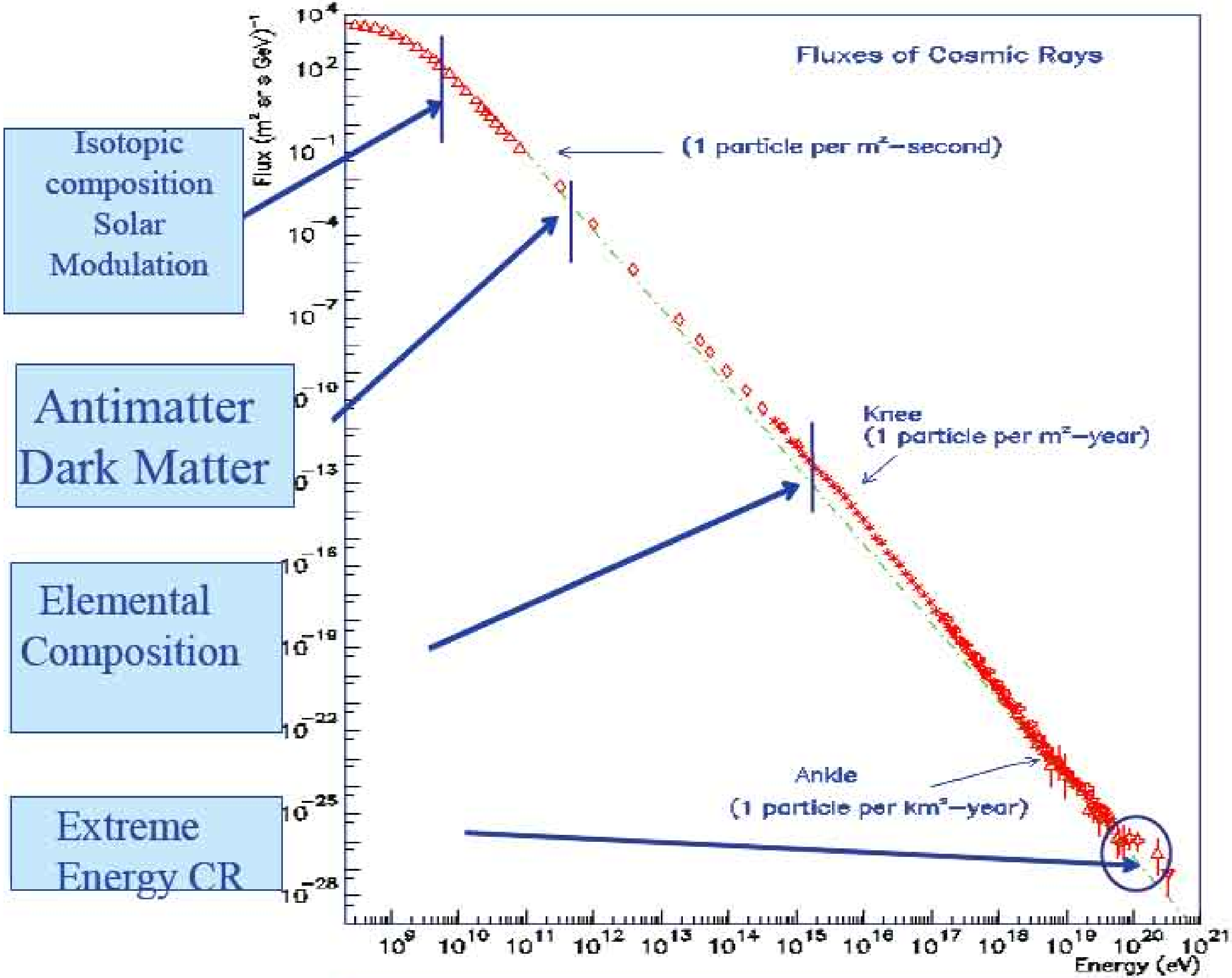
Recent results from the Alpha Magnetic Spectrometer (AMS) Experiment on the International Space Station

R. Battiston

Italian Space Agency
University and INFN-TIFPA,Trento

GSI, June 30th 2015



Isotopic composition Solar Modulation

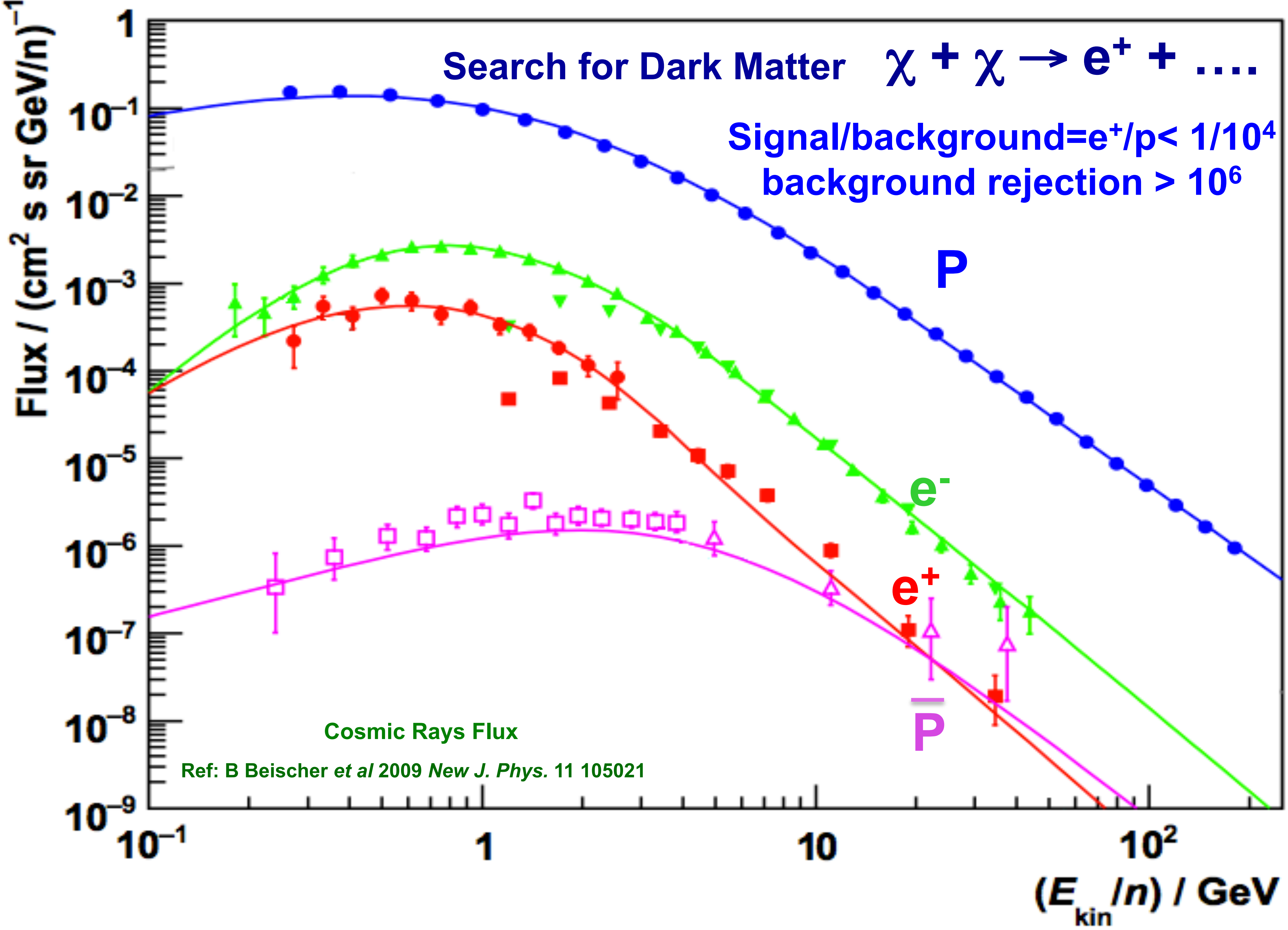
Antimatter Dark Matter

Elemental Composition

Extreme Energy CR

J. Cronin ,T.K. Gaisser & S.P. Swordy, Sci. Amer. 276 (1997) 44

Experimental Challenges



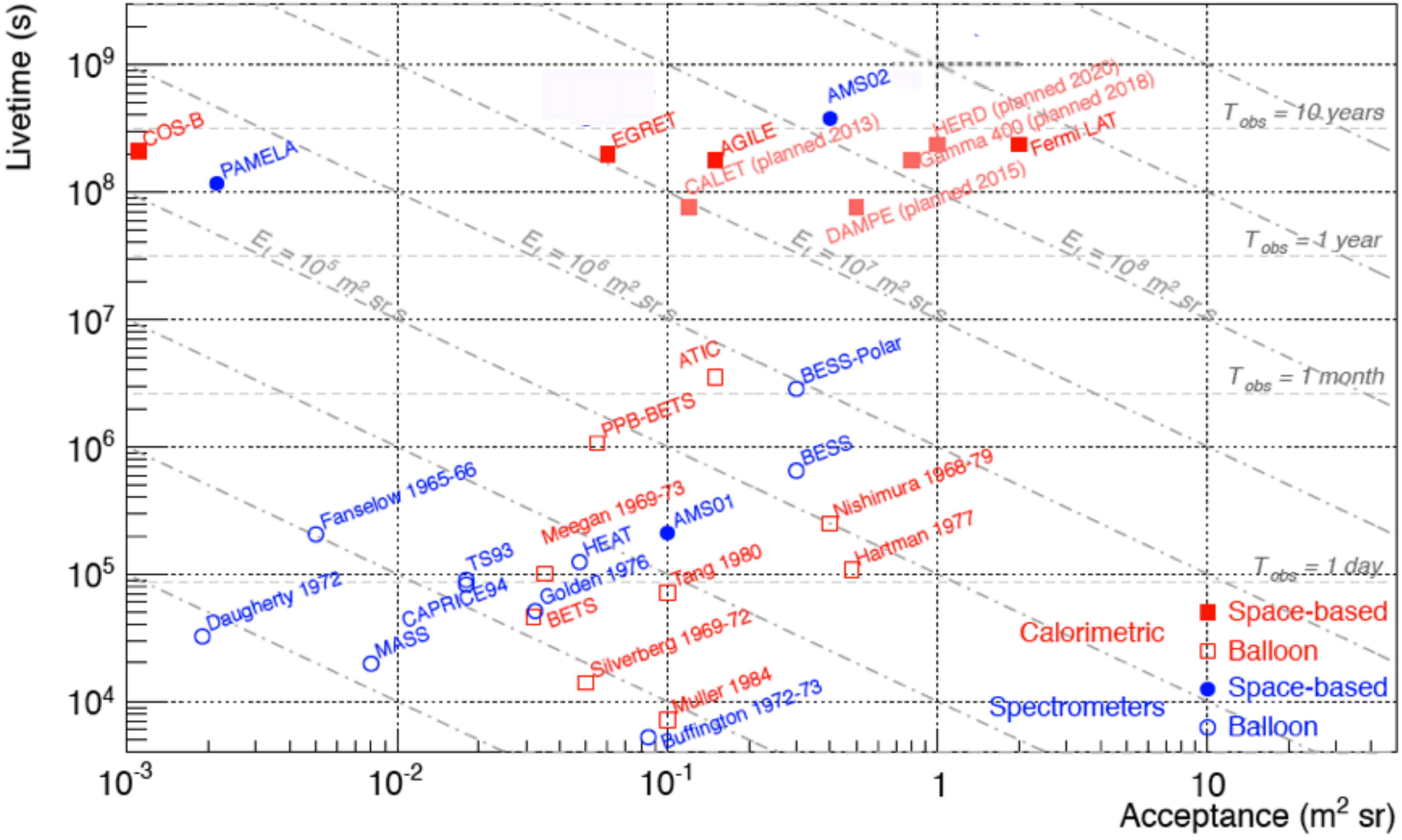
Search for Dark Matter $\chi + \chi \rightarrow e^+ + \ldots.$

Signal/background=$e^+/p < 1/10^4$
background rejection > 10^6

Cosmic Rays Flux

Ref: B Beischer *et al* 2009 *New J. Phys.* 11 105021

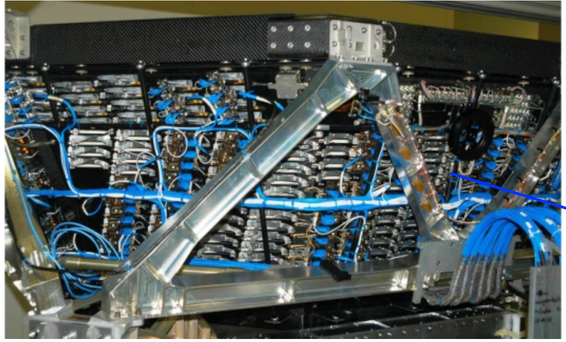
A Large Magnetic Spectrometer in Space :
a game changing for the study of Cosmic Ray



L. Baldini 2012

AMS: A TeV precision, multipurpose spectrometer

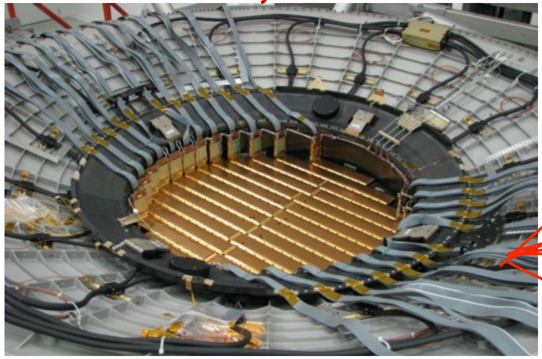
TRD
Identify e^+, e^-

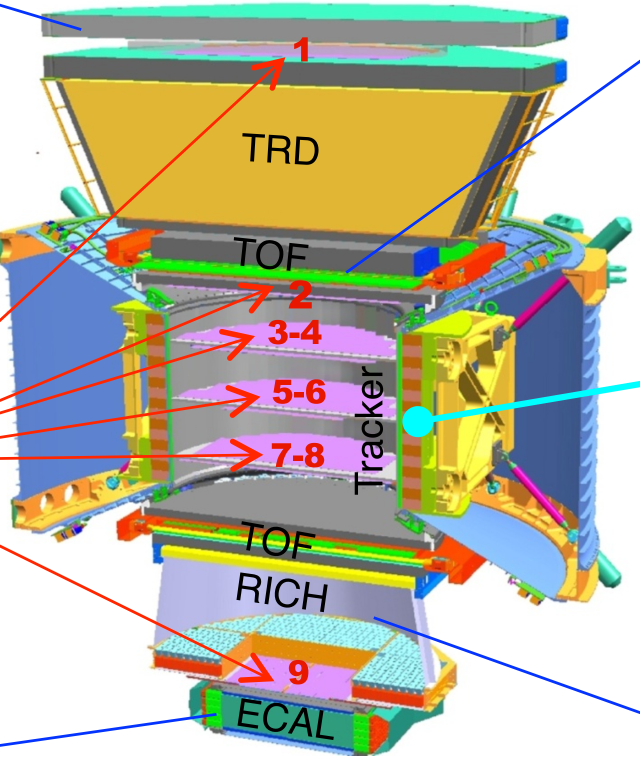


Particles and nuclei are defined by their charge (**Z**) and energy (**E ~ P**)

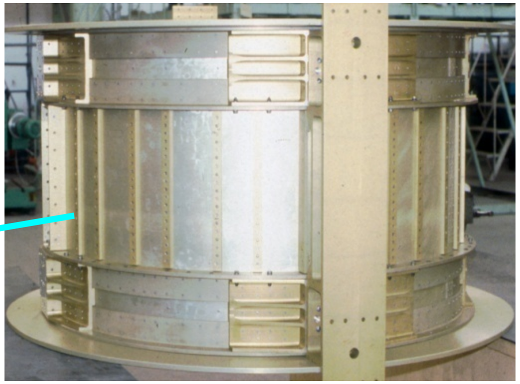
TOF
Z, E

Silicon Tracker
Z, P

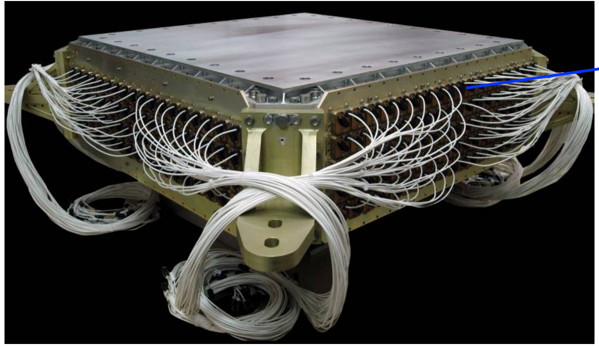




Magnet
±Z

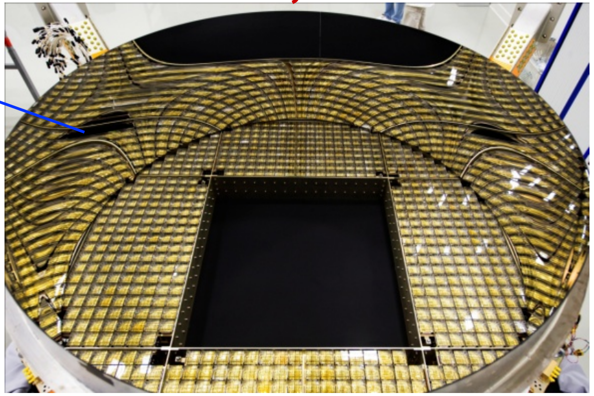


ECAL
E of e^+, e^-, γ



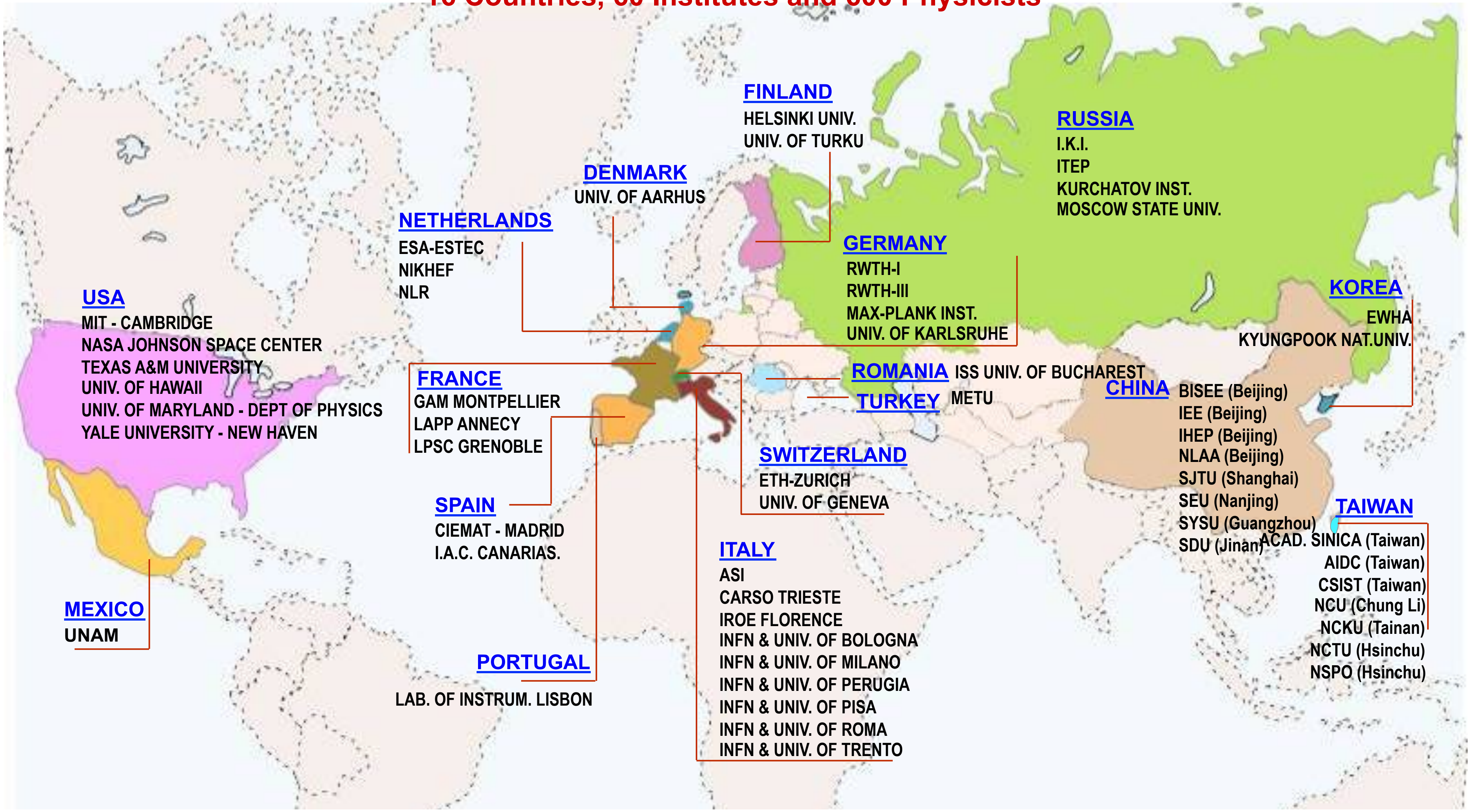
Z, P are measured independently by the Tracker, RICH, TOF and ECAL

RICH
Z, E



AMS International Collaboration

16 Countries, 60 Institutes and 600 Physicists



USA
MIT - CAMBRIDGE
NASA JOHNSON SPACE CENTER
TEXAS A&M UNIVERSITY
UNIV. OF HAWAII
UNIV. OF MARYLAND - DEPT OF PHYSICS
YALE UNIVERSITY - NEW HAVEN

MEXICO
UNAM

NETHERLANDS
ESA-ESTEC
NIKHEF
NLR

DENMARK
UNIV. OF AARHUS

FINLAND
HELSINKI UNIV.
UNIV. OF TURKU

RUSSIA
I.K.I.
ITEP
KURCHATOV INST.
MOSCOW STATE UNIV.

GERMANY
RWTH-I
RWTH-III
MAX-PLANK INST.
UNIV. OF KARLSRUHE

FRANCE
GAM MONTPELLIER
LAPP ANNECY
LPSC GRENOBLE

SPAIN
CIEMAT - MADRID
I.A.C. CANARIAS.

PORTUGAL
LAB. OF INSTRUM. LISBON

ROMANIA ISS UNIV. OF BUCHAREST

TURKEY METU

SWITZERLAND
ETH-ZURICH
UNIV. OF GENEVA

ITALY
ASI
CARSO TRIESTE
IROE FLORENCE
INFN & UNIV. OF BOLOGNA
INFN & UNIV. OF MILANO
INFN & UNIV. OF PERUGIA
INFN & UNIV. OF PISA
INFN & UNIV. OF ROMA
INFN & UNIV. OF TRENTO

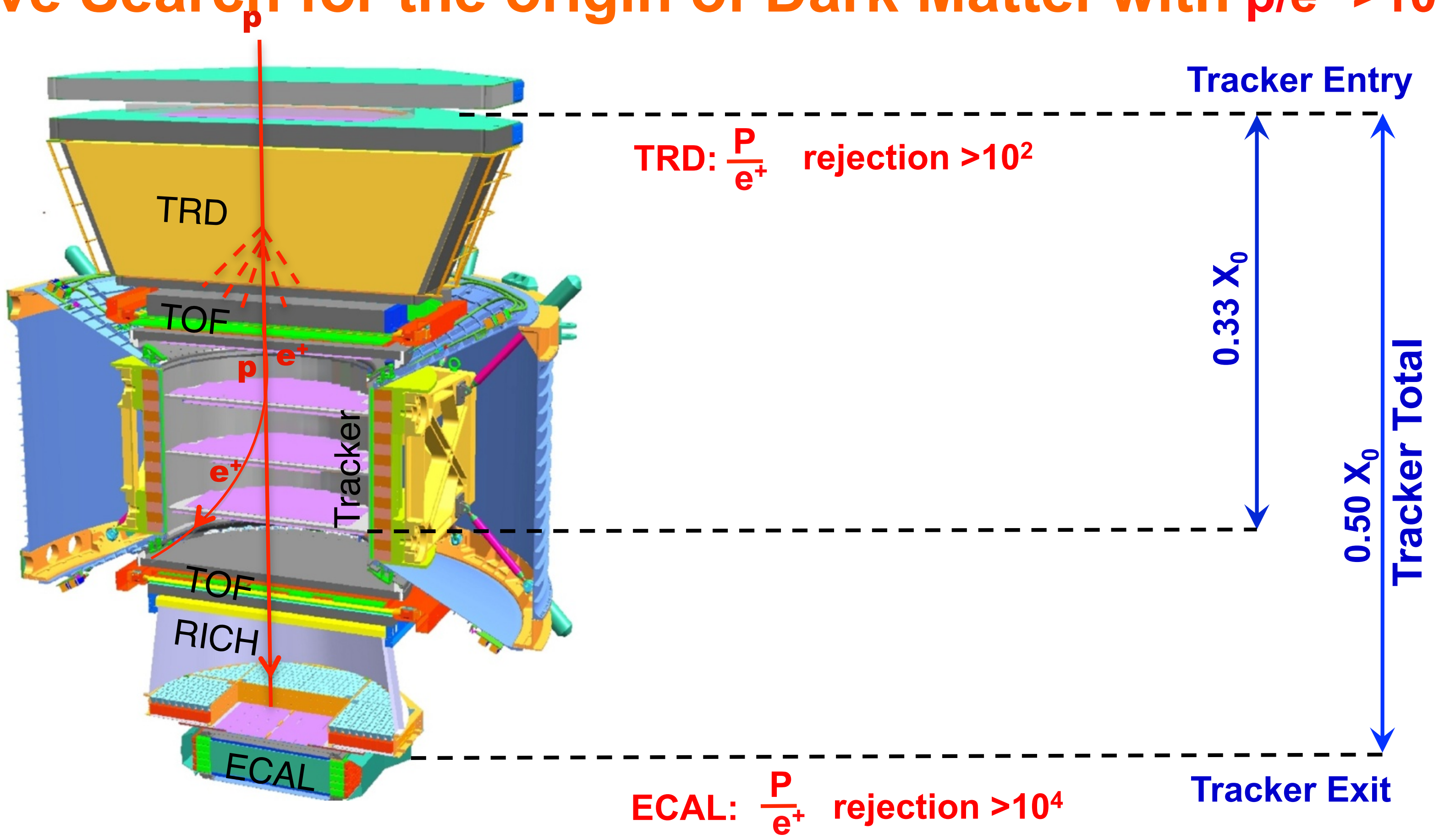
KOREA
EWHA
KYUNGPOOK NAT.UNIV.

CHINA
BISEE (Beijing)
IEE (Beijing)
IHEP (Beijing)
NLAA (Beijing)
SJTU (Shanghai)
SEU (Nanjing)
SYSU (Guangzhou)
SDU (Jinan)

TAIWAN
ACAD. SINICA (Taiwan)
AIDC (Taiwan)
CSIST (Taiwan)
NCU (Chung Li)
NCKU (Tainan)
NCTU (Hsinchu)
NSPO (Hsinchu)

95% construction from Europe and Asia
DOE sponsored experiment, NASA space operation

Sensitive Search for the origin of Dark Matter with $p/e^+ > 10^6$



TRD: $\frac{P}{e^+}$ rejection $>10^2$

ECAL: $\frac{P}{e^+}$ rejection $>10^4$

a) Minimal material in the TRD and TOF
So that the detector does not become a source of e^+.

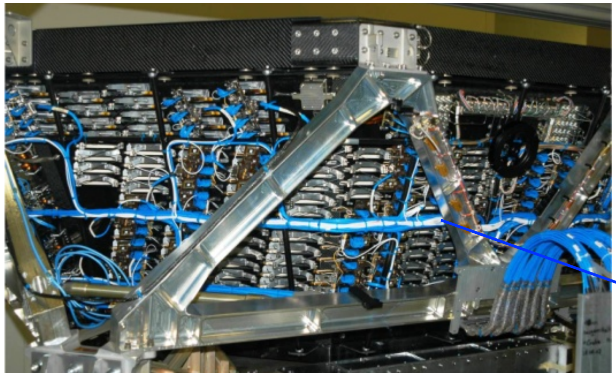
b) A magnet separates TRD and ECAL so that e^+ produced in TRD will be swept away and not enter ECAL
In this way the rejection power of TRD and ECAL are independent

c) Matching momentum of 9 tracker planes with ECAL energy measurements

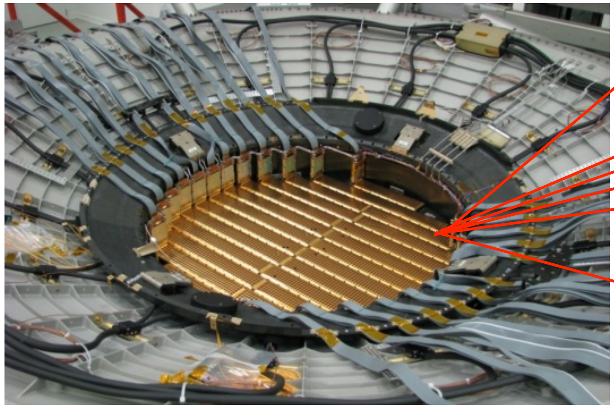
AMS Flight Electronics for Data Acquisition (DAQ)

300,000 channels at 2 KHz,
650 computers
designed and built by AMS

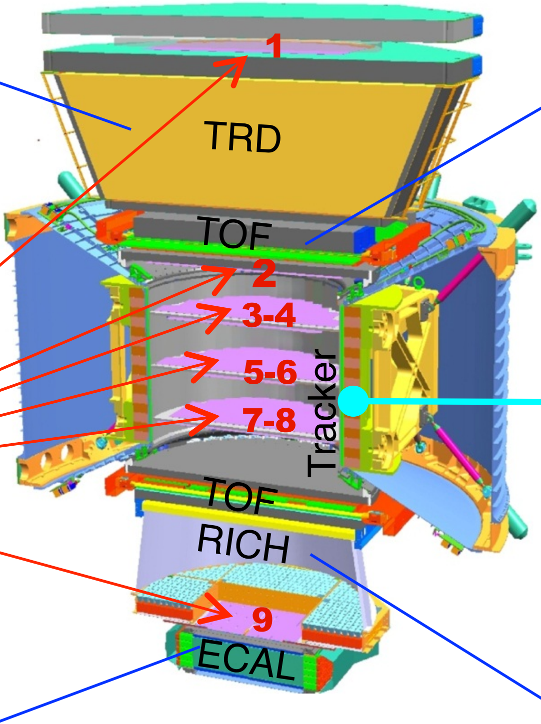
TRD: 5248 Signals



Silicon Tracker:
196,608 Signals

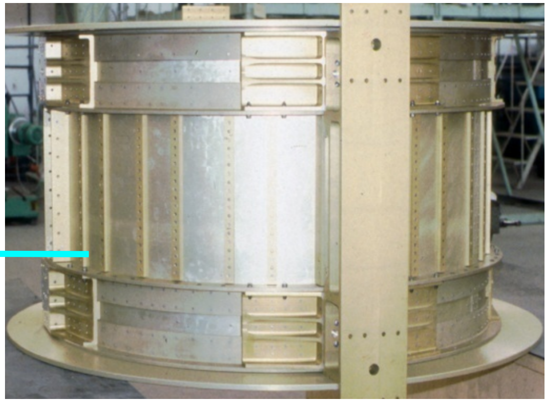


ECAL: 2,916 Signals

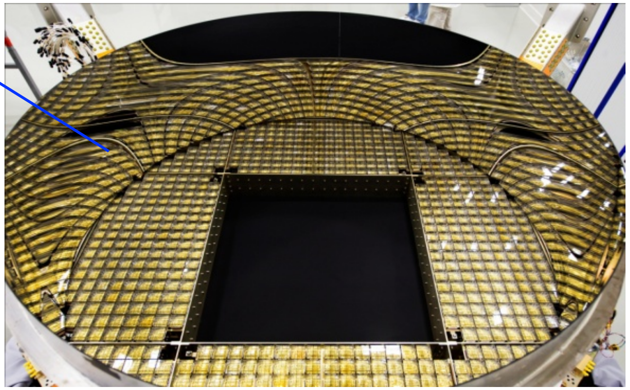


TOF & ACC: 88 Signals

Magnet

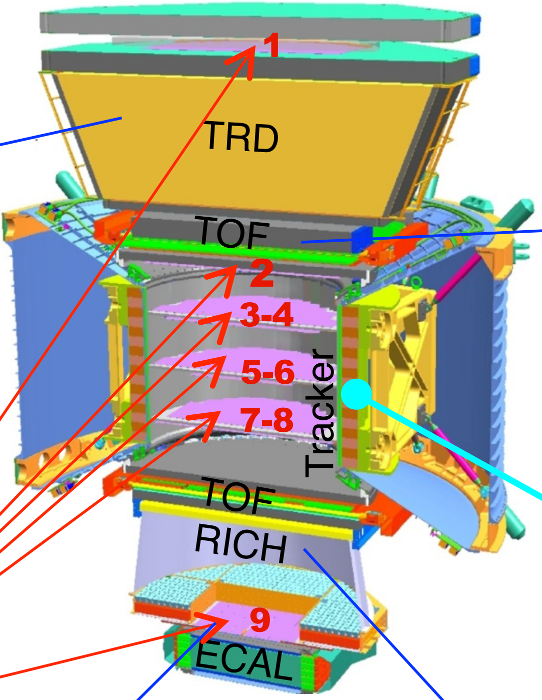


RICH: 10,800 * 2 Signals

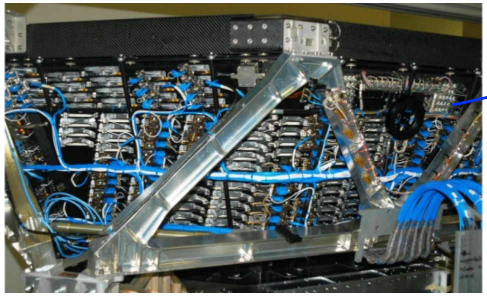


AMS Flight Electronics for Thermal Control

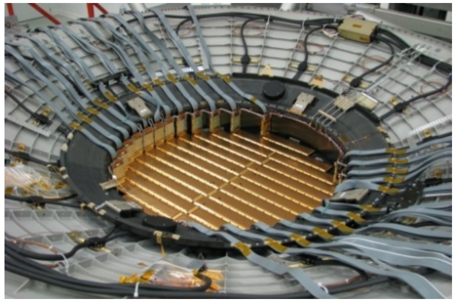
1118 temperature sensors, 298 heaters



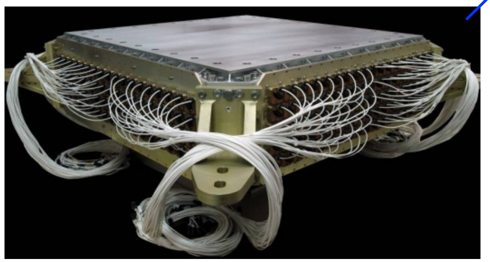
TRD
24 Heaters
8 Pressure Sensors
482 Temperature Sensors



Silicon Tracker
4 -Pressure Sensors
32 Heaters
142 Temperature Sensors

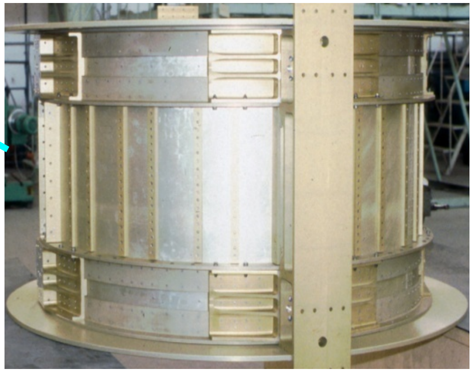


ECAL
80 Temperature Sensors

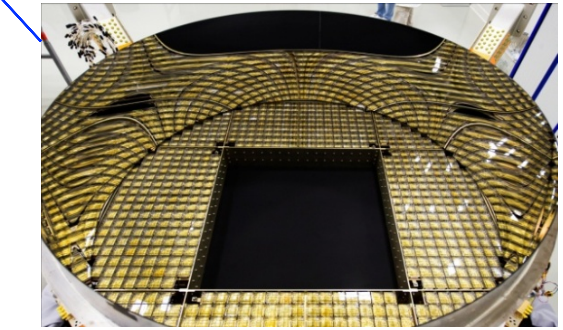


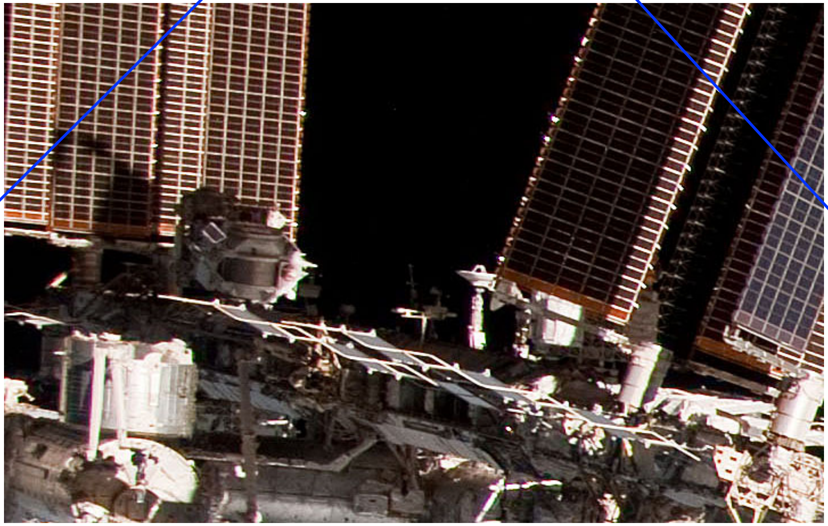
TOF & ACC
64 Temperature Sensors

Magnet
68 Temperature Sensors

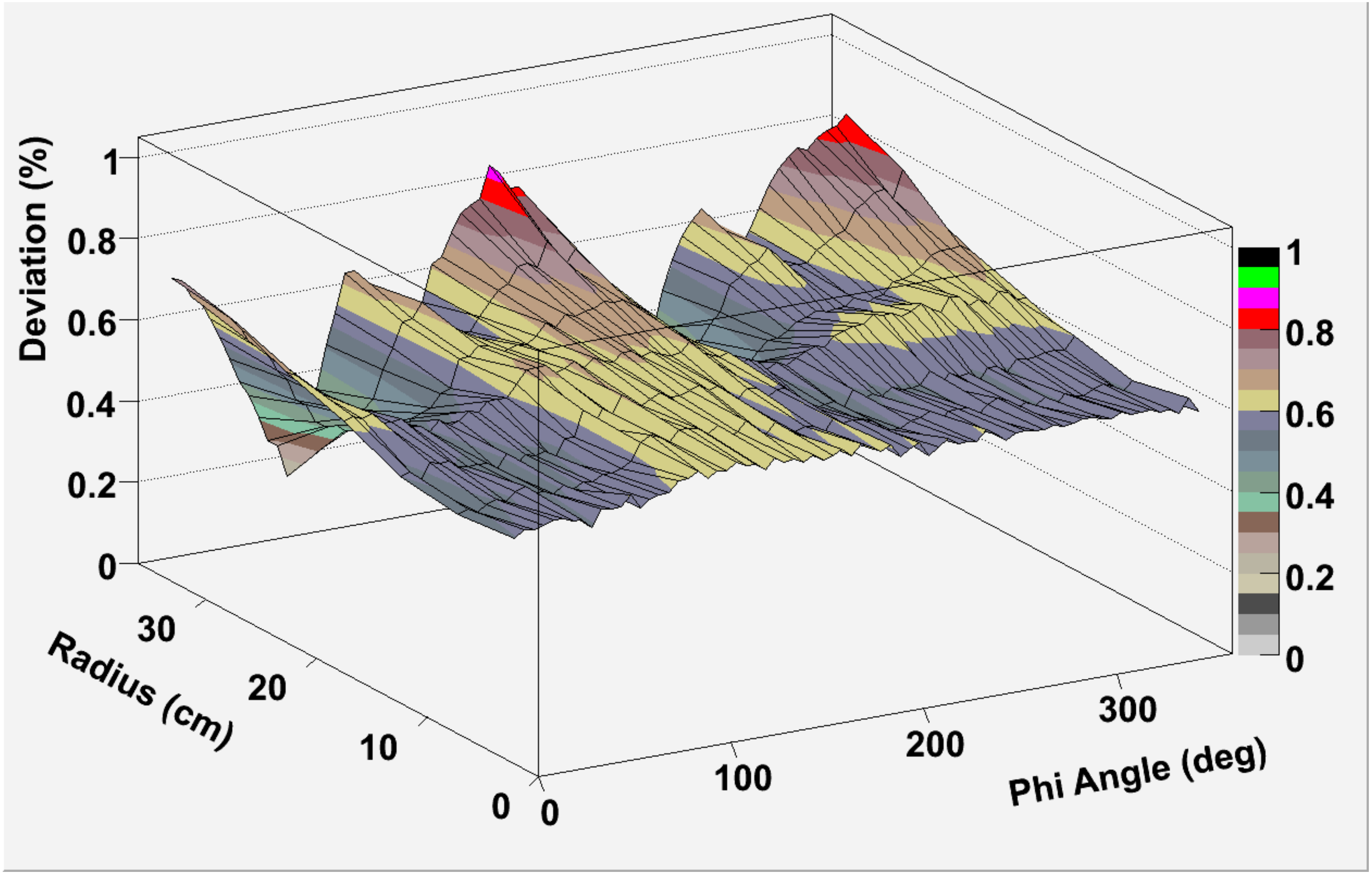


RICH
96 Temperature Sensors

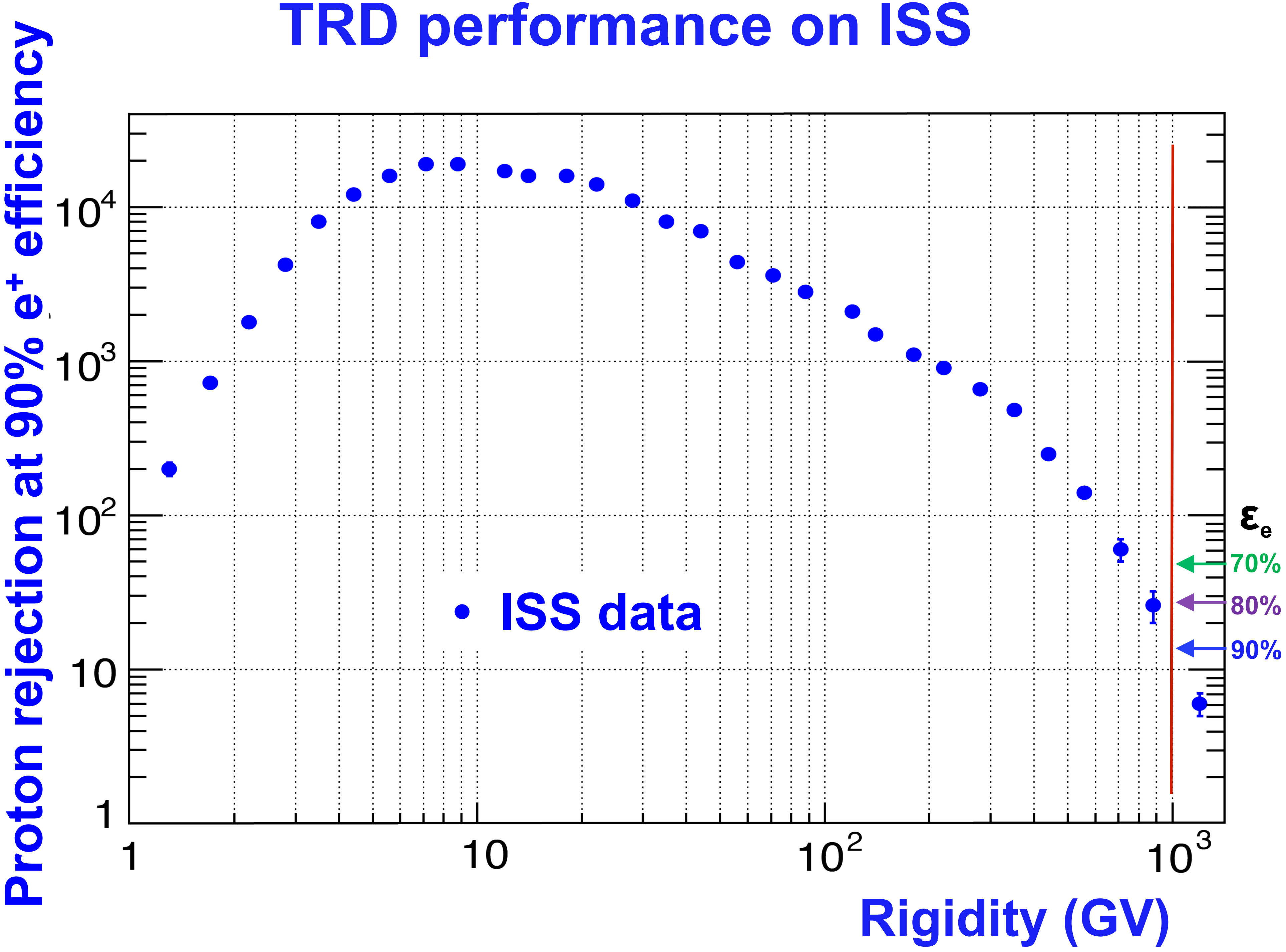




Deviation from 1997 measurements in R-Phi coordinates, Z=0

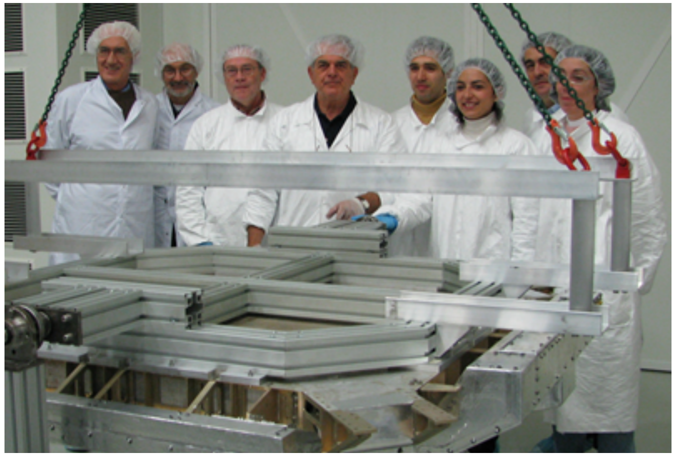


TRD performance on ISS



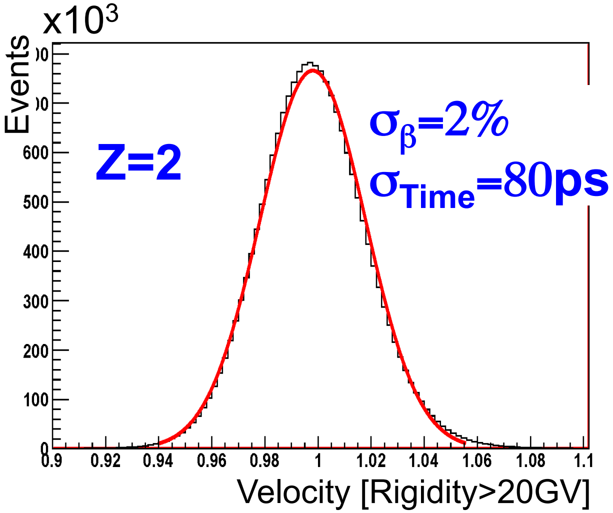
Data from ISS Time of Flight System

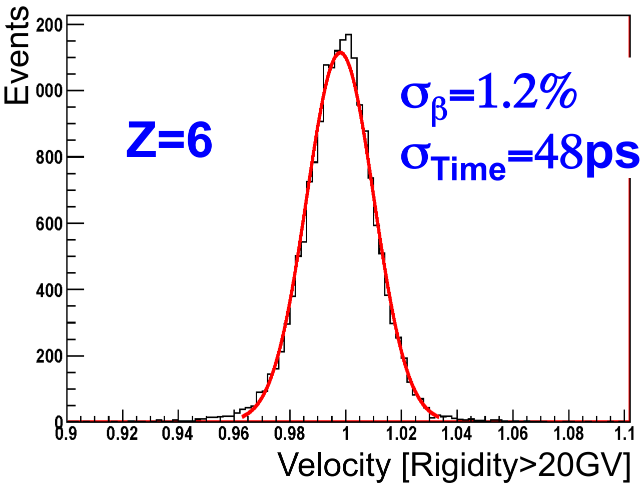
Measures Velocity and Charge of particles

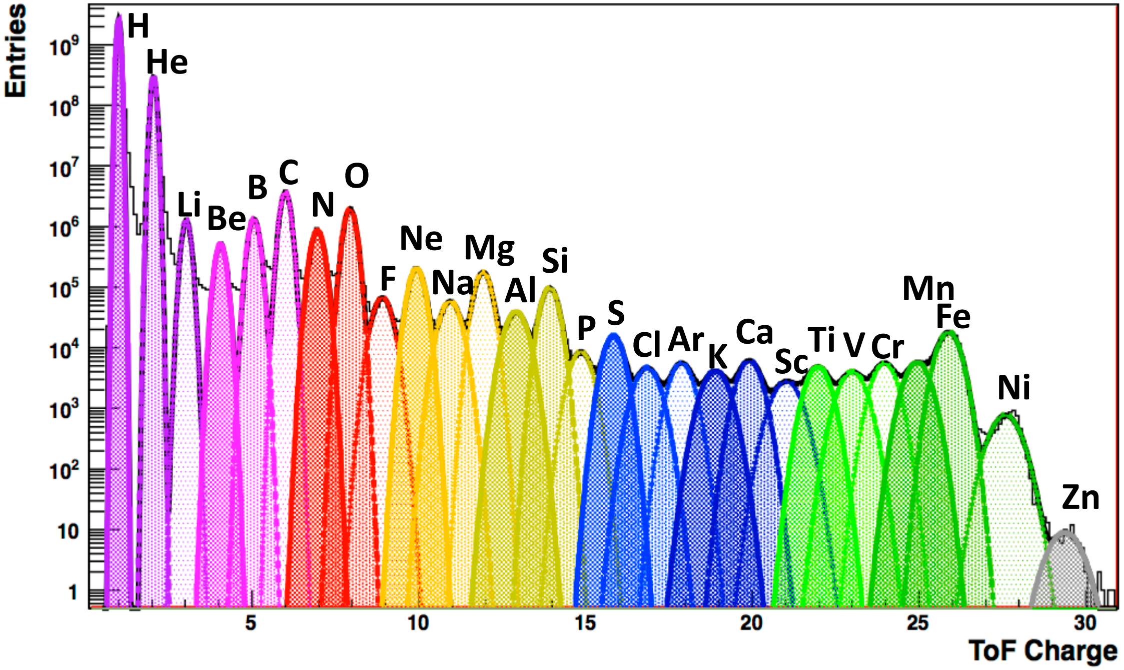


Bologna

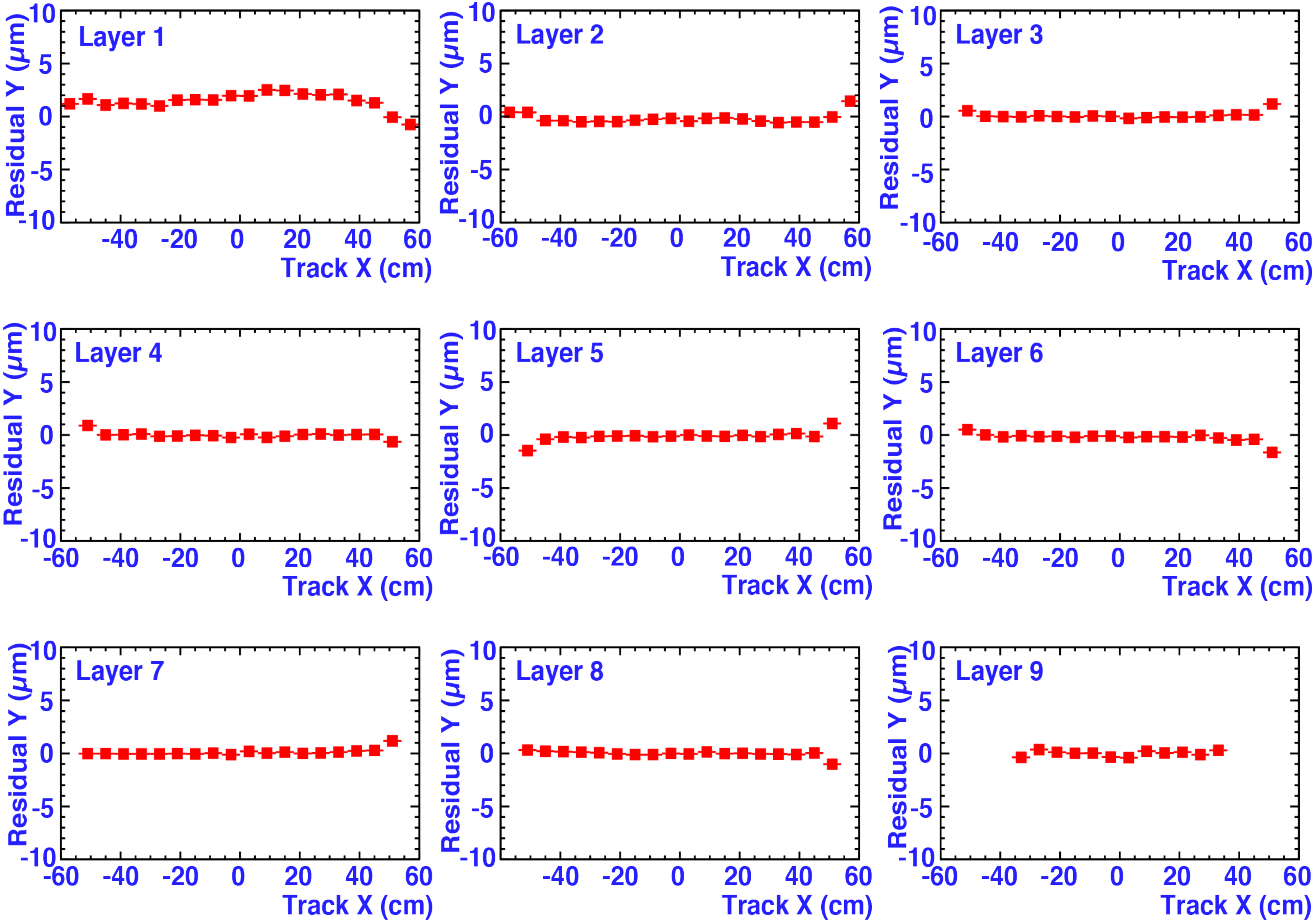
Professors A. Contin, G. Laurenti, F. Palmonari



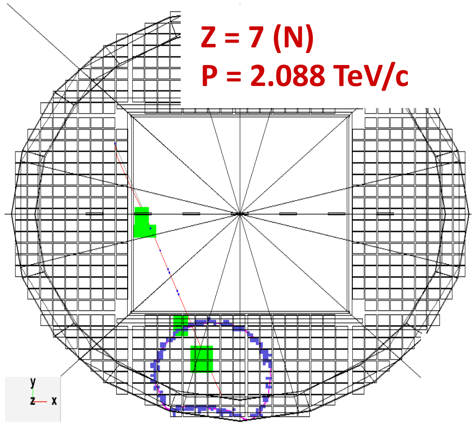


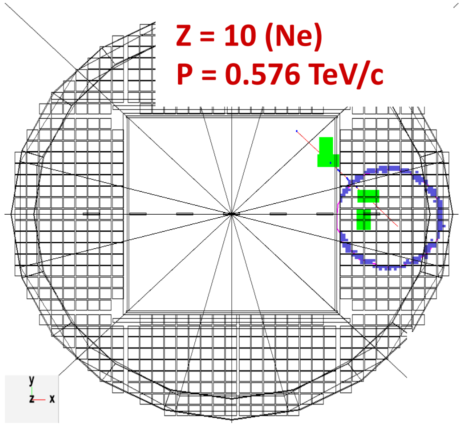


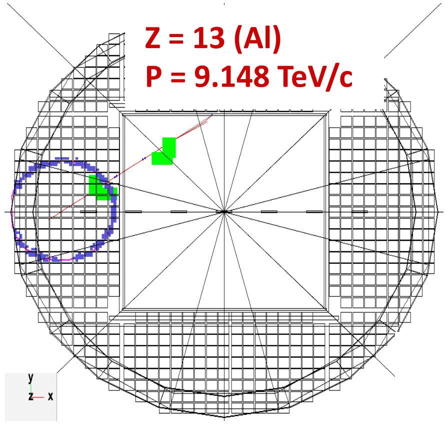
Alignment accuracy of the 9 Tracker layers over 18 months

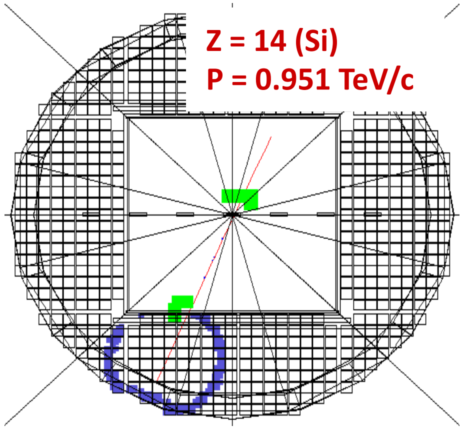


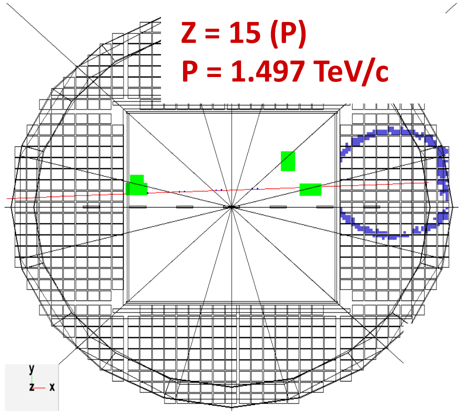
Detector performance on ISS RICH

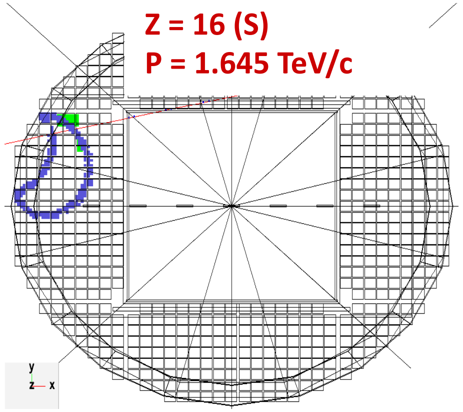

Z = 7 (N)
P = 2.088 TeV/c

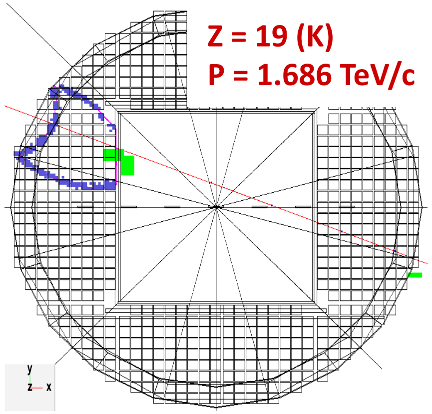

Z = 10 (Ne)
P = 0.576 TeV/c

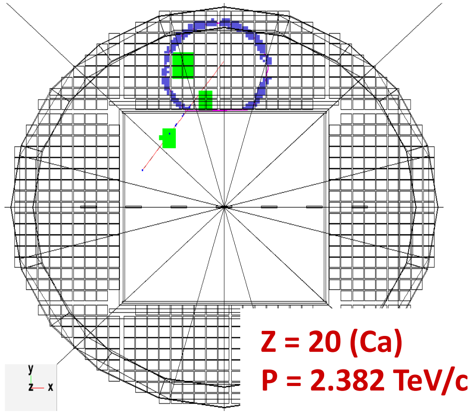

Z = 13 (Al)
P = 9.148 TeV/c

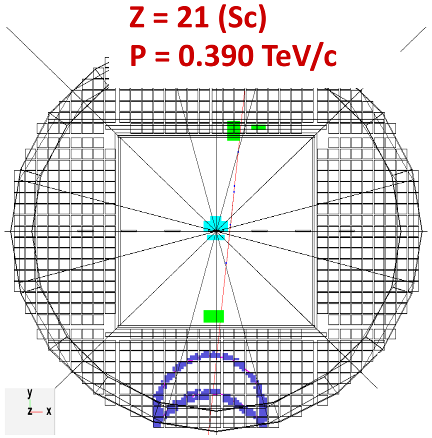

Z = 14 (Si)
P = 0.951 TeV/c

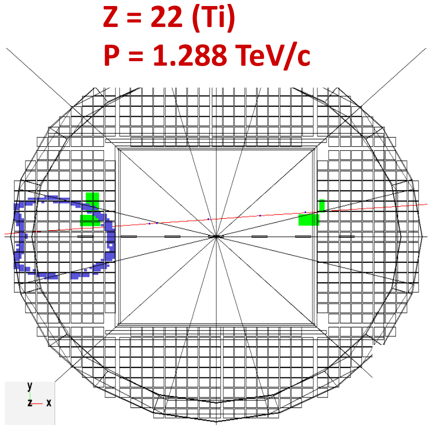

Z = 15 (P)
P = 1.497 TeV/c

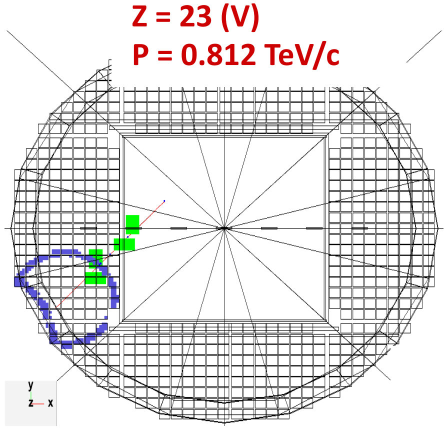

Z = 16 (S)
P = 1.645 TeV/c

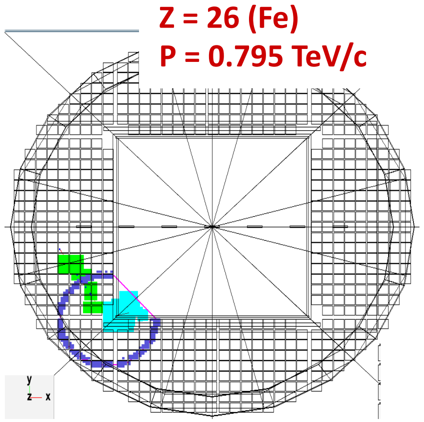

Z = 19 (K)
P = 1.686 TeV/c


Z = 20 (Ca)
P = 2.382 TeV/c

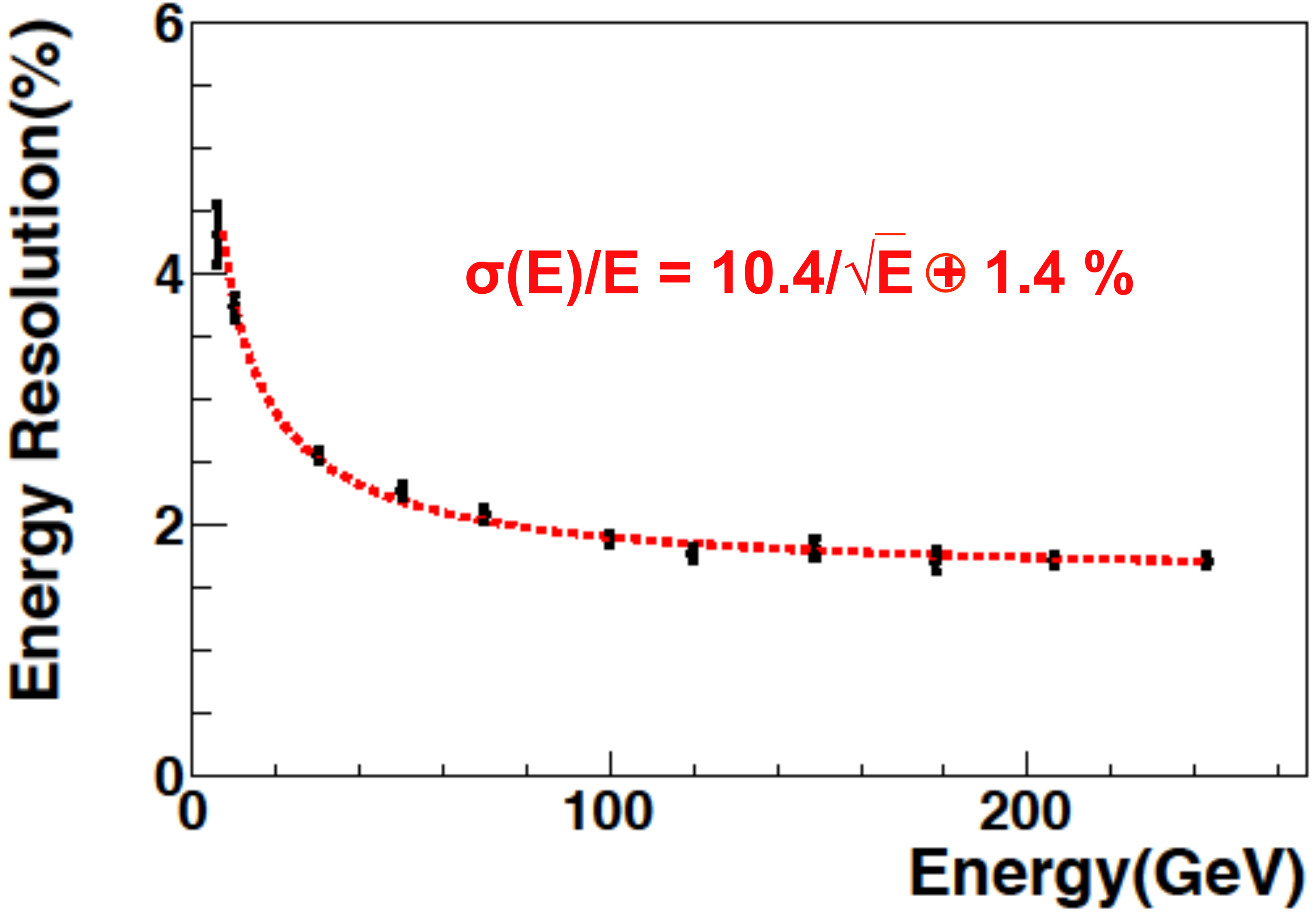

Z = 21 (Sc)
P = 0.390 TeV/c


Z = 22 (Ti)
P = 1.288 TeV/c


Z = 23 (V)
P = 0.812 TeV/c

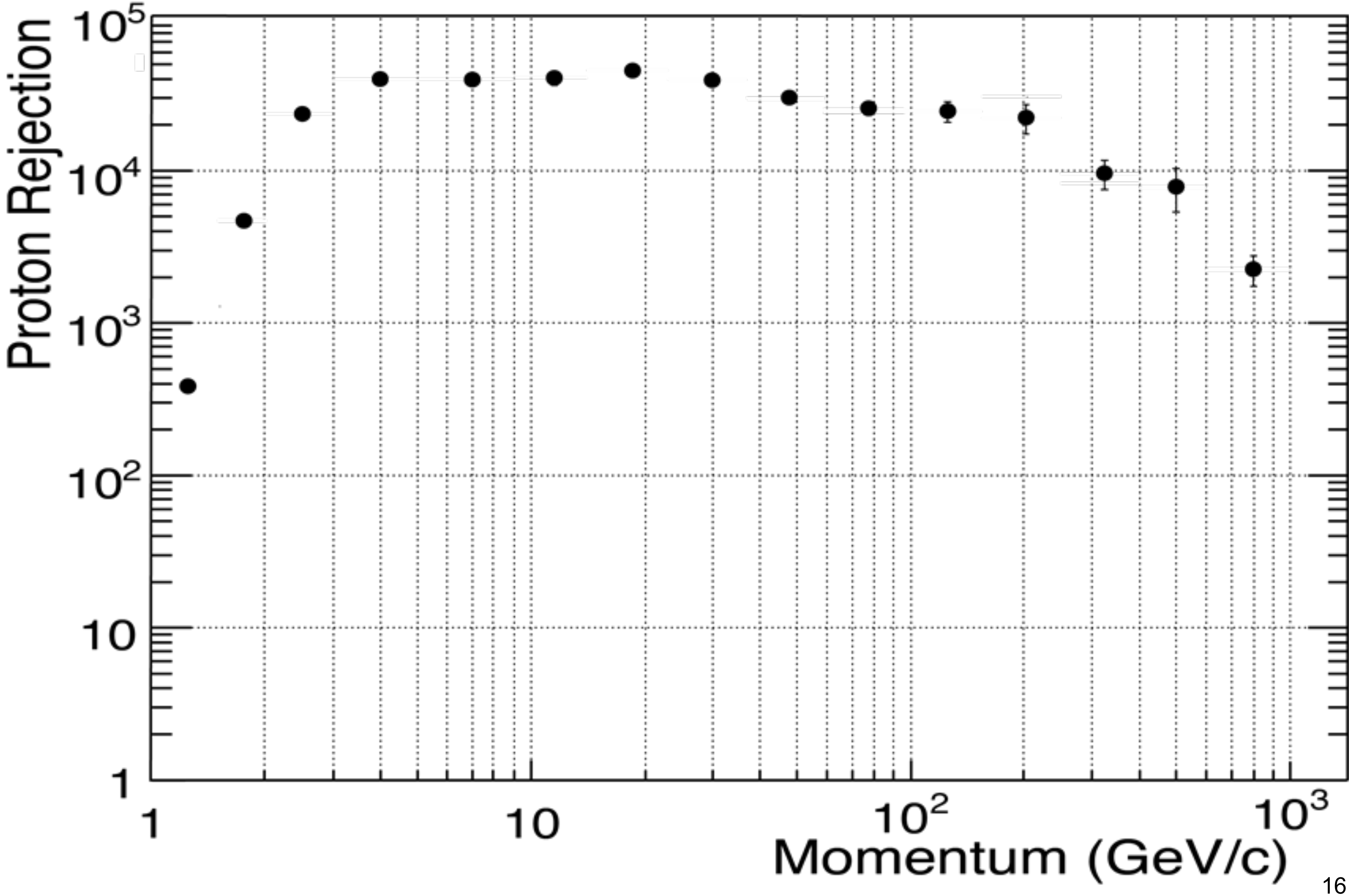

Z = 26 (Fe)
P = 0.795 TeV/c

ECAL Performance

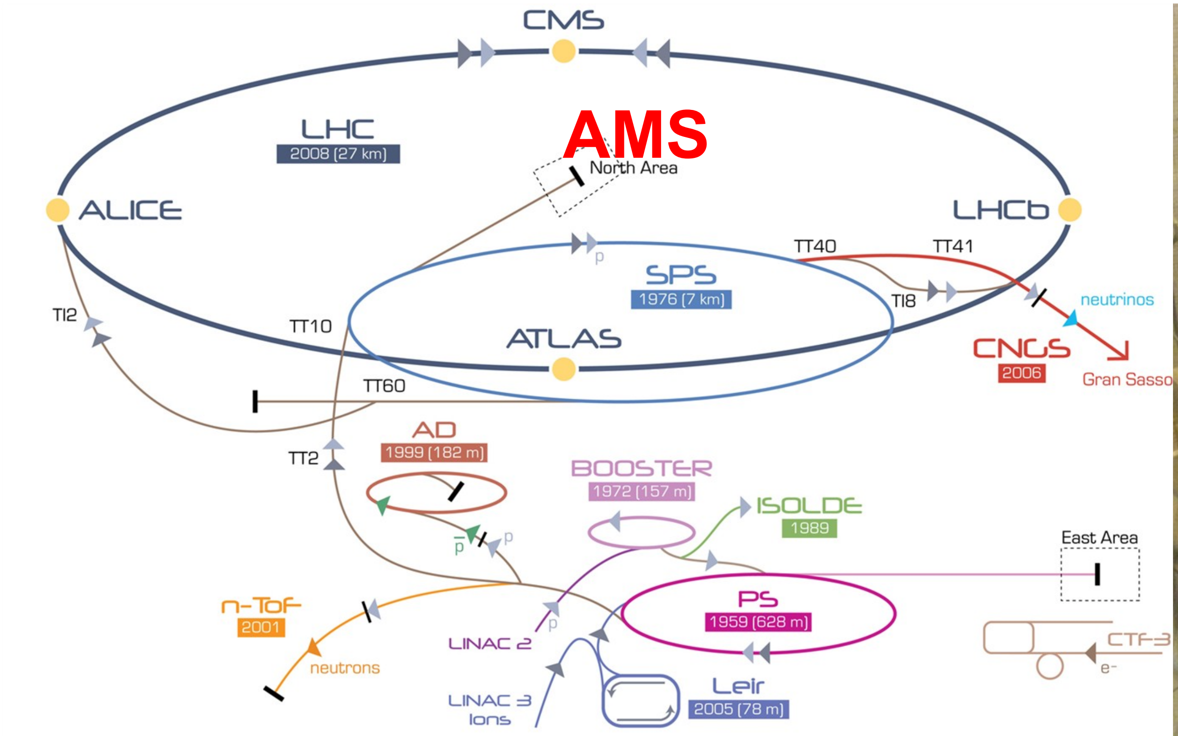


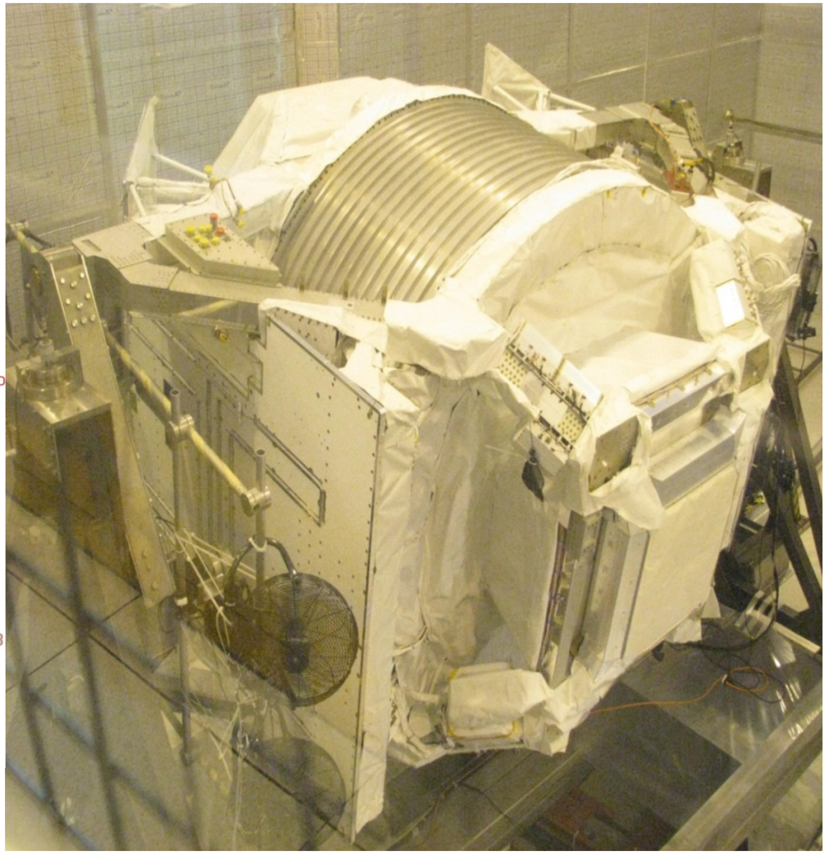
$\sigma(E)/E = 10.4/\sqrt{E} \oplus 1.4\ \%$

Data from ISS: Proton rejection using the ECAL



Intensive Beam Tests at CERN





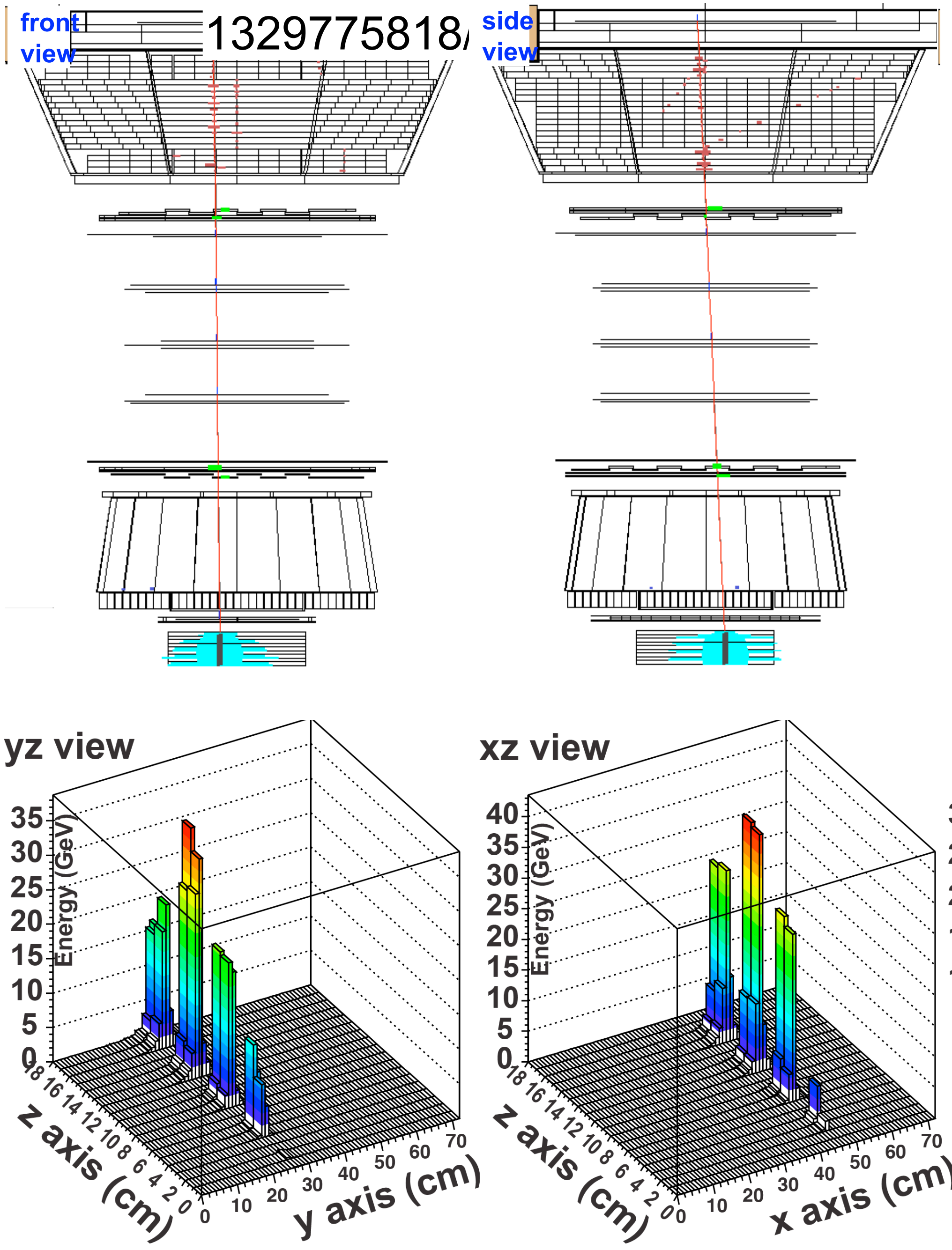
AMS in SPS Test Beam, 2010

Particle	Momentum (GeV/c)	Positions	Purpose
Protons	400 + 180	1,650	Full Tracker alignment, TOF calibration, ECAL uniformity
Electrons	100, 120, 180, 290	7 each	TRD, ECAL performance study
Positrons	10, 20, 60, 80, 120, 180	7 each	TRD, ECAL performance study
Pions	20, 60, 80, 100, 120, 180	7 each	TRD performance to 1.2 TeV

Electron E=982 GeV

Run/Event

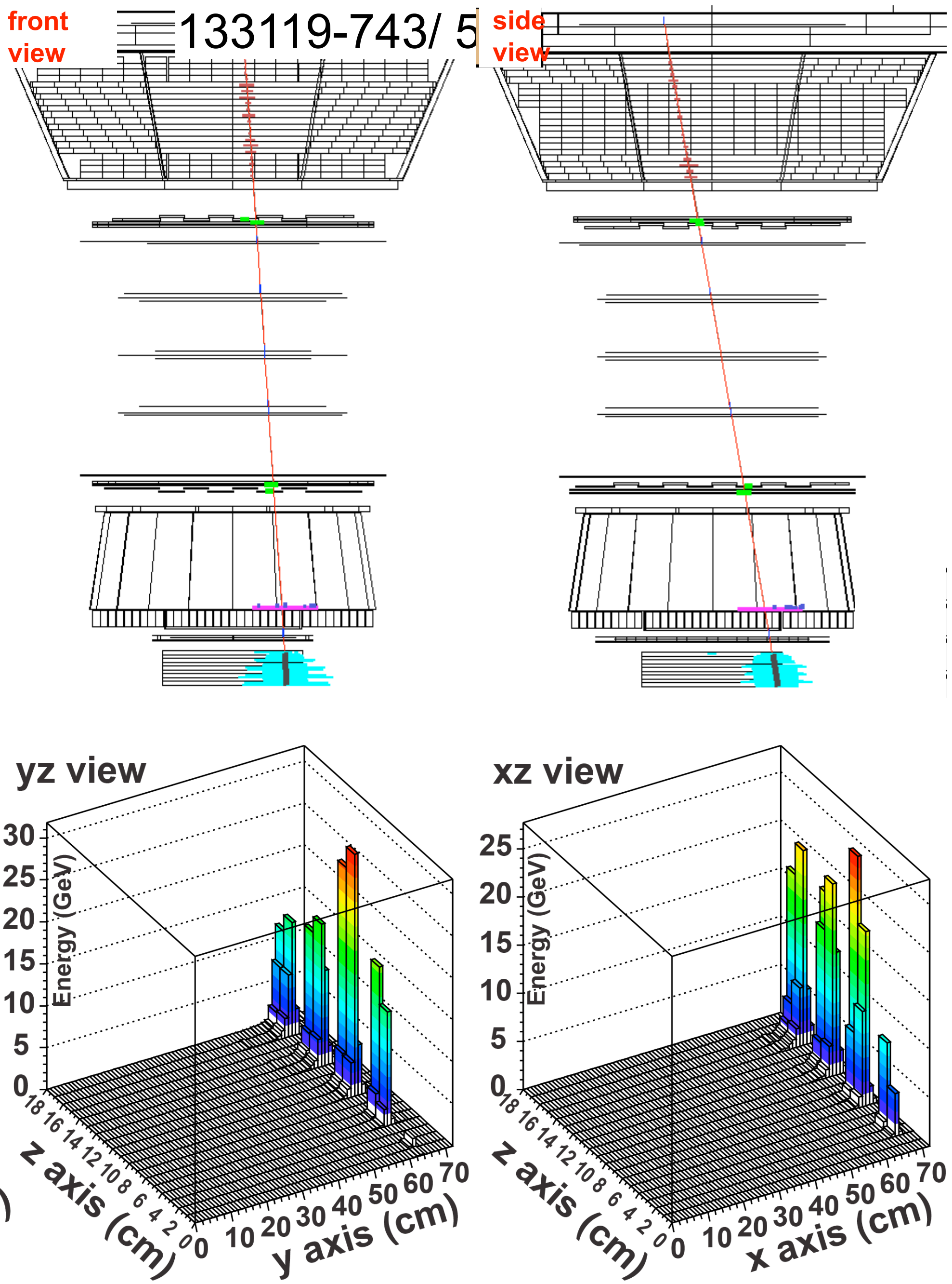
1329775818/



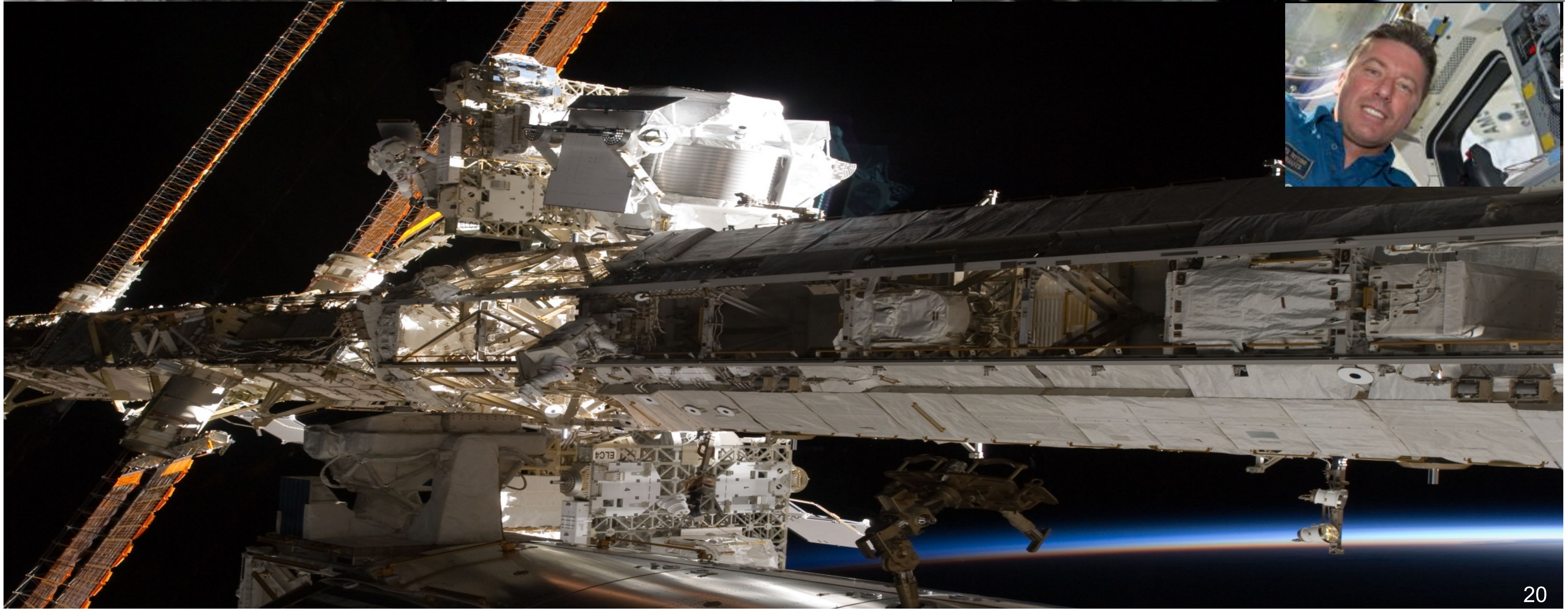
Positron E=636 GeV

Run/Event

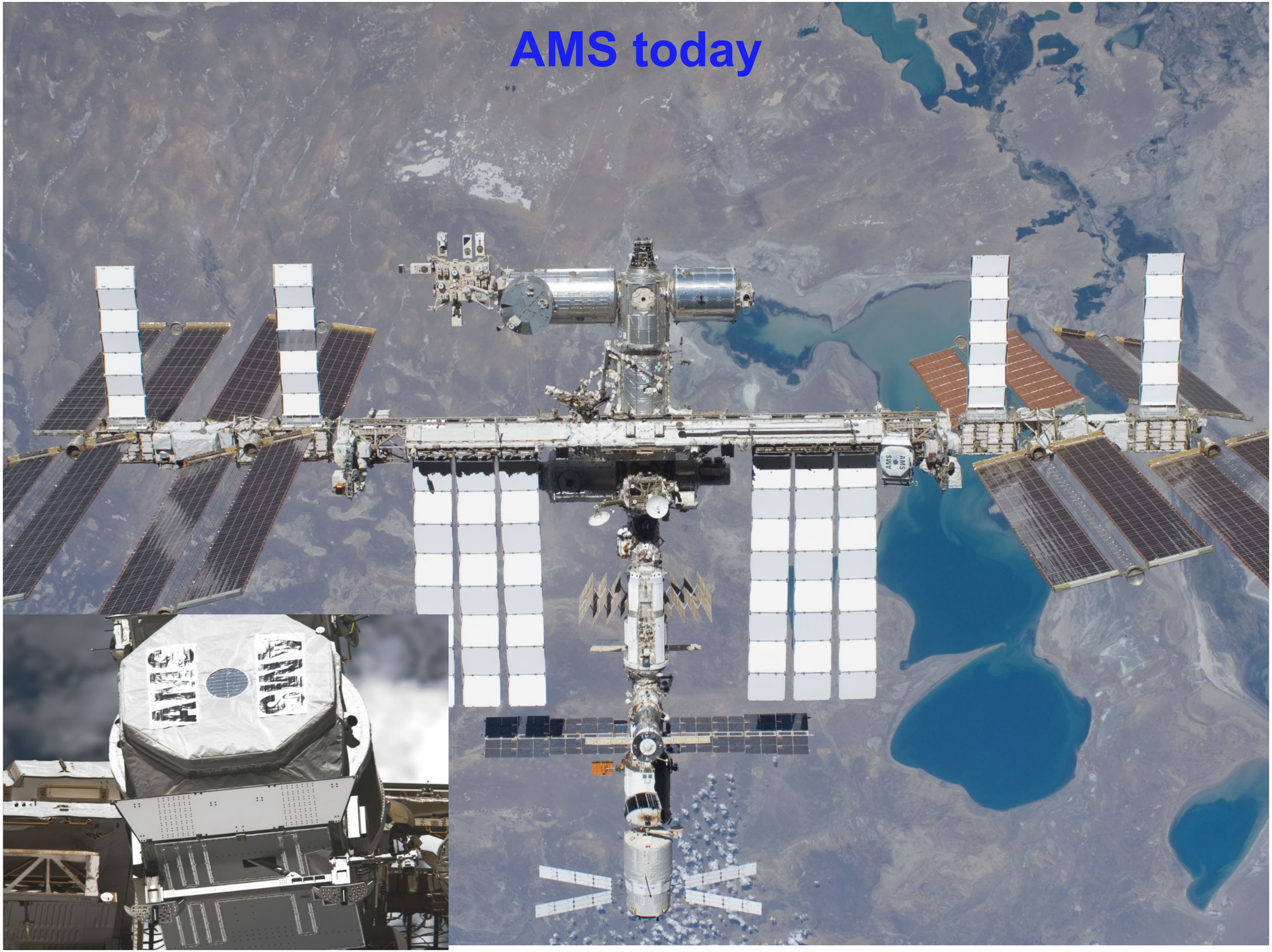
133119-743/ 5



May 16th, 2011



AMS today



AMS Operations

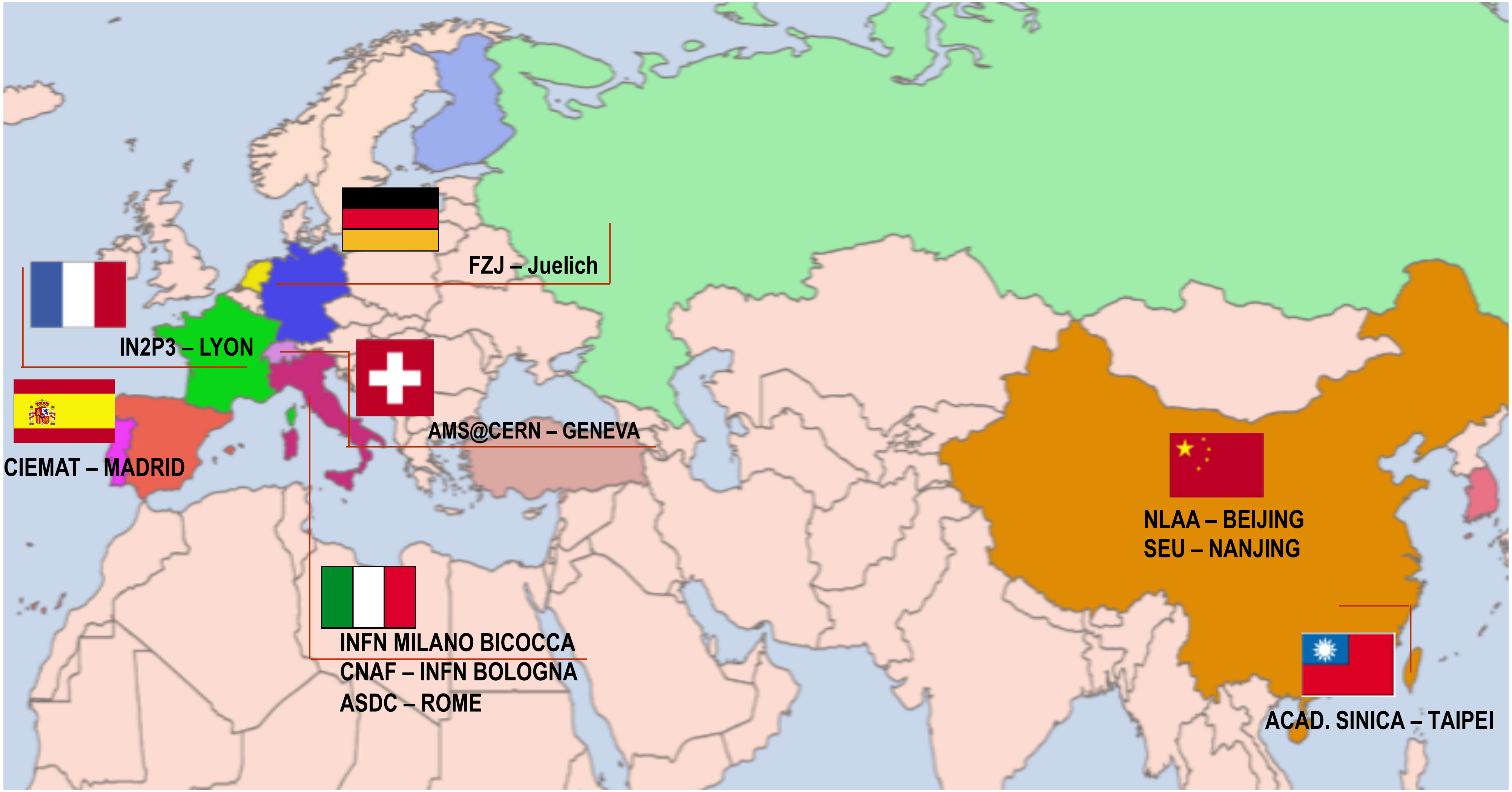
24 hours
x 365 days
x 10-20 years

White Sands, NM

Payload Operations Control
Center at CERN

AMS Data Analysis

Conducted at the Science Operations Center at CERN and in the regional centers around the world.



In the past hundred years, measurements of charged cosmic rays by balloons and satellites have typically contained ~30% uncertainty.

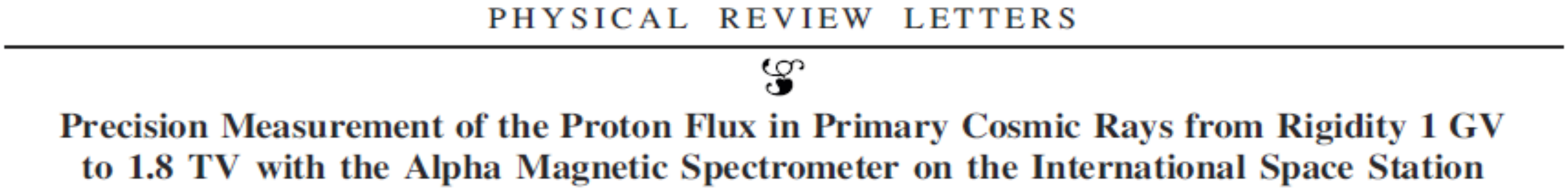
AMS is providing cosmic ray information with ~1% uncertainty.

The improvement in accuracy will provide new insights.

The Space Station has become a unique platform for precision physics research.

AMS recent results

Protons


PHYSICAL REVIEW LETTERS

Precision Measurement of the Proton Flux in Primary Cosmic Rays from Rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station

The isotropic proton flux Φ_i for the i th rigidity bin (R_i , $R_i + \Delta R_i$) is

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

N_i is the number of events, 300 million proton events have been selected;
A_i is the effective acceptance;
ε_i is the trigger efficiency;
T_i is the collection time (which depends on the geomagnetic cutoff).

To match the statistics, extensive systematic errors study has been made.

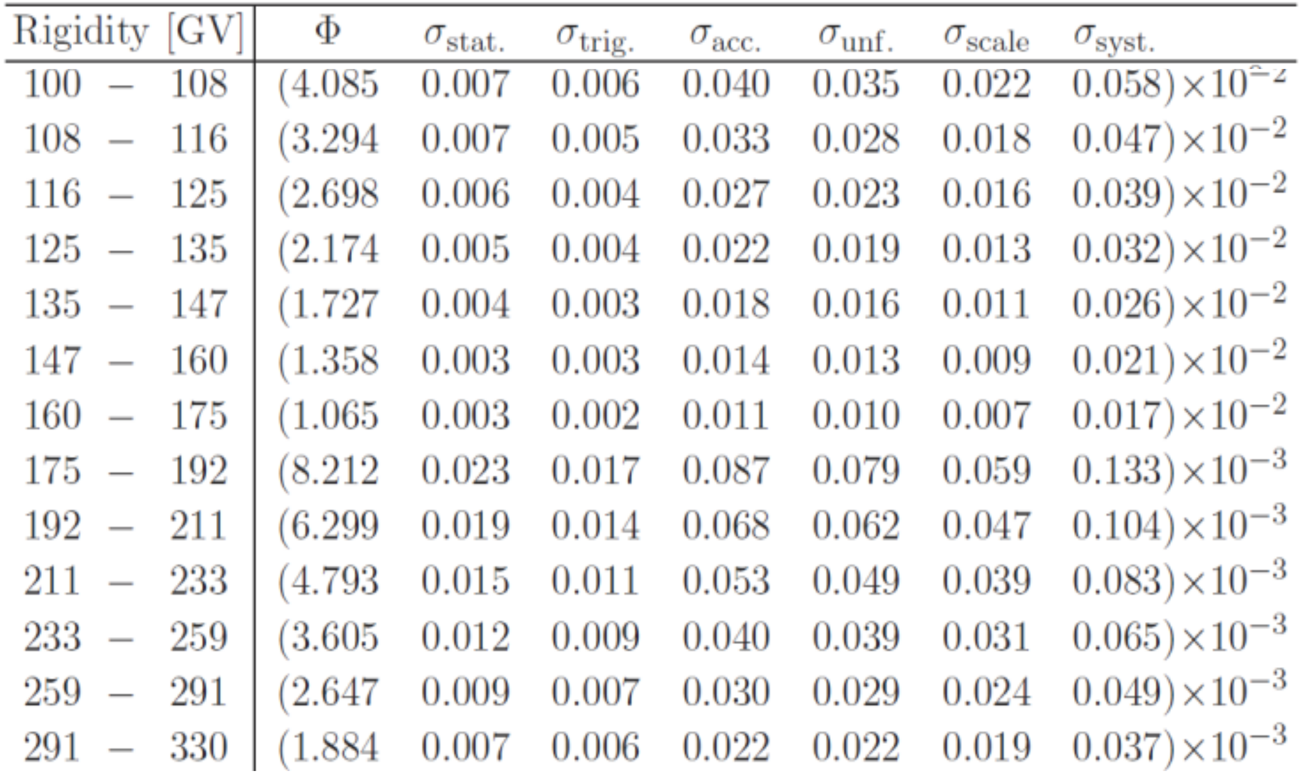
Systematic errors on the Proton Flux:

1) $\sigma_{trig.}$:trigger efficiency

2) $\sigma_{acc.}$:
   - a. the acceptance and event selection
   - b. background contamination
   - c. geomagnetic cutoff

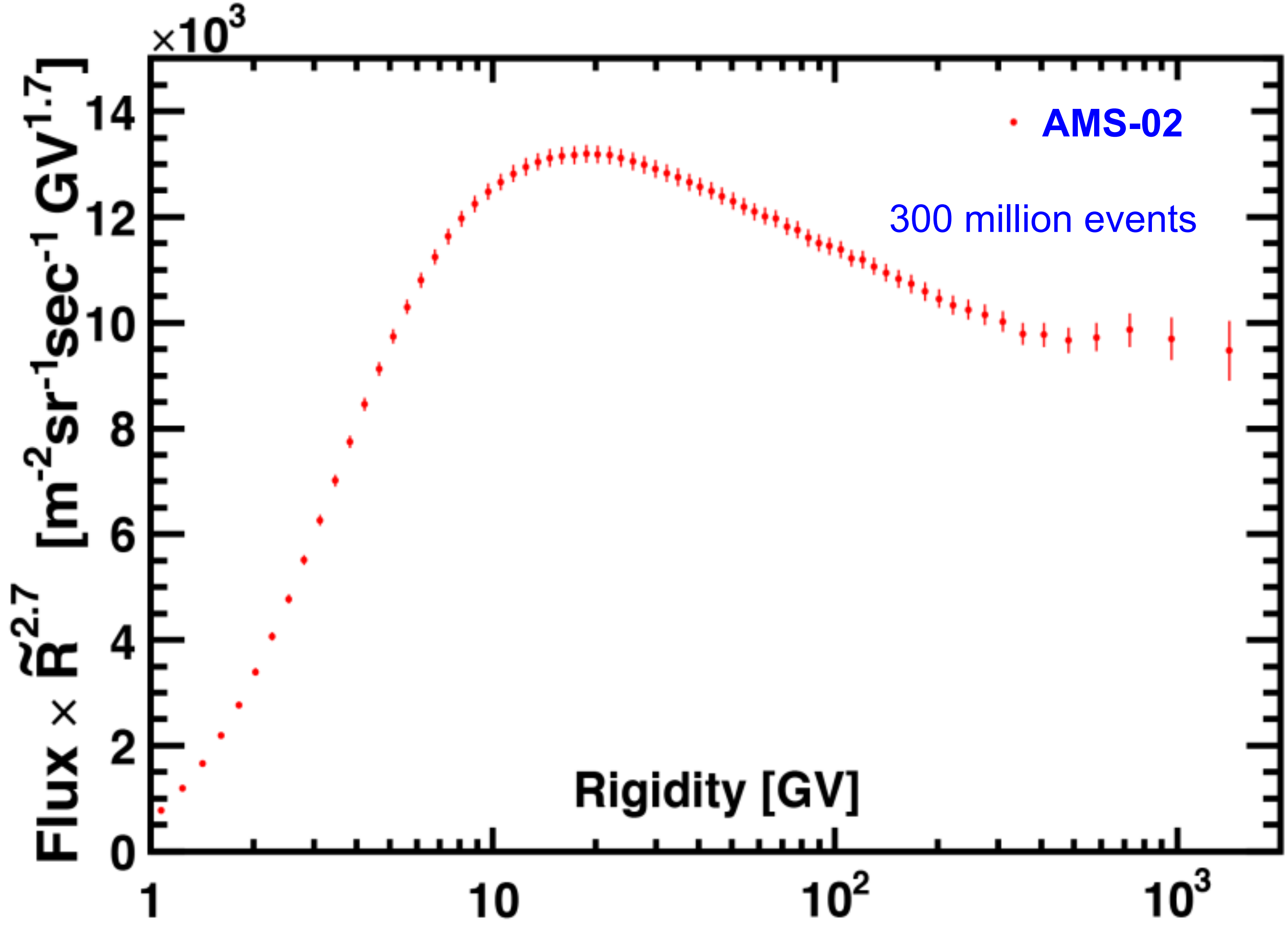
3) $\sigma_{unf.}$
   - a. unfolding
   - b. the rigidity resolution function

4) $\sigma_{scale.}$: the absolute rigidity scale

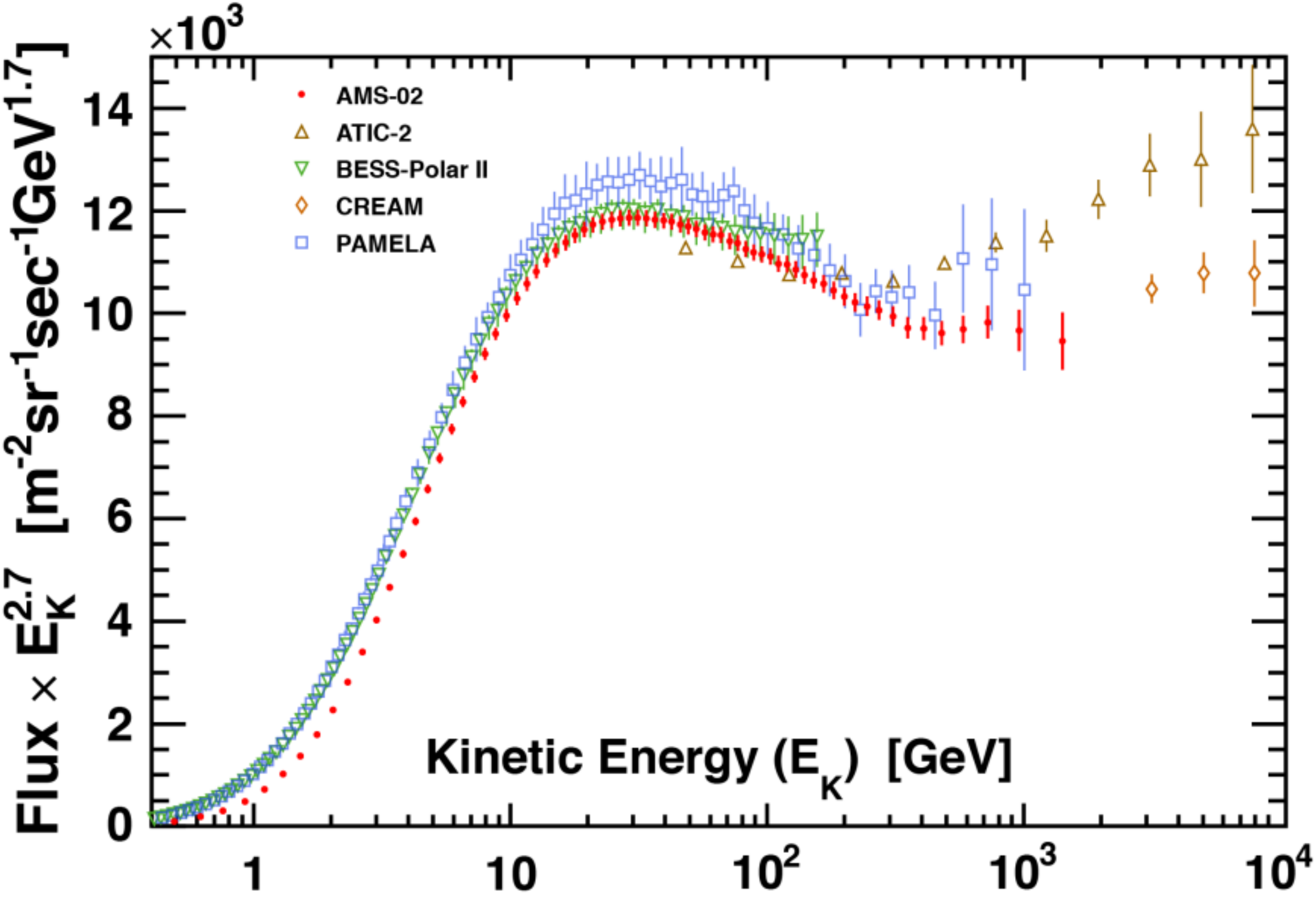


Rigidity [GV]	Φ	$\sigma_{\text{stat.}}$	$\sigma_{\text{trig.}}$	$\sigma_{\text{acc.}}$	$\sigma_{\text{unf.}}$	σ_{scale}	$\sigma_{\text{syst.}}$
100 – 108	(4.085	0.007	0.006	0.040	0.035	0.022	0.058) $\times 10^{-2}$
108 – 116	(3.294	0.007	0.005	0.033	0.028	0.018	0.047) $\times 10^{-2}$
116 – 125	(2.698	0.006	0.004	0.027	0.023	0.016	0.039) $\times 10^{-2}$
125 – 135	(2.174	0.005	0.004	0.022	0.019	0.013	0.032) $\times 10^{-2}$
135 – 147	(1.727	0.004	0.003	0.018	0.016	0.011	0.026) $\times 10^{-2}$
147 – 160	(1.358	0.003	0.003	0.014	0.013	0.009	0.021) $\times 10^{-2}$
160 – 175	(1.065	0.003	0.002	0.011	0.010	0.007	0.017) $\times 10^{-2}$
175 – 192	(8.212	0.023	0.017	0.087	0.079	0.059	0.133) $\times 10^{-3}$
192 – 211	(6.299	0.019	0.014	0.068	0.062	0.047	0.104) $\times 10^{-3}$
211 – 233	(4.793	0.015	0.011	0.053	0.049	0.039	0.083) $\times 10^{-3}$
233 – 259	(3.605	0.012	0.009	0.040	0.039	0.031	0.065) $\times 10^{-3}$
259 – 291	(2.647	0.009	0.007	0.030	0.029	0.024	0.049) $\times 10^{-3}$
291 – 330	(1.884	0.007	0.006	0.022	0.022	0.019	0.037) $\times 10^{-3}$

AMS proton flux

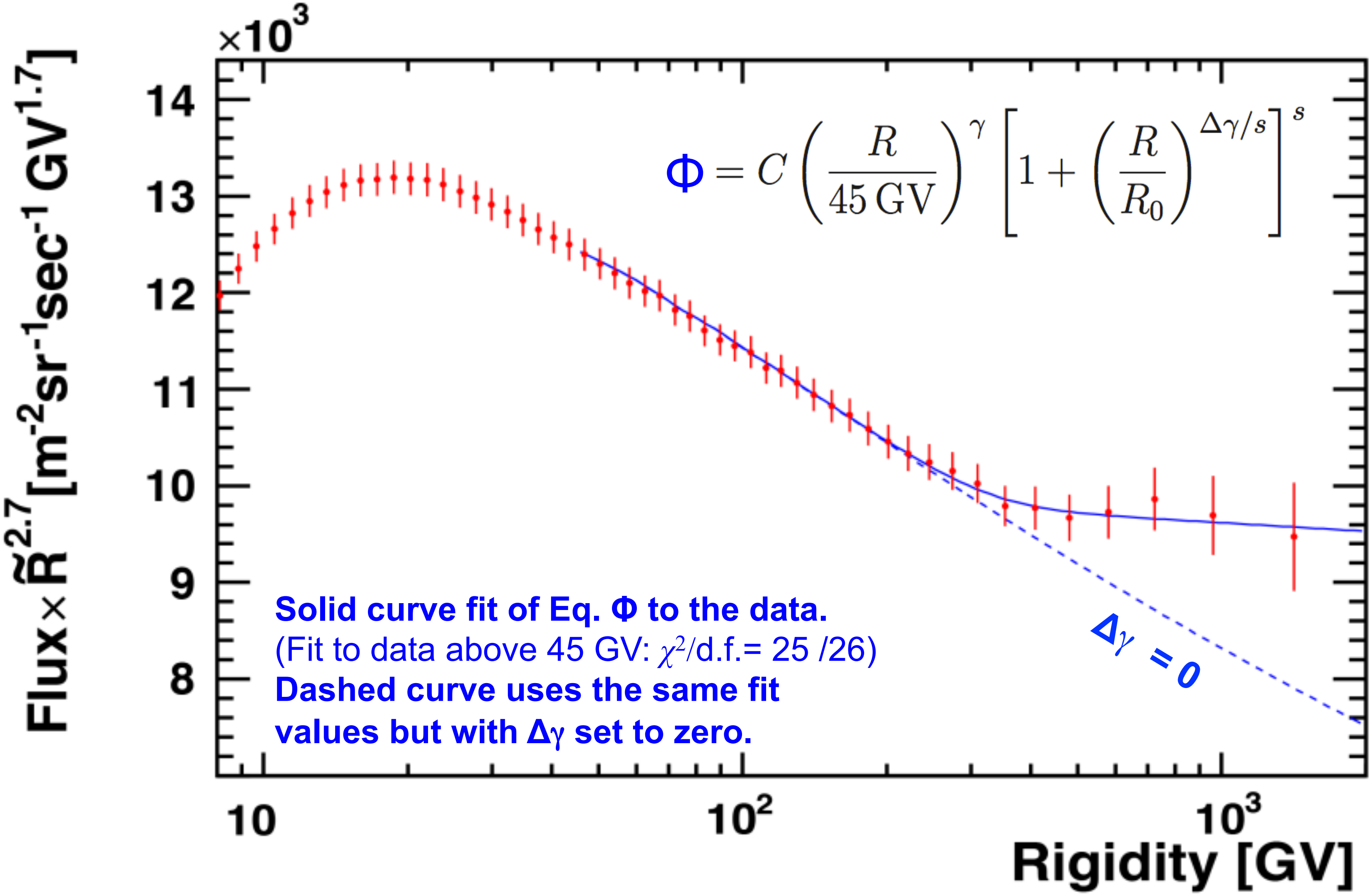


AMS proton flux



AMS proton flux fit with two power laws:

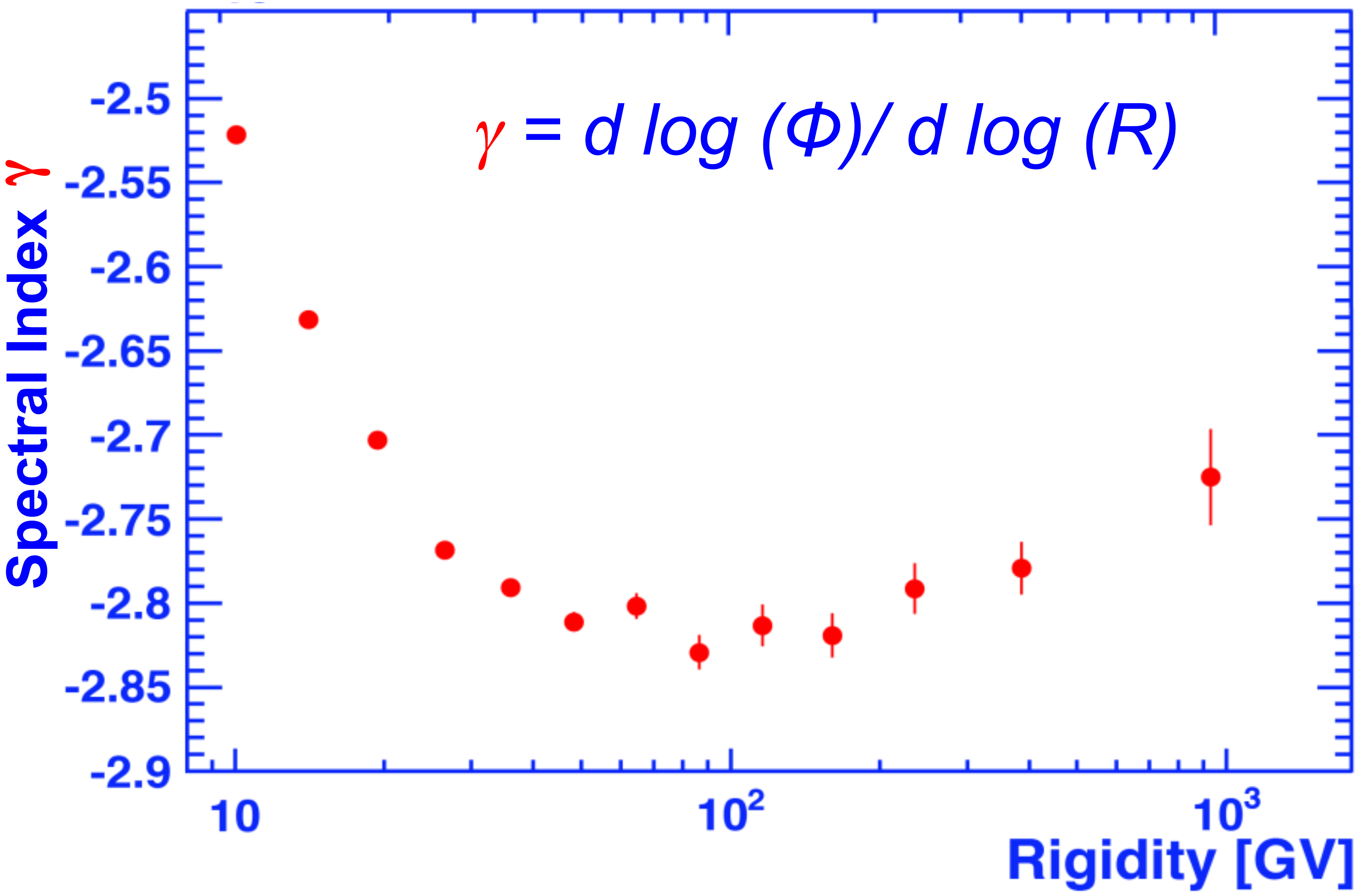
R^{γ}, $R^{\gamma+\Delta\gamma}$ with a characteristic transition rigidity R_0 and smoothness s



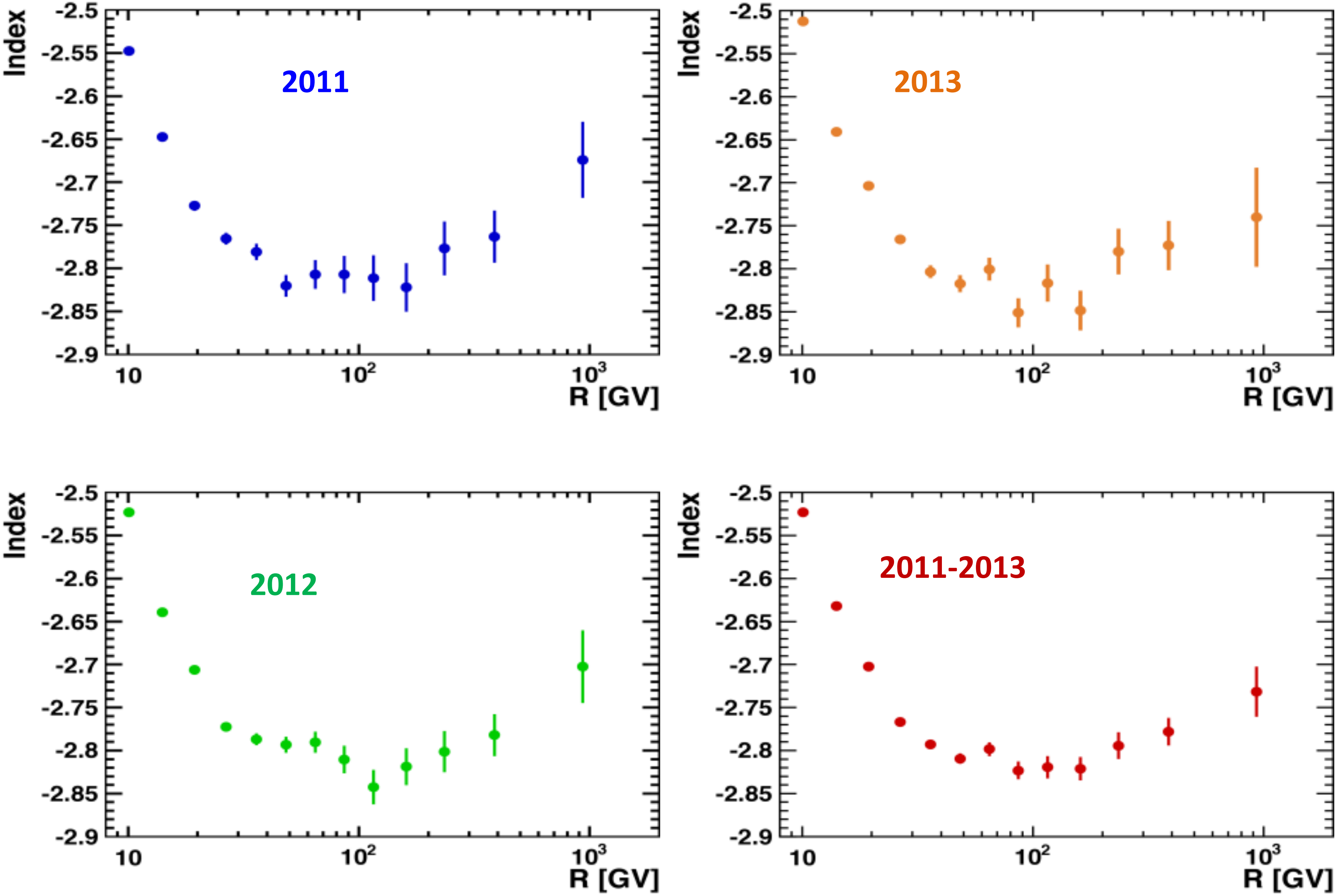
$$\Phi = C\left(\frac{R}{45\,\mathrm{GV}}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/s}\right]^{s}$$

Solid curve fit of Eq. Φ to the data.
(Fit to data above 45 GV: χ^2/d.f.= 25 /26)
Dashed curve uses the same fit values but with Δγ set to zero.

AMS proton spectral index variation:
Model independent measurement of spectral index



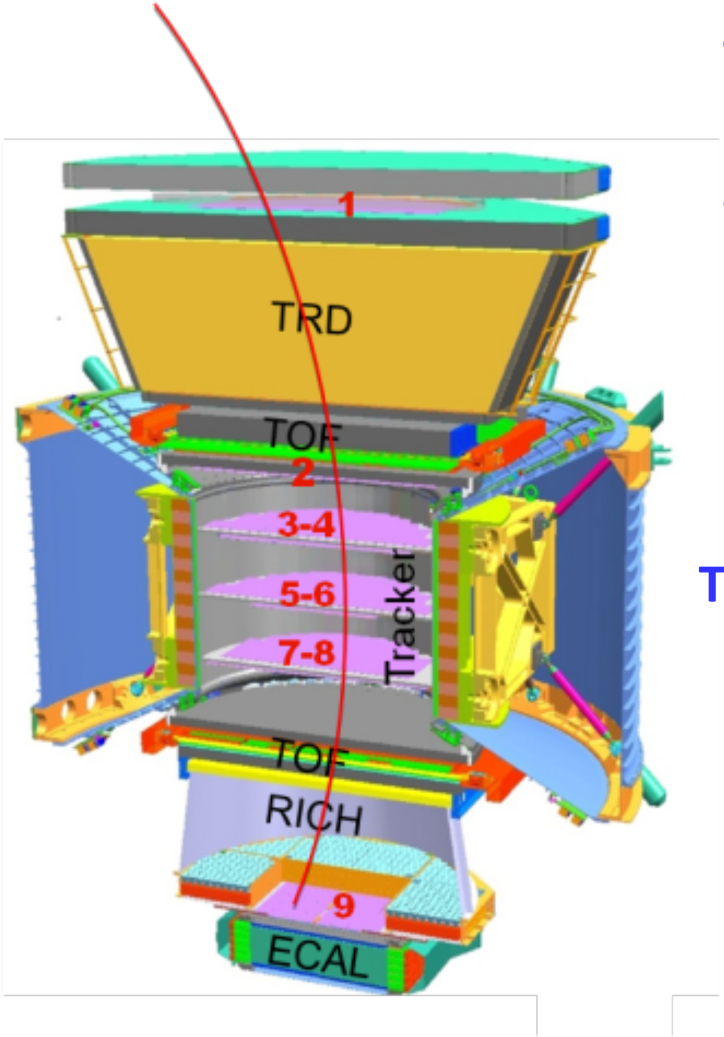
Spectral index of the proton flux for 2011 to 2013



Electrons and positrons

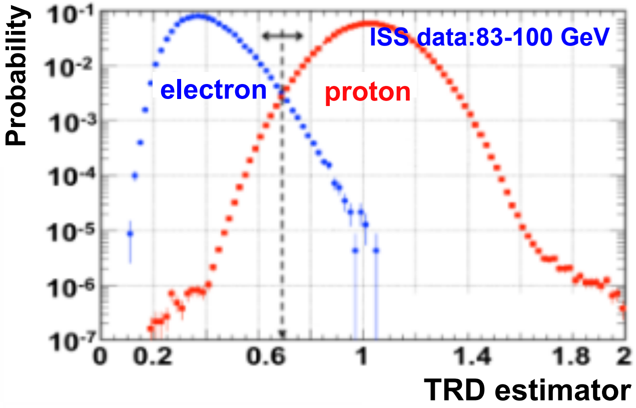
Physics of 11 million e^+, e^- events

Measuring electrons and positrons



TRD

(transition radiation) to identify $e^\pm$

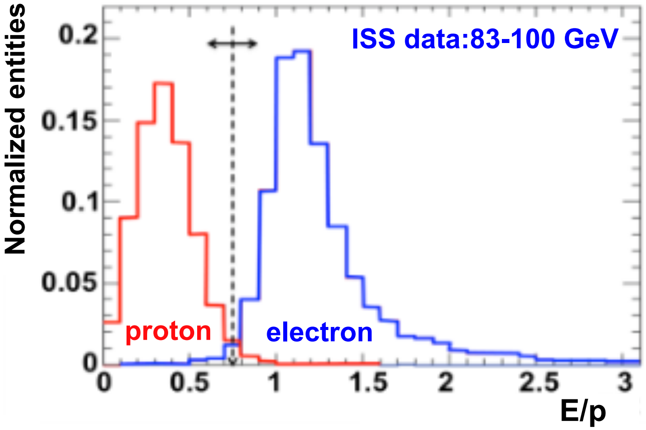


ECAL measures E

Tracker measures p

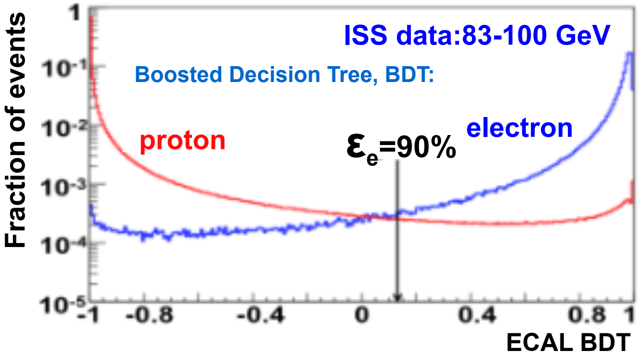
$e^\pm$: E=p

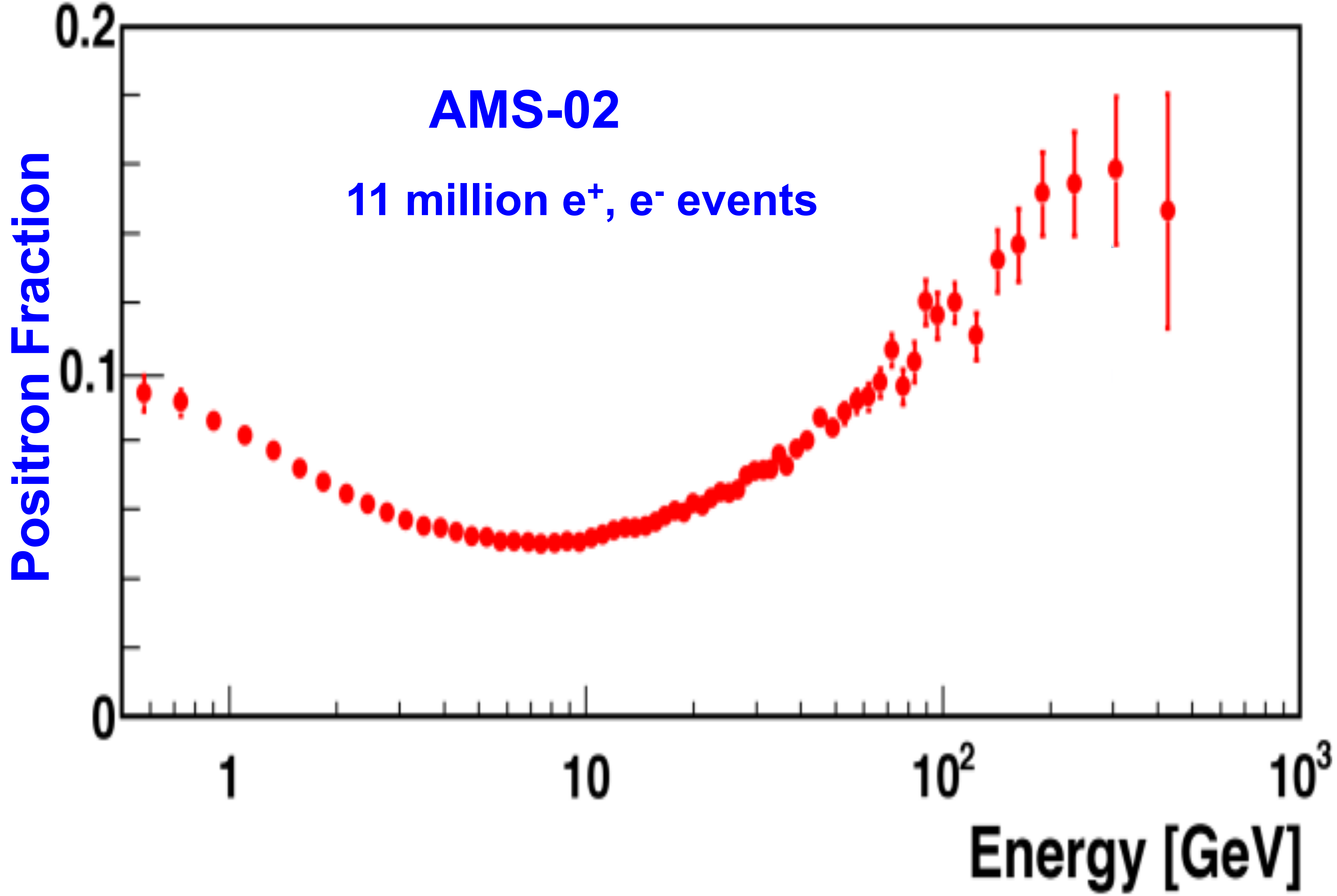
proton: E<p



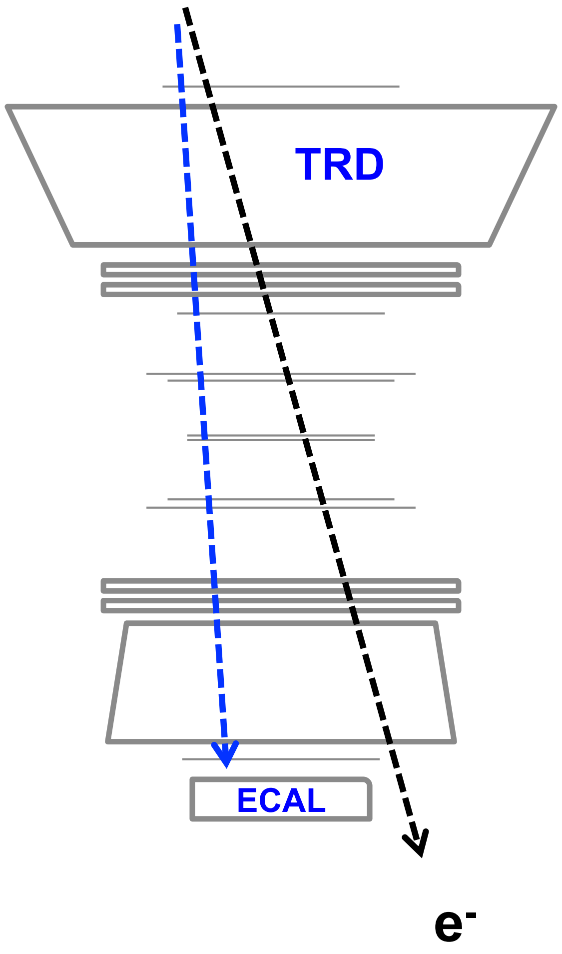
ECAL

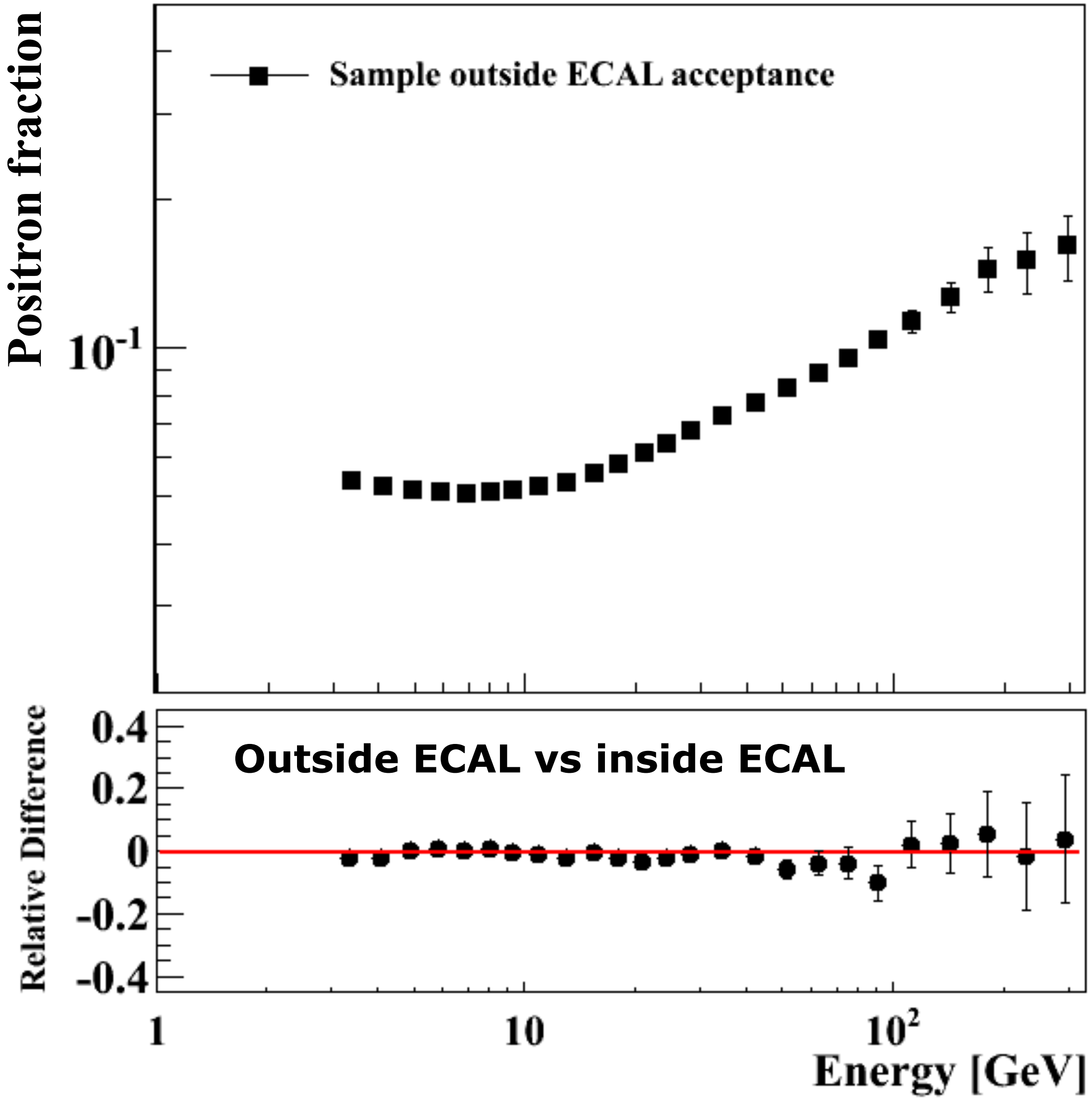
(shower shape) to separate $e^\pm$ from protons




AMS-02
11 million e⁺, e⁻ events
Positron Fraction
0.2
0.1
0
1
10
10^2
10^3
Energy [GeV]

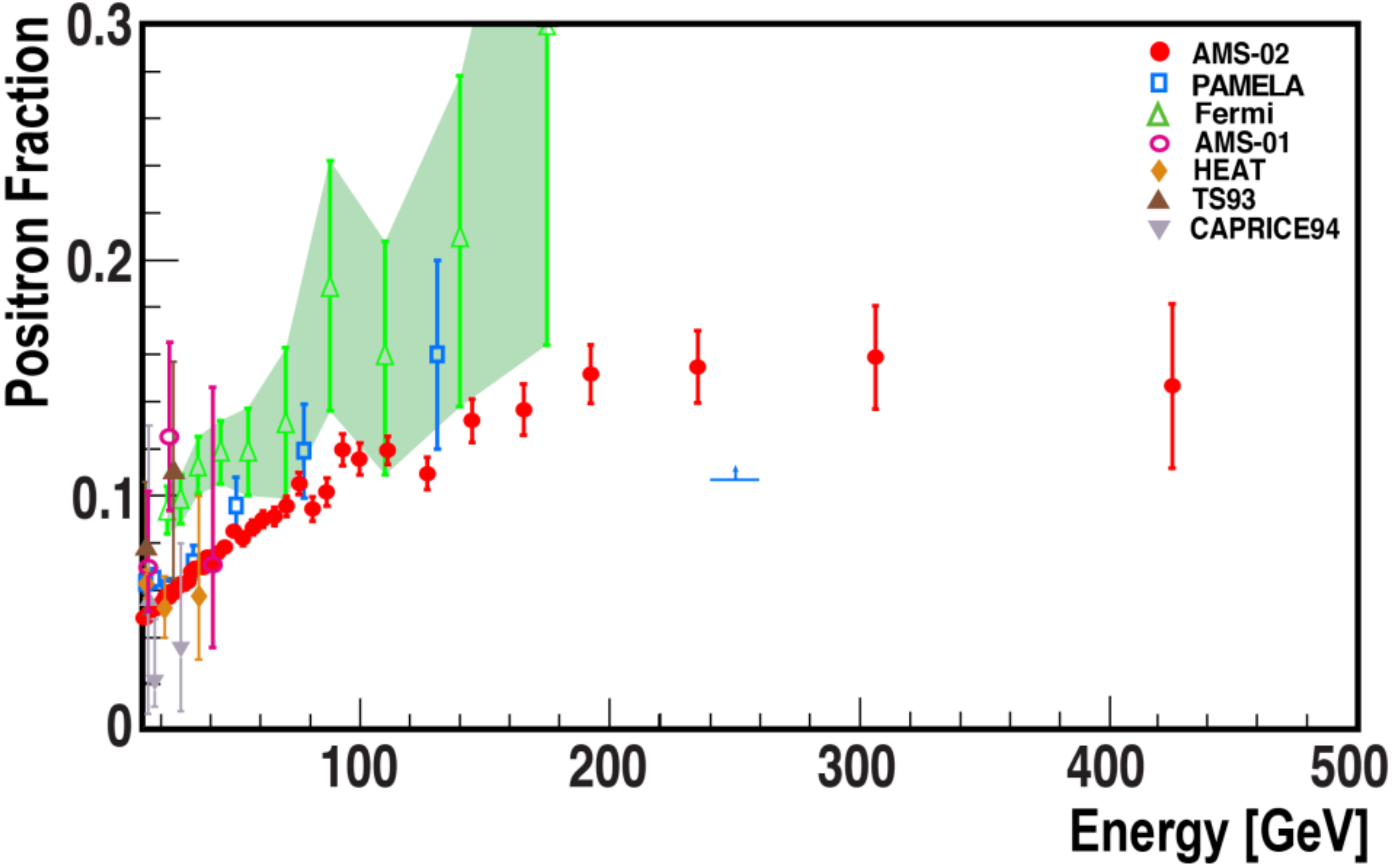
Verification of Positron Fraction
with two independent samples
Positron fraction analysis with TRD Only



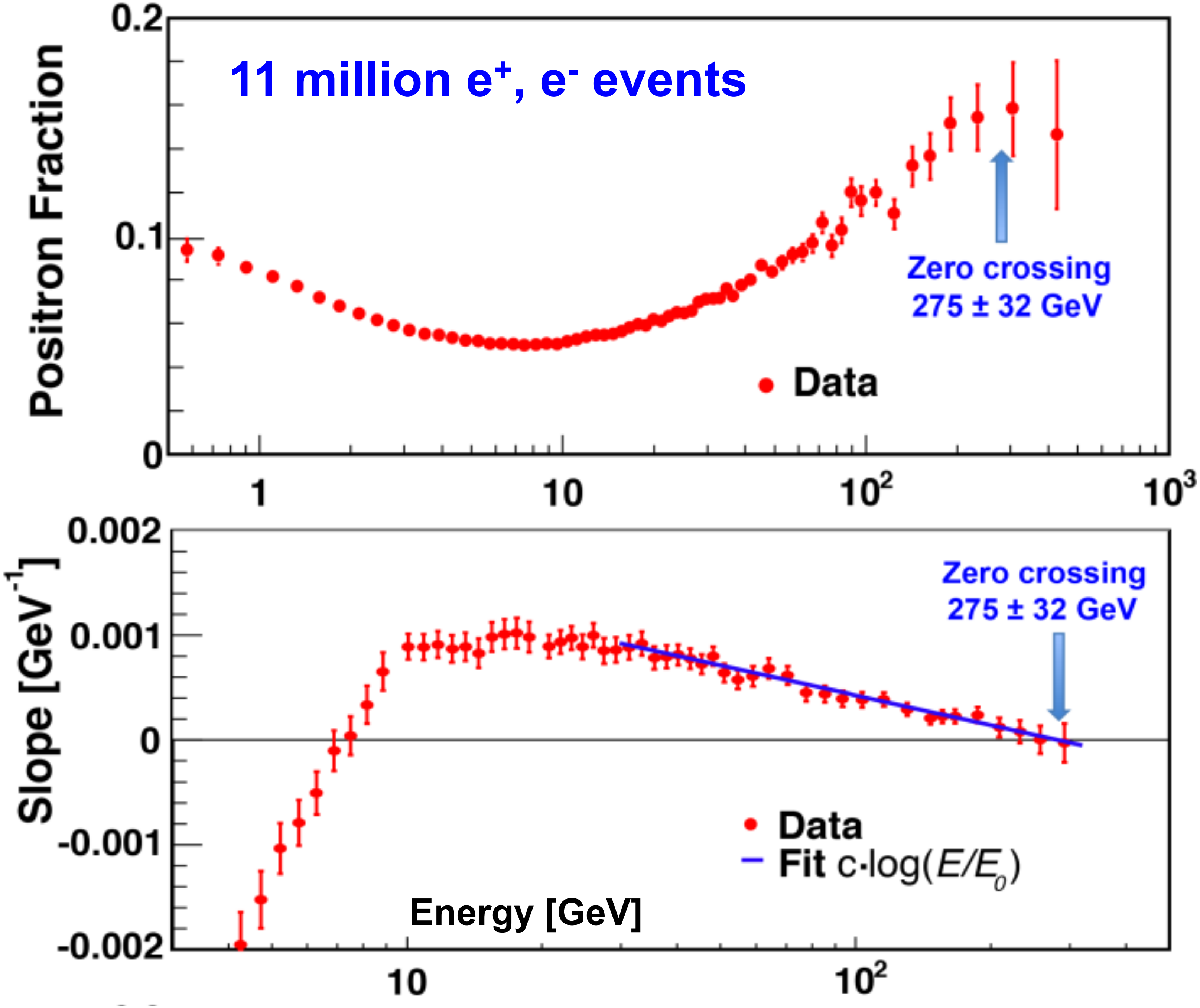


Good agreement between two independent samples

Positron Fraction from AMS



The energy beyond which it ceases to increase.



Measurement of the flux of electrons and positrons

$$\Phi_{e^\pm}(\mathrm{E}) = \frac{\mathrm{N}_{e^\pm}(\mathrm{E})}{\mathrm{A}_{eff}(\mathrm{E}) \cdot \varepsilon_{trig}(\mathrm{E}) \cdot \mathrm{T}(\mathrm{E}) \cdot \Delta\mathrm{E}}$$

$\mathbf{N_{e\pm}}$ is the number of electron or positron events

$\mathbf{A_{eff}}$ is the effective acceptance

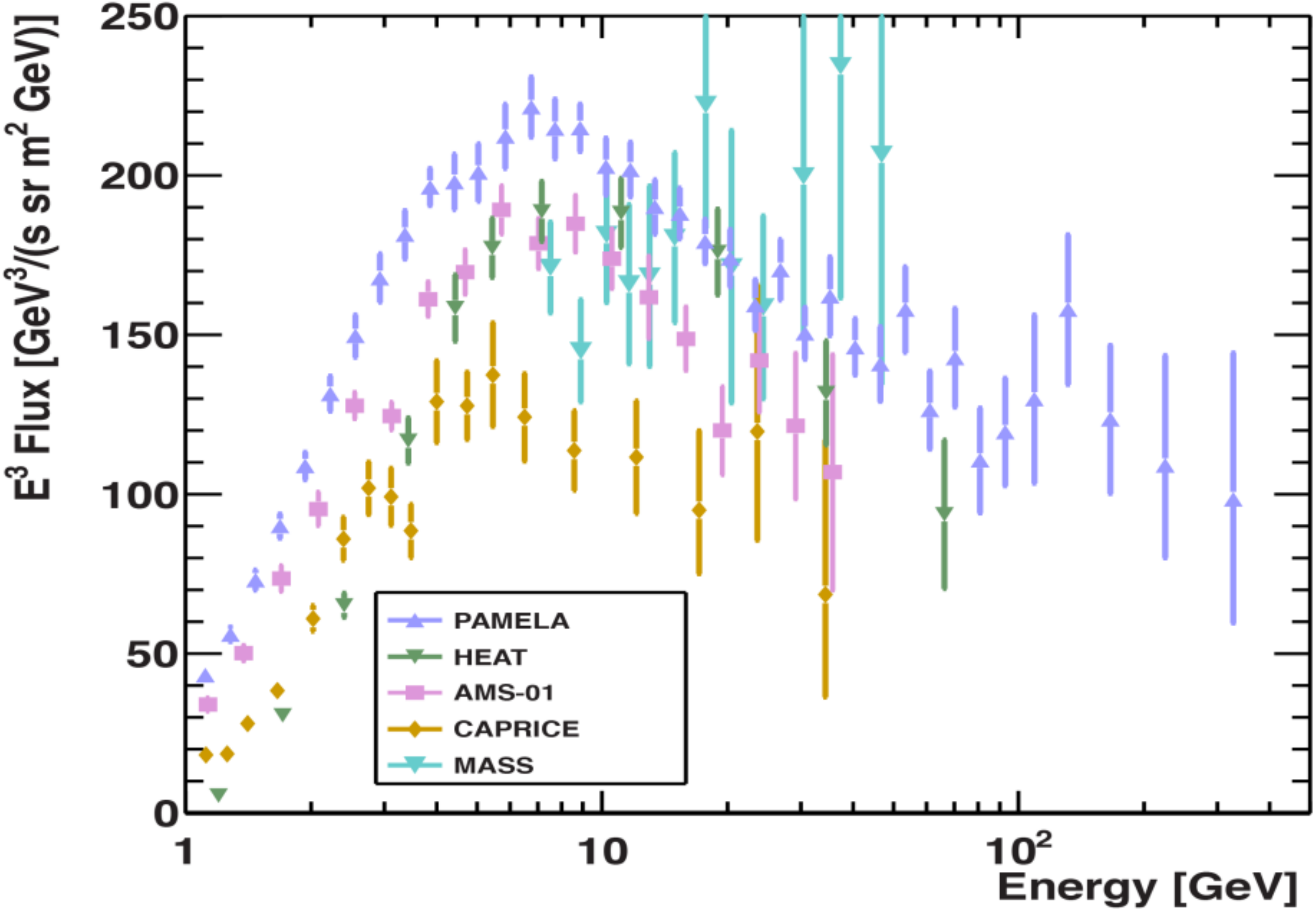
$\boldsymbol{\varepsilon_{trig}}$ is the trigger efficiency

T is the exposure time

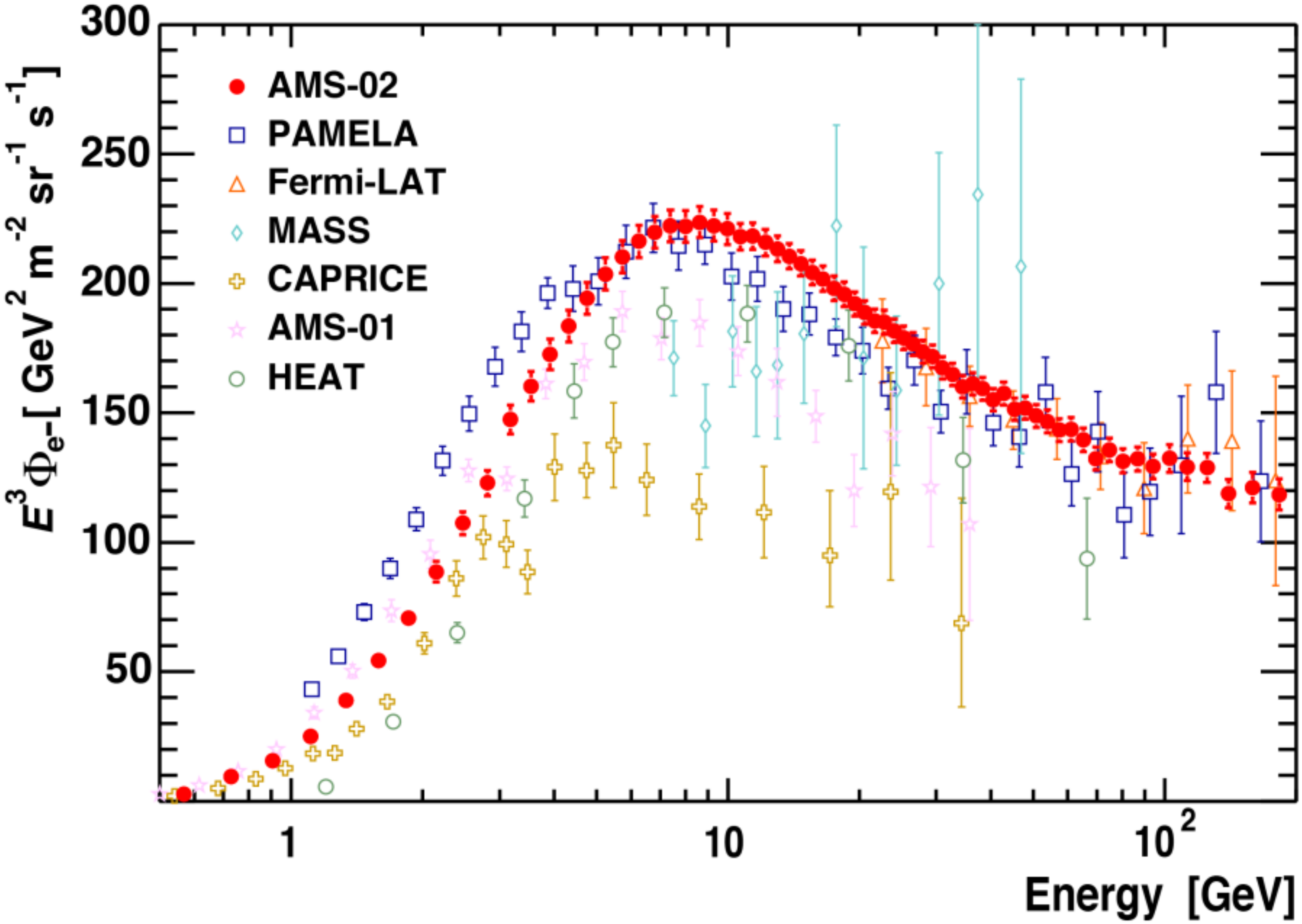
to be presented by Professor S. Schael (RWTH-Aachen)

Electron flux

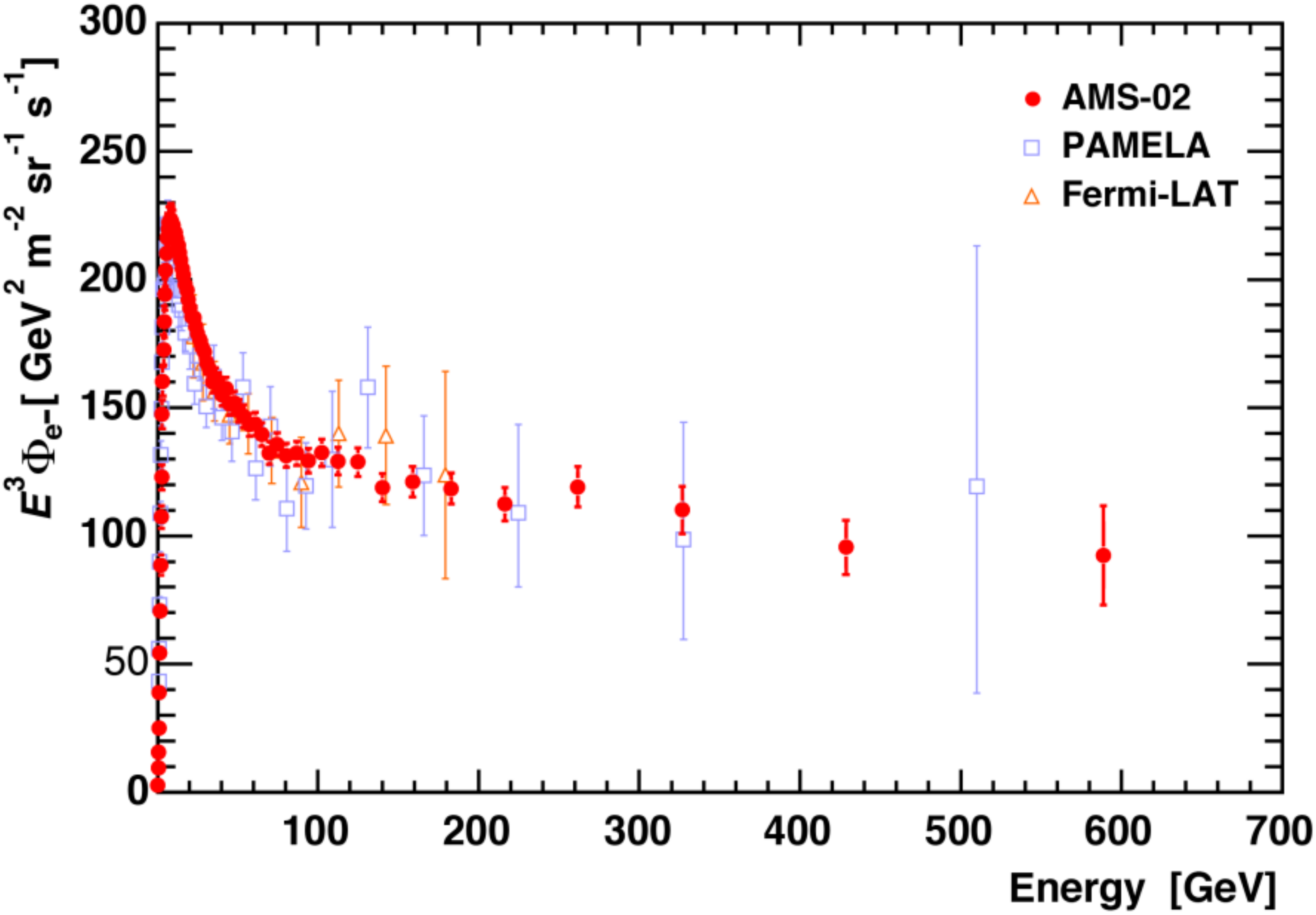
(before AMS)



Electron Flux

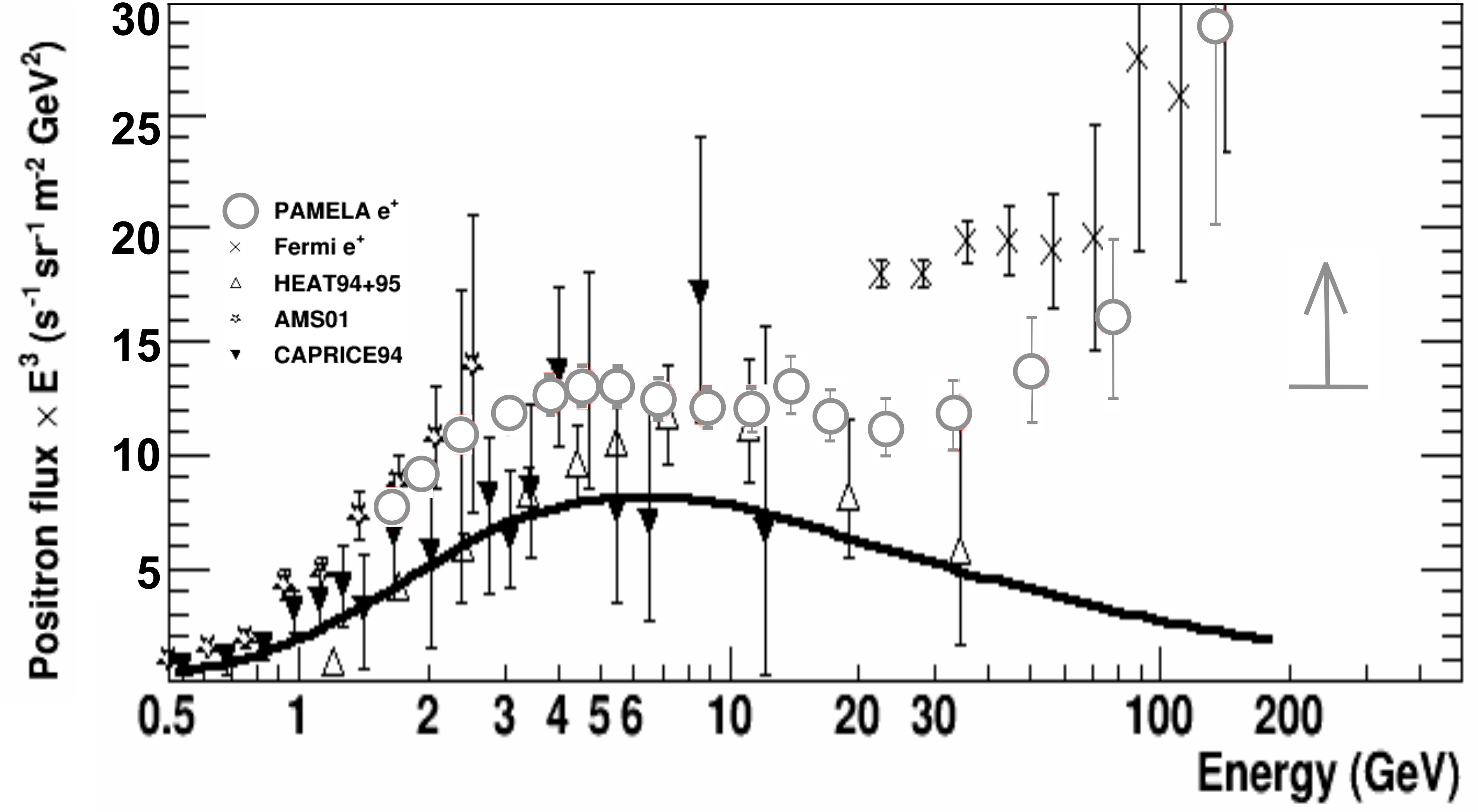


Electron Flux



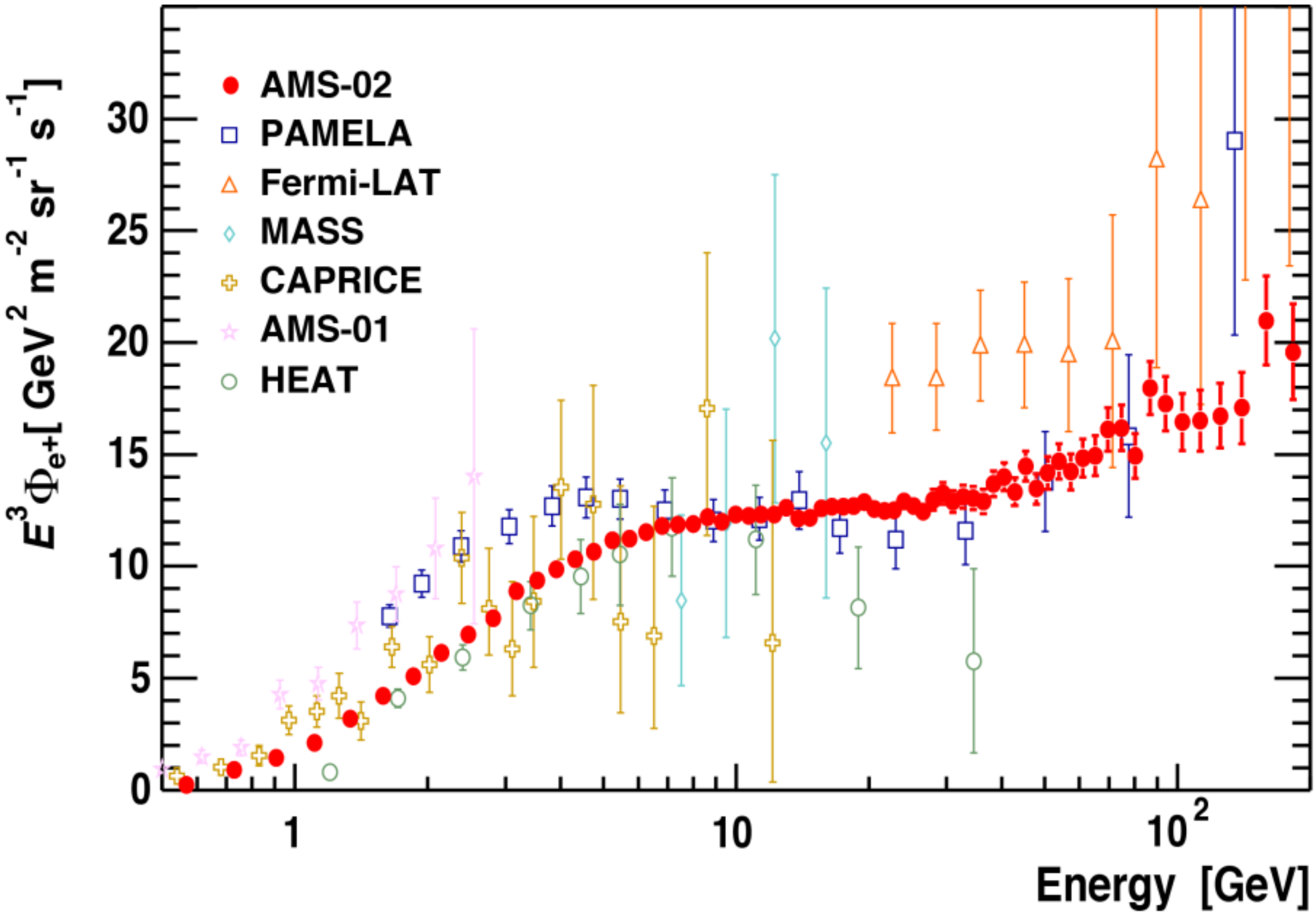
Positron flux

(before AMS)

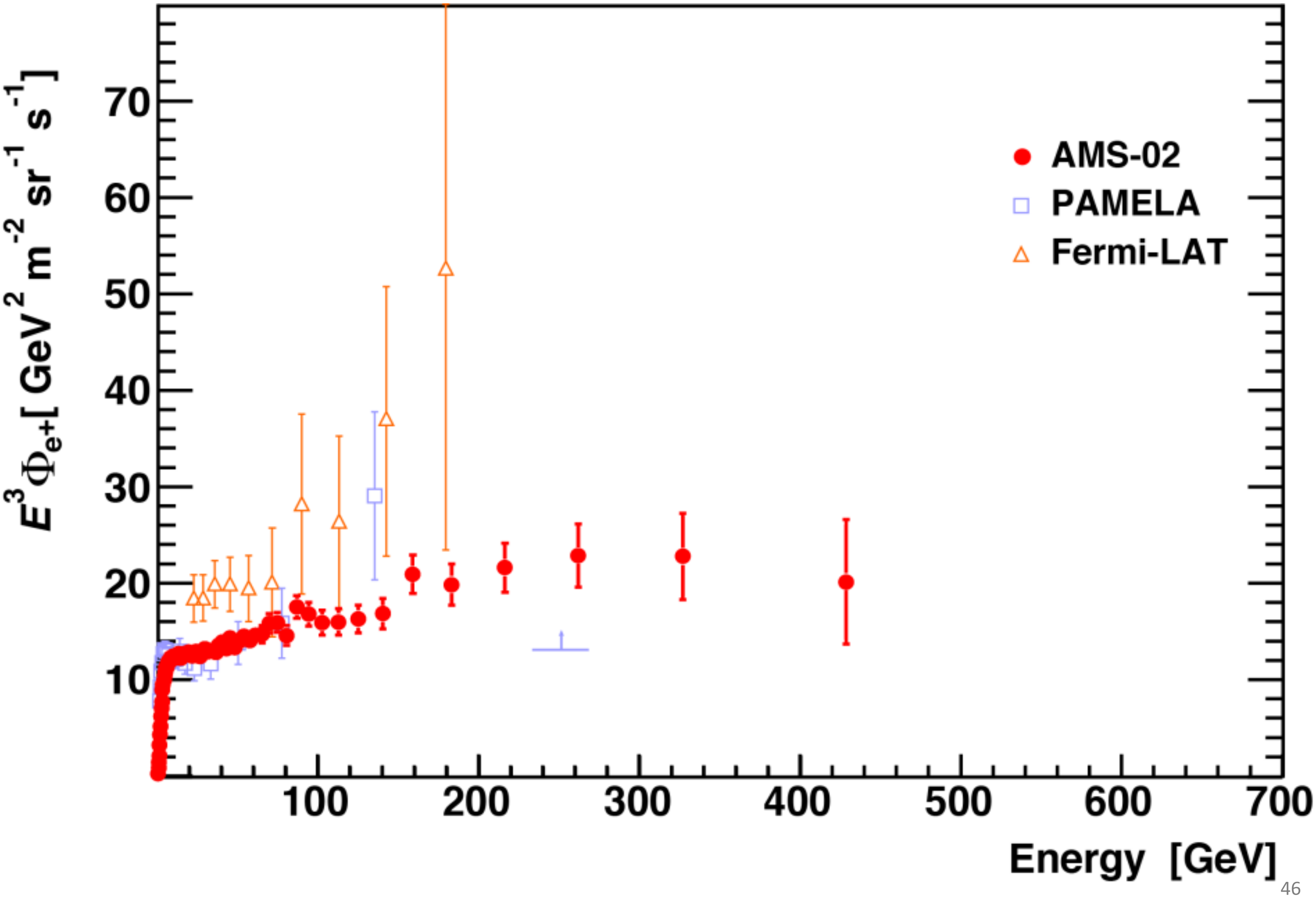


See O. Adriani et al., PRL 111 (2013) 081102

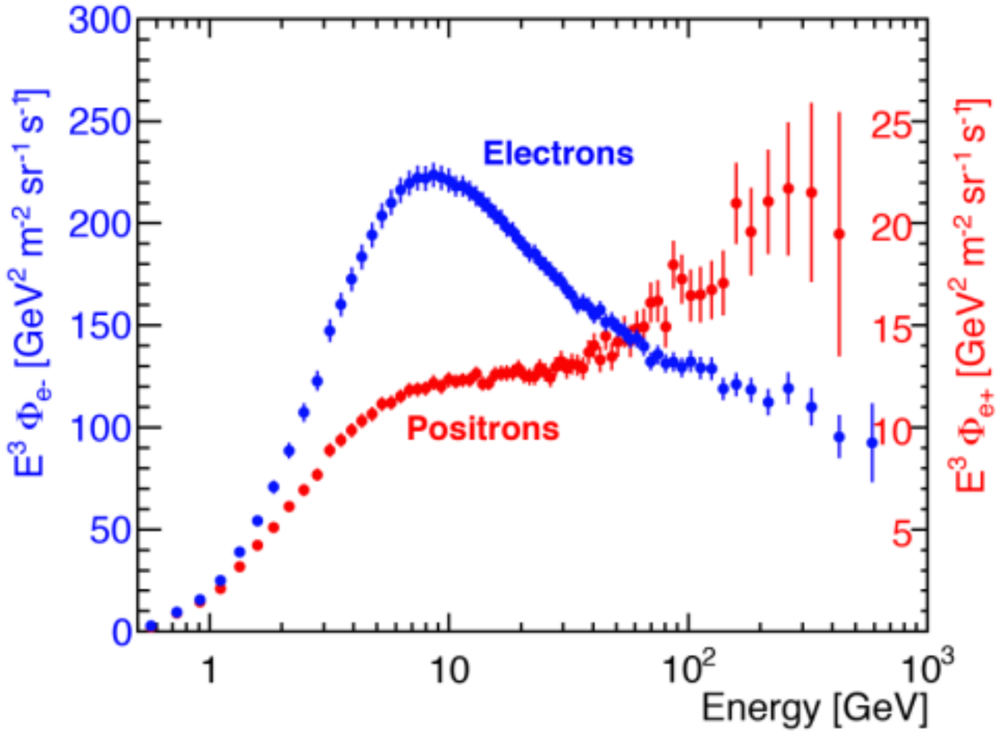
Positron Flux

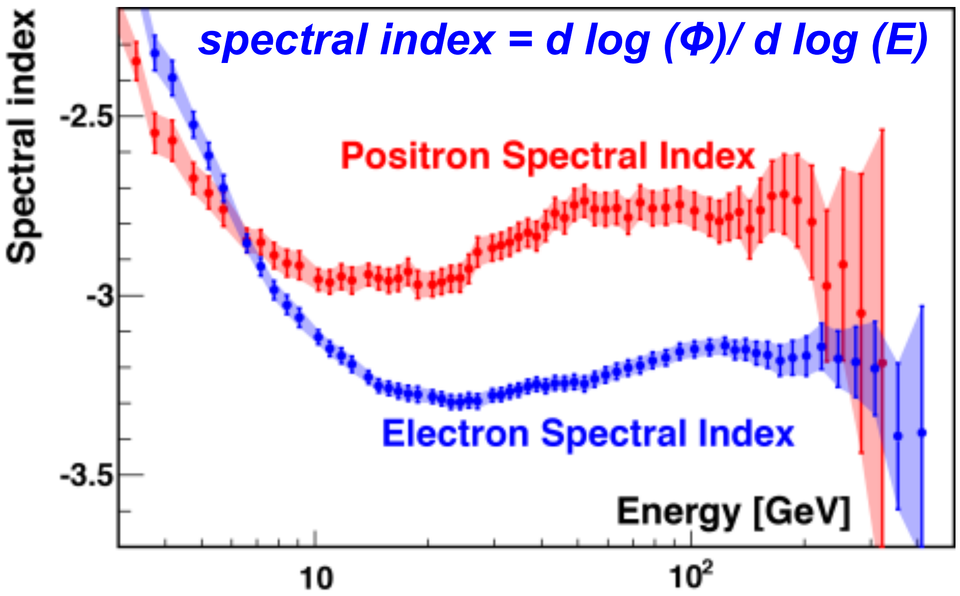


Positron Flux



The Electron Flux and the Positron Flux

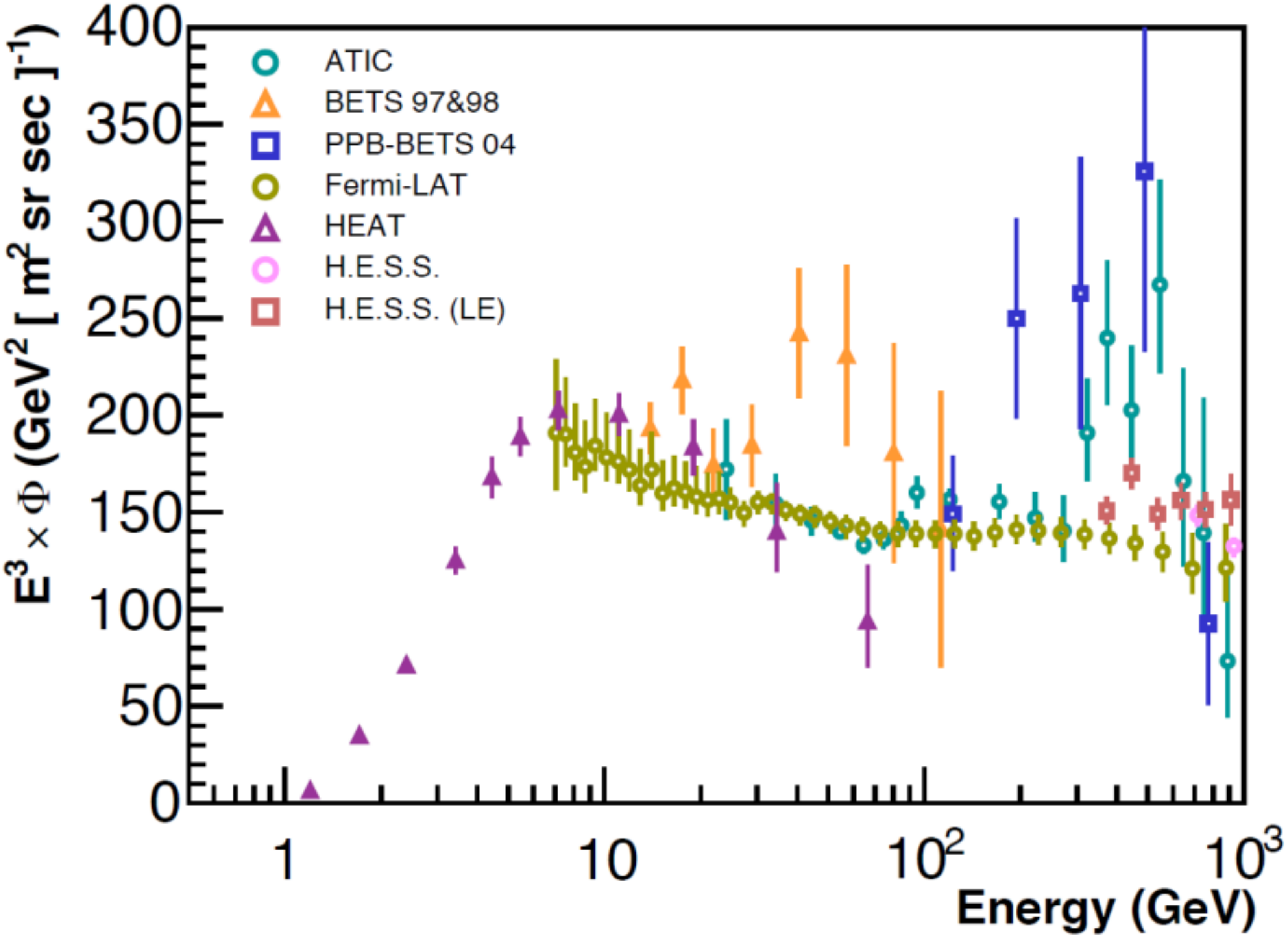




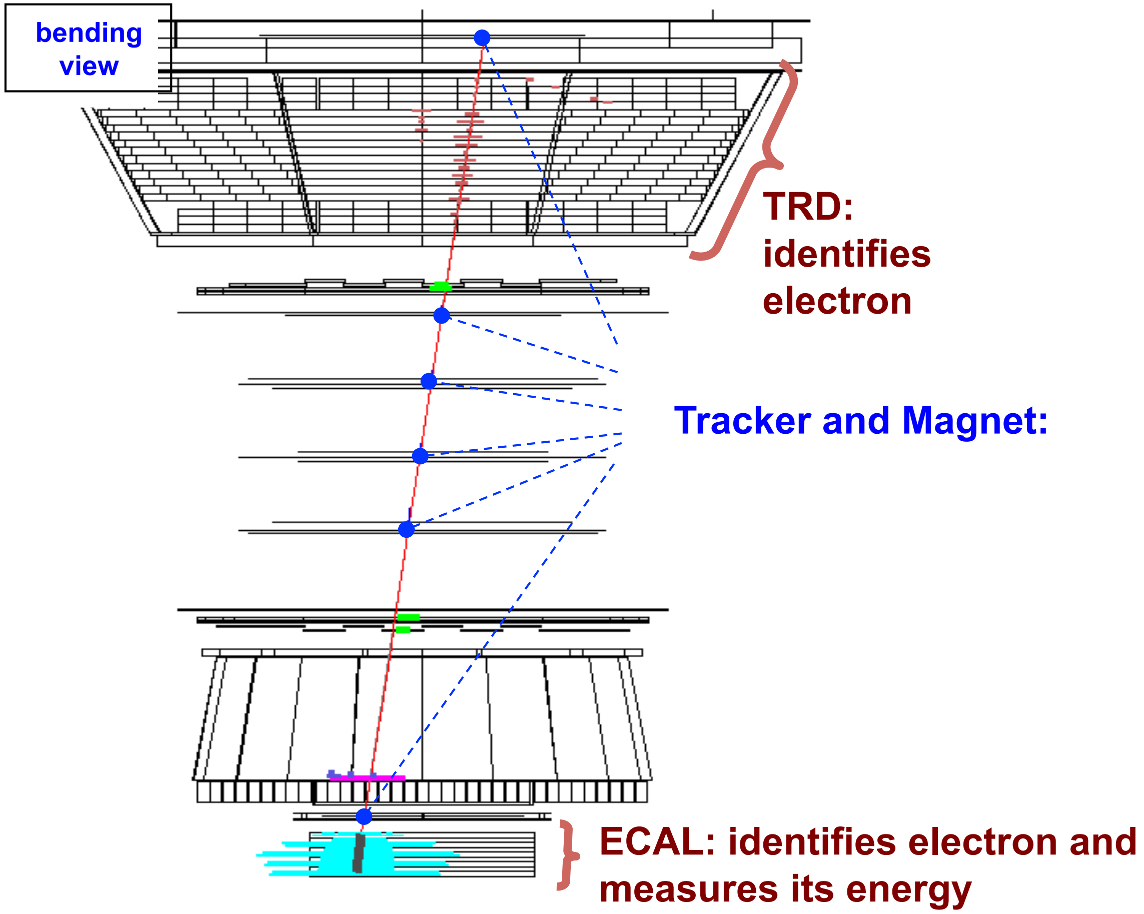
Observations:

1. The electron flux and the positron flux are different in their magnitude and energy dependence.
2. Both spectra cannot be described by single power laws.
3. The spectral indices of electrons and positrons are different.
4. Both change their behavior at ~30GeV.
5. The rise in the positron fraction from 20 GeV is due to an excess of positrons, not the loss of electrons (the positron flux is harder).

The ($e^+ + e^-$) flux before AMS



Combined ($e^+ + e^-$) Flux: event selection



TRD: identifies electron

Tracker and Magnet:

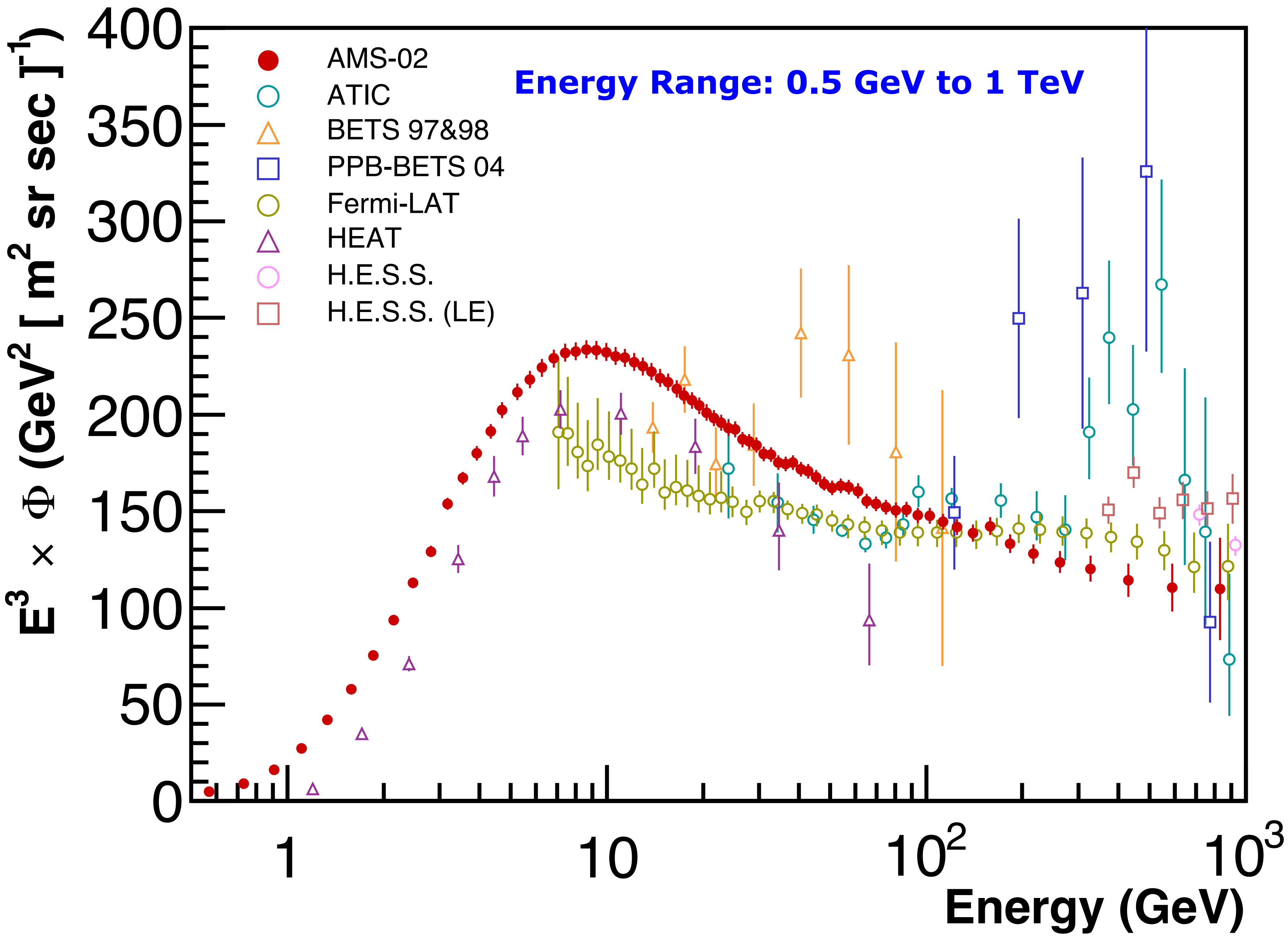
ECAL: identifies electron and measures its energy

Independent of charge sign measurement → no charge confusion

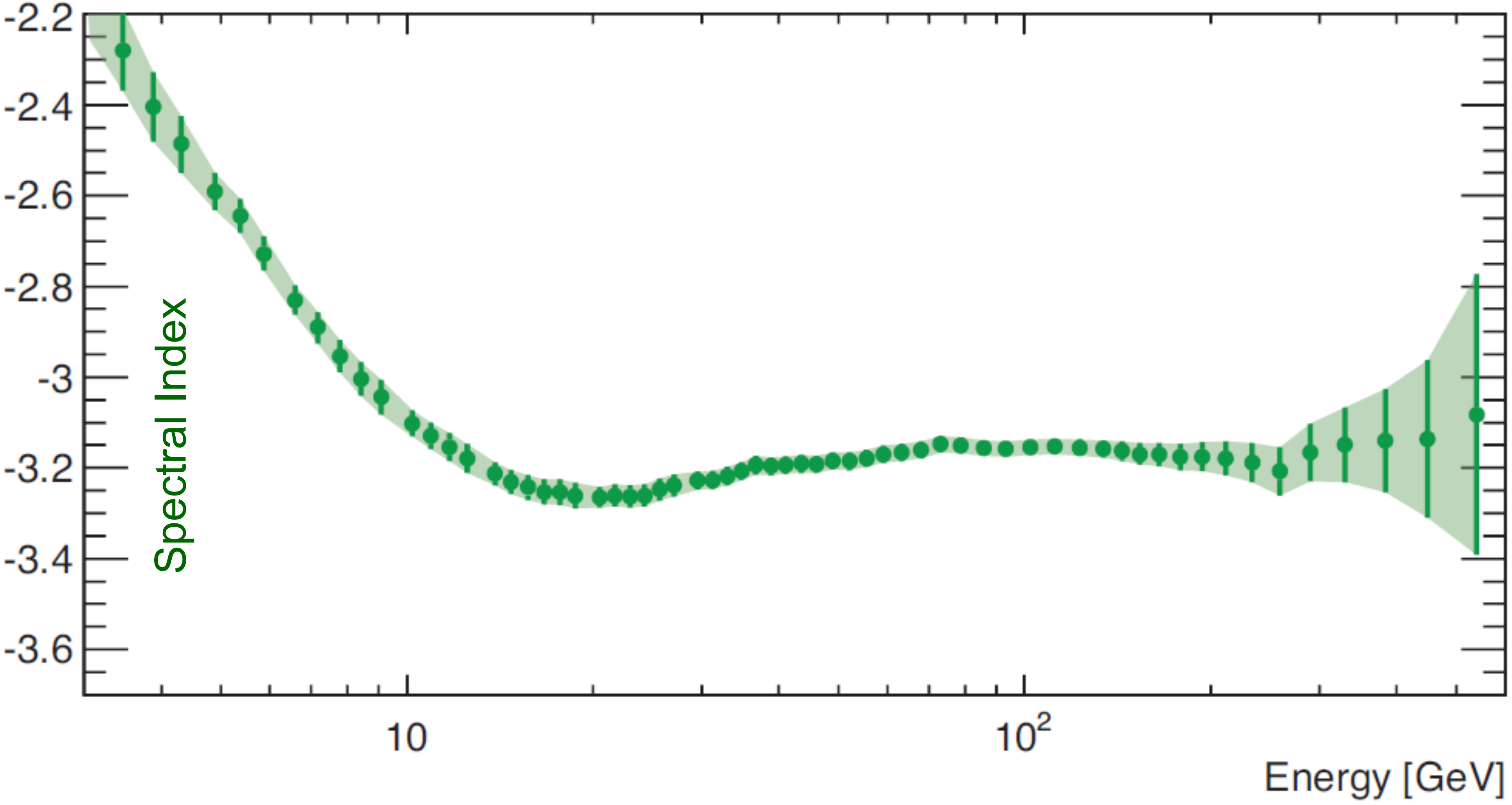
High selection efficiency : 70% @ TeV

Small systematics on acceptance: 2% @ TeV

AMS Results: $(e^+ + e^-)$ flux



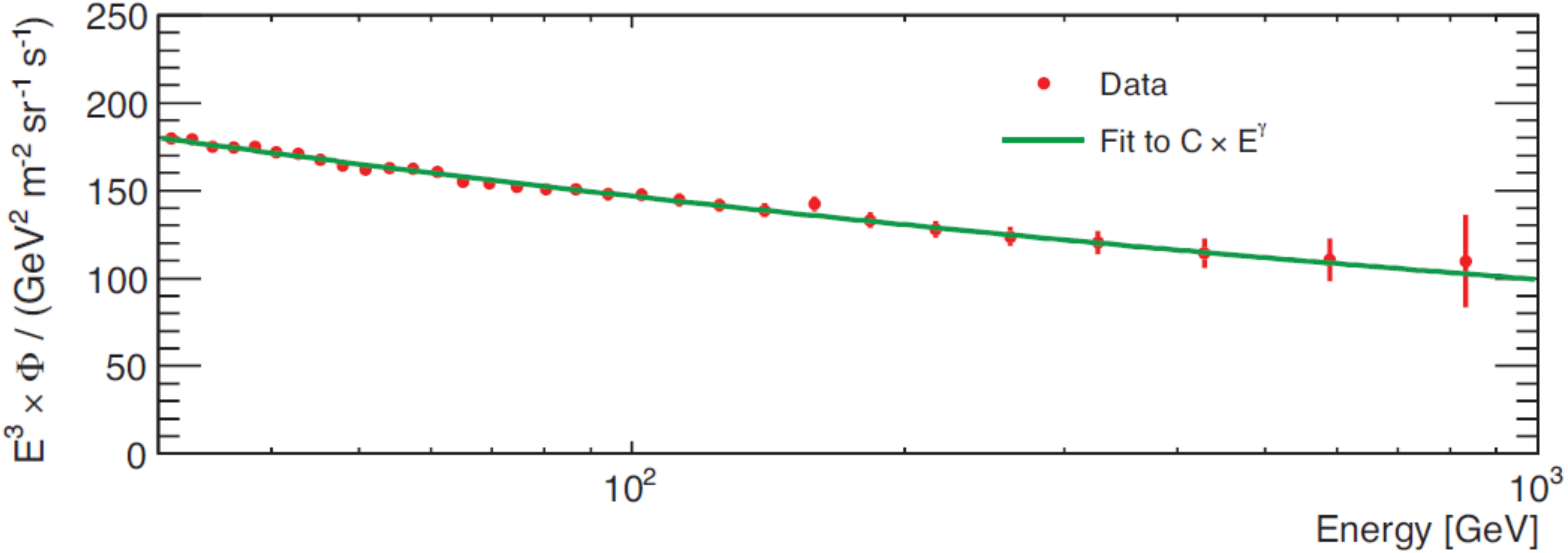
$$\gamma = d \log(\Phi) / d \log(E)$$



$\Phi(e^{+}+e^{-}) = C\,E^{\gamma}$

$\gamma=-3.170 \pm 0.008$ (stat + syst.) $\pm\ 0.008$ (energy scale)

$E > 30$ GeV

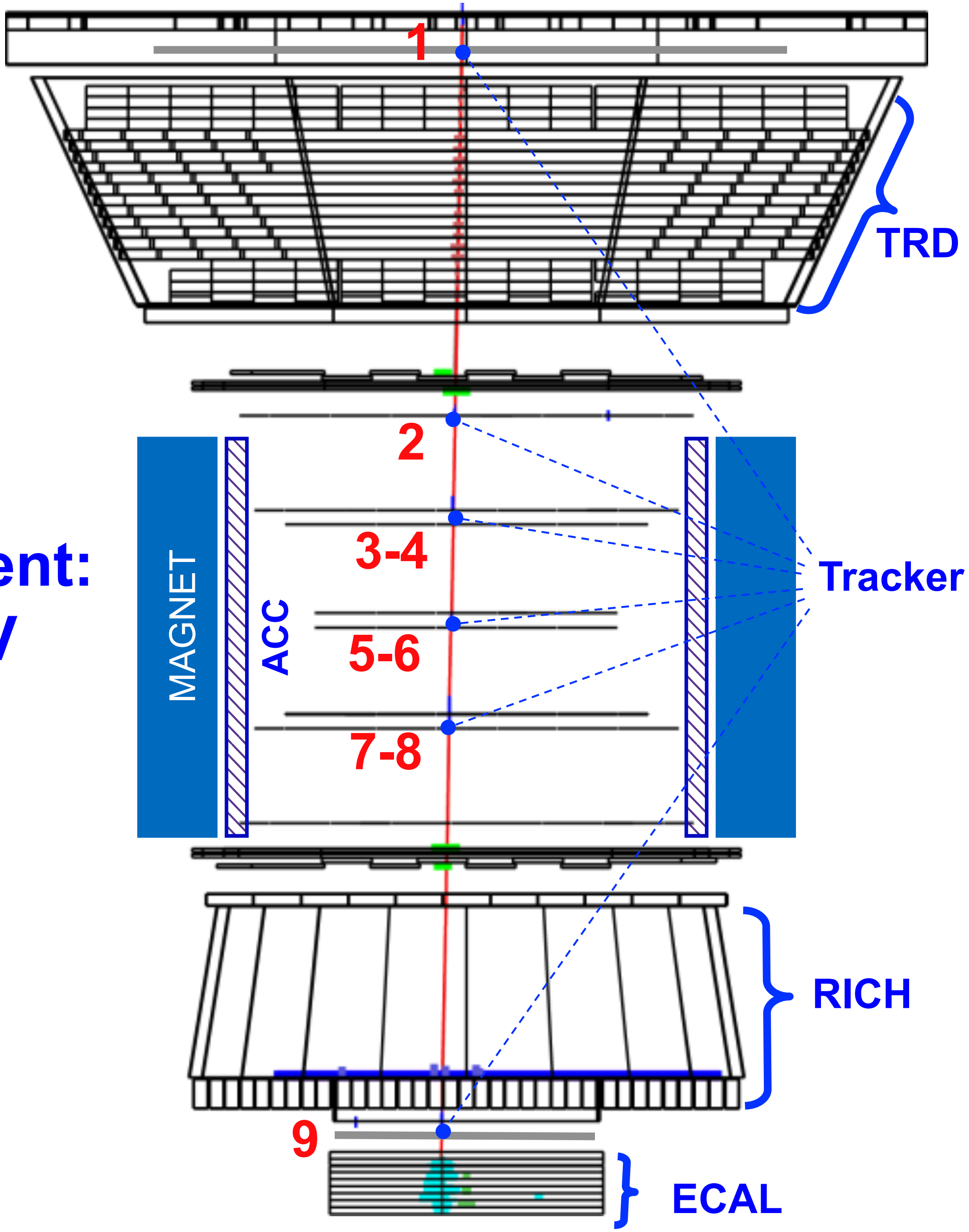


The flux is consistent with a single power law above 30 GeV.

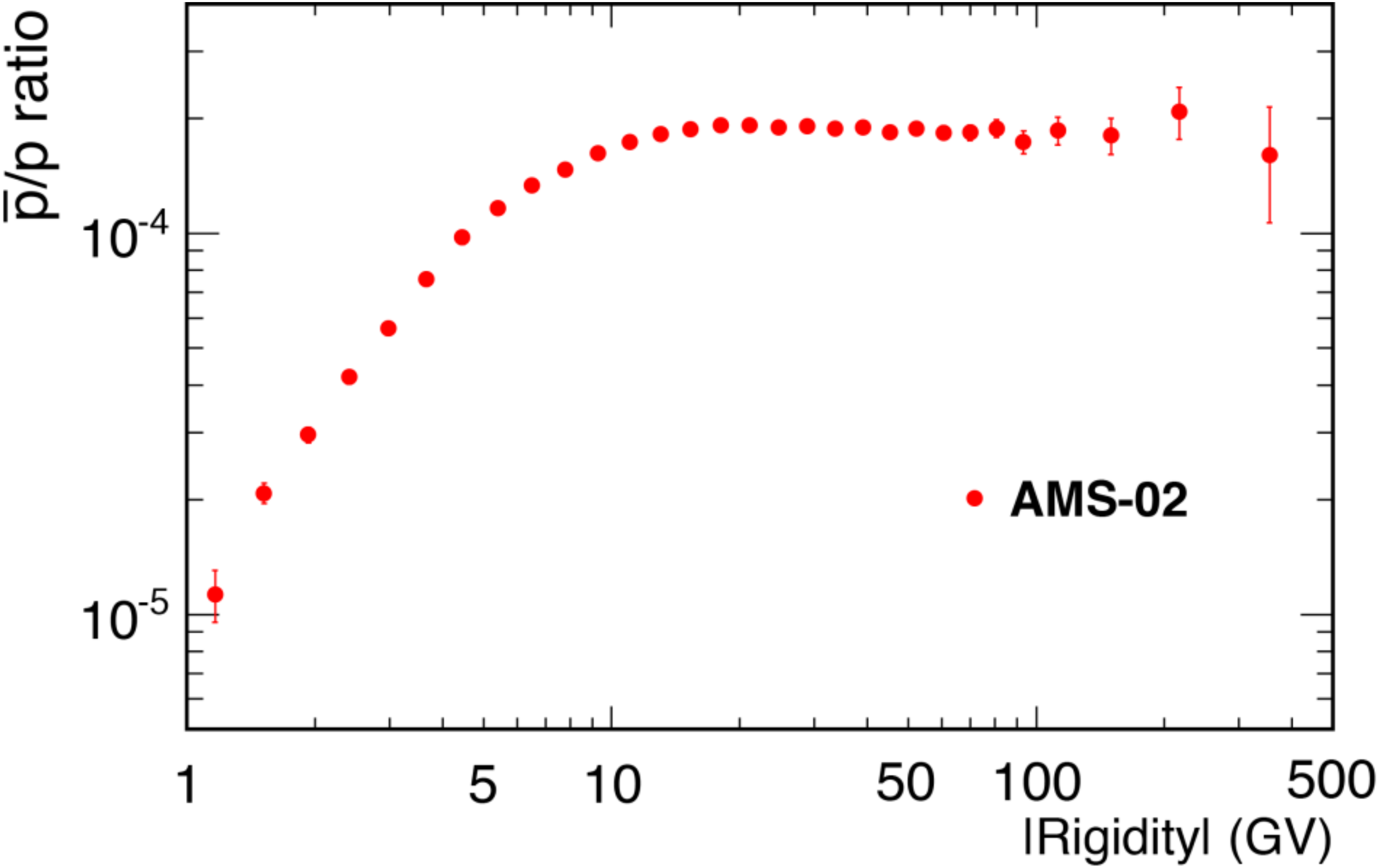
Anti-protons

Antiproton/proton ratio

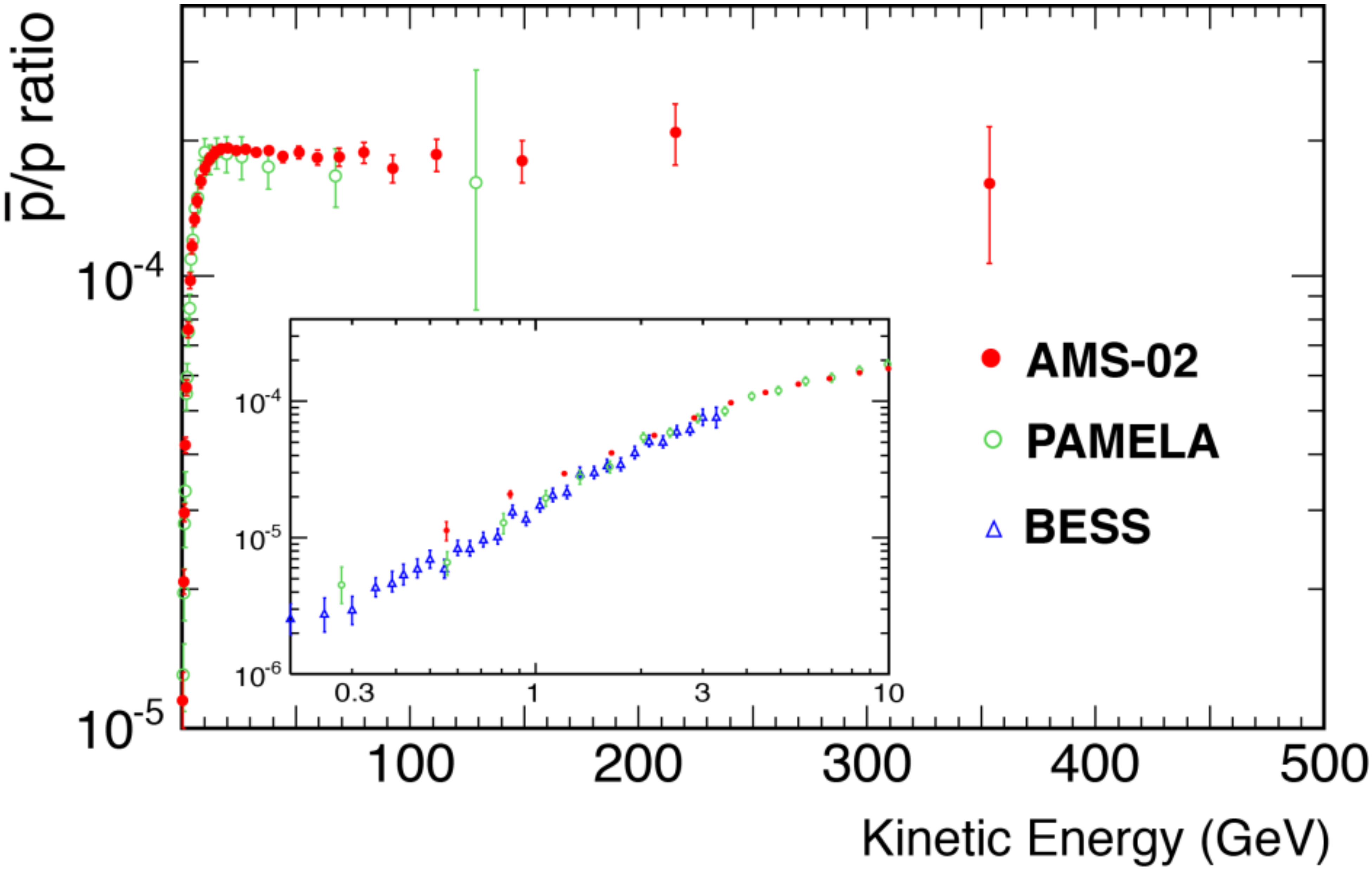
Antiproton event:
R = −423 GV



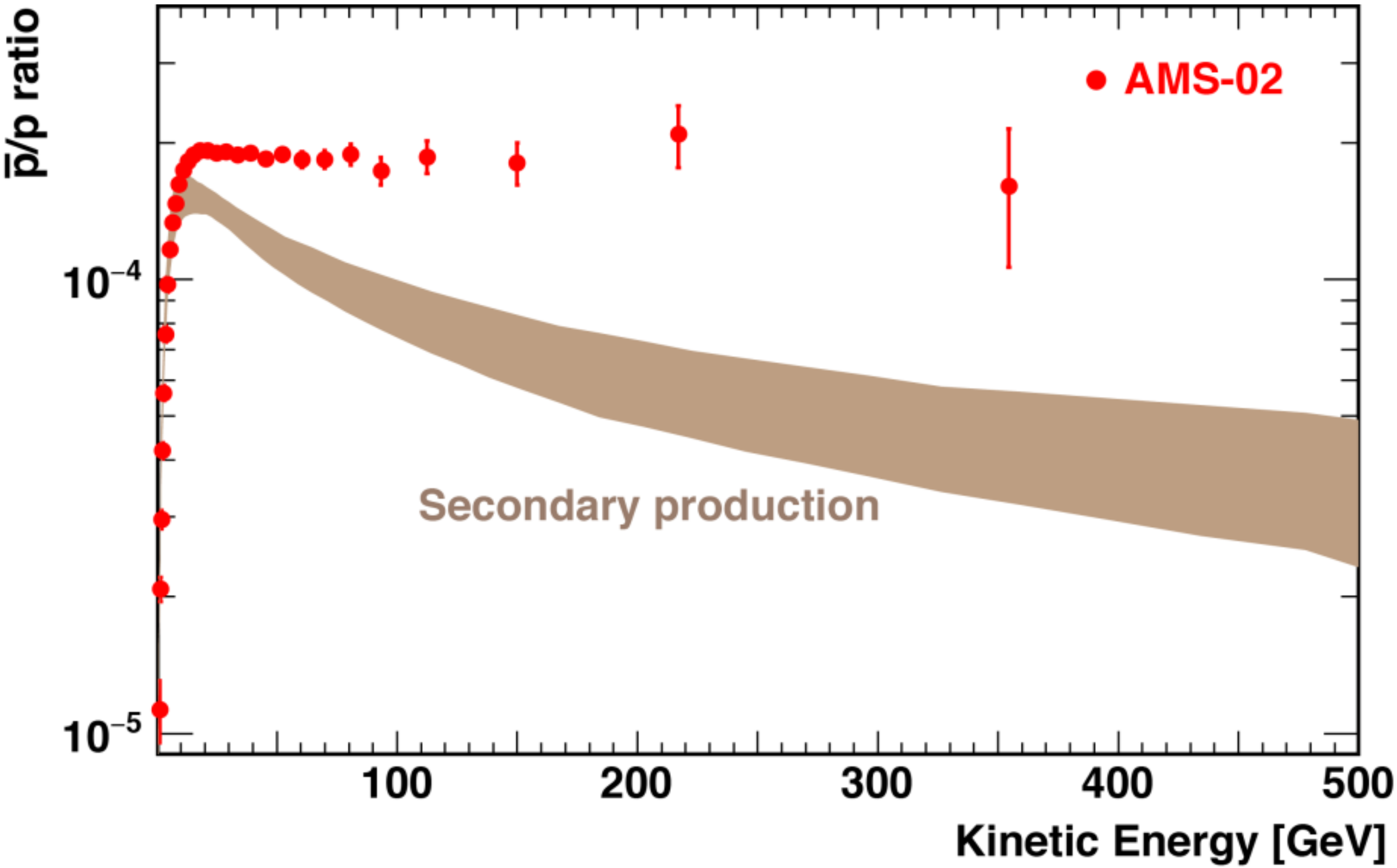
AMS $\bar{p}/p$ results



AMS $\bar{p}/p$ results



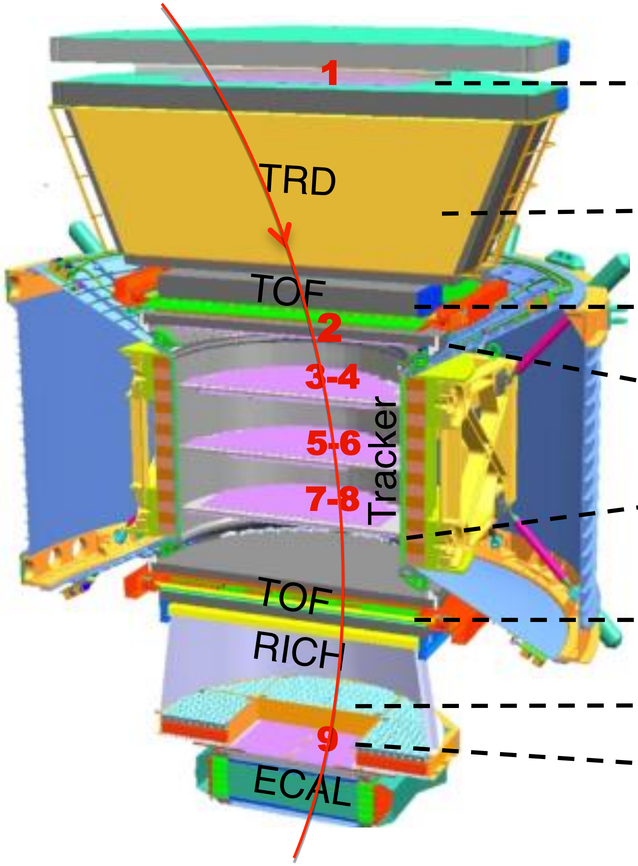
AMS $\bar{p}/p$ results and modeling



Nuclei

Measurement of Nuclei with AMS

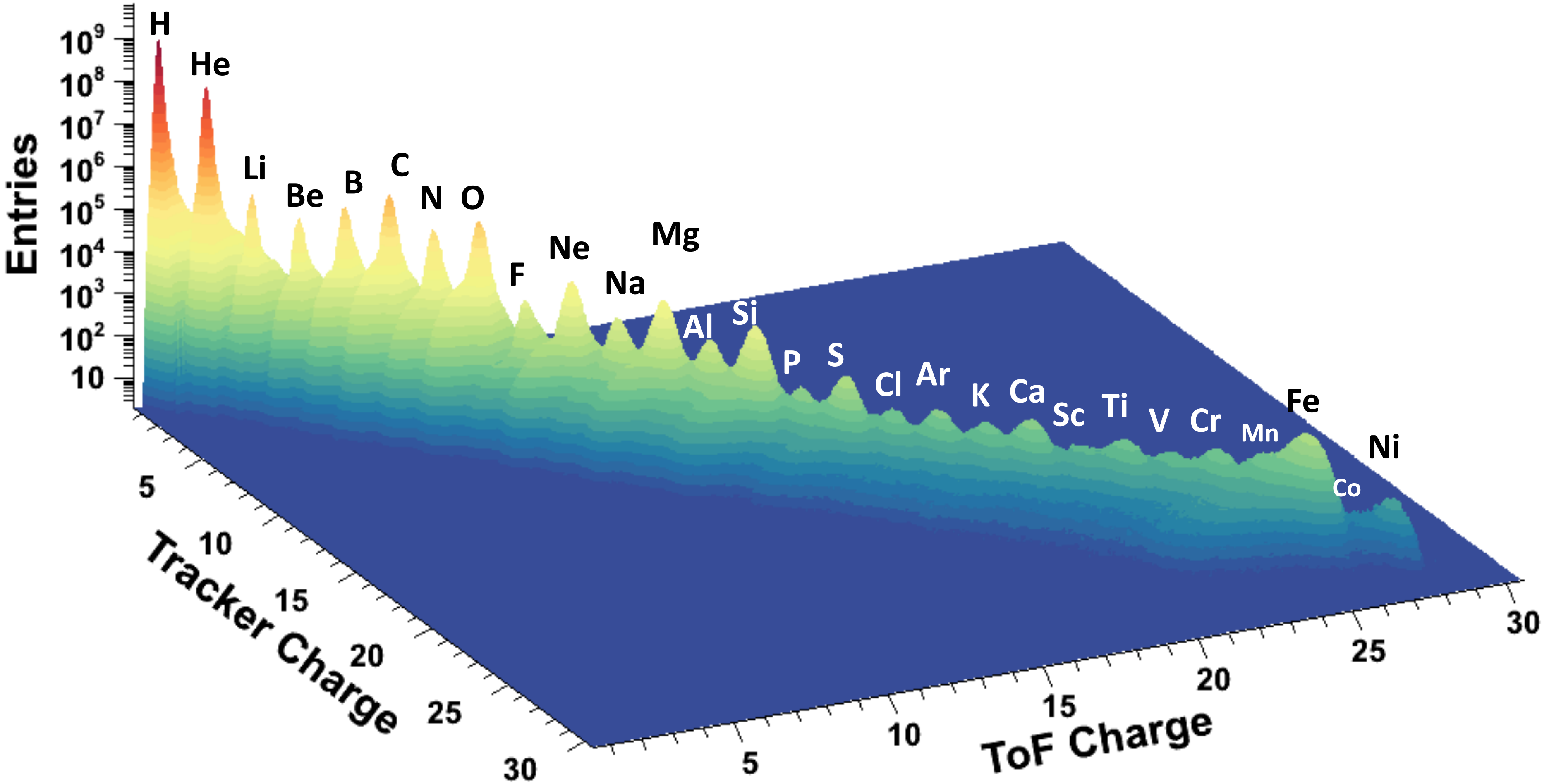
AMS: Multiple Independent Measurements of the Charge (|Z|)



Carbon (Z=6)

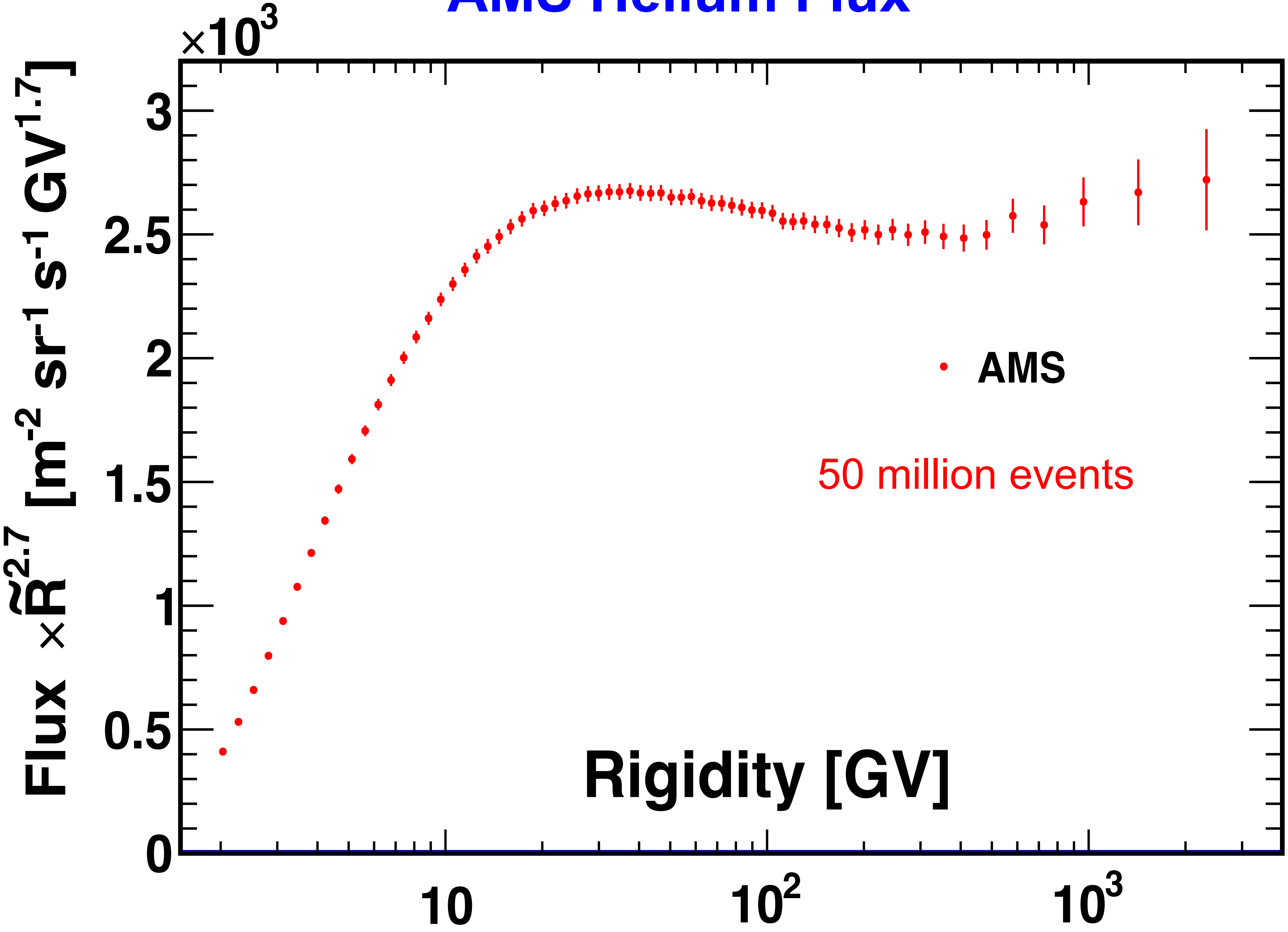
	ΔZ (cu)
1. Tracker Plane 1	0.30
2. TRD	0.33
3. Upper TOF (1 counter)	0.16
4. Tracker Planes 2-8	0.12
5. Lower TOF (1 counter)	0.16
6. RICH	0.32
7. Tracker Plane 9	0.30

AMS Nuclei Measurement on ISS



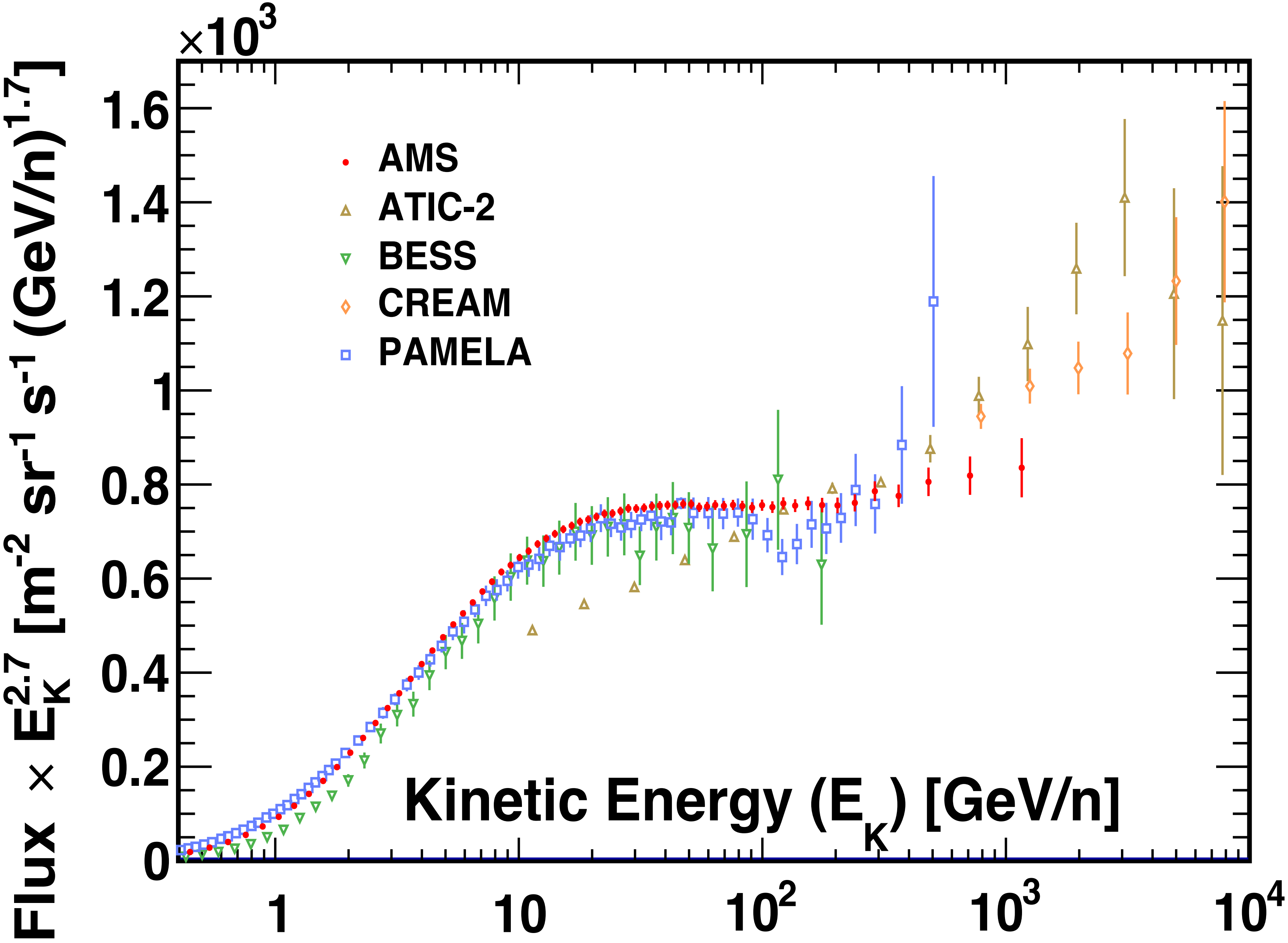
To be presented by V. Choutko, L. Derome, S. Haino, M. Heil, A. Oliva

AMS Helium Flux

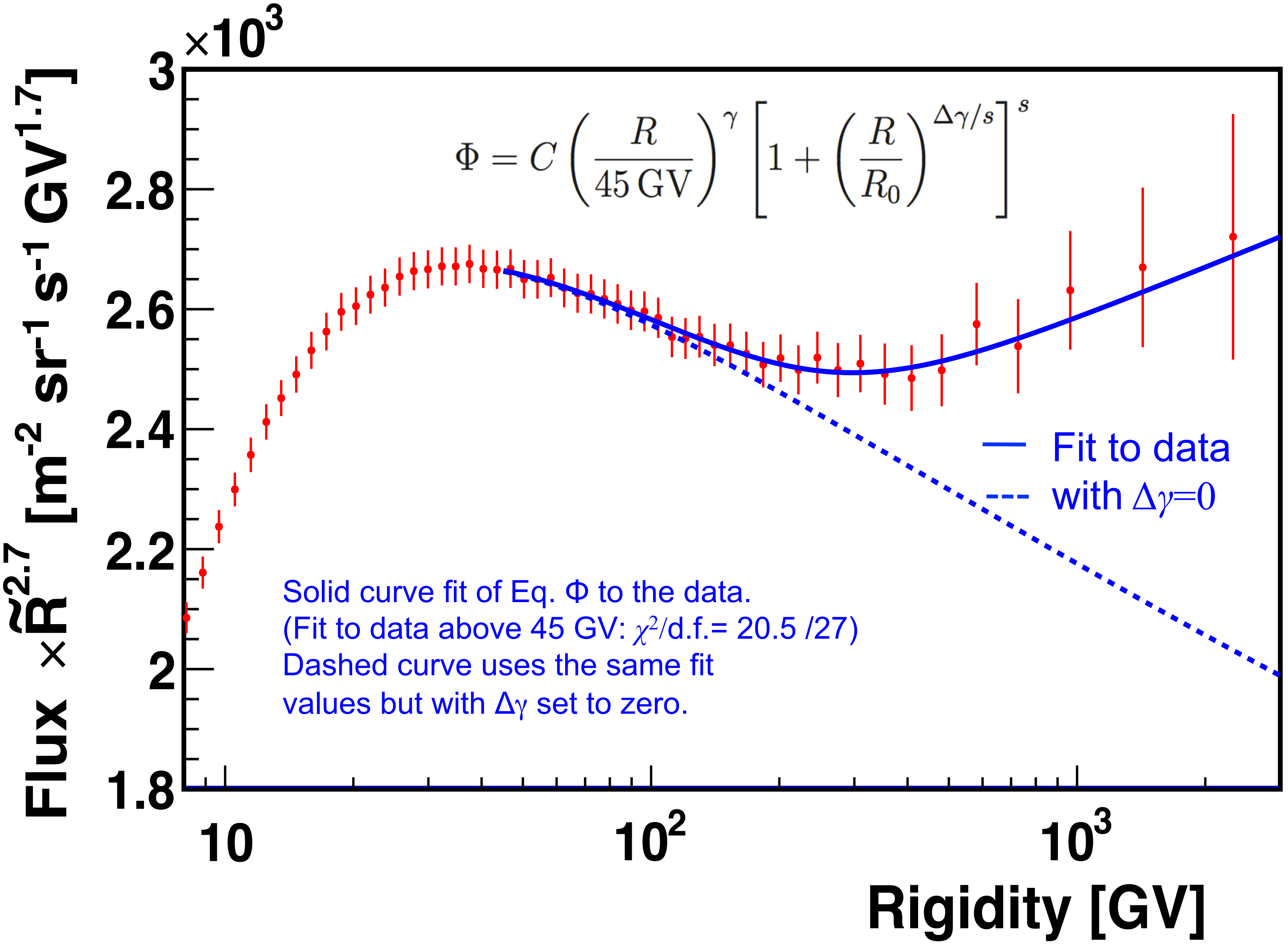


To be presented by S. Haino (Academia Sinica, Taiwan)

AMS Helium Flux



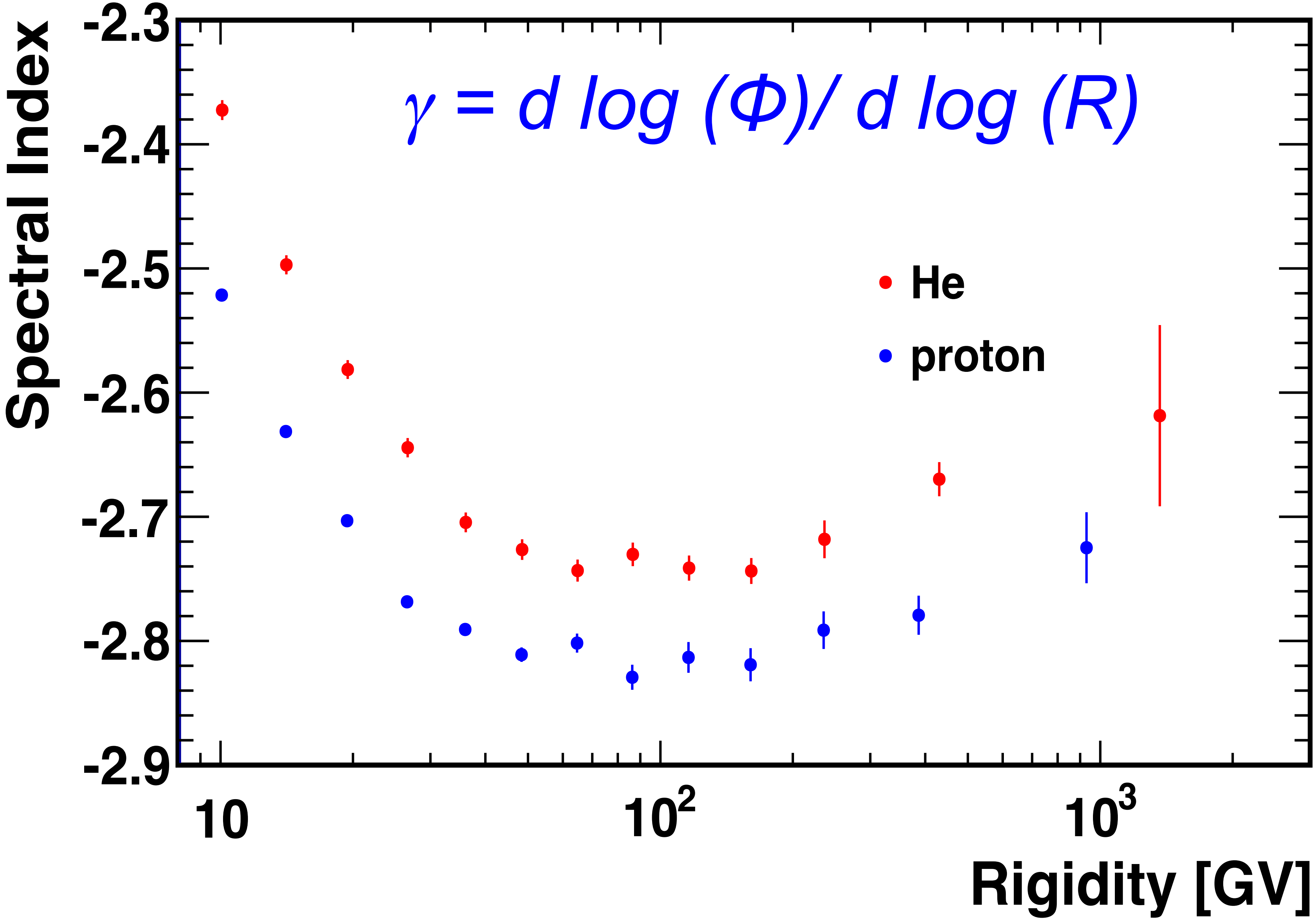
AMS Helium Flux



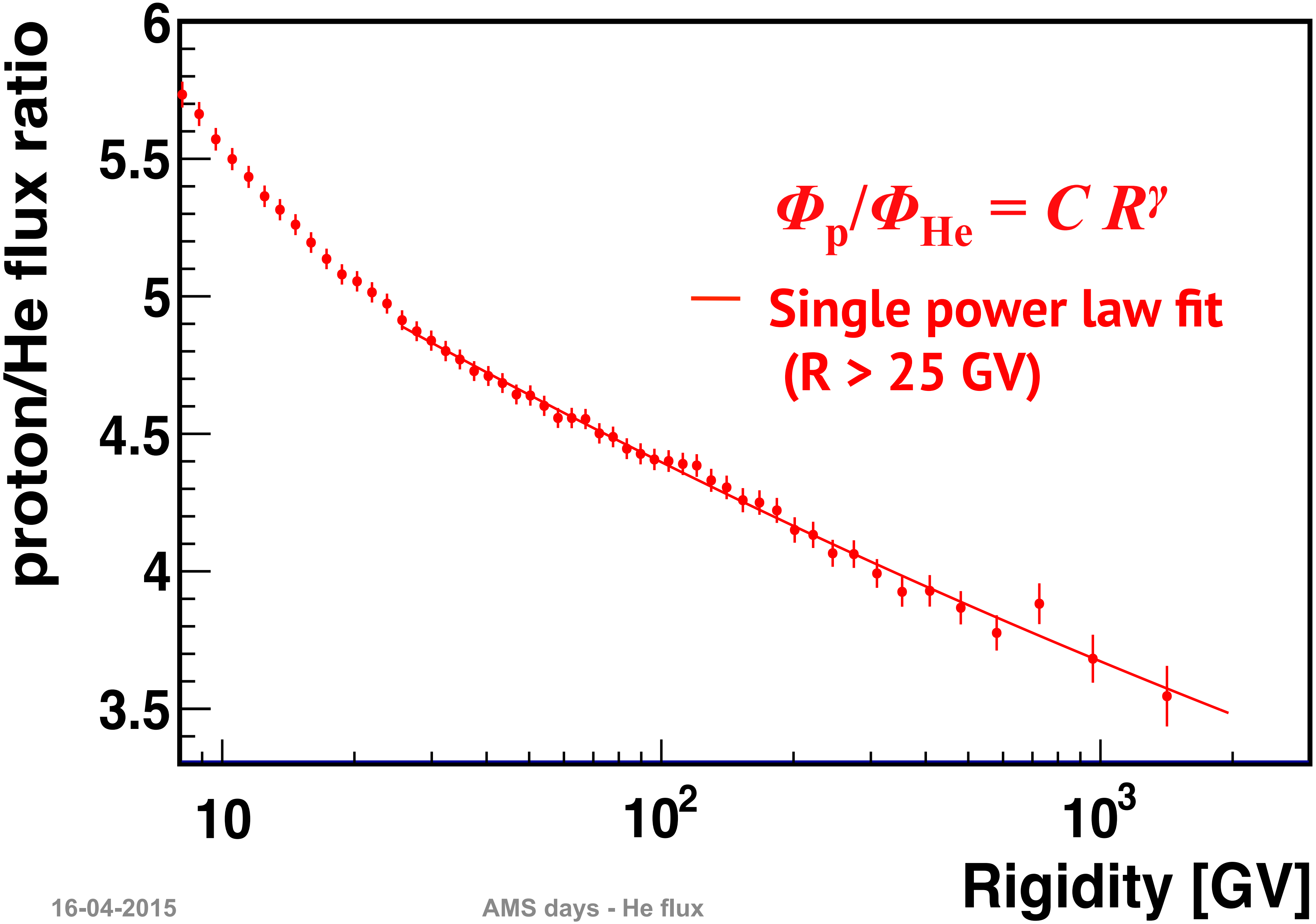
$$\Phi = C\left(\frac{R}{45\,\mathrm{GV}}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/s}\right]^{s}$$

Solid curve fit of Eq. Φ to the data.
(Fit to data above 45 GV: χ^2/d.f.= 20.5 /27)
Dashed curve uses the same fit
values but with Δγ set to zero.

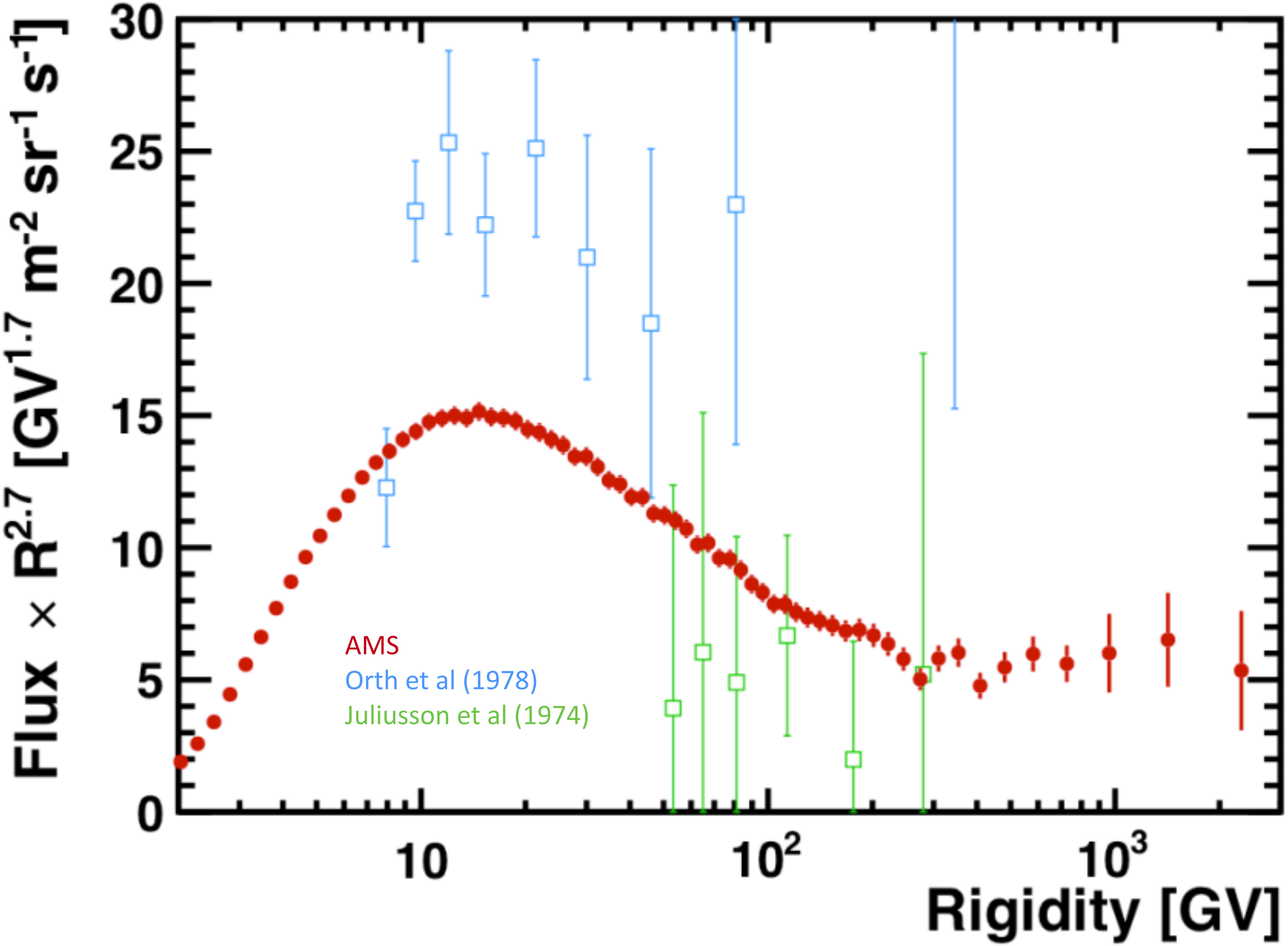
Model Independent
Spectral Indices Comparison



proton/He flux ratio

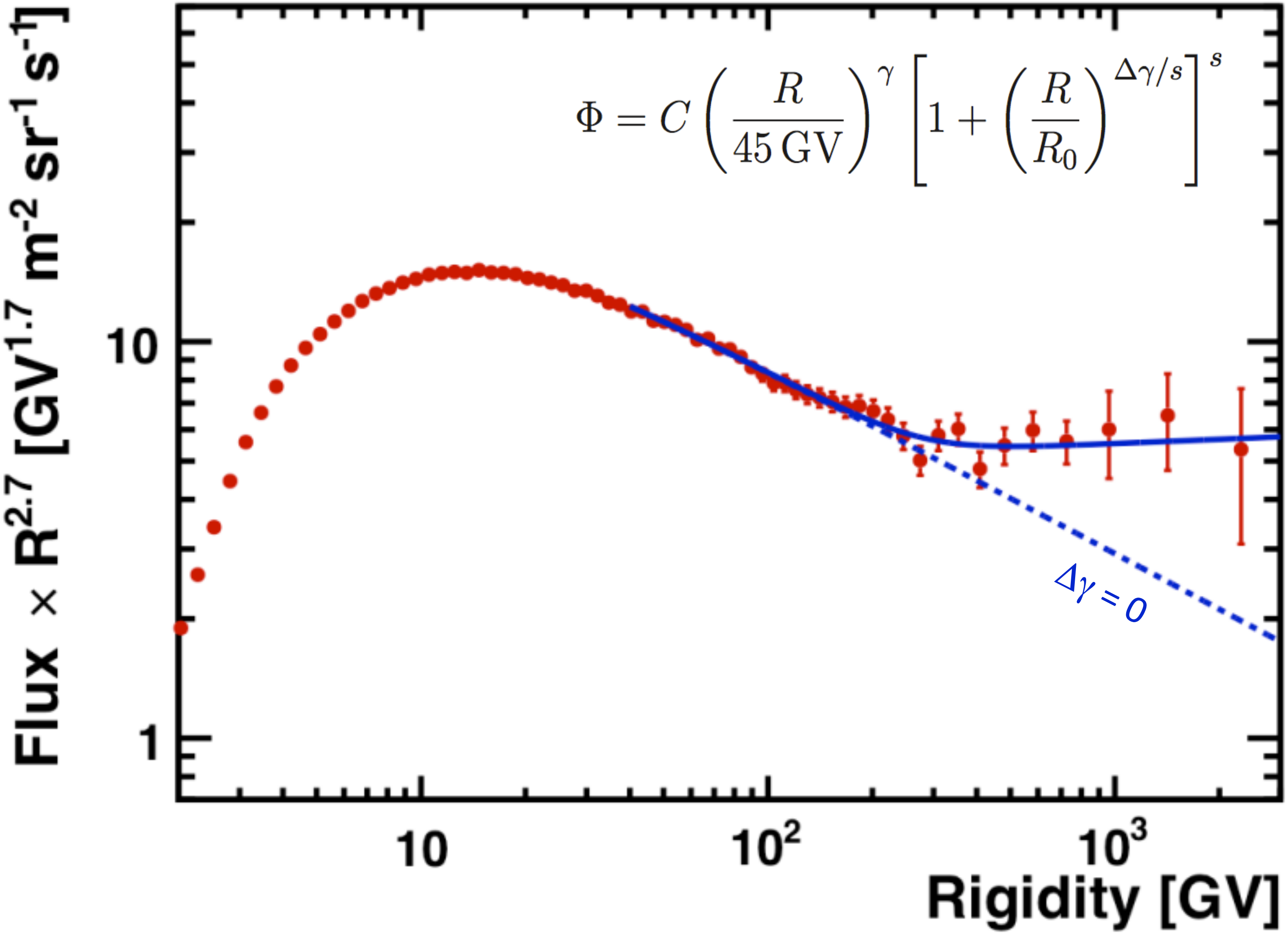


AMS Lithium flux – current status



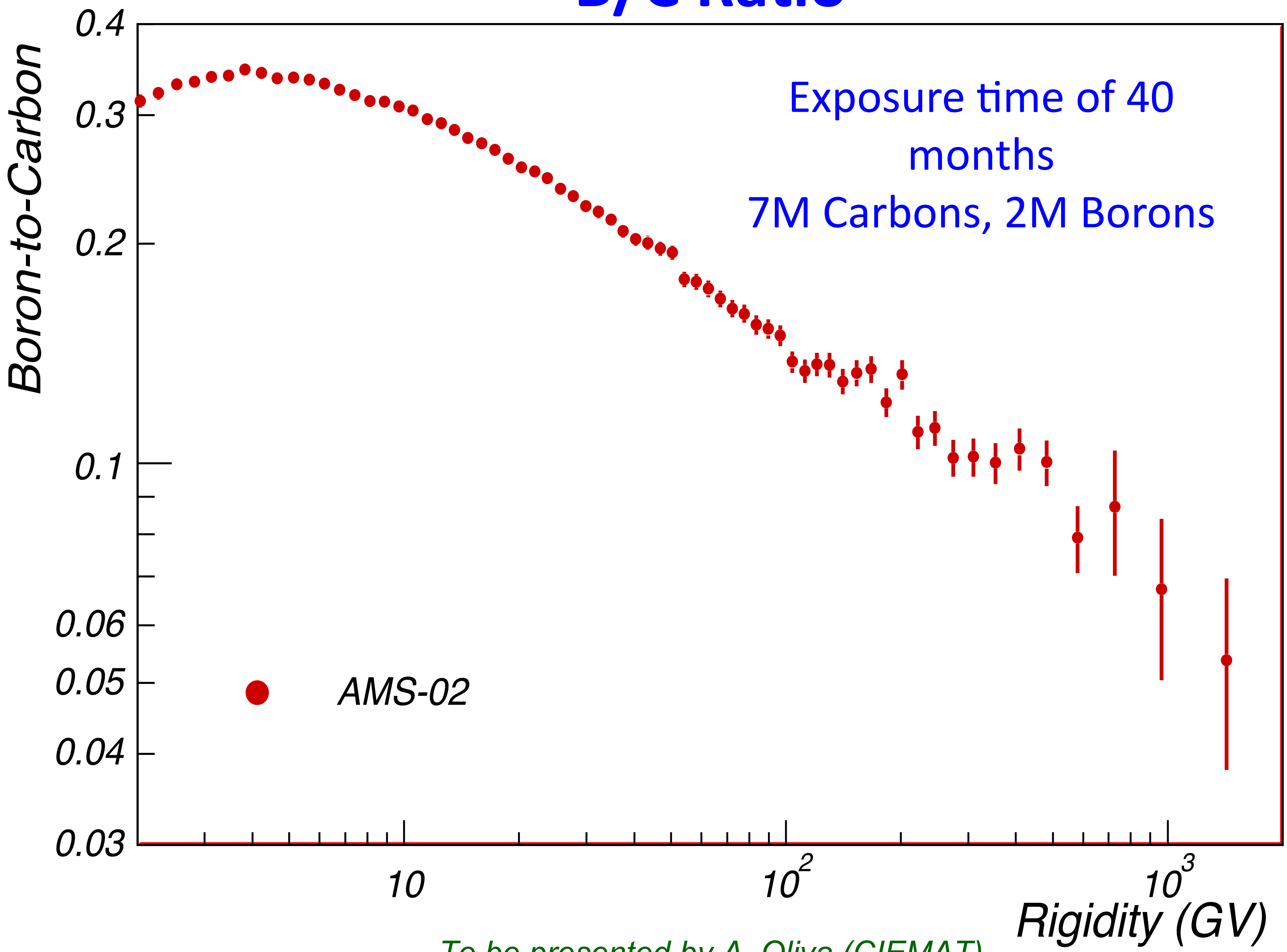
To be presented by L. Derome (LPSC, Grenoble)

Lithium flux with two power law fit



Slope changes at about the same rigidity as for protons and helium

B/C Ratio

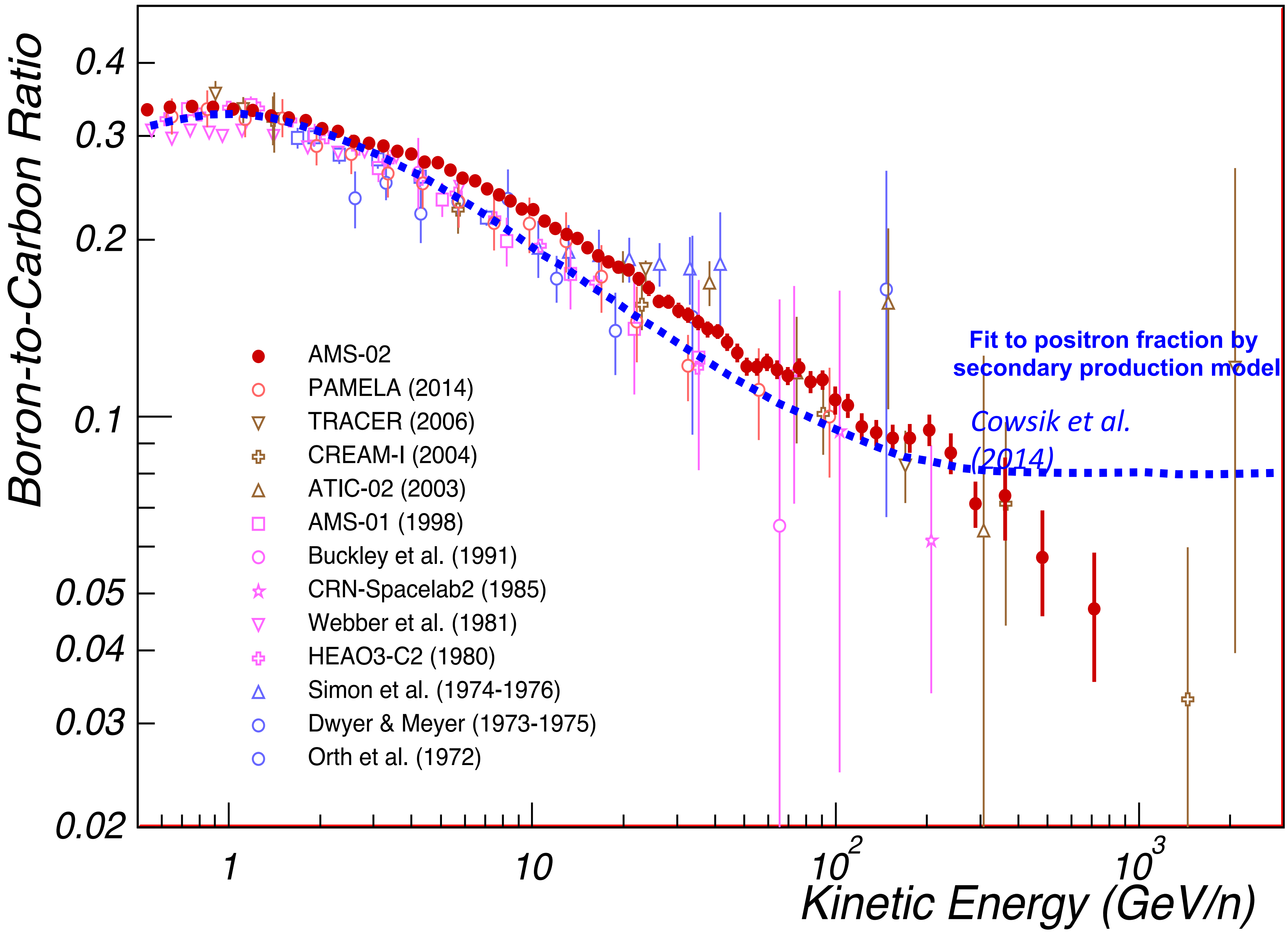


Exposure time of 40 months

7M Carbons, 2M Borons

To be presented by A. Oliva (CIEMAT)

B/C Ratio converted in Kinetic Energy

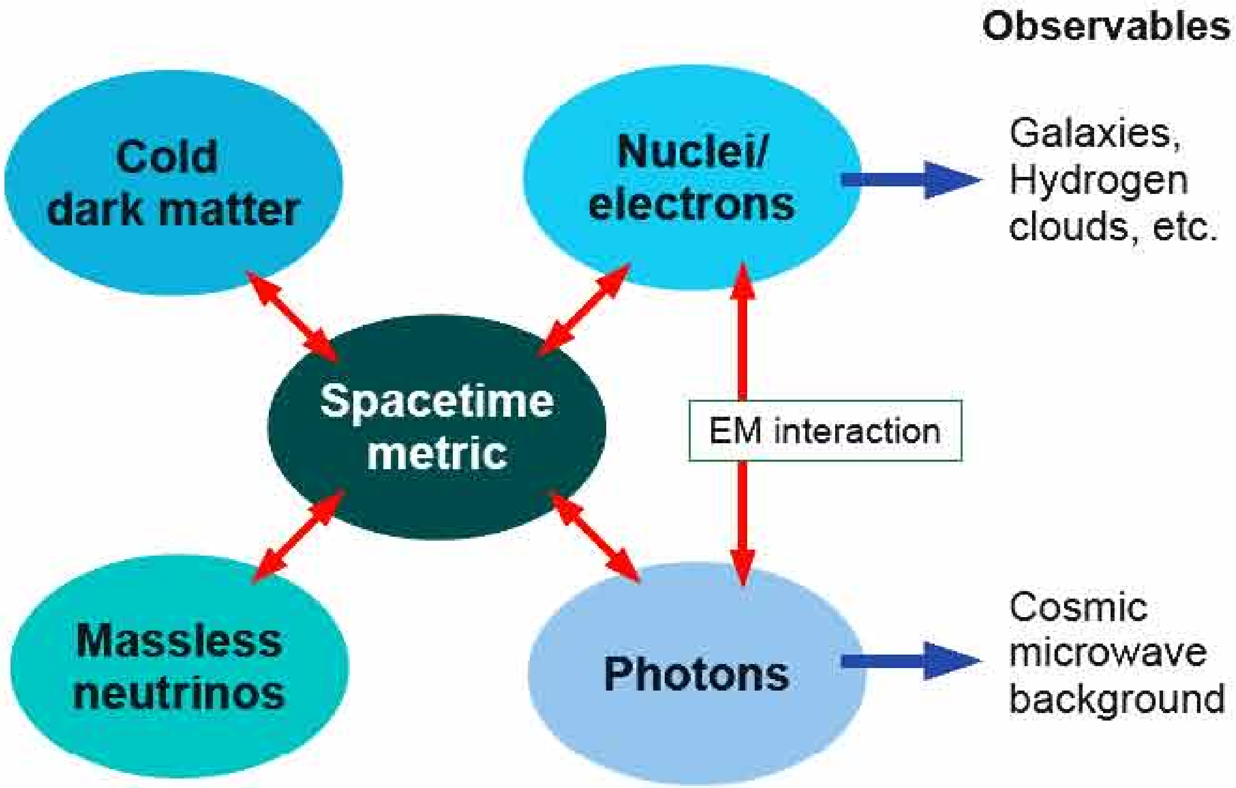


Will dark matter mistery be solved by Cosmic Rays ?

Why dark matter ?

…because of cosmological observations !

Particle content of the concordance ΛCDM model...



Observables

Cold dark matter

Nuclei/ electrons

Galaxies, Hydrogen clouds, etc.

Spacetime metric

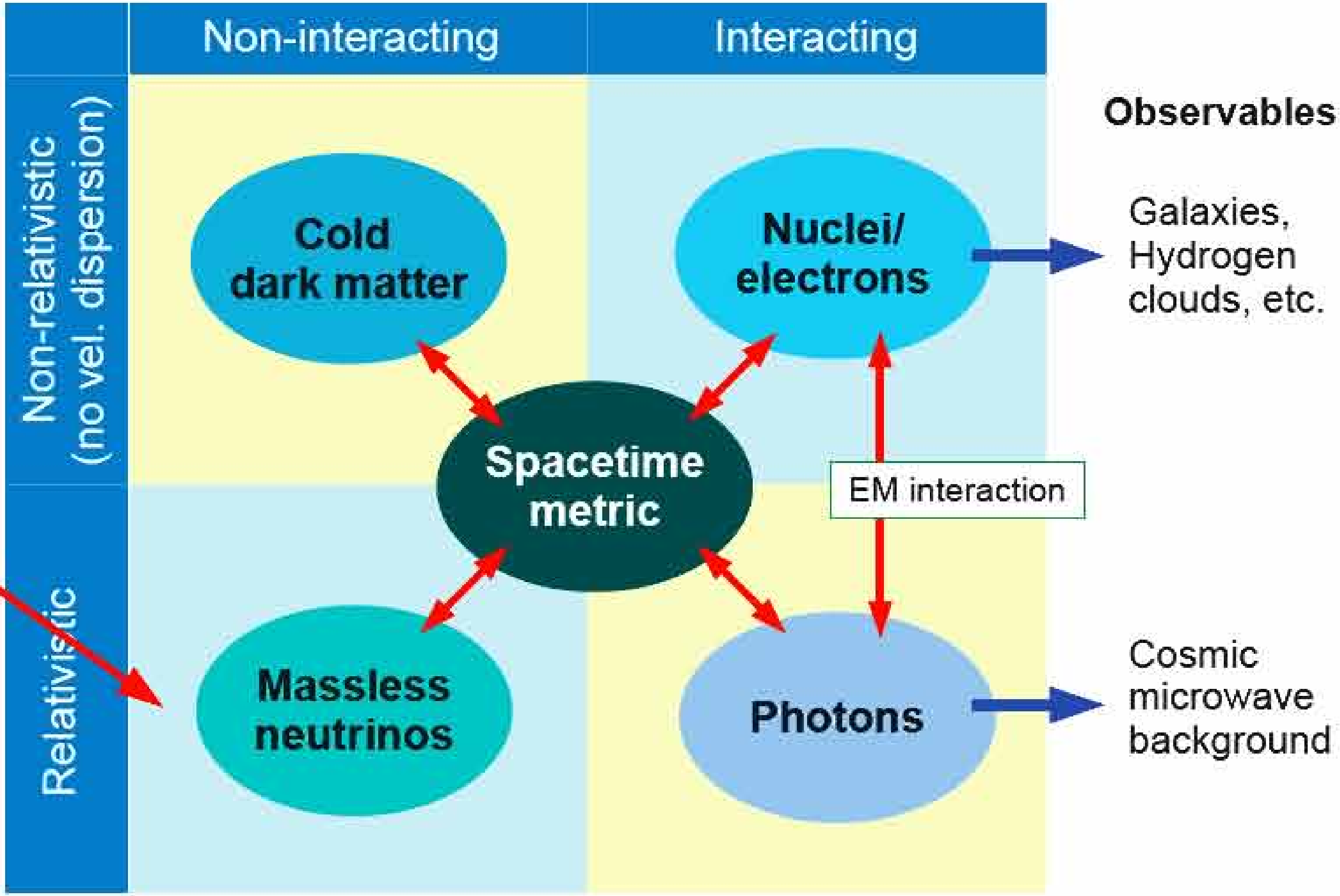
EM interaction

Massless neutrinos

Photons

Cosmic microwave background

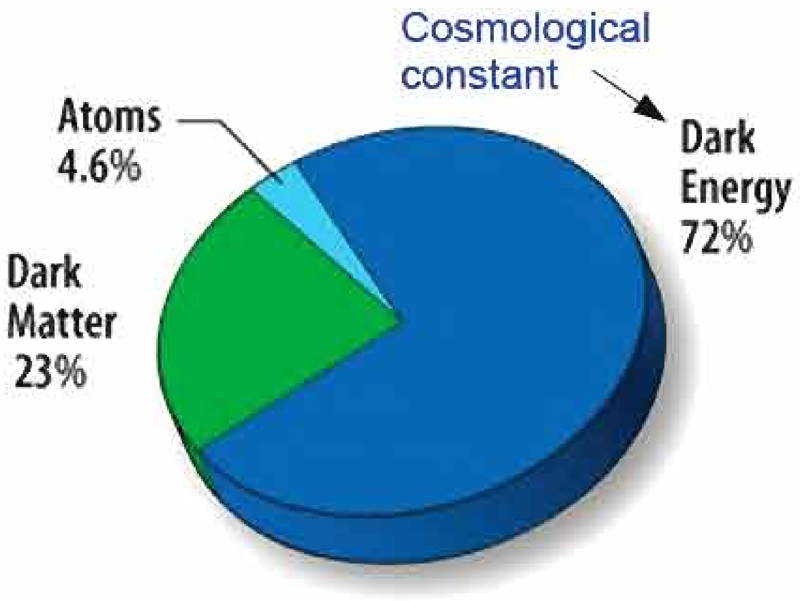
Particle content of the concordance ΛCDM model...



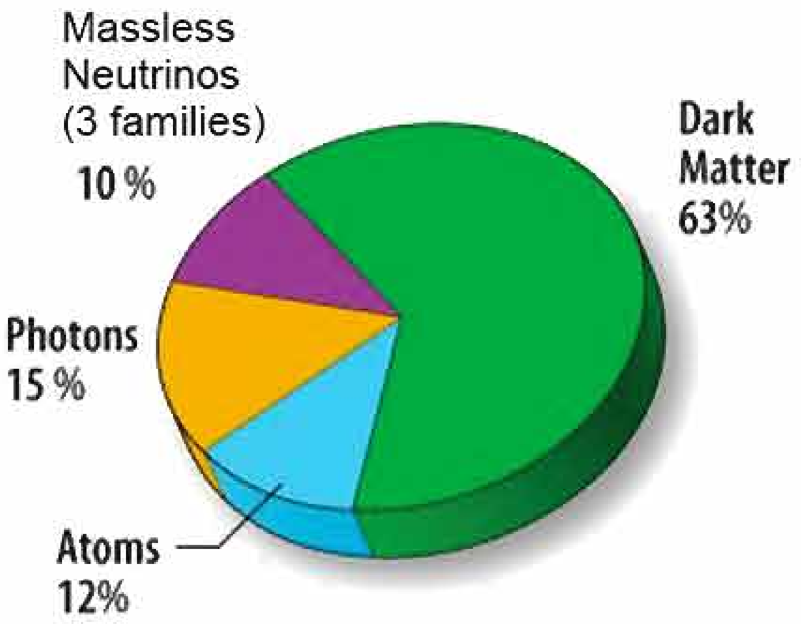
Extra neutrinos
= extra relativistic, non-interacting stuff (no requirement on the quantum numbers or statistics)

The concordance flat ΛCDM model...

- The simplest model consistent with **observations**.



Composition today



13.4 billion years ago
(at photon decoupling)

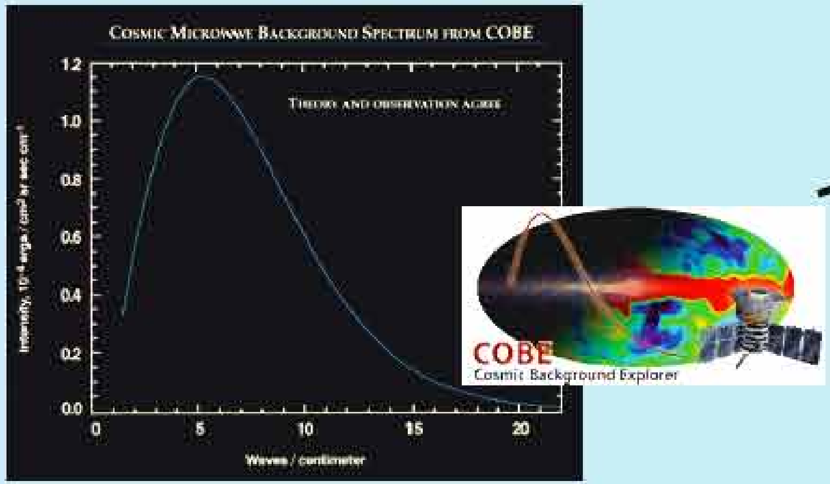
Plus flat spatial geometry+initial conditions from single-field inflation

The concordance flat ΛCDM model...

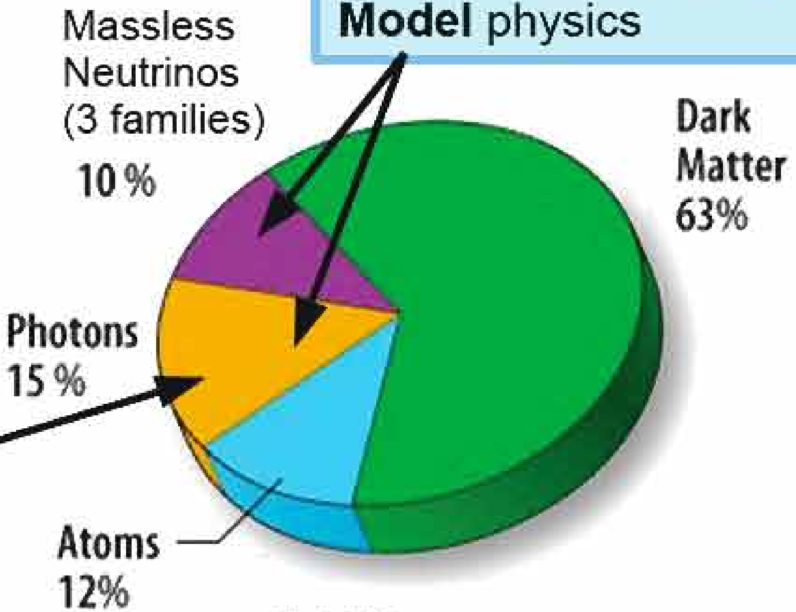
- The simplest model consistent with **observations**.

Photon energy density fixed by CMB temperature & spectrum measurements:

$$T_{\mathrm{CMB}} = 2.725 \pm 0.001\,\mathrm{K}$$



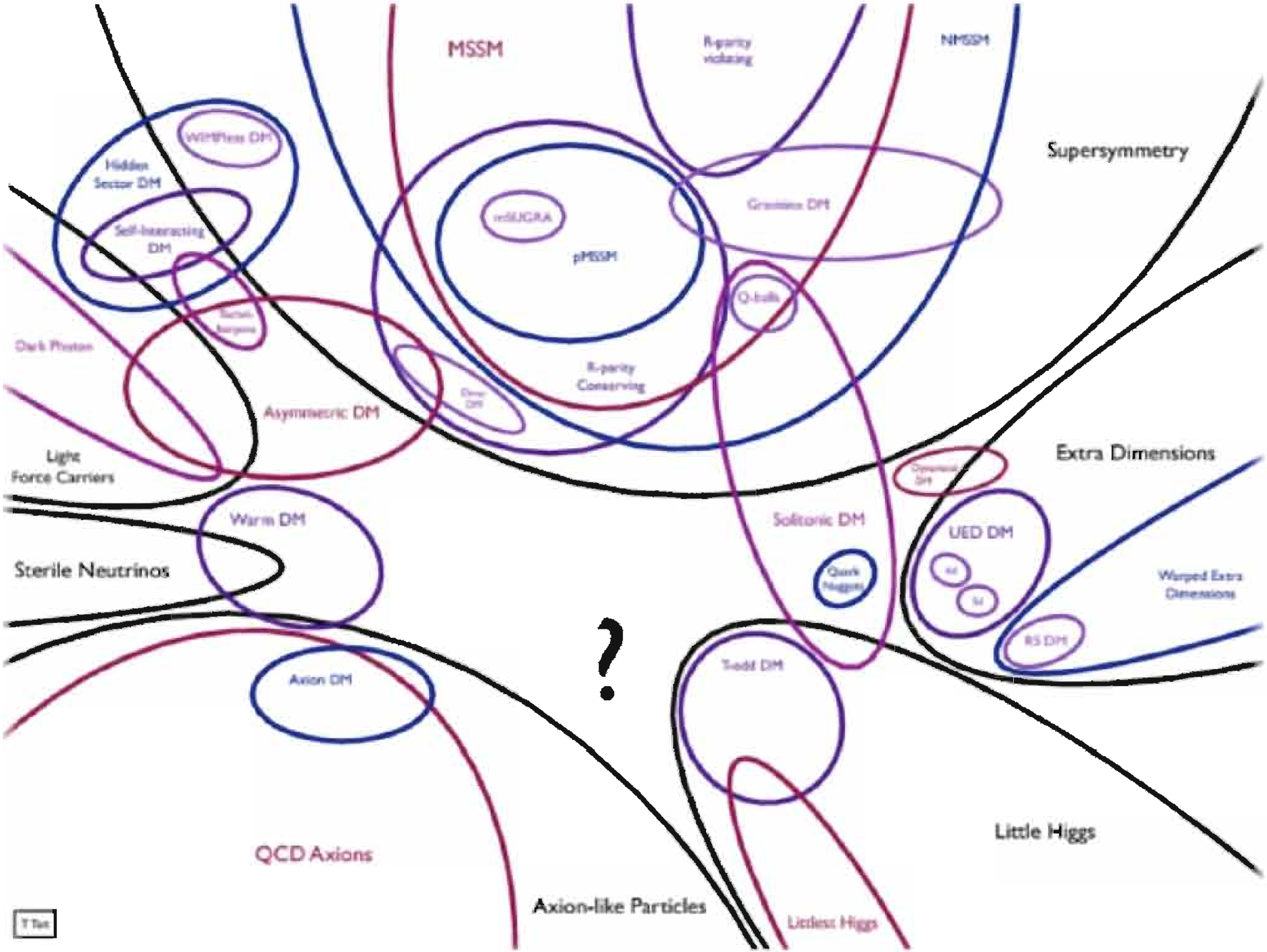
ν-to-γ energy density ratio fixed by **Standard Model** physics



13.4 billion years ago
(at photon decoupling)

What is dark matter ?

…we do not really know !


MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Dark Photon
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Dynamical DM
Extra Dimensions
Warm DM
Solitonic DM
UED DM
6d
5d
Warped Extra Dimensions
Sterile Neutrinos
Quark Nuggets
RS DM
?
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

Pride and ....

- Non-gravitational interactions between DM and Standard Model particles are highly constrained by the lack of observations of particle DM: this strongly **disfavors DM that is electrically charged or interacts by the strong nuclear force**.
- DM must clump gravitationally to form galaxies. This requires **DM to be “cold”, that is non-relativistic** at the time of structure formation, or possibly “warm”.
- So the theoretically best-motivated candidates for a DM particle are a **weakly interacting massive particle (WIMP) or an axion**.
- Typically WIMPs are considered to be **thermal relics** left over from the Early Universe.
- The abundance today is inversely proportional to the WIMP self-annihilation cross section, which sets the “relic density” from the Big Bang. The fractional abundance, relative to the critical density, is

$$\Omega_{WIMP} \approx \frac{0.1}{h^2}\left(\frac{3\ \cdot 10^{-26} cm^3 s^{-1}}{\langle \sigma v \rangle}\right) \qquad \begin{cases} \Omega_{WIMP} h^2 = 0.1199 \\ h = 0.6778 \end{cases}$$

- This is a typical value expected for a particle with mass near the weak scale [O(100 GeV)]: the fact that the observed abundance of DM points to new physics at the weak scale, completely independent of particle physics motivations, is the so-called **WIMP miracle.**

……prejudice

- The only real bound on a thermal relic DM particle is that it should be **heavier than 1 keV** so that it is cold instead of hot. On the other hand DM particles must be relatively "light", meaning **lighter than a few hundred TeV**.
- This limit is a consequence of the existence of a maximum annihilation cross section for a particle of a given mass, m_{DM}, set by the so-called *unitarity bound*.
- Griest and Kamionkowski applied this bound and the constraint on the relic density to infer an upper limit on the dark matter particle mass: using PLANCK constraints, this bound is something like: $m_{DM} \lesssim 120$ TeV.

So it's possible to identify some well spread paradigms, or "theoretical prejudice", for this type of unknown matter:

1. DM is dark, i. e. it has a zero electromagnetic cross section;
2. DM particles are thermal relics: this would imply, **without new physics contributions**, that m_{DM} should be less than 1 TeV. But it can be in principle very massive.
3. DM resembles usual Standard Model "simplest" particles, stable and not affected by Standard Model-like anomalies and violations.

Searches with CR with space borne satellites ?

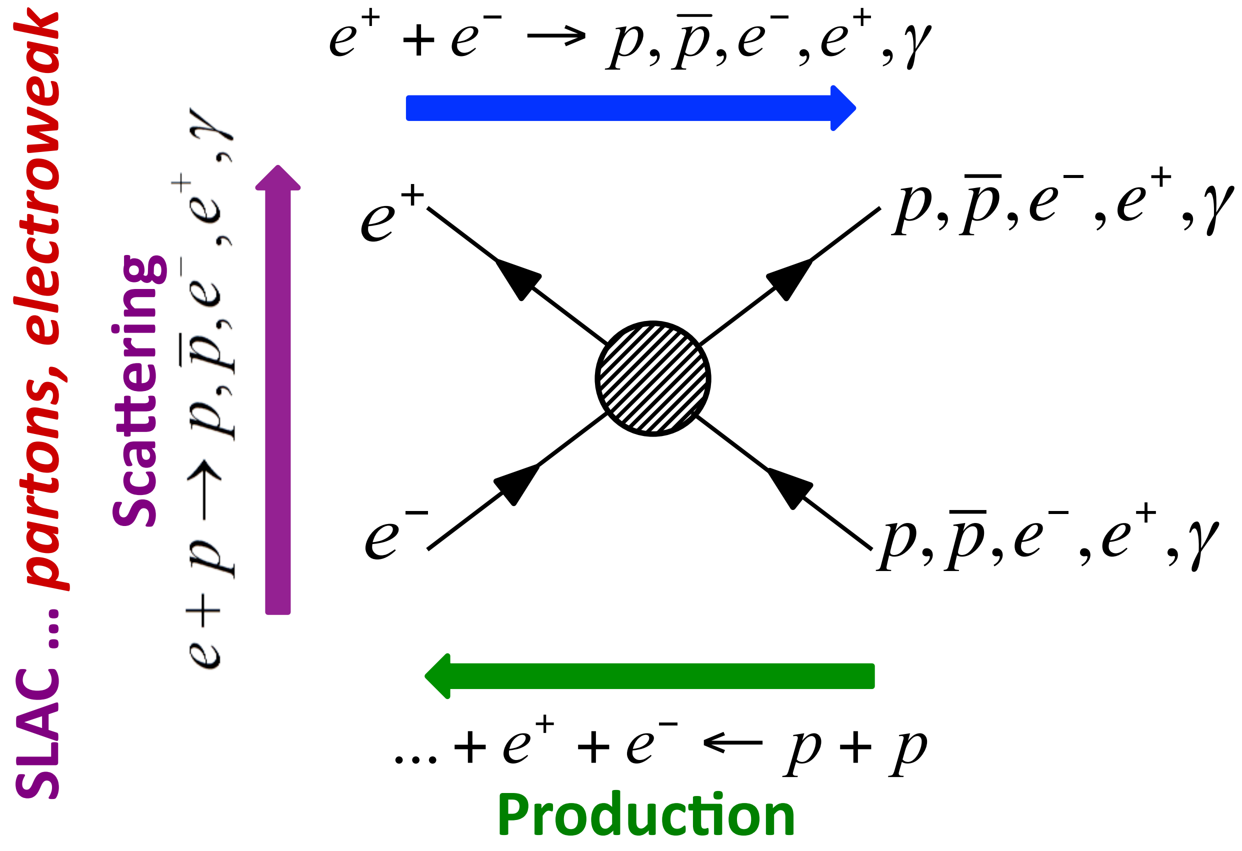
…some advantages :

- it must be somewhere out there
- no limit in the mass range

…some disadvantages :

- only indirect effects of its presence
- uncertainties in propagation, clustering

Physics of electrons and protons



SPEAR, DORIS, PEP, PETRA, LEP, … *Ψ, τ*

Annihilation

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

SLAC … *partons, electroweak*

Scattering

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

$\ldots + e^+ + e^- \leftarrow p + p$

Production

BNL, FNAL, LHC …*CP, J, Υ, t, Z, W,* h^0

Three independent methods to search for Dark Matter

AMS, Fermi-LAT, HESS, …

Annihilation

$$\chi + \chi \rightarrow e^{+}, \overline{p}, \gamma, \ldots$$

LUX

DARKSIDE

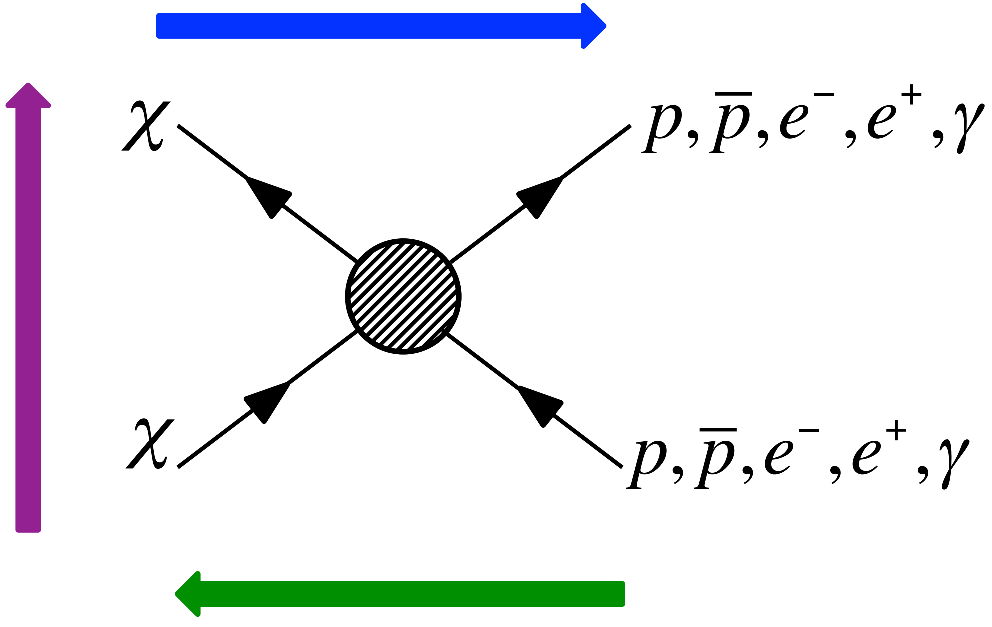
XENON 100

CDMS II

…

Scattering

$$\chi + N \rightarrow \chi + N$$



$$\ldots + \chi + \chi \leftarrow p + p$$

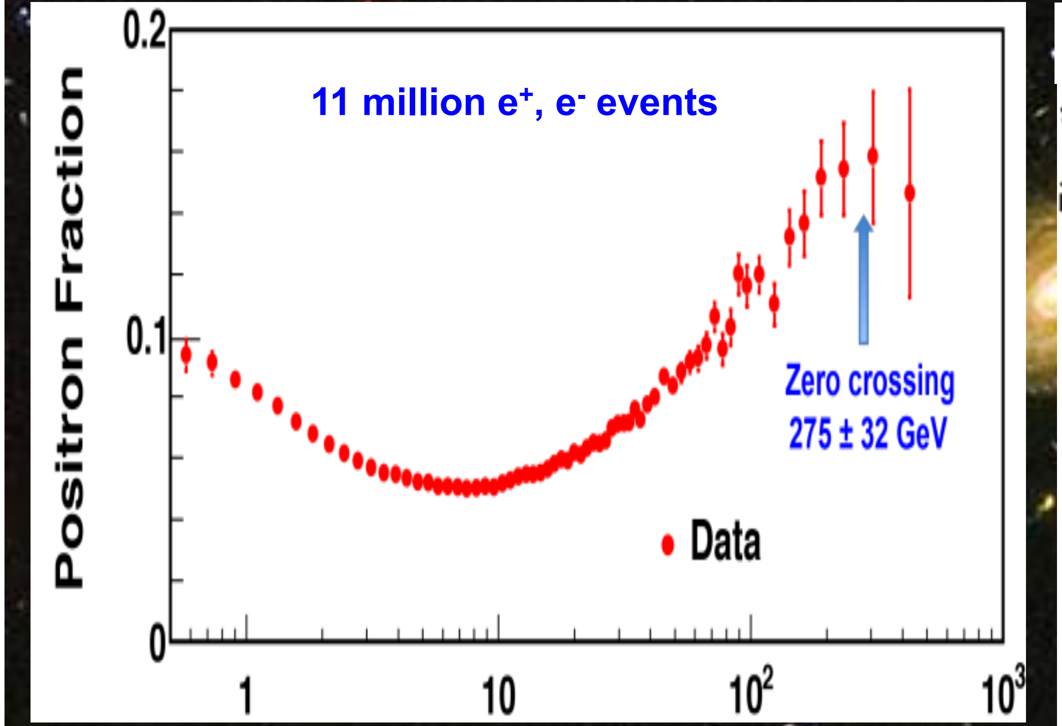
Production

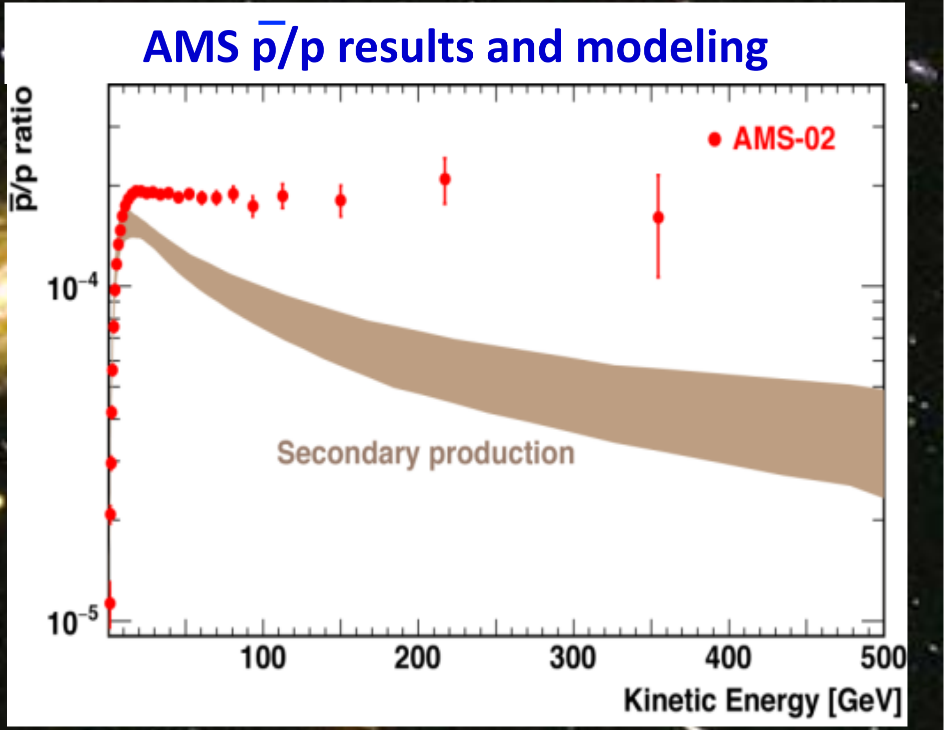
LHC

The Origin of Dark Matter

Collision of “ordinary” Cosmic Rays produce e+, $\bar{p}$..

Collisions of Dark Matter (neutralinos, χ) will produce additional e+, $\bar{p}$, …

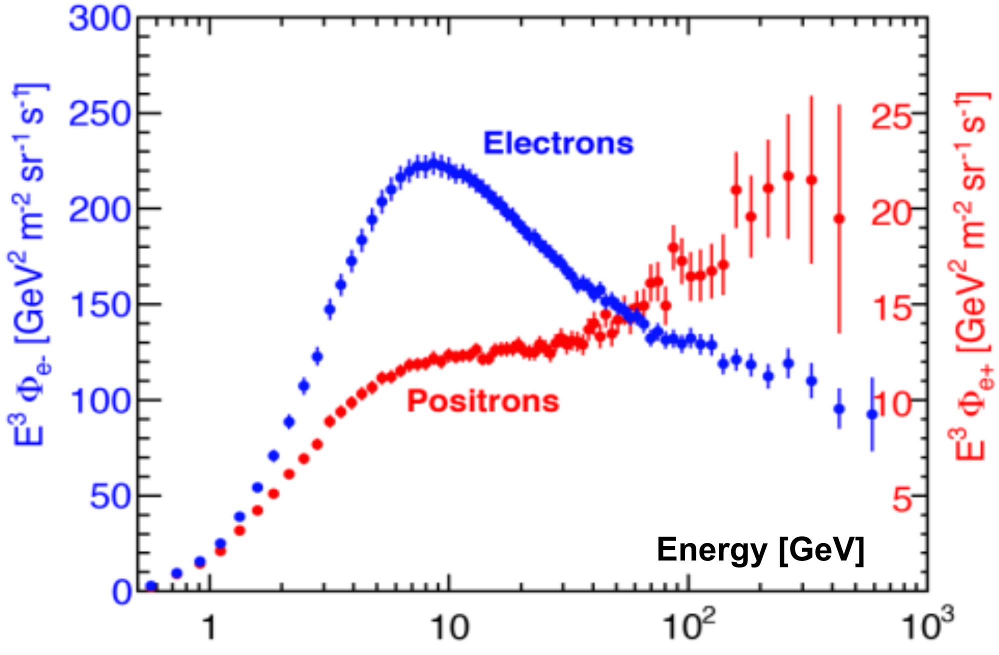


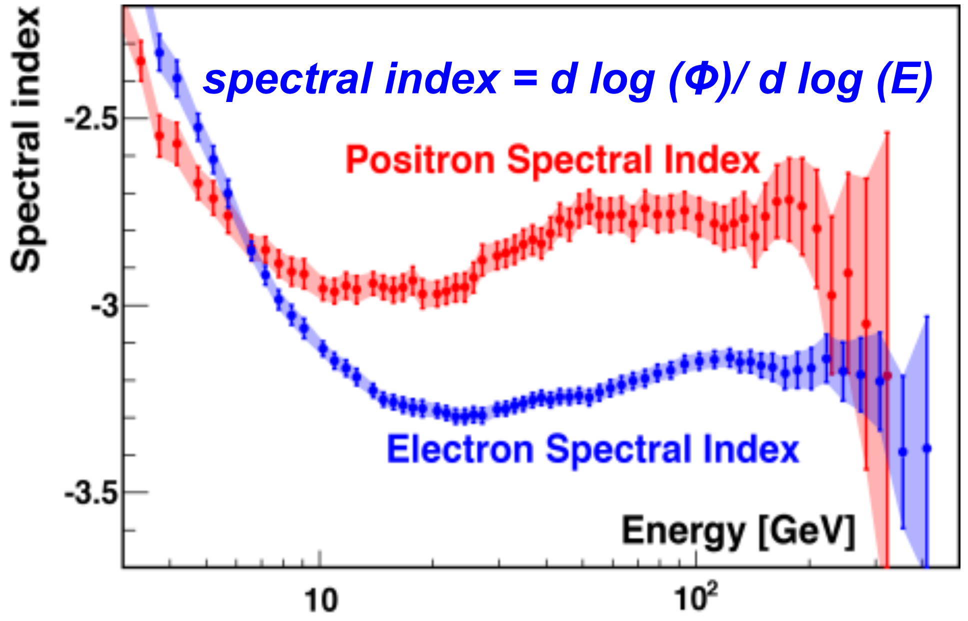

AMS $\bar{p}$/p results and modeling

To identify the Dark Matter signal we need

1. Measurement of e+, e−, and p-bar.
2. Precise knowledge of the cosmic ray fluxes (p, He, C, …)
3. Propagation and Acceleration (Li, B/C, …)

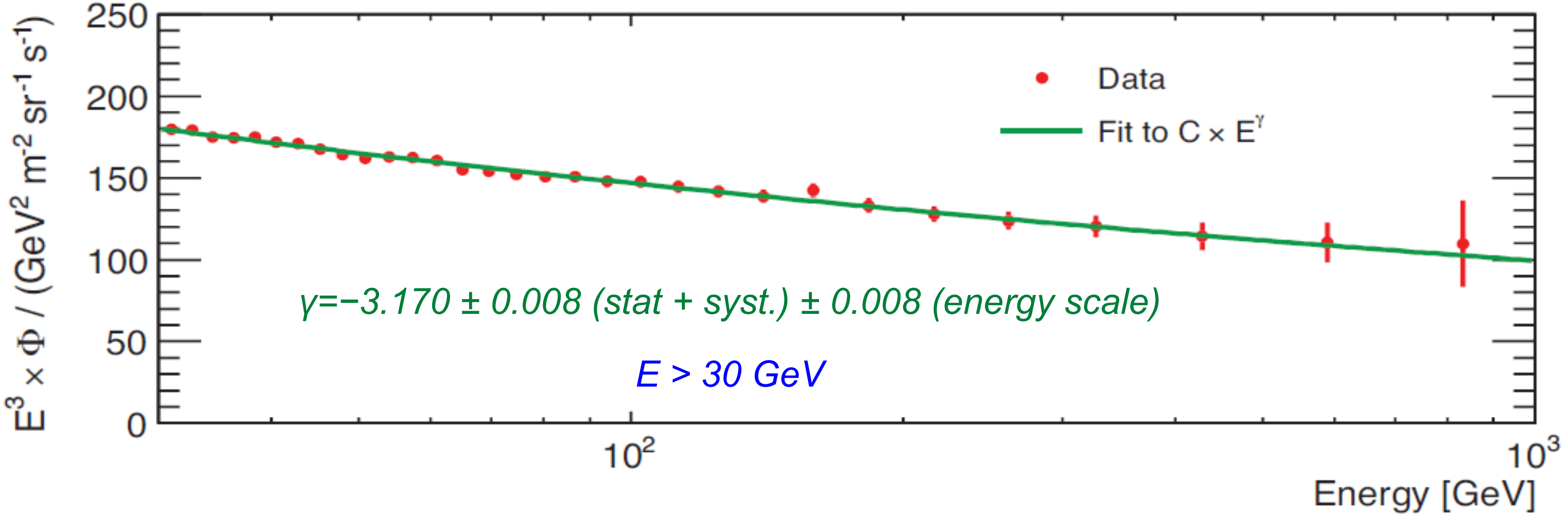
The Electron Flux and the Positron Flux





spectral index = d log (Φ)/ d log (E)

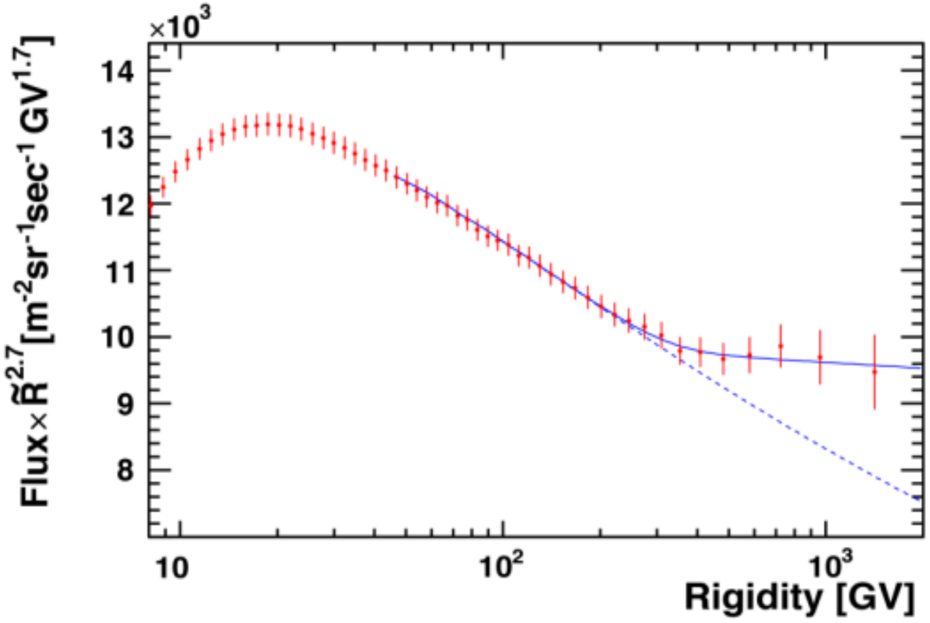
$$\Phi(e^{+}+e^{-}) = C\,E^{\gamma}$$



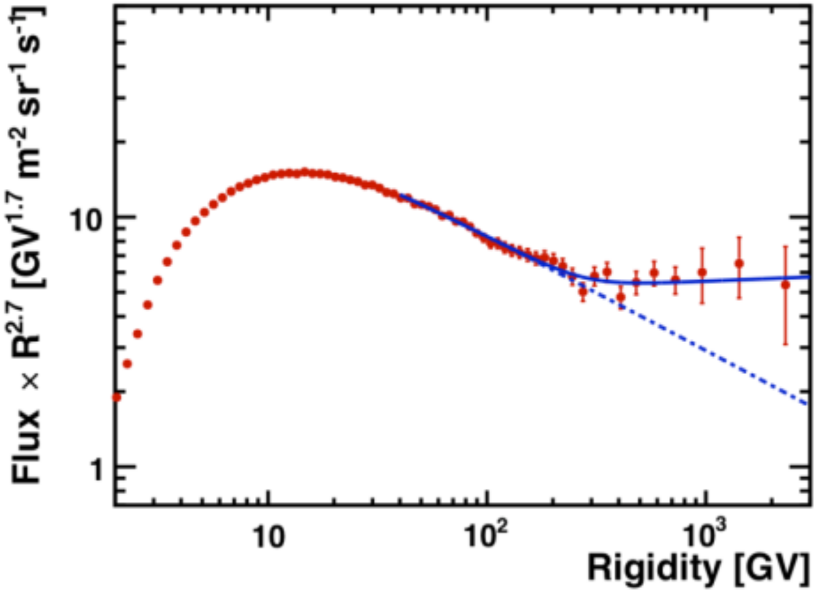
γ=−3.170 ± 0.008 (stat + syst.) ± 0.008 (energy scale)

E > 30 GeV

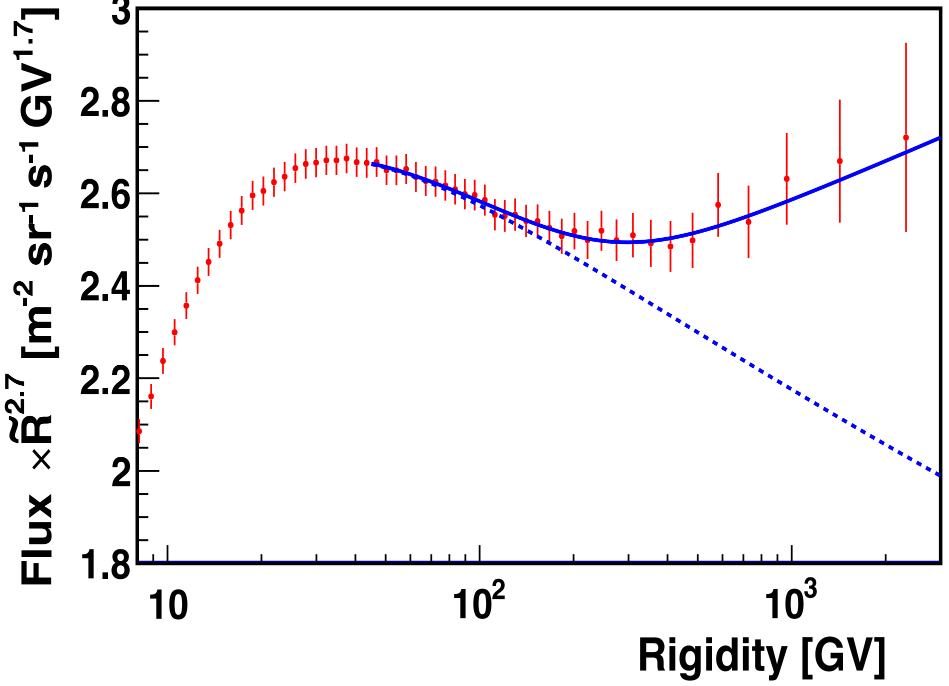
AMS proton flux



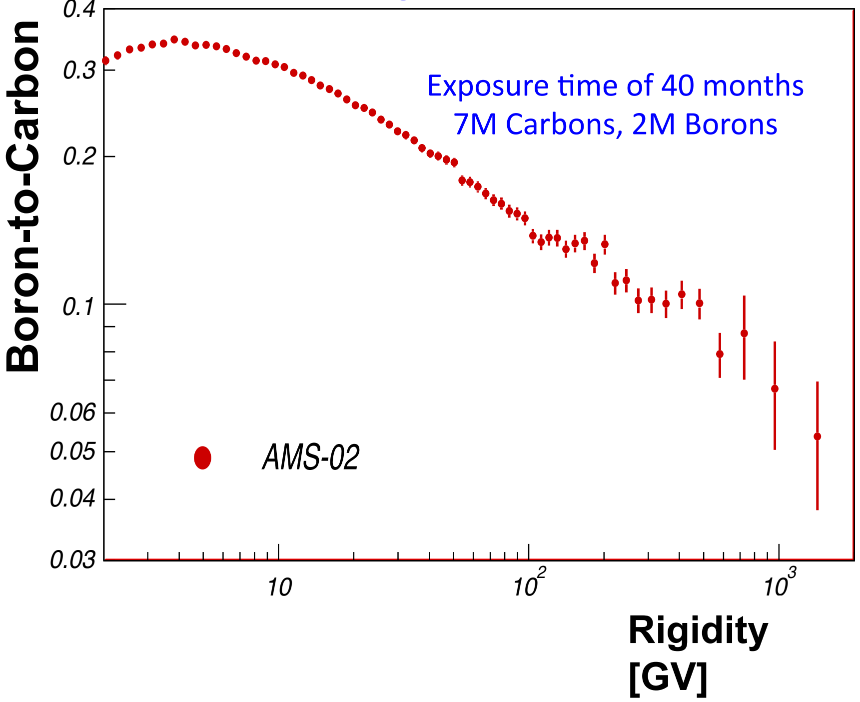
Lithium flux



AMS Helium Flux



B/C Ratio


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

DM Halo and CR Propagation Parameters

DM Halo Candidates: Isothermal, three parameters spherical halo (NFW, Moore, Cored isothermal), Burkert, Einasto… - function of α, β, γ, a astrophysical/gravitational parameters and solar system ones, $r_\odot$ and $\rho_\odot$

$$\rho(r) = \rho_\odot \left(\frac{r_\odot}{r}\right)^{\gamma} \left[\frac{1 + (r_\odot/a)^{\alpha}}{1 + (r/a)^{\alpha}}\right]^{(\beta-\gamma)/\alpha}$$

Spherical Generic DM Halo

CR Propagation Models with DM: Steady-state Parker Equation with a primary flux source term

$$Q(T, \vec{r}) = \frac{1}{2} \frac{\rho^2(\vec{r})}{m_\chi^2} \sum_f \langle \sigma v \rangle_f \frac{dN^f}{dT}$$

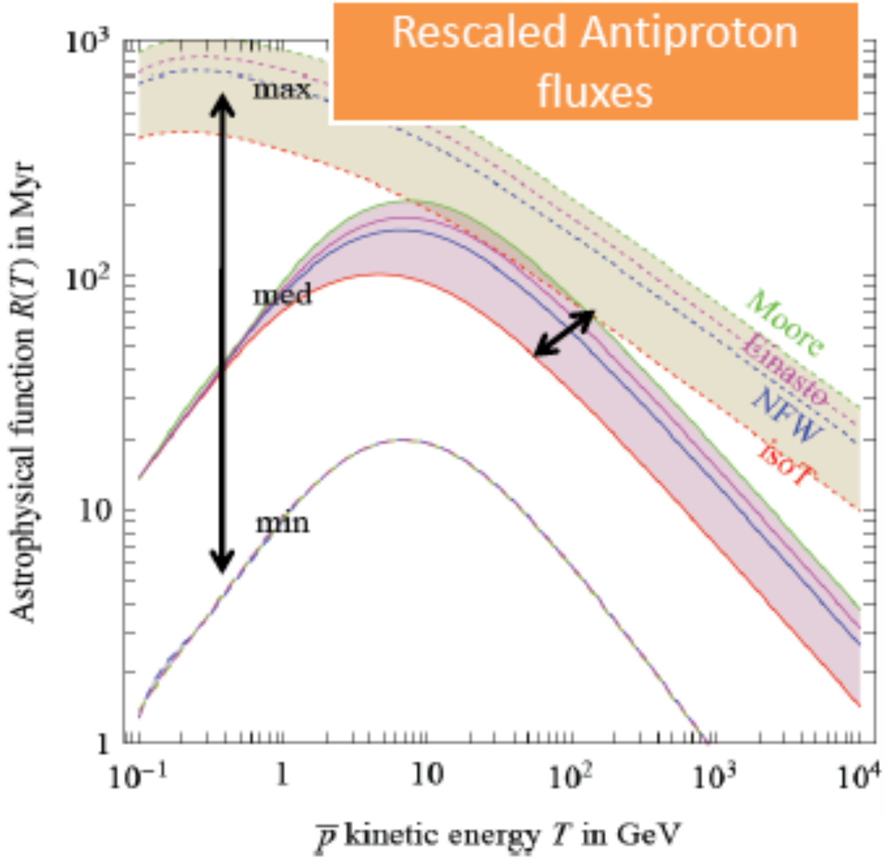
DM Flux Source

Propagation Parameters From B/C, C/O, H/He and Be Isotopes Measurements

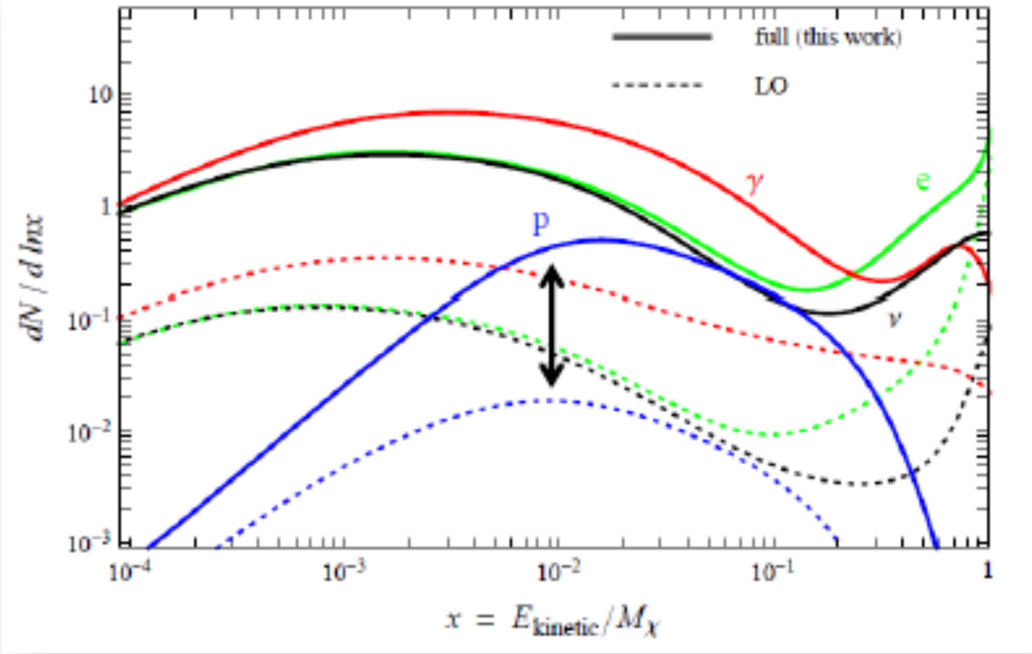
Set	z (kpc)	R (kpc)	$D_0/10^{28}$ (cm^2)	δ	V_A (km/s)	V_C (km/s)
MIN	1	10	1	0.8	15	13
MED	4	20	3	0.6	30	10
MAX	10	30	6	0.3	80	5

N. Masi 2014

Flux Uncertainties



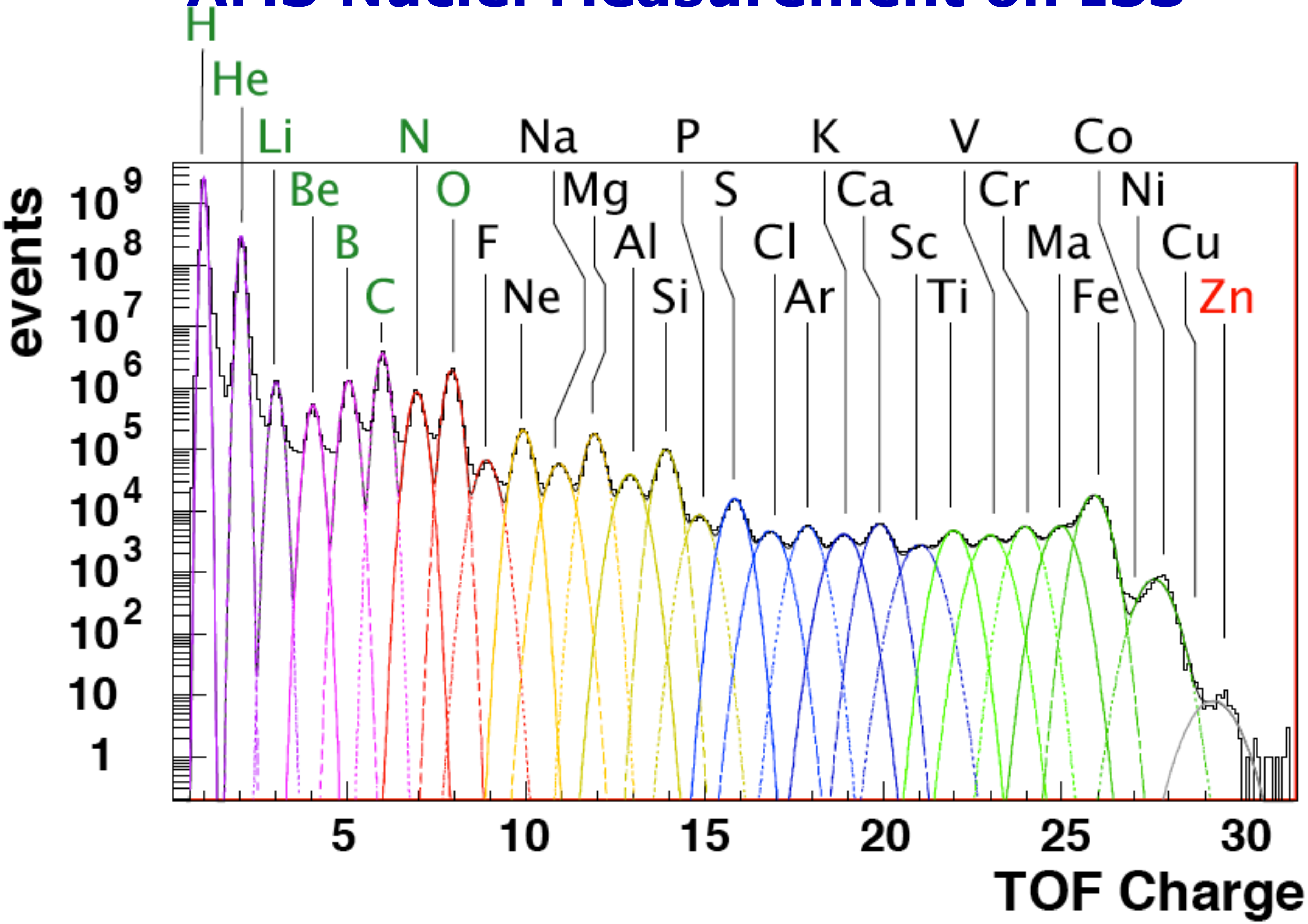
Rescaled Antiproton fluxes



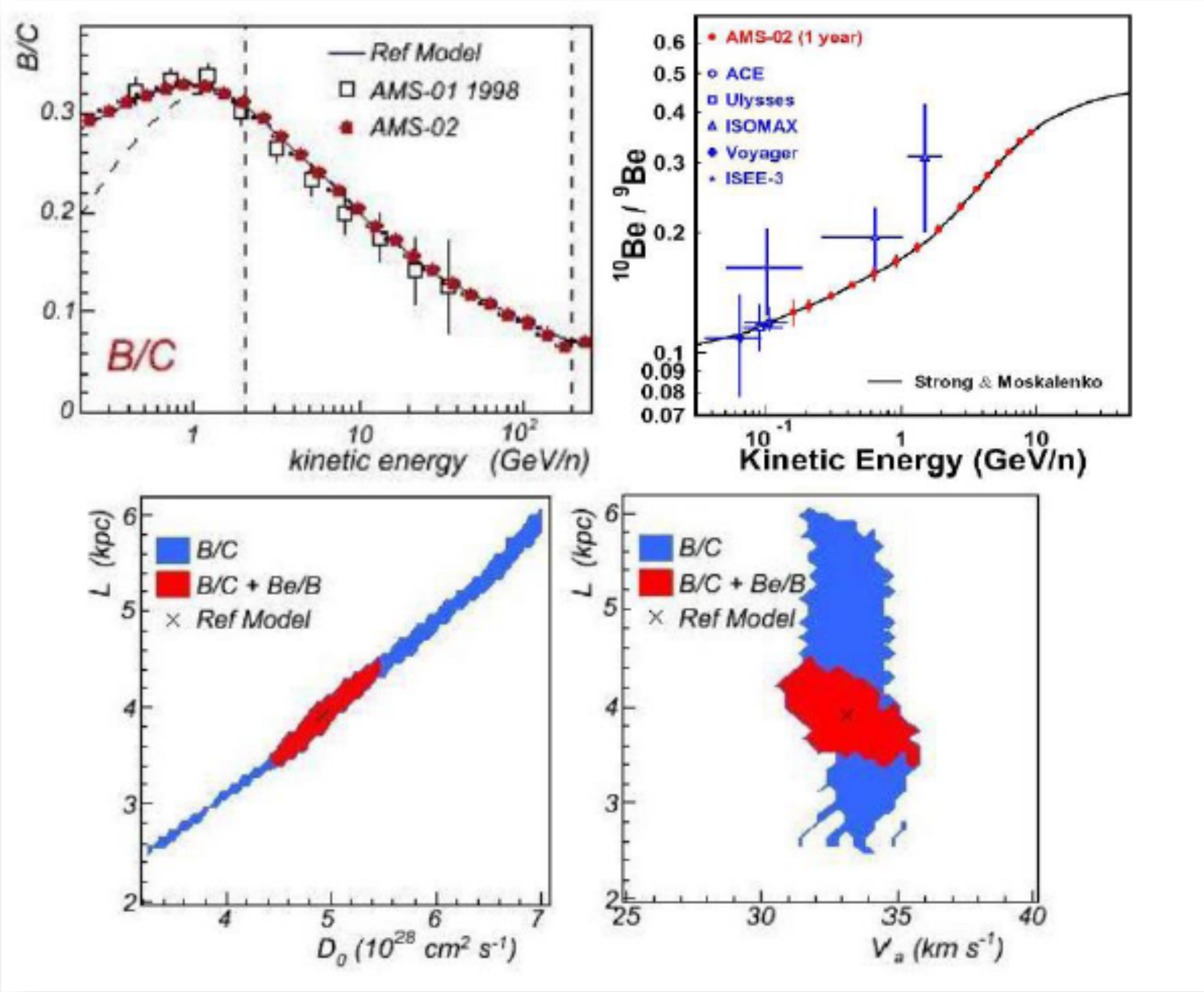
Next to Leading Order Corrections to the primary flux source term

1. ~~**Propagation models**~~: about two orders of magnitude of uncertainty, one above one below the MED set
2. **Decay models**: about one order of magnitude, because of electroweak NLO corrections
3. **Radial distribution of the halo:** modulates spectra in a less significant way, even if higher DM density regions in the inner Galaxy could induce a greater annihilation cross section

AMS Nuclei Measurement on ISS



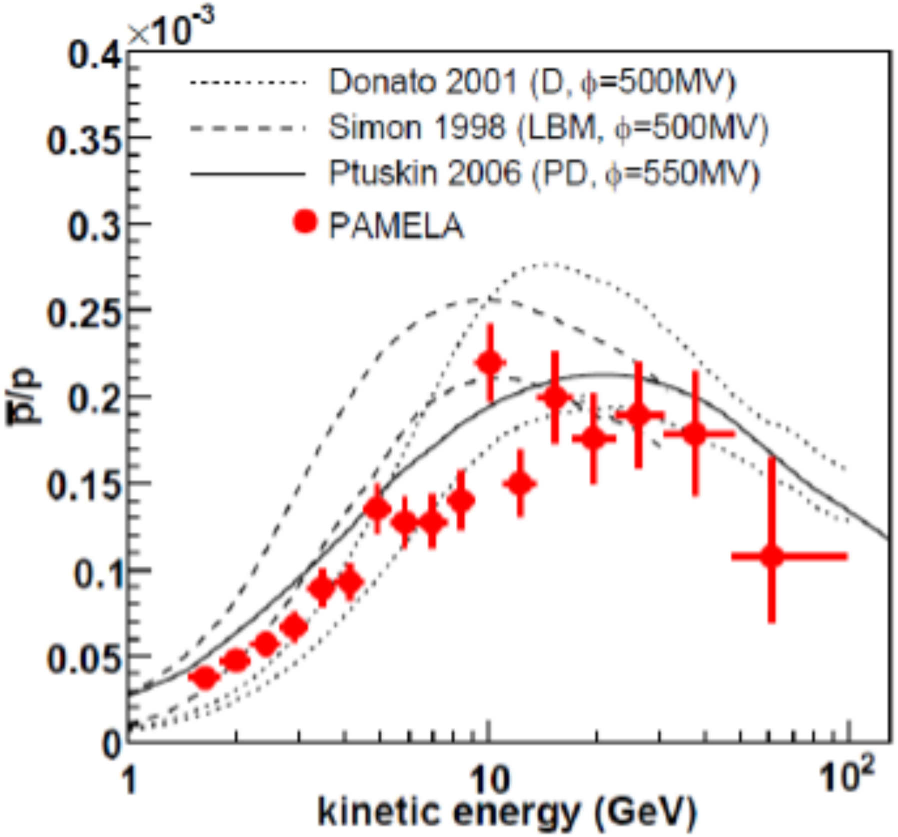
Propagation uncertainties after AMS-02, with multiple nuclei constraints

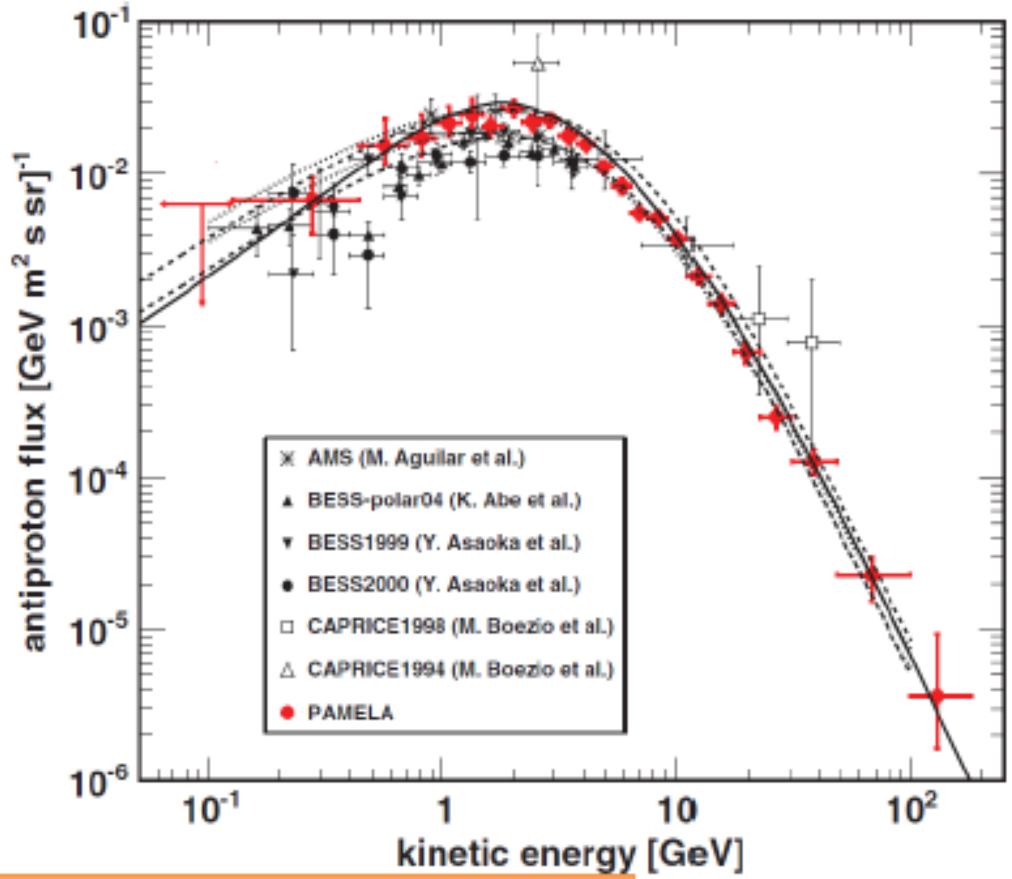


State of the art before AMS-02

PAMELA

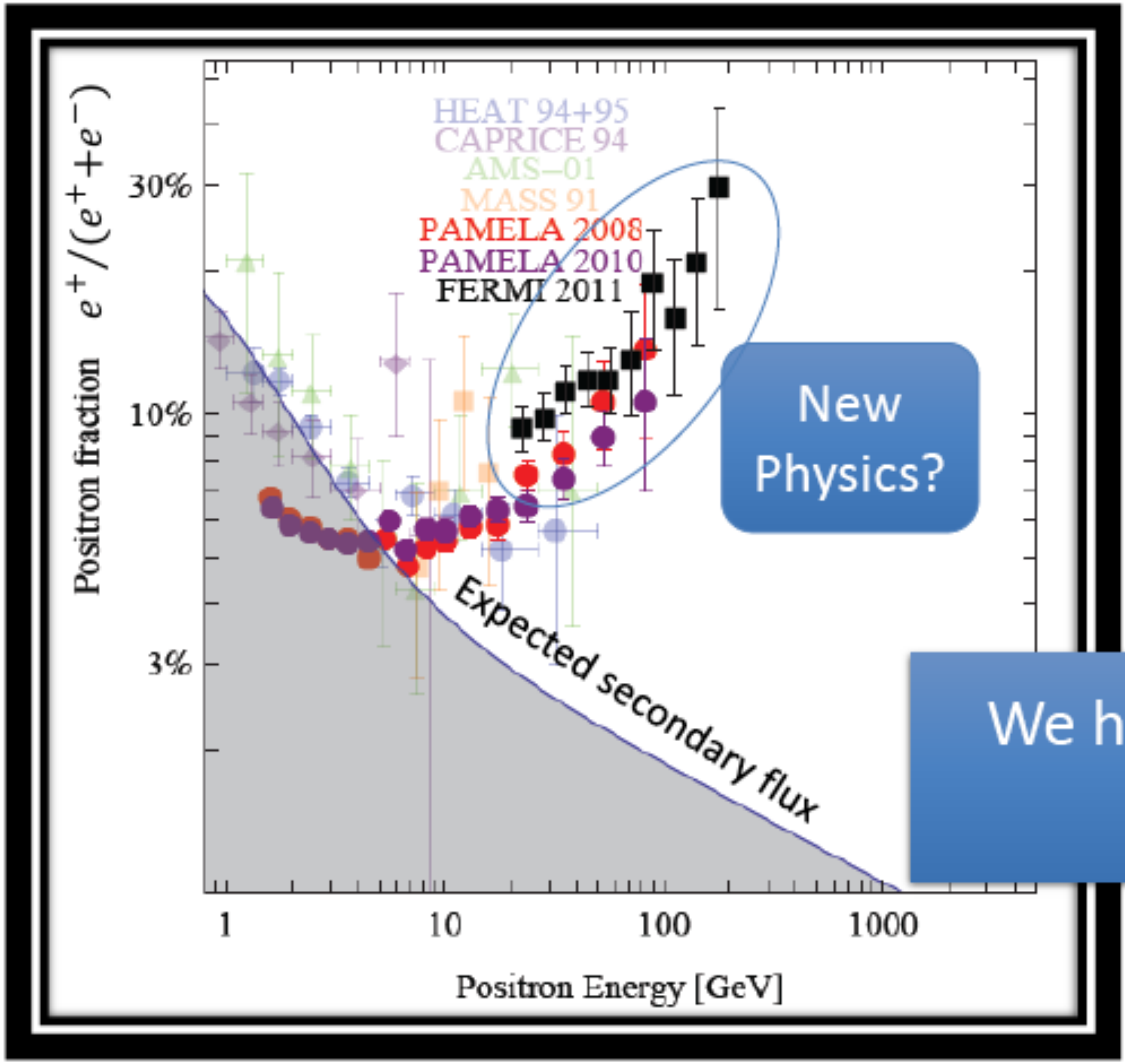
Antiproton Channel





A perfect secondary spectrum: **No Dark Matter Signal**

PAMELA & FERMI



New Physics?

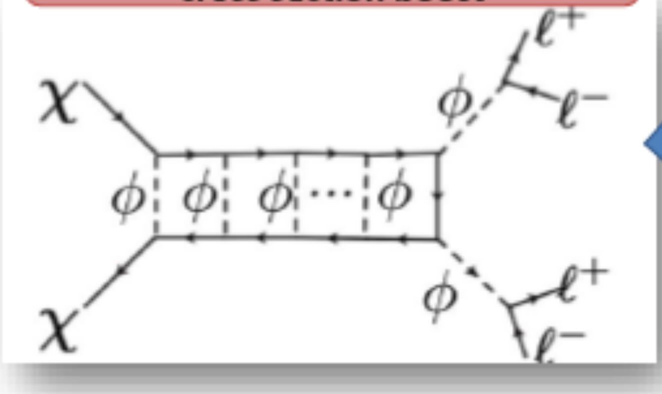
Positron Channel

We have to explain this **tension**

The Sommerfeld Enhancement

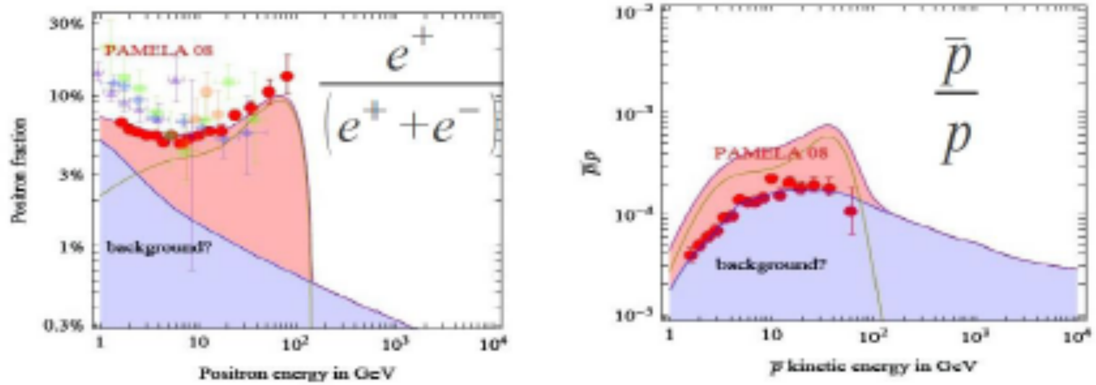
$$\langle\sigma v\rangle_{ann} \sim a + bv^2 + c\frac{1}{v}$$

Feynman diagram of Sommerfeld cross section boost

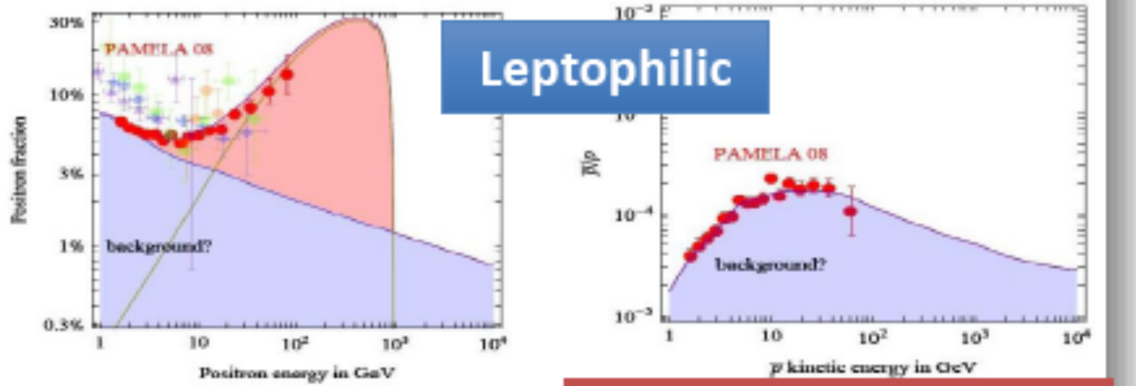


Inadequate production for <2 TeV WIMP : to grant PAMELA results we need heavier candidates and high BF: **new antiproton physics for AMS-02 in the 100 GeV - 2 TeV range for $M_{DM} \lesssim 10$ TeV**

DM with mass 150 GeV that annihilates into W^+W^-

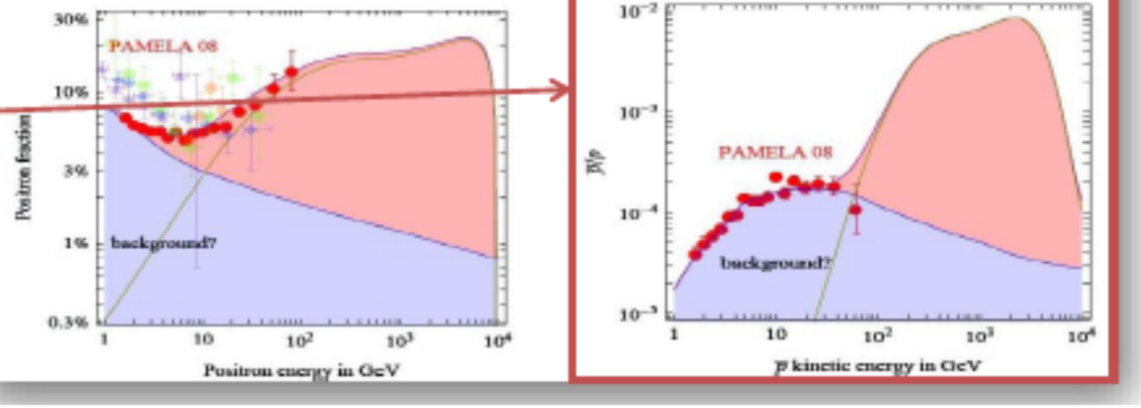


DM with mass 1 TeV that annihilates into $\mu^+\mu^-$



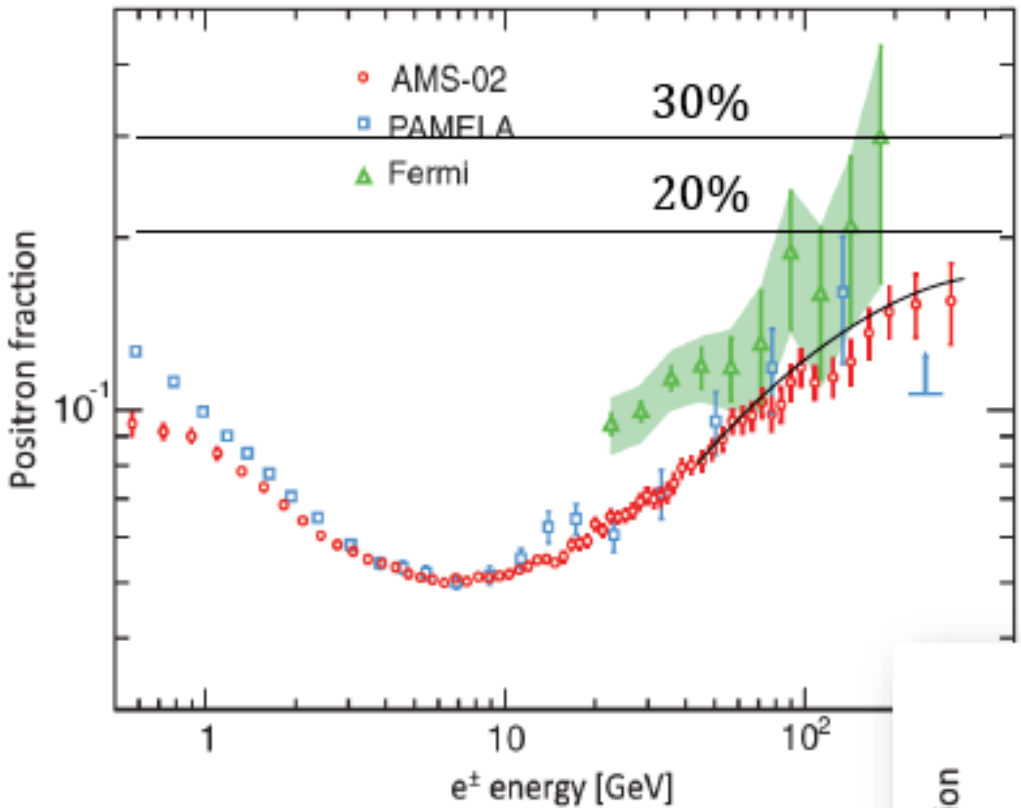
Leptophilic

DM with mass 10 TeV that annihilates into W^+W^-



On may 19 2011 AMS-02 begins operating on the ISS

AMS-02 First Measurement: Positron Fraction Interpretation



1. Sum of a diffuse spectrum and a **single power law source**

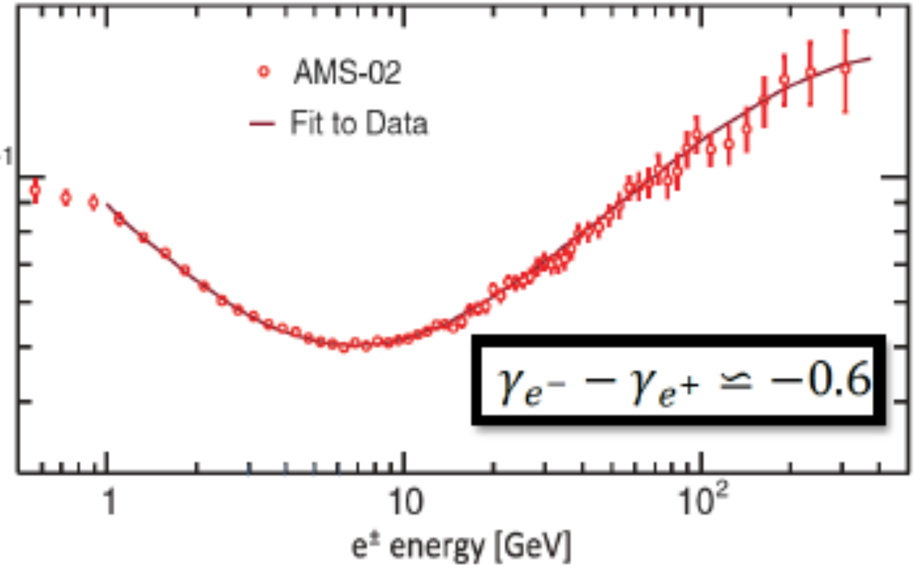
2. The proportion between the **DM mass** and the positron fraction maximum can be worth up to 3(2) : 1, whereas for $\bar{p}/p$ up to 4 : 1

3. **No** clear sign of **substructures**

4. **Isotropy**

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

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



$$\gamma_{e^-} - \gamma_{e^+} \simeq -0.6$$

A fit to the data in the energy range 1 to 350 GeV yields:

$\gamma_{e-} - \gamma_{e+} = -0.63 \pm 0.03$, *i.e.*, the diffuse positron spectrum is less energetic than the diffuse electron spectrum;

$\gamma_{e-} - \gamma_{S} = 0.66 \pm 0.05$, *i.e.*, the source spectrum is more energetic than the diffuse electron spectrum;

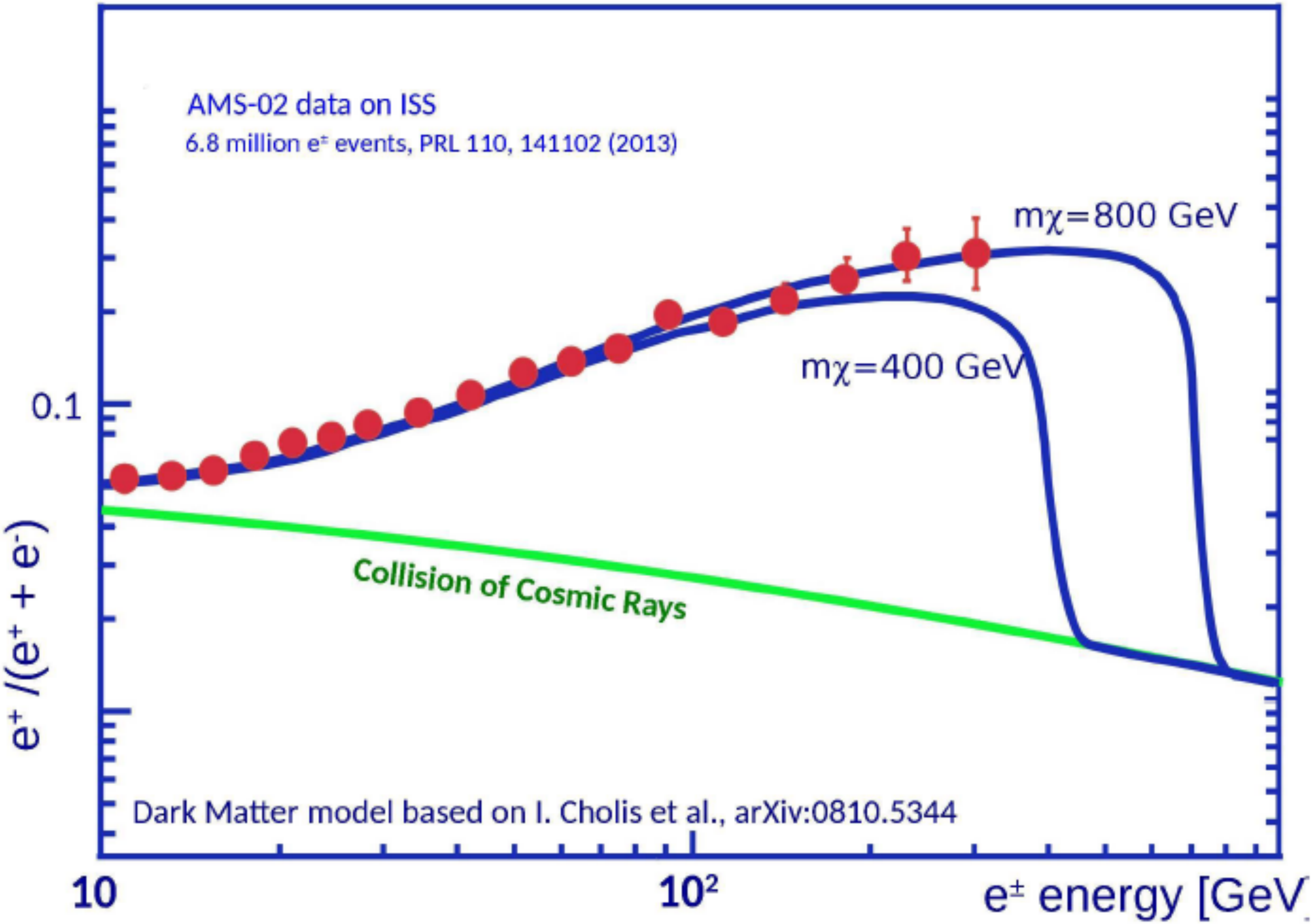
$C_{e+}/C_{e-} = 0.091 \pm 0.001$, *i.e.*, the weight of the diffuse positron flux amounts to ~10% of that of the diffuse electron flux;

$C_S/C_{e-} = 0.0078 \pm 0.0012$, *i.e.*, the weight of the common source constitutes only ~1% of that of the diffuse electron flux;

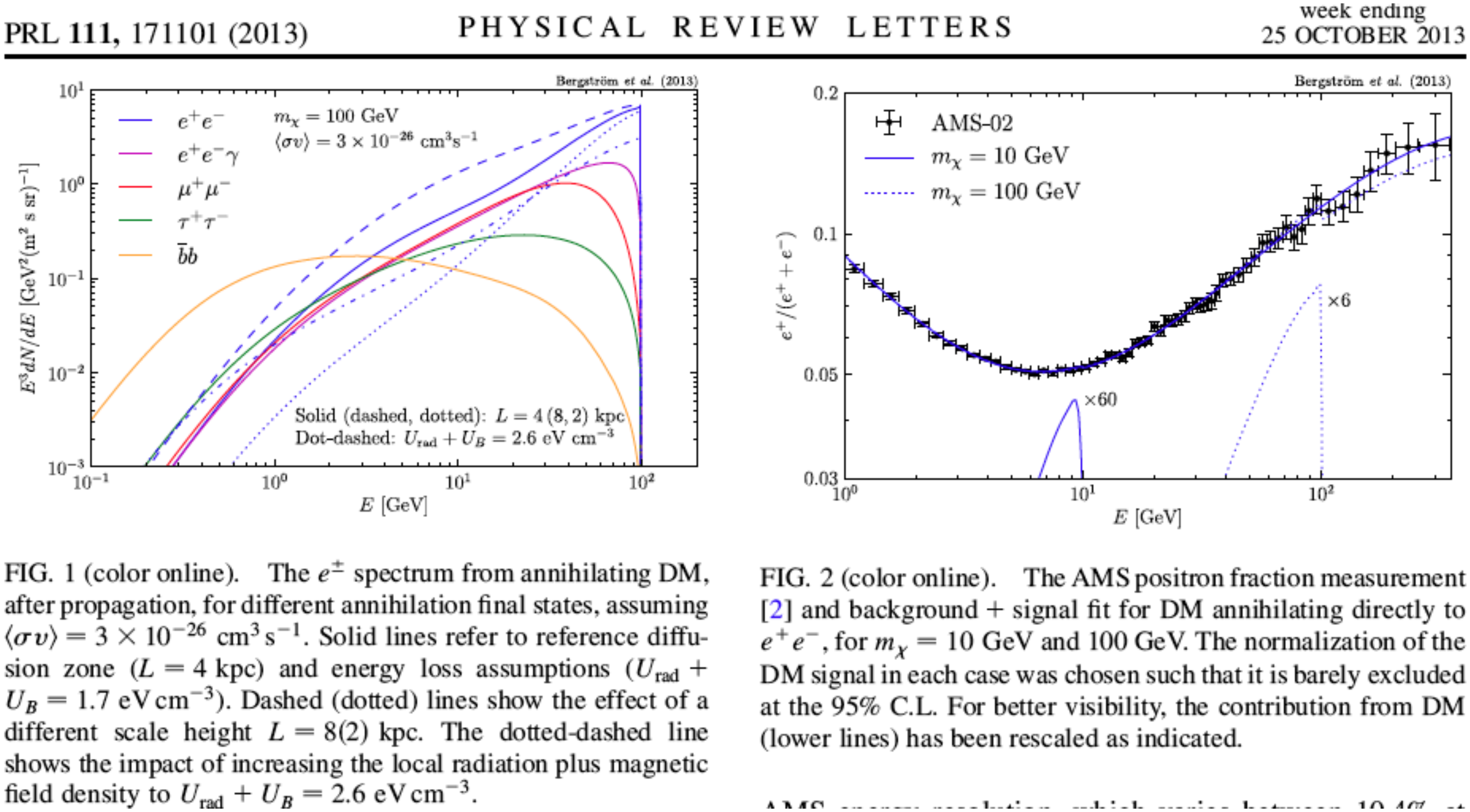
$1/E_s = 0.0013 \pm 0.0007\ \mathrm{GeV}^{-1}$,

corresponding to a cutoff energy of 760^{+1000}_{-280} **GeV**.

Comparison with theoretical Dark Matter Models



Bergstrom,Bringmann,Cholis,Hooper,Weniger 2013



PRL **111,** 171101 (2013) PHYSICAL REVIEW LETTERS week ending 25 OCTOBER 2013

FIG. 1 (color online). The $e^\pm$ spectrum from annihilating DM, after propagation, for different annihilation final states, assuming $\langle\sigma v\rangle = 3\times10^{-26}$ cm^3 s^{-1}. Solid lines refer to reference diffusion zone ($L = 4$ kpc) and energy loss assumptions ($U_{\rm rad} + U_B = 1.7$ eV cm^{-3}). Dashed (dotted) lines show the effect of a different scale height $L = 8(2)$ kpc. The dotted-dashed line shows the impact of increasing the local radiation plus magnetic field density to $U_{\rm rad} + U_B = 2.6$ eV cm^{-3}.

FIG. 2 (color online). The AMS positron fraction measurement [2] and background + signal fit for DM annihilating directly to e^+e^-, for $m_\chi = 10$ GeV and 100 GeV. The normalization of the DM signal in each case was chosen such that it is barely excluded at the 95% C.L. For better visibility, the contribution from DM (lower lines) has been rescaled as indicated.

AMS energy resolution, which varies between 10.4% at

Also : Ibarra,Lamperstorfer,Silk 2013

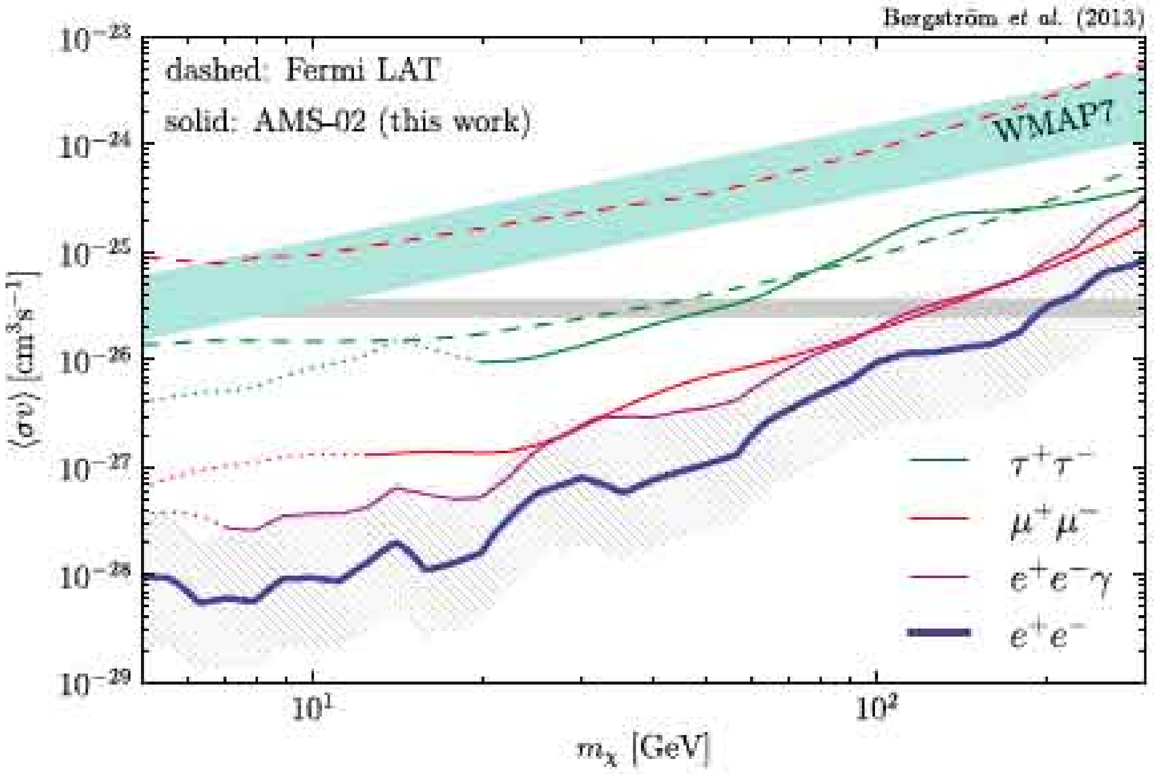
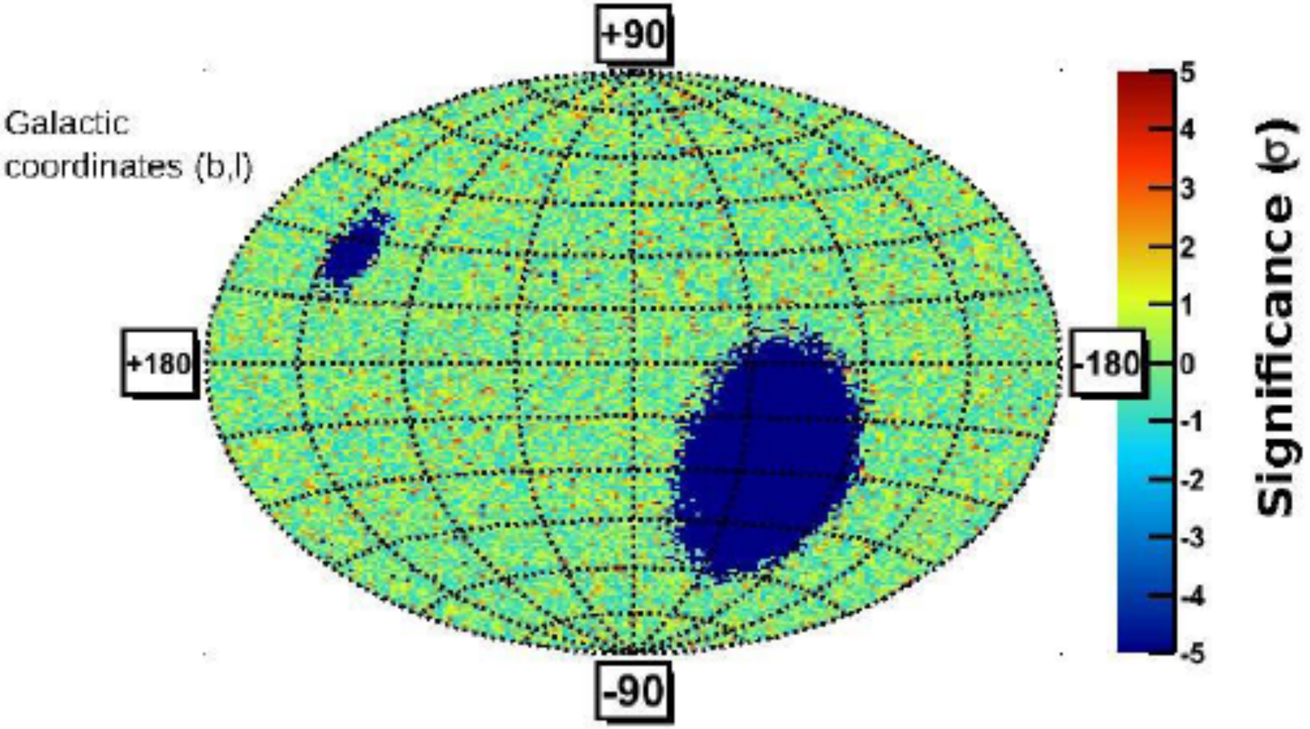


FIG. 3 (color online). Upper limits (95% C.L.) on the DM annihilation cross section, as derived from the AMS positron fraction, for various final states (this work), WMAP7 (for $\ell^+\ell^-$) [44], and Fermi LAT dwarf spheroidals (for $\mu^+\mu^-$ and $\tau^+\tau^-$) [43]. The dotted portions of the curves are potentially affected by solar modulation. We also indicate $\langle\sigma v\rangle_{\text{therm}} \equiv 3\times10^{-26}$ cm^3 s^{-1}. The AMS limits are shown for reasonable reference values of the local DM density and energy loss rate (see text), and can vary by a factor of a few, as indicated by the hatched band (for clarity, this band is only shown around the e^+e^- constraint).

On the origin of excess positrons

If the excess has a particle physics origin, it should be isotropic



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

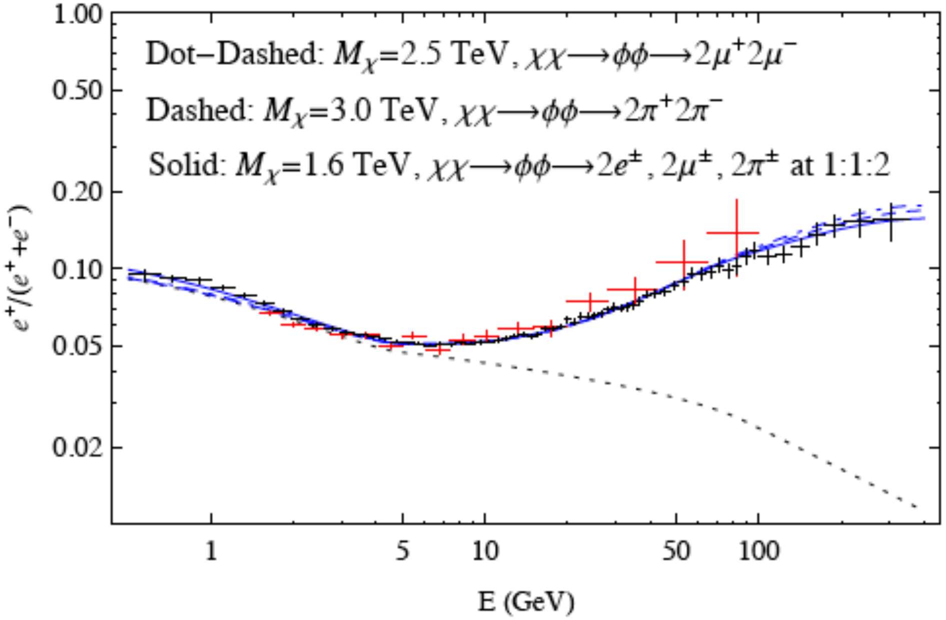
The anisotropy in galactic coordinates:

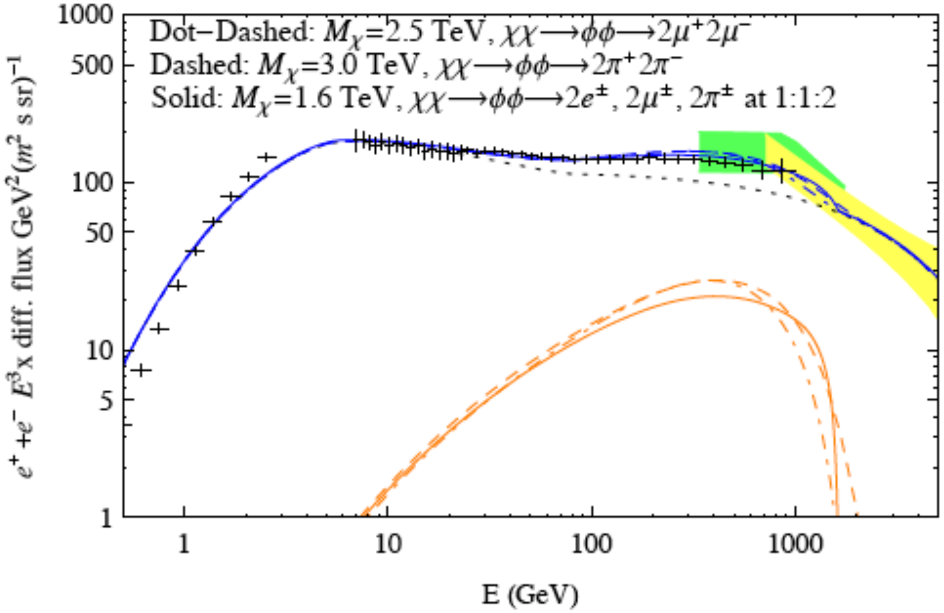
$\delta \leq 0.030$ at the 95% confidence level

10 years Projection

$\boxed{\delta \leq 0.010}$

Cholis,Hooper 2013



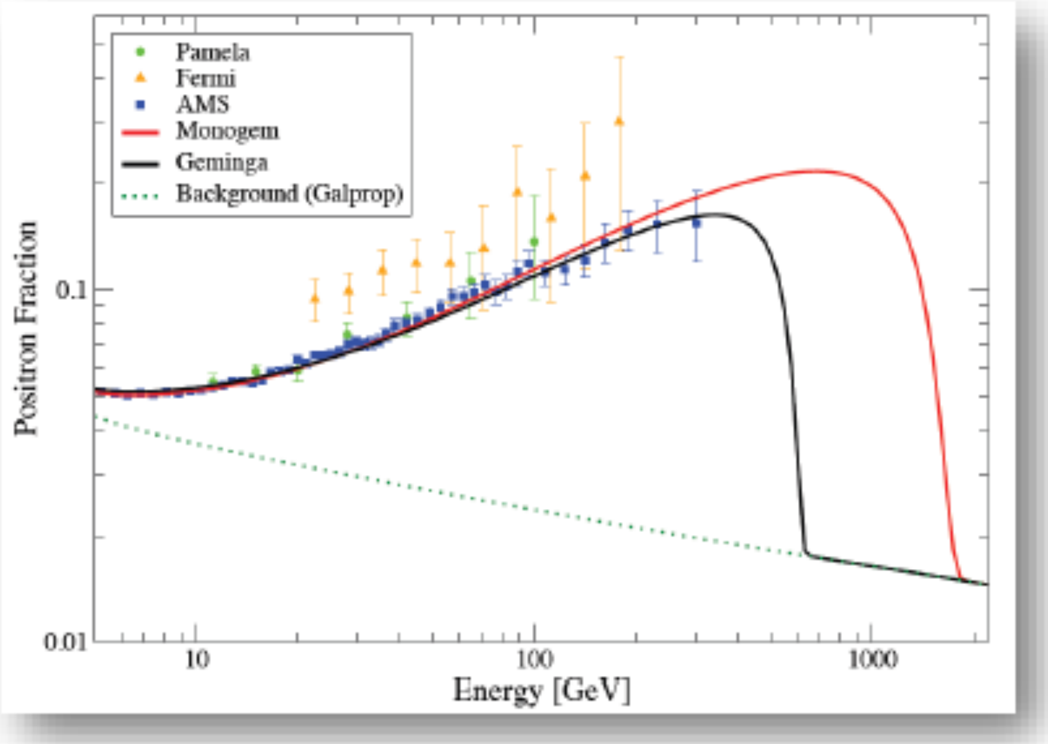


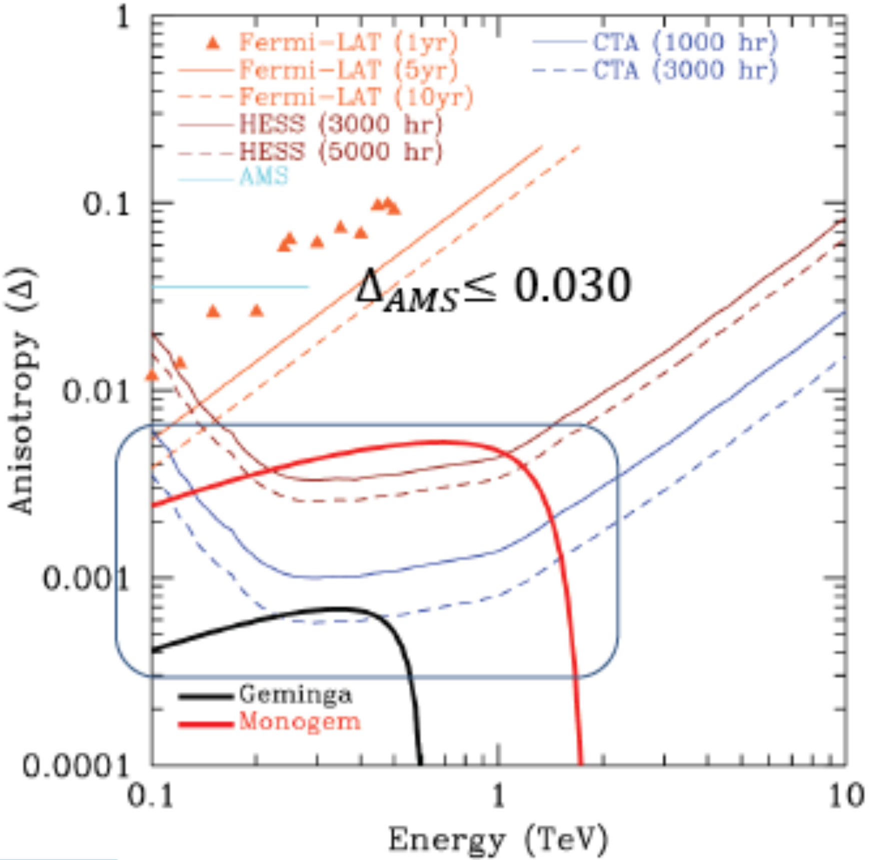
$dN_{e^-}/dE_{e^-} \propto E_e^{-2.65}$ below 85 GeV and $dN_{e^-}/dE_{e^-} \propto E_e^{-2.3}$ above 85 GeV

$L = 8$ kpc

Pulsars Signals

Anyone of two well-known nearby pulsars, Geminga and Monogem, can satisfactorily provide enough positrons to reproduce AMS-02 observations:

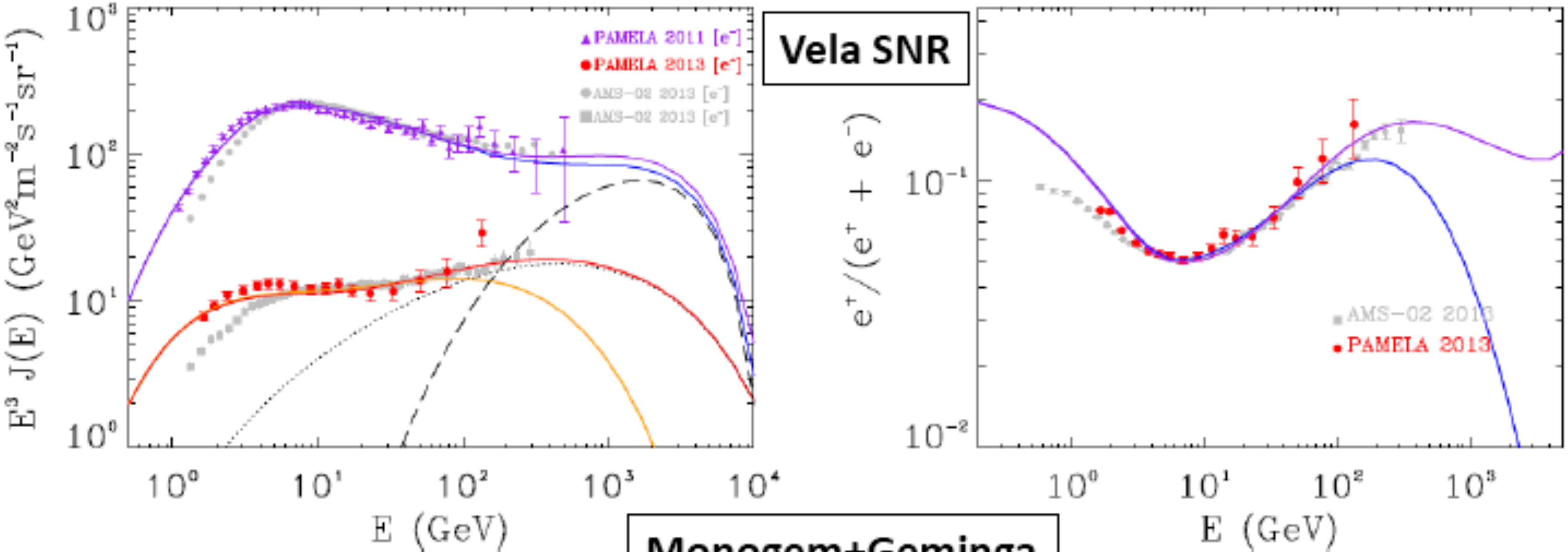




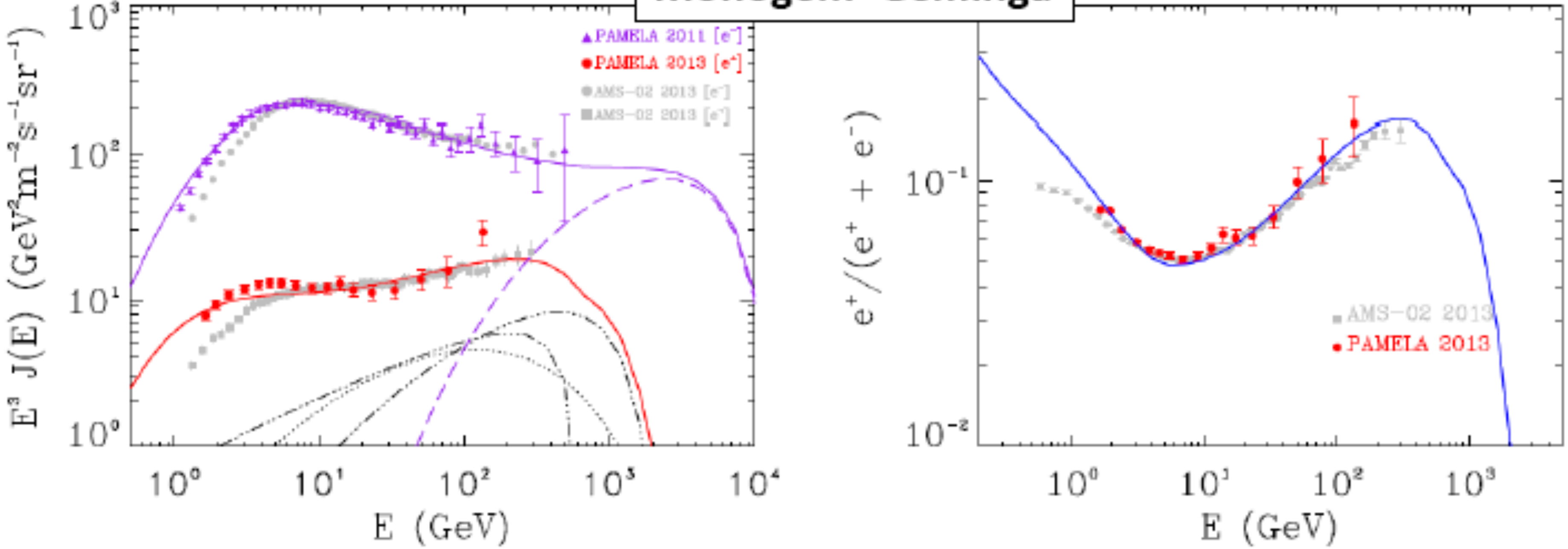
The predicted anisotropy level is, at present, consistent with limits from Fermi-LAT and AMS-02

Pulsars vs SNRs Signals

Vela SNR

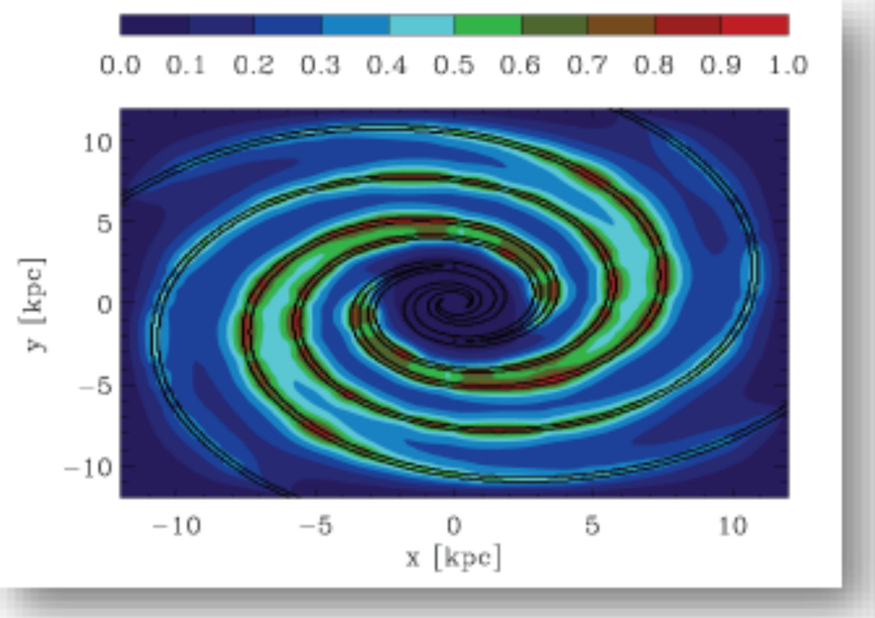


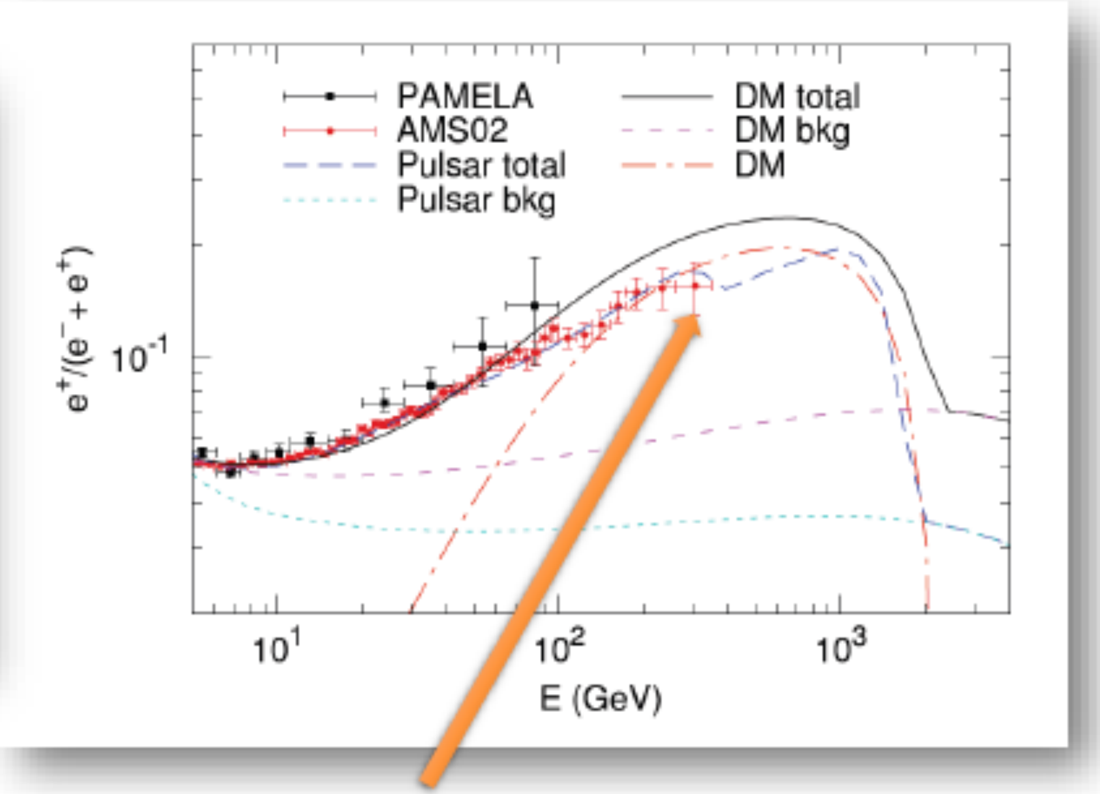
Monogem+Geminga



A novel propagation configuration: the leptons spectra are computed assuming the extra-component sources are located only in spiral arms.

The contributions to the positron fraction of all the 178 pulsars in the ATNF catalogue with d < 3 kpc fit AMS data very well:





Both the pulsar (nearby or altogether) and the DM scenarios can fit the observations: it is a fundamental problem to distinguish these two scenarios. **If the positron excess is from pulsars, it may have a characteristic spectrum with many structures or *steps***, because the parameters of pulsars might differ from one to another. If such fine structures are not discovered, it would be a strong support to the DM interpretation.

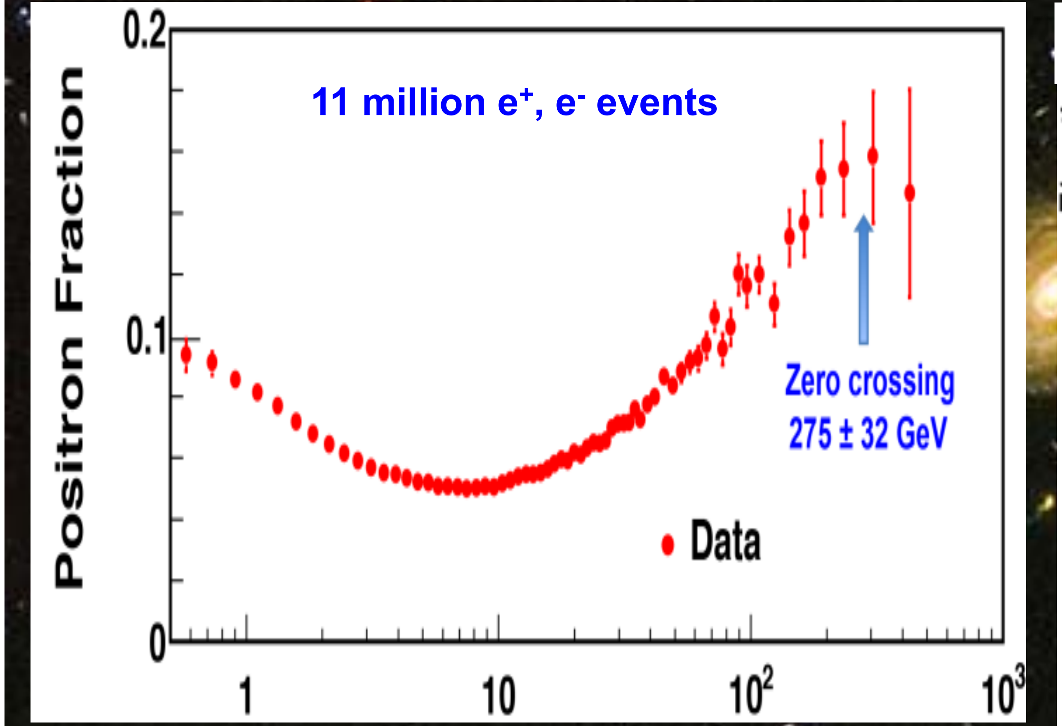
N. Masi 2014

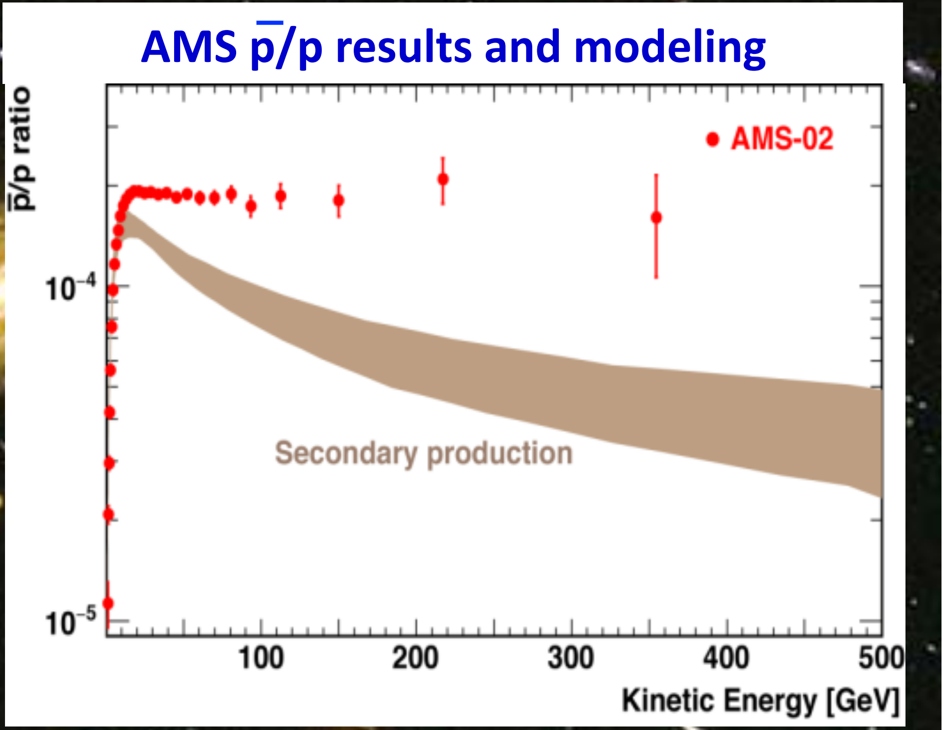
CR perspectives on DM

The Origin of Dark Matter

Collision of “ordinary” Cosmic Rays produce e+, $\bar{p}$..

Collisions of Dark Matter (neutralinos, χ) will produce additional e+, $\bar{p}$, …



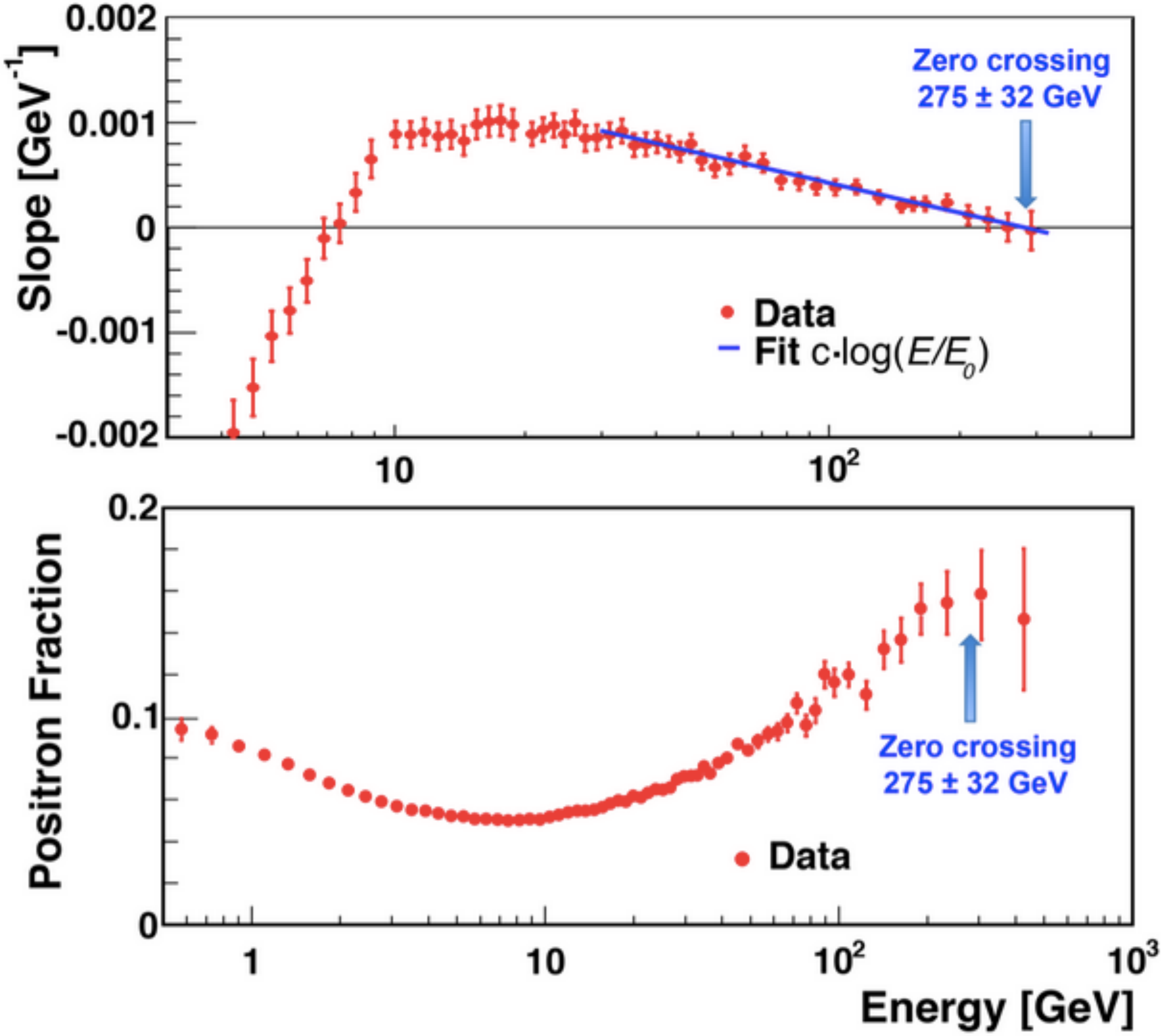

AMS $\bar{p}$/p results and modeling

To identify the Dark Matter signal we need

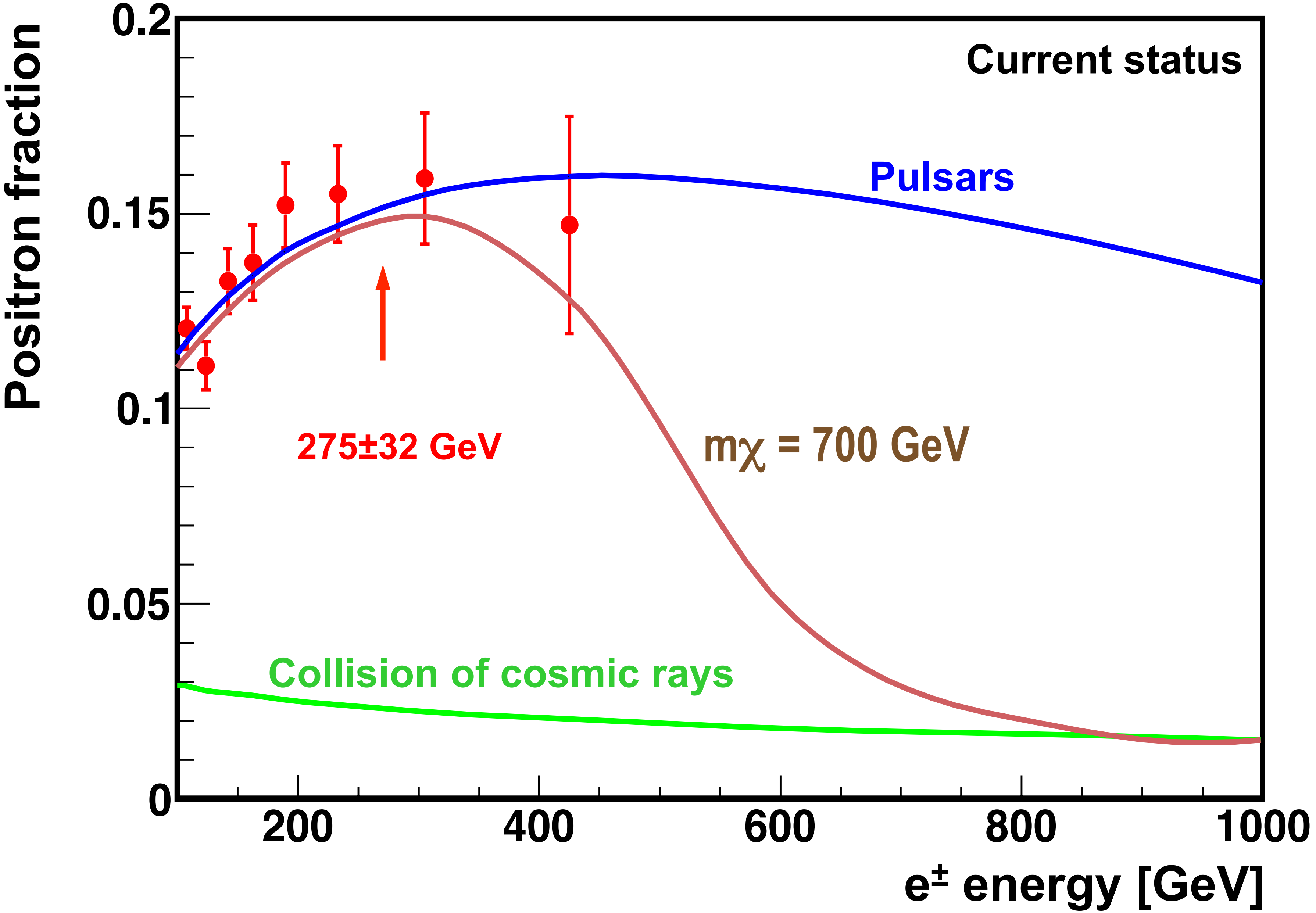
1. **Measurement of e+, e−, and p-bar.**
2. **Precise knowledge of the cosmic ray fluxes (p, He, C, …)**
3. **Propagation and Acceleration (Li, B/C, …)**

AMS-02: entering the era of precision cosmic ray measurement

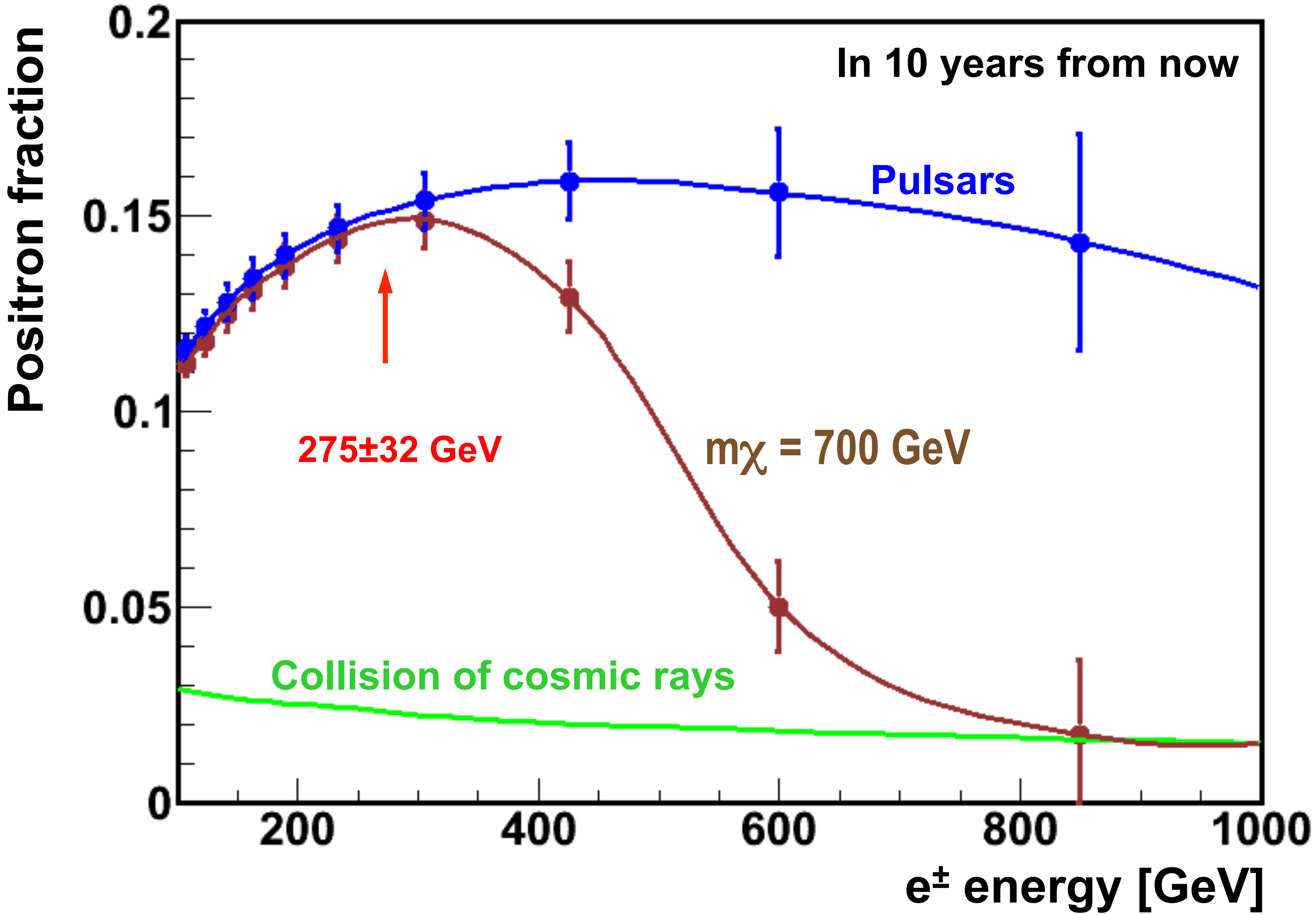
e+ / e+ + e- ratio



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

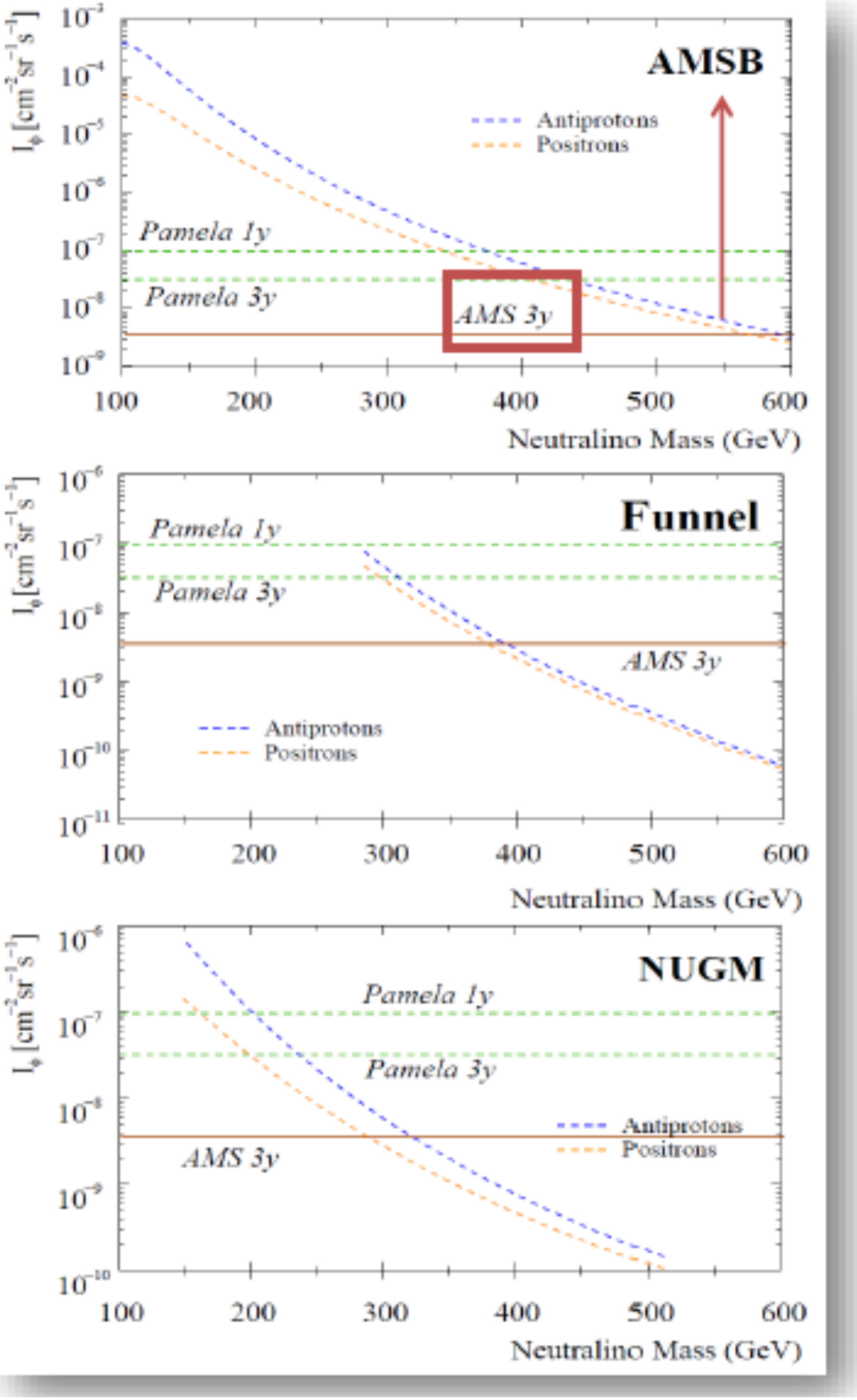


The expected rate at which it falls beyond the turning point.

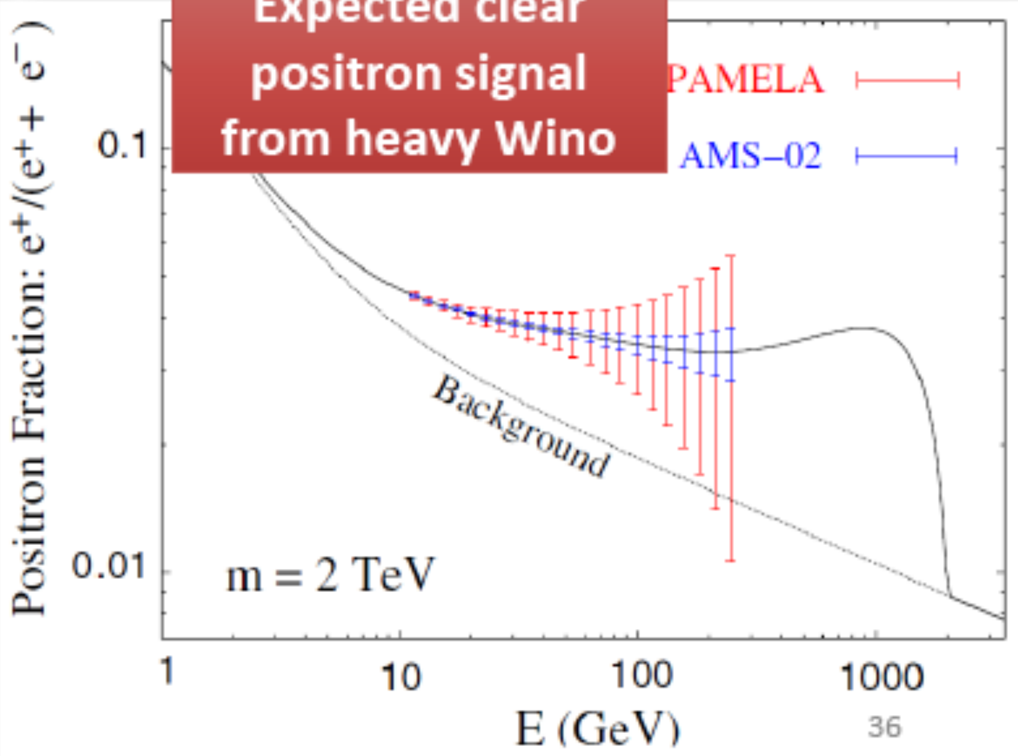


Neutralino

Discrimination parameter I_ϕ for signal and background: the **AMSB Wino MSSM is the most suitable for AMS-02**, both in antiproton and positron channels

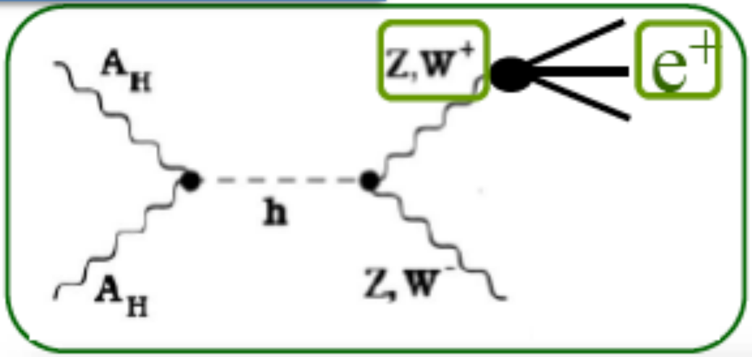


Expected clear positron signal from heavy Wino



Little Higgs Theory

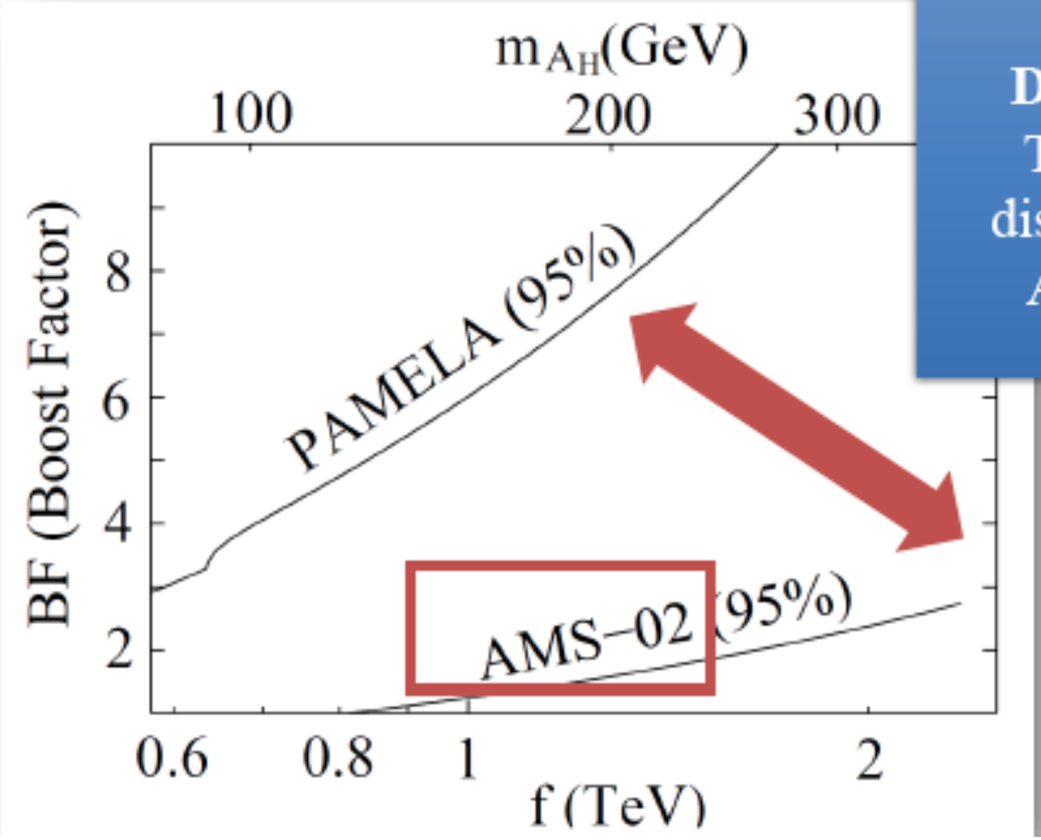
Massive LTP Photon Annihilation



$$W^{\pm} \rightarrow hadrons \rightarrow \pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$$

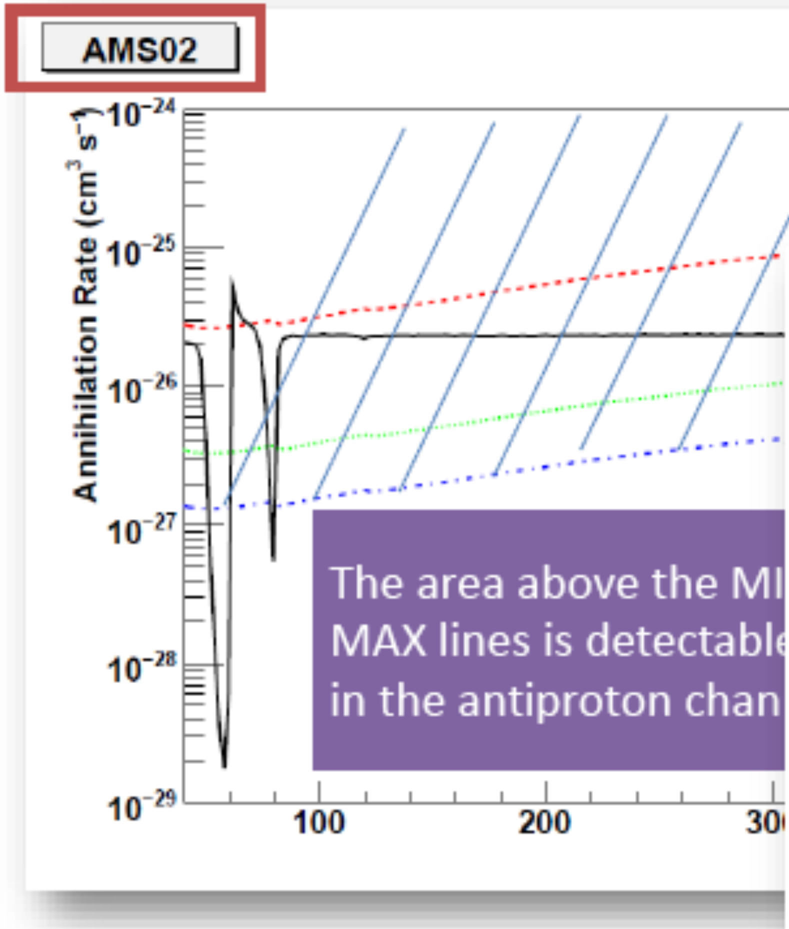
$$W^{+} \rightarrow \mu^{+} \nu \rightarrow e^{+} \nu \bar{\nu} \nu$$

$$W^{+} \rightarrow e^{+} \nu$$

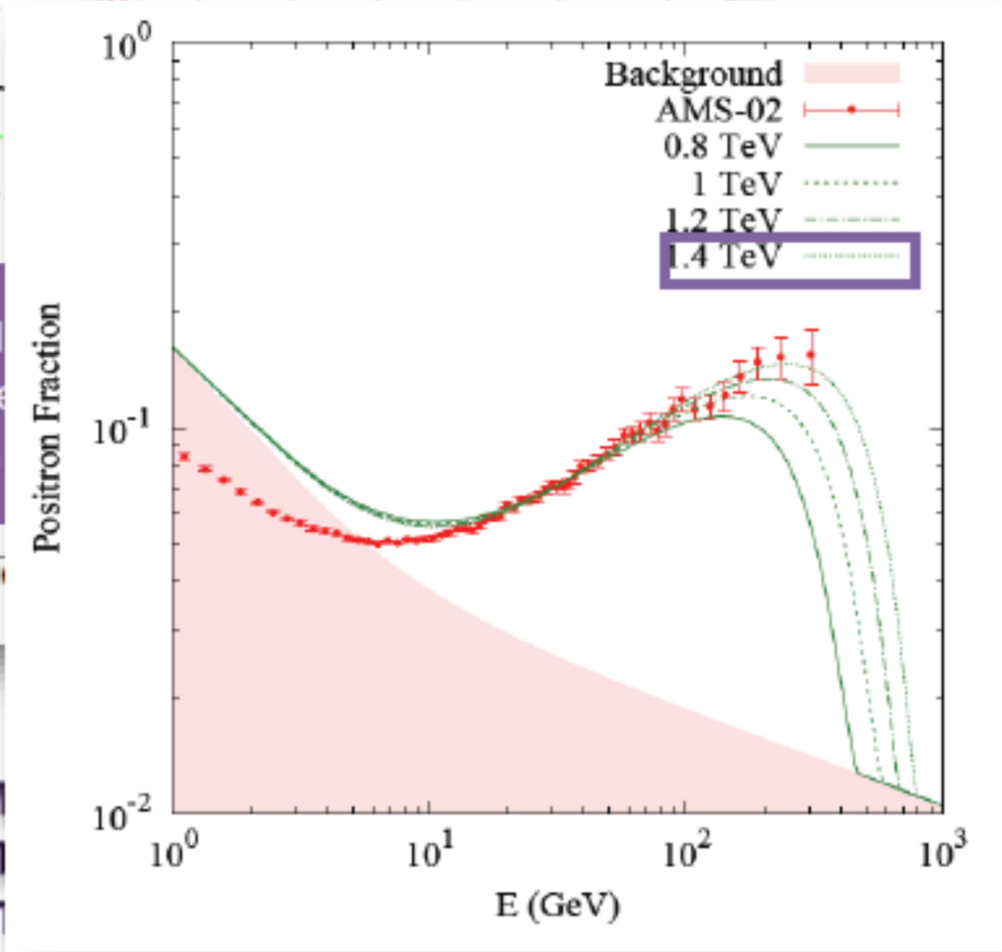


Little Higgs
Dark Matter parameters space:
The region above the line can be distinguished from the background: AMS can sweep a wide window

Scalar Singlet/Multiplet

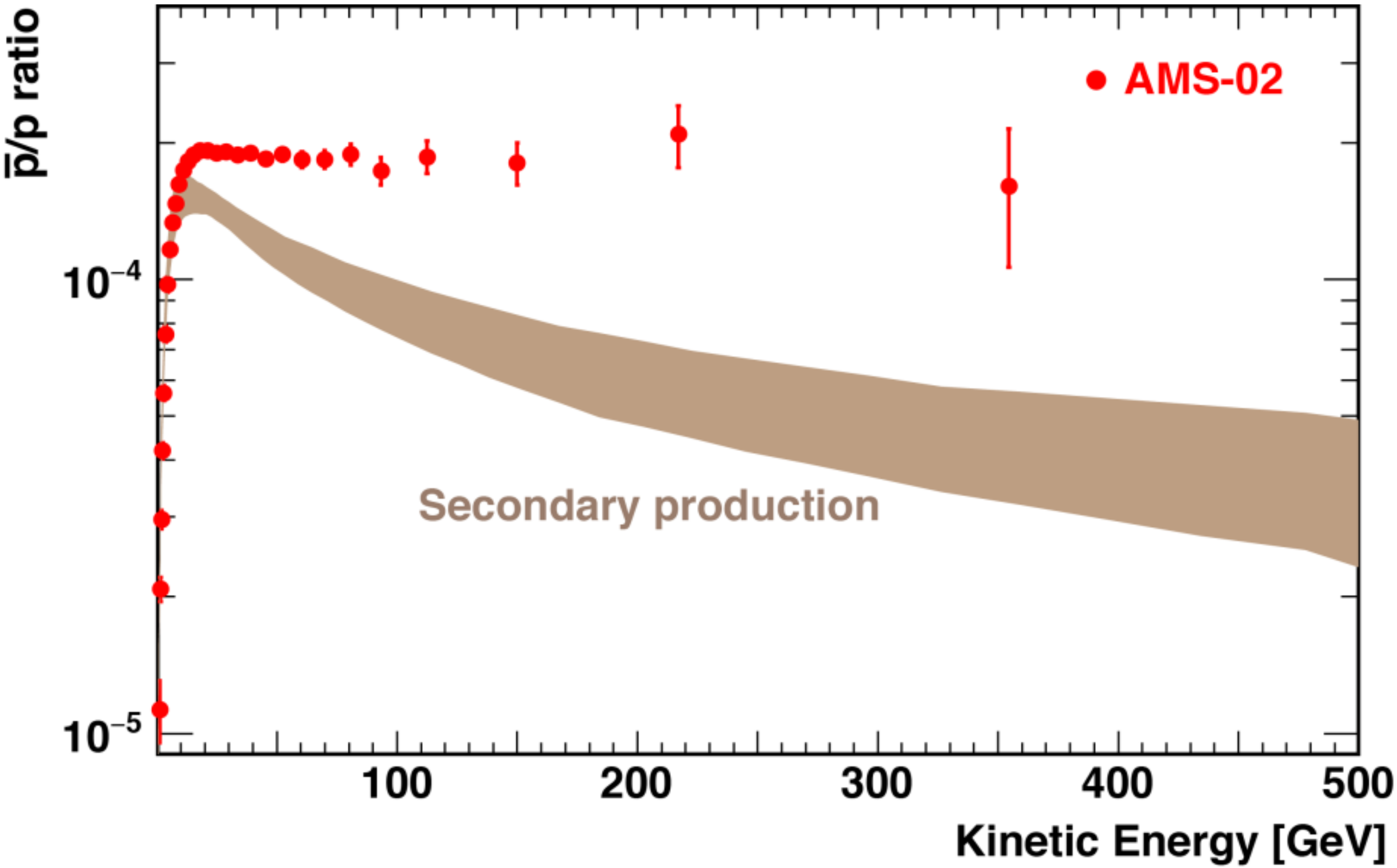


The area above the MI
MAX lines is detectable
in the antiproton chan

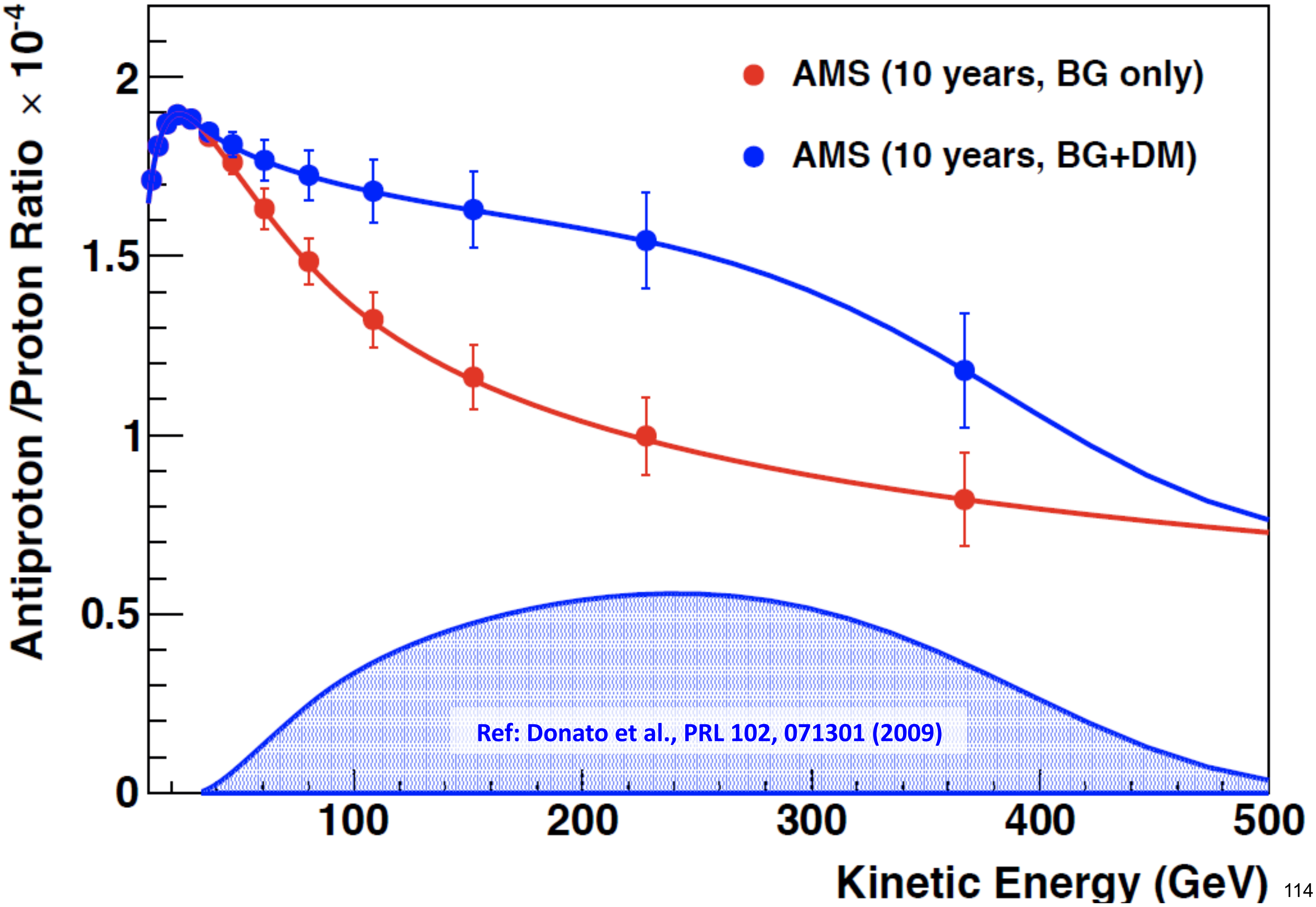


- SCALAR CANDIDATES HAVE MASSES FROM
- THEY ARE SUCCESSFUL IN REPRODUCING T
- A GOOD FIT TO AMS-02 DATA WAS RECENT
  A MASS OF ABOUT 1. 5 TEV

AMS $\bar{p}/p$ results and modeling

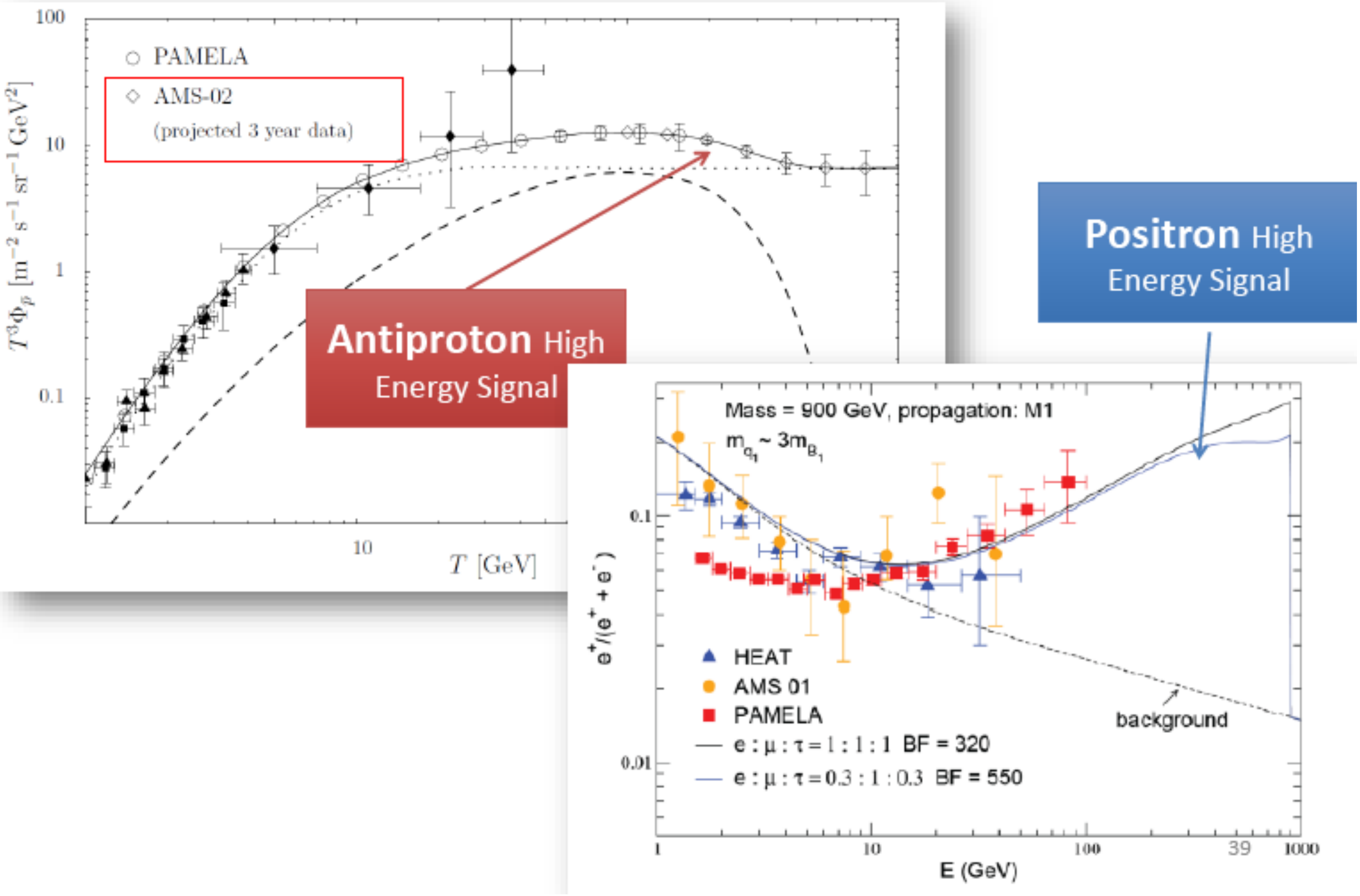


Comparison of $\overline{p}/p$ with Models in 10 more years



Ref: Donato et al., PRL 102, 071301 (2009)

Kaluza-Klein Theories: Universal Extra Dimension

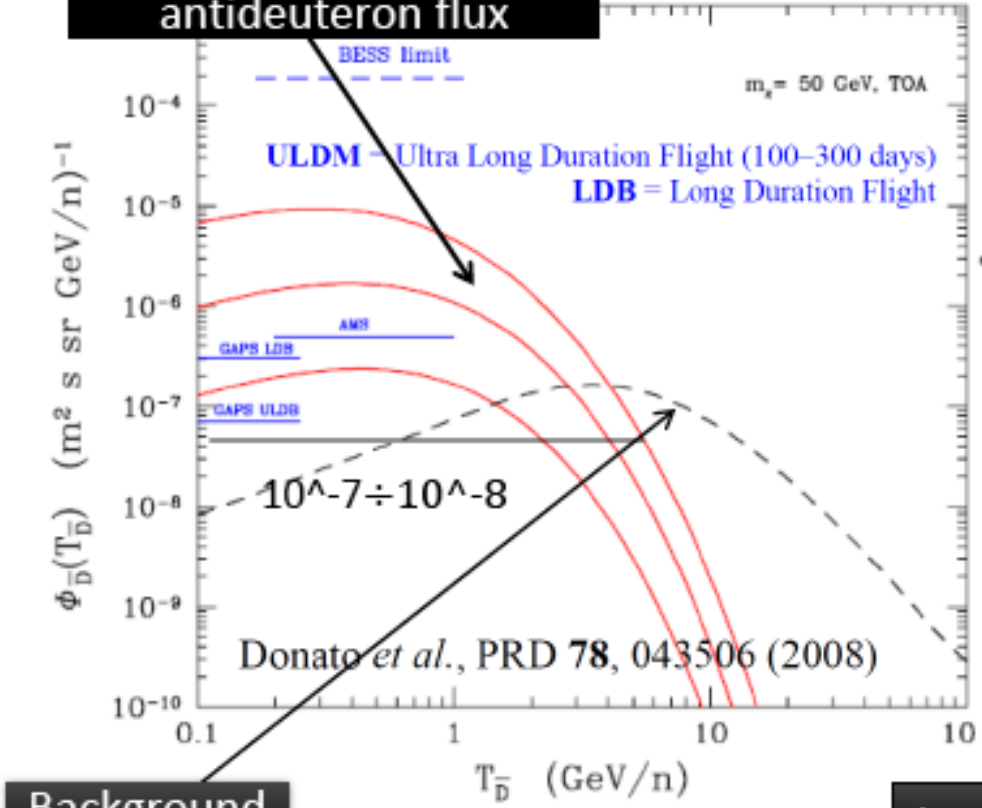


Antiproton High
Energy Signal

Positron High
Energy Signal

Antideuteron Channel: a Low Energy Hunting

PAMELA can't reconstruct an absolute antideuteron flux



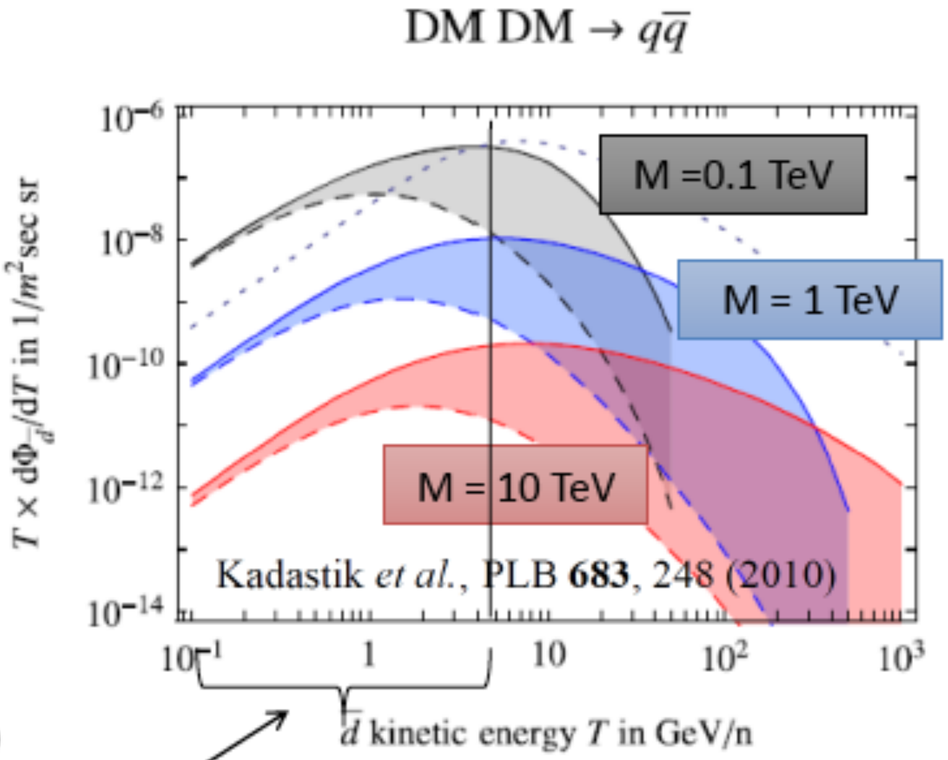
10^-7÷10^-8

Donato *et al.*, PRD **78**, 043506 (2008)

Background secondary flux

MIN, MED, MAX propagation

Light Dark Matter



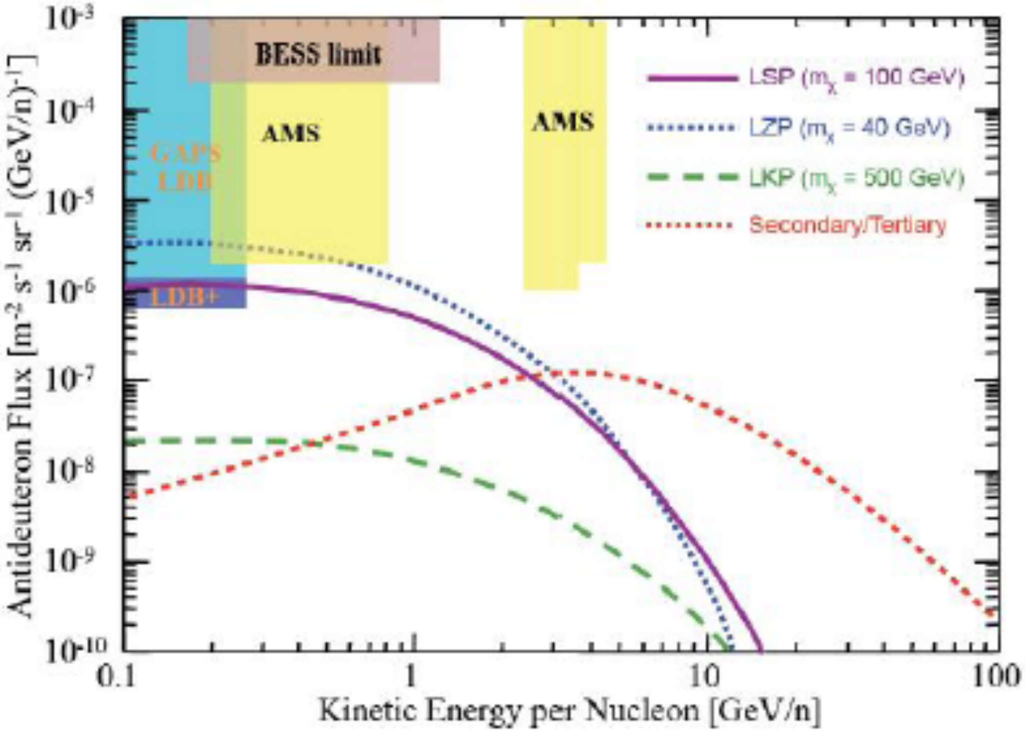
Kadastik *et al.*, PLB **683**, 248 (2010)

Low energy range

MED propagation and NFW profile

Not Light Dark Matter

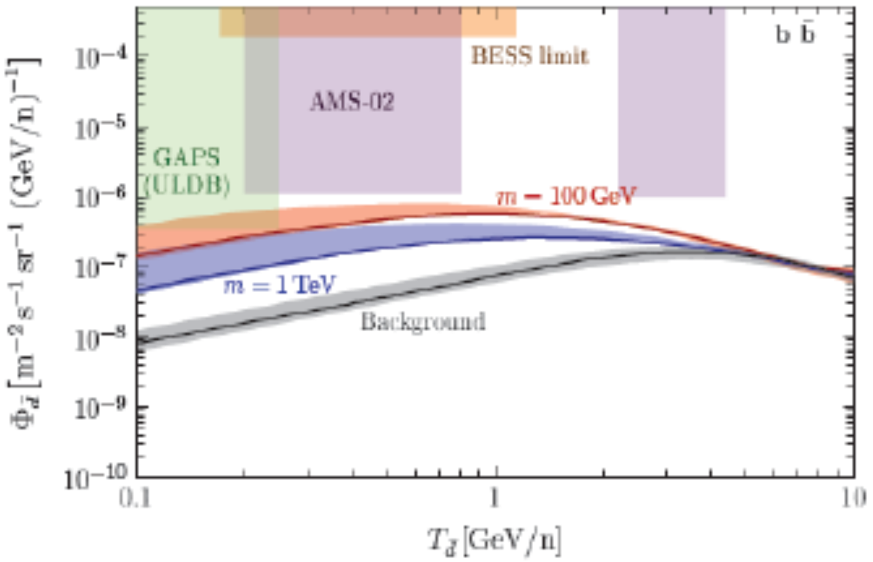
Current situation: GASP & AMS-02

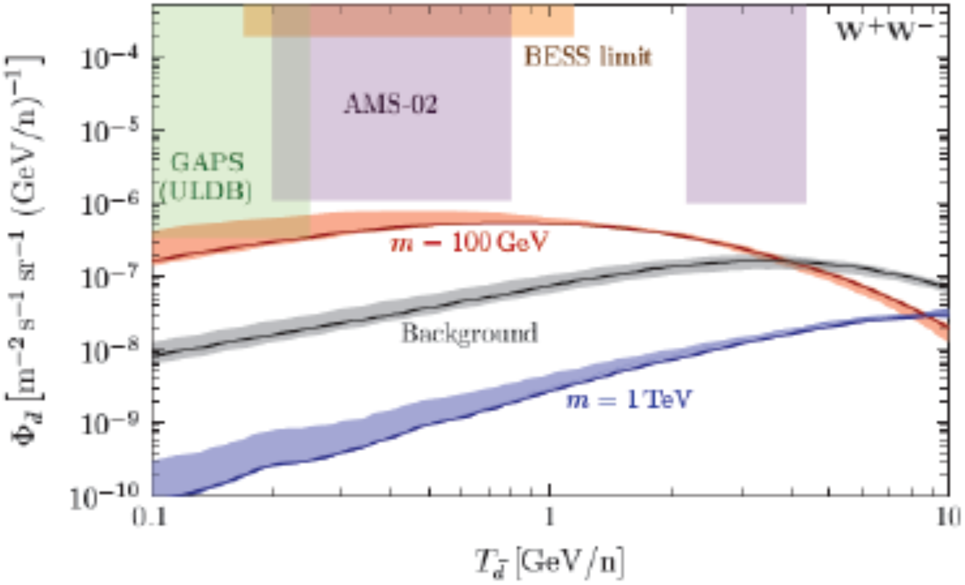


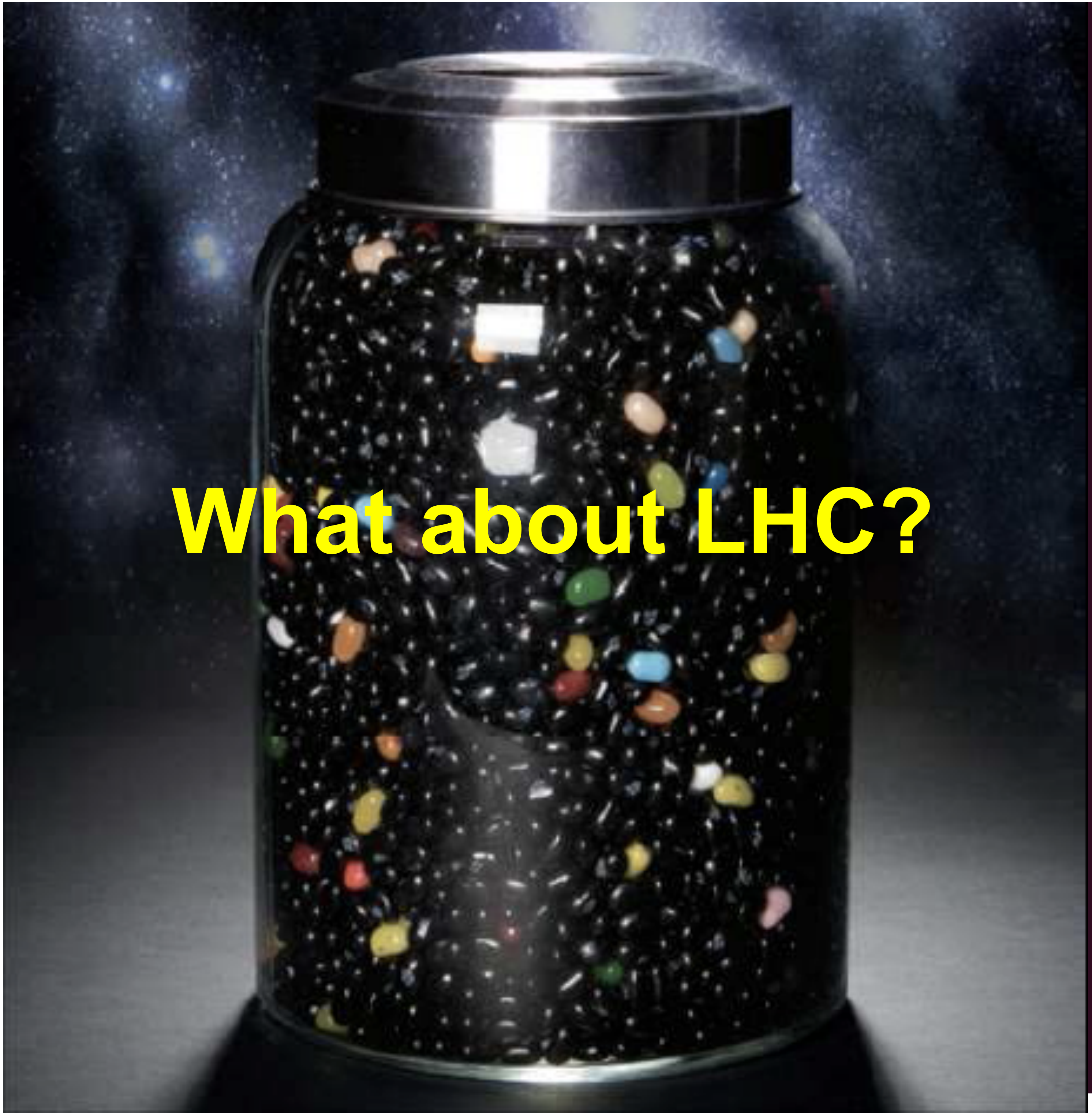
AMS-02 sensitivity: 10^-6

GASP sensitivity: 10^-7

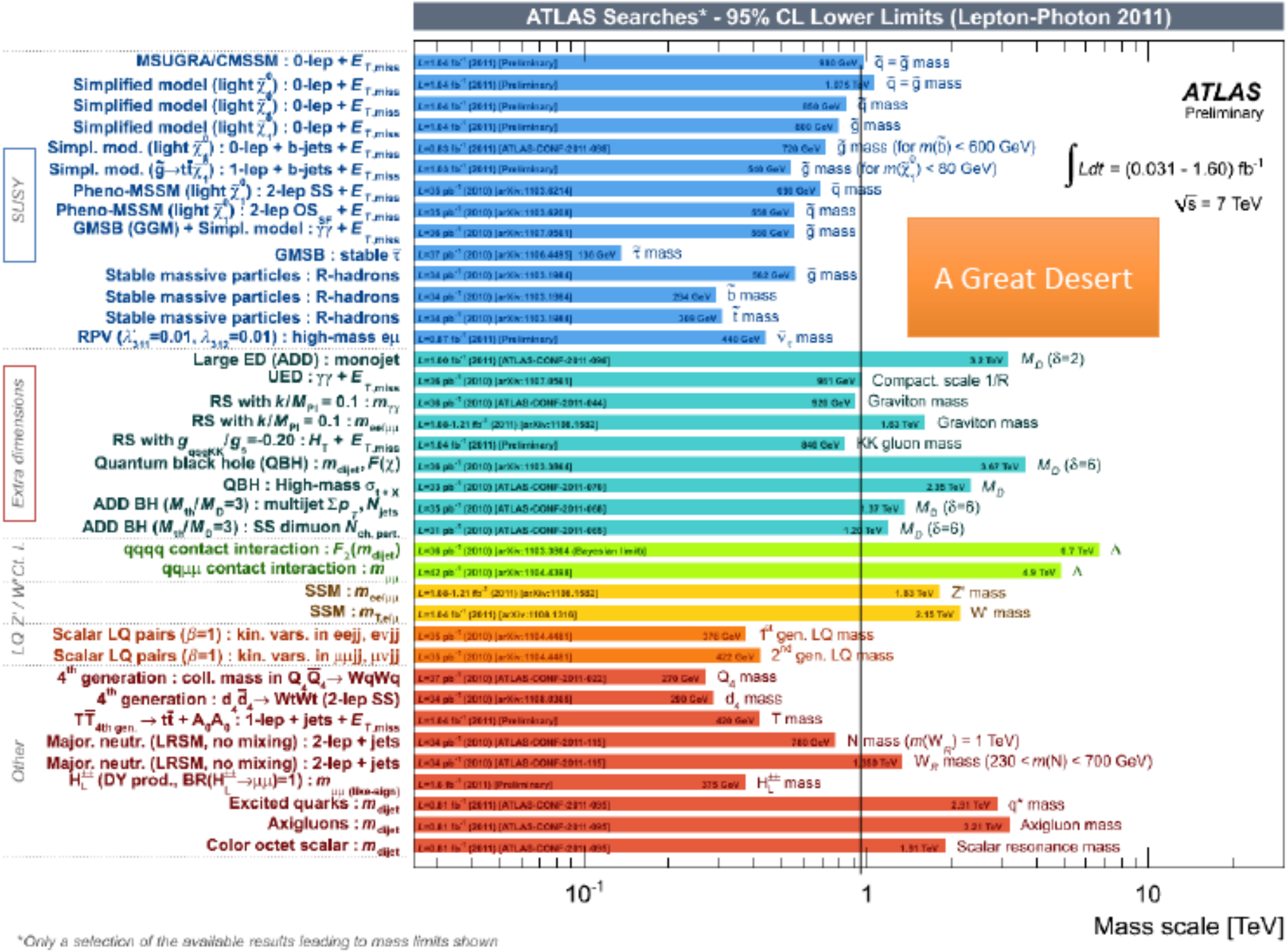
AMS-02 will be approximately an order of magnitude less constraining than GAPS







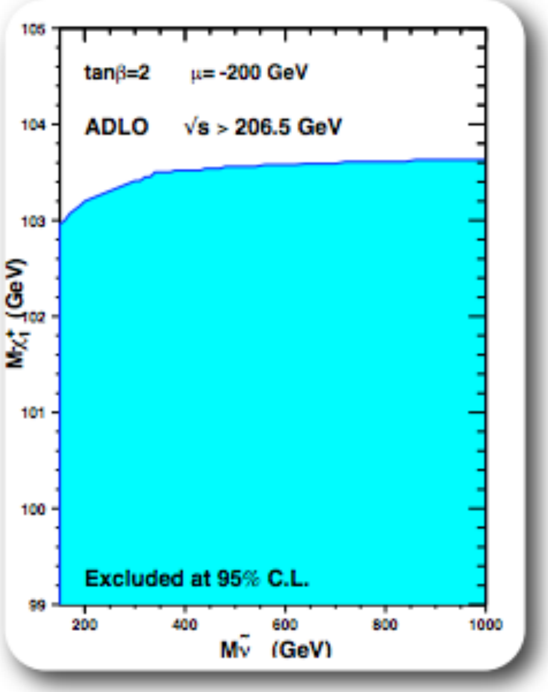
What about LHC?



A Great Desert

Current limits: neutralino/chargino

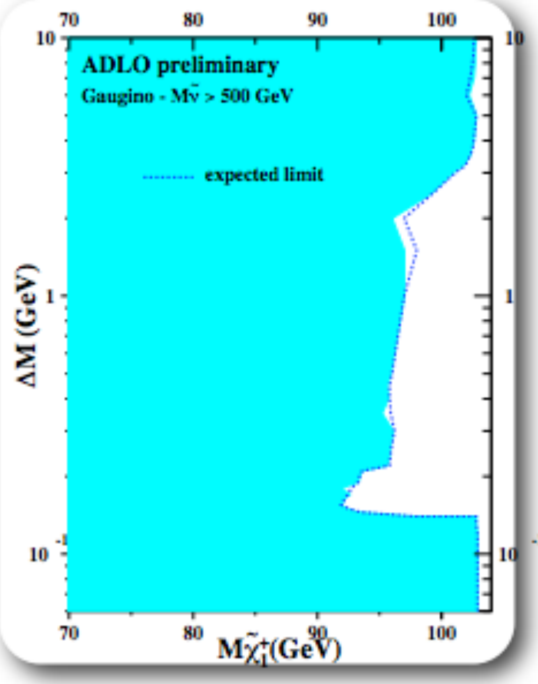
canonical case



$m\chi_1^\pm$ > 103.5 GeV for m_{snue} > 300 GeV

LEPSUSYWG/01-03.1

degenerate case

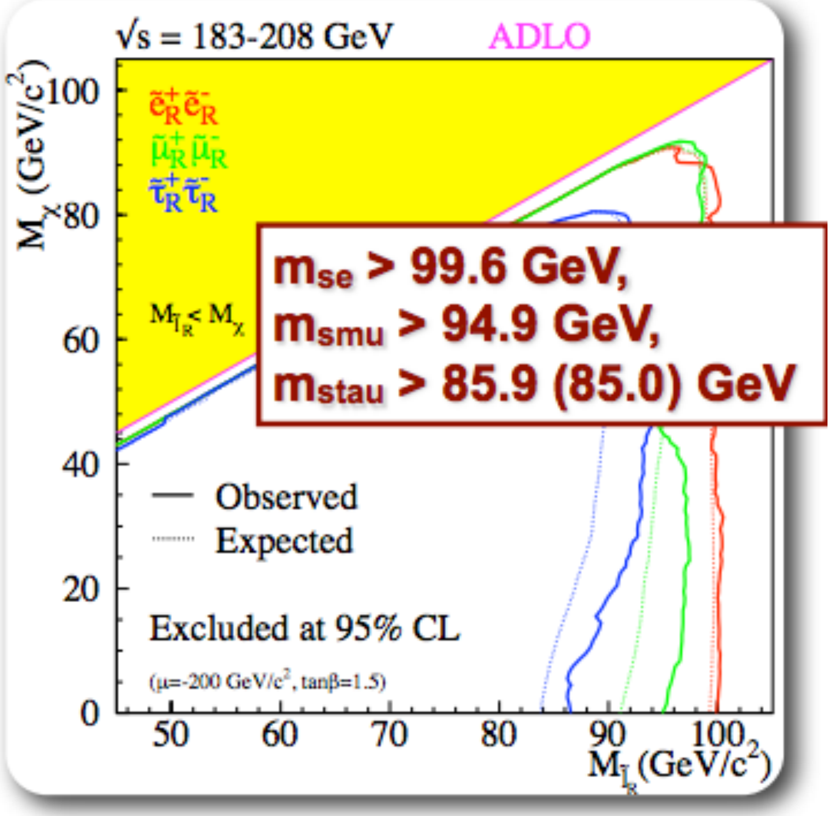


$m\chi_1^\pm$ > 91.9 /92.4 GeV

LEPSUSYWG/02-04.1

$m\chi_1^0$ > 47/50 GeV (CMSSM, mSUGRA)

No mass limit in general



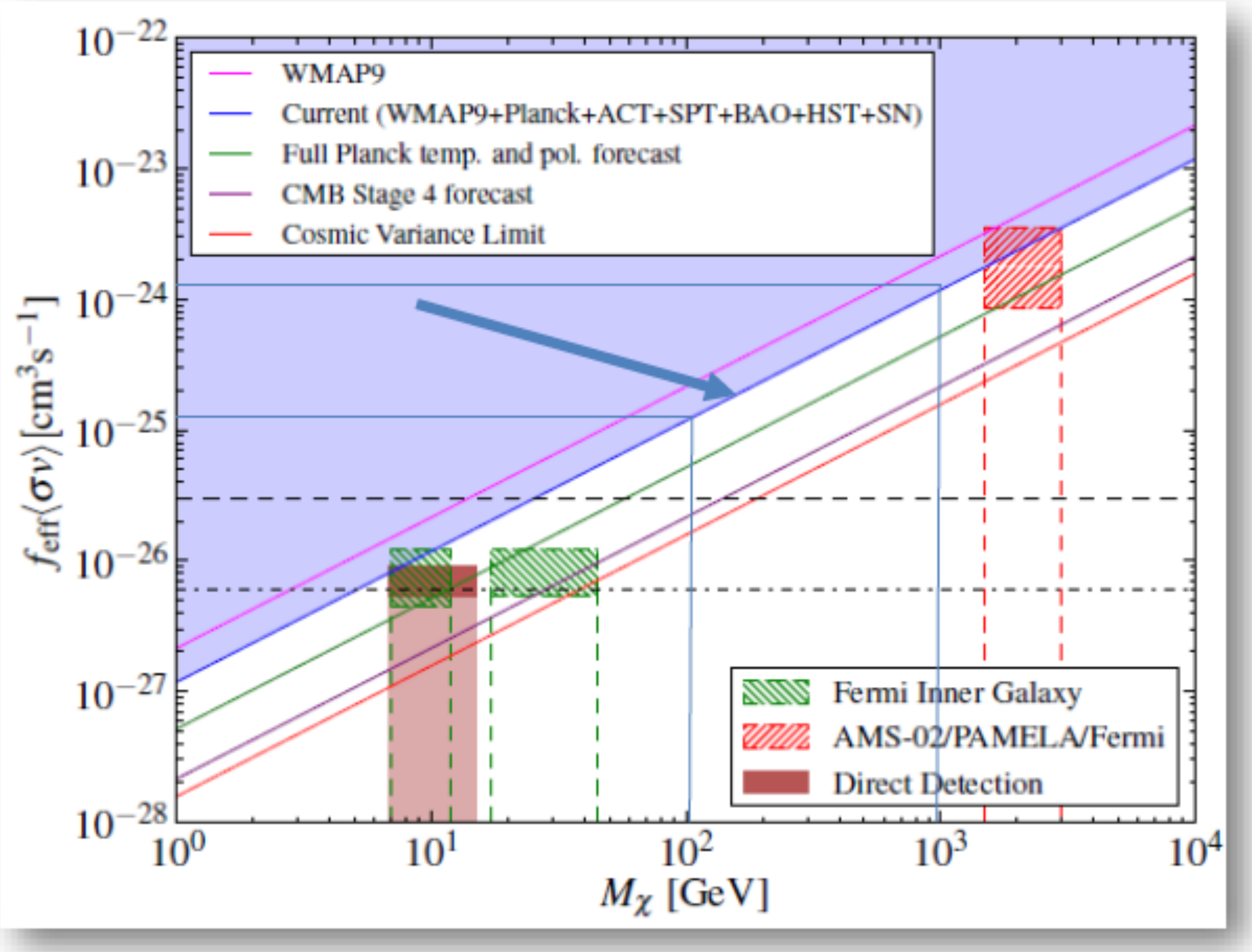
m_{se} > 99.6 GeV,
m_{smu} > 94.9 GeV,
m_{stau} > 85.9 (85.0) GeV

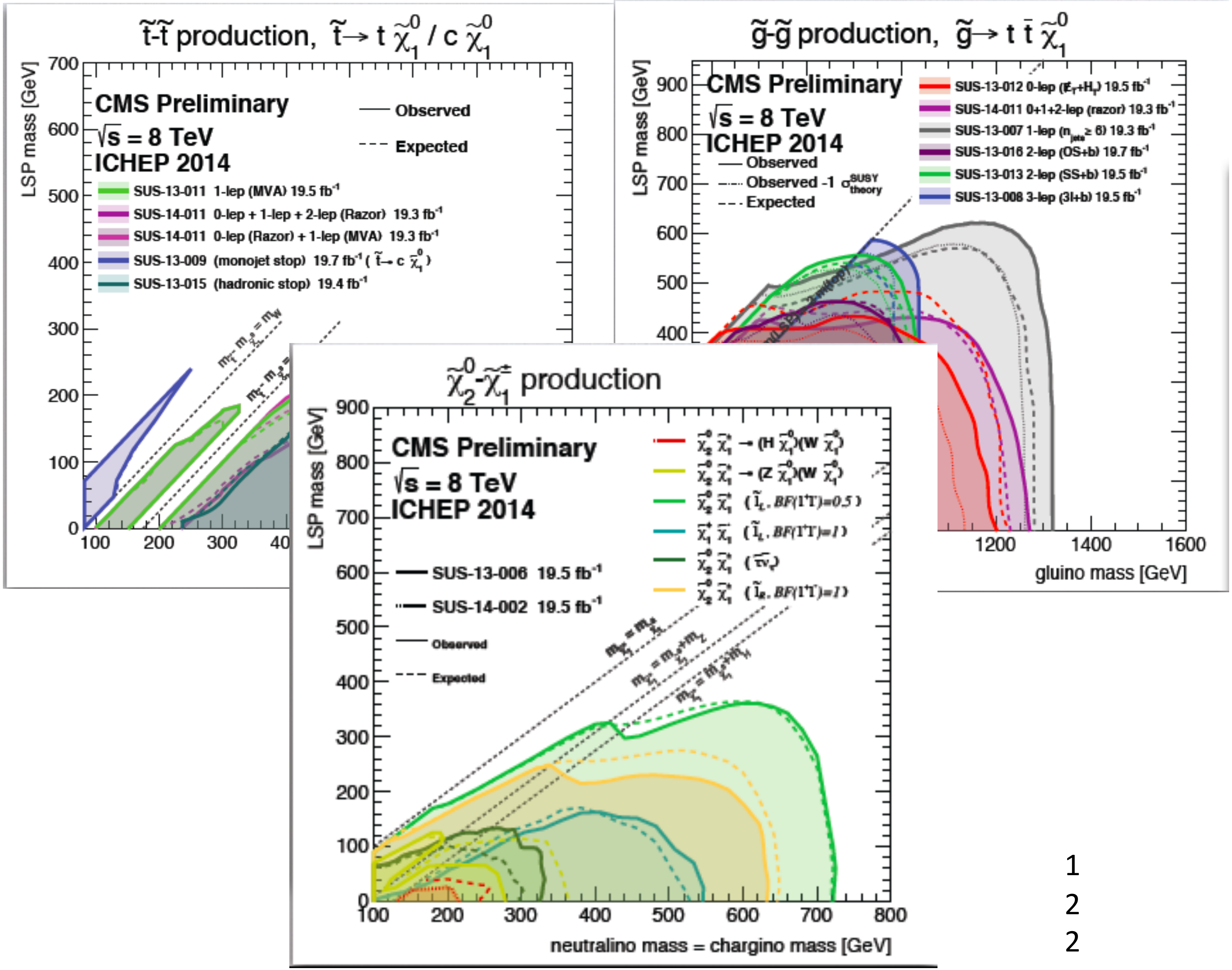
LEPSUSYWG/04-01.1

S. Su

CMB vs direct/indirect searches

arXiv:1310.3815




t̃-t̃ production, t̃→ t $\tilde{\chi}_1^0$ / c $\tilde{\chi}_1^0$
CMS Preliminary
√s = 8 TeV
ICHEP 2014
Observed
Expected
SUS-13-011 1-lep (MVA) 19.5 fb⁻¹
SUS-14-011 0-lep + 1-lep + 2-lep (Razor) 19.3 fb⁻¹
SUS-14-011 0-lep (Razor) + 1-lep (MVA) 19.3 fb⁻¹
SUS-13-009 (monojet stop) 19.7 fb⁻¹ (t̃→ c $\tilde{\chi}_1^0$)
SUS-13-015 (hadronic stop) 19.4 fb⁻¹
$m_{\tilde{t}} - m_{\tilde{\chi}_1^0} = m_W$
$m_{\tilde{t}} - m_{\tilde{\chi}_1^0} = m_t$
LSP mass [GeV]
0
100
200
300
400
500
600
700
100
200
300
40
g̃-g̃ production, g̃→ t t̄ $\tilde{\chi}_1^0$
CMS Preliminary
√s = 8 TeV
ICHEP 2014
Observed
Observed -1 σ^{SUSY}_{theory}
Expected
SUS-13-012 0-lep (E_T+H_T) 19.5 fb⁻¹
SUS-14-011 0+1+2-lep (razor) 19.3 fb⁻¹
SUS-13-007 1-lep (n_{jets} ≥ 6) 19.3 fb⁻¹
SUS-13-016 2-lep (OS+b) 19.7 fb⁻¹
SUS-13-013 2-lep (SS+b) 19.5 fb⁻¹
SUS-13-008 3-lep (3l+b) 19.5 fb⁻¹
LSP mass [GeV]
400
500
600
700
800
900
1200
1400
1600
gluino mass [GeV]
$\tilde{\chi}_2^0$-$\tilde{\chi}_1^\pm$ production
CMS Preliminary
√s = 8 TeV
ICHEP 2014
$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ → (H $\tilde{\chi}_1^0$)(W $\tilde{\chi}_1^0$)
$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ → (Z $\tilde{\chi}_1^0$)(W $\tilde{\chi}_1^0$)
$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ ($\tilde{l}_L$, BF(l⁺l⁻)=0.5)
$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ ($\tilde{l}_L$, BF(l⁺l⁻)=1)
$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ ($\tilde{\tau}\nu_\tau$)
$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ ($\tilde{l}_R$, BF(l⁺l⁻)=1)
SUS-13-006 19.5 fb⁻¹
SUS-14-002 19.5 fb⁻¹
Observed
Expected
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + m_Z$
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + m_H$
LSP mass [GeV]
0
100
200
300
400
500
600
700
800
900
100
200
300
400
500
600
700
800
neutralino mass = chargino mass [GeV]

1

2

2

High mass DM could justify the physics case for a precision post-AMS-02 large acceptance, high resolution CR space spectrometer to explore the 10 TeV energy range

Conclusions

- On Earth experiments are reaching technical limits, whereas indirect searches still show a promising potential for heavy WIMPs
- Nuclear uncertainties affect every sector of particle physics: DM direct detection (nuclear recoil matrix), indirect searches (spallationin the ISM) and cosmology (primordial nucleosynthesis)
- A careful study of the dark matter profile and its hypothetical dark disk is challenging but fundamental
- Exotic candidates, SUSY candidates and SUSY antagonist: a full exhaustive theory which accounts for Dark Matter and fundamental SM problems in not available yet
- A multi-TeV DM would grant a decoupling temperature comparable with the electroweak symmetry-breaking one, bringing out dark matter at the same scale and with a possible interconnected mechanism
- AMS-02 should soon demonstrate the presence or absence of WIMPs annihilation products in the multi 100 GeV region
- To explore the positron ratio increase in to the 10 TeV range and the antiproton ratio well into the 1 TeV range a new generation of precise particle spectrometer in space would be needed