Recent Results from the AMS-02 experiment

LC 13
September 16th
2013
Trento (Italy)

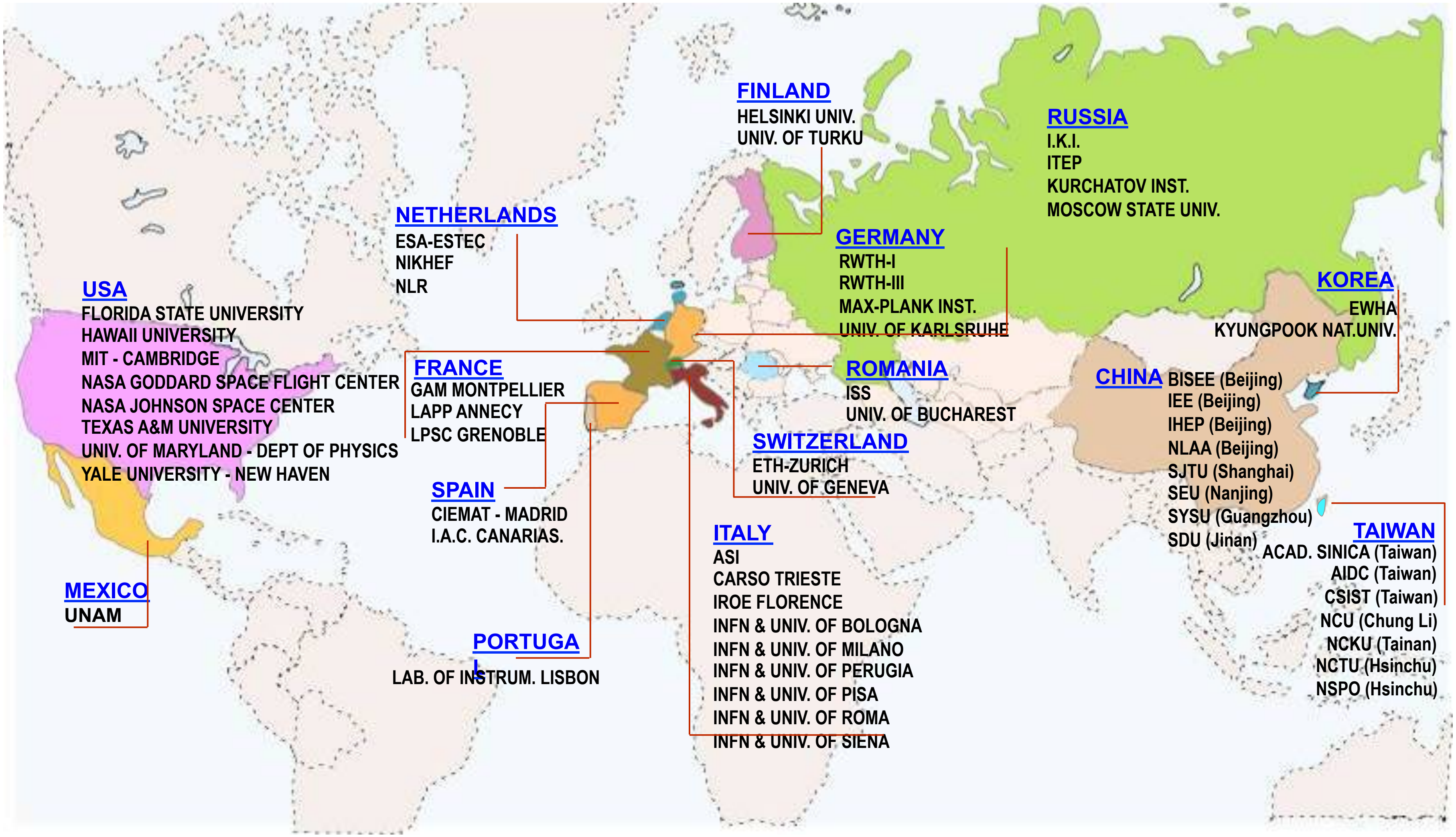
D.D'Urso (Perugia INFN,CERN)

on behalf of the AMS Collaboration

Outline

1. Introduction to AMS
2. Physics Goals
3. Physics results from the first two years
4. Conclusions

On behalf of the AMS Collaboration
16 Countries, 60 Institutes and 600 Physicists



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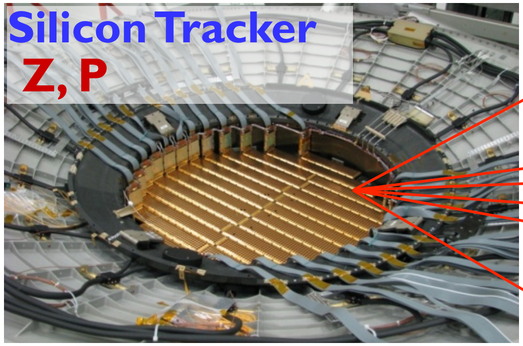
A precise, multipurpose spectrometer

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

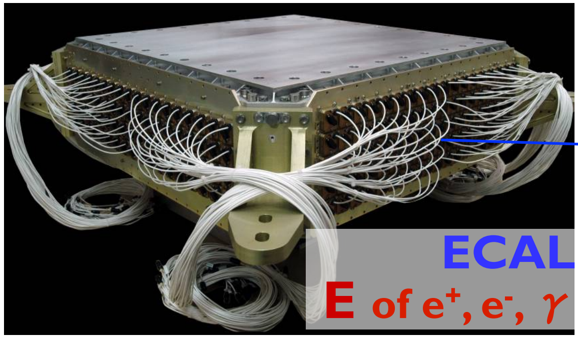
TRD

Identify e^+, e^-



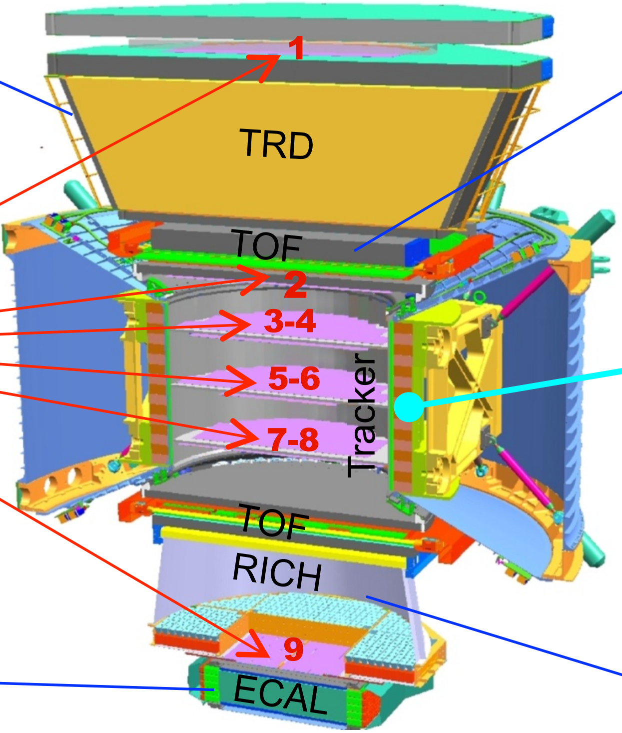
Silicon Tracker

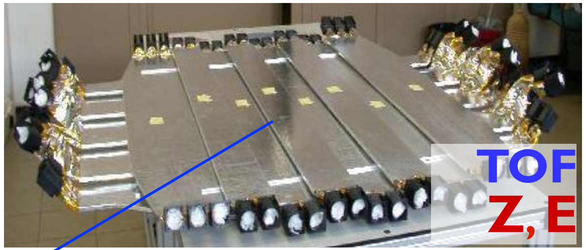
Z, P



ECAL

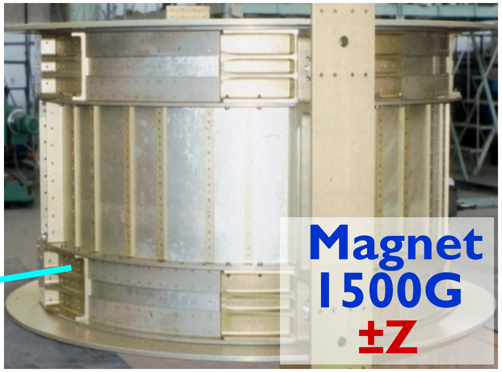
E of e^+, e^-, γ





TOF

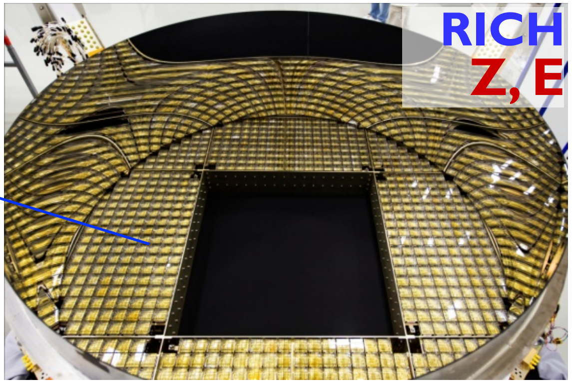
Z, E



Magnet

1500G

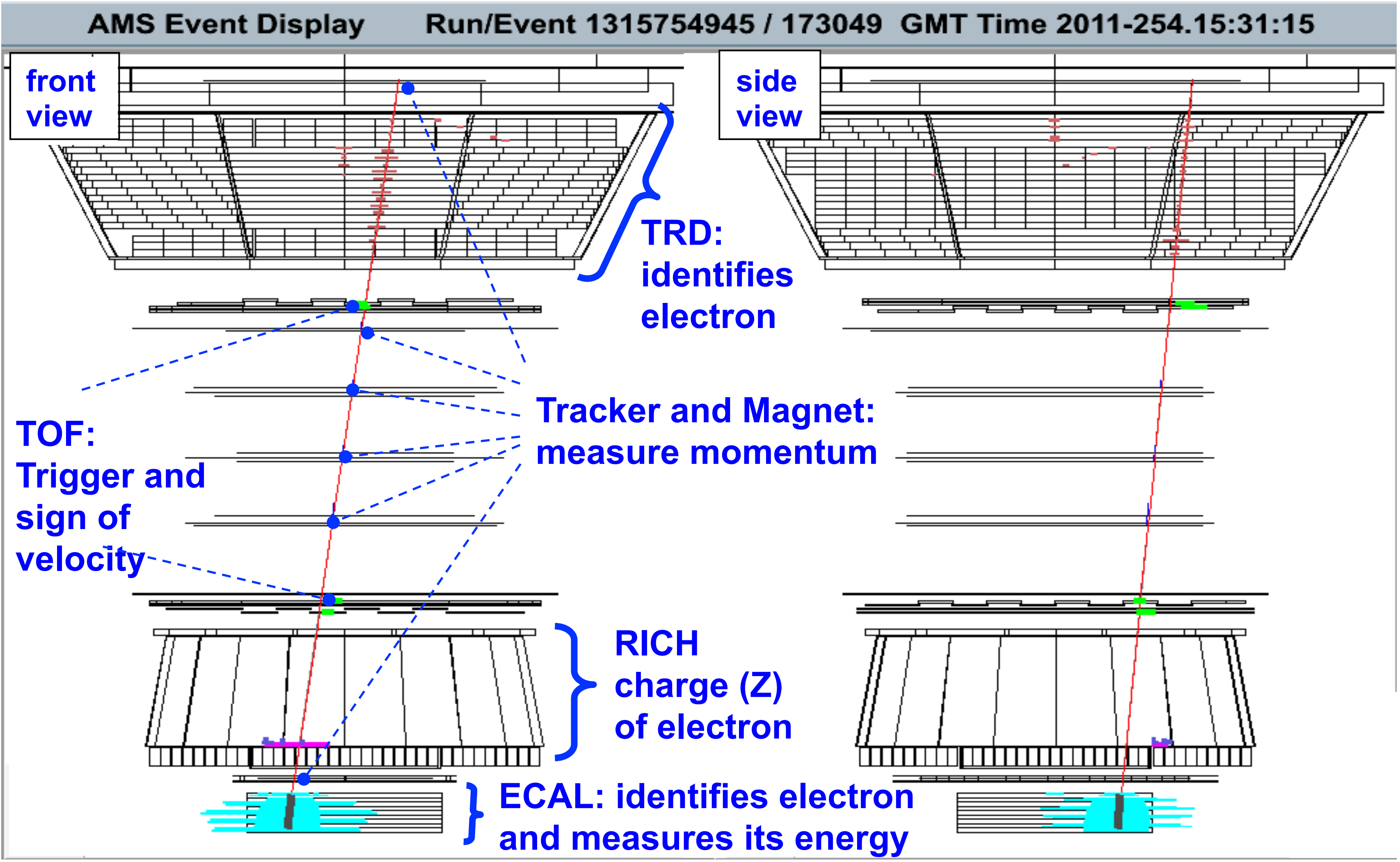
±Z



RICH

Z, E

AMS data on ISS: 1.03 TeV electron



front view

side view

TRD: identifies electron

Tracker and Magnet: measure momentum

TOF: Trigger and sign of velocity

RICH charge (Z) of electron

ECAL: identifies electron and measures its energy

Objectives

1. Fundamental physics & Antimatter :
    - Primordial origin (signal : anti-nuclei)
    - Exotic sources (signal: positrons, anti-p, anti-D)

2. The CR composition and energy spectrum

The CR composition and energy spectrum

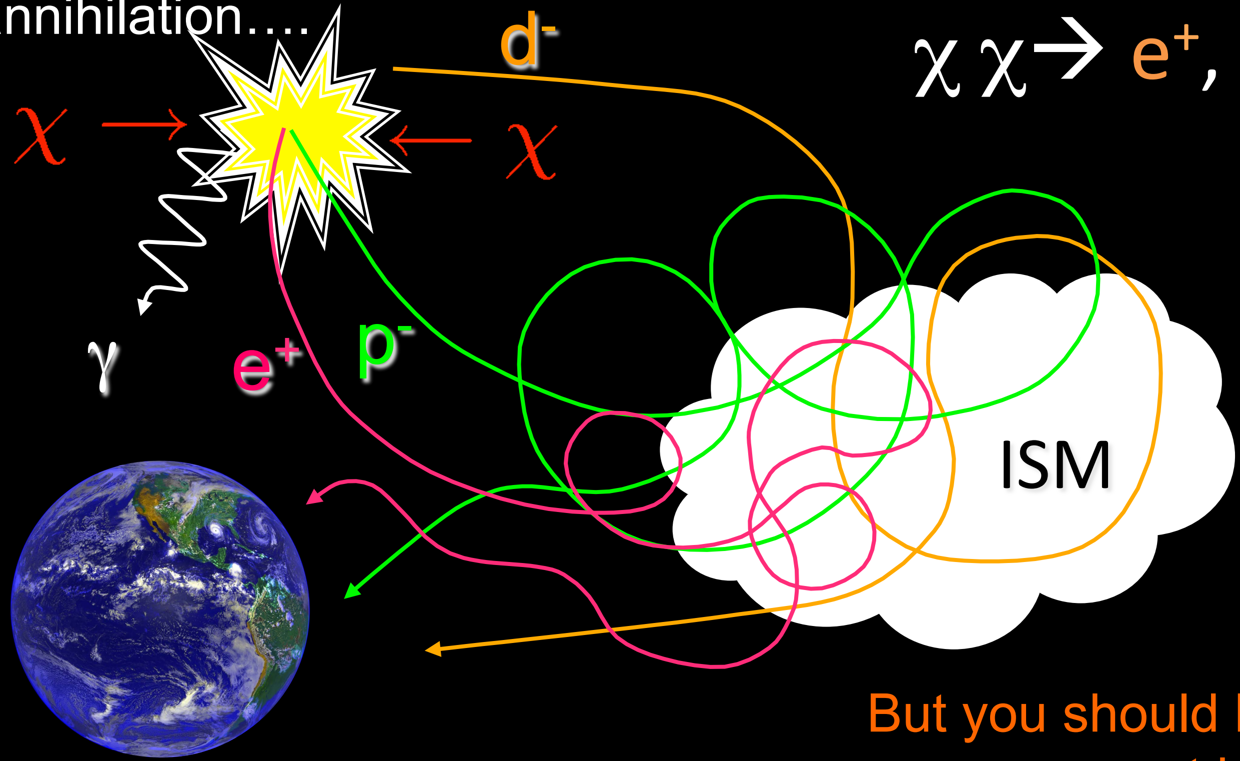
- Sources & acceleration : Proton and He
- Propagation in the ISM: secondaries (B/C, ...)

Dark Matter

WIMP as the responsible of Dark Matter (?)

Indirect DM search → search for (rare in CR) products from their annihilation….

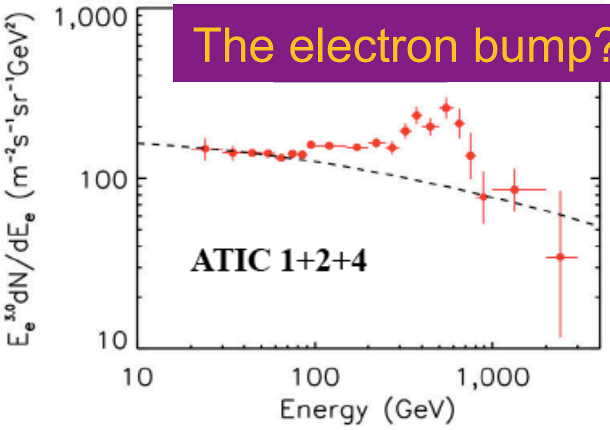
$\chi\chi \rightarrow e^+, e^-, p, p^-, \gamma$



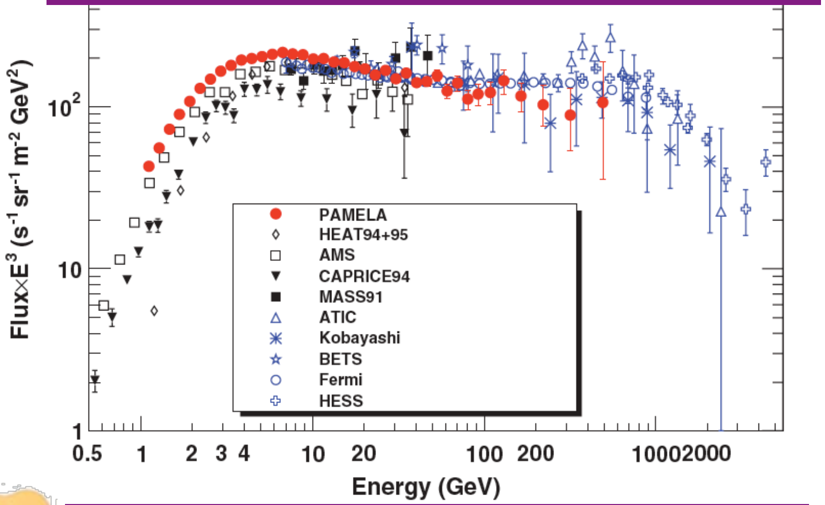
But you should know what you expect in the ISM !!

Exotic sources (DM ?)

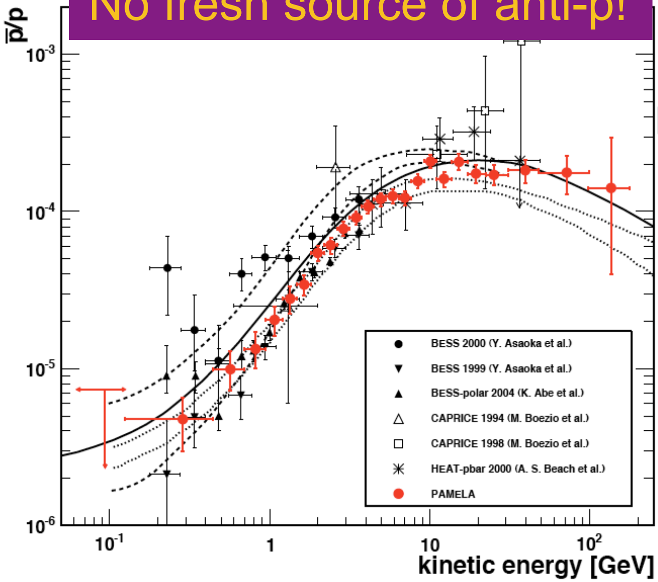
The electron bump?



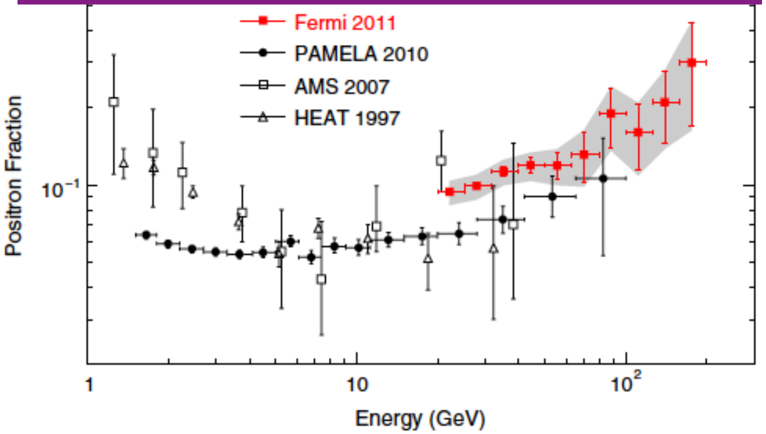
No bump in Fermi / PAMELA data



No fresh source of anti-p!

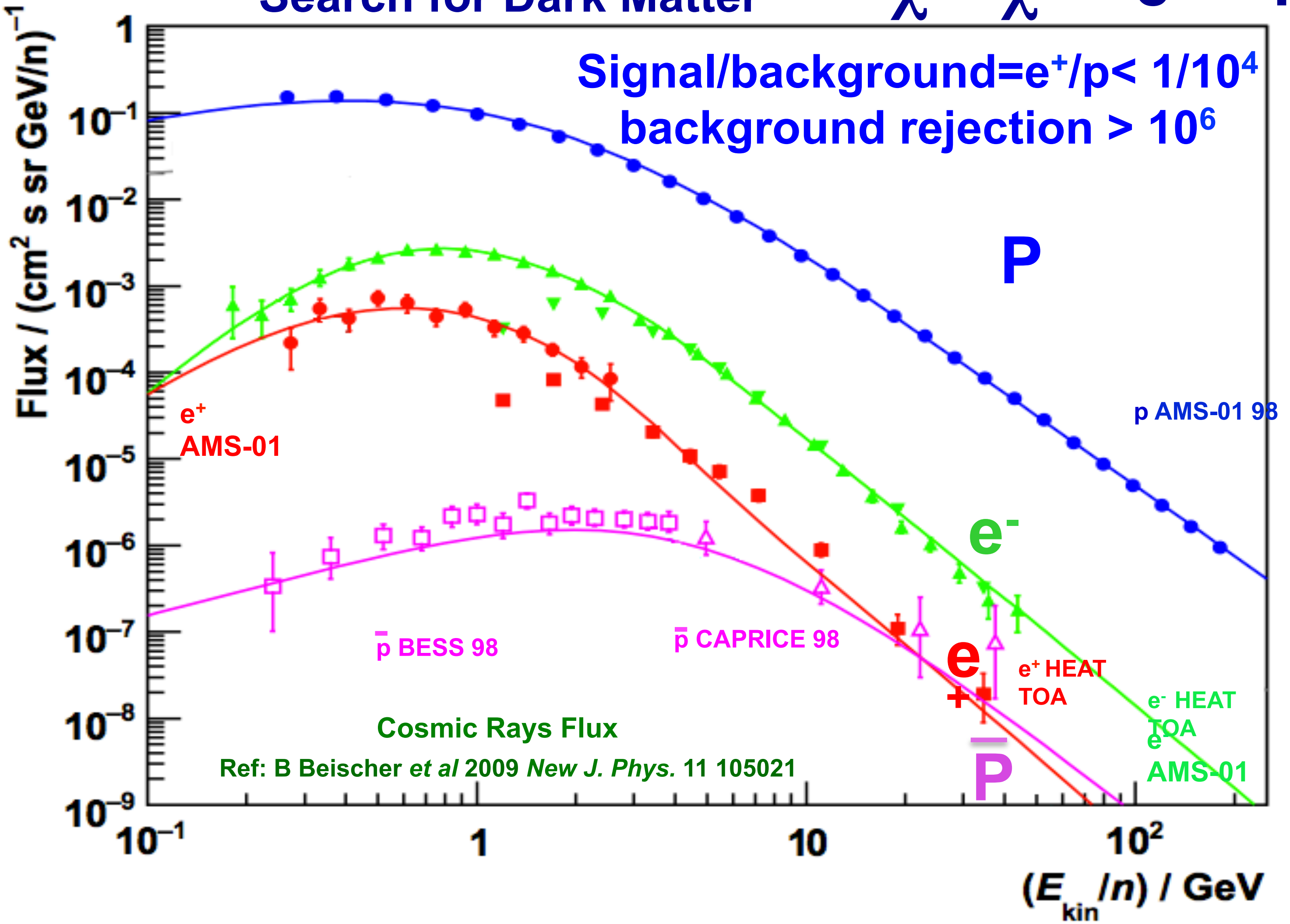


A confirmed positron "excess"



The Experimental challenge

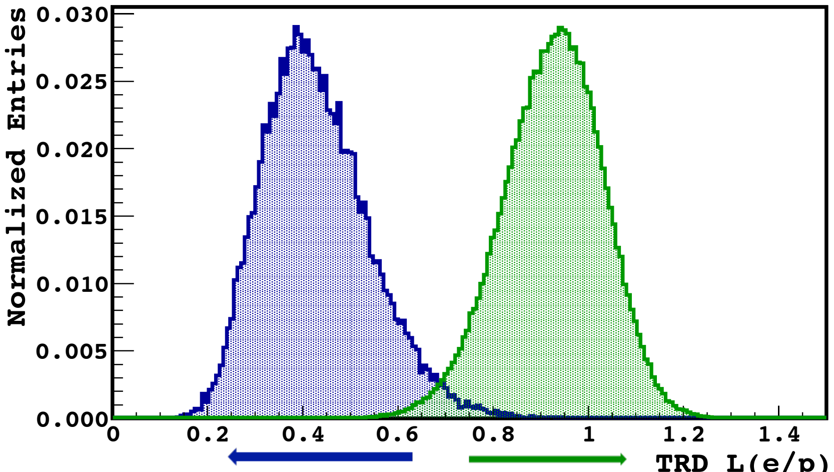
Search for Dark Matter $\chi + \chi \rightarrow e^{+} + ...$



Signal/background=$e^{+}/p < 1/10^{4}$

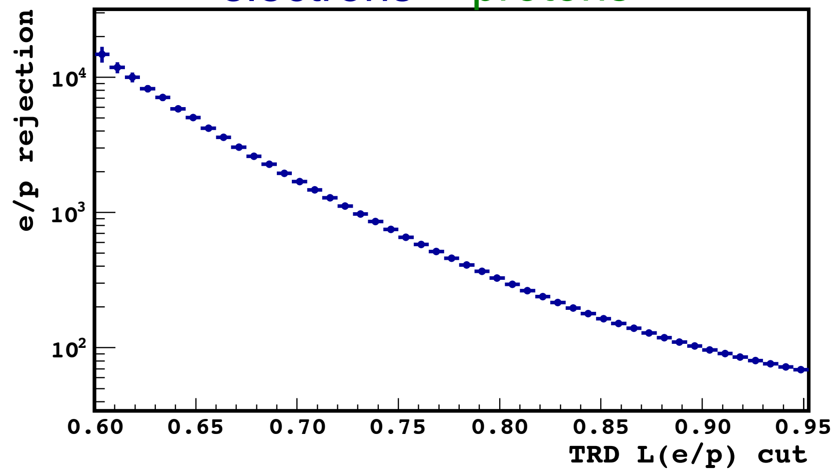
background rejection > 10^{6}

Particle identification in TRD



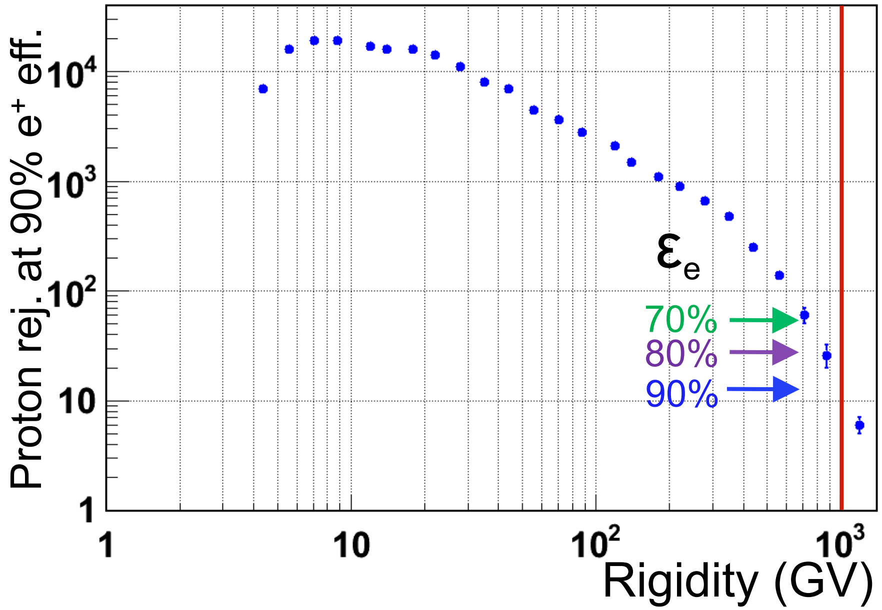
Select electrons

Select protons



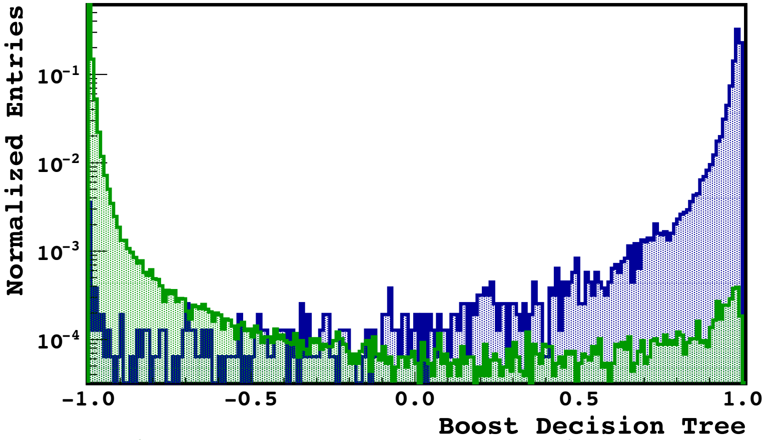
Normalized probabilities ***P*$_e$** and ***P*$_p$**

$$P_e = \sqrt[n]{\prod_i^n P_e^{(i)}(A)} \qquad P_p = \sqrt[n]{\prod_i^n P_p^{(i)}(A)}$$



TRD estimator = -ln(***P*$_e$**/(***P*$_e$**+***P*$_p$**))

Particle identification in ECAL

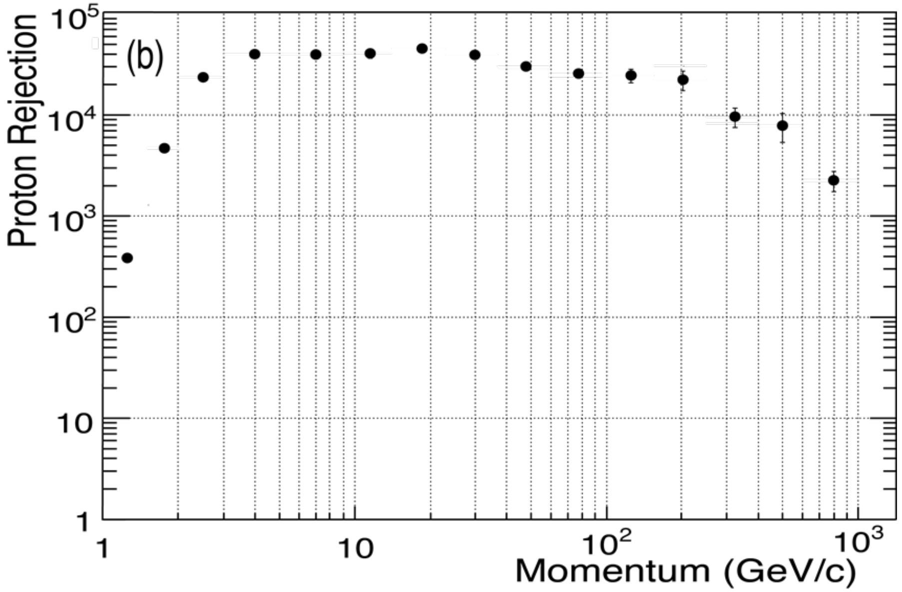


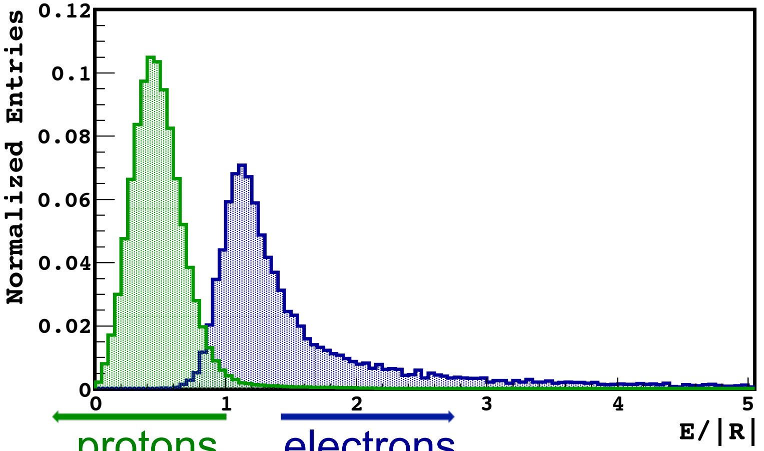
Select protons

Select electrons

Boosted Decision Tree, BDT:

19 variables describing
3D shower shape combined
(B.Roe et al., NIM A543 (2005) 577)



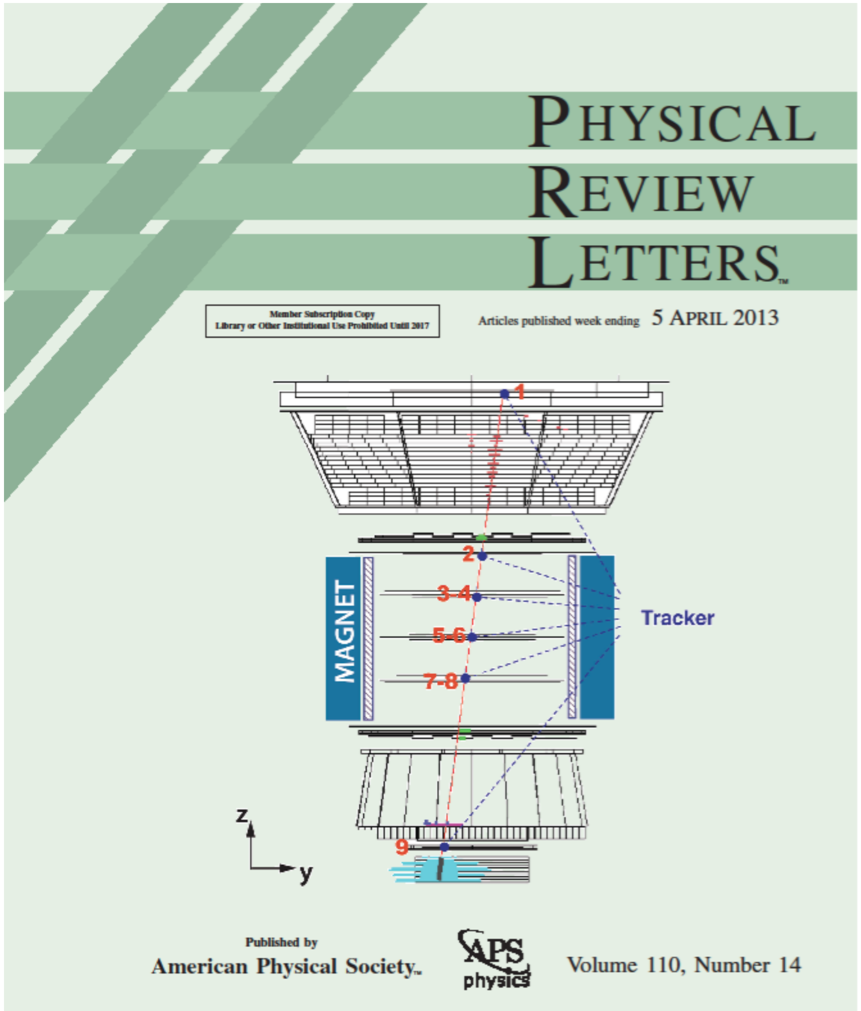


protons

electrons

Precise Measurement of Positron Fraction

1. Measurement technique
2. Systematic errors
3. Minimal model interpretation



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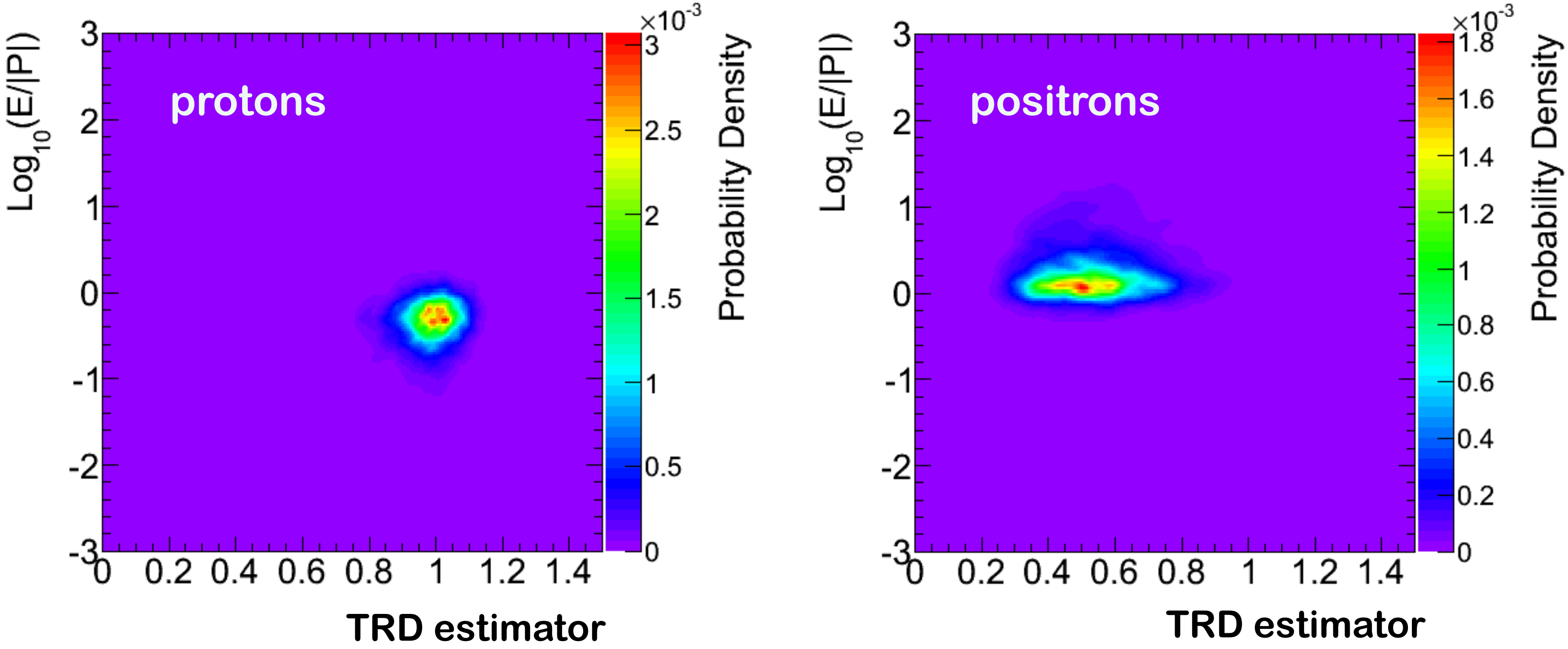
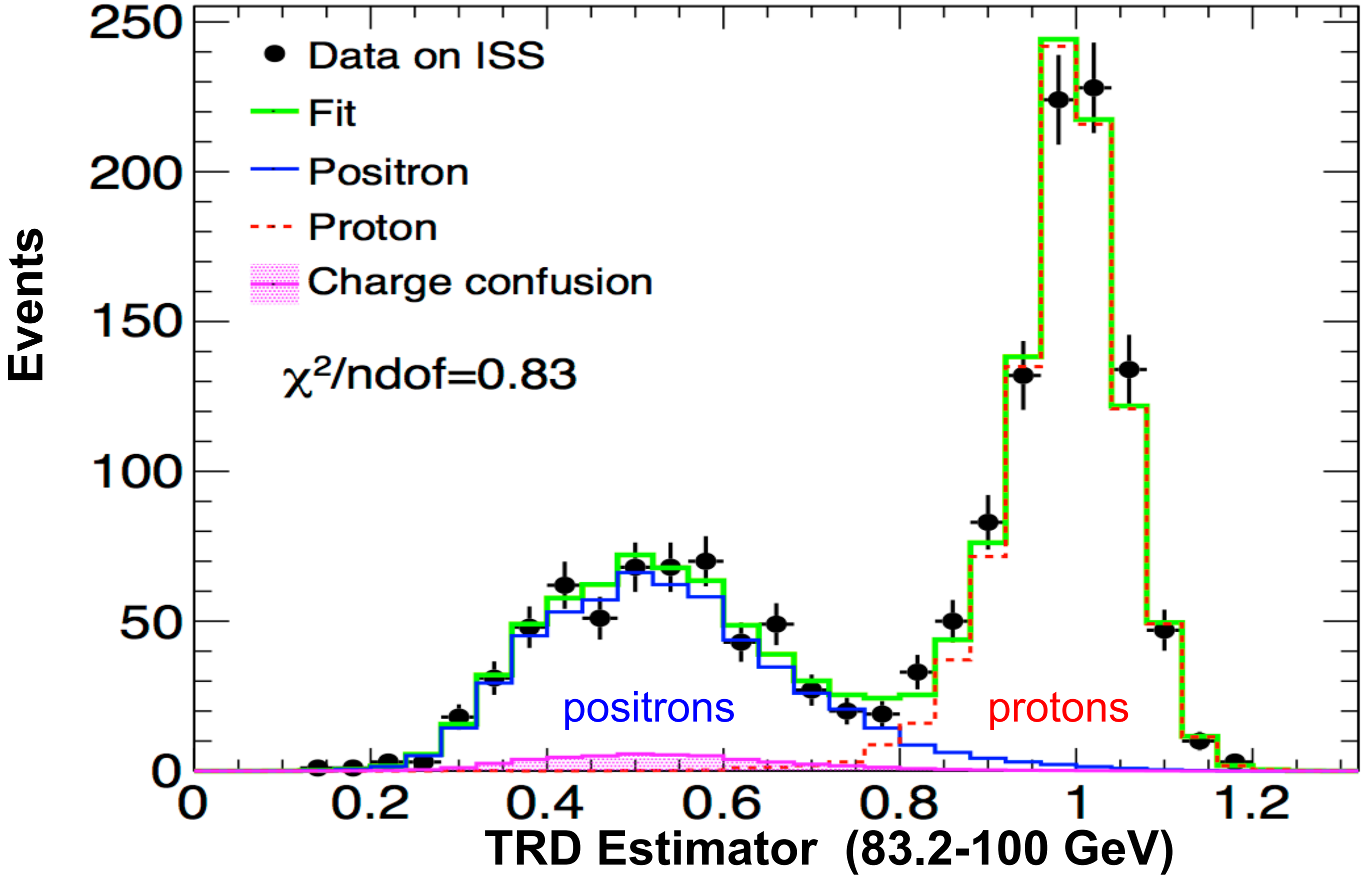
Analysis:2D fit to estimate Ne$^{\pm}$ and Np

2D reference spectra for the signal and the background are fitted to data in the [TRD estimator- log(E/|P|)] plane

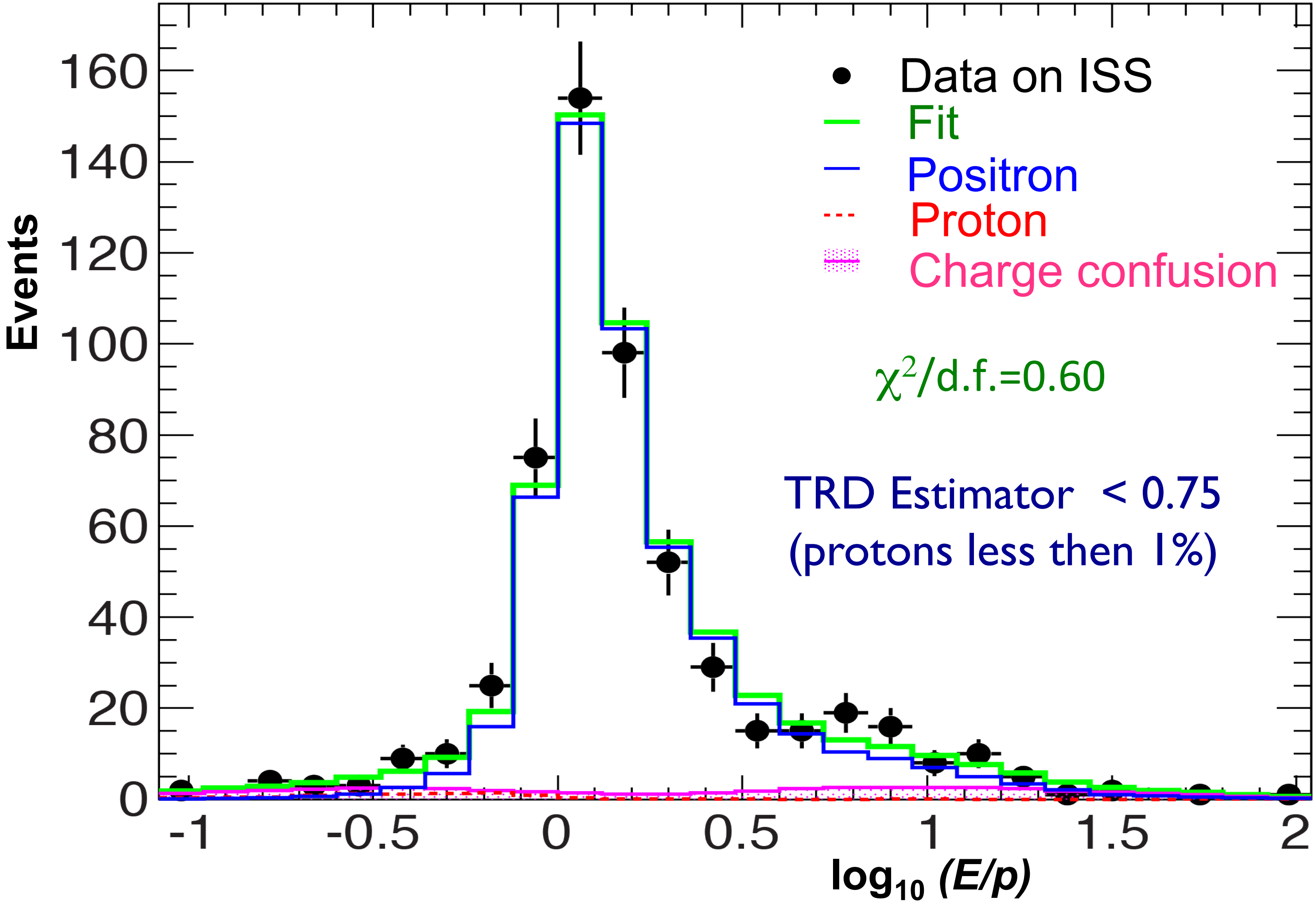


Projection on TRD Estimator

Clear separation between protons and positrons with a small charge confusion background



Fit Results

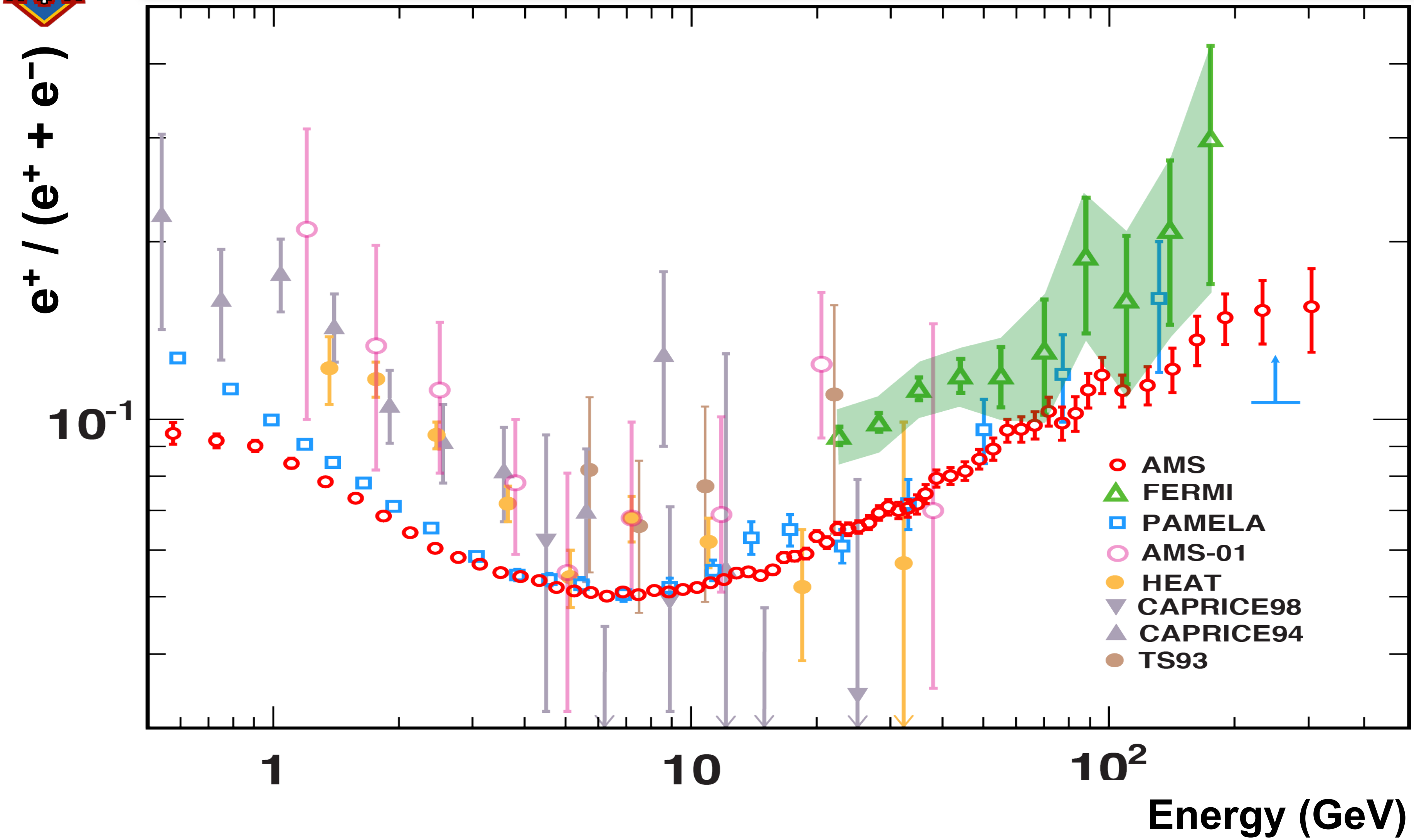


TRD Estimator < 0.75
(protons less then 1%)

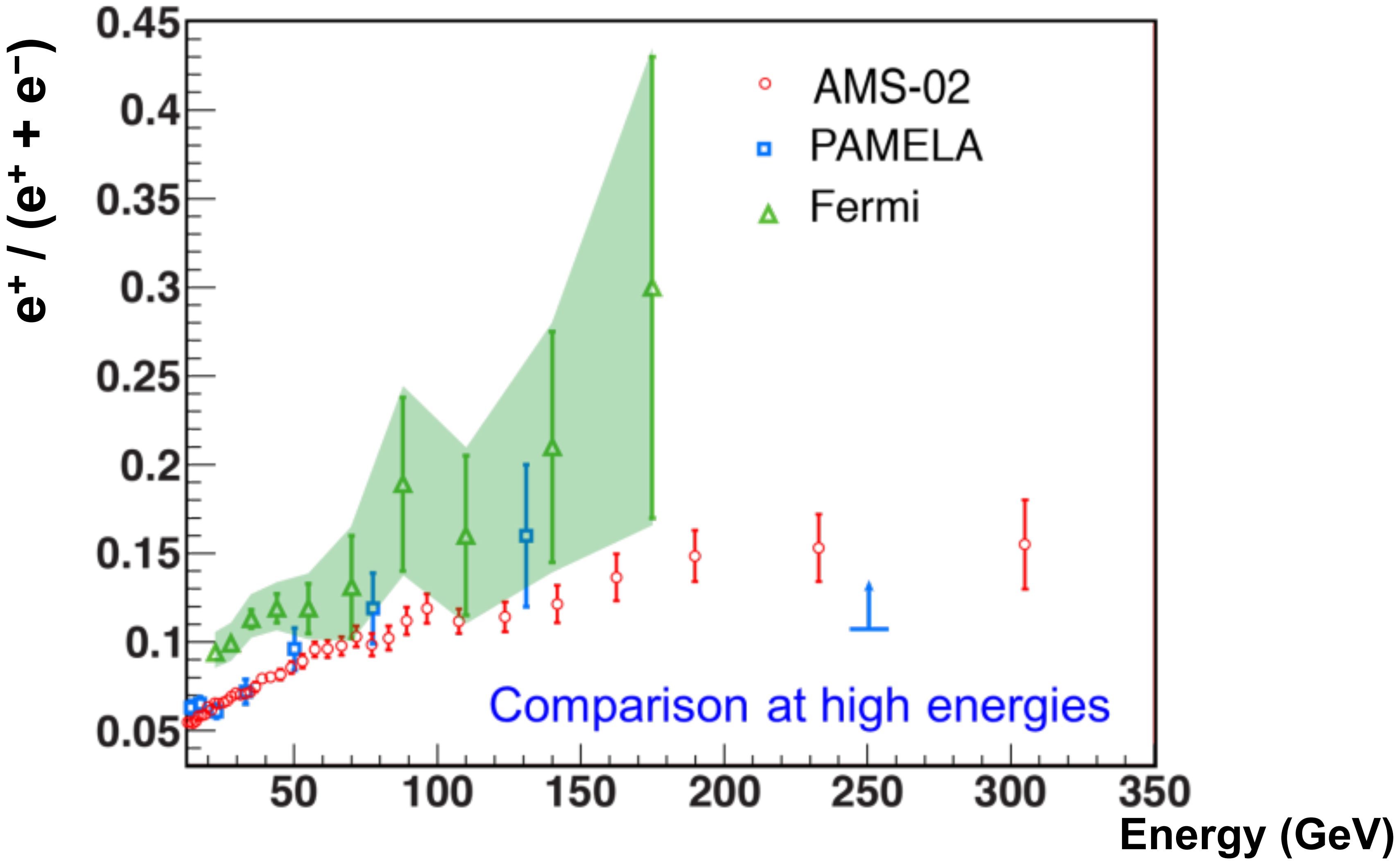
Systematic errors on positron fraction

1. Acceptance asymmetry
   - Difference between positron and electron acceptance due to known minute tracker asymmetry → err.rel = 1% - 0.2%
2. Selection dependence
   - Dependence of the result on the cut values → err.rel = 2% - 0.4%
3. Migration bin-to bin
   - Migration of electron and positron events from the neighboring bins affects the measured fraction → err.rel = 0.5% - 0.01%
4. Reference spectrum
   - Definition of the reference spectra is based on pure samples of electrons and protons of finite statistics → err.rel = 0.2% - 1%
5. Charge confusion
   - Two sources: large angle scattering and production of secondary tracks along the path of the primary track. Both are well reproduced by MC. Systematic errors correspond to variations of these effects within their statistical limits → err.rel = 1% - 10%

Positron fraction (0.5 - 350 GeV)



Positron fraction (0.5 - 350 GeV)

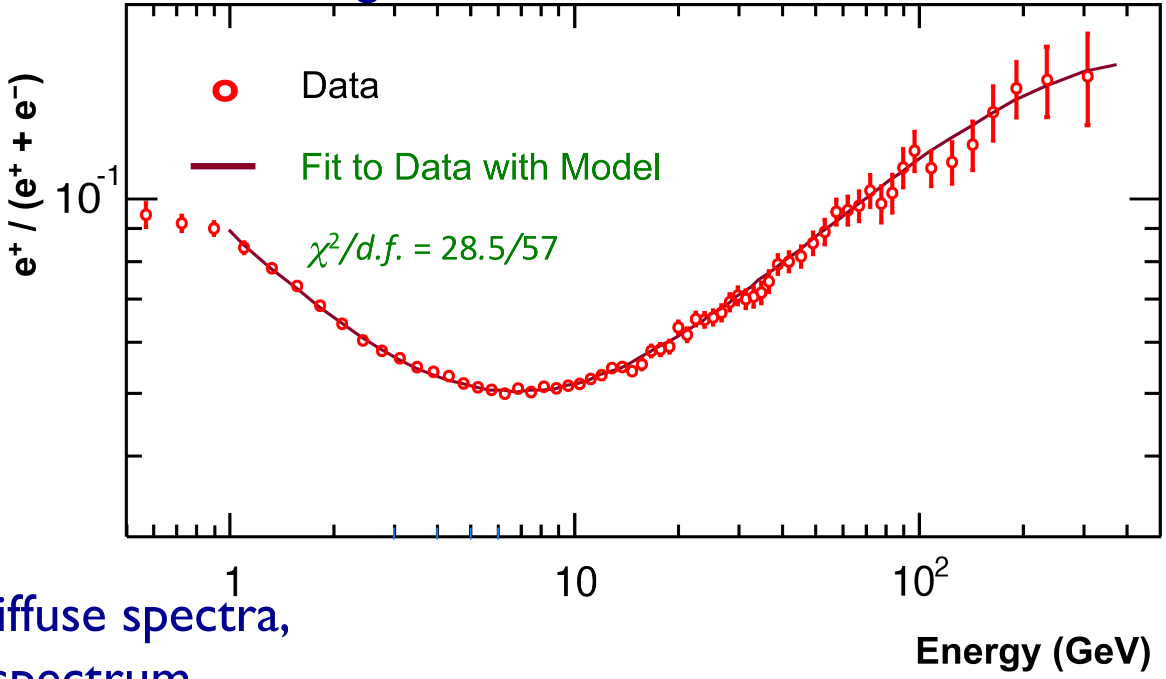


Comparison at high energies

Primary/secondary: minimal model

e^+ (Φ_{e+})and e^- (Φ_{e-}) fluxes can be parametrized as the sum of individual diffuse power law spectra and the contribution of a single common source of $e^\pm$:

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



C_{e+} and C_{e-} are the weights of diffuse spectra,

C_s is the weight of the source spectrum

γ_{e+}, γ_{e-} and γ_s are the corresponding spectral indexes

E_s is a characteristic cutoff energy for the source

Positron fraction is consistent with a scenario in which e± fluxes are the sum of a diffuse spectrum and a single common power law source

Primary/secondary: minimal model

A fit to the data in the energy range 1 to 350 GeV yields a $\chi^2/d.f. = 28.5/57$:

$\gamma_{e-} - \gamma_{e+} = -0.63 \pm 0.03$, *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;

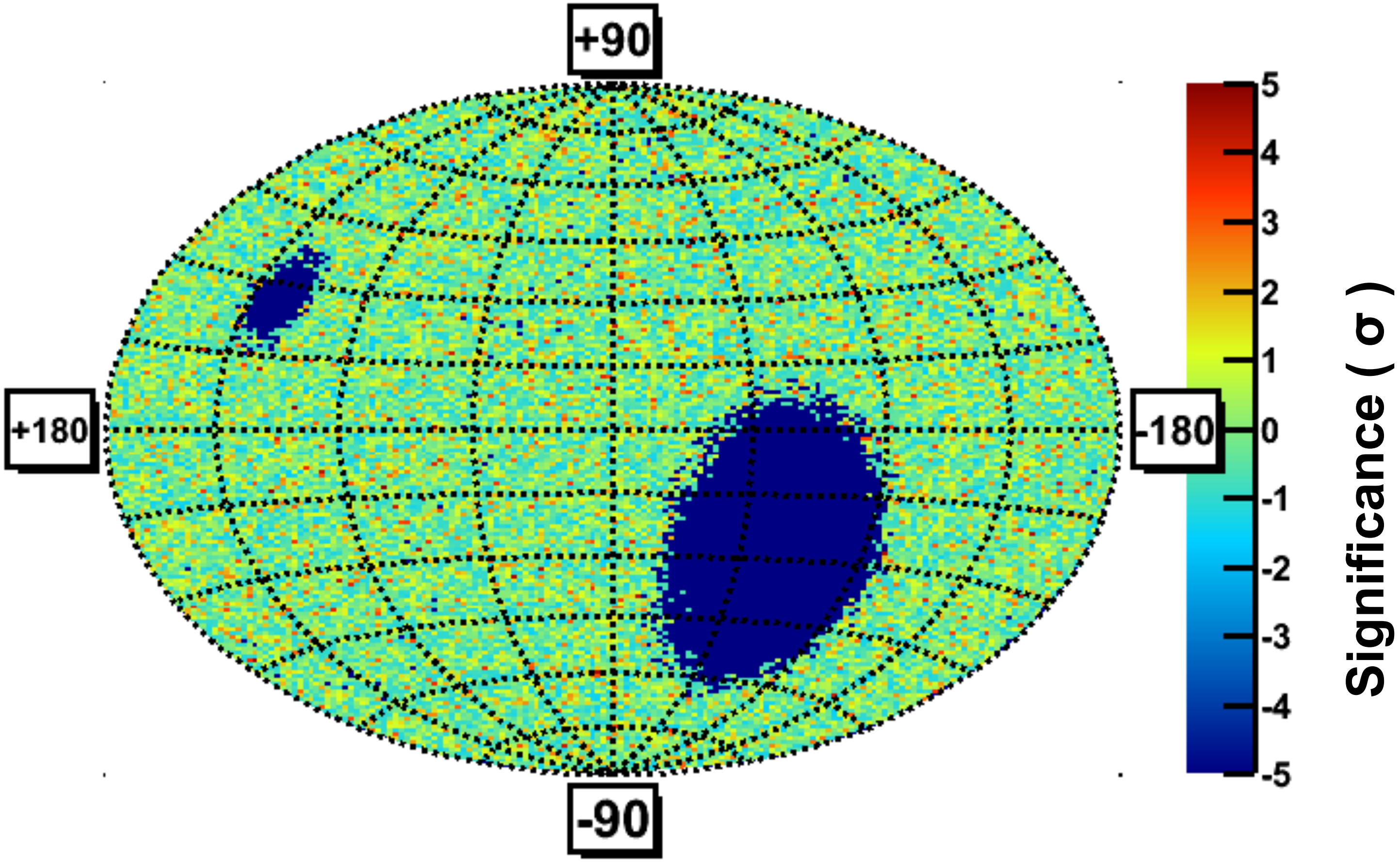
$C_{e+}/C_{e-} = 0.091 \pm 0.001$, *i.e.*, the weight of the diffuse positron flux amounts to ~10% of that of the diffuse electron flux;

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

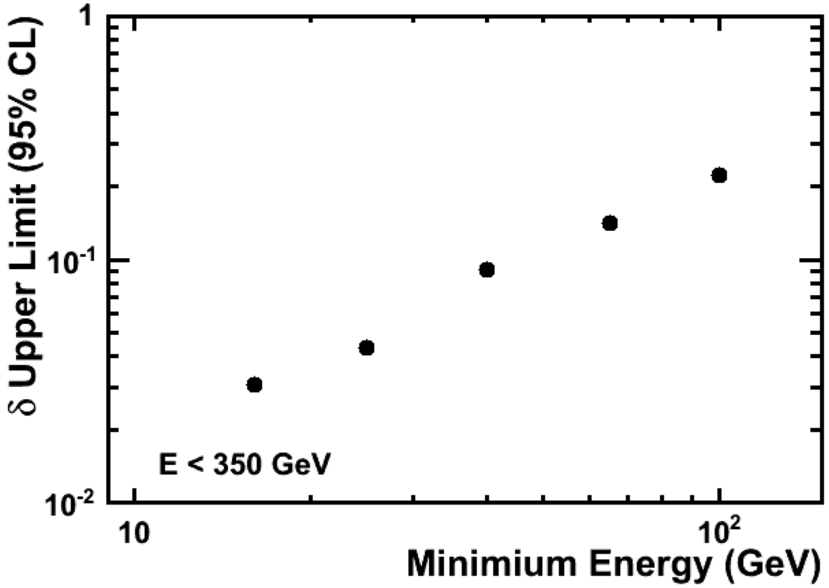
$1/E_s = 0.0013 \pm 0.0007\ \mathrm{GeV}^{-1}$,corresponding to a cutoff energy of 760^{+1000}_{-280} GeV.

Positron anisotropy

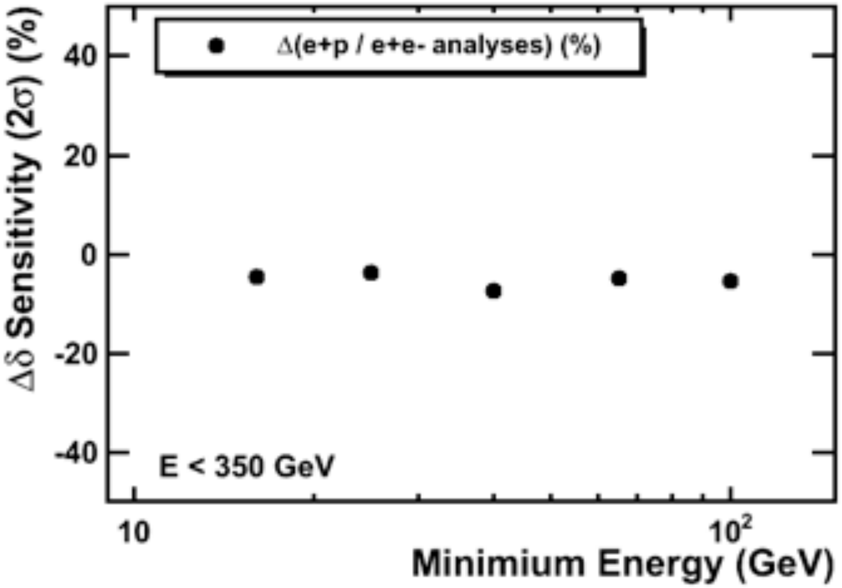
The relative fluctuations of the positron ratio, e^+/e^-, across the observed sky map show no evident pattern



Limit on dipole anisotropy



Limits on the amplitude of a dipole anisotropy in any axis in galactic coordinates on the positron to electron ratio in the energy range from 16 GeV to 350 GeV (<0.030)



The sensitivity to a dipole anisotropy using the positron to proton ratio is consistent with the one obtained on the positron to electron analysis

Spectrum Measurement

$$F(R) = \frac{N_{\mathrm{obs.}}(R)}{T_{\mathrm{exp.}}(R)\, A_{\mathrm{eff.}}(R)\, \varepsilon_{\mathrm{trig.}}(R)\, \mathrm{d}R}$$

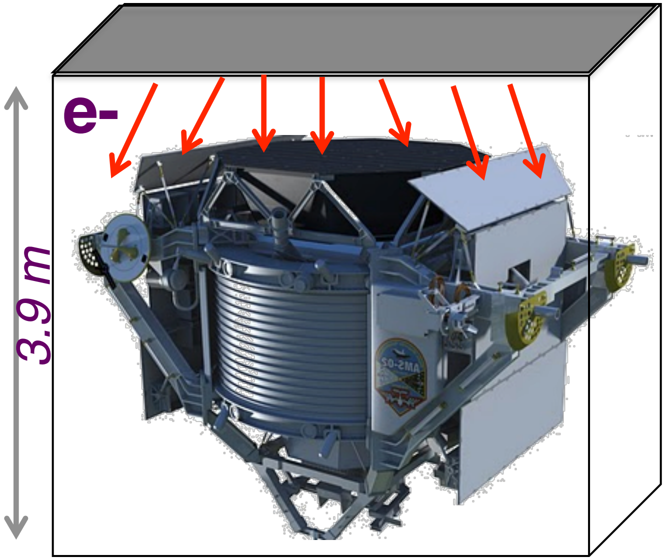
(For isotropic flux
with $\theta_{\mathrm{zen}} < 20°$)

- F : Absolute differential flux ($\mathrm{m}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}\mathrm{GV}^{-1}$)
- R : Measured rigidity (GV)
- $N_{\mathrm{obs.}}$: Number of events after proton selection
- $T_{\mathrm{exp.}}$: Exposure life time (s)
- $A_{\mathrm{eff.}}$: Effective acceptance (m^2 sr)
- $\varepsilon_{\mathrm{trg.}}$: Trigger efficiency
- $\mathrm{d}R$: Rigidity bin (GV)

Detector acceptance

Estimated with MC (Geant 4)

$$A_{\mathrm{eff.}}(E) = A_{\mathrm{generated}} \times \frac{N_{\mathrm{selected}}(E)}{N_{\mathrm{generated}}(E)}$$



$A_{\mathrm{generated}}$ = acceptance of the generation surface

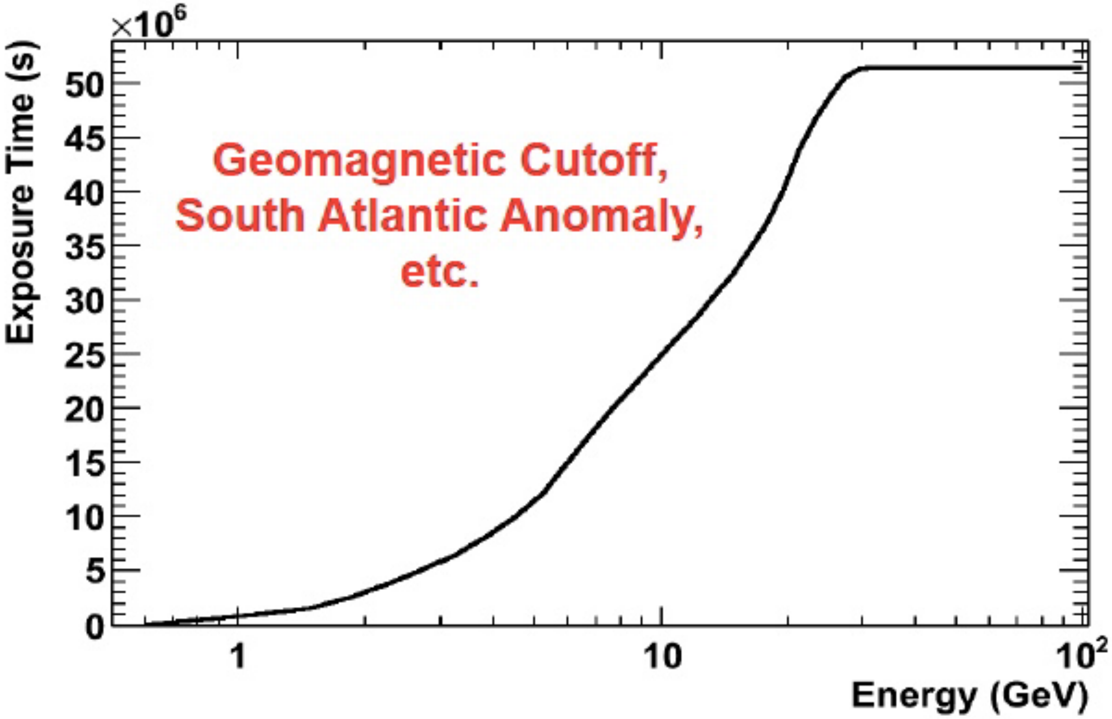
N_{selected} = events passing the selection criteria

→During the analysis chain, efficiencies for different requests on the event will appear as multiplicative factors.
→For each selection request the efficiency measured in data is compared with that on MC

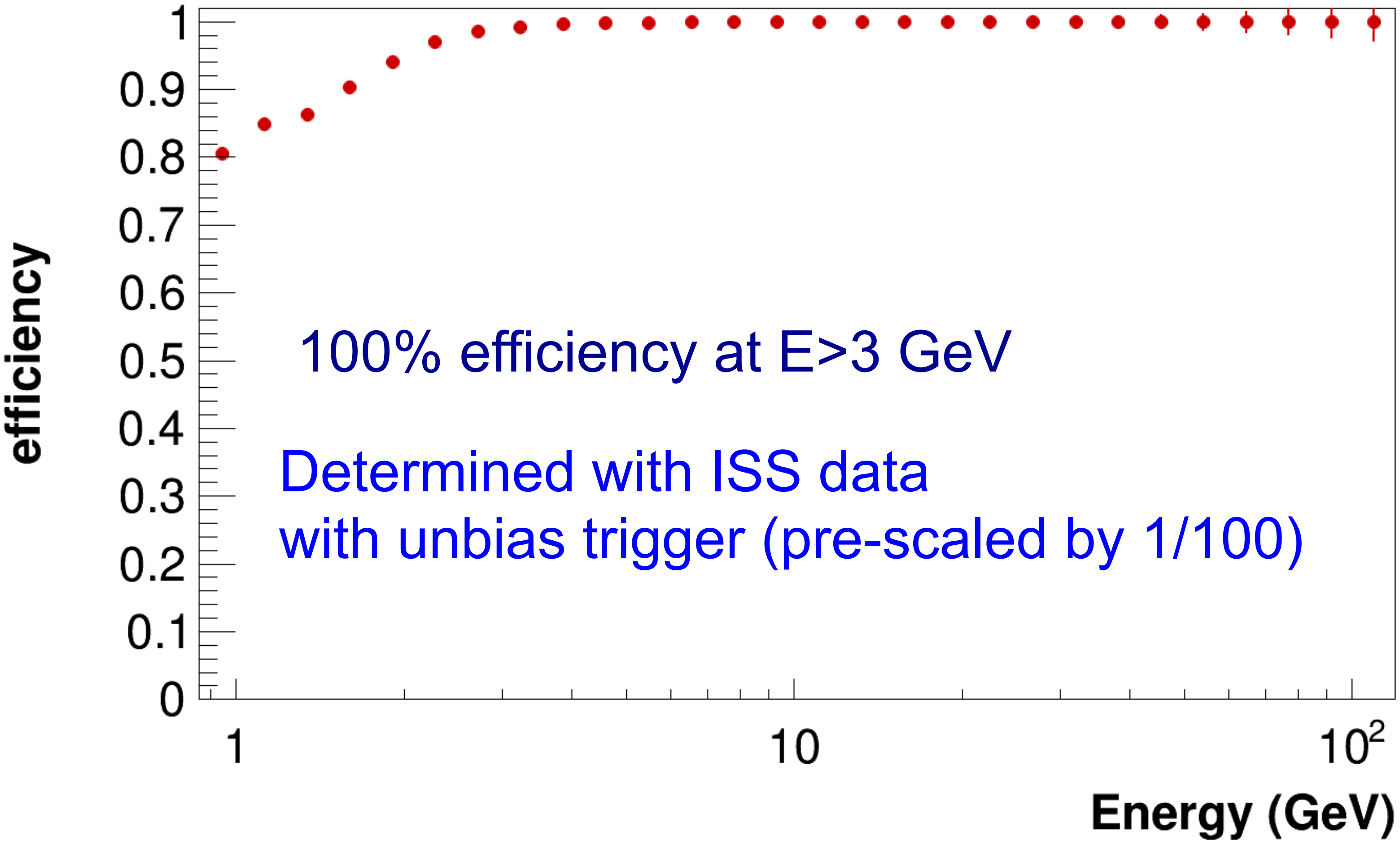
Exposure Time

Data period: May 19th, 2011 to May 19th, 2013

1. Total exposure time (R>25 GV): 51.2 x 10^6 s
2. Average Live time: Texp/2 years = 81.6%



Trigger efficiency : electrons

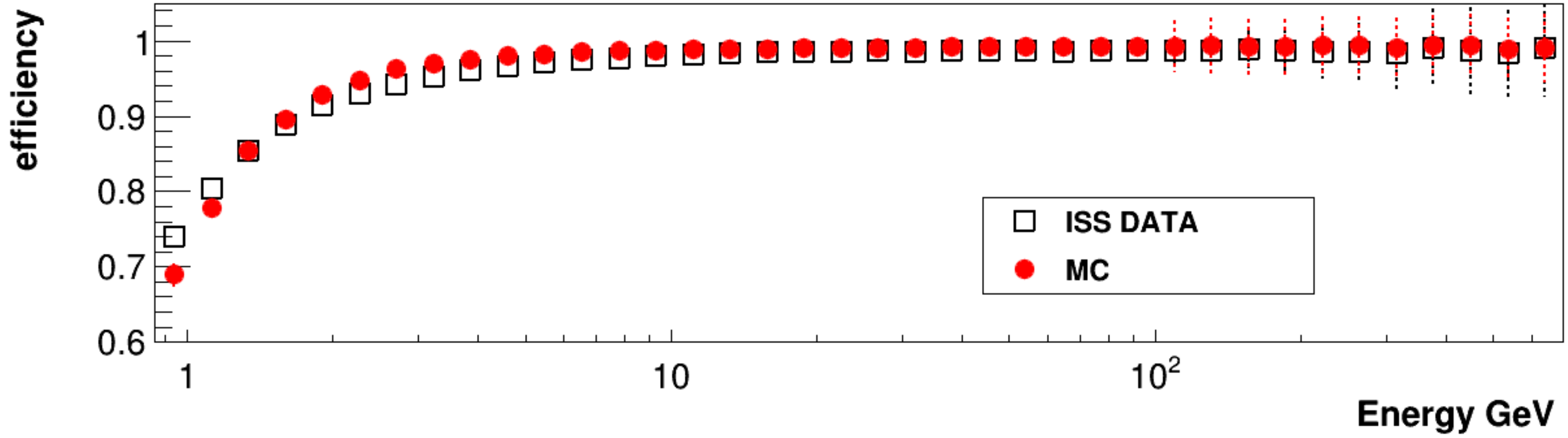


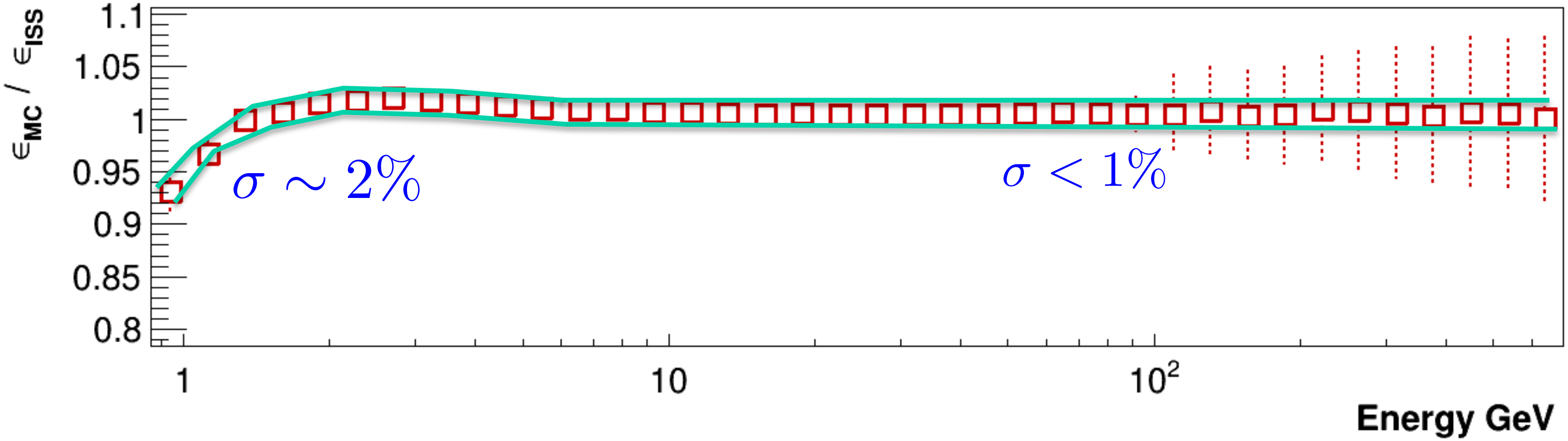
100% efficiency at E>3 GeV

Determined with ISS data
with unbias trigger (pre-scaled by 1/100)

Systematics example: TRD efficiency

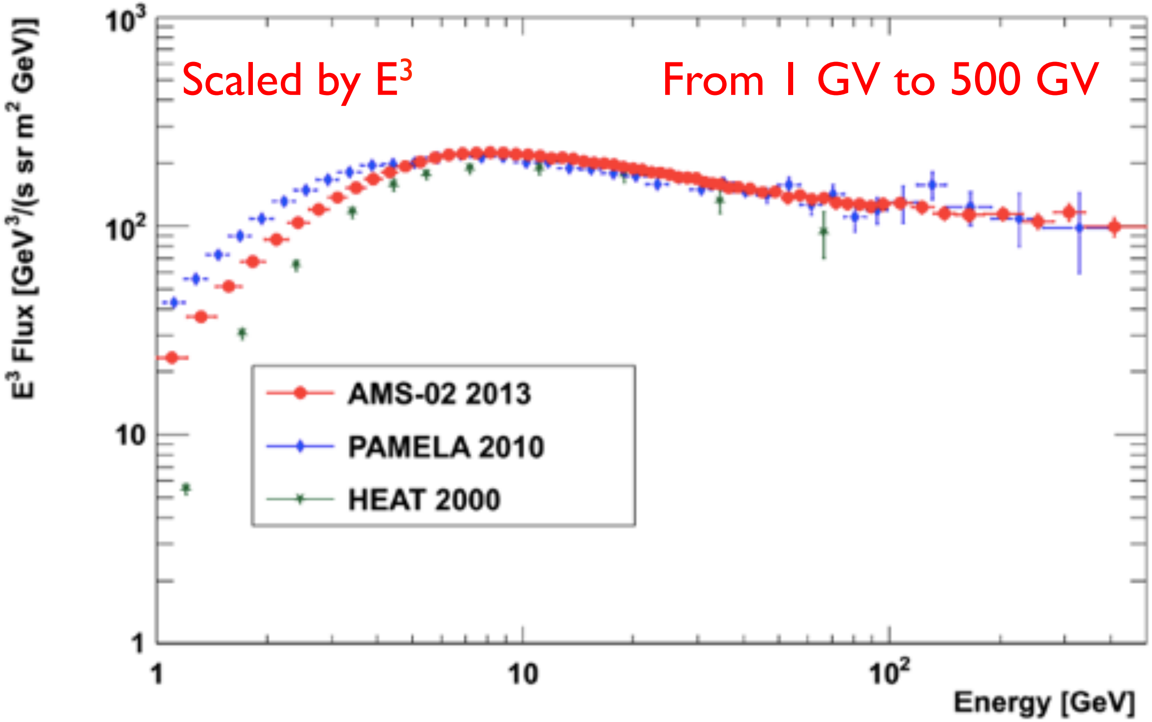
≥ 8 TRD hits used in the estimator





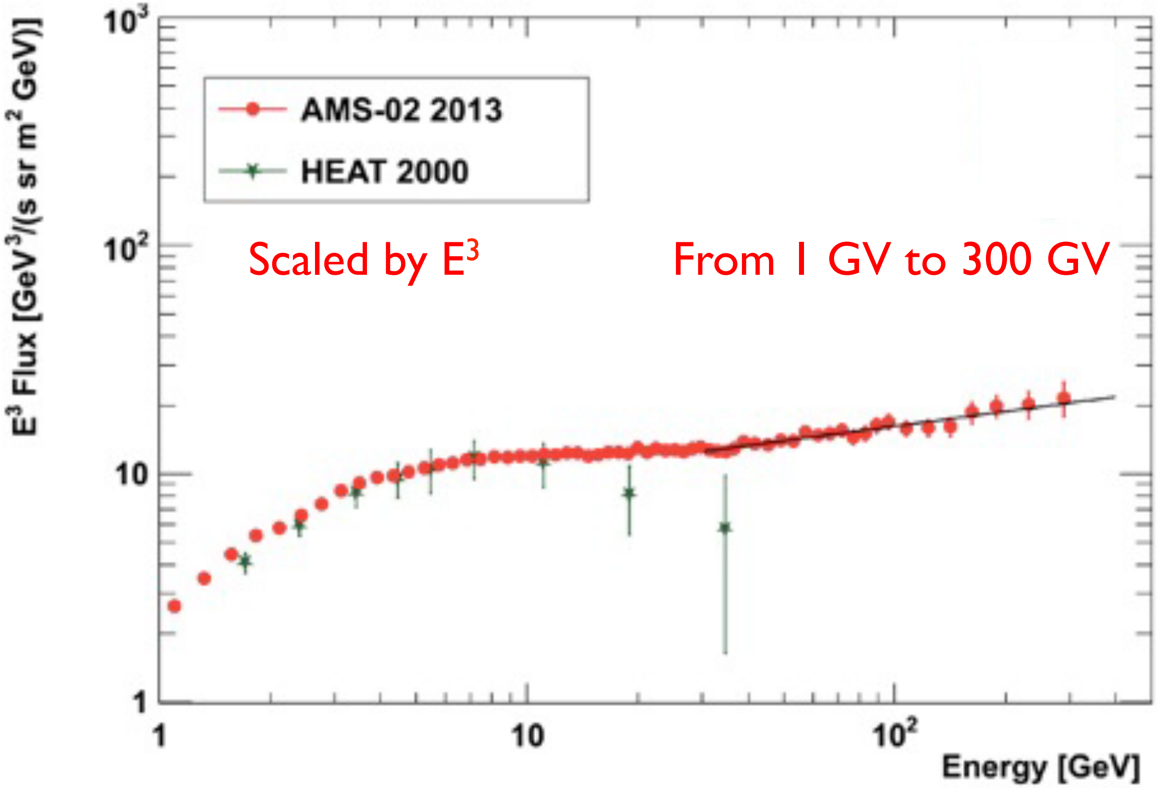
Electron Flux (May 2011-May 2013)

- ✓ It is rising up to 10 GeV and appears to be on a smooth, slowly falling curve above.
- ✓ The measurement is in good agreement with the previous data.
- ✓ The differences at low energies can be attributed to the effect of the solar modulation.



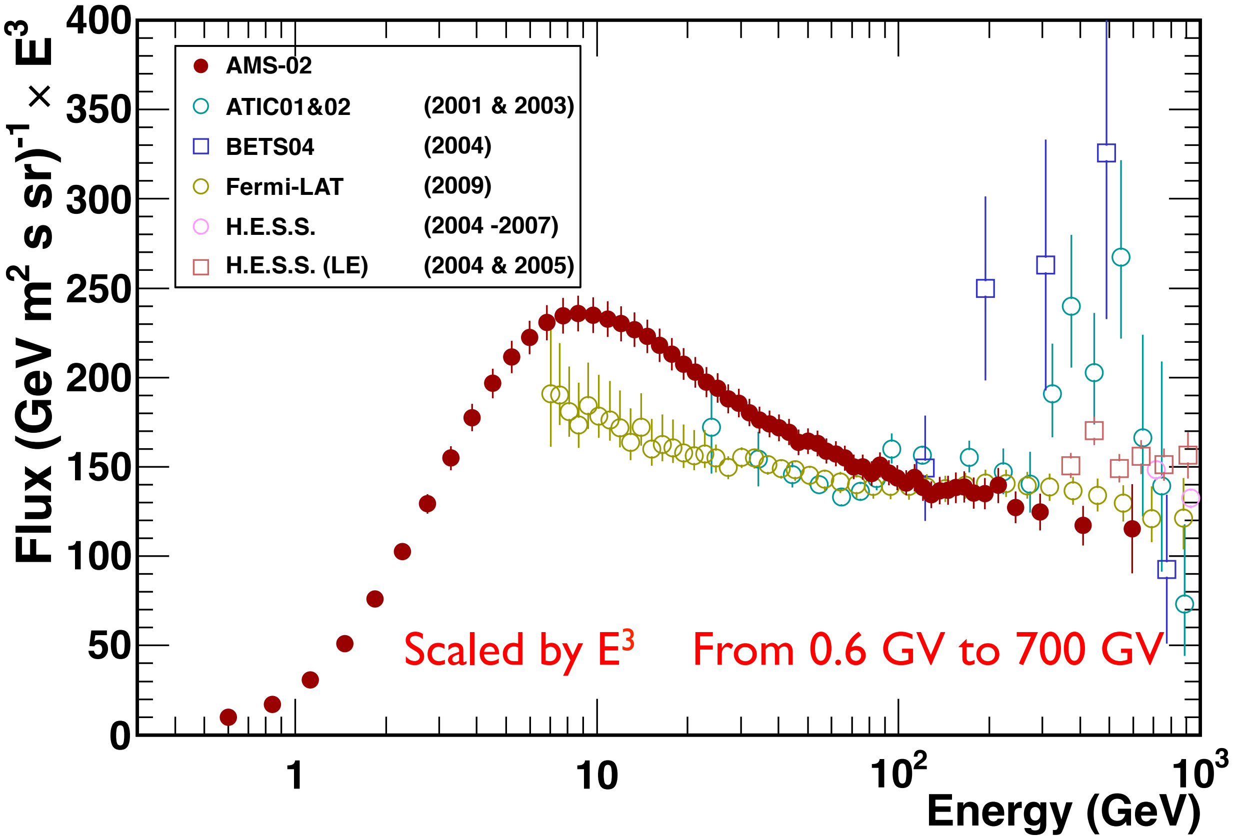
Positron Flux (May 2011-May 2013)

- ✓ It is rising up to 10 GeV, from 10 to 30 GeV the spectrum is flat and above 30 GeV is rising again (completely different from the electron spectrum)
- ✓ In agreement with HEAT below 10 GeV



All Electron Flux (May2011-May2013)

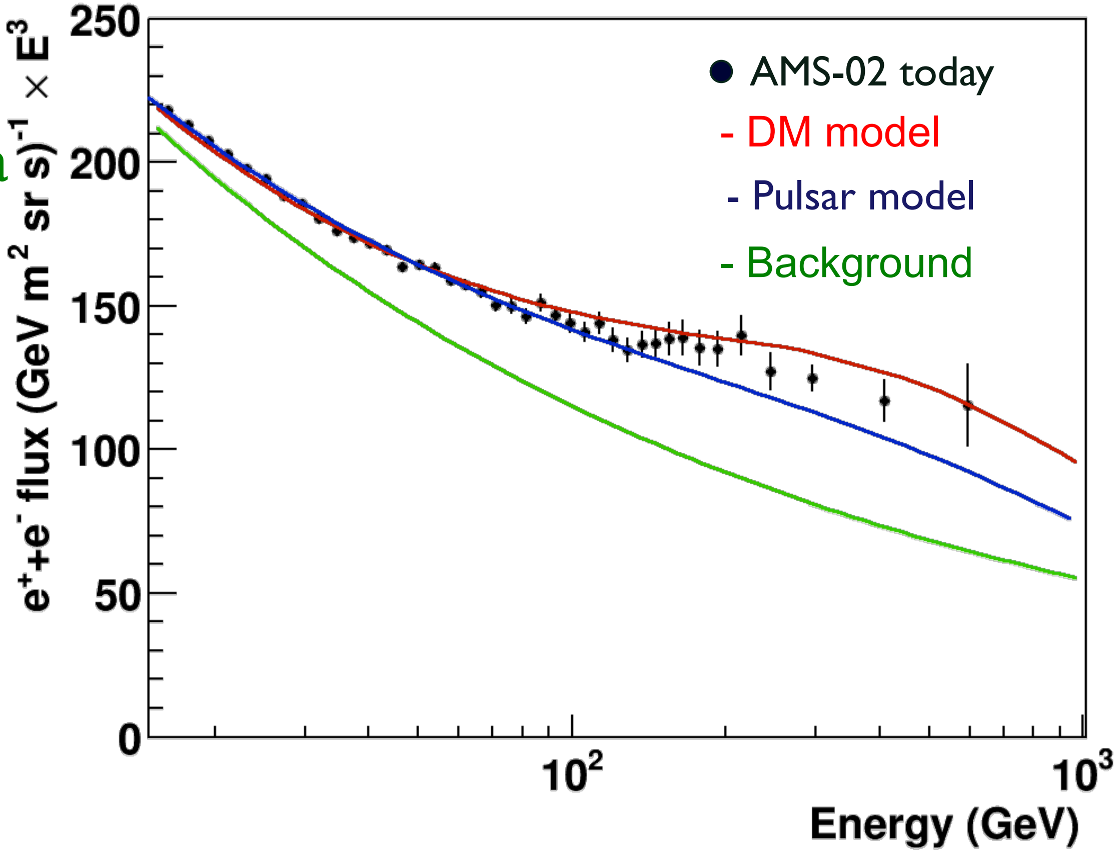
- ✓ Rising up to 10 GeV (as for each of the single spectrum)
- ✓ A change in the spectral distribution with increasing energy is seen compatible with the fraction.



Scaled by E^3 From 0.6 GV to 700 GV

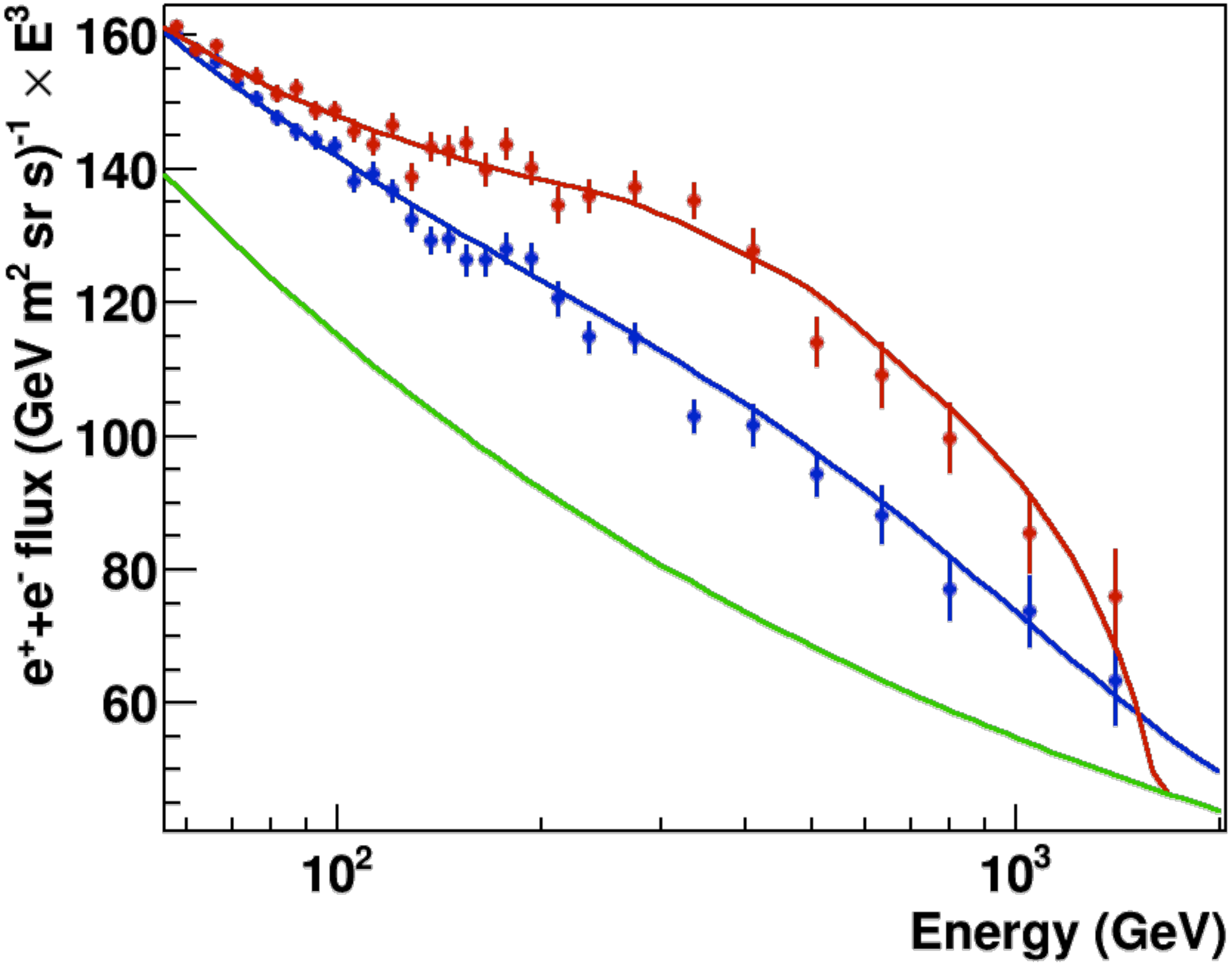
AMS data and phenomenological models: what can we say about "exotic signals?"

Background evaluated from a simple power law for e+ and e-, with differences in the spectral index and normalization fixed by the AMS-02 positron fraction measurement.



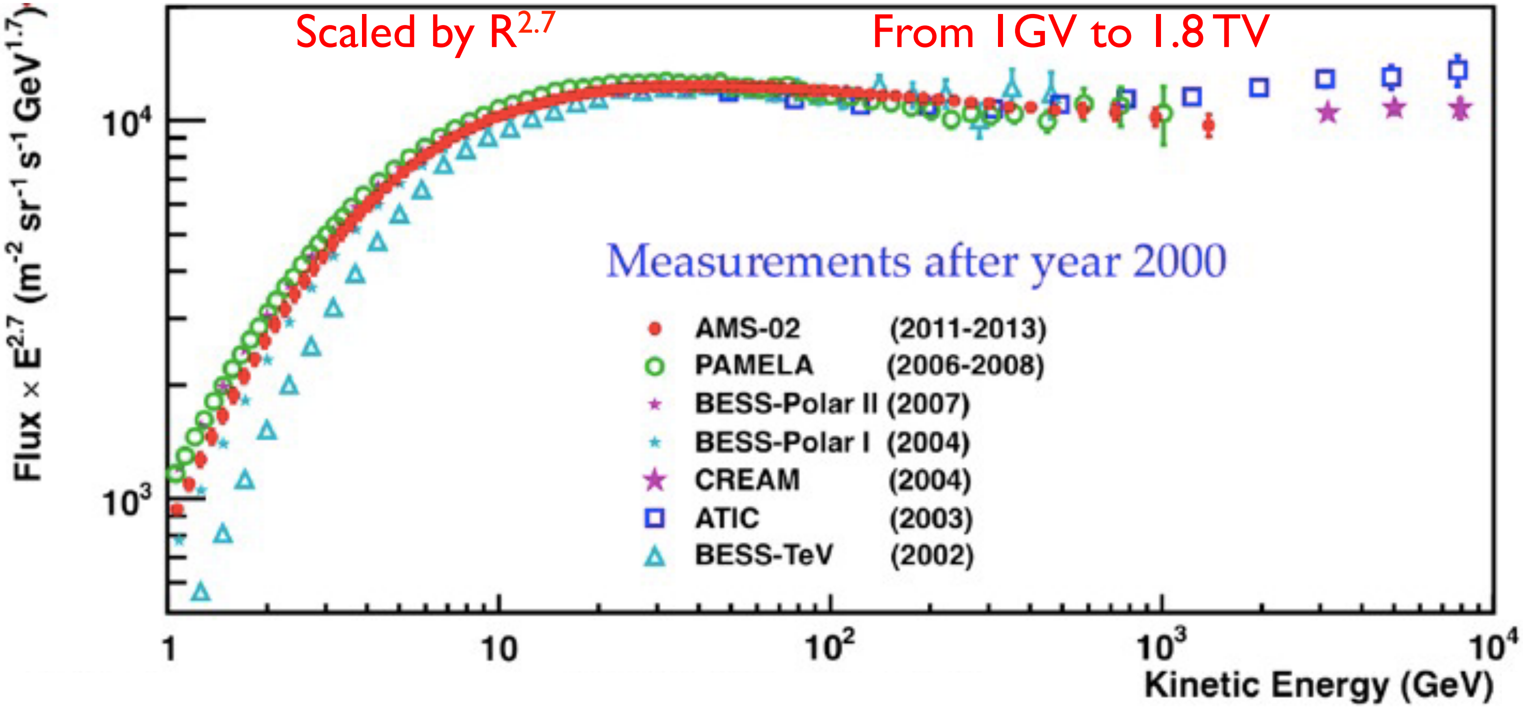
DM and Pulsar signal shapes adapted from Cholis et al, arxiv hep-ph1304.1840

AMS data and phenomenological models: what can we say in 10 years from now?”



Proton Flux (May 2011-May 2013)

- ✓ In the low rigidity region (R < 20 GV) the flux is determined every day with stat. Errors <1%
- ✓ In the high rigidity region (R >100 GV) the spectrum is consistent with a single power law, no fine structures nor break were found



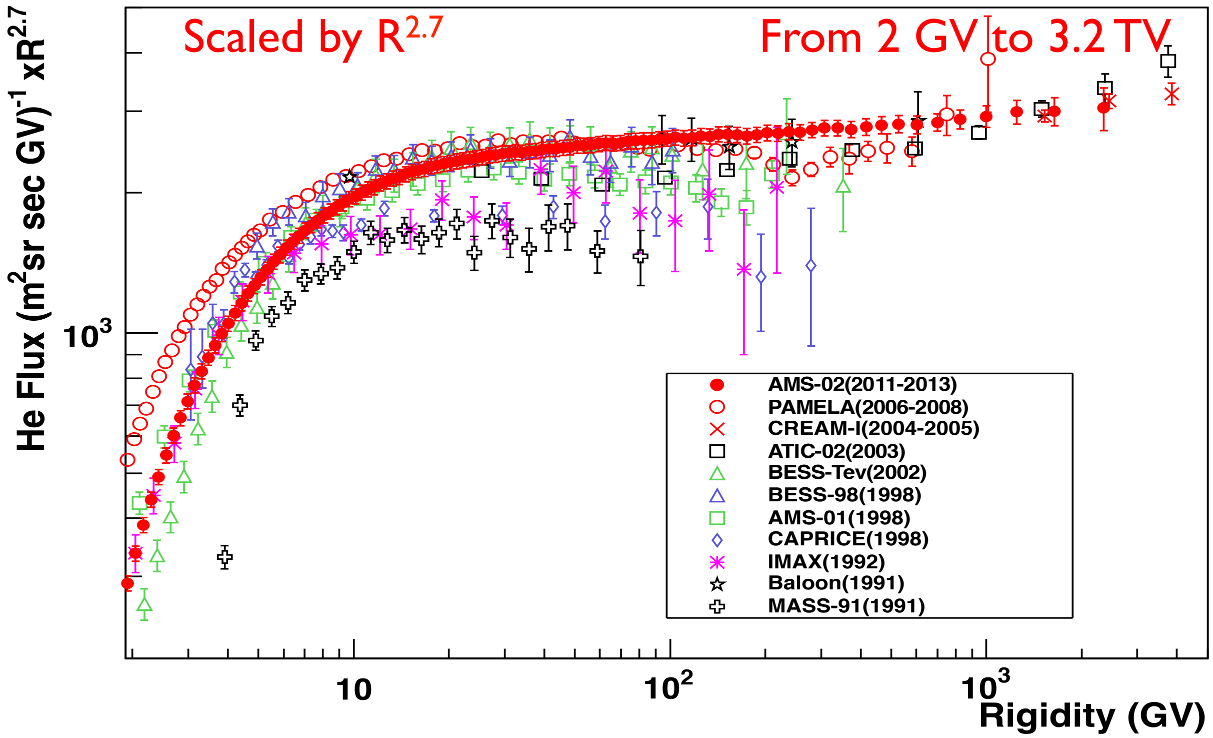
Scaled by $R^{2.7}$

From 1GV to 1.8 TV

Helium Flux (May 2011-May 2013)

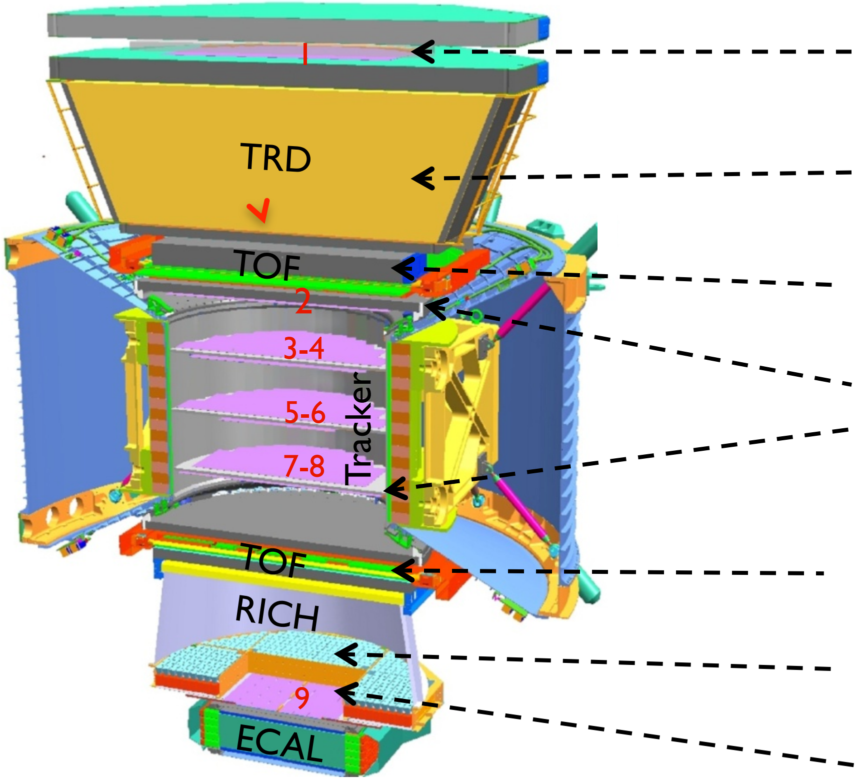
- ✓ Above 10 GV the spectrum can be parametrized by a single power law

No fine structures nor break were found



B/C ratio

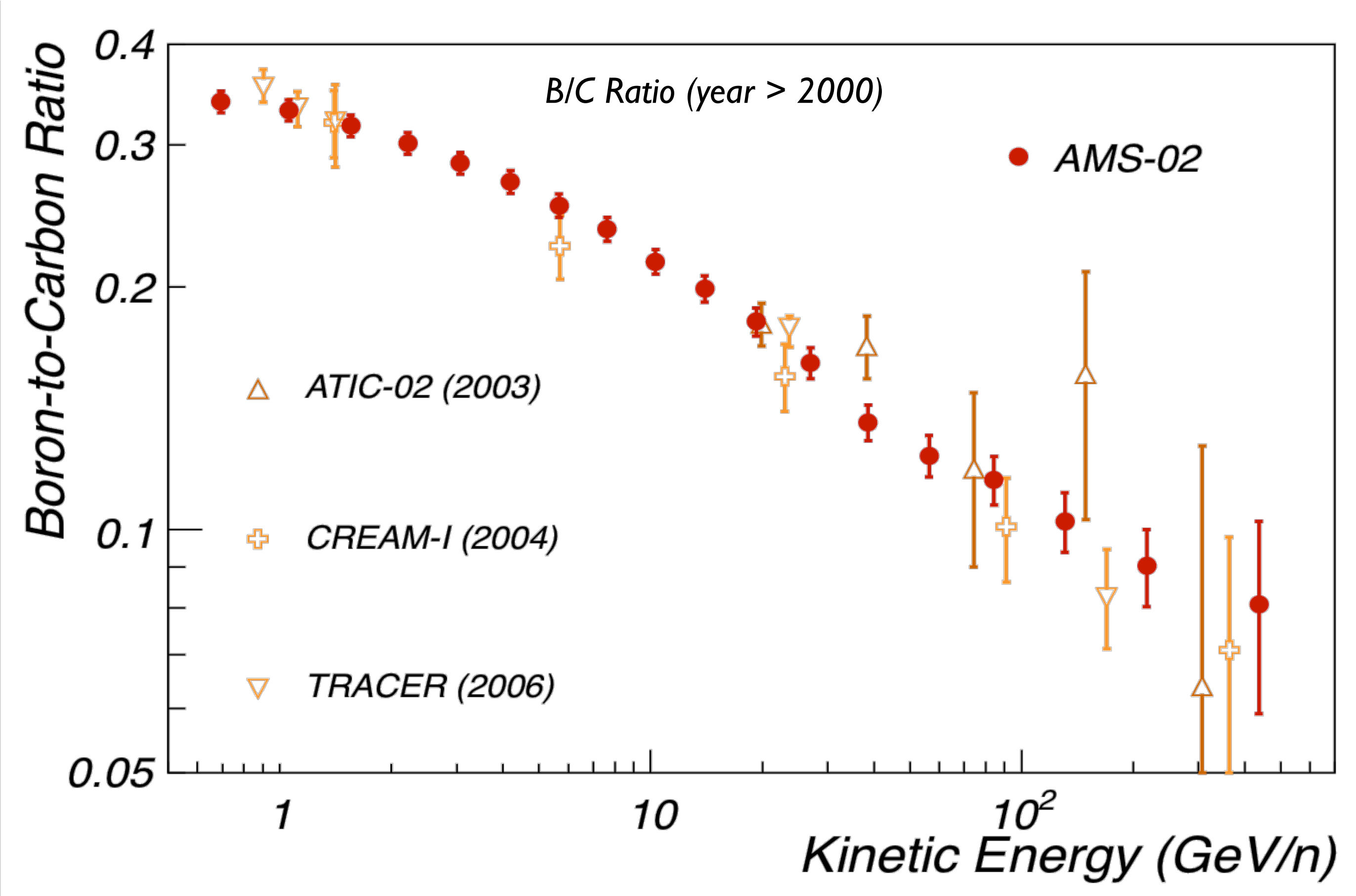
Multiple Independent Measurements of Charge (Z) allow to identify fragmentation events



	Carbon (Z=6) *ΔZ (cu)*
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*

B/C ratio

- ✓ Statistics is the main limitation for the measurement
- ✓ The B/C behavior at high energy will be become more clear with more data



Conclusions

Electron and positron fluxes and their fraction are measured in AMS-02 with unprecedented accuracy and in an extended energy range:

- ✓ the positron fraction spectrum is consistent with $e^{\pm}$ fluxes giving by the sum of a diffuse spectrum and a single common power law source.
- ✓ No anisotropy is found on the positron to electron and to proton ratio at any angular scale and limits are set on the dipole anisotropy parameter (<0.030 at 95% CL 16<E<350GeV).
- ✓ The positron and the electron + positron fluxes show a change in the spectral distribution increasing with the energy confirming the positron fraction measurement. Systematics still under investigations.

SOME NEW SOURCE IS NEEDED ….PULSAR? Dark Matter ??

- ✓ Precise measurement of the primary proton and helium fluxes and of the B/C between will be useful to pin down the "background" uncertainties
- ✓ The AMS Proton (up to 1.8TV), Helium (up to 3.2TV) and electron (up to 500 GeV) fluxes at high energy are consistent with a single power law with no fine structures nor break.
- ✓ Measurement of B/C from 0.5 to 670 GeV/n has been reported. Systematics still under study.
- ✓ Anti-protons are coming !!
- ✓ Reported results have been obtained with only 10% of the expected AMS statistics…

Thank you for your attention!

BACKUP SLIDES

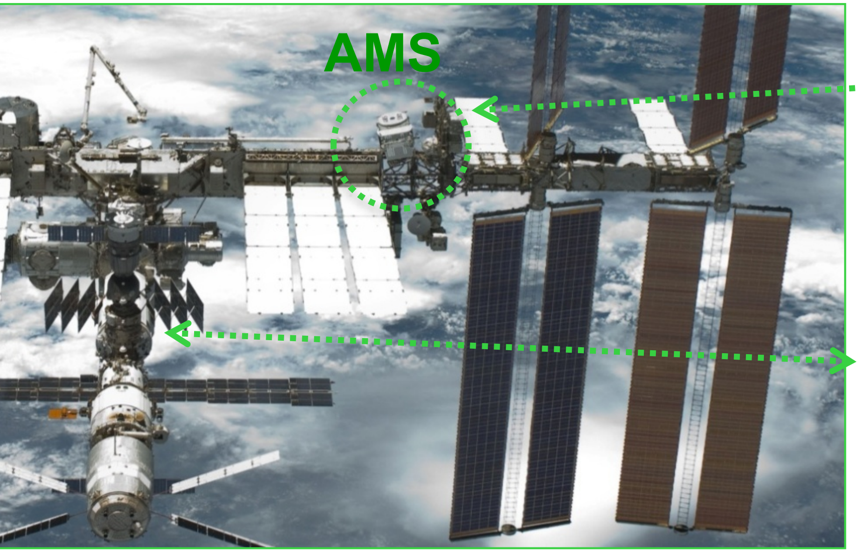
Antimatter

Primordial origin (Signal: anti-nuclei)

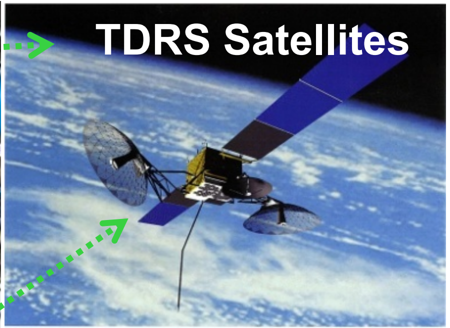
Dirac's Nobel speech

"We must regard it rather as an accident that the Earth [...] contains a preponderance of negative electrons and positive protons. It is quite possible that for some stars it is the other way about."

AMS operation : 24/24 – 7/7 – 365/year




Astronaut at ISS AMS Laptop


TDRS Satellites

Flight Operations

Ku-Band
High Rate (down):
Events <10Mbit/s>

Ground Operations

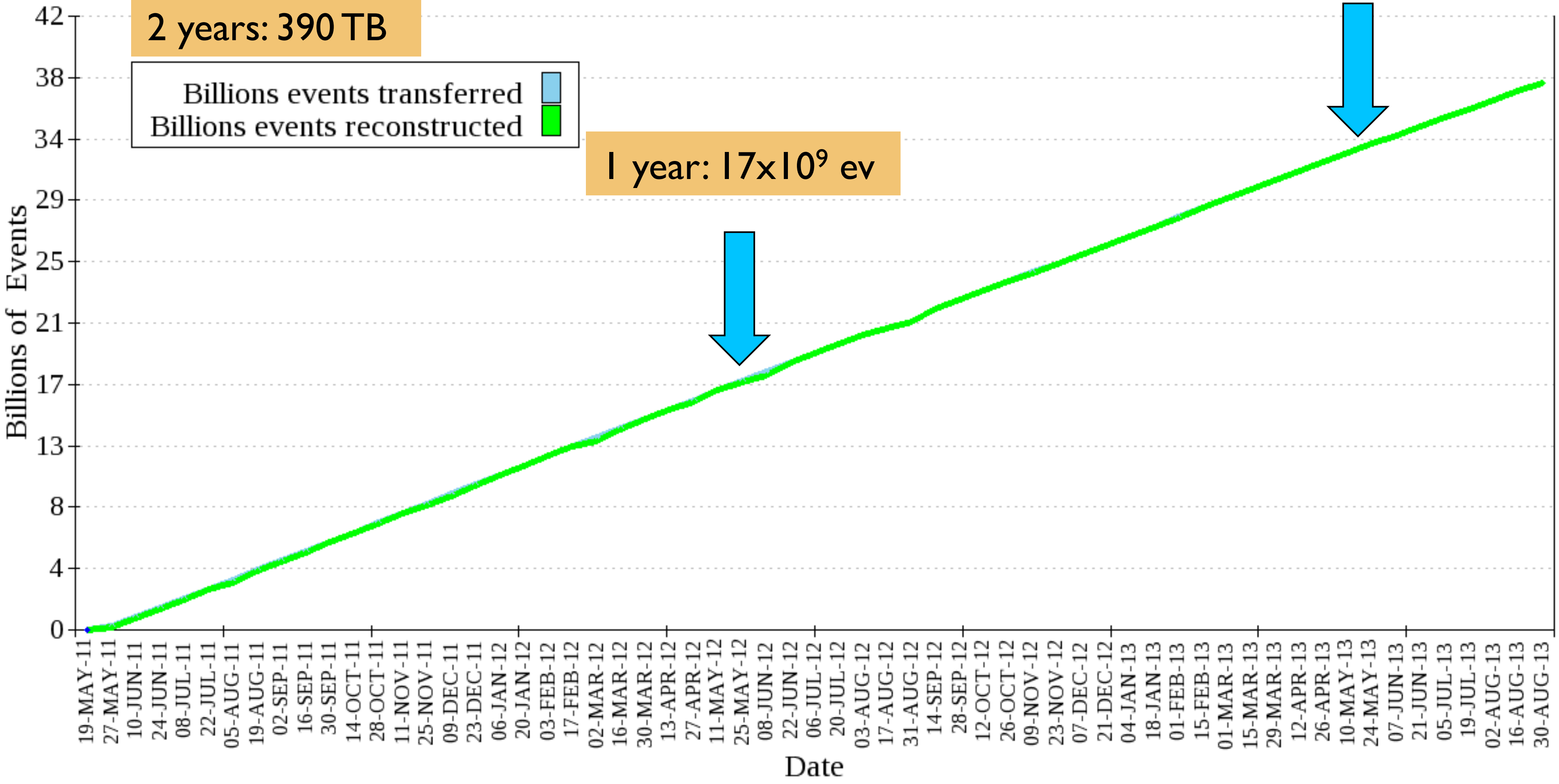
S-Band
Low Rate (up & down):
Commanding: 1 Kbit/s
Monitoring: 30 Kbit/s


AMS Payload Operations Control and Science Operations Centers (POCC, SOC) at CERN


AMS Computers at MSFC, AL


White Sands Ground Terminal, NM

AMS Event Production



1 year: 145 TB

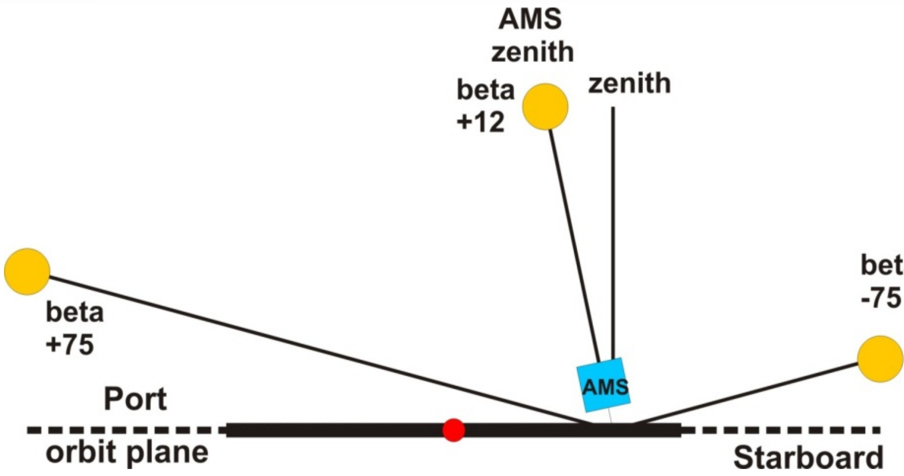
2 years: 390 TB

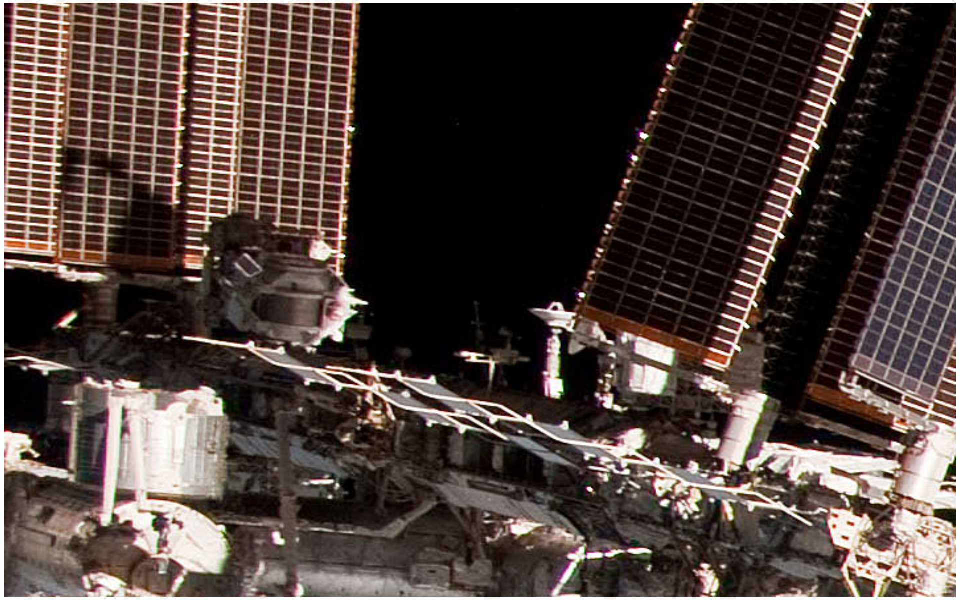
2 years: 34×10^9 ev

1 year: 17×10^9 ev

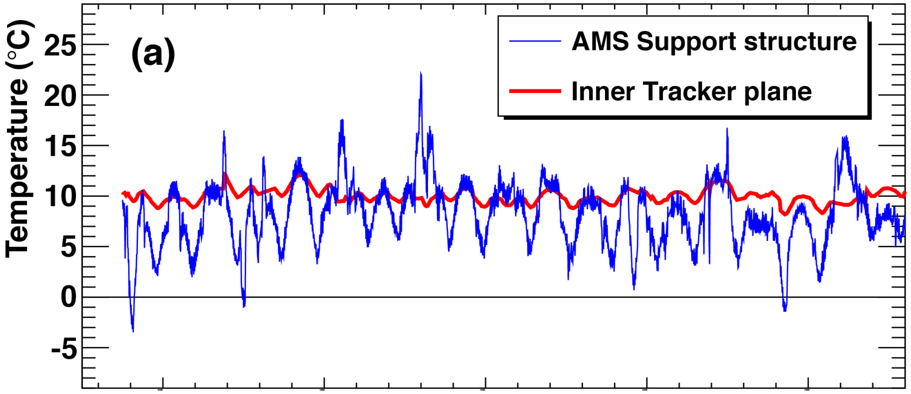
The thermal environment

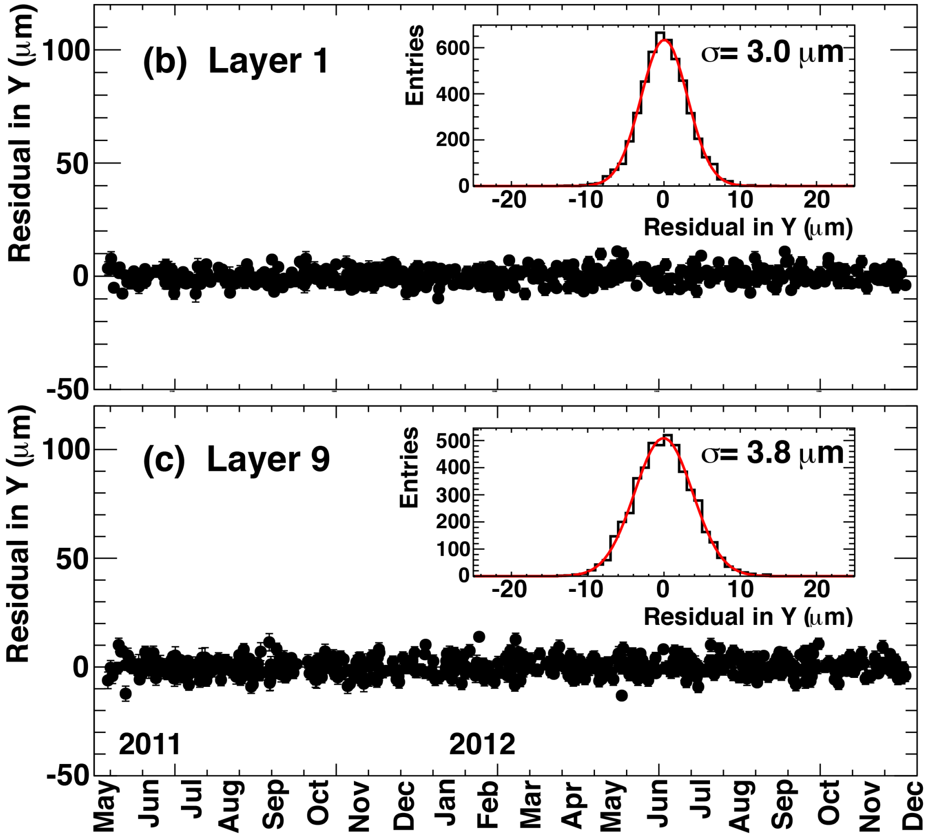
1. Sun position: along the orbit + seasonal variation
2. Solar array and ISS radiator position
3. ISS attitude and visiting vehicles





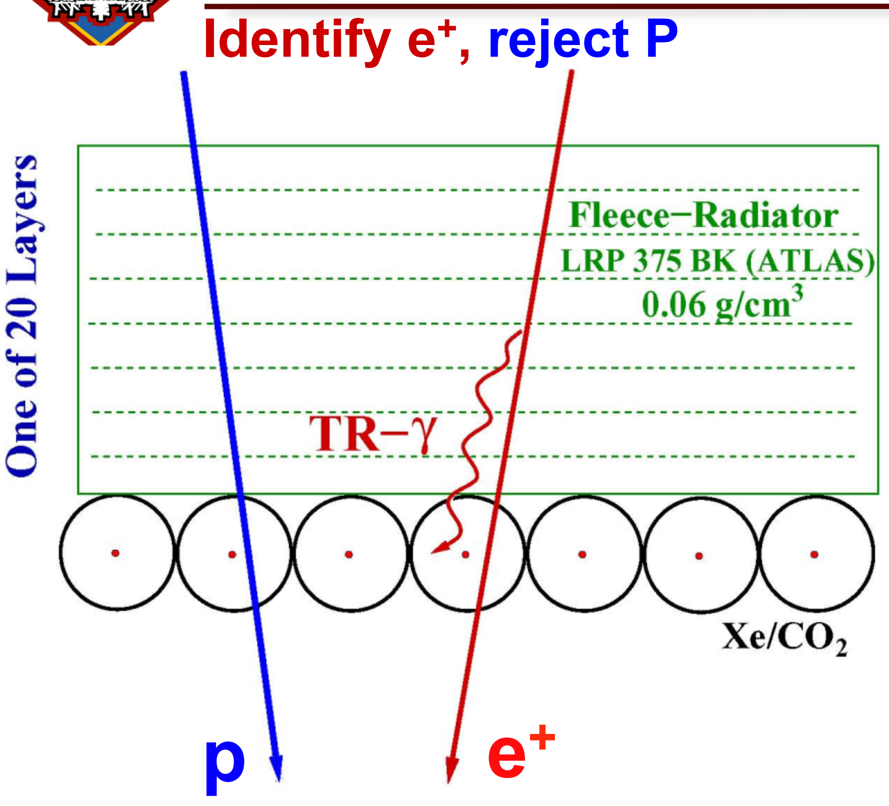
Tracker alignment & Calibration

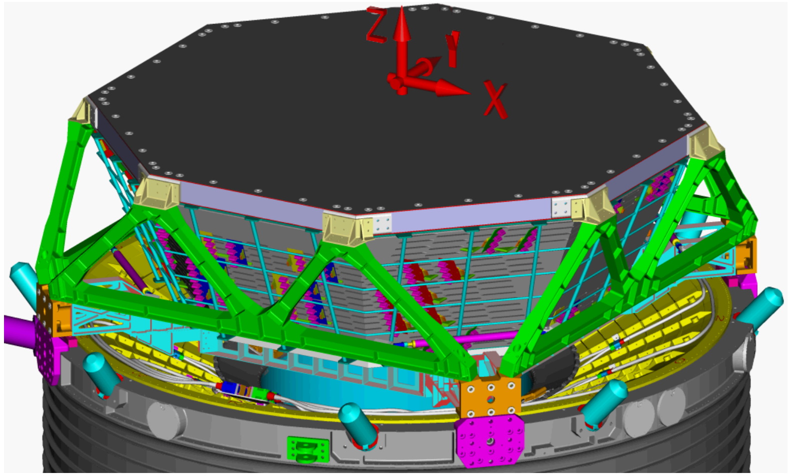


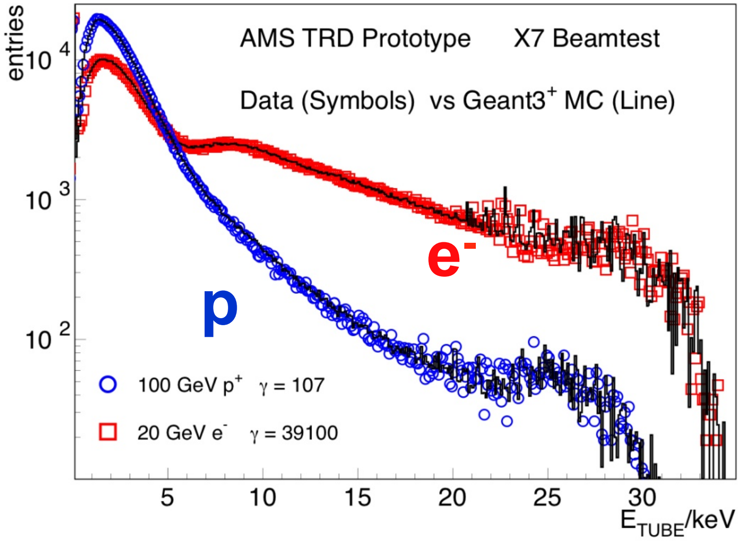


The tracker has been aligned and particular care has been used for the two external layers

Transition Radiation Detector (TRD)



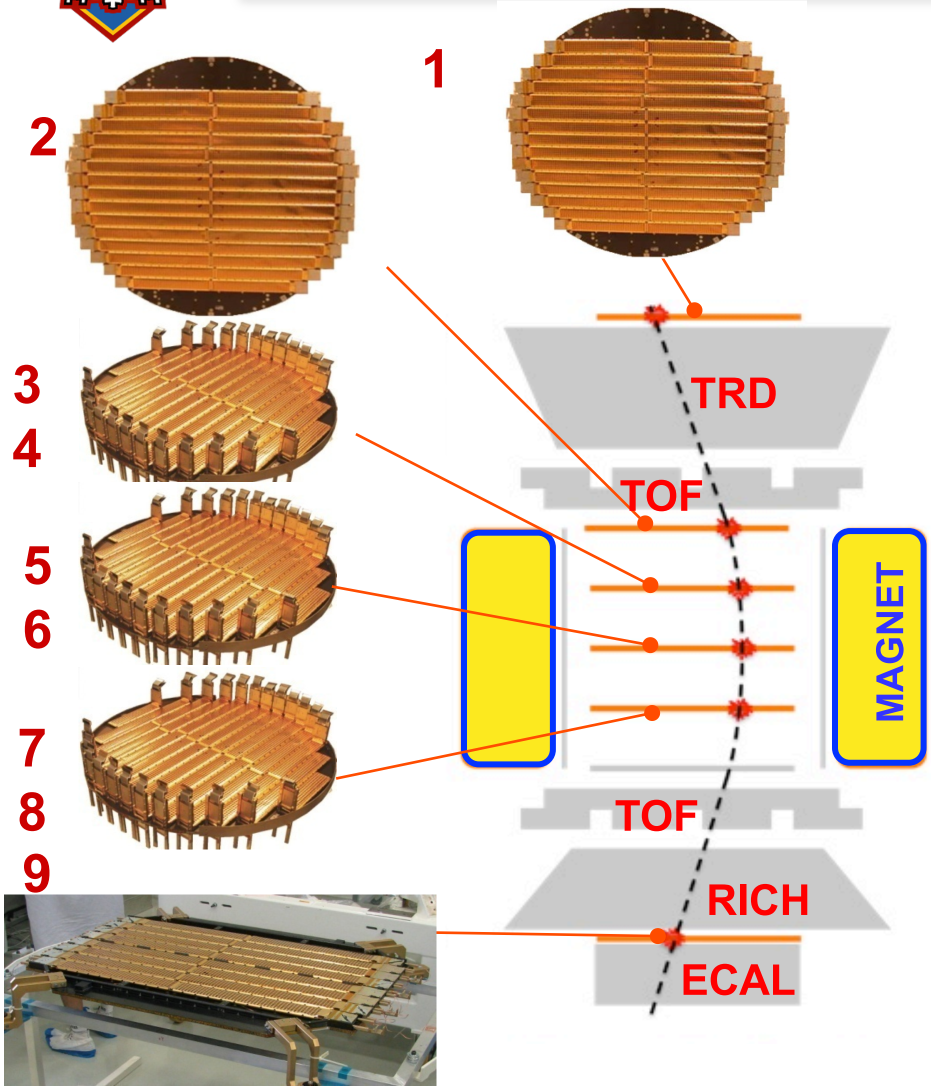




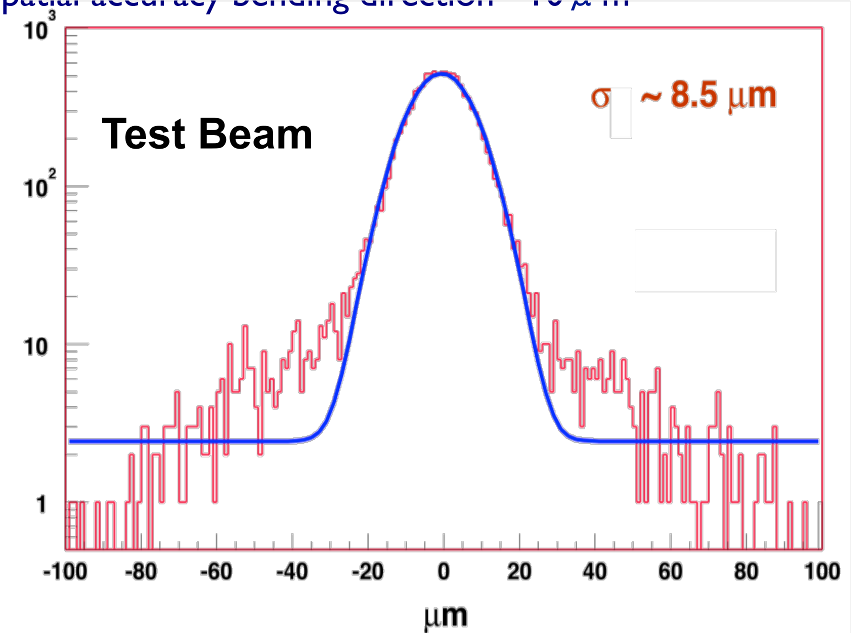
Leak rate: CO2 ≈ 5 μg/s

Storage: 5 kg, >20 years lifetime

Silicon Tracker



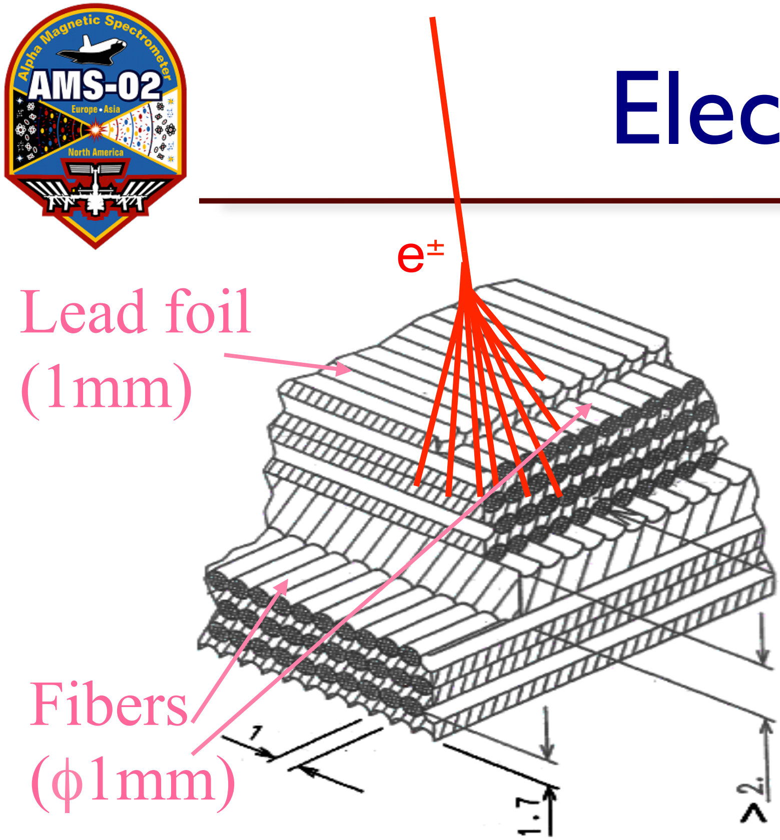
- ✓ 9 layers of double-sided microstrip silicon sensors
- ✓ 6.4m^2 active area, ~200k channels
- ✓ Permanent magnet: 0.14T
- ✓ Max detectable rigidity ~2TeV
- ✓ Spatial accuracy bending direction ~10 μ m

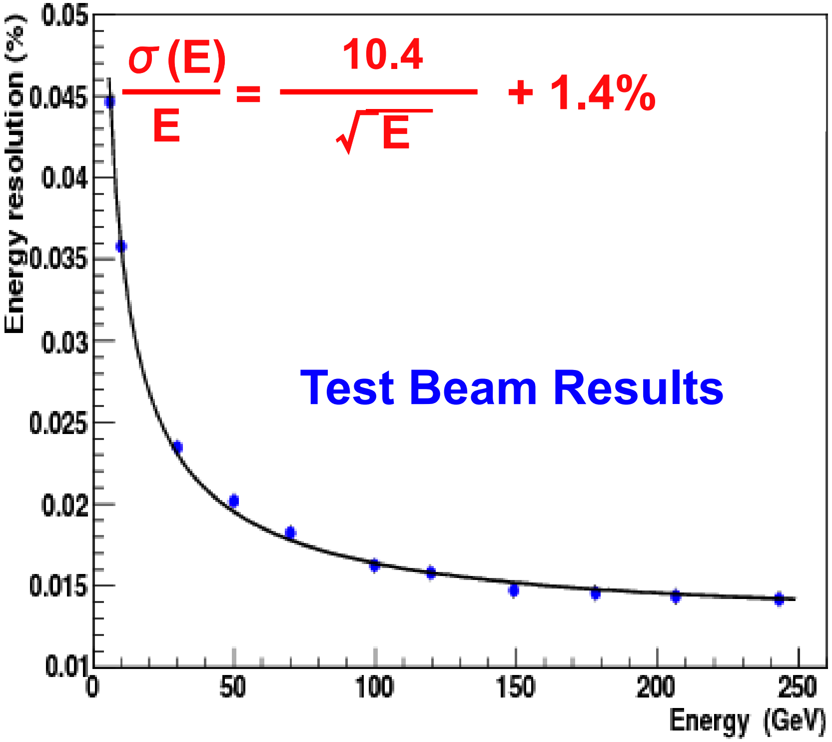


MDR ~2.0 TV

E / |p| matching

Electromagnetic Calorimeter

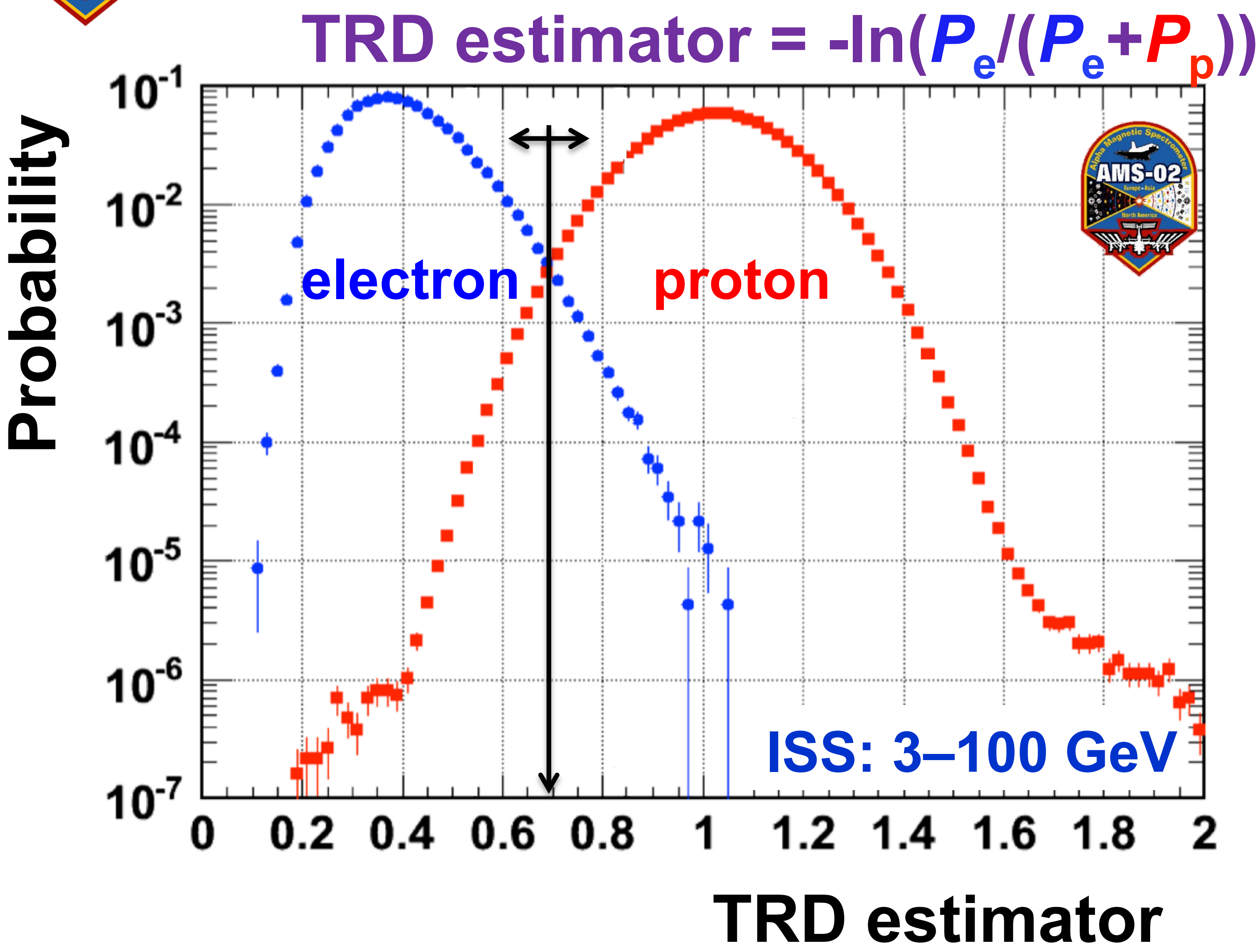




$$\frac{\sigma(E)}{E} = \frac{10.4}{\sqrt{E}} + 1.4\%$$

- ✓ 3D imaging calorimeter
- ✓ 9 super-layers made of a lead /scintillation fiber sandwich
- ✓ Fibers are alternatively read at one end by 4 anode PMTs (1296 anodes)
- ✓ 50 000 fibers, f = 1 mm, distributed uniformly Inside 1,200 lb of lead
- ✓ 648 x 648 x 167 mm3
- ✓ 17 radiation lengths and 0.64 interaction length in the calorimeter

TRD Performance

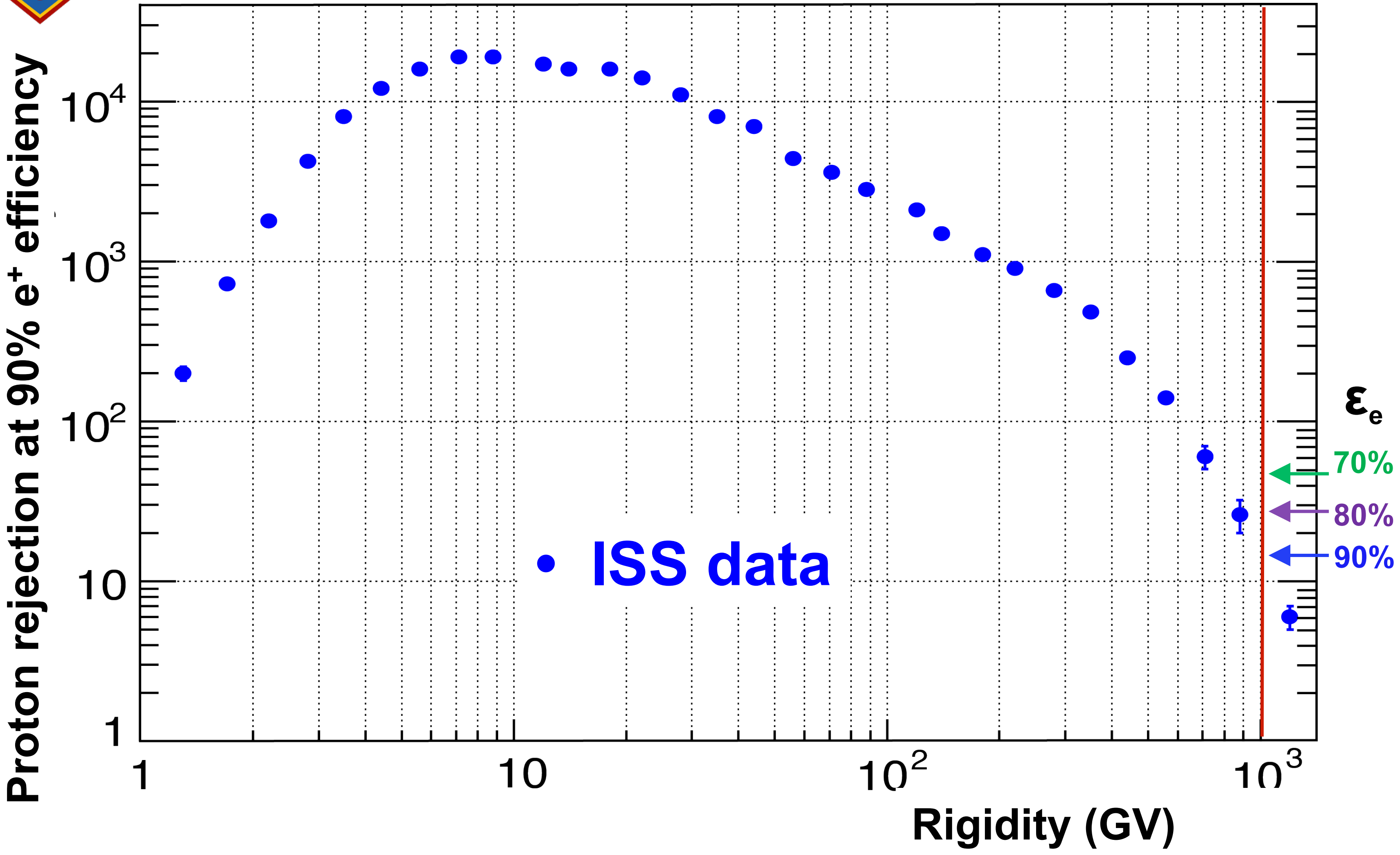


Normalized probabilities P_e and P_p

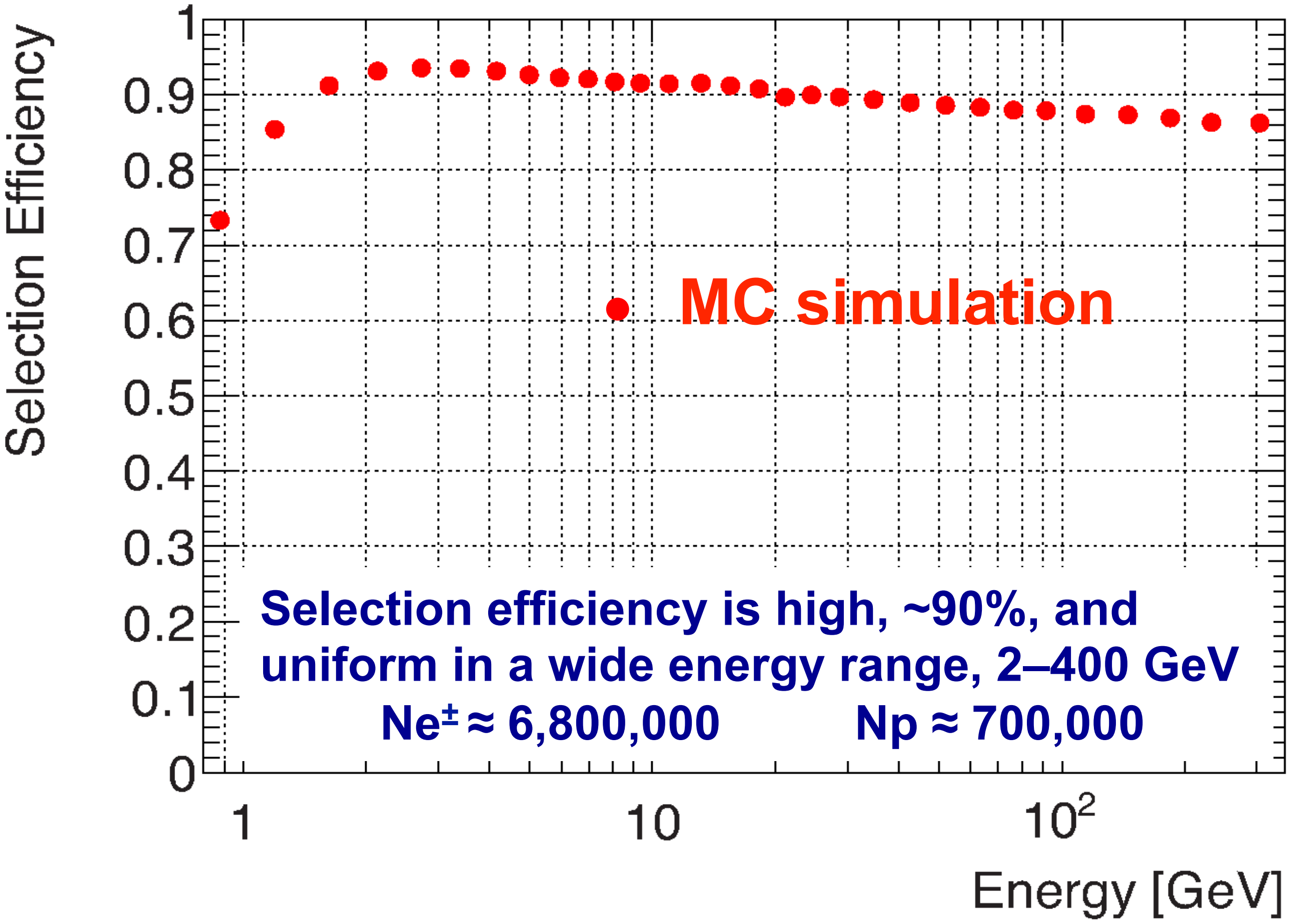
$$P_e = \sqrt[n]{\prod_i^n P_e^{(i)}(A)}$$

$$P_p = \sqrt[n]{\prod_i^n P_p^{(i)}(A)}$$

TRD Performance



Selection Efficiency

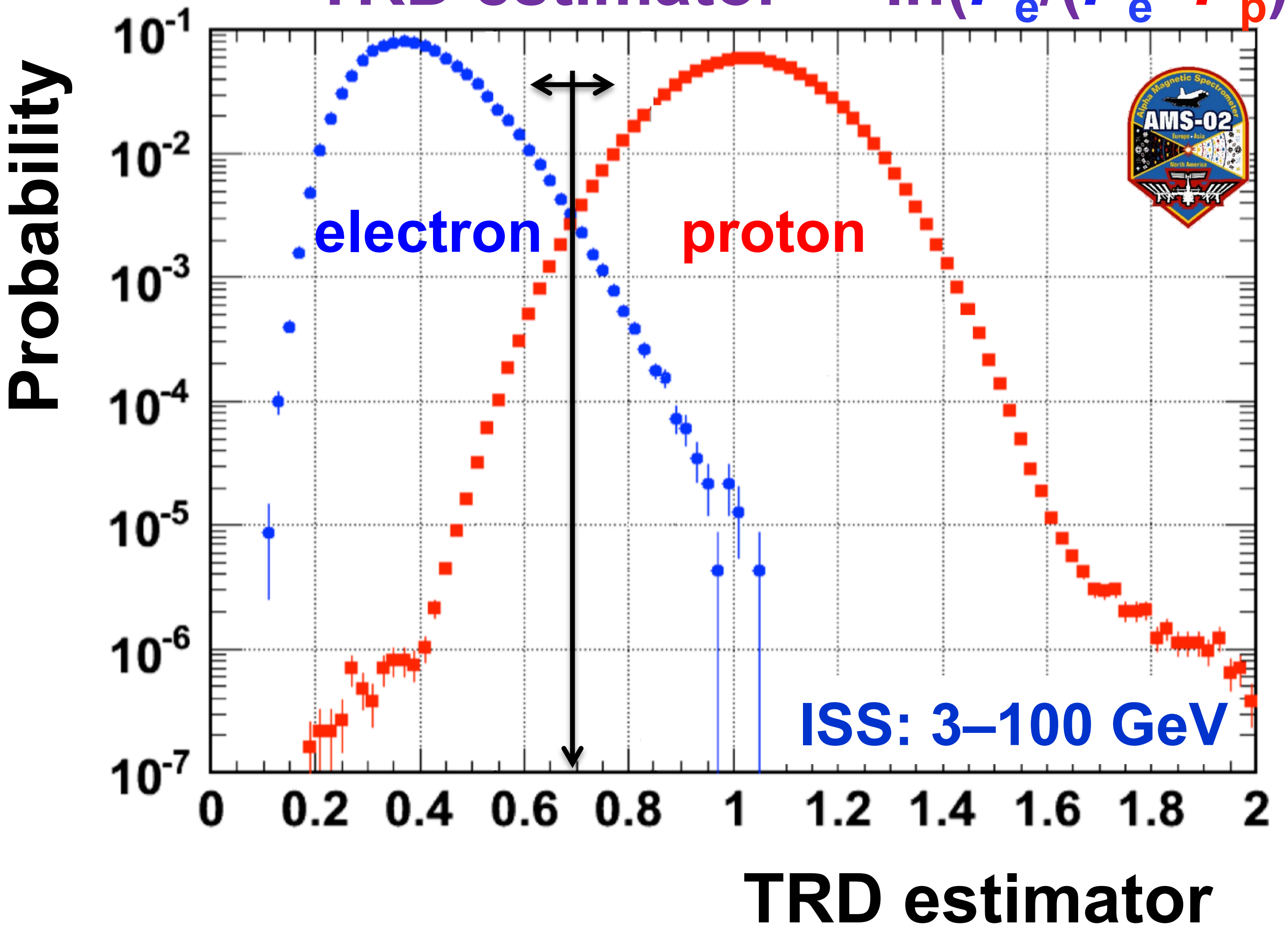


Selection efficiency is high, ~90%, and uniform in a wide energy range, 2–400 GeV

$N_{e^\pm} \approx$ 6,800,000 $N_p \approx$ 700,000

Particle Identification:TRD Estimator

TRD estimator = $-\ln(P_e/(P_e+P_p))$

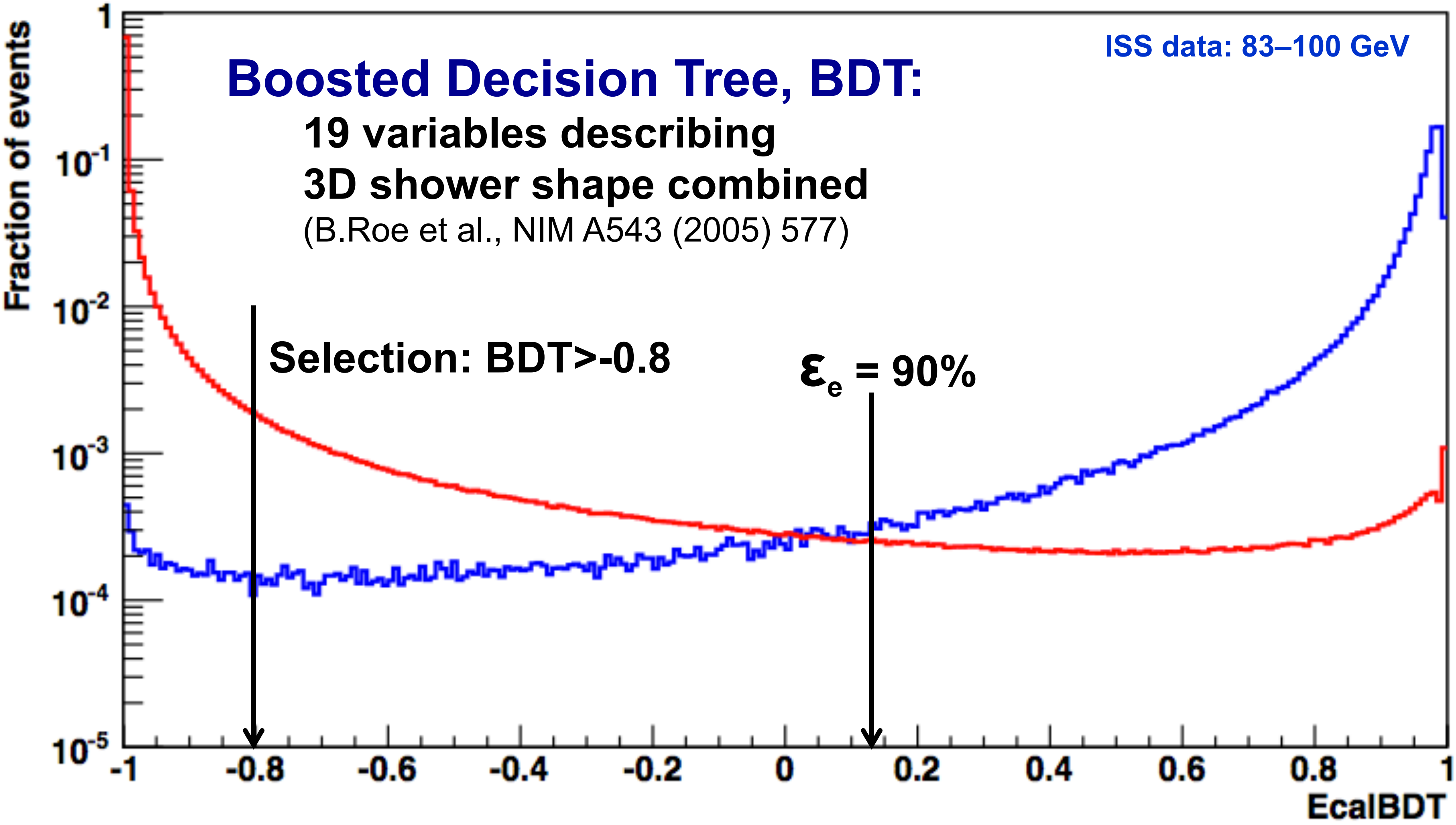


Normalized probabilities P_e and P_p

$$P_e = \sqrt[n]{\prod_i^n P_e^{(i)}(A)}$$

$$P_p = \sqrt[n]{\prod_i^n P_p^{(i)}(A)}$$

Particle Identification: ECAL BDT



ISS data: 83–100 GeV

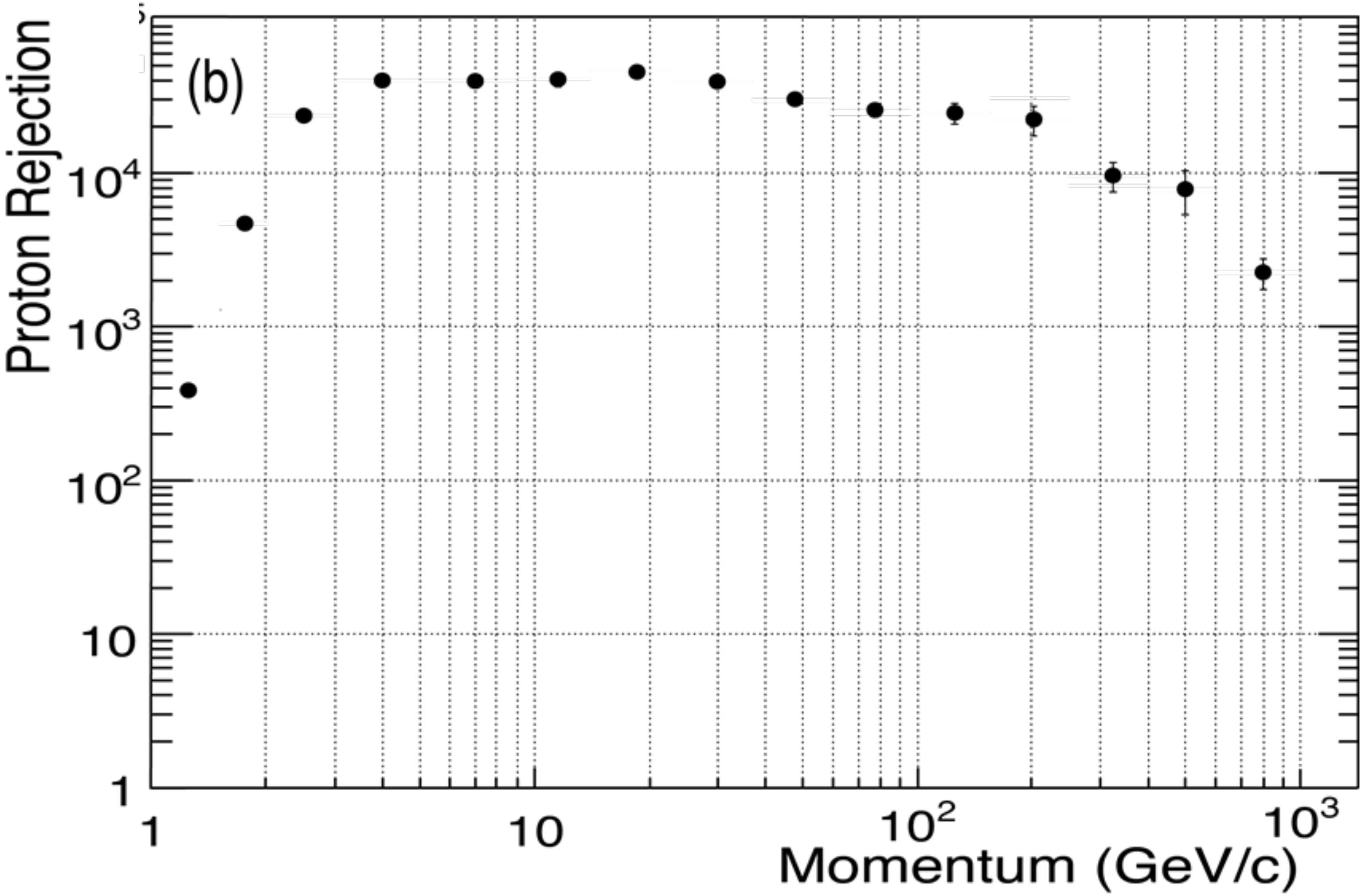
Boosted Decision Tree, BDT:

19 variables describing
3D shower shape combined
(B.Roe et al., NIM A543 (2005) 577)

Selection: BDT>-0.8

ε_e = 90%

ECAL Proton rejection



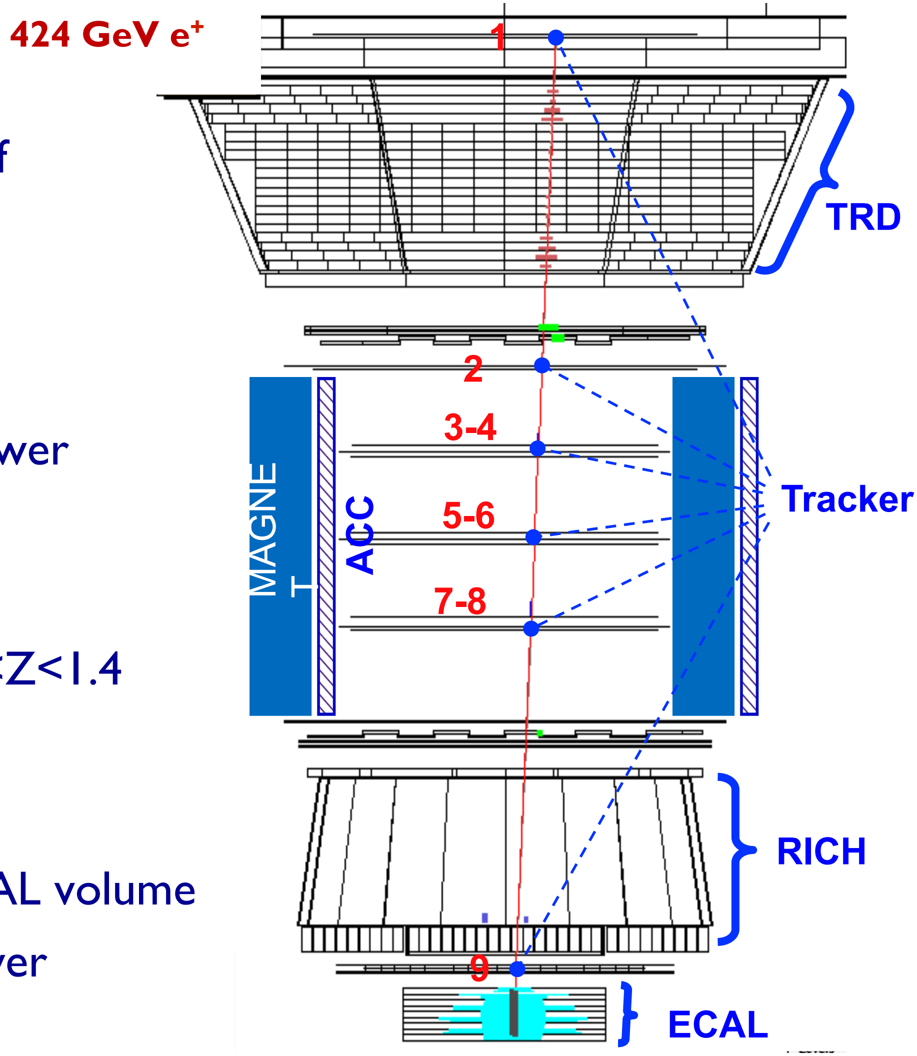
Event Selection

- **DAQ:** efficiency > 50% (no SAA)
- **Geomagnetic cutoff:** E>1.2·max cutoff

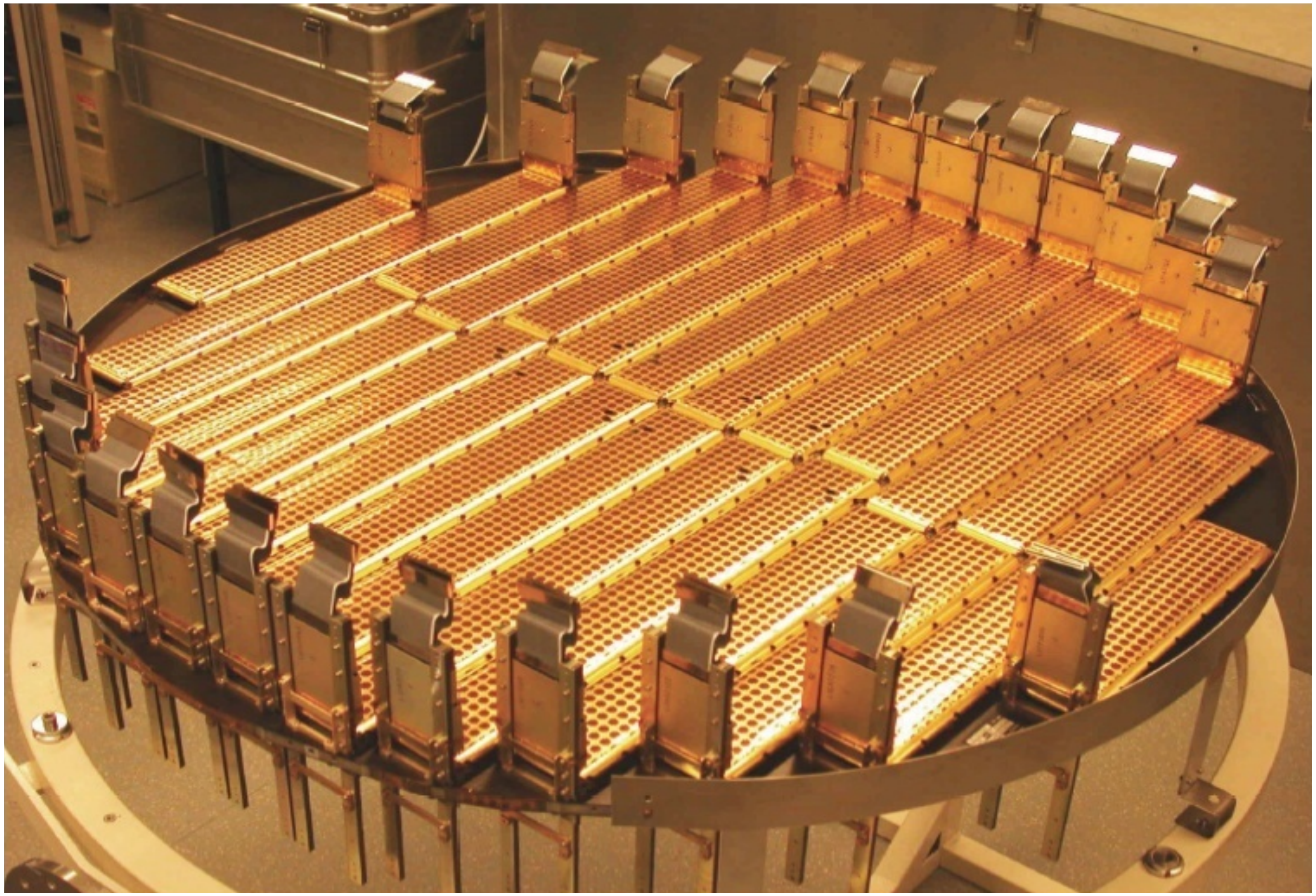
- **TRACKER:**
  - Track quality
  - geometrical match with ECAL shower

- **TRD:** at least 15 hits
- **TOF:** downgoing particle, β >0.8, $0.8<Z<1.4$

- **ECAL:**
  - shower axis within the fiducial ECAL volume
  - electromagnetic shape of the shower

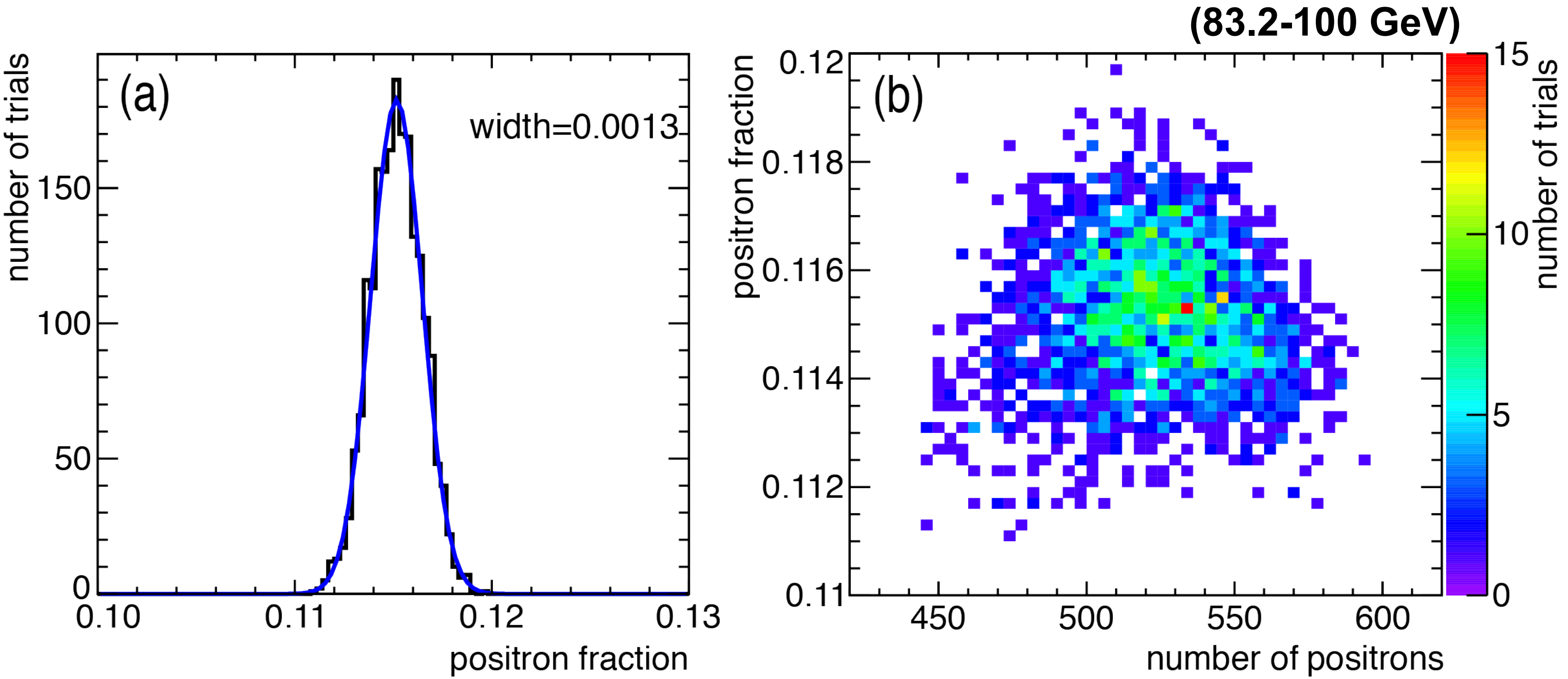


Systematic error on the positron fraction: 1. acceptance asymmetry



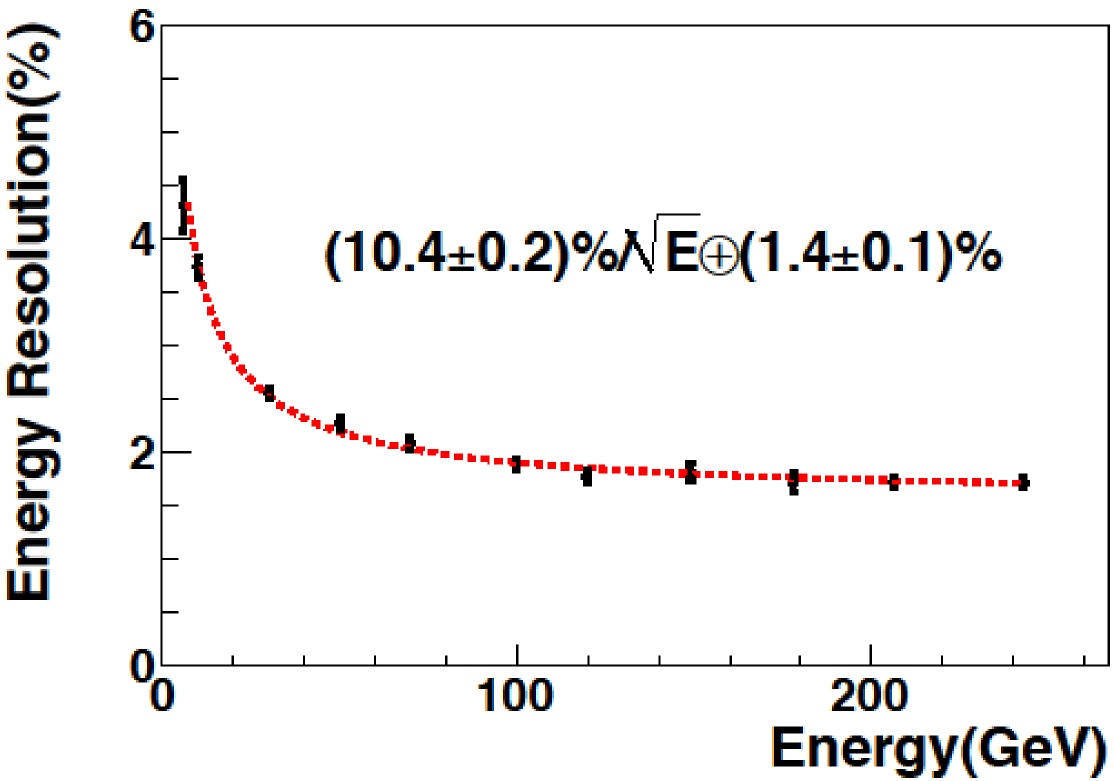
Difference between positron and electron acceptance due to known minute tracker asymmetry

Systematic error on the positron fraction: 2. Selection dependence



The measurement is stable varying the cuts
For each energy bin, over 1,000 sets of cuts were analyzed.

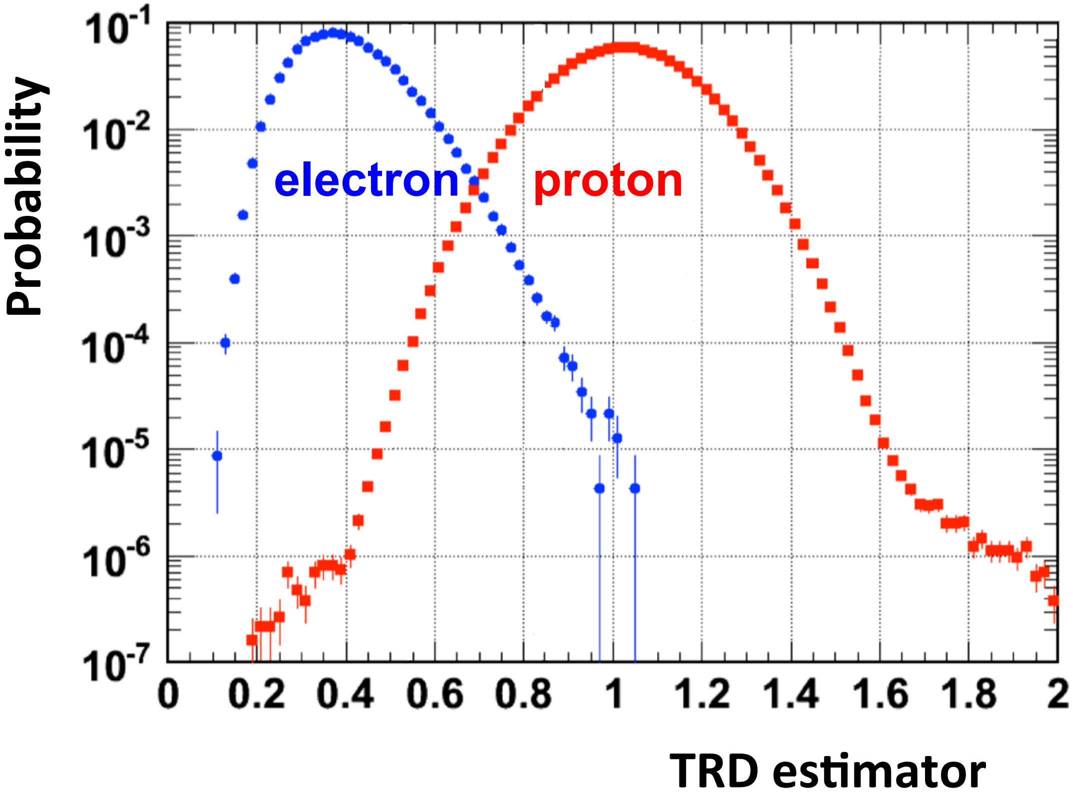
Systematic error on the positron fraction
3. Bin-to-bin migration



Event migration effects are obtained folding the measured spectra of positrons and electrons with the ECAL energy resolution.

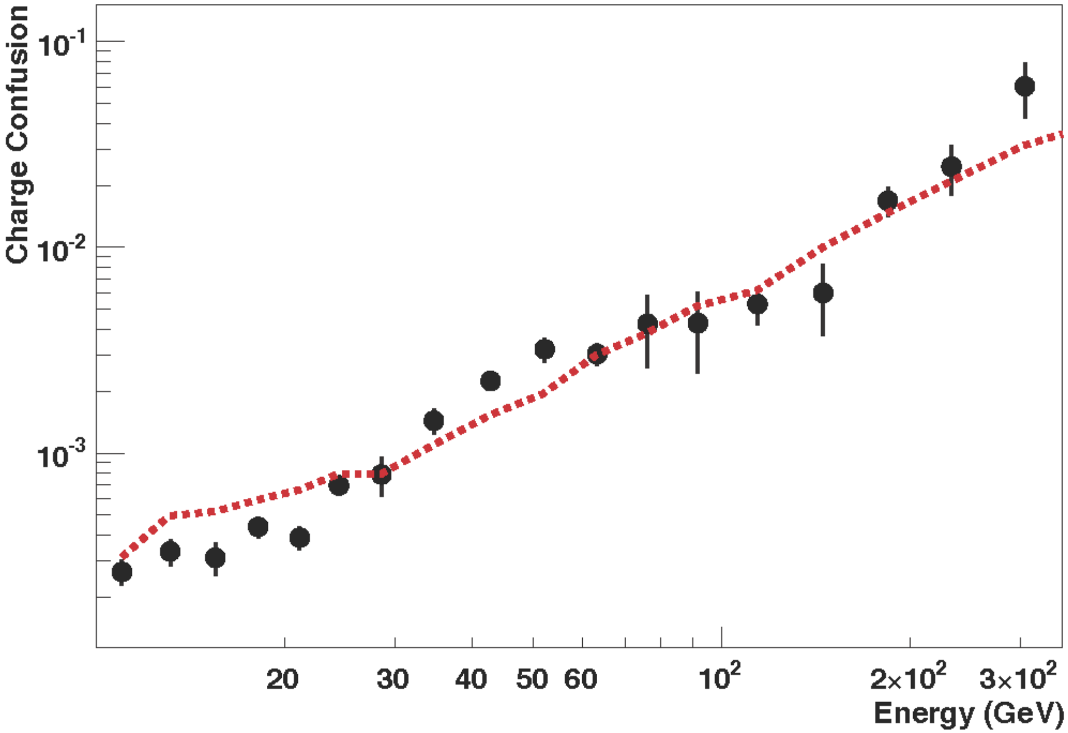
Bin width: 2 σ at 5 GeV; 4 σ at 50 GeV; 8 σ at 100 GeV; 19 σ at 300 GeV.

Systematic error on the positron fraction: 4. Reference spectra



Definition of the reference spectra is based on pure samples of electrons and protons of finite statistics.

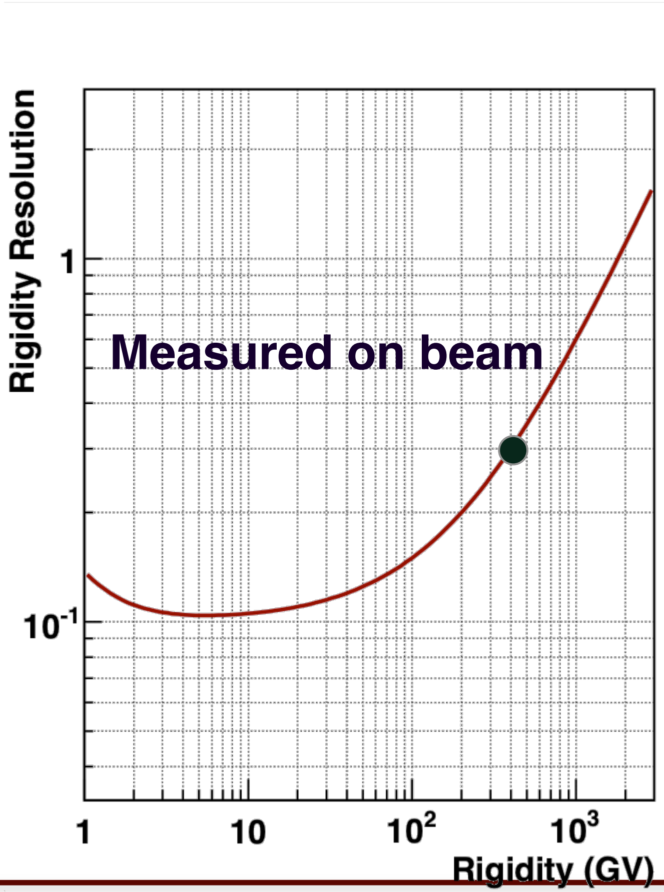
Systematic error on the positron fraction: 5. e+/- Charge confusion

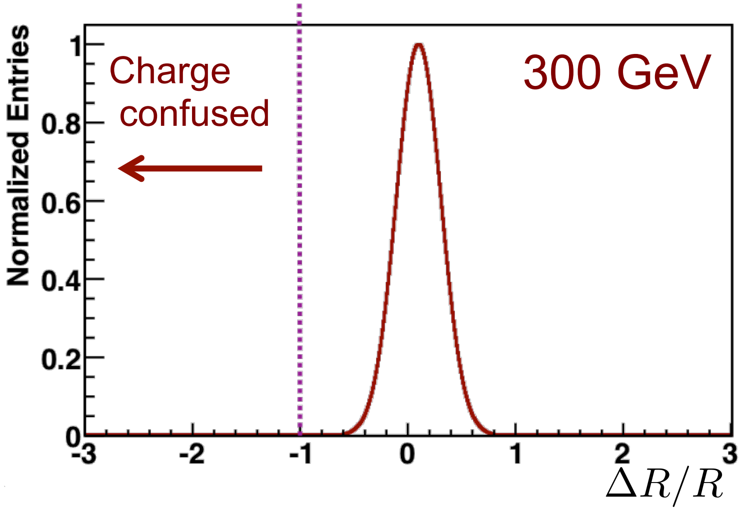


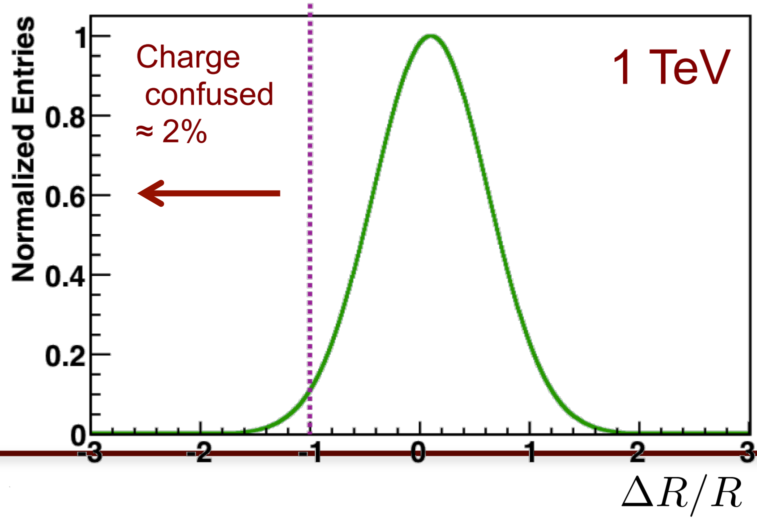
Two sources: large angle scattering and production of secondary tracks along the path of the primary track. Both are well reproduced by MC. Systematic errors correspond to variations of these effects within their statistical limits.

e+/e- separation:
the charge sign reconstruction

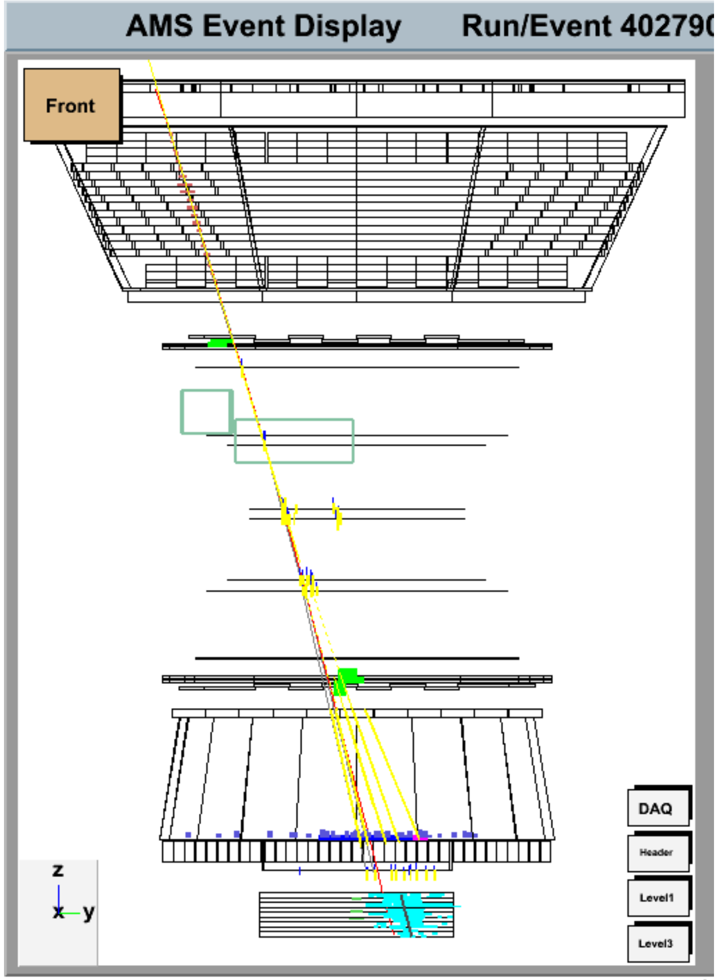
Momentum resolution contributes at the O(%) level in the charge confusion at the TeV energies



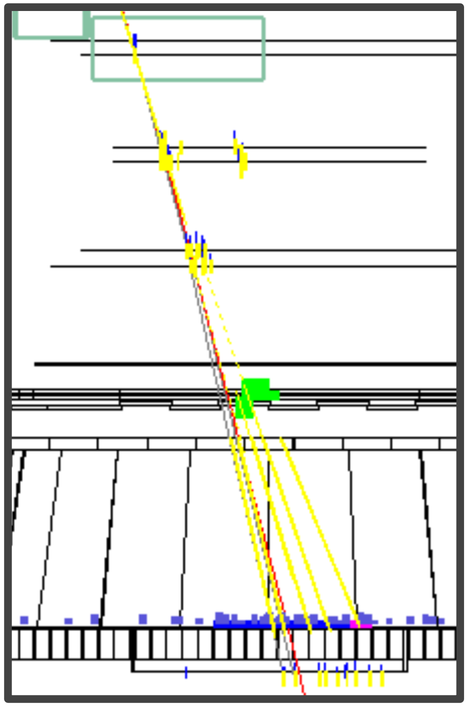




e+/e- separation:
the charge sign reconstruction



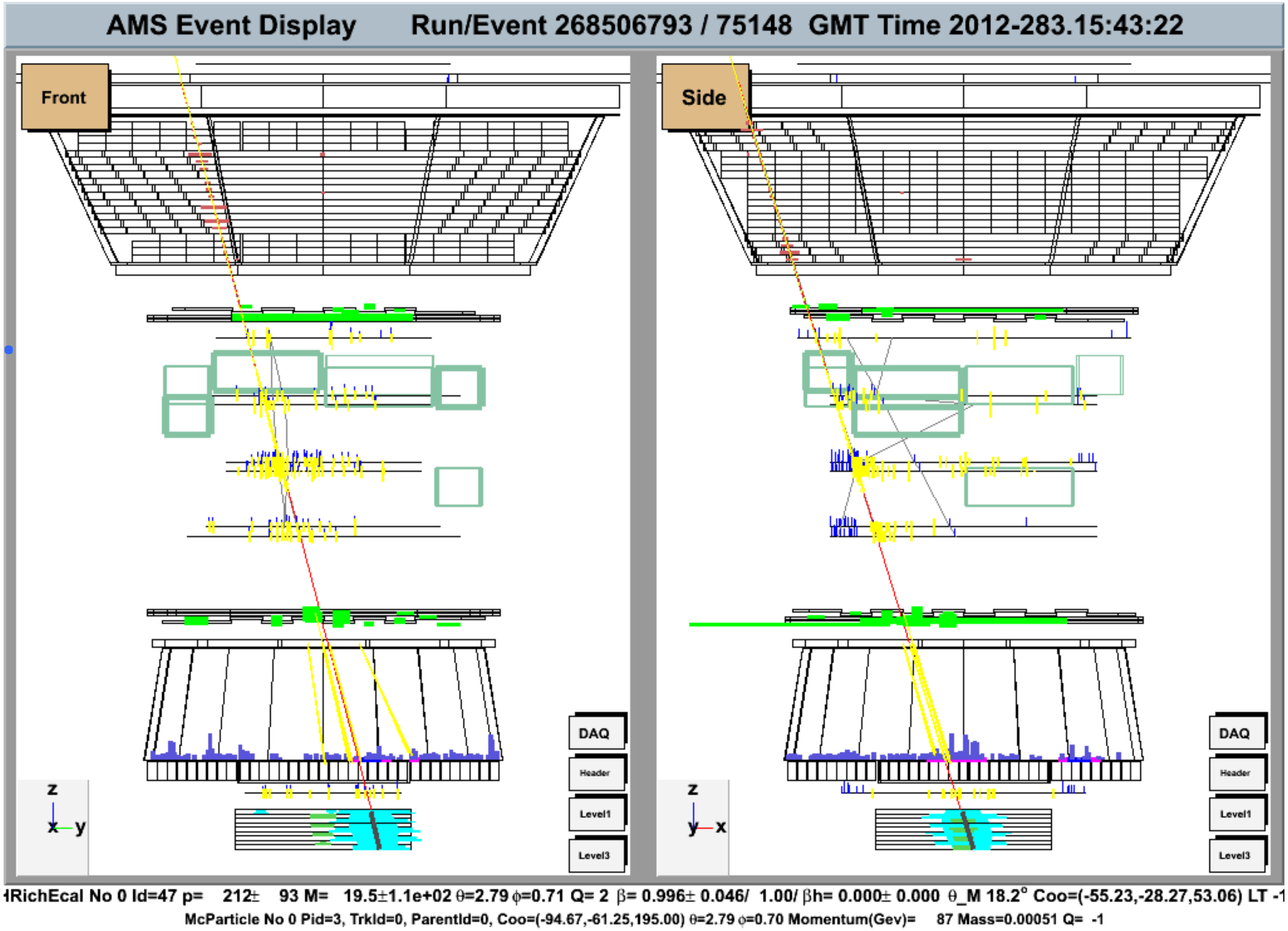
8 GeV electron reconstructed as 1 GeV positron



. Bremsstrahlung and delta rays provide many nearby tracks with high probability for association of a wrong hit to the main track.

Charge confusion sources: Interactions in the detector

38 GeV electron reconstructed as 0.8 GeV positron.



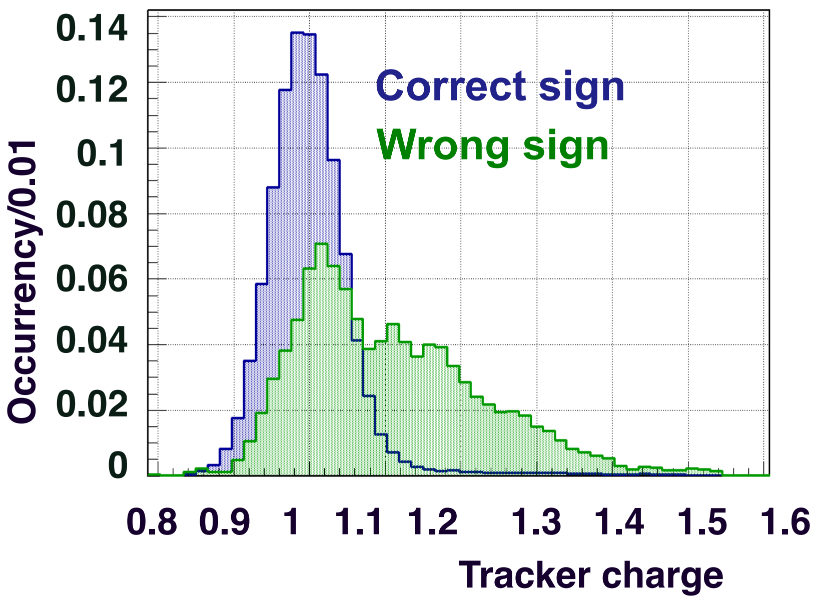
AMS Event Display Run/Event 268506793 / 75148 GMT Time 2012-283.15:43:22

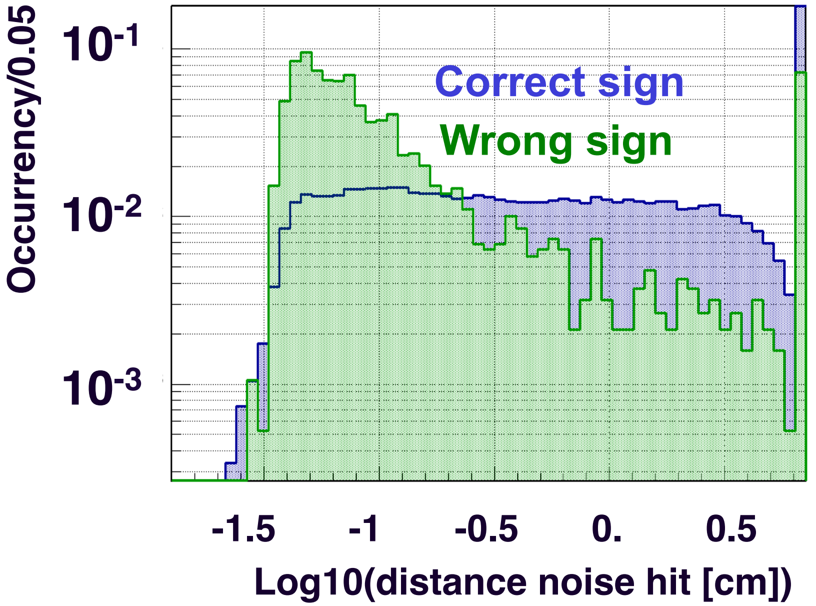
RichEcal No 0 Id=47 p= 212± 93 M= 19.5±1.1e+02 θ=2.79 ϕ=0.71 Q= 2 β= 0.996± 0.046/ 1.00/ βh= 0.000± 0.000 θ_M 18.2° Coo=(-55.23,-28.27,53.06) LT -1

McParticle No 0 Pid=3, TrkId=0, ParentId=0, Coo=(-94.67,-61.25,195.00) θ=2.79 ϕ=0.70 Momentum(Gev)= 87 Mass=0.00051 Q= -1

Charge Confusion from interaction

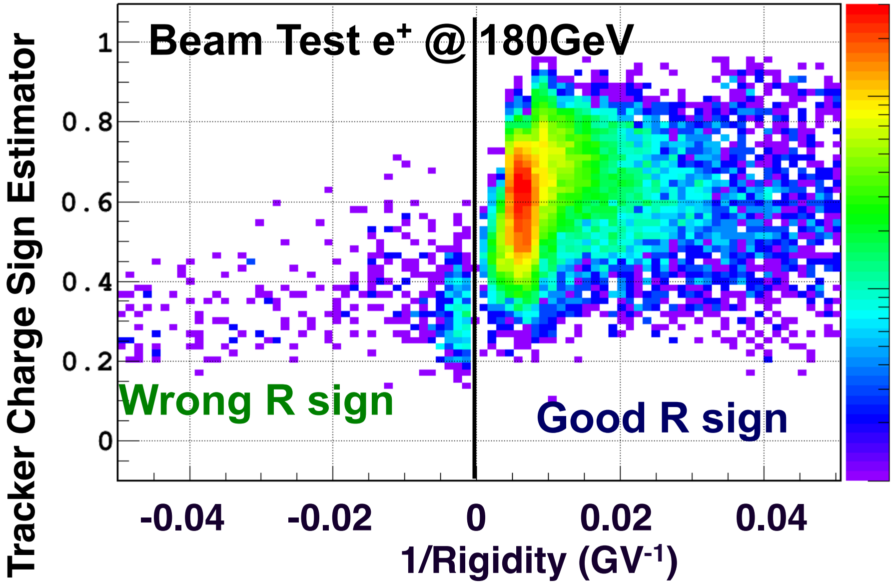
Different reconstructed quantities are sensitive to interactions and can be used to separate **Correct** and **Wrong** Charge Sign assignment

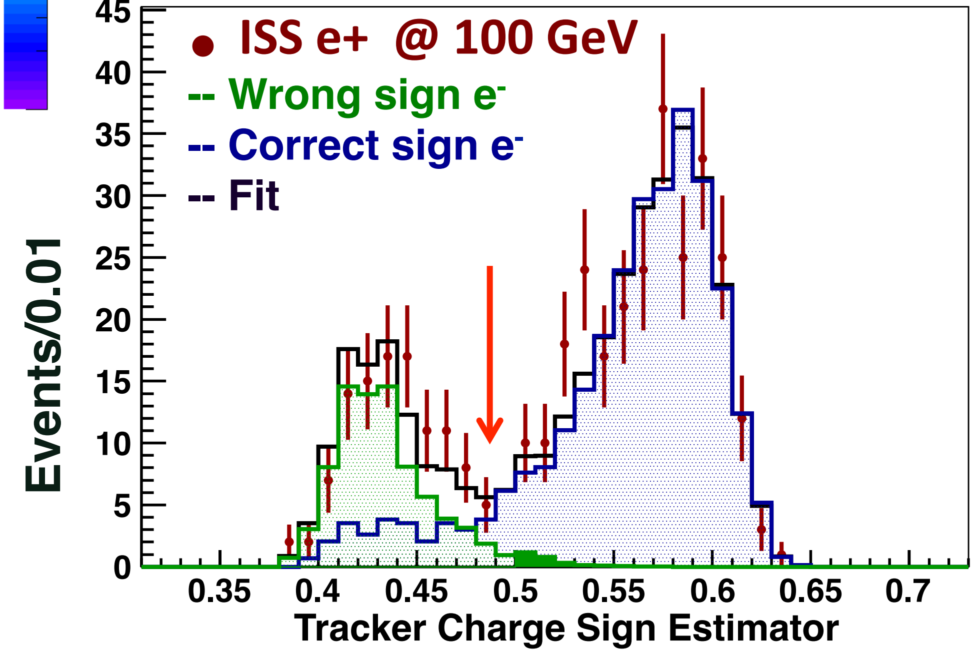




Use a statistical estimator to build a tracker charge sign discriminating variable

Tracker charge sign estimator

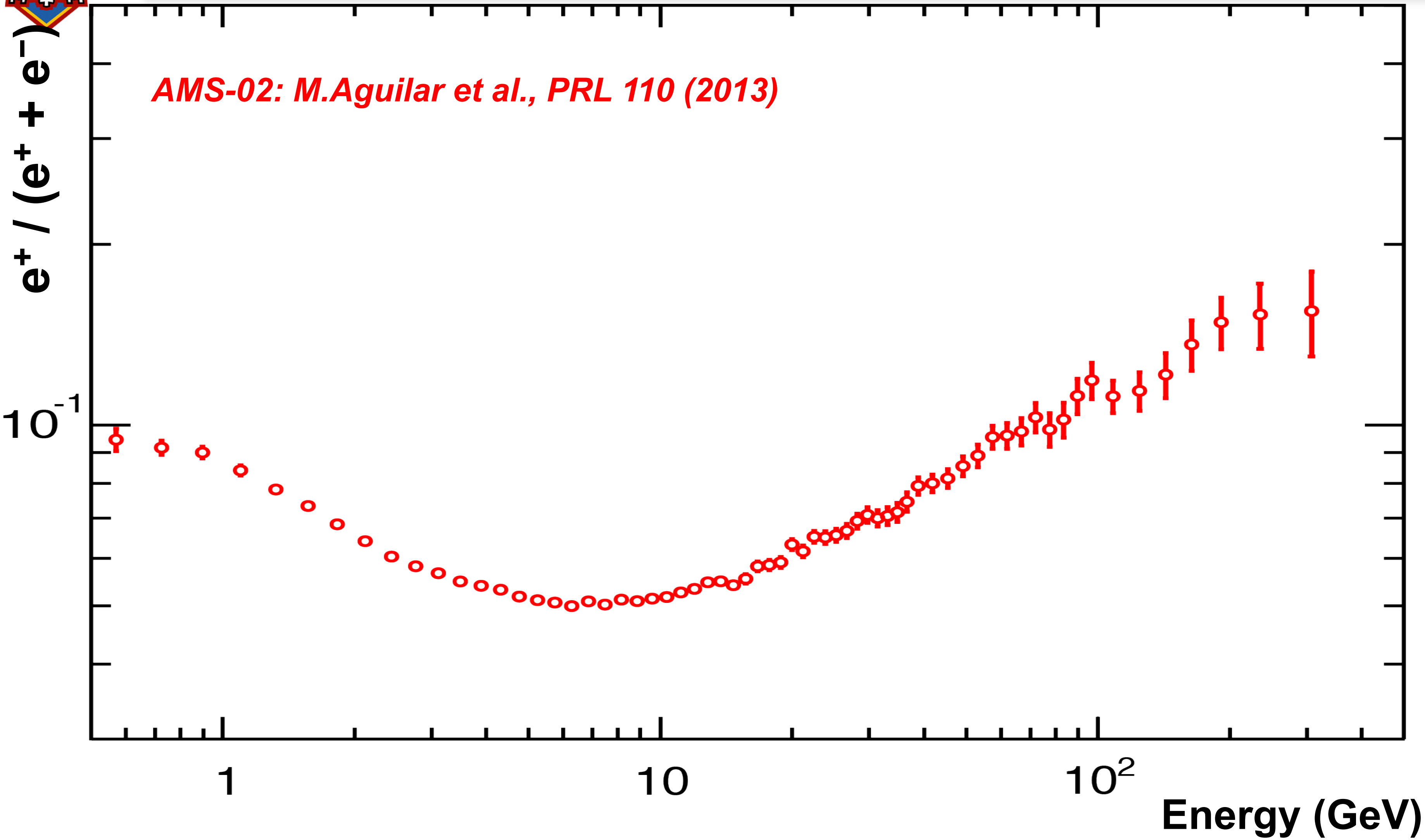




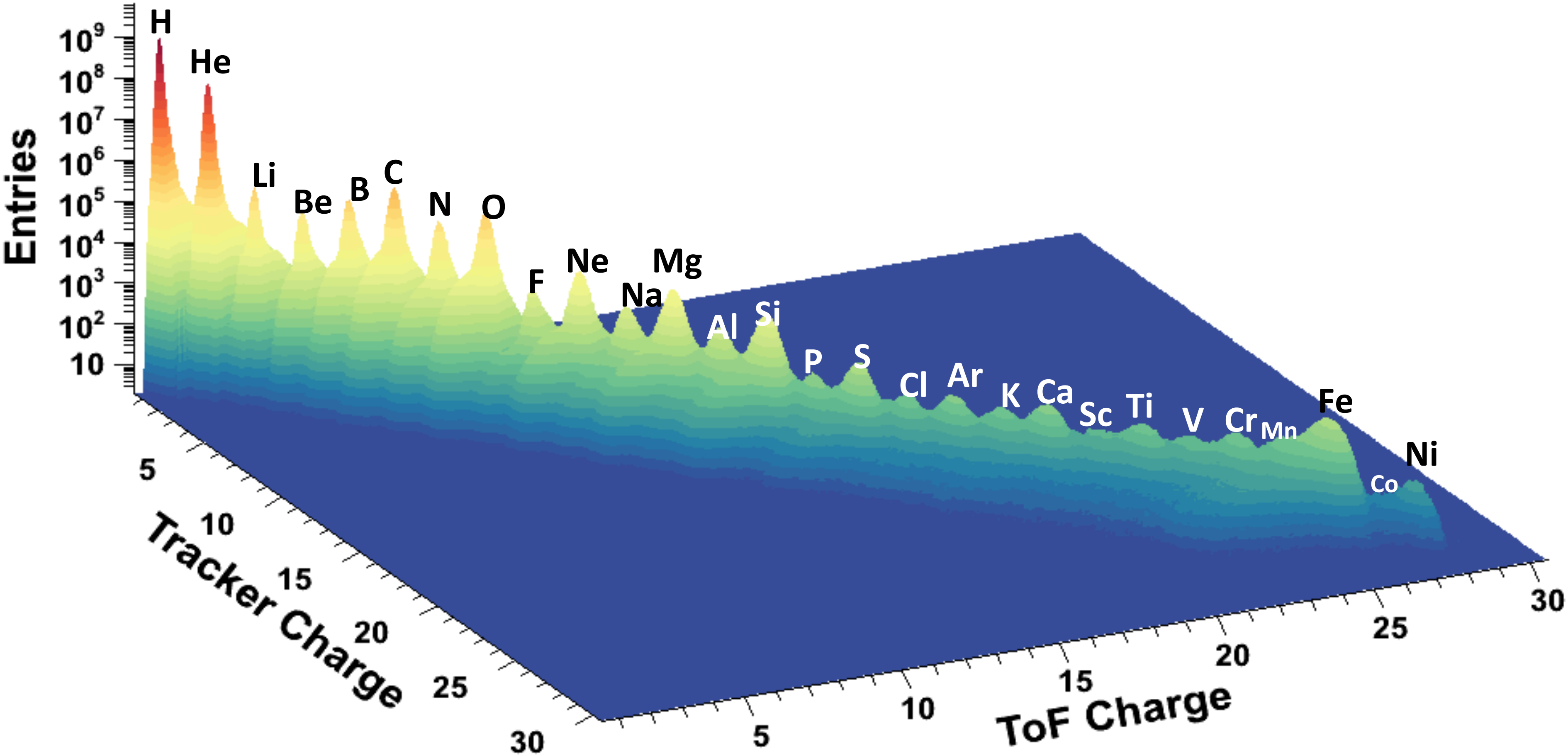
Measurement of the positron fraction

Positron events, positron fraction in each energy bin				Systematic Errors					
Energy [GeV]	N_{e+}	Fraction	statistical error	acceptance asymmetry	event selection	bin-to-bin migration	reference spectra	charge confusion	total systematic uncertainty
Energy[GeV]	N_{e+}	Fraction	$\sigma_{stat.}$	$\sigma_{acc.}$	$\sigma_{sel.}$	$\sigma_{mig.}$	$\sigma_{ref.}$	$\sigma_{c.c.}$	$\sigma_{syst.}$
1.00-1.21	9335	0.0842	0.0008	0.0005	0.0009	0.0008	0.0001	0.0005	0.0014
1.97-2.28	23893	0.0642	0.0004	0.0002	0.0005	0.0002	0.0001	0.0002	0.0006
3.30-3.70	20707	0.0550	0.0004	0.0001	0.0003	0.0000	0.0001	0.0002	0.0004
6.56-7.16	13153	0.0510	0.0004	0.0001	0.0000	0.0000	0.0001	0.0002	0.0002
09.95-10.73	7161	0.0519	0.0006	0.0001	0.0000	0.0000	0.0001	0.0002	0.0002
19.37-20.54	2322	0.0634	0.0013	0.0001	0.0001	0.0000	0.0001	0.0002	0.0003
30.45-32.10	1094	0.0701	0.0022	0.0001	0.0002	0.0000	0.0001	0.0003	0.0004
40.00-43.39	976	0.0802	0.0026	0.0002	0.0005	0.0000	0.0001	0.0004	0.0007
50.87-54.98	605	0.0891	0.0038	0.0002	0.0006	0.0000	0.0001	0.0004	0.0008
64.03-69.00	392	0.0978	0.0050	0.0002	0.0010	0.0000	0.0002	0.0007	0.0013
74.30-80.00	276	0.0985	0.0062	0.0002	0.0010	0.0000	0.0002	0.0010	0.0014
86.00-92.50	240	0.1120	0.0075	0.0002	0.0010	0.0000	0.0003	0.0011	0.0015
100.0-115.1	304	0.1118	0.0066	0.0002	0.0015	0.0000	0.0003	0.0015	0.0022
115.1-132.1	223	0.1142	0.0080	0.0002	0.0019	0.0000	0.0004	0.0019	0.0027
132.1-151.5	156	0.1215	0.0100	0.0002	0.0021	0.0000	0.0005	0.0024	0.0032
151.5-173.5	144	0.1364	0.0121	0.0002	0.0026	0.0000	0.0006	0.0045	0.0052
173.5-206.0	134	0.1485	0.0133	0.0002	0.0031	0.0000	0.0009	0.0050	0.0060
206.0-260.0	101	0.1530	0.0160	0.0003	0.0031	0.0000	0.0013	0.0095	0.0101
260.0-350.0	72	0.1550	0.0200	0.0003	0.0056	0.0000	0.0018	0.0140	0.0152

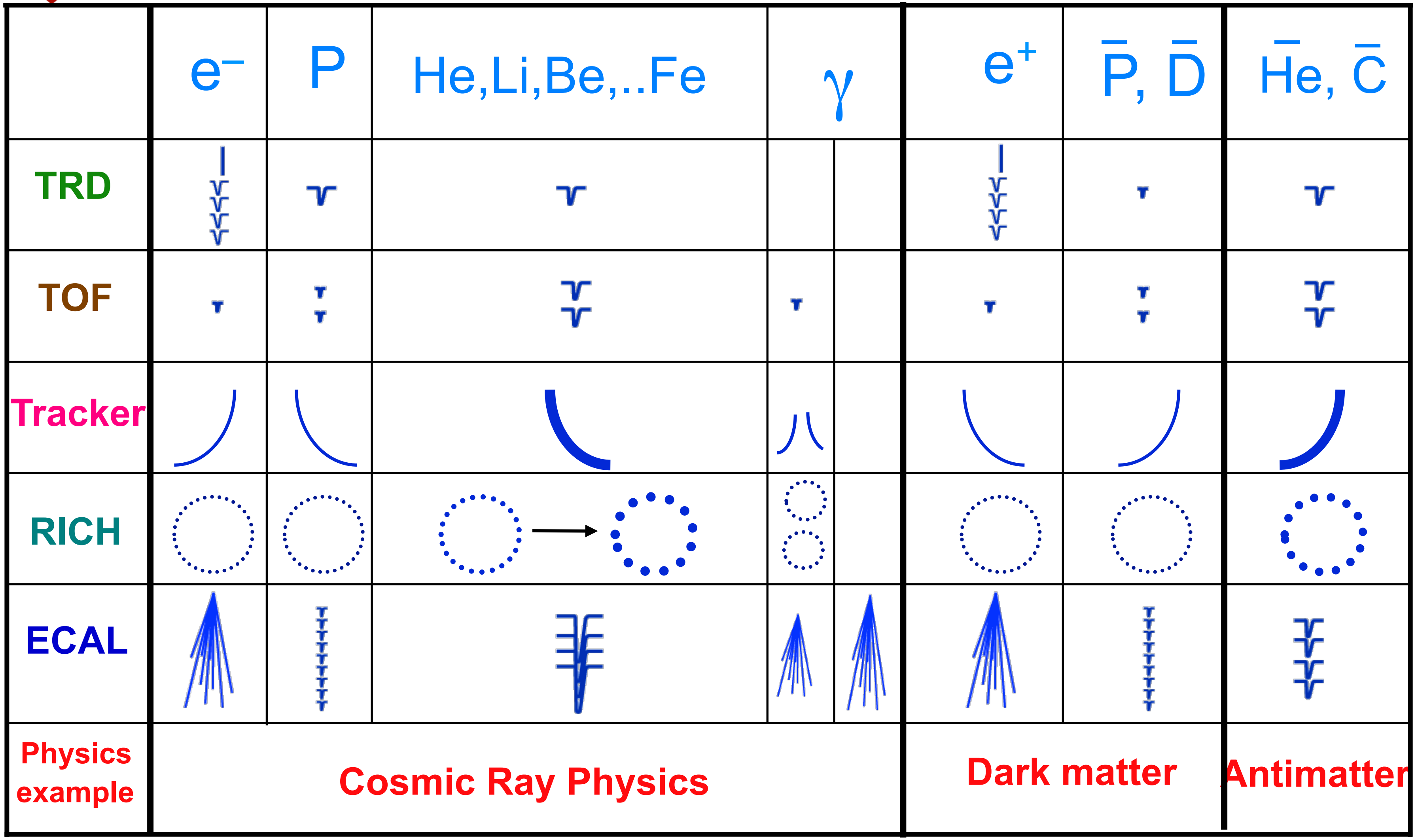
Positron fraction (0.5 - 350 GeV)



Nuclei Identification in AMS

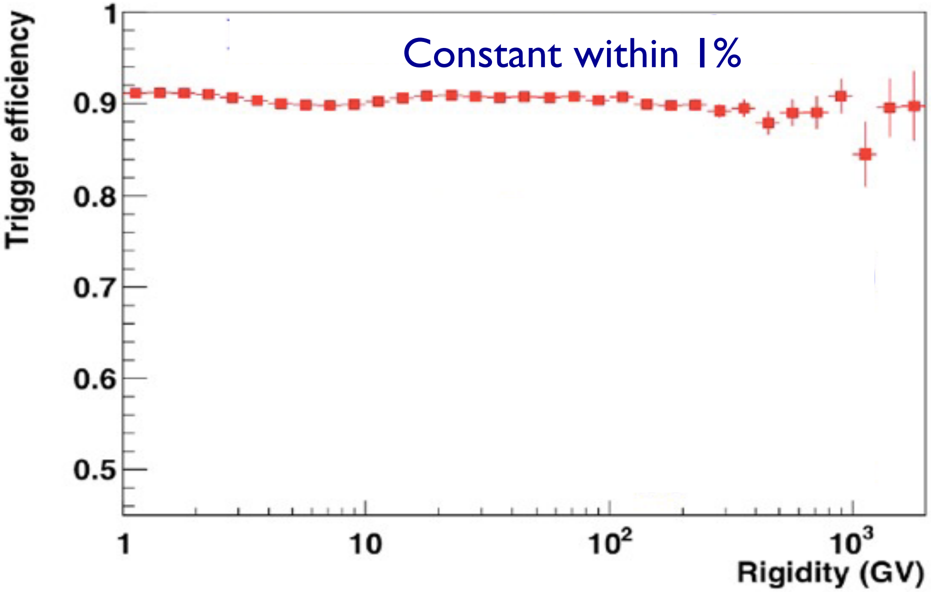


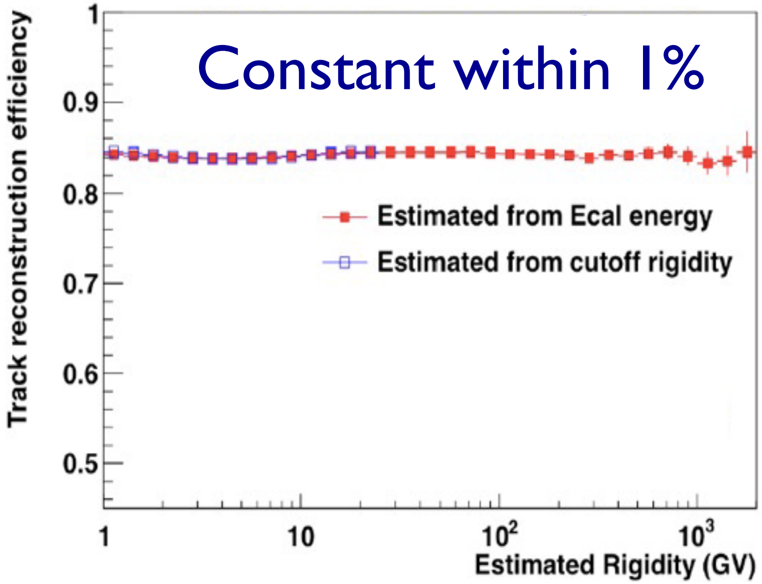
Full coverage of anti-matter & CR physics



	e^-	P	He,Li,Be,..Fe	γ	e^+	$\bar{P}$, $\bar{D}$	$\overline{He}$, $\bar{C}$
TRD							
TOF							
Tracker							
RICH							
ECAL							
Physics example	**Cosmic Ray Physics**				**Dark matter**		**Antimatter**

Proton Flux: Trigger and Tracker Reconstructed Efficiency





Determined with un-bias trigger (pre-scaled events 1/100)

Systematic Error: ±1.0%

Uncertainty due to the limited statistics of un-bias trigger events

Systematic Error: ±1.0%

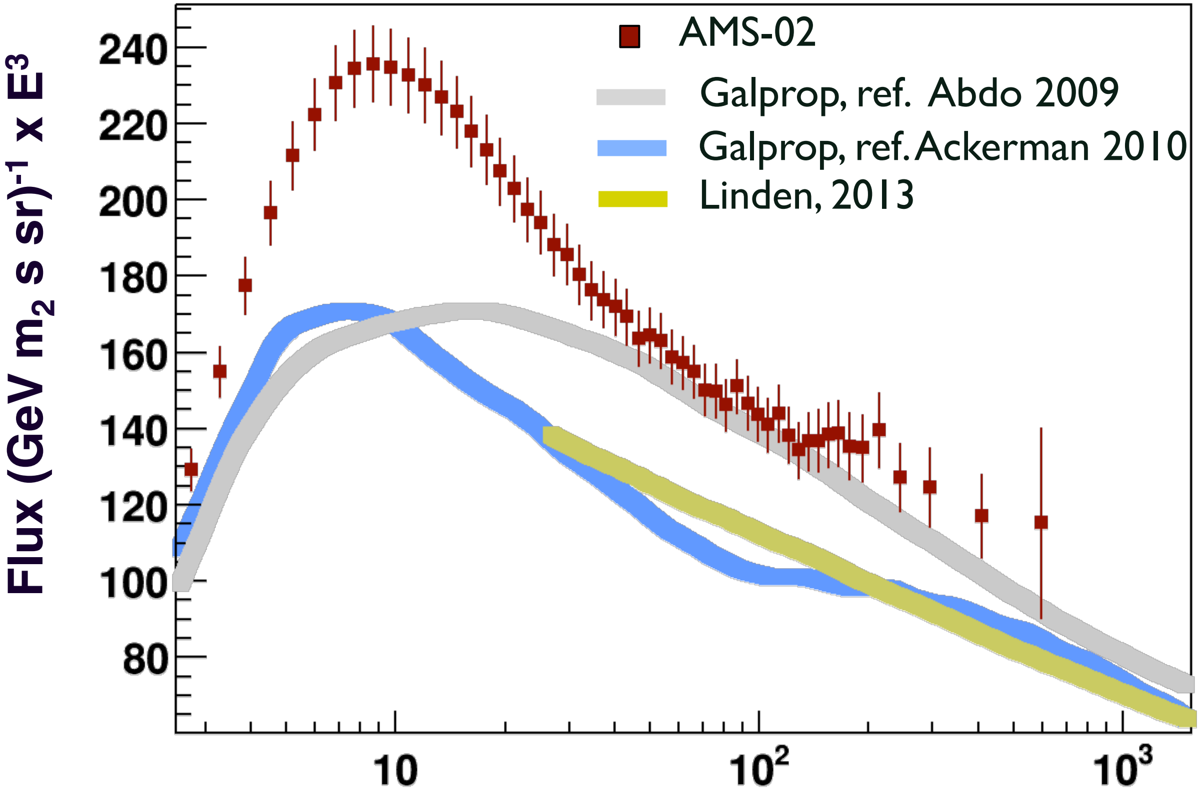
due to the uncertainty of the rigidity dependence

Events passing out of tracker sensitive area (91%) are taken into account

Proton Flux: Systematic errors

	Errors
Acceptance	σ_{acc} =2.8%
Trigger efficiency	σ_{trg} =1.0%
Track reconstruction eff.	σ_{trk} =1.0%
Total errors on flux normalization	$\sigma_{norm}=(\sigma_{acc}^2+\sigma_{acc}^2+\sigma_{acc}^2)^{1/2}$ $= 3.1\%$
Unfolding	$\sigma_{unfold} \begin{cases} <1\% & R<100GV \\ 5.4\% & R=1TV \end{cases}$
Total Systematic Errors	$\sigma_{unfold} \begin{cases} 3.2\% & R<100GV \\ 6.3\% & R=1TV \end{cases}$

AMS data and phenomenological models: what can we say about "standard production?"



No firm prediction as of today of the "standard" $e^+ + e^-$ fluxes