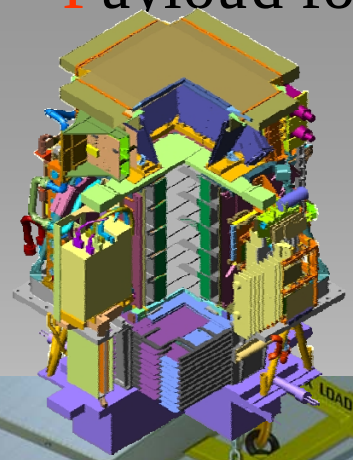
Recent results from PAMELA

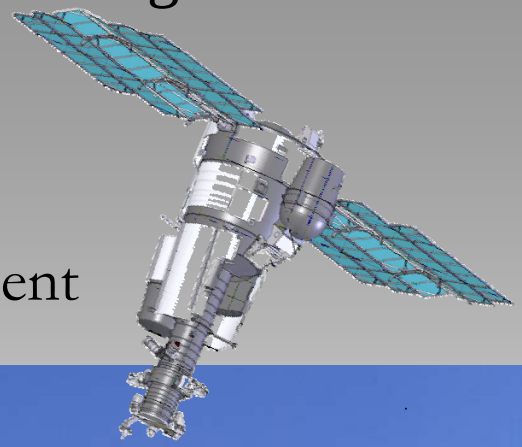
Elena Vannuccini

INFN – Florence, Italy

PAMELA

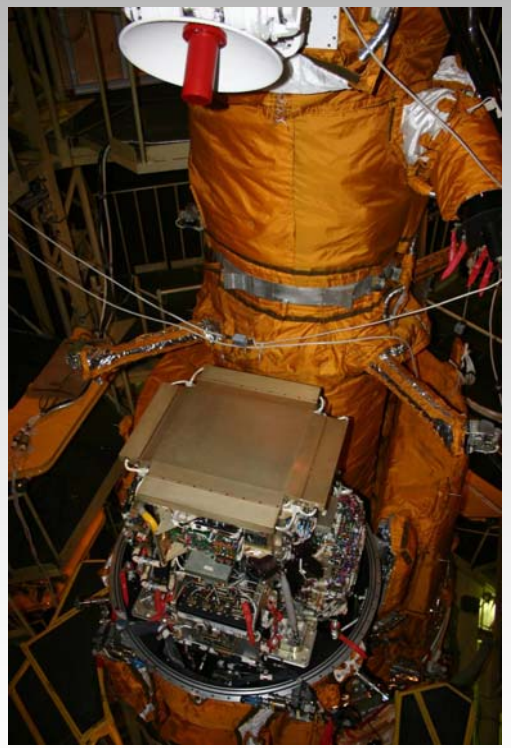
Payload for Antimatter/Matter Exploration and Light-nuclei Astrophysics



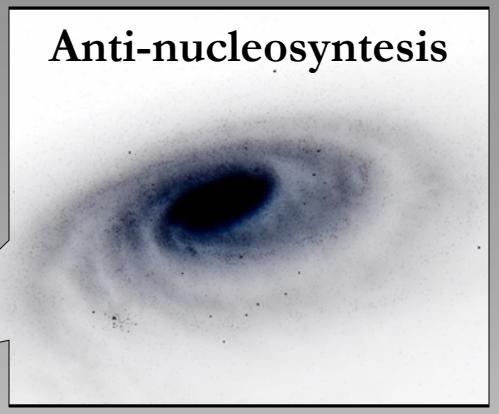


→ Direct detection of CRs in **space**

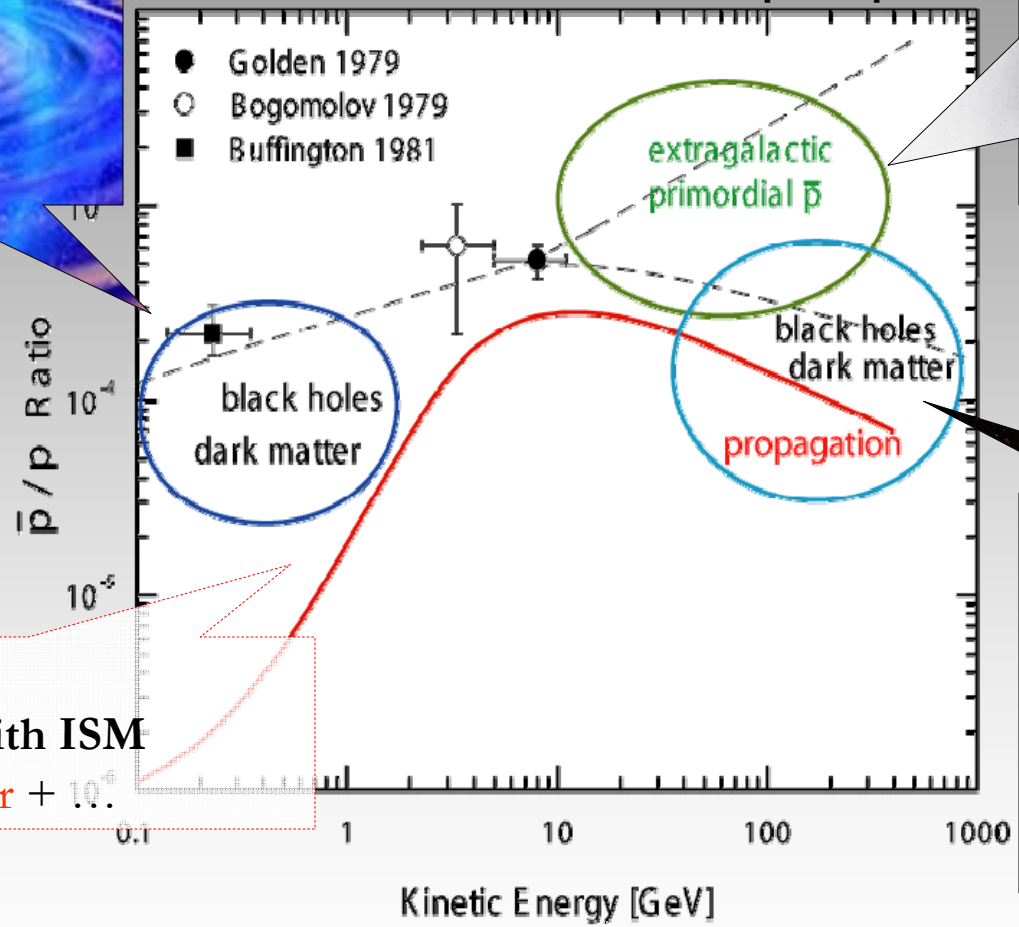
→ Main focus on **antimatter** component

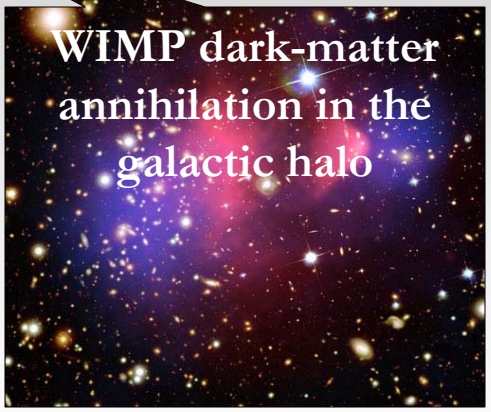


Why CR antimatter?



First historical measurements of p-bar/p ratio





<u>Background</u>:

CR interaction with ISM

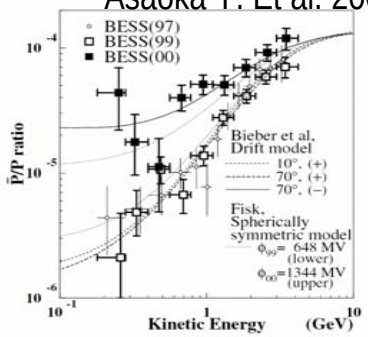
CR + ISM → p-bar + ...

CR antimatter

Present status

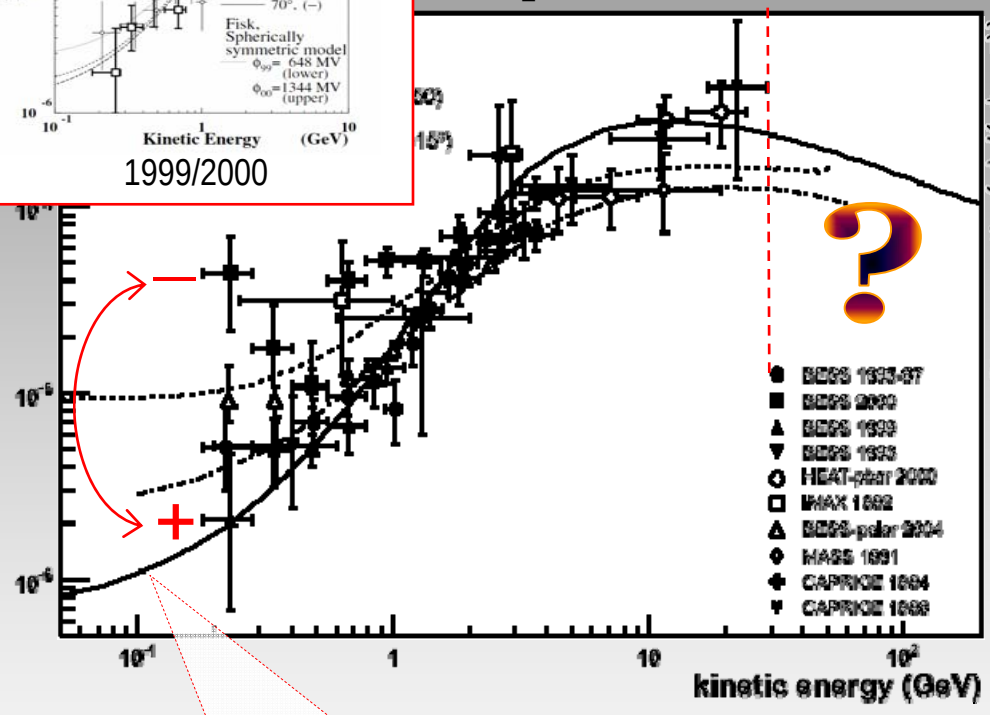
Charge-dependent solar modulation

Asaoka Y. Et al. 2002

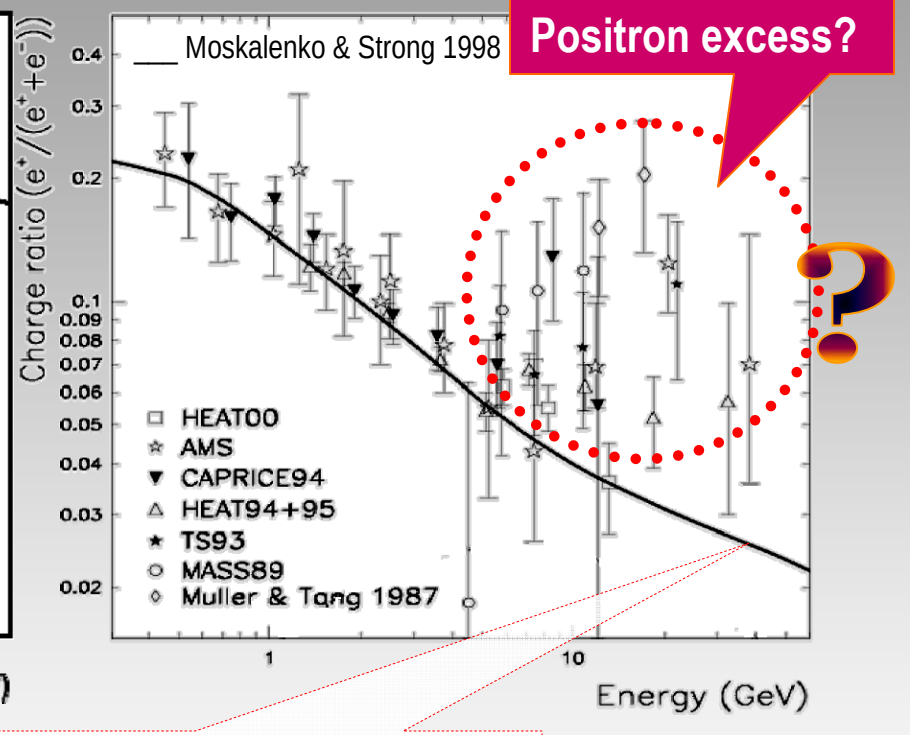


1999/2000

Antiprotons



Positrons



CR + ISM → **p-bar** + …

kinematic treshold:

5.6 GeV for the reaction

$pp \rightarrow \bar{p}ppp$

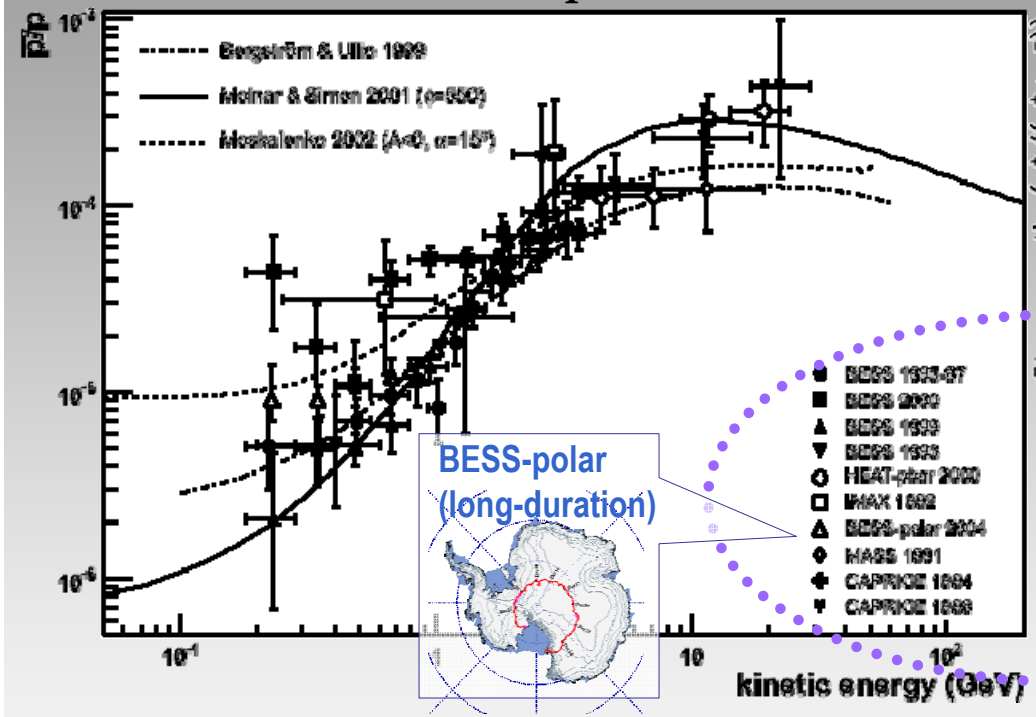
CR + ISM → $\pi^{\pm}$ + x → $\mu^{\pm}$ + x → $e^{\pm}$ + x

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

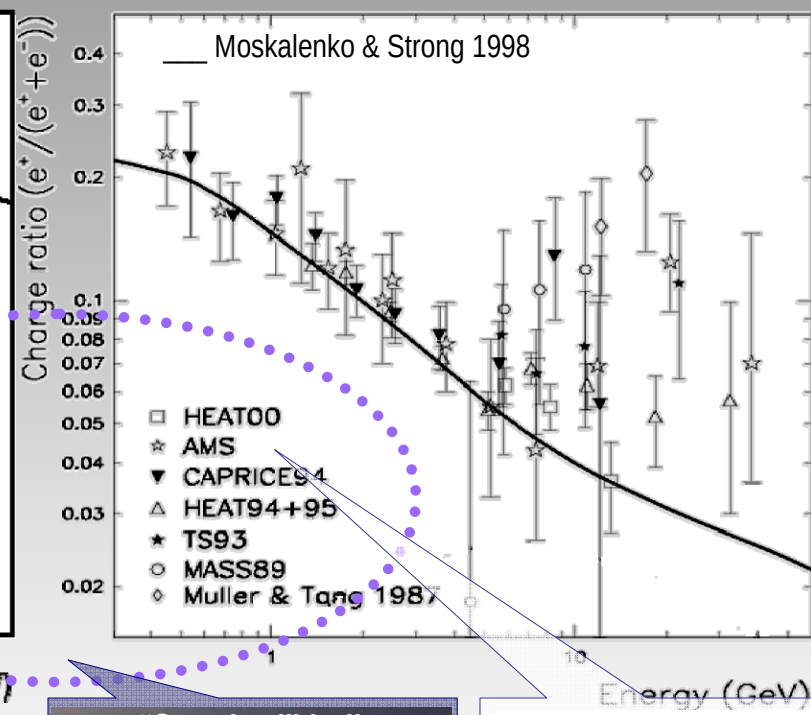
CR antimatter: available data

Why in space?

Antiprotons



Positrons



BESS-polar (long-duration)

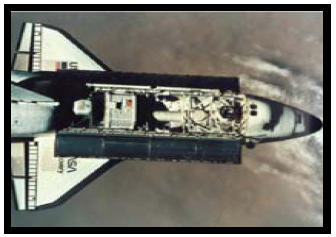
- low exposure (~20h)

⇒ large statistical errors

- atmospheric secondaries (~5g/cm2)

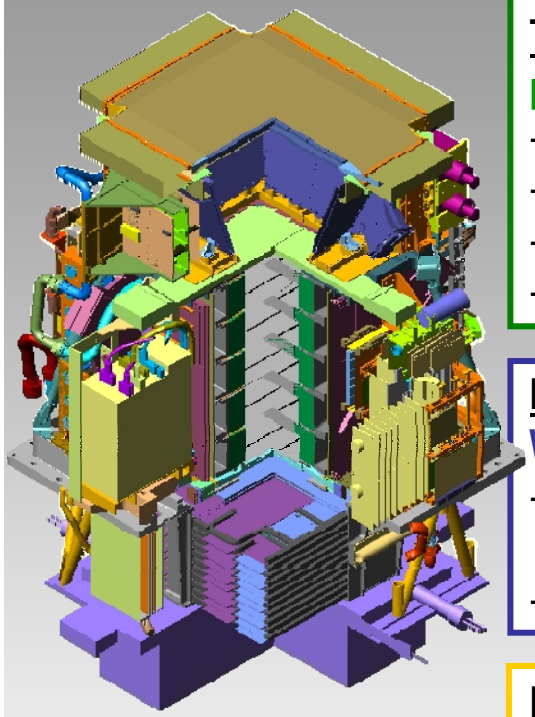
⇒ additional systematic uncertainty @low-energy

AMS-01: space shuttle, 1998



PAMELA detectors

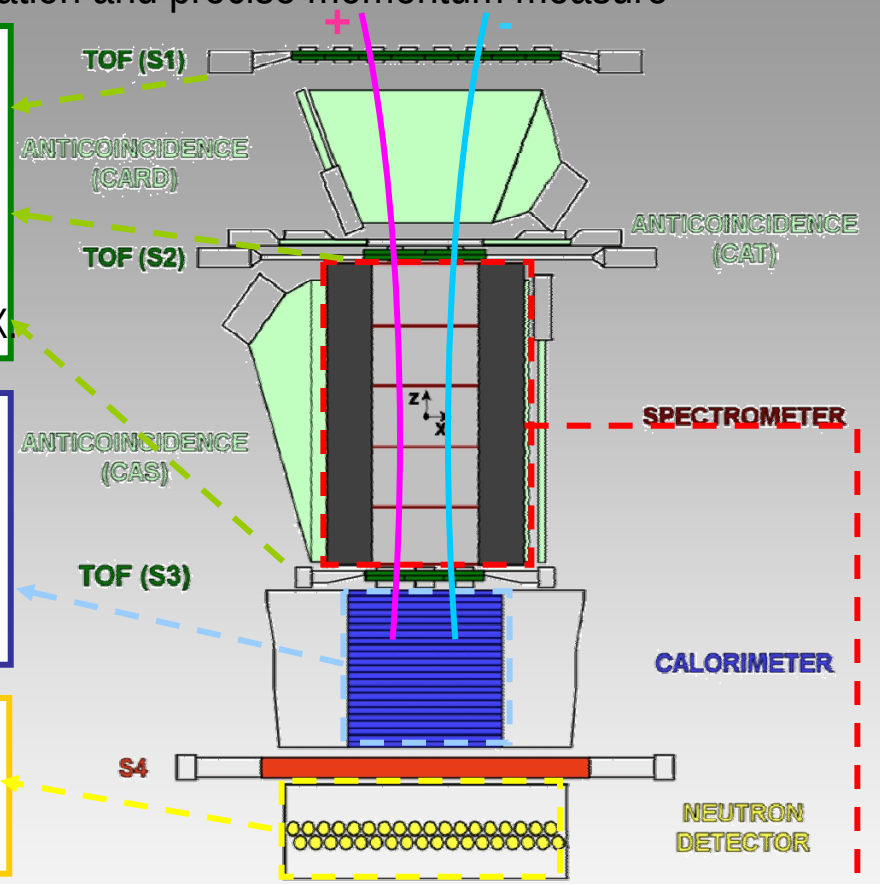
Main requirements → high-sensitivity antiparticle identification and precise momentum measure



Time-Of-Flight
plastic scintillators + PMT:
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX

Electromagnetic calorimeter
W/Si sampling (16.3 X0, 0.6 λI)
- Discrimination e+ / p, anti-p / e^- (shower topology)
- Direct E measurement for e^-

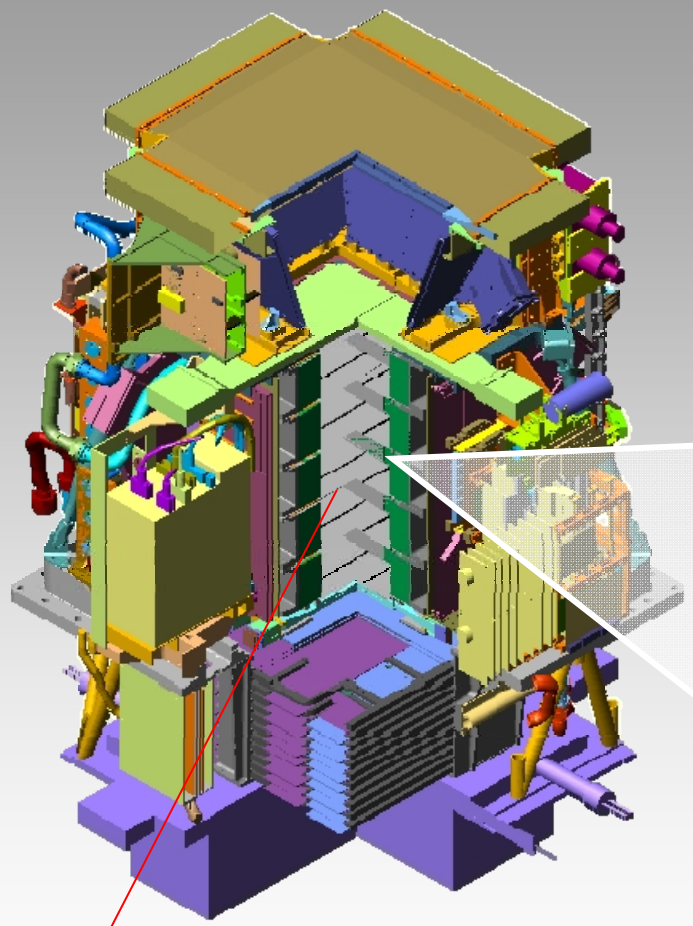
Neutron detector
plastic scintillators + PMT:
- High-energy e/h discrimination



GF: 21.5 cm² sr
Mass: 470 kg
Size: 130x70x70 cm³
Power Budget: 360W

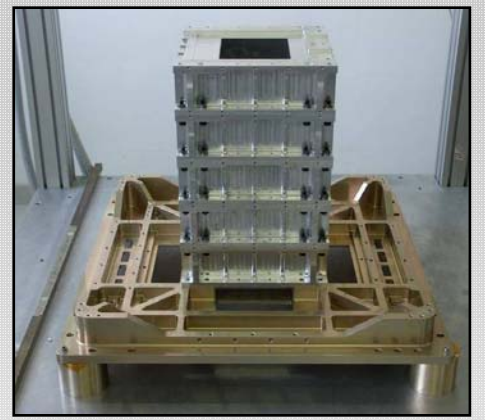
Spectrometer
microstrip silicon tracking system + permanent magnet
It provides:
- ***Magnetic rigidity*** → R = pc/Ze
- ***Charge sign***
- ***Charge value from dE/dx***

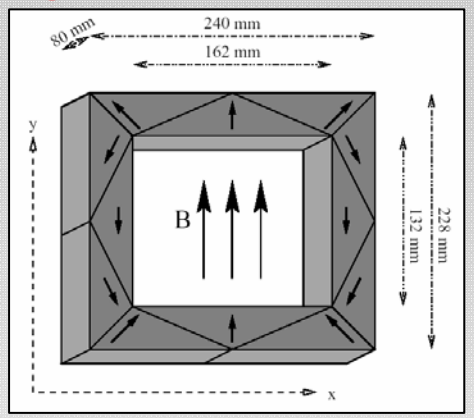
PAMELA apparatus



SPECTROMETER

The magnet

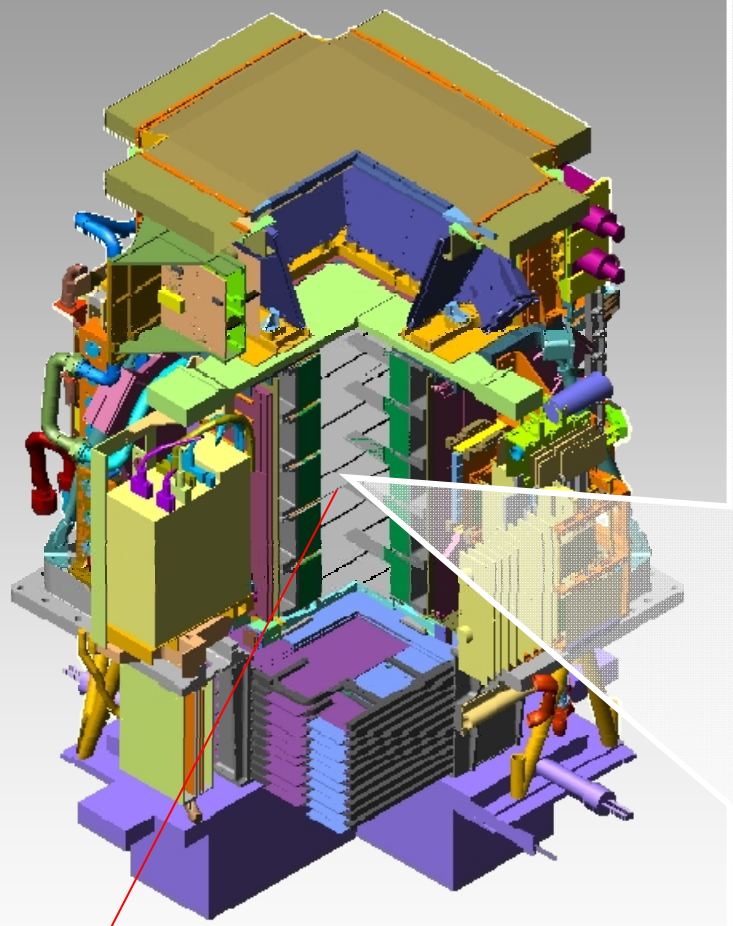




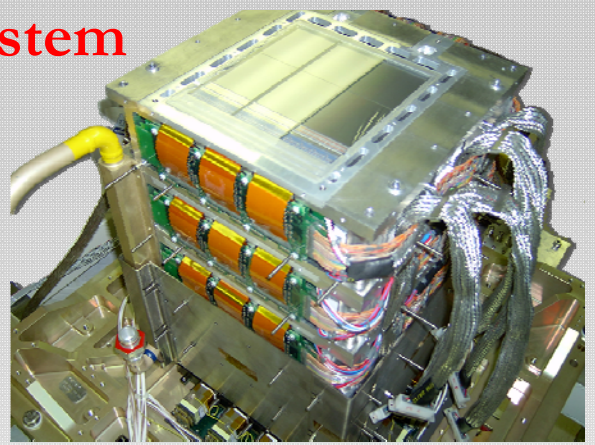
Characteristics:

- **5 modules of permanent magnet (Nd-B-Fe alloy) in aluminum mechanics**
- Cavity dimensions 162x132x445 cm^3
  →GF 21.5 cm^2sr
- Magnetic shields
- 5mm-step field-map
- **B=0.43 T** (average along axis), B=0.48 T (@center)

PAMELA apparatus



The tracking system



Main tasks:

- Rigidity measurement
- Sign of electric charge
- dE/dx

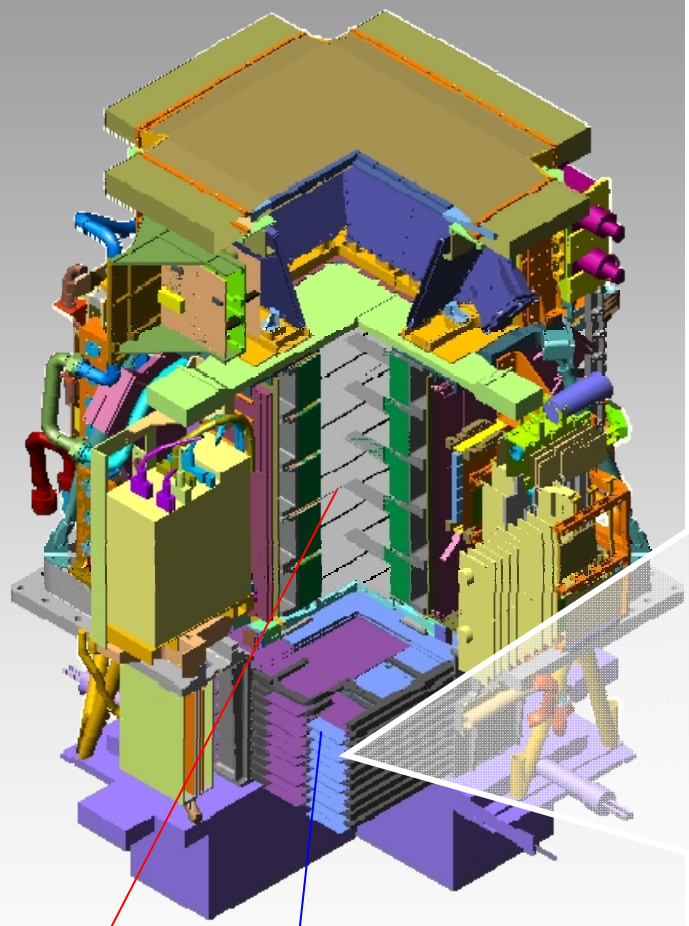
Characteristics:

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

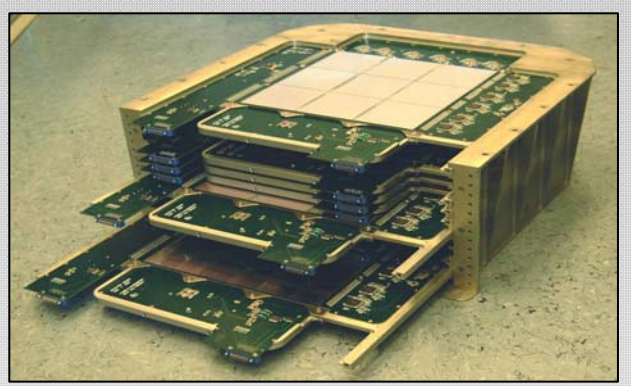
Performances:

- Spatial resolution: **3÷4 μm**
- **MDR ~1TV** (from test beam data)

PAMELA apparatus



The electromagnetic calorimeter



Main tasks:

- e/h discrimination
- $e^{+/-}$ energy measurement

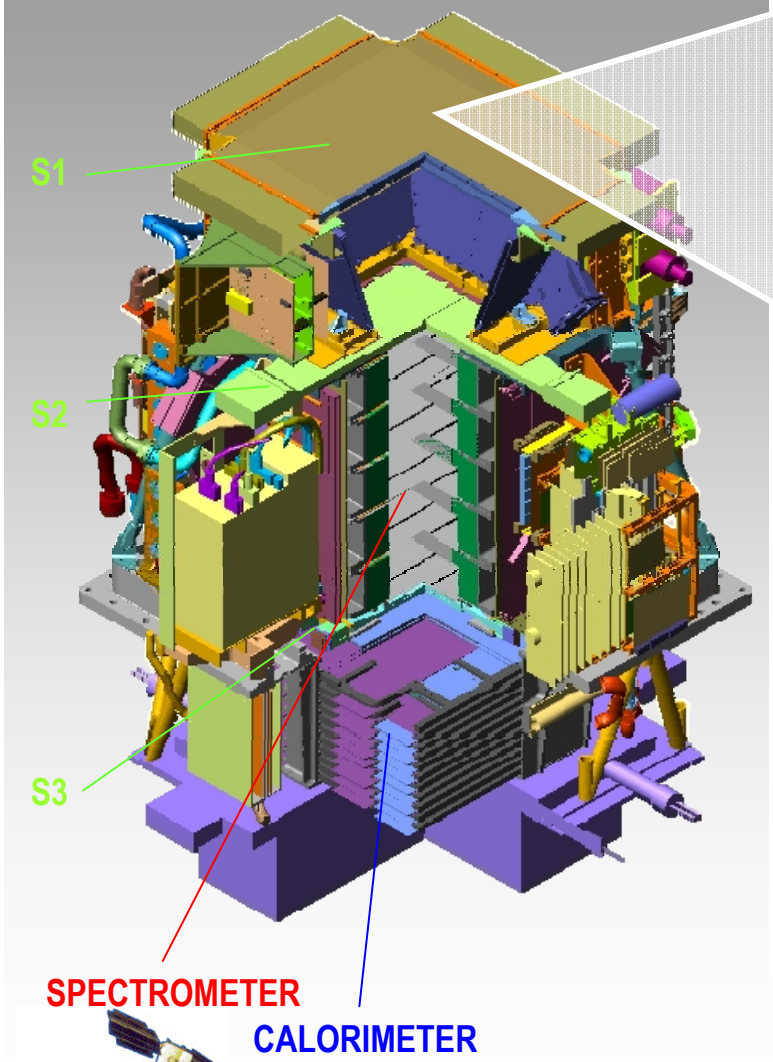
Characteristics:

- **44 Si layers (X/Y) +22 W planes**
- **16.3 X_o / 0.6 l_0**
- 4224 channels
- Dynamic range 1400 mip
- Self-trigger mode (> 300 GeV GF~600 cm^2 sr)

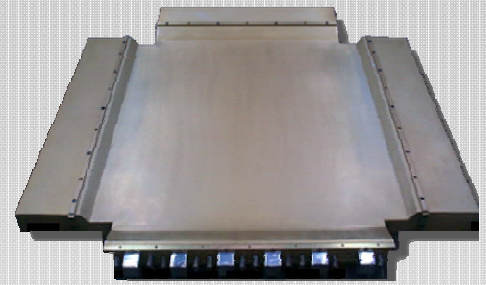
Performances:

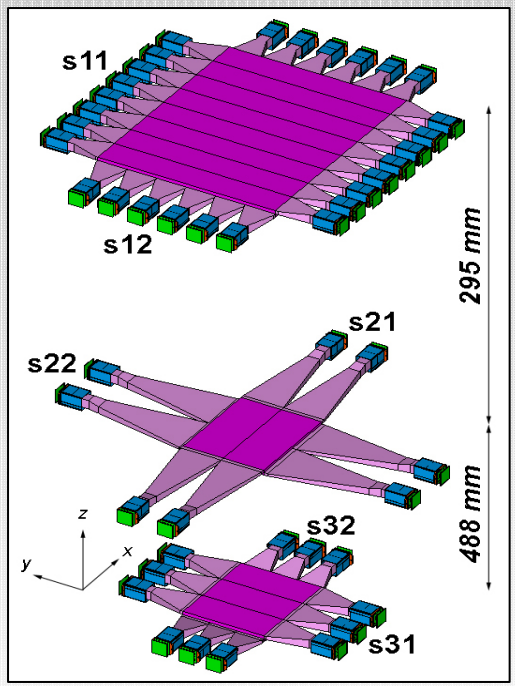
- p/e^+ selection efficinecy ~ 90%
- p rejection factor **10^6**
- e rejection factor **$>10^4$**
- Energy resolution **~5%** @200GeV

PAMELA apparatus



The time-of-flight system



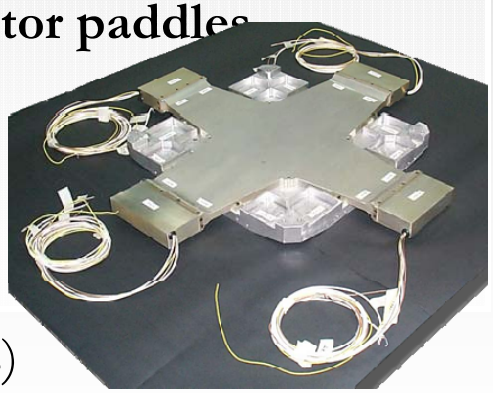


Main tasks:

- First-level trigger
- Albedo rejection
- dE/dx
- Particle identification (<1GeV/c)

Characteristics:

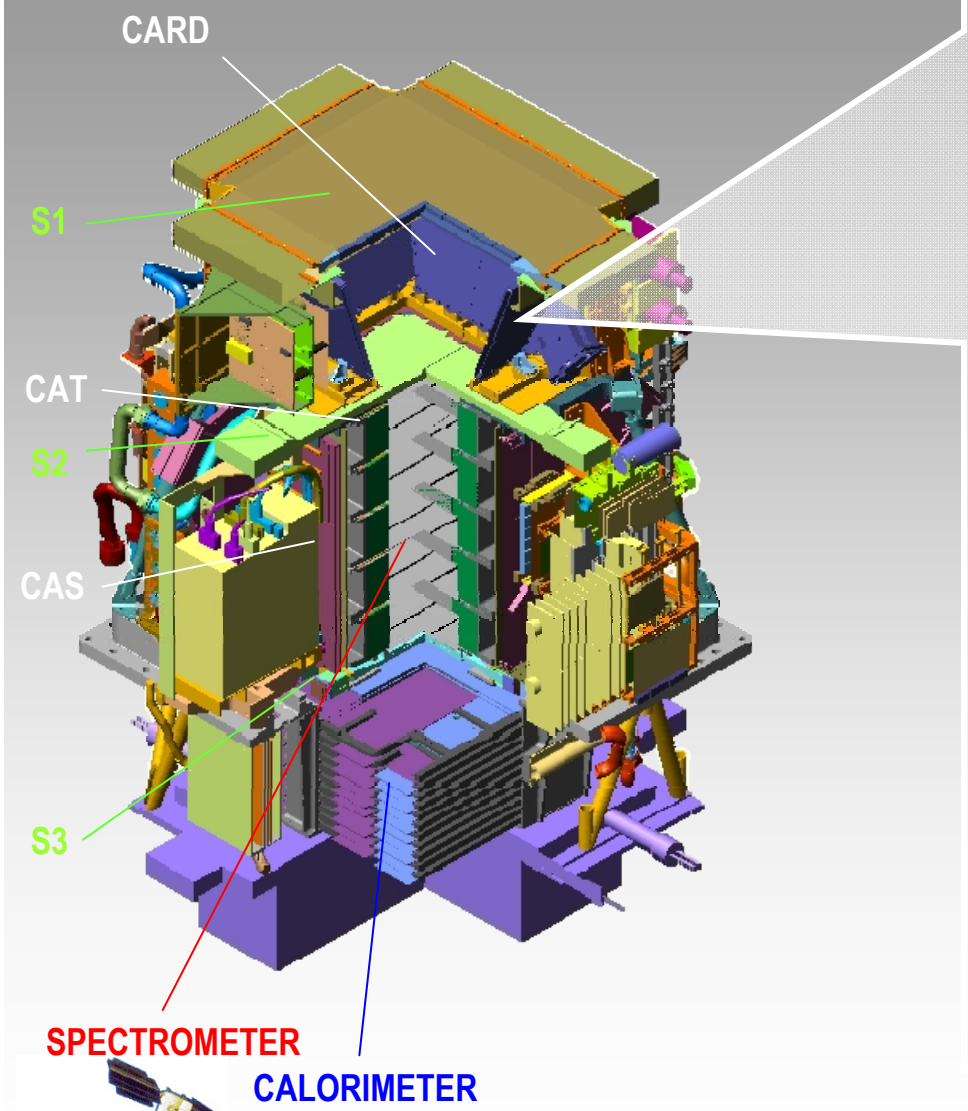
- **3 double-layer scintillator paddles**
- X/Y segmentation
- Total: 48 Channels



Performances:

- σ_{paddle} ~ 110ps
- σ_{TOF} ~ **330ps** (for MIPs)

PAMELA apparatus



The anticounter shields

Main tasks:

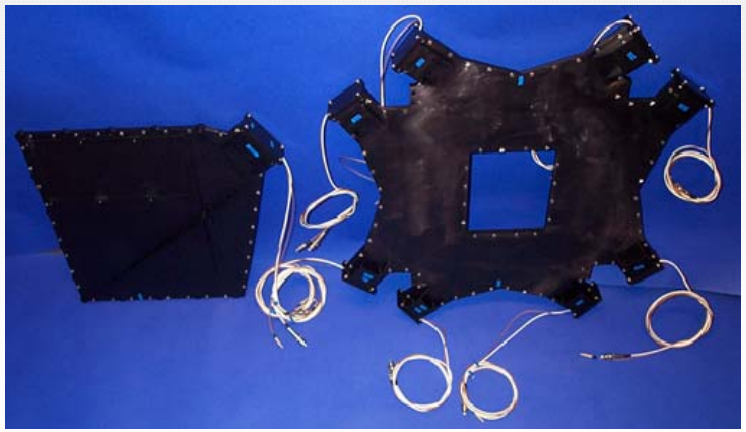
- Rejection of events with particles interacting with the apparatus (off-line and second-level trigger)

Characteristics:

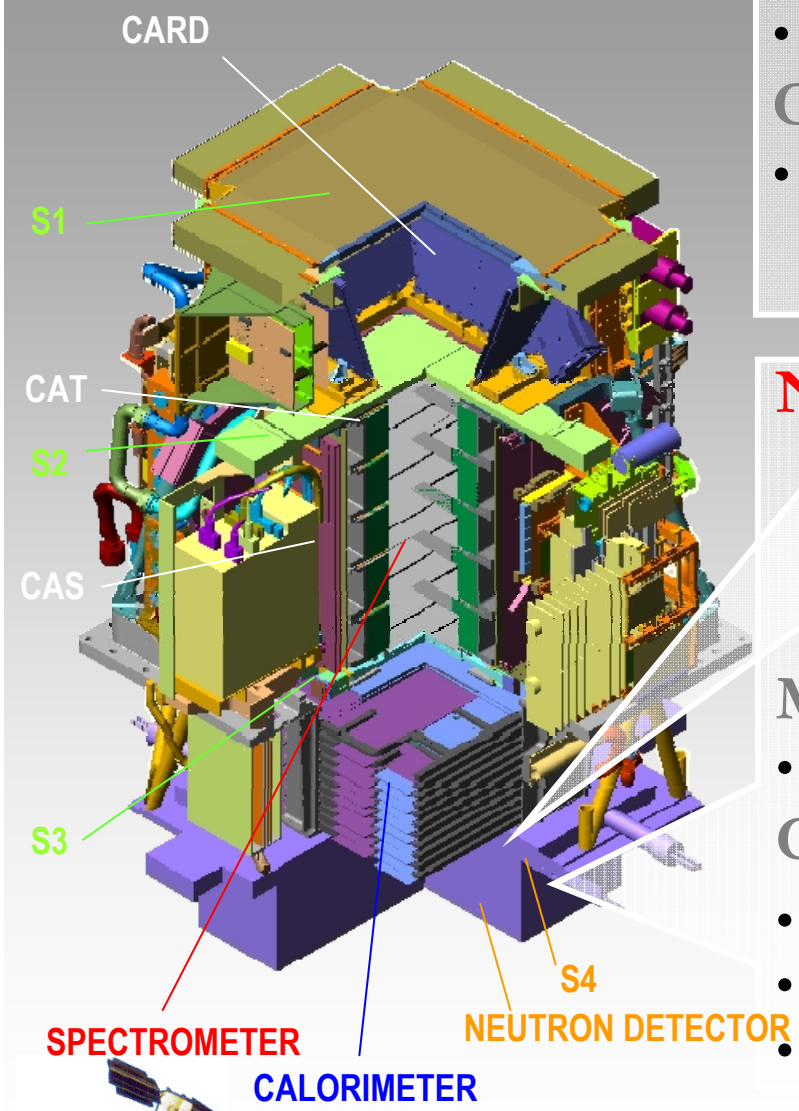
- **scintillator paddles 10mm thick**
- 4 up (**CARD**), 1 top (**CAT**), 4 side (**CAS**)

Performances:

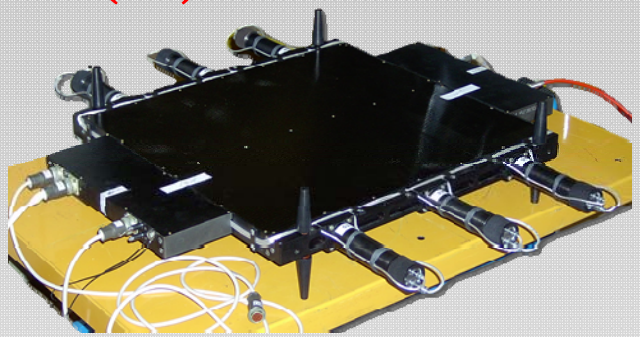
- Efficiency > 99.9%



PAMELA apparatus



Shower-tail catcher (S4)



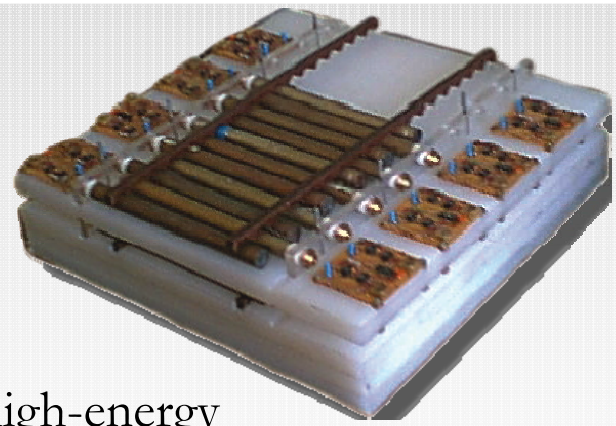
Main tasks:

- ND trigger

Characteristics:

- 1 scintillator paddle 10mm thick

Neutron detector



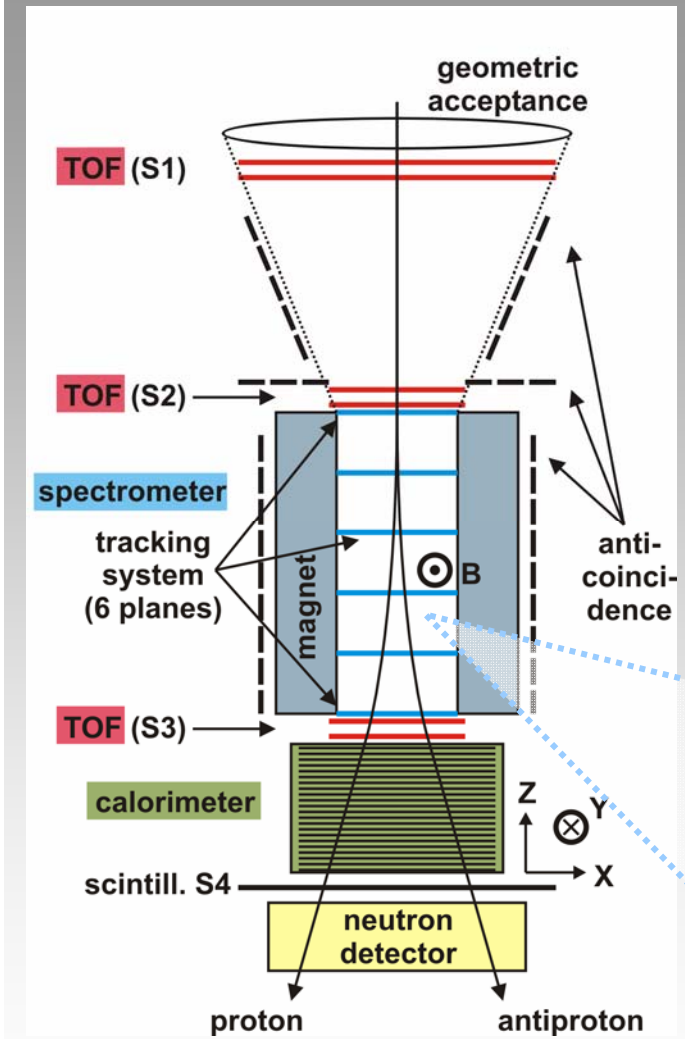
Main tasks:

- e/h discrimination @high-energy

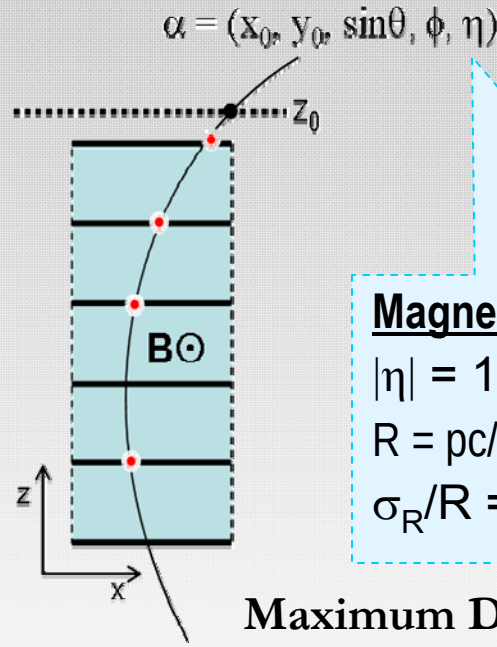
Characteristics:

- **36 ^{3}He counters**: ^{3}He(n,p)T $\rightarrow$ Ep=780 keV
- 1cm thick polyetilene moderators
- n collected within 200 μs time-window

Principle of operation



Track reconstruction



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

Magnetic deflection

$|\eta| = 1/R$

$R = pc/Ze \rightarrow$ **magnetic rigidity**

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

Maximum Detectable Rigidity (MDR)

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

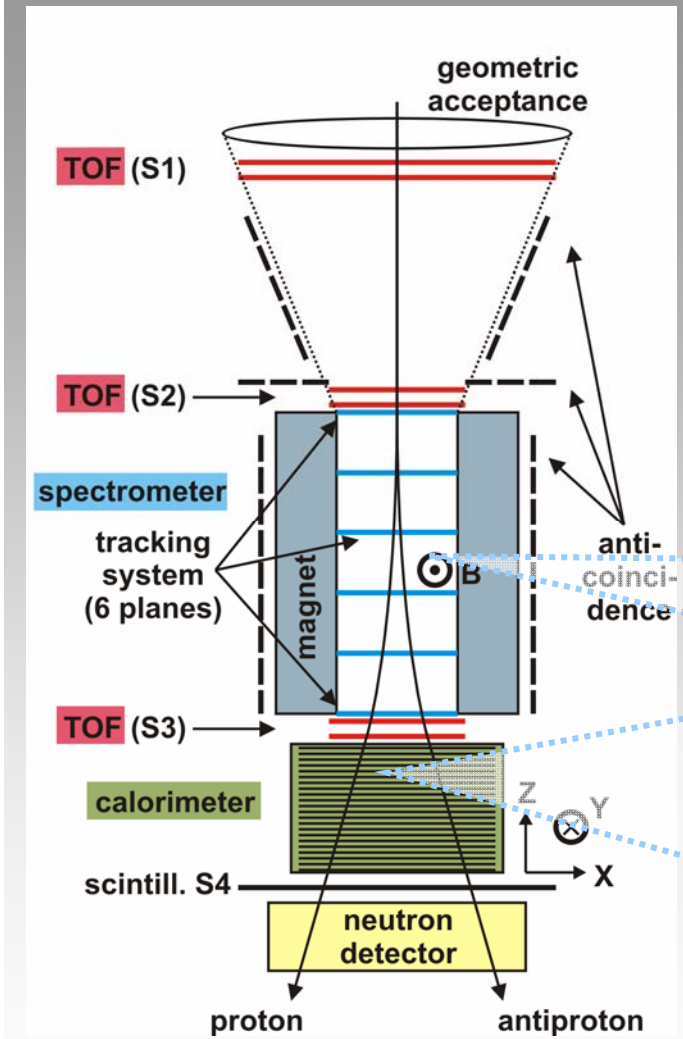
$$\mathbf{MDR = 1/\sigma_\eta}$$

- Measured @ground with protons of known momentum

$\rightarrow$ **MDR~1TV**

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

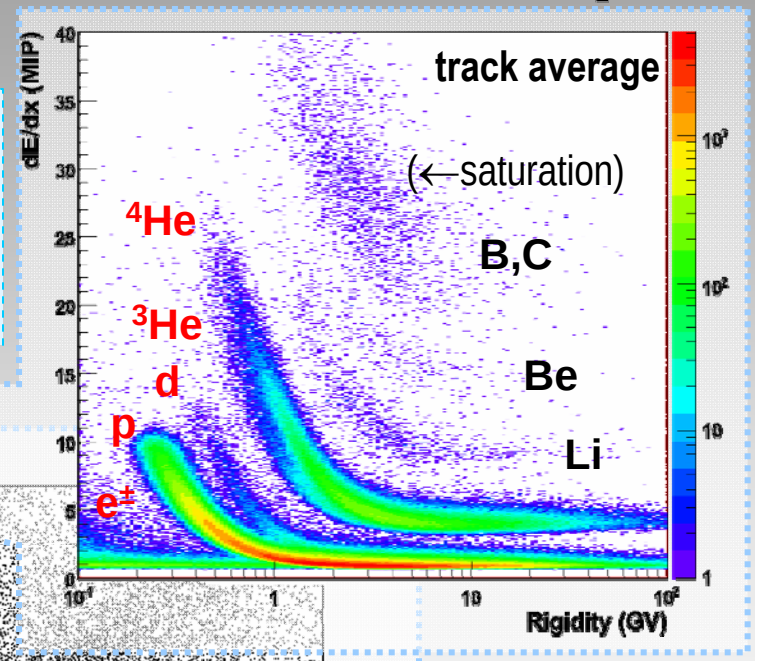
Principle of operation

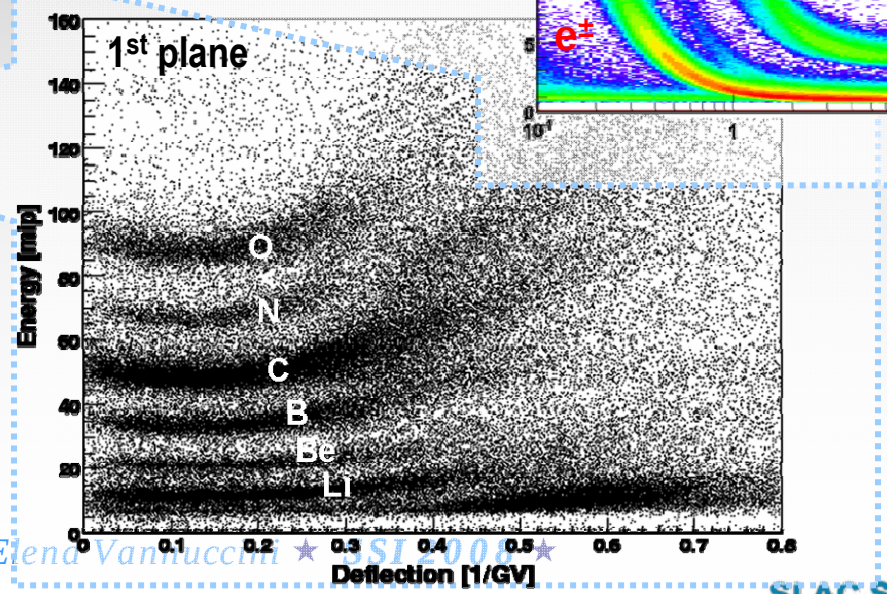


Z measurement

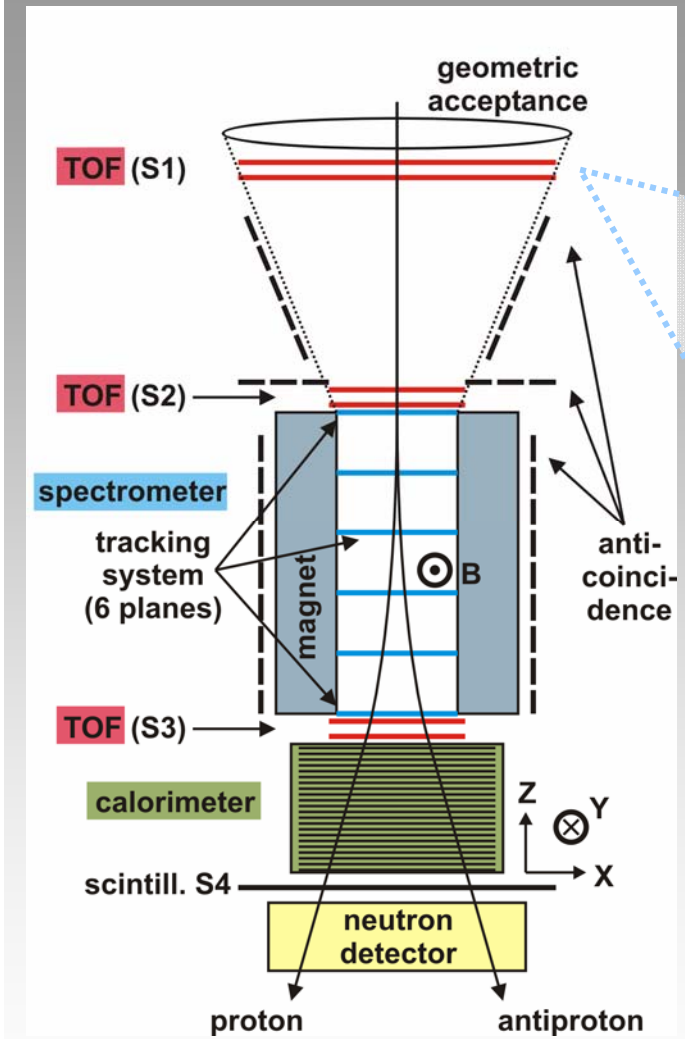
$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

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

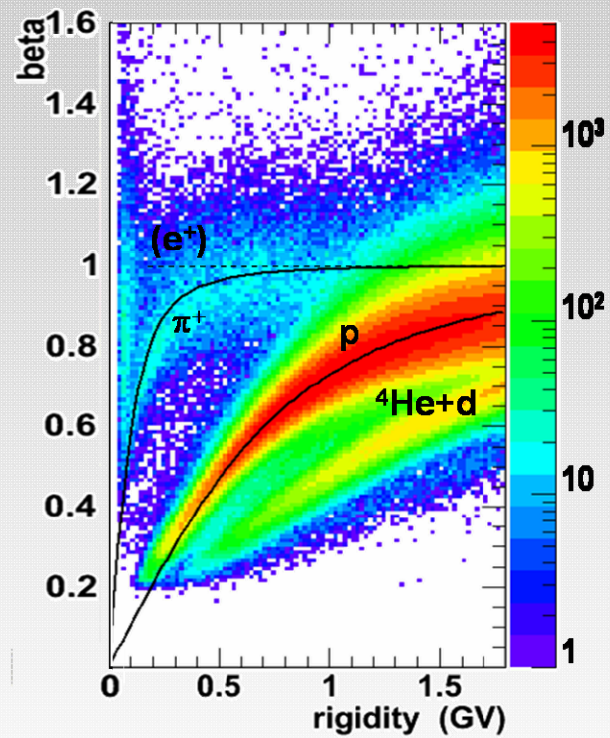




Principle of operation



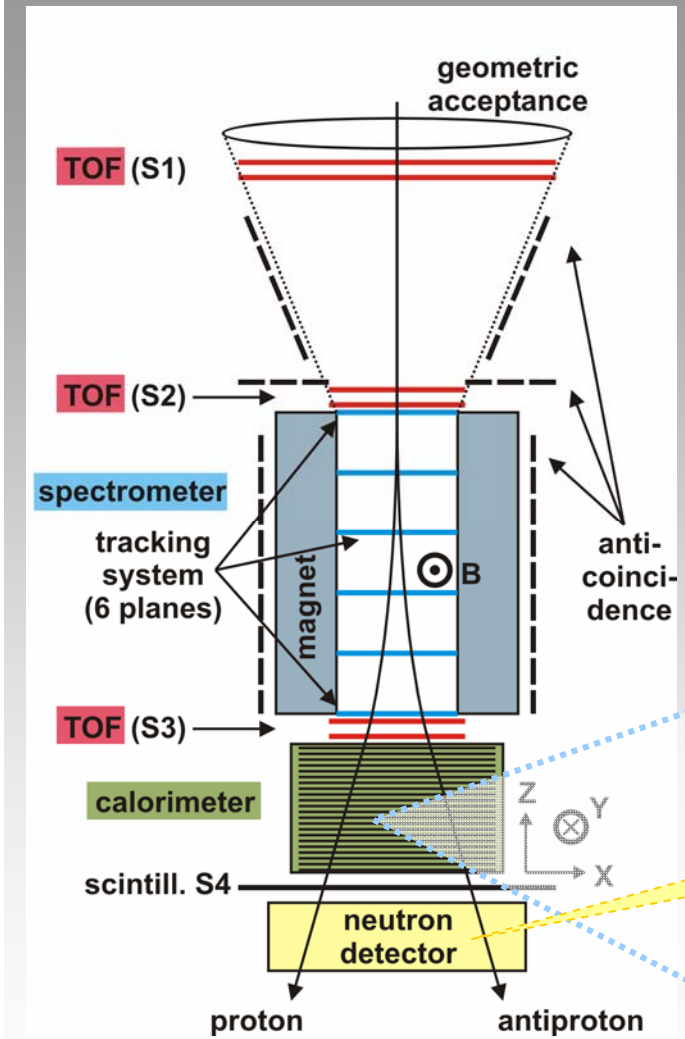
Velocity measurement



- Particle identification @ low energy
- Identify **albedo** (up-ward going particles $\rightarrow \beta < 0$)

  → NB! They mimic antimatter!

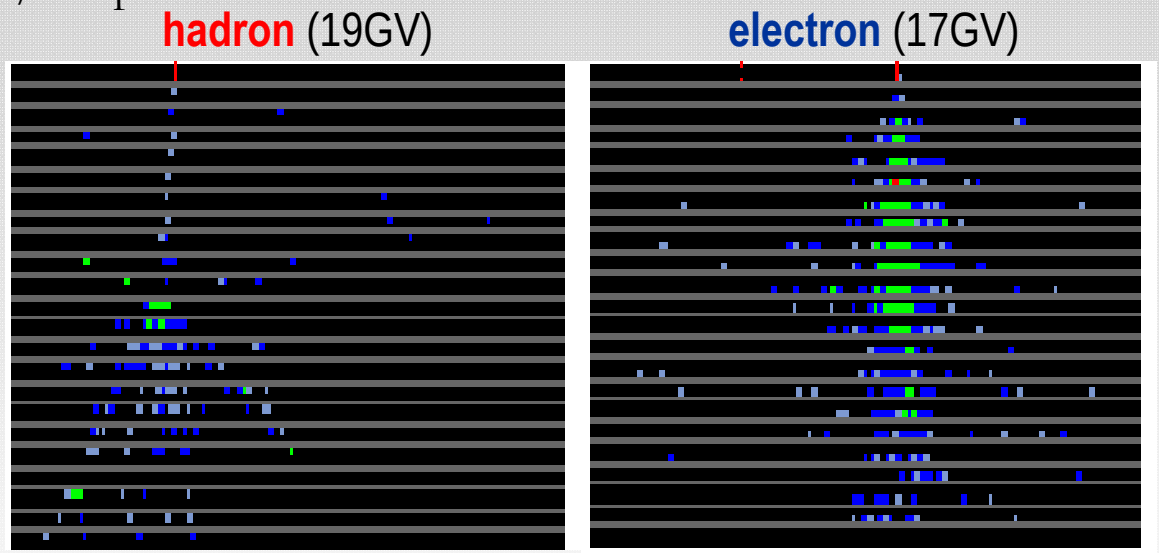
Principle of operation



Electron/hadron separation

- **Interaction topology**

e/h separation

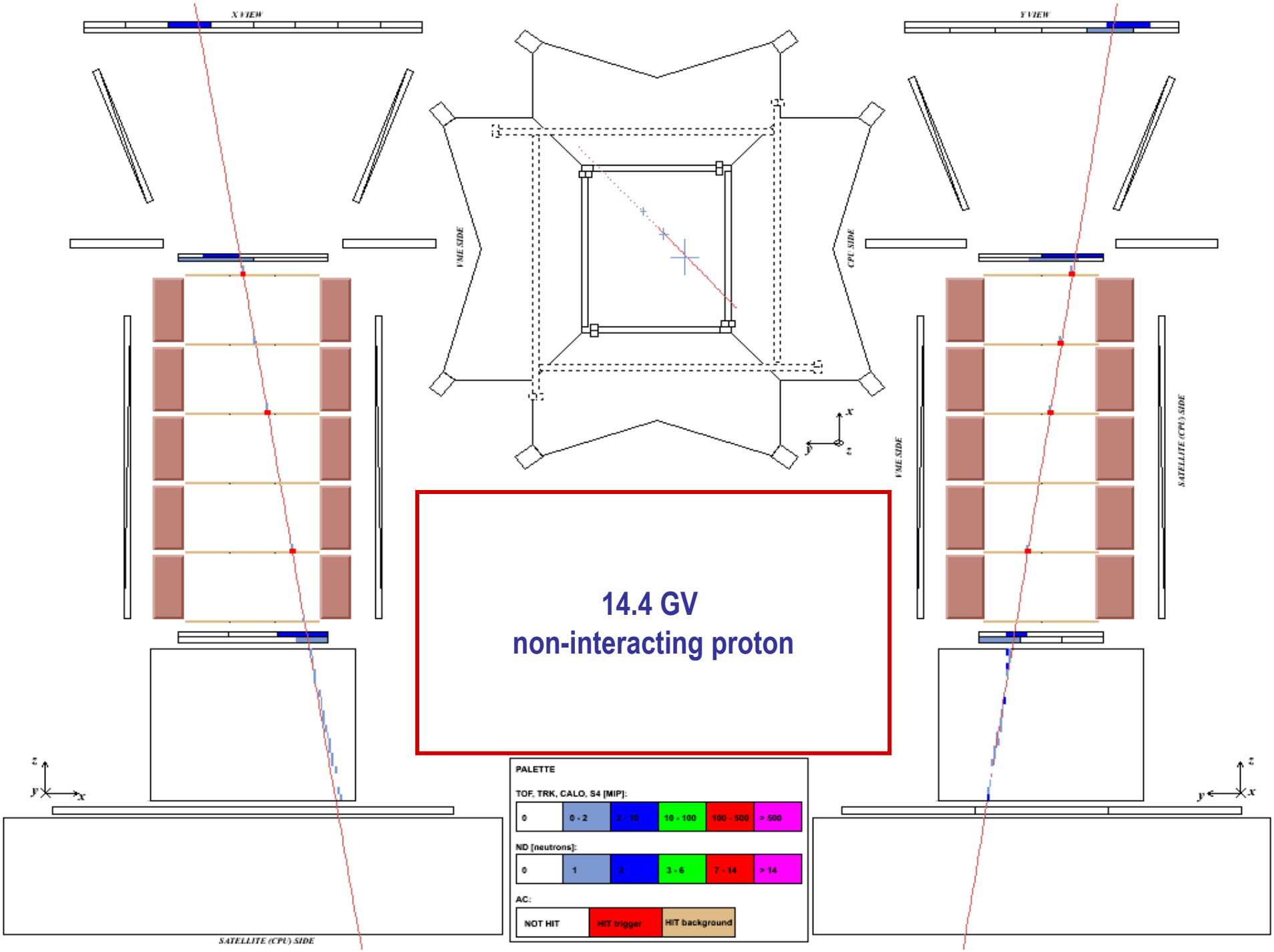


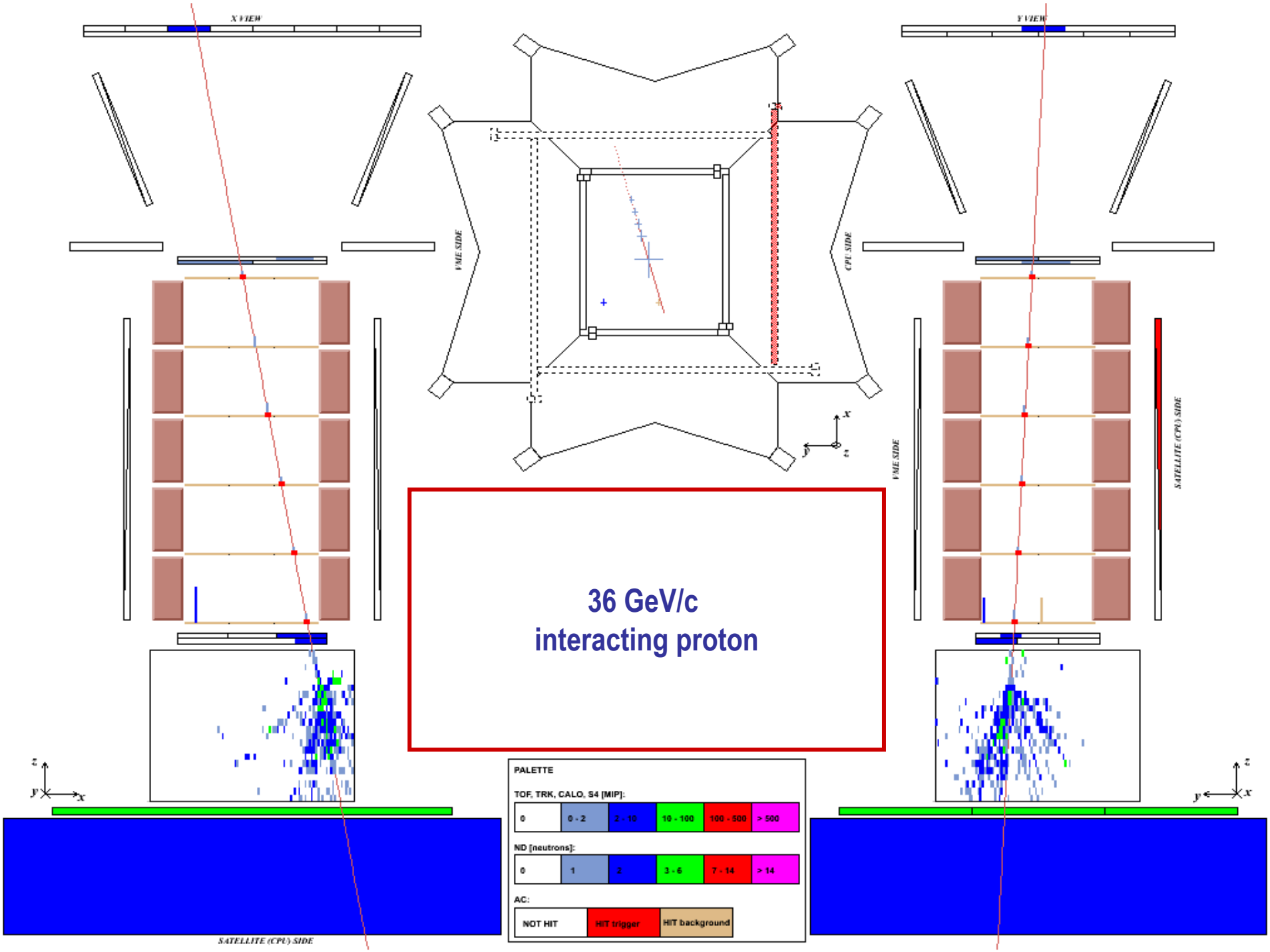
+ NEUTRONS!!

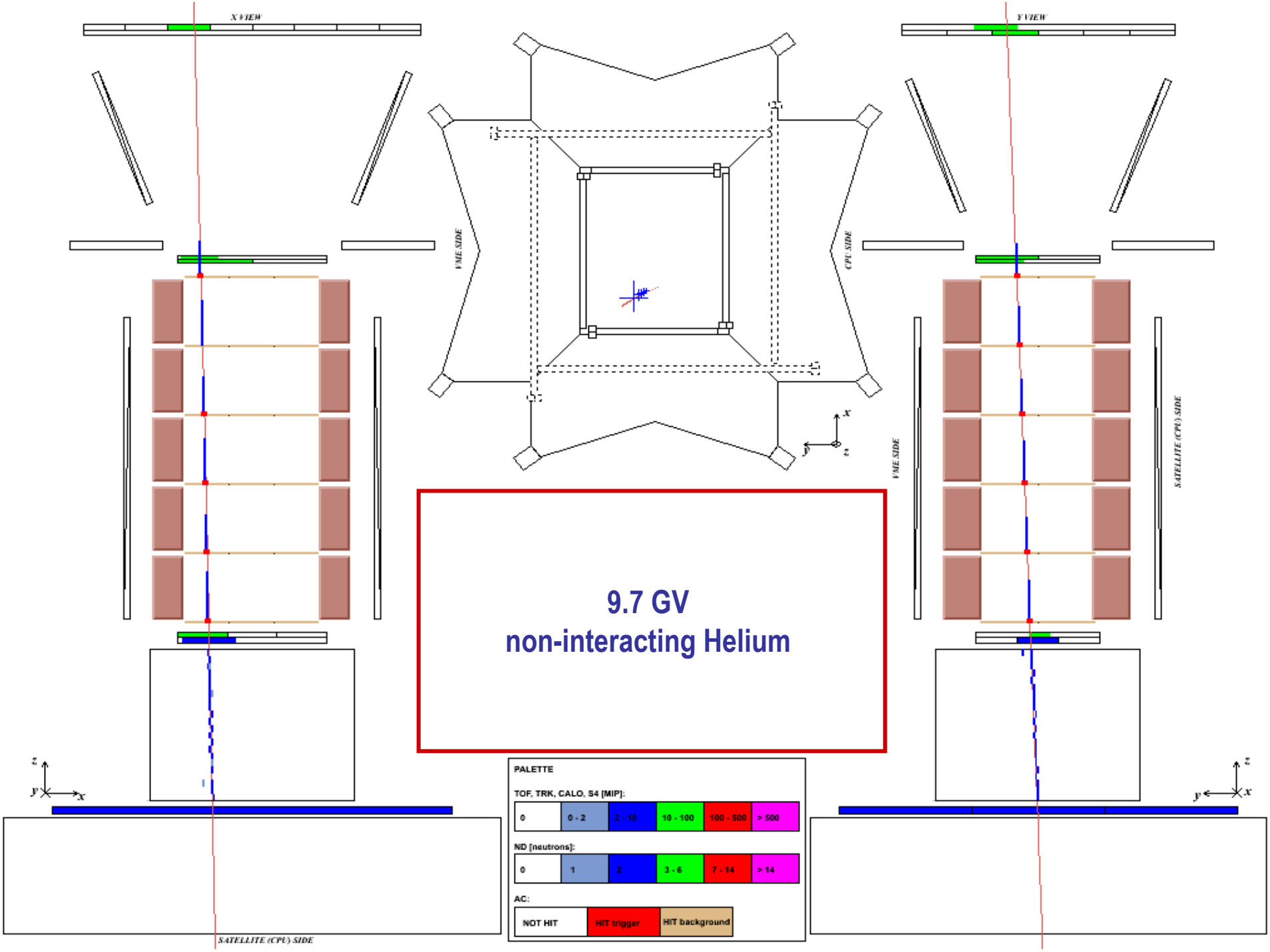
- **Energy measurement of electrons and positrons**

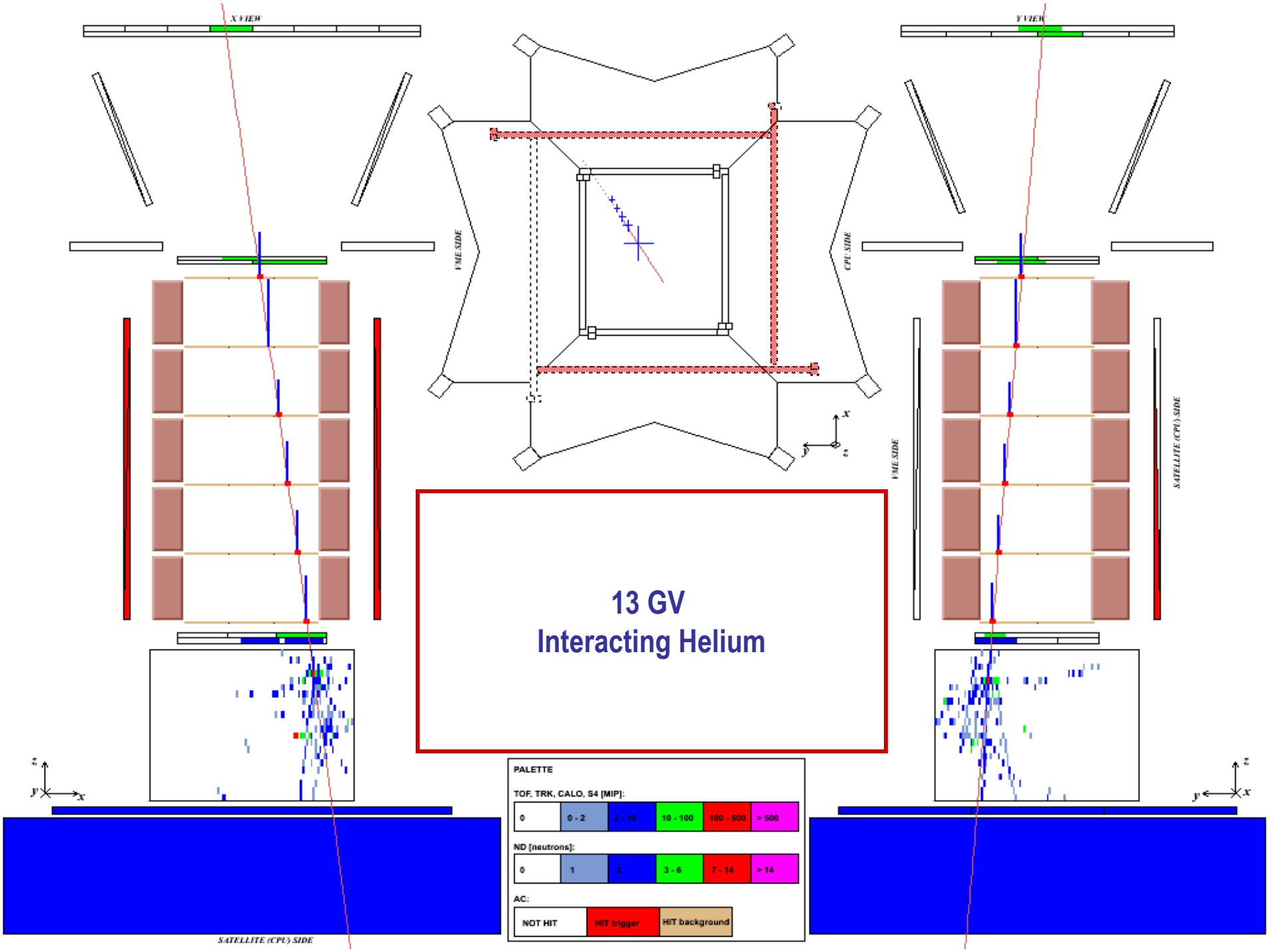
(~full shower containment)

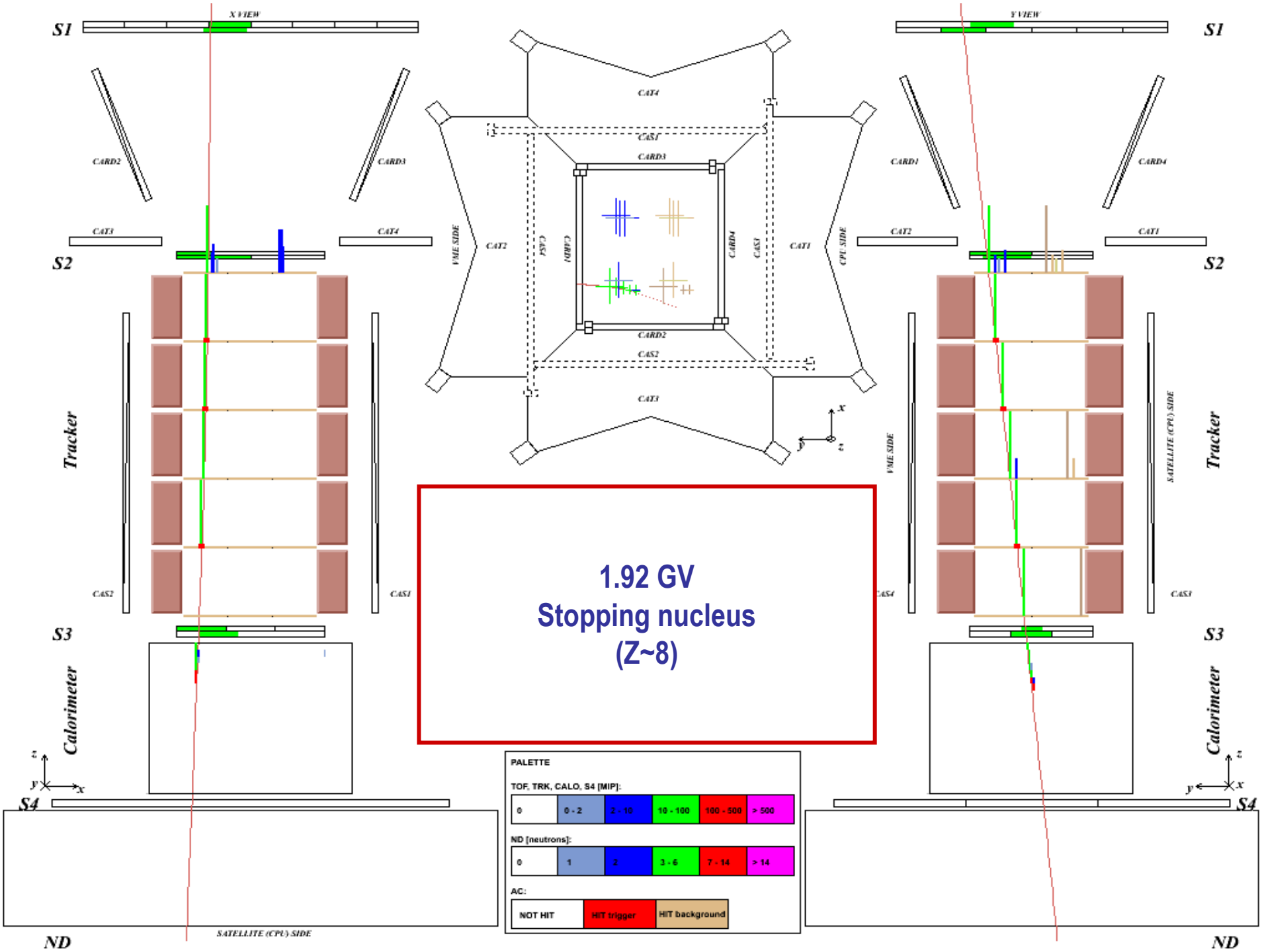
$$\frac{\sigma_E}{E} = a \oplus \frac{b}{\sqrt{E}} \qquad \rightarrow a < 5\%$$

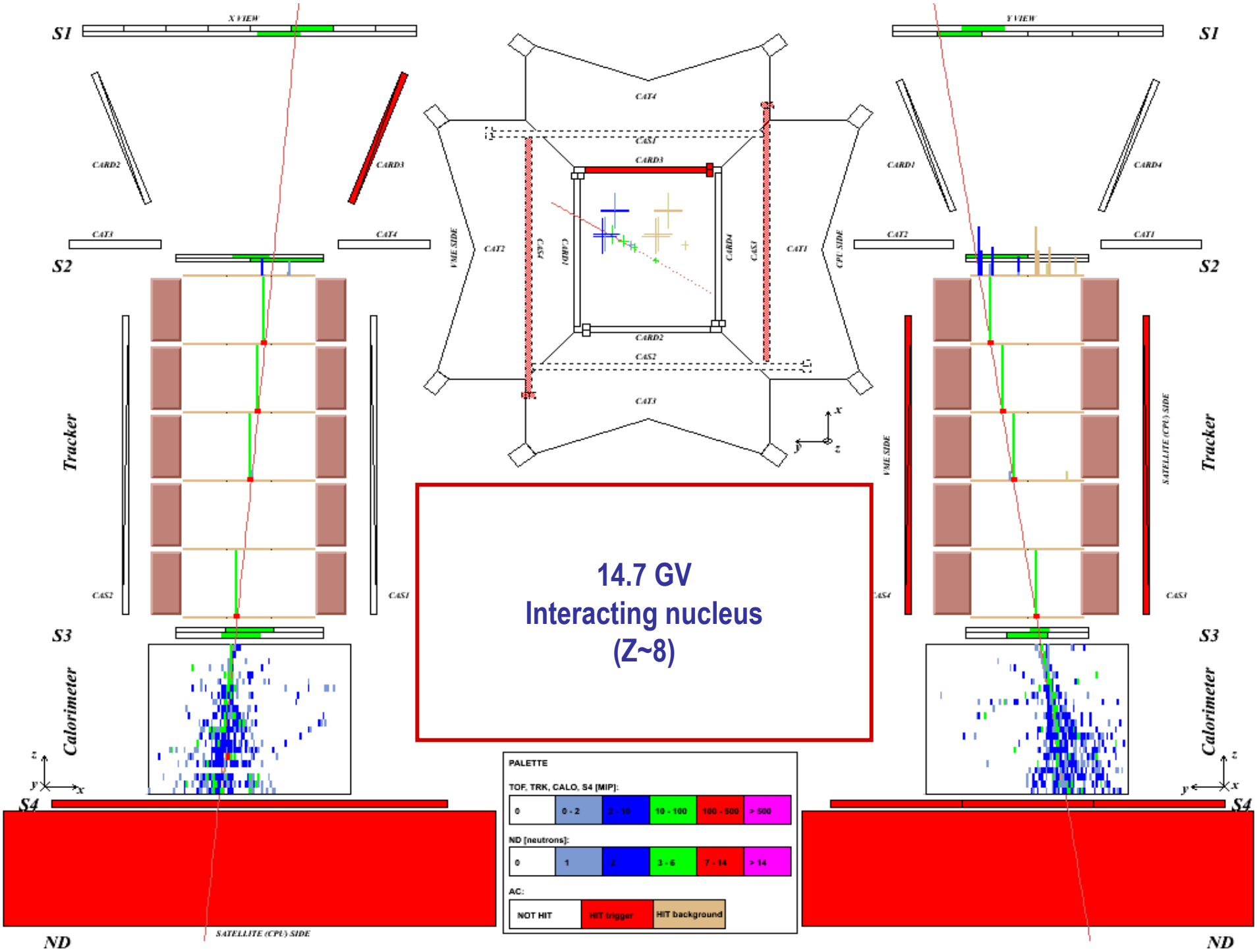

X VIEW
Y VIEW
VME SIDE
CPU SIDE
VME SIDE
SATELLITE (CPU) SIDE
SATELLITE (CPU) SIDE
14.4 GV
non-interacting proton
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background

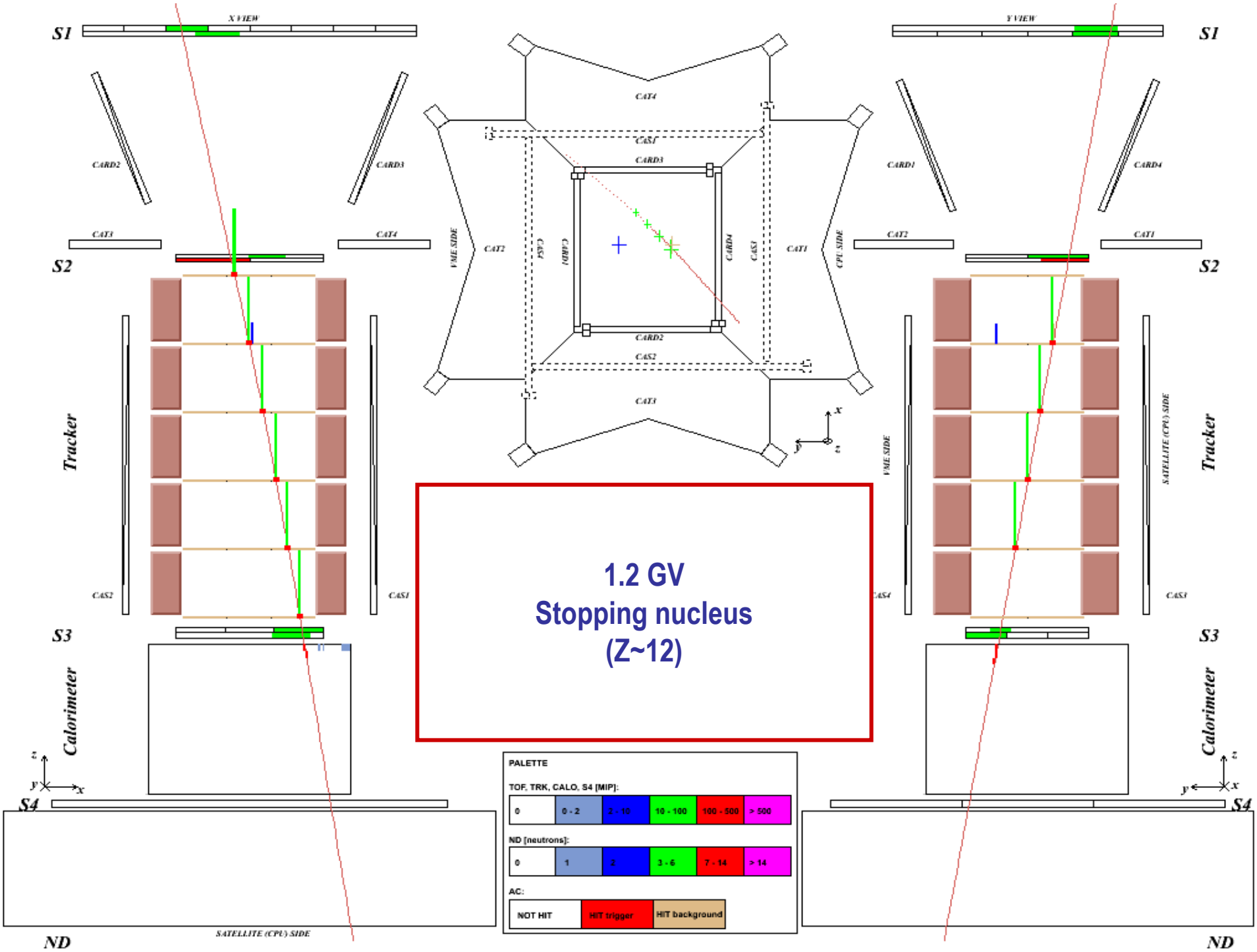

X VIEW
Y VIEW
VME SIDE
CPU SIDE
VME SIDE
SATELLITE (CPU) SIDE
SATELLITE (CPU) SIDE
36 GeV/c
interacting proton
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background


X VIEW
Y VIEW
VME SIDE
CPU SIDE
VME SIDE
SATELLITE (CPU) SIDE
SATELLITE (CPU) SIDE
9.7 GV
non-interacting Helium
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

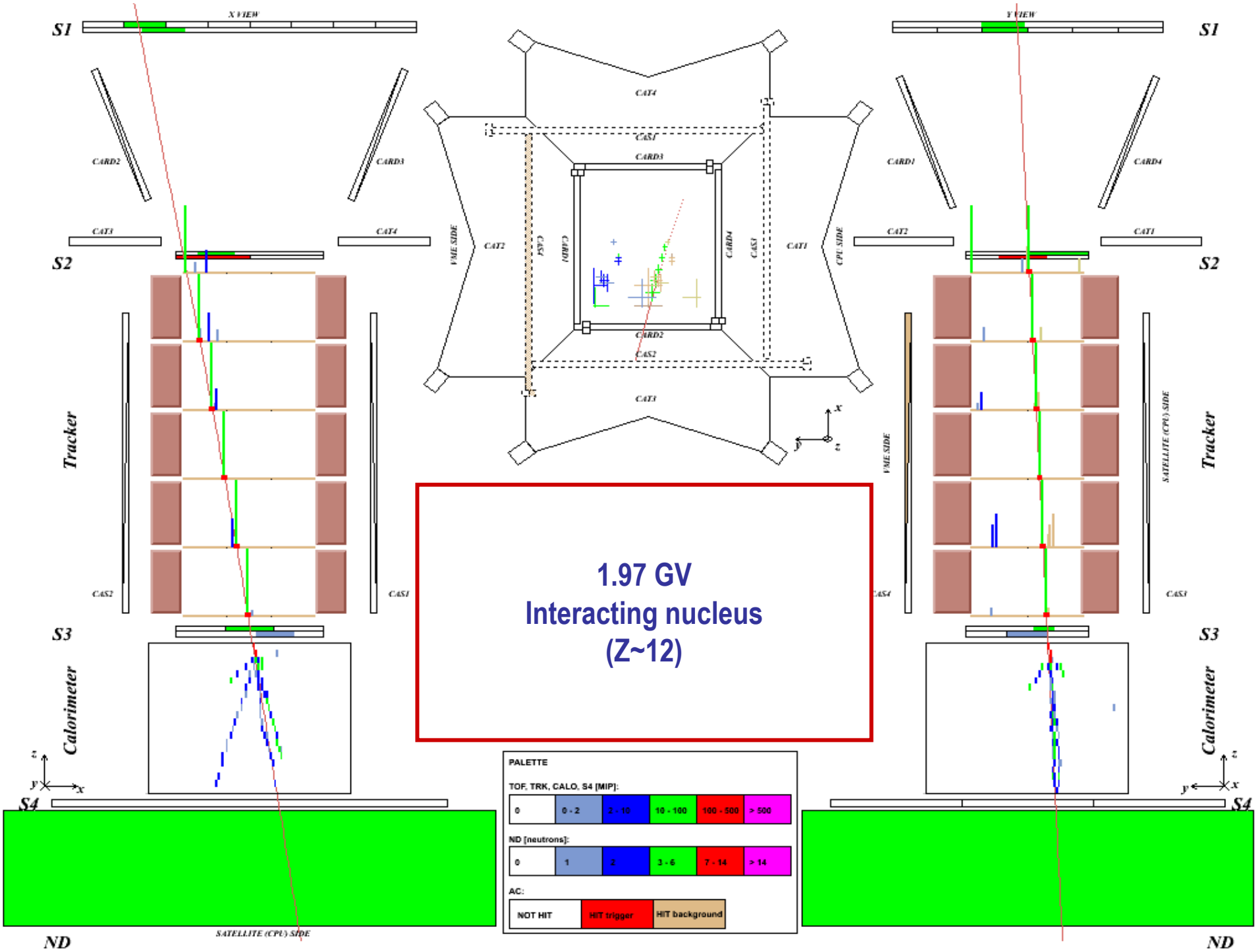

X VIEW
Y VIEW
VME SIDE
CPU SIDE
VME SIDE
SATELLITE (CPU) SIDE
SATELLITE (CPU) SIDE
13 GV
Interacting Helium
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background

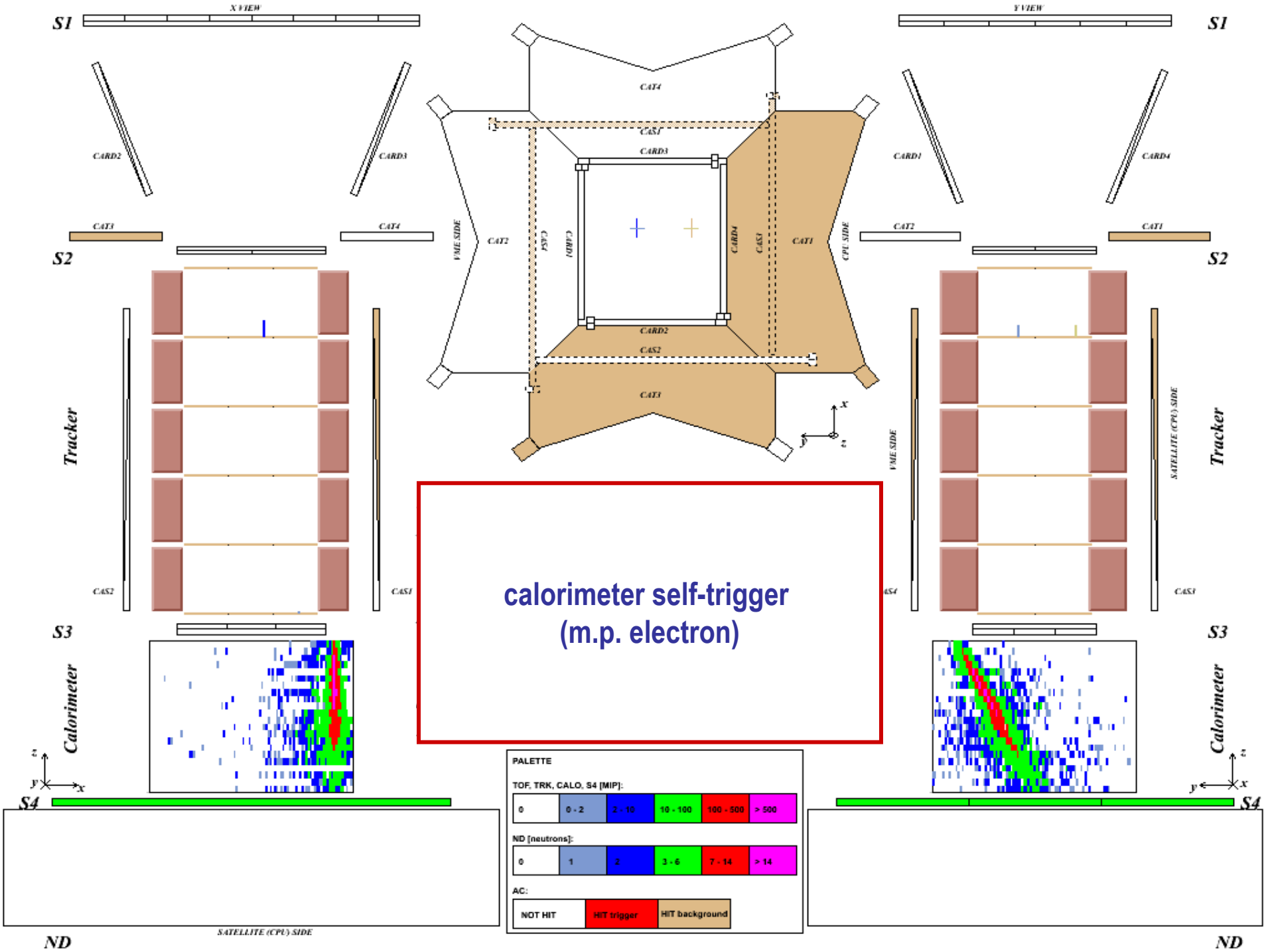

1.92 GV
Stopping nucleus
(Z~8)
S1
S2
S3
S4
ND
X VIEW
Y VIEW
Tracker
Calorimeter
CARD1
CARD2
CARD3
CARD4
CAT1
CAT2
CAT3
CAT4
CAS1
CAS2
CAS3
CAS4
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT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

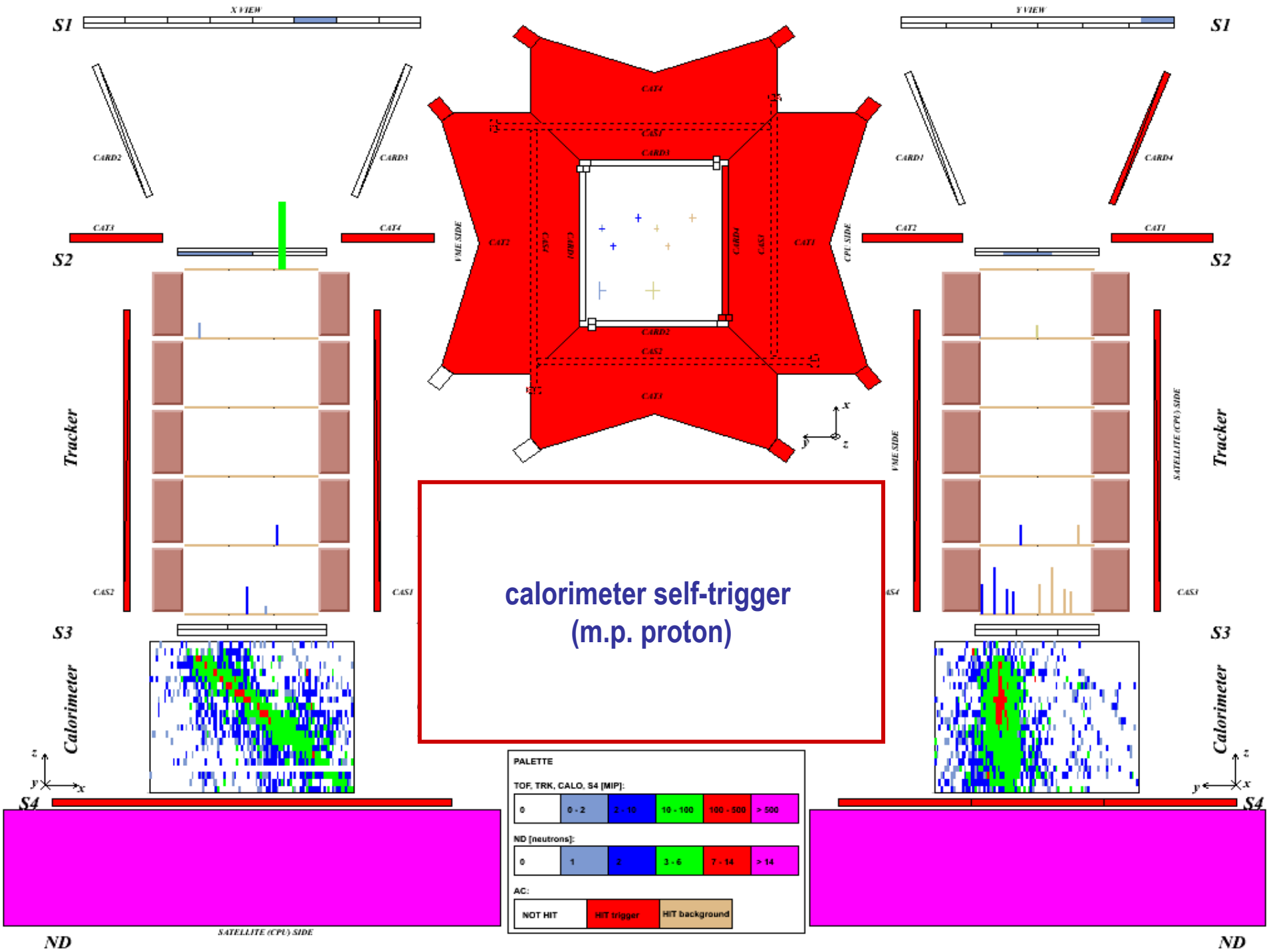

S1
X VIEW
Y VIEW
CARD2
CARD3
CARD1
CARD4
CAT3
CAT4
CAT2
CAT1
S2
Tracker
CAS2
CAS1
CAS4
CAS3
S3
Calorimeter
S4
ND
SATELLITE (CPU) SIDE
VME SIDE
CPU SIDE
CAT4
CAS1
CARD3
CARD2
CAS2
CAT3
14.7 GV
Interacting nucleus
(Z~8)
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]: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



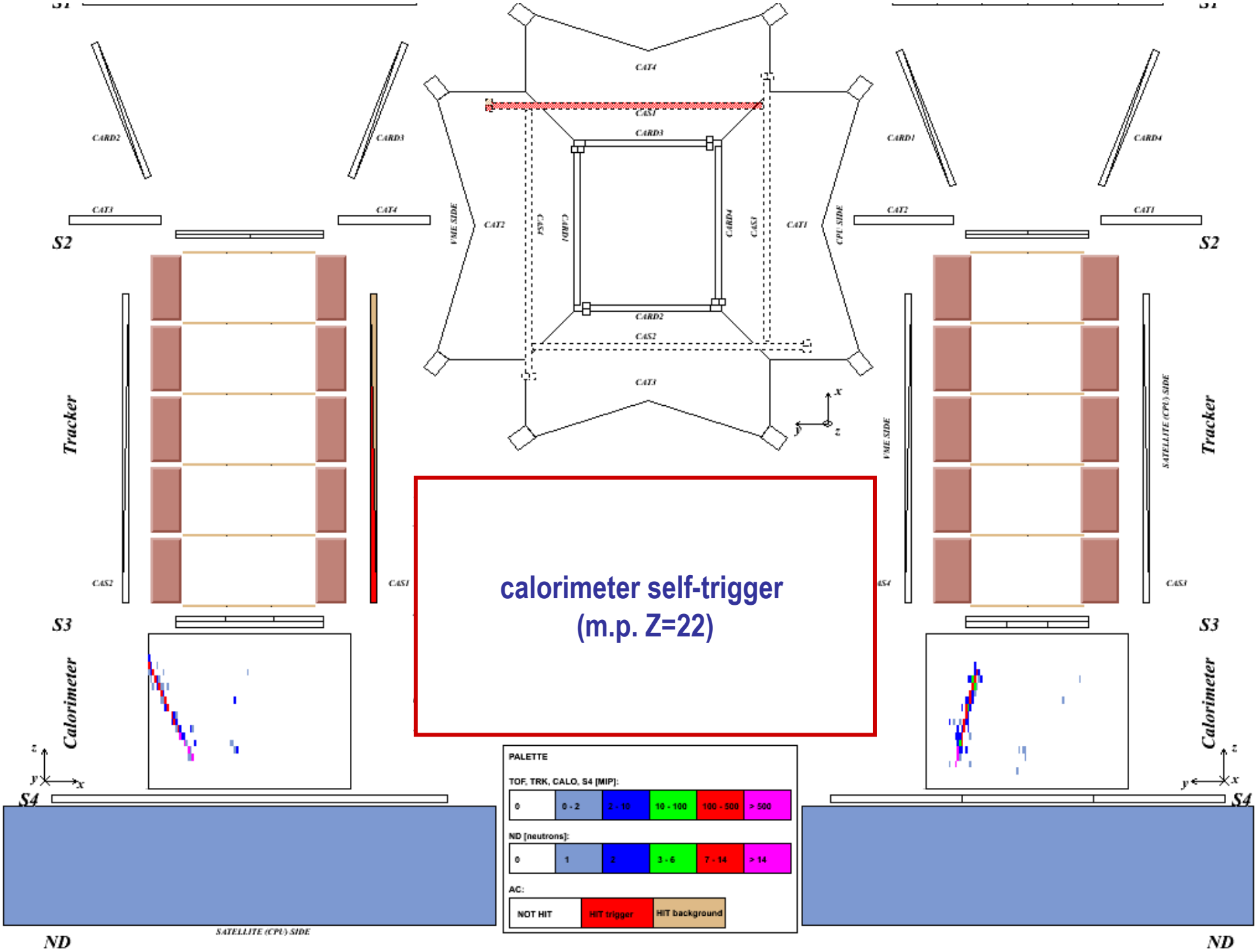
1.2 GV
Stopping nucleus
(Z~12)

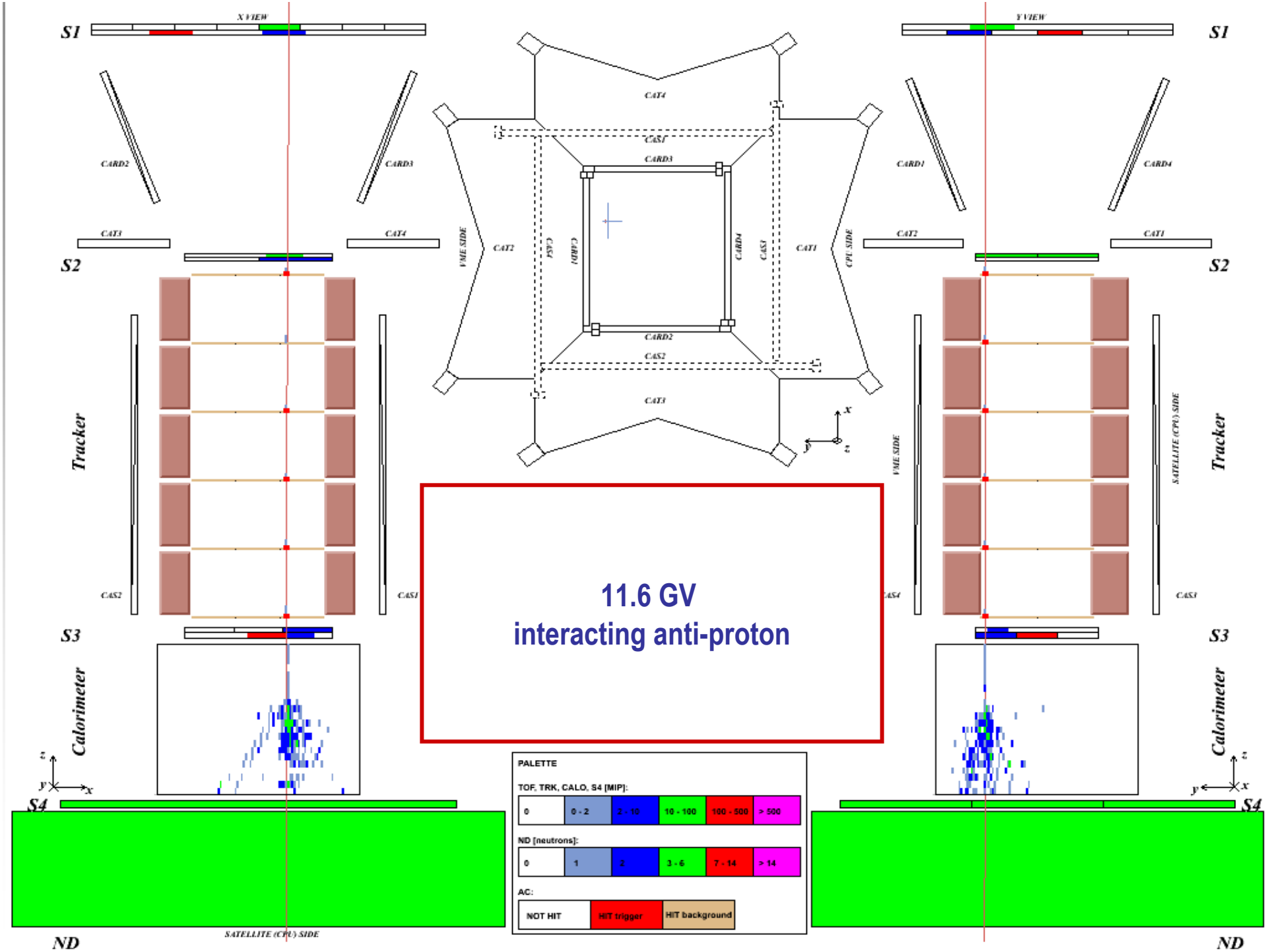

S1
X VIEW
Y VIEW
S1
CARD2
CARD3
CARD1
CARD4
CAT3
CAT4
CAT2
CAT1
S2
S2
Tracker
Tracker
CAS2
CAS1
CAS4
CAS3
S3
S3
Calorimeter
Calorimeter
S4
S4
ND
ND
SATELLITE (CPU) SIDE
VME SIDE
CAT4
CAS1
CARD3
CARD2
CAS2
CAT3
1.97 GV
Interacting nucleus
(Z~12)
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background

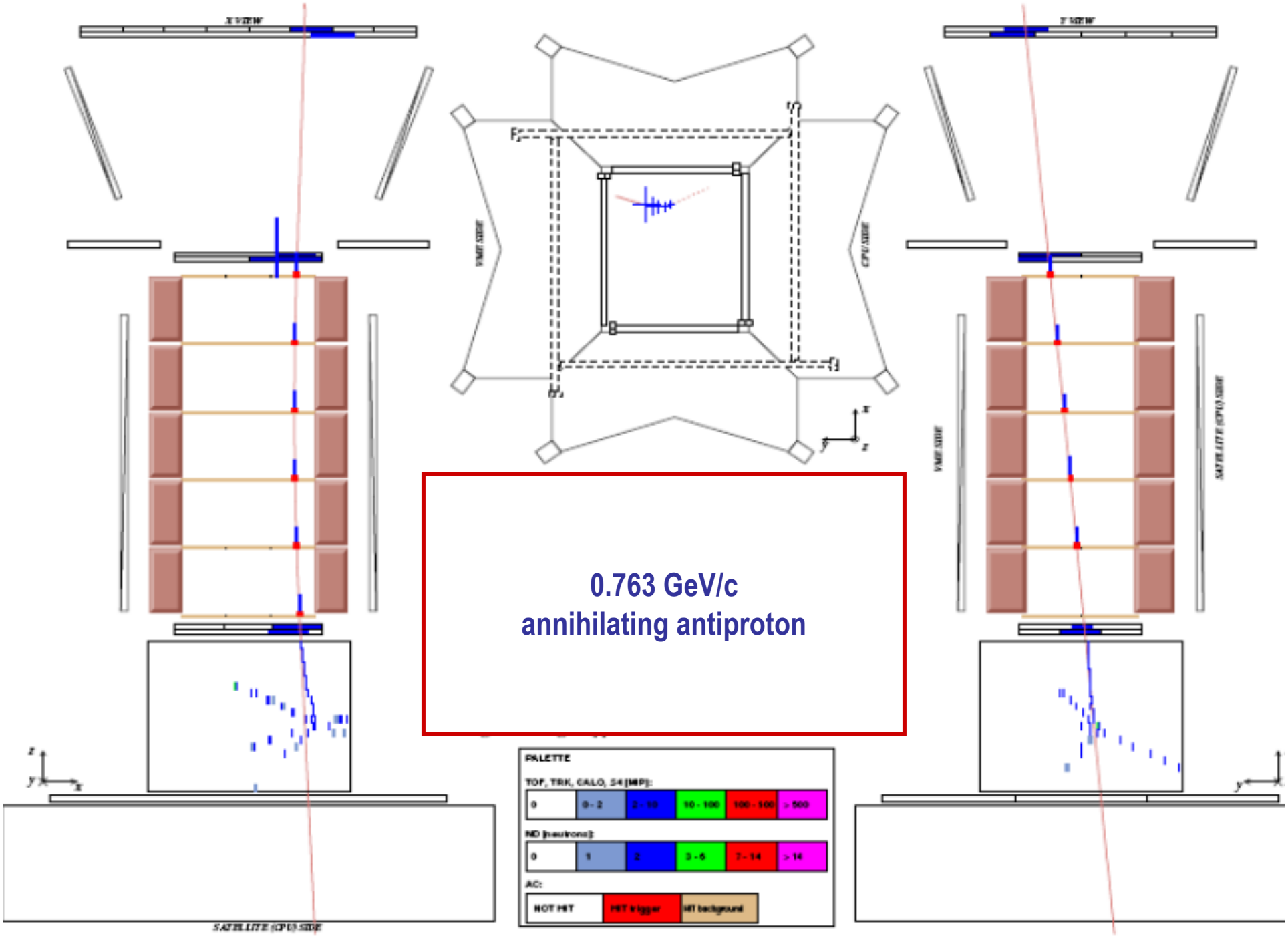

S1
X VIEW
Y VIEW
CARD2
CARD3
CARD1
CARD4
CAT3
CAT4
CAT2
CAT1
S2
VME SIDE
CPU SIDE
CAS4
CARD0
CAS1
CAS2
CAS3
Tracker
SATELLITE (CPU) SIDE
S3
Calorimeter
S4
ND
SATELLITE (CPU) SIDE
calorimeter self-trigger
(m.p. electron)
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background



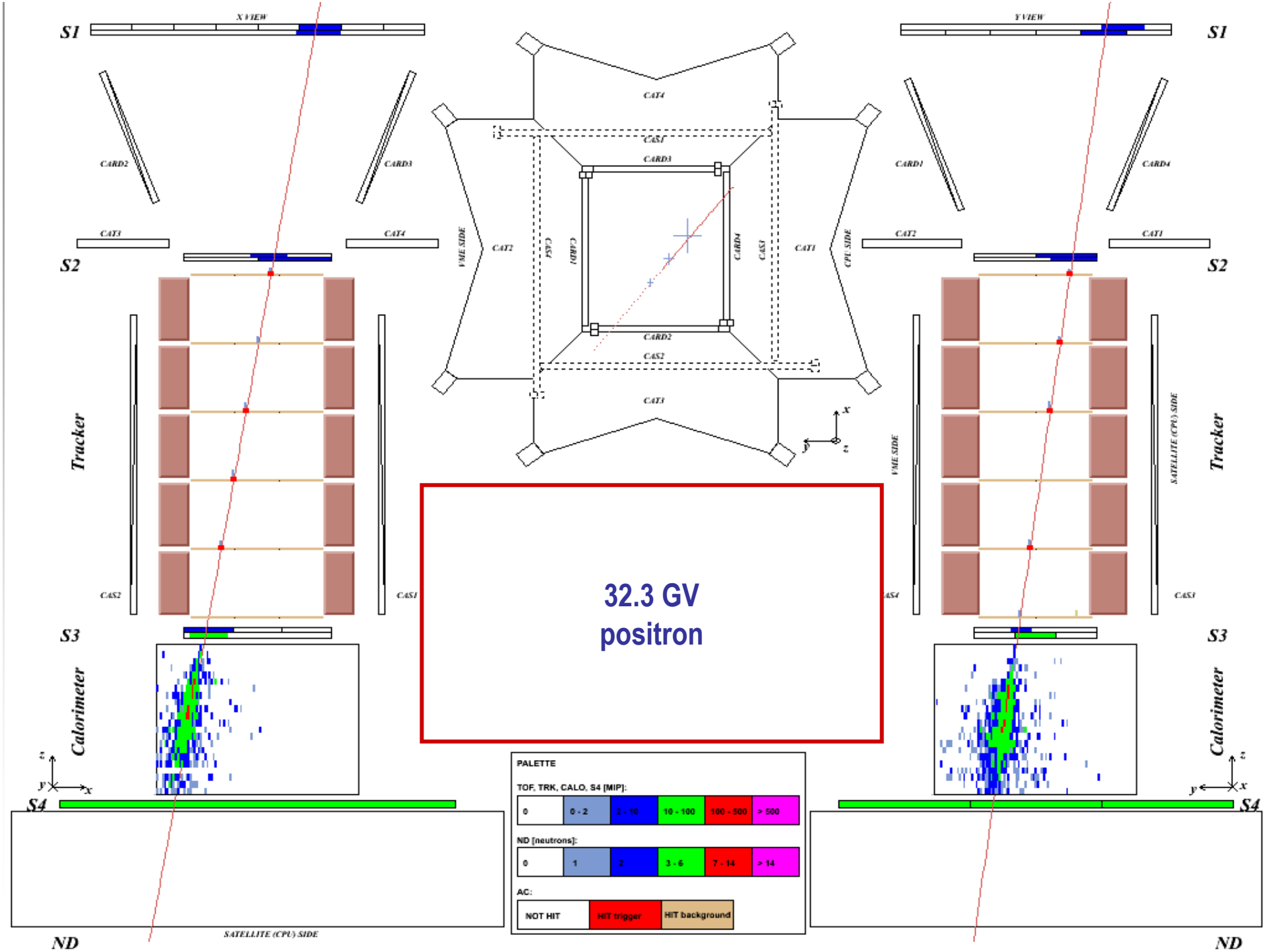
calorimeter self-trigger
(m.p. proton)


S1
S2
S3
S4
ND
Tracker
Calorimeter
CARD1
CARD2
CARD3
CARD4
CAT1
CAT2
CAT3
CAT4
CAS1
CAS2
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
calorimeter self-trigger
(m.p. Z=22)
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


S1
X VIEW
Y VIEW
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
11.6 GV
interacting anti-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



0.763 GeV/c
annihilating antiproton


S1
X VIEW
Y VIEW
CARD1
CARD2
CARD3
CARD4
CAT1
CAT2
CAT3
CAT4
CAS1
CAS2
CAS3
CAS4
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
S2
Tracker
S3
Calorimeter
S4
ND
32.3 GV
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

PAMELA design performance

Magnetic curvature & trigger

spillover

shower containment

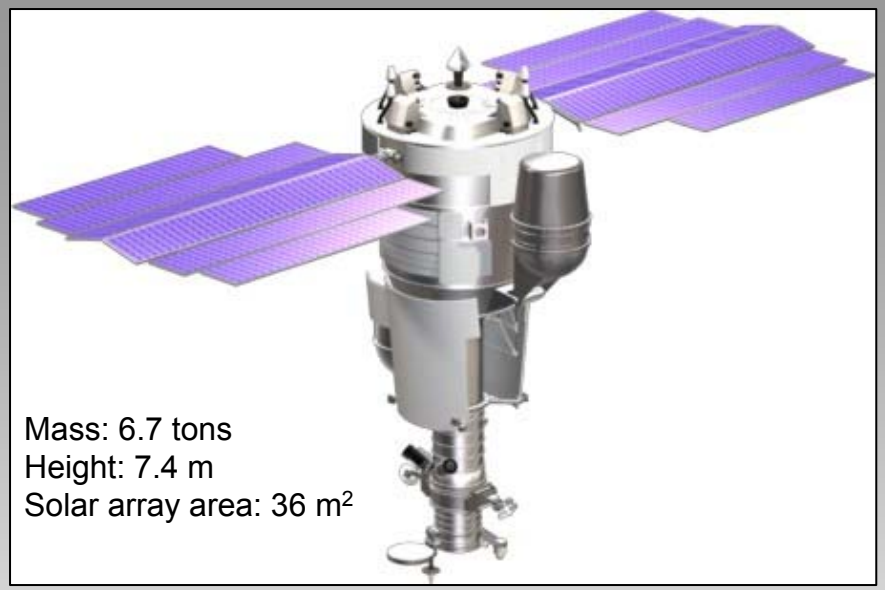
Maximum detectable rigidity (MDR)

	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: $O(10^{7/4/5})$
Anti-Nuclei search	sensitivity of 3×10^{-8} in anti-He/He	

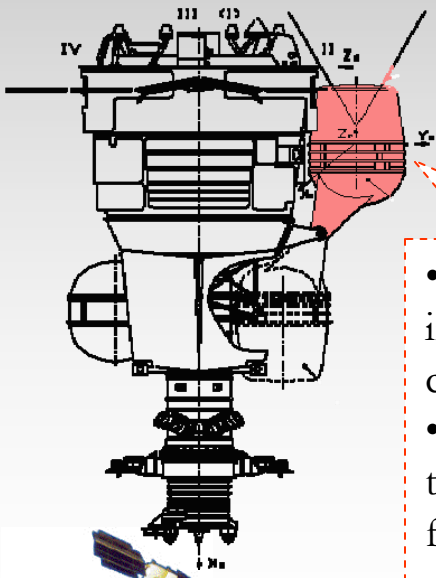
→ **Unprecedented statistics and new energy range for cosmic ray physics**
(e.g. contemporary antiproton and positron maximum energy ~ 40 GeV)

→ **Simultaneous measurements of many species**

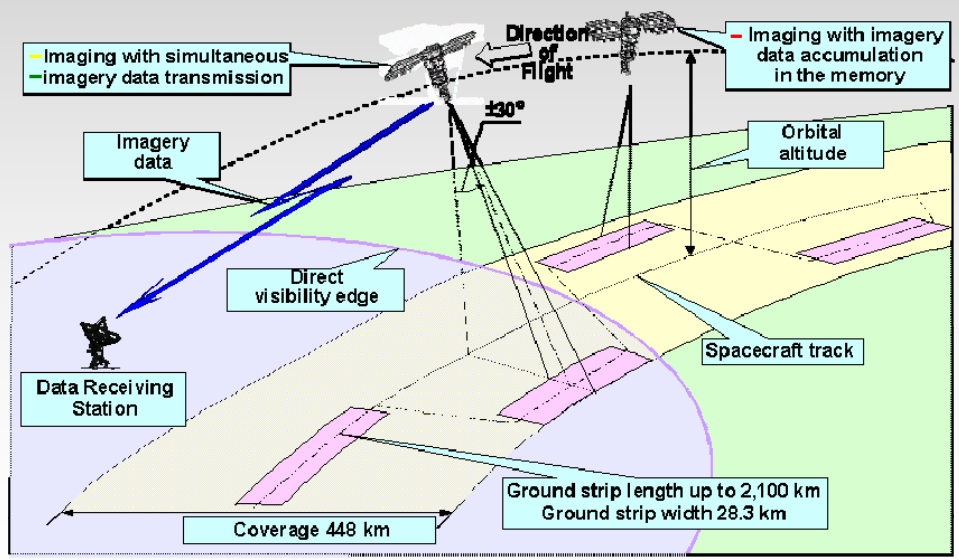
The Resurs DK-1 spacecraft



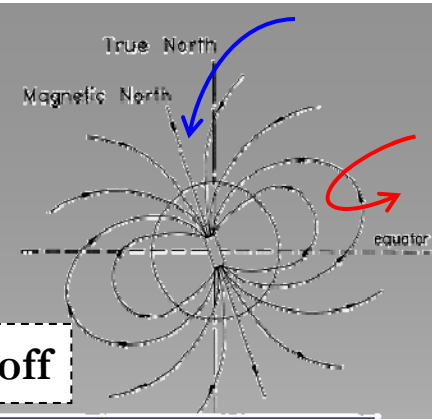
- Multi-spectral remote sensing of earth's surface
  -near-real-time high-quality images
- Built by the Space factory TsSKB Progress in Samara (Russia)
- **Operational orbit parameters:**
  -inclination ~70°
  -altitude ~ 360-600 km (elliptical)
- **Active life >3 years**
- Data transmitted via Very high-speed Radio Link (VRL)



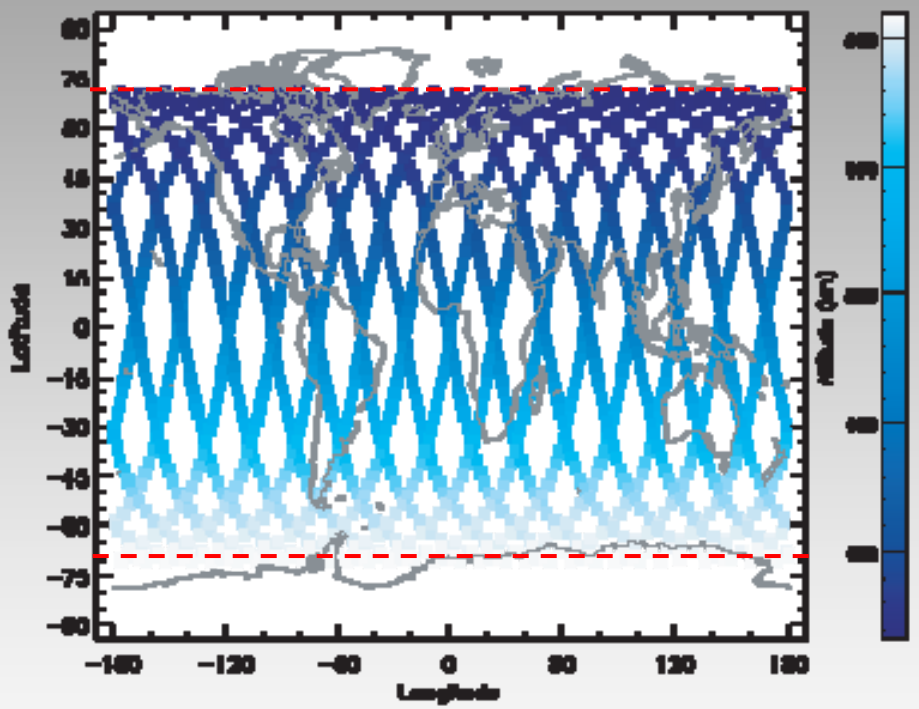
- PAMELA mounted inside a pressurized container
- moved from parking to data-taking position few times/year



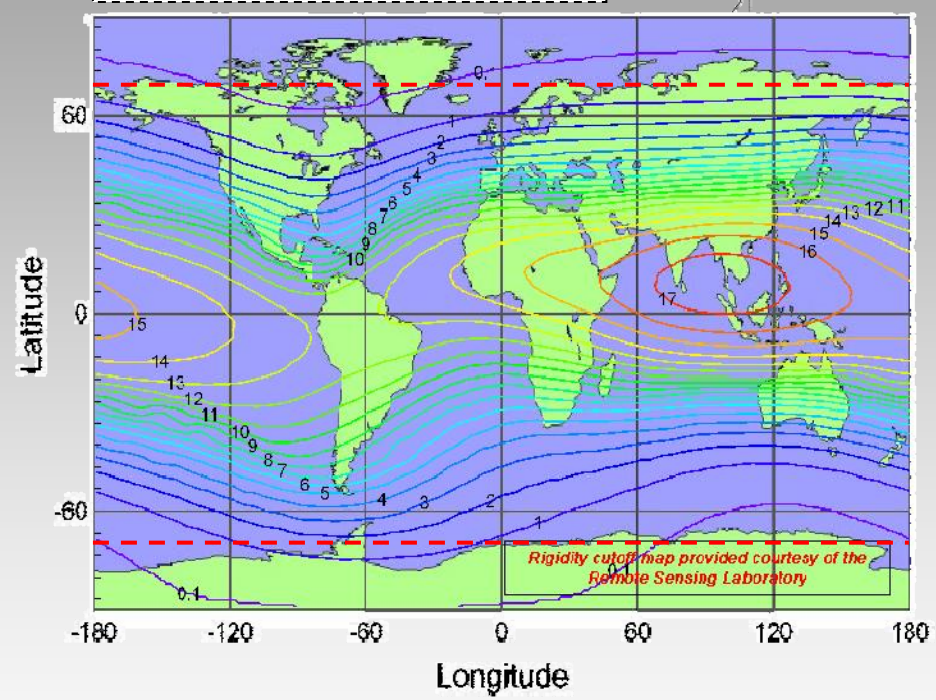
Satellite orbit



PAMELA orbit
inclination ~70°
altitude ~ 360-600 km

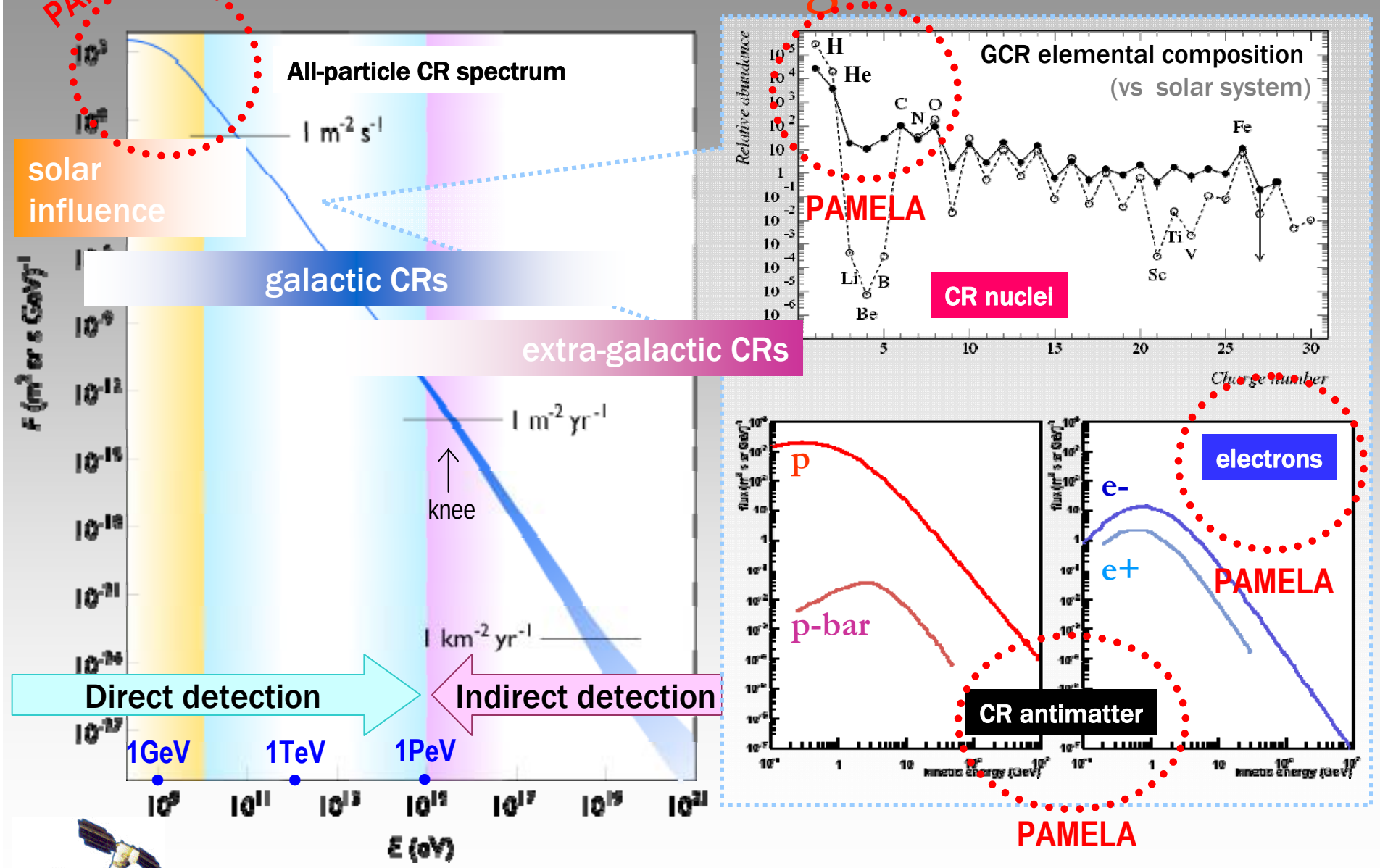


Vertical rigidity cutoff

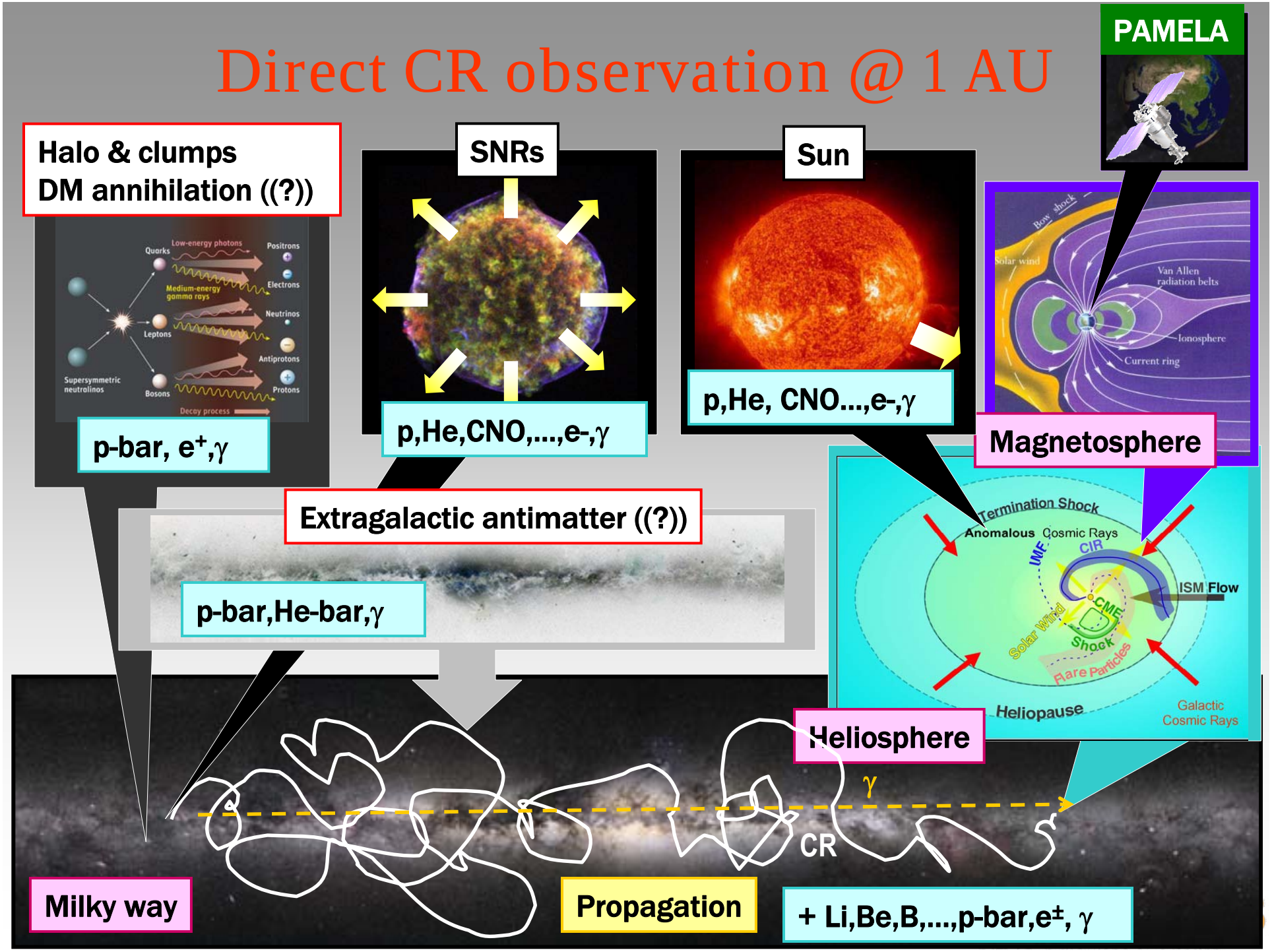


→ the quasi-polar orbit allows to study low-energy cosmic rays (R>100MV)

Direct detection of galactic CRs



Direct CR observation @ 1 AU

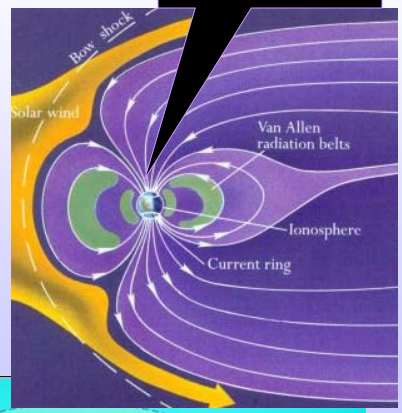


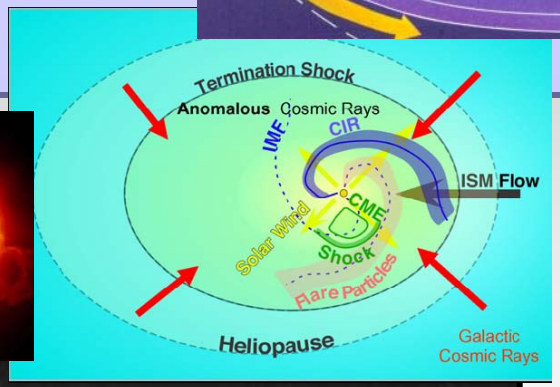
PAMELA science

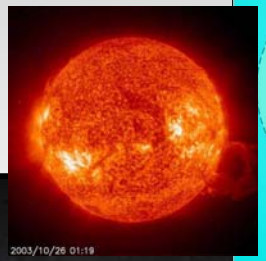
- **Search for dark matter**
- **Search for primordial antimatter**

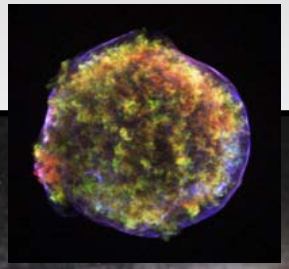
… but also:

- Study of cosmic-ray origin and propagation
- Study of solar physics and solar modulation
- Study of terrestrial magnetosphere









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

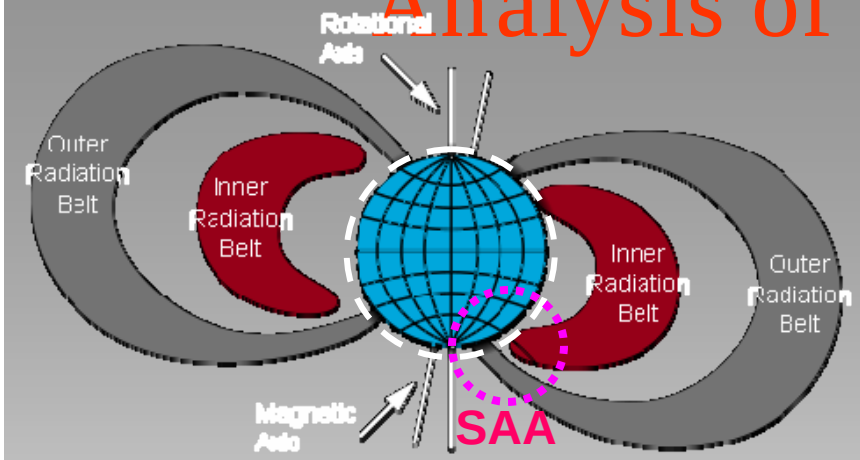
→ **PAMELA in continuous data-taking mode since commissioning phase ended on July 11th 2006**

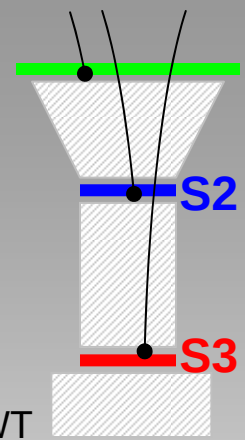
Main antenna in NTsOMZ

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)

Till May 2008:
~500 days of data taking
~10 TByte of raw data downlinked
~$12 \cdot 10^8$ triggers recorded and analysed
(Data from May till now under analysis)

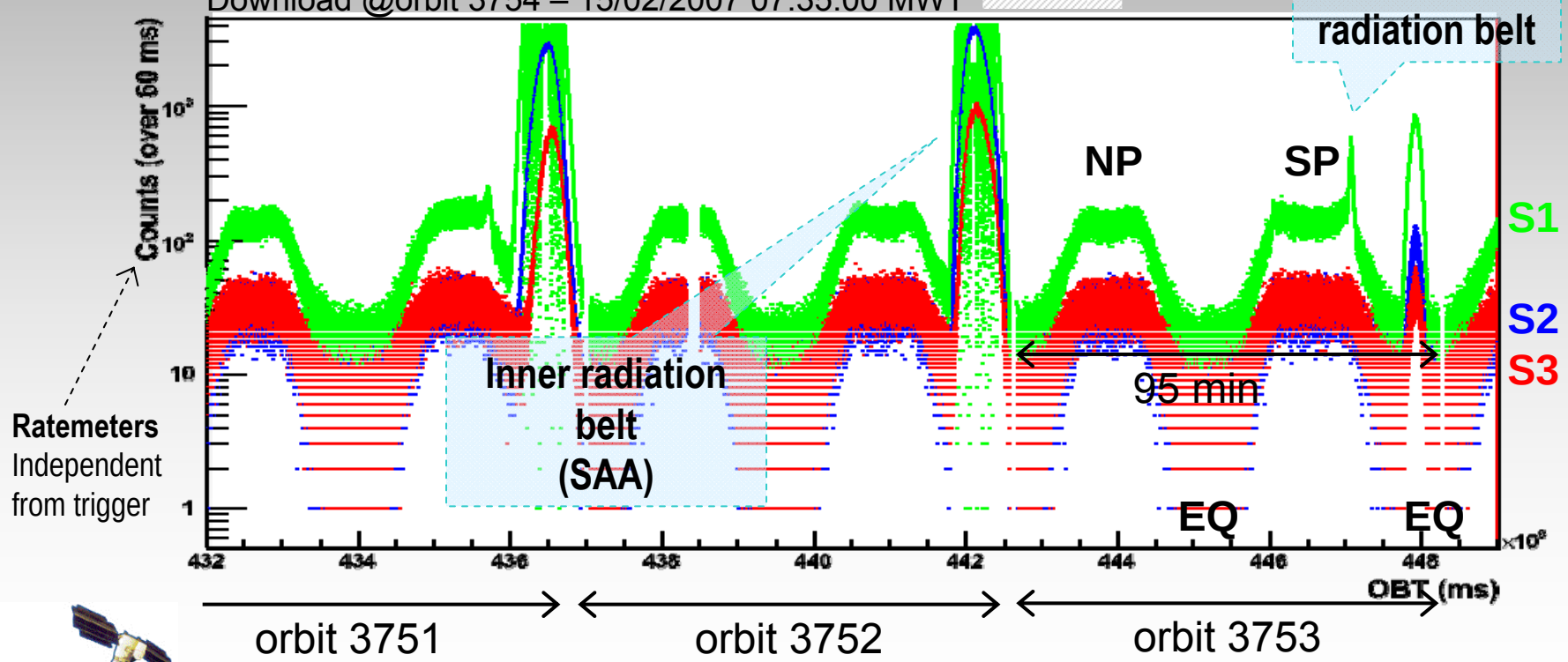
Analysis of a PAMELA orbit



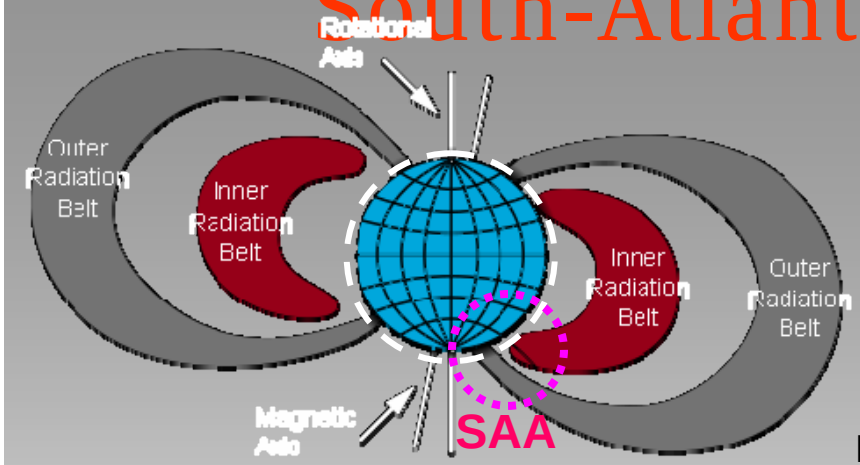


Low energy particles stops inside the apparatus
⇒ Counting rates: S1>S2>S3

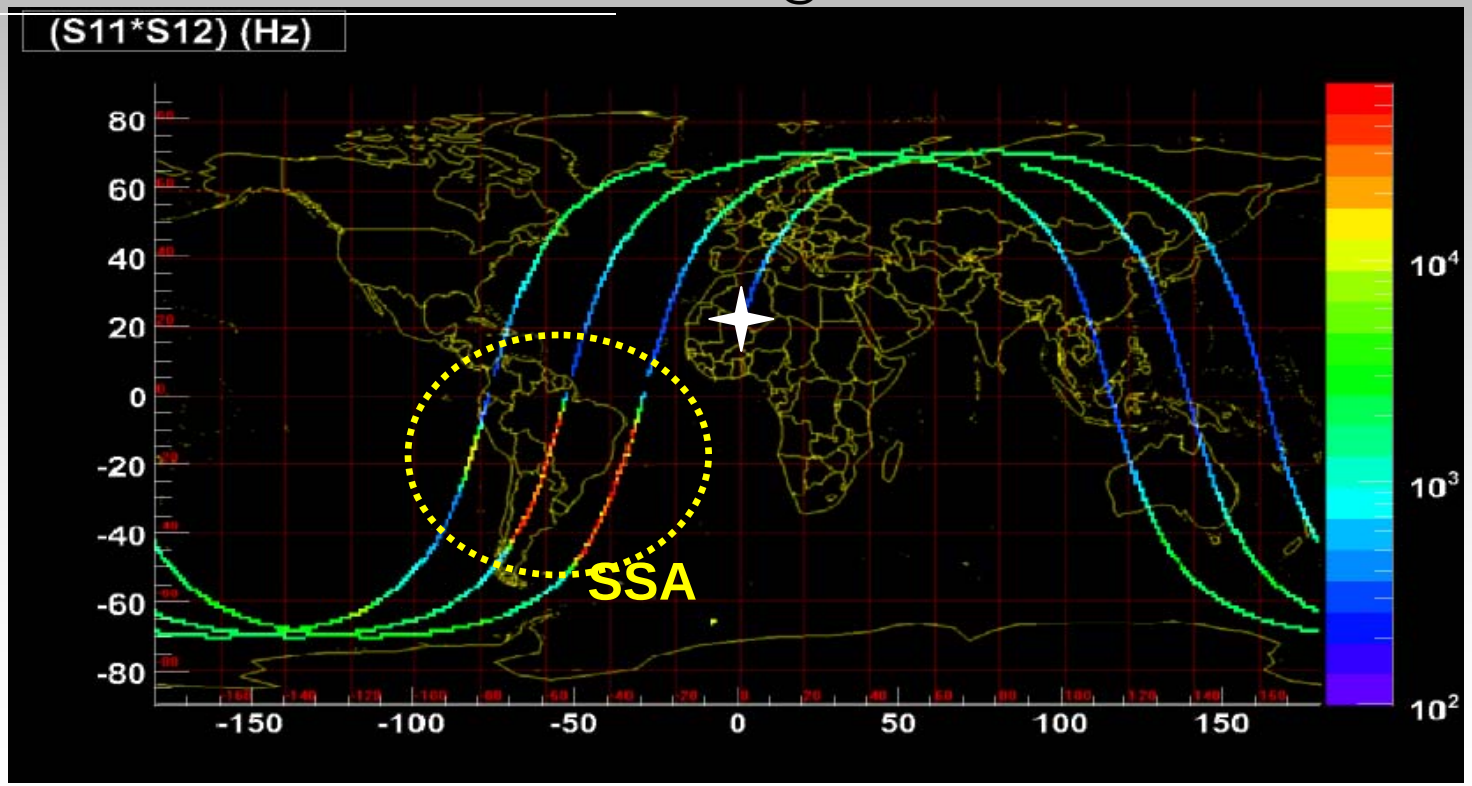
Download @orbit 3754 – 15/02/2007 07:35:00 MWT



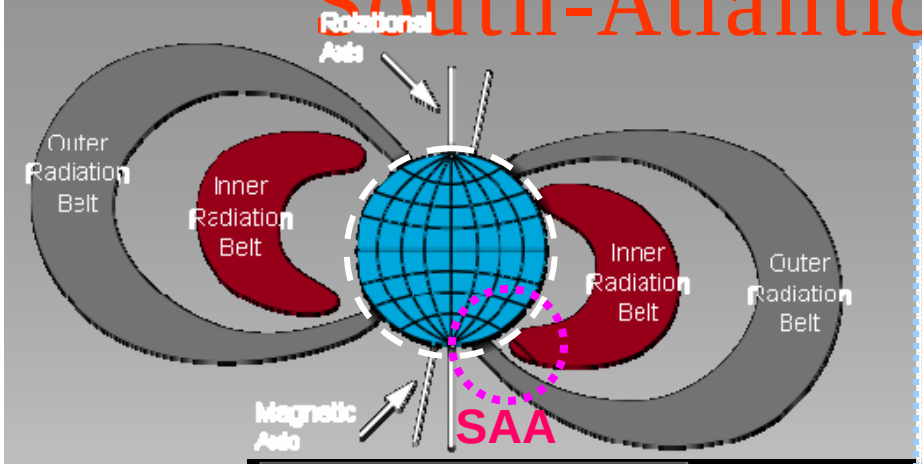
South-Atlantic Anomaly (SAA)

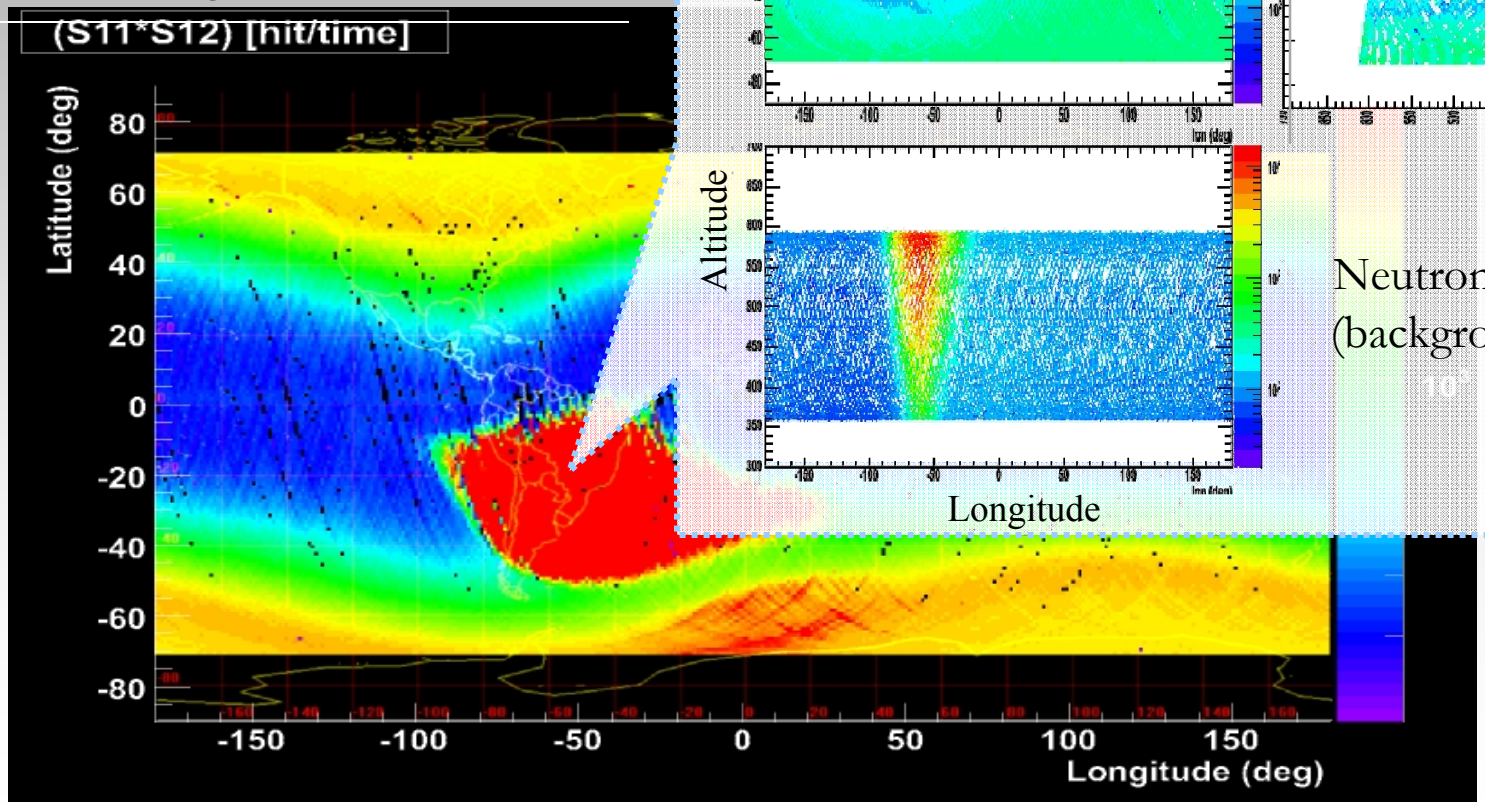


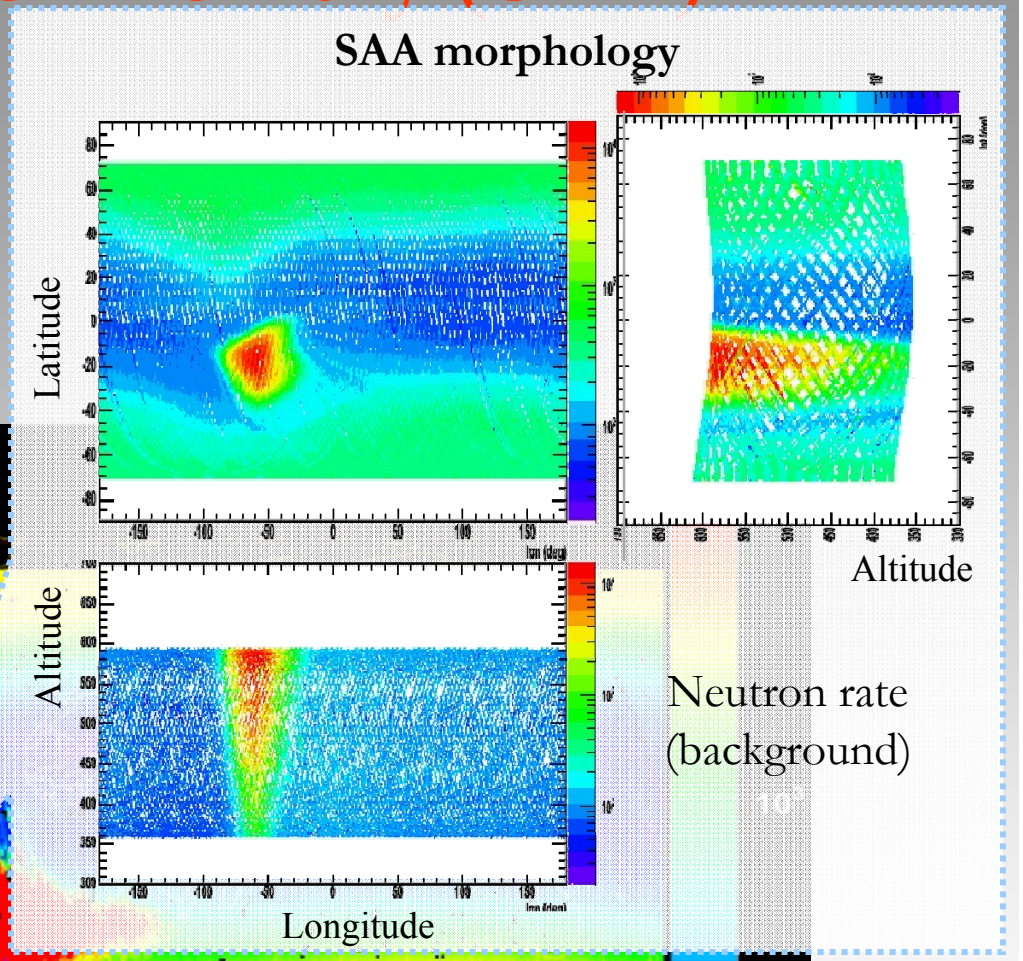
Download @orbit 3754 – 15/02/2007 07:35:00 MWT



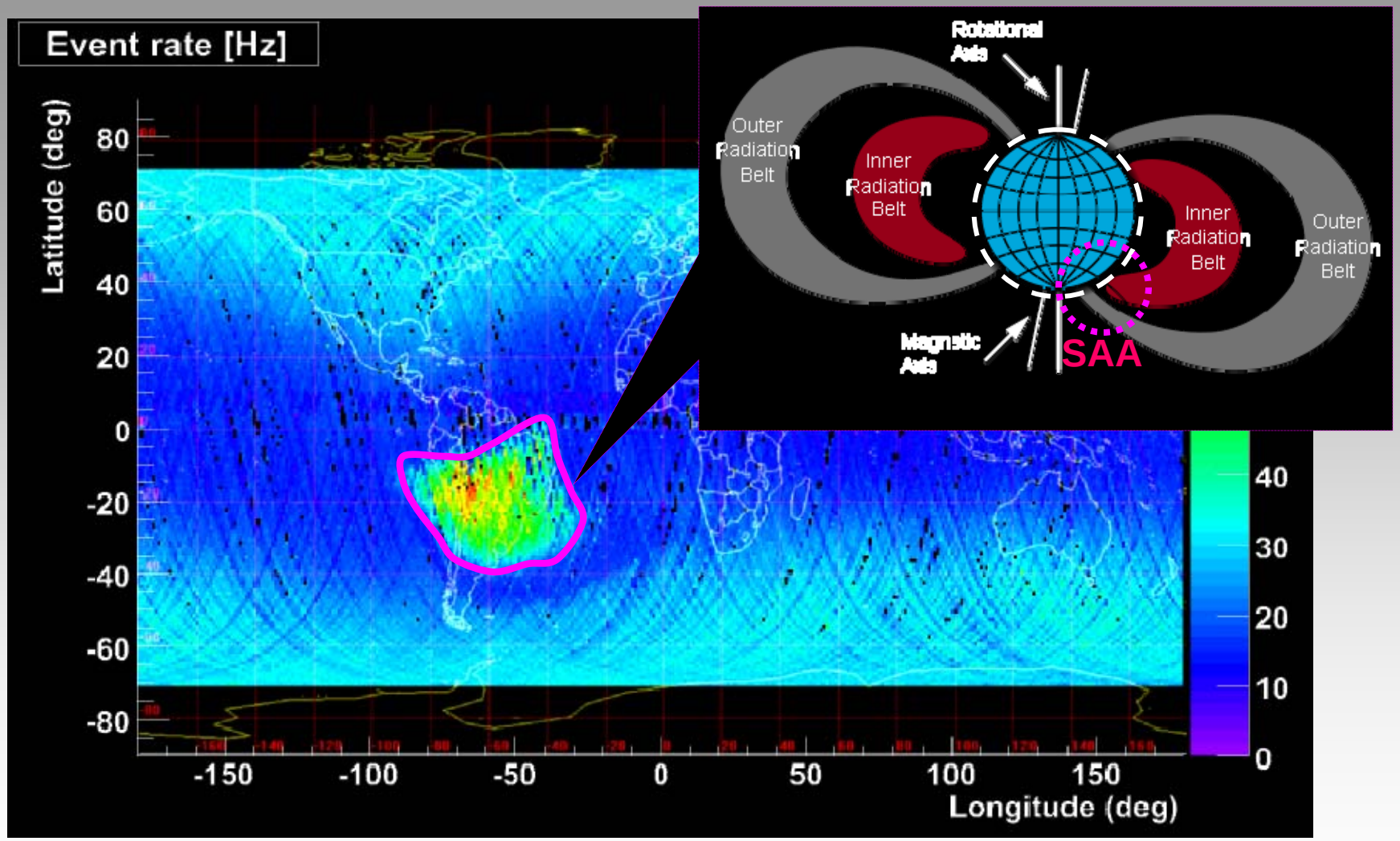
South-Atlantic Anomaly (SAA)



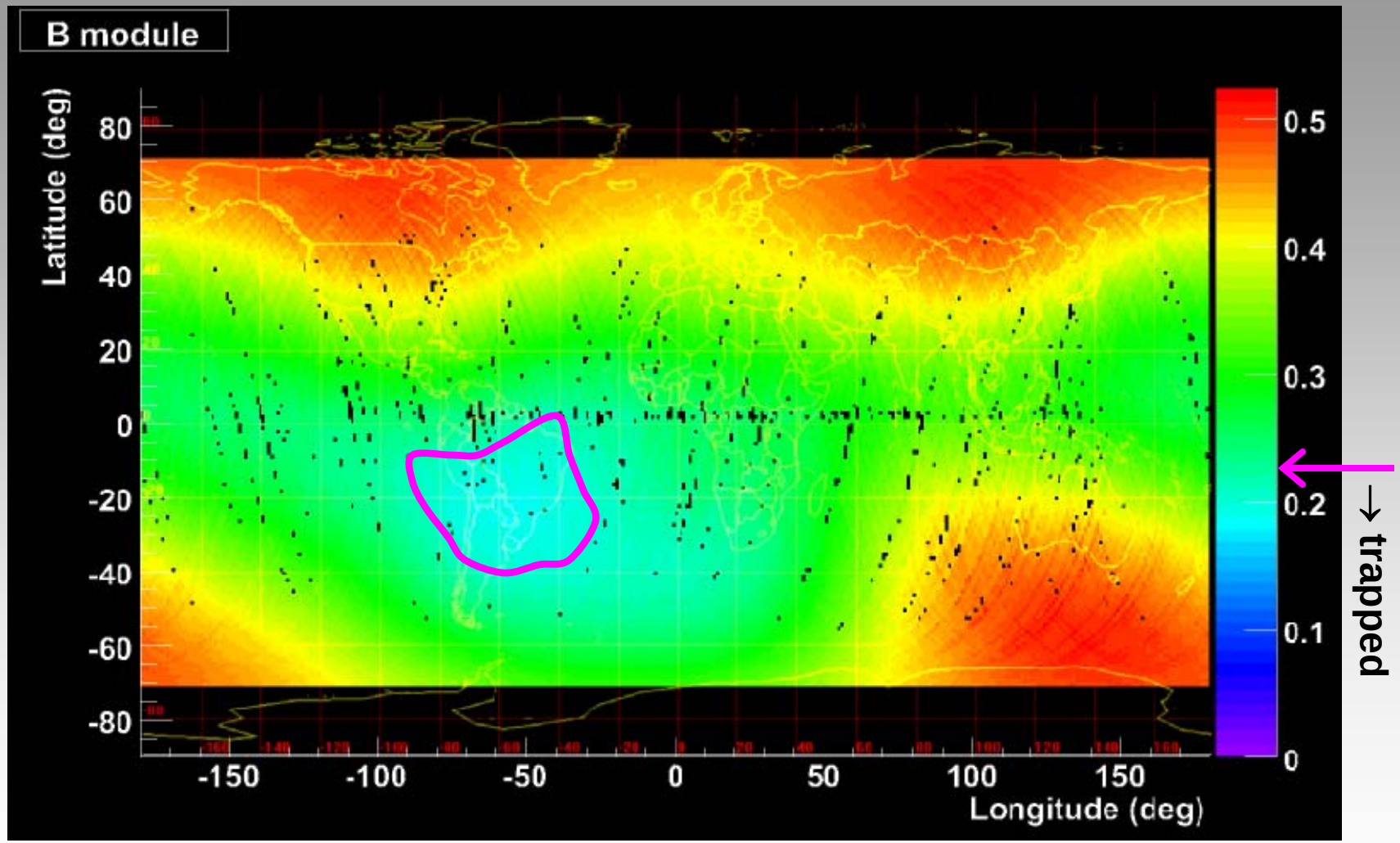




Trigger rate



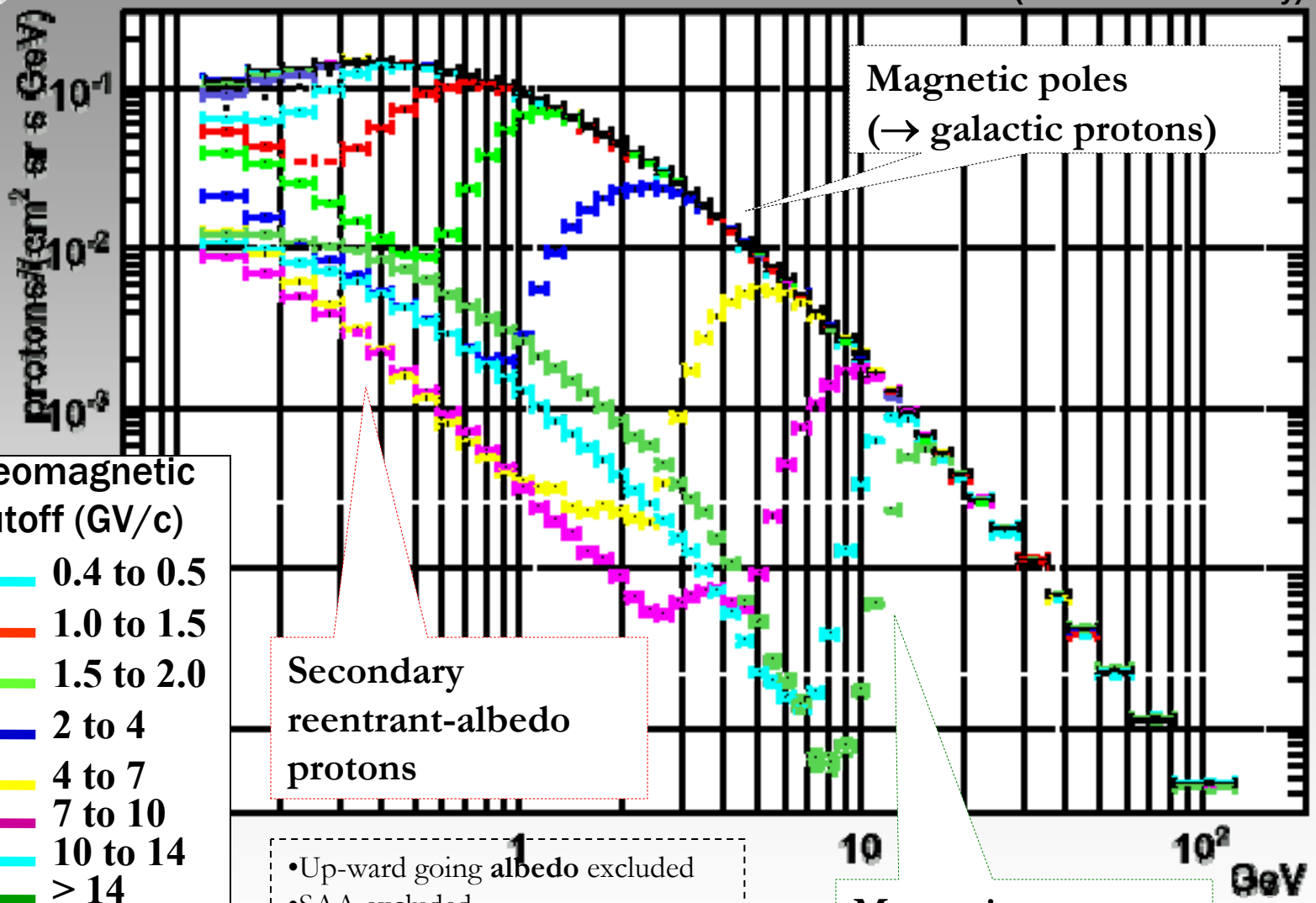
Magnetic Field (IGRF)



Geomagnetic cutoff

Preliminary!!

(statistical errors only)



Magnetic poles
(→ galactic protons)

Geomagnetic cutoff (GV/c)
- 0.4 to 0.5
- 1.0 to 1.5
- 1.5 to 2.0
- 2 to 4
- 4 to 7
- 7 to 10
- 10 to 14
- > 14

Secondary reentrant-albedo protons

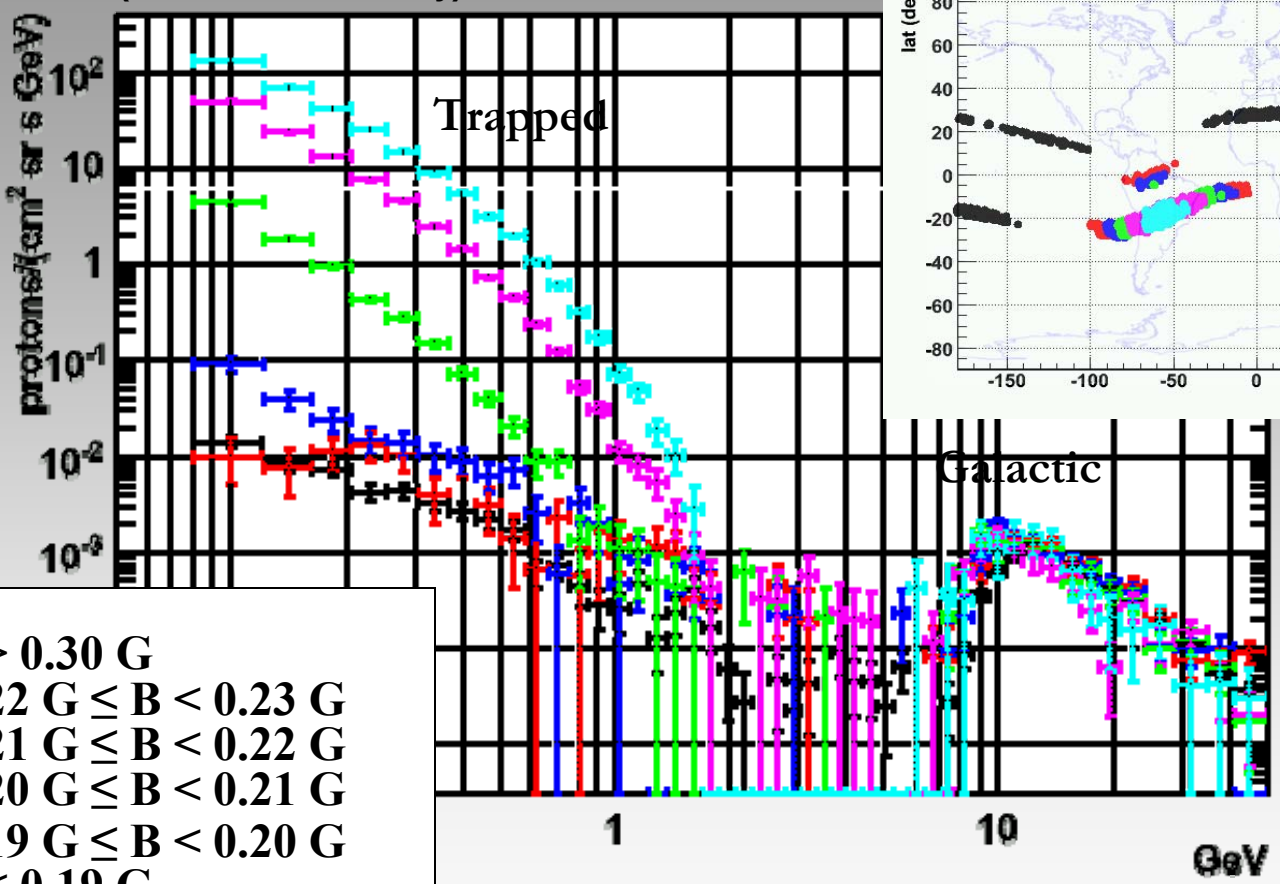
- Up-ward going **albedo** excluded
- SAA excluded

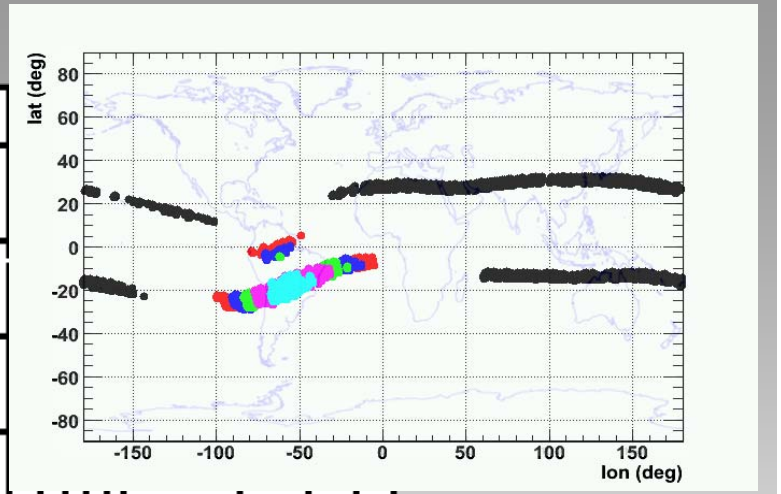
Magnetic equator

Trapped-particle spectrum

Preliminary!!

(statistical errors only)



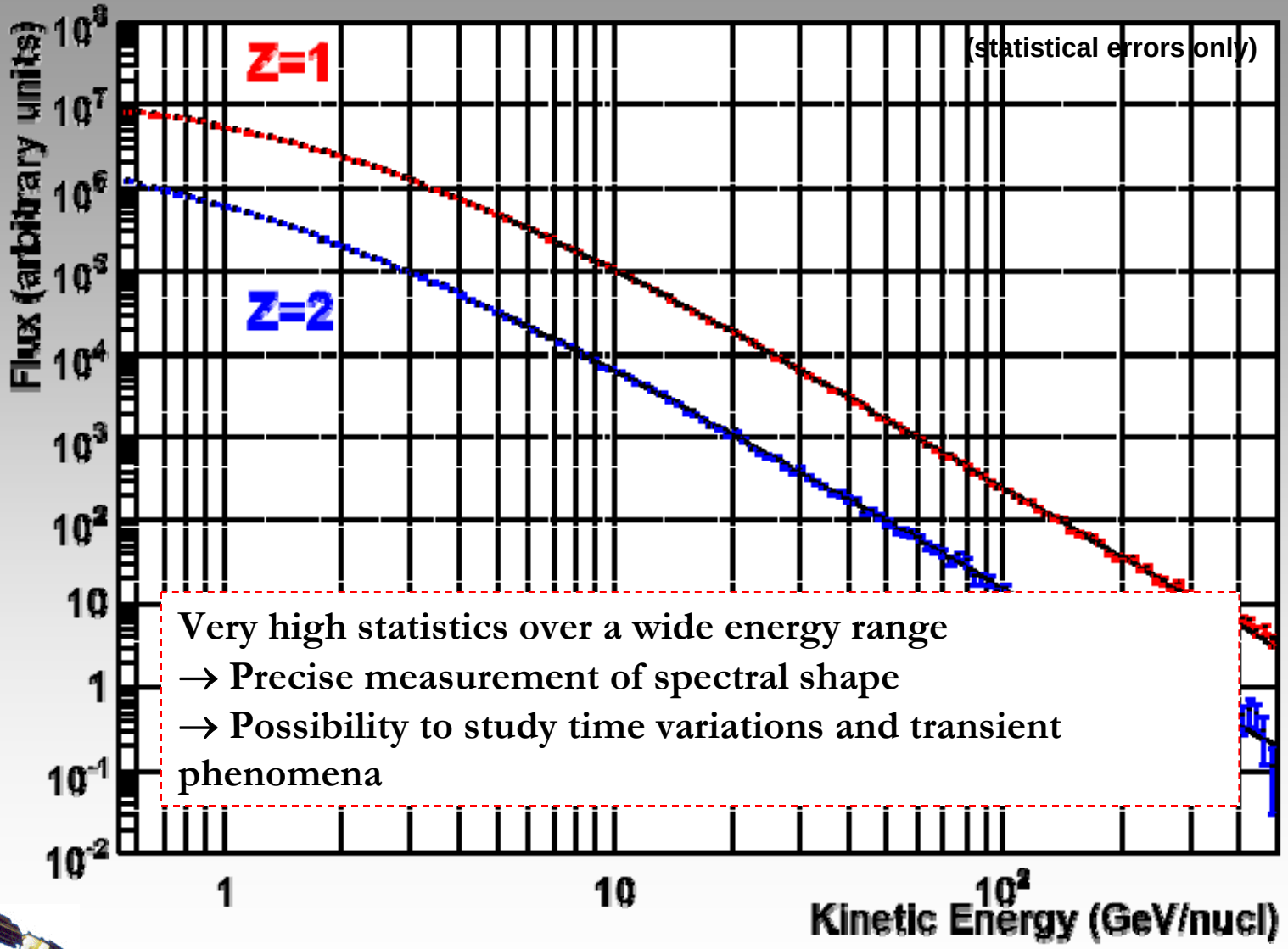


- B > 0.30 G
- 0.22 G ≤ B < 0.23 G
- 0.21 G ≤ B < 0.22 G
- 0.20 G ≤ B < 0.21 G
- 0.19 G ≤ B < 0.20 G
- B < 0.19 G

Always: 10 GV < cutoff < 11

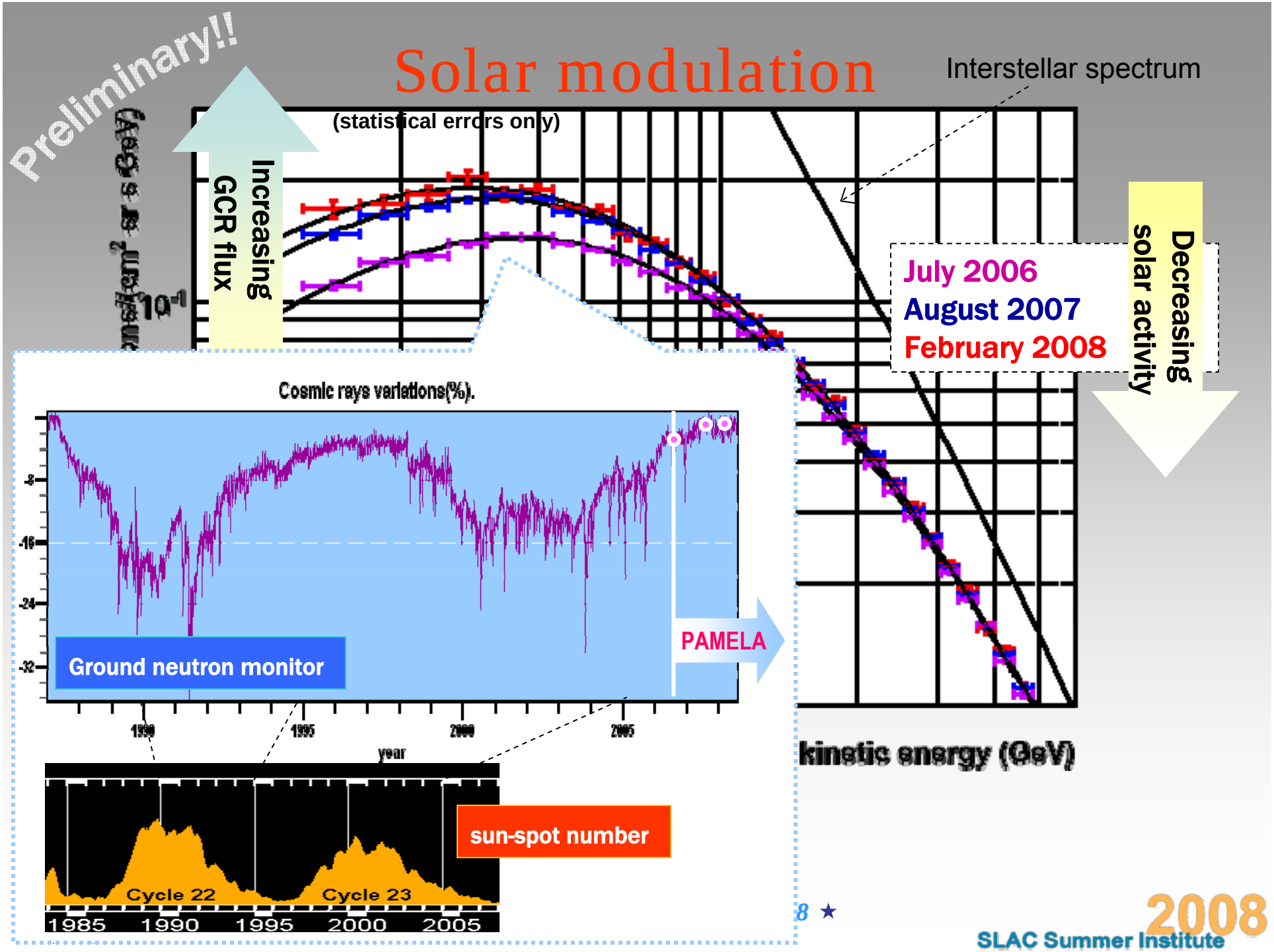
Galactic H and He spectra

Preliminary!!

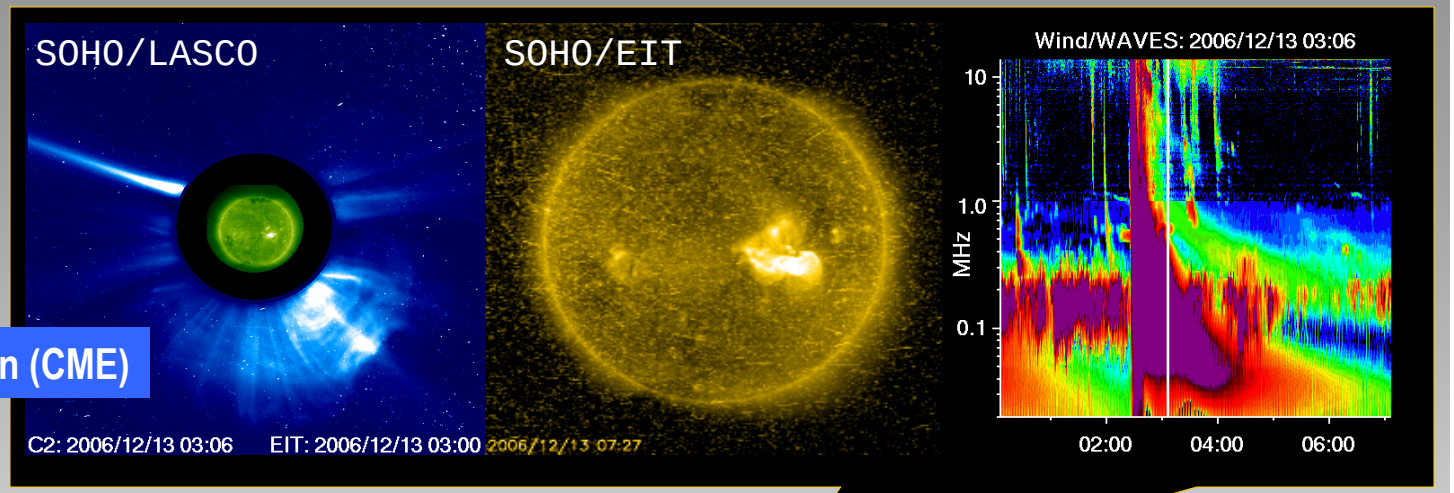


Very high statistics over a wide energy range
→ Precise measurement of spectral shape
→ Possibility to study time variations and transient phenomena

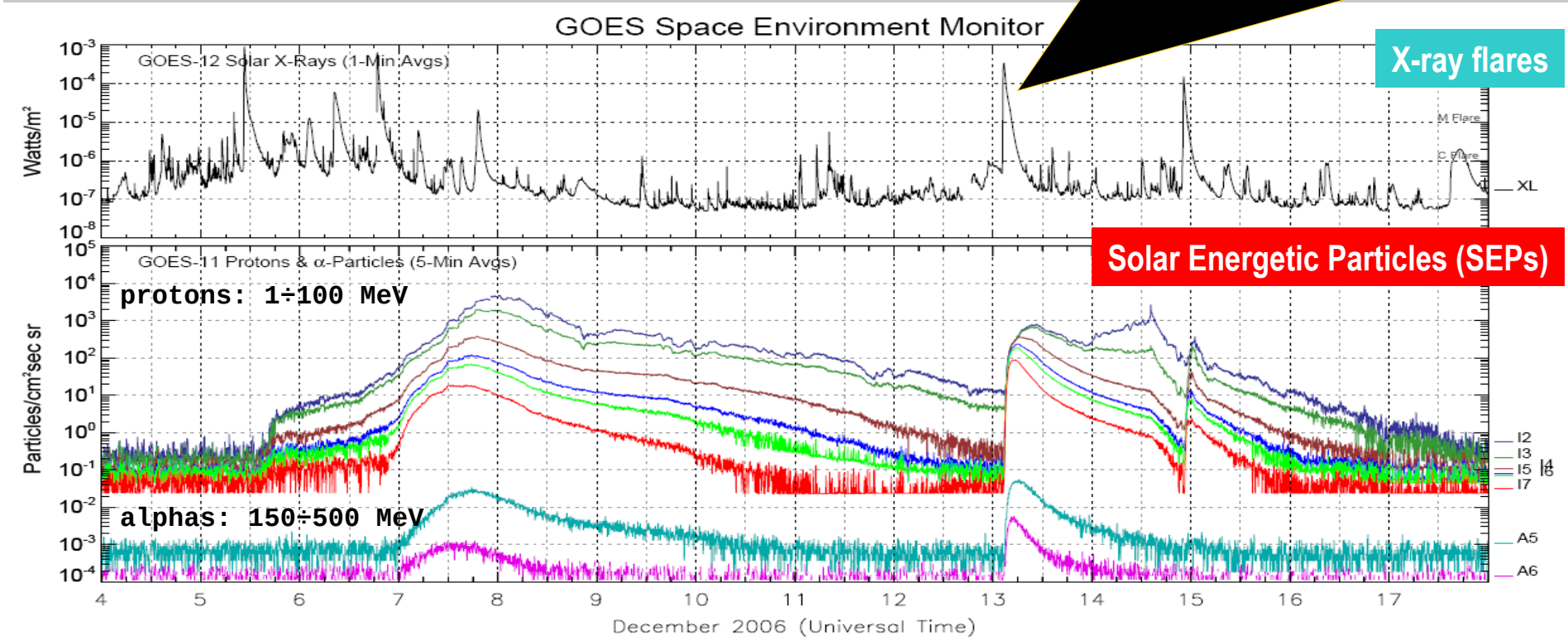
Solar modulation



December 2006 CME/SEP events



Coronal Mass Ejection (CME)



December 13th 2006 SEP event

Preliminary!!

(statistical errors only)

SEPs

Solar quiet spectrum

protons / (cm^2 sr s GeV)

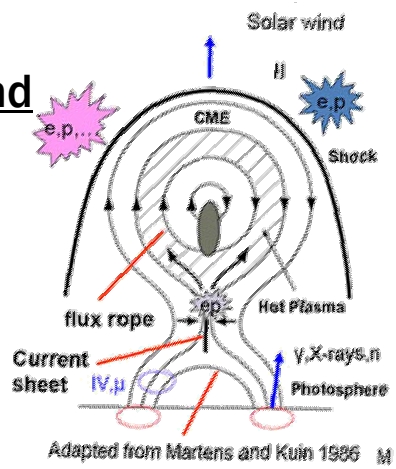
GeV

from 2006-12-1 to 2006-12-4
from 2006-12-13 00:23:02 to 2006-12-13 02:57:46
from 2006-12-13 02:57:46 to 2006-12-13 03:49:09
from 2006-12-13 03:49:09 to 2006-12-13 04:32:56
from 2006-12-13 04:32:56 to 2006-12-13 04:59:16
from 2006-12-13 08:17:54 to 2006-12-13 09:17:34

SEPs accelerated during CMEs

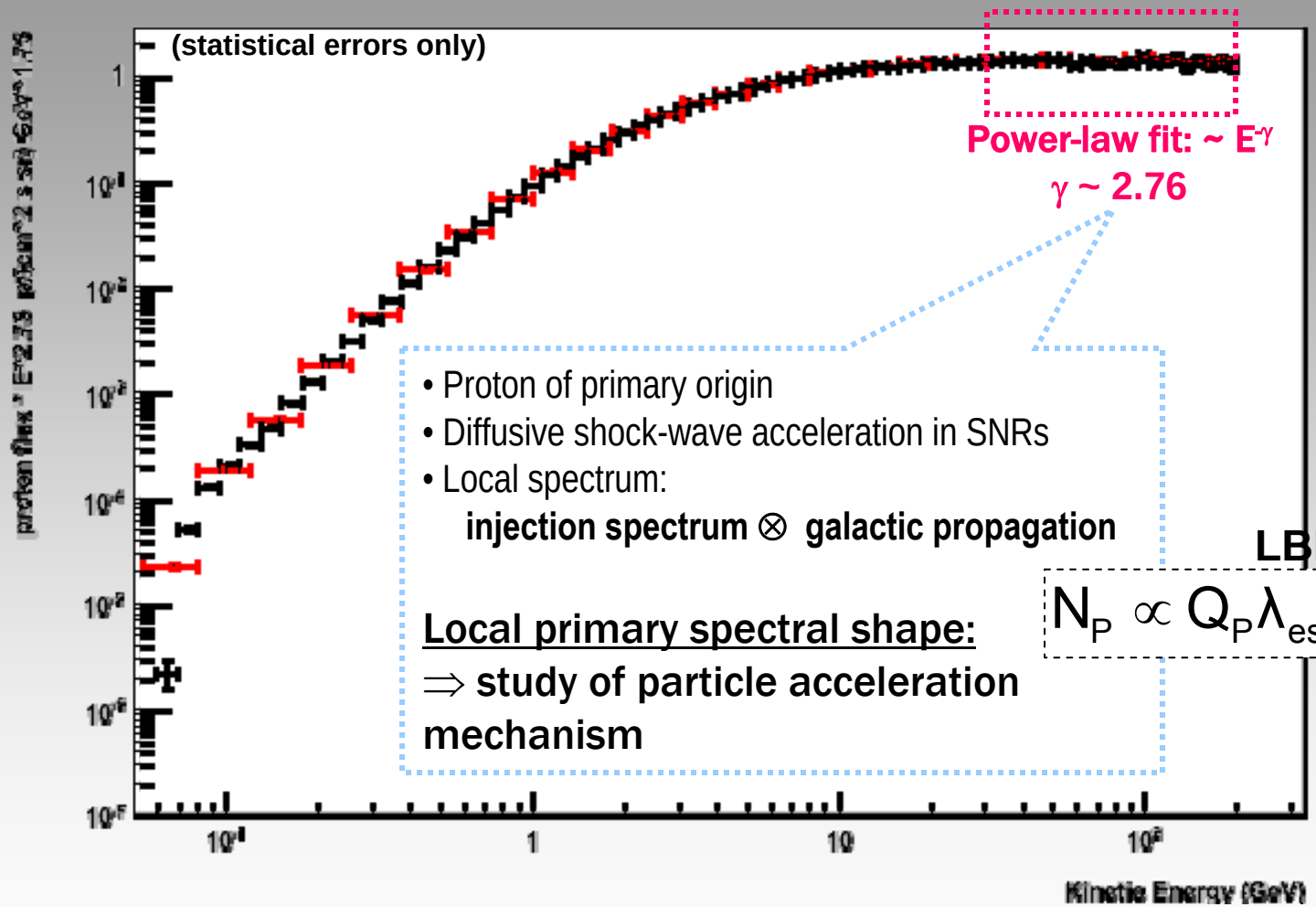
SEP spectral shape and time evolution

⇒ study of particle acceleration mechanisms in CME



Proton flux * $E^{2.75}$

Preliminary!!



- Proton of primary origin
- Diffusive shock-wave acceleration in SNRs
- Local spectrum:
  injection spectrum ⊗ galactic propagation

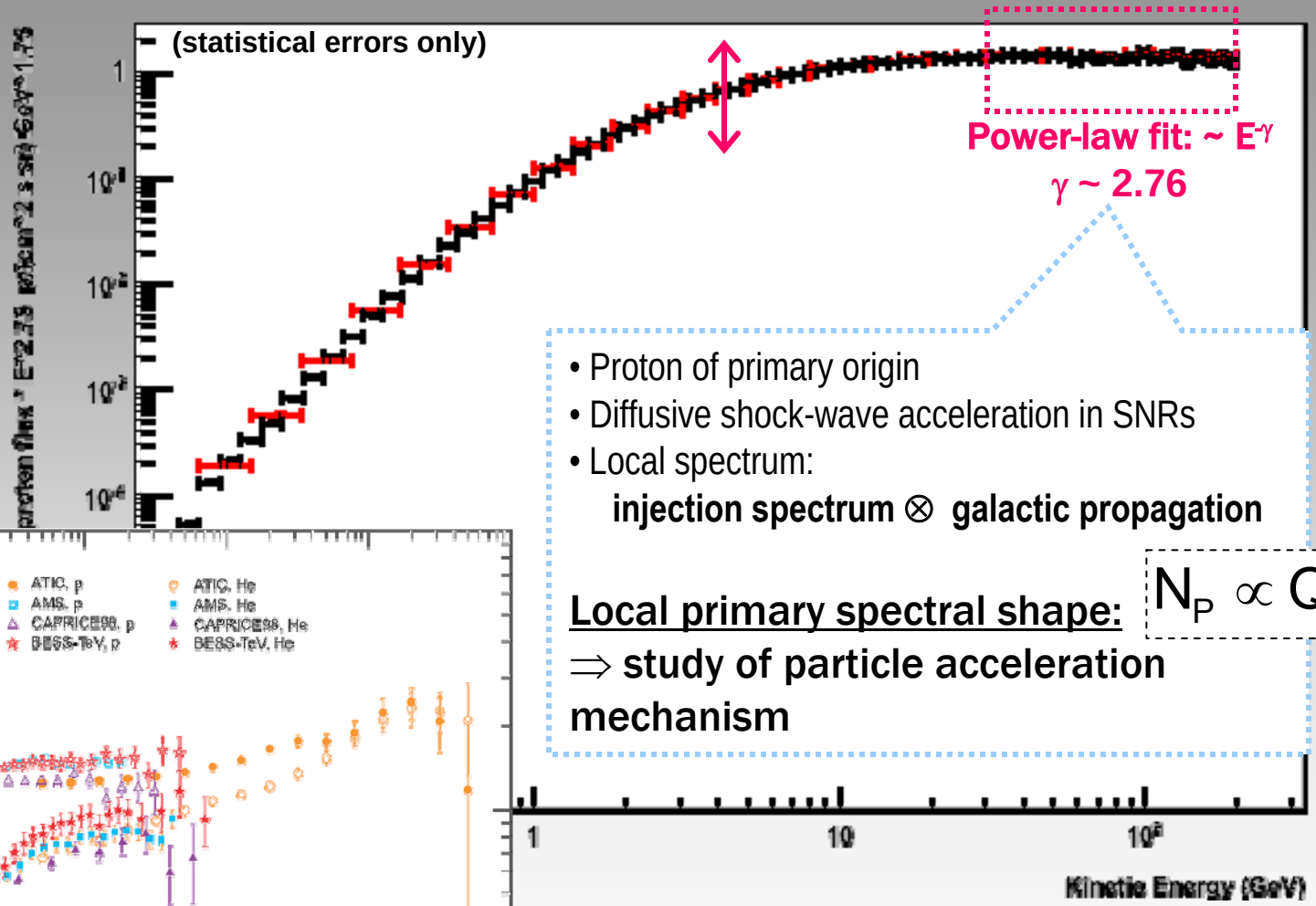
LBM

$$N_P \propto Q_P \lambda_{esc}$$

<u>Local primary spectral shape:</u>
⇒ study of particle acceleration mechanism

Proton flux * $E^{2.75}$

Preliminary!!

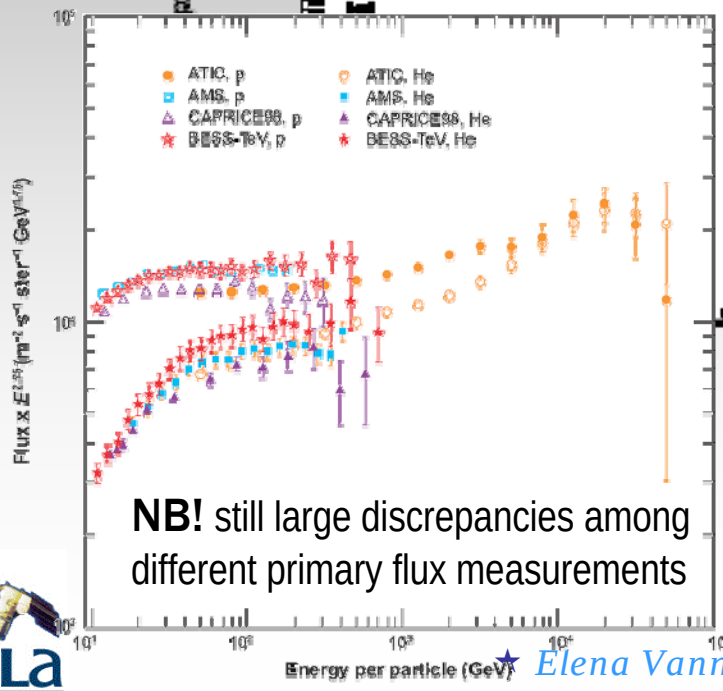


- Proton of primary origin
- Diffusive shock-wave acceleration in SNRs
- Local spectrum:
  injection spectrum ⊗ galactic propagation

LBM

$$N_P \propto Q_P \lambda_{esc}$$

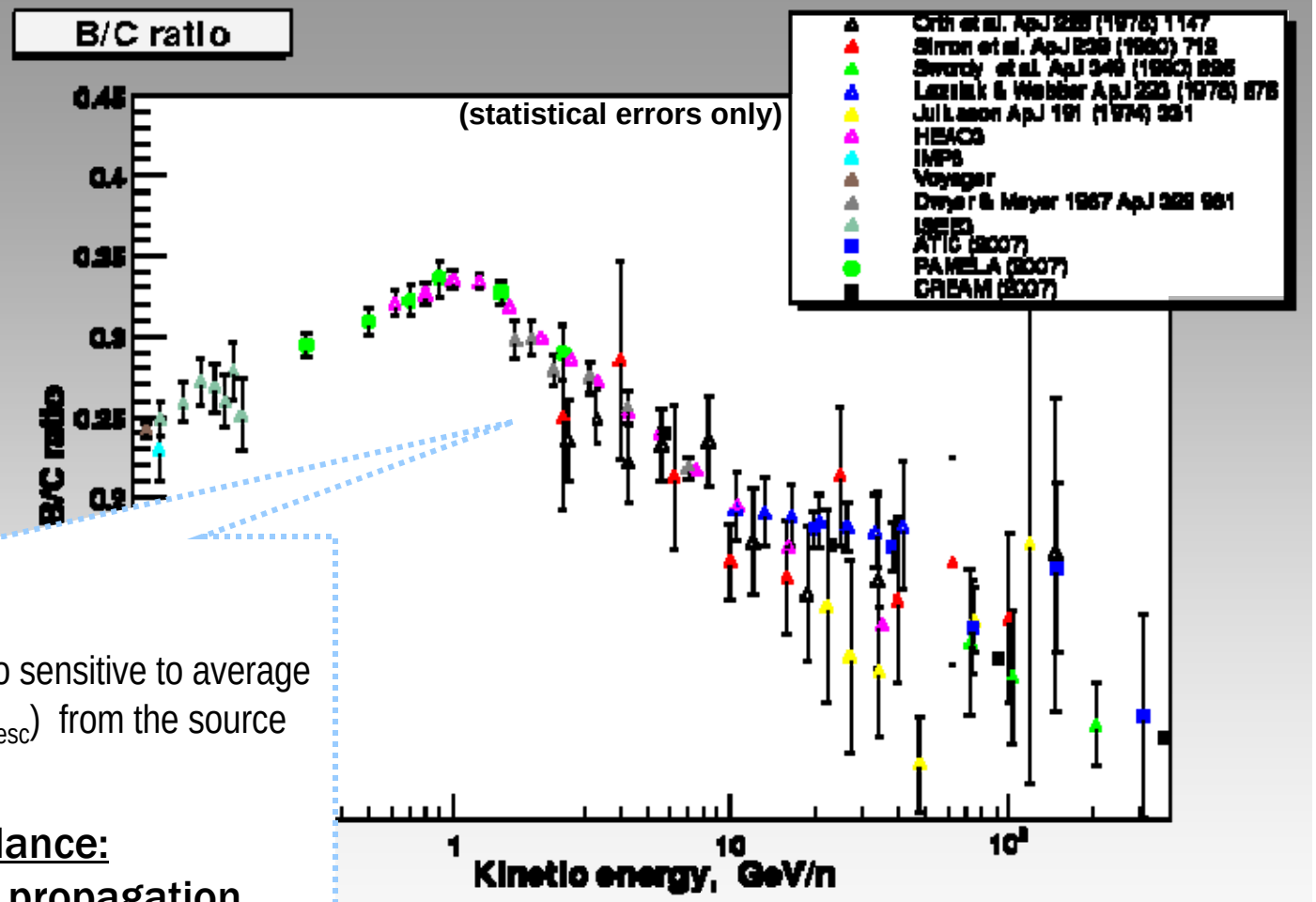
Local primary spectral shape:
⇒ study of particle acceleration mechanism



NB! still large discrepancies among different primary flux measurements

Secondary nuclei

Preliminary!!



LBM

$$\frac{N_S}{N_P} \propto \lambda_{esc} \cdot \sigma_{P \to S}$$

- B nuclei of secondary origin:
  CNO + ISM $\rightarrow$ B + ...
- Local secondary/primary ratio sensitive to average amount of traversed matter (λ_{esc}) from the source to the solar system

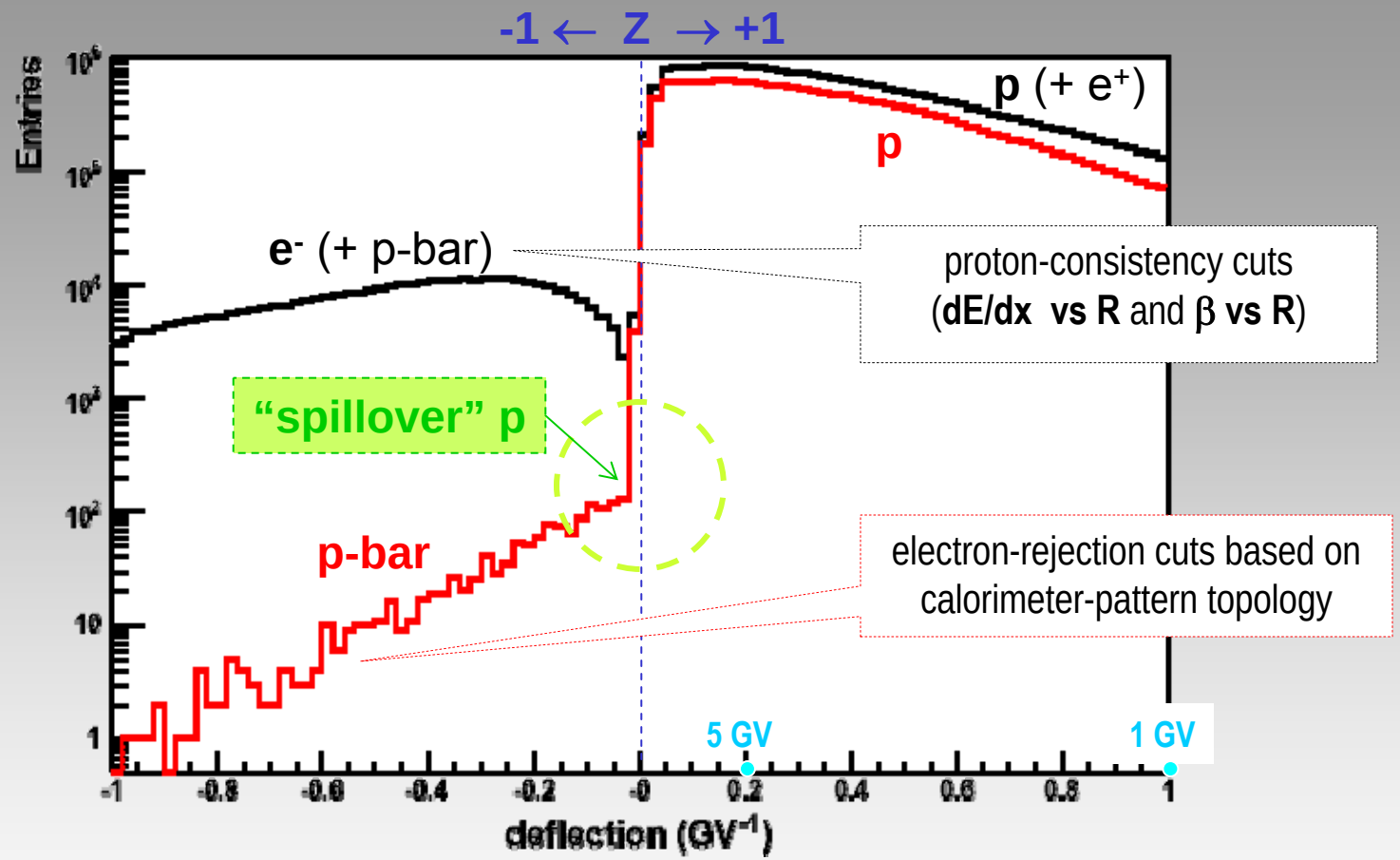
<u>Local secondary abundance:</u>

$\Rightarrow$ **study of galactic CR propagation**

(B/C used for tuning of propagation models)

Antiproton identification

Preliminary!!



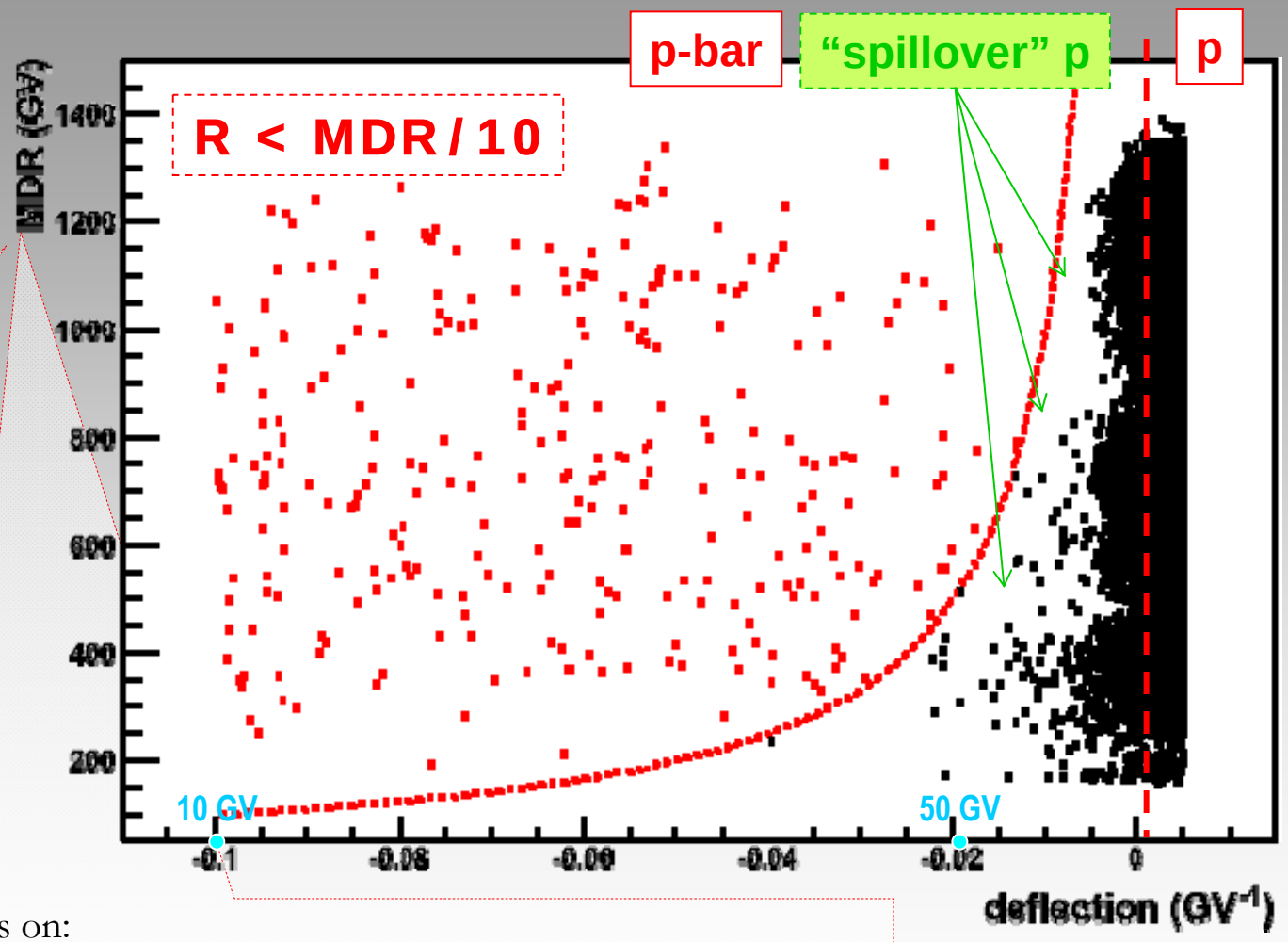
The main difficulty for the antiproton measurement is the **spillover proton bk** @ high energy:

→ finite deflection resolution of the spectrometer

→ p/p-bar ~ 10^4 !!

Preliminary!!

High-energy antiproton selection



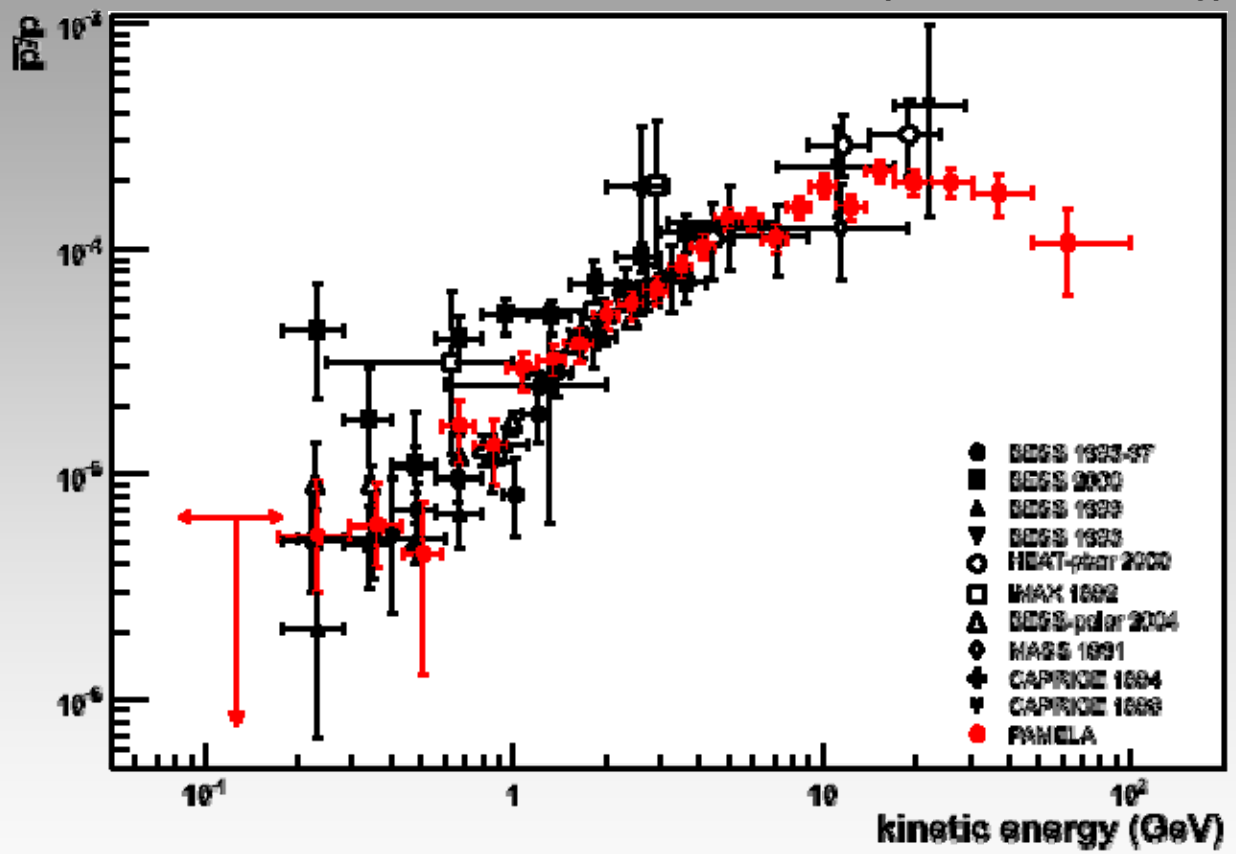
MDR = $1/\sigma_\eta$
(evaluated event-by-event by the fitting routine)

MDR depends on:
- number and distribution of fitted points along the trajectory
- spatial resolution of the single position measurements
- magnetic field intensity along the trajectory

Preliminary!!

Antiproton-to-proton ratio

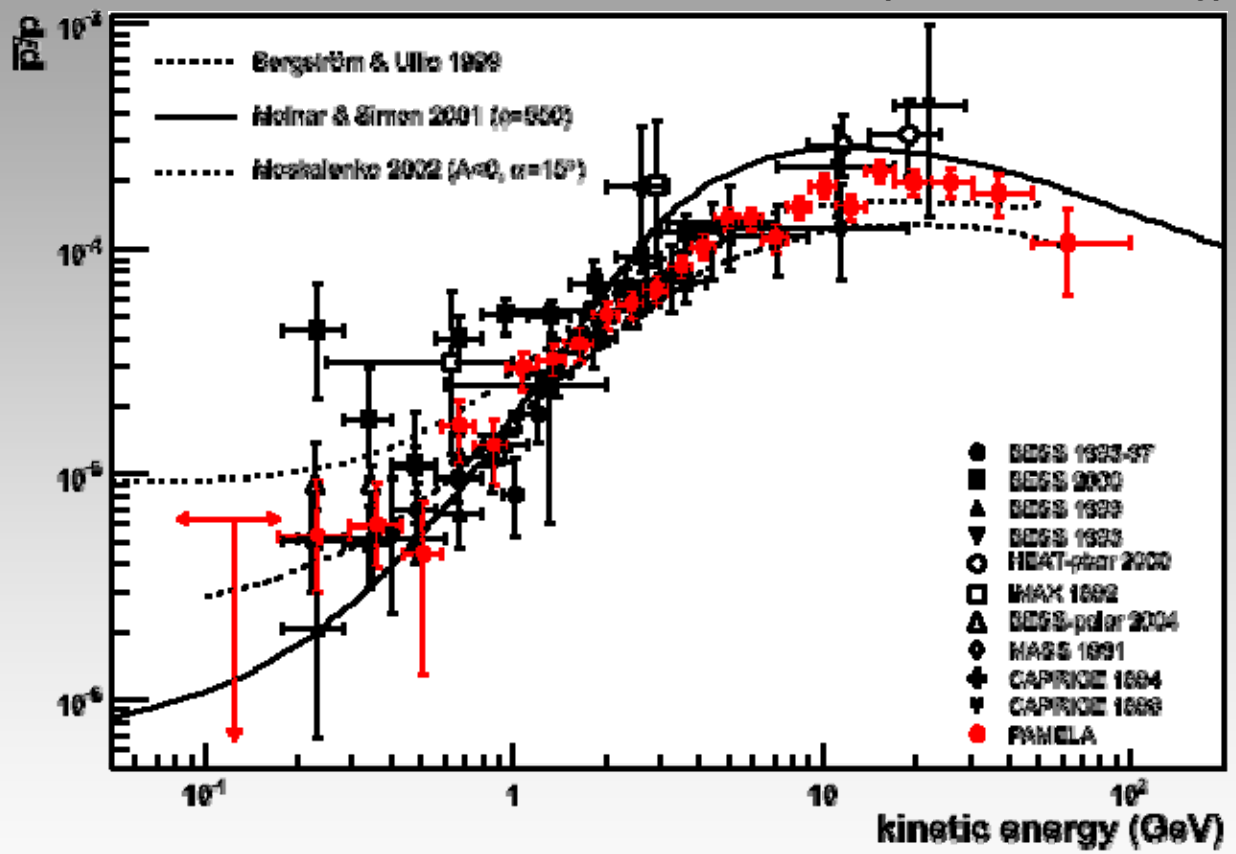
(statistical errors only)



Preliminary!!

Antiproton-to-proton ratio

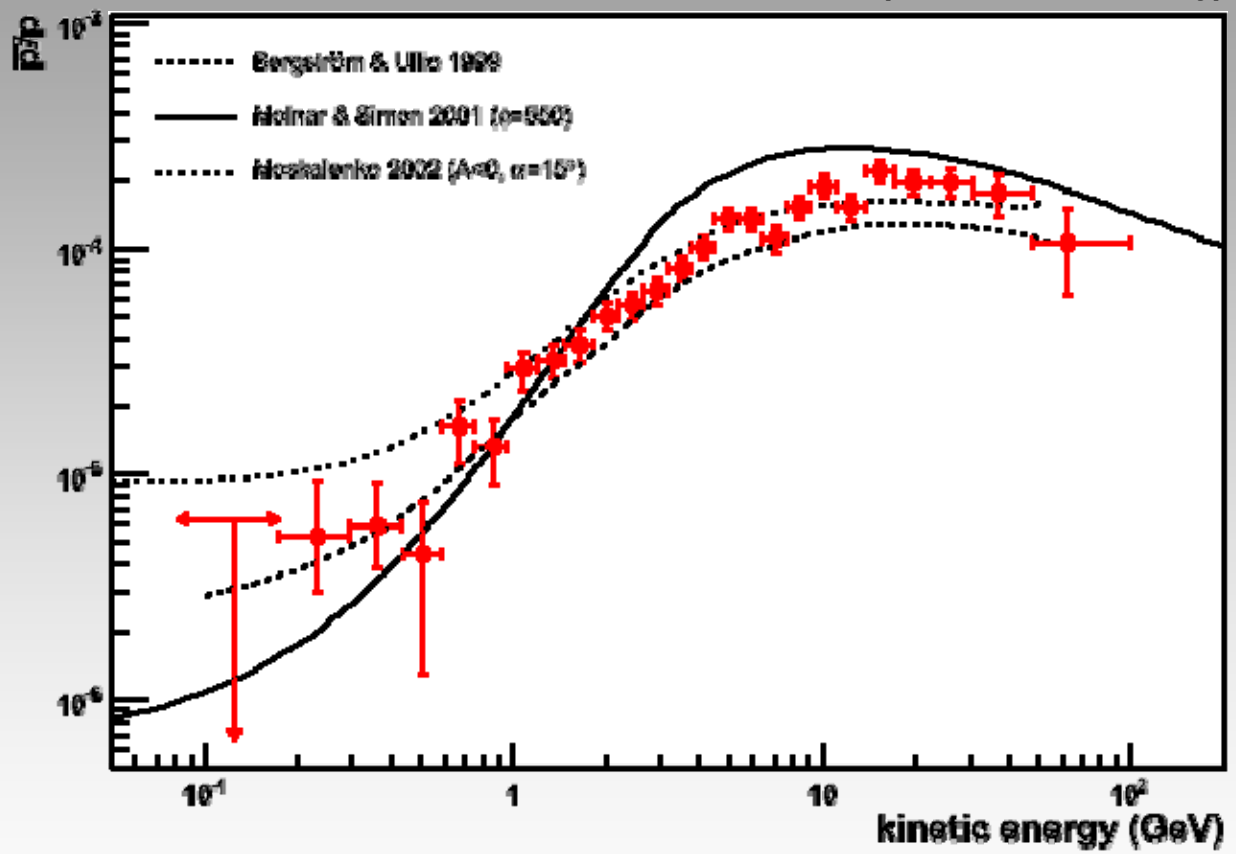
(statistical errors only)



Preliminary!!

Antiproton-to-proton ratio

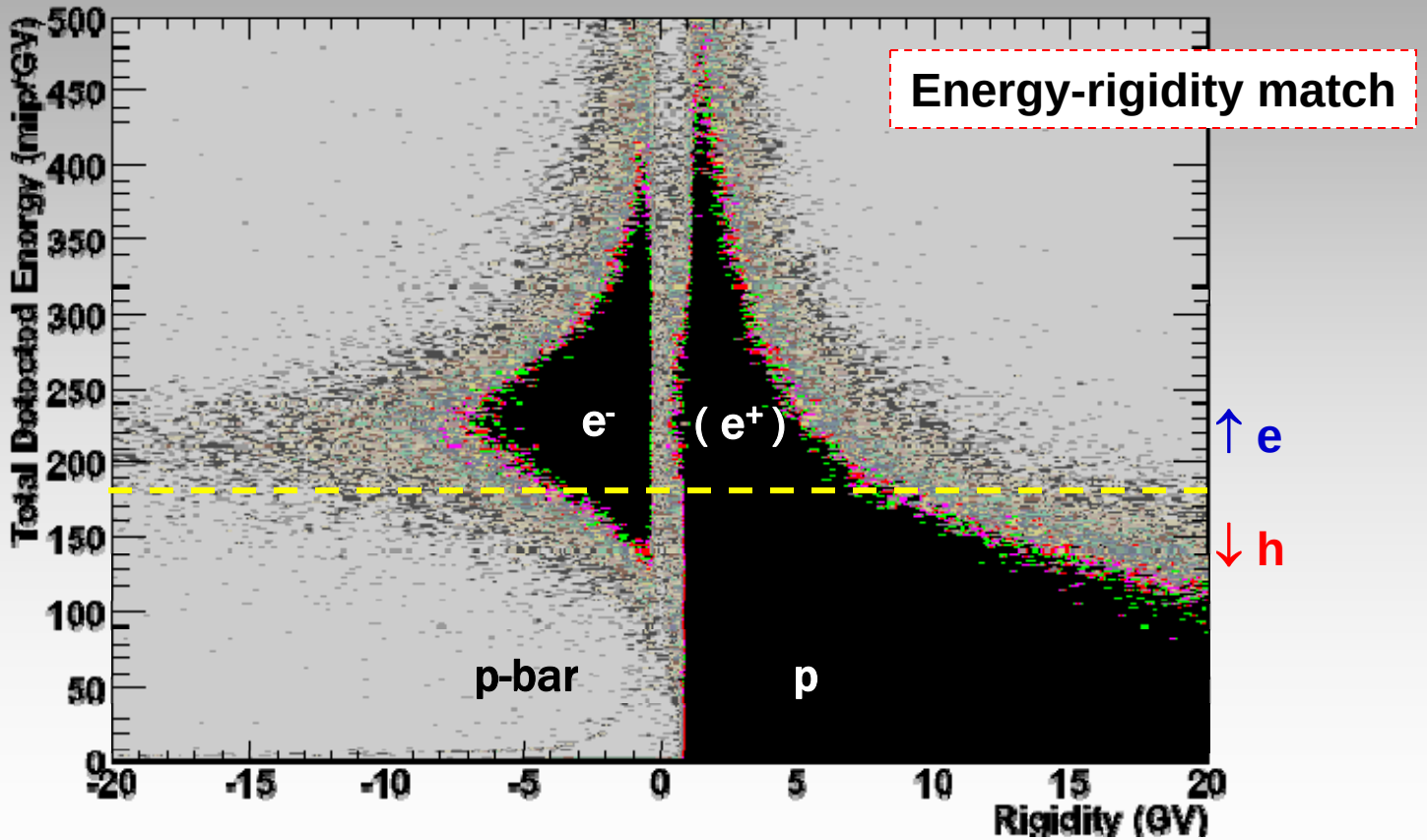
(statistical errors only)



Positron identification

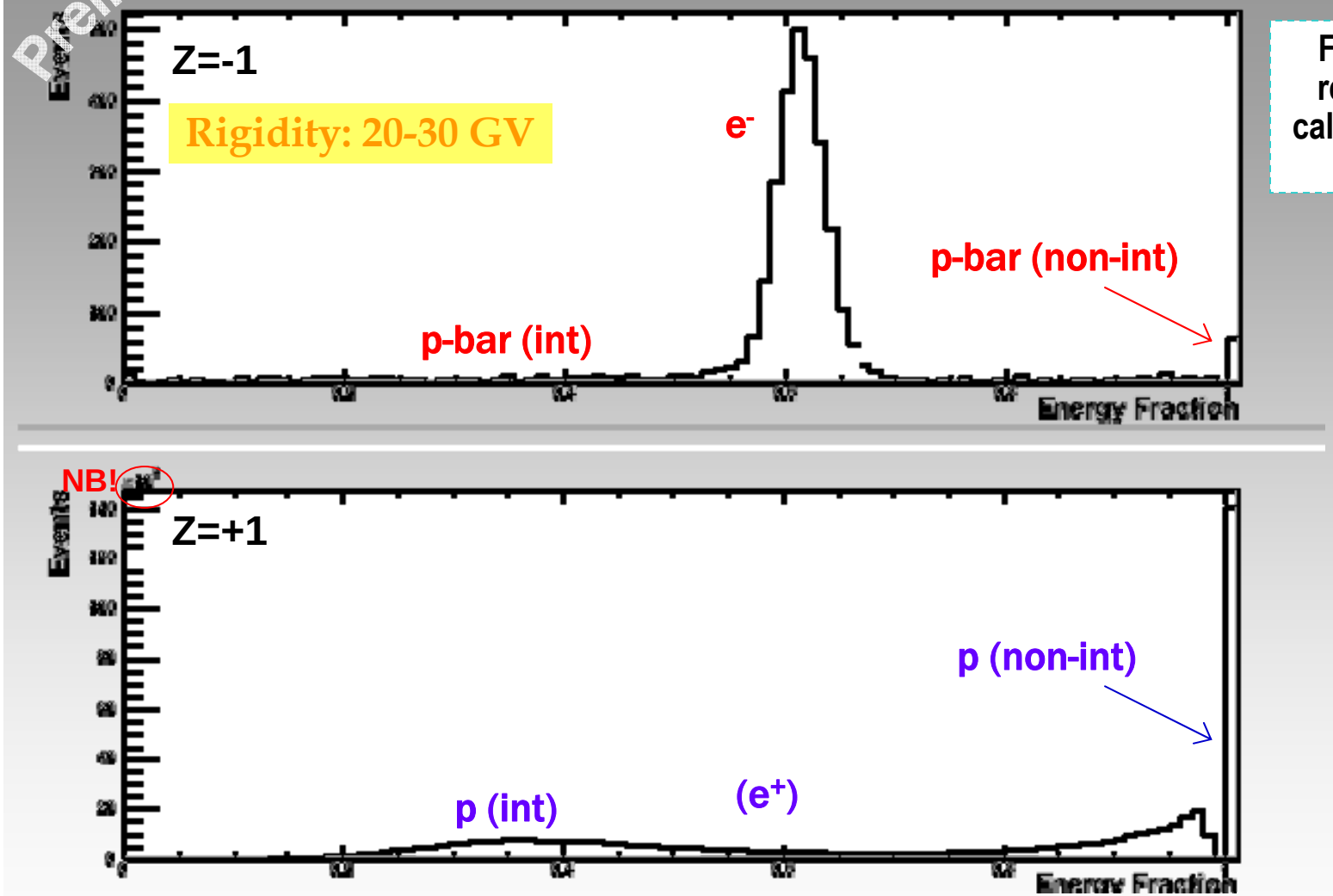
The main difficulty for the positron measurement is the **interacting-proton bk**:

- fluctuations in hadronic shower development $\Rightarrow \pi_0 \rightarrow \gamma\gamma$ might mimic pure em showers
- proton spectrum harder than positron $\Rightarrow p/e^+$ increase for increasing energy



Proton background suppression

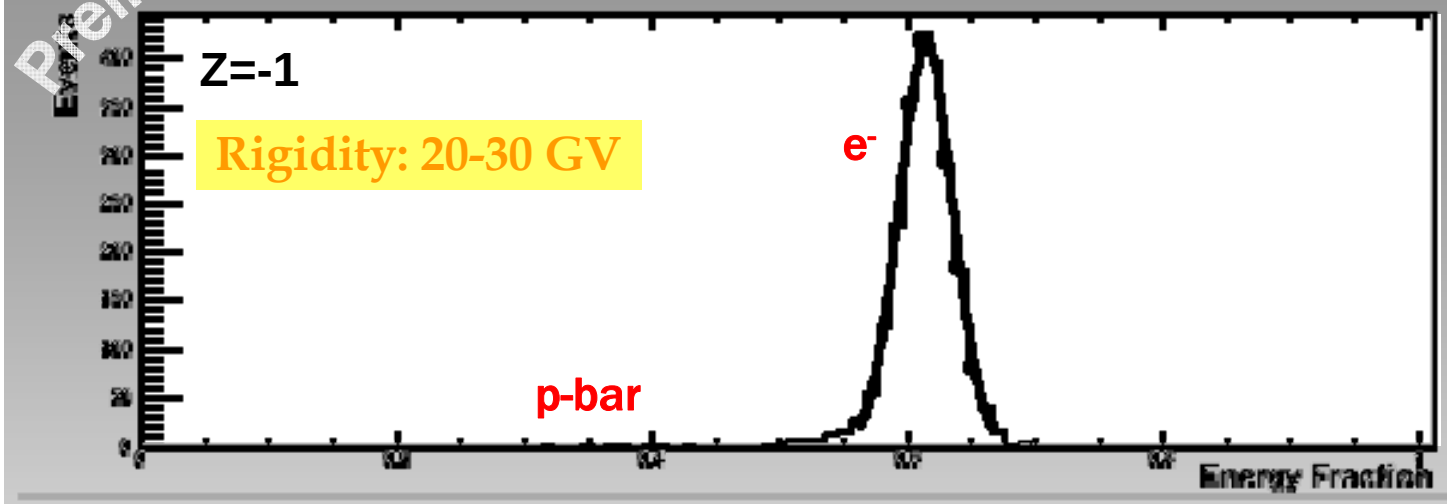
Preliminary!!

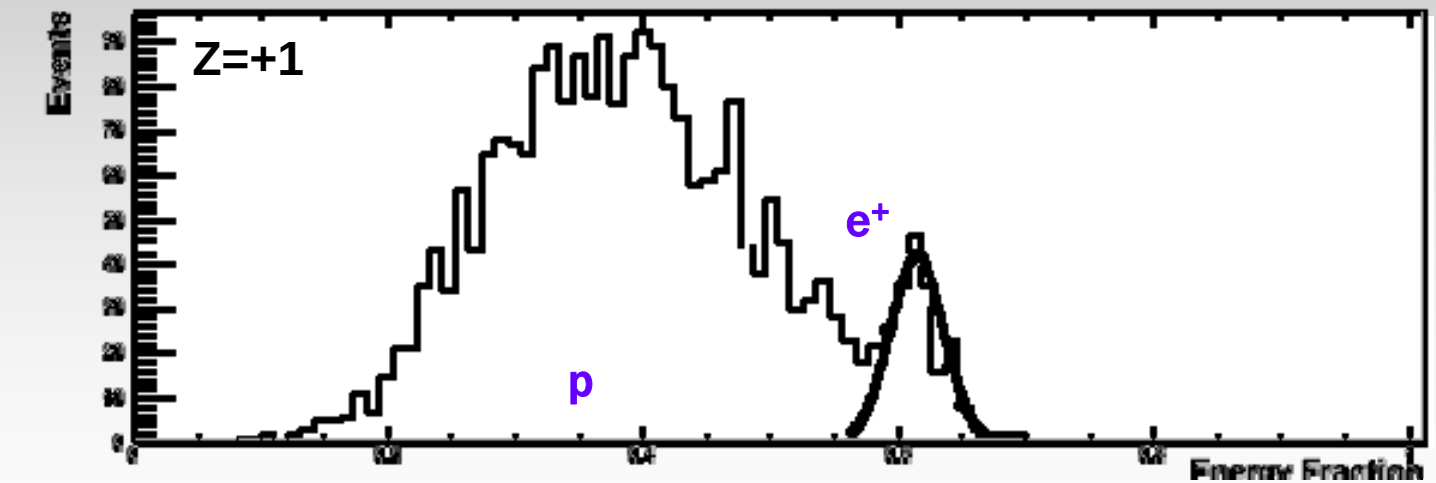


Fraction of charge released along the calorimeter track (left, hit, right)

Proton background suppression

Preliminary!!





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

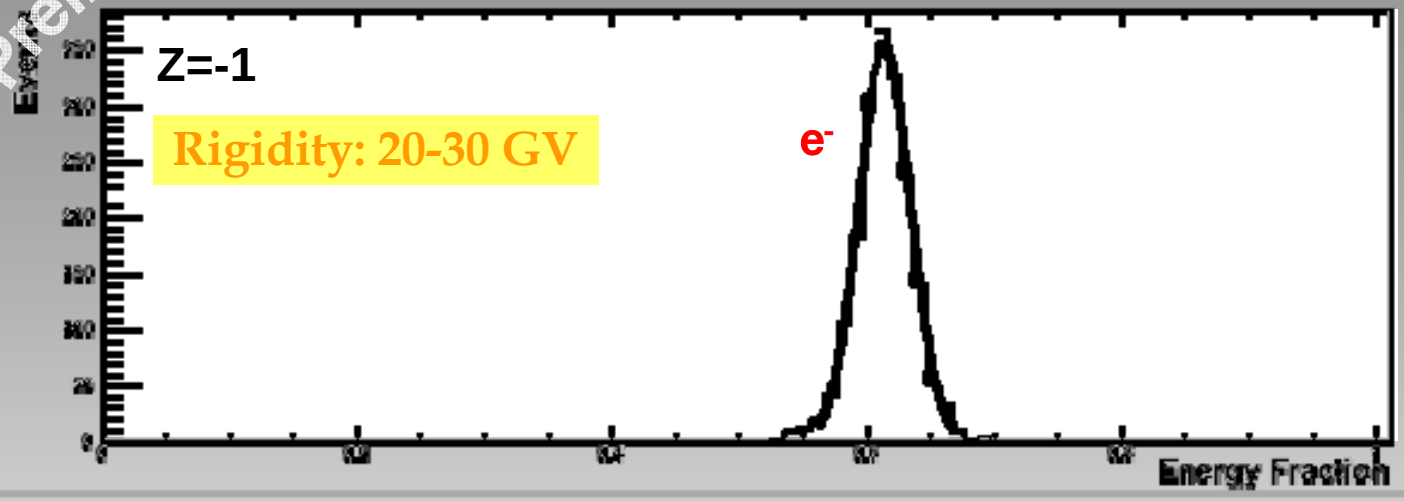
+

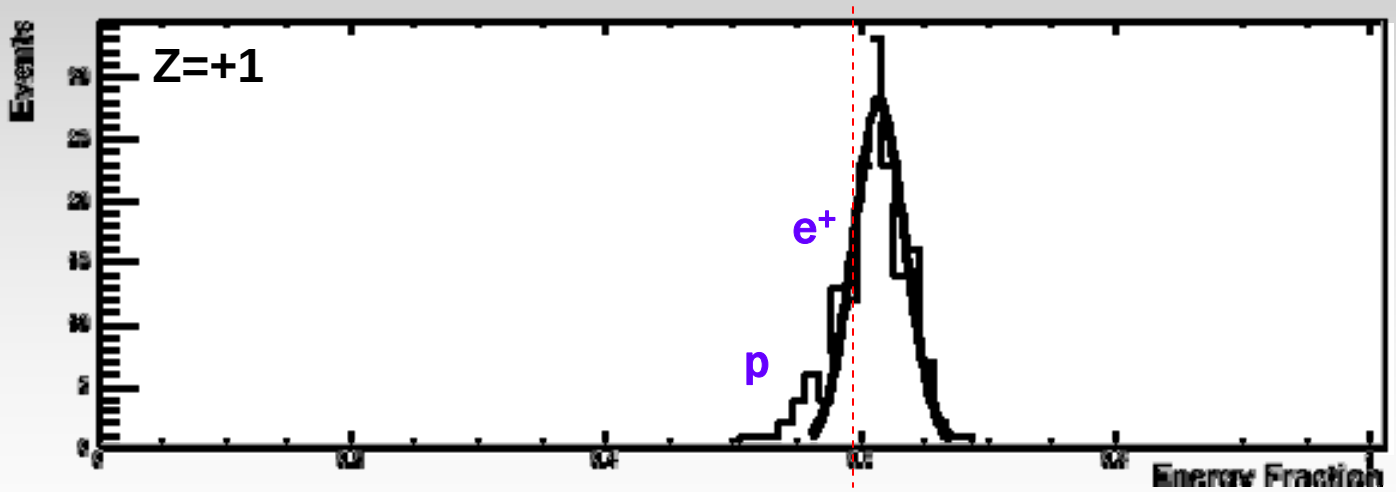
Constraints on:

Energy-momentum match

Proton background suppression

Preliminary!!





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

+

Constraints on:

Energy-momentum match

Shower starting-point

Longitudinal profile

Proton background evaluation

Preliminary!!

Rigidity: 6-8 GV

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

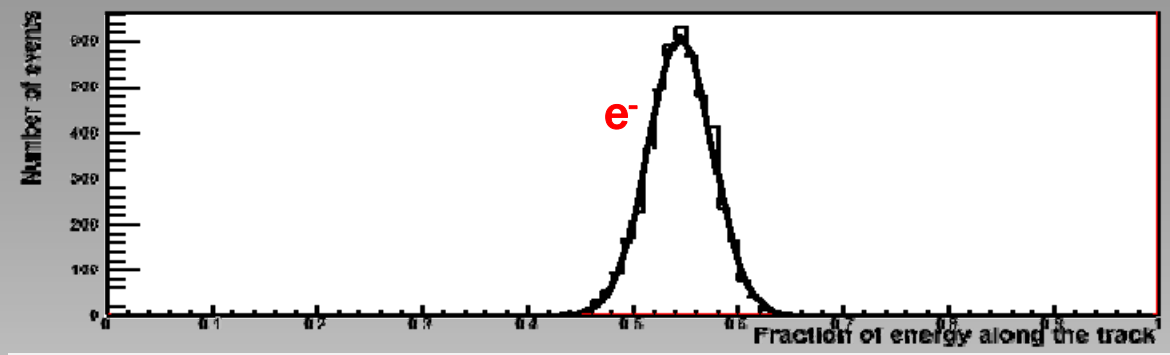
+

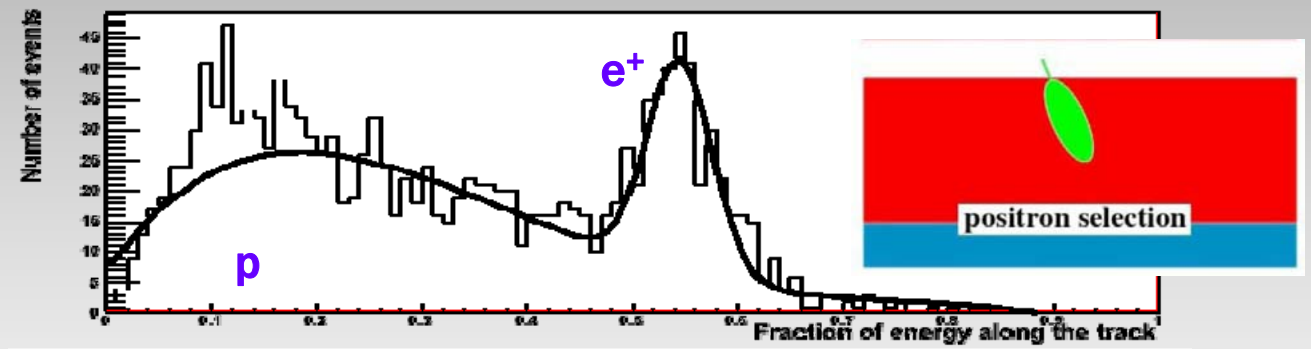
Constraints on:

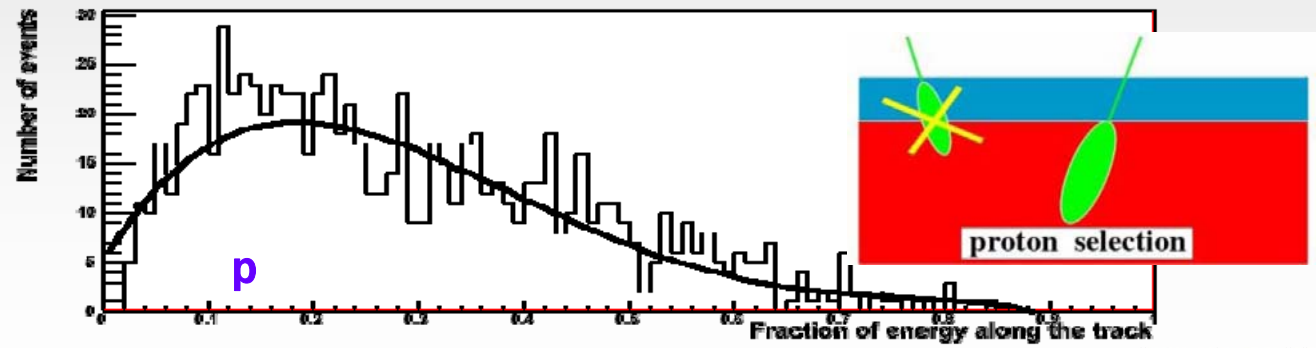
Energy-momentum match

Shower starting-point

~~Longitudinal profile~~

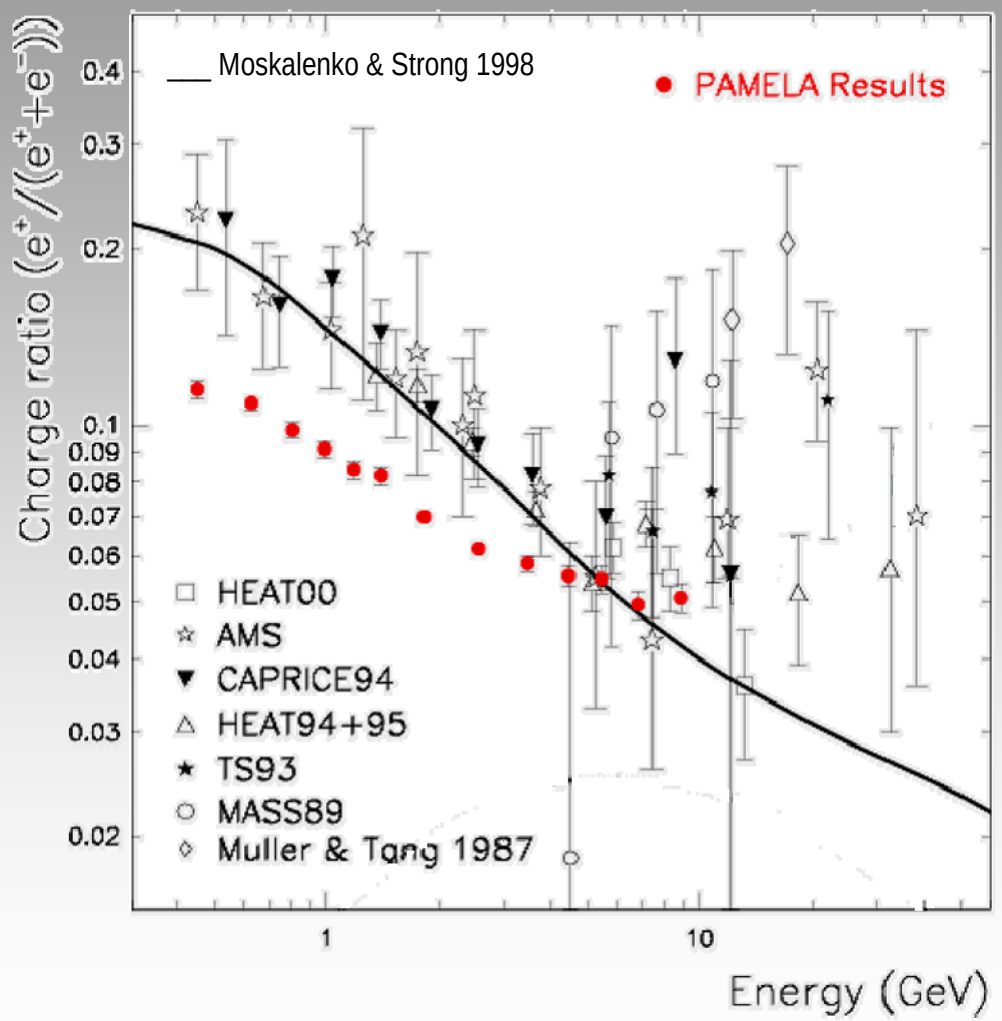






Preliminary!!

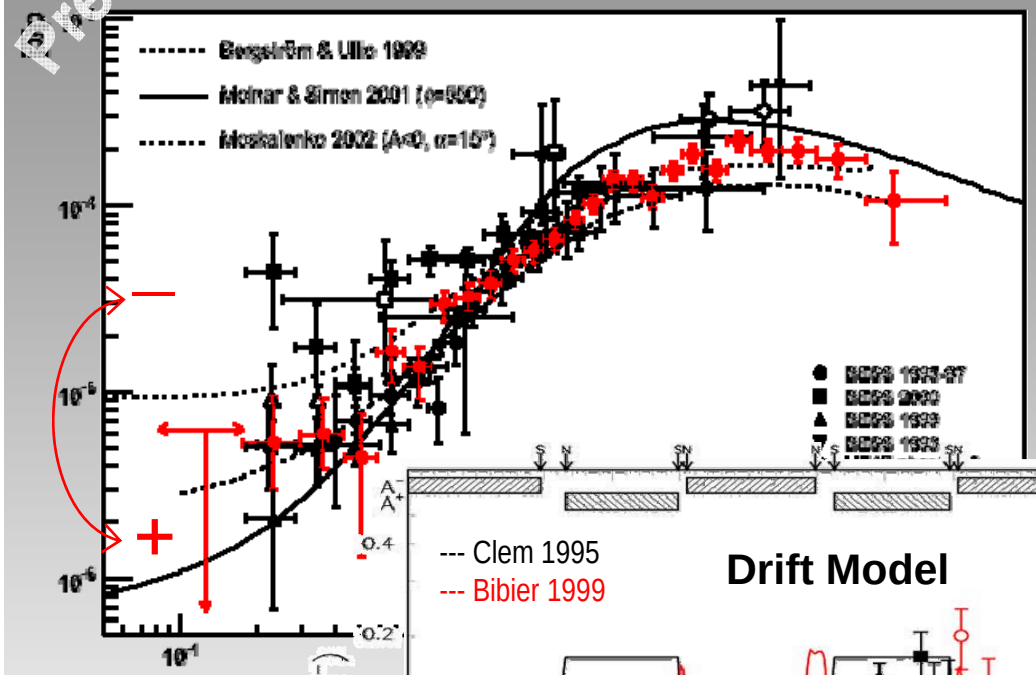
Positron charge ratio

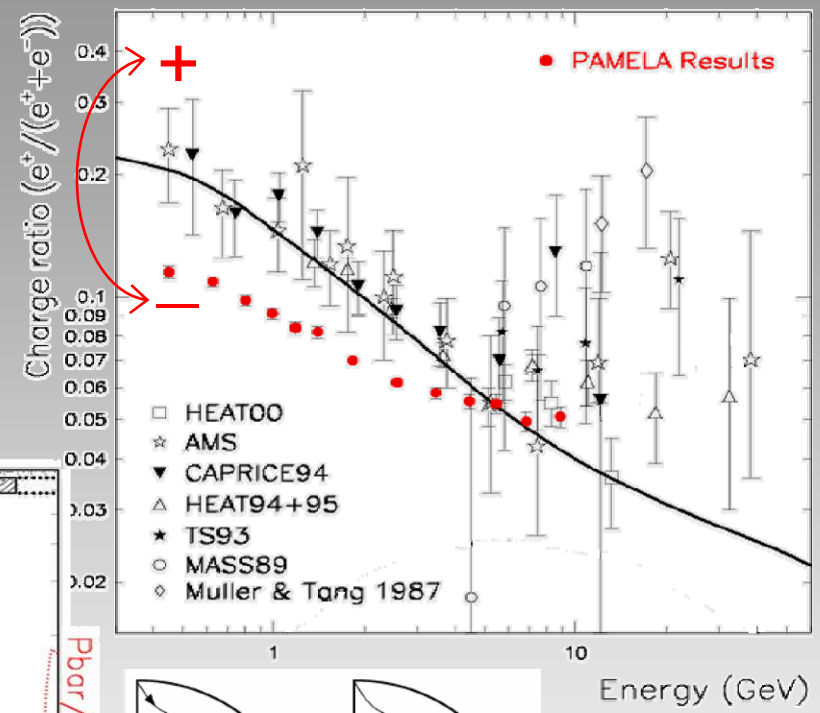


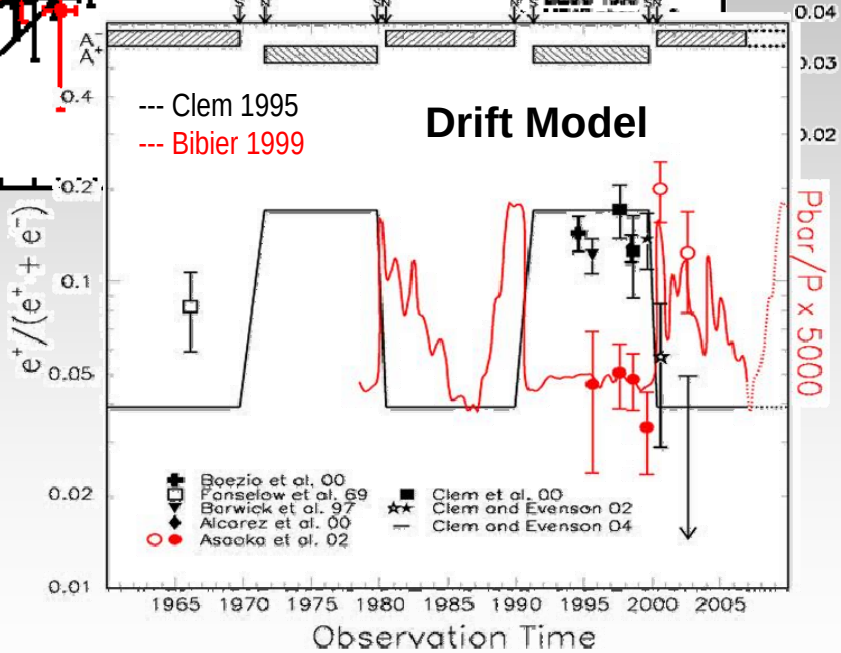
statistical errors only
energy in the spectrometer

Charge dependent solar modulation

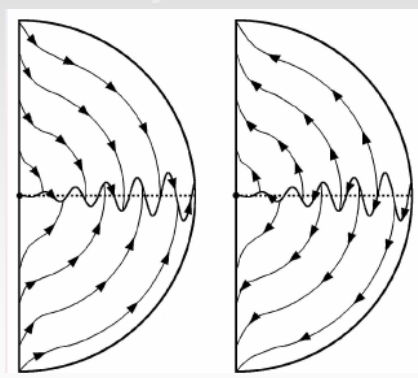
Preliminary!!







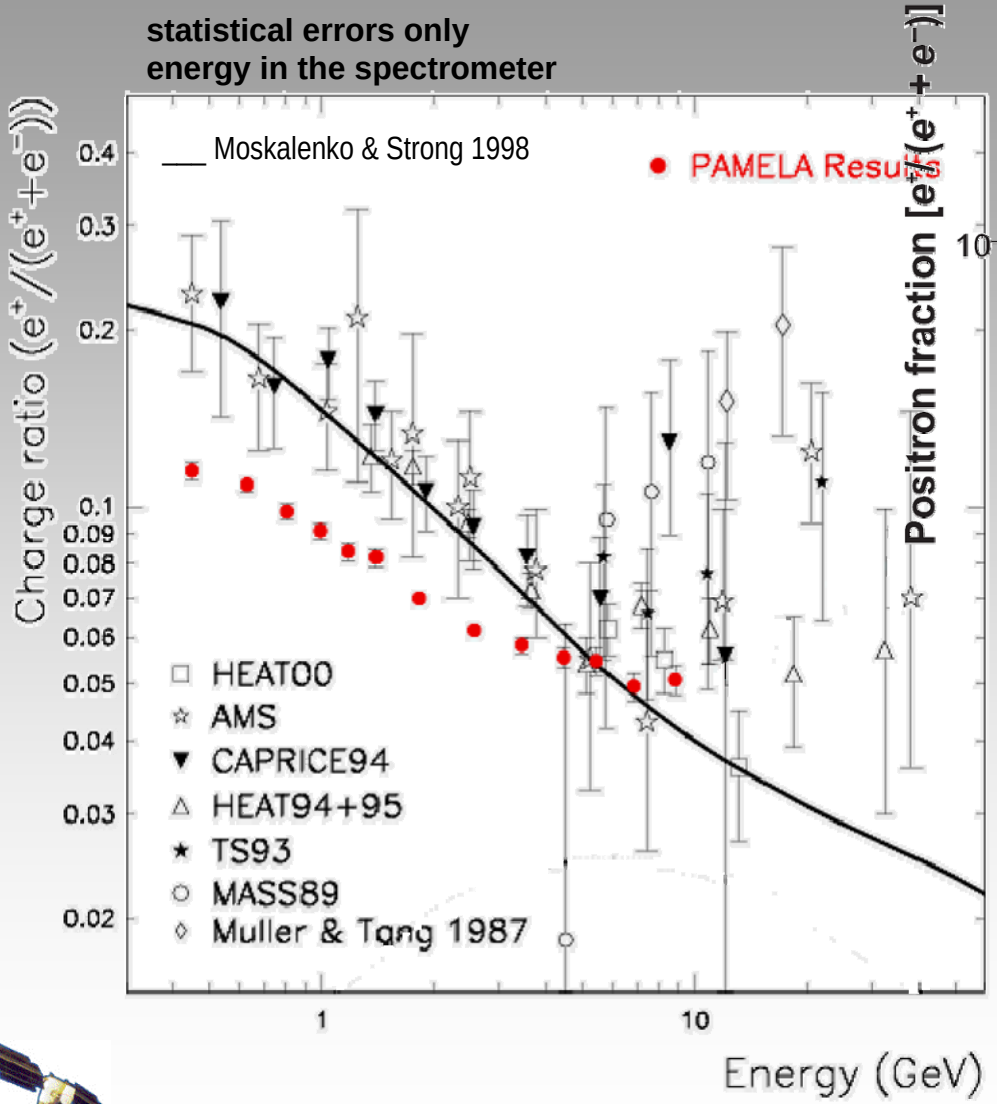
Clem J. & Evenson 2007

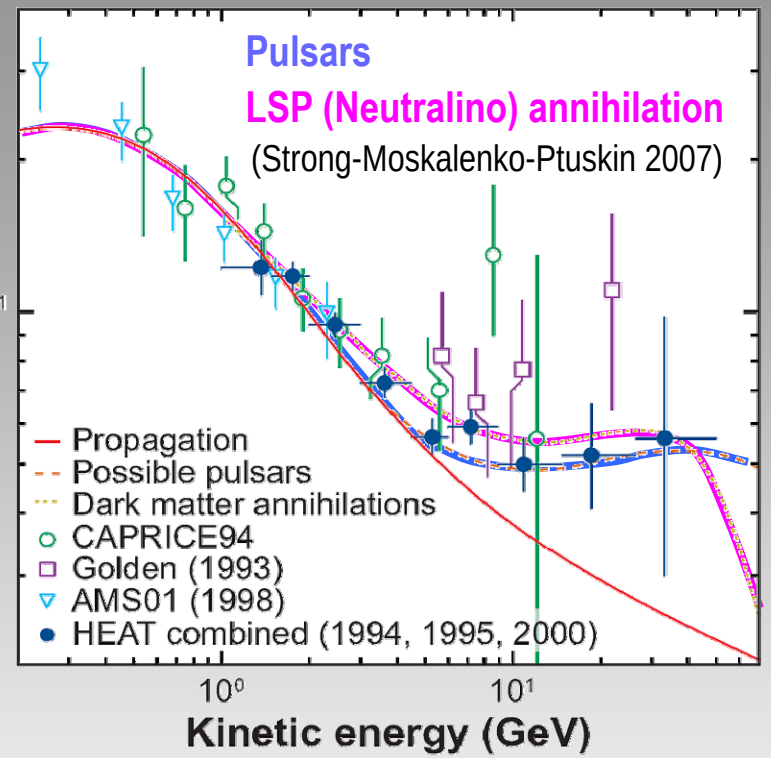


A > 0 **A < 0**

Positive particles

High-energy positrons





Contribution from pulsars

Contribution from WIMP annihilation in the galactic halo

Conclusions

- **PAMELA is taking data since July 2006**
- (lot of fun analyzing the data!)
- **Presented preliminary results from ~600 days of data:**
  - → **Antiproton charge ratio (~100 MeV ÷100 GeV)**
    - → **no evident deviations from secondary expectations**
    - → more high energy data to come (up to ~150 GeV)
  - → **Positron charge ratio (~400 MeV ÷10 GeV)**
    - → **indicates charge dependent modulation effects**
    - → more data to come at lower and higher energies (up to ~200 GeV)
  - → **Galactic primary proton spectra**
    - → primary spectra up to Z=8 to come
  - → **Galactic secondary-to-primary ratio (B/C)**
    - → abundance of other secondary elements (Li,Be) and isotopes (d,^{3}He) to come
  - → **High energy tail of proton SEP events**
    - → spectra of other components (electrons, isotopes,…) to come

→ **PAMELA is providing significant experimental results, which will help in understanding CR origin and propagation**

Many thanks to all my colleagues for providing me the material for the presentation!