The cosmic electron and positron flux measurement with the AMS-02 experiment

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Bad Liebenzell GK workshop 2014

KIT Karlsruhe, IEKP Institut fuer Experimentelle Kernphysik

Outline

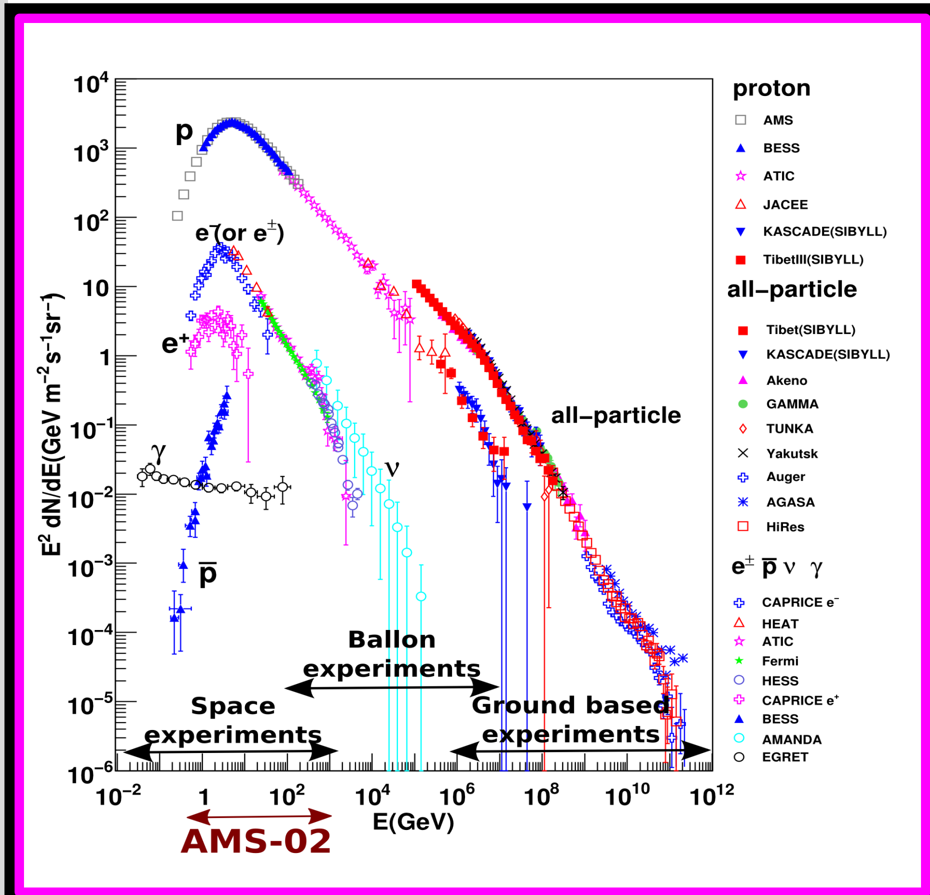
Introduction to cosmic rays

The AMS-02 experiment

Measurement of the $e^+ + e^-$ flux

Results and discussion

Cosmic Rays



Cosmic rays cover an energy range up to 10^{20} eV

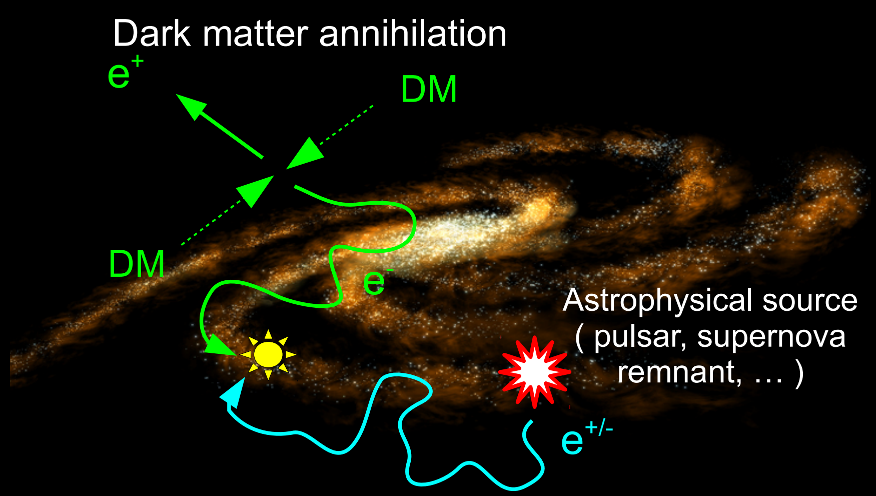
Most of cosmic rays are protons and nuclei produced by standard astrophysical mechanisms

New physics signature can be hidden in rare components spectra ($e^{+/-}$, $\bar{p}$, $\bar{D}$, γ, ….)

The nature of the incoming cosmic rays can be identified only outside the Earth atmosphere

→ Particle physics in space

Cosmic Electrons and Positrons



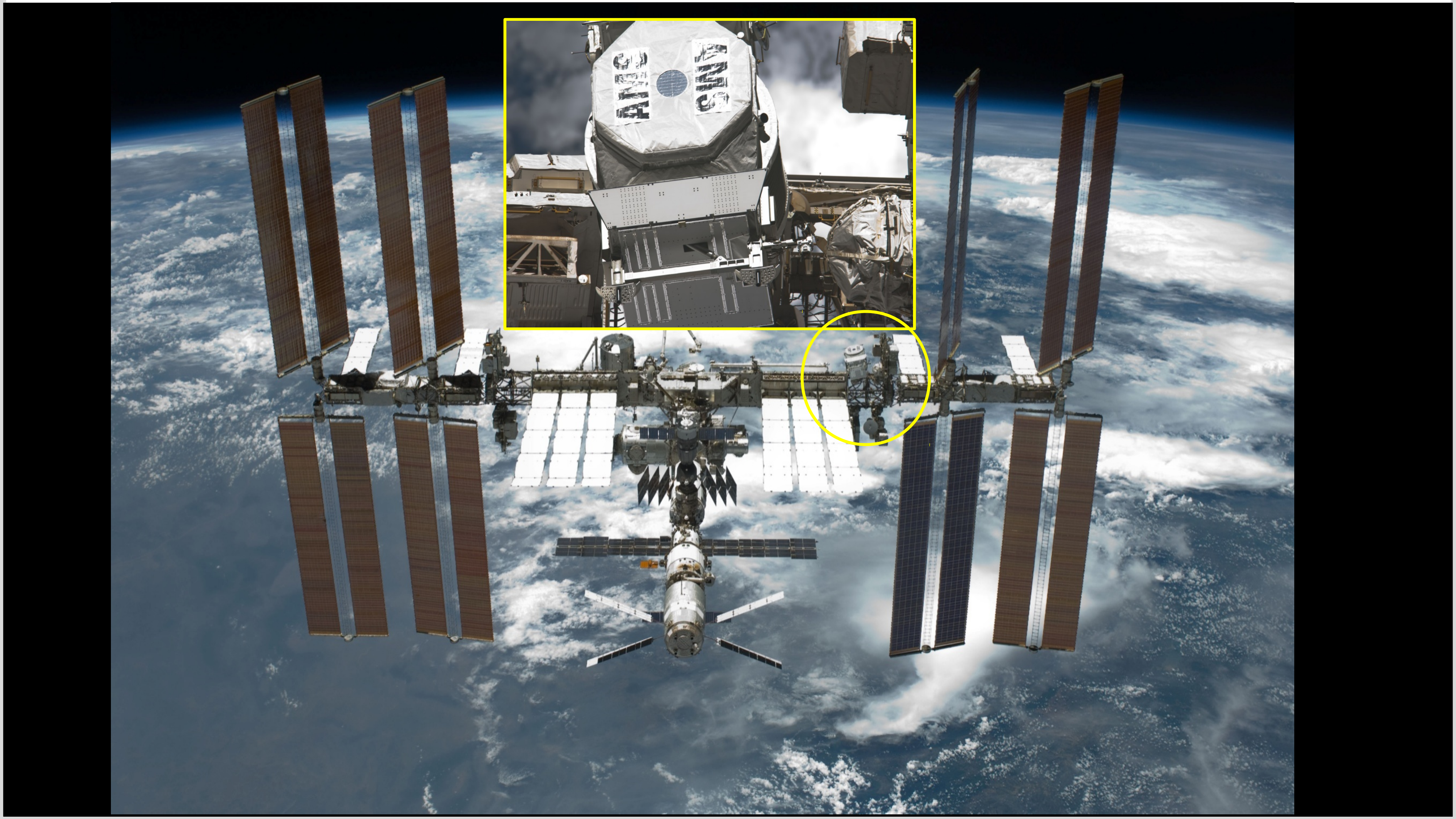
Electrons and Positrons in the cosmic radiation

- Sensitive to the local galactic environment
- Possible indirect detection of dark matter
- Low abundance in cosmic radiation
  $\Phi(p)/\Phi(e^+) = O(10^3 \sim 10^4)$

Detector designed to have

- High ($>10^6$) proton rejection
- Precise energy measurement
- High acceptance and lifetime

AMS on the International Space Station



AMS-02 Science

Indirect Dark Matter search: e^+, $\bar{p}$, $\bar{D}$, …
Direct search for primordial antimatter: $\overline{He}$, $\bar{C}$, ….
Cosmic ray spectra up to TeV
Solar physics effects over 11 years solar cycle
Gamma physics (high energy photons local sources, photon spectra)

AMS-02
Multi purpose spectrometer on the ISS

AMS-02 Science

Indirect Dark Matter search: e^+, $\bar{p}$, $\bar{D}$, …

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Cosmic ray spectra up to TeV

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Gamma physics (high energy photons local sources, photon spectra)

New results shown by Prof. Ting last week at CERN

e^+/e^++e^- up to 500 GeV

e^+ flux up to 500 GeV

e^- flux up to 700 GeV

$e^+ + e^-$ flux up to 1000 GeV

AMS-02 Science

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$e^{+}/e^{+}+e^{-}$ up to 500 GeV
e^{+} flux up to 500 GeV
e^{-} flux up to 700 GeV
$e^{+} + e^{-}$ flux up to 1000 GeV

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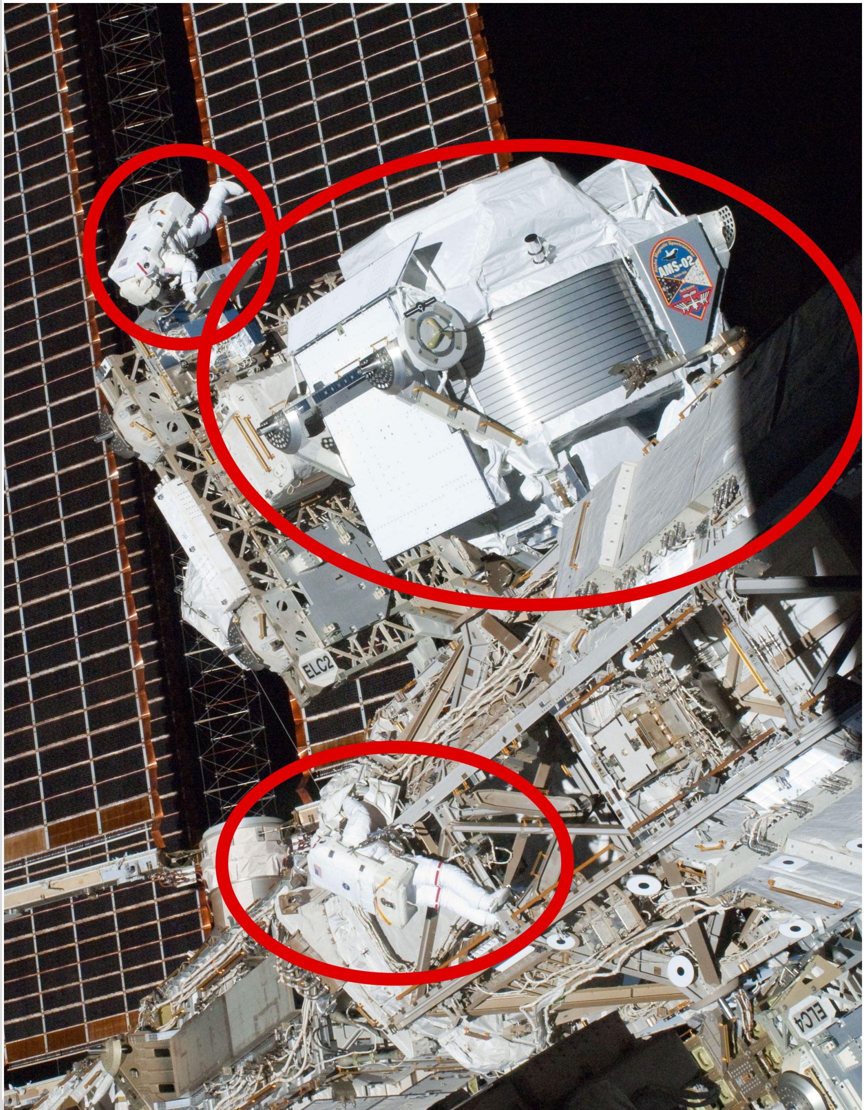
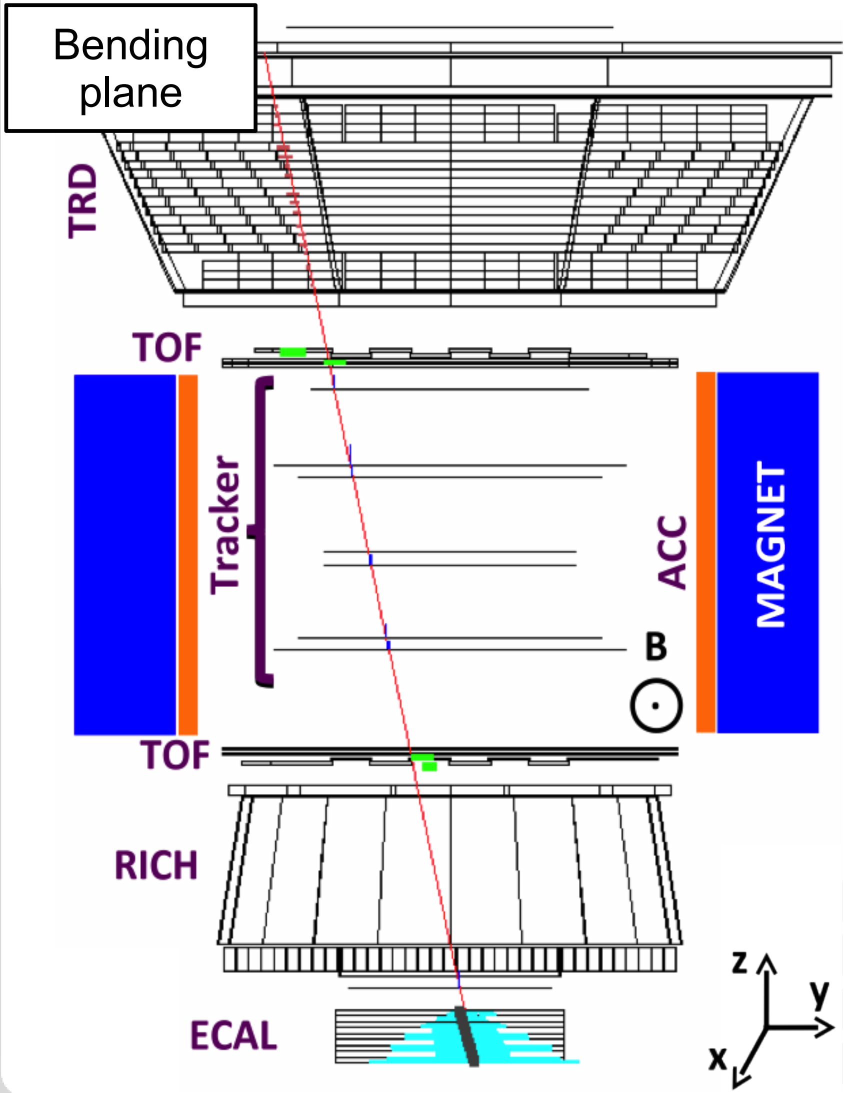
AMS-02 detector



- **Volume** 64 m^3, height 4 m
- **Weight** 8500 kg
- **Power** 2500 W
- **Data downlink** 17 Mbps
- **Magnetic field** 0.15 T (400 x Earth)
- **Launch** May 16th, 2011 (Endeavour shuttle)
- **Data taking** as of May 19th, 2011
- **Construction** 1999-2010 (> 3 PhD generations)
- **Mission duration:** until the end of ISS operation (currently 2024)

AMS-02 detector

600 GeV electron



Transition Radiation Detector **TRD**
Identifies $e^{+/-}$ (Xrays)

Time Of Flight **TOF**
Trigger / Charge Q / Flight direction / Velocity β

Magnet + Silicon Tracker **TRK**
Momentum / sign(Q) / Charge Q

Ring Imaging Cherenkov **RICH**
Velocity β / Charge Q

Electromagnetic Calorimeter **ECAL**
$e^{+/-}$ Energy / Identifies $e^{+/-}$ (shower shape)

Redundant measurement of most particle properties

Flux measurement

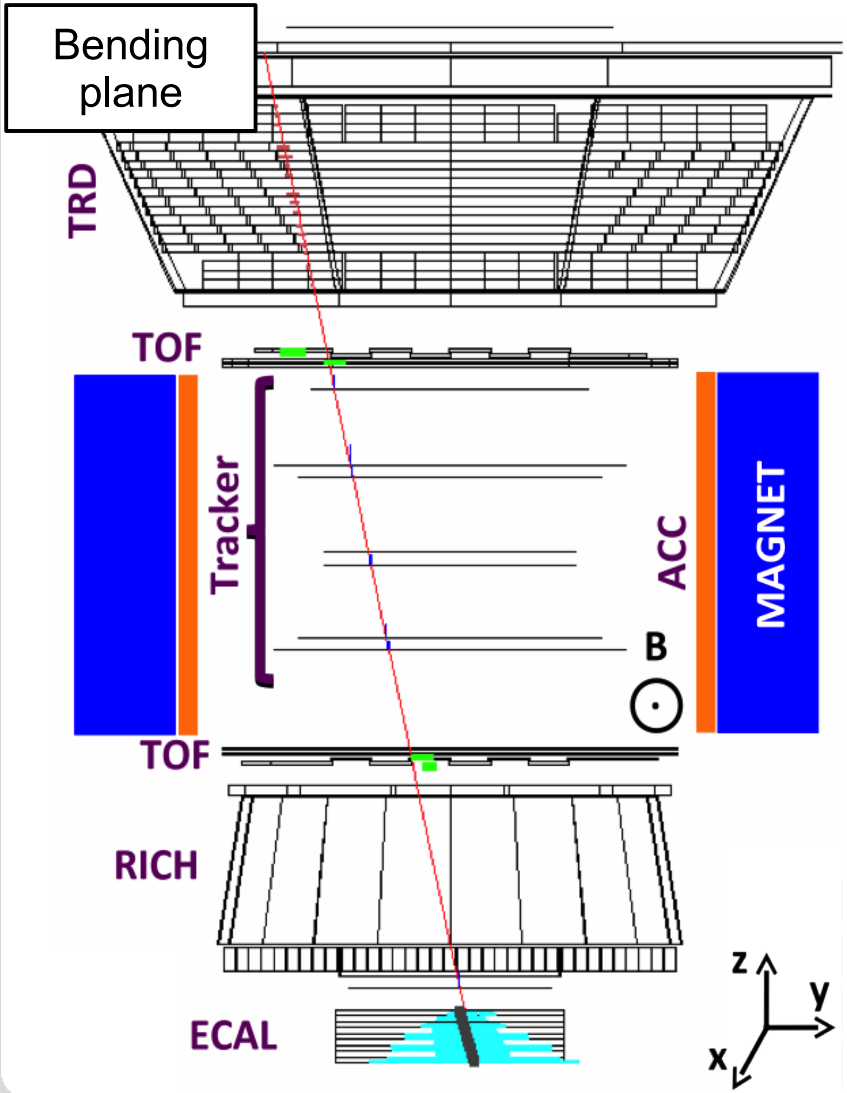
Φ= Absolute flux ($m^{-2}\ sr^{-1}\ GeV^{-1}\ sec^{-1}$)

$$\phi(E, E+\Delta E) = \frac{N_{obs}(E, E+\Delta E)}{\Delta E\, A(E)\, \Delta T_{\mathrm{exp}}}$$

- N_{obs} = Number of collected events
- ΔE = Bin width
- ΔT_{exp} = Exposure time (s)
- A = Effective acceptance ($m^2 sr$)
  → includes trigger efficiency

AMS-02 detector

600 GeV electron



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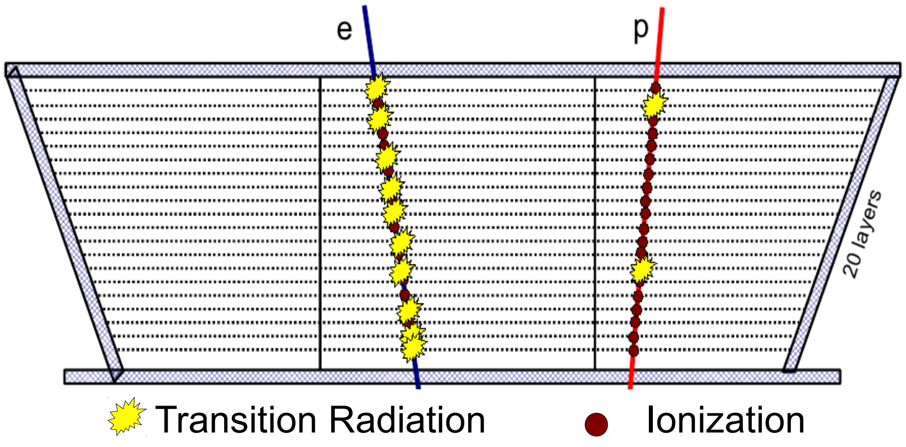
Electromagnetic Calorimeter ECAL
$e^{+/-}$ Energy / Identifies $e^{+/-}$ (shower shape)

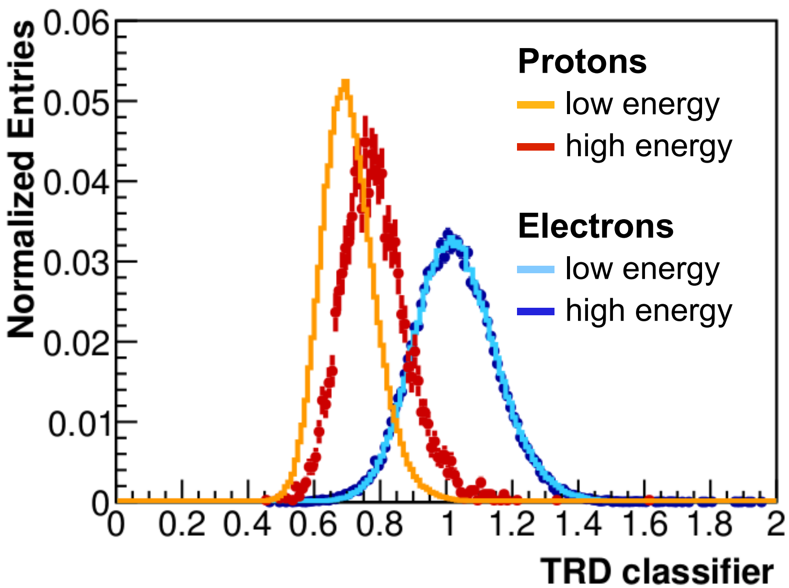
Electrons and positrons are separated by background protons using ECAL and TRD

Signal identification

Transition Radiation Detector TRD



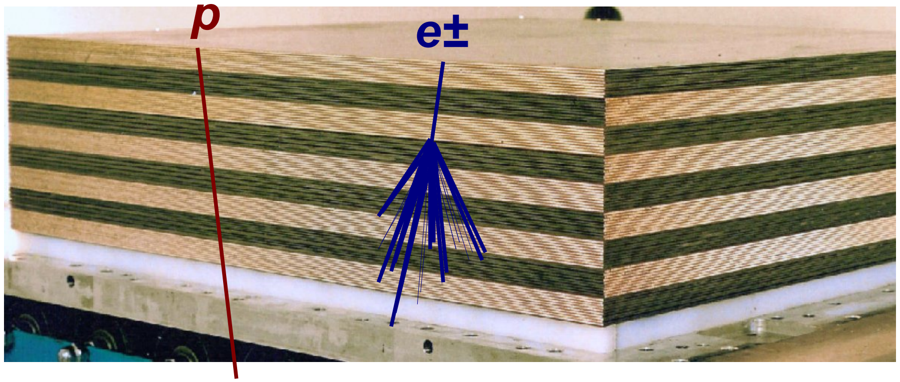
- 20 layers of radiators + Xe/C02 proportional tubes (5248 total tubes)
- Transition Radiation emission:
  Probability ~ $\gamma \rightarrow$ e/p separation



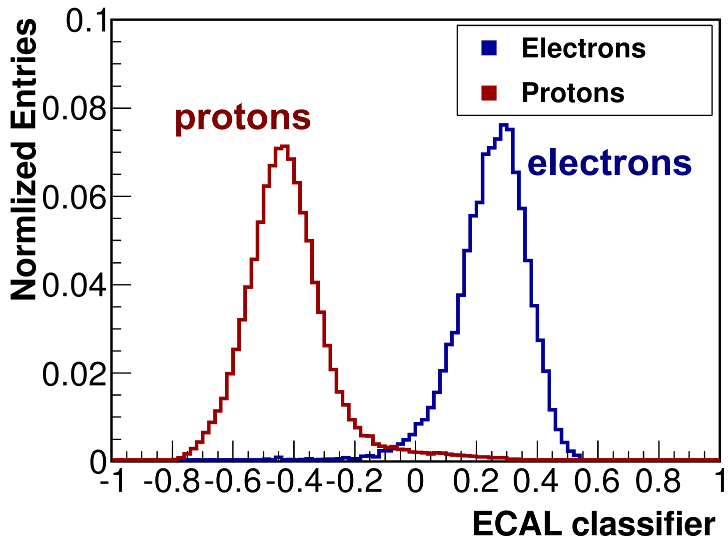
- TRD energy deposit used to build likelihood classifier
- TRD classifier shapes defined from data (using uncorrelated ECAL selection)
- Electron response does not depend on energy $\rightarrow$ stable tool up to TeV energies.

Signal identification

Electromagnetic Calorimeter ECAL

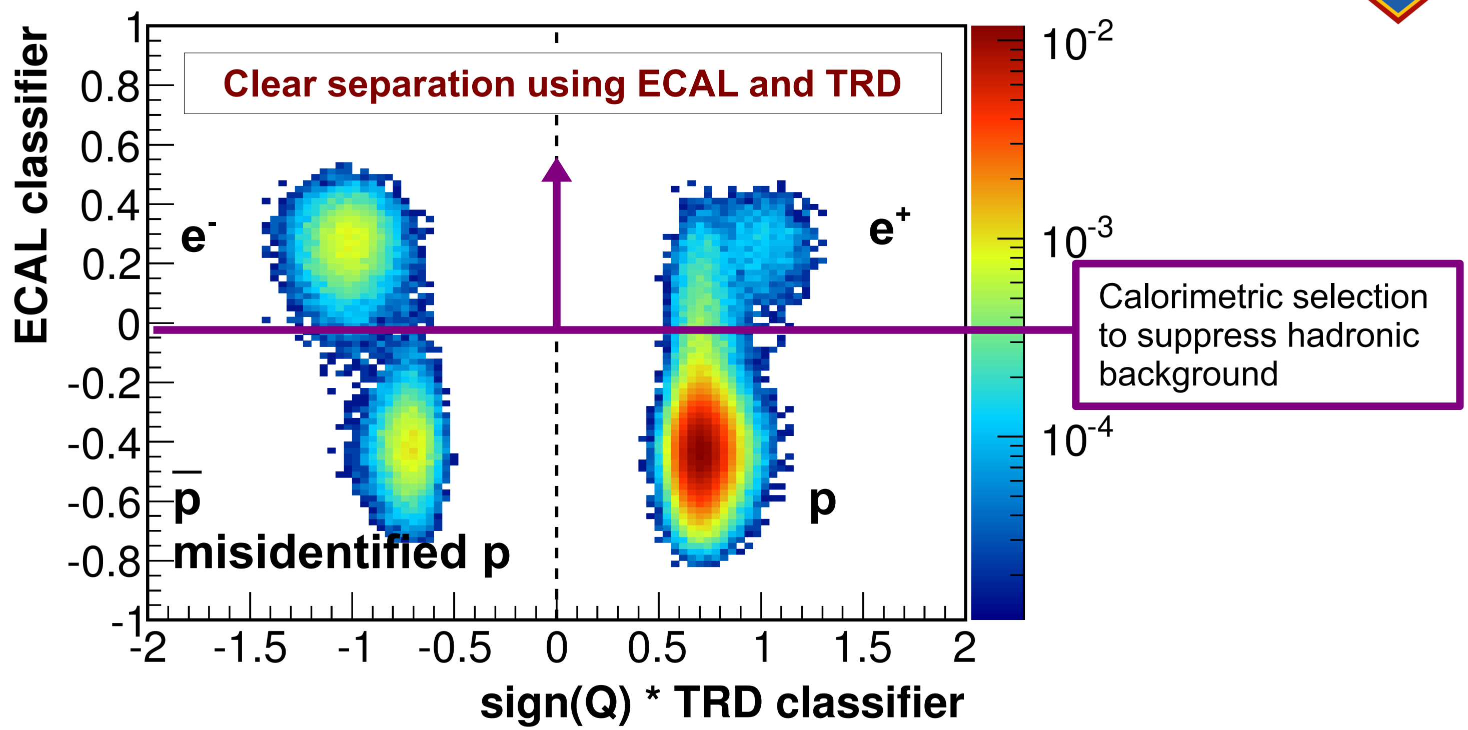


- 18 layers lead/scintillating fibers ECAL (1296 9mmx9mm cells)
- 17 X_0, 0.6 λ → e/p separation
- Accurate $e^{+/-}$ energy measurement



- Multivariate analysis of particle energy deposit in the calorimeter
- ECAL shower shape 3D accurate reconstruction allows high proton rejection up to TeV energies
- ECAL classifier shapes defined from data (using uncorrelated TRD selection)

Signal Selection

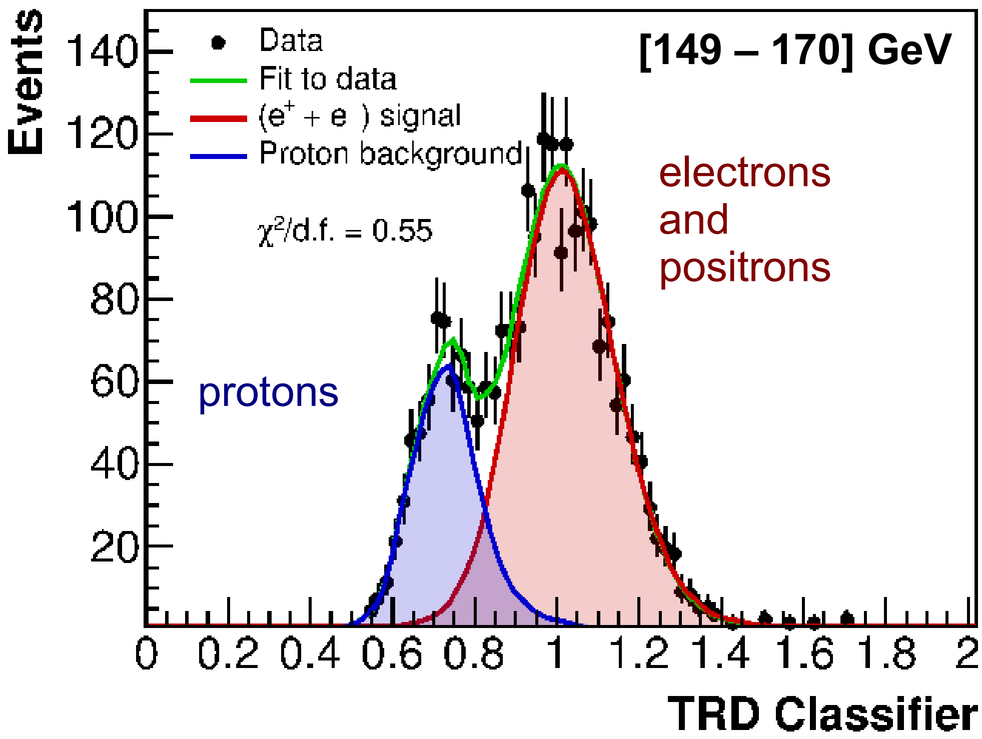


Data driven signal extraction

- Remove background using a selection on the calorimeter shower shape
- Extract the signal using template fits based on TRD energy deposit distribution

Signal Selection

$e^{\pm}$ counts extracted fitting **TRD classifier reference shapes** to selected data.



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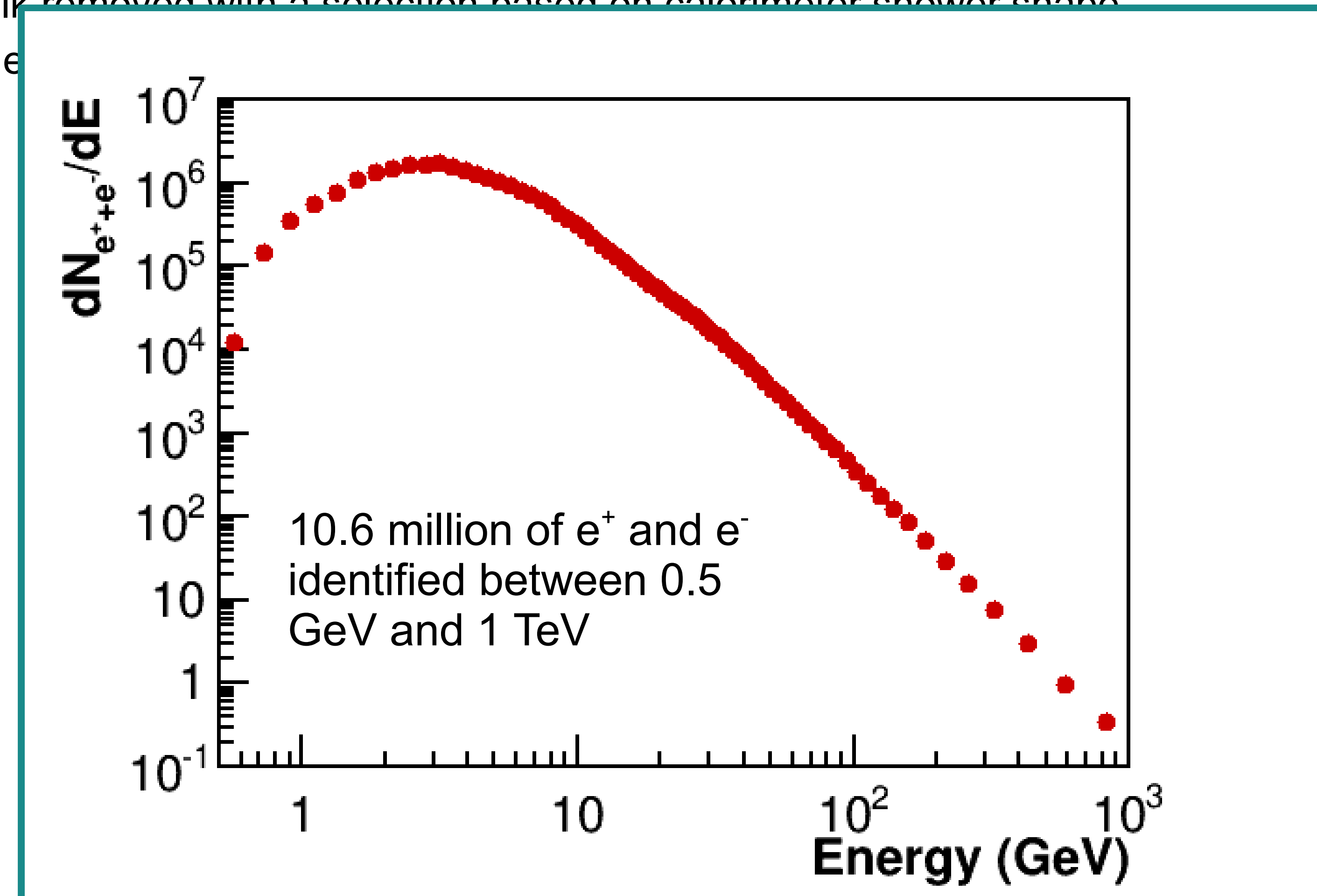
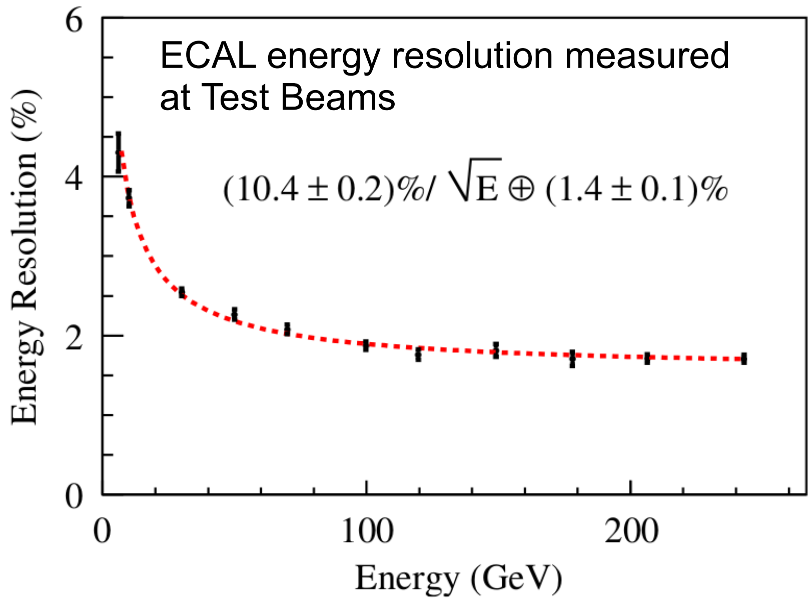
Signal Selection

- Proton bulk removed with a selection based on calorimeter shower shape
- e± counts e

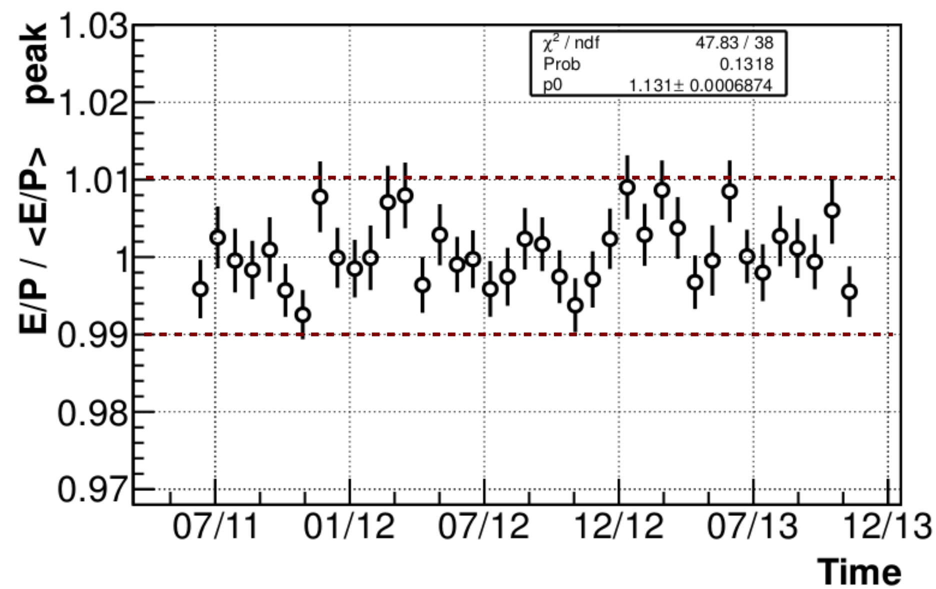


Measurement performed with the calorimetric selection which maximizes the signal sensitivity

Energy Measurement



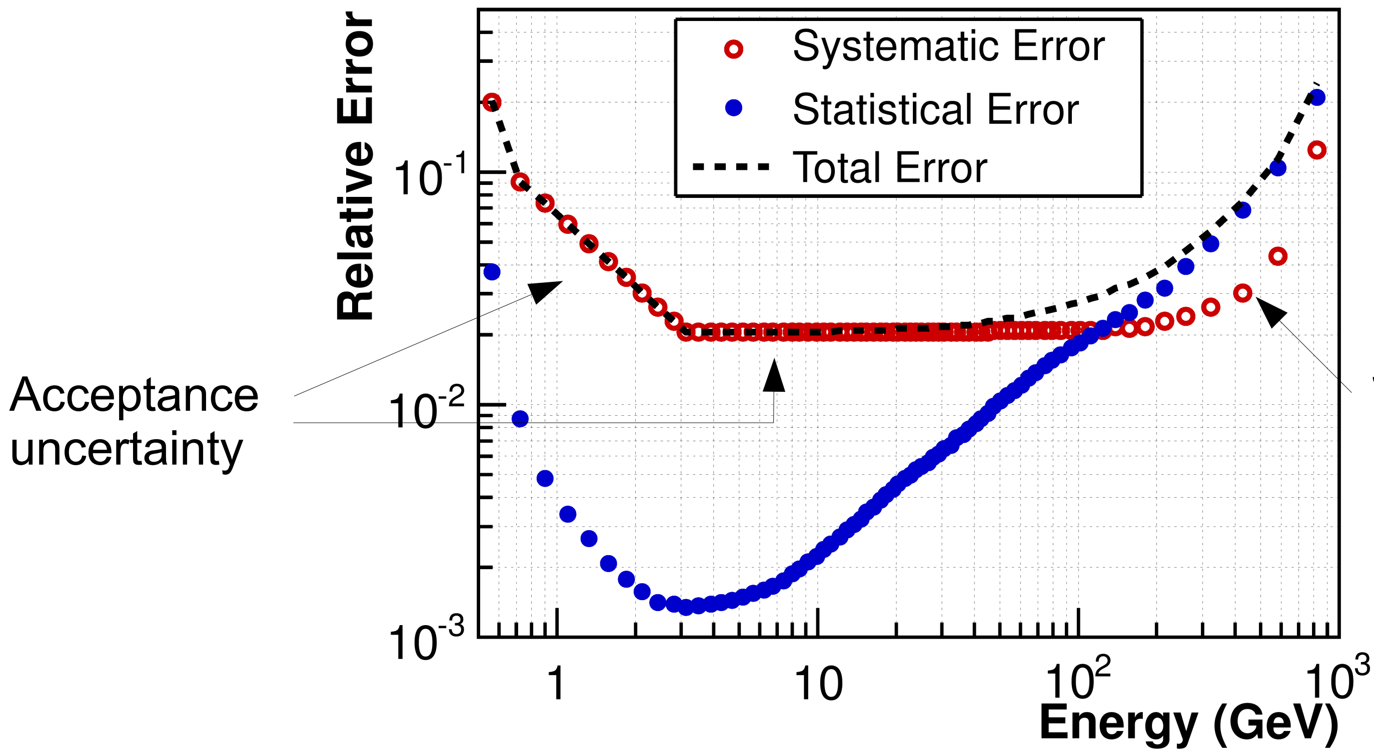
- **ECAL energy resolution ~2%**
- **ECAL energy absolute scale** tested during test beams on ground
- We have no line in space (as in collider exp.) to calibrate the energy scale in orbit!
  → MIP ionization used to cross-calibrate the energy scale in orbit



- Cosmic ray energy measured by
  → ECAL (em shower energy deposit)
  → Tracker (curved of track in mag. field)
- ECAL energy comparison with Tracker rigidity (E/P) used to assure the stability of the scale over time

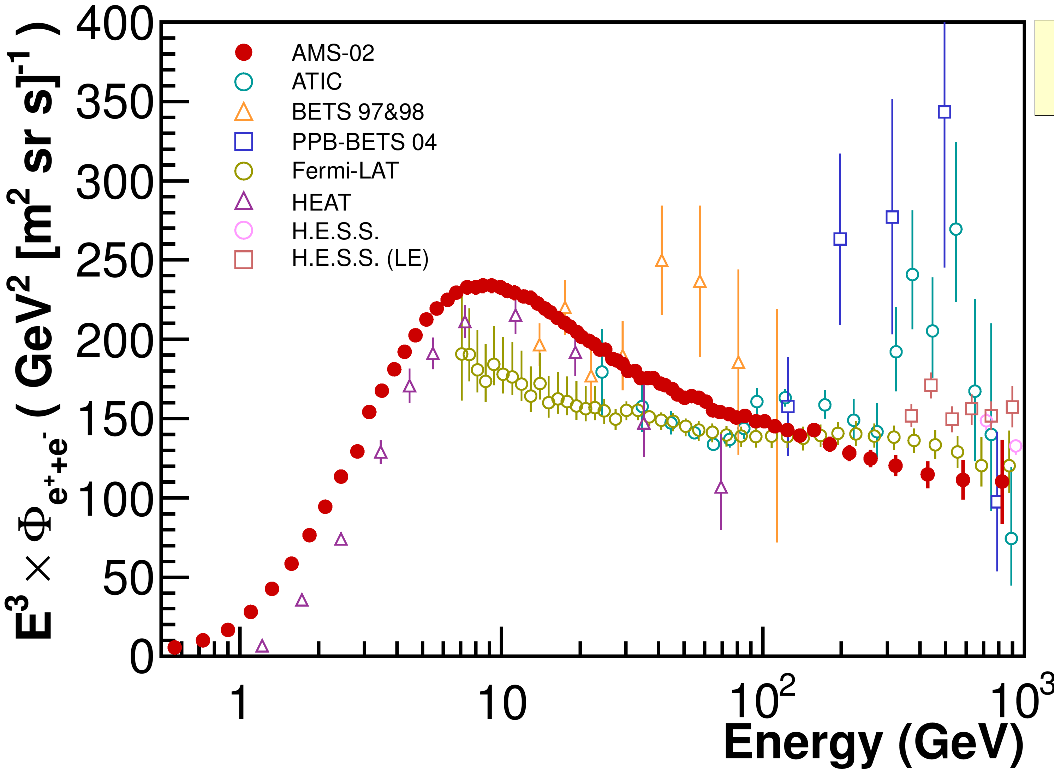
ECAL energy scale known at 2% level in [10.0 – 290.0] GeV

Measurement Systematic



- Measurement error dominated by the acceptance systematic below 100 GeV
  - Statistical fluctuation dominates the error above 200 GeV

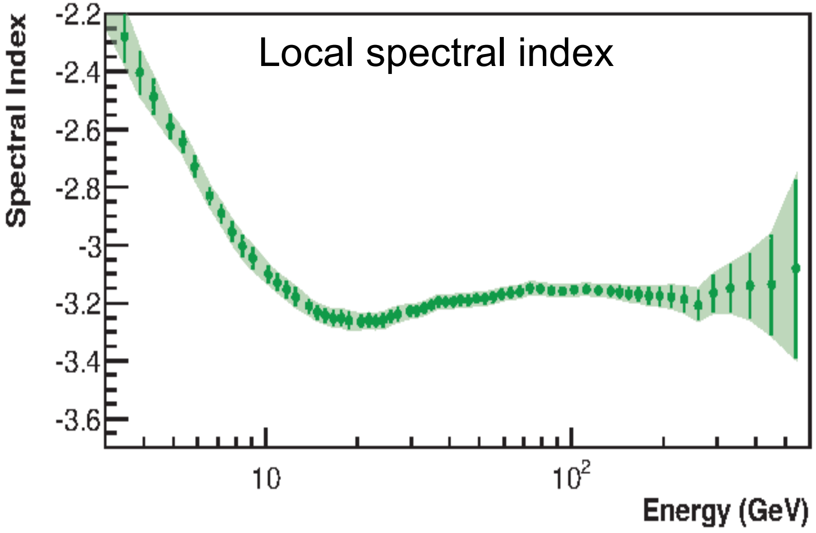
Cosmic $e^+ + e^-$ flux measurement



Submitted
To PRL

- Flux measured up to 1 TeV using 2.5 years of data (~ 15% of the total expected statistics)
- 10.6 millions of electrons and positrons selected to measure the flux.
- No evidence of prominent feature observed
- The flux is softer than previous experiments at high energies

$e^+ + e^-$ spectral index analysis



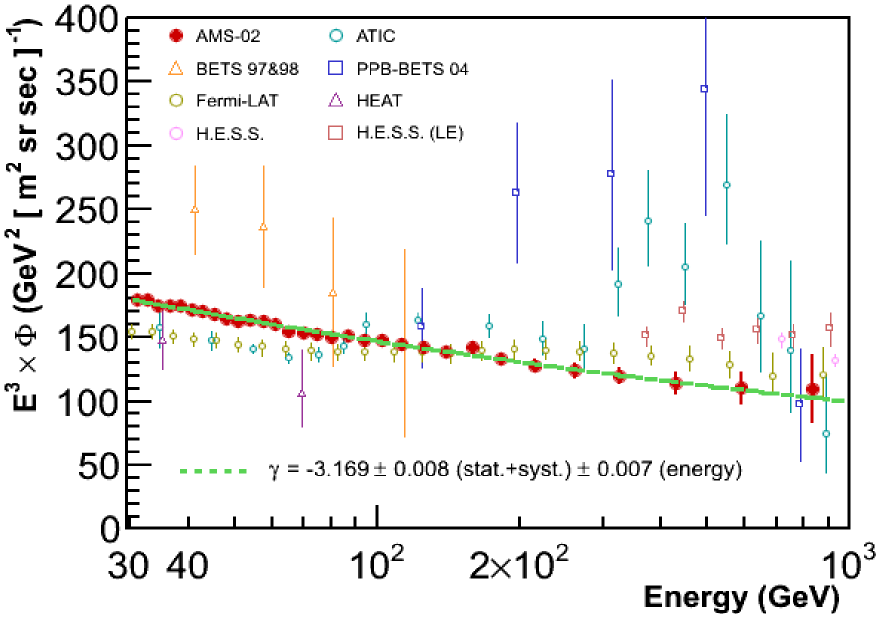
- Power law parametrization

$$\Phi(e^{\pm}) = A\,E^{-\gamma}$$

- Local spectral index drops from -2.2 to -3.2

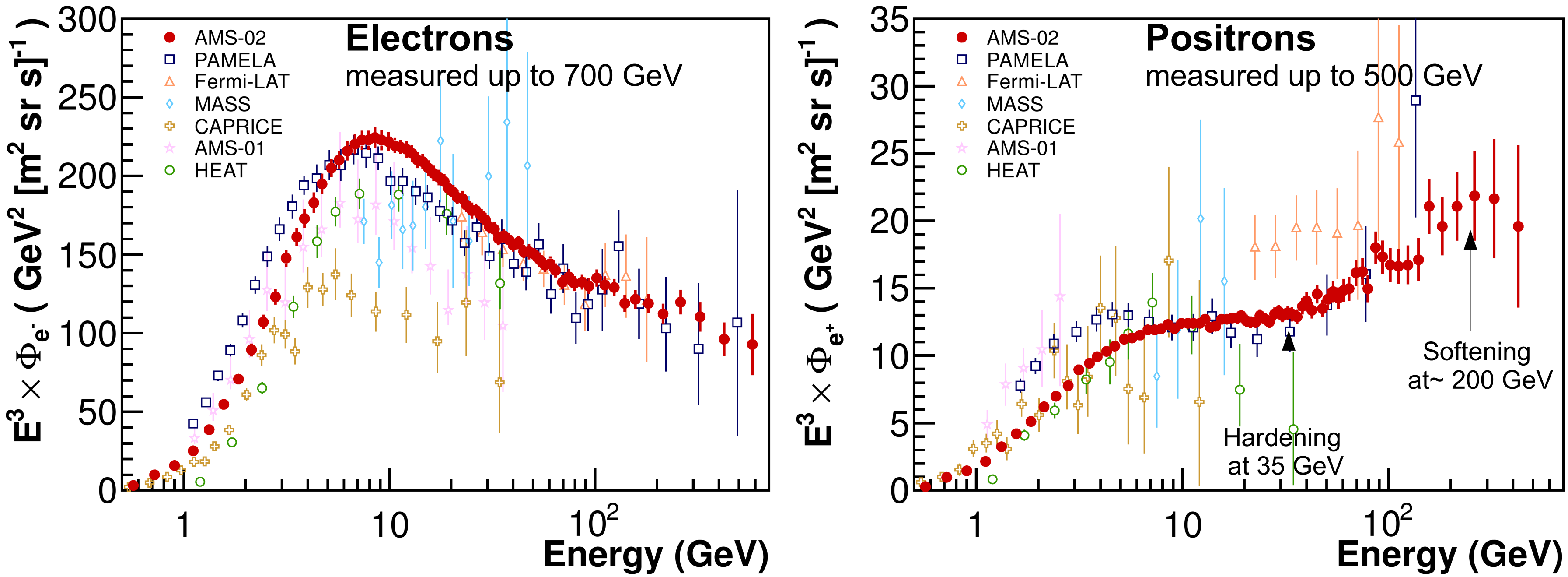
- Above 30 GeV, the $e^+ + e^-$ flux can be described by a single power law at 90% CL

- γ = -3.169 ± 0.008 (stat.+syst.) ± 0.008 (energy)



Measurement of separate e^+ and e^- fluxes

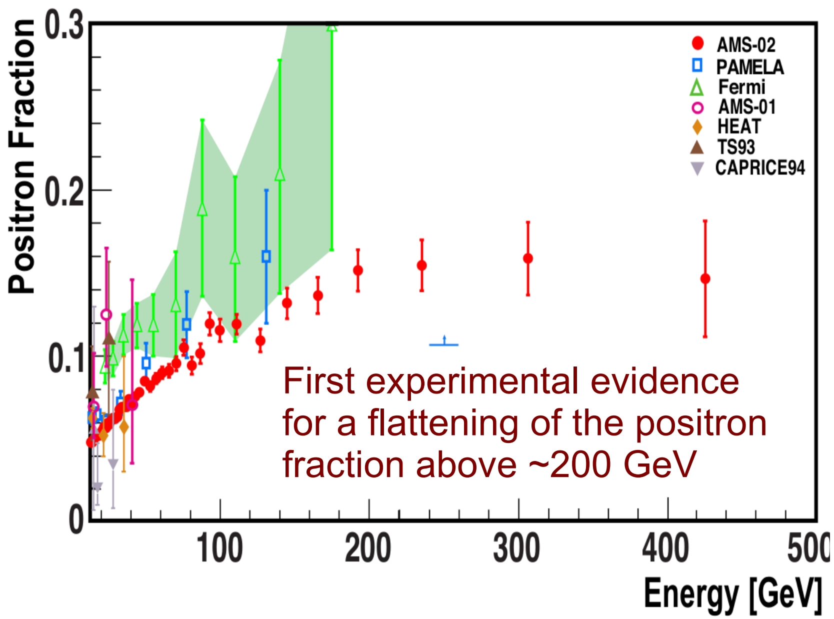
- The separate e+ and e- fluxes have been measured using 30 months of collected data

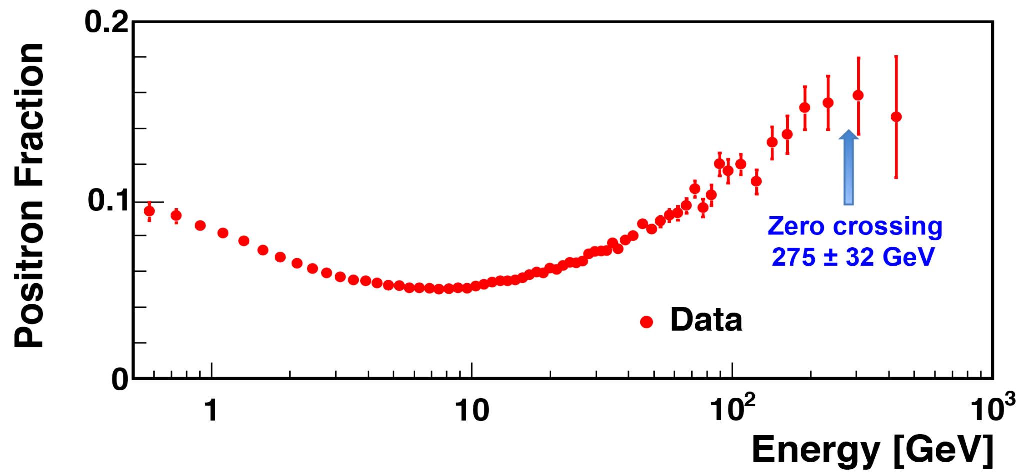


- No feature observed in the e^- flux
- The e^+ flux shows a change of slope at 35 GeV and above 200 GeV
- The e^+ flux is harder than the e- flux → the rise in the positron fraction is is due to an additional source of e^+ and not to a decrease of the e^- flux

Measurement of positron fraction $e^+/(e^++e^-)$

- The positron fraction has been updated using 30 months of collected data





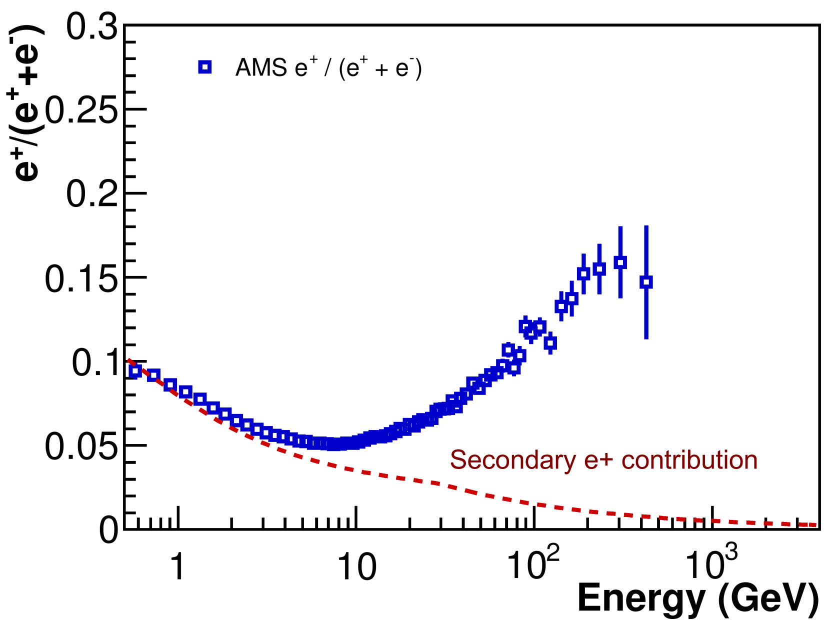
- The local fit to the slope shows that the measurement is unrevealing the maximum of the positron fraction

- The future extension of the measurement to higher energies will confirm (?) the PF drop

- The measurement is extended up to 500 GeV

The poor-experimentalist approach to data analysis

- e^-: primary particles accelerated by SRN → simple power law
- e^+: secondary produced by interaction of nucleons with the ISM → simple power law



- Such models do not describe the rise in the positron fraction.

- Additional production of primary $e^{+/-}$ by pulsar or DM annihilation can be parametrized as a power law with cutoff energy

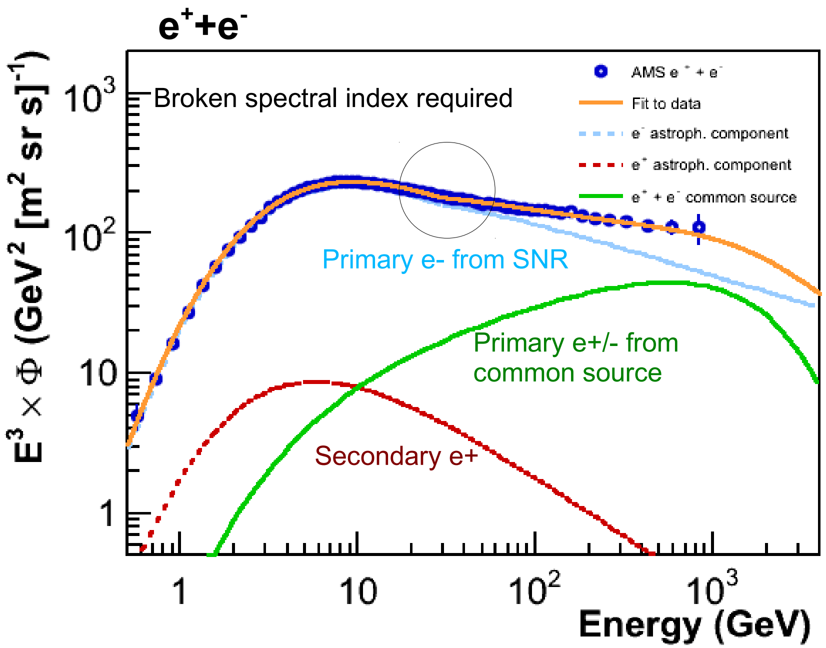
primary e^- from SNR
secondary e^+ from ISM interactions

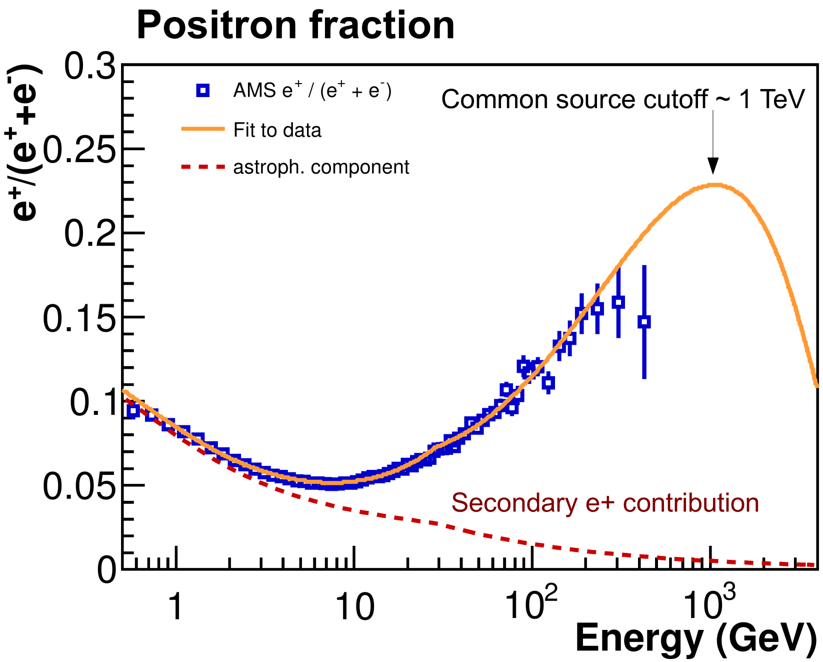
primary $e^{+/-}$ common source

$$\Phi(\mathrm{e}^{\pm}) = A\,E^{-\gamma} + C\,E^{-\gamma_c}\,e^{-E/E_c}$$

Minimal model fit to data

$$\Phi(e^{\pm}) = A\,E^{-\gamma} + C\,E^{-\gamma_c}\,e^{-E/E_c}$$



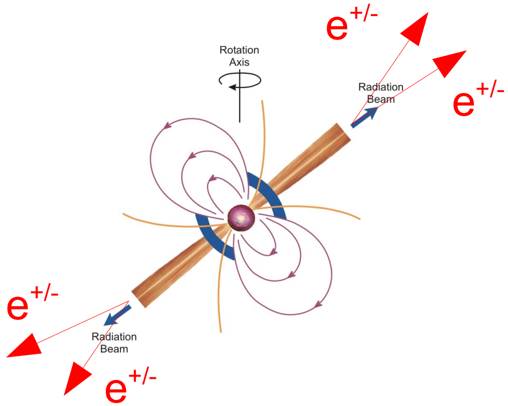


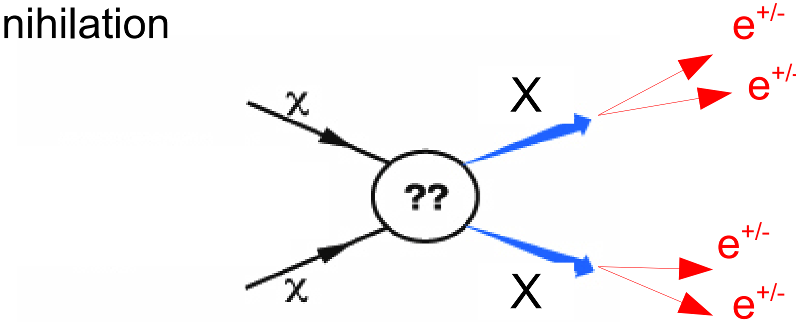
- A common source for $e^{+/-}$ dominates over the diffuse e^{+} starting at ~ 15 GeV
- The common source exhibits an expected cutoff at ~ 1 TeV, driven by the flattening of the PF

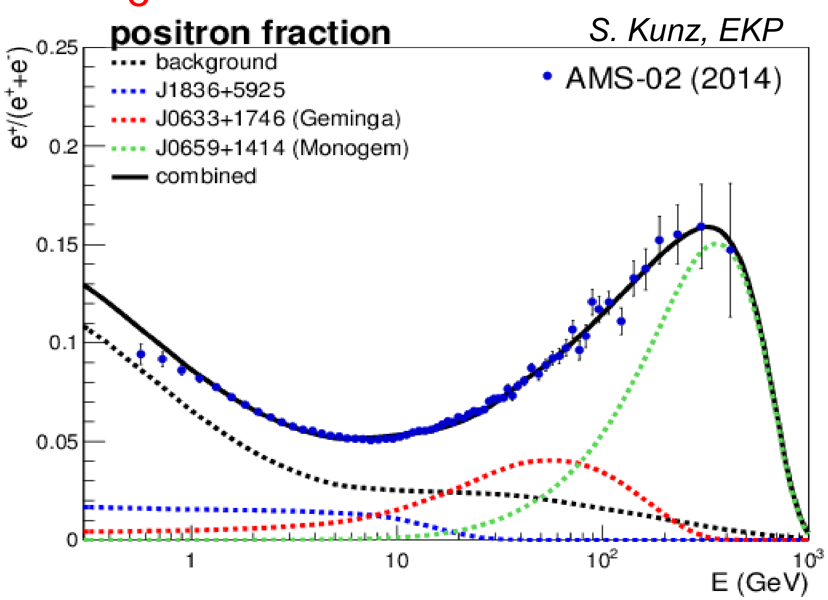
Pulsar VS Dark Matter annihilation

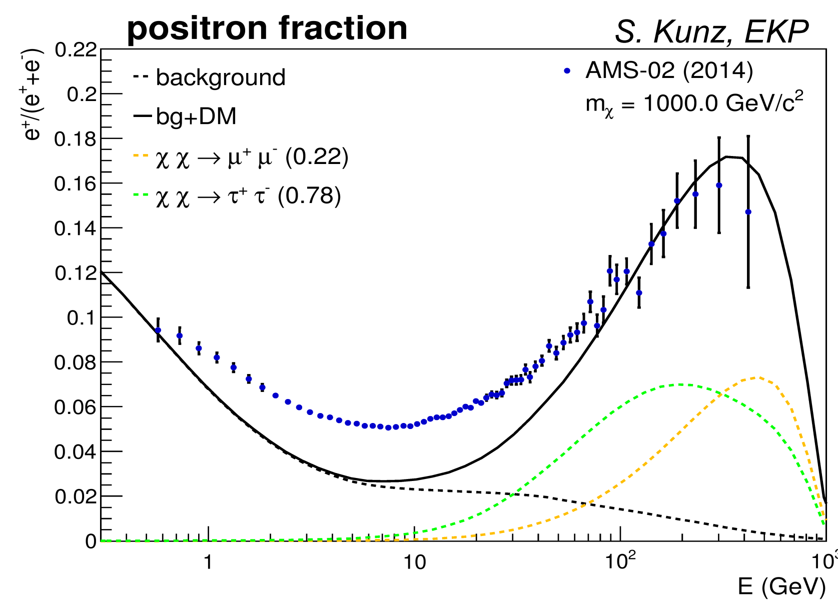
Additional contribution to the $e^{+/-}$ can be produced by

- PULSARS
- Dark Matter annihilation





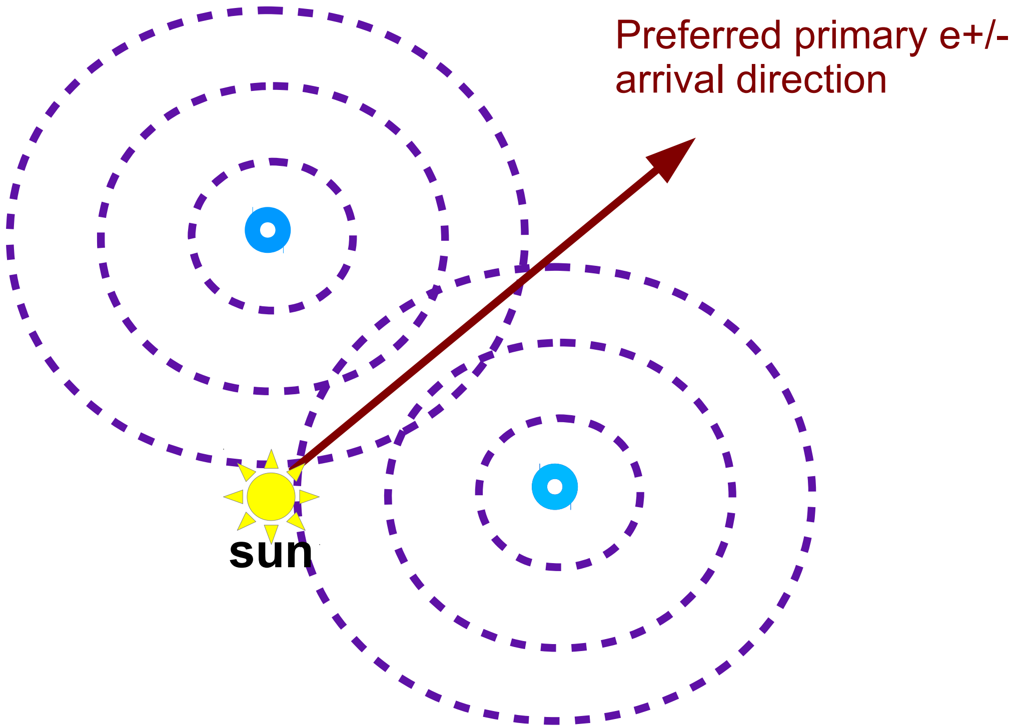




- Both mechanisms can be tuned to explain the data.
- The measurement of the spectral shape alone cannot disentangle between the two sources......

Pulsar VS Dark Matter annihilation

- **IF** the e+ excess is due to pulsar production, an anisotropy in the $e^{+/-}$ arrival direction is expected



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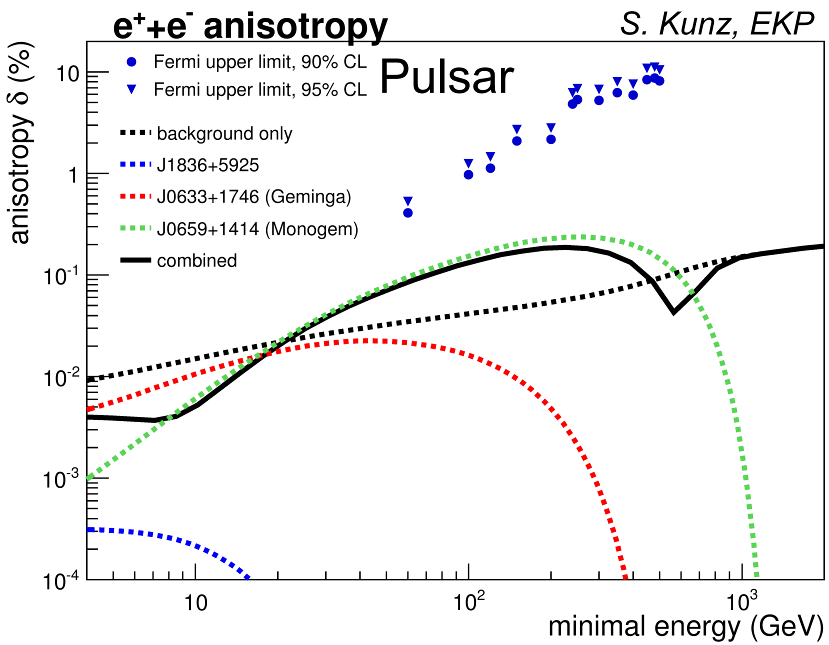

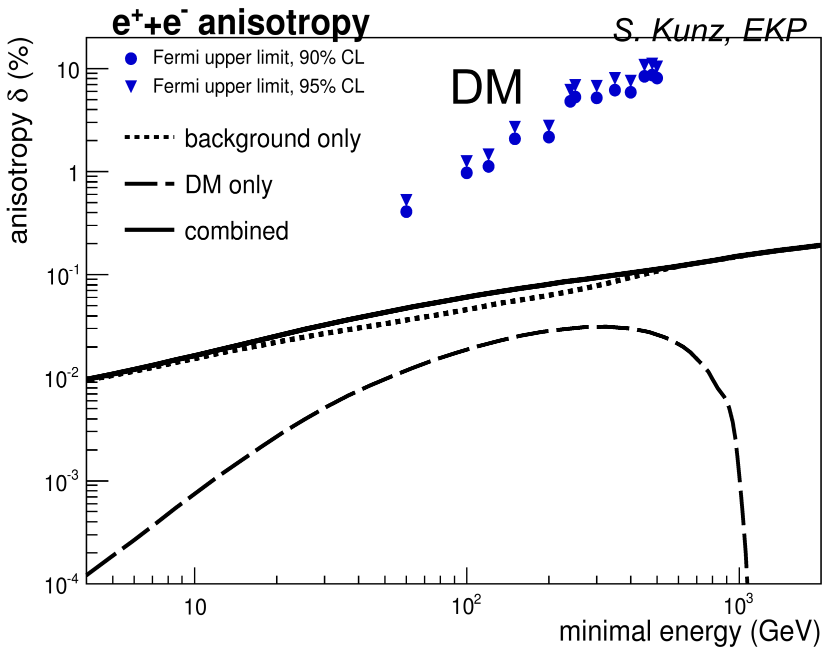

- No detected anisotropy so far
- Huge involvement of the KIT group to the anisotropy study (I. Gebauer. F. Keller, S. Kunz, C. Merx, M. Nieslony, D. Schuckardt, M. Weinreuter, S. Zeissler)

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Final Overview

AMS-02 detector has **continuously** collected ~ 42×10^9 million of cosmic particles in 30 months of data taking, in the energy range GeV to TeV.

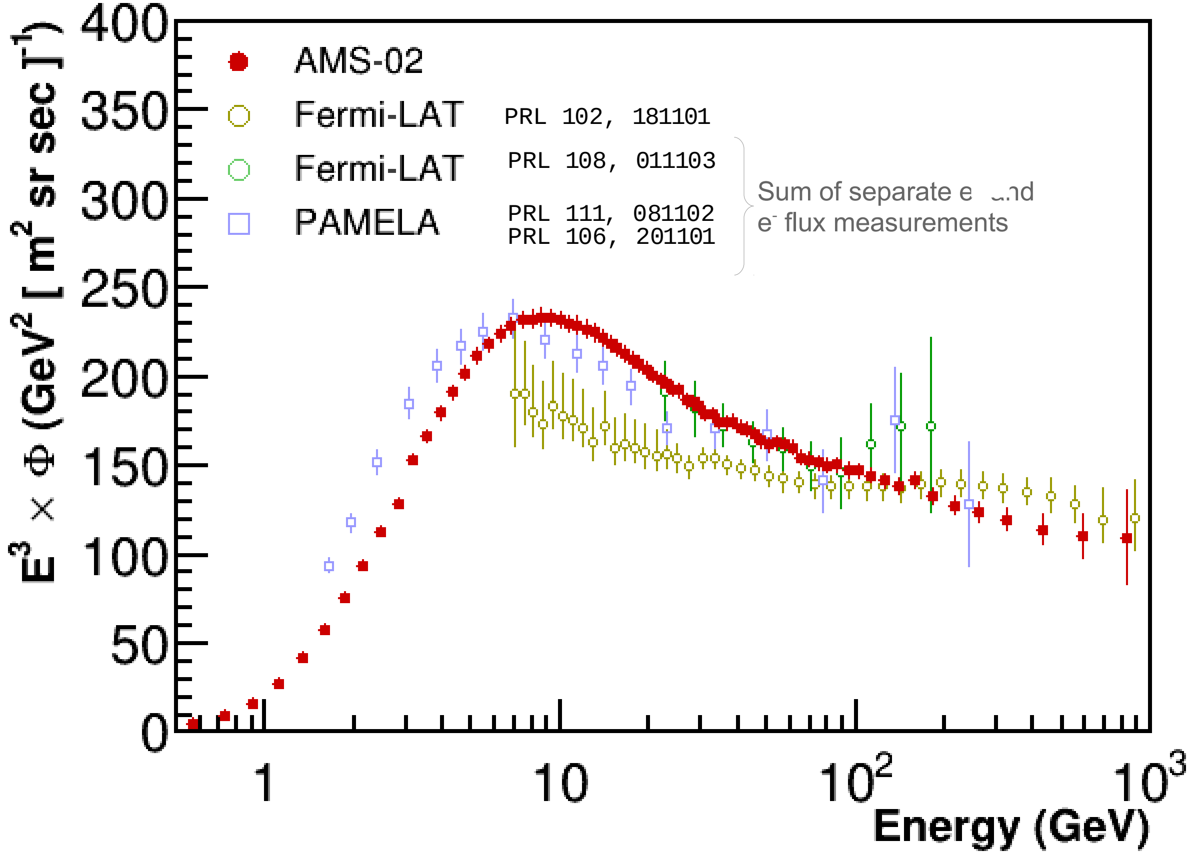
The AMS-02 particle identification capabilities and precise energy measurement allow to produce **high accuracy** cosmic flux measurements in a wide energy range.

The **$e^+ + e^-$ flux** has been measured up to 1 TeV. The latest results show **no evidence of any feature in the $e^+ + e^-$ spectrum.**

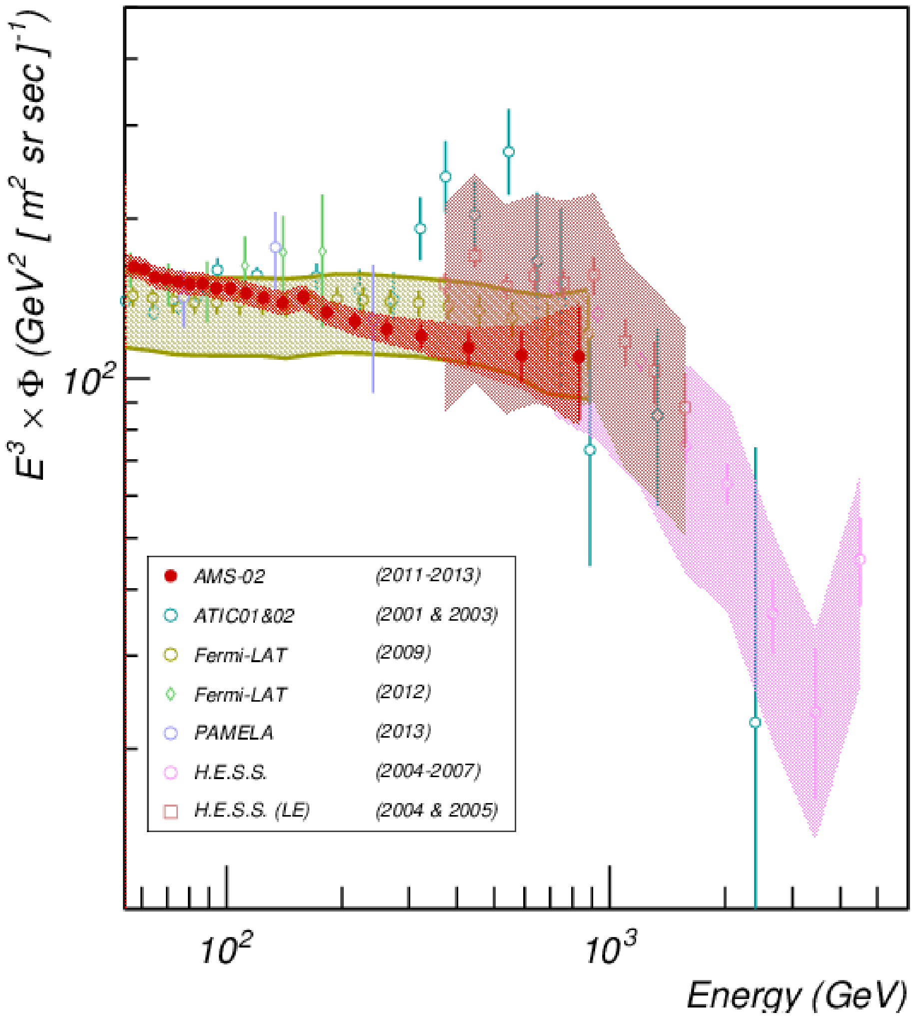
The road to solve the positron/electron origin puzzle in cosmic rays is still long....

Backup Slides

Comparison with latest space results



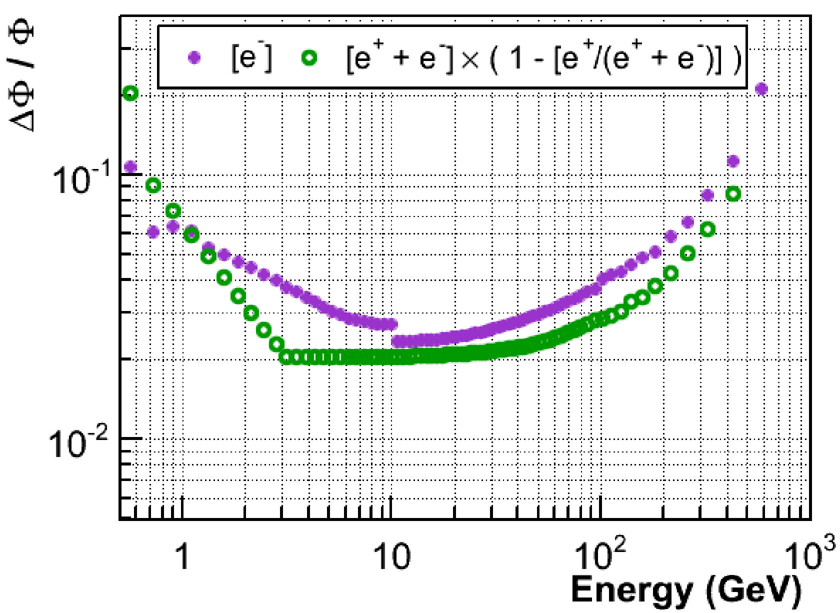
Comparison with latest results

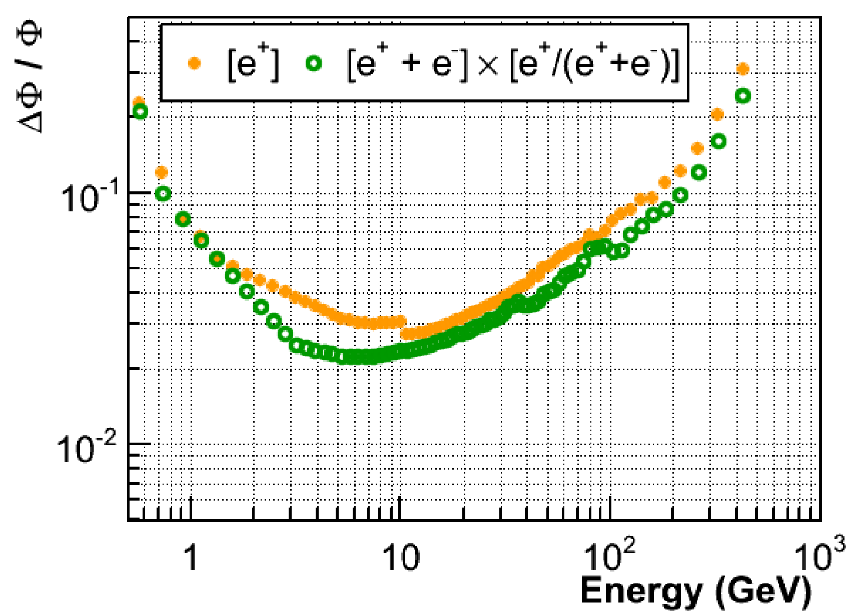


The bands represent the systematic on the flux introduced by the energy measurement scale uncertainty

Separate fluxes VS Sum flux

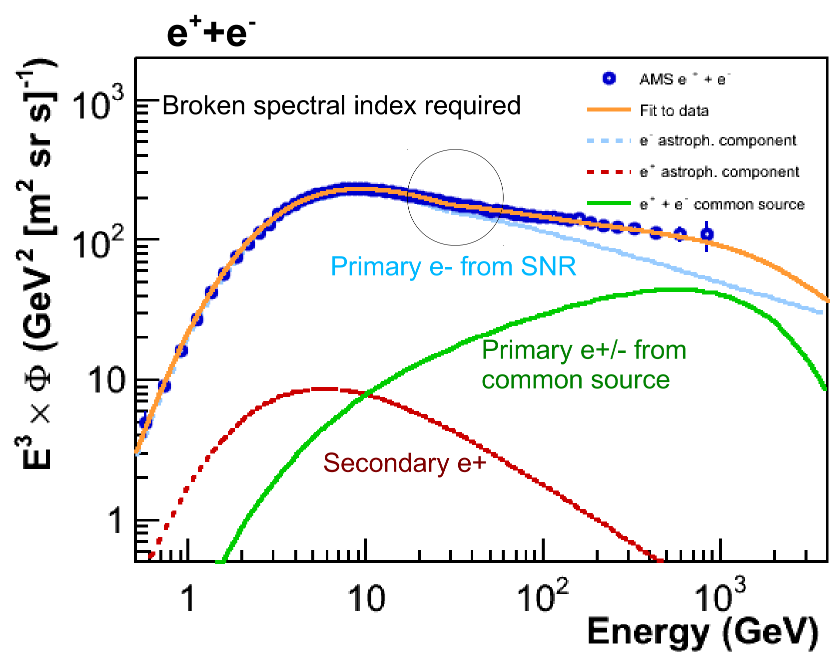
- The separate e- and e+ flux measurements need more stringent selection on the tracker quality for the charge sign identification (9.8 VS 10.6 million events)
- Additional error is introduced by the charge confusion and the uncertainty on the acceptance introduced by additional cuts
- The sum flux can be used together with the PF measurement to derive the separate e+ and e- fluxes with better accuracy

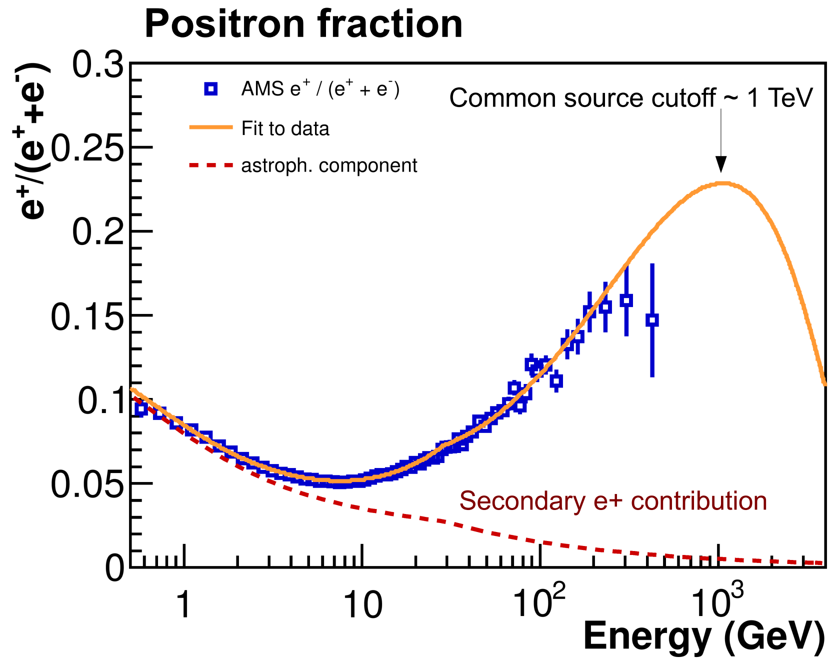




Minimal model fit to data

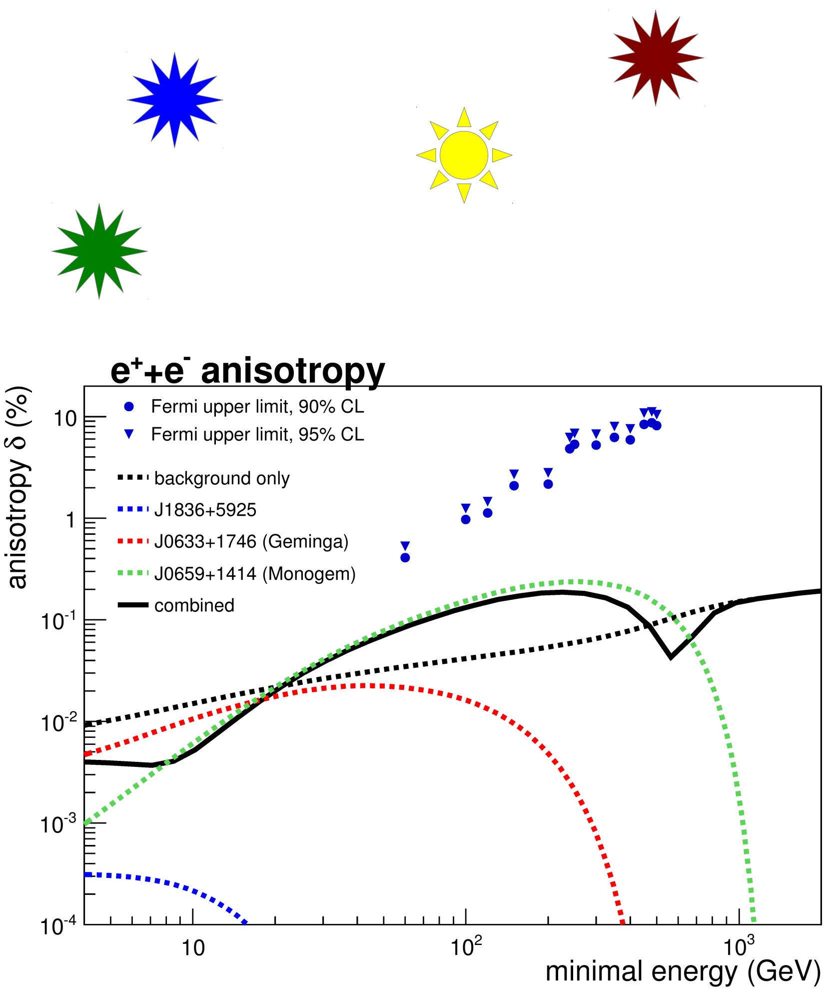
$$\Phi(e^{\pm}) = A\,E^{-\gamma} + C\,E^{-\gamma_c}\,e^{-E/E_c}$$

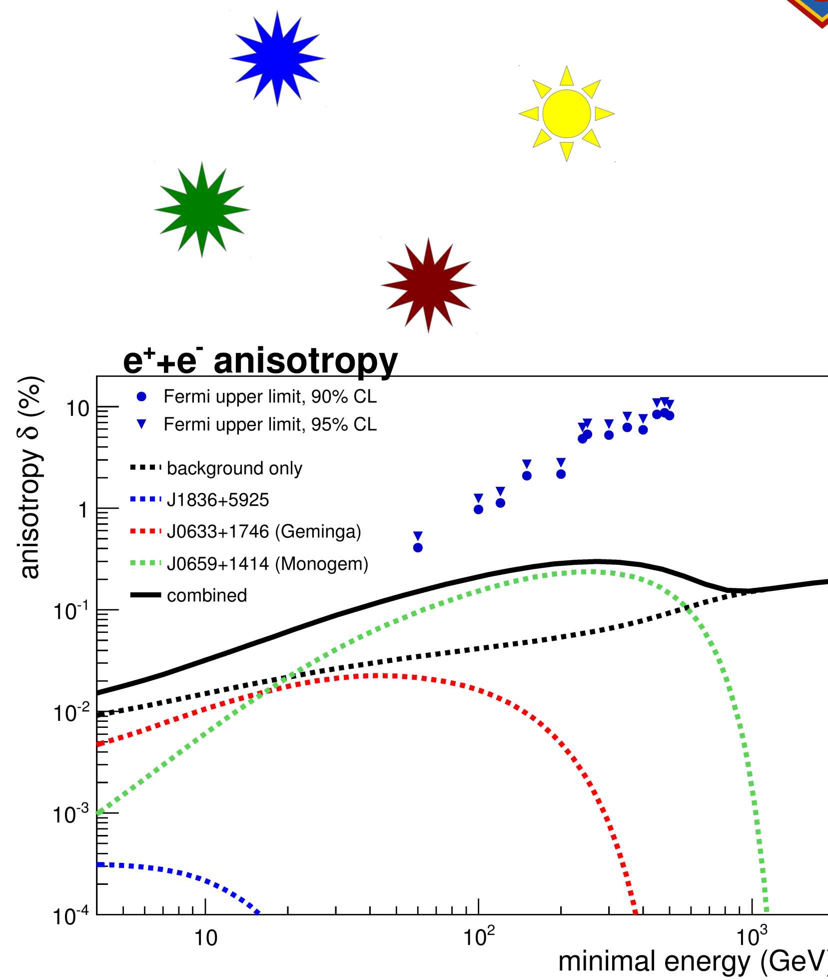




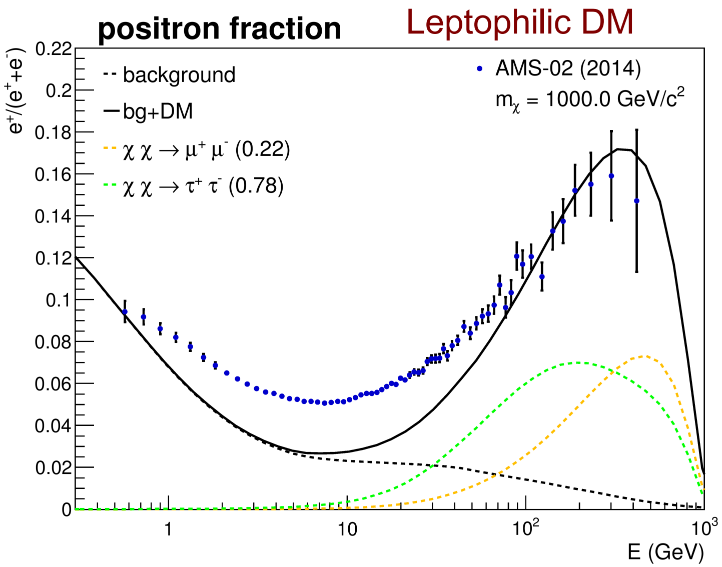
χ^2 / ndf	71.92 / 129	
Prob	1	
A ele	2148 ± 141.2	e- flux normalization
γ ele (a)	3.702 ± 0.01904	e- flux spectral index (below energy break)
E ele (break)	28.96 ± 1.008	e- spectral index energy break (GeV)
γ ele (b)	3.39 ± 0.01072	e- flux spectral index (above energy break)
A pos	99.7 ± 17.23	e+ flux normalization
γ pos	3.862 ± 0.1026	e+ spectral index
A common	2.535 ± 1.13	common source normalization
γ common	2.589 ± 0.103	common source spectral index
$1/E_{co}$	0.0007451 ± 0.0005984	common source energy cutoff (inverse) (1/TeV)
ϕ ele	1.262 ± 0.03224	e- effective solar potential (GV)
ϕ pos	0.9881 ± 0.0453	e+ effective solar potential (GV)

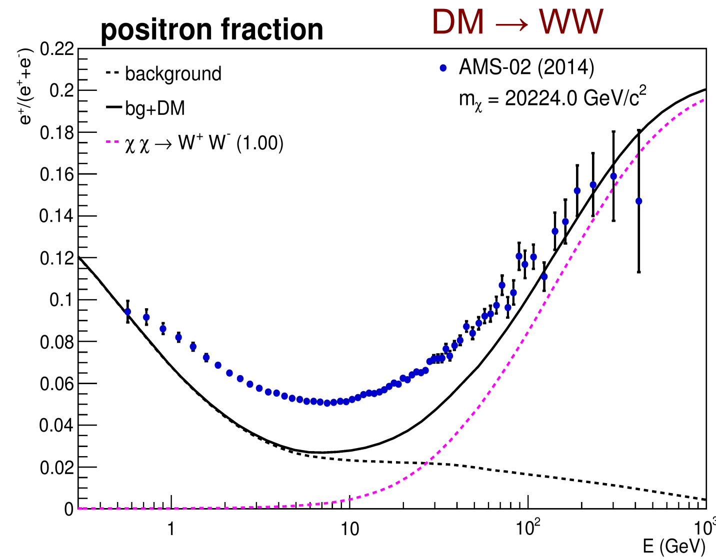
Pulsar anisotropy

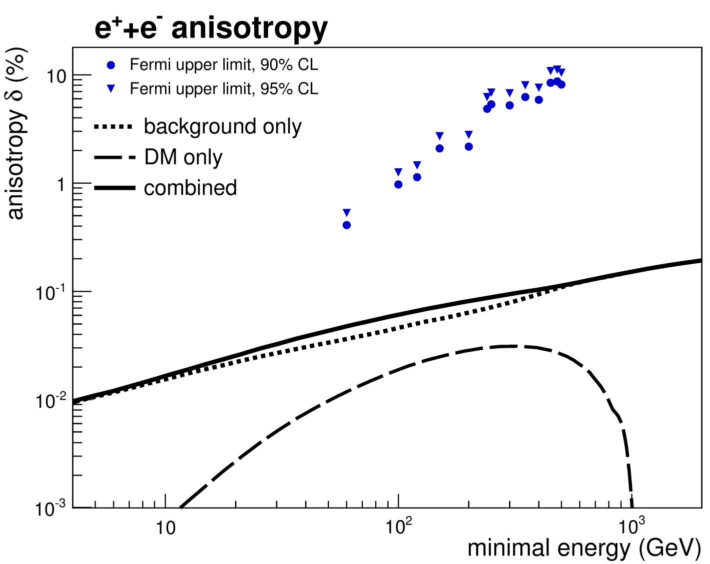


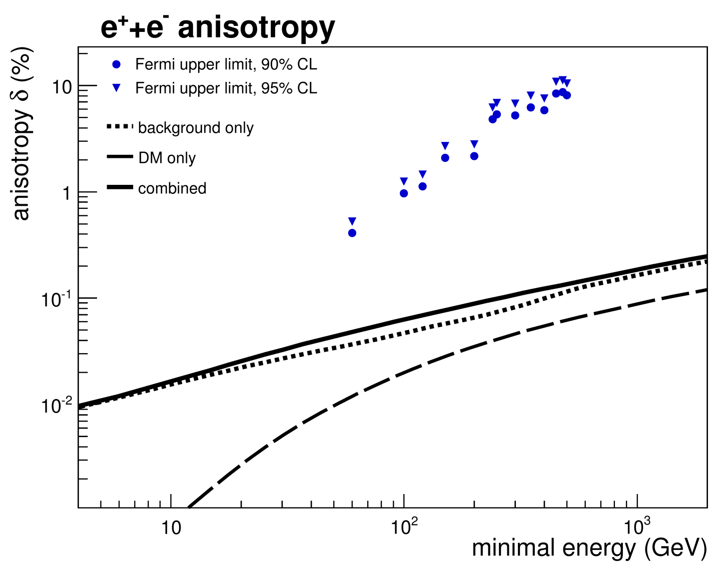


Dark Matter Positron Fraction

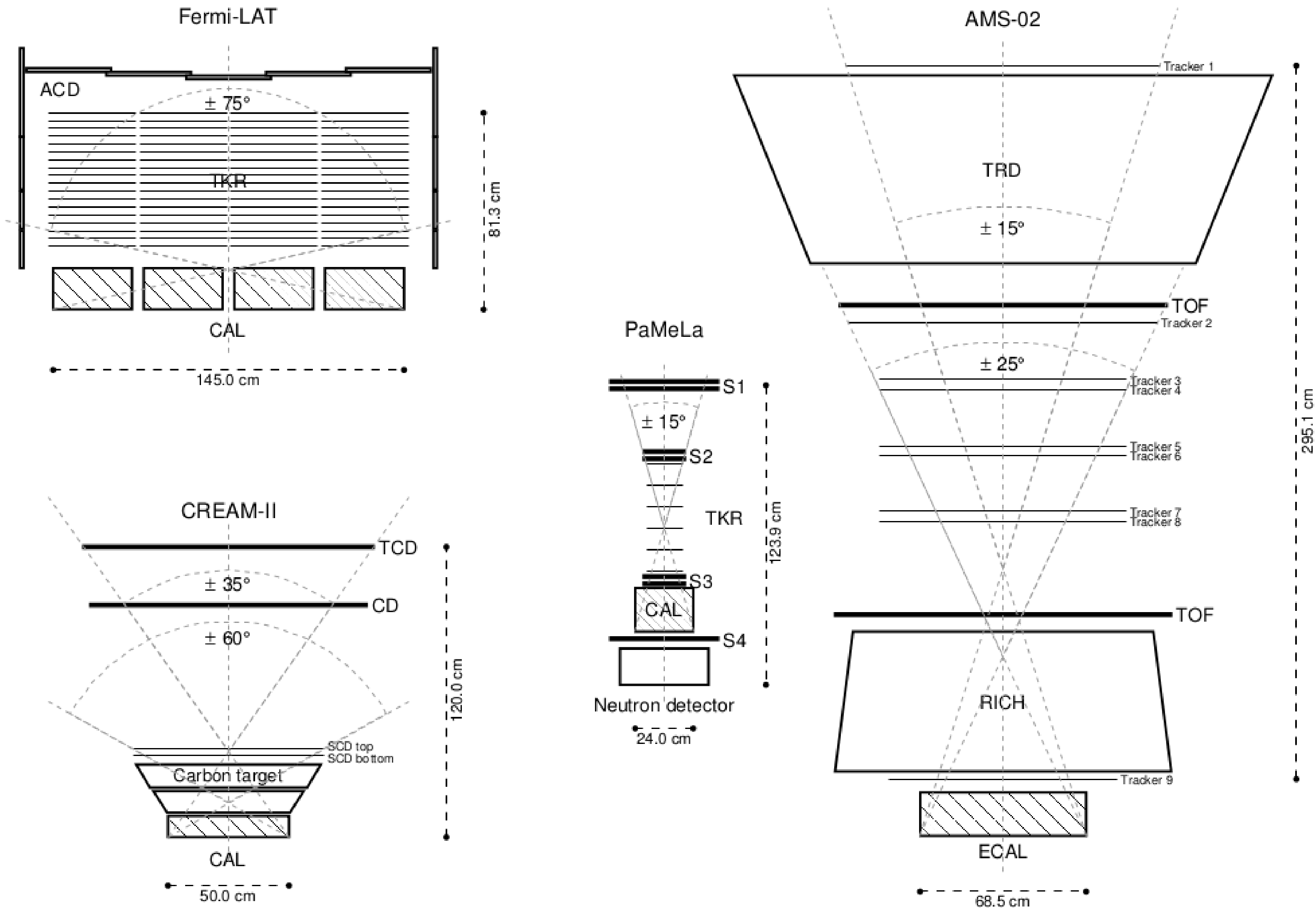




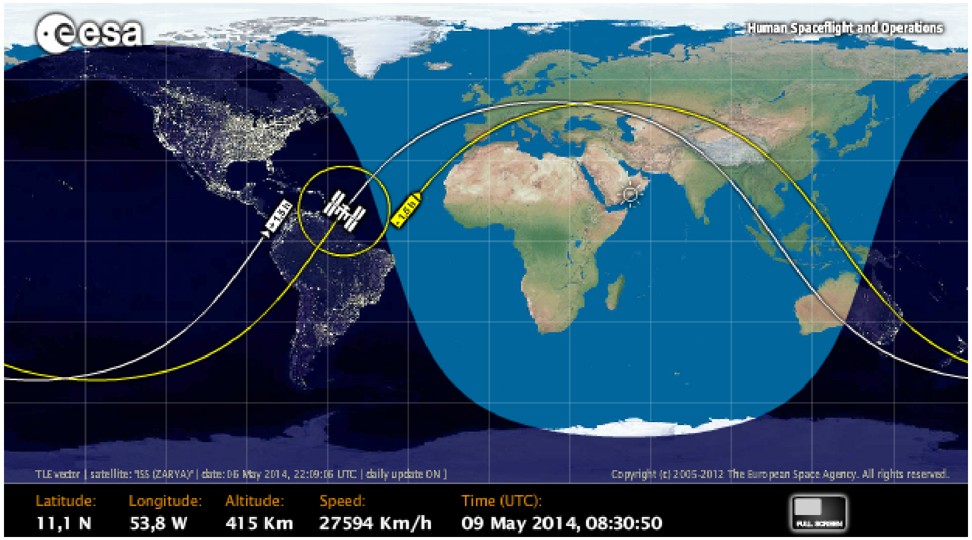




AMS-02 detector



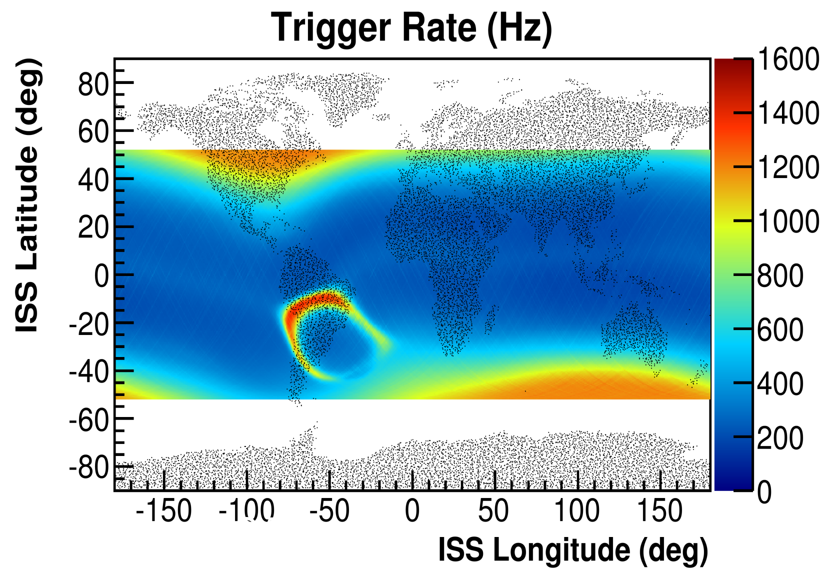
AMS orbit



ISS orbit period ~ 90min
+/- 50 deg latitude covered

DAQ operations depend on orbit position

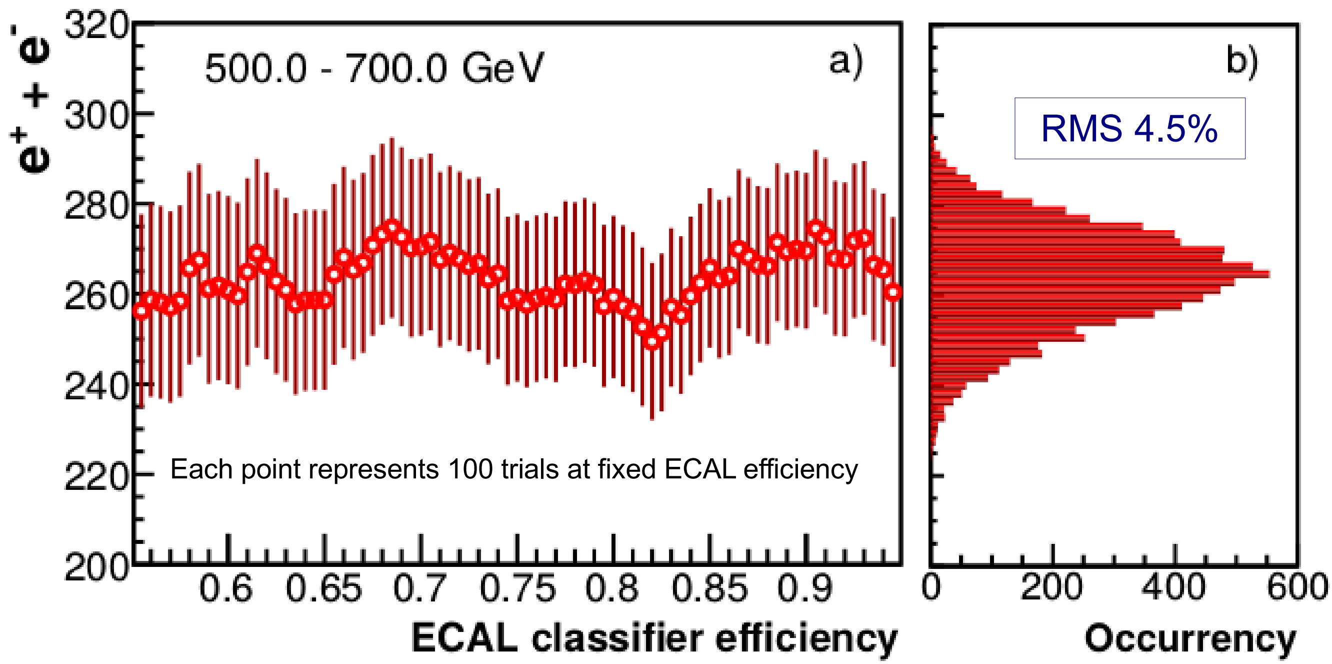
Increase of trigger rate in polar region (low magnetic field and trapped particles) and in the South Atlantic Anomaly



Detector operated continuously around the clock since May 2011 with no major interruptions

Signal Selection Systematic

Effect of calorimetric selection, efficiency calculation, template definitions



Systematic error due to the spread of the results in a wide sample of different analyses

- For each energy bin, ~O(10,000) analyses are performed varying all possible parameters
- Signal selection systematic negligible under 200 GeV.
- The result is robust up to the TeV energy.

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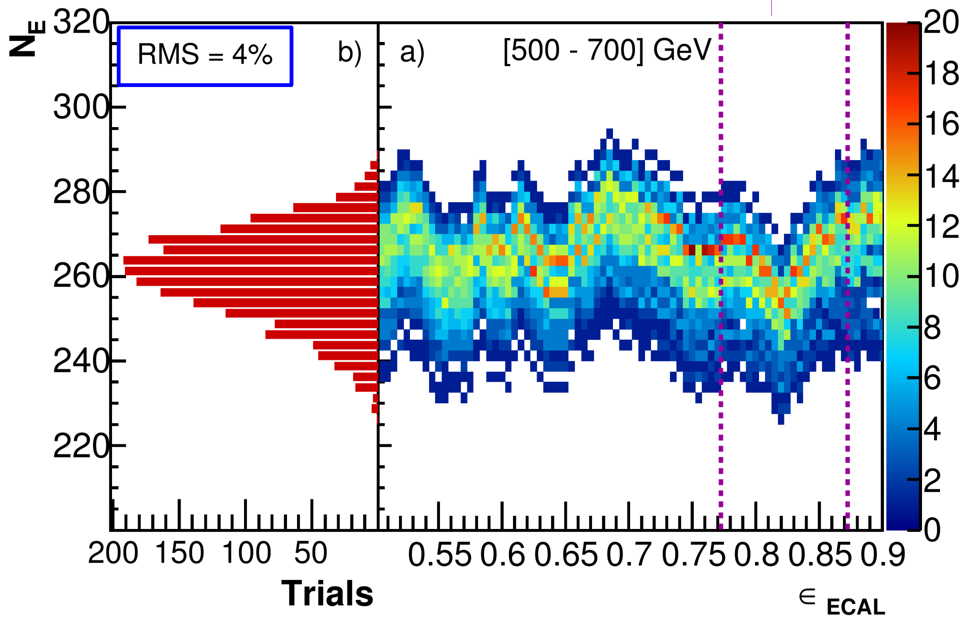
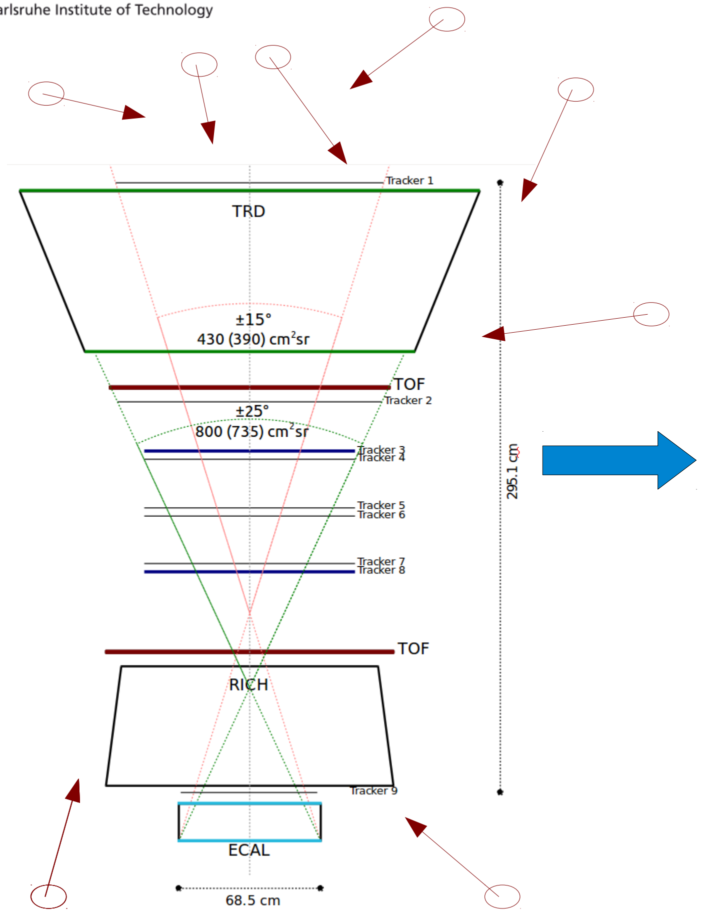
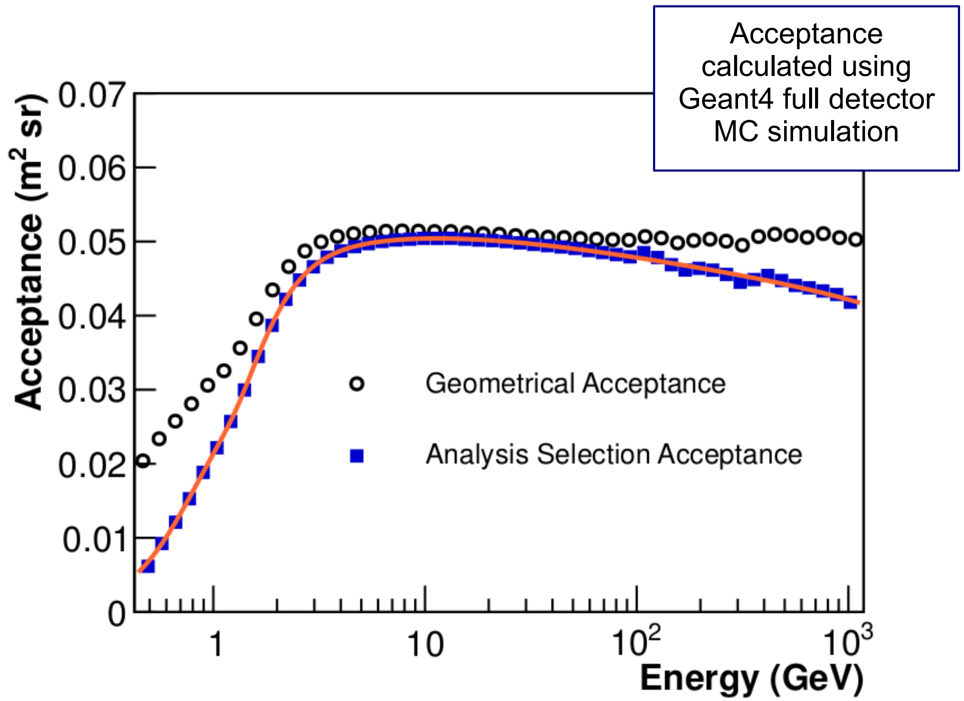


The signal is evaluated in the window with minimum statistical and systematic uncertainty

- For each energy bin, ~O(10,000) analyses are performed varying all possible parameters
- Signal selection systematic negligible under 200 GeV.
- The result is robust up to the TeV energy.

Acceptance

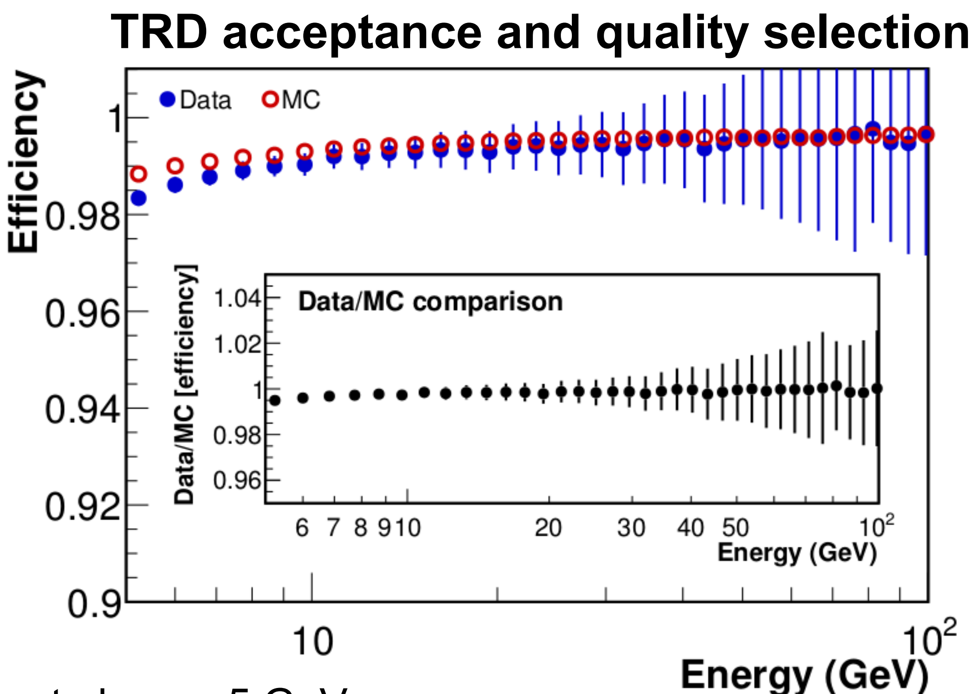




- Geometrical acceptance plateau at 500 $cm^2 sr$ defined by calorimeter volume
- **Very efficient particle selection** does not suppress the acceptance, even at high energies

Acceptance Systematic

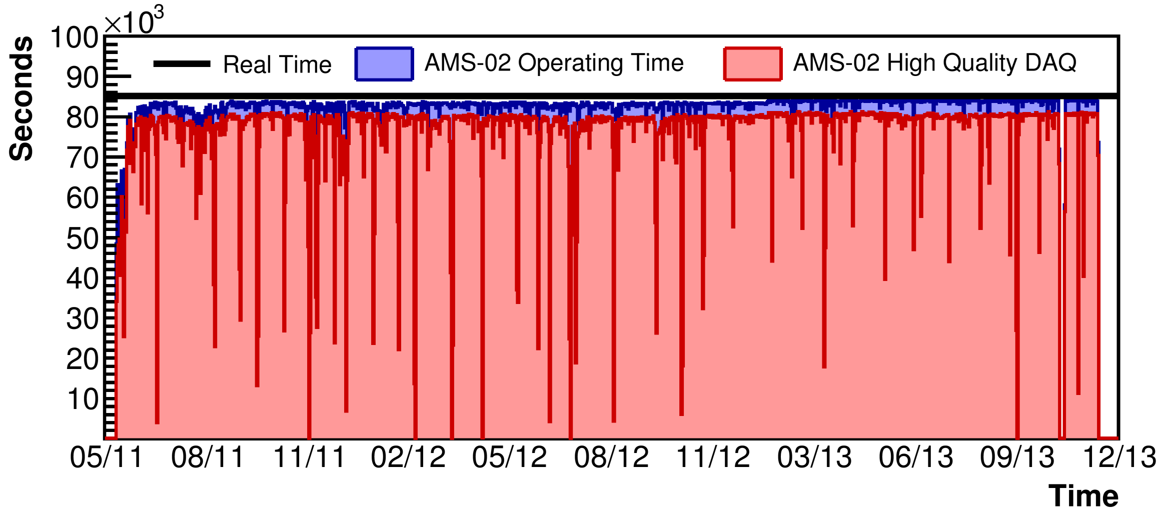
- For **every selection cut** and for **trigger**, acceptance systematics is assessed by comparing the effect of selection on data and MC



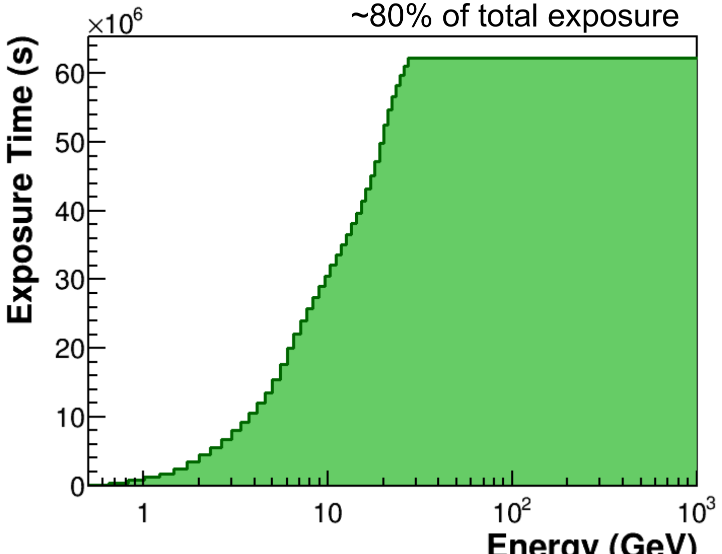
- Very good agreement above ~5 GeV
- Any deviation contributes to the final systematic

A global systematic from acceptance evaluation of few % from all the analyses cuts contributes to the measurement uncertainty

AMS-02 Exposure



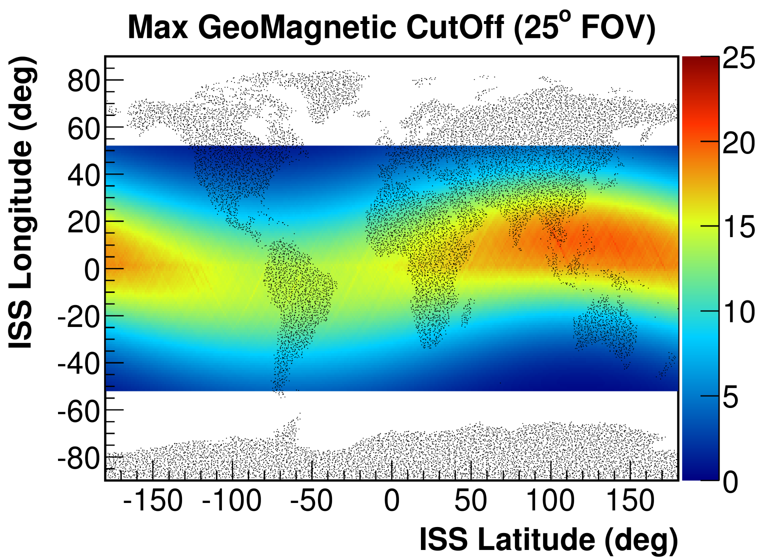
~62x10^6 s analyzed
~80% of total exposure



- 41x10^9 recorded events analyzed for the lepton fluxes

- Secondaries trapped in the geomagnetic field are rejected
  → Exposure time is energy dependent

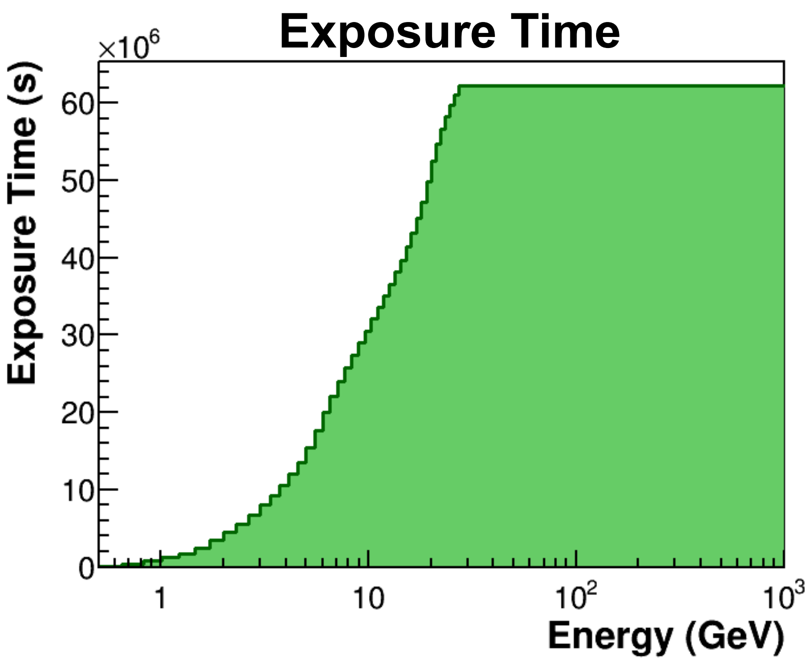
AMS-02 Exposure



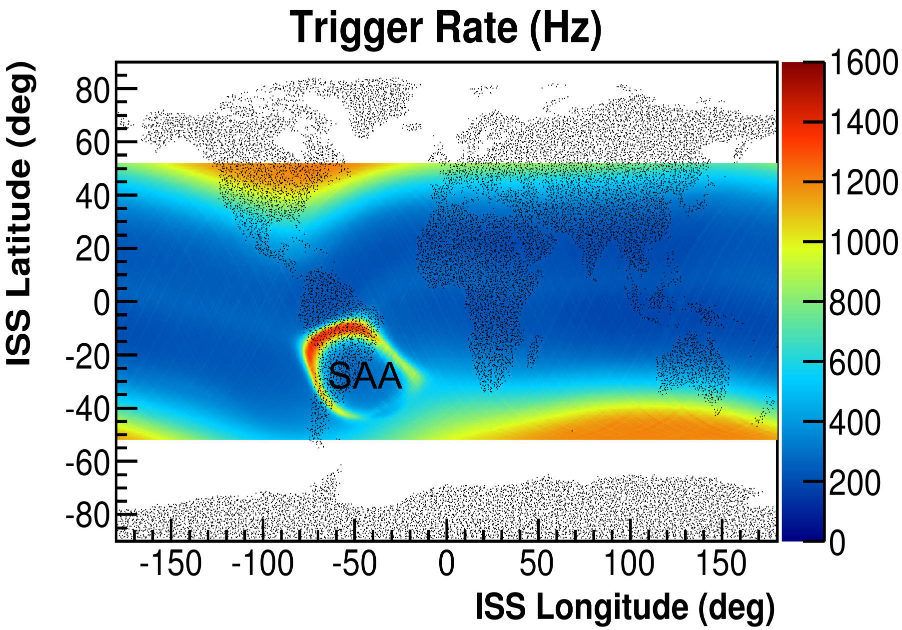
- Secondaries trapped in the geomagnetic field are rejected
  → Exposure time is energy dependent

- $41x10^9$ recorded events analyzed for the lepton fluxes

- ~$62x10^6$ seconds analyzed (~80% total exposure)

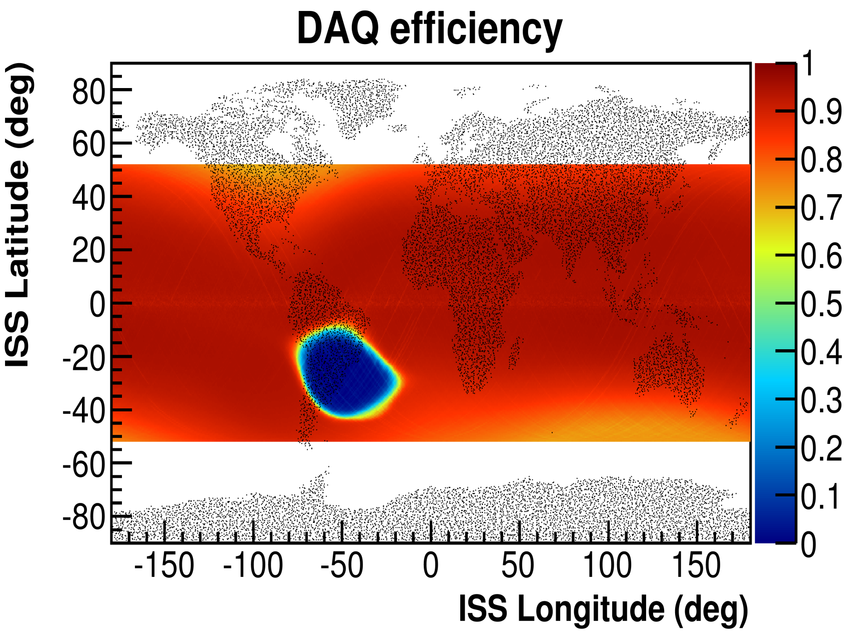


AMS orbit



Average DAQ efficiency ~ 88%
Average downlink 17 Mbps

Orbit period 90 mins
Equator trigger rate ~ 200 Hz
Polar trigger rate ~ 1500 Hz
Average trigger rate ~ 600 Hz



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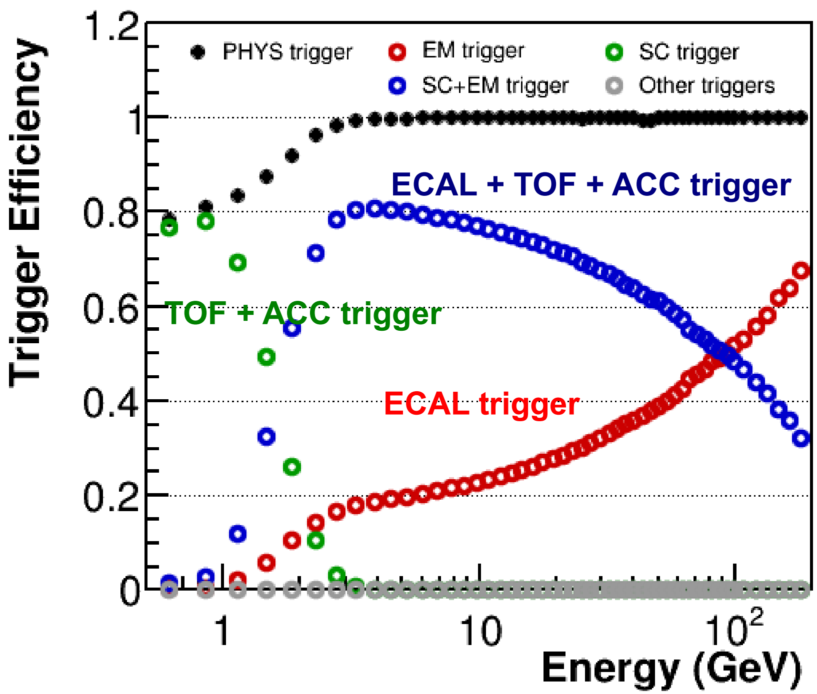
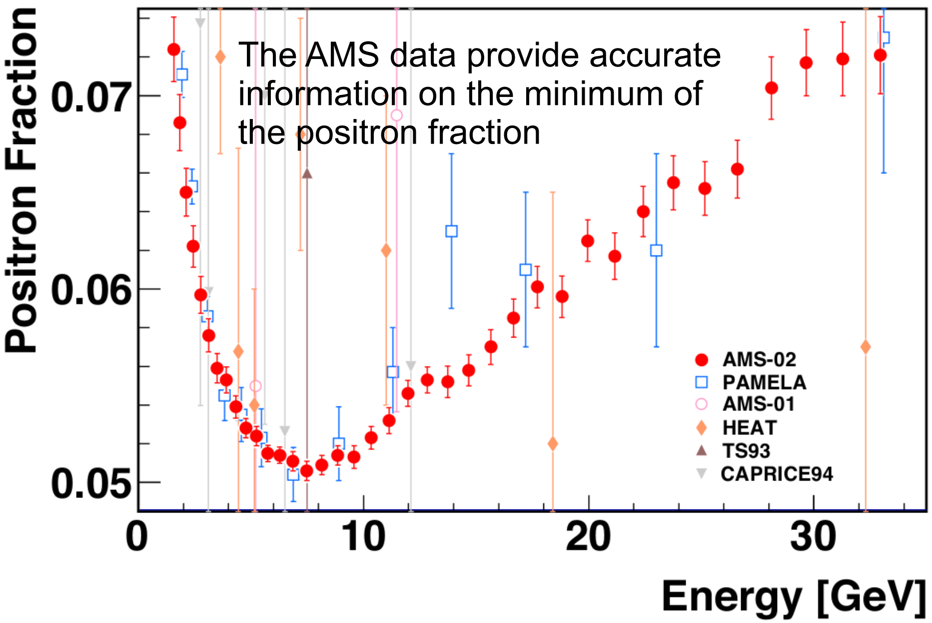
Trigger

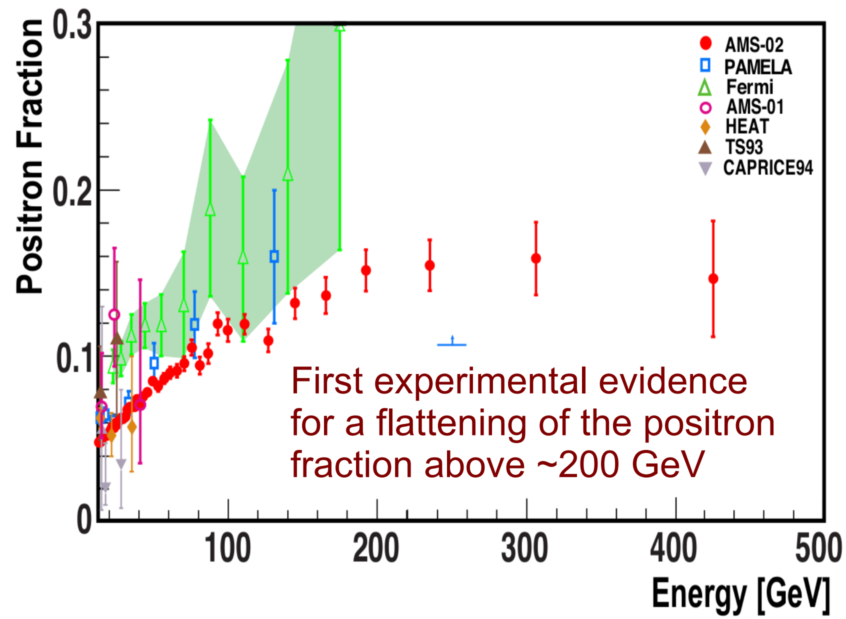


- Trigger efficiency measured from data using a dedicated, loose trigger channel
- The combination of TOF and ECAL trigger allows to achieve **100% trigger efficiency above 4 GeV**

Measurement of positron fraction

- The positron fraction has been updated using 30 months of collected data

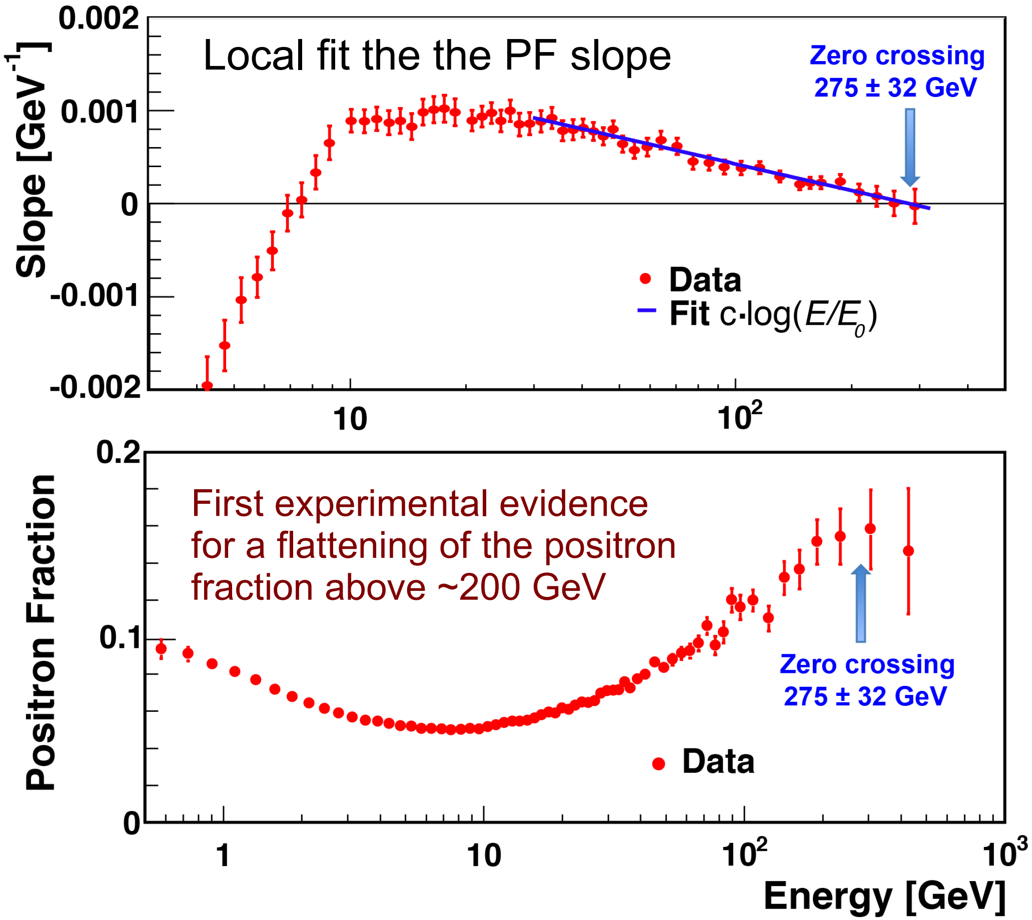




- The measurement is extended up to 500 GeV
- The e+/e- ratio arrival direction consistent with isotropy, with a dipole anisotropy upper limit $\delta < 0.03$ @ 95% CL above 16 GeV

Measurement of positron fraction

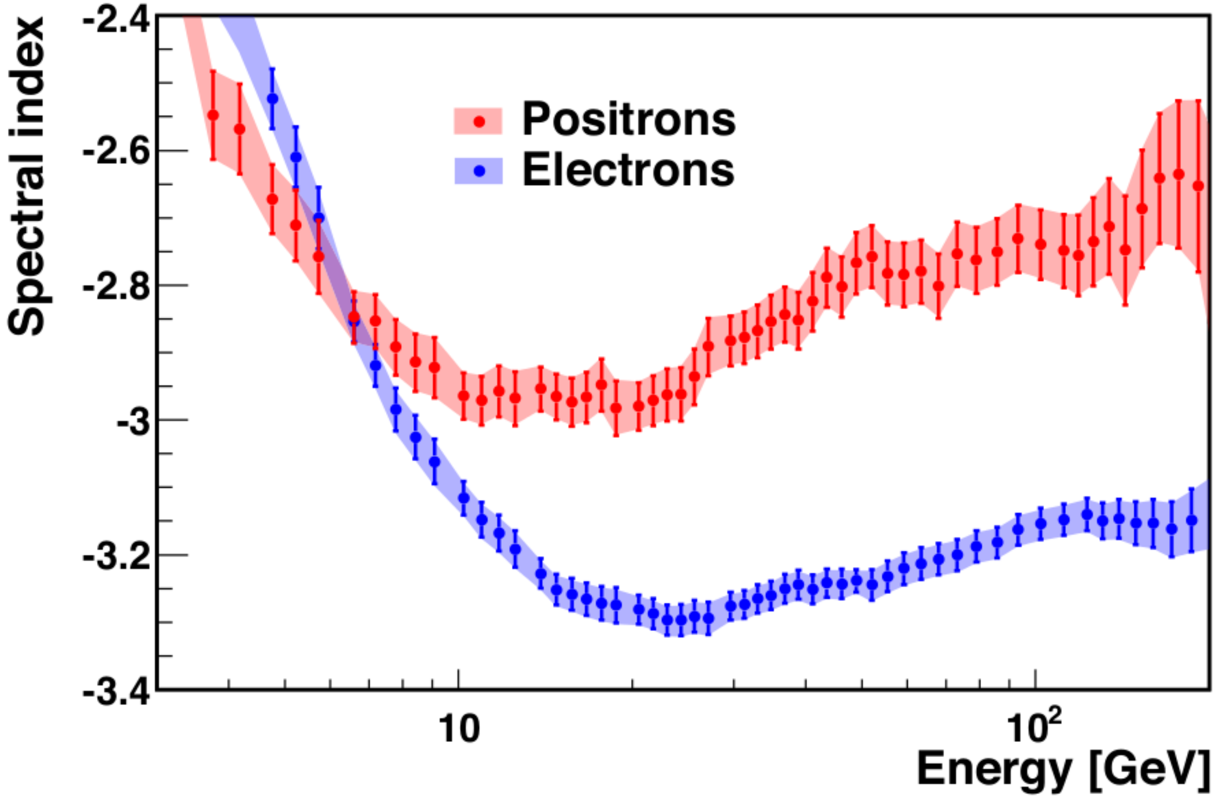
- The positron fraction has been updated using 30 months of collected data



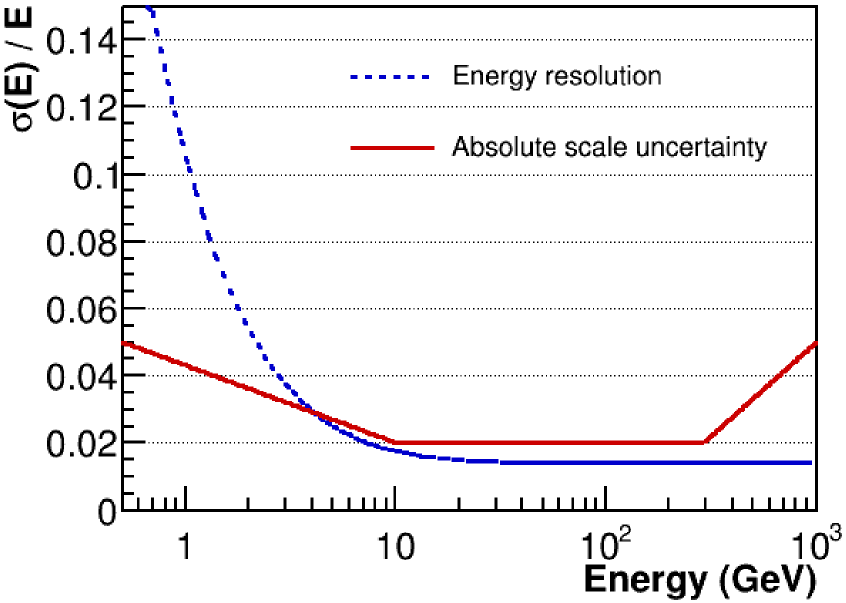
- The local fit to the slope shows that the measurement is unrevealing the maximum of the positron fraction

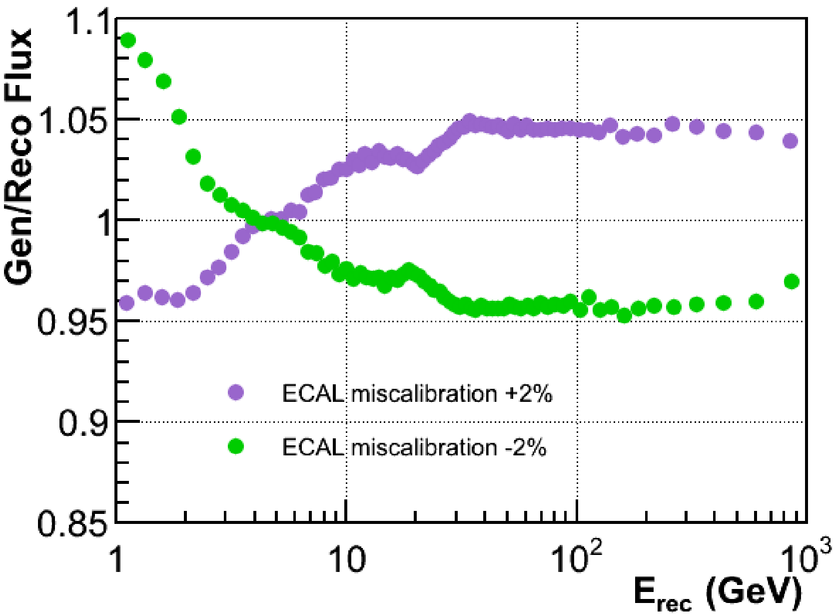
- The future extension of the measurement to higher energies will confirm (?) the PF drop

Electron and positron spectral indexes



ECAL miscalibration effect

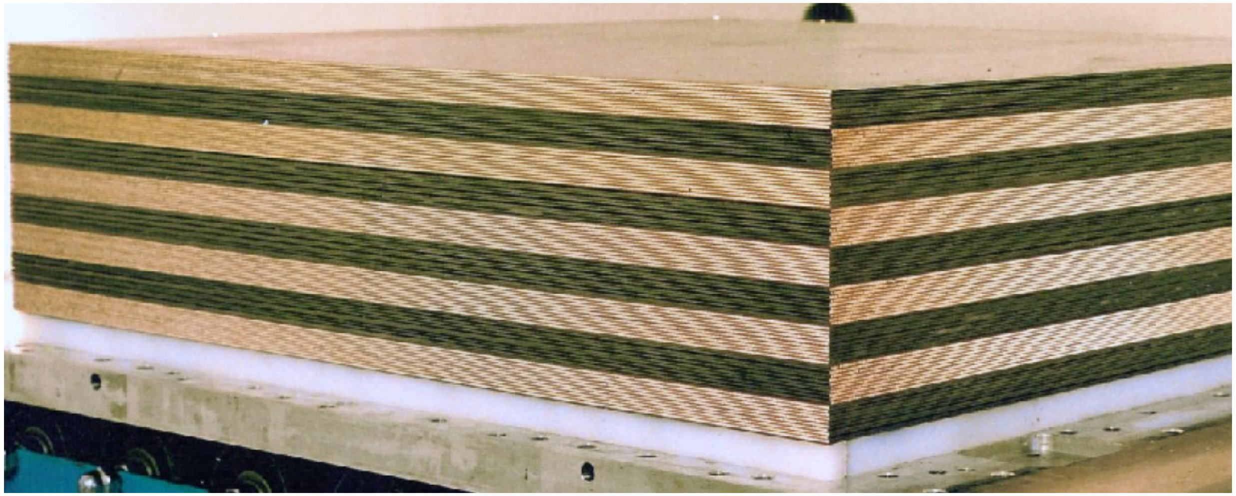




- ECAL miscalibration effect studied using MC.

- Rule of thumb: systematic on the flux ~ 2x systematic on the energy measurement

Electromagnetic Calorimeter ECAL

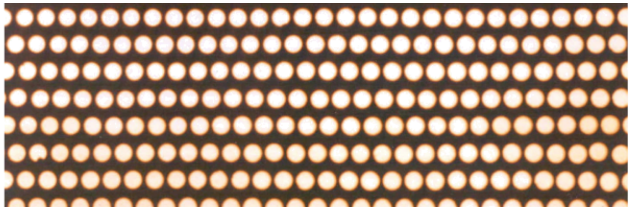


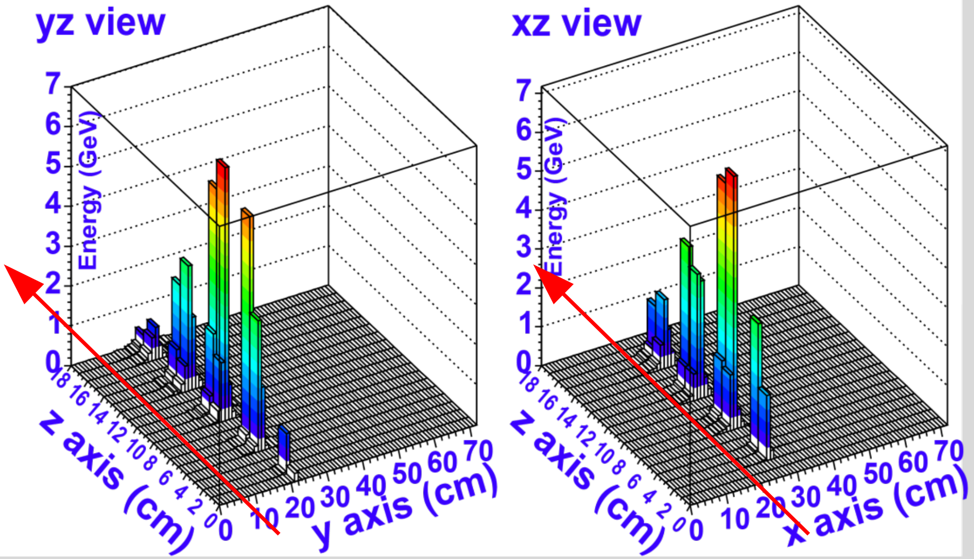
Sampling calorimeter
Lead (58%), scintillating fibers (33%), optic glue (9%)

658x658x167 mm, 18 Layers
(**17 X0, 0.6** λ_{nuc})

1296 readout cells

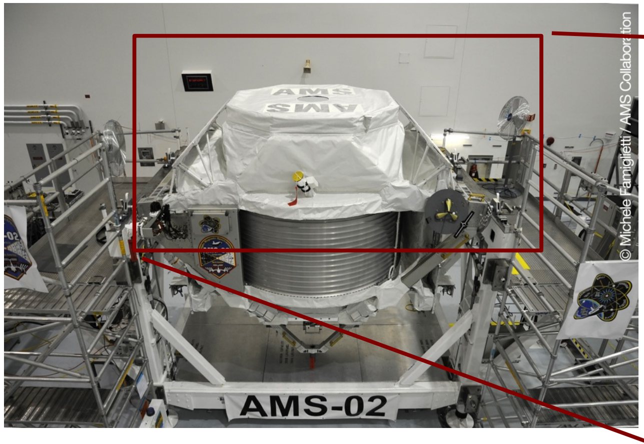
1 superlayer

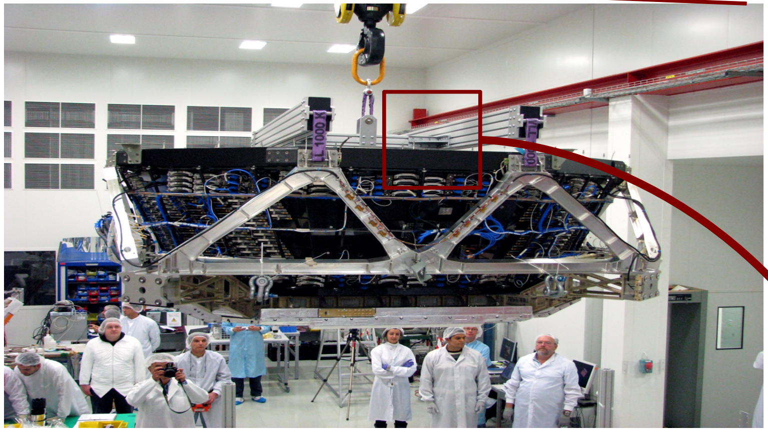


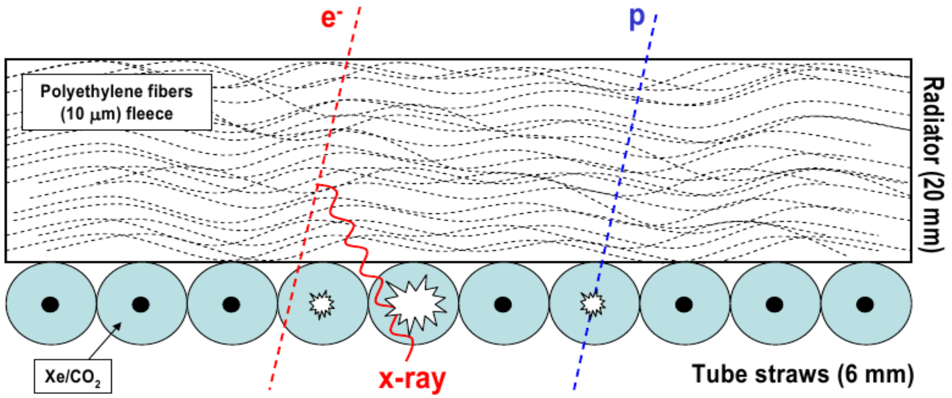


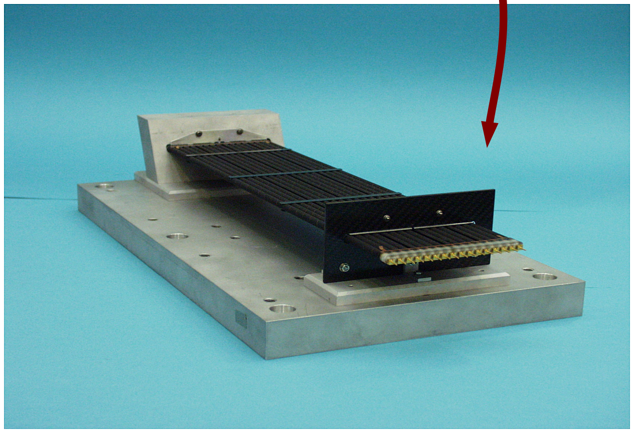
Energy and arrival direction measurement of electrons and photons up to 1 TeV

TRD Transition Radiation Detector





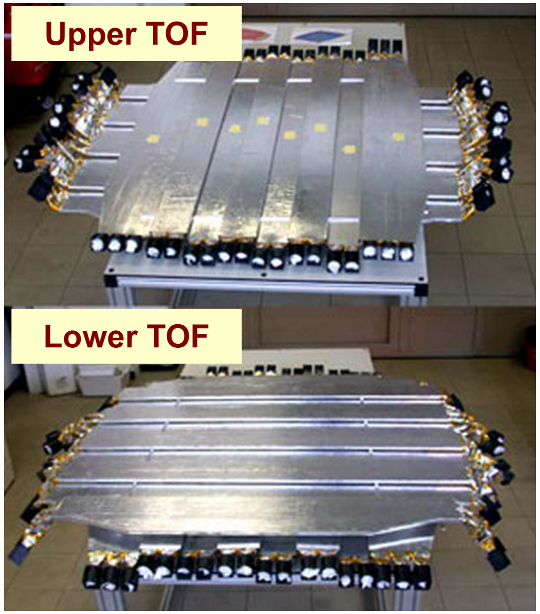




20 layer of radiator (fleece) and straw tubes for Xrays (~KeV) detection

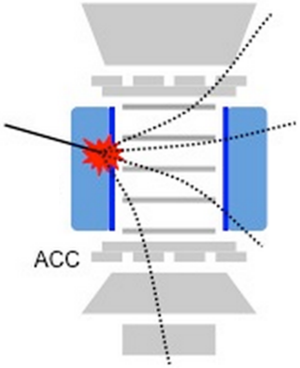
5,248 tubes selected from 9.000, 2 m length centered to 100μm, verified by CAT scanner

TOF Time Of Flight



4 scintillator planes (2 above,2 under magnet)
8-10 paddles / plane
2/3 readout PMTs in each end
Fine mesh PMTs + tilted guide lines to reduce the effect of stray magnetic field

The TOF provides to AMS-02
– Fast trigger to charged particles through different thresholds
– Time-Of-Flight dT (res ~160ps) to determine velocity with few % resolution
– Particle charge Z up to Z=15
– Upgoing/downgoing discrimination ~ 10^{-9}

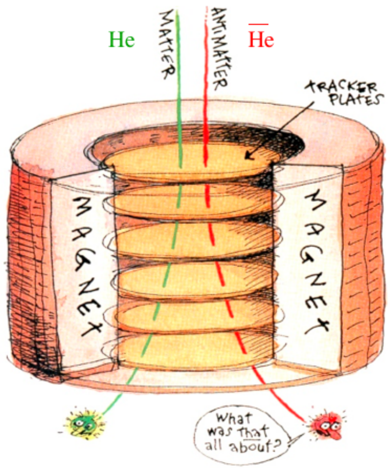


ACC – Anticoincidence Counters

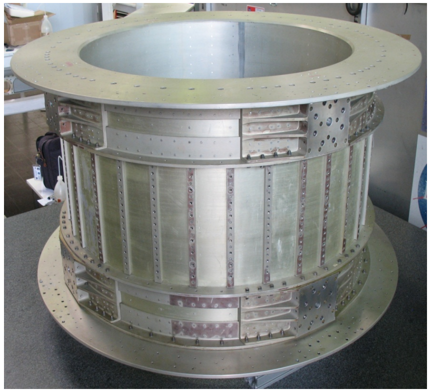
16 paddles placed around the magnet.
Same scintillator/PMT technology as TOF
Used as VETO for particles outside AMS-02 Field Of View

Permanent Magnet

Fundamental for matter/antimatter discrimination

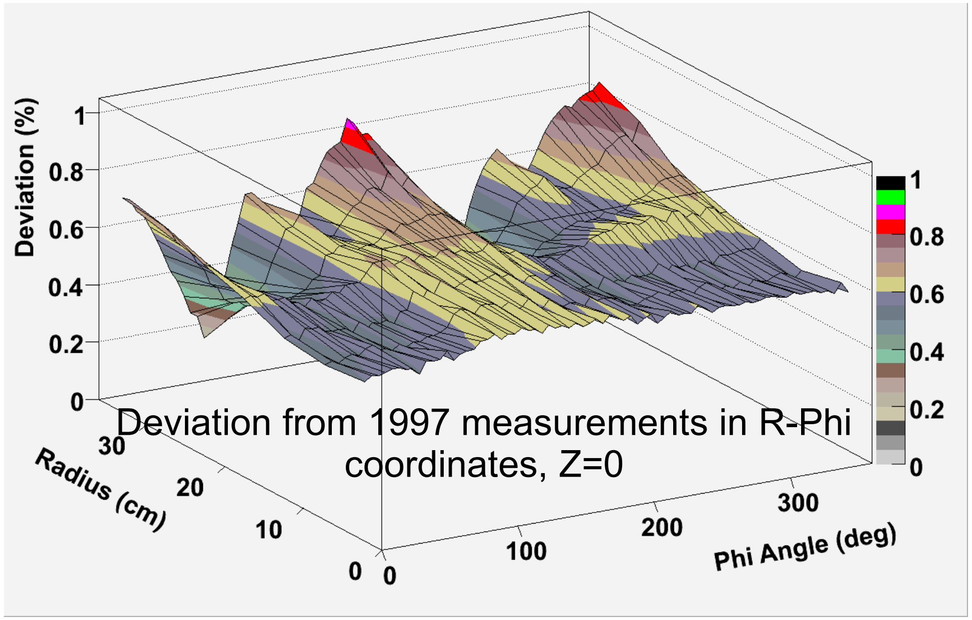


1. Stable: no torque
2. Safety : no field leak out of the magnet (B_{out}<0.02T)
3. Low weight: no iron



The detailed 3D field map (120k locations) was measured in May 2010

Deviation from the 1997 (AMS-01) measurement <1%



Silicon Tracker TRK

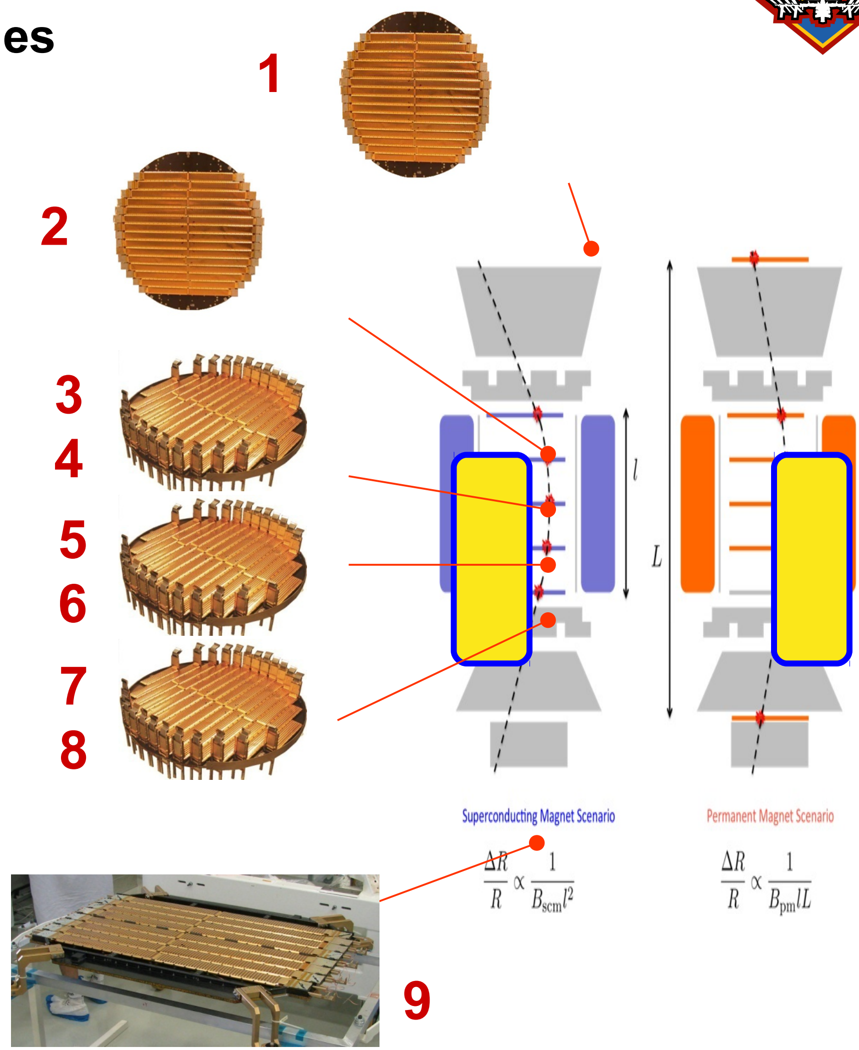
9 Silicon planes

Single coordinates resolution
10μm (bend plane) 30μm (not-bend plane)

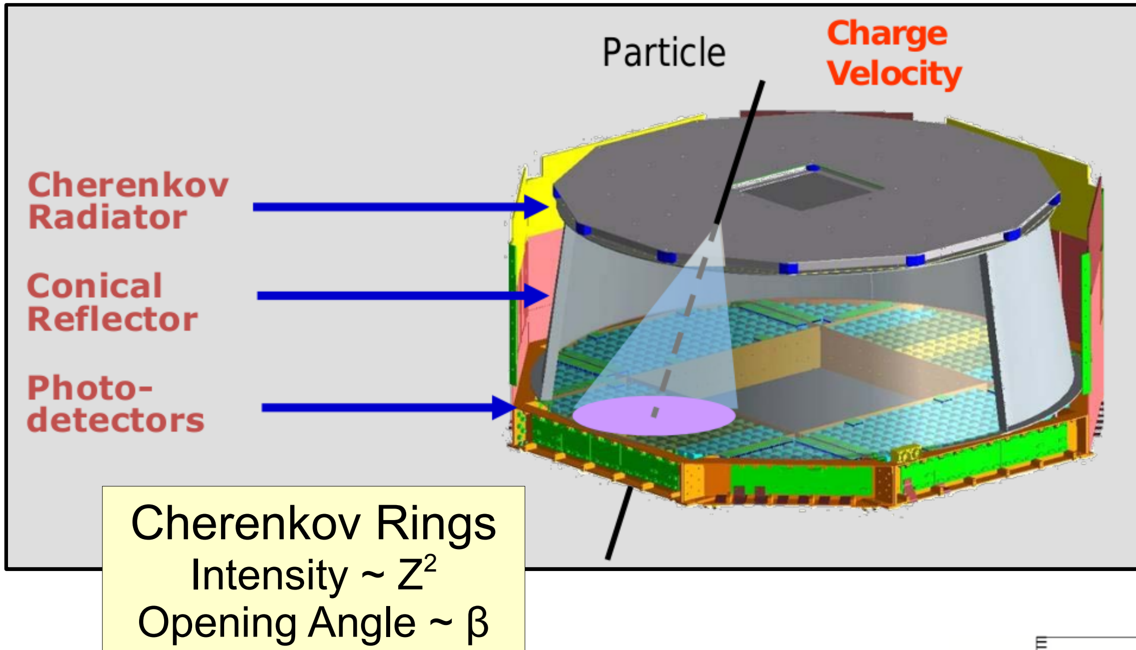
2264 double-sided Si micro-strip sensors
For a total of 6.4m^2 active area

Channels aligned to 3μm using
• 20 UV laser (inner tracker)
• cosmic rays (outer planes)

Maximum detectable rigidity ~ 2TeV



Ring Imaging Cherenkov RICH



– 134 cm diameter collection surface
– 640 4X4 PMTs
– Conical reflector to increase RICH acceptance

- β measurement with a resolution ~ 0.1% for Z=1 particles, and ~ 0.01% for ions (Z>1).
- Particle charge measurement with a charge confusion of the order of 10 % up to Z=30