AMS-02 on the International Space Station

January, 21st, 2015

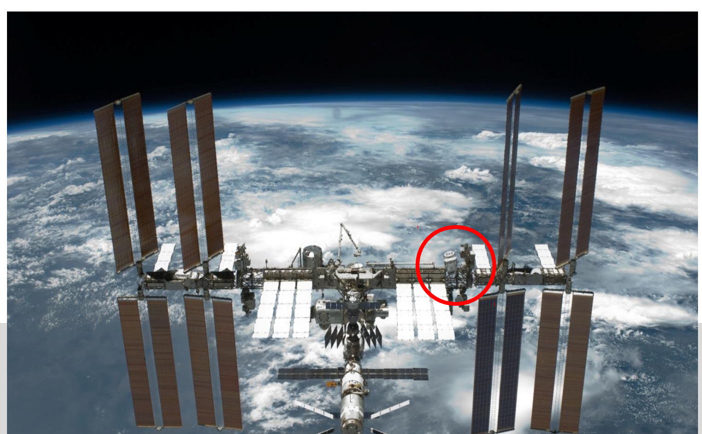
Iris Gebauer for the AMS collaboration

INSTITUT FÜR EXPERIMENTELLE KERNPHYSIK

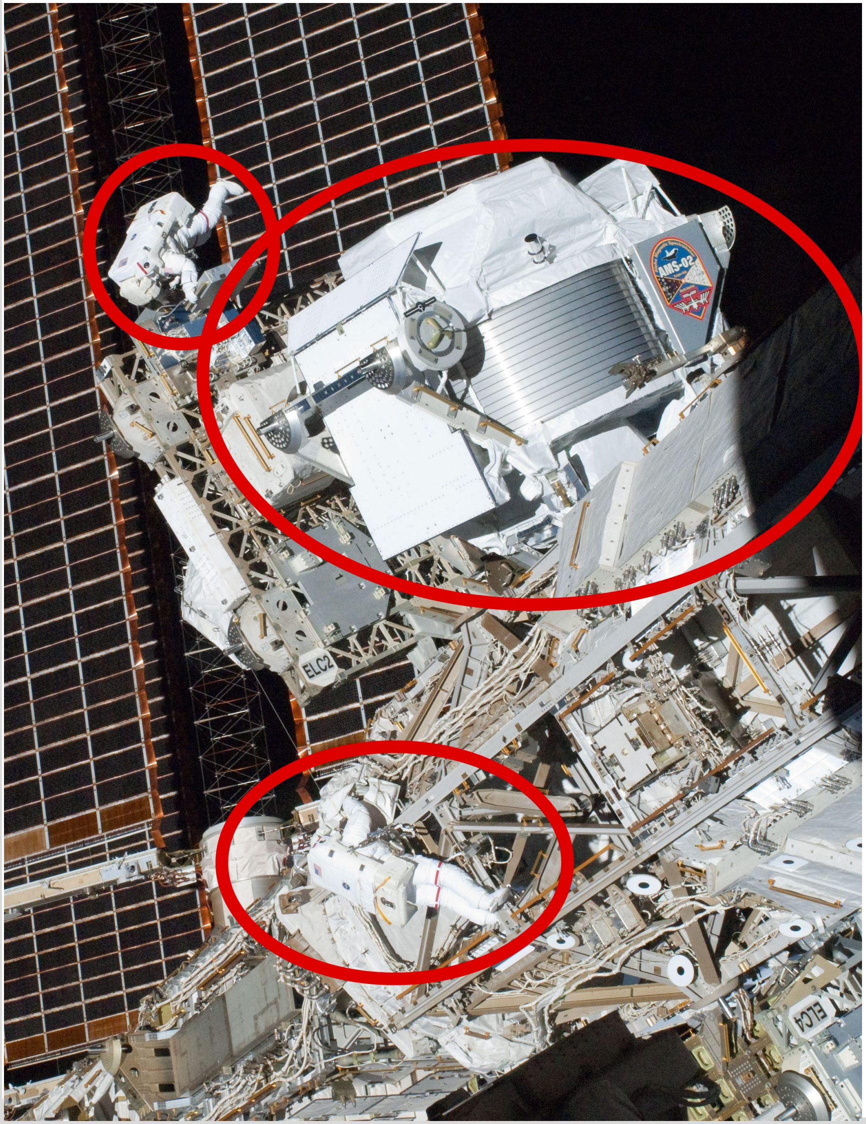

16th May 2011


19th May 2011
ELC2


Endeavour



AMS-02: THE ALPHA MAGNETIC SPECTROMETER 02



- **Volume** 64 m^3, height 4 m
- **Weight** 8500 kg
- **Power** 2500 W
- **Data downlink** 9 Mbps (minimum)
- **Magnetic field** 0.15 T (400 x Earth, PAMELA: 0.4 T, but H=44.5 cm)
- **Launch** May 16th, 2011 (Endeavour)
- **Data taking** as of May 19th, 2011
- **Construction** 1999-2010 (>3 PhD generations)
- **Mission duration:** until the end of ISS operation (currently 2024)

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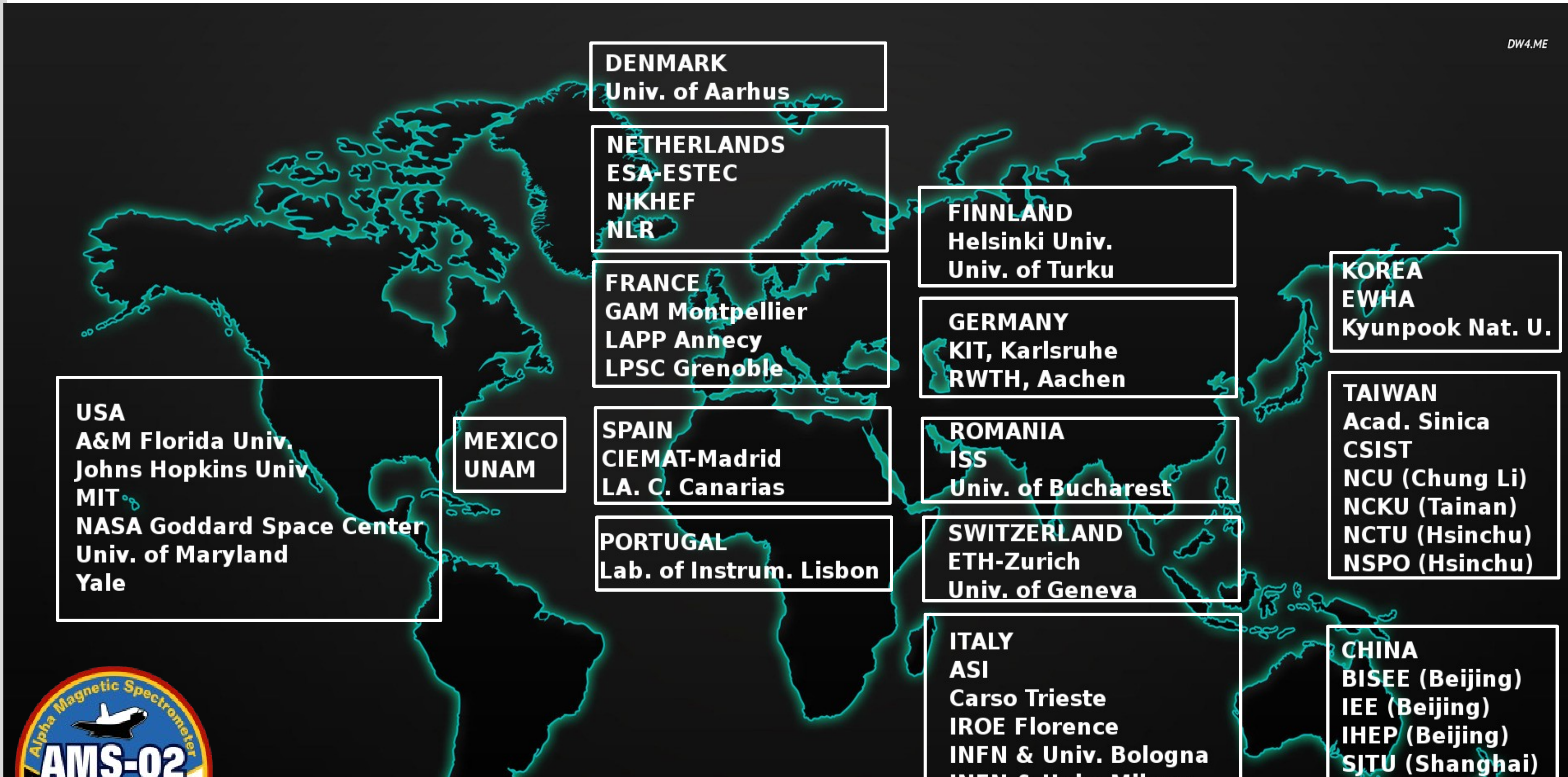
AMS-02 COLLABORATION



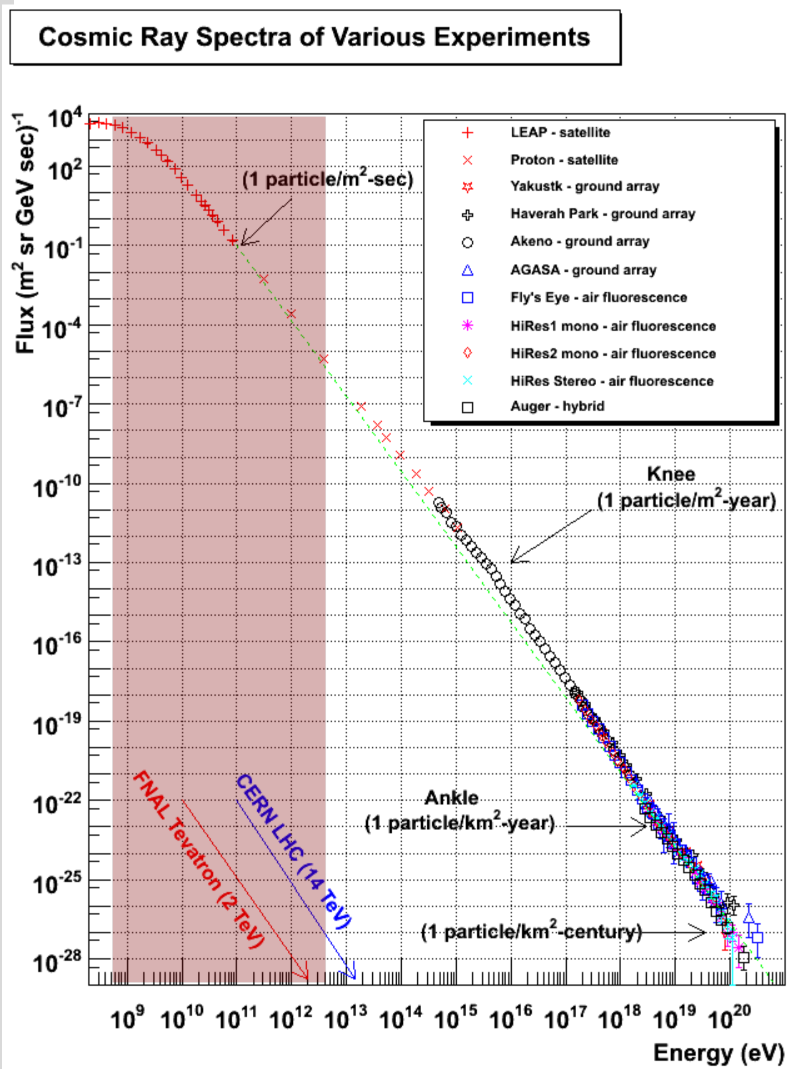
16 countries, 56 institutes, ~500 physicists
95% of AMS was constructed in Europe and Asia

AMS-02 SCIENCE AGENDA

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

Currently ongoing analyses:
P, He, B/C, Be/B, C/O…., $\bar{p}$/p
Positron fraction, e^+, e^- spectra
Solar activity

CHARGED **COSMIC RAYS** (CRs)



Protons ~90% He ~10%, heavy nuclei (mainly C) ~1%, e^- ~1%, traces of e+, anti-p, …

Power law:

$$\Phi(E)\,dE \propto E^{-\gamma}\,dE$$

$\gamma \approx 2.6 - 2.7$, $E<10^{15}$eV

$\gamma \approx 3$, $E>10^{15}$eV

Low energies (<10 GeV): shape of flux is dominated by 'local' effects:

- solar wind
- magnetosphere

High energies (>10-20 GeV): shape reflects interstellar spectra → probe for galactic cosmic ray transport

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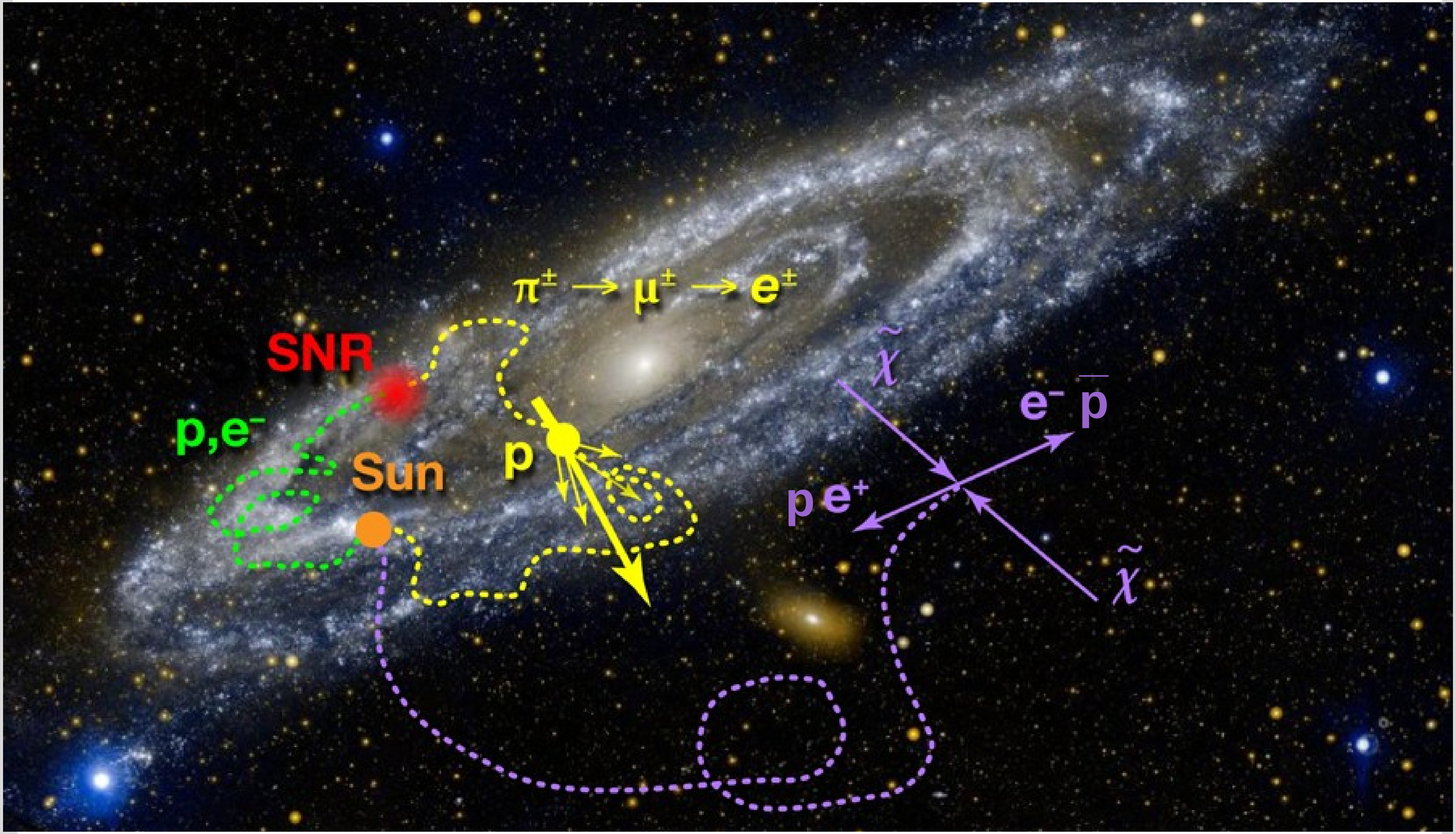
GALACTIC COSMIC RAYS: SOURCE → US



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GALACTIC COSMIC RAYS: SOURCE → US

Transport inside the galaxy:

$$\frac{dN_i}{dt} = D\nabla^2 N_i + \frac{\partial}{\partial E}\left[b\,N_i\right] + Q_i - \frac{N_i}{\tau_i} + \sum_{j>i} \frac{P_{ij}}{\tau_j} N_i$$

Diffusion in the galaxy volume → Motion in the galactic magnetic field

Energy losses →

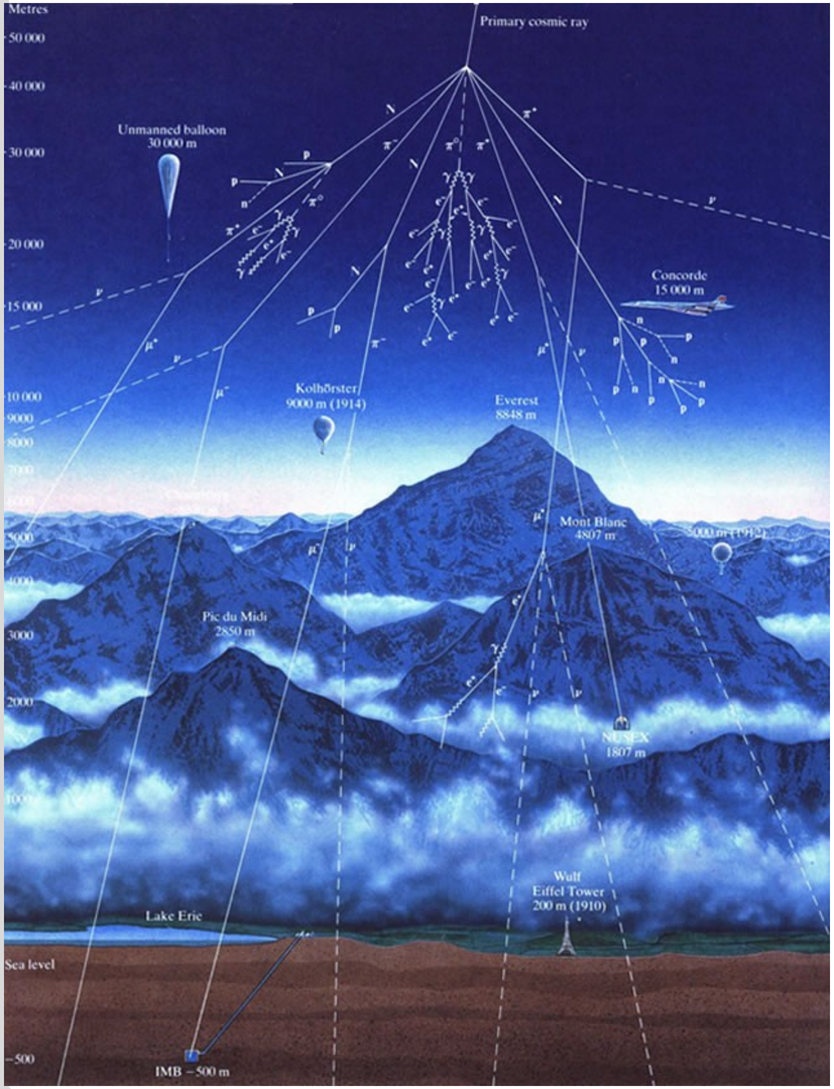
- Ionization
- Coulomb losses
- Bremsstrahlung
- **Synchrotron radiation**
- **Inverse Compton effect**

Sources → SNR at least up to sub-PeV energies

Decay and secondary production → Interaction with the ISM (i.e. spallation) and decay into/from another specie

COSMIC RAY OBSERVATION LEVEL

Karlsruhe Institute of Technology



Most of cosmic rays do not reach the ground due to interactions with the atmosphere

Let’s go ‘above’ the atmosphere (at least above the troposphere, in the stratosphere, reachable via a balloon flight)

Particle physics in space E< 10^4 GeV

Let's use the Earth's atmosphere as a calorimeter to indirectly measure primary particles

Particle physics on ground E> 10^4 GeV

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OPERATING AMS ON THE ISS

AMS-02-DETECTOR OVERVIEW

NEW RESULTS FROM AMS

SUMMARY

OPERATING AMS-02 ON THE ISS

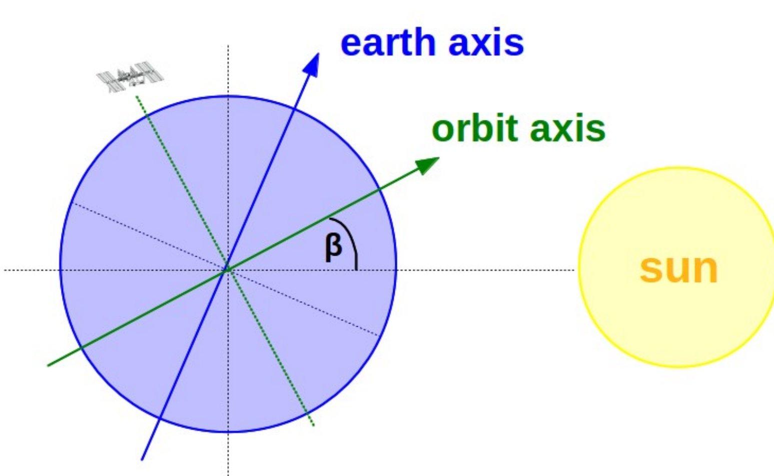
OPERATING AMS-02 ON THE ISS

One of the major challenges for an experiment onboard ISS is the extreme thermal environment to which it is exposed

OPERATING AMS-02 ON THE ISS

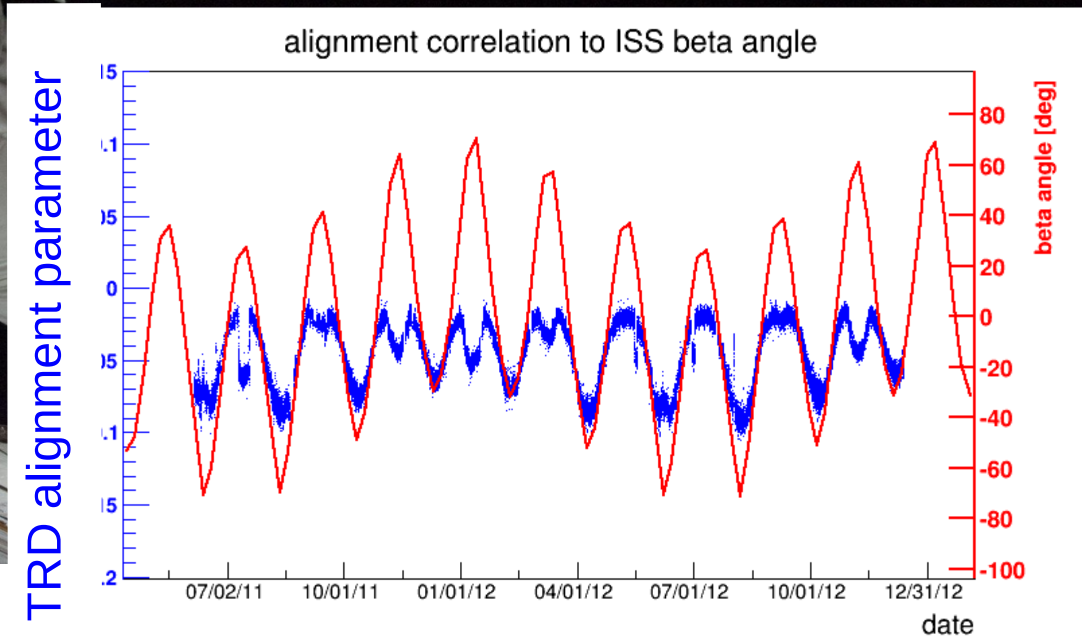
We have no control over the ISS orientation, attitude and beta angle -all of which affect the thermal conditions

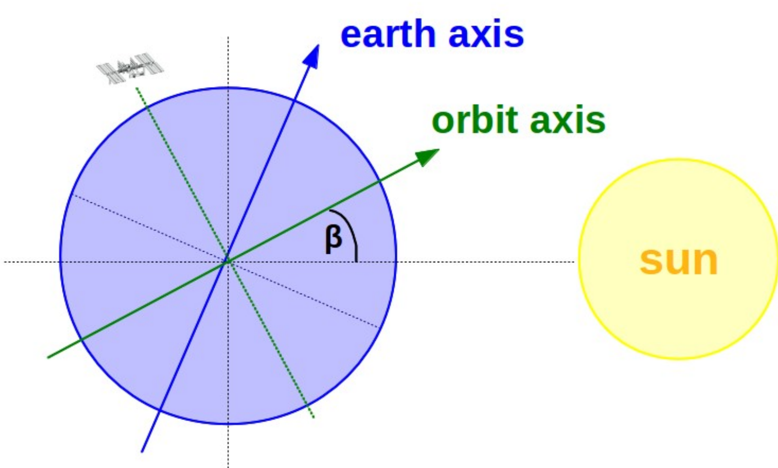
$\Delta T = 100^o C$ every 90 min

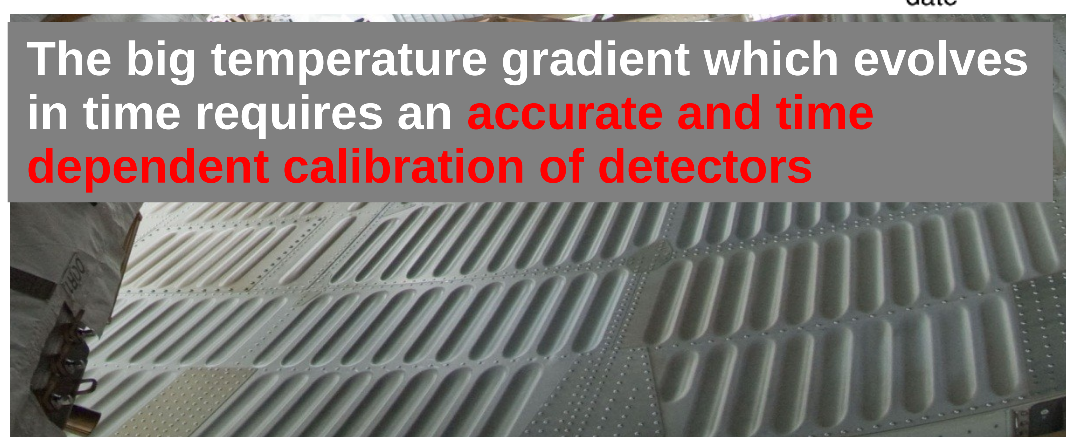


Beta-angle: angle between ISS orbit axis and Sun-Earth axis

OPERATING AMS-02 ON THE ISS





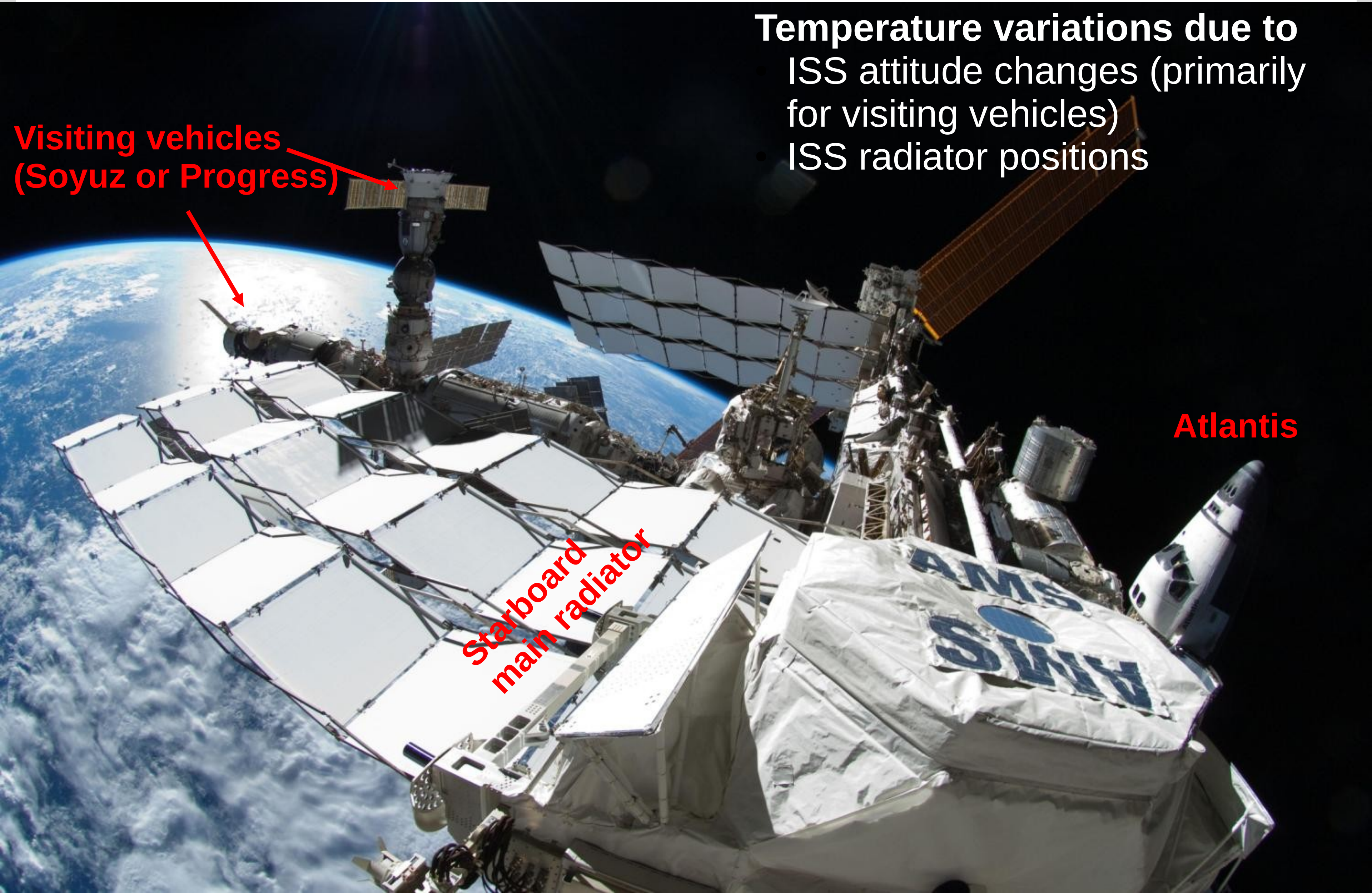


The big temperature gradient which evolves in time requires an accurate and time dependent calibration of detectors

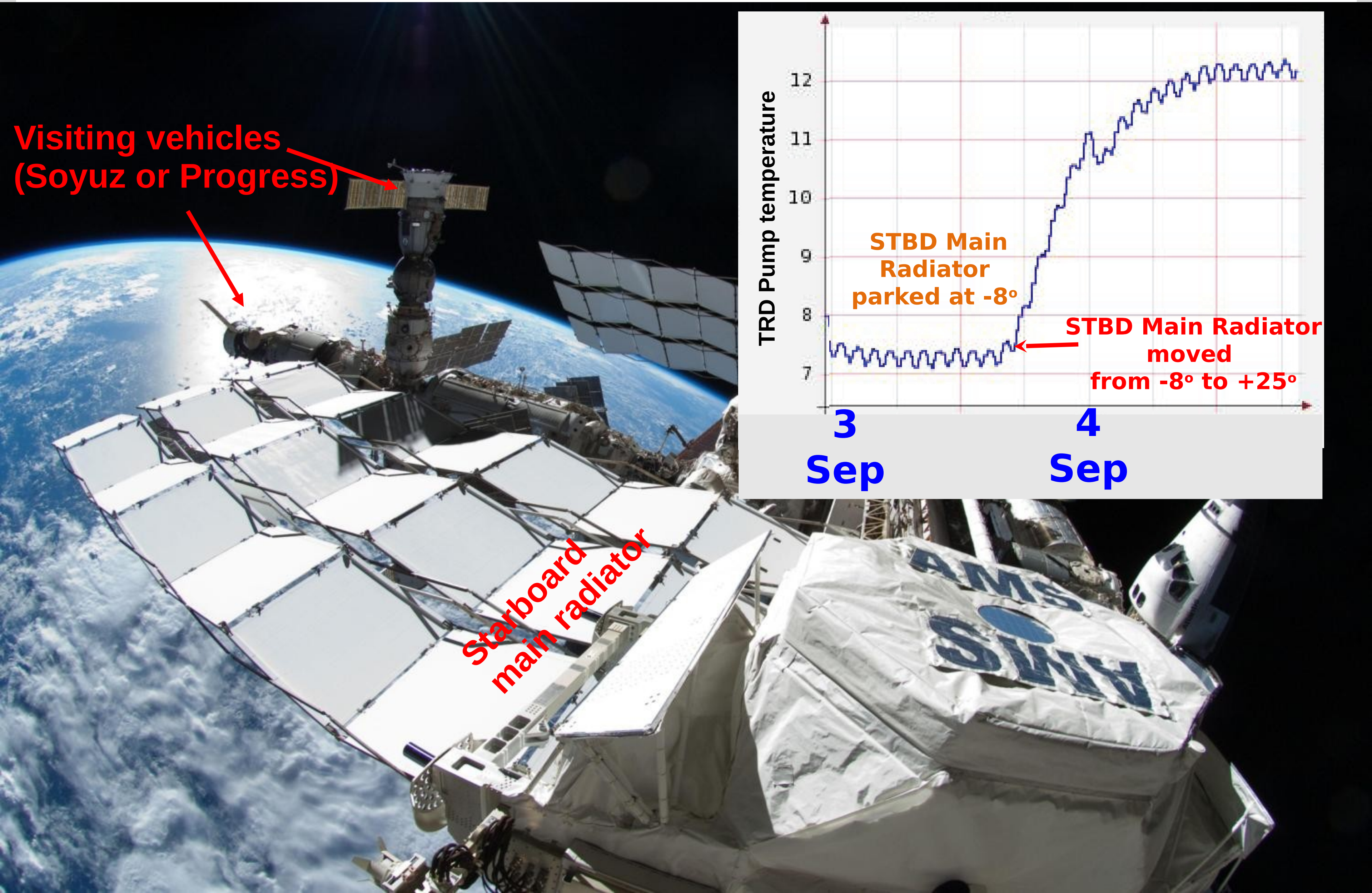
OPERATING AMS-02 ON THE ISS

Temperature variations due to

- ISS attitude changes (primarily for visiting vehicles)
- ISS radiator positions



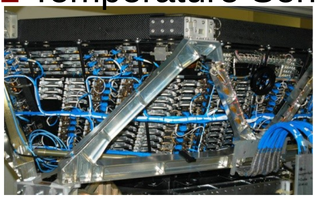
OPERATING AMS-02 ON THE ISS

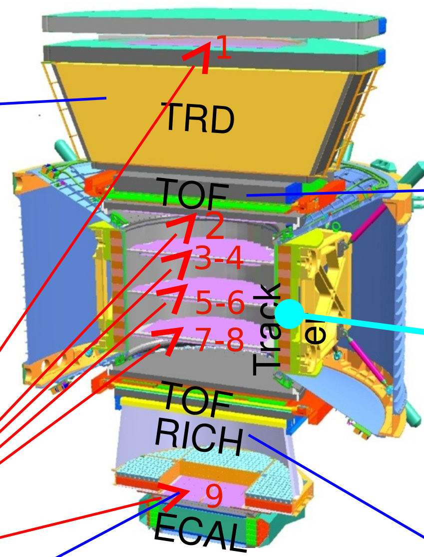


OPERATING AMS-02 ON THE ISS

KIT Karlsruhe Institute of Technology

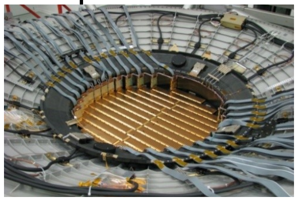
TRD
24 Heaters
8 Pressure Sensors
482 Temperature Sensors



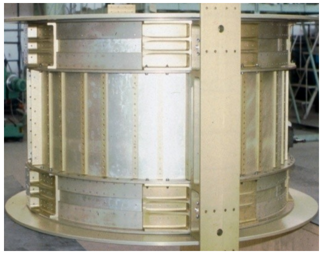


TOF & ACC
64 Temperature Sensors

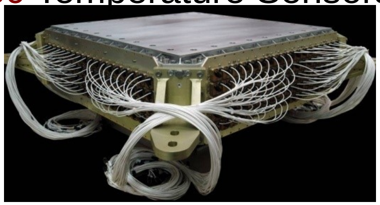
Silicon Tracker
4 Pressure Sensors
32 Heaters
142 Temperature Sensors



Magnet
68 Temperature Sensors



ECAL
80 Temperature Sensors



1118 temperature sensors
5 radiators
298 thermostatically controlled heaters

RICH
96 Temperature Sensors

Tracker front-end electronics are kept stable to 1ºC (optimal performance) radiating ~ 150W to Space

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POCC: PAYLOAD OPERATIONS CONTROL CENTER


CERN, Geneve


CSIST, Taiwan

POCC
Payload **O**perations **C**ontrol **C**enter

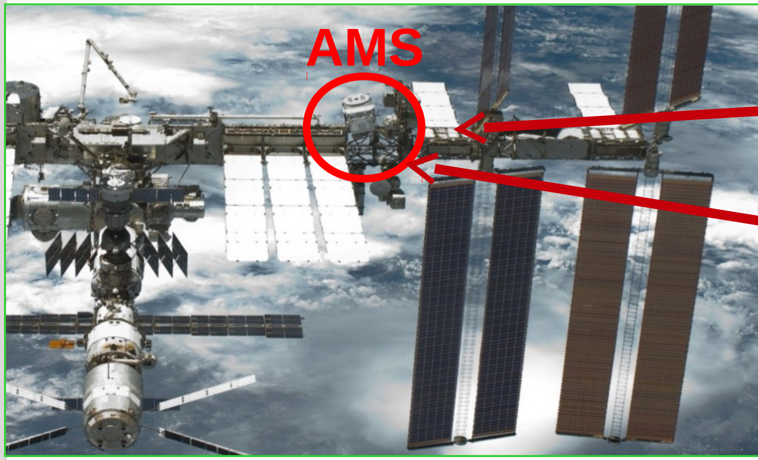
Monitoring + Commanding

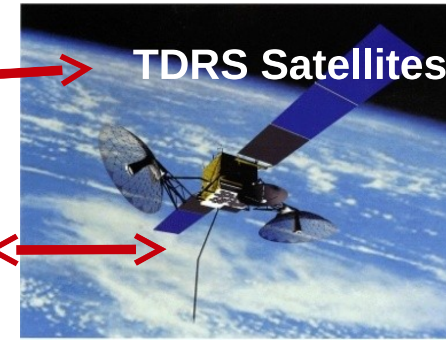
Communication with NASA

4 positions monitoring
11 Subdetectors (24/7)

LEAD position monitoring the entire system

AMS-02 ↔ GROUND





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

Flight Operations

Ground Operations

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

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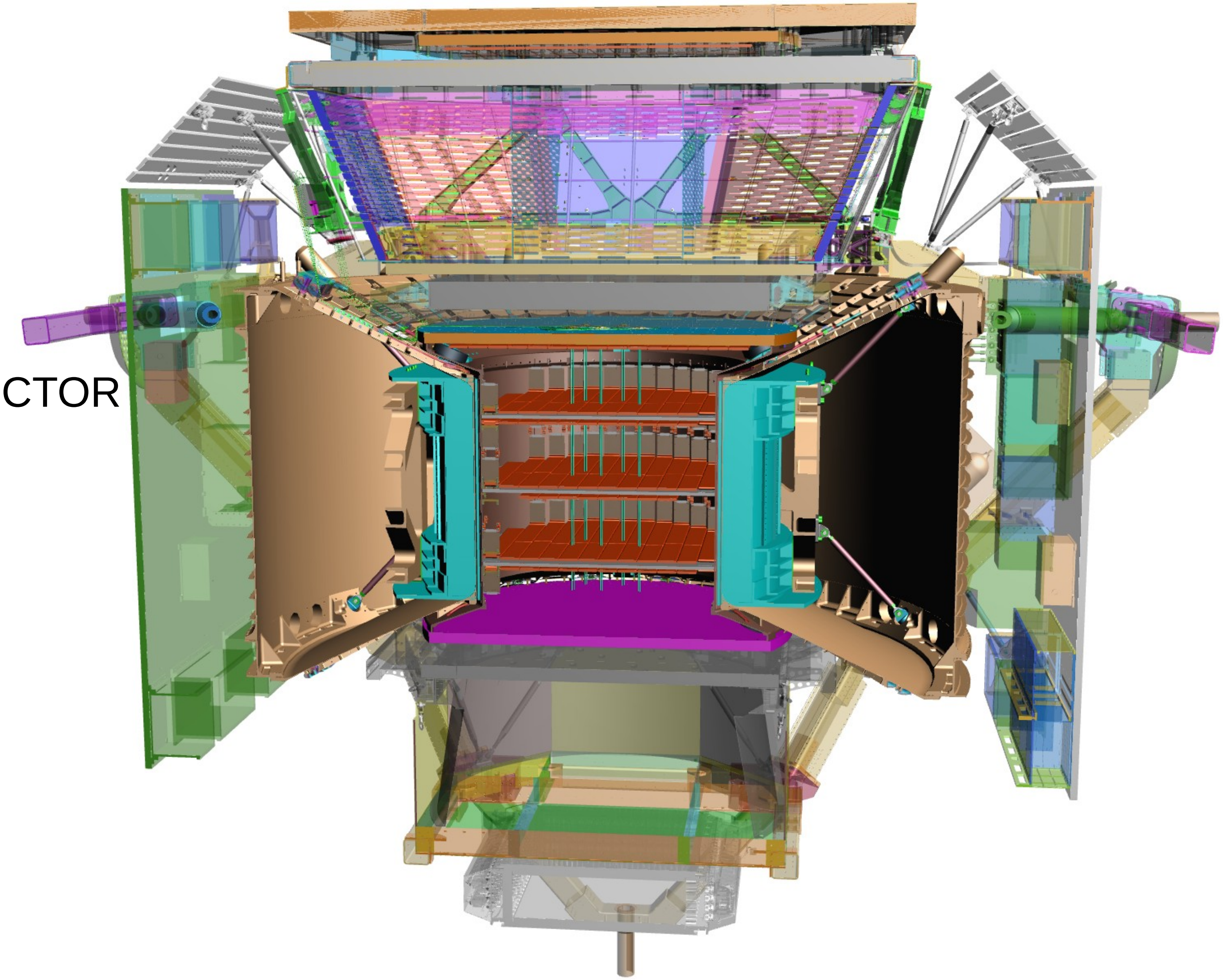
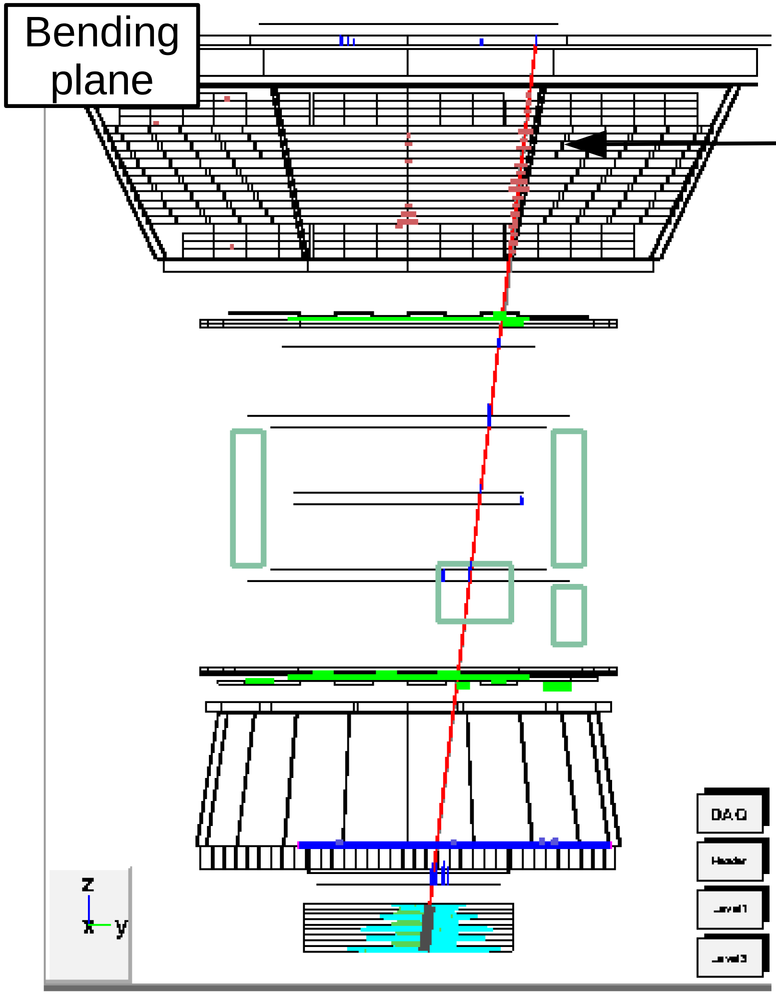
THE AMS-02 DETECTOR



TRANSITION **R**ADIATION **D**ETECTOR



320 GeV positron

Transition Detector Radiation TRD
Identifies e+/e- (Xrays)

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

Magnet + Silicon Tracker TRK
Measure momentum / sign(Q) / Charge Q

Ring Imaging Cherenkov RICH
Velocity β / Charge Q /

Electromagnetic Calorimeter ECAL
Measure energy / Identifies e+/e- (shower shape)

Most particle properties are measured redundantly

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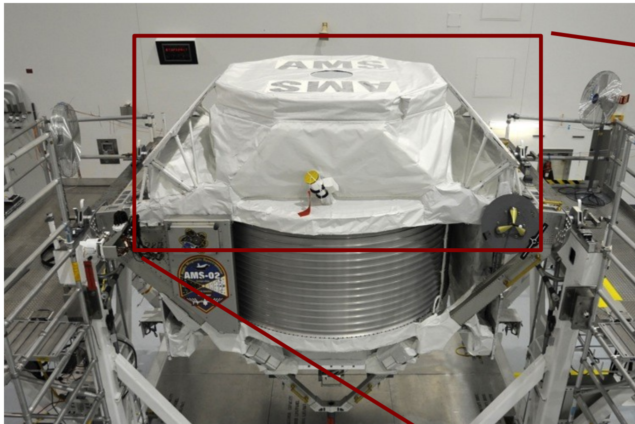
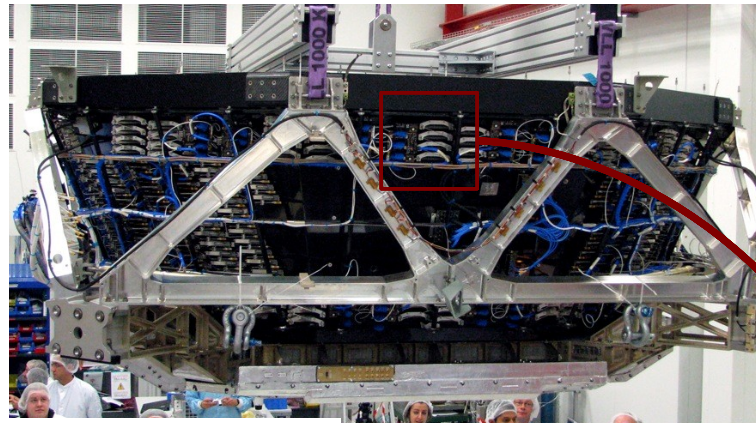
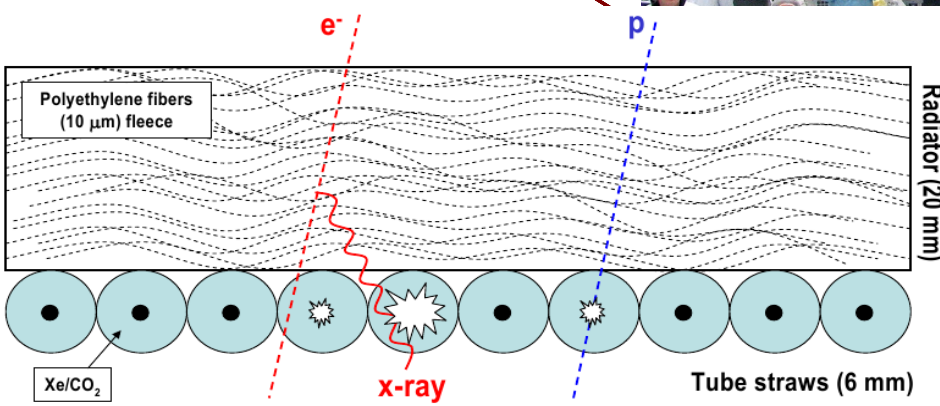
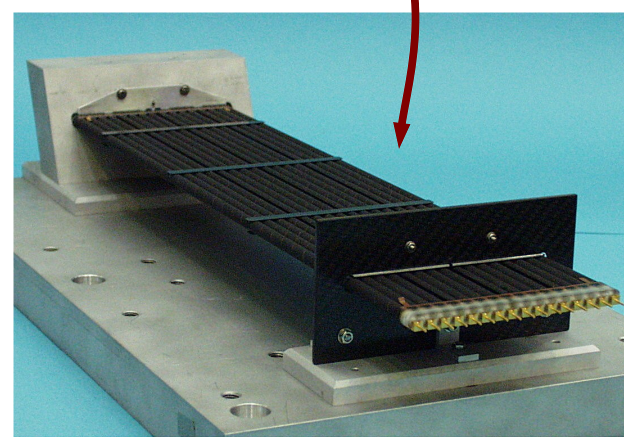
TRANSITION RADIATION DETECTOR







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



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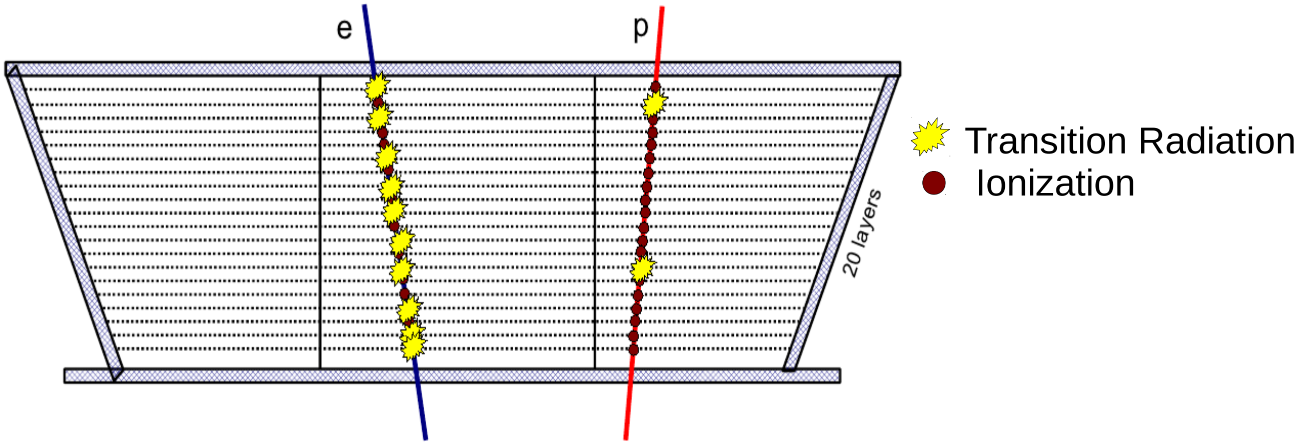
LEPTON/HADRON SEPARATION WITH THE TRD

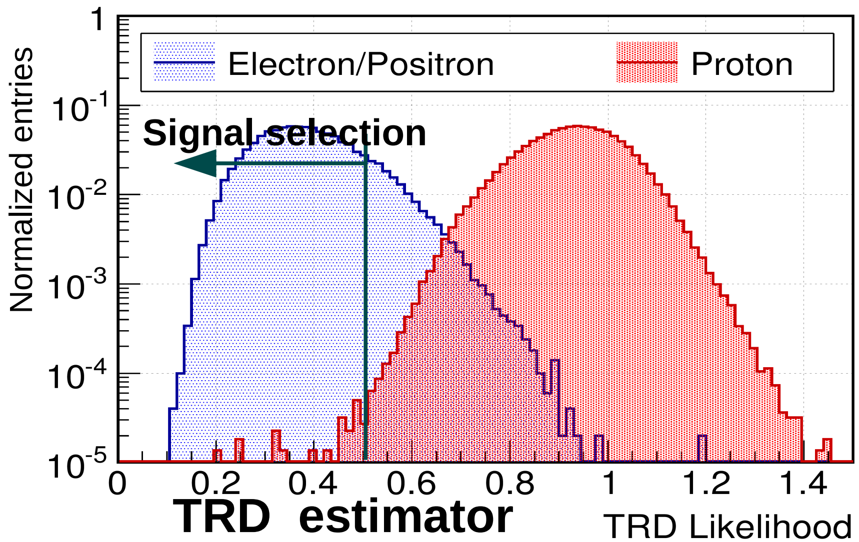
$$\mathbf{P_e(E)} = \sqrt{\prod_{\mathbf{i}}^{\mathbf{n}} \mathbf{P_e^i(E)}}$$

$$\mathbf{P_p(E)} = \sqrt{\prod_{\mathbf{i}}^{\mathbf{n}} \mathbf{P_p^i(E)}}$$



Energy deposit sampled 20 times → $P(e^+)$, $P(p)$

→ TRD estimator $= -\ln(P(e^+)/(P(e^+)+P(p))$



TRD estimator

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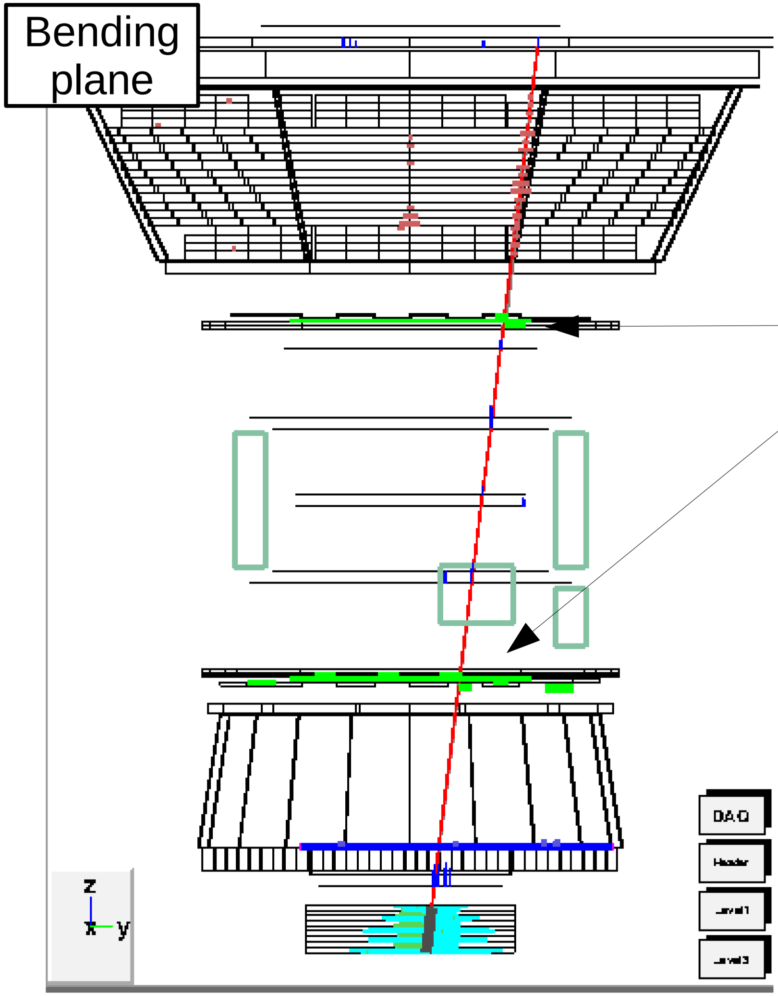
TIME OF FLIGHT



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Most particle properties are measured redundantly

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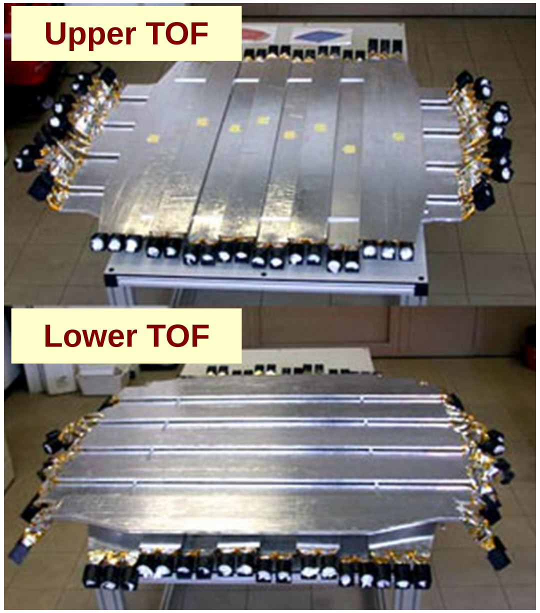
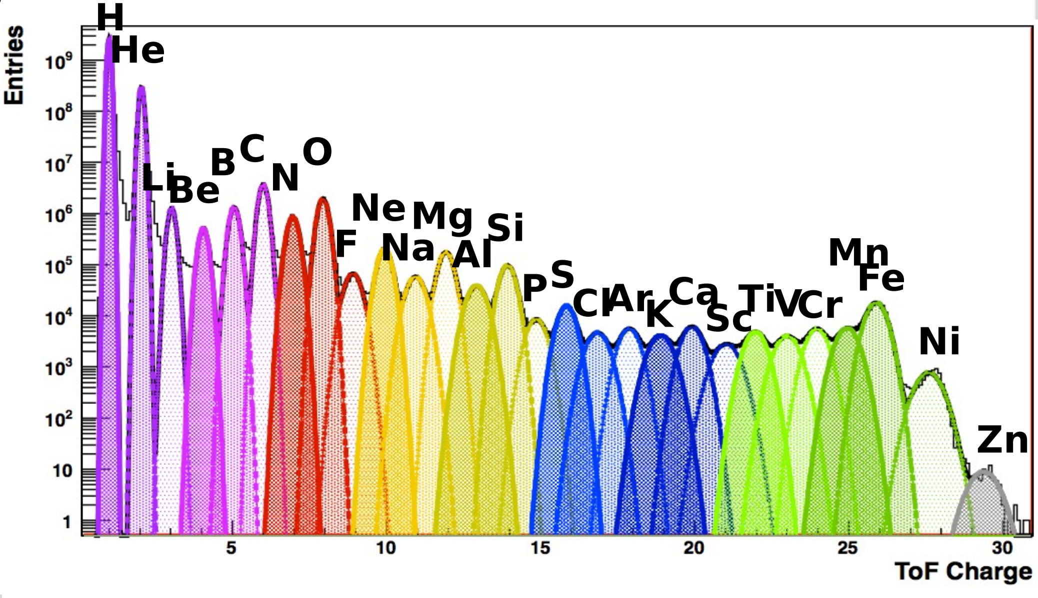
TIME OF FLIGHT



4 scintillator planes (2 above,2 under magnet)

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 rejection power~ 10^{-9}



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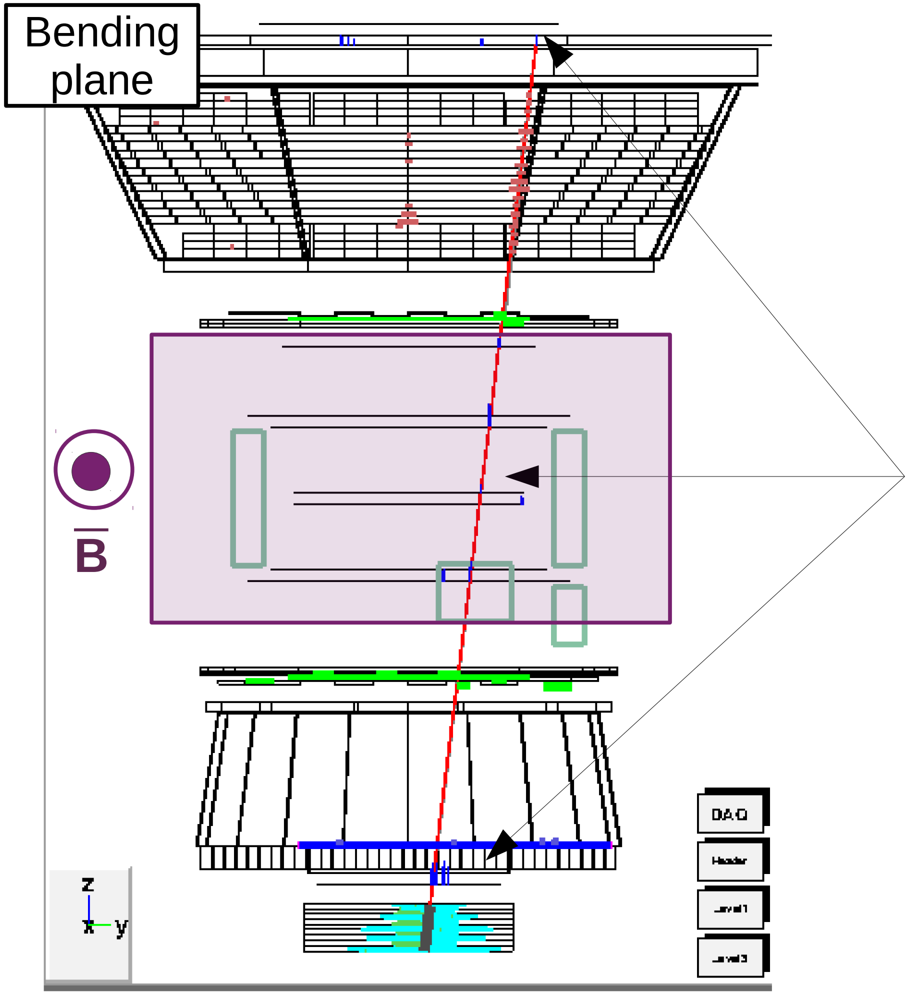
SILICON TRACKER AND MAGNET



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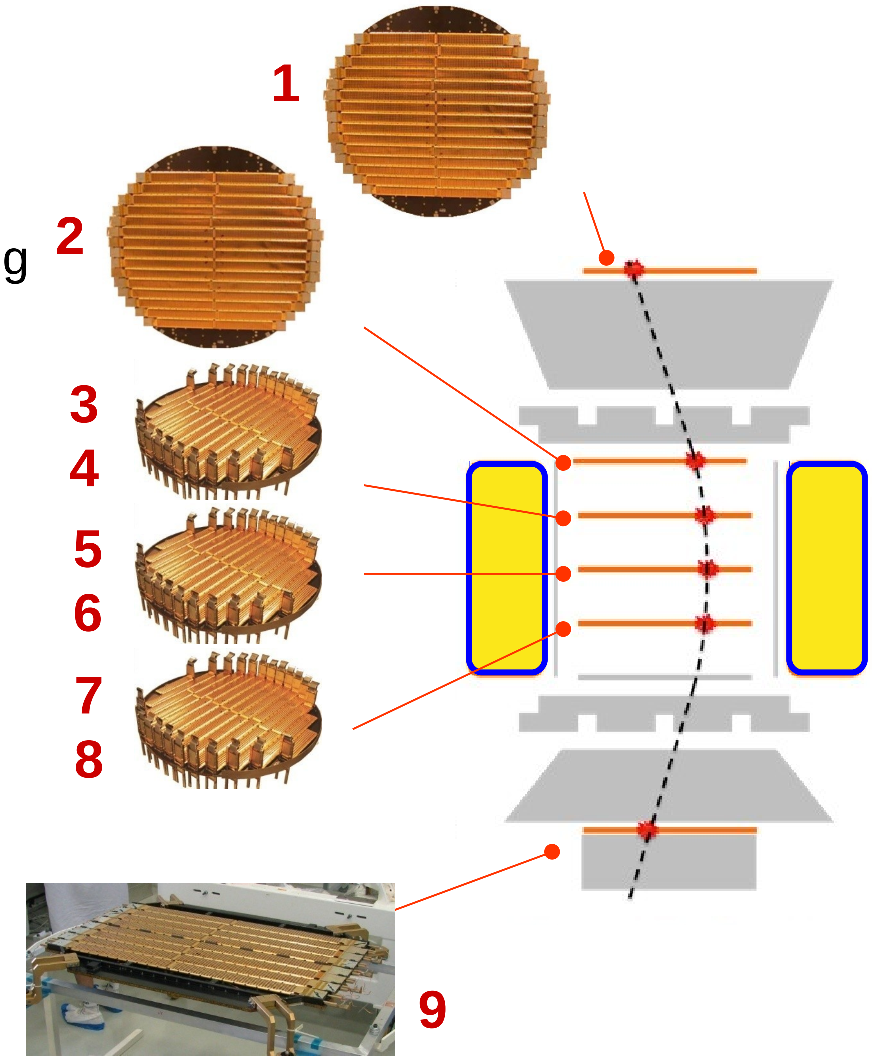
SILICON TRACKER

9 silicon planes

Single coordinates resolution
10µm (bending plane) 30µm (non-bending plane)

2264 double-sided Si micro-strip sensors
For a total of 6.4m^2 active area
200K readout channels

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



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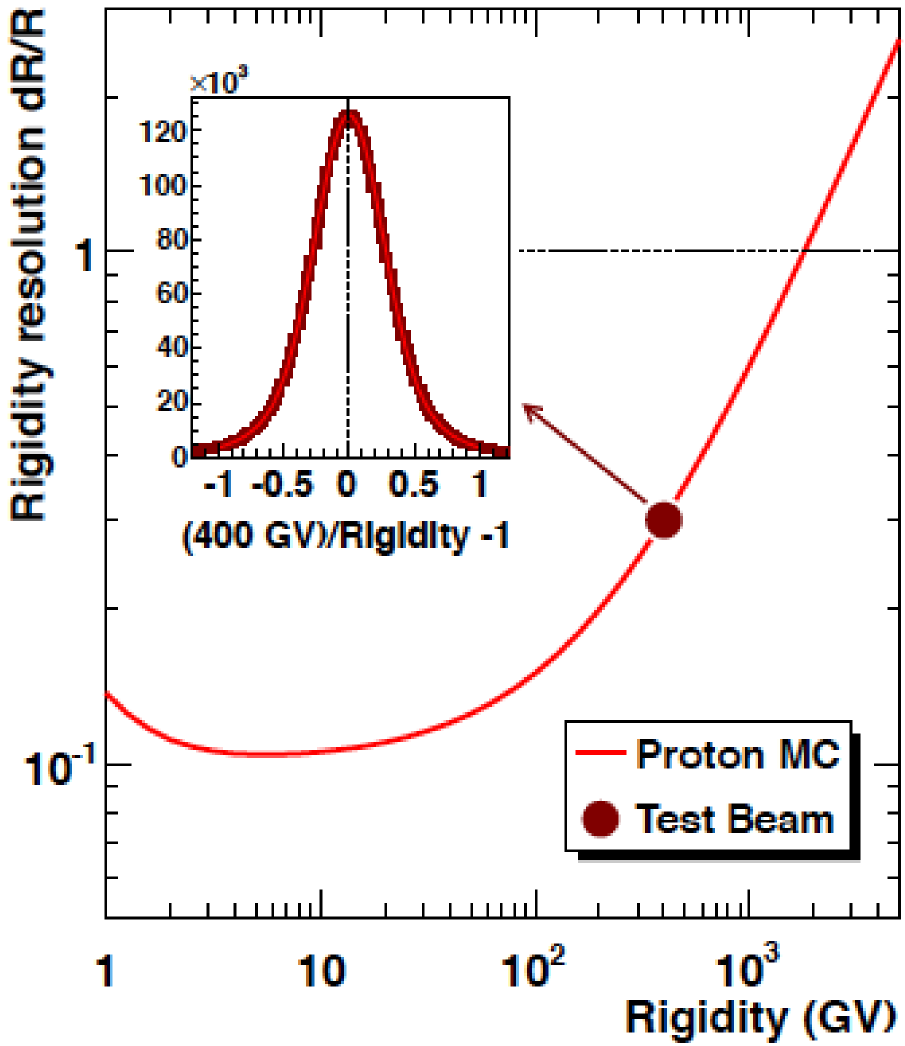
SILICON TRACKER



Maximum detectable rigidity ~ 2TeV

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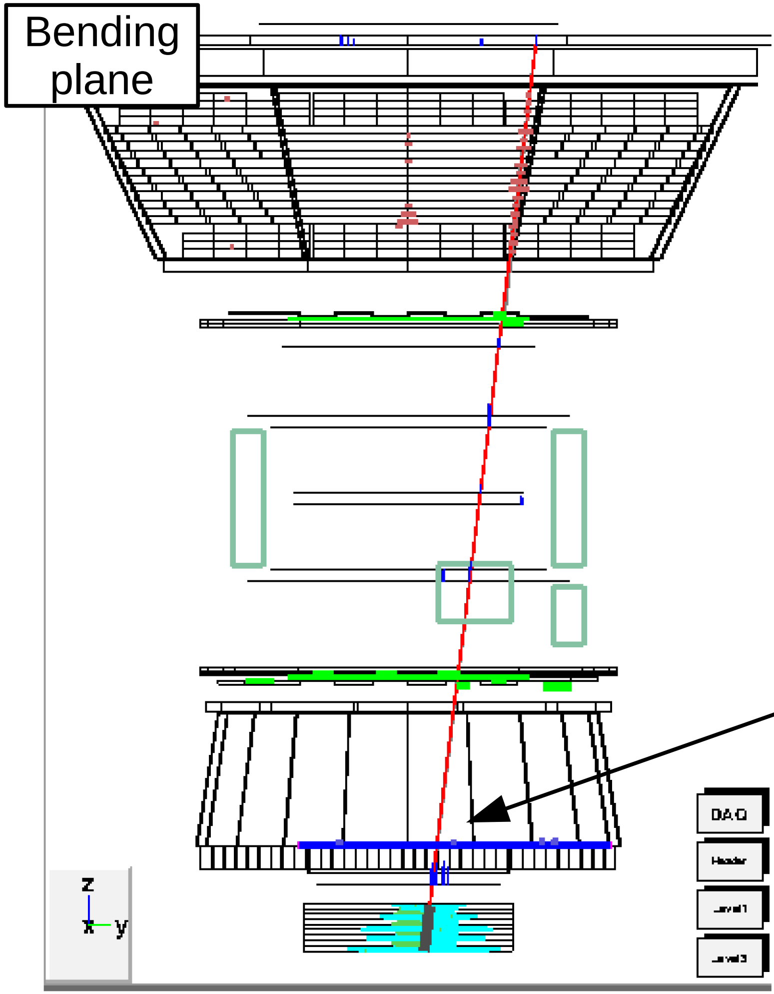
RING IMAGING CHERENKOV DETECTOR



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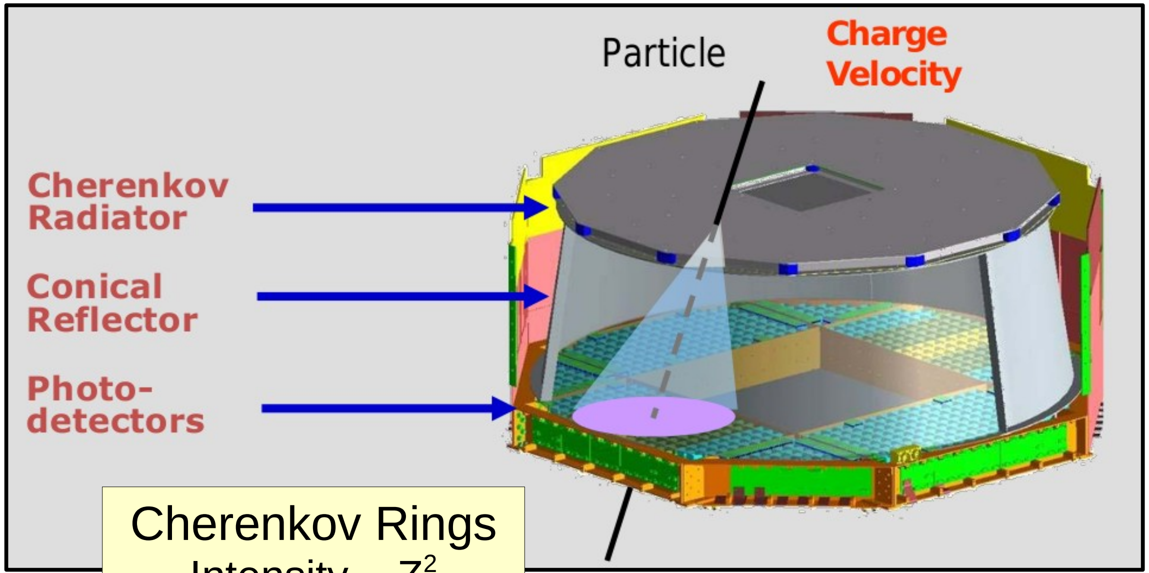
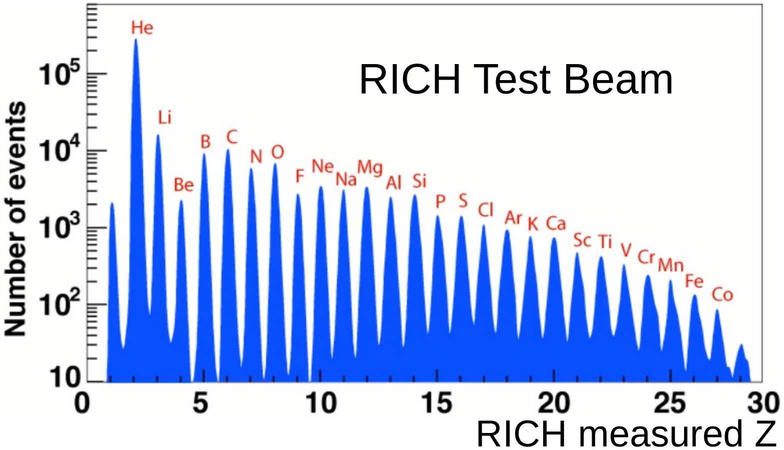


Cherenkov Rings
Intensity ~ Z^2
Opening Angle ~ β

– 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



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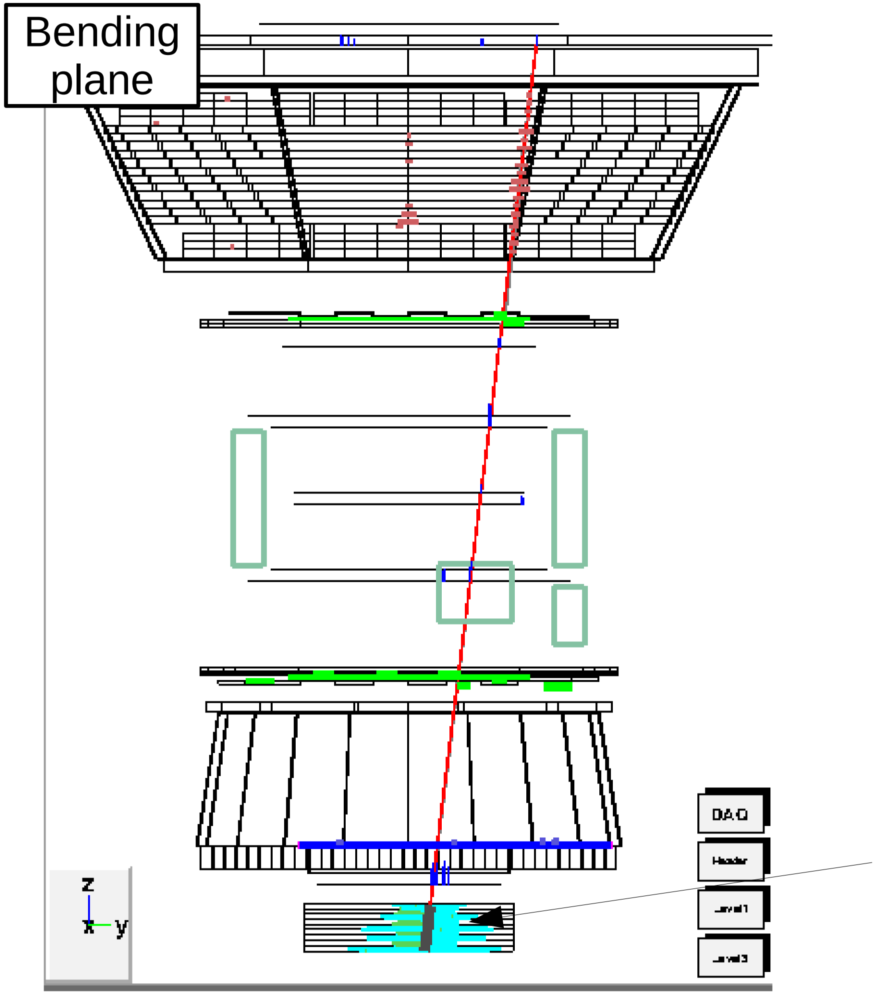
ELECTROMAGNETIC **CAL**ORIMETER



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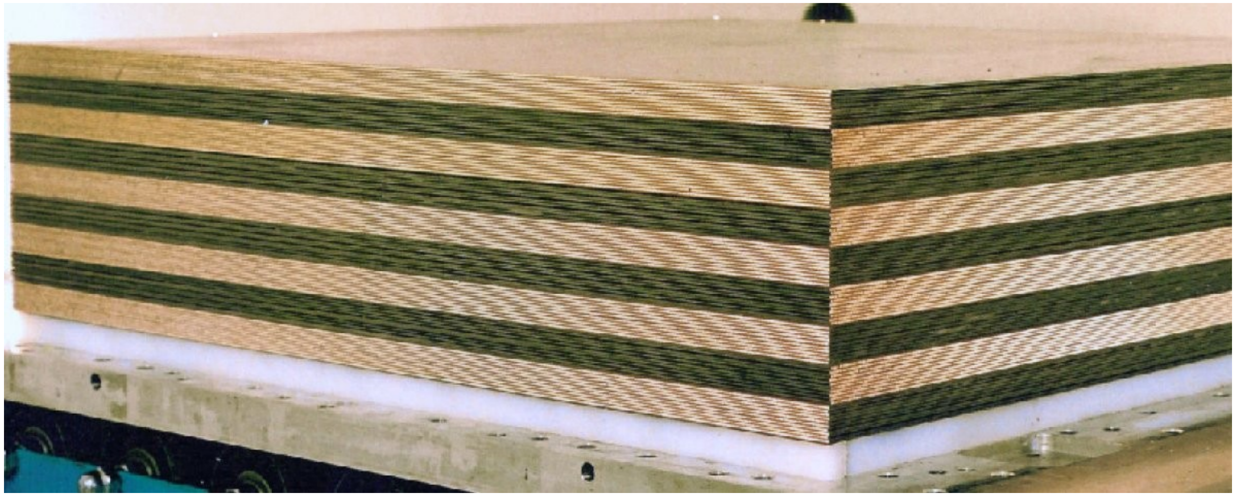
LEPTON/HADRON SEPARATION WITH ECAL

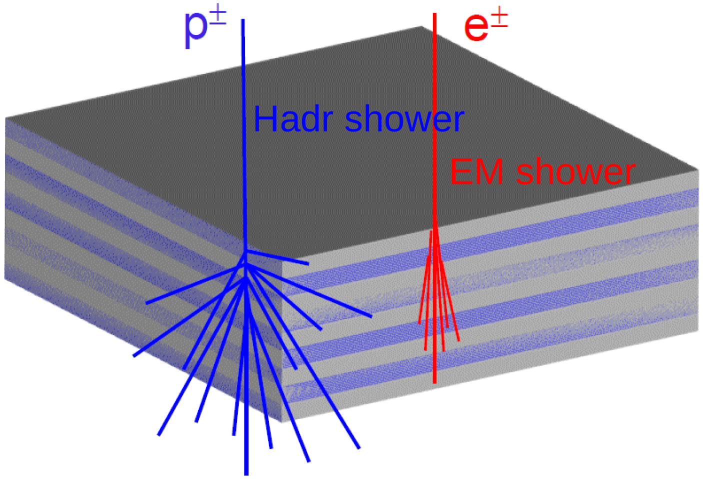


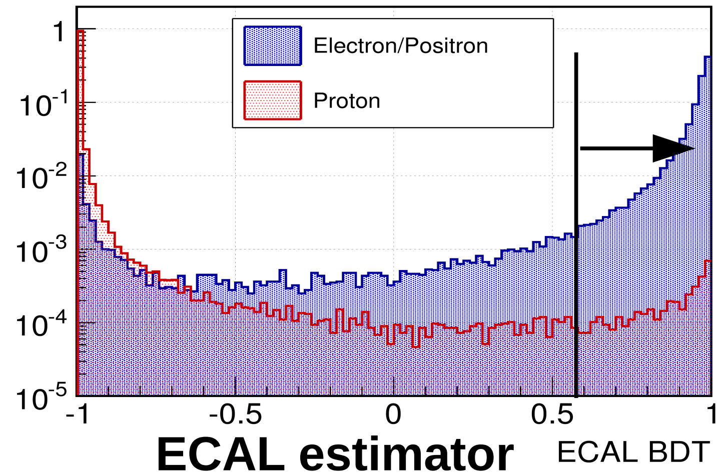
Sampling calorimeter
Lead (58%), scintillating fibers (33%), optic glue (9%)

65.8x65.8x16.7 cm, 18 Layers
(**17 X_0, 0.6** λ_{nuc})

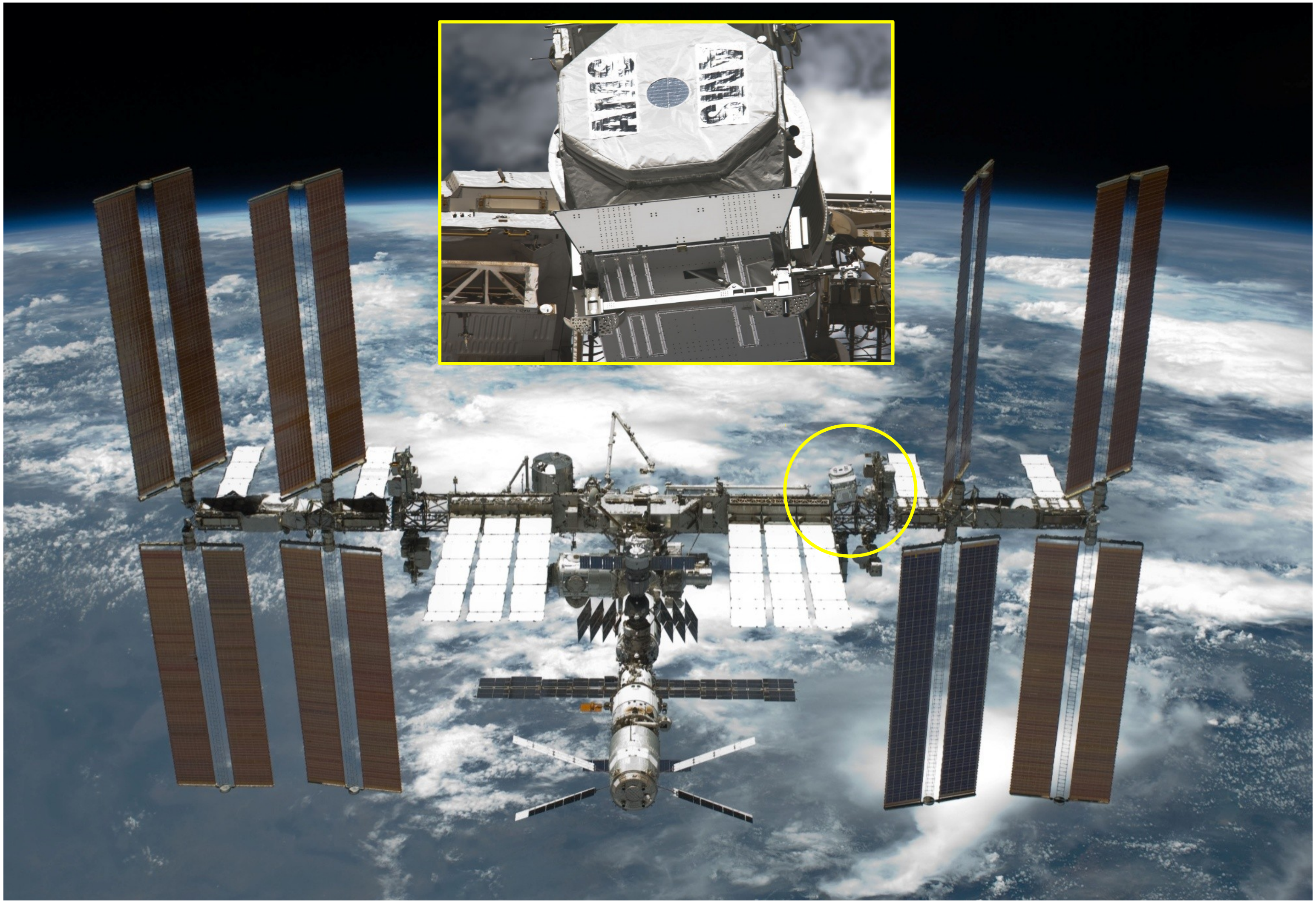
1296 readout cells

Accurate 3D sampling of shower development ⇨ Maximize hadron rejection





AMS-02 IN ORBIT



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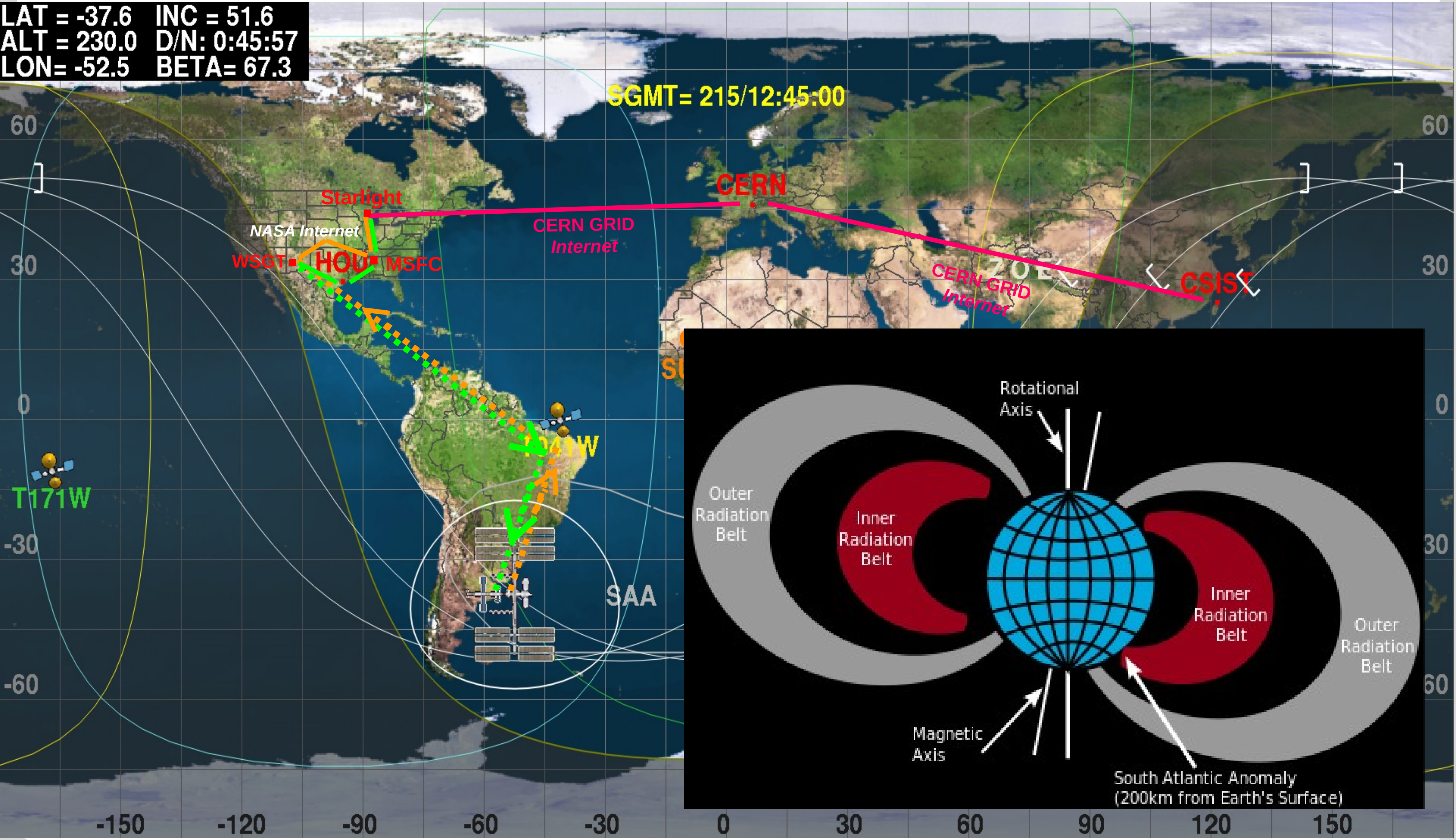
AMS-02 IN ORBIT @ 400 km



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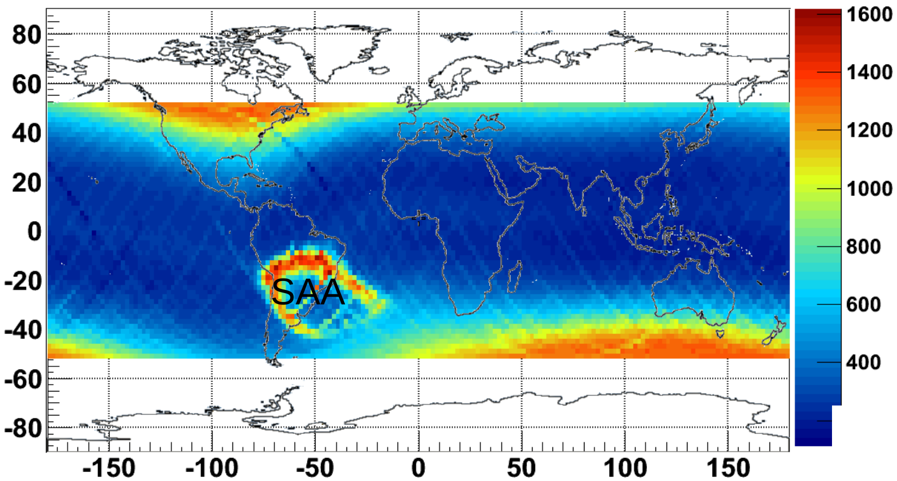
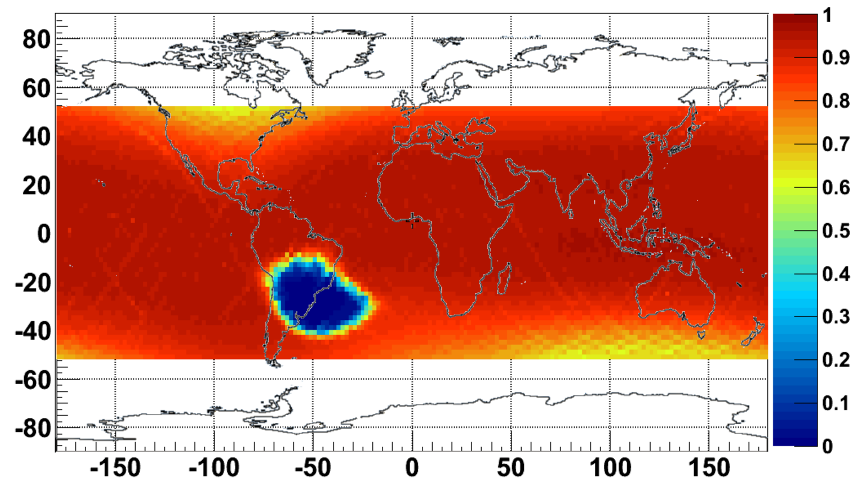
AMS-02 IN ORBIT

<Trigger rate [Hz]> =500Hz



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

DAQ efficiency



Average DAQ efficiency ~ 88%
(inefficiency dominated by SAA)
Average downlink 10 Mbps

The stability of electronic response is ensured by **calibrations of all channels every half-orbit** (~46 mins)

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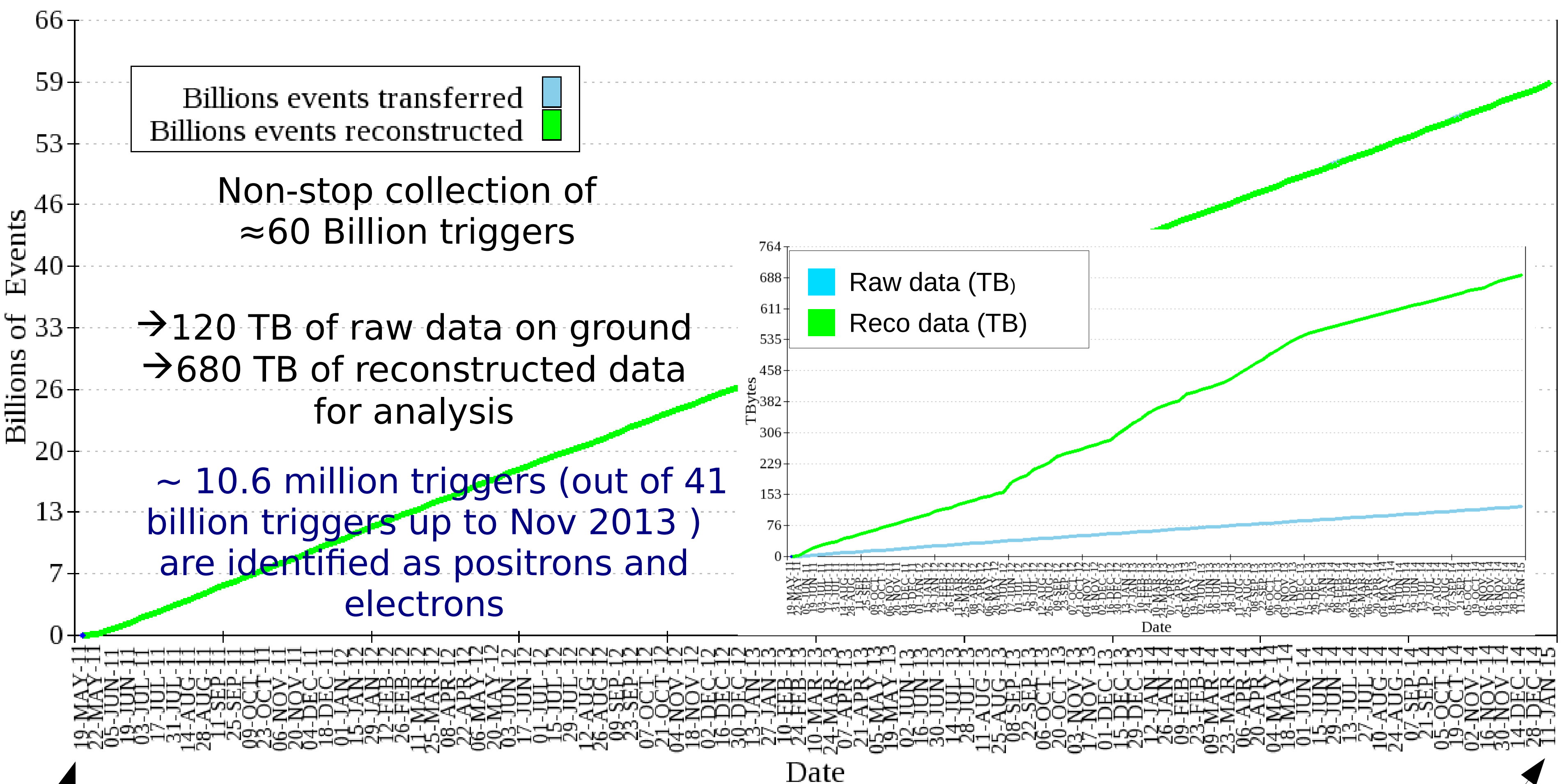
COLLECTED DATA



Non-stop collection of
≈60 Billion triggers

→120 TB of raw data on ground
→680 TB of reconstructed data for analysis

~ 10.6 million triggers (out of 41 billion triggers up to Nov 2013) are identified as positrons and electrons

Installation on ISS

Last week

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LEPTON FLUX MEASUREMENTS

INGREDIENTS FOR A FLUX MEASUREMENT

N_{obs}=number of observed events

$$\Phi(E, E+\Delta E) = \frac{N_{obs}(E+\Delta E)}{\Delta E\, \Delta T_{\exp}\, A_{eff}\, \epsilon_{trig}}$$

ϵ_{trig}=trigger efficiency

$\Delta T_{\exp}$=exposure Time (s)

A_{eff}=effective acceptance ($m^2\, sr^1$)

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

E = Energy measured by ECAL (or tracker rigidity)

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INGREDIENTS FOR A FLUX MEASUREMENT

N_{obs}=number of observed events

$$\Phi(E, E+\Delta E) = \frac{N_{obs}(E+\Delta E)}{\Delta E \, \Delta T_{exp} \, A_{eff} \, \epsilon_{trig}}$$

ϵ_{trig}=trigger efficiency

ΔT_{exp}=exposure Time (s)

A_{eff}=effective acceptance ($m^2 sr^1$)

1. Count number of electrons+positrons in energy bin

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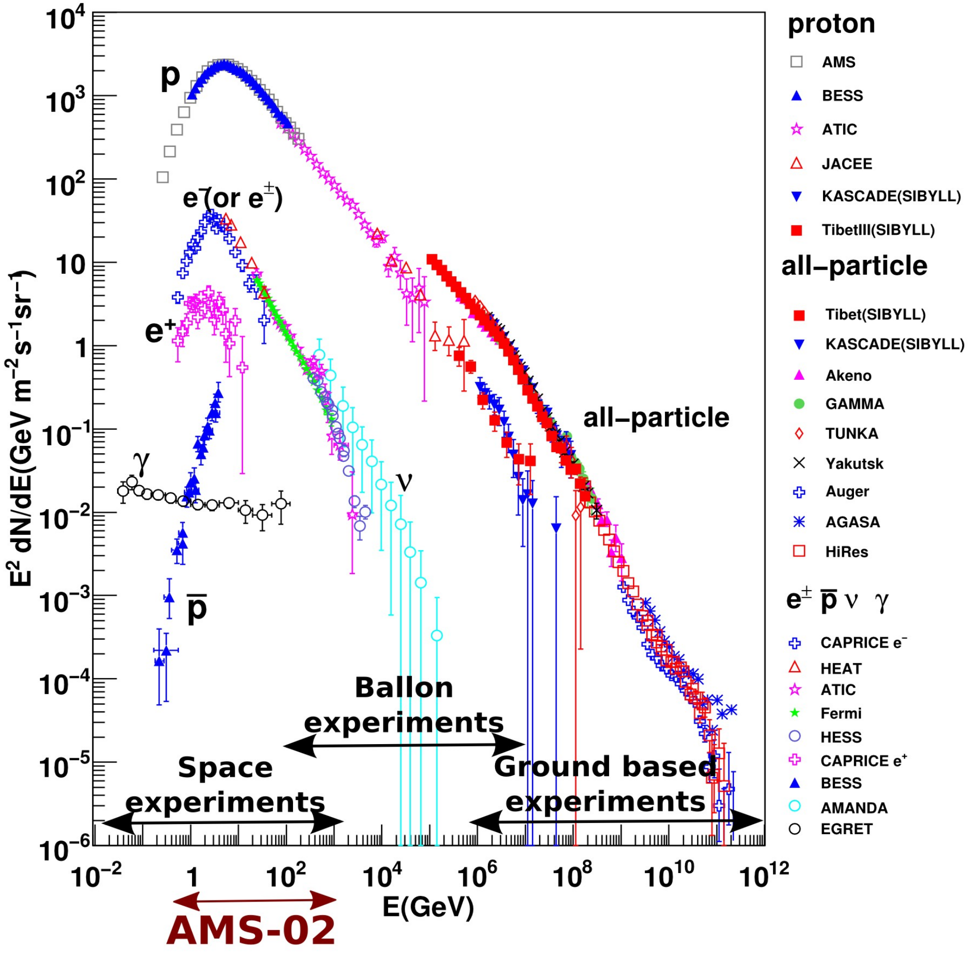
Institut für Experimentelle Kernphysik

WHAT WE MEASURE



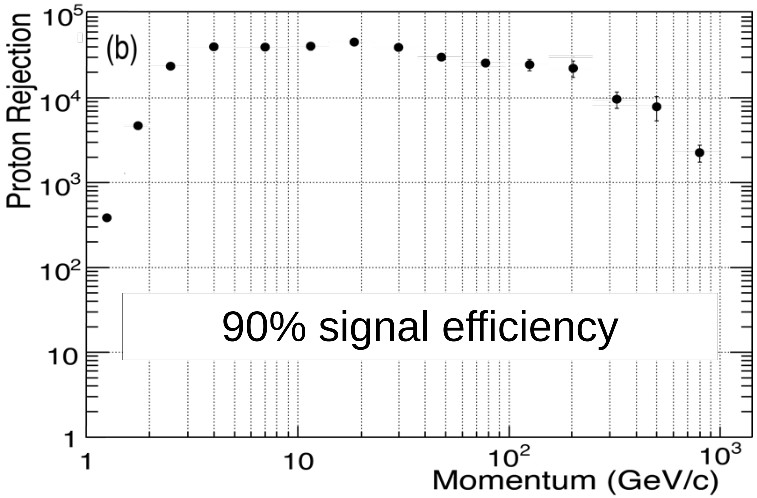
Sources of background:

- $\Phi(p) / \Phi(e^+) \sim 10^3$-$10^4$
  Misidentified protons
- $\Phi(e^-) / \Phi(e^+) \sim O(10)$
  Wrong charge sign measured

Lepton/hadron separation and charge confusion is the most crucial issue!

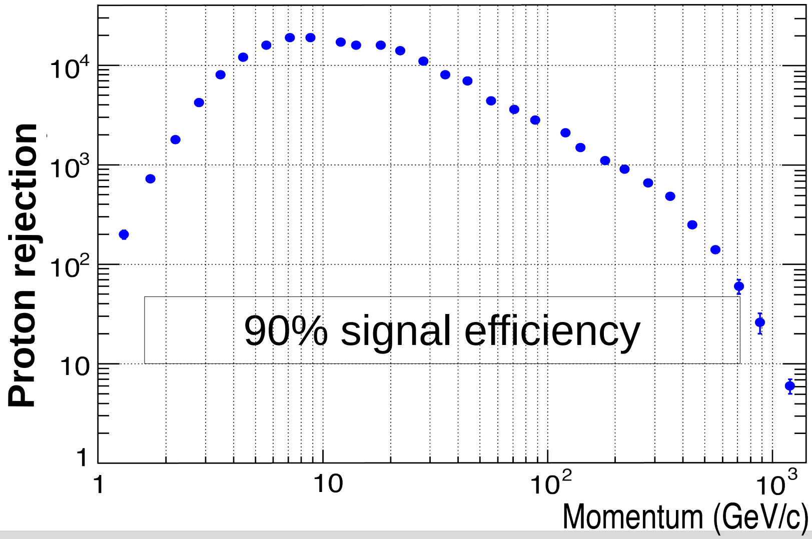
Among all triggered events, we have to find the 0.1%-0.01% signal ($e^{+/-}$)

PROTON REJECTION WITH TRD AND ECAL



ECAL proton rejection (on ISS data)
based on energy deposit and 3D shower development per layer

Rejection > 10^4
In the analyzed energy range



TRD proton rejection (on ISS data)
based on energy deposit in 20 layers

Rejection > 10^3
In the analyzed energy range

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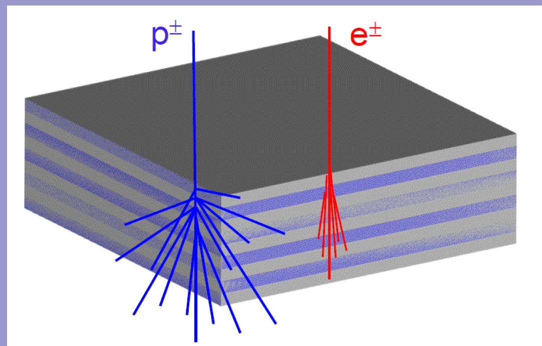
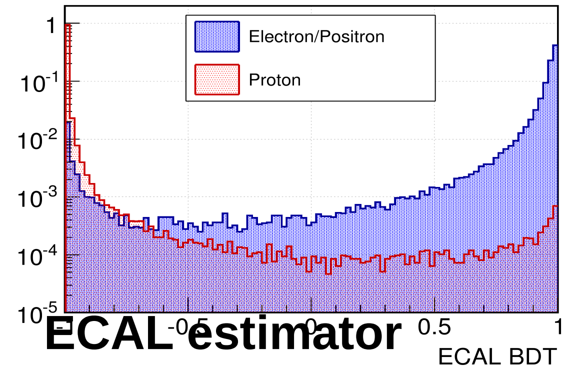
TOOLS FOR LEPTON IDENTIFICATION

ECAL



ECAL shower topology



ECAL estimator

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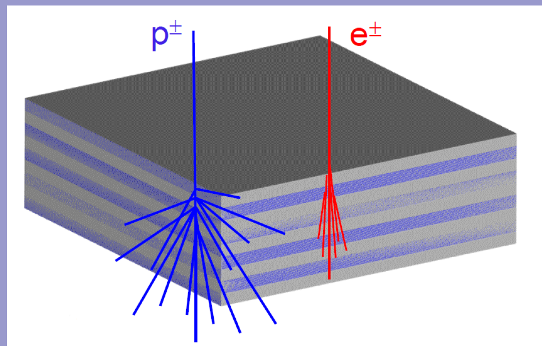
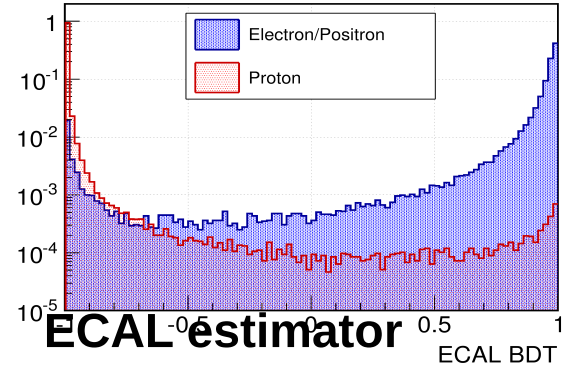
TOOLS FOR LEPTON IDENTIFICATION

ECAL

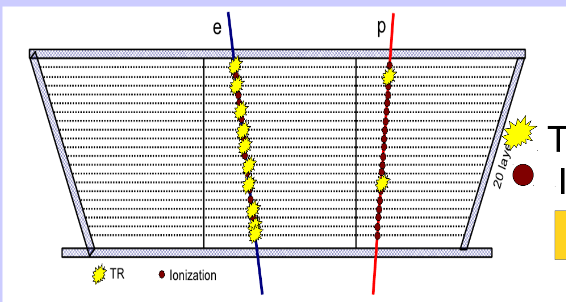


ECAL shower topology

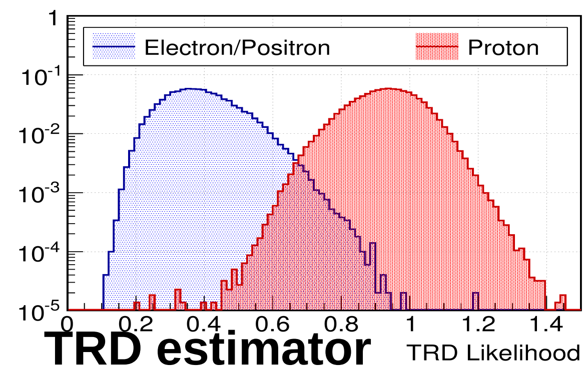


ECAL estimator

TRD



Transition rad.
Ionization



TRD estimator

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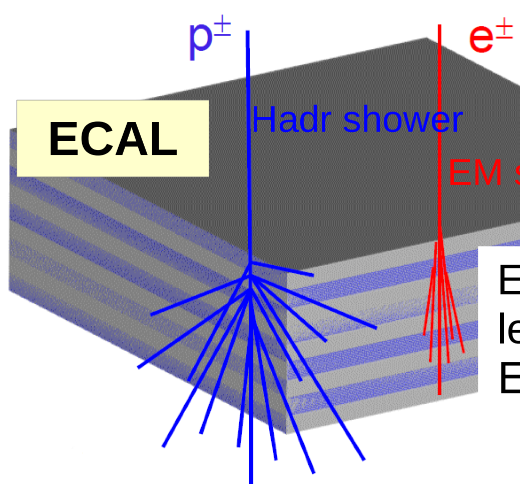
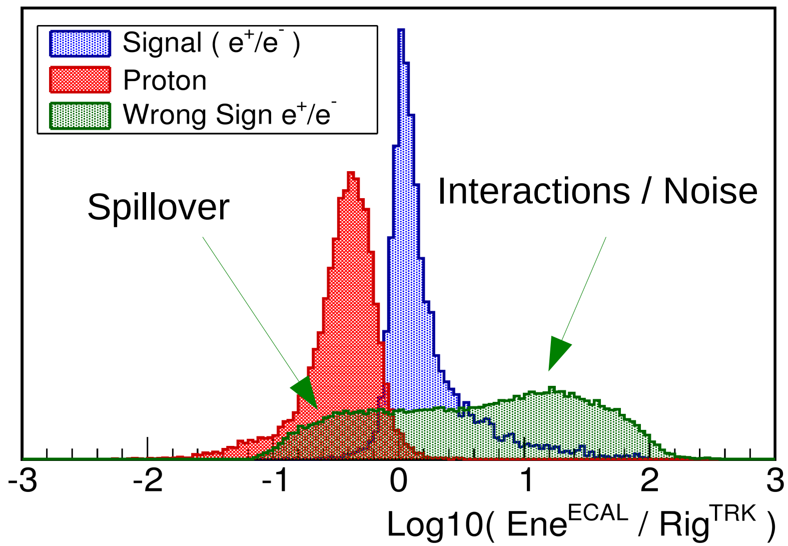
ECAL ENERGY AND TRACKER RIGIDITY

Proton ($E_{ECAL} << P_{TRK}$)



Electrons: energy leakage corrected E~P

Protons: high energy leakage E<<P



ECAL: **17 X_0, 0.6 λ_{nuc}**

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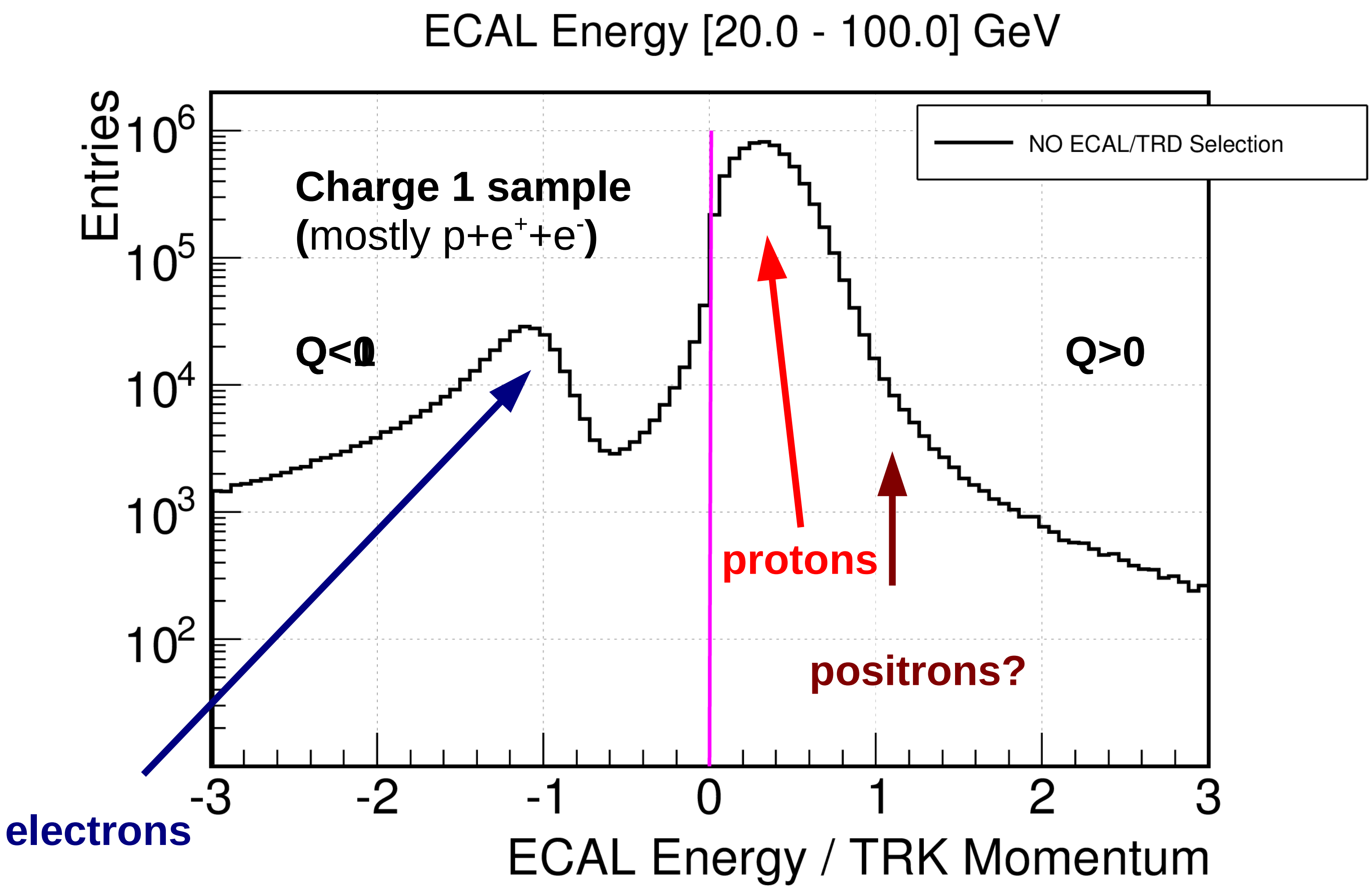
BACKGROUND REDUCTION



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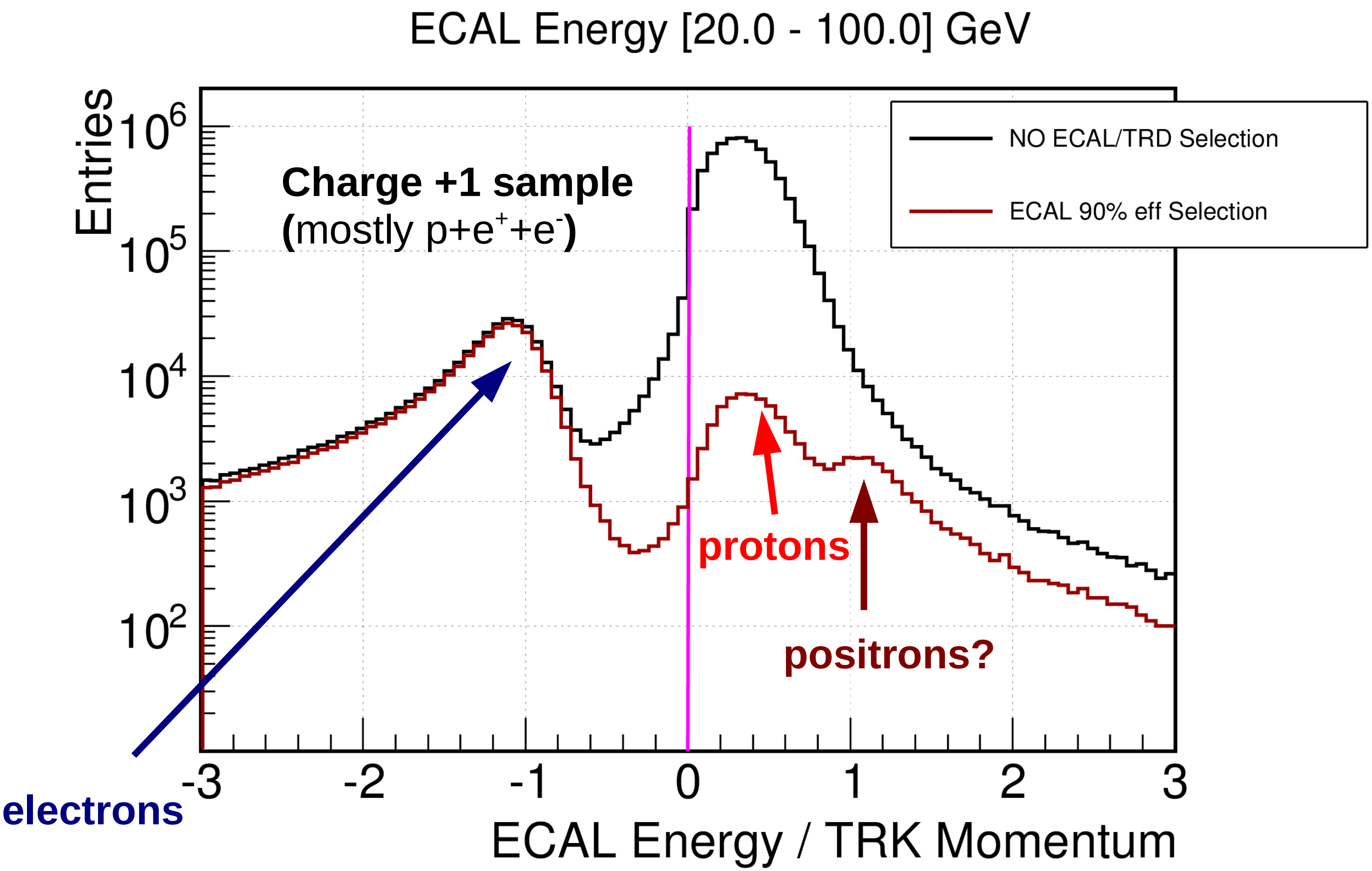
BACKGROUND REDUCTION



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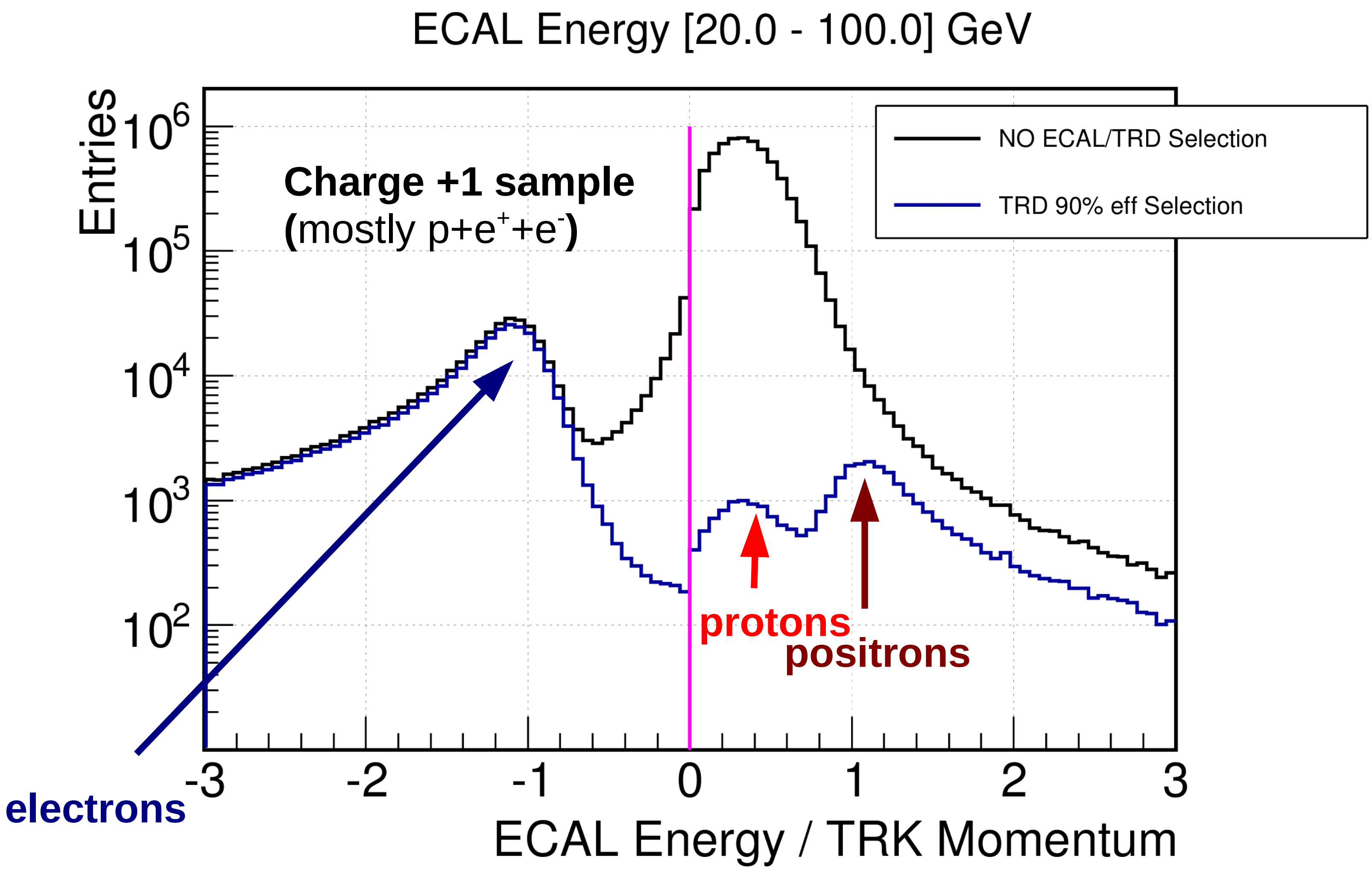
BACKGROUND REDUCTION



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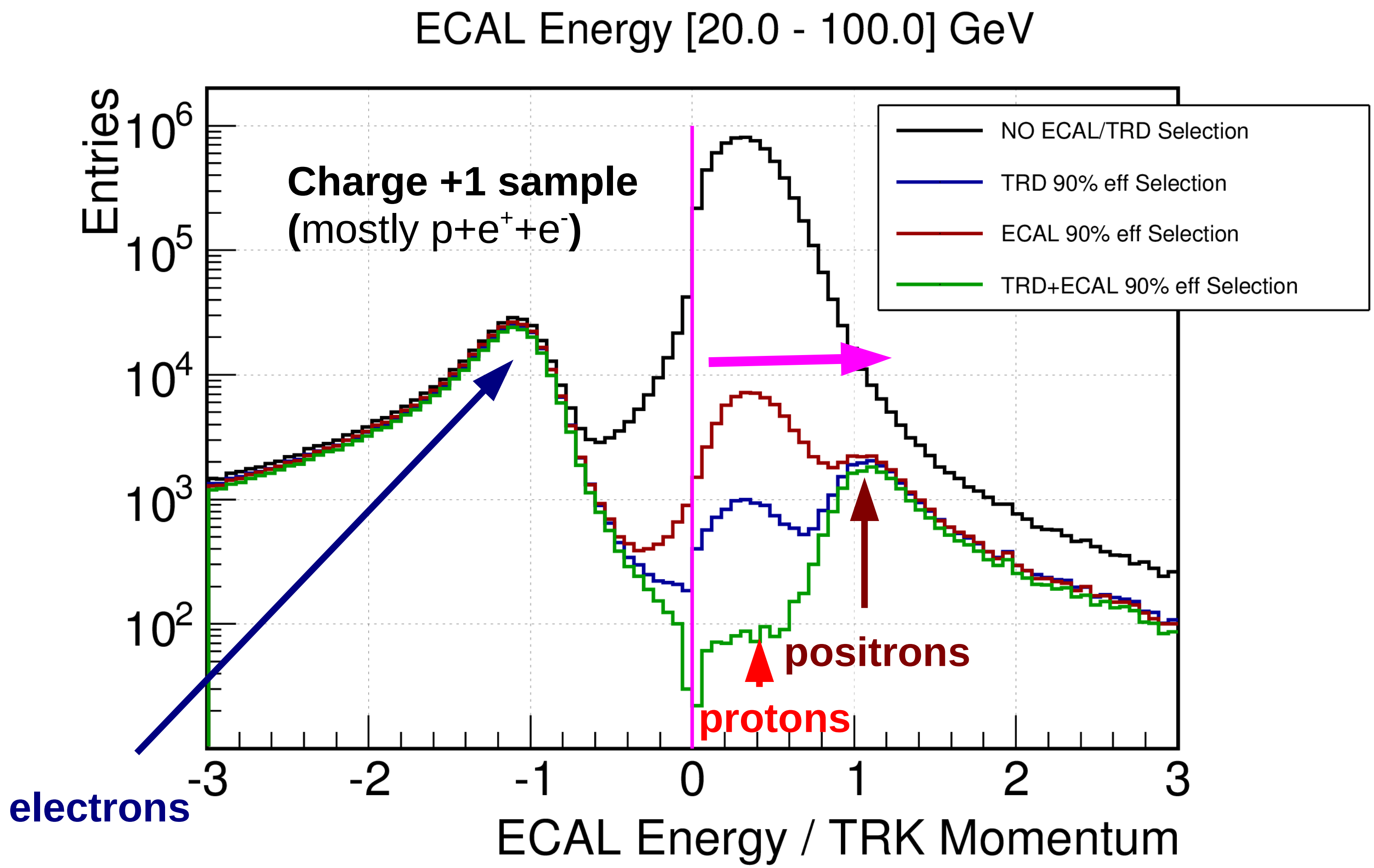
BACKGROUND REDUCTION



What is the fraction of positrons in the remaining sample?
What is the fraction of protons and wrong sign electrons?

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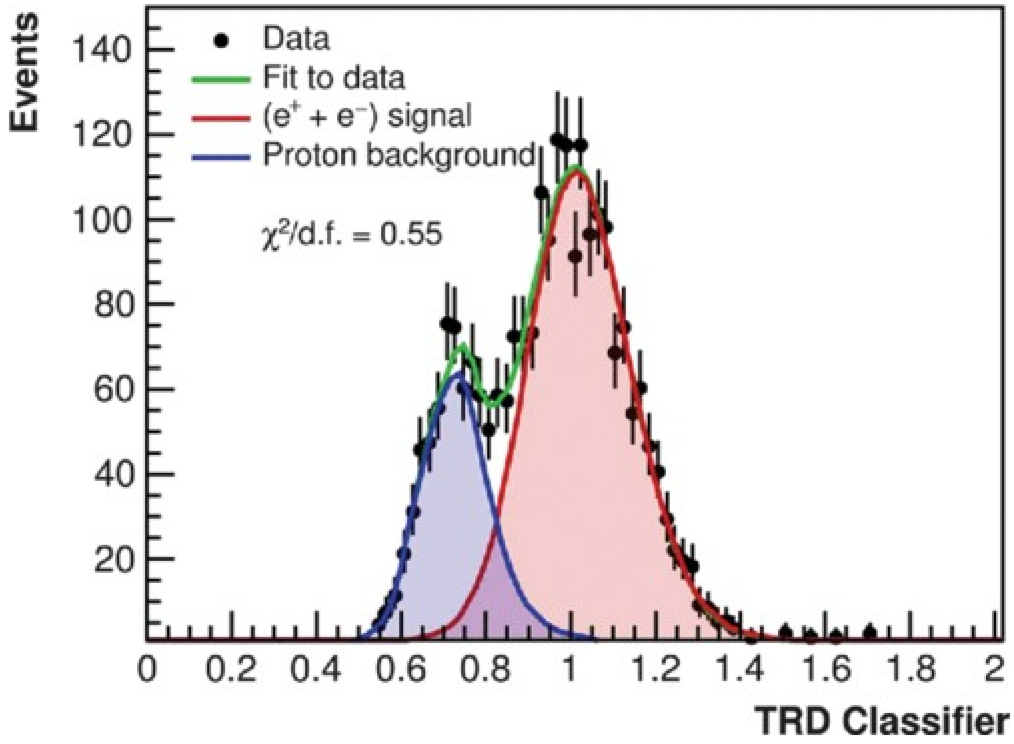
ELECTRON-POSITRON SUM FLUXES: TEMPLATE FIT

$e^{\pm}$ counts extracted fitting TRD classifier templates (reference shapes) to selected data



Template fits optimized for each analysis.

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INGREDIENTS FOR A FLUX MEASUREMENT

Karlsruhe Institute of Technology

N_{obs}=number of observed events

$$\Phi(E, E+\Delta E) = \frac{N_{obs}(E+\Delta E)}{\Delta E \, \Delta T_{exp} \, A_{eff} \, \epsilon_{trig}}$$

ϵ_{trig}=trigger efficiency

ΔT_{exp}=exposure Time (s)

A_{eff}=effective acceptance ($m^2 \, sr^1$)

2. Determine exposure time

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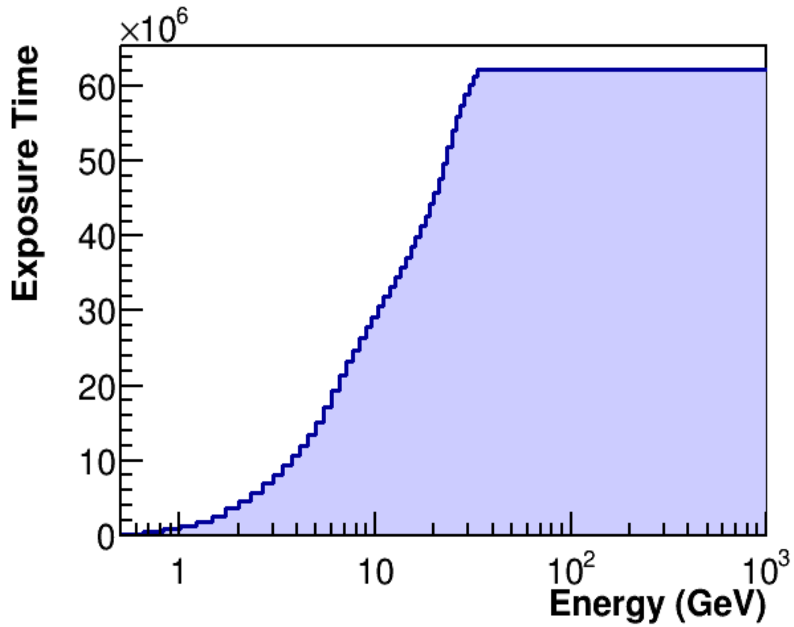
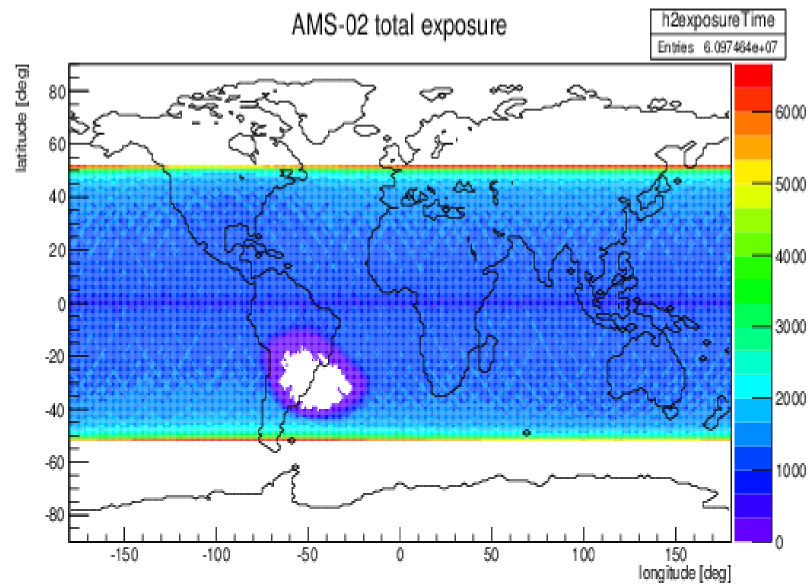
Institut für Experimentelle Kernphysik

EXPOSURE TIME

$\Delta T_{\exp}$ =Time in which we could take data= $\Delta T_{obs} \, x \, \tau_{life}$





Depends on energy due to geomagnetic cutoff cut

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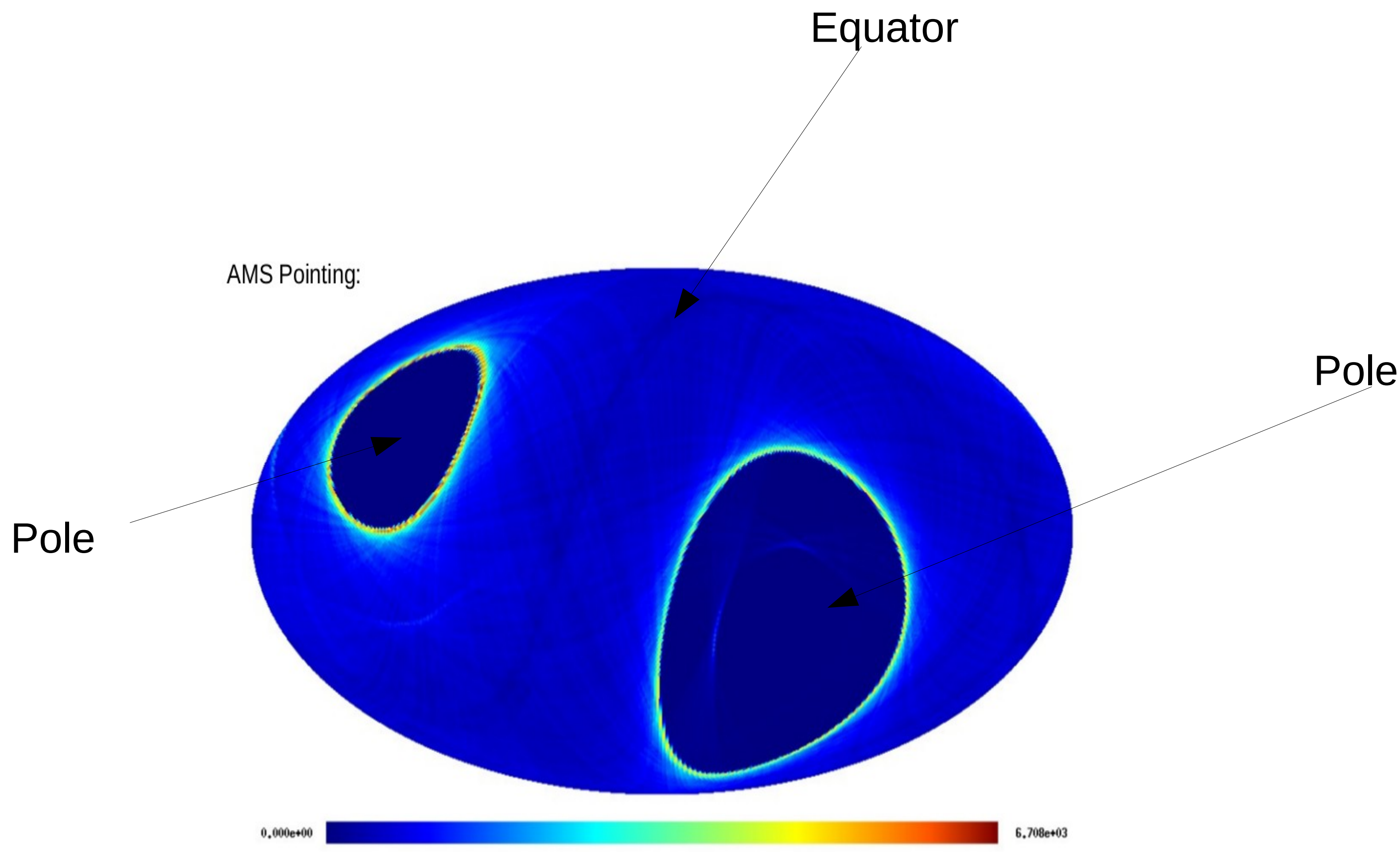
POINTING DIRECTION



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Karlsruhe Institute of Technology

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ϵ_{trig}=trigger efficiency

ΔT_{exp}=exposure Time (s)

A_{eff}=effective acceptance ($m^2 \, sr^1$)

3. Determine acceptance

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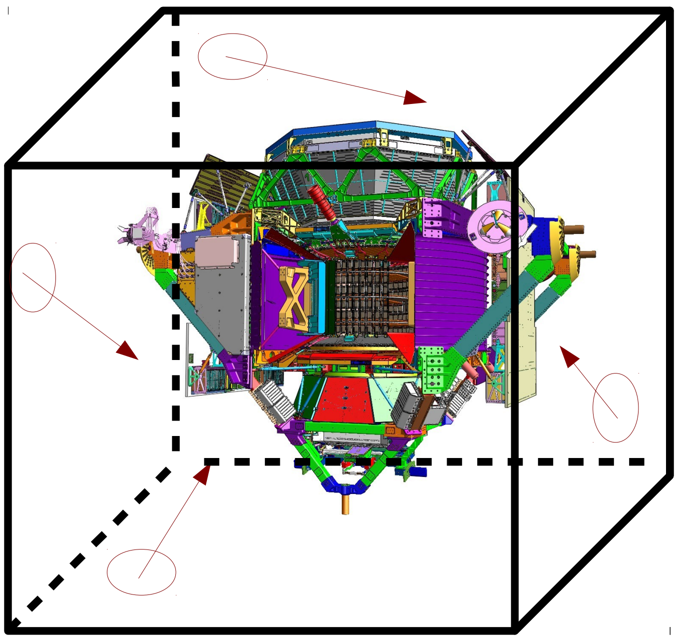
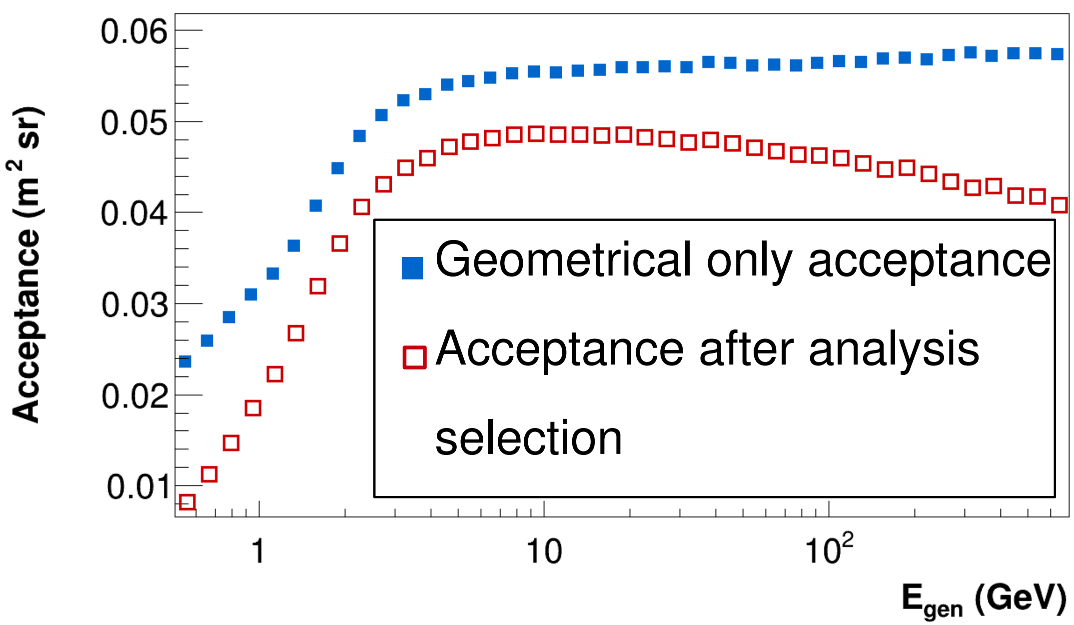
ACCEPTANCE



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



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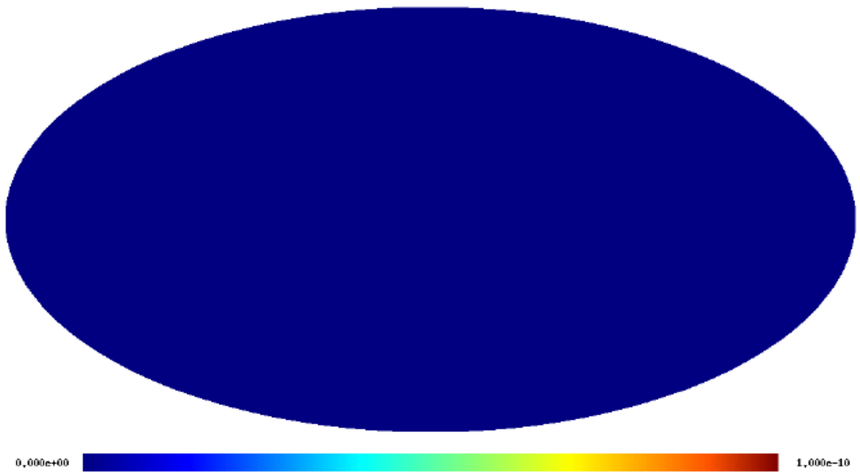
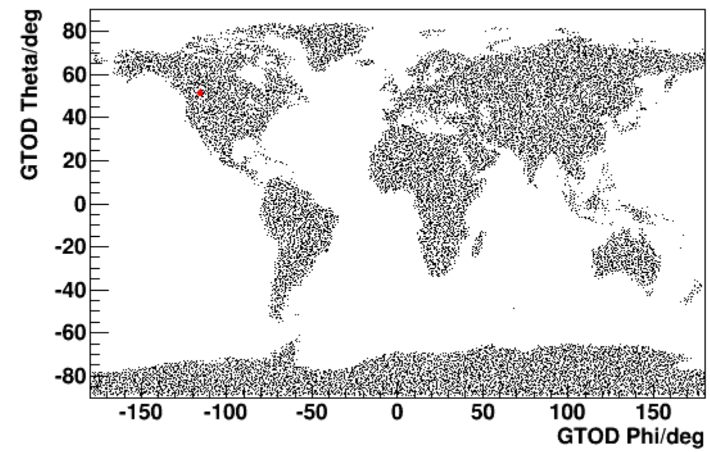
EXPOSURE TIME x ACCEPTANCE

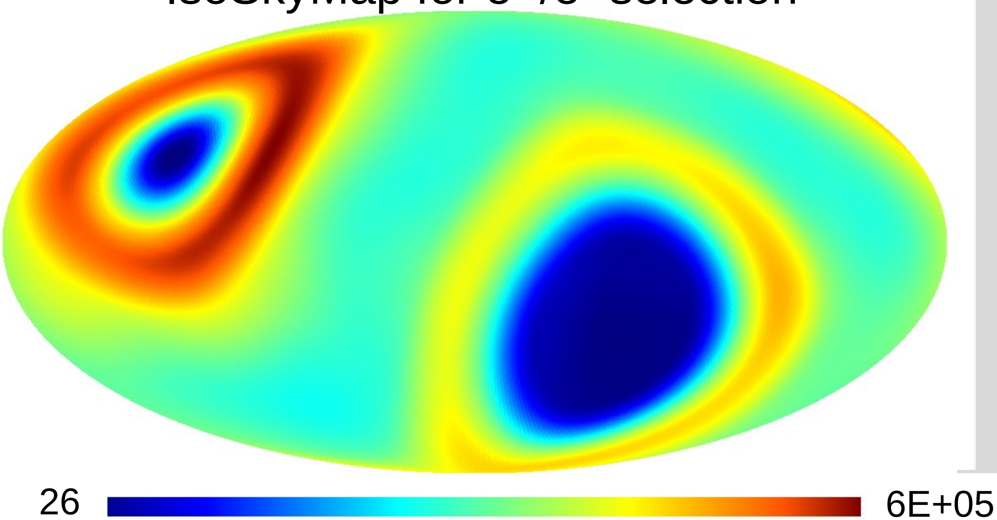


T_{exp} x Acc [m^2 rad s]



Sum over all pass4
May 2011-Nov 2013

IsoSkyMap for e+/e- selection



T_{exp} x Acc [m^2 rad s]

ELECTRON-POSITRON SUM FLUXES

N_{obs}=number of observed events

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ϵ_{trig}=trigger efficiency

ΔT_{exp}=exposure Time (s)

A_{eff}=effective acceptance ($m^2 \, sr^1$)

3. Determine trigger efficiency

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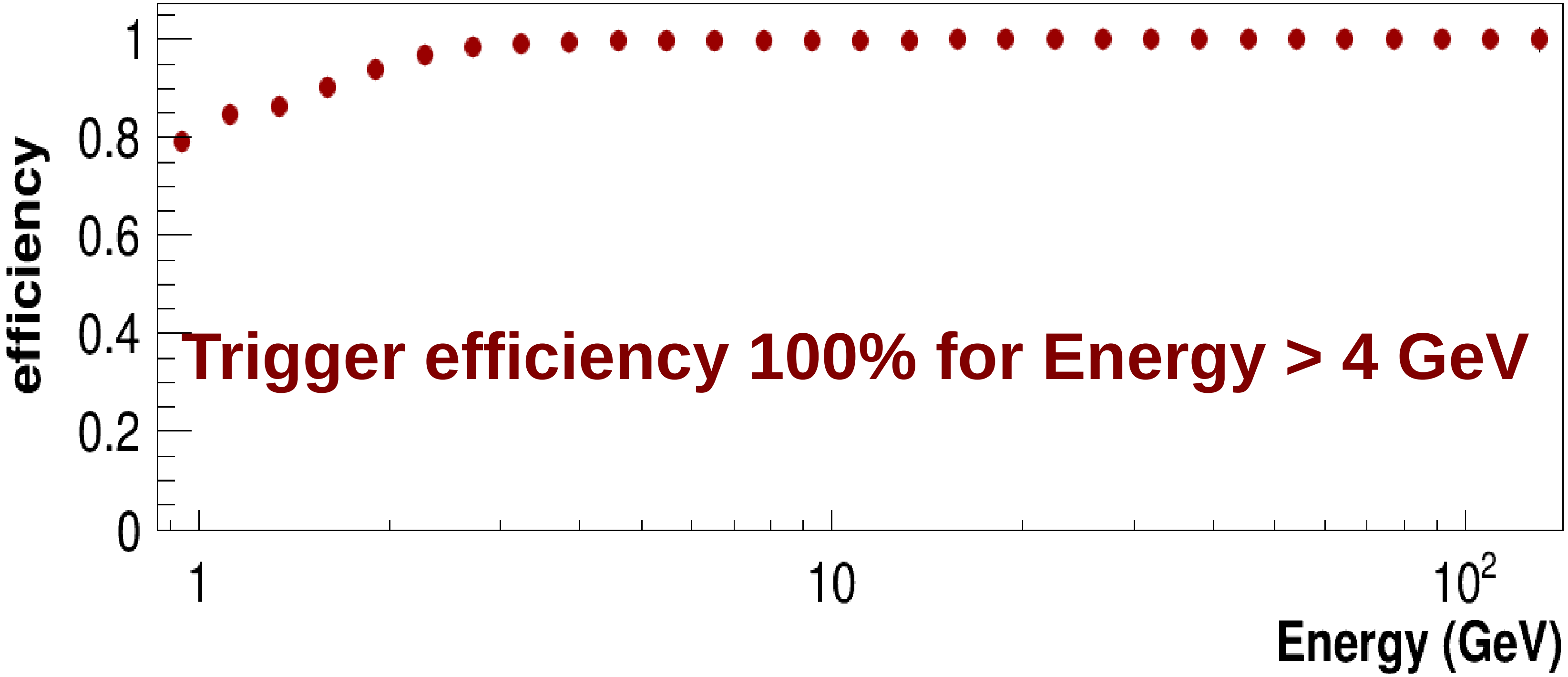
TRIGGER EFFICIENCY

Determined with ISS unbiased triggers
(pre-scaled by 1/100)



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AMS-02 RESULTS

NEW LEPTON SUM FLUXES

NEW SEPARATE e^+ e^- FLUXES

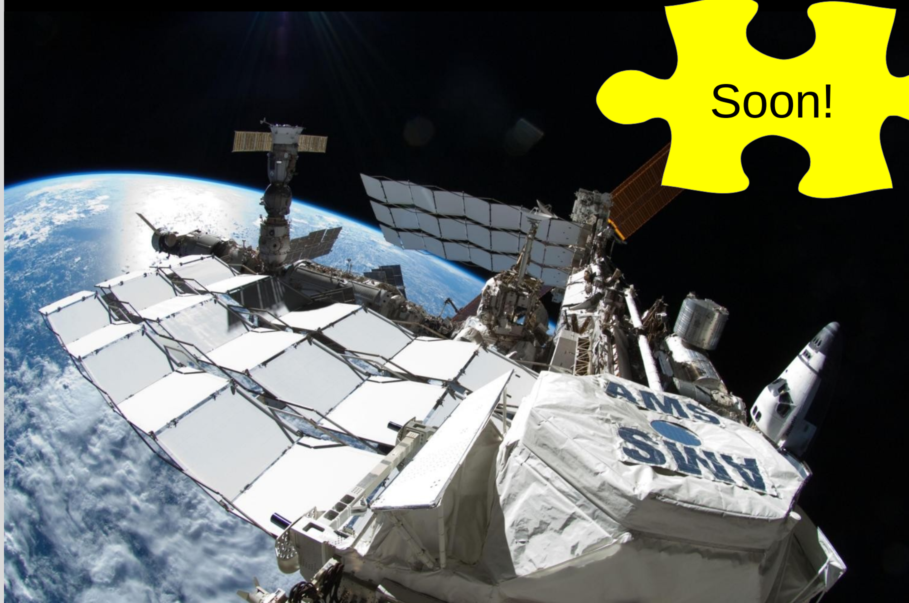
NEW POSITRON FRACTION

PROTON AND HELIUM FLUXES

BORON/CARBON + and other ratios

Soon!

NEW ANISOTROPY STUDIES



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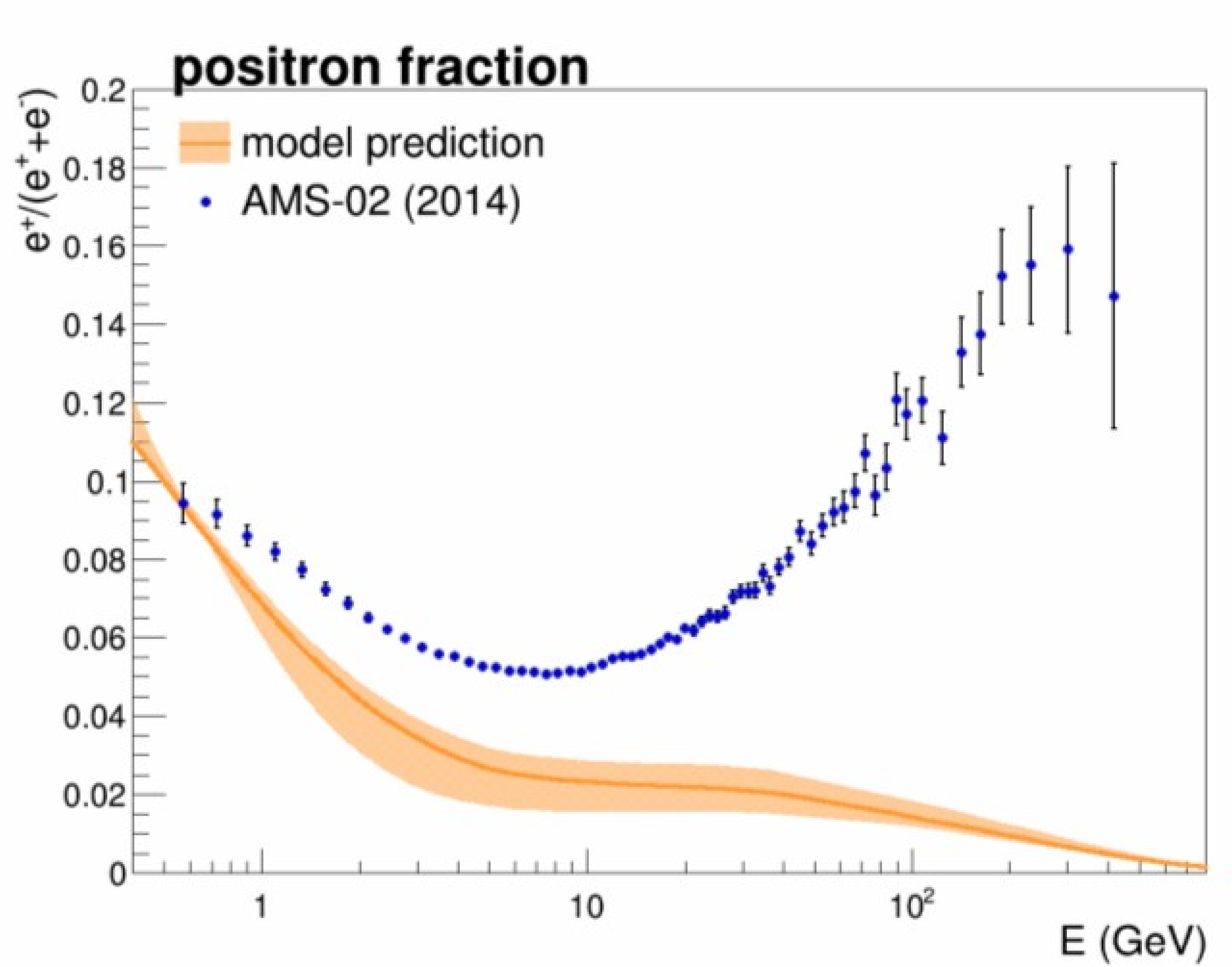
POSITRON FRACTION UPDATE 2014

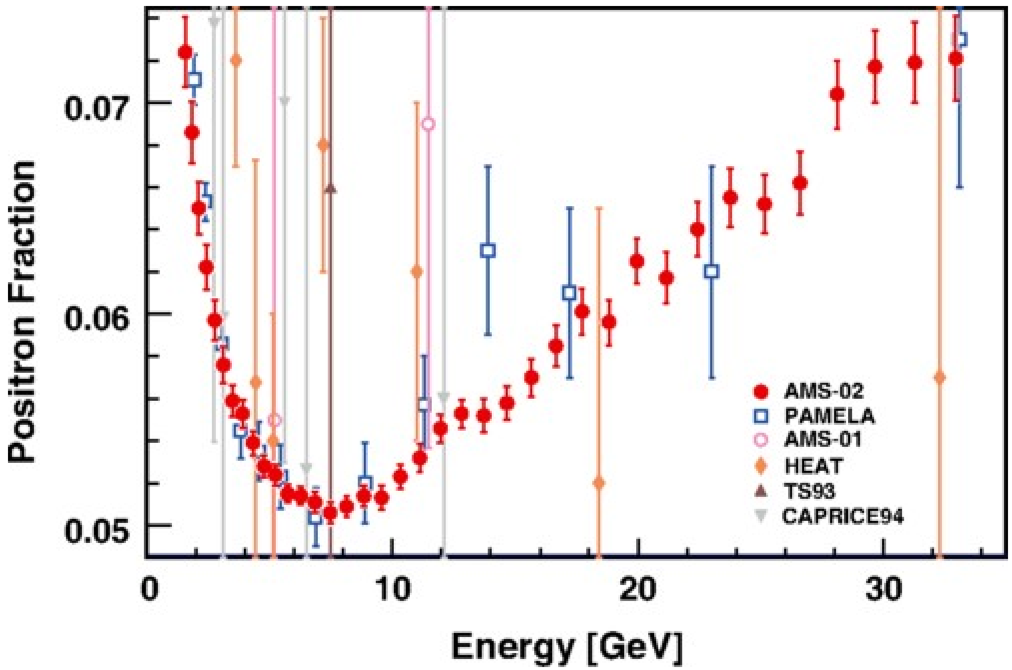


- based on 10.9 million e+ and e- events
- Fraction measured from 0.5-500 GeV
- unexpected rise above a few GeV

Prediction for “standard comsic ray” electrons (from SNR) + positrons (from proton-gas interactions).

POSITRON FRACTION UPDATE 2014

Phys. Rev. Lett. 113, 121101 (Sept. 2014)



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POSITRON FRACTION UPDATE 2014

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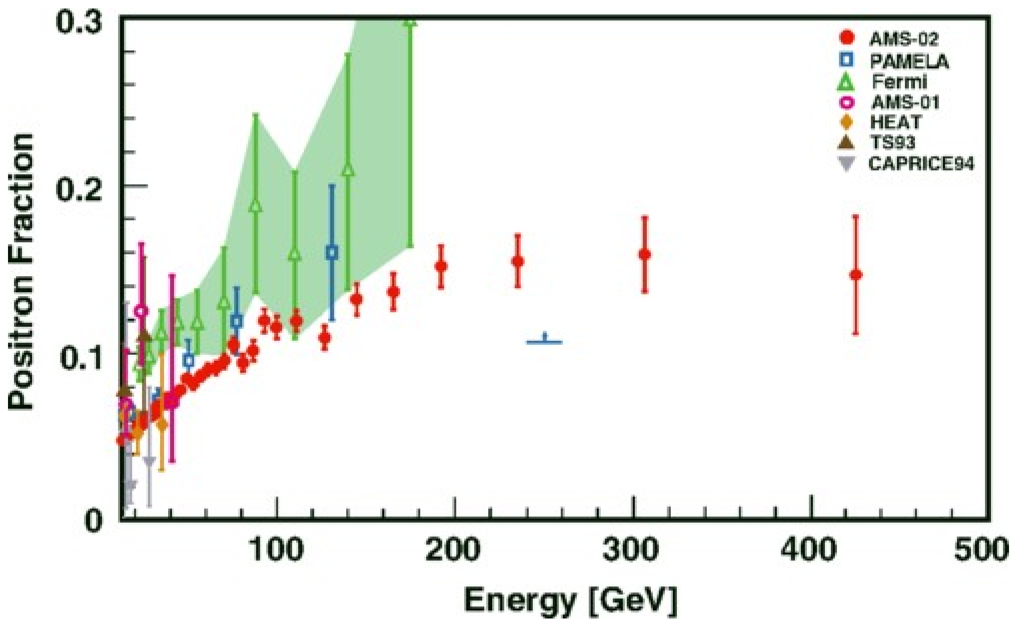
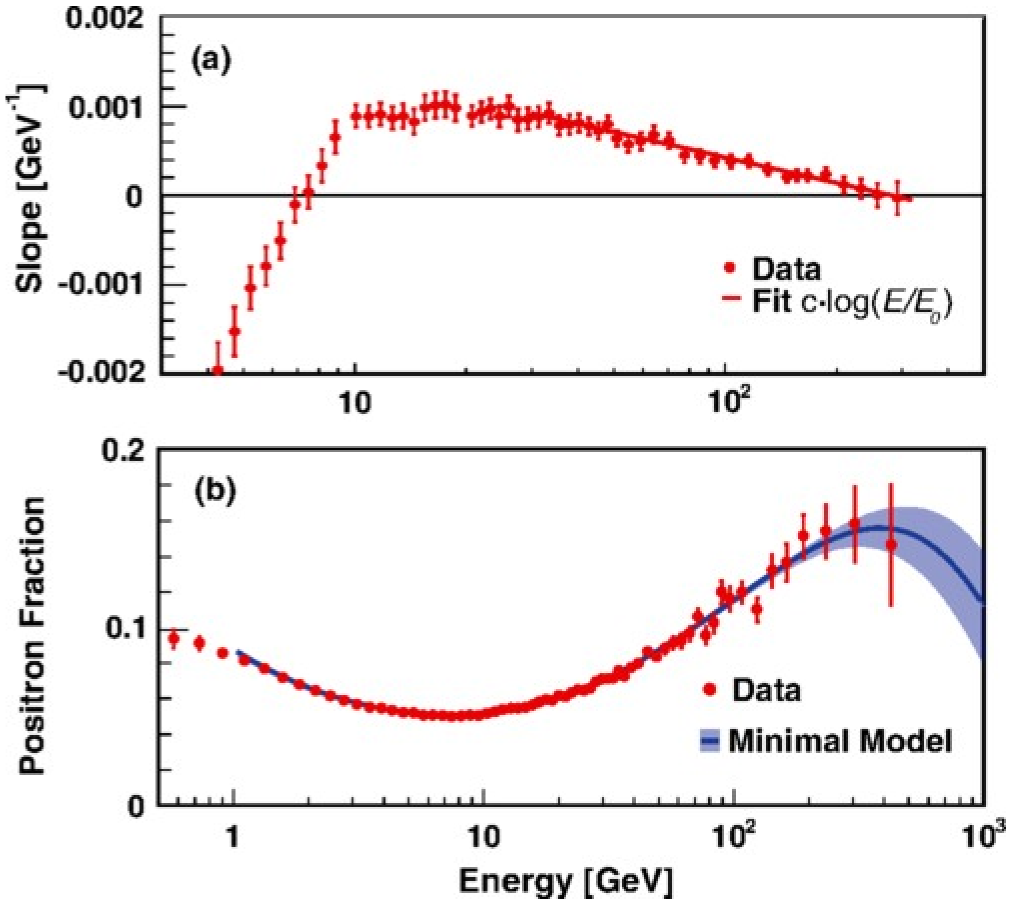


- Flattening above 200 GeV confirmed
- Relative error on last point ~20%
- No hint at structure

POSITRON FRACTION UPDATE 2014

Phys. Rev. Lett. 113, 121101 (Sept. 2014)



- Above 200 GeV the fraction no longer exhibits an increase with energy

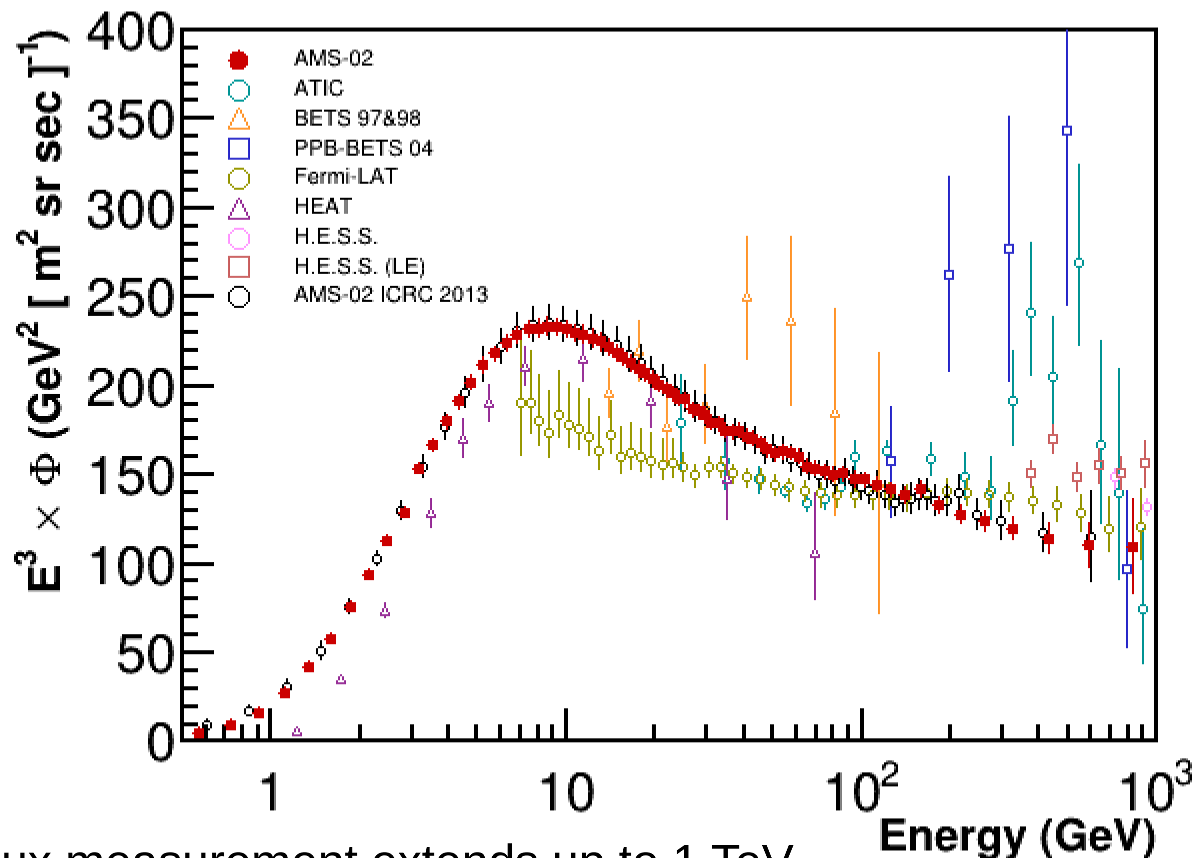
- "Minimal model":

$$\Phi_{e+} = C_{e+} E^{-\gamma_{e+}} + C_c E^{-\gamma_c} e^{E\zeta_c}$$

$$\Phi_{e-} = C_{e-} E^{-\gamma_{e-}} + C_c E^{-\gamma_c} e^{E\zeta_c}$$

common source

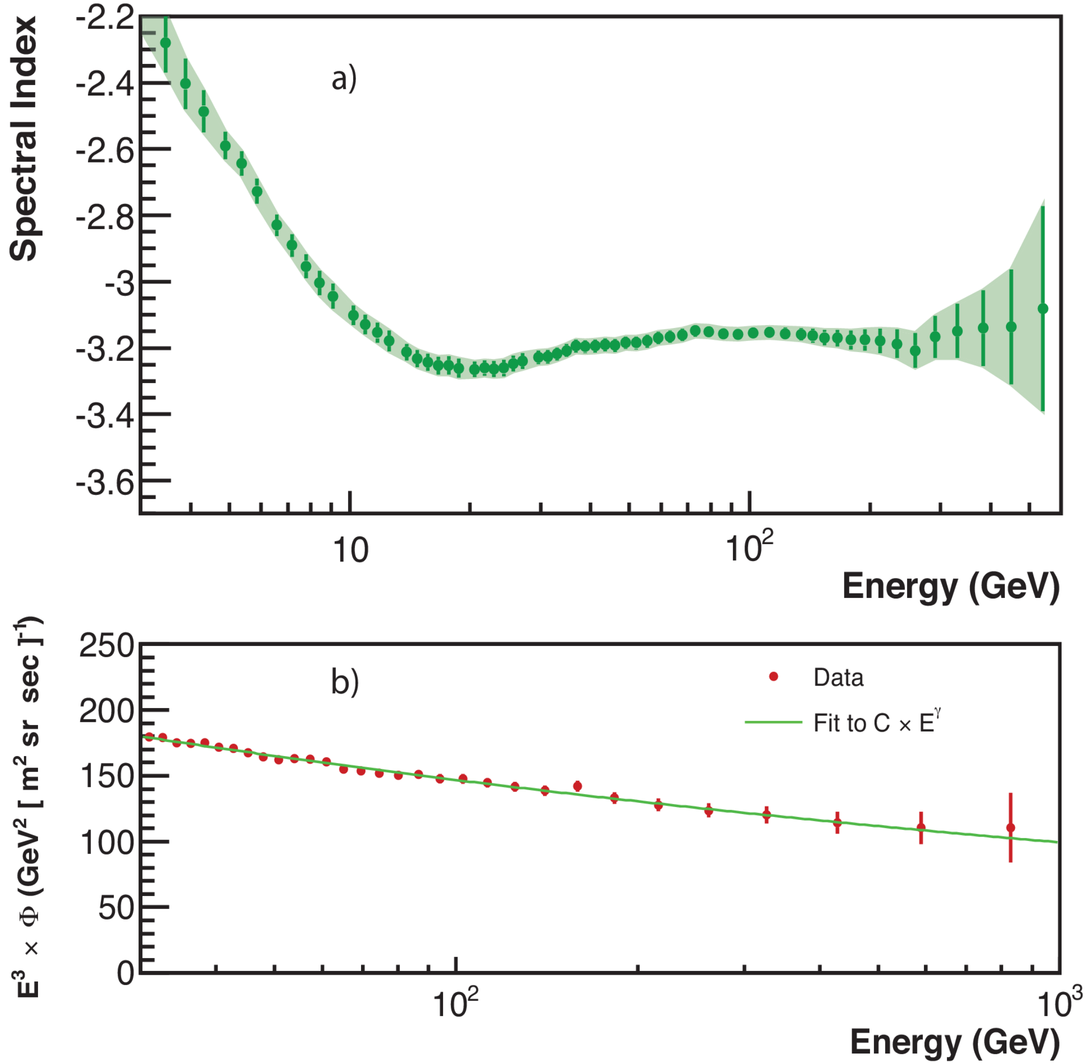
ELECTRON+POSITRON SUM FLUX



Phys. Rev. Lett. 113, 221102 (Nov 2014)

- Sum flux measurement extends up to 1 TeV
- No feature in the sum flux

ELECTRON+POSITRON SUM FLUX

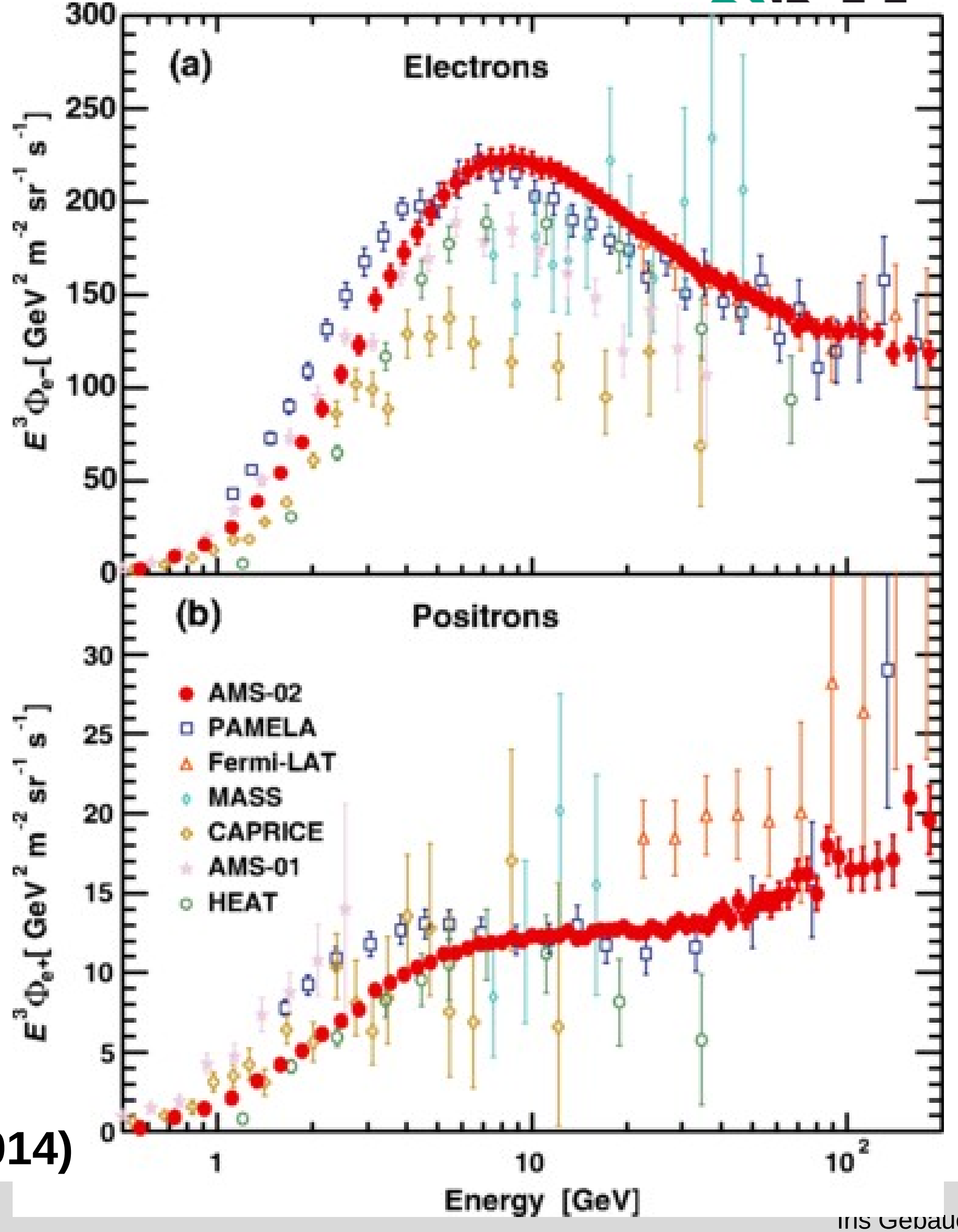


- Spectral index drops from -2.2 at 3 GeV to -3.2 above 10 GeV
- Remains constant above 30 GeV
- Single power law describes data above 30 GeV
- Below 30 GeV harder spectrum required

ELECTRON AND POSTRON FLUX

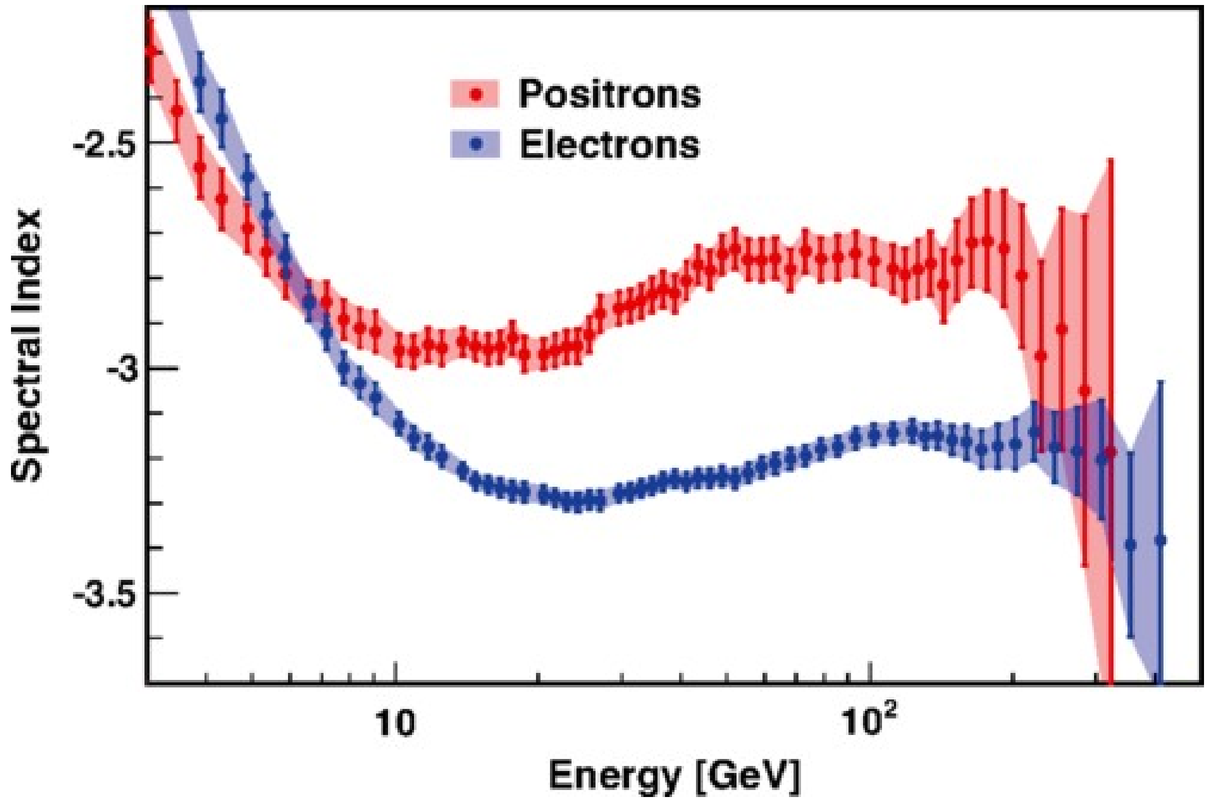
Mainly primaries
(produced in SNR)

Pure secondaries
(produced in ISM (p+gas))



Phys. Rev. Lett. 113, 121102 (Sept. 2014)

ELECTRON AND POSTRON FLUX



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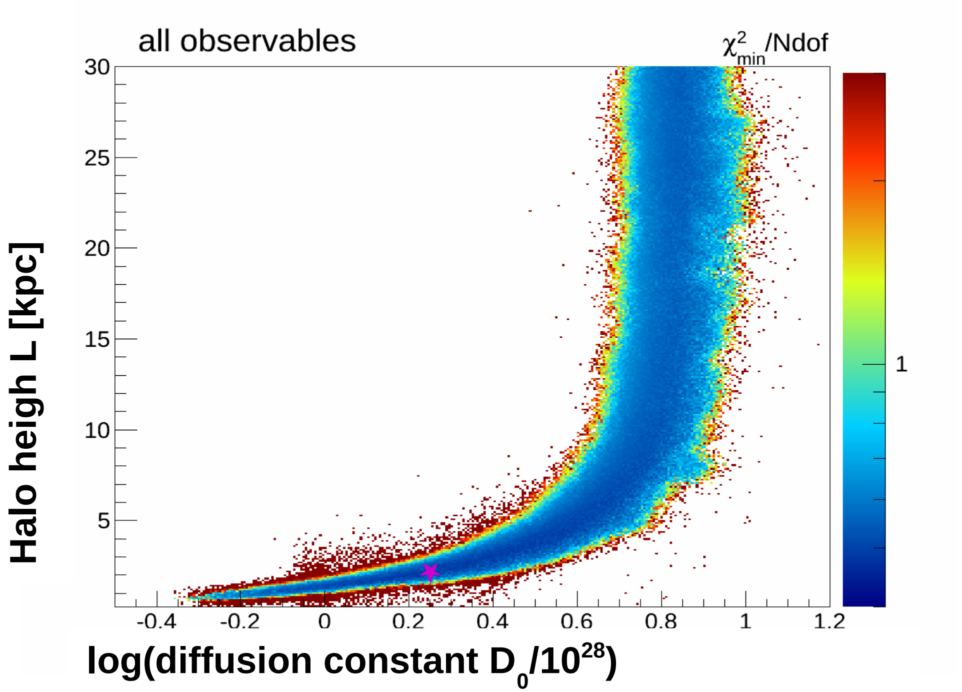
MODELLING CR TRANSPORT

USE:
- Protons, antiprotons (PAMELA)
- B/C (**ACE, HEAO, CREAM**)
- ^{10}Be/^{9}Be (ACE, ISOMAXX)

→ constrain transport parameter space using MCMC

PREDICT: secondary e+ (e-), secondary $\bar{p}$ (+p), diffuse γ, synchrotron radiation.

Analysis was performed at KIT using 15 Mio. evaluated models and public data → will serve as a starting point for similar studies using exclusively AMS-02 data.



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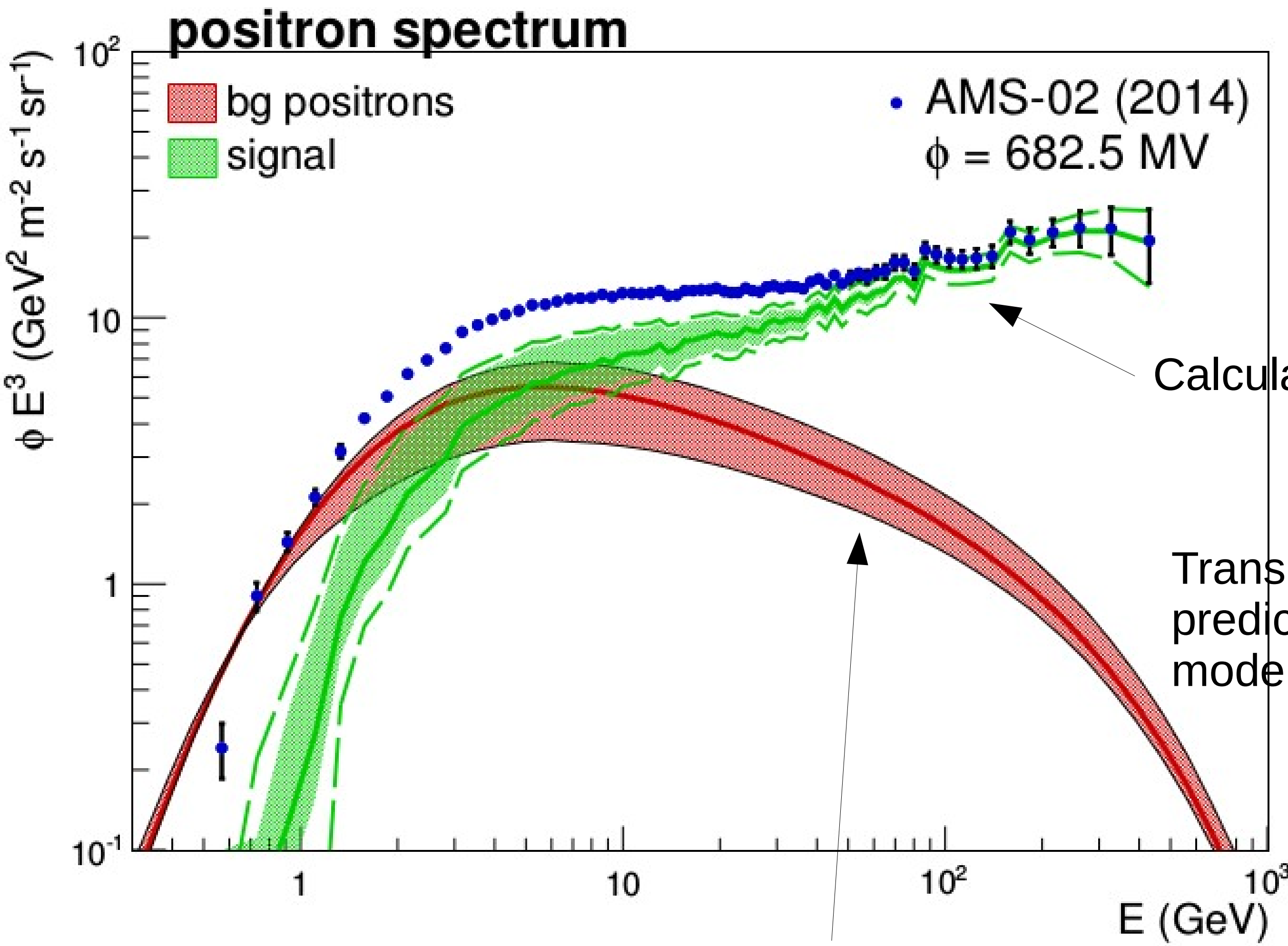
MODELLING CR TRANSPORT



Calculated from data

Transport model prediction (15 Mio models)

Uncertainty from transport parameters!

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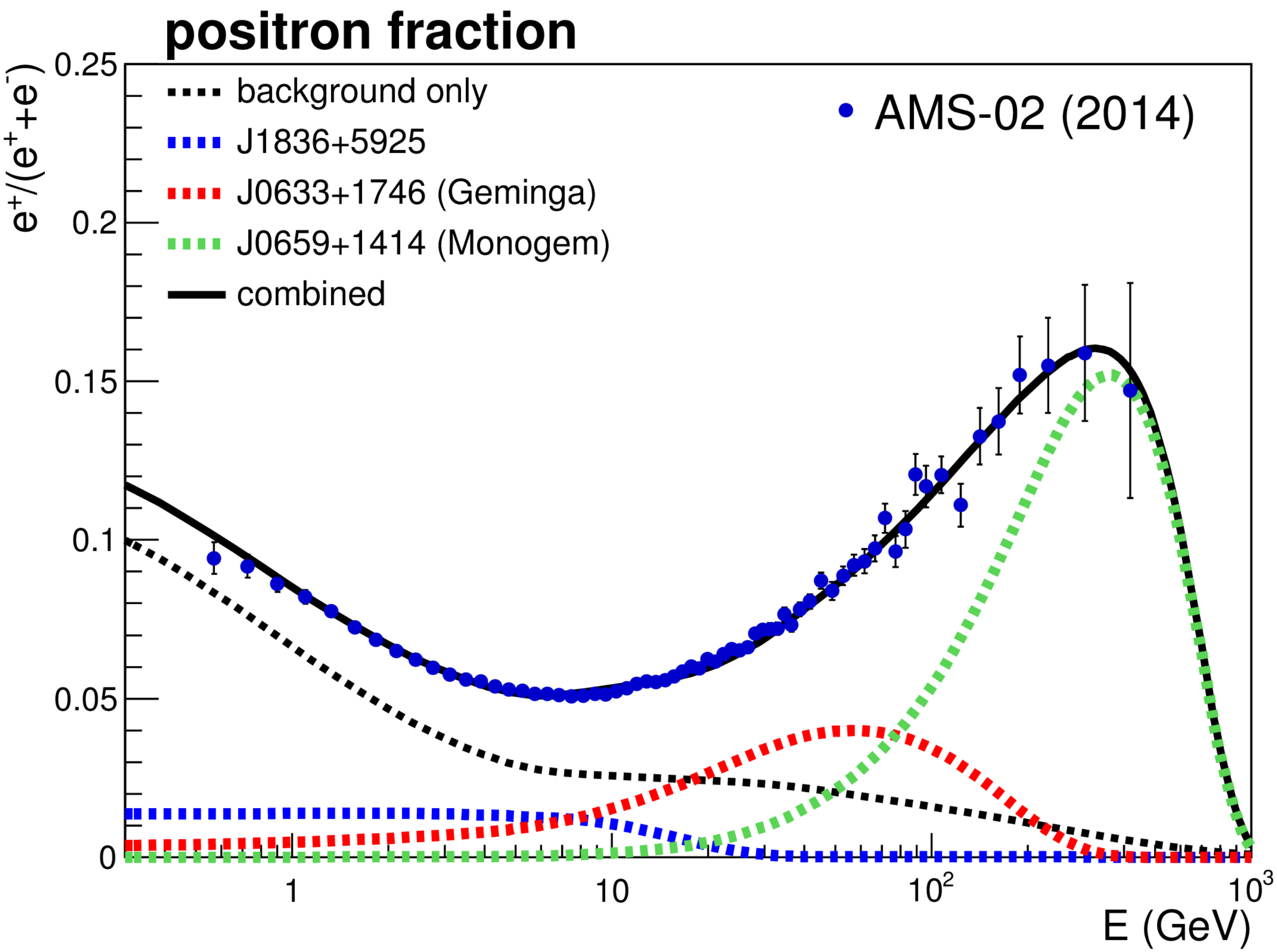
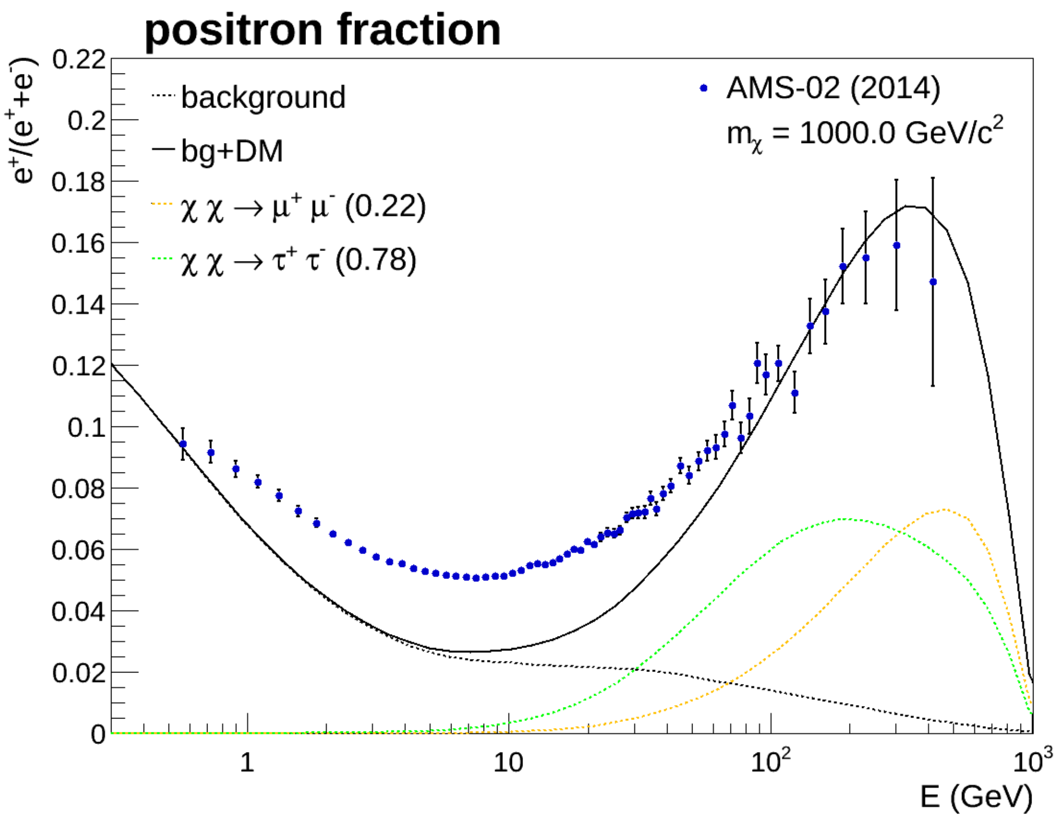
PULSARS AS A POSSIBLE SOURCE



Pulsars tuned to AMS data.

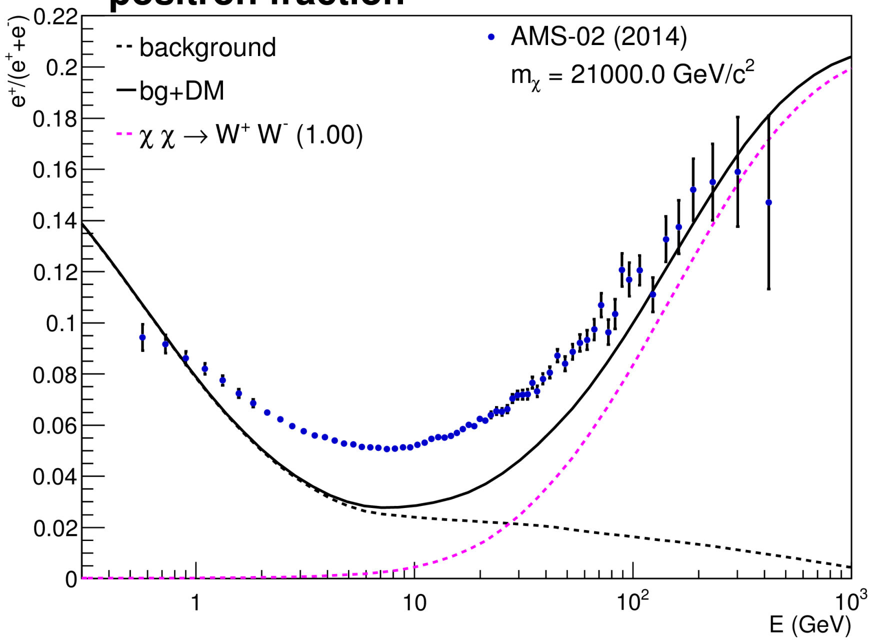
DARK MATTER ANNIHILATION AS A POSSIBLE SOURCE

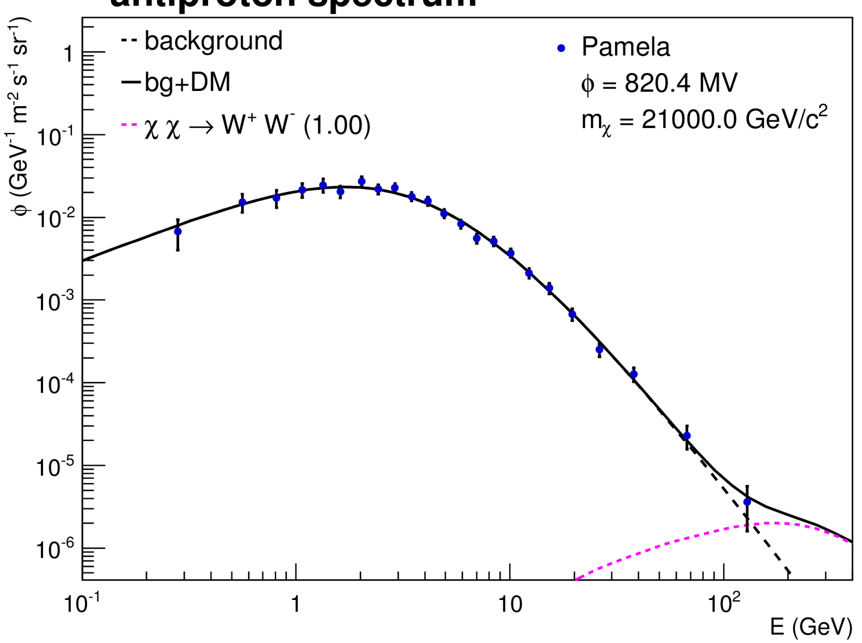
Karlsruhe Institute of Technology



"Leptophilic" DM candidate tuned to high energy data.

DARK MATTER ANNIHILATION AS A POSSIBLE SOURCE



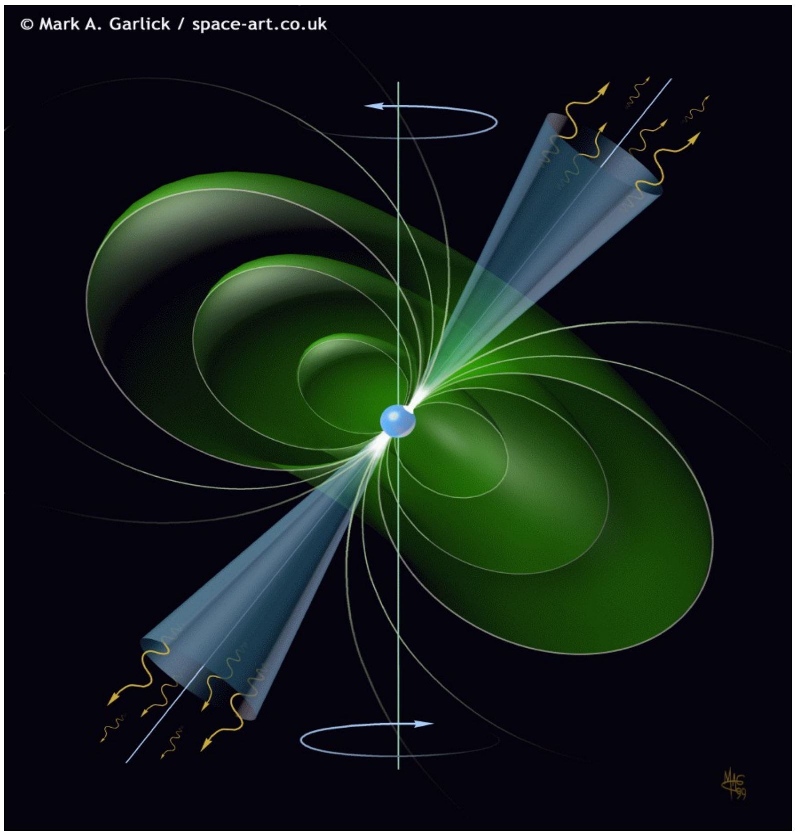


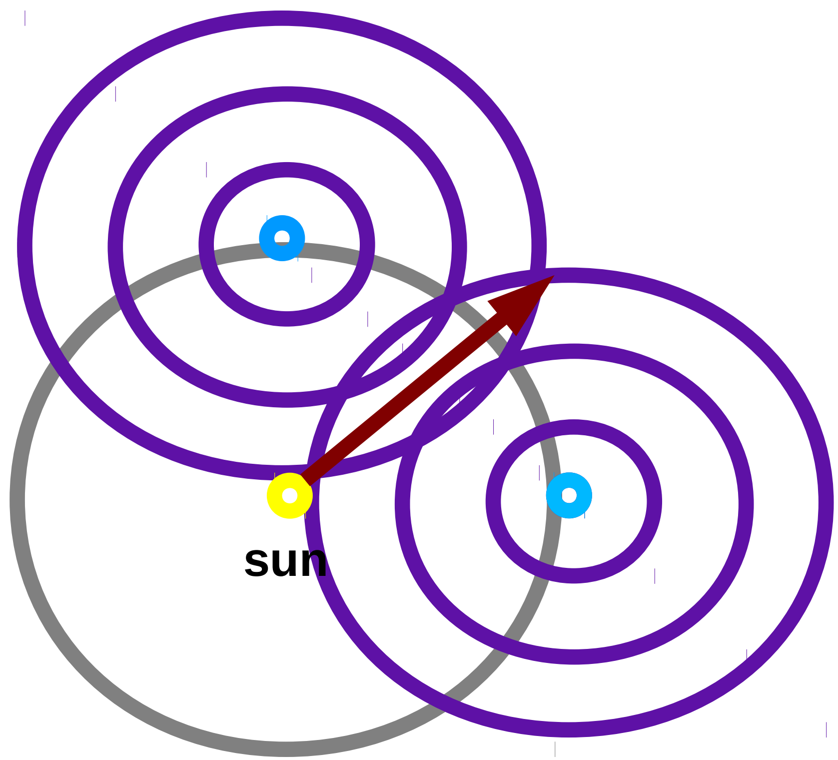
Hadronic contributions require very high DM masses to not violate antiproton constraints.

HOW TO TELL PULSARS FROM DMA: ANISOTROPIES

Pulsar contribution?

Expect anisotropies!
Not the fluxes, but the arrival directions are the key to the lepton puzzle





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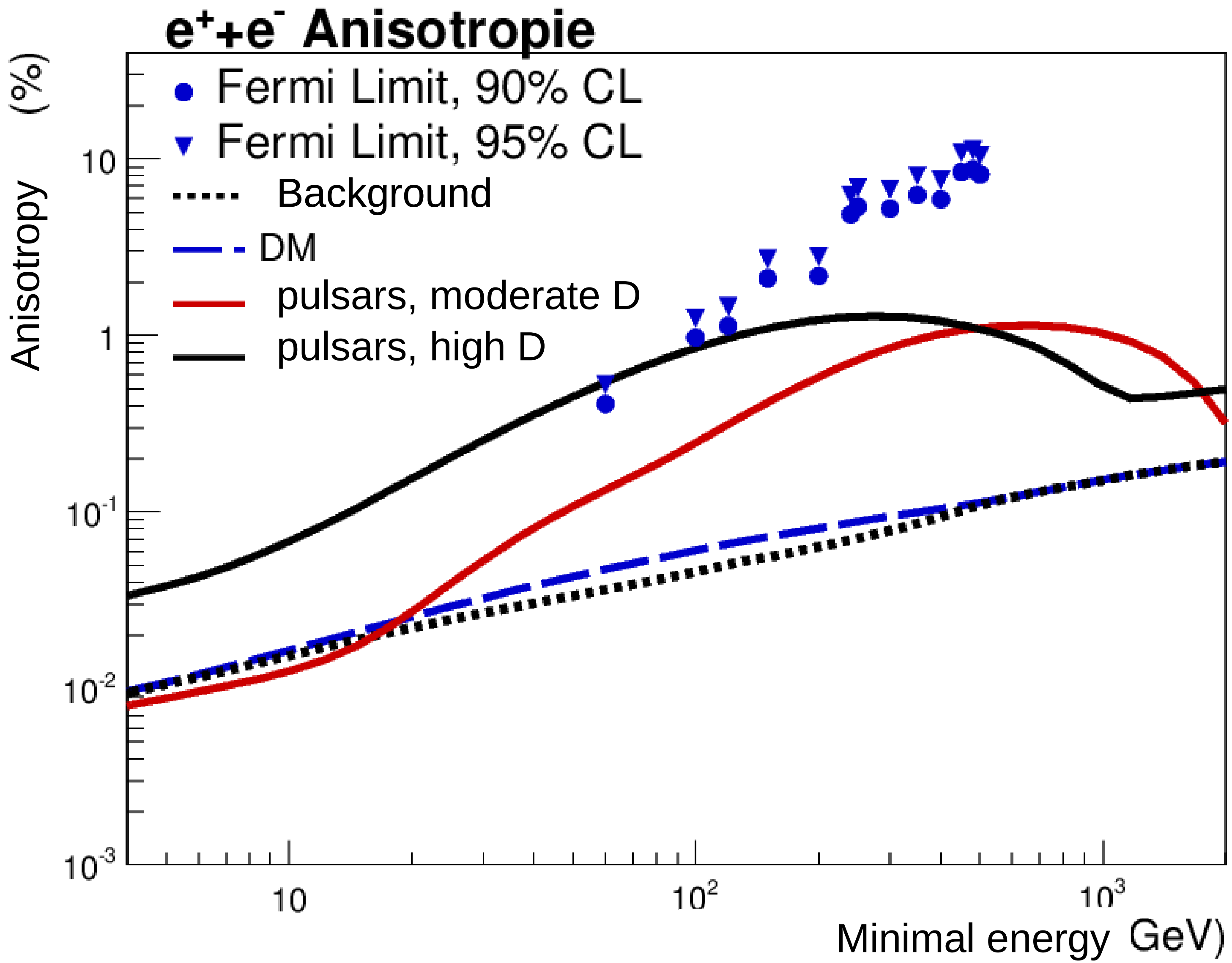
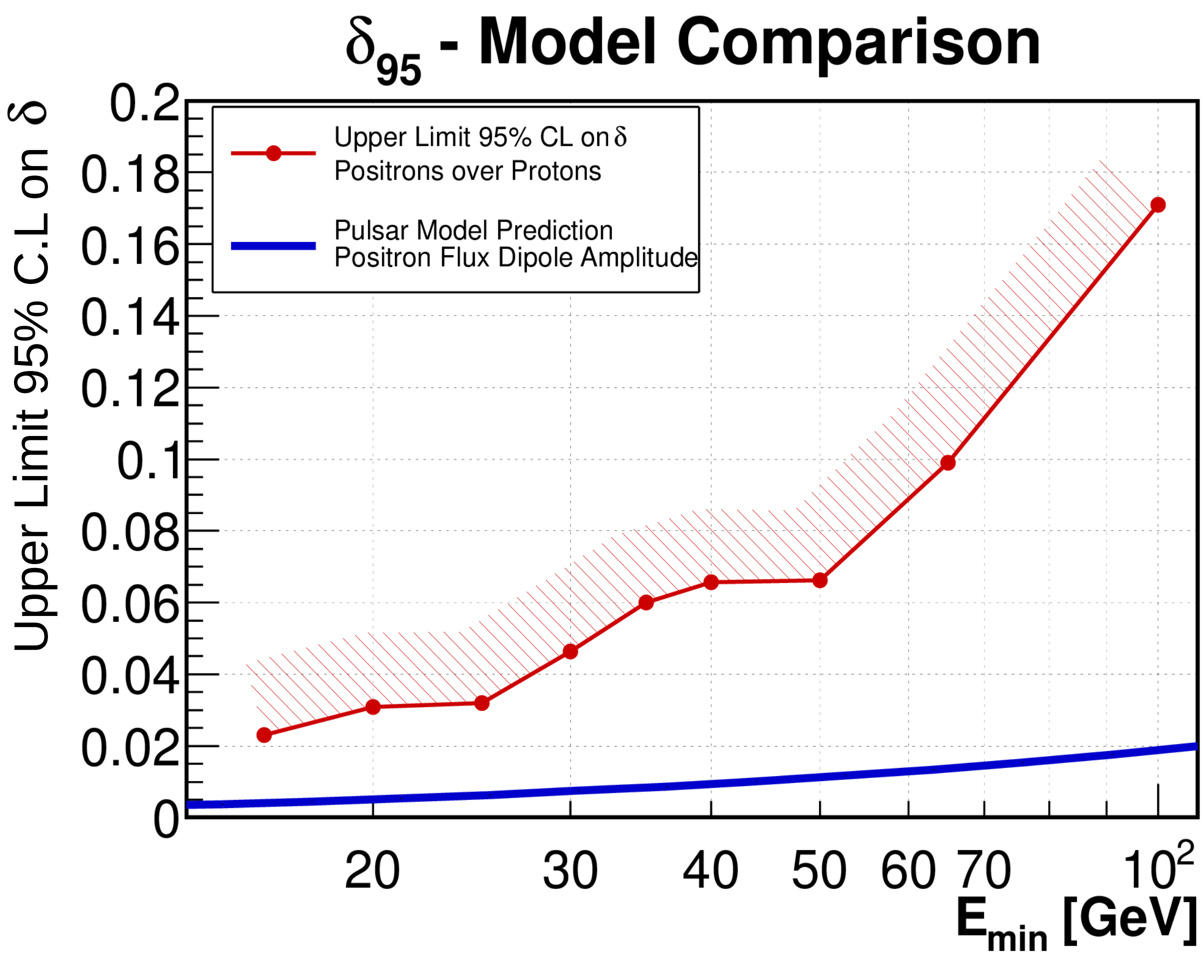
PHYSICS MOTIVATION: ANISOTROPIES



Expansion into spherical harmonics



- requires assumption on signal shape

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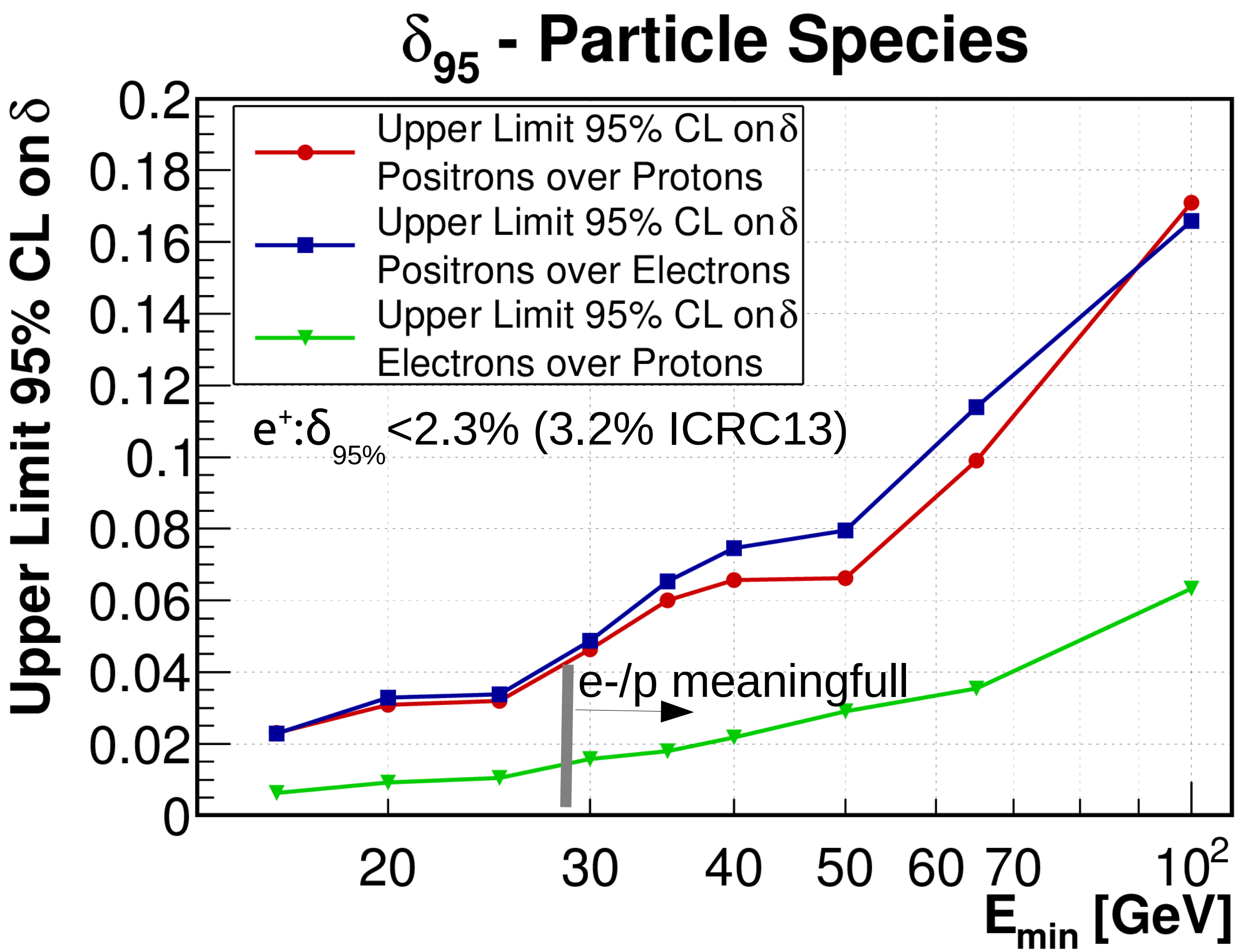
Expansion into spherical harmonics



- Can elctrons help? No, different charge signs require **only** over cutoff events
- limit calculation for

$$\delta = \sqrt{\rho_1^2 + \rho_2^2 + \rho_3^2}$$

(profile likelihood)

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Institut für Experimentelle Kernphysik

SUMMARY

AMS-02 is operating stable since May 2011. We collected 60 **Billion** events, out of which **10.6 Million** were identified as leptons so far.

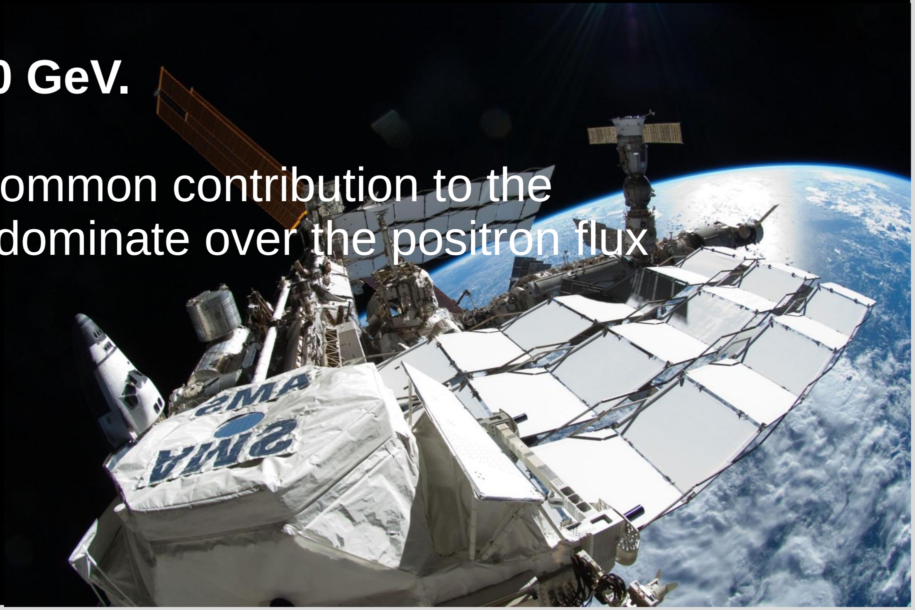
We measured the flux of positrons up to **500 GeV**, electrons up to **750 GeV**, electrons+positrons up to **1 TeV** and the positron fraction up to **500 GeV**.

The positron fraction is compatible with a turnover beyond **200 GeV.**

The electron spectrum hardens beyond **30 GeV.**

All measurements are compatible with a common contribution to the positron and electron flux, which starts to dominate over the positron flux in the range 1 GeV to 10 GeV.

Proton and helium fluxes will be published in the near future!



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