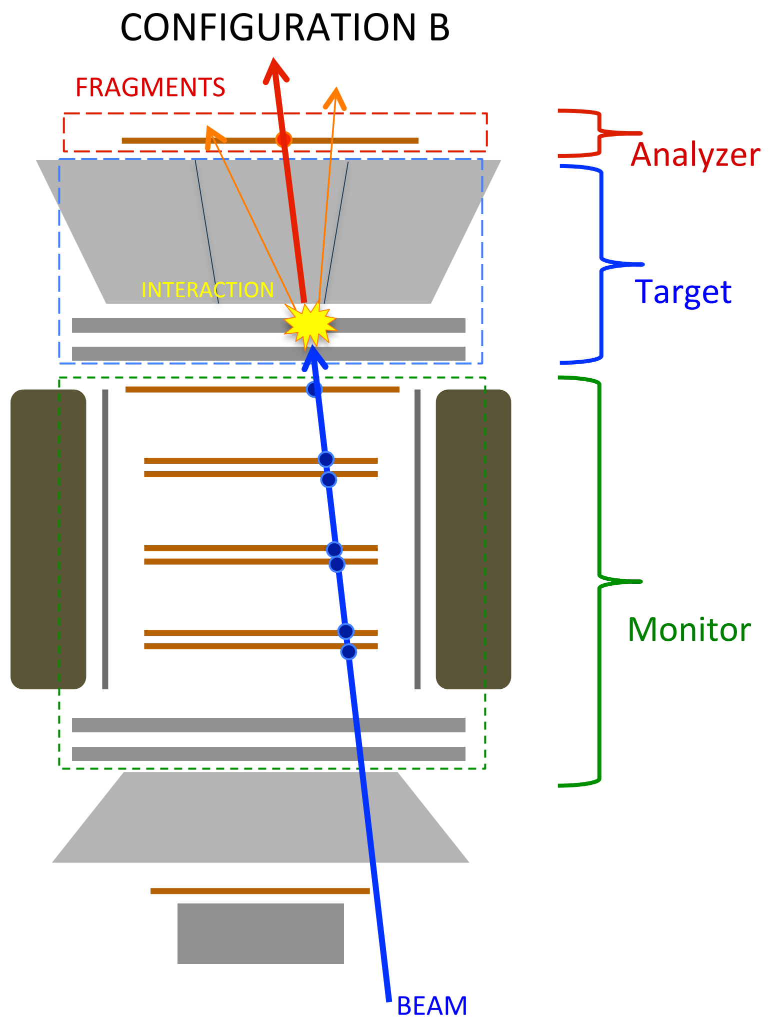


Nuclear Interactions Studies

CR collisions off C and Al: cross section data exist only below 10 GV

New method to determine interactions from ISS data with AMS pointing in horizontal direction

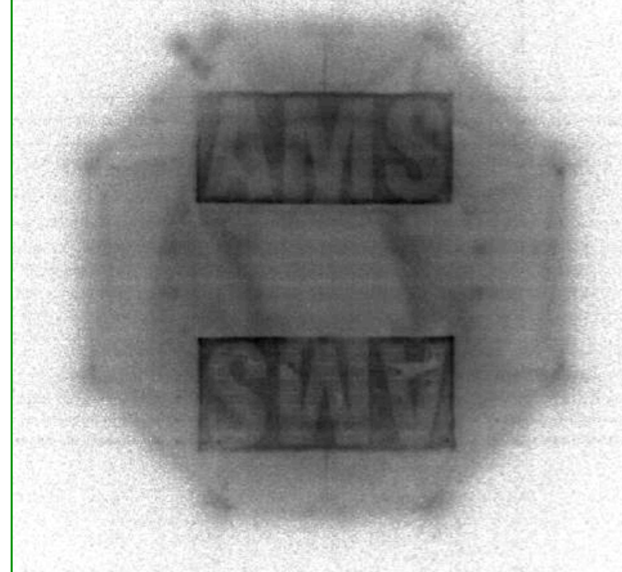


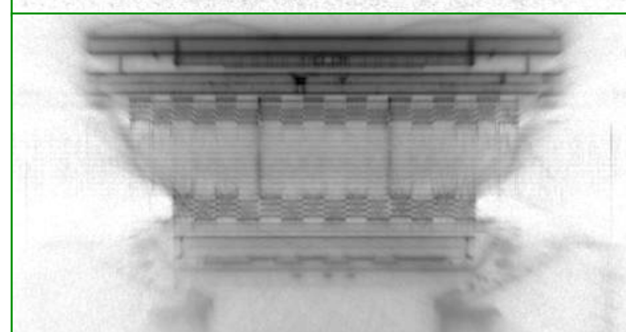


Hadronic tomography with cosmic rays

MATERIAL RECONTRUCTION USING INTERACTION VERTICES RECONSTRUCTED BY TRD

AMS ON ISS - PHOTO


TOP COVER TOMOGRAPHY

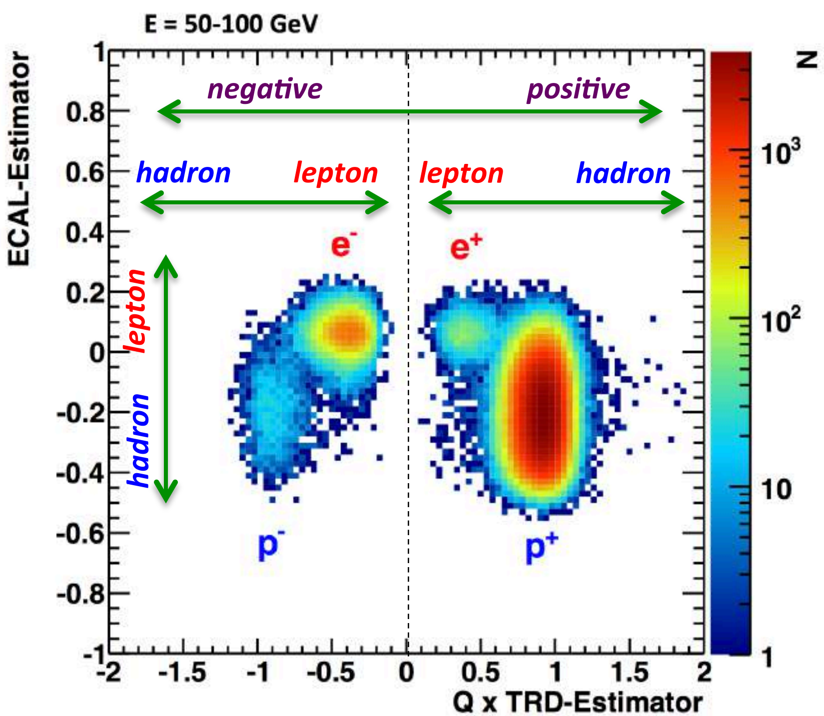

TRD MATRERIAL FINE STRUCTURE

2013, first results: positron fraction

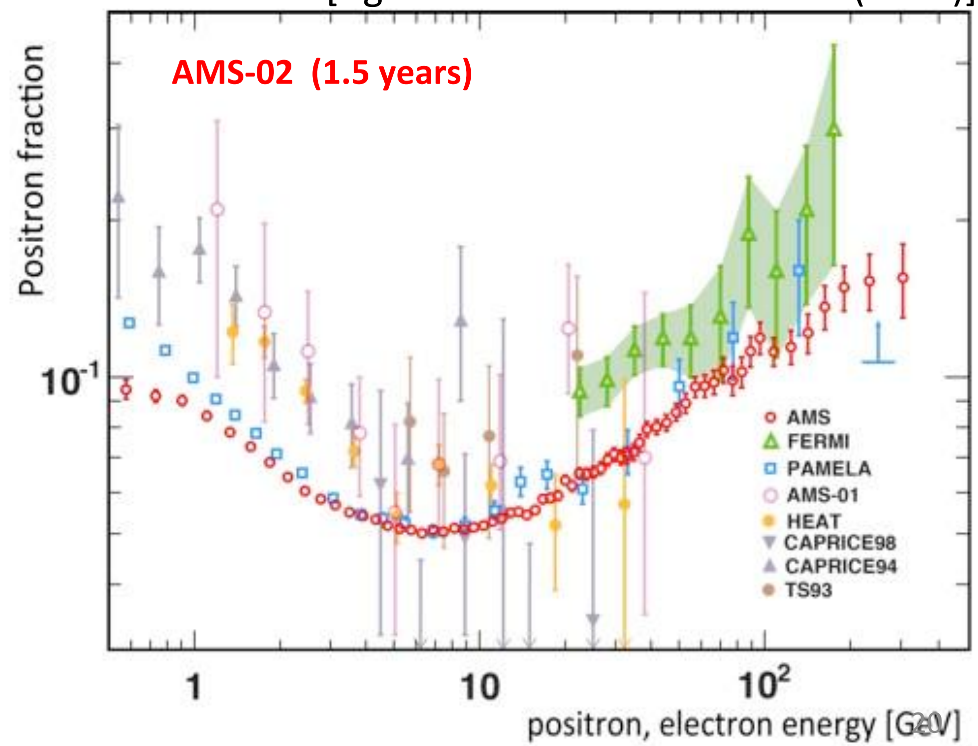
Positron fraction measured between 0.5 to 350 GeV of energy

- ✓ *1.5 years of data. 74,000 events.*
- ✓ *72 events in the last energy bin*
- ✓ *No fine structure in the spectra.*
- ✓ *Persistent rise up ~ 200 GeV*

The e+ secondary production is expected to decrease monotonically, while results indicate a persistent rise. The positron fraction increases steadily from 10 to 250 GeV.



[Aguilar et al. PRL 110 121101 (2013)]

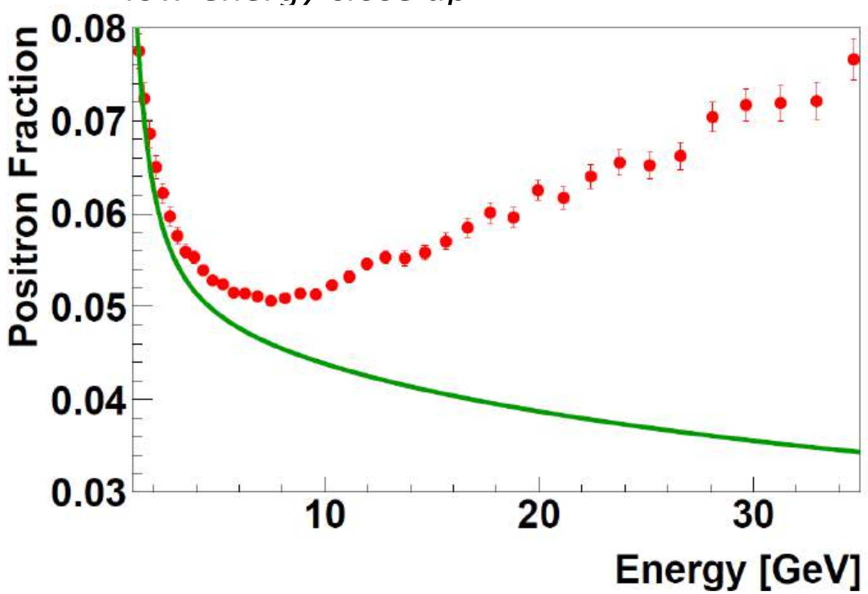


2014, positron fraction at high energies

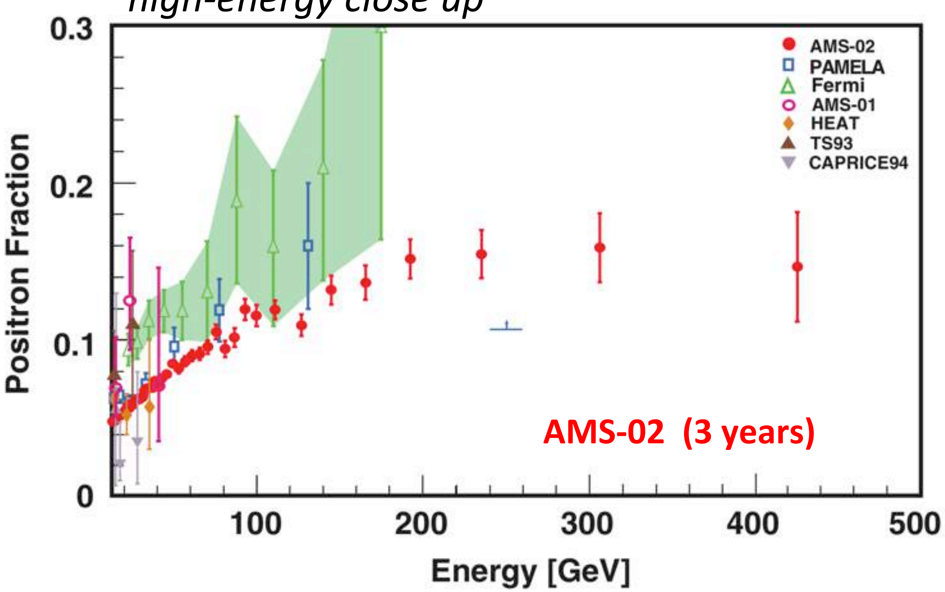
PRL 113 (2014)121101 : Positron fraction from 0.5 to 500 GeV. With 3yrs data

- New high-energy data (3 yrs statistics) released. 0.5 GeV – 500 GeV
- The Positron fraction above ~200 GeV *does not increase anymore*

low-energy close up



high-energy close up



2014, lepton fluxes: e^+, e^-, and "*all electron*"

- ✓ ***September 2014 –positron fraction in 0.5 - 500 GeV***
- ✓ ***October 2014 – electron and positron fluxes up to 700 GeV***
- ✓ ***November 2014 – electron + positron total flux up to 1 TeV***

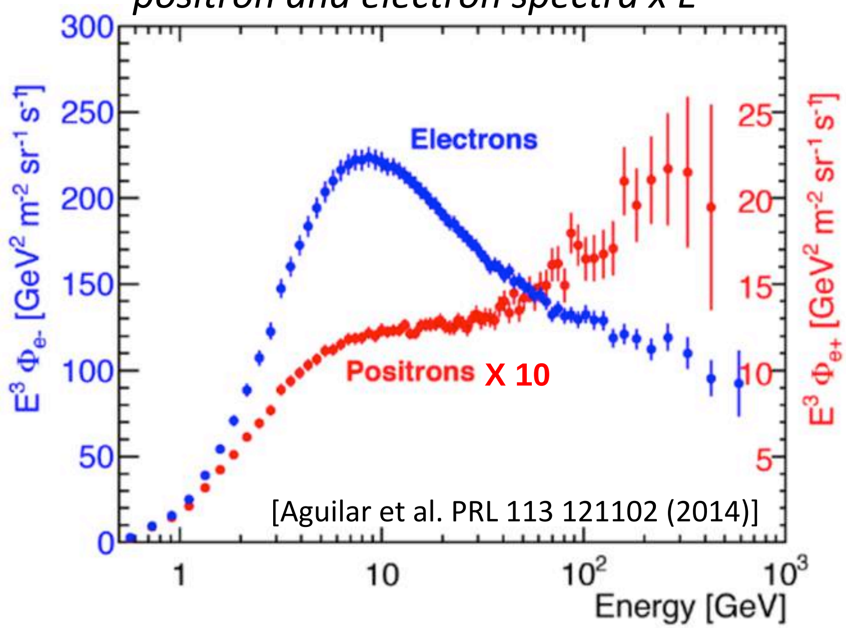
Electron spectrum x E^3

Above 10 GeV: smooth, slowly falling curve. Fairly good agreement with the PAMELA data. Different solar modulation at low energies.

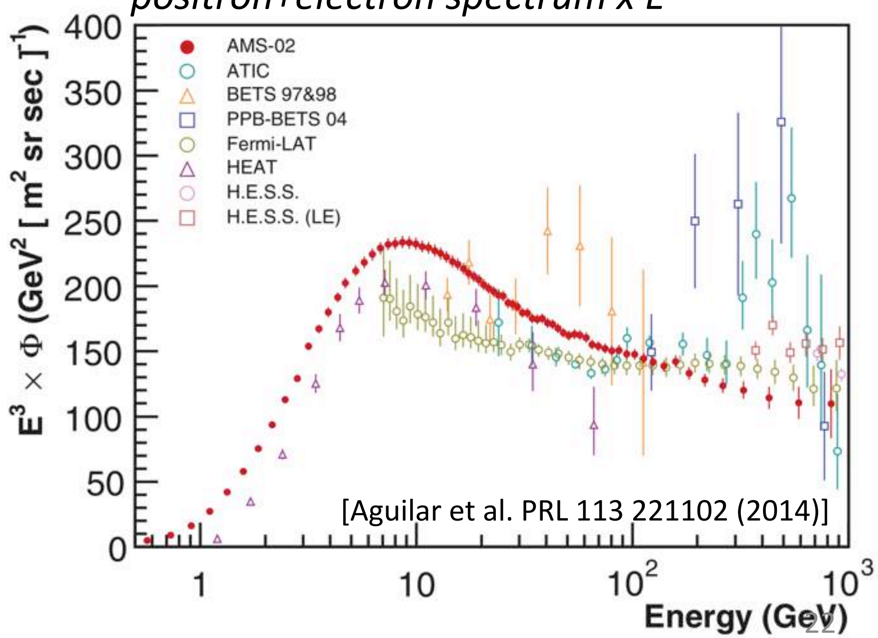
Positron spectrum x E^3

Flat spectrum from ~10 to 30 GeV. Change of slope above 30 GeV, harder than E-3, completely different from the e- spectrum.

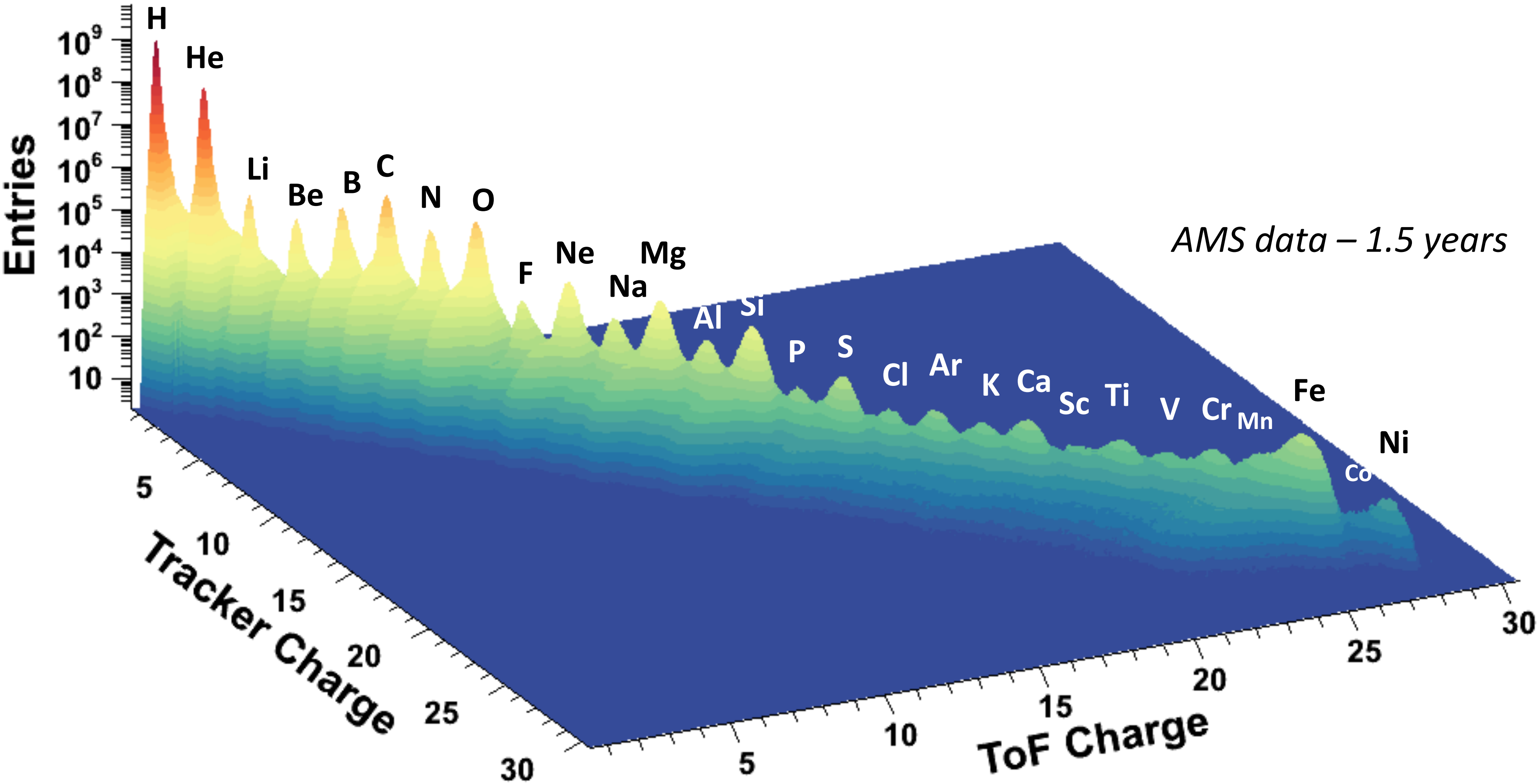
positron and electron spectra x E^3



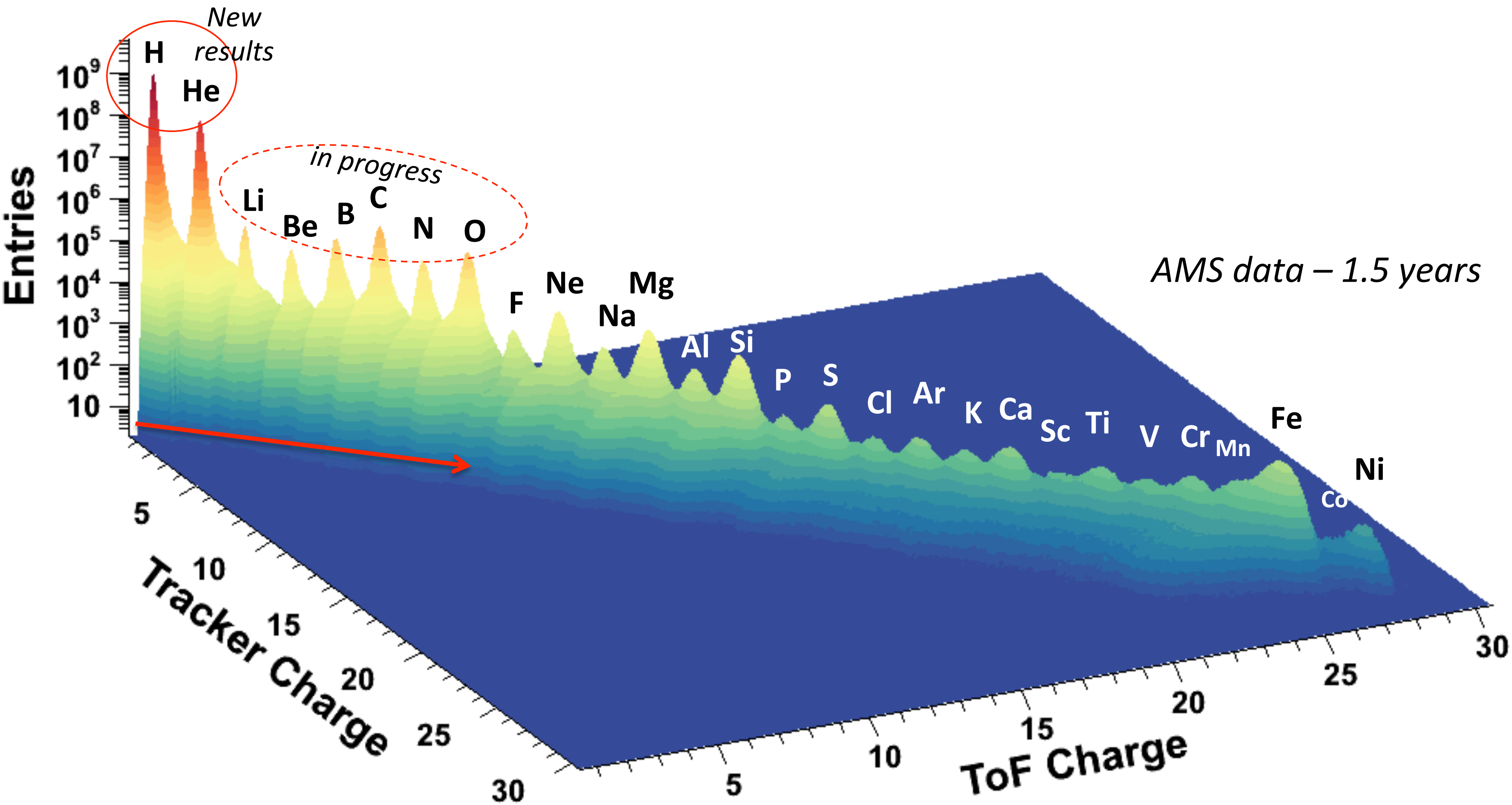
positron+electron spectrum x E^3



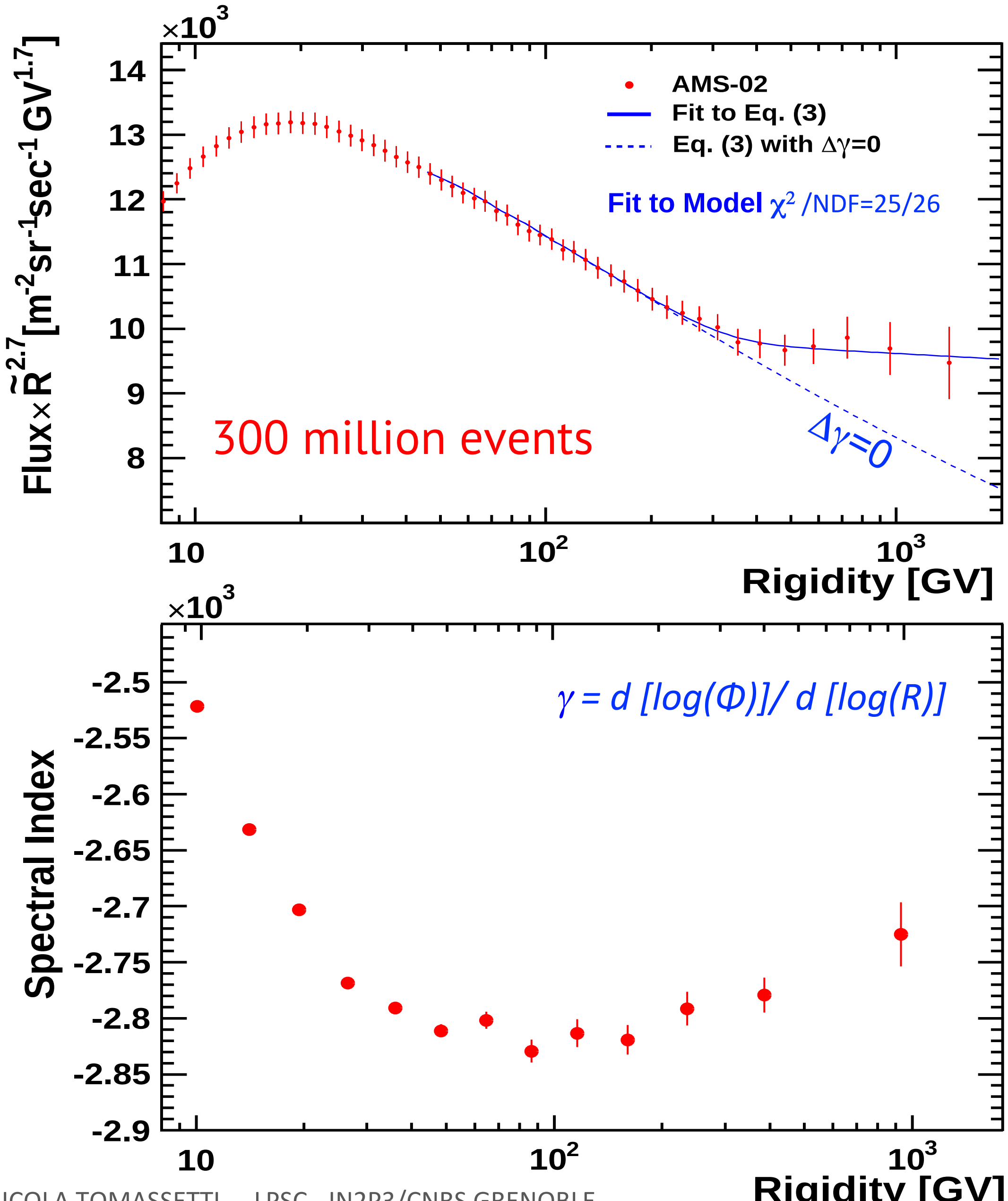
Nuclear component



Nuclear component



New results: Proton Flux at TeV



[Phys. Rev. Lett. 114 (2015) 171103]

The spectrum cannot be described by a single power-law function. We obtain a good description using a double power-law:

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

$\gamma = -2.849^{+0.002}_{-0.002}(\mathrm{fit})^{+0.004}_{-0.003}(\mathrm{sys})$ low-rigidity slope

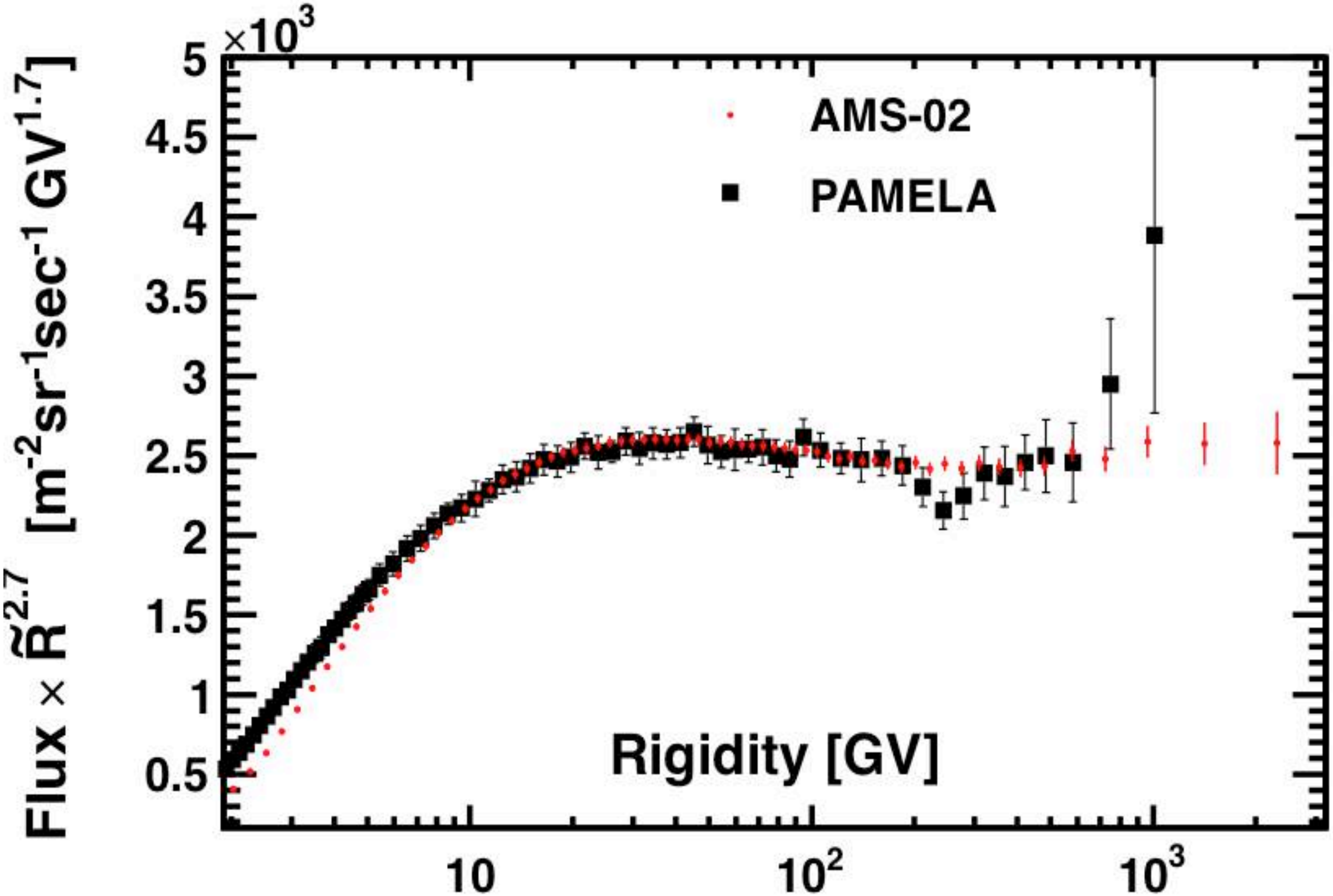
$\Delta\gamma = 0.133^{+0.032}_{-0.021}(\mathrm{fit})^{+0.046}_{-0.030}(\mathrm{sys})$ delta-slope

$R_0 = 336^{+68}_{-44}(\mathrm{fit})^{+66}_{-28}(\mathrm{sys})$ [GV] critical rigidity

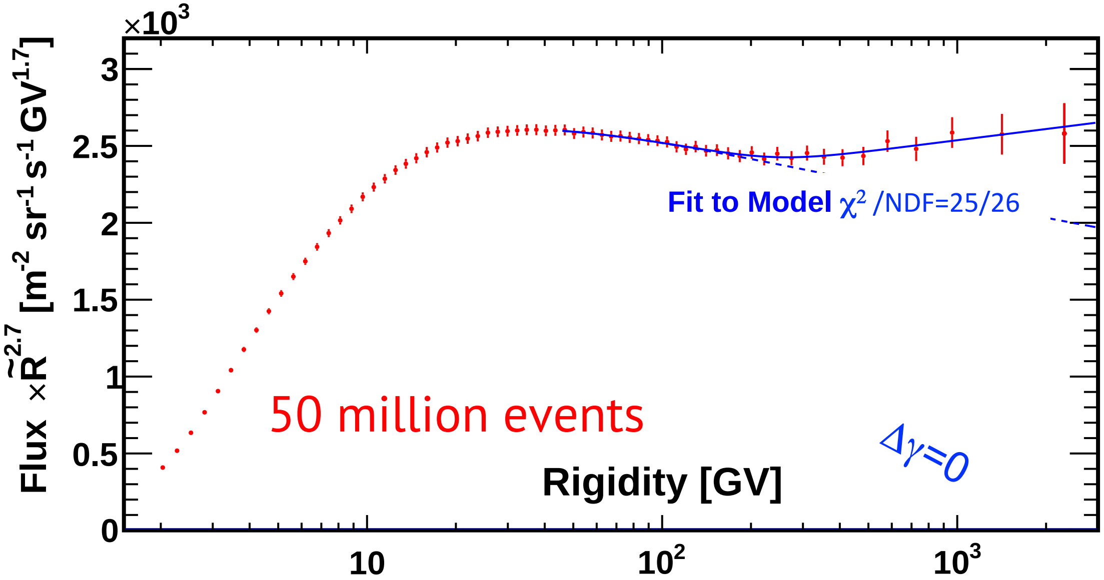
The detailed variation of the high-energy flux can be characterized by measuring the log-slope. As shown, the proton flux experiences a progressive hardening above ~100 GV of rigidity.

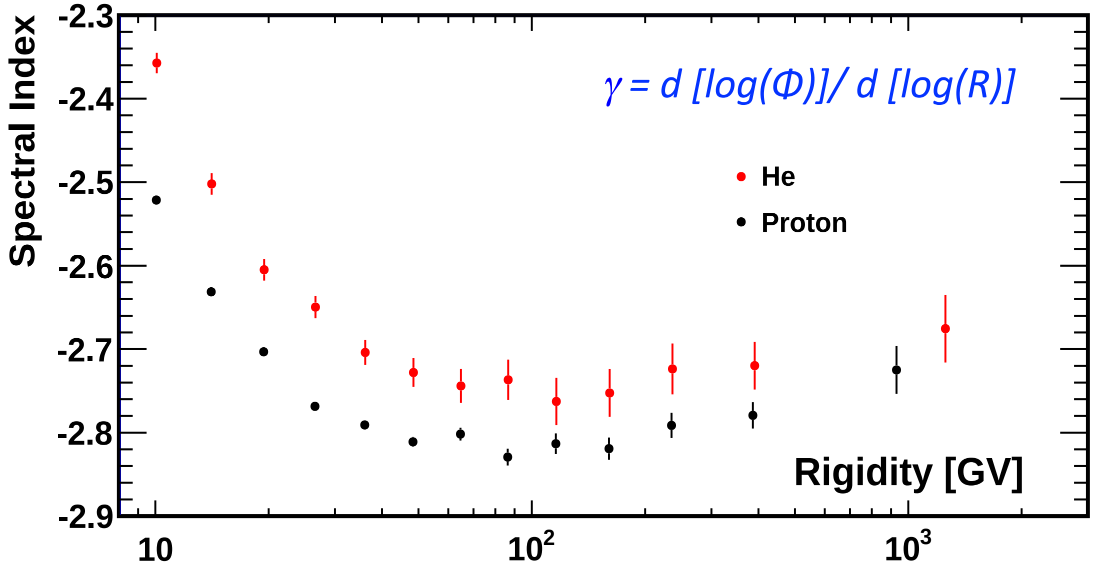
New results: Helium Flux at TeV

[Phys. Rev. Lett. 115 (2015) 201101]



New results: Helium Flux at TeV





[Phys. Rev. Lett. 115 (2015) 201101]

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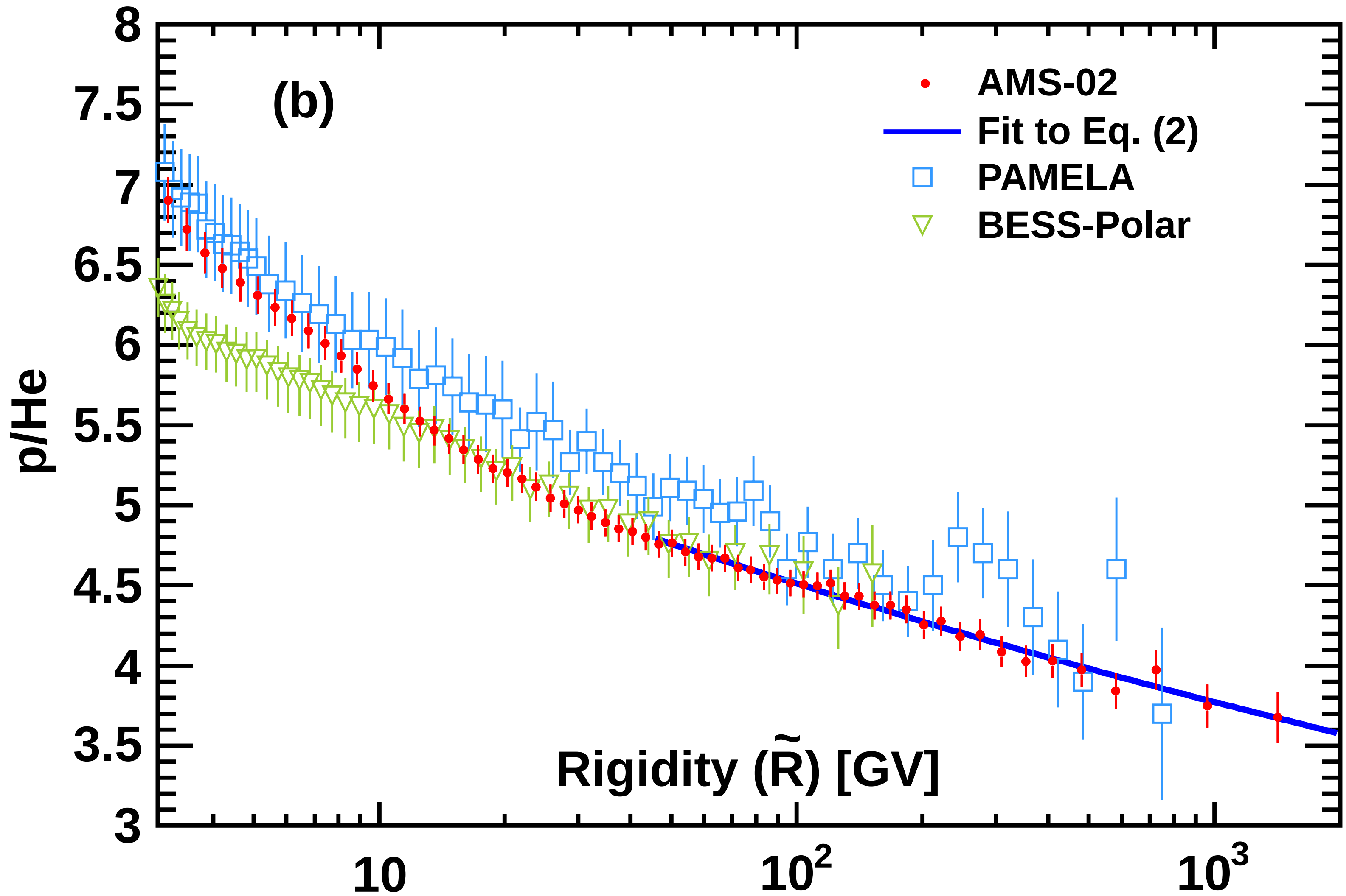
$$\Phi = C\left(\frac{R}{45\,\text{GV}}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/s}\right]^{s}$$

$$\gamma = -2.780 \pm 0.005(\text{fit}) \pm 0.001(\text{sys})$$
$$\Delta\gamma = 0.119^{+0.013}_{-0.010}(\text{fit})^{+0.033}_{-0.028}(\text{sys})$$
$$R_0 = 245^{+35}_{-31}(\text{fit})^{+33}_{-30}(\text{sys})$$

The detailed variation of the high-energy flux can be characterized by measuring the log-slope. As shown, the proton flux experiences a progressive hardening above ~100 GV of rigidity.

New results: p/He ratio

[Phys. Rev. Lett. 115 (2015) 201101]

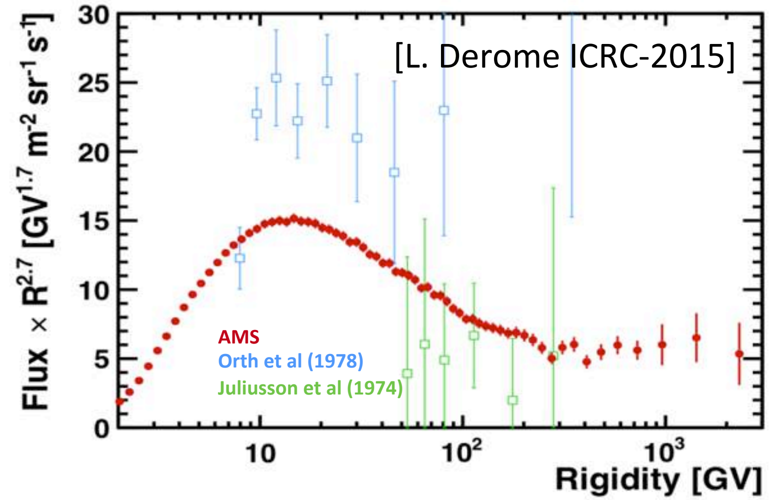


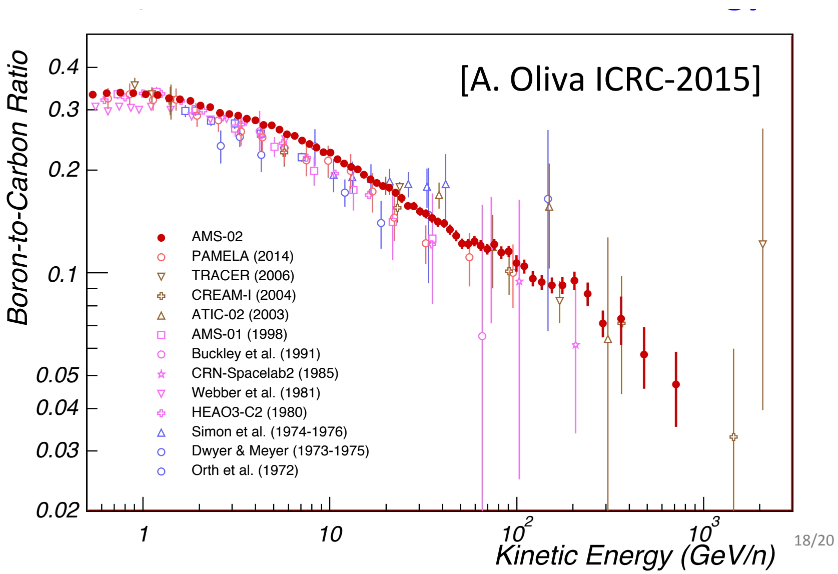
Light nuclei – current status

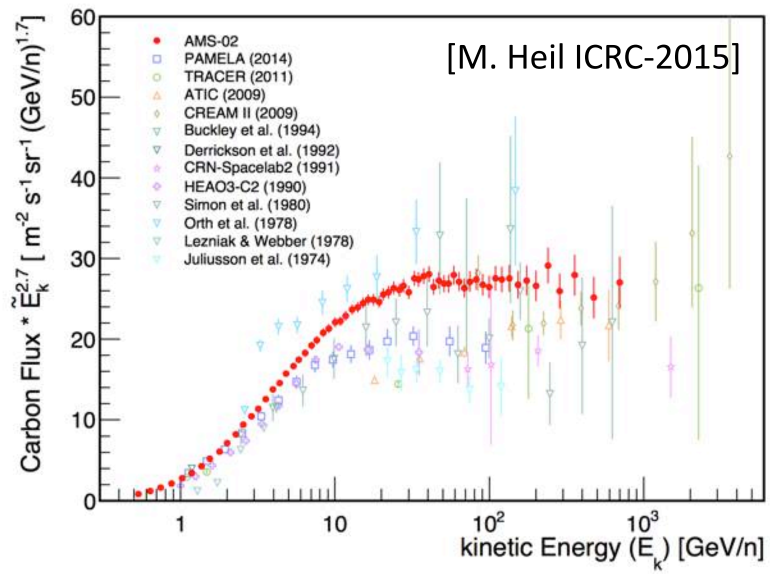
✓ **B/C ratio at 0.5 GeV/n – 1 TeV/n**
Standard observable for CR transport

✓ **Lithium spectrum at 2 GV- 3 TV**
Highly sensitive to CR propagation

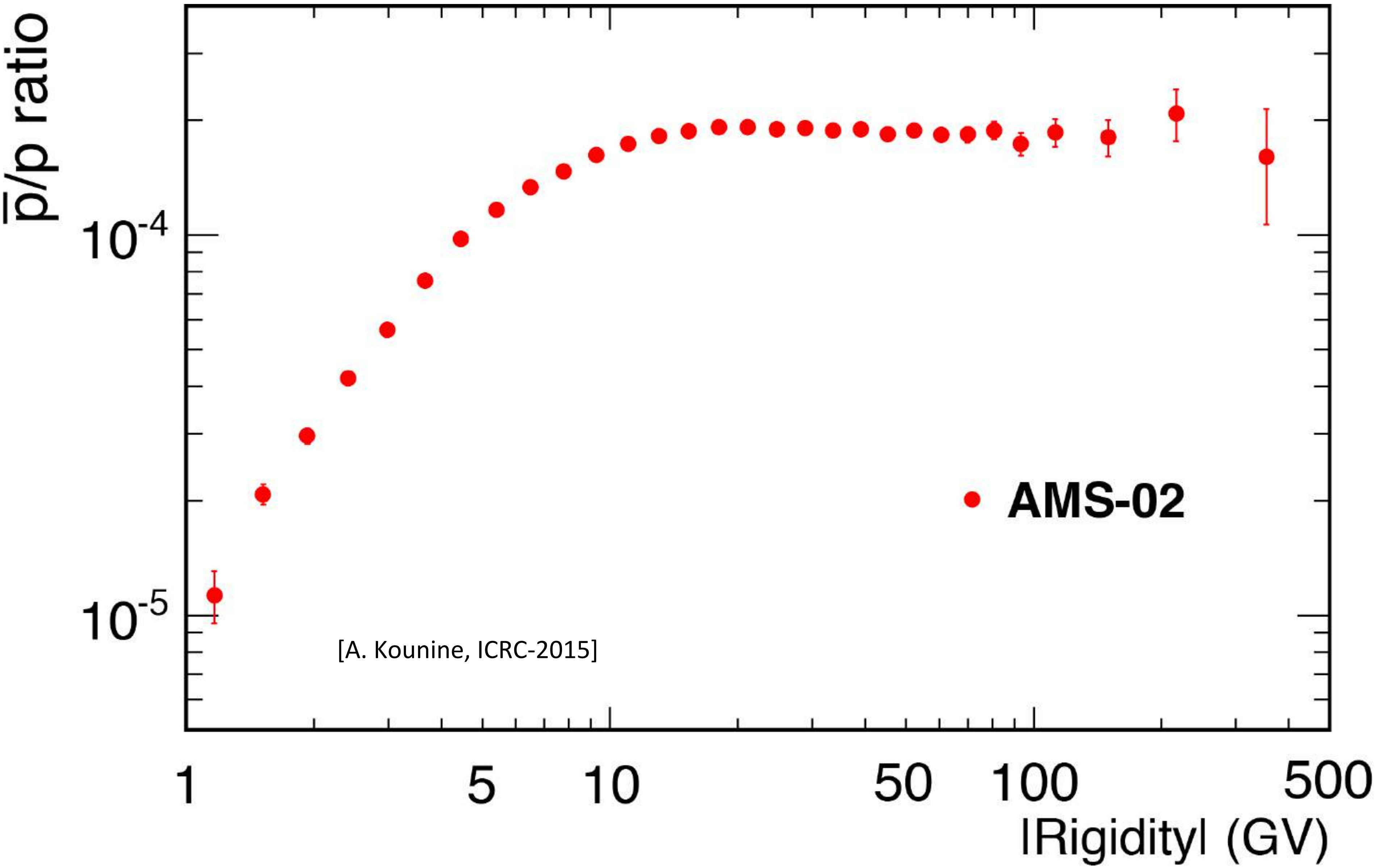
✓ **Carbon spectrum at 0.5 GeV/n– 1 TeV/n**
Similar spectral shape as Helium





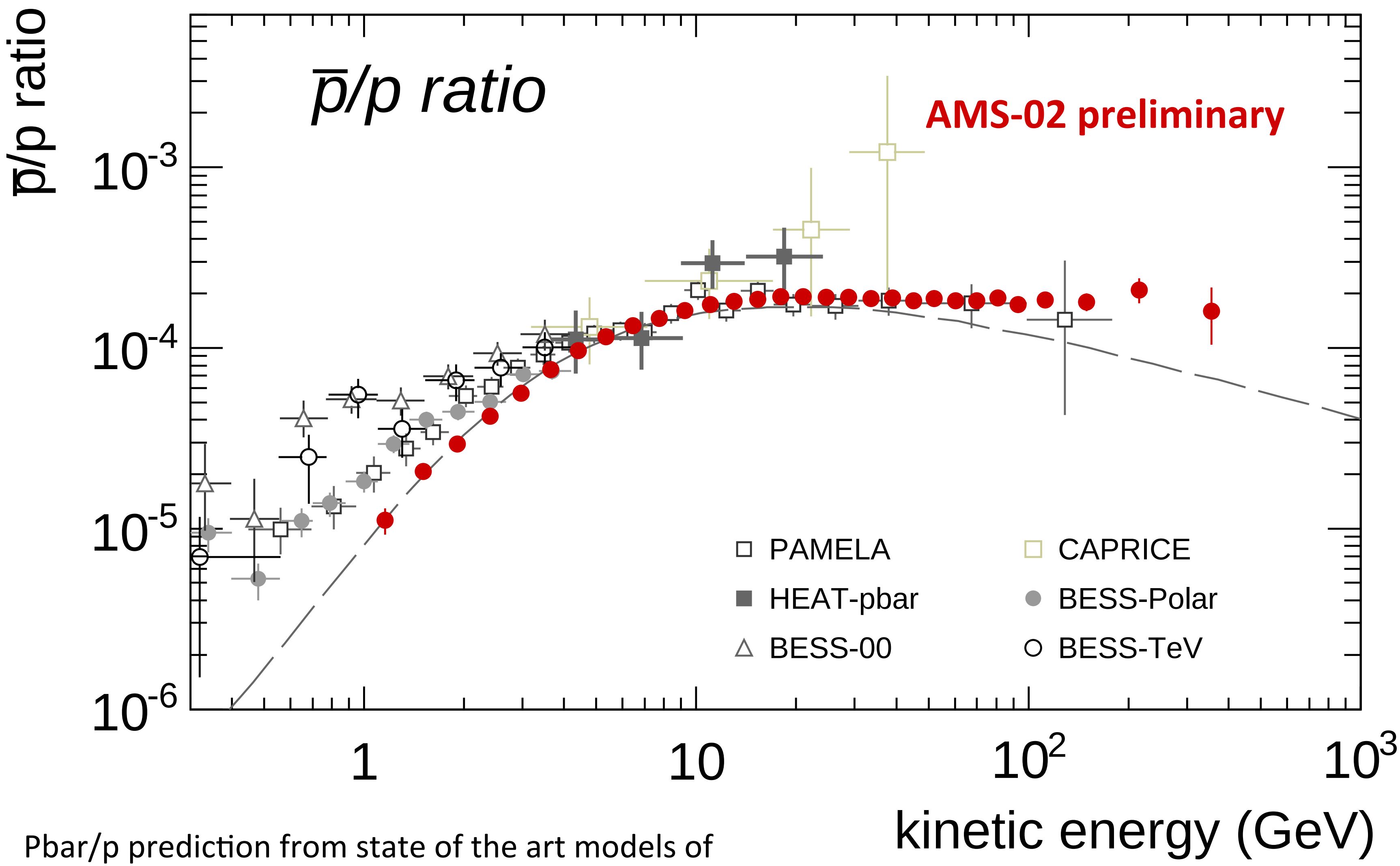


antiproton/proton – progress status



[A. Kounine, ICRC-2015]

antiproton/proton – progress status



Pbar/p prediction from state of the art models of CR propagation with Kraichnan-like diffusion

Summary

Lepton fluxes

Clear *excess* of high-energy positron at E>10 GeV. Hint of cutoff above 250 GeV

- ✓ Cannot be accounted in standard diffusion models.
- ✓ Need of an extra nearby source of high-energy leptons.

→ AMS data at higher energy may clarify the origin of the excess

Antiproton/proton ratio

- o AMS-02 data are still preliminary.
- o Clear tension with standard model expectation

→ Final pbar/p measurements at full statistics in the range 0.5 – 500 GeV

→ Improve model predictions, pin down uncertainties

Proton, helium and nuclei

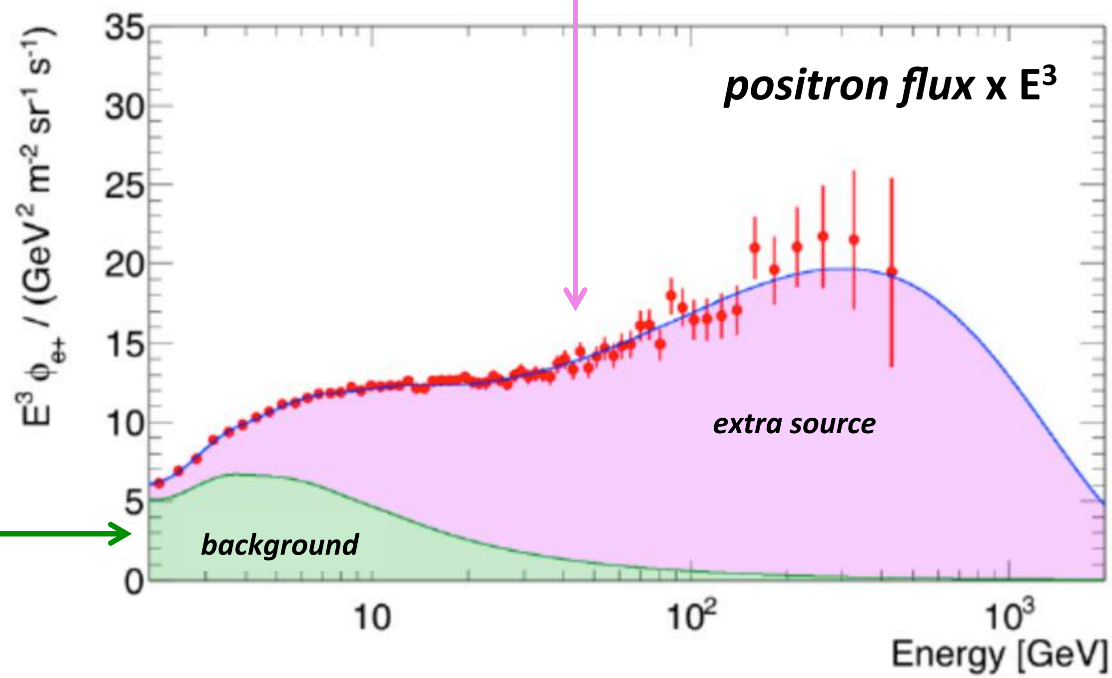
- o Progressive spectral hardening Proton and He fluxes above ~100 GeV/n
- o The p/He ratio decreases power-law at rigidity 45-1800 GV, with slope ~0.08
- o Lithium, Carbon, B/C ratio measurements at GeV-TeV energies are in progress

→ High-energy behaviour of Z>2 nuclei may bring precious insights

Positron excess: sources of HE positrons

Standard prediction: of e+ from p+ISM collisions
→Cannot account for the observed positron data
→Background for new physics/astrophysicssignals

- Dark Matter particles?
- Astrophysical sources (SNR/PWN)
- ✓ CR collisions with ISM

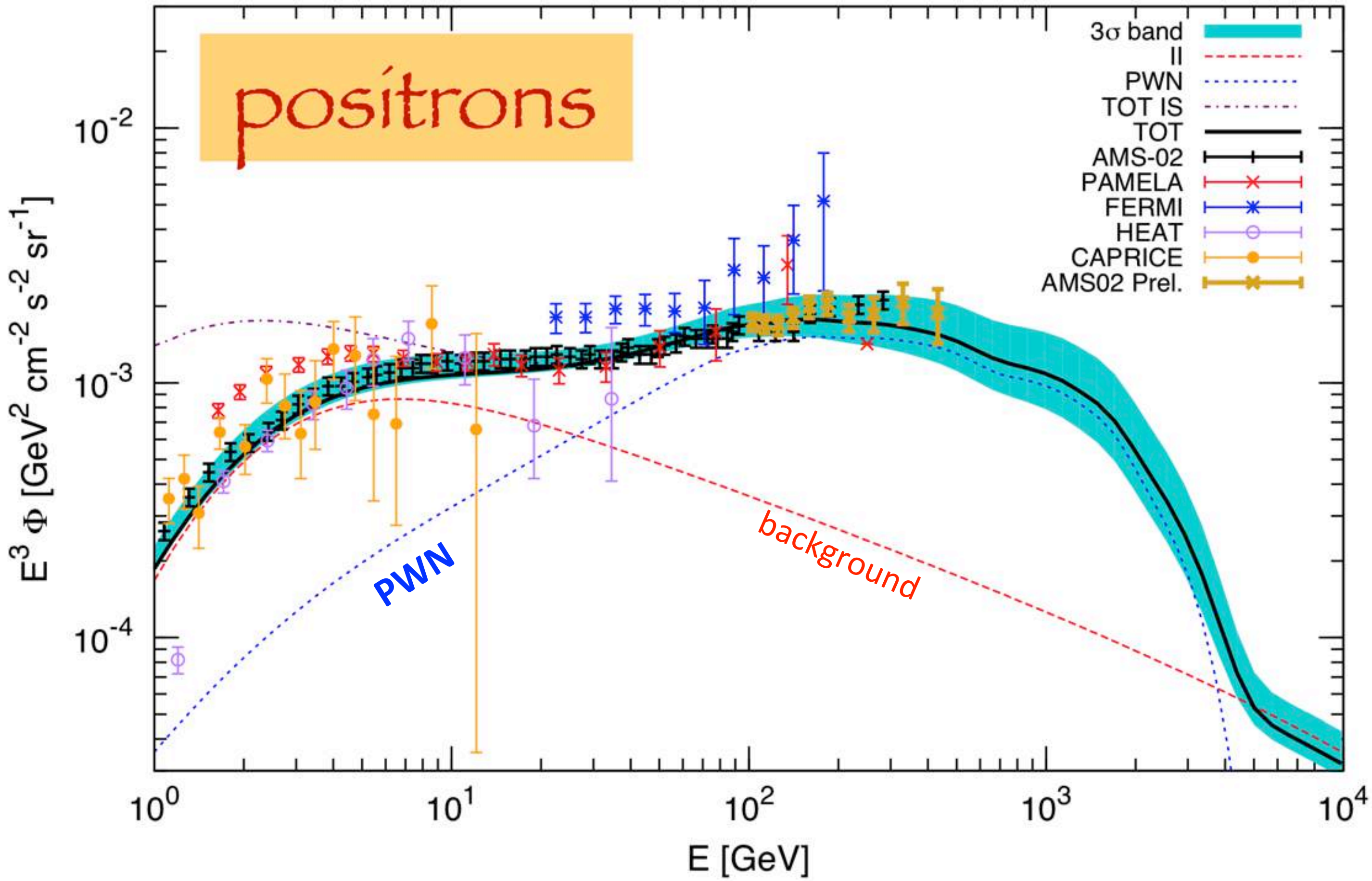


Nearby source of high-energy positrons: pulsar

Nearby Pulsar scenario

- ✓ **SNRs: electron, hadrons**
- ✓ **hadrons+ ISM collisions: secondary e+ and e-**
- ✓ **PWN: primary e+ and e-**

[Di Mauro et al. arXiv:1402.0321 (2014)]

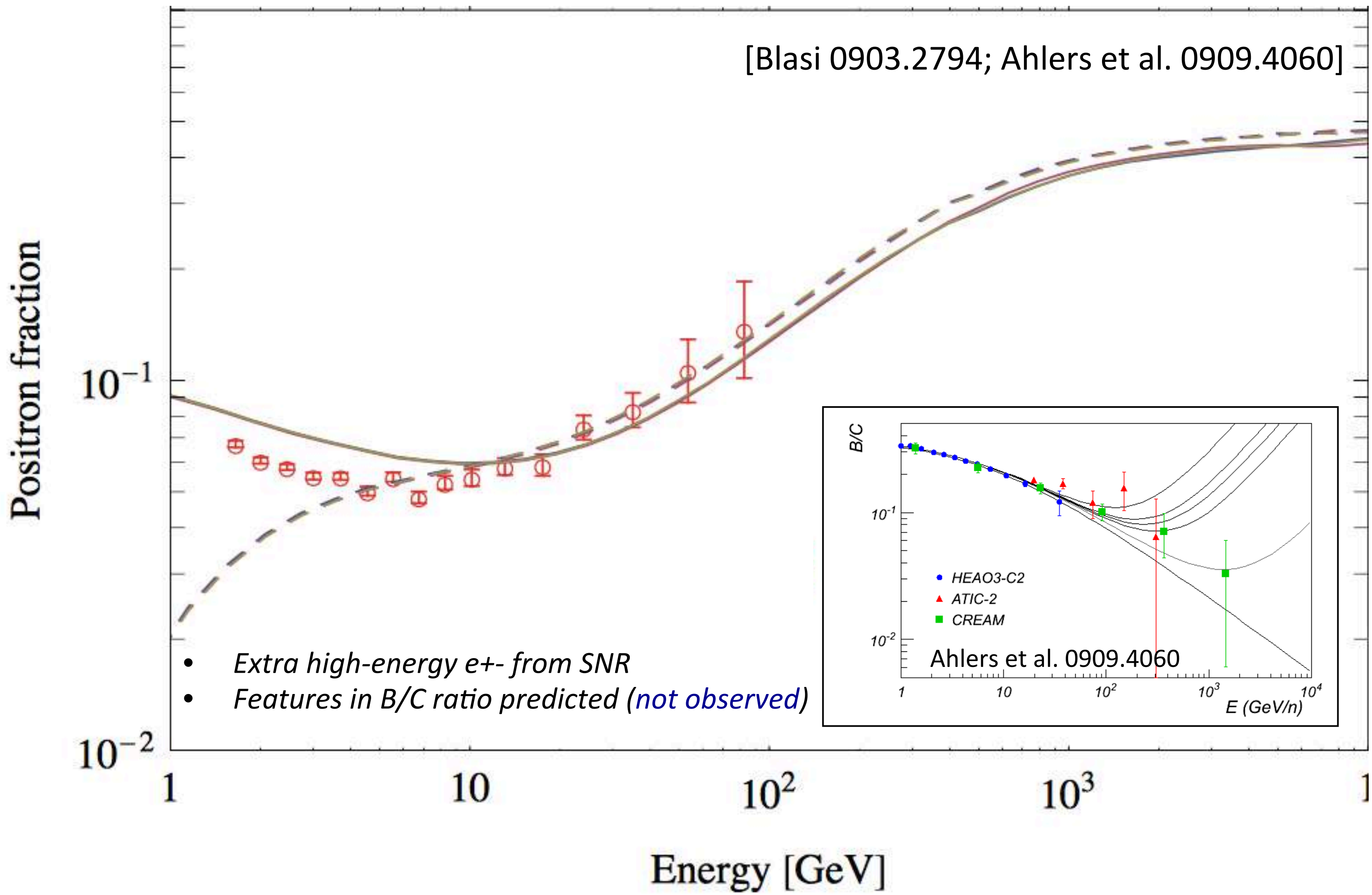


No consequences for the phenomenology of CR hadrons

Nearby source of high-energy positrons: SNR

Old SNR scenario

- ✓ SNRs: electron, hadrons, e+ from p-p collisions
- ✓ hadrons+ ISM collisions: secondary e+ and e-



- *Extra high-energy e+- from SNR*
- *Features in B/C ratio predicted (not observed)*

Two components scenario: local SNR + Galactic enseble

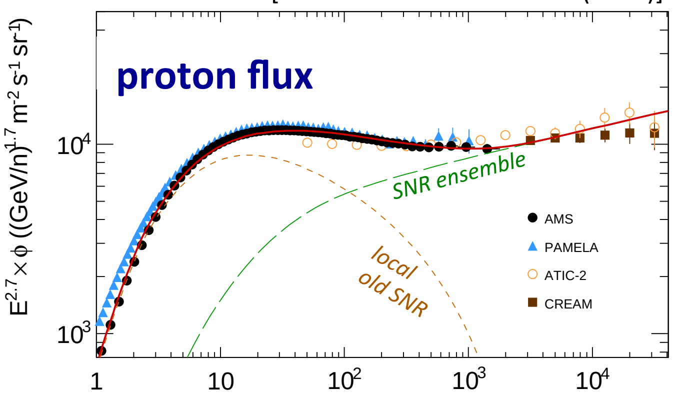
two SNR components in the CR flux

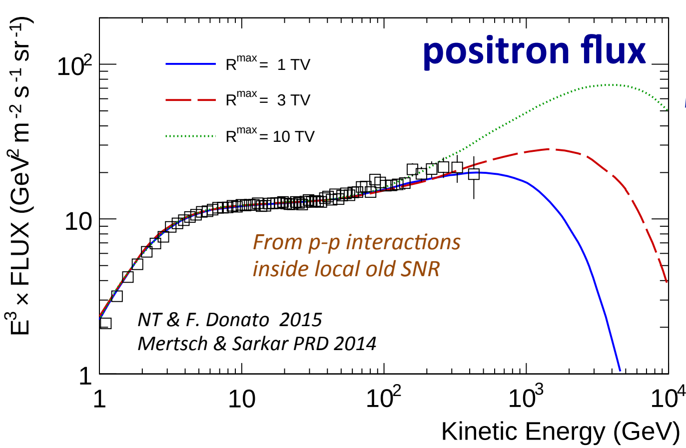
- *Nearby source component for the GeV-TeV flux (and e+ excess)*
- *Large-scale SNR distribution in the Galaxy*

✓ **Connection between hadron spectra and positron excess** [NT & F.Donato, 1502.06150 (2015)]

✓ **No expected rise in the B/C ratio. In agreement with PAMELA & AMS-02 data.**

[NT & Donato: 1502.06150 (2015)]

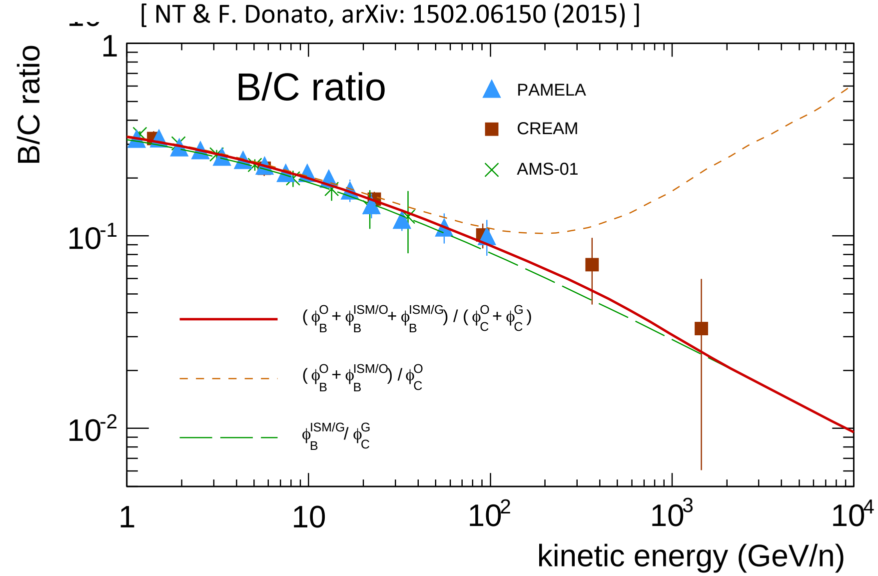




✓ **Explanation for the p/He ratio [NT 1511.04460]**

✓ **Explanation for C/Fe and O/Fe ratios [NT 1509.05774]**

[NT & F. Donato, arXiv: 1502.06150 (2015)]

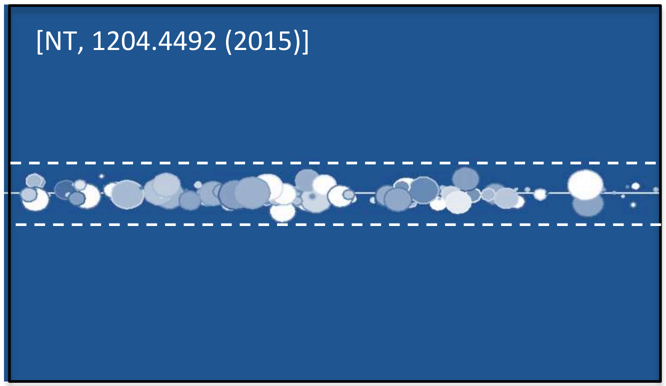


Explanation for pbar flux [Kachelriess et al 1504.06472]

Nearby type-Ia SNR exploded ~2 Myr ago w/ E~10^50 erg

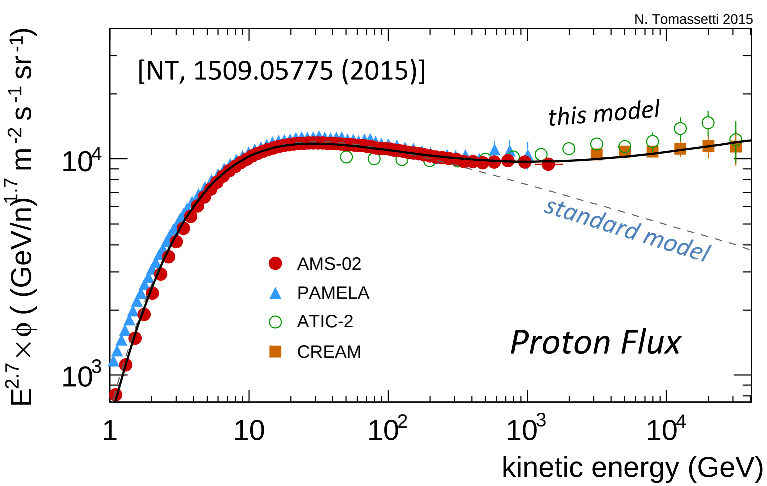
New phenomena in cosmic-ray propagation?

Diffusion coefficient is not separable into energy and space coordinates → no power-law
Shallower diffusivity in the region close to the Galactic disk → high-energy flattening

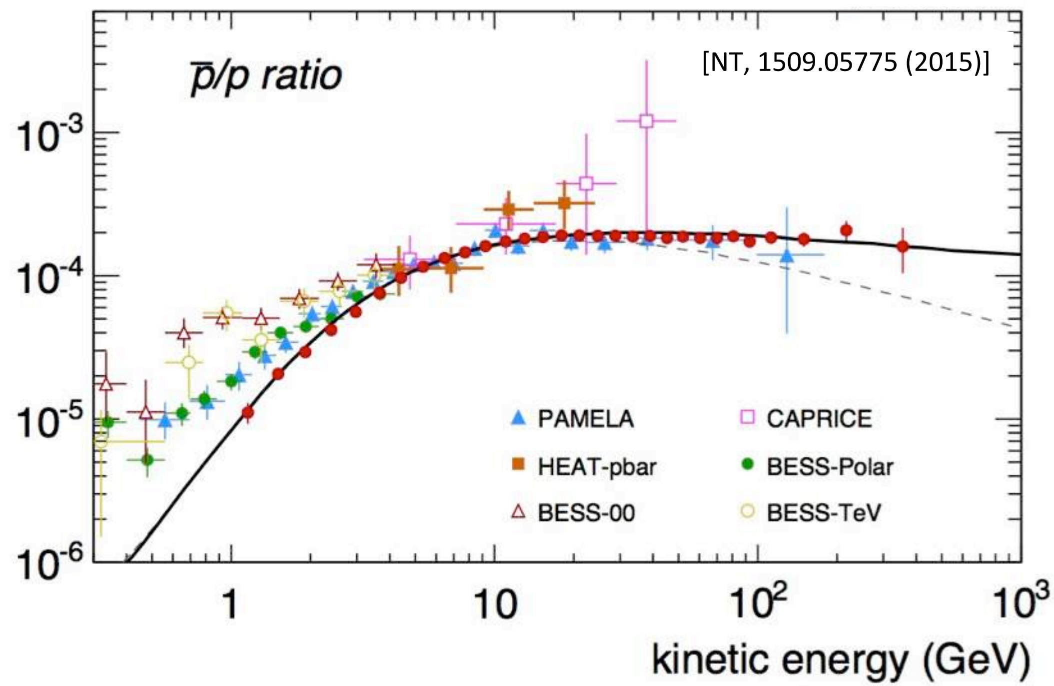


Two-halo model

- ✓ **Predicted flattening in all nuclei and sec/pri ratios**
- ✓ **Enhanced antimatter production at high energy**
- ✓ **Connection with gamma-rays and anisotropy**



→ ***Predicts*** **a flat pbar/p ratio at high energies**



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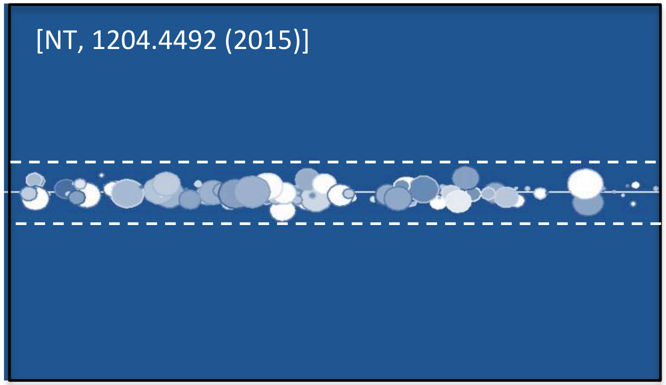
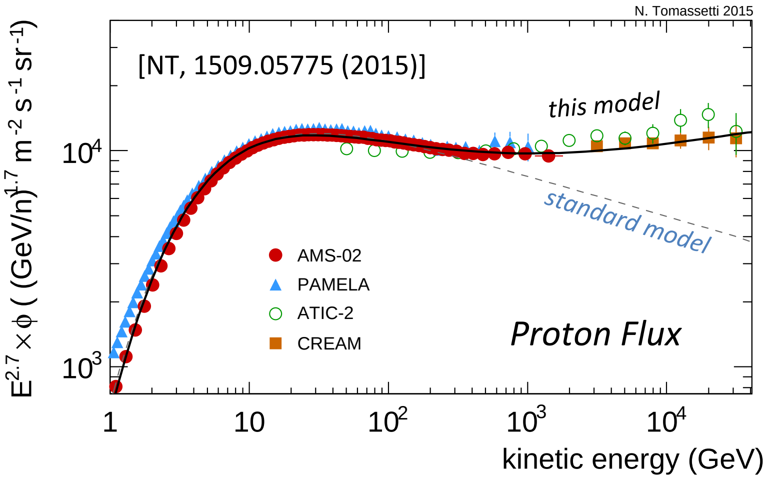
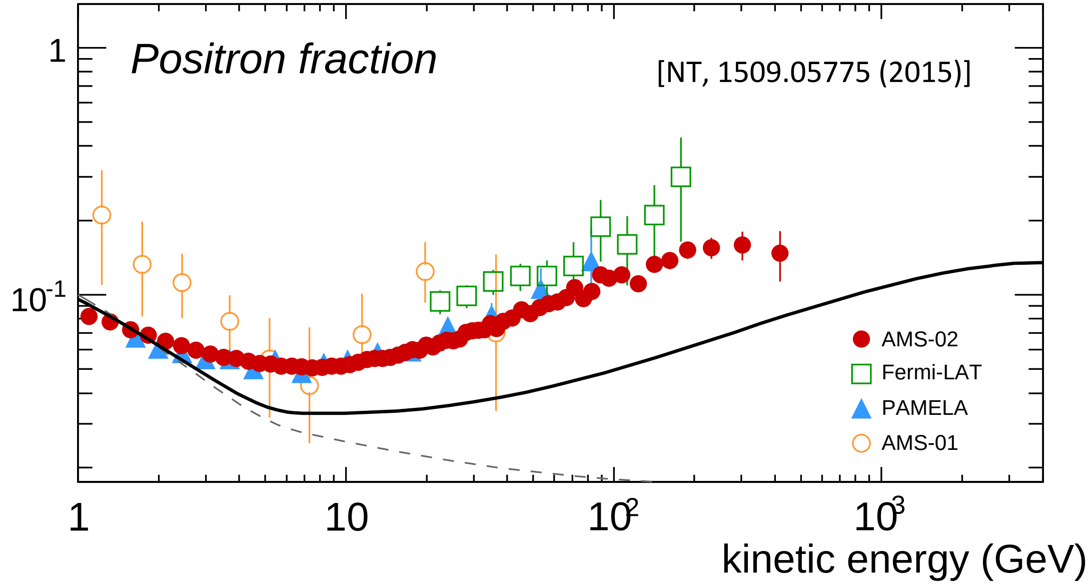


Two-halo model: NT 1204.4492 (2012)

- ✓ **Predicted flattening in all nuclei and sec/pri ratios**
- ✓ **Enhanced antimatter production at high energy**
- ✓ **Connection with gamma-rays and anisotropy**

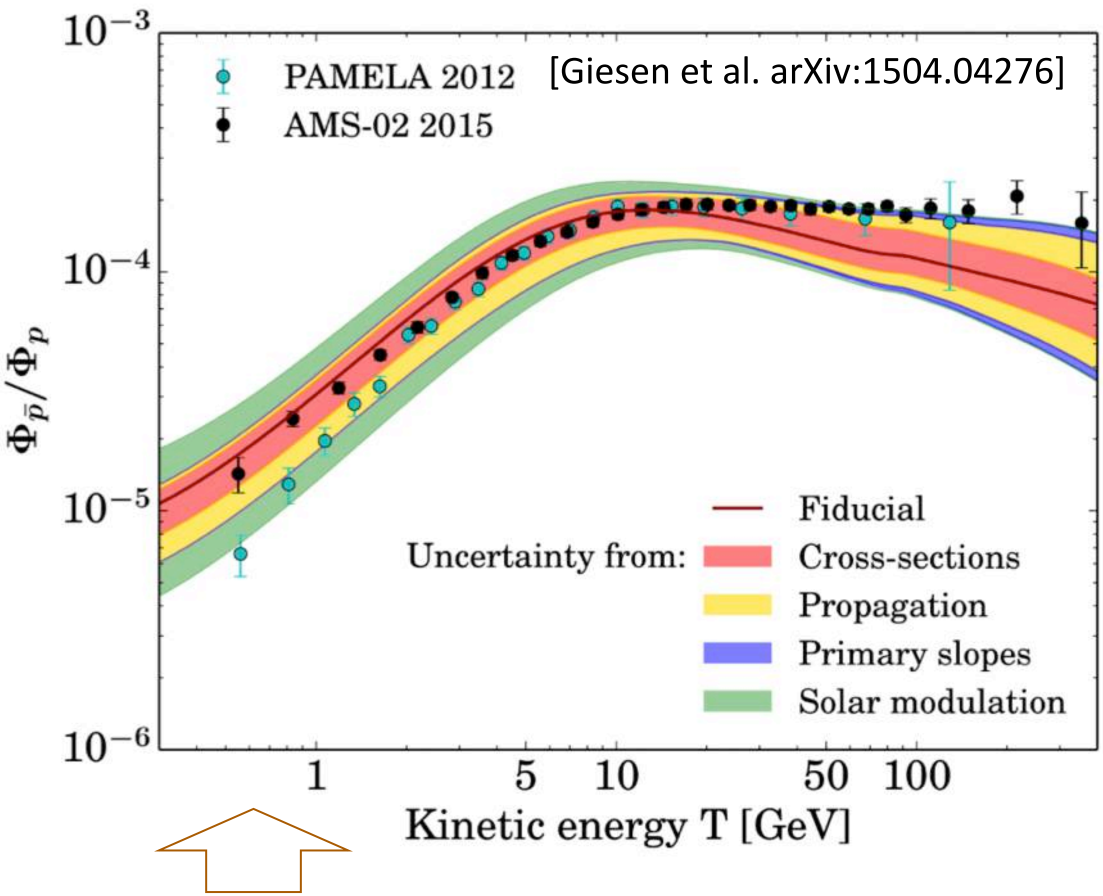


→ **Predicts a enhanced positron flux at high-energy**



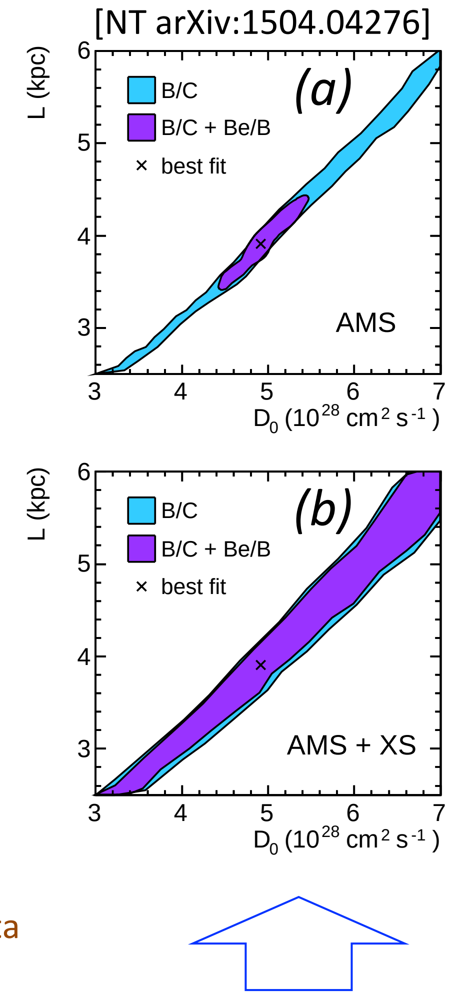
Uncertainties in CR propagation and antiproton production

Uncertainties in p/p ratio



From standard diffusion models with p/He injection spectra based on new AMS data

In CR propagation



AMS capability in constraining the transport parameters before (a) and after (b) accounting for intrinsic nuclear uncertainties in CR propagation models

Summary

Lepton fluxes

Clear *excess* of high-energy positron at E>10 GeV. Hint of cutoff above 250 GeV

- ✓ Cannot be accounted in standard diffusion models.
- ✓ Need of an extra nearby source of high-energy leptons.

→ AMS data at higher energy may clarify the origin of the excess

Antiproton/proton ratio

- AMS-02 data are still preliminary.
- Clear tension with standard model expectation

→ Final pbar/p measurements at full statistics in the range 0.5 – 500 GeV

→ Improve model predictions, pin down uncertainties

Proton, helium and nuclei

- Progressive spectral hardening Proton and He fluxes above ~100 GeV/n
- The p/He ratio decreases power-law at rigidity 45-1800 GV, with slope ~0.08
- Lithium, Carbon, B/C ratio measurements at GeV-TeV energies are in progress

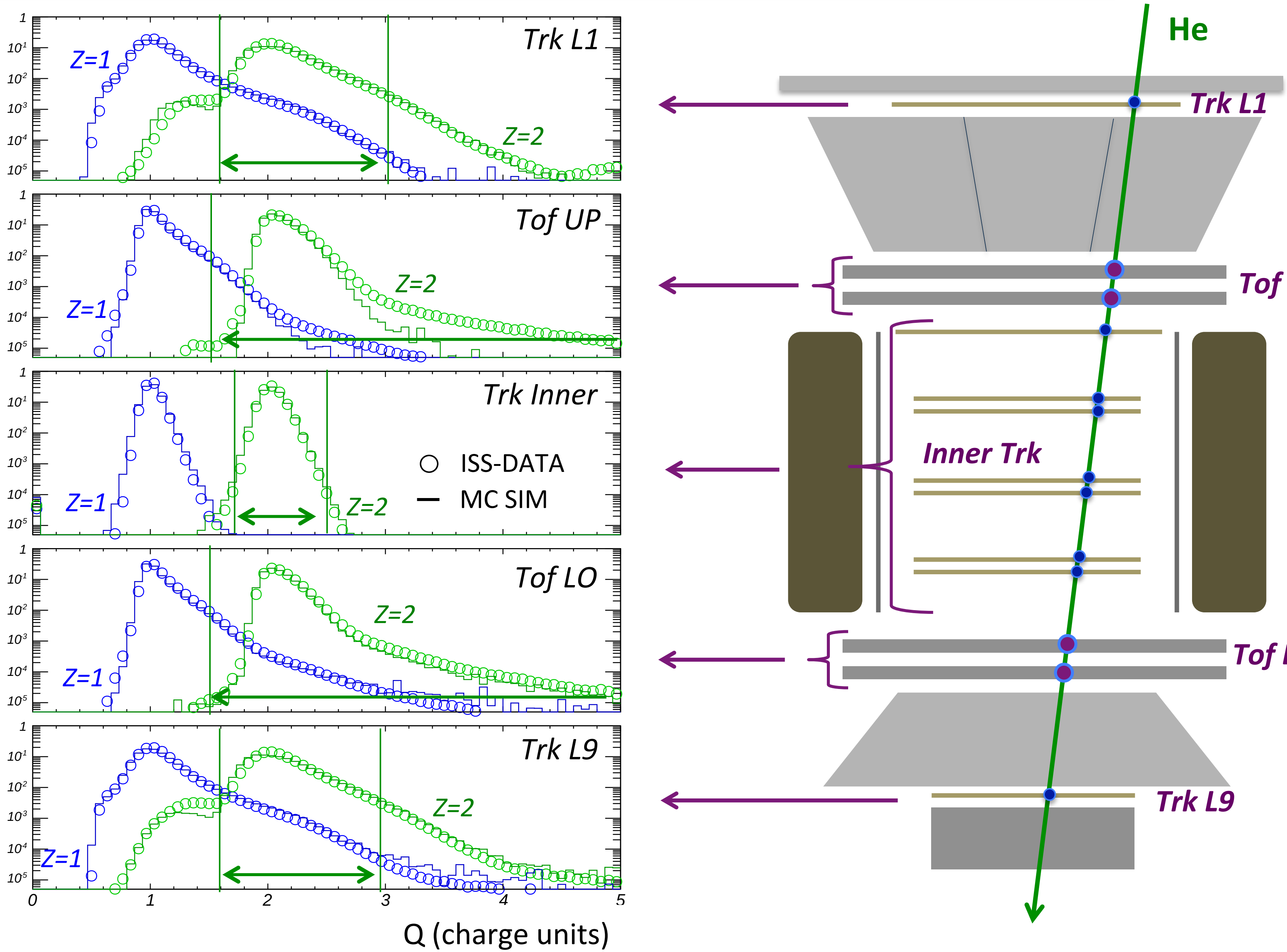
→ High-energy behaviour of Z>2 nuclei may bring precious insights

In 4.5 years, AMS has collected >80 billion events.

The accuracy of the AMS data is tremendously improving our understanding of cosmic ray transport and will help to shed a light on the nature of dark matter

Selection of Proton and Helium signals

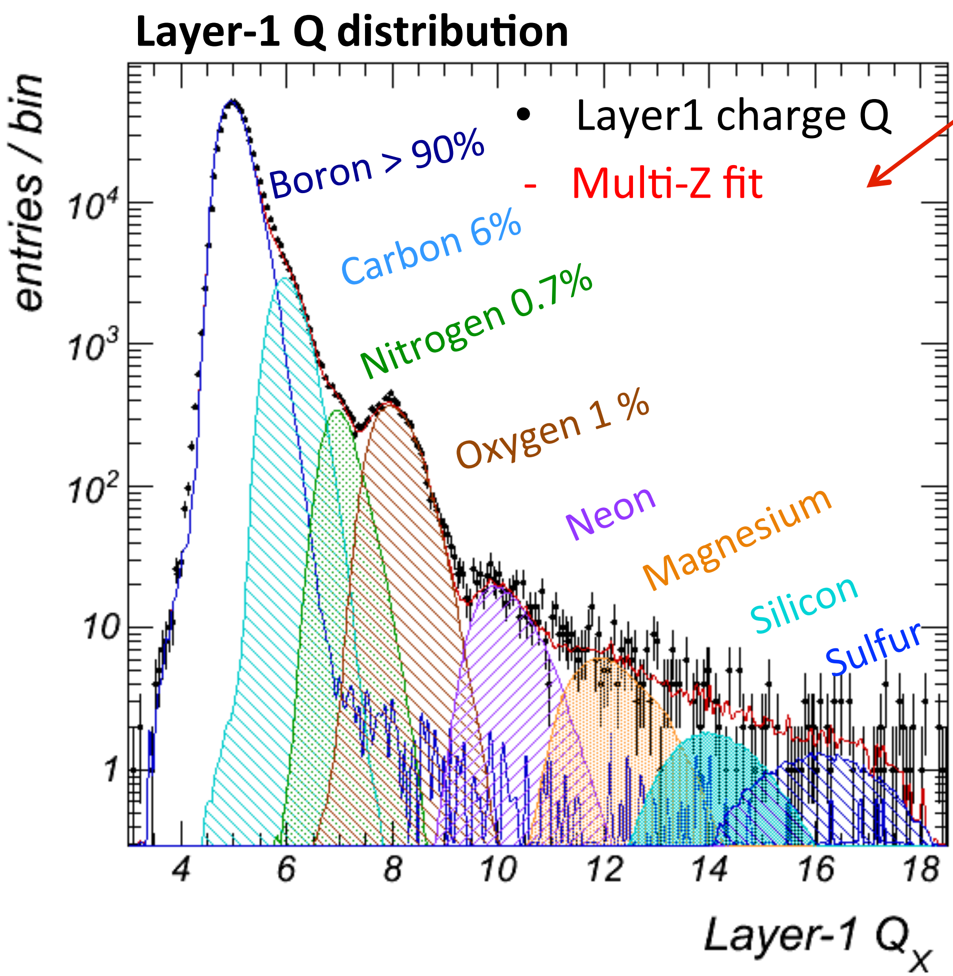
$$\Phi_i(R_i) = \frac{N_i}{T_i\,\varepsilon_i\,A_i\,\Delta R_i}$$

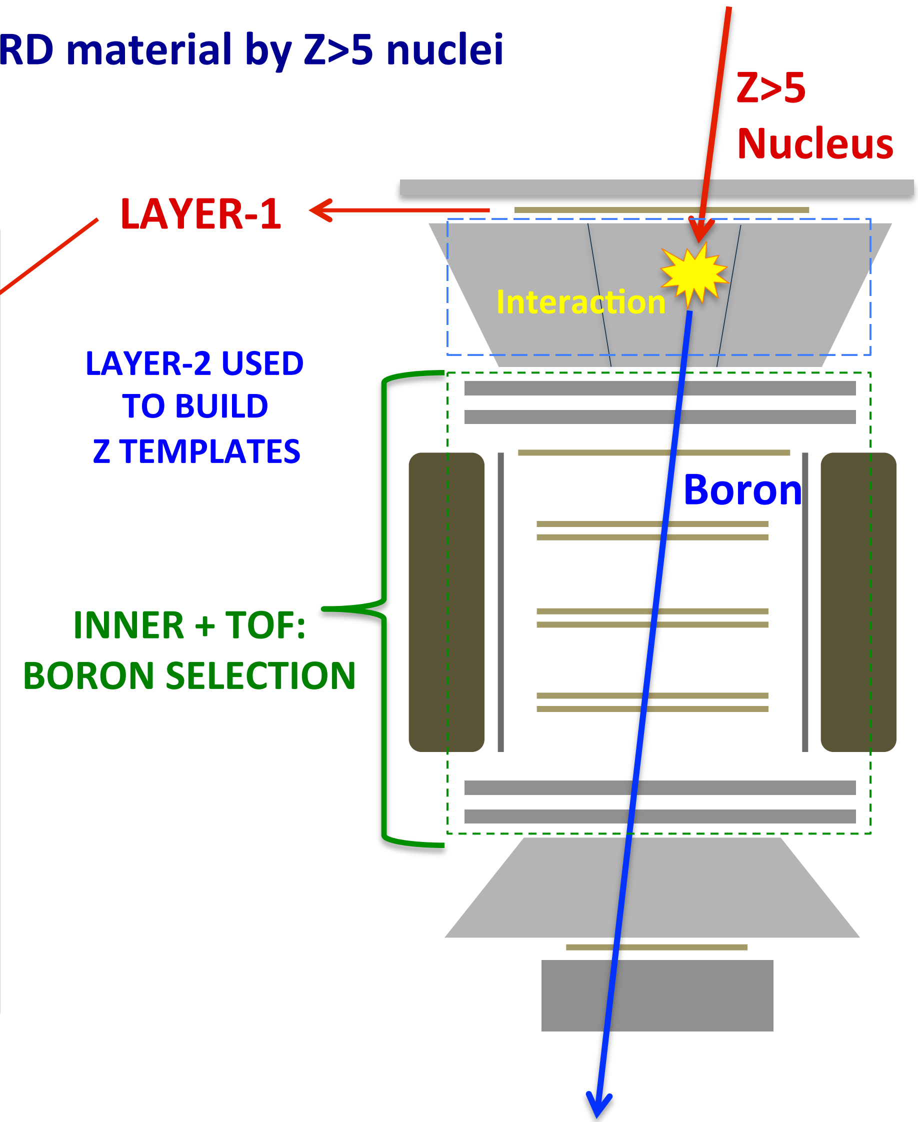


Fragmentation studies in the detector

Redundancy in Z-measurements allows us to study different fragmentation processes appearing at different levels in the detector.

Example: secondary production of Boron in TRD material by Z>5 nuclei





AMS-02 : Evidence of fragmentation Carbon → Boron

Carbon → Boron in Upper TOF

Optimized for high-Z measurements

-Large dinamical range: Z~ 1 - 30

-Many layers of active material.

-Many independent evaluations of Z.

Dedicated Trigger for Z>1:

-4/4 TOF planes fired

-Multiple TOF hits allowed

-NACC <5

Minimum bias trigger:

-1/100 prescaling!!

-3/4 TOF fired

-No conditions on NACC