L'esperimento PAMELA: un apparato su satellite per lo studio della radiazione cosmica

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OUTLINE:

1. Scientific goals of PAMELA
2. The PAMELA instrument
3. Principle of operation
4. Orbital environment and in-flight performance
5. Some results (antiproton and positron fractions)
6. Conclusions

The PAMELA Collaboration

Italy:
Bari | Florence | Frascati | Naples | Rome | Trieste | CNR, Florence

Russia:
Ioffe Physico-Technical Institute
Moscow
St. Petersburg

Germany:
Universität Gesamthochschule Siegen
Siegen

Sweden:
Kungl Tekniska Högskolan
KTH, Stockholm

PAMELA scientific objectives

(A Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics)

PAMELA design performance

- Study antiparticles in cosmic rays
- Search for antimatter
- Search for dark matter
- Study cosmic-ray propagation
- Study solar physics and solar modulation
- Study the electron spectrum (local sources?)

PAMELA scientific objectives

(A Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics)

PAMELA design performance

	energy range	particles in 3 years
Antiprotons	80 MeV - 190 GeV	$O(10^4)$
Positrons	50 MeV - 270 GeV	$O(10^5)$
Electrons	up to 400 GeV	$O(10^6)$
Protons	up to 700 GeV	$O(10^8)$
Electrons+positrons	up to 2 TeV (from calorimeter)	
Light Nuclei	up to 200 GeV/n He/Be/C:	$O(10^{7/4/5})$
AntiNuclei search	sensitivity of $3x10^{-8}$ in He/He	

Cosmic-ray Antimatter from Dark Matter annihilation

Annihilation of relic Weakly Interacting Massive Particles (WIMPs) gravitationally confined in the galactic halo

→ Distortion of antiproton and positron spectra from purely secondary production

- **A plausible dark matter candidate is neutralino (χ), the lightest SUSY Particle (LSP).**

Most likely processes:

- **χχ → qq → hadrons→ anti-p, e^+,…**
- **χχ → W^+W^-,Z^0Z^0,… → e^+,…**

⇒ positron peak E(e+) ~ Mχ/2

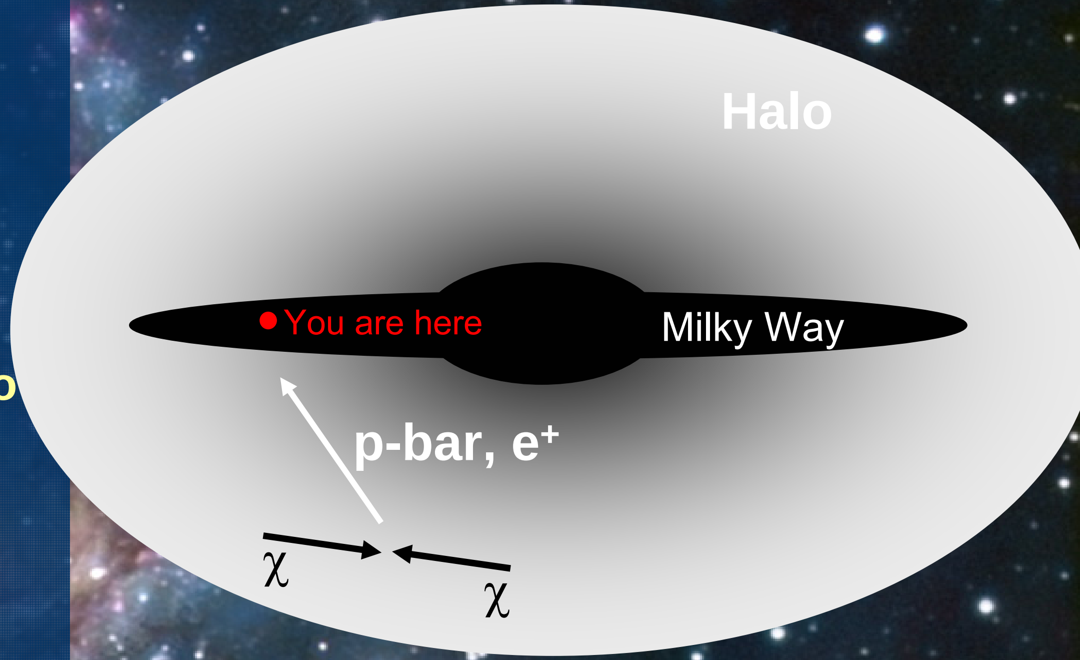
⇒ positron continuum E(e+) ~ Mχ/20

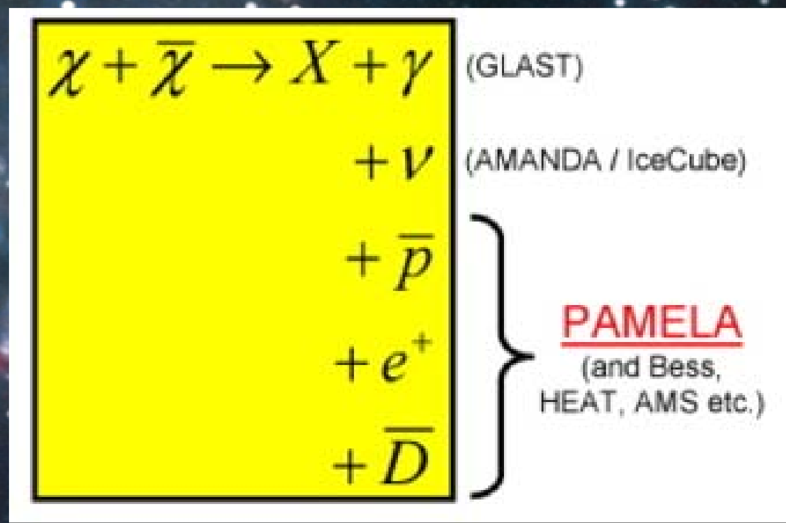
- **Another possible candidate is the lightest Kaluza-Klein Particle (LKP): $B^{(1)}$**

Fermionic final states no longer suppressed:

- **$B^{(1)}B^{(1)}$ → e^+e^-**

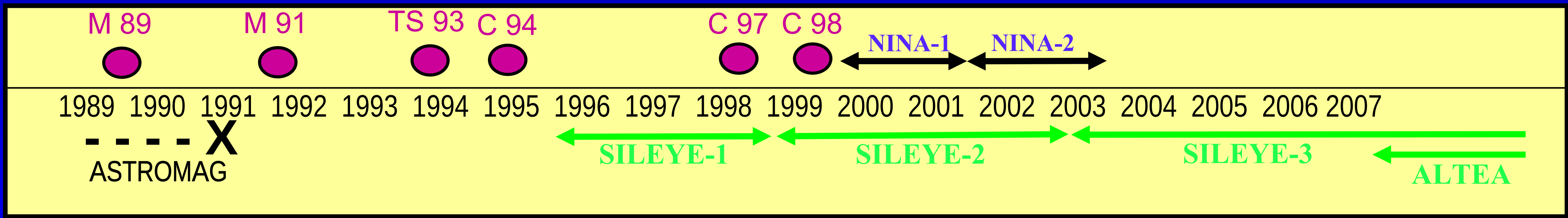
direct decay ⇒ positron peak E(e+) ~ $M_{B(1)}$

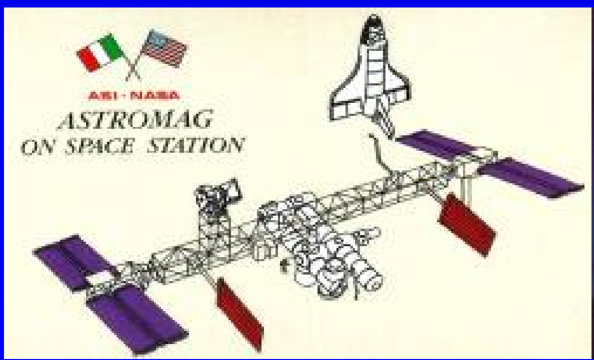


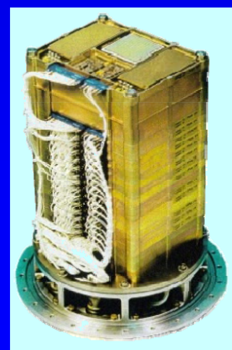


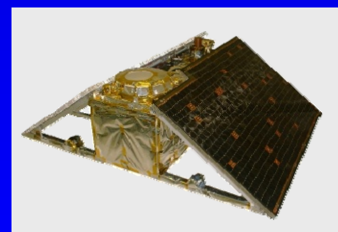
PAMELA prehistory

- Astromag/WiZard project (PAMELA precursor) on board of the Space Station Freedom ⇒ CANCELED
- Balloon-borne experiments: MASS-89/91, TS-93 and CAPRICE-94/97/98
- Space experiments*: NINA-1,2 SILEYE-1,2,3 and ALTEA
  (*study of low energy nuclei and space radiation environment)







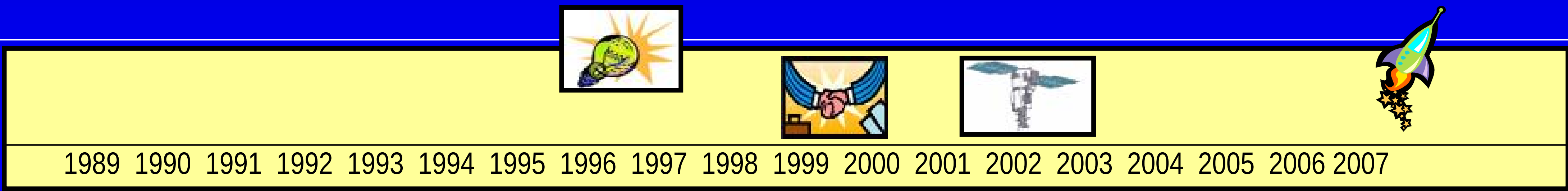


PAMELA history

- 1996: PAMELA proposal
- 22/12/1998: agreement between RSA (Russian Space Agency) and INFN to build and launch PAMELA.

  Three models required by the RSA:
  - Mass-Dimensional and Thermal Model (MDTM)
  - Technological Model (TM)
  - Flight Model (FM)

  ⇒ ***Start of PAMELA construction***
- 2001: change of the satellite ⇒ ***complete redesign of mechanics!***
- 2006: flight!!!

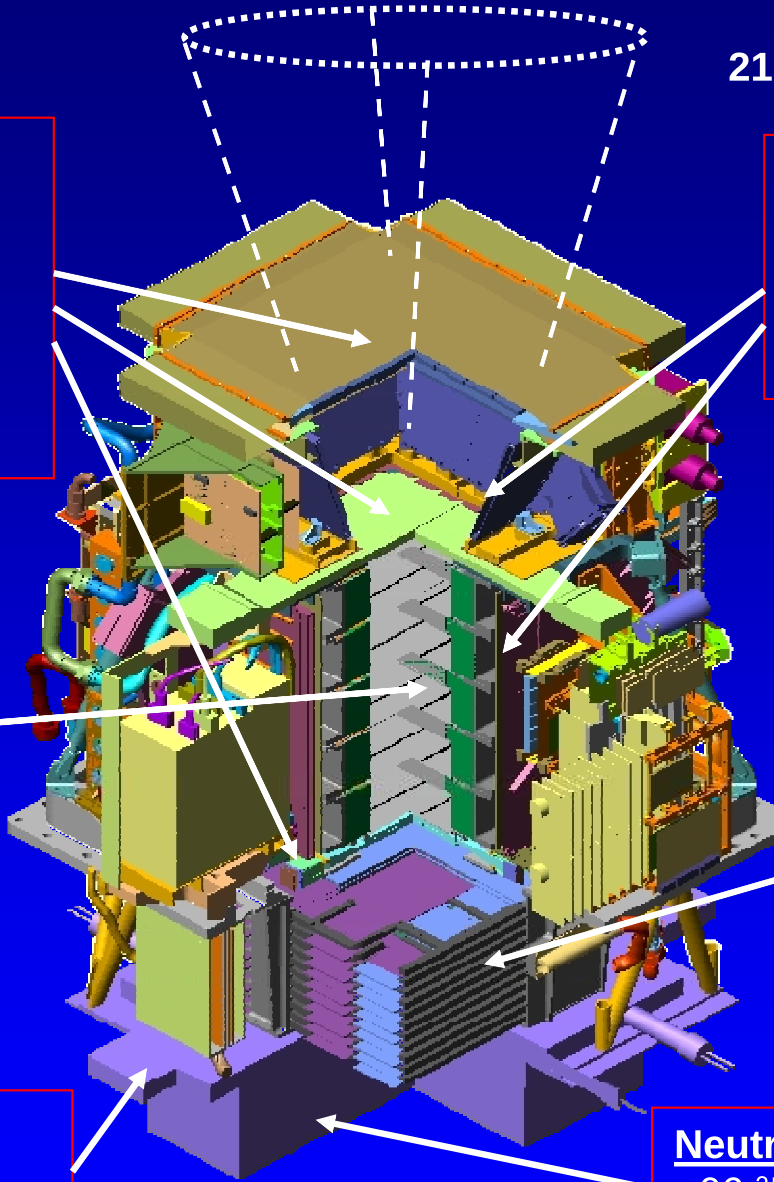


The PAMELA instrument

Time-of-flight
- Trigger / Albedo rejection / Particle identification (up to 1 GeV/c) / dE/dx
- 3 double-layer scintillator paddles
- Timing resolution:
  - σ(paddle) $\approx$ 110 ps
  - σ(ToF) $\approx$ 330 ps (MIPs)

Si Tracker + magnet
- Measures rigidity
- 5 Nd-B-Fe modules (0.43T)
- 6 planes of double-sided Si microstrip detectors
- ~3 μm resolution (bending view) demonstrated, ie: MDR $\approx$ 1 TV/c

Shower-tail catcher (S4)
- Plastic scintillator paddle, 1 cm thick
- Main task: ND trigger



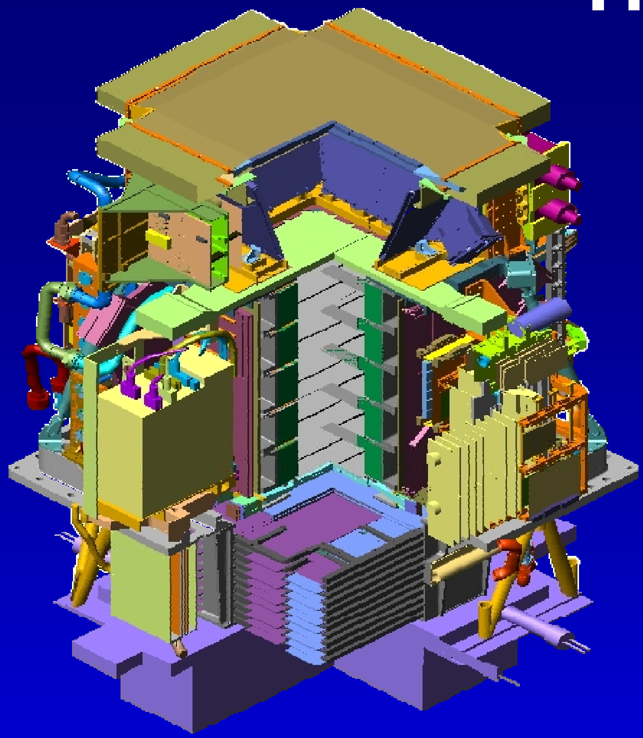
Anticoincidence system
- Rejection of events with particles interacting with the apparatus
- Plastic scintillator paddles
- MIP efficiency > 99.9%

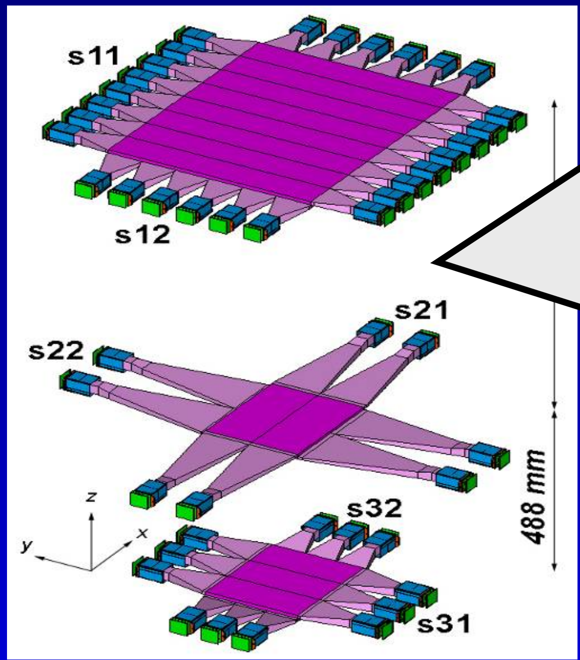
Mass: 470 kg
Power: ~ 360 W
Size: 130x70x70 cm^3

Si-W Imaging Calorimeter
- Lepton/hadron discrimination
- $e^{+/-}$ energy measurement
- 44 Si planes (x/y) + 22 W layers
- 16.3 X_0/0.6 λ_I
- p rejection factor ~ 10^5
- e rejection factor > 10^4

Neutron detector
- 36 ^{3}He counters
- e/h discrimination at high energies

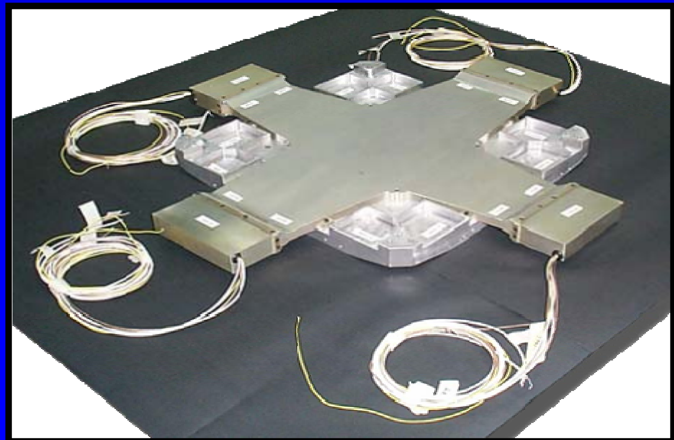
The time-of-flight system



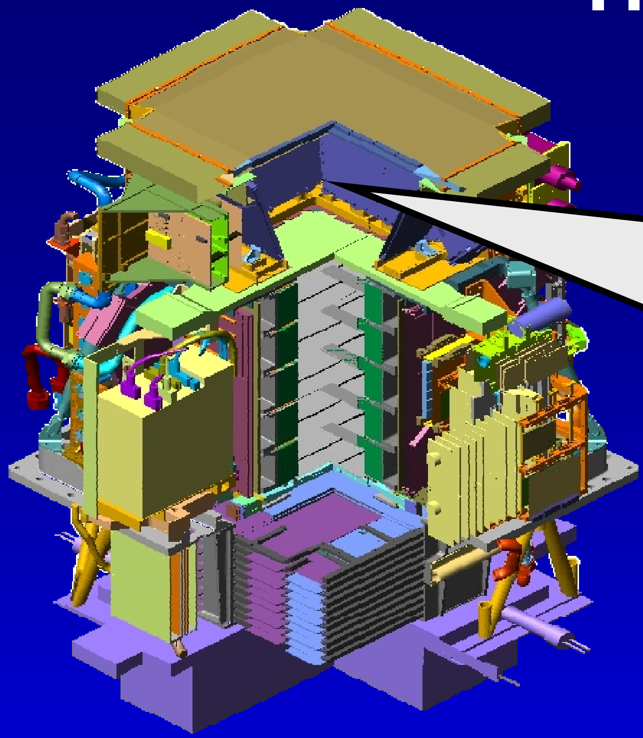


- **Main tasks:**
- **First-level trigger**
- **Albedo rejection**
- **dE/dx (ionisation losses)**
- **Time of flight particle identification (<1GeV/c)**

- **Characteristics:**
- **3 double-layer scintillator paddles**
- **x/y segmentation**
- Total: 48 channels
- **Performance:**
- σ(paddle) ~ 110ps
- **σ(ToF) ~ 330ps (for MIPs)**



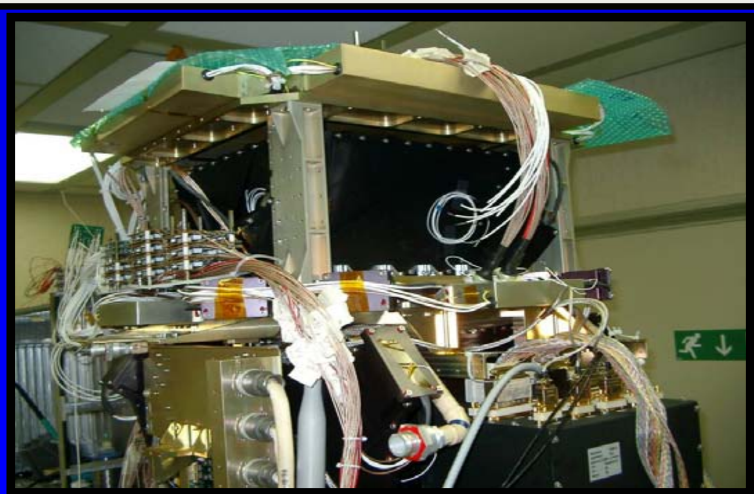
The anticounter system



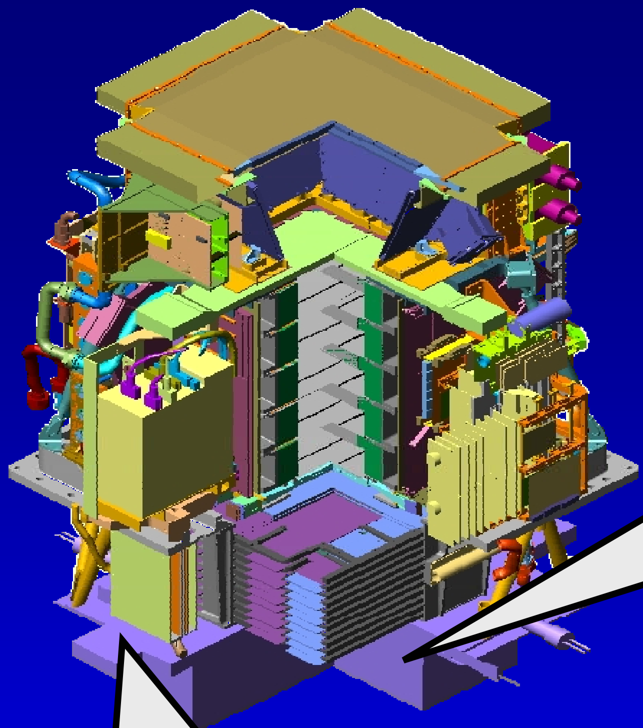
- **Main tasks:**
- **Rejection of events with particles interacting with the apparatus** (off-line and second-level trigger)

- **Characteristics:**
- **Plastic scintillator paddles, 8mm thick**
- 4 upper (CARD), 1 top (CAT), 4 side (CAS)

- **Performance:**
- MIP efficiency > 99.9%

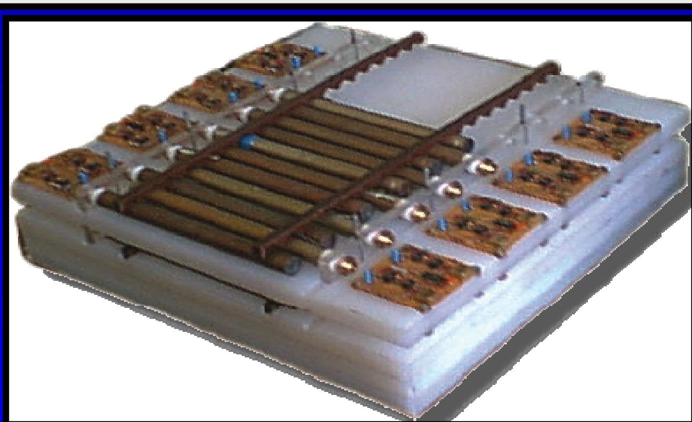


Neutron detector



- **Main tasks:**
- **e/h discrimination at high energy**

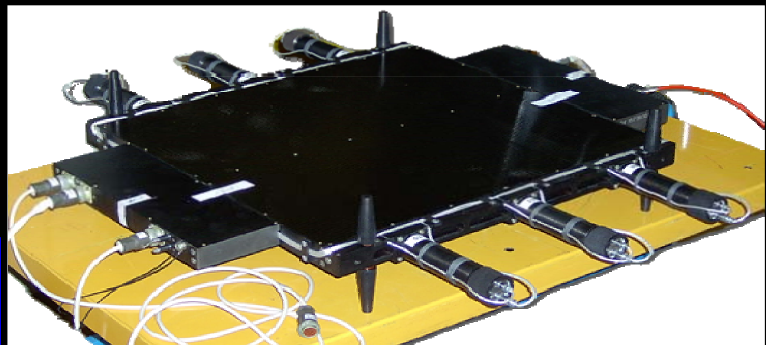
- **Characteristics:**
- **36 ^{3}He counters**:
- ^{3}He(n,p)T - Ep=780 keV
- 1cm thick polyethylene + Cd moderators
- n collected within 200 μs time-window



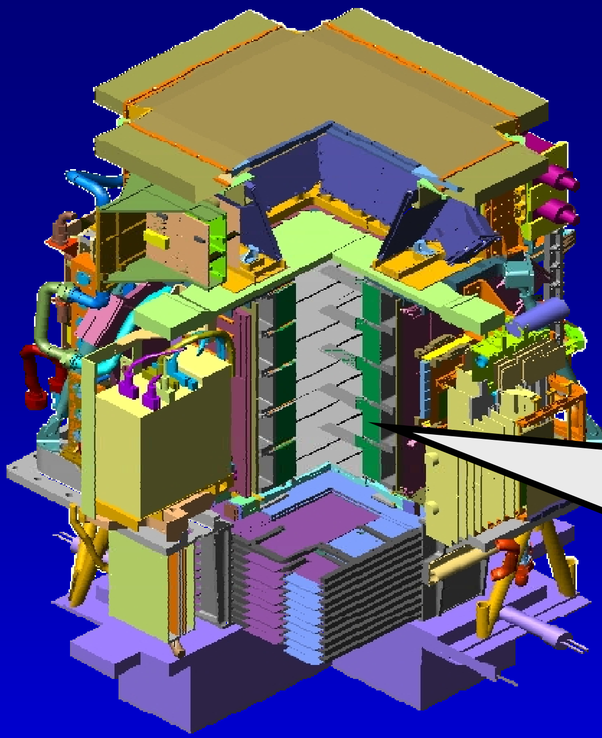
Main tasks:
- **Neutron detector trigger**

Characteristics:
- **Plastic scintillator paddle, 1 cm thick**

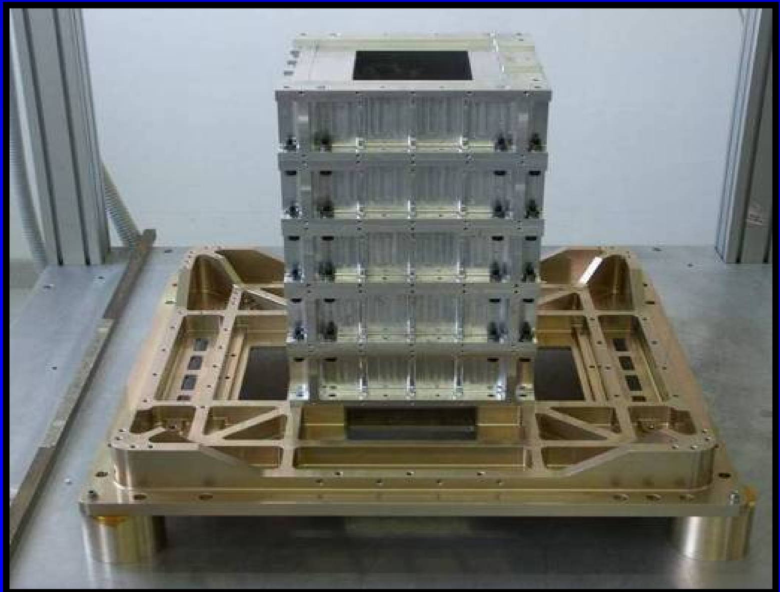
Shower-tail catcher

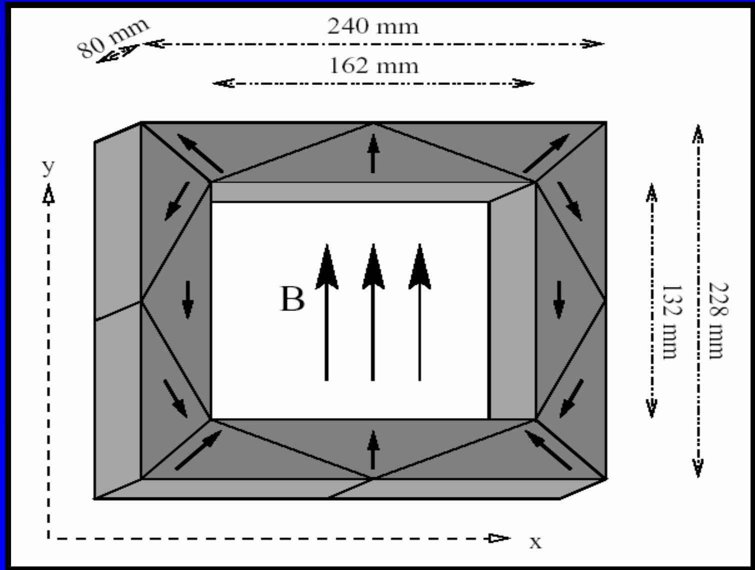


The magnet

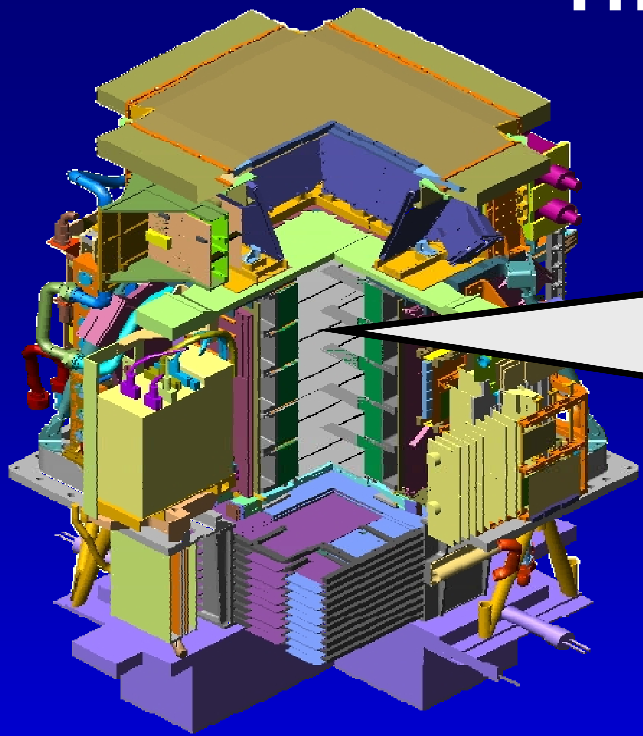


- **Characteristics:**
- **5 modules of permanent magnet (Nd-B-Fe alloy) in aluminum mechanics**
- Cavity dimensions (162 x 132 x 445) cm^3
- **→ GF ~ 21.5 cm^2sr**
- Magnetic shields
- 5mm-step field-map on ground:
  - **B=0.43 T (average along axis),**
  - **B=0.48 T (@center)**





The tracking system - 1



- **Main tasks:**
- **Rigidity measurement**
- **Sign of electric charge**
- **dE/dx (ionisation loss)**

- **Characteristics:**
- **6 planes double-sided (x&y view) microstrip Si sensors**
- 36864 channels
- Dynamic range: 10 MIP

- **Performance:**
- **Spatial resol.: 3-4 μm (bending view)**
- **MDR ~ 1 TV (from test beam data)**

The tracking system - 2

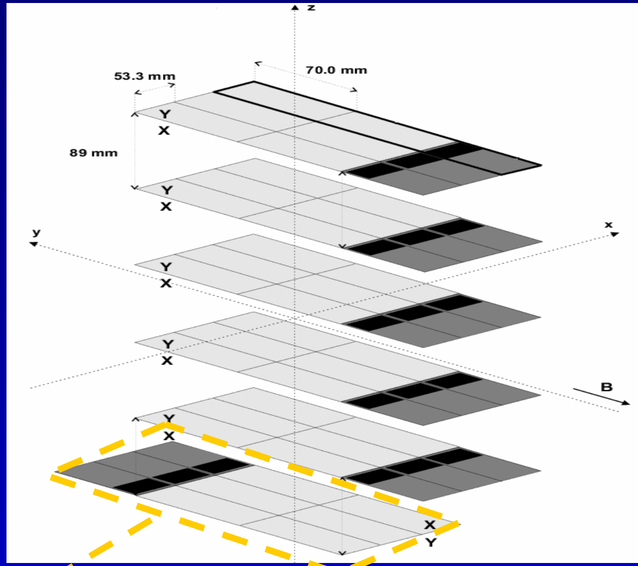
6 detector planes, each composed by 3 ladders

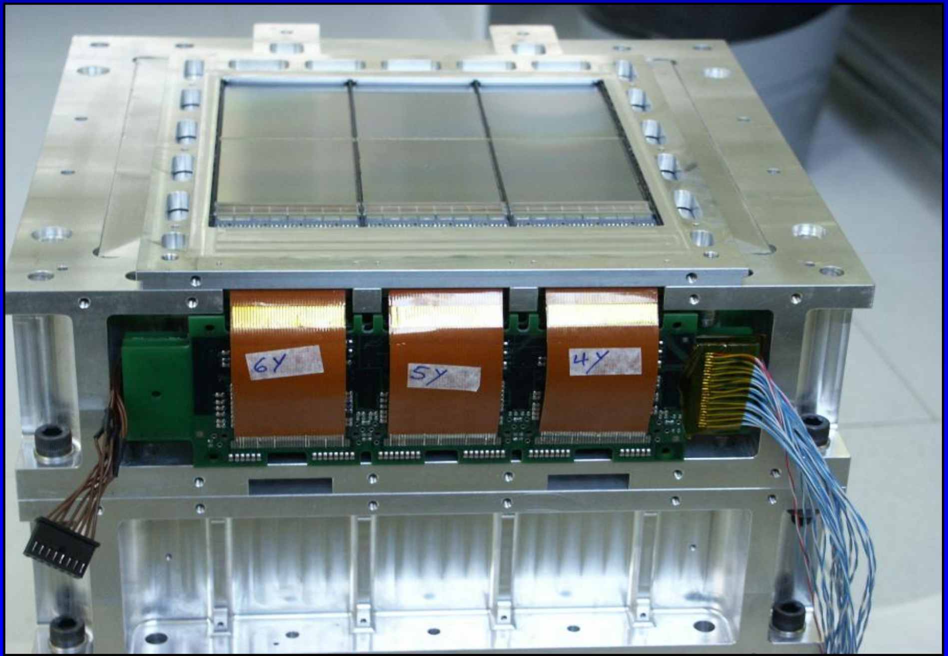
Mechanical assembly

- aluminum frames
- carbon fibers stiffeners glued laterally to the ladders
- no material above/below the plane

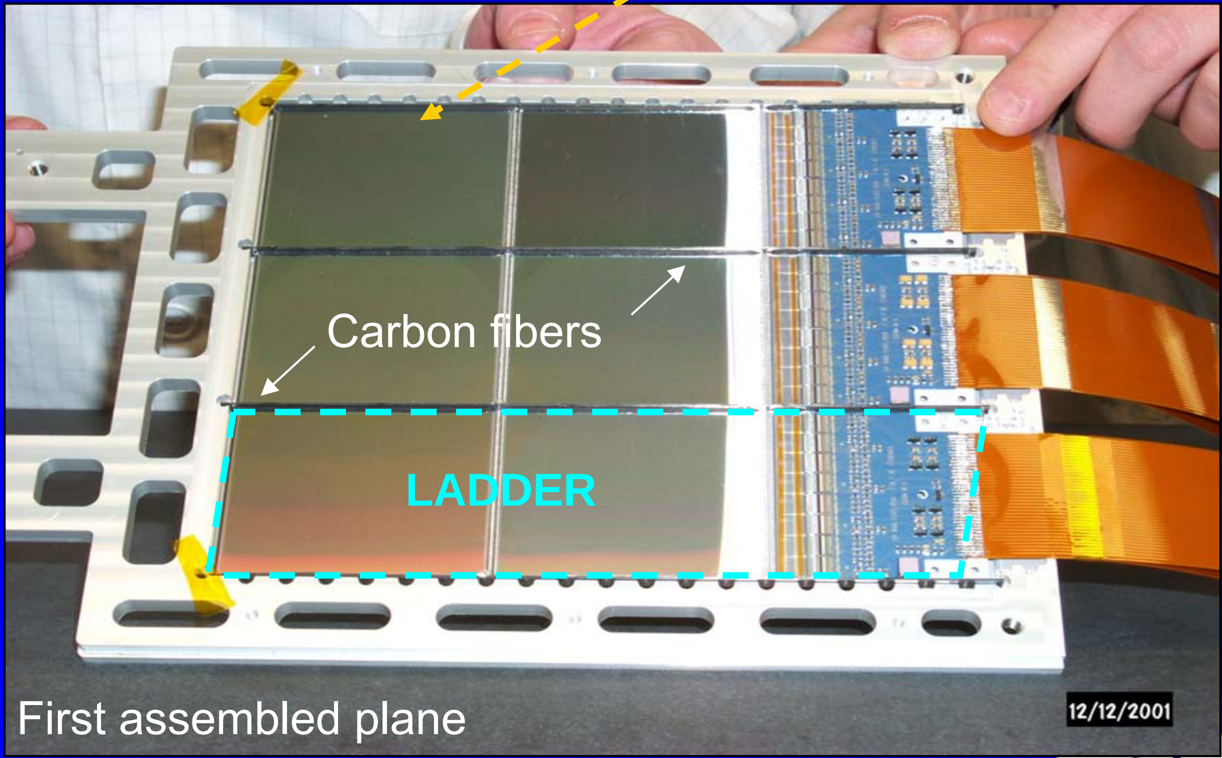
    1 plane = **0.3% X_0** $\Rightarrow$ reduced multiple scattering

- elastic + rigid gluing



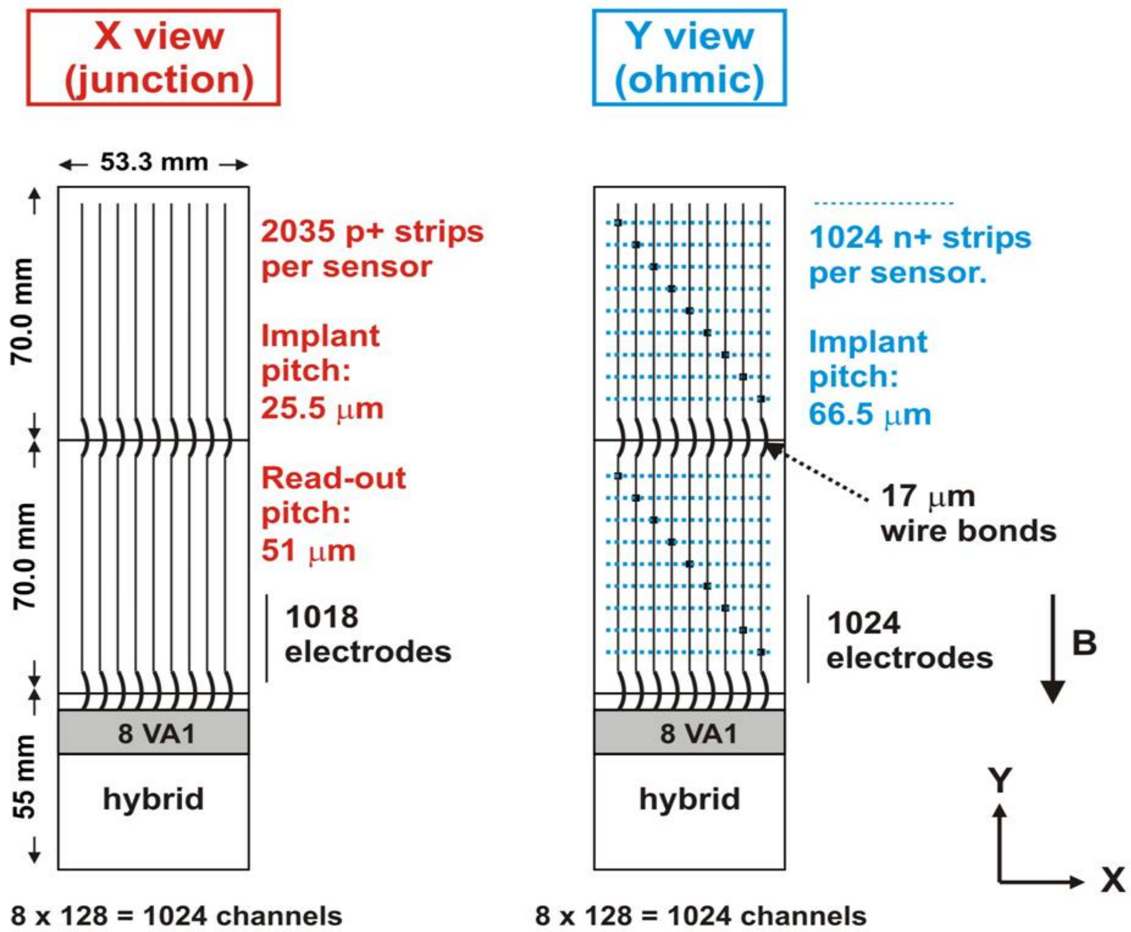


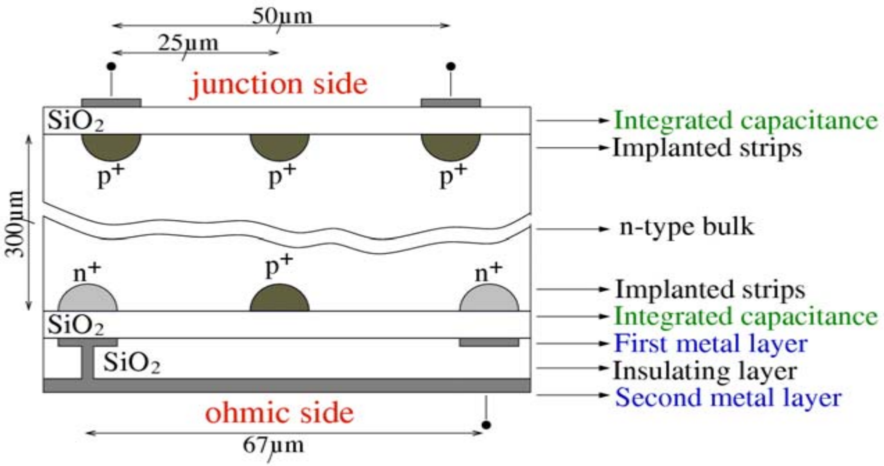
Test of plane lodging inside the magnet



First assembled plane

The tracking system - 3





Ladder structure:
- 2 microstrip silicon detectors
- 1 "hybrid" with front-end electronics

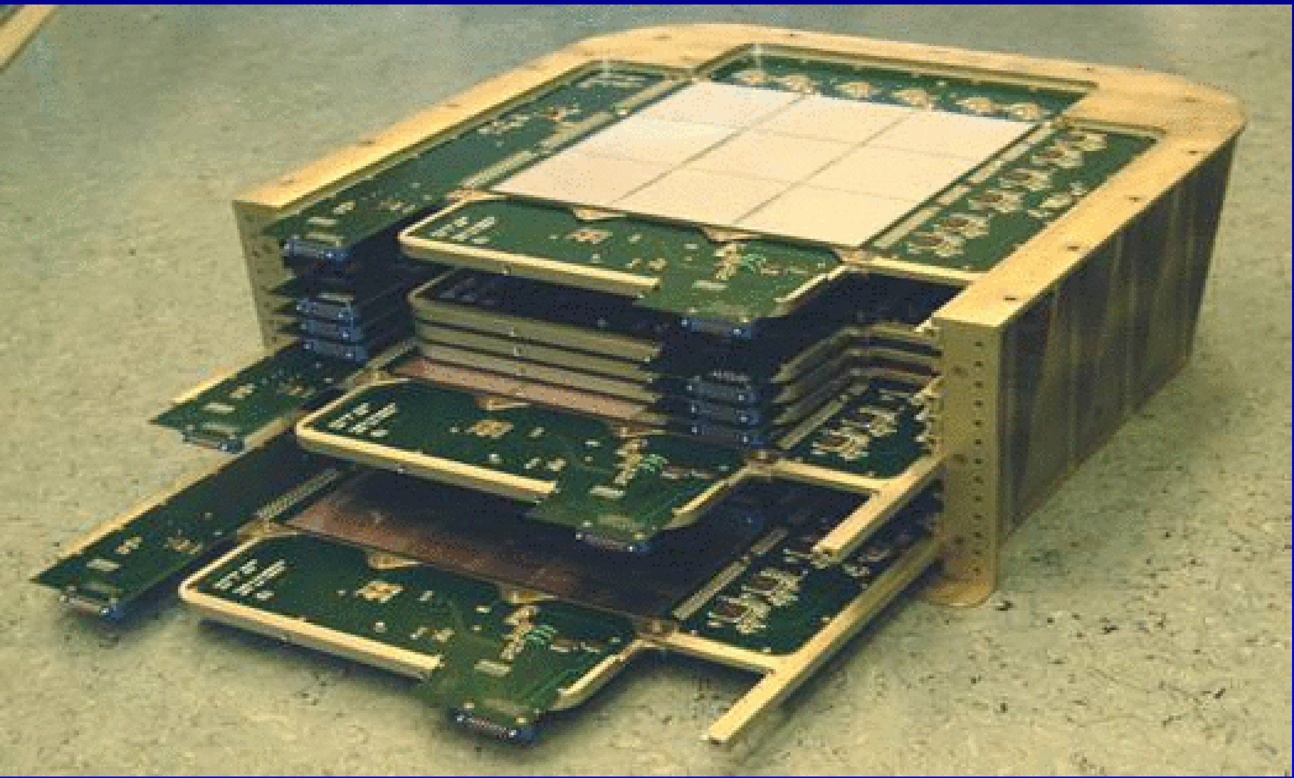
Silicon detectors (Hamamatsu):
- **300 µm, double sided - x & y view**
- **AC coupled** (no external chips)
- **Double metal** (ohmic side)

Front-end electronics (VA-1):
- 16 chip/ladder → 288 chips
- 1.2 µm CMOS ASIC (Ideas, Norway)
- 128 low-noise charge preamplifier/shaper channels, shaping time 1 µs)
- Voltage gain 7.0 mV/fC → *range 10 MIP*

ADC:
- 1 ADC/ladder → 36 ADCs
- event acquisition time 2.1 ms

DSP:
- 1 DSP/view (ADSP2187L) → 12 DSPs
- control logic on FPGA chips (A54SX)

The Imaging Calorimeter - 1

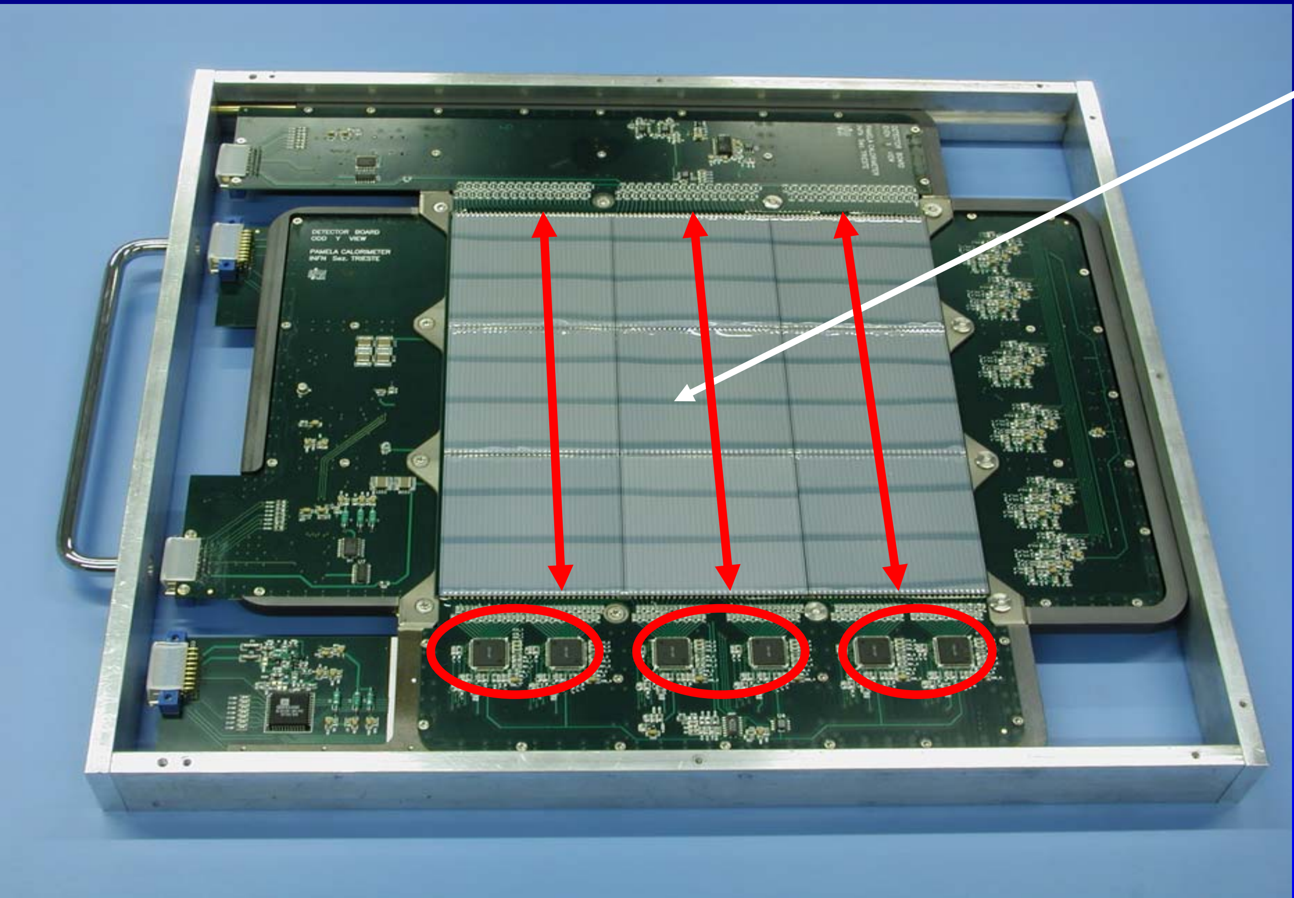


- **Main tasks:**
- **lepton/hadron discrimination**
- **$e^{+/-}$ energy measurement**

- **Characteristics:**
- **22 W plates (2.6 mm / 0.74 X_0)**
- **44 Si layers (X-Y), 380 μm thick**
- **Total depth: 16.3 X_0 / 0.6 λ_I**
- **4224 channels**
- **Self-triggering mode option (> 300 GeV; GF ~ 600 cm^2 sr)**
- **Mass: 110 kg**
- **Power Consumption: 48 W**

- **Design performance:**
- **$\bar{p}$,e^+ selection efficiency ~ 90%**
- **p rejection factor ~ 10^5**
- **e rejection factor > 10^4**
- **Energy resolution ~ 5% @ 200 GeV**

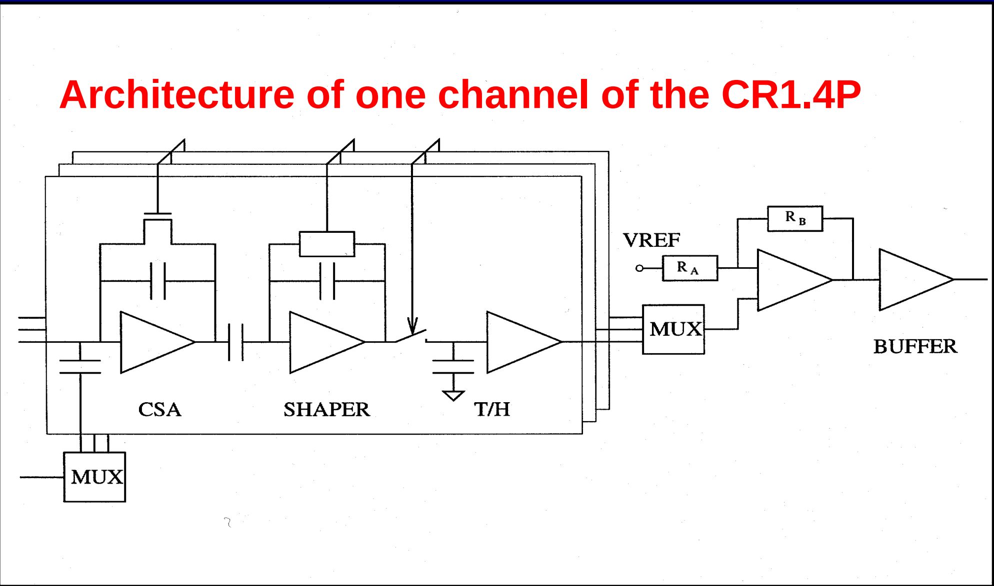
The Imaging Calorimeter - 2

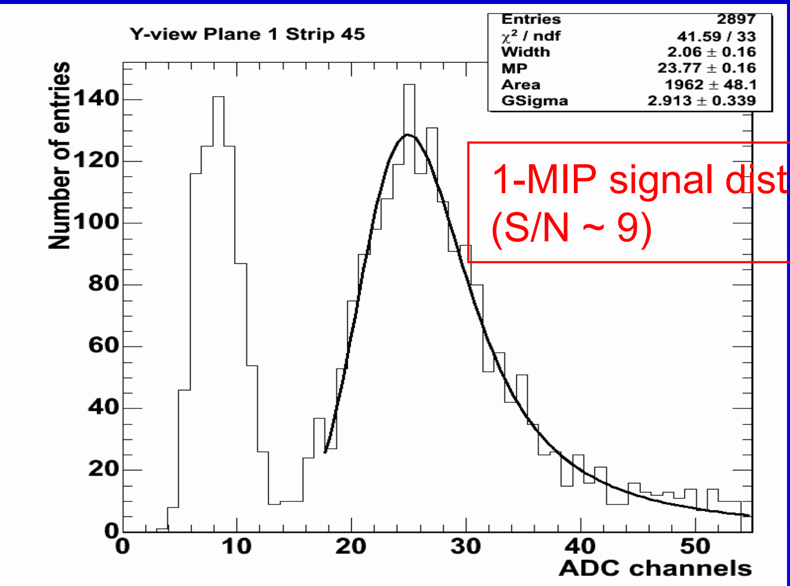


44 Si detector views (22X and 22Y)

- 8x8 cm^2 detectors arranged in a 3x3 matrix
- 32 strips/detector, 2.4 mm pitch
- Strips of detectors in the same row (column) are bonded together (ladder) ⇒ 24 cm long strips
- Each ladder (32 channels) is read out by 2 CR1.4P front-end chips ⇒ 6 front-end chips/view
- In total:
  - 396 silicon detectors
  - 264 CR1.4P chips
  - 4224 channels

The Imaging Calorimeter - 3



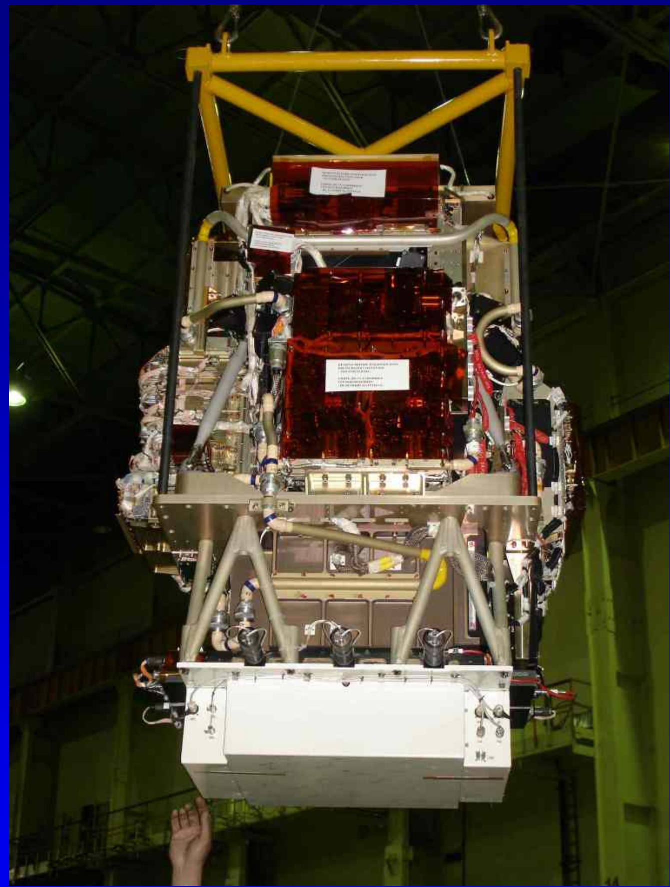


- Front-end ⇒ **CR1.4P ASIC** **(full custom design)**
  Design characteristics:
  - 16 channels/chip
  - channel structure: CSA, shaper, T/H, out. mux.
  - input-selectable calibration circuit
  - integrated self-trigger circuit
  - shaping time = 1 μs
  - sensitivity = 5 mV/MIP
  - wide dynamic range: 7.1 pC = 1400 MIP (1 MIP = 4.9 fC)
  - ENC ≈ 2700 e^- rms + 5 e^- /pF
- ADC:
  - 1 16-bit ADC/view ⇒ 44 ADCs (AD977A)
  - total calorimeter proc. time ~ 700 μs
- Readout:
  - Calorimeter divided into 4 sections: Odd_X, Odd_Y, Even_X, Even_Y
  - 1 DSP/section (ADSP2187) ⇒ 4 DSPs
    - on-line calibration
    - data compression
  - 1 FPGA/section (A54SX72) ⇒ 4 FPGAs

Satellite and space environment

- Large mechanical loads during launch phase
  ⇒ random vibrations (all axis) 7.4 g rms, SRS (Shock Response Spectrum) -all axis- up to 400 g
- Low mass budget
- Thermal variations (5 - 40 ^{o}C in normal operations)
- Low power budget (⇒ small power consumption)
- Redundancy and safety (accurate design, no SPF)
- Protection against highly ionizing events (SEU and SEL)
- EMI/EMC issues
- Limited telemetry

PAMELA models

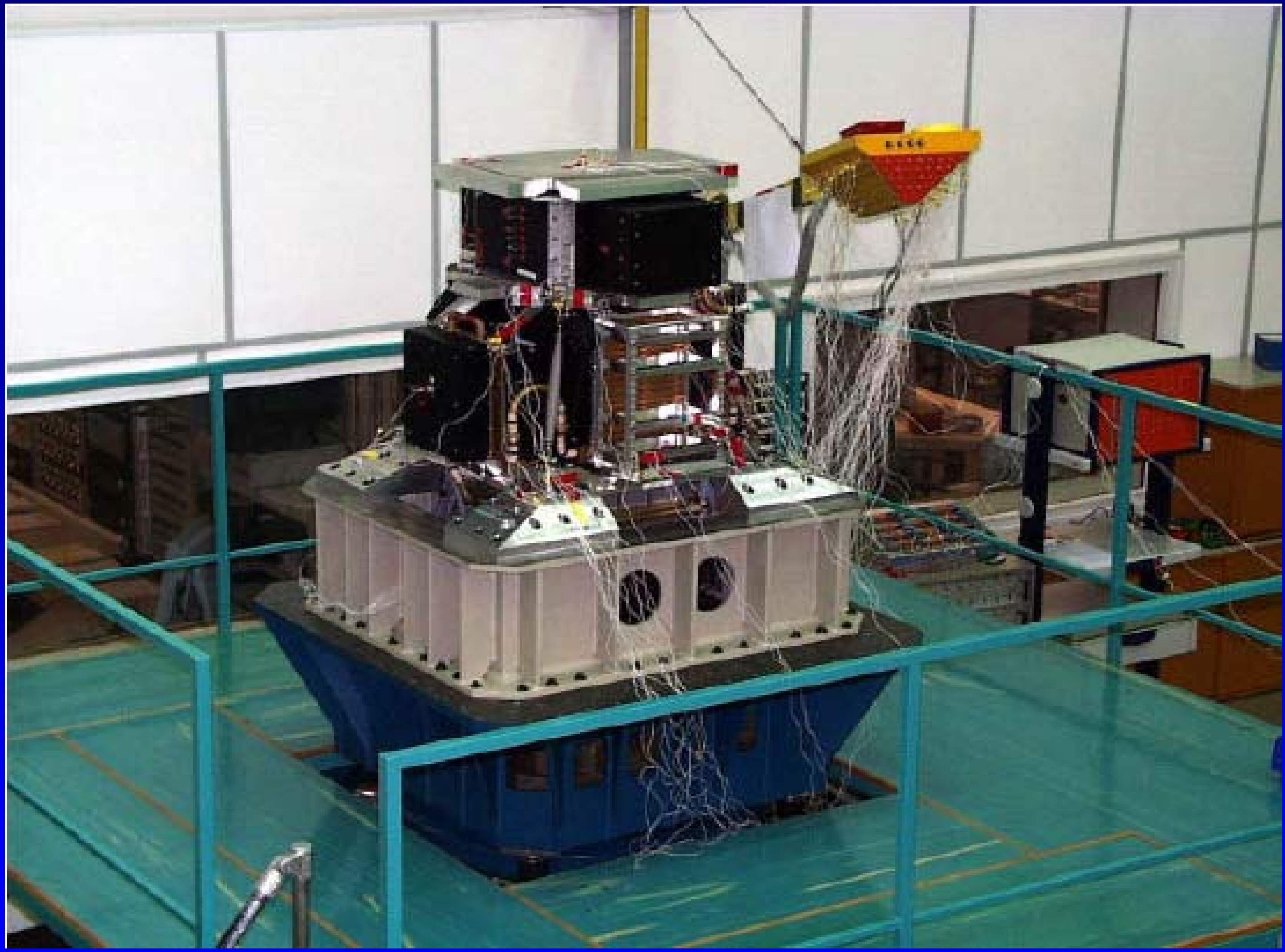


Mass/Thermal Model (MDTM):
⇒ Full cycle of vibration/shock
⇒ Thermal tests
⇒ Dimensional/transp. tests

Technological Model (TM):
⇒ Preliminary acceptance tests
⇒ Power on/off,telecommands
⇒ Data transmission to VRL
⇒ EMI/EMC tests

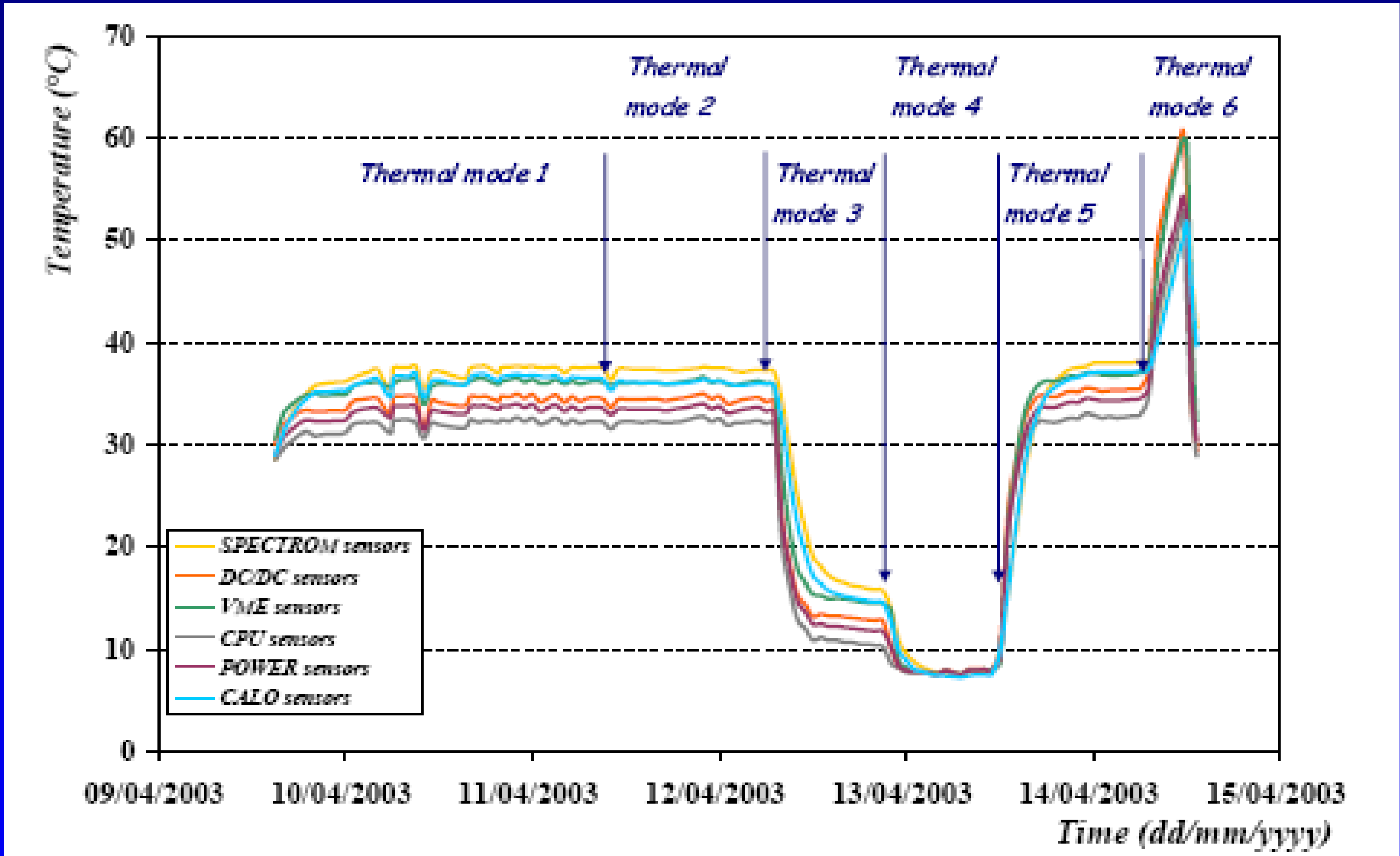
Flight Model (FM):
⇒ Beam tests;
⇒ Integration in the satellite
⇒ Pre-flight tests
⇒ Launch

Mechanical tests



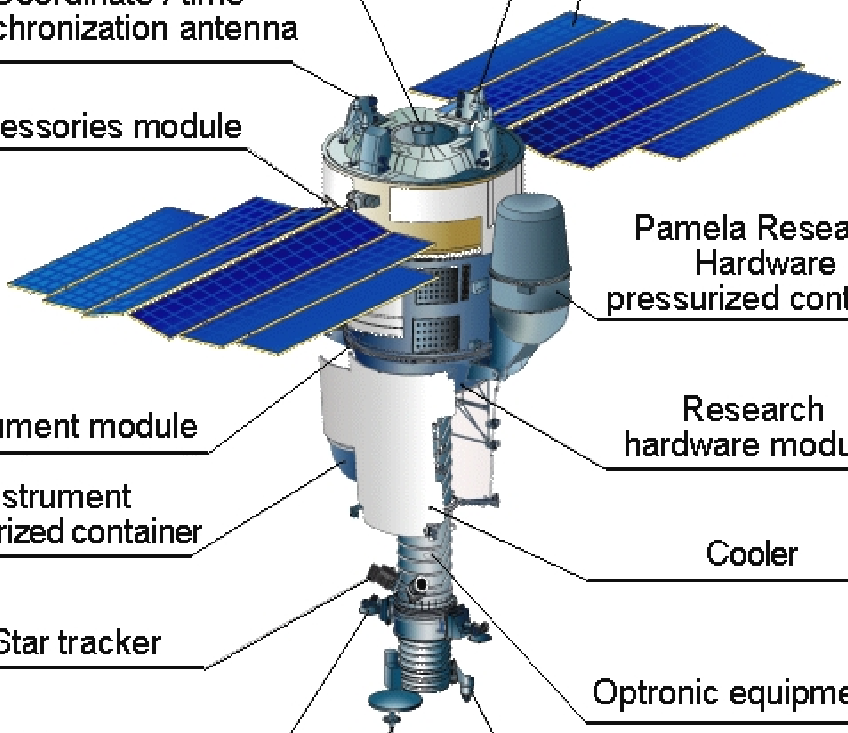
The PAMELA MDTM during the vibration and shock tests at IABG mbH (Munich), August 2002

Thermal tests



Results of the PAMELA thermal qualification tests, April 2003. Temperatures in different subsystems are shown during the execution of 6 different thermal modes.

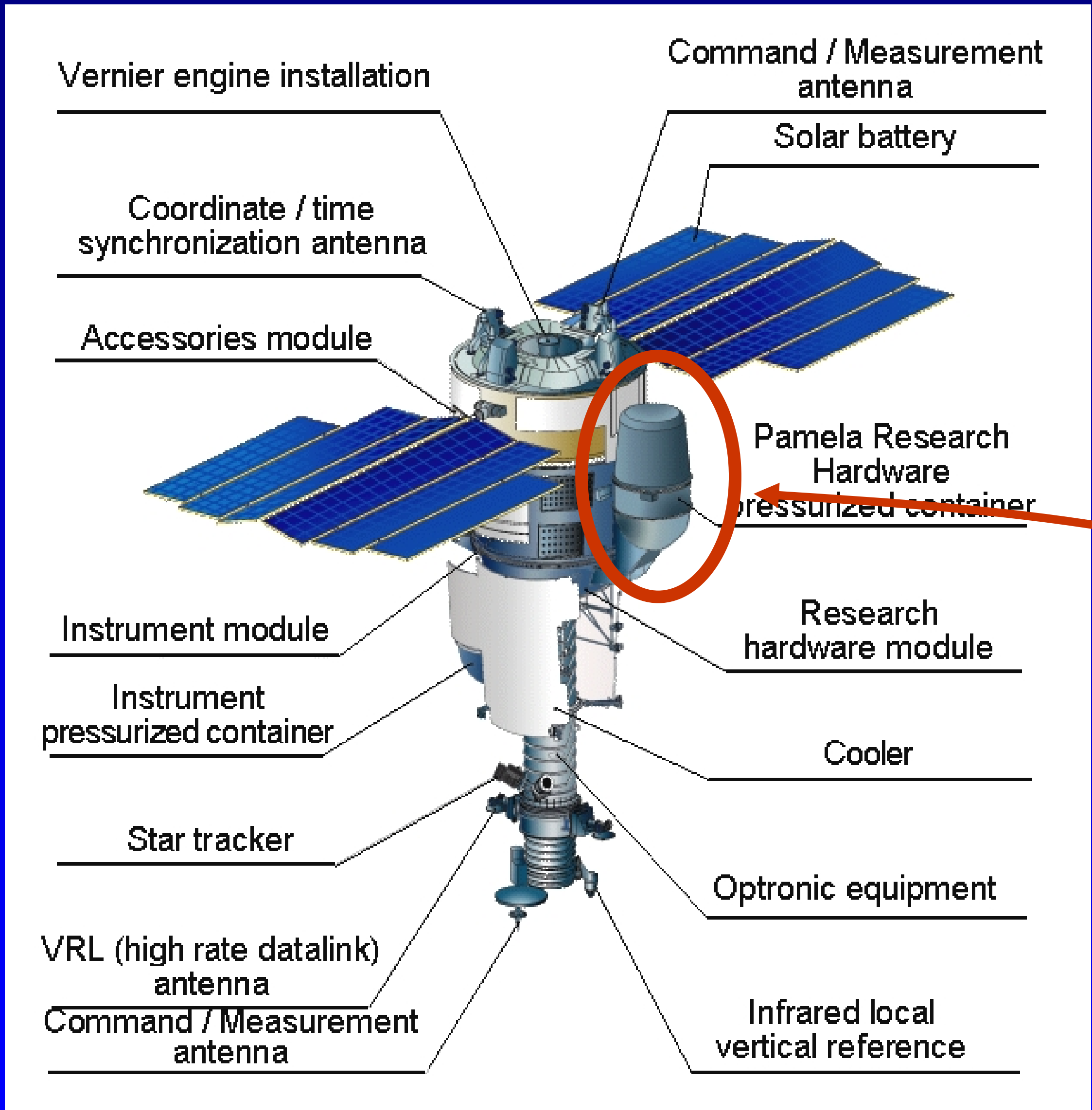
The Resurs-DK1 satellite

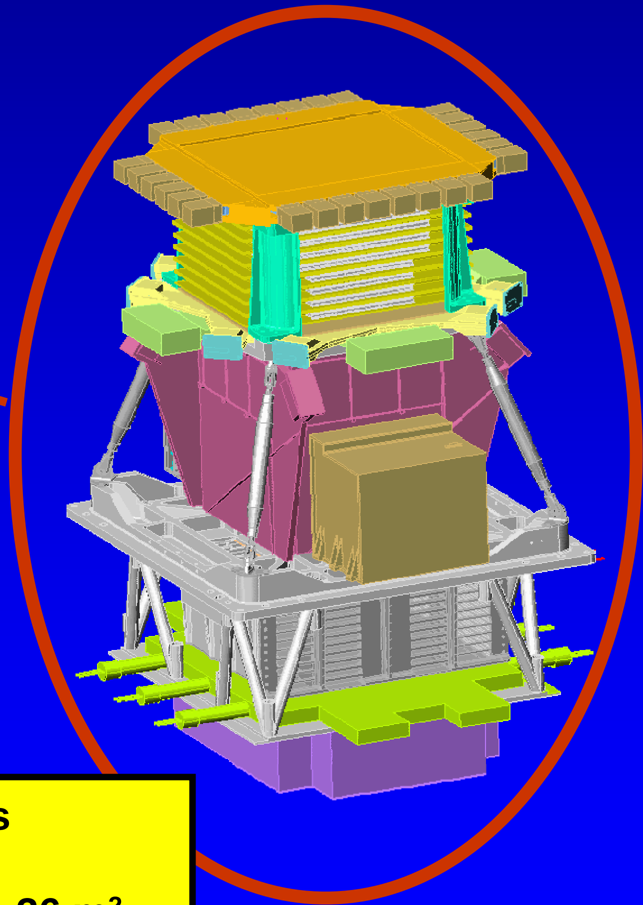


- Main task: multi-spectral remote sensing of earth's surface
- Built by TsSKB Progress in Samara, Russia (as well as the Soyuz-TM launcher)
- Lifetime >3 years (assisted)
- Data transmitted to ground via high-speed radio downlink
- PAMELA mounted inside a pressurized container

Mass: 6.7 tonnes
Height: 7.4 m
Solar array area: 36 m^2

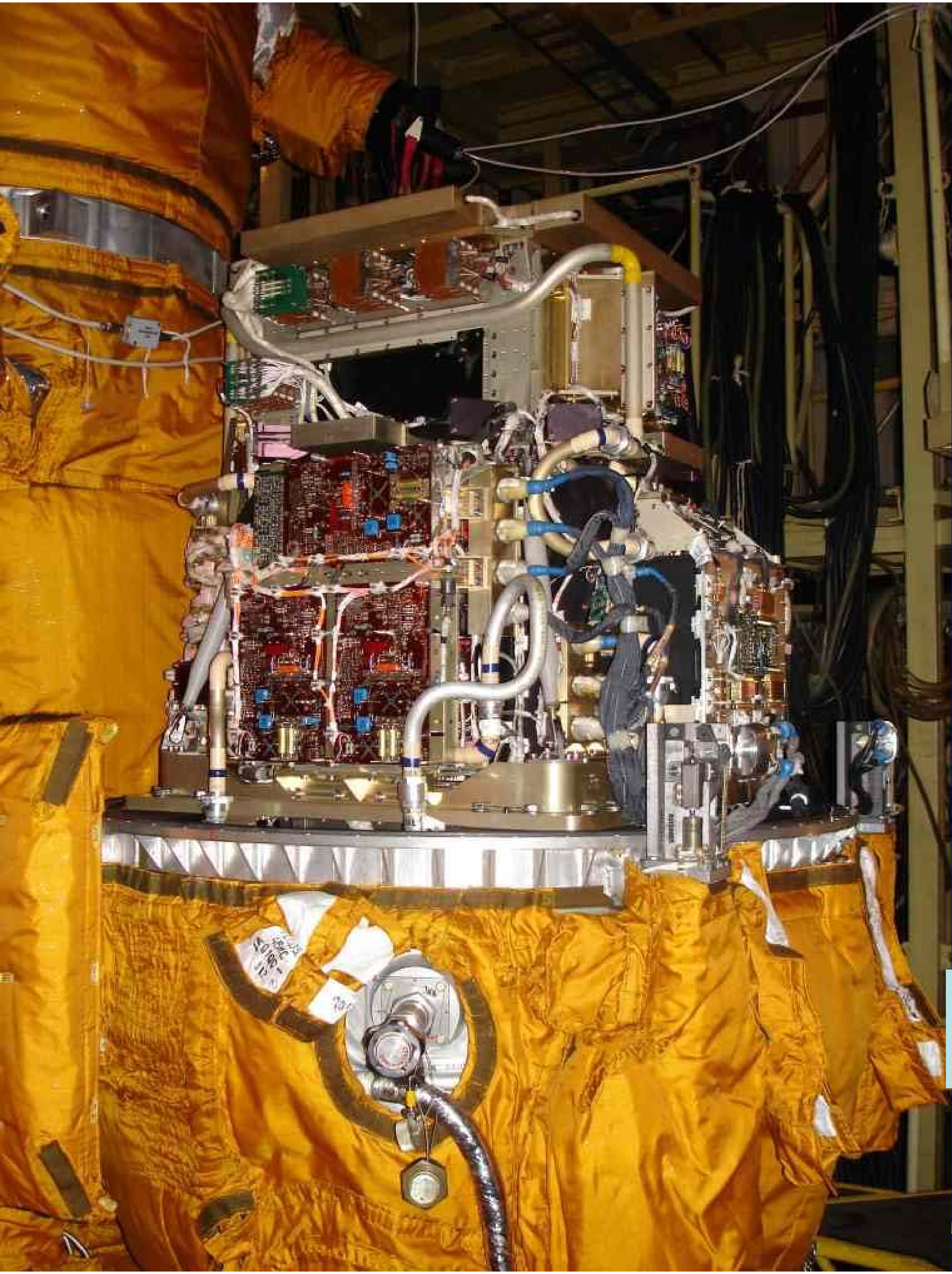
The Resurs-DK1 satellite

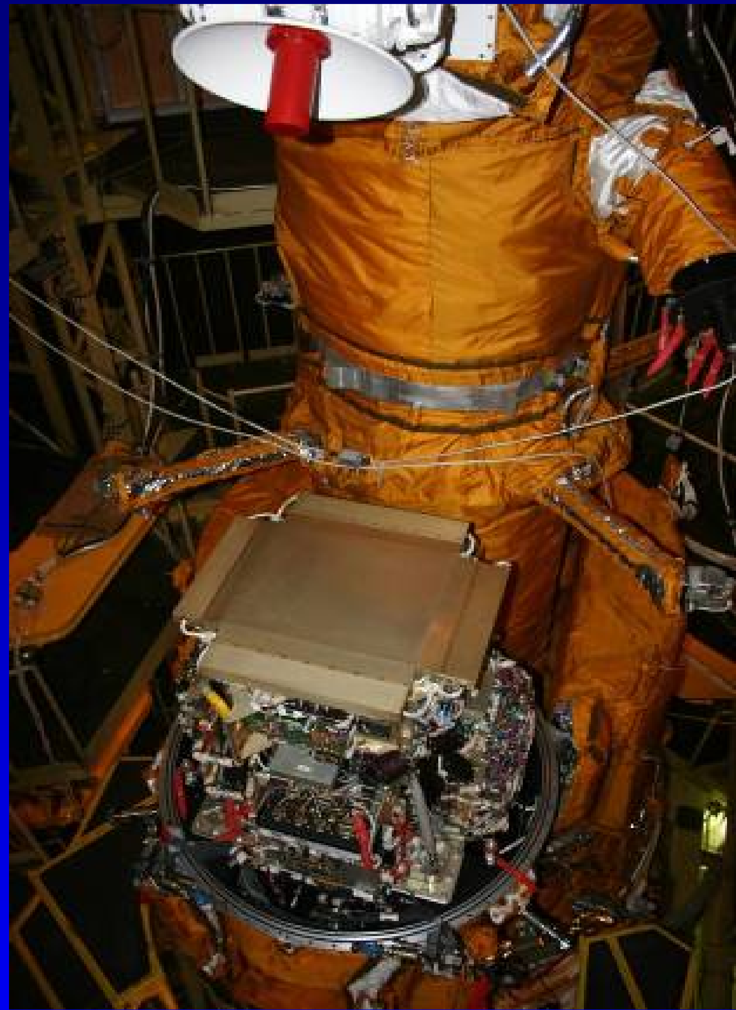




Mass: 6.7 tonnes
Height: 7.4 m
Solar array area: 36 m^2

PAMELA INTEGRATION in the RESURS-DK1 satellite





PAMELA INTEGRATION in the RESURS-DK1 satellite

PAMELA milestones

Launch from Baikonur → June 15th 2006, 0800 UTC.

‘First light’ → June 21st 2006, 0300 UTC.

- Detectors operated as expected after launch
- Different trigger and hardware configurations evaluated

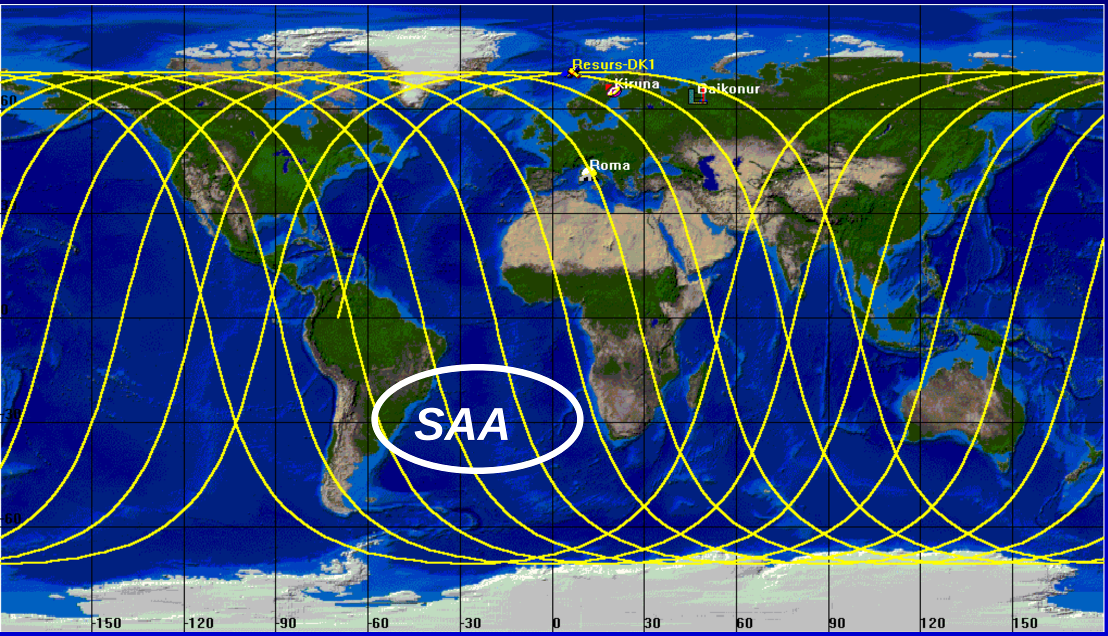
⇒**PAMELA in continuous data-taking mode since commissioning phase ended on July 11th 2006**

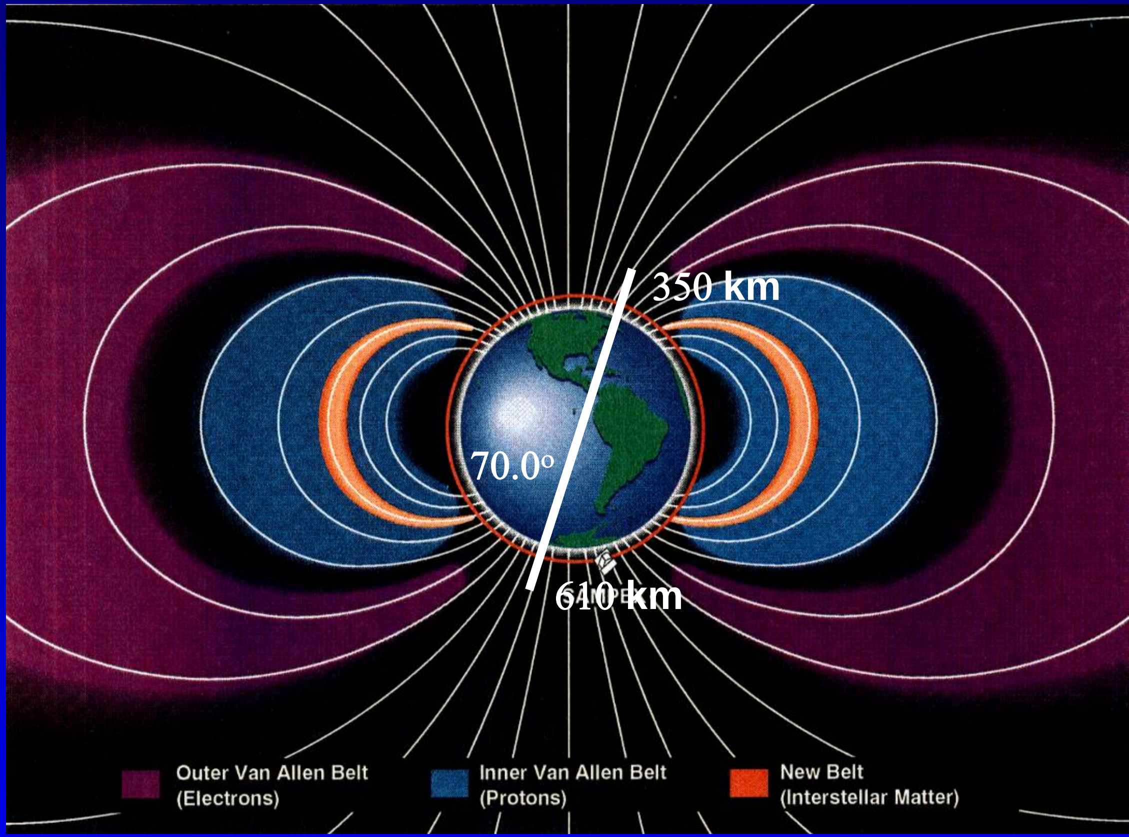
Main antenna in NTsOMZ

Trigger rate* **~25Hz**
Fraction of live time* **~ 75%**
Event size (compressed mode) **~ 5kB**
25 Hz x 5 kB/ev → **~ 10 GB/day**
(*outside radiation belts)

As of ~ now:
~ 1000 days of data taking
~ 13 TByte of raw data downlinked
> 10^9 triggers recorded and analysed
(Data from April to December 2008 under analysis)

Orbit characteristics





- Quasi-polar (70.4º)
- Elliptical (350 – 610 km)
- PAMELA traverses the South Atlantic Anomaly
- At the South Pole PAMELA crosses the outer (electron) Van Allen belt
- Quasi-polar orbit allows to study also low-energy cosmic rays (R > 100 MV)

Downlink station

- **Main downlink station:** Research Centre for Earth Operative Monitoring **‘NtsOMZ’**, Moscow, Russia.

- Science data stored in PAMELA mass-memory (2 GB)
- Transferred PAMELA to satellite 7-8 times/day → 14-16 GB
- Downlinked to ground in 2-3 sessions/day
  - Bit Error Rate $<10^{-9}$

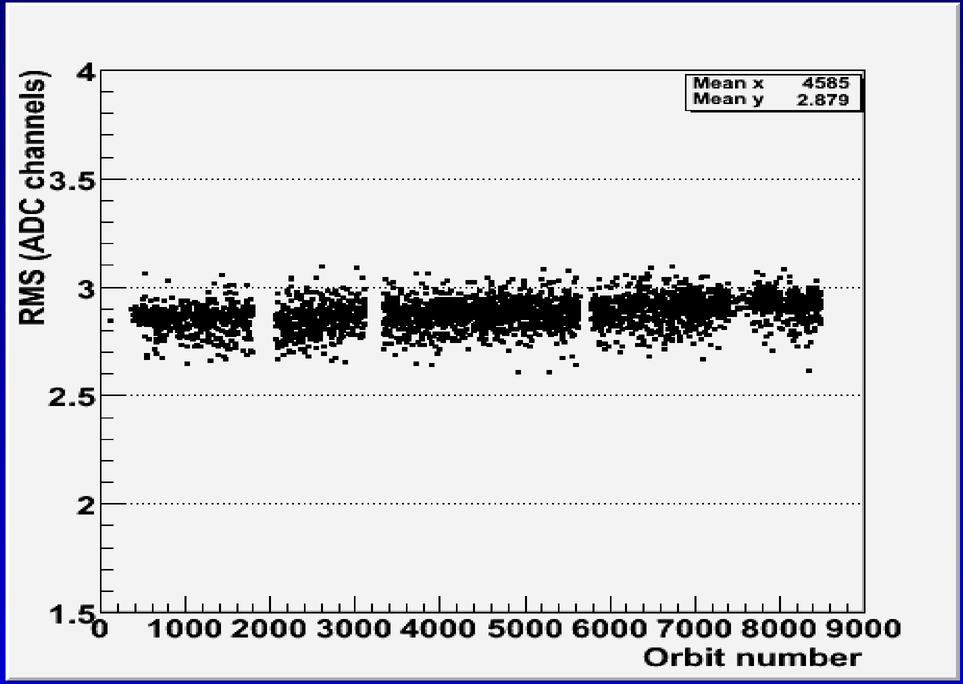
- Command uplinks are possible

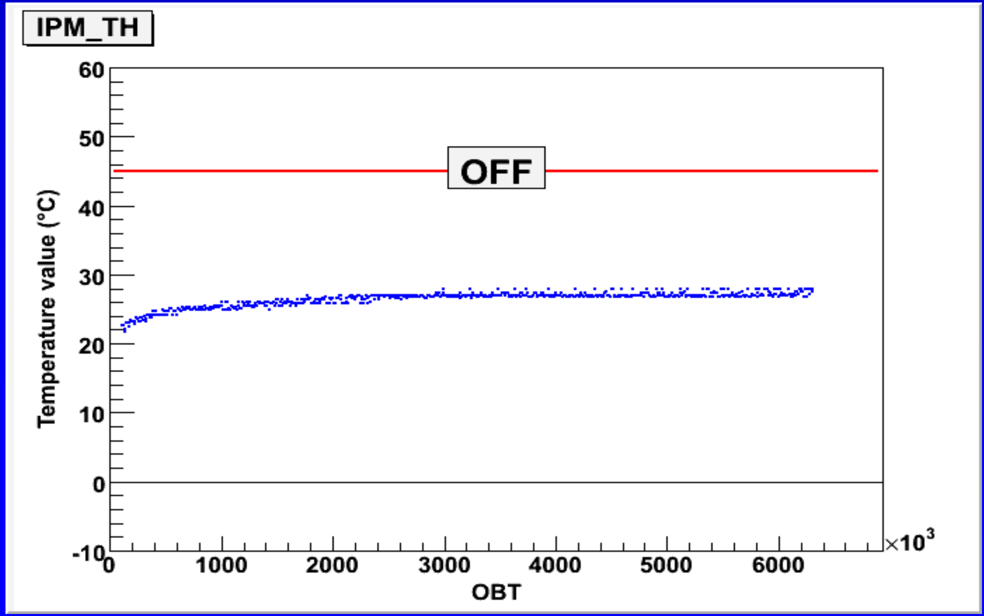
- ‘Real time’ Quicklook at NtsOMZ

- Data distributed to MePHI (Moscow Engineering and Physics Institute) and then to CNAF, Bologna via GridFTP for reduction and calibration, and distribution to Institutes

Operational experience

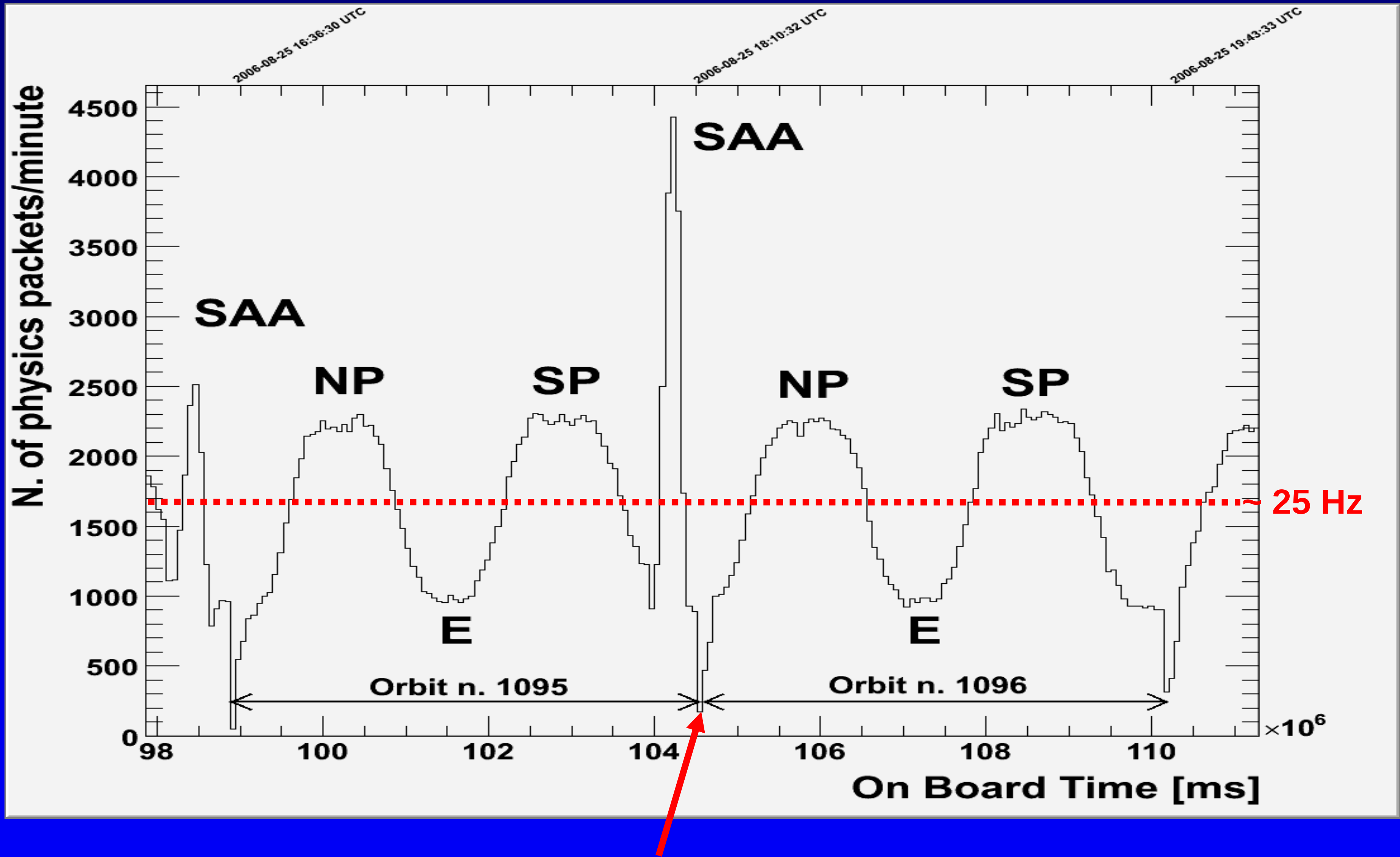
- **System is very stable**, examples:



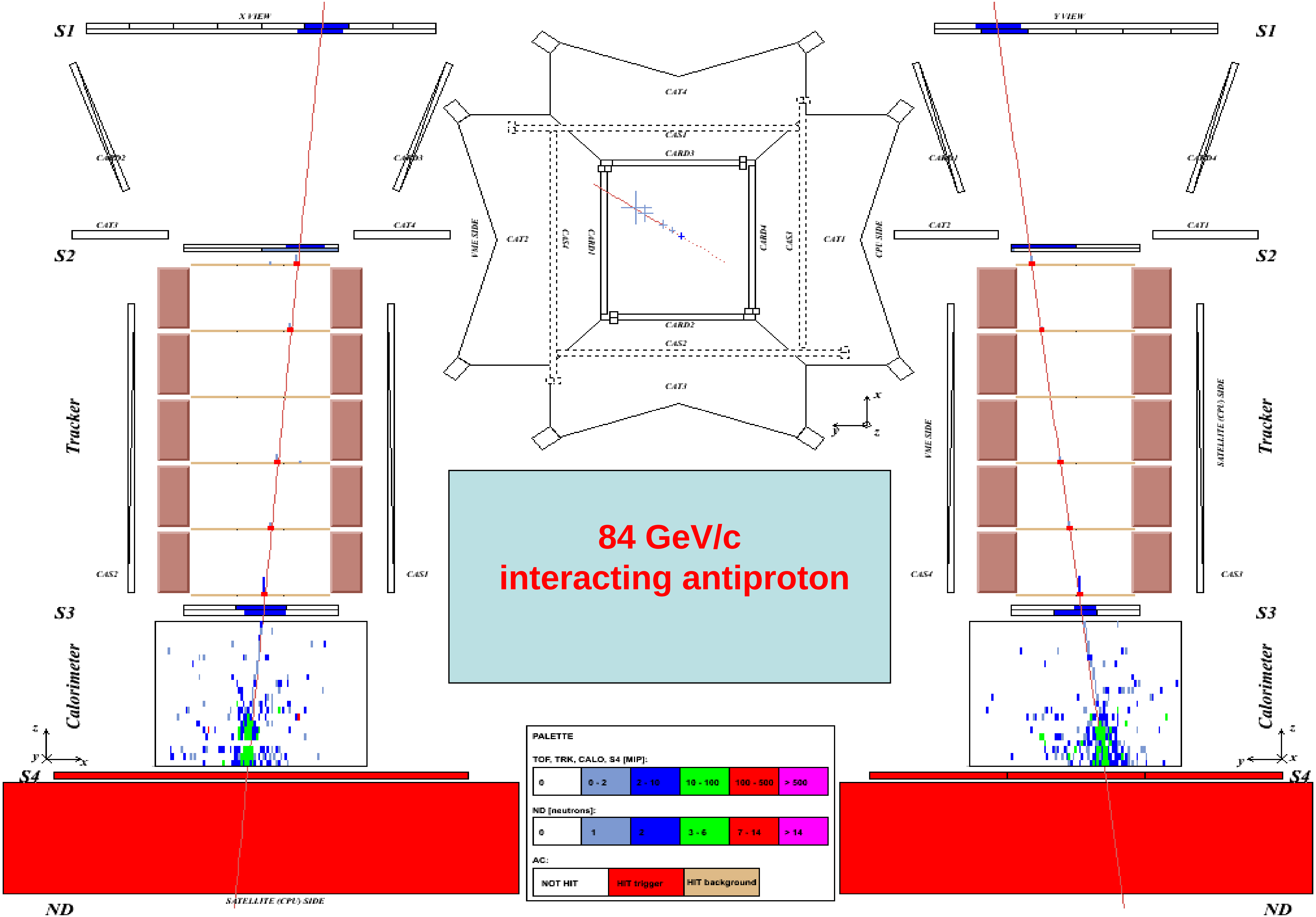


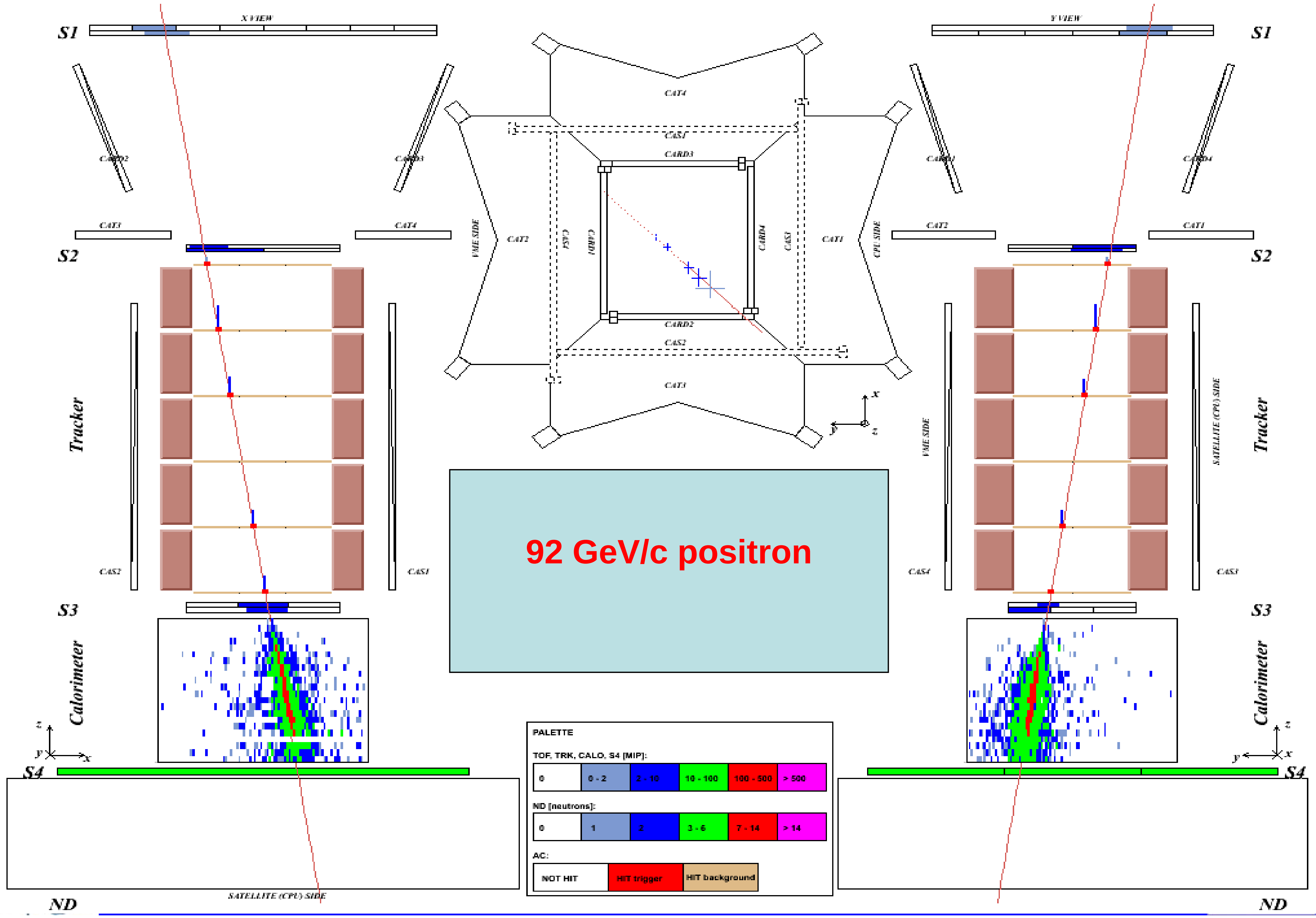
- Remote monitoring via web-based Quicklook
- Relatively few up-link interventions have been necessary
- Approximately 1 alarm per day. Usually anomalous electronics conditions. Weak correlation to SAA, radiation belts.
- The majority of alarms are handled automatically by hardware resets. < 1 per month require power cycling.

Trigger rate

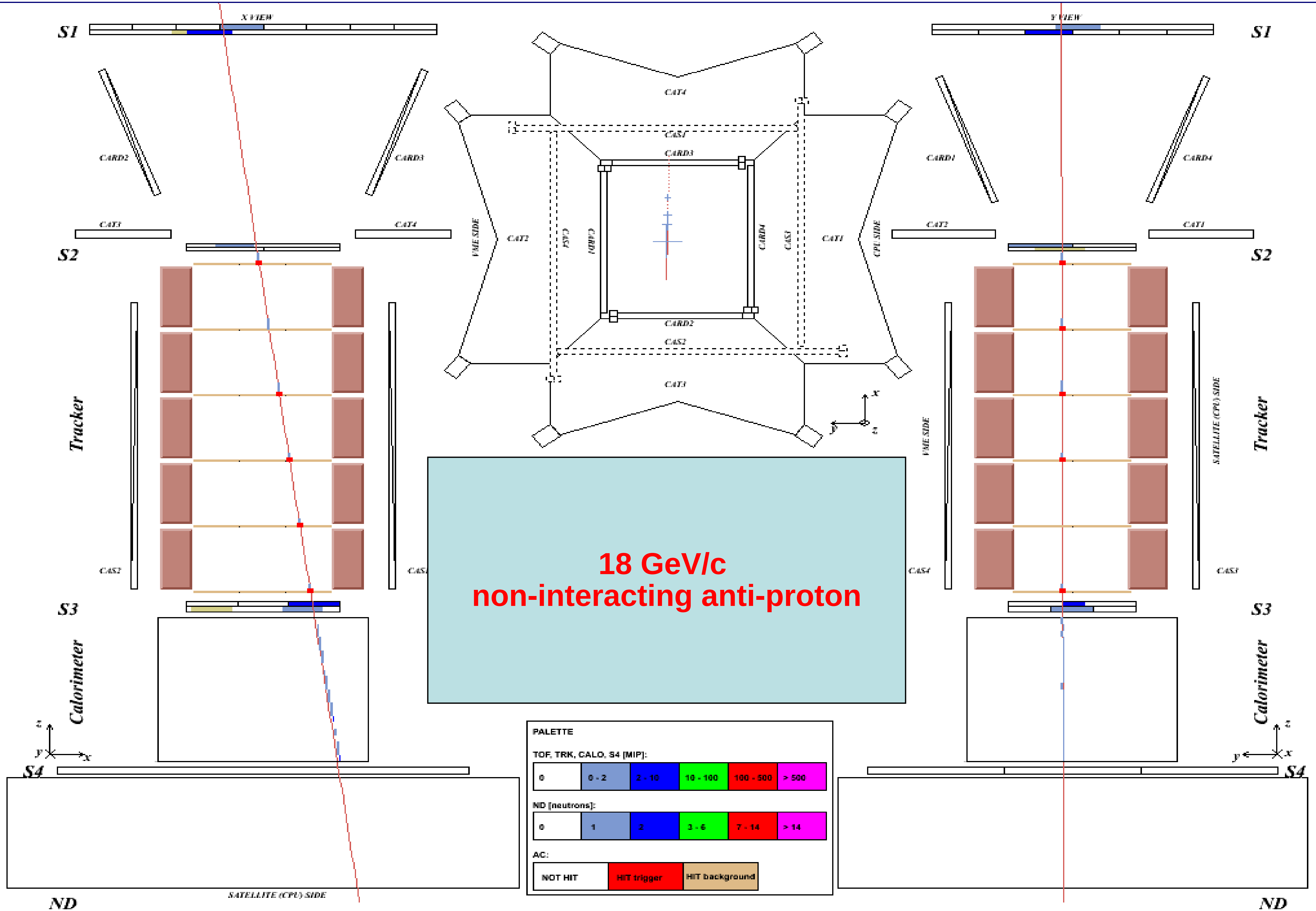


Calibration @ ascending node

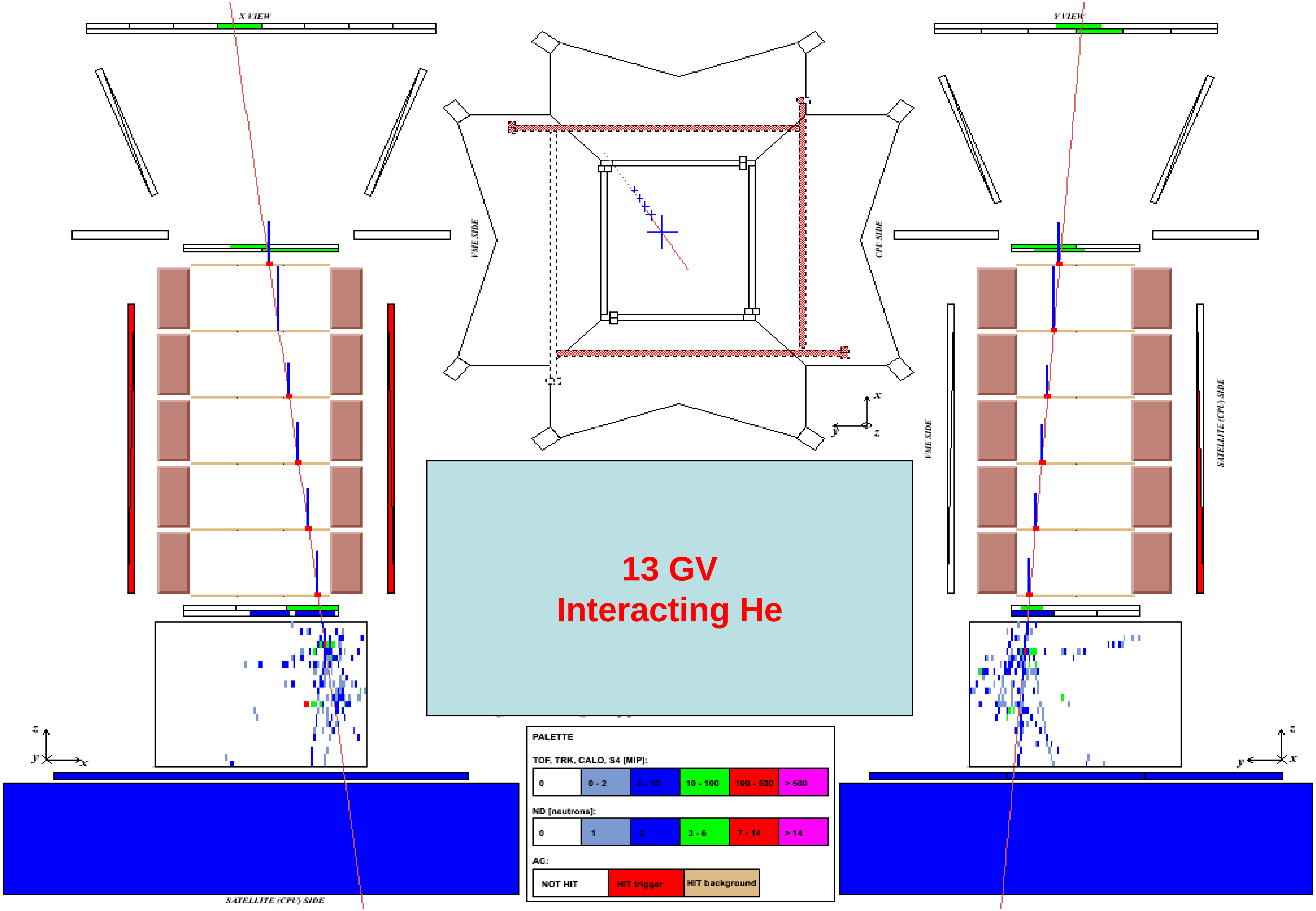

X VIEW
Y VIEW
S1
S2
S3
S4
ND
Tracker
Calorimeter
CAT1
CAT2
CAT3
CAT4
CARD1
CARD2
CARD3
CARD4
CAS1
CAS2
CAS3
CAS4
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
84 GeV/c
interacting antiproton
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background



X VIEW
Y VIEW
S1
S2
S3
S4
ND
CARD2
CARD3
CARD1
CARD4
CAT1
CAT2
CAT3
CAT4
CAS1
CAS2
CAS3
CAS4
CARD2
CARD3
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
Tracker
Calorimeter
92 GeV/c positron
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background



18 GeV/c
non-interacting anti-proton
X VIEW
Y VIEW
S1
S2
S3
S4
ND
Tracker
Calorimeter
CARD1
CARD2
CARD3
CARD4
CAT1
CAT2
CAT3
CAT4
CAS1
CAS2
CAS3
CAS4
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background


X VIEW
Y VIEW
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
13 GV
Interacting He
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background

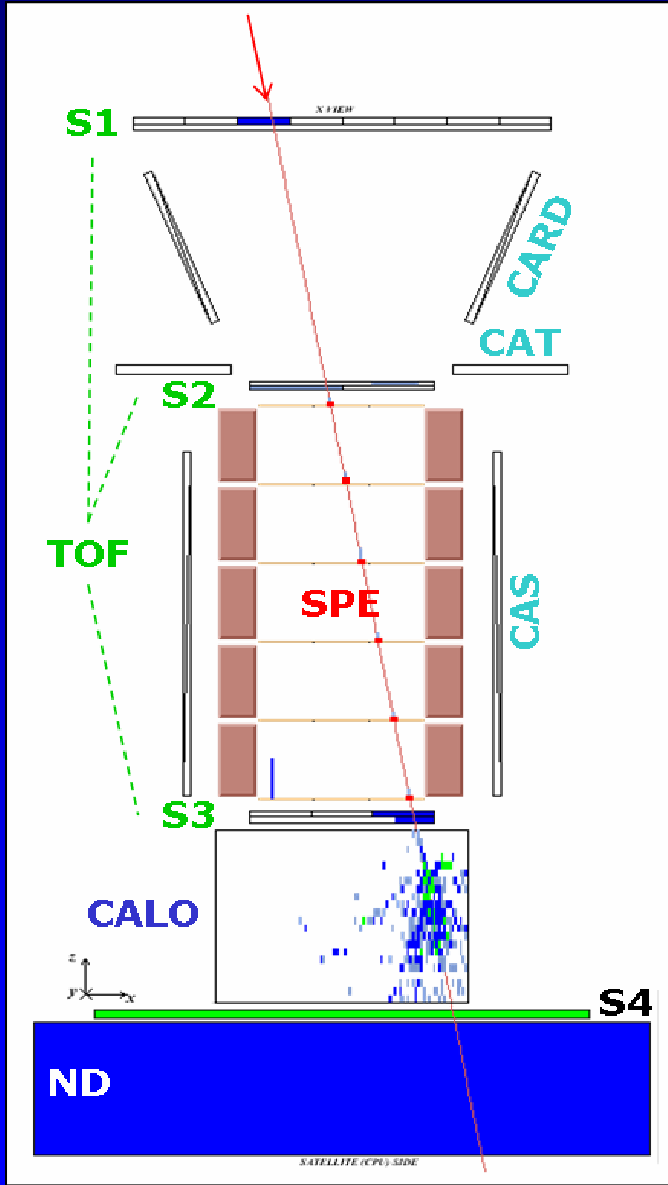
High-energy antiproton analysis

- Analyzed data July 2006 – March 2008 (~550 days)
- Collected triggers ~10^8
- Identified **~ 10^7 protons** and **~ 10^3 antiprotons** between 1.5 and 100 GeV (**100 p- bar above 20GeV**)

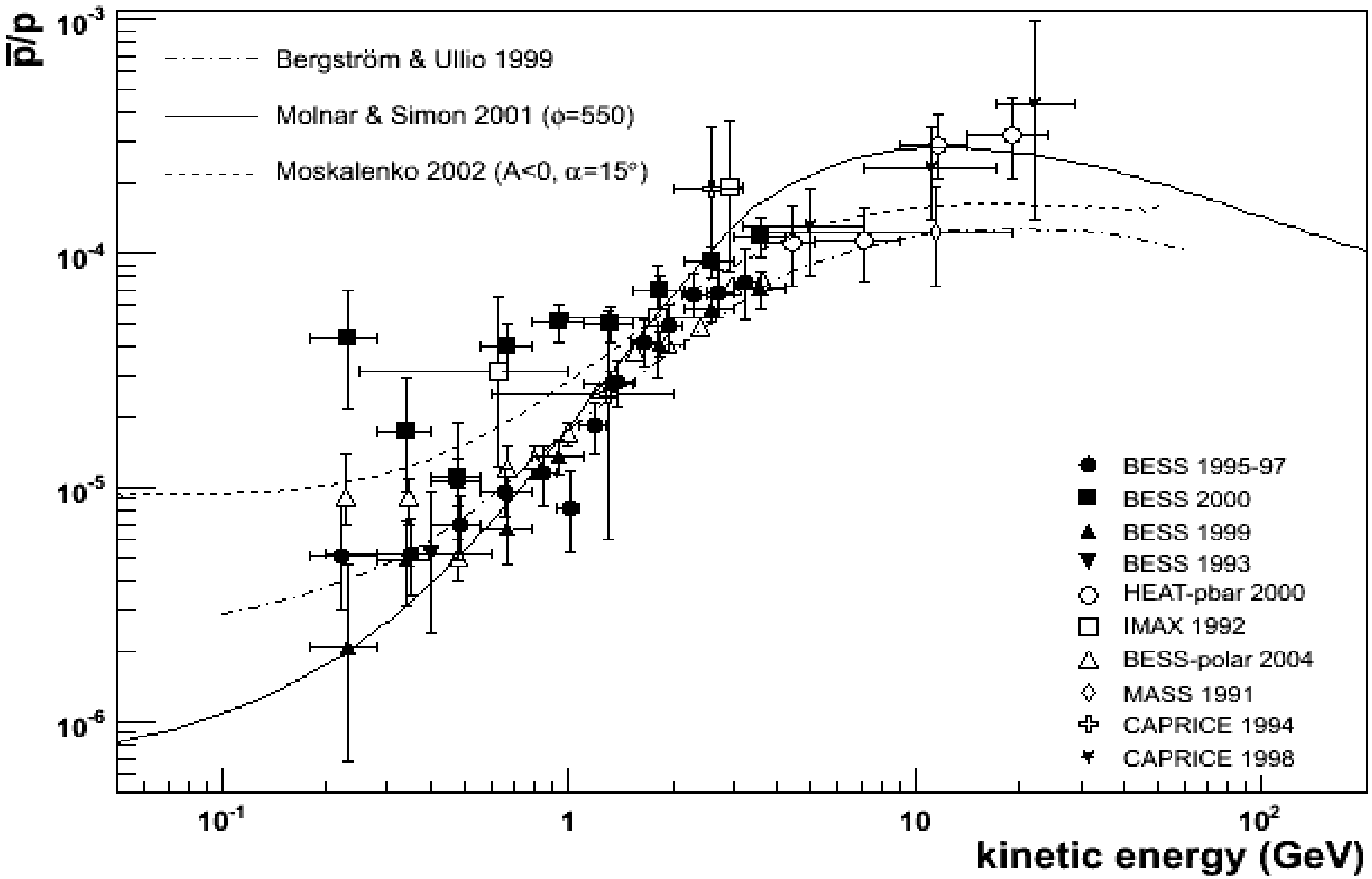
- Antiproton/proton identification:
  - rigidity (R) → SPE
  - |Z|=1 (dE/dx vs R) → SPE&ToF
  - b vs R consistent with M_p → ToF
  - p-bar/p separation (charge sign) → SPE
  - p-bar/e^- (and p/e^+) separation → CALO

- Dominant background at high energies → **spillover protons**:
  - finite deflection resolution of the SPE ⇒ wrong assignment of charge-sign @ high energy

→ Required strong SPE selection

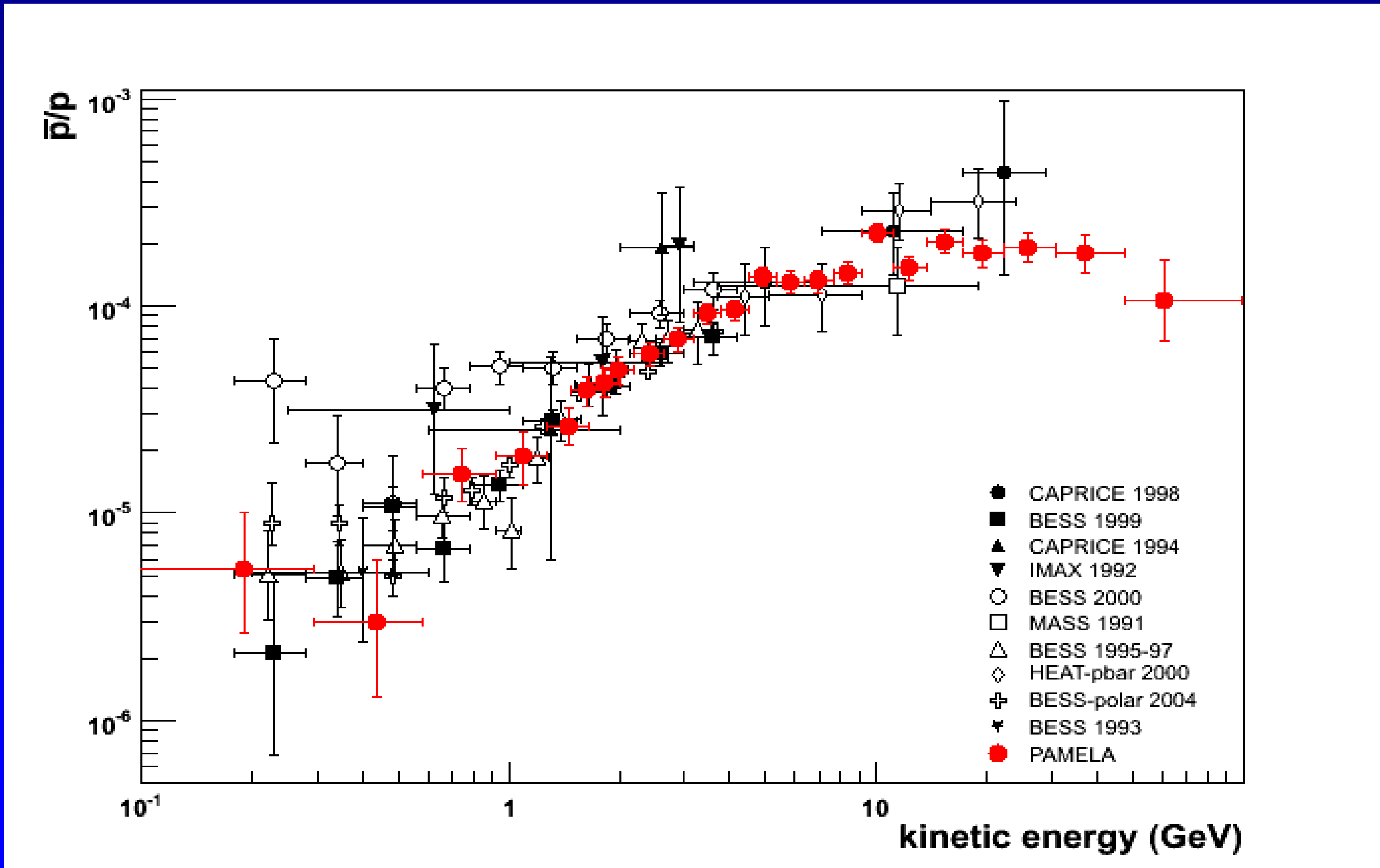


Pre-PAMELA antiproton-to-proton ratio



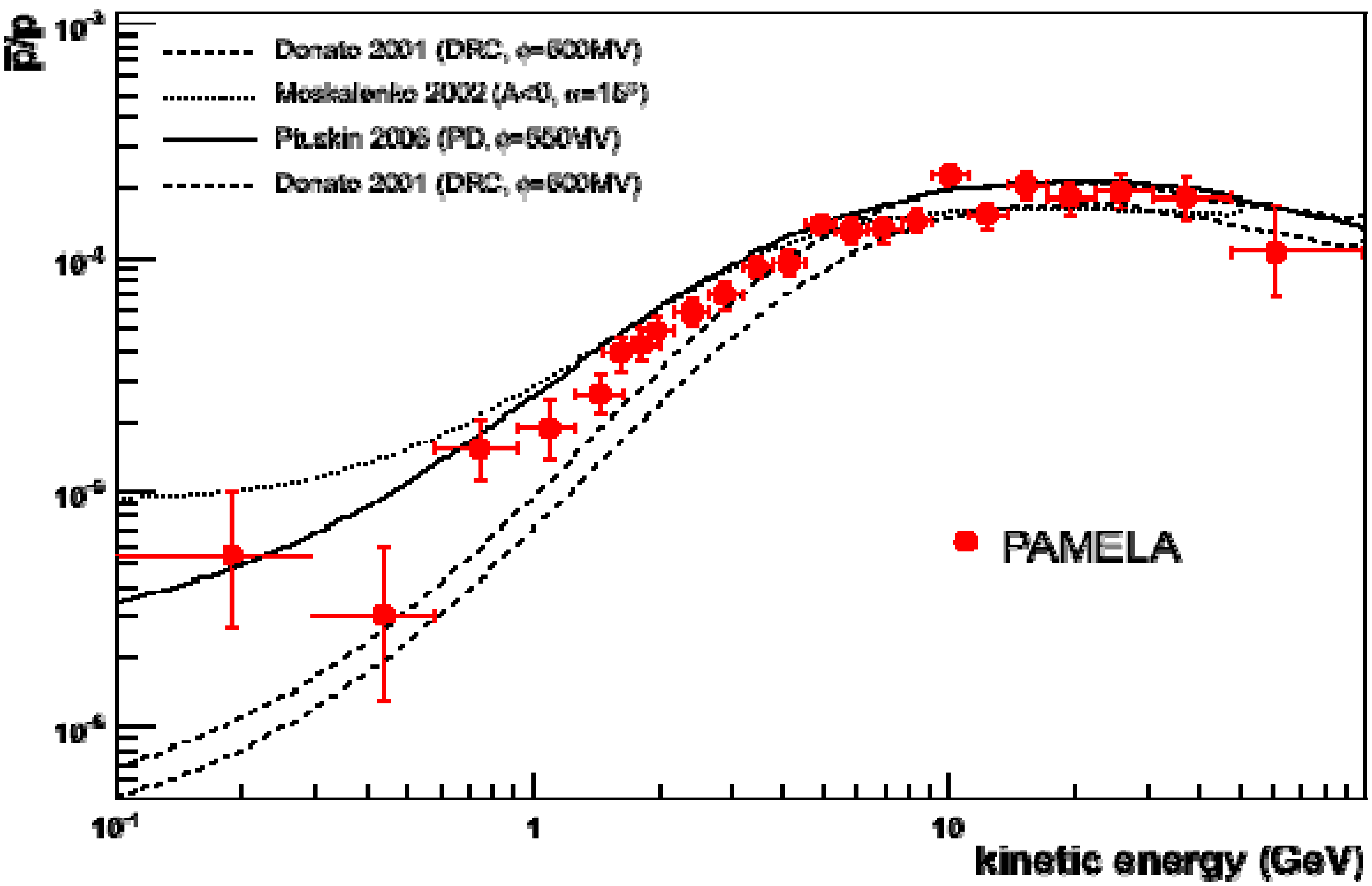
Pre-PAMELA antiproton-to-proton ratio

PRL 102, (2009) 051101, Astro-ph 0810.4994



Antiproton-to-proton ratio
Secondary Production Models

CR + ISM → **p-bar** + …



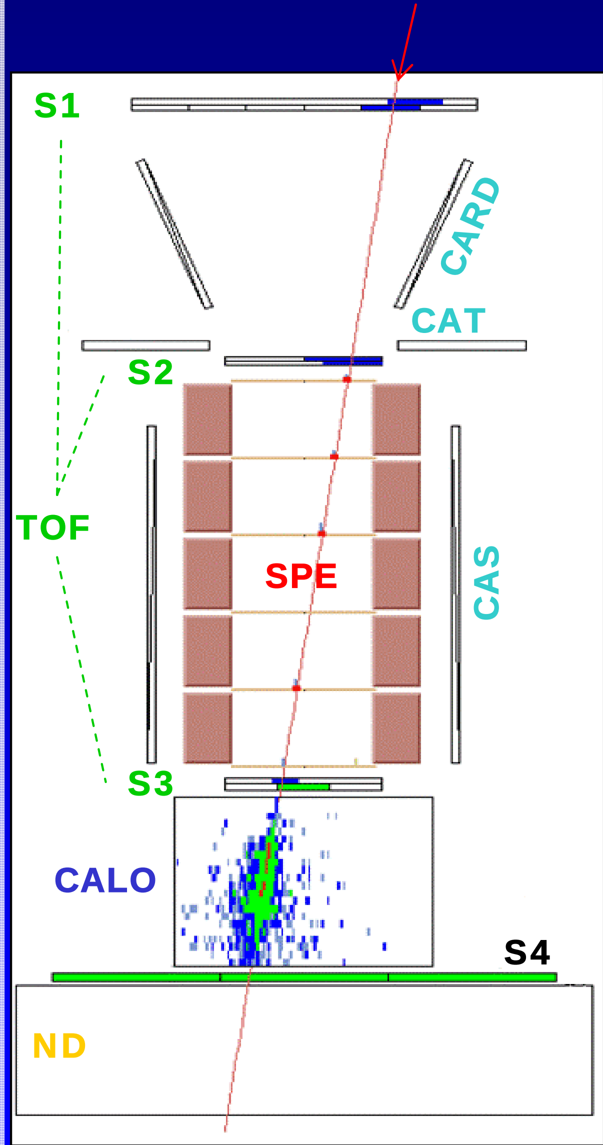
High-energy positron analysis

- Analyzed data July 2006 – March 2008 (~550 days)
- Collected triggers ~10^8
- Identified ~ **$150 \cdot 10^3$ electrons** and ~ **$9 \cdot 10^3$ positrons** between 1.5 and 100 GeV (**180 positrons above 20GeV**)

- Electron/positron identification:
  - rigidity (R) → SPE
  - |Z|=1 (dE/dx=MIP) → SPE&ToF
  - β=1 → ToF
  - e^-/e^+ separation (charge sign) → SPE
  - e^+/p (and e^-/p-bar) separation → CALO

- **Dominant background → interacting protons:**
  - **fluctuations in hadronic shower development ⇒ $\pi_0 \rightarrow \gamma\gamma$ might mimic pure em showers**
  - **proton spectrum harder than positron ⇒ p/e^+ increase for increasing energy (10^3 @1GV 10^4 @100GV)**

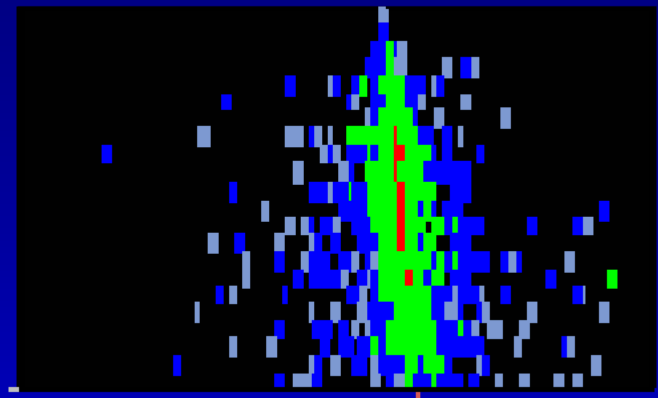
⇒ Required strong CALO selection



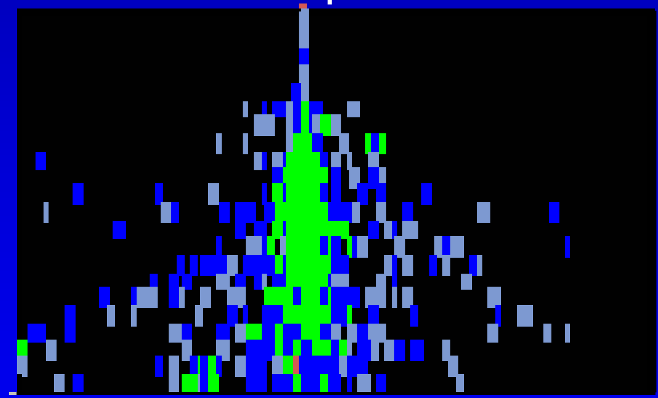
Positron selection with the calorimeter - 1

- Identification based on:
  - **Shower topology** (lateral and longitudinal profile, shower starting point)
  - **Total detected energy** (energy-rigidity match)
- Analysis key points:
  - **Tuning/check of selection criteria with:**
    - test-beam data
    - simulation
    - flight data → dE/dx from SPE & neutron yield from ND
  - **Selection of pure proton sample from flight data** ("pre-sampler" method):
    - ***Background-suppression method***
    - ***Background-estimation method***

51 GV positron



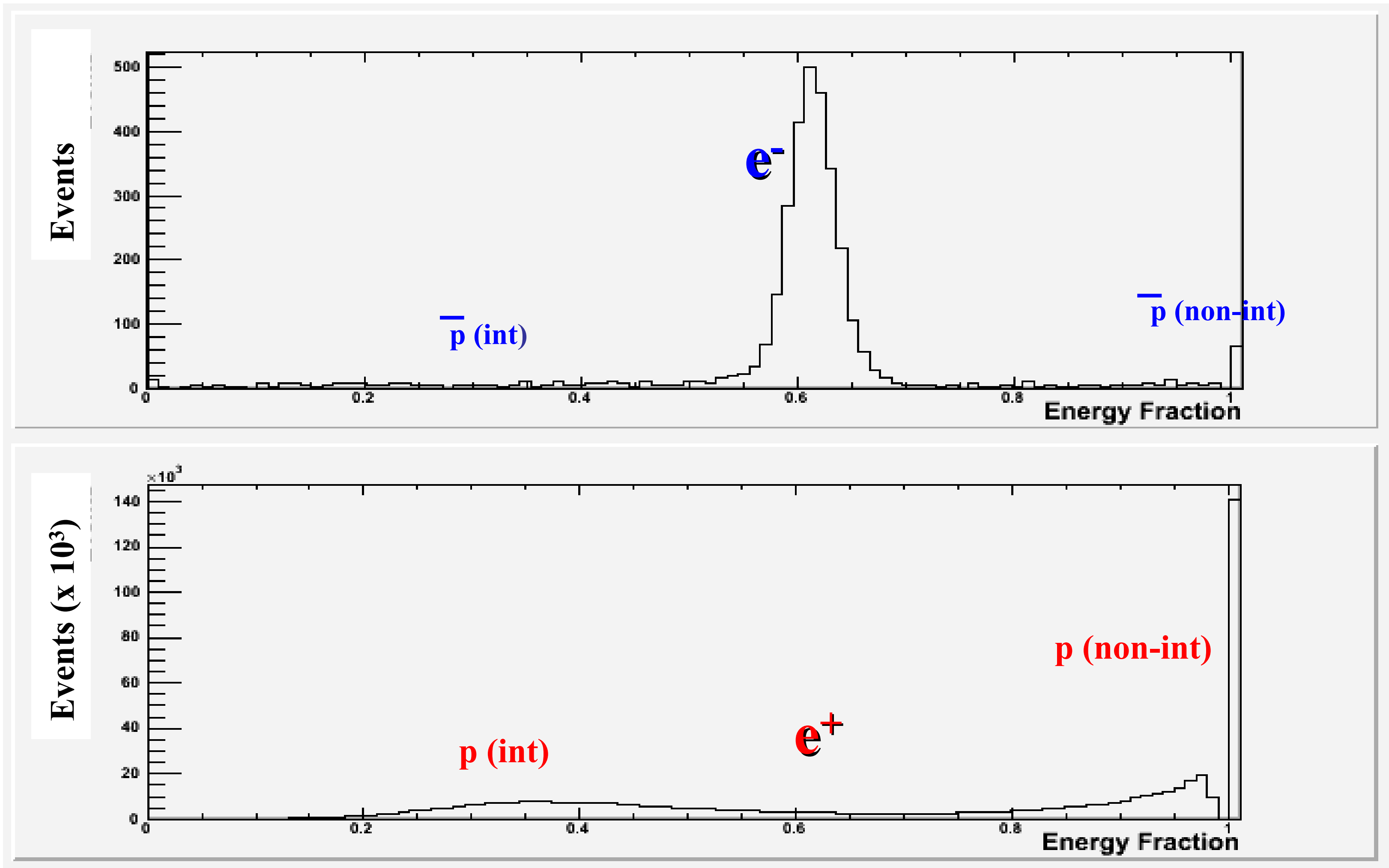
80 GV proton



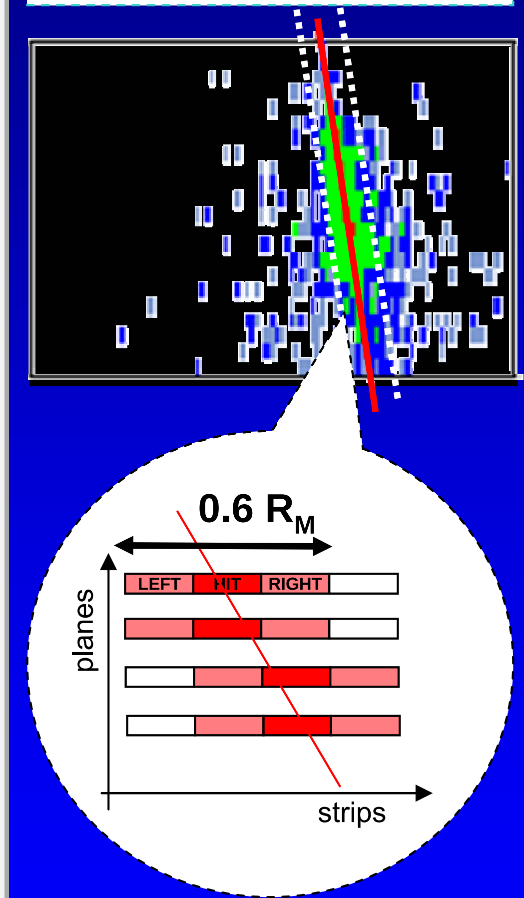
Final results <u>DON'T MAKE USE</u> of test-beam and/or simulation calibrations.
The measurement is based only on flight data
with the <u>background-estimation</u> method

Positron selection with the calorimeter - 2

Rigidity: 20-30 GV

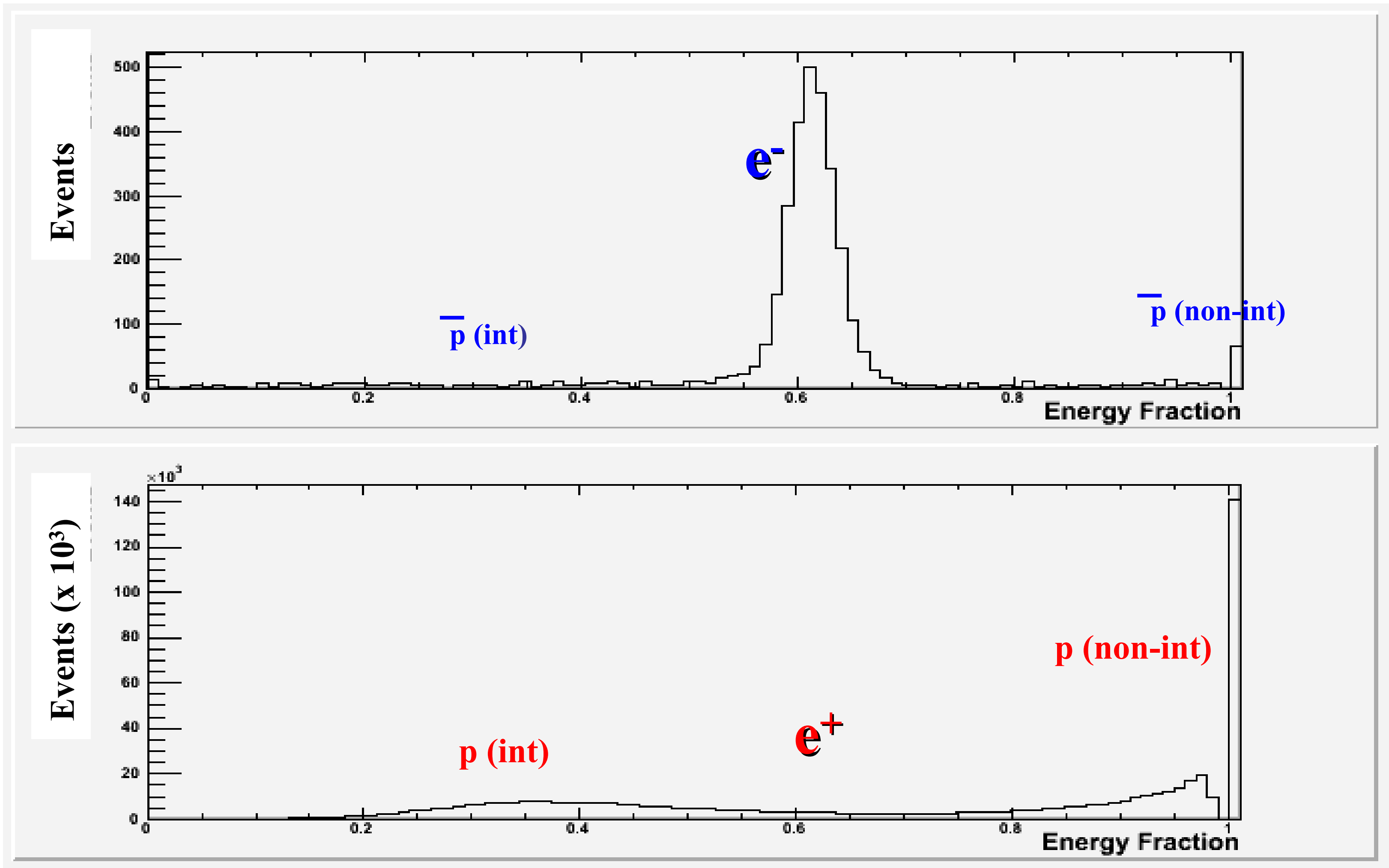


Fraction of charge released along the calorimeter track



Positron selection with the calorimeter - 3

Rigidity: 20-30 GV



Fraction of charge released along the calorimeter track

+

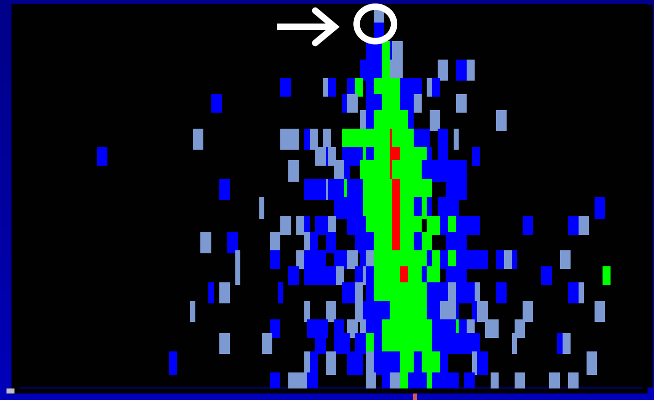
Constraints on:

Energy-momentum match

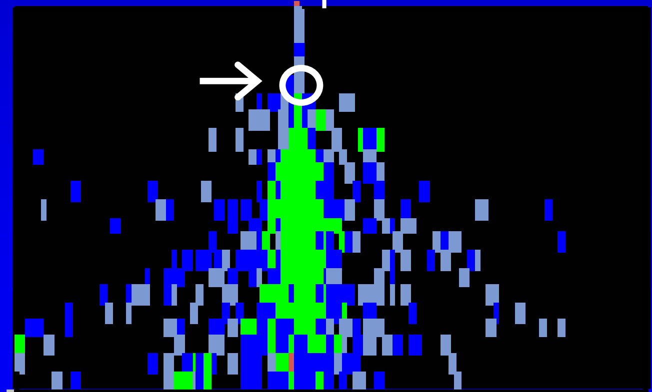
Positron selection with the calorimeter - 4

Shower starting-point

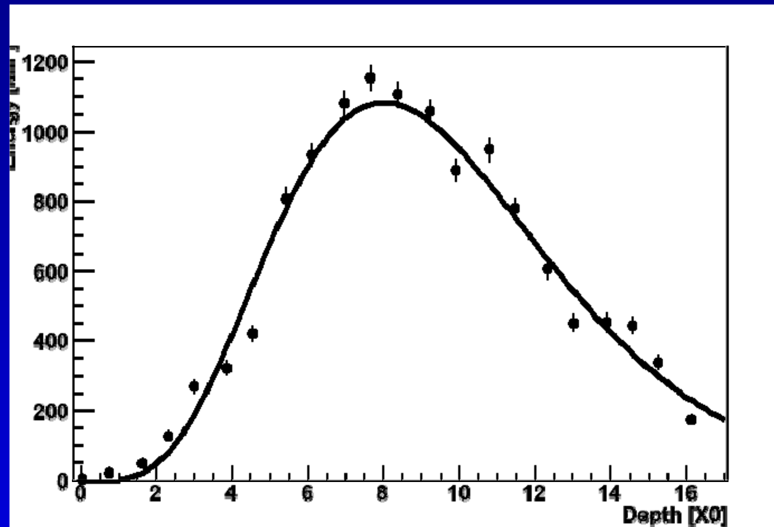
51 GV positron



80 GV proton

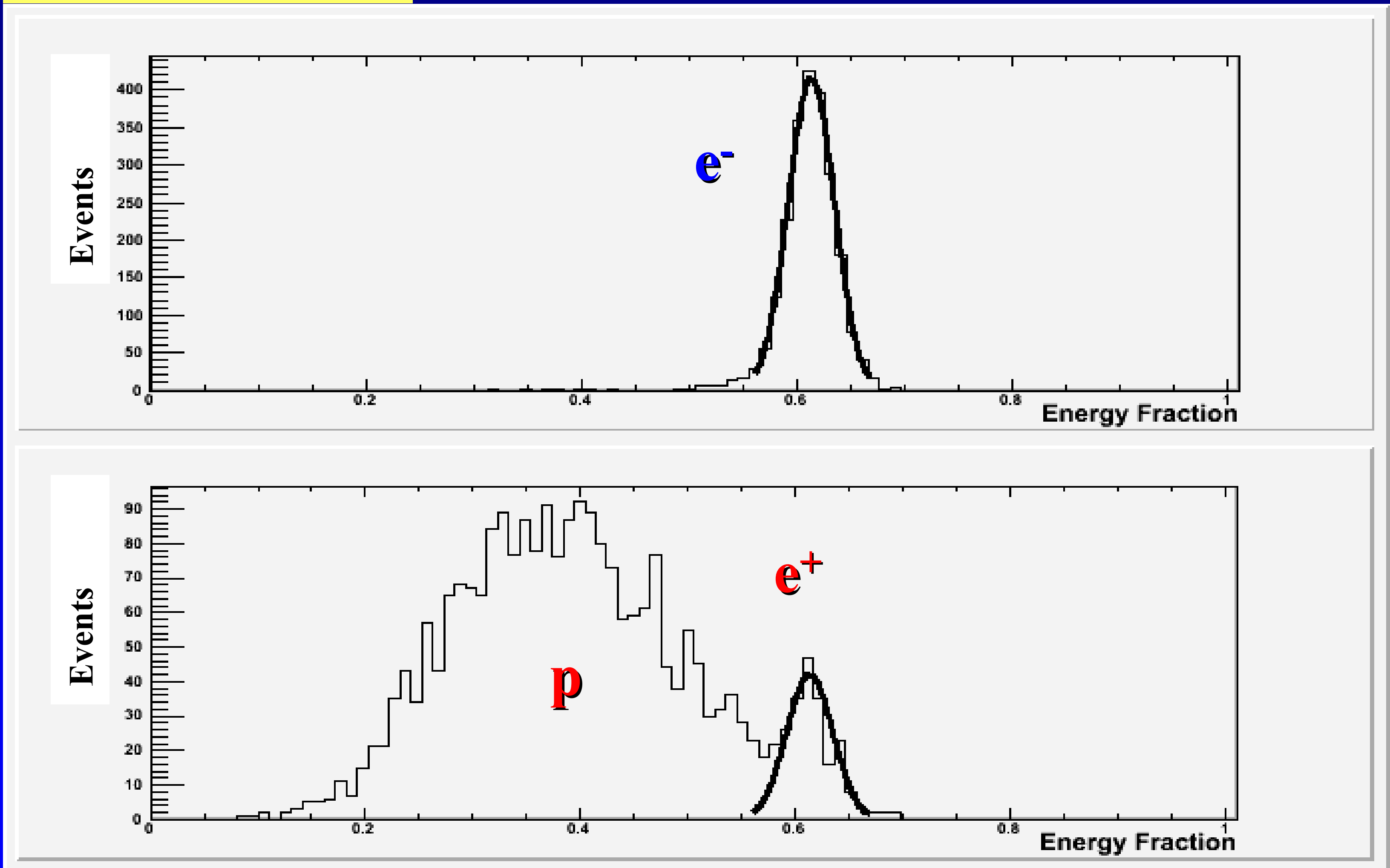


Longitudinal profile



Positron selection with the calorimeter - 5

Rigidity: 20-30 GV



Fraction of charge released along the calorimeter track

+

Constraints on:

Energy-momentum match

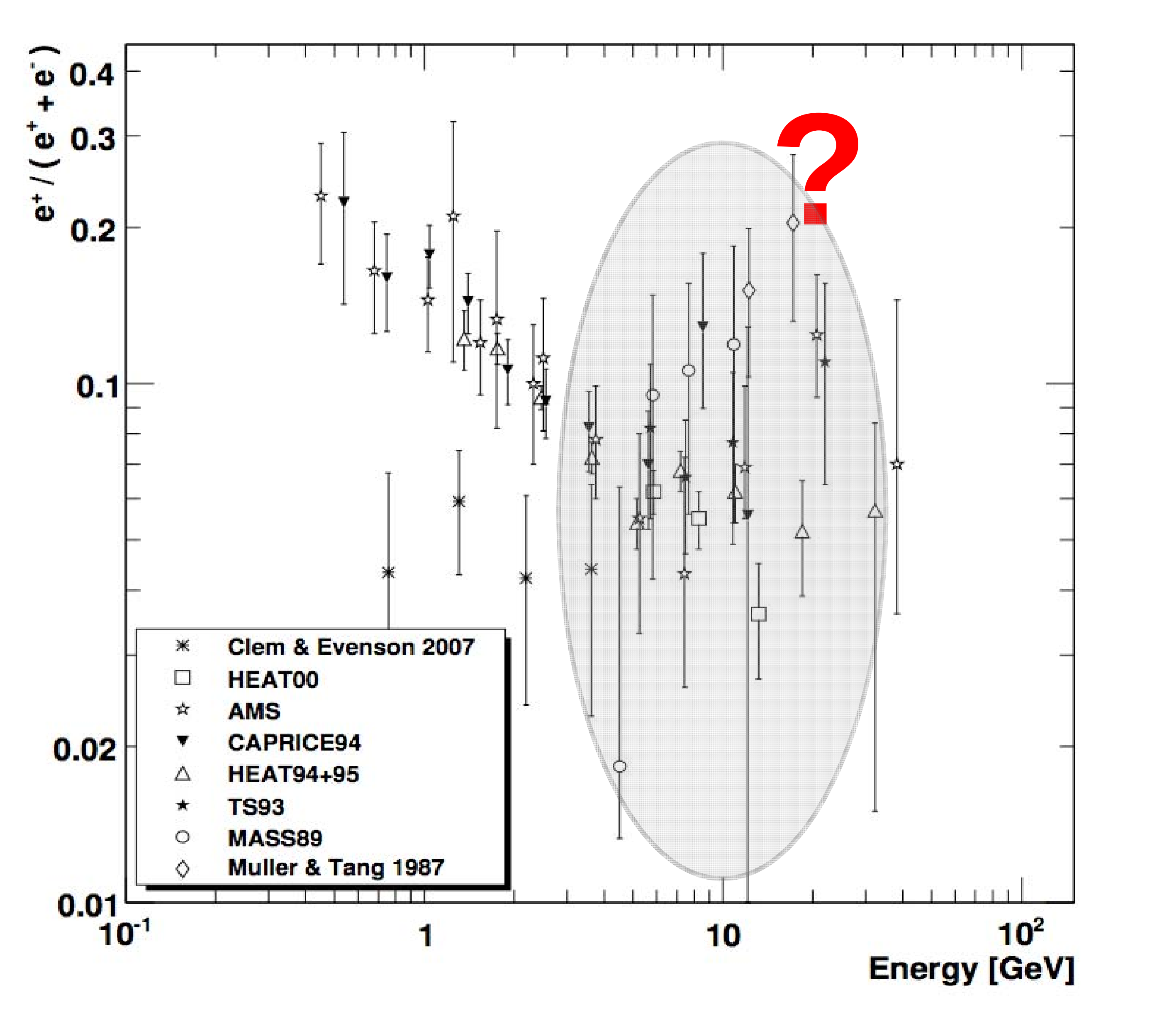
Shower starting-point

Longitudinal profile

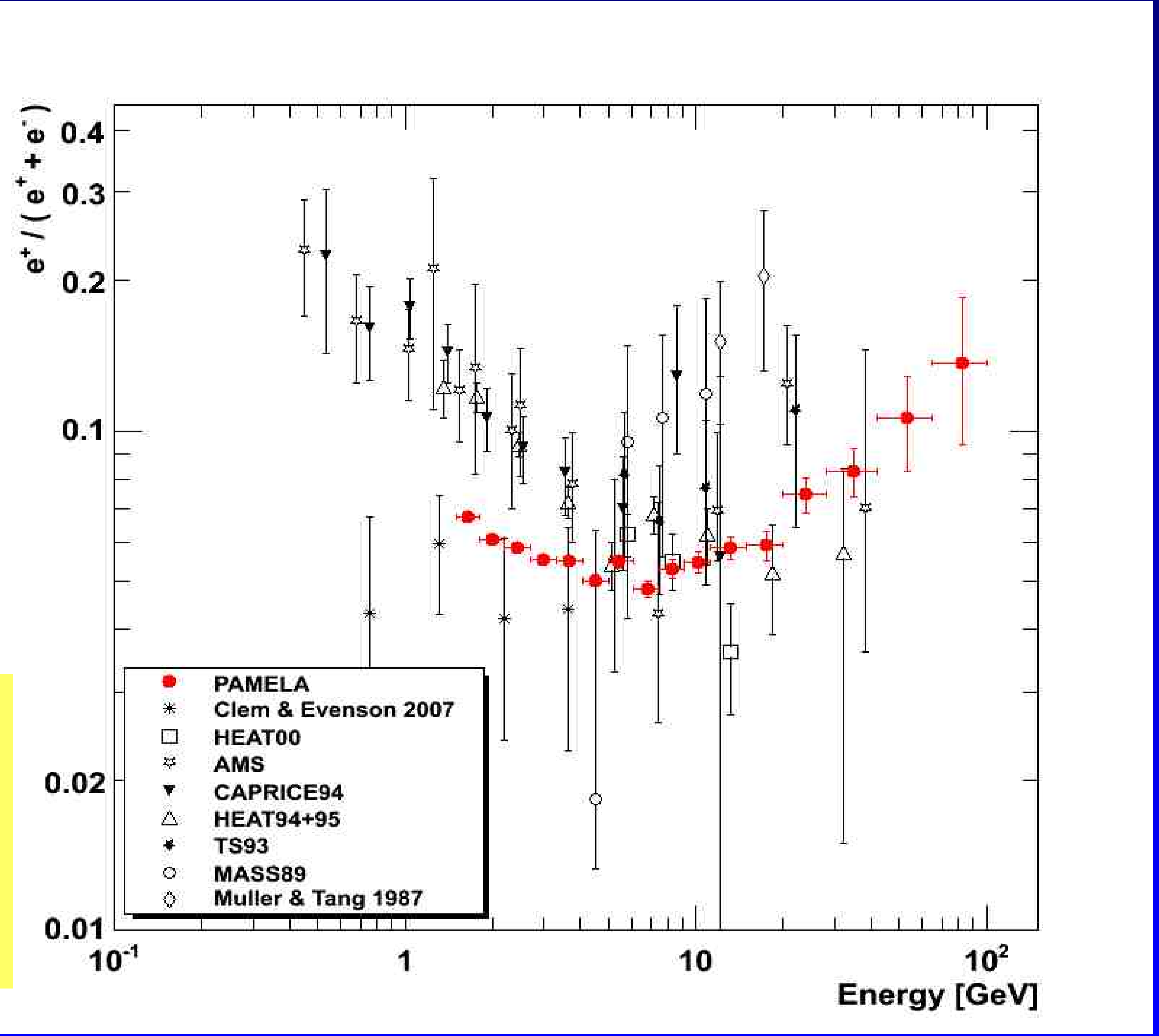
Lateral profile

BK-suppression method

Pre-PAMELA positron fraction



Positron fraction



End 2007:
~ 10 000 e^+ > 1.5 GeV

~ 2000 > 5 GeV

Nature 458 (2009) 607, Astro-ph 0810.4995

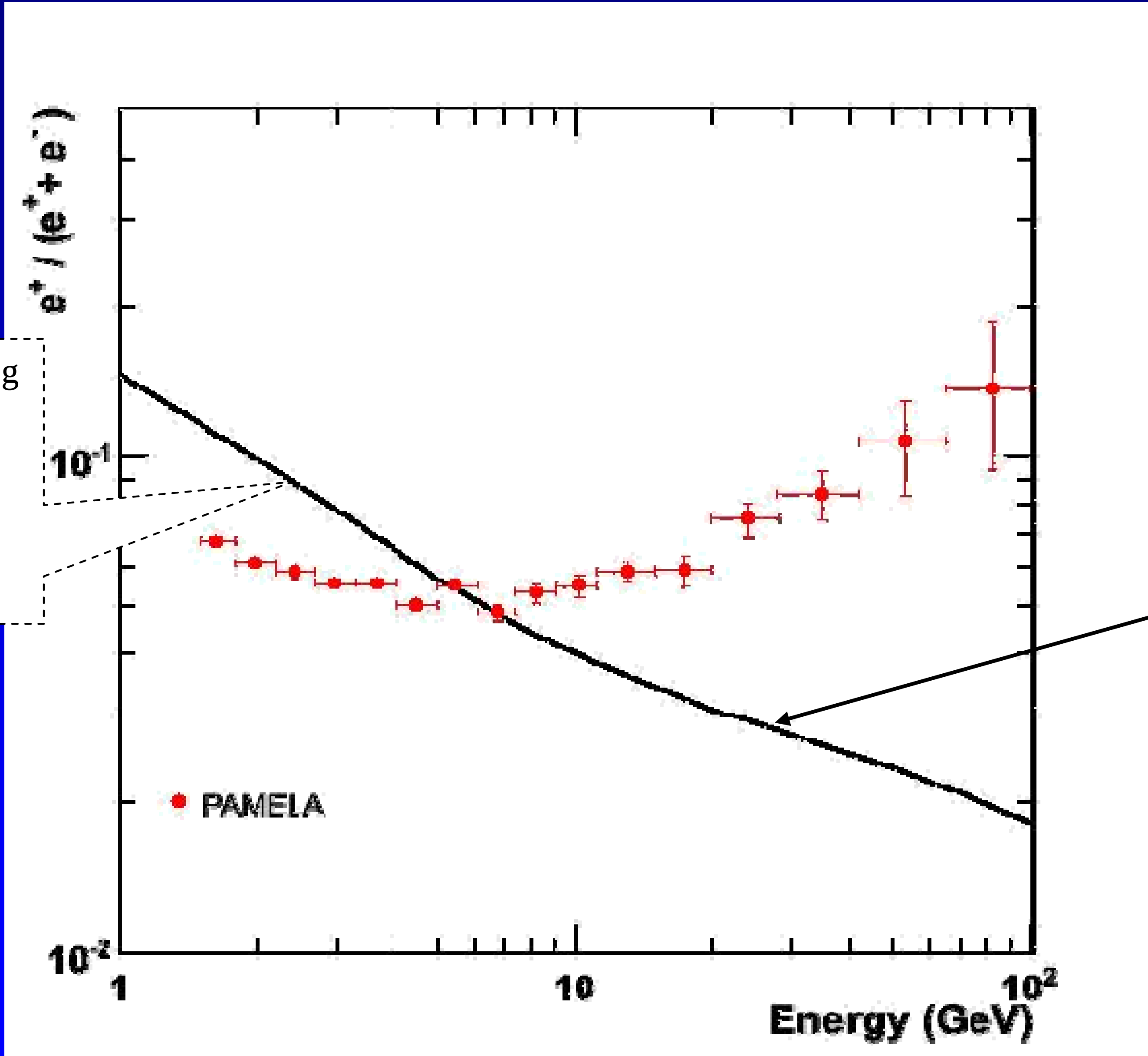
Positron fraction

Secondary Production Models

$CR + ISM \rightarrow \pi^{\pm} + \ldots \rightarrow \mu^{\pm} + \ldots \rightarrow e^{\pm} + \ldots$

$CR + ISM \rightarrow \pi^{0} + \ldots \rightarrow \gamma\gamma \rightarrow e^{\pm}$

(Moskalenko & Strong 1998)
GALPROP code
- **Plain diffusion model**
- Interstellar spectra



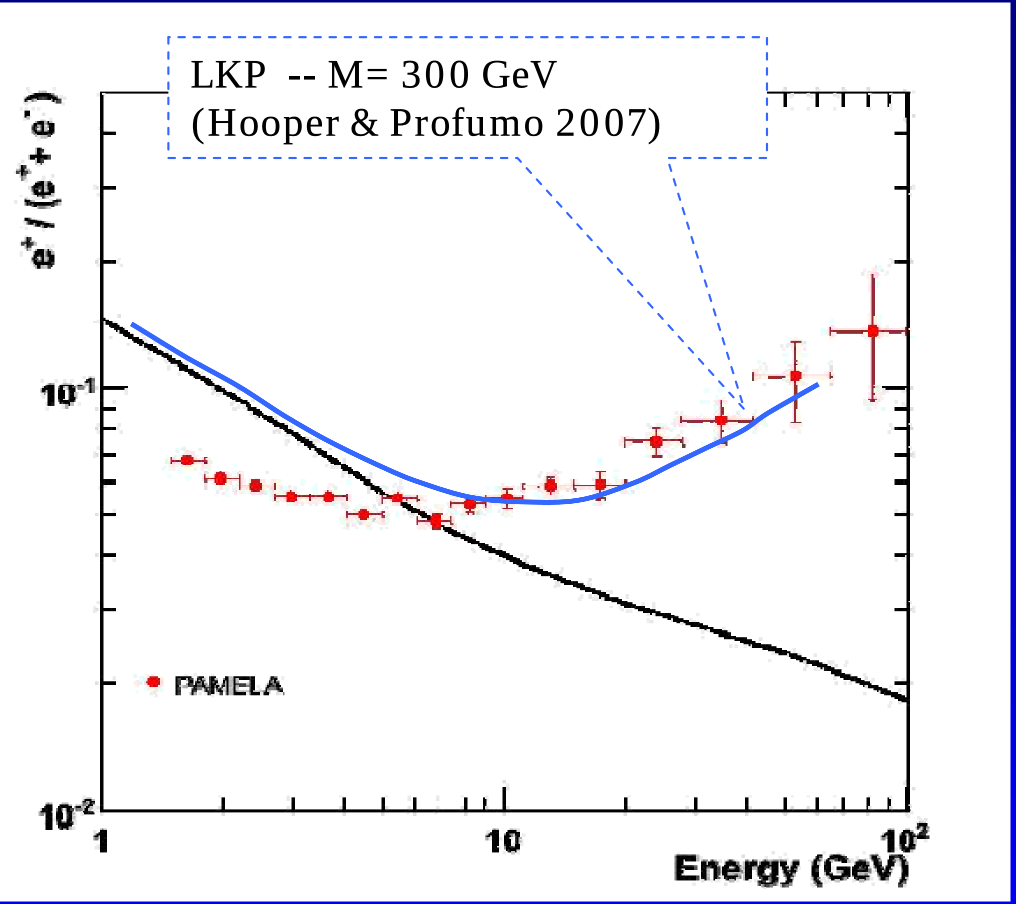
But uncertainties on:
- **Secondary production (primary fluxes, cross section)**
- **Propagation models**
- **Electron spectrum**

Possible primary positron sources

Dark Matter

- e^+ yield depend on the dominant decay channel
  - → **LSPs** seem disfavored due to suppression of e^+e^- final states
    - → low yield (relative to p-bar)
    - → soft spectrum from cascade decays
  - → **LKPs** seem favored because can annihilate directly in e^+e^-
    - → high yield (relative to p-bar)
    - → hard spectrum with pronounced cutoff @ M_{LKP} (>300 GeV)

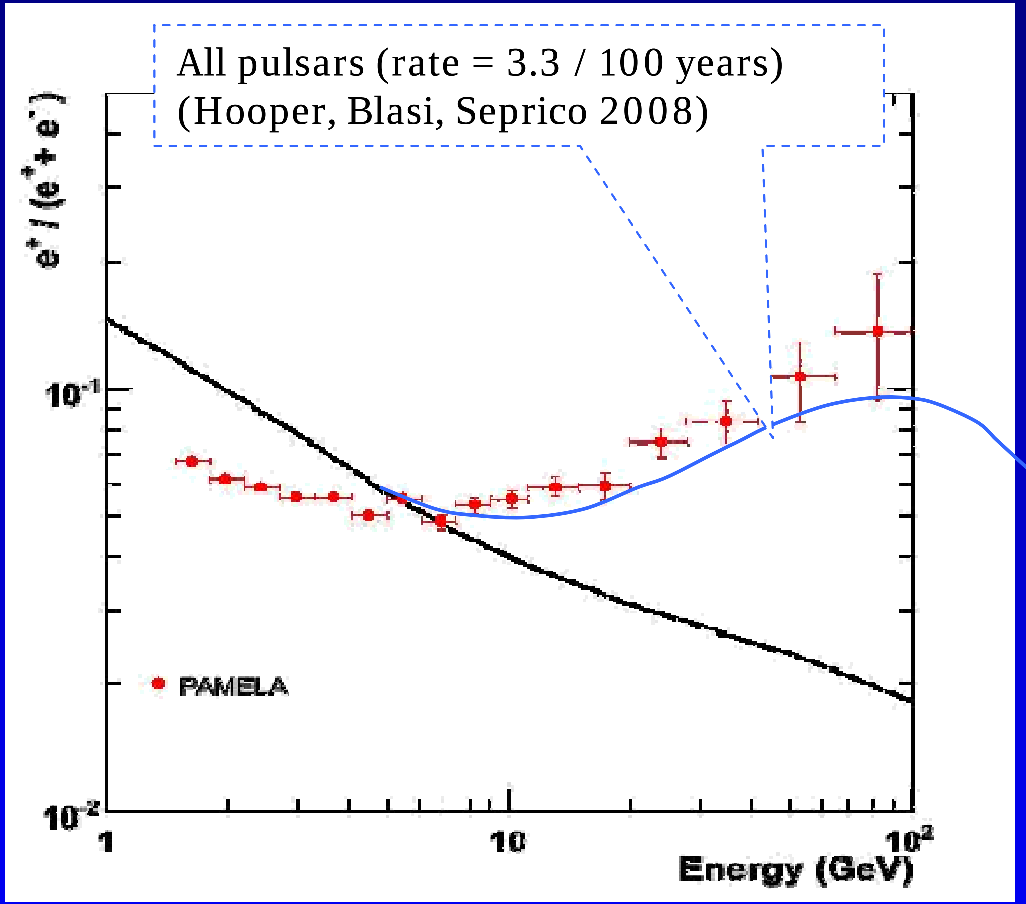
- Boost factor required to have a sizable e^+ signal
  - → NB: constraints from p-bar data!!



Possible primary positron sources

Astrophysical processes

- Local **pulsars** are well-known sites of e^+e^- pair production:
  - → they can individually and/or coherently contribute to the e^+e^- galactic flux and explain the PAMELA e^+ excess (both spectral feature and intensity)
    - → No fine tuning required
  - → if one or few nearby pulsars dominate, anisotropy could be detected in the angular distribution
    - → possibility to discriminate between pulsar and DM origin of e^+ excess



> 80 theoretical paper on Pamela data since our ArXiv publication!!!!!

Possible primary positron sources

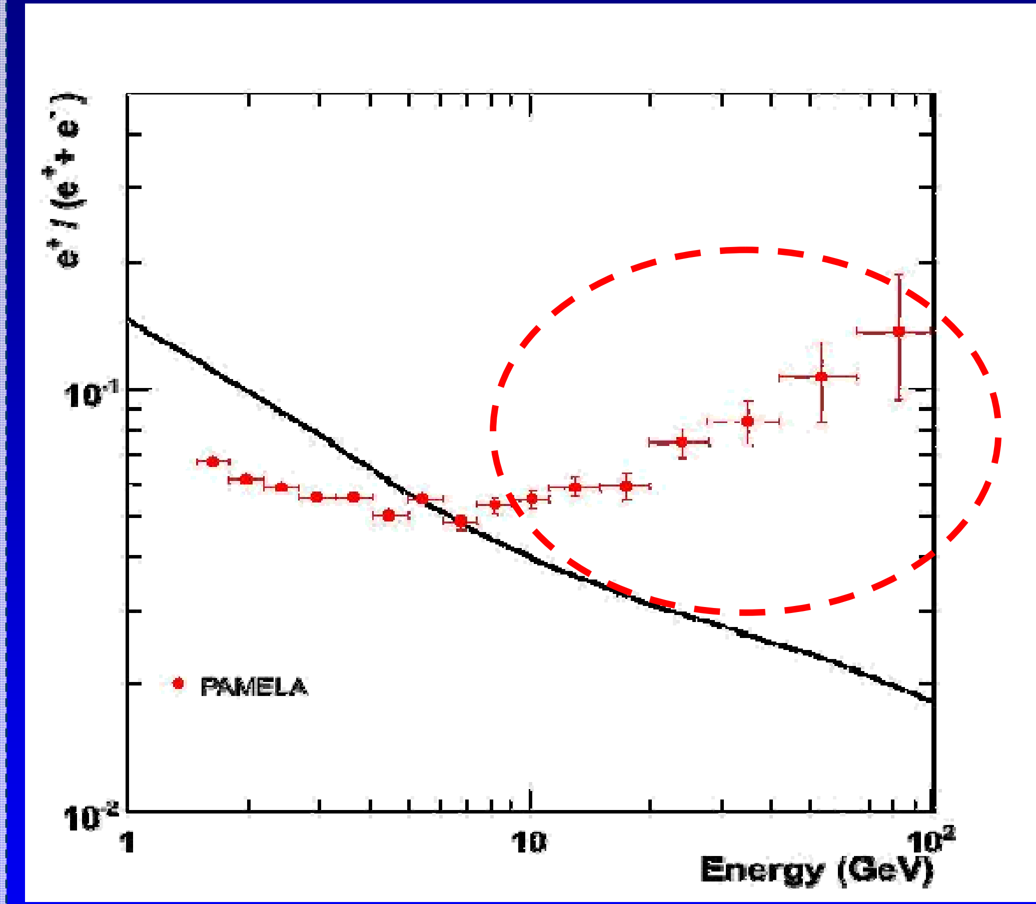
PAMELA positron fraction alone insufficient to understand the origin of positron excess

Additional experimental data will be provided by PAMELA:

- e^+ fraction @ higher energy (up to 300 GeV)
- individual e^- e^+ spectra
- anisotropy (…maybe)
- high energy $e^+ + e^-$ spectrum (up to 2 TV)

Complementary information from:

- gamma rays
- neutrinos



Conclusions

- PAMELA has been in orbit and studying cosmic rays for almost three years

- PAMELA is the first space experiment which is measuring the antiproton and positron cosmic-ray components to the high energies (> 100GeV) with unprecedented statistical precision

  - search for evidence of DM candidates
  - "direct" measurement of particle acceleration in astrophysical sources (pulsars?)

- Antiproton-to-proton flux ratio (100 MeV - 100 GeV) shows no significant deviations from secondary production expectations. Additional high energy data in preparation (up to ~150 GeV).

- High energy positron fraction (> 10 GeV) increases significantly (and unexpectedly!) with energy. Primary source?
  Data at higher energies will help to resolve origin of rise (spillover limit ~300 GeV).

Furthermore:

- PAMELA is providing high-precision measurements on low-mass elemental (and isotopical) spectra (study of particle origin and propagation in the interstellar medium)

- PAMELA is able to measure the high energy tail of solar particles.

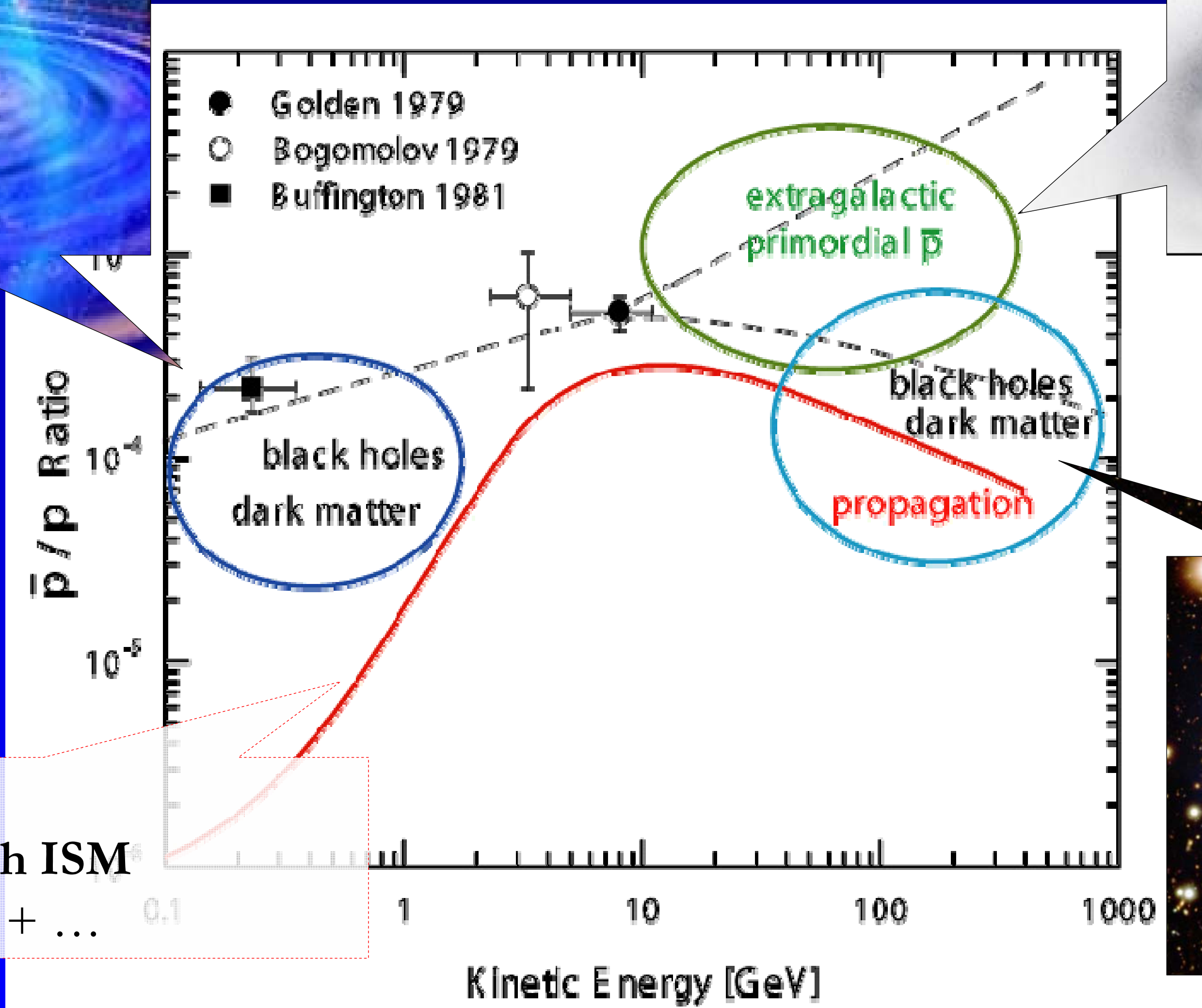
- PAMELA is measuring composition and spectra of trapped and re-entrant albedo particles in the Earth magnetosphere

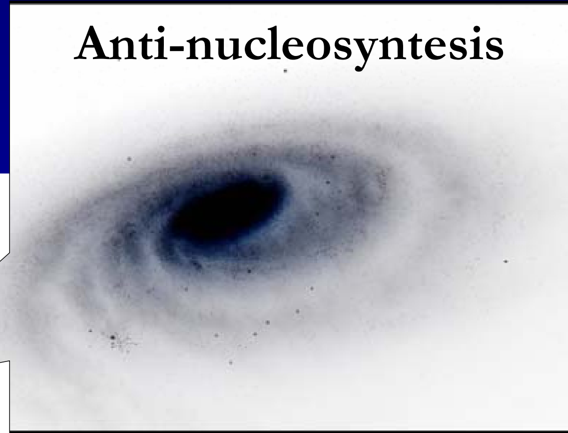
◈ **Thanks!!** ◈

~ Spare slides ~

Why CR antimatter?

First historical measurements of p / p̄ ratio
and various ideas of theoretical interpretations





Background:
CR interaction with ISM
CR + ISM → p-bar + …

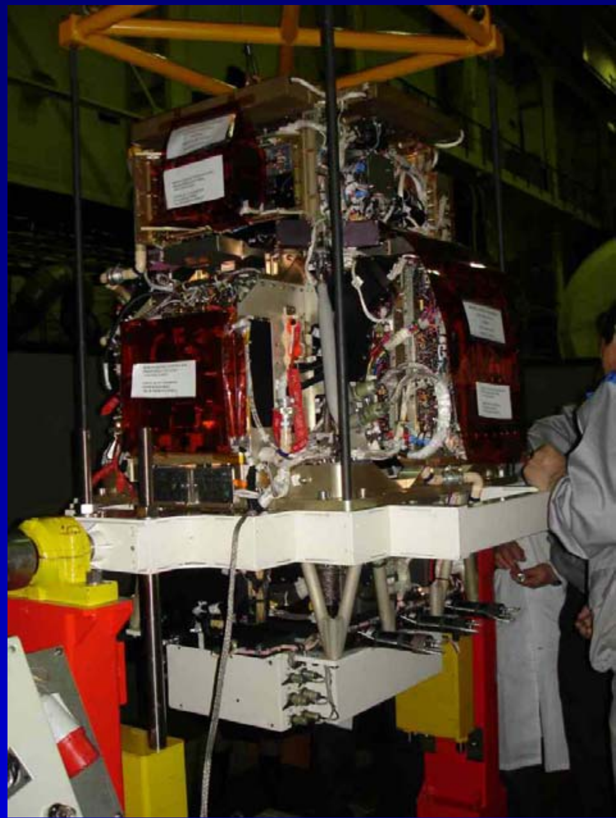
Preparation for the launch

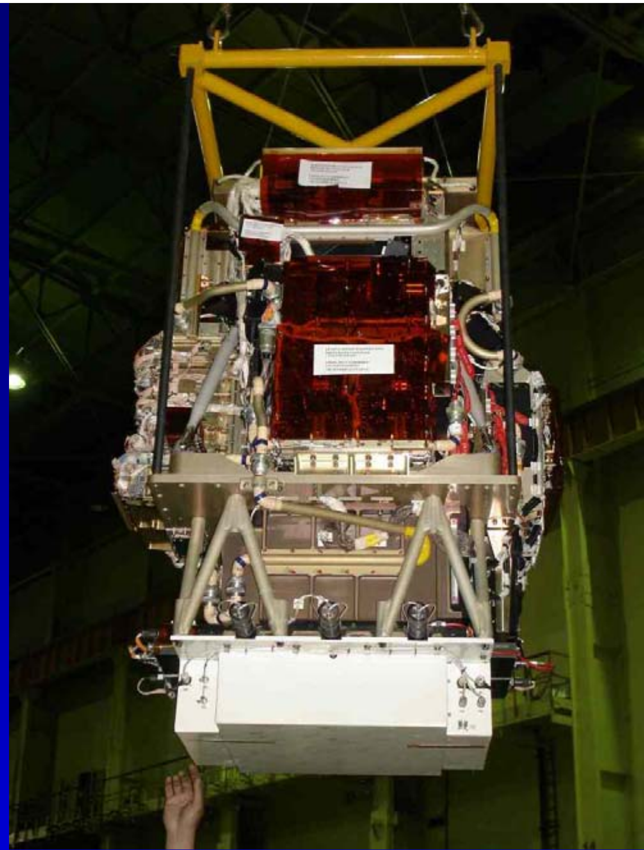
Loading Operations in Samara (Russia)

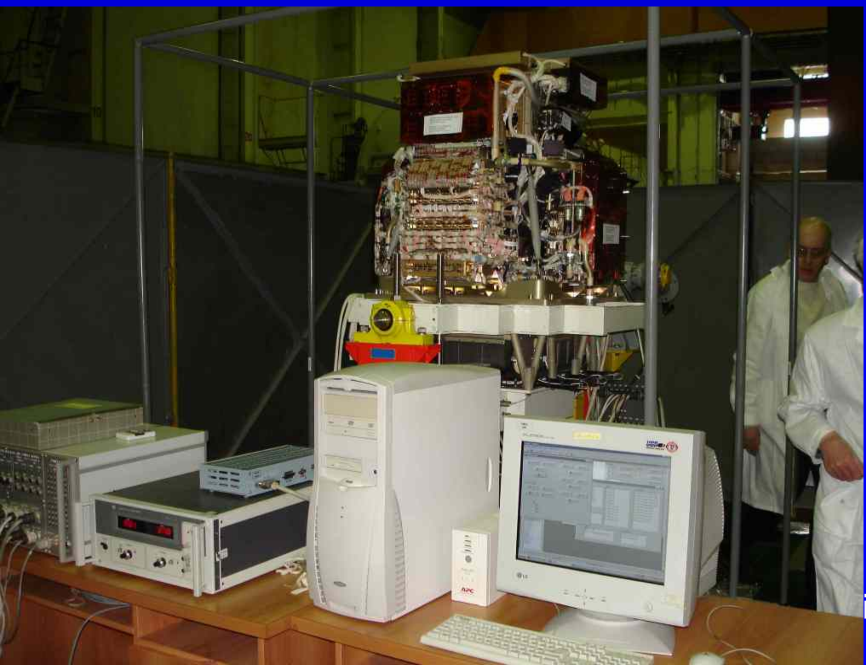
March 28th, 2006

Unloading in Baikonur

Transportation by rail to test area



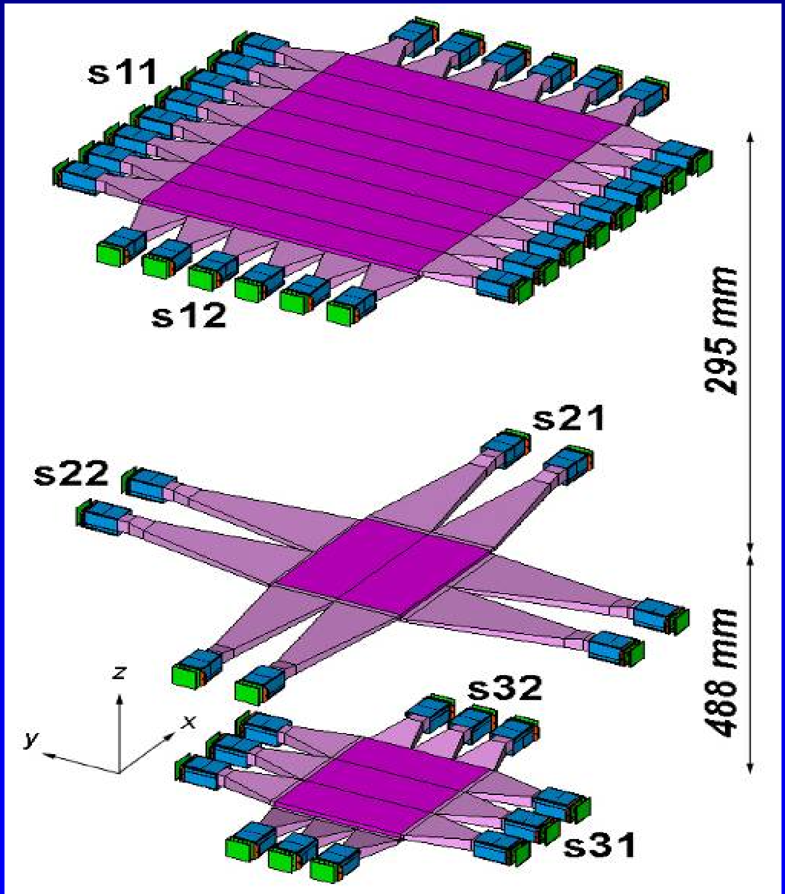




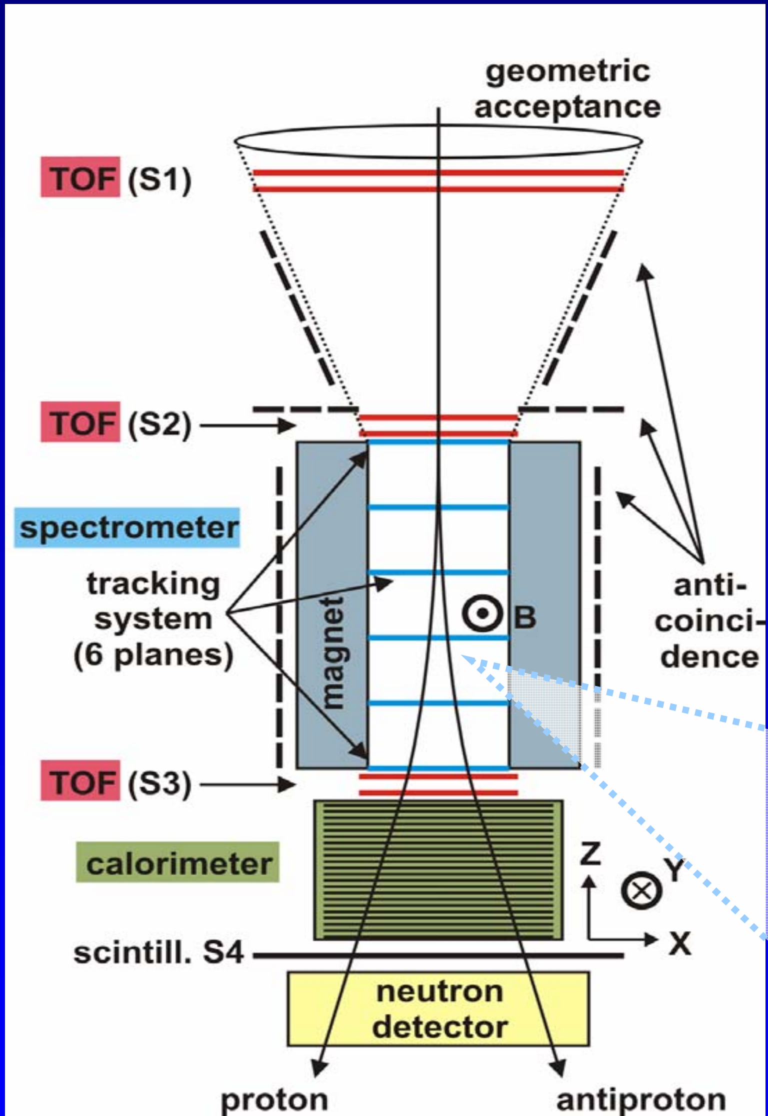
Baikonur March 30, 2006
Initial operations, stand-alone tests

Data acquisition details

- Trigger configurations (selected by S1 counting rate):
  - **High-radiation environment**
    - ⇒ (S21 OR S22) AND (S31 OR S32) + CALORIMETER
  - **Low-radiation environment**
    - ⇒ (S11 OR S12) AND (S21 OR S22) AND (S31 OR S32) + CALORIMETER
- NB:
  - High voltage to PMTs, etc. is not changed during passage through SAA and radiation belts, or solar particle events.
- Average trigger rate ~25Hz
- Fraction of live time ~ 75%
- Event size (compressed mode) ~ 5kB
  - ⇒ 25 Hz x 5 kB/ev ~ 10 GB/day

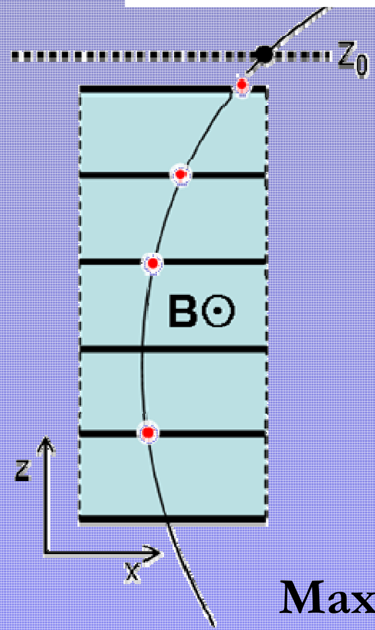


Principle of operation



Track reconstruction

$\alpha = (x_0, y_0, \sin\theta, \phi, \eta)$



Iterative χ^2 minimization as a function of track state-vector components α

Magnetic deflection $\rightarrow |\eta| = 1/R$

Magnetic rigidity $\rightarrow R = pc/Ze$

$\sigma_R/R = \sigma_\eta/\eta$

Maximum Detectable Rigidity (MDR)

def: @ R=MDR $\Rightarrow \sigma_R/R=1$

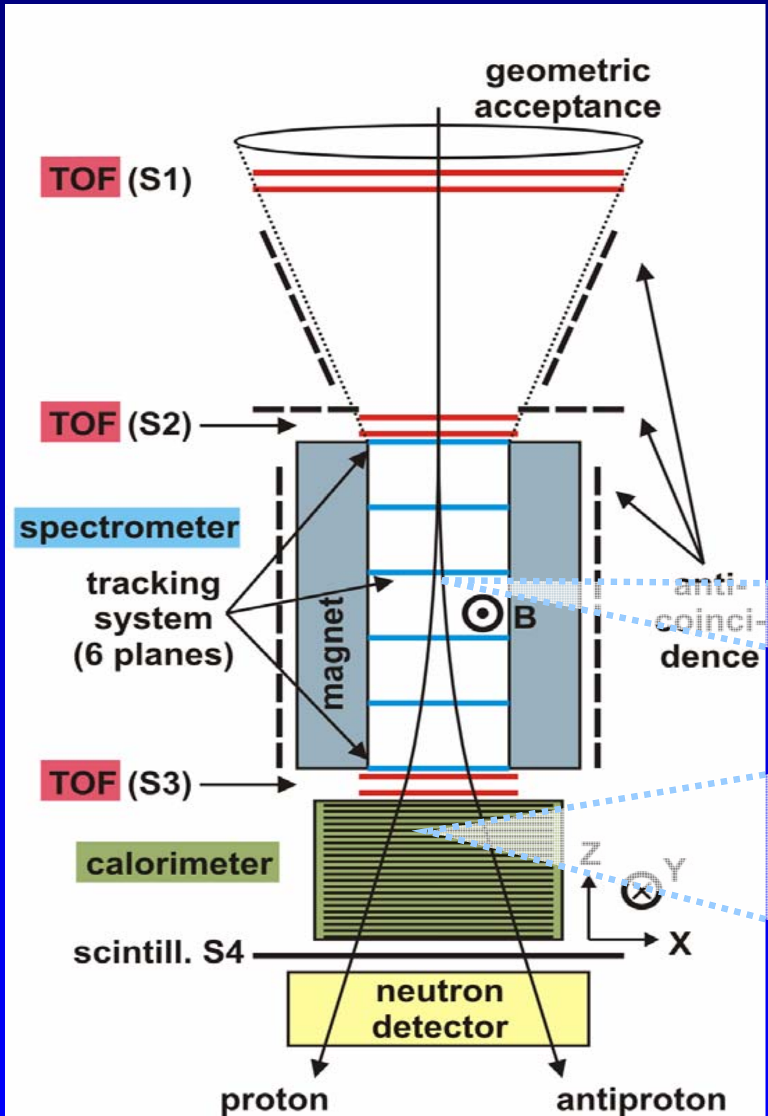
$MDR = 1/\sigma_\eta$

- Measured @ground with protons of known momentum

$\rightarrow$ MDR ~ 1 TV

- Cross-check in flight with protons (alignment) and electrons (energy from calorimeter)

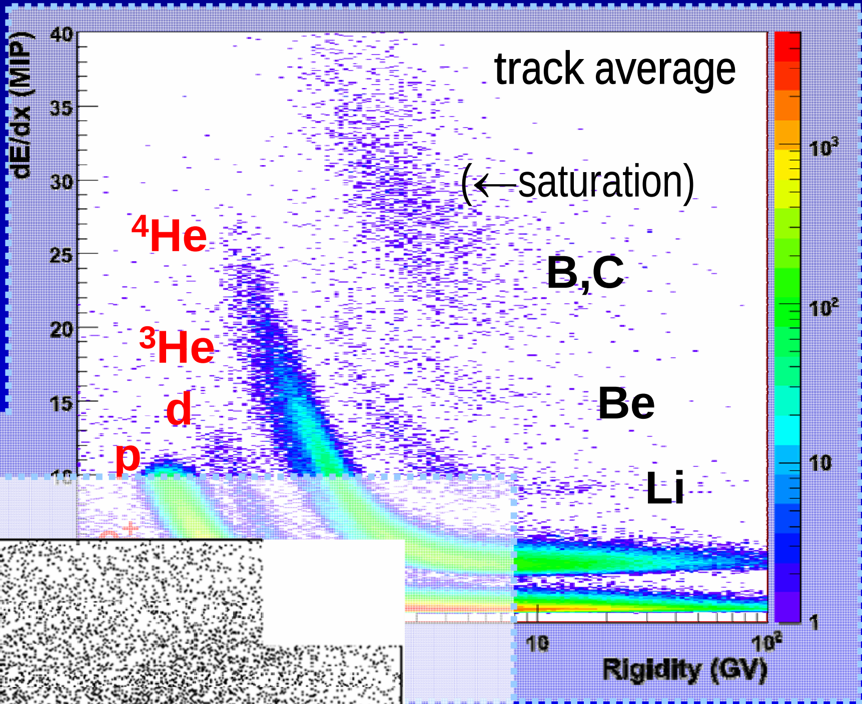
Principle of operation

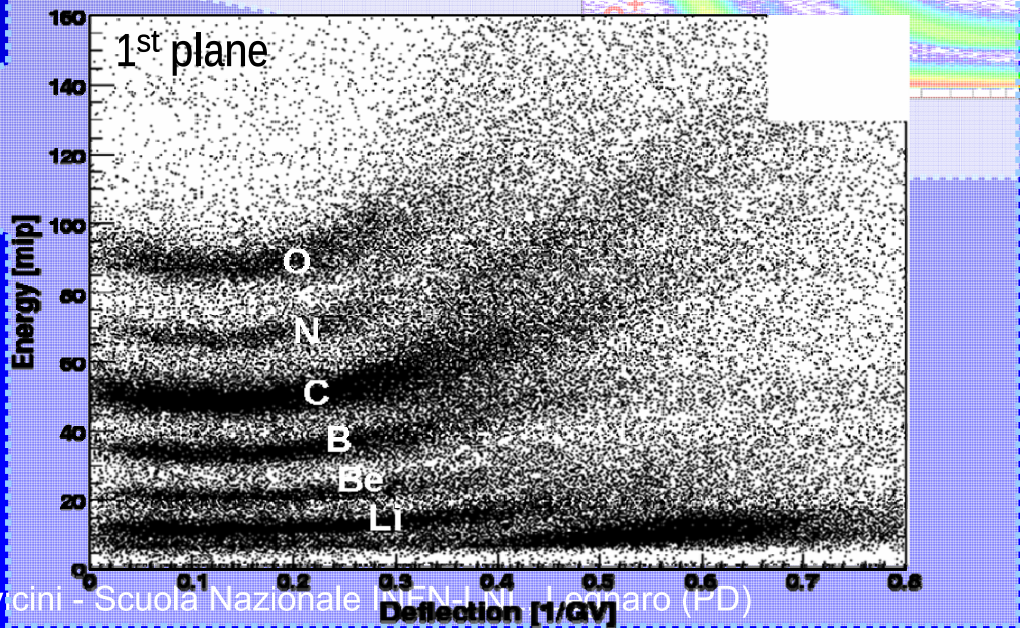


Z measurement

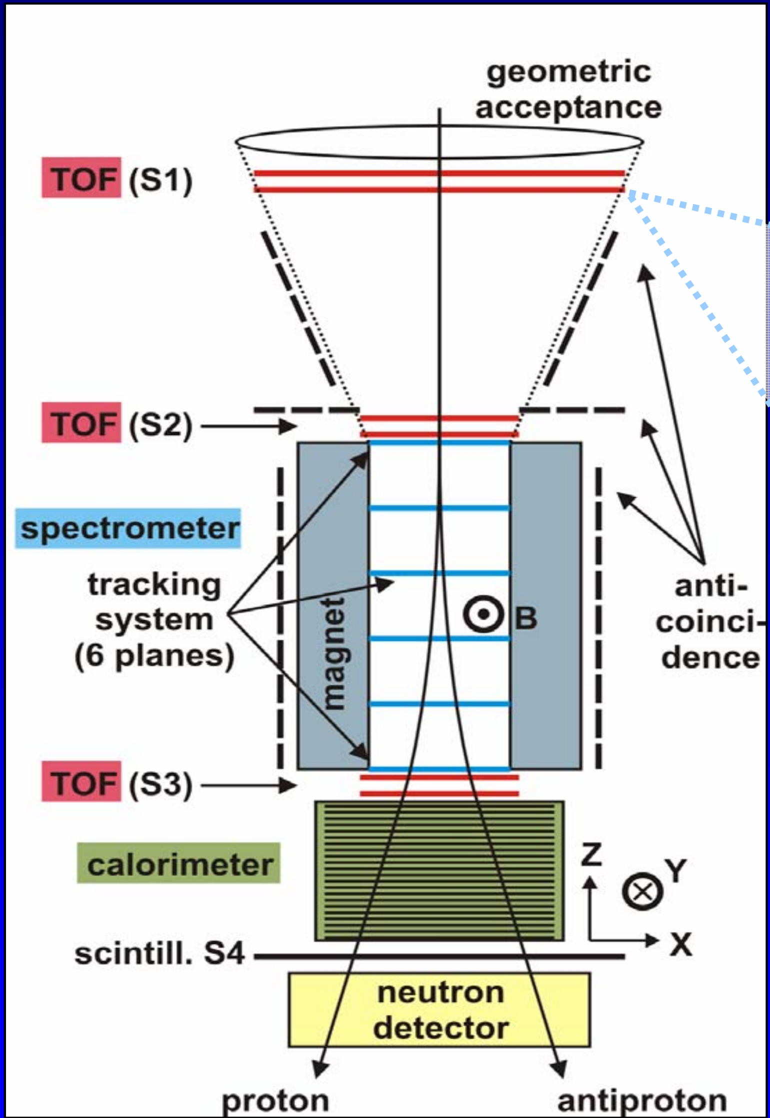
$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Bethe Bloch
ionization energy-loss of heavy (M>>me) charged particles

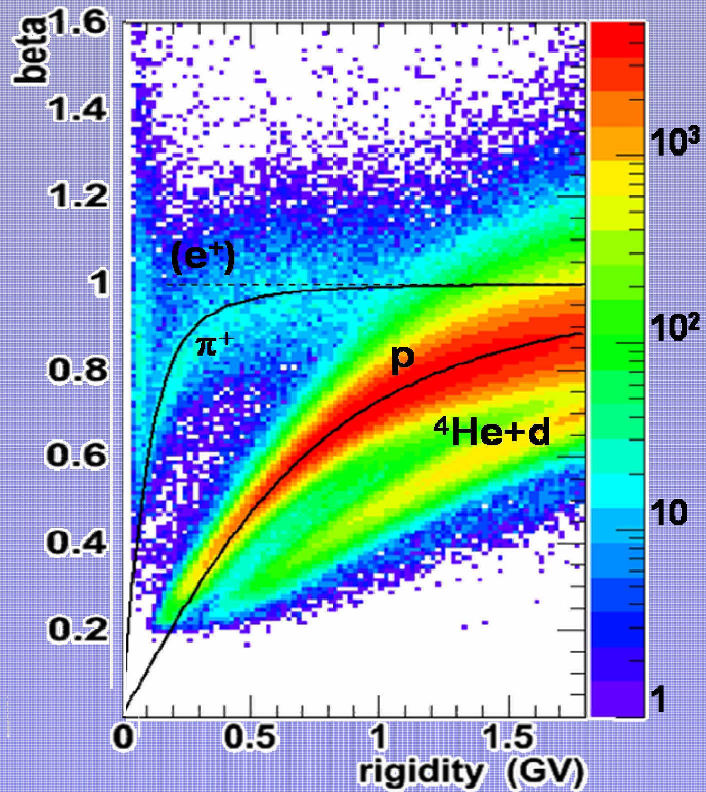




Principle of operation



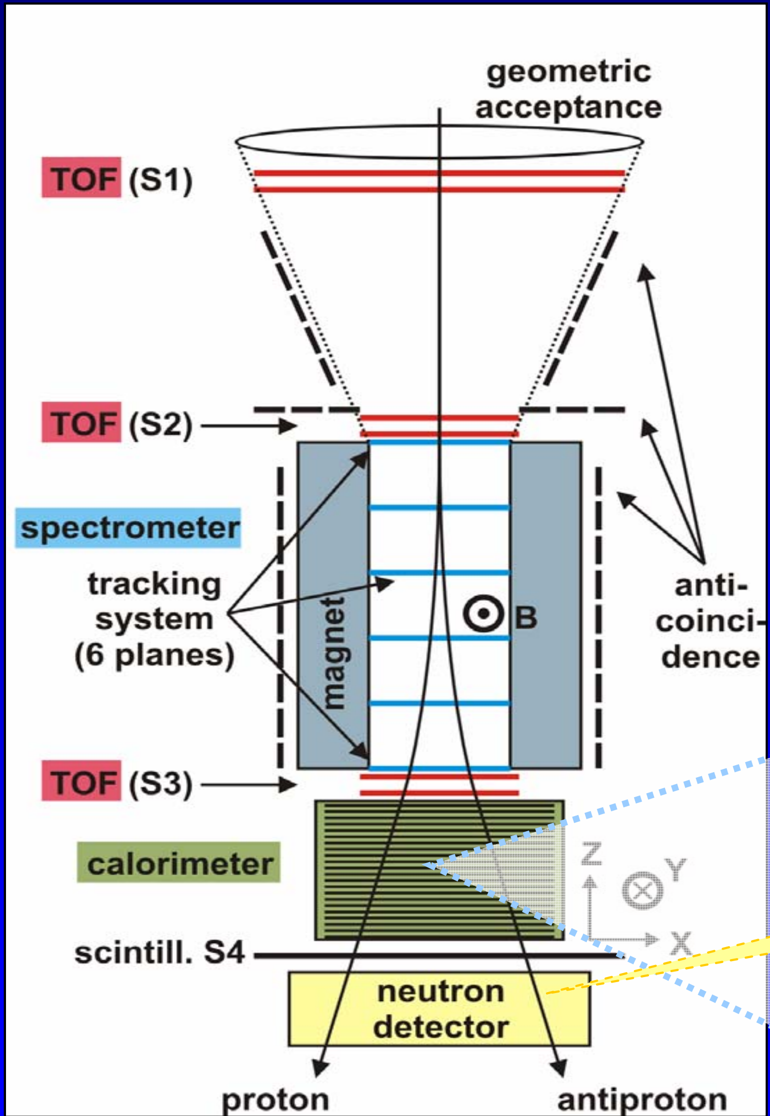
Velocity measurement



- Particle identification @ low energy
- Identify **albedo** (upward going particles →**b < 0**)

→ NB! They mimic antimatter!

Principle of operation

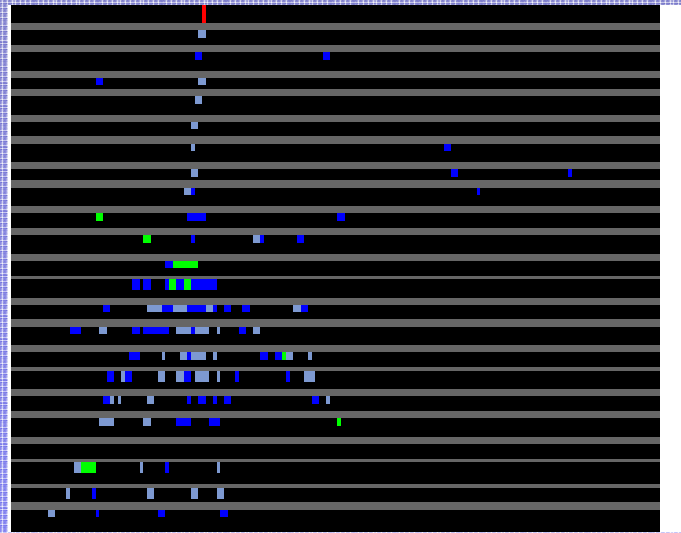


Electron/hadron separation

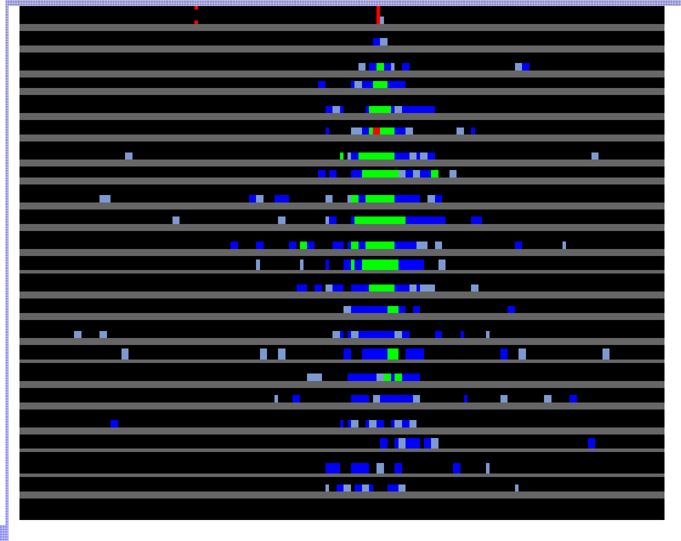
- **Interaction topology**

e/h separation

hadron (19GV)



electron (17GV)



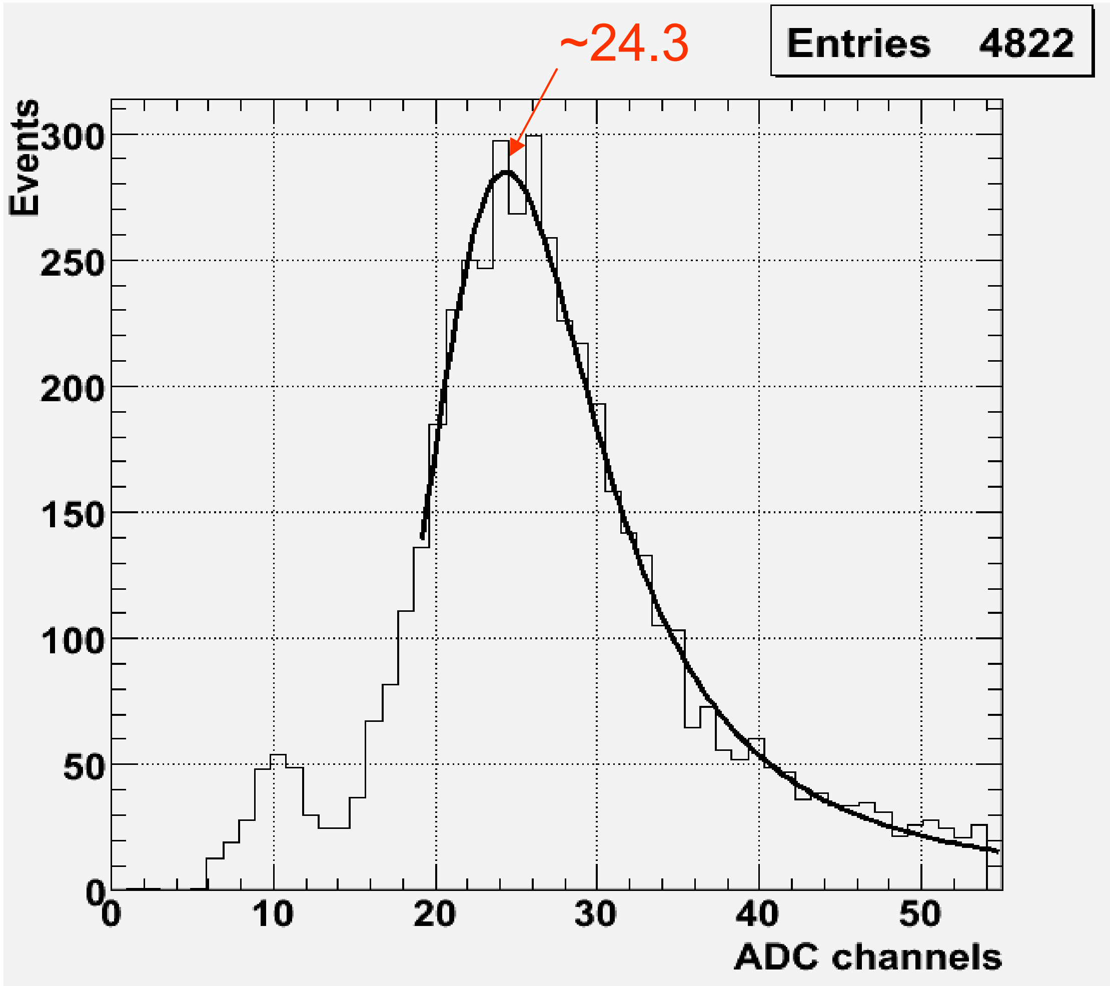
+ NEUTRONS!!

- **Energy measurement of electrons and positrons**

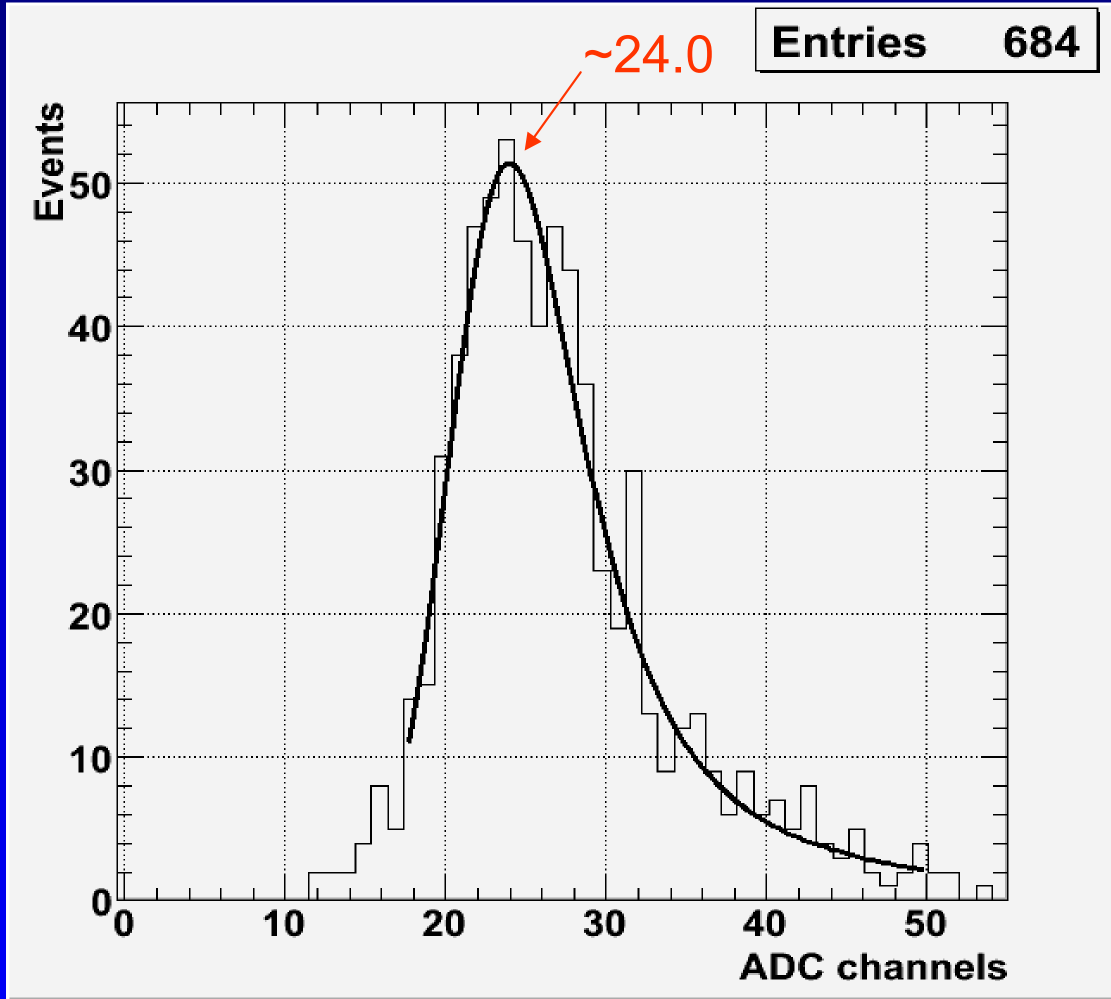
(~full shower containment)

$$\frac{\sigma_E}{E} = a \oplus \frac{b}{\sqrt{E}} \qquad \rightarrow a < 5\%$$

Calorimeter in-flight performance - 2

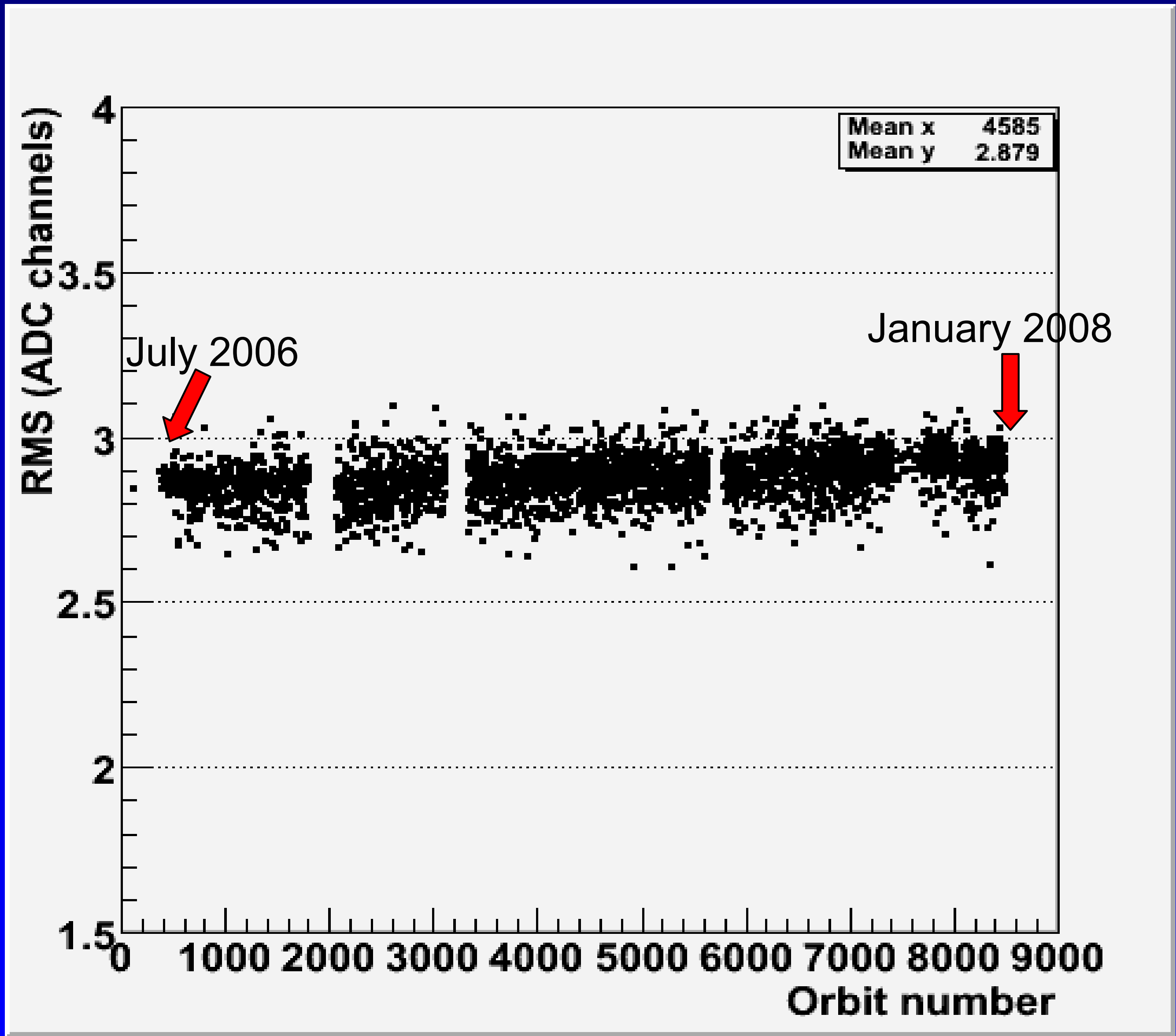


GROUND (muons)

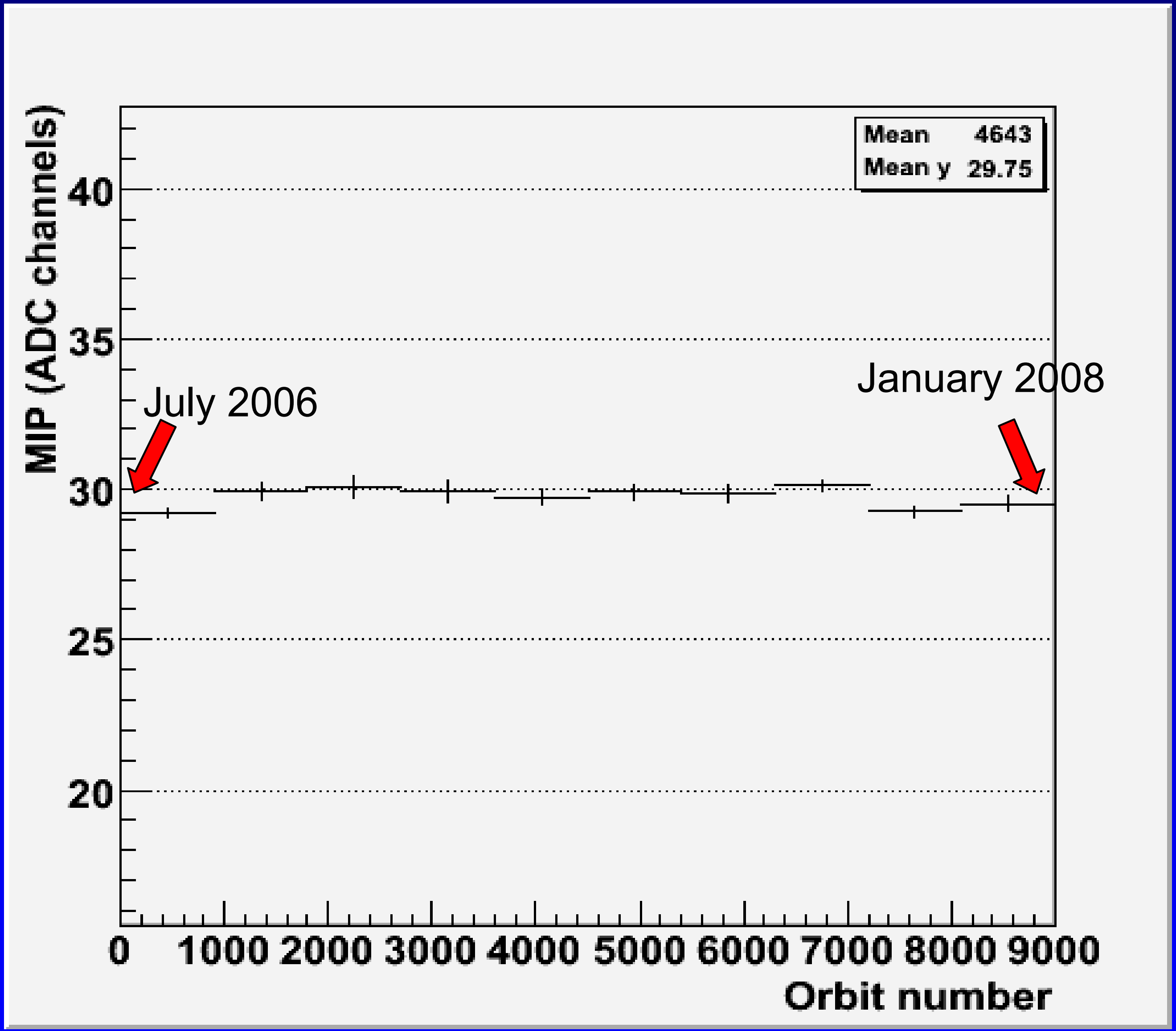


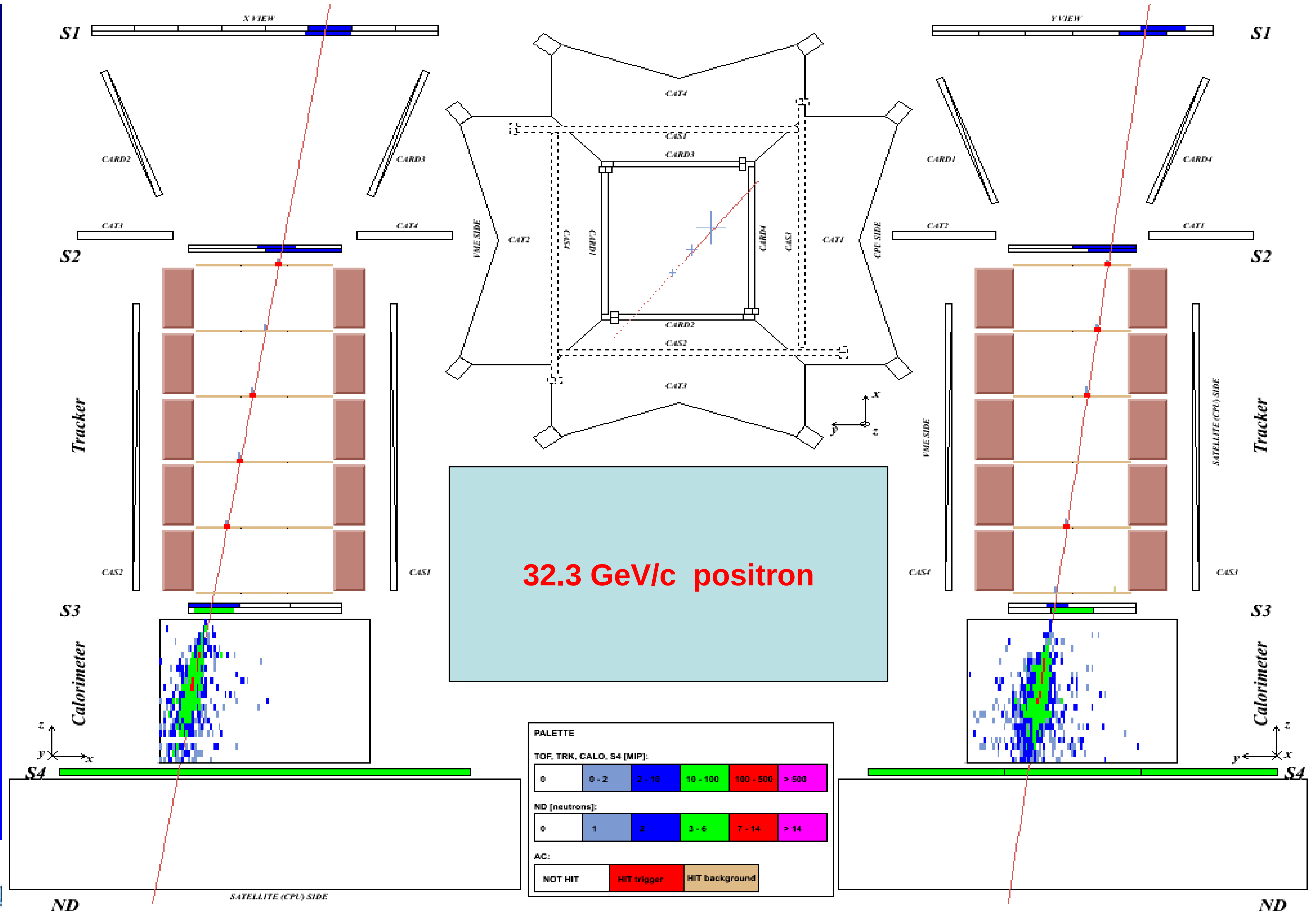
FLIGHT (relativistic particles)

Calorimeter in-flight performance - 1

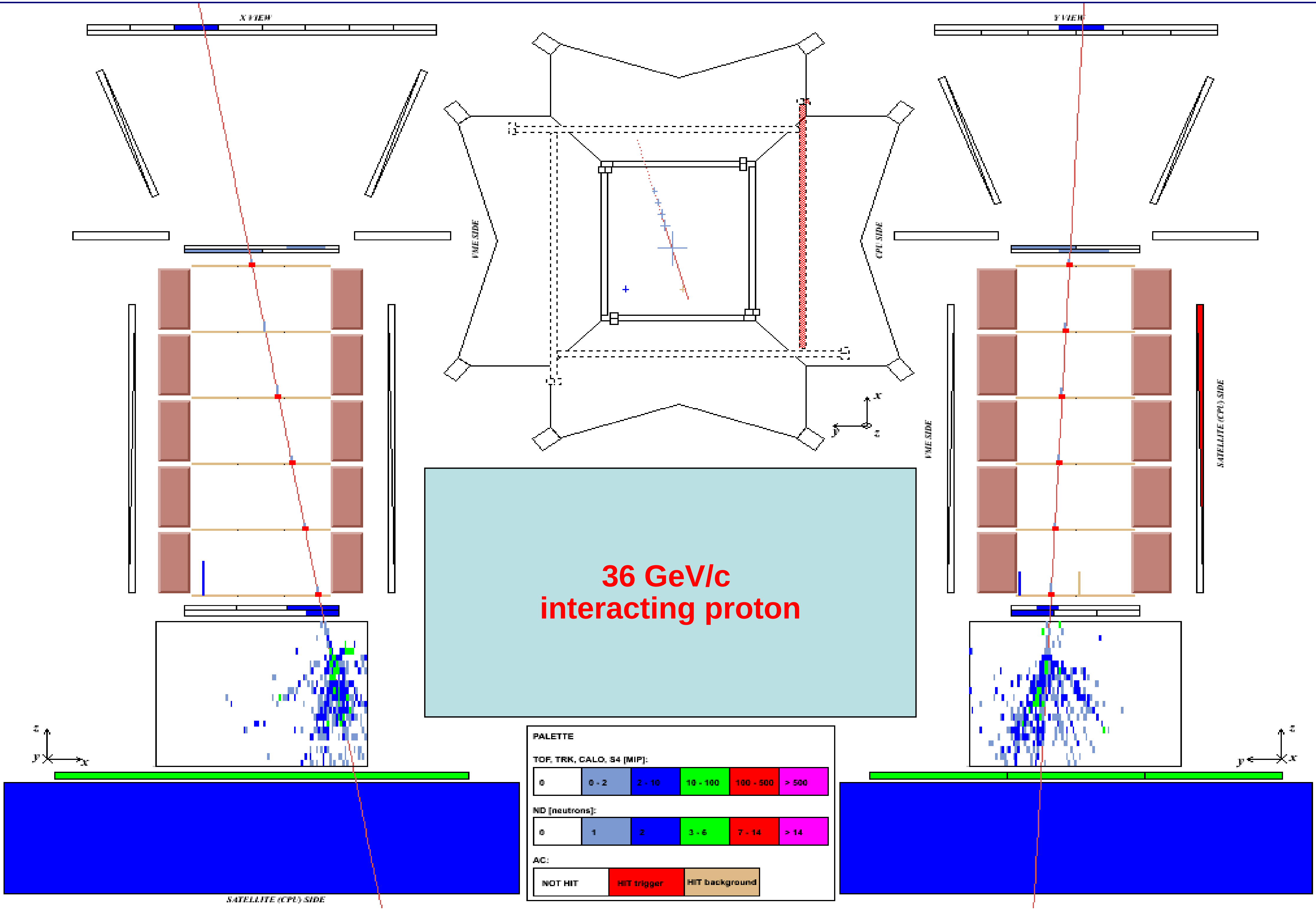


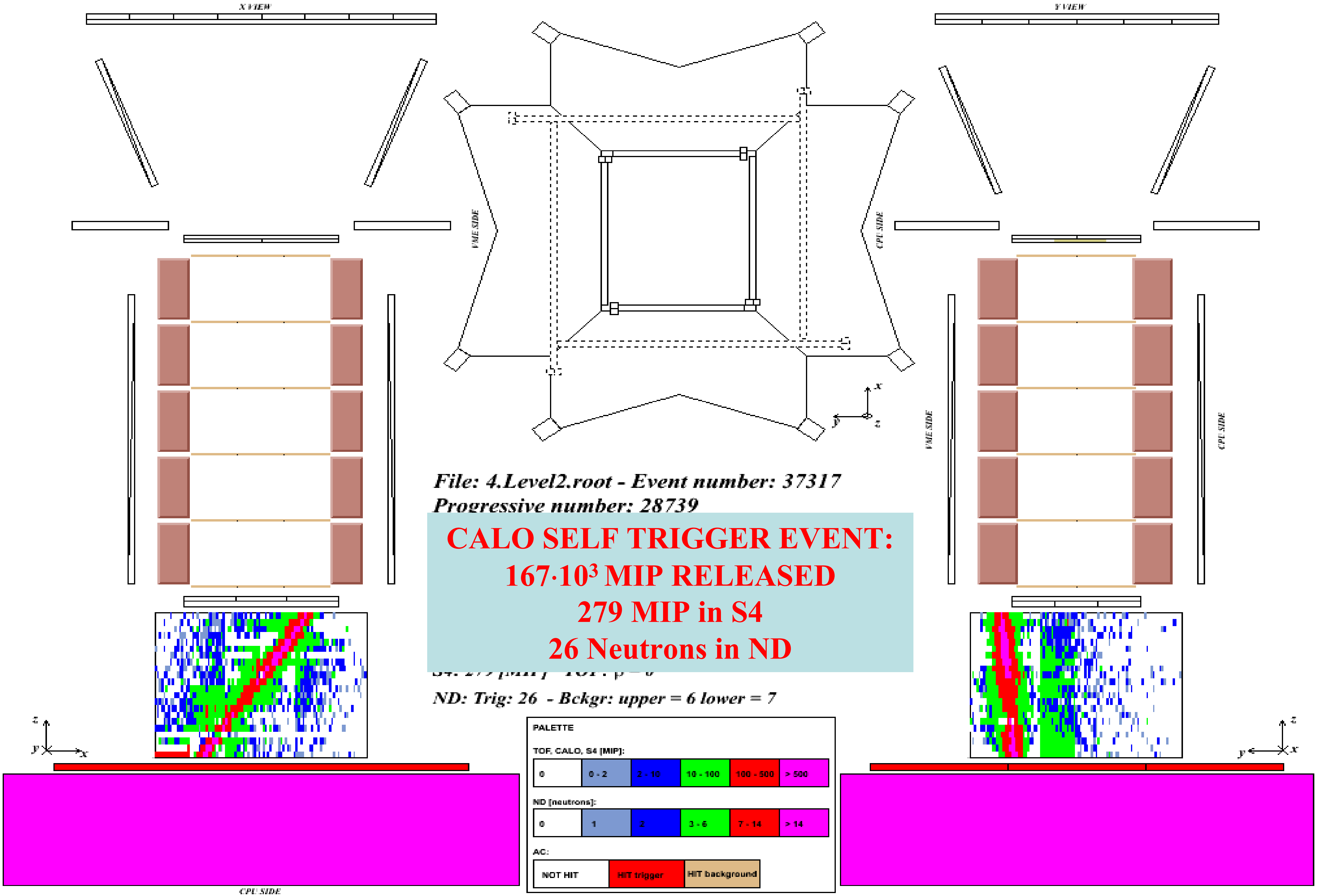
Calorimeter in-flight performance - 2



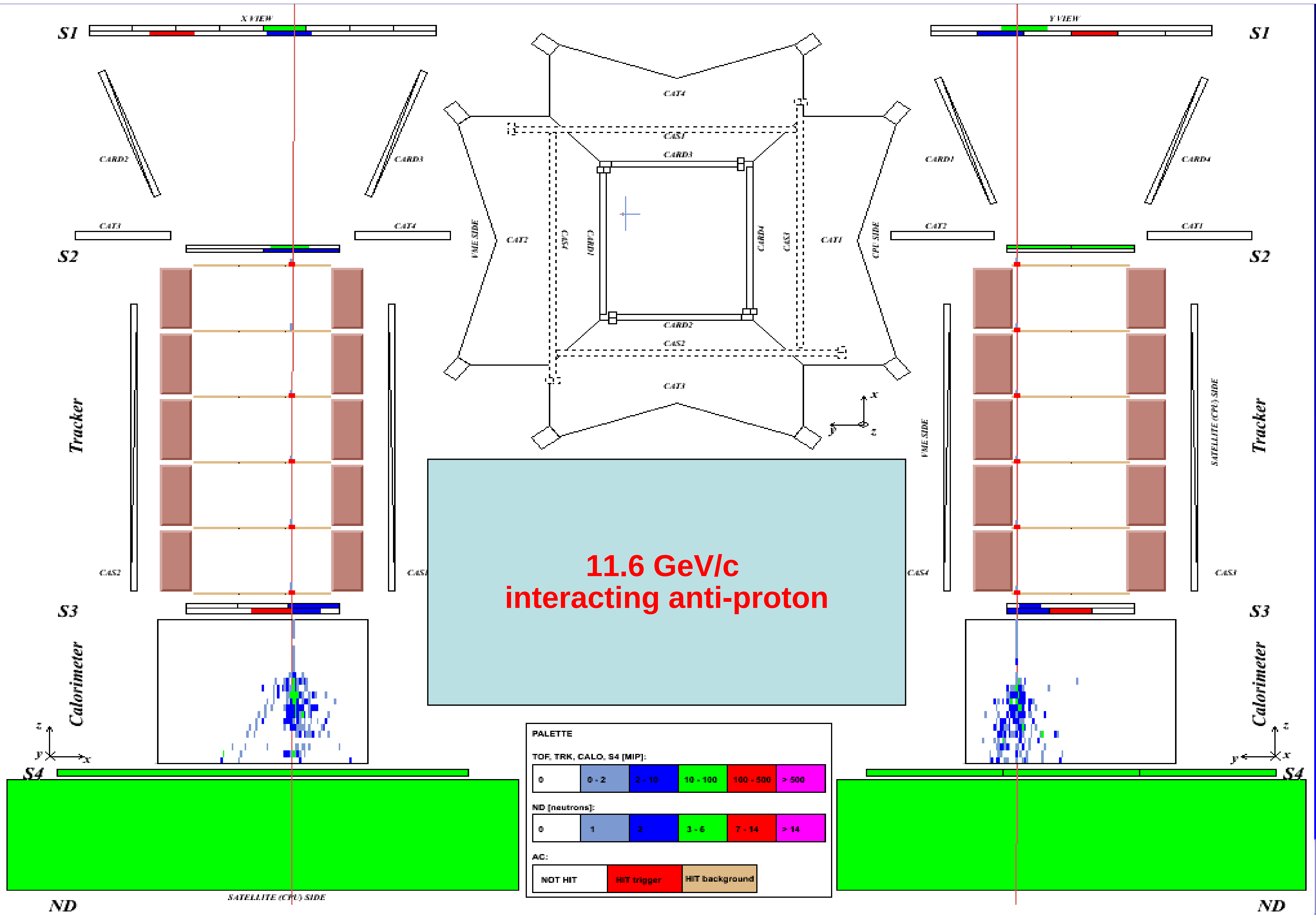


X VIEW
Y VIEW
S1
S1
CARD2
CARD3
CARD1
CARD4
CAT3
CAT4
CAT2
CAT1
S2
S2
Tracker
Tracker
CAS2
CAS1
CAS4
CAS3
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
S3
S3
Calorimeter
Calorimeter
S4
S4
ND
ND
SATELLITE (CPU) SIDE
32.3 GeV/c positron
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background

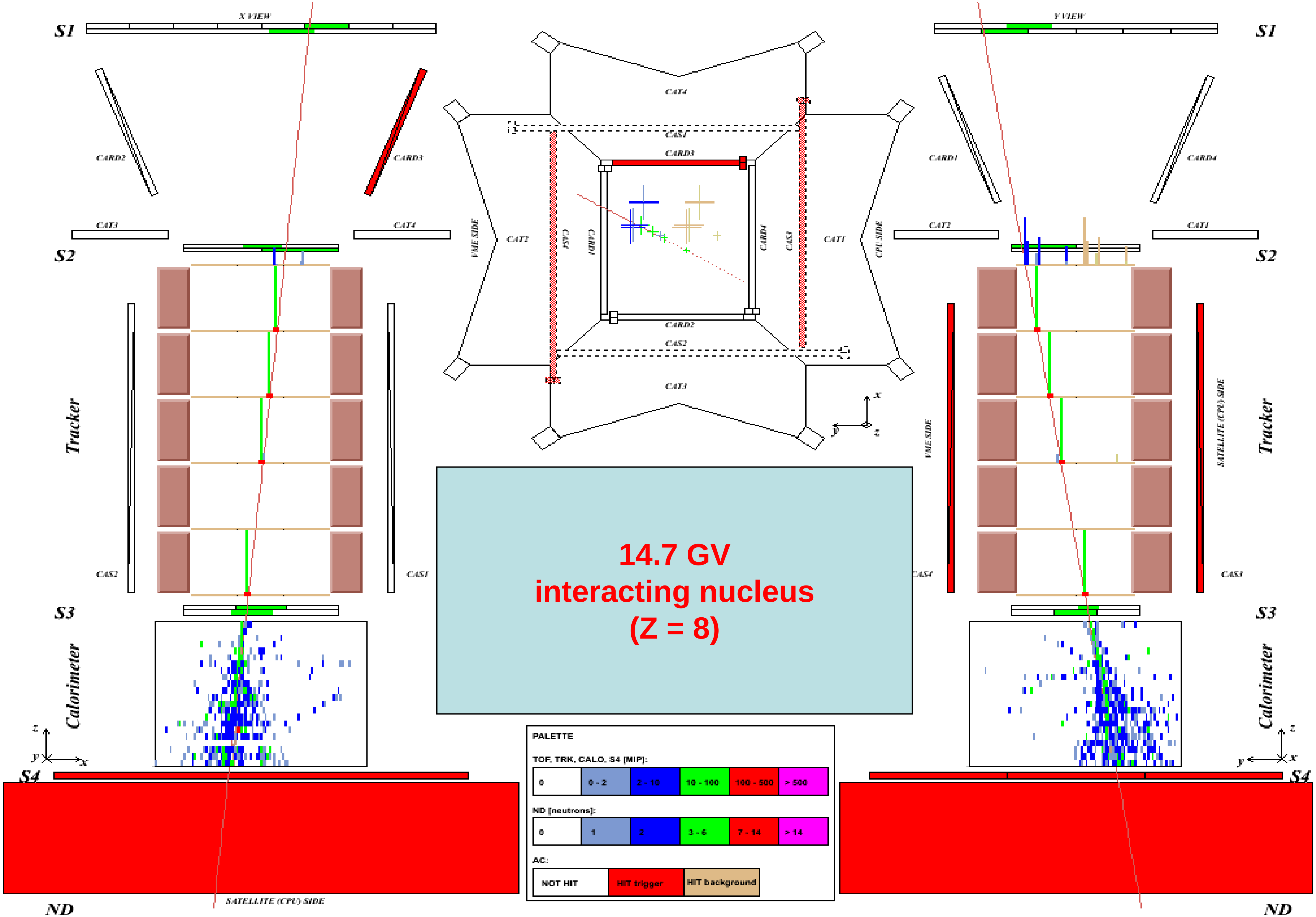

X VIEW
Y VIEW
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
36 GeV/c
interacting proton
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background

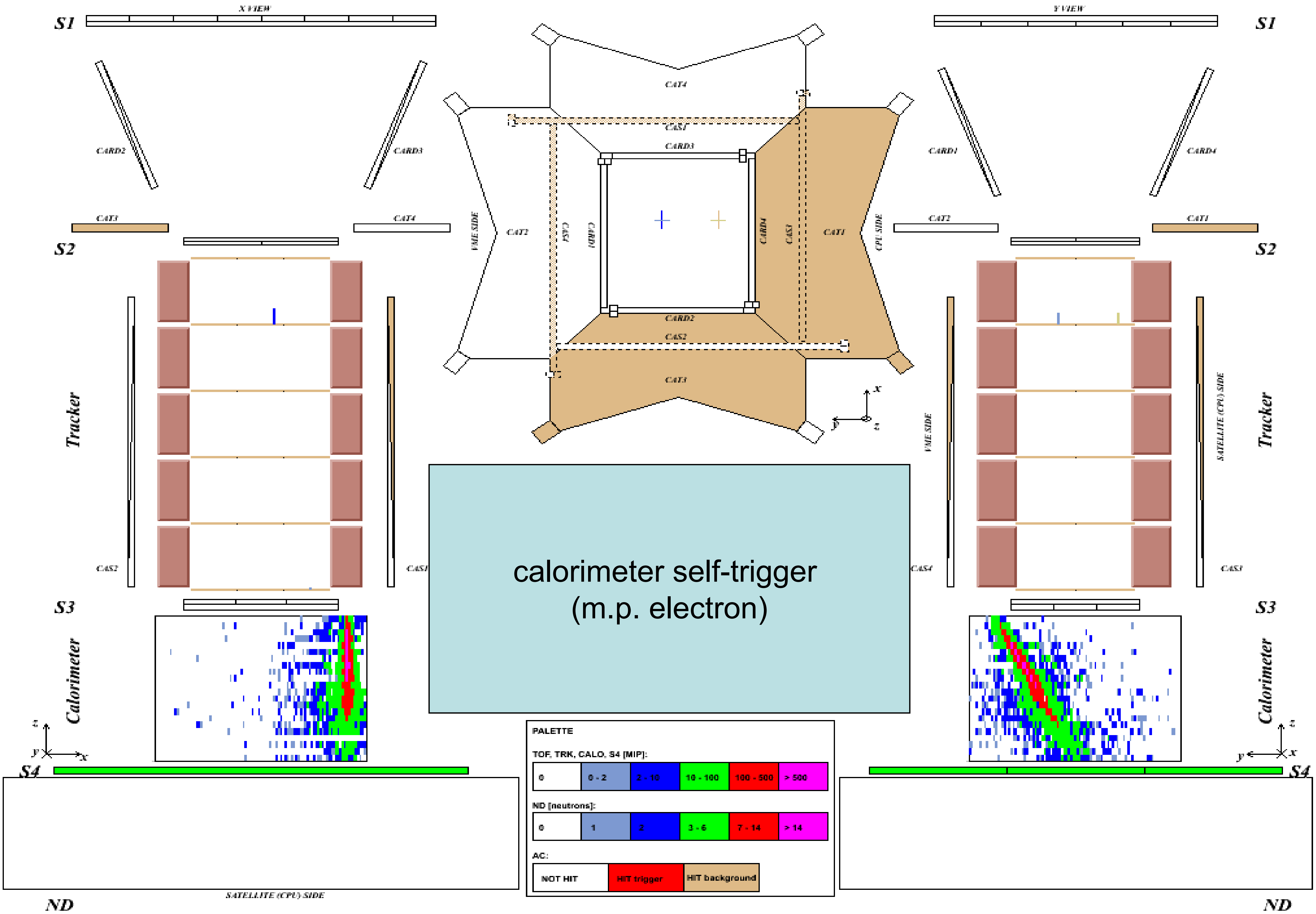


X VIEW
Y VIEW
VME SIDE
CPU SIDE
VME SIDE
CPU SIDE
CPU SIDE
File: 4.Level2.root - Event number: 37317
Progressive number: 28739
CALO SELF TRIGGER EVENT:
167·10³ MIP RELEASED
279 MIP in S4
26 Neutrons in ND
ND: Trig: 26 - Bckgr: upper = 6 lower = 7
PALETTE
TOF, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background



11.6 GeV/c
interacting anti-proton
X VIEW
Y VIEW
S1
S2
S3
S4
ND
Tracker
Calorimeter
CARD1
CARD2
CARD3
CARD4
CAT1
CAT2
CAT3
CAT4
CAS1
CAS2
CAS3
CAS4
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background

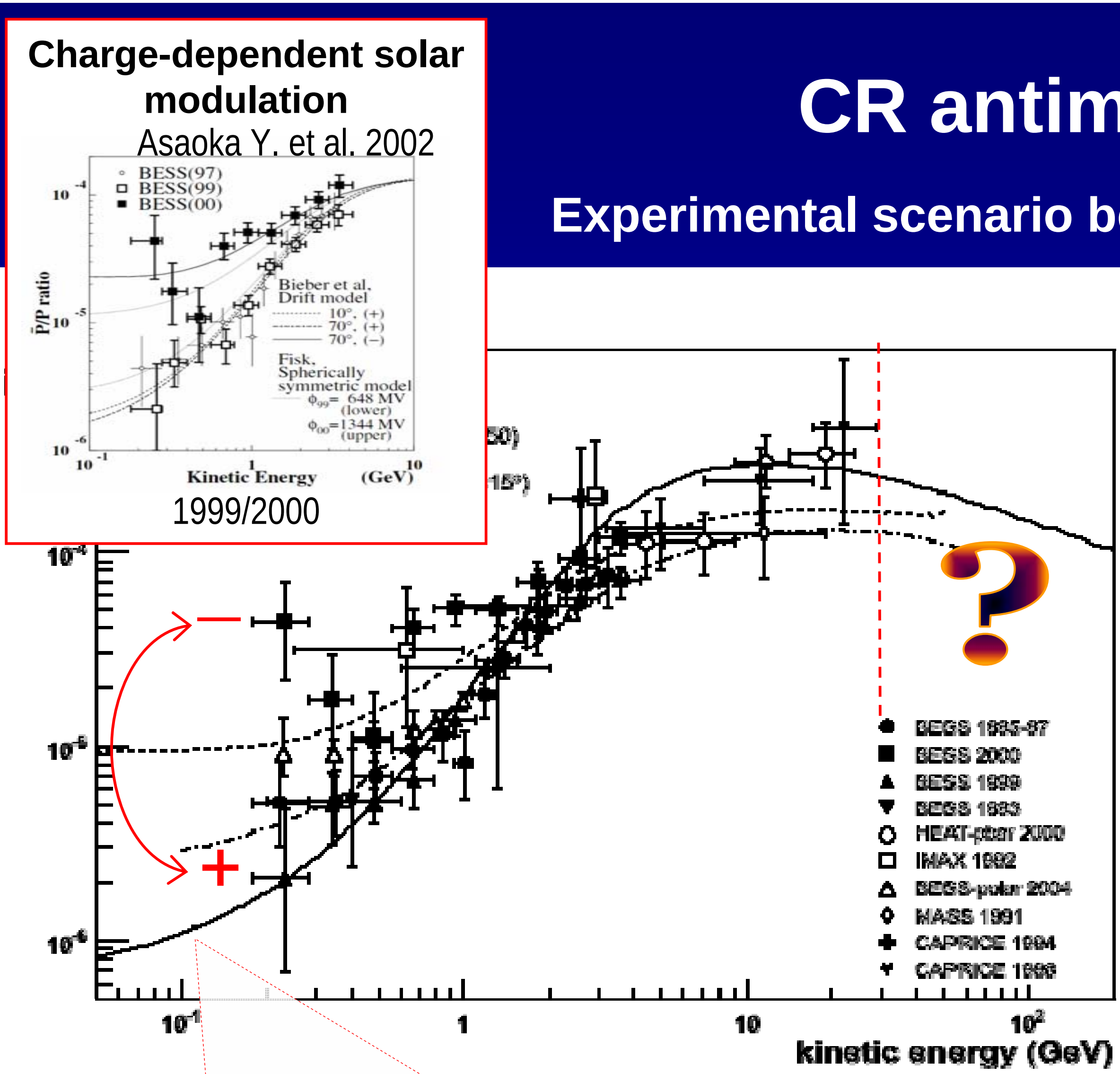

X VIEW
Y VIEW
S1
S2
S3
S4
ND
CARD1
CARD2
CARD3
CARD4
CAT1
CAT2
CAT3
CAT4
CAS1
CAS2
CAS3
CAS4
Tracker
Calorimeter
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
14.7 GV
interacting nucleus
(Z = 8)
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background

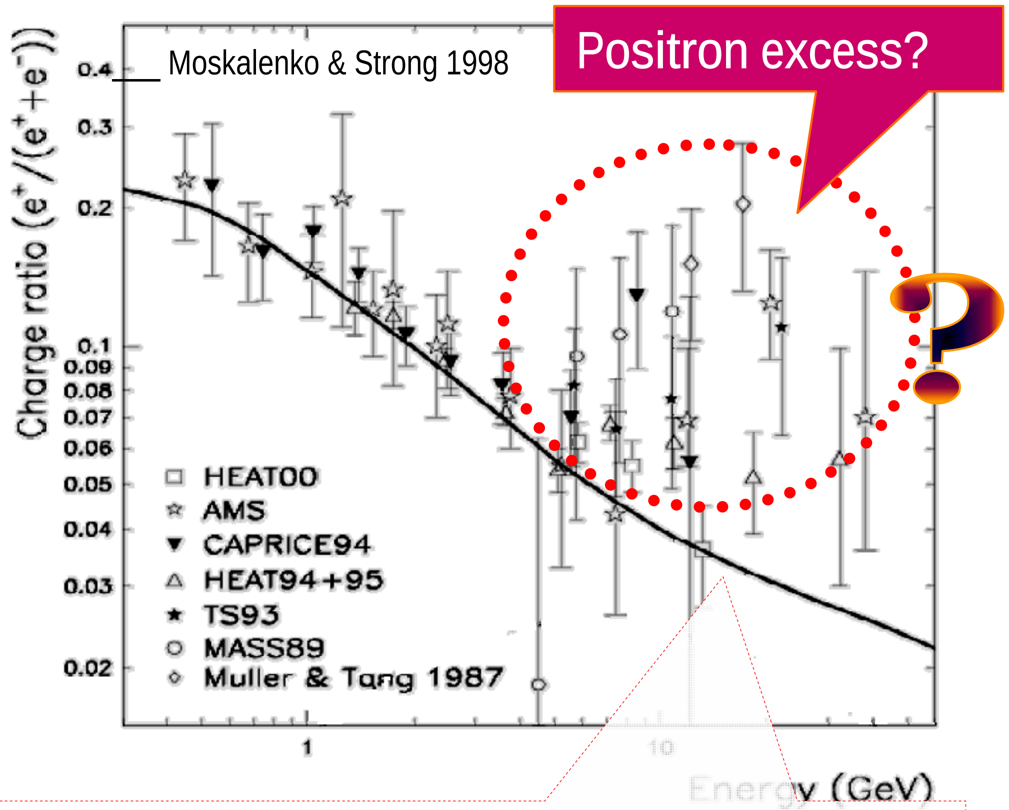


X VIEW
Y VIEW
S1
S2
S3
S4
ND
Tracker
Calorimeter
CARD1
CARD2
CARD3
CARD4
CAT1
CAT2
CAT3
CAT4
CAS1
CAS2
CAS3
CAS4
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
calorimeter self-trigger
(m.p. electron)
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background

CR antimatter

Experimental scenario before PAMELA





CR + ISM → **p-bar** + …

- Propagation dominated by nuclear interactions
- Kinematical threshold: E_{th}~5.6 for the reaction

$$pp \rightarrow \bar{p}ppp$$

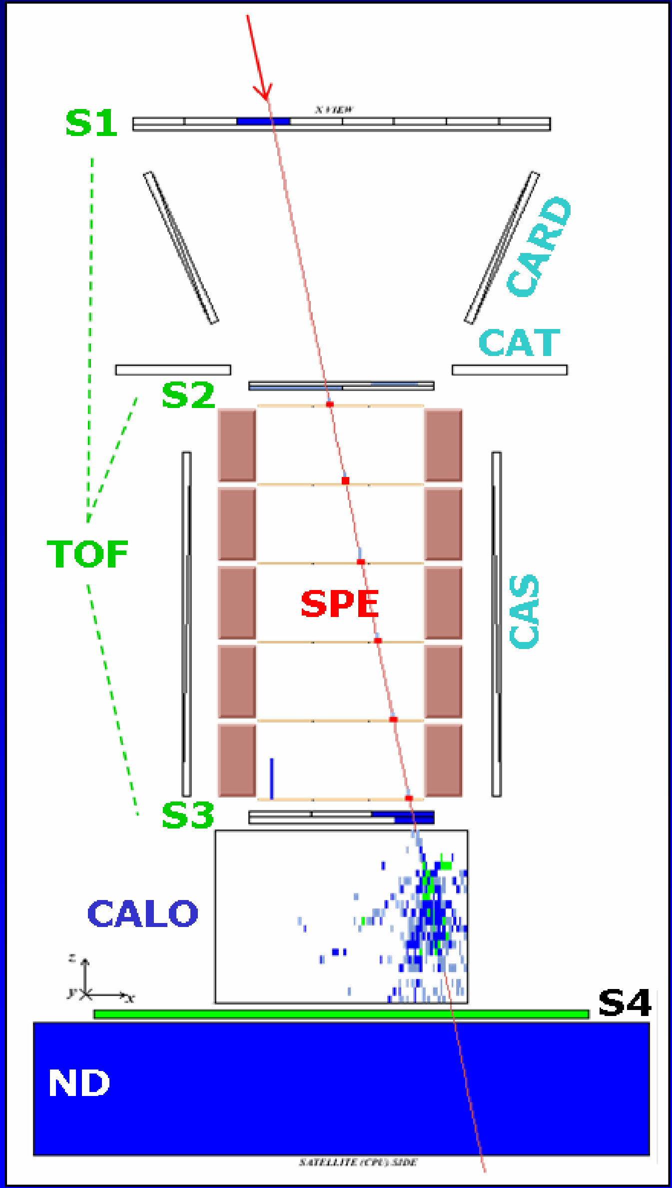
CR + ISM → $\pi^{\pm}$ + x → $\mu^{\pm}$ + x → $\mathbf{e^{\pm}}$ + x

CR + ISM → π^{0} + x → $\gamma\gamma$ → $\mathbf{e^{\pm}}$

- Propagation dominated by energy losses (inverse Compton & synchrotron radiation)
- Local origin (@100GeV 90% from <2kpc)

High-energy antiproton analysis - 2

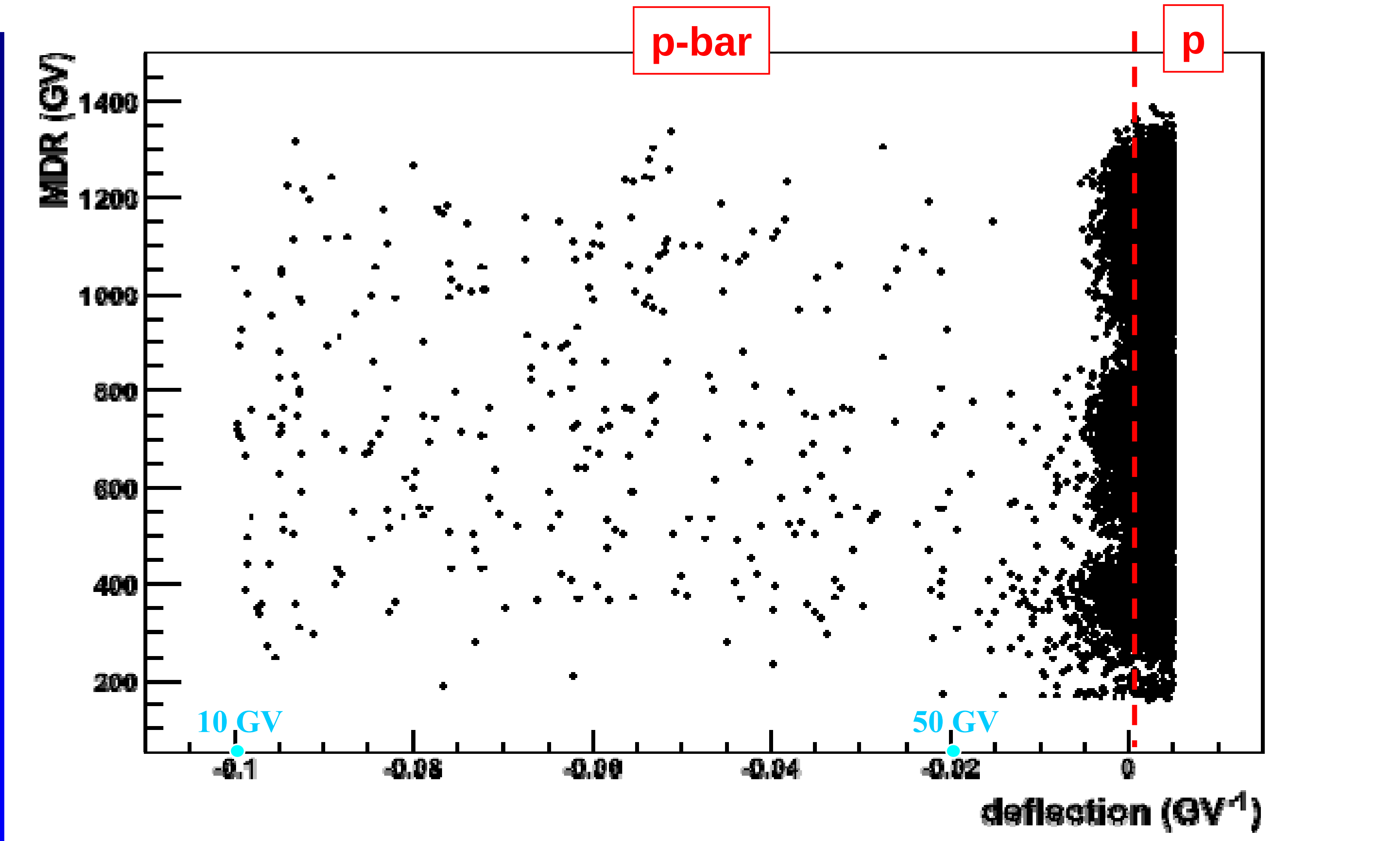
Event selected from 590 days of data



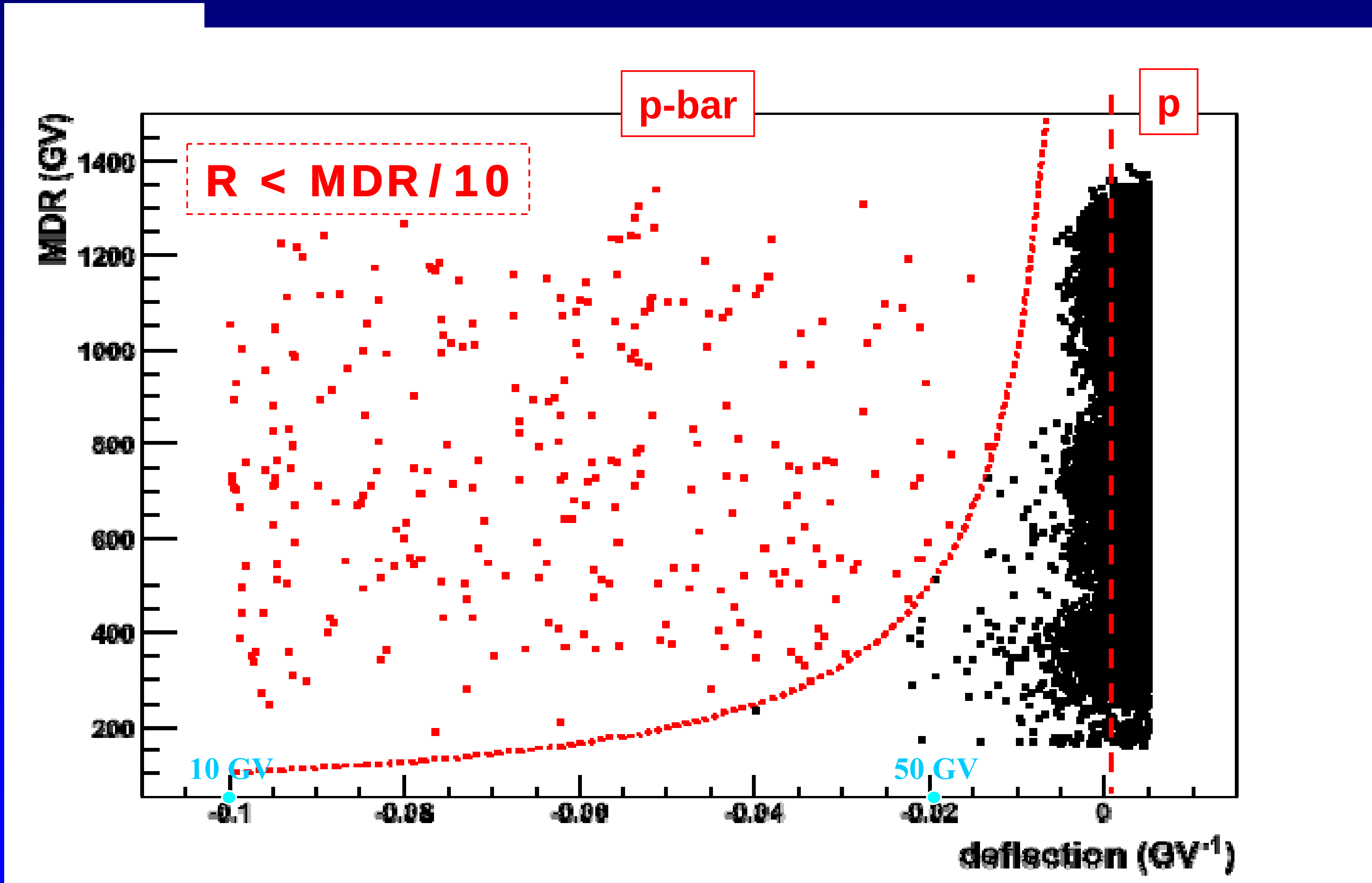
Basic requirements:

- **Clean pattern inside the apparatus**
  - single track inside TRK
  - no multiple hits in S1+S2
  - no activity in CARD+CAT
- **Minimal track requirements**
  - energy-dependent cut on track χ^2 (~95% efficiency)
  - consistency among TRK, TOF and CAL spatial information
- **Galactic particle**
  - measured rigidity above geomagnetic cutoff
  - down-ward going particle (no albedo)

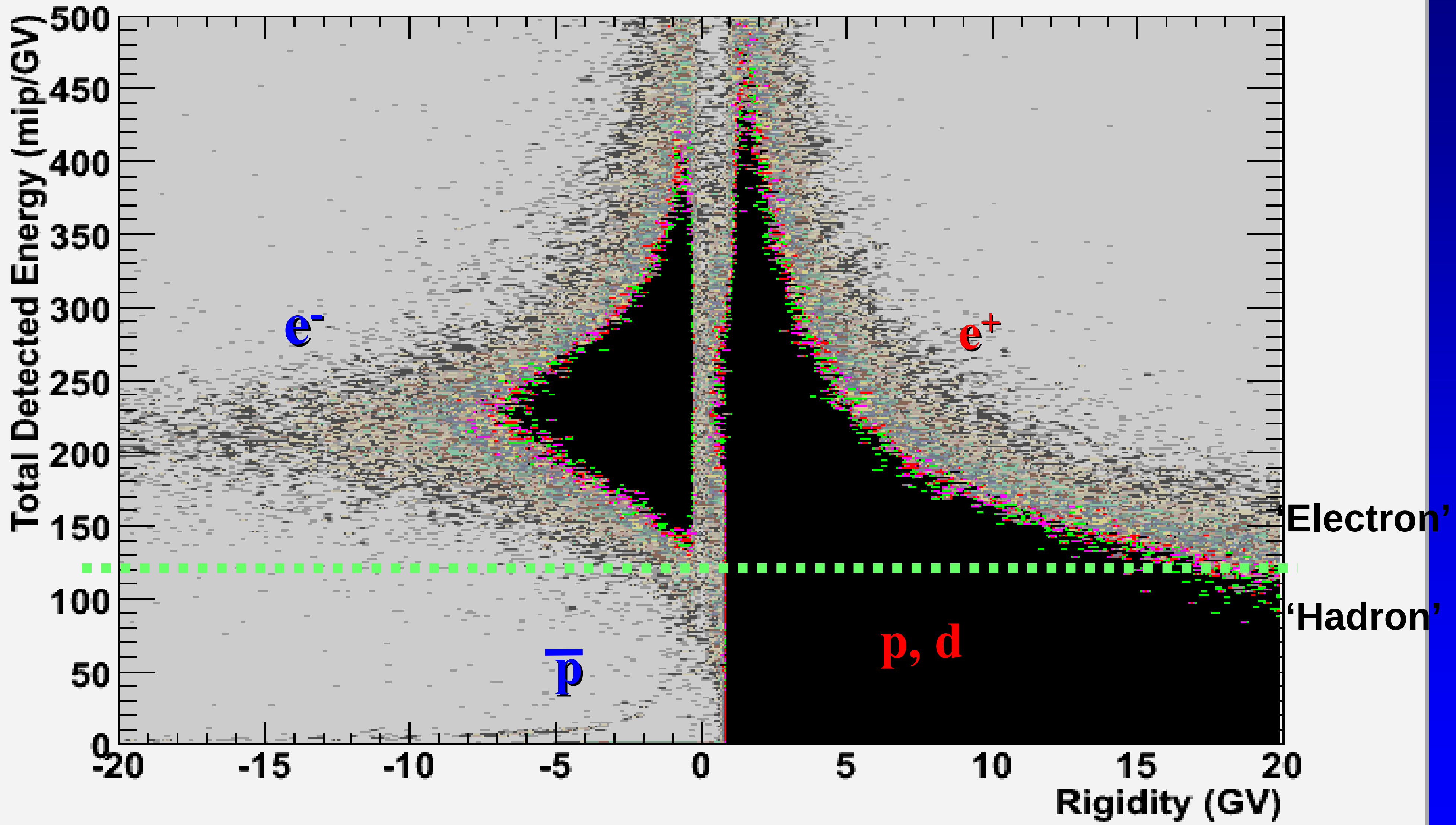
High-energy antiproton selection



High-energy antiproton selection

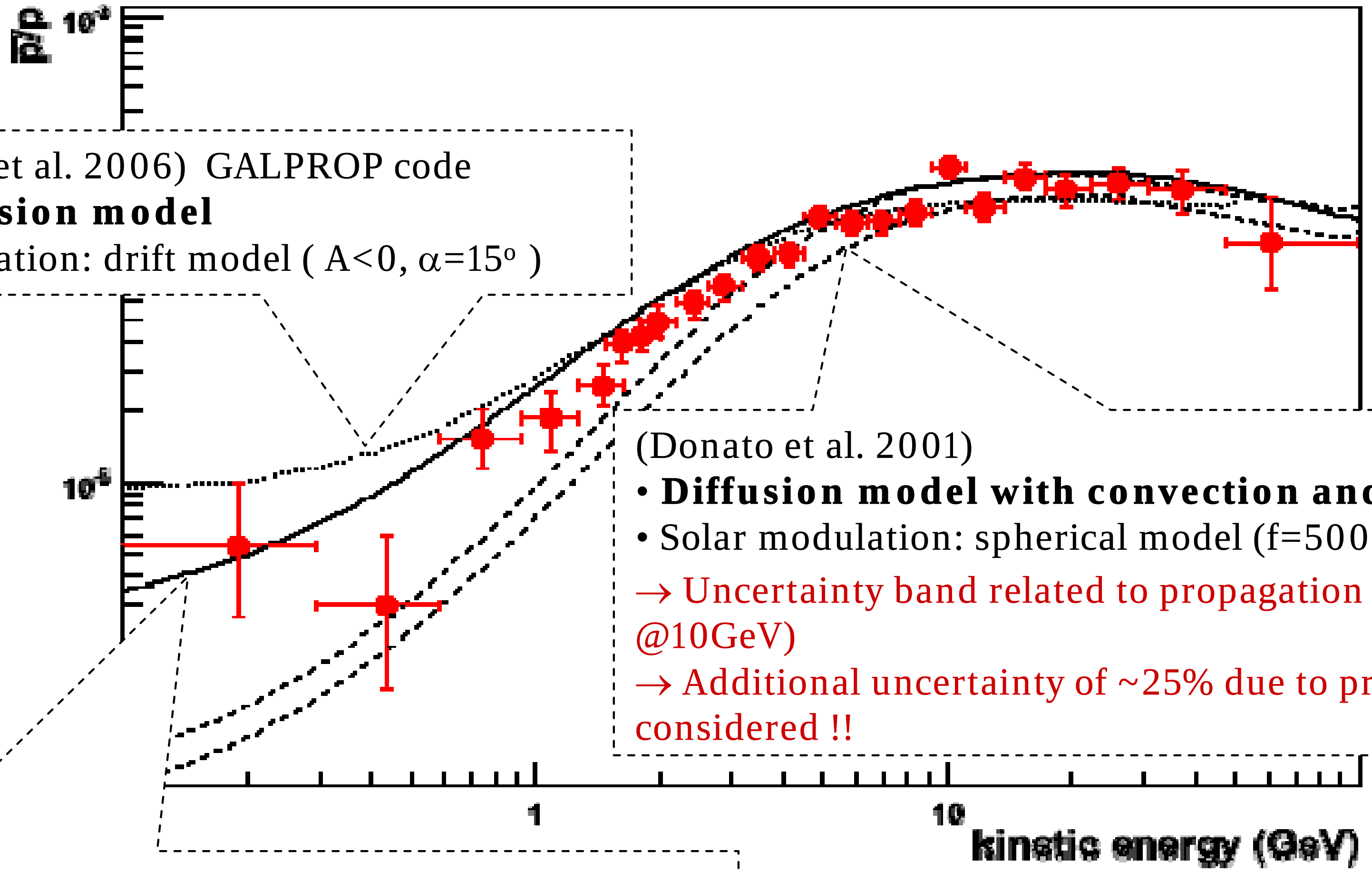


Energy-momentum match



Antiproton-to-proton ratio
Secondary Production Models

CR + ISM → **p-bar** + …



(Moskalenko et al. 2006) GALPROP code
- **Plain diffusion model**
- Solar modulation: drift model (A<0, α=15^{o})

(Donato et al. 2001)
- **Diffusion model with convection and reacceleration**
- Solar modulation: spherical model (f=500MV)

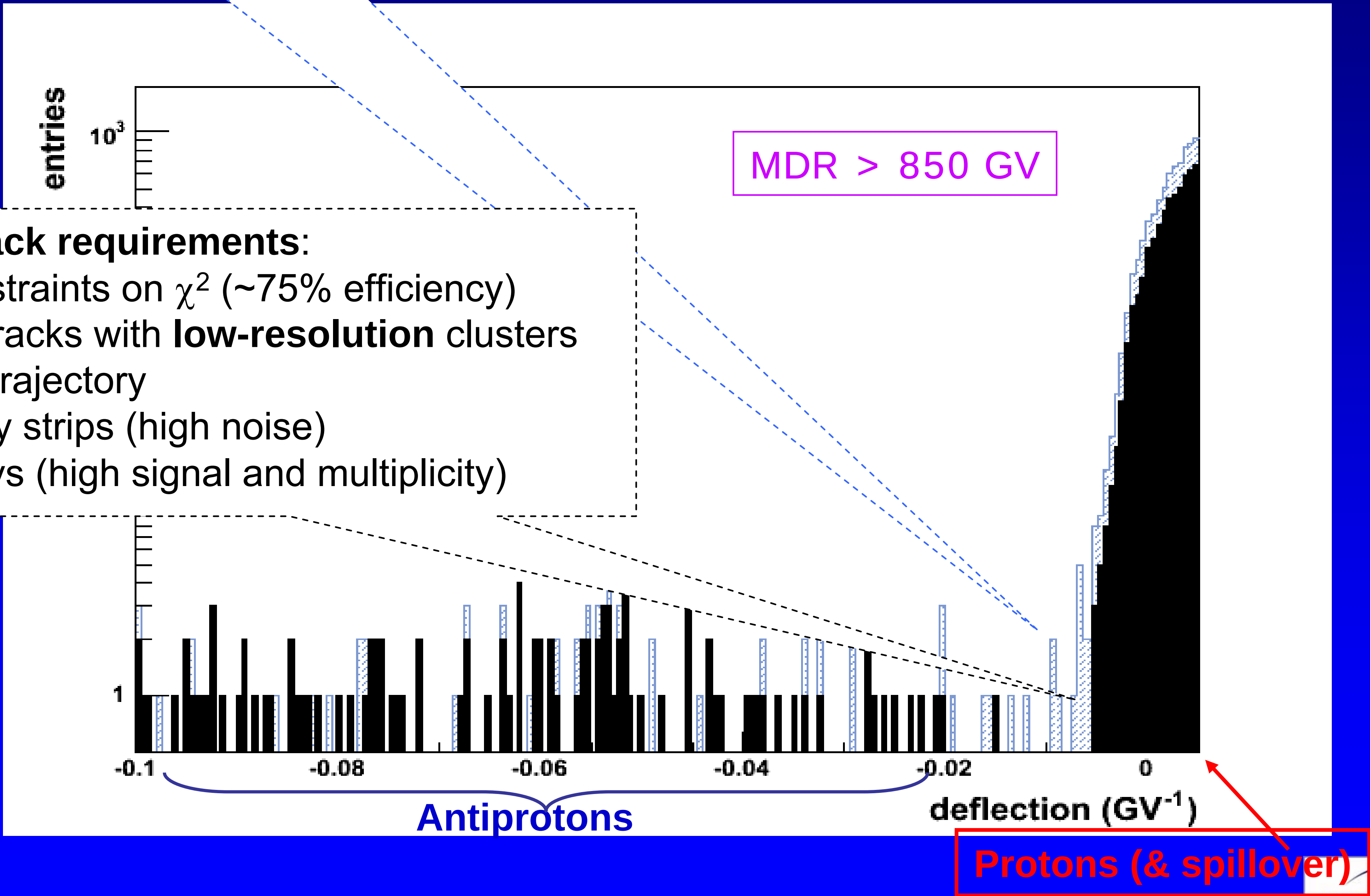
→ Uncertainty band related to propagation parameters (~10% @10GeV)

→ Additional uncertainty of ~25% due to production cs should be considered !!

(Ptuskin et al. 2006) GALPROP code
- **Plain diffusion model**
- Solar modulation: spherical model (f=550MV)

Proton spillover background

Minimal track requirements



Strong track requirements:

•strict constraints on χ^2 (~75% efficiency)

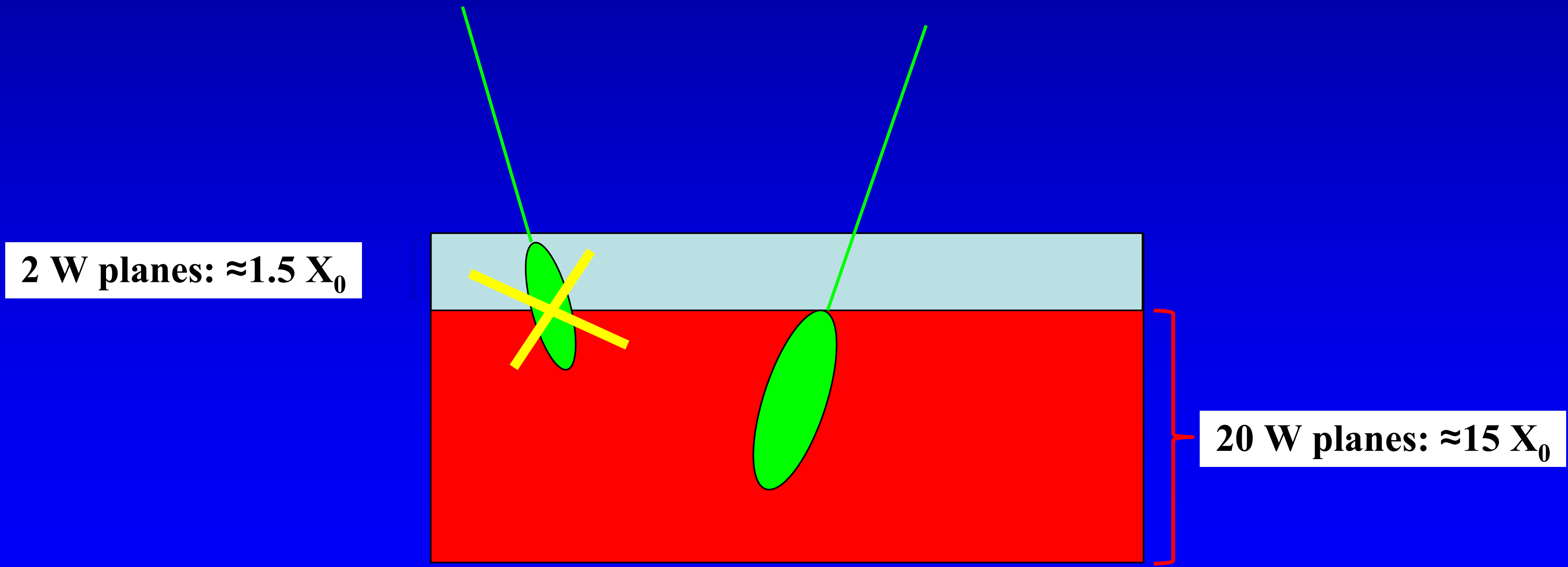
•rejected tracks with **low-resolution** clusters along the trajectory

- faulty strips (high noise)
- δ-rays (high signal and multiplicity)

The "pre-sampler" method

Selection of a pure sample of protons from flight data

CALORIMETER: 22 W planes: 16.3 X_0



Proton background evaluation

Rigidity: 6.1-7.4 GV

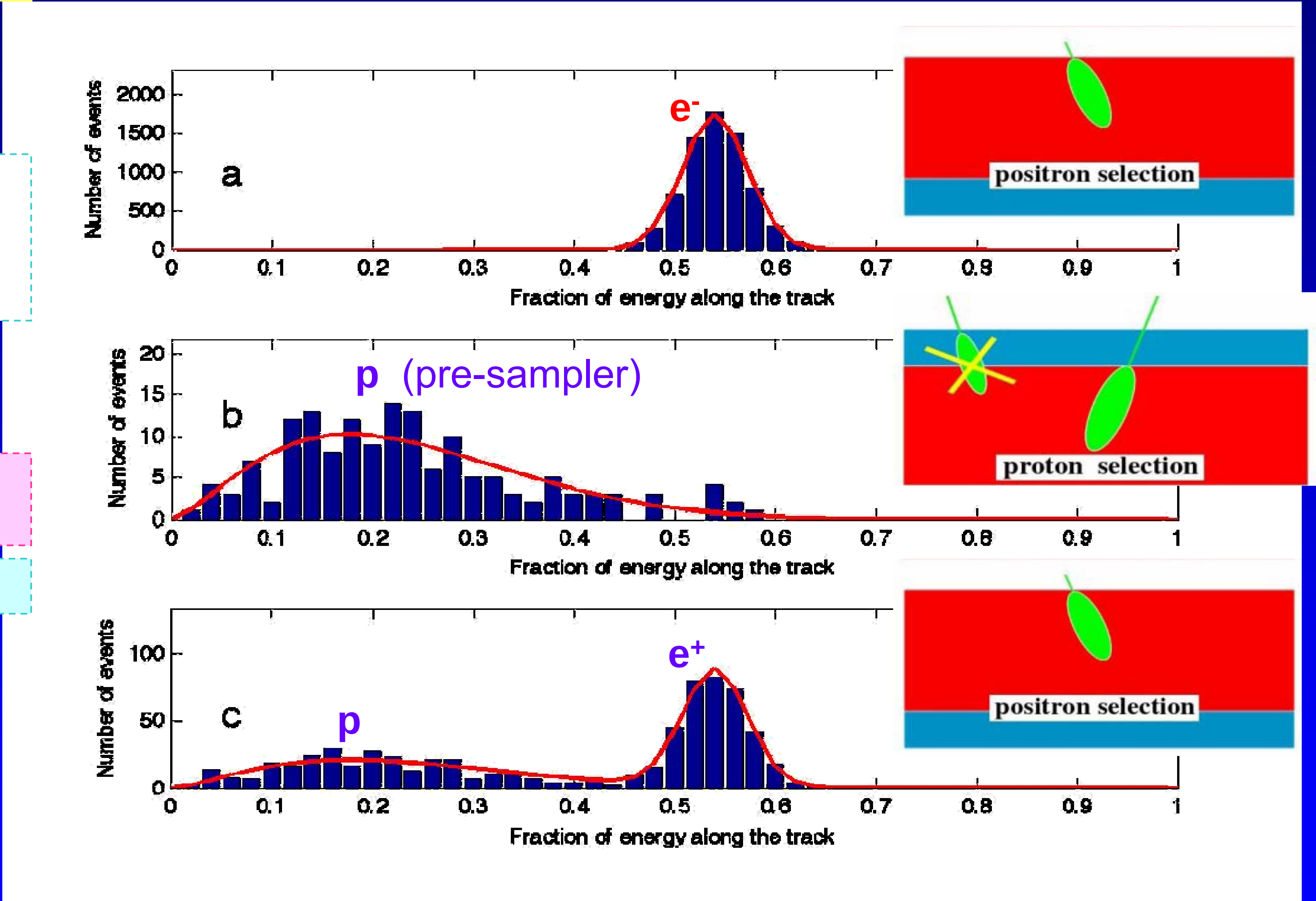
Fraction of charge released along the calorimeter track (left, hit, right)

+

Constraints on:

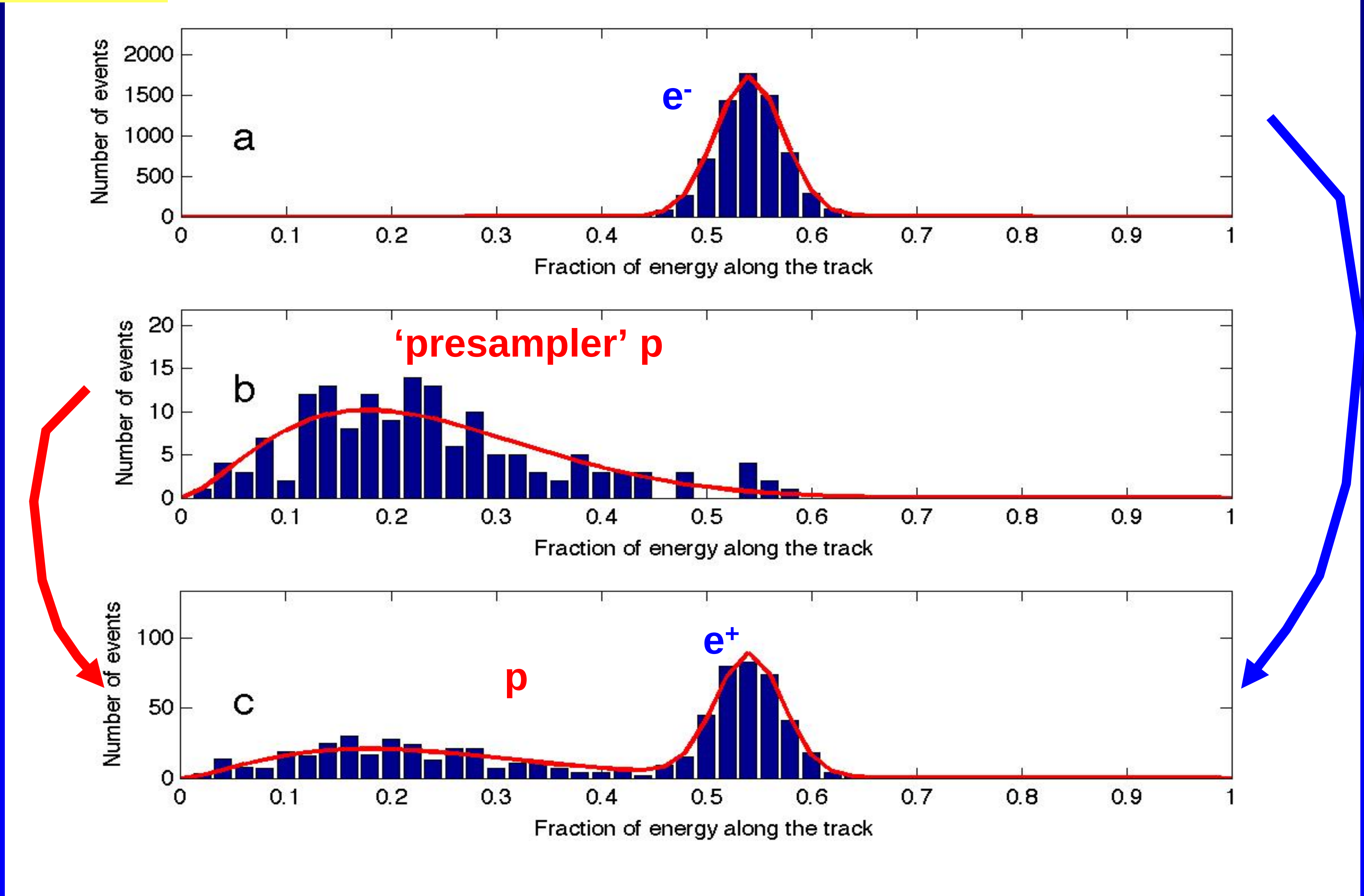
Energy-momentum match

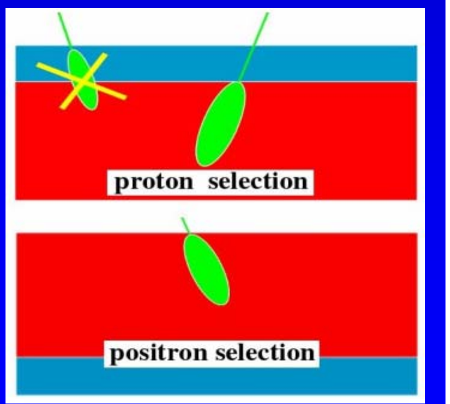
Shower starting-point



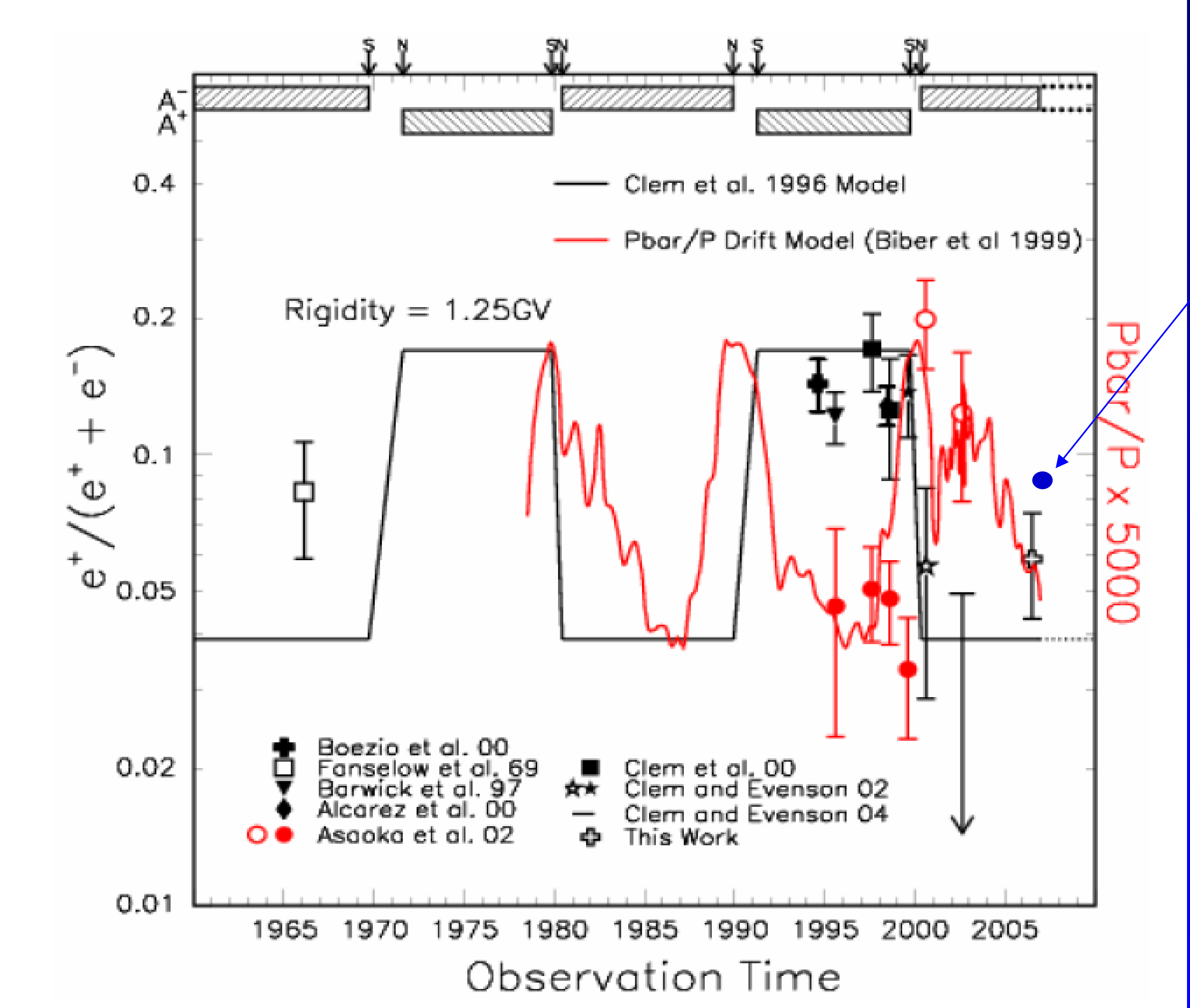
Proton background estimation from data

Rigidity: 6.1-7.4 GV





+
- **Energy-momentum match**
- **Starting point of shower**



Pamela

2006

(Preliminary!)

Clem at al.
30th ICRC 2007

EVALUATION OF PION CONTAMINATION FOR ANTIPROTONS

protons interacting in the material surrounding PAMELA can generate π^- which can mimic an antiproton

Extensive simulation (using GRID)

Pions passing antiprotons selections

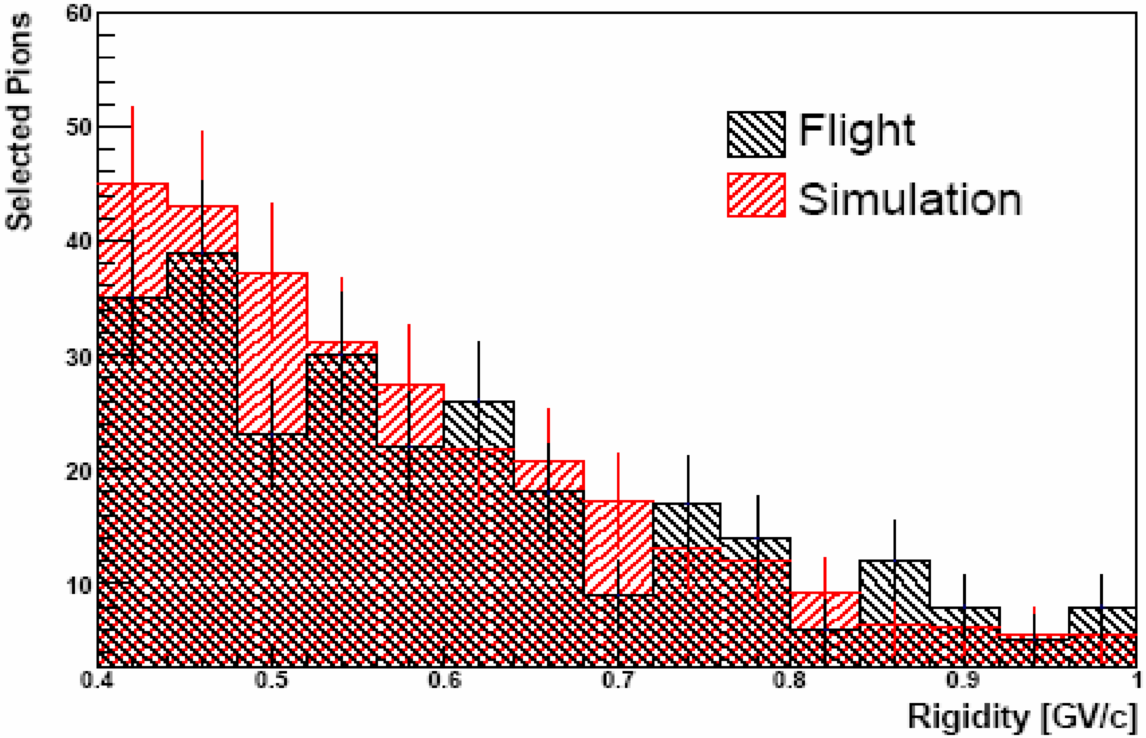


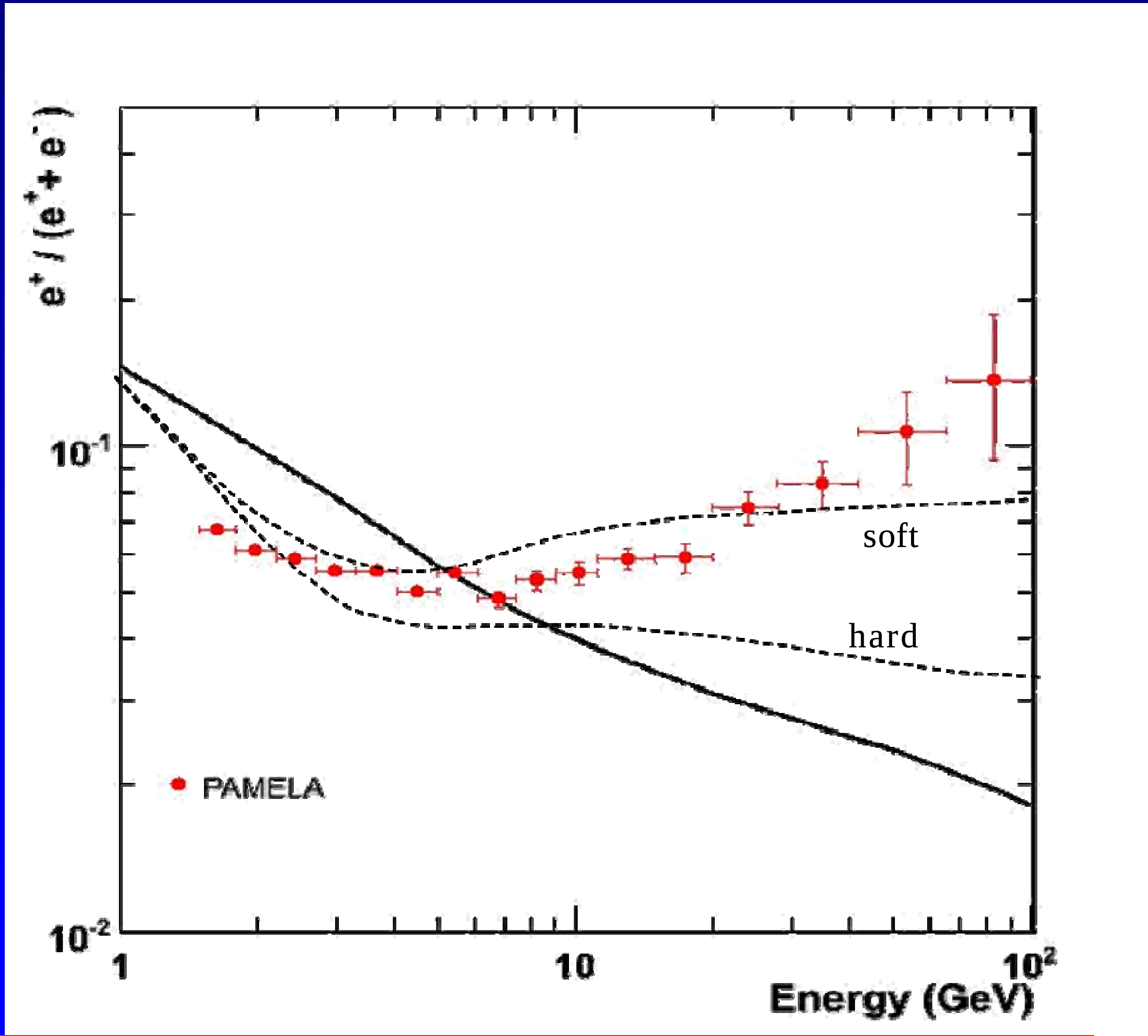
Figure 3.19. Selected flight (black) and simulated (red) negative pions.

Below 1 GV the pions can be recognized using time of flight and be compared with simulation. Above 1 GV the pion contamination is <u>extrapolated from simulation</u>.

Above 5 GV the contamination Is less than 1%.

Positron fraction

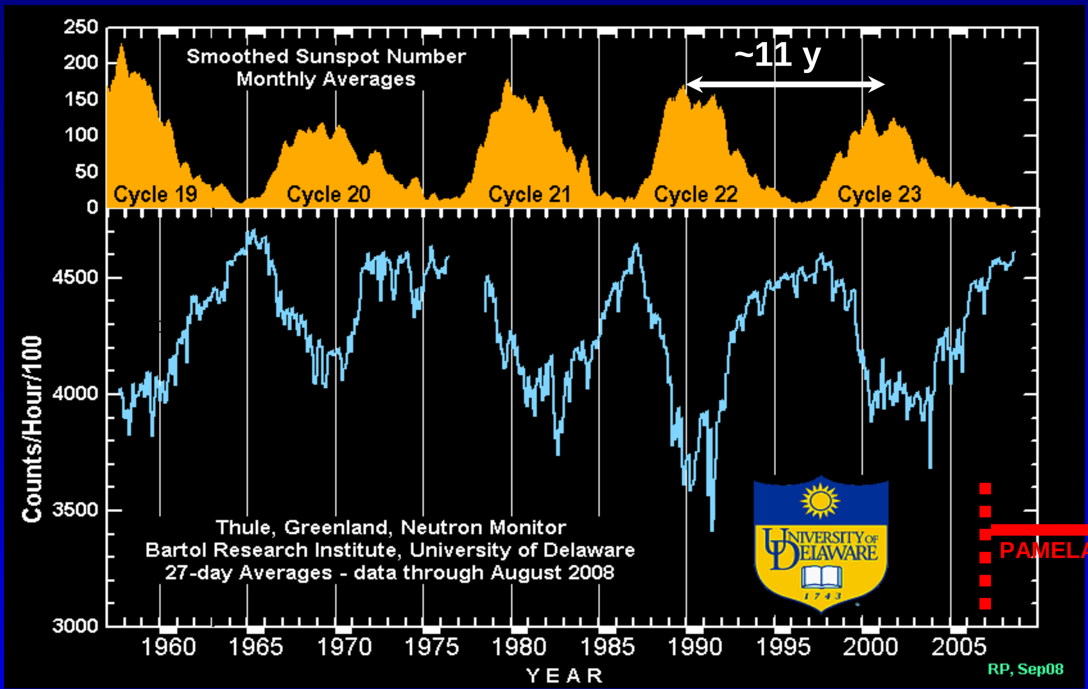
Secondary Production Models

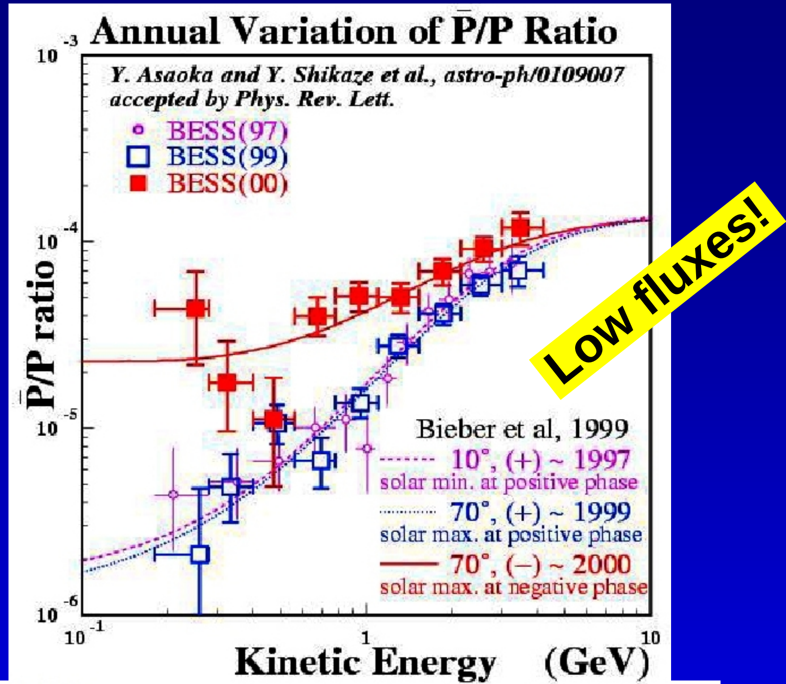


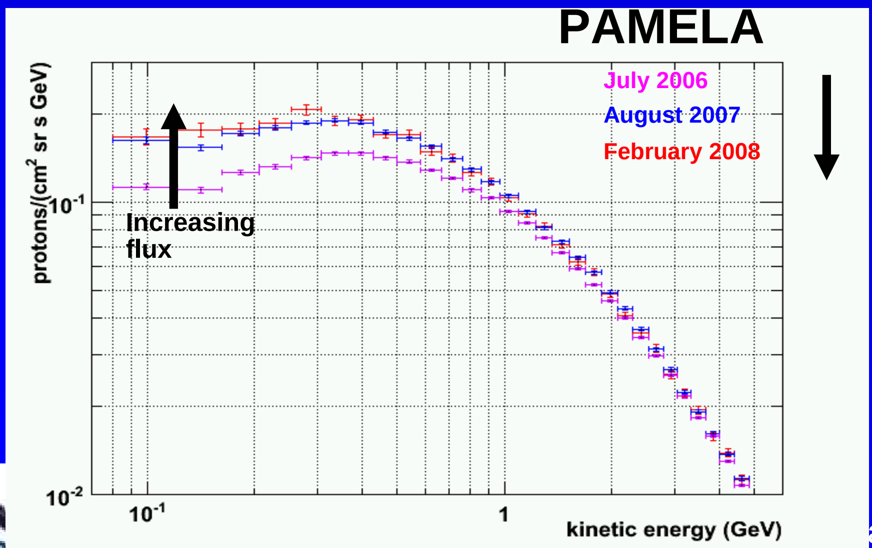
Quite robust evidence for a positron excess

Solar modulation

A^+ A^- A^+ A^-







Decreasing solar activity