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a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

Oskar Klein centre

# Studies of positron identification with the PAMELA calorimeter

**Laura Rossetto**

*Licentiate seminar, November 10th 2010, Stockholm*

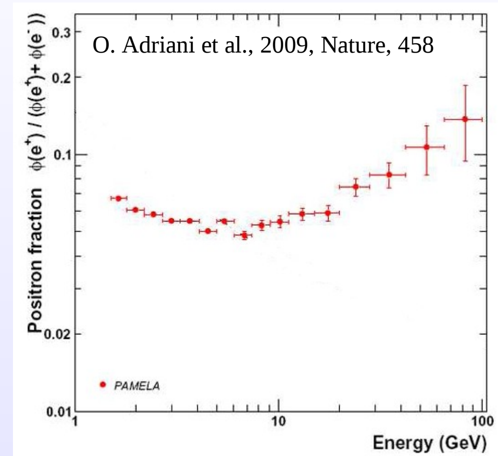
# Outline

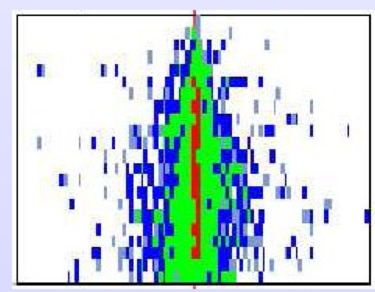
- Basic concepts of cosmic rays
  → acceleration and propagation mechanisms
  → solar modulation
  → cosmic ray positrons and
  the PAMELA positron fraction

- The PAMELA experiment
  → description of the components

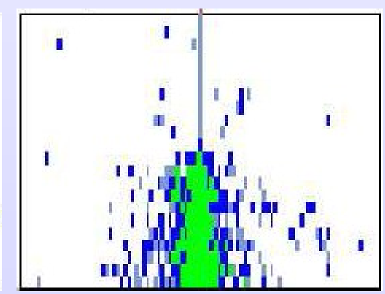
- Shower development in the PAMELA calorimeter
  → description of electromagnetic and hadronic
  shower development inside the calorimeter
  → $\pi^0$ contamination of hadronic showers

- Simulation studies of $\pi^0$ contamination
  → the "Nature analysis" approach applied to
  simulations
  → a new approach for positron identification



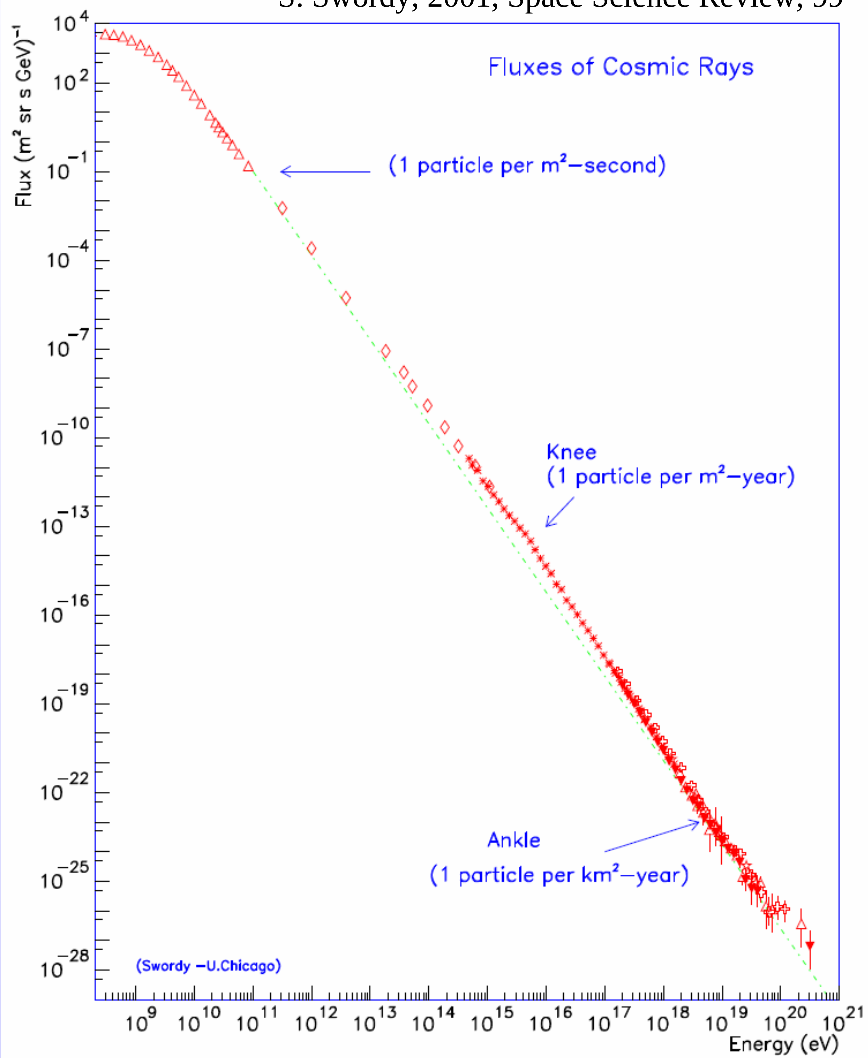
electromagnetic
cascade



hadronic
cascade

# Cosmic rays

S. Swordy, 2001, Space Science Review, 99




- Cosmic rays:
  ~ 98% protons and nuclei
  ~ 2% electrons

- all particle energy spectrum follows a power-law distribution $E^{-\alpha}$
  → for $E > 10^9$ eV, $\alpha = 2.7$
  → **knee** at $E \sim 3 \cdot 10^{15}$ eV, $\alpha = 3.1$
  → **ankle** at $E \sim 10^{18}$ eV, $\alpha = 2.7$

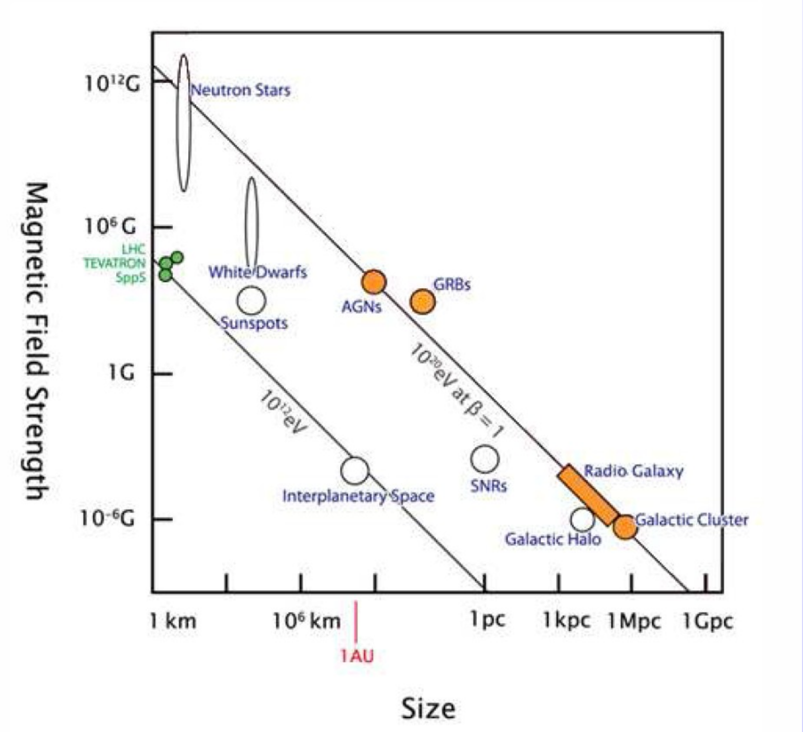
- for $E \leq 10$ GeV
  → solar modulation effect

- **primary** elements are accelerated in sources of high energy particles
- **secondary** elements are produced by spallation processes

# Acceleration mechanisms

- First order Fermi acceleration (1949) → $< \Delta E / E > = (2 / 3) \cdot (V / c)$
  → acceleration in strong shock waves, e.g. **supernovae explosions**
  → a power-law energy spectrum is obtained
  → acceleration phase ~ $10^5$ years → upper limit E ~ $10^{14}$ eV
  → acceleration to higher energies → pulsar magnetosphere, AGN, GRB...

Crab nebula

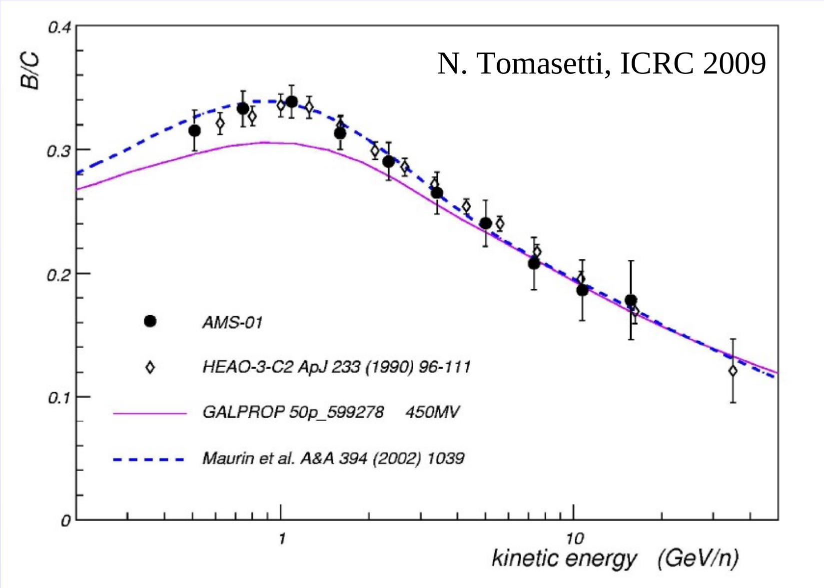



http://jemeuso.riken.jp/en/about2.html

# Propagation mechanisms

- Cosmic rays propagate through the interstellar medium losing energy

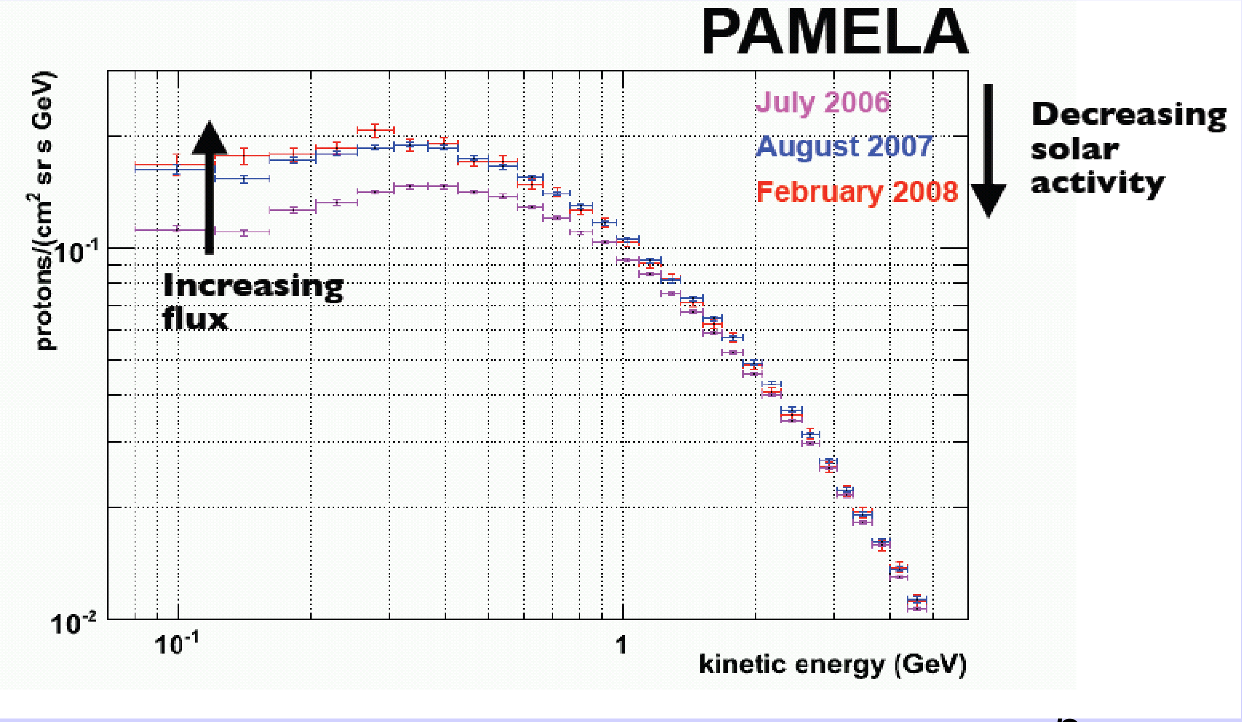
- the processes which participate in the particles transportation are
  → **diffusion**: it depends upon the particle density and the diffusion coefficient
  → **convection**: galactic winds of charged particles
  → **reacceleration**: inhomogeneities in the galactic magnetic field (Alfvén velocity)



# Solar modulation

- Energy spectra of cosmic rays with **E < 10 GeV** are modified by the solar wind

- the intensity of the solar activity is periodic with a **11-year cycle**
- at each maximum the polarity of the solar magnetic field reverses
  → **22-year cycle**
- at the solar maximum → the flux of low energy particles is minimum

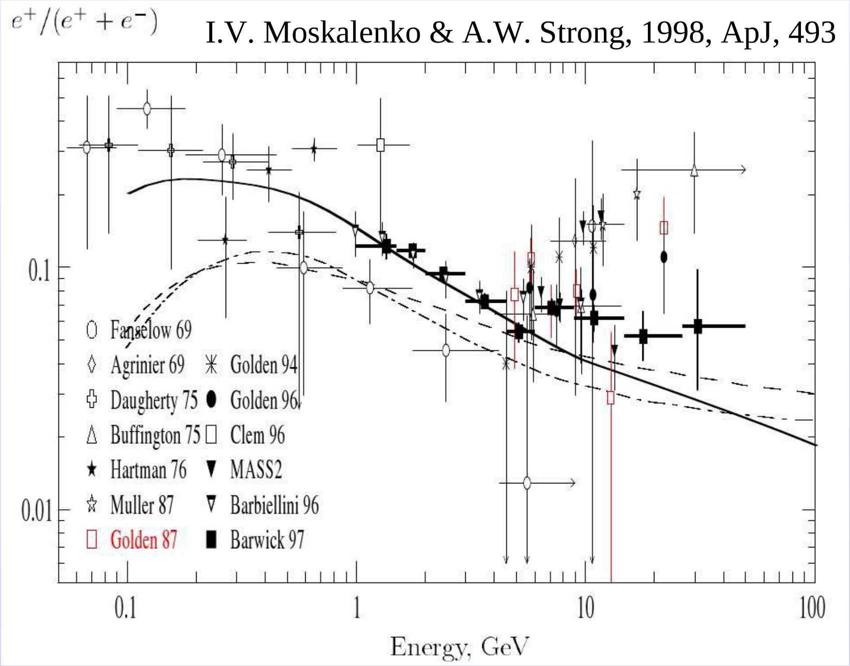


# Cosmic ray positrons

- electrons account for ~ 2% of the cosmic ray particles
- proton-to-positron flux ratio is ~ $10^4$ at 100 GV
  $\rightarrow$ positrons can probe acceleration and propagation mechanisms in a galactic region of ~ 1 kpc (synchrotron radiation, inverse Compton scattering)

- positrons are believed to be mainly secondary particles: $p + p \rightarrow \pi^\pm , K^\pm$

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu \rightarrow e^\pm + \nu_e$$
$$K^\pm \rightarrow \mu^\pm + \nu_\mu , \pi^0 + \pi^\pm$$



I.V. Moskalenko & A.W. Strong, 1998, ApJ, 493

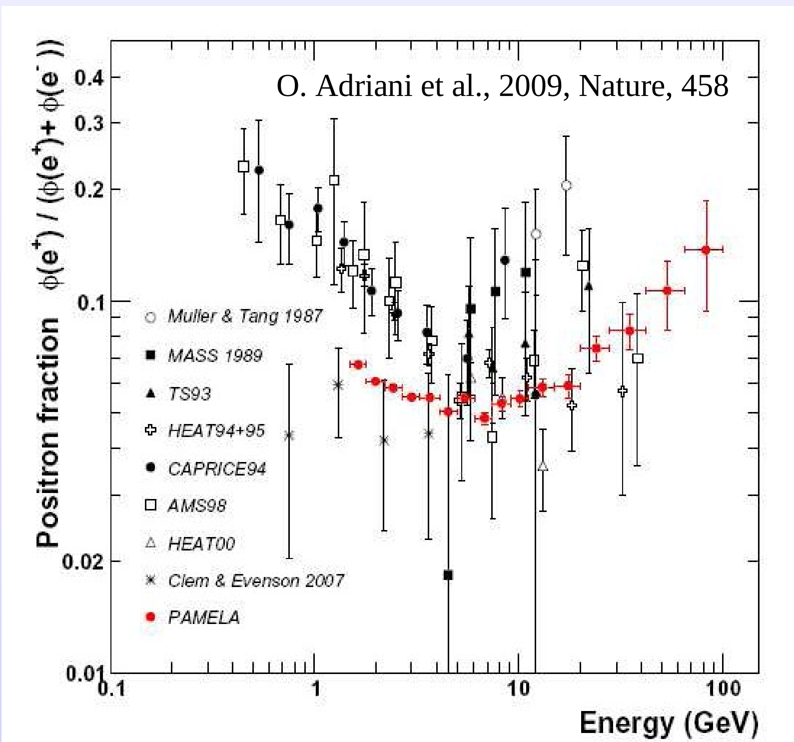
—— pure secondary production without reacceleration

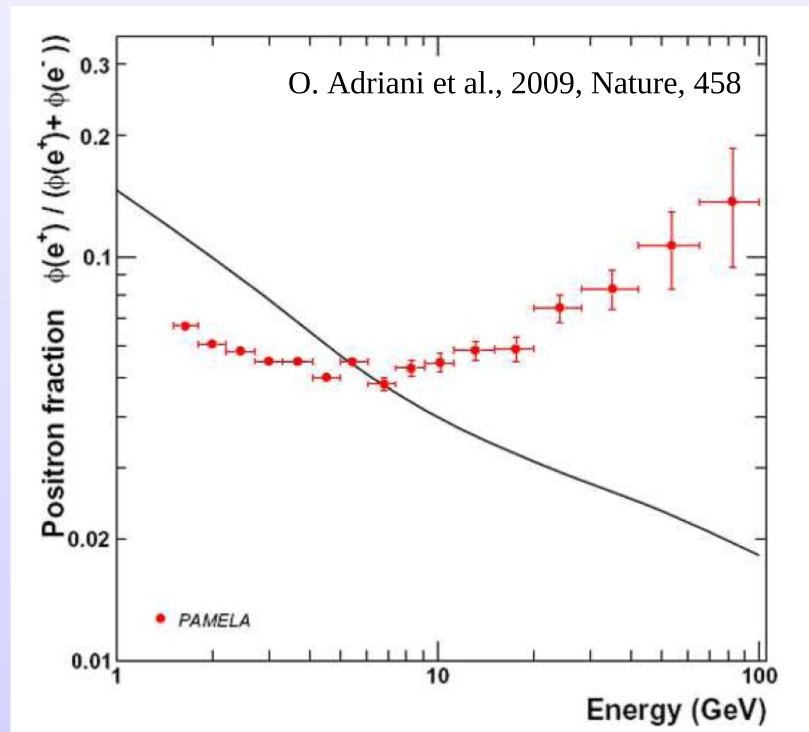
– · – leaky-box model

– – diffusion model

# PAMELA positron fraction

- Positron fraction measured between **1.5** and **100 GeV**
- result based on the data collected between July 2006 and February 2008
  → ~ $10^9$ triggers, total acquisition time of ~ 500 days
- published in the journal Nature → widely discussed, more than **600 citations**!

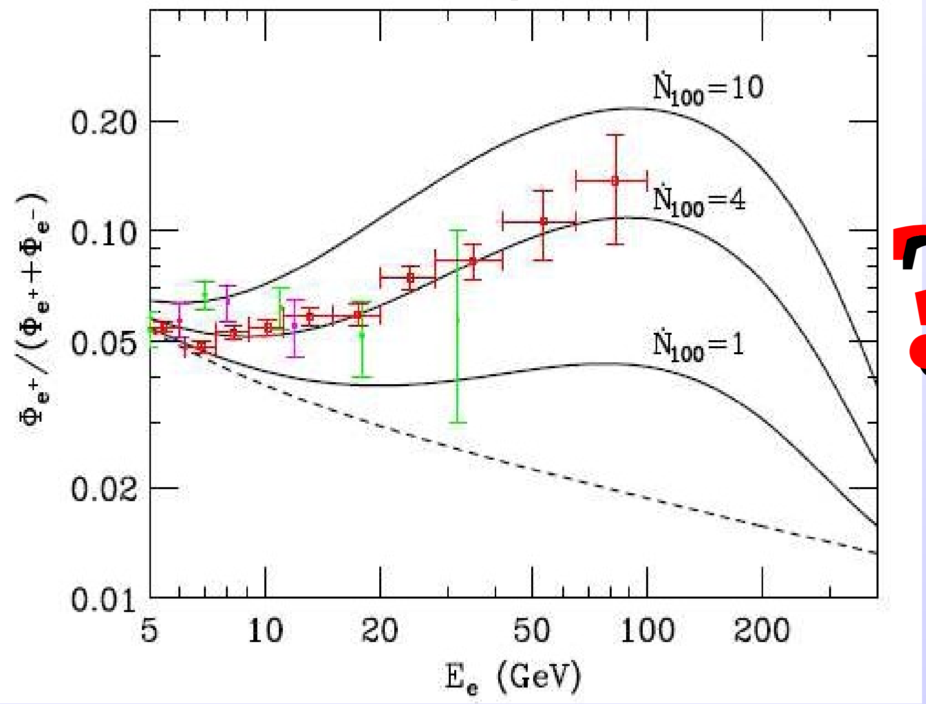


# PAMELA positron fraction

- Widely discussed → what is the reason to the rise at high energies?
- **Possible answers**:
  → pulsar magnetosphere could be source of primary cosmic ray positrons
  → primary positrons could be produced via annihilation of dark matter particles

D. Hooper et al., 2009, JCAP, 0901

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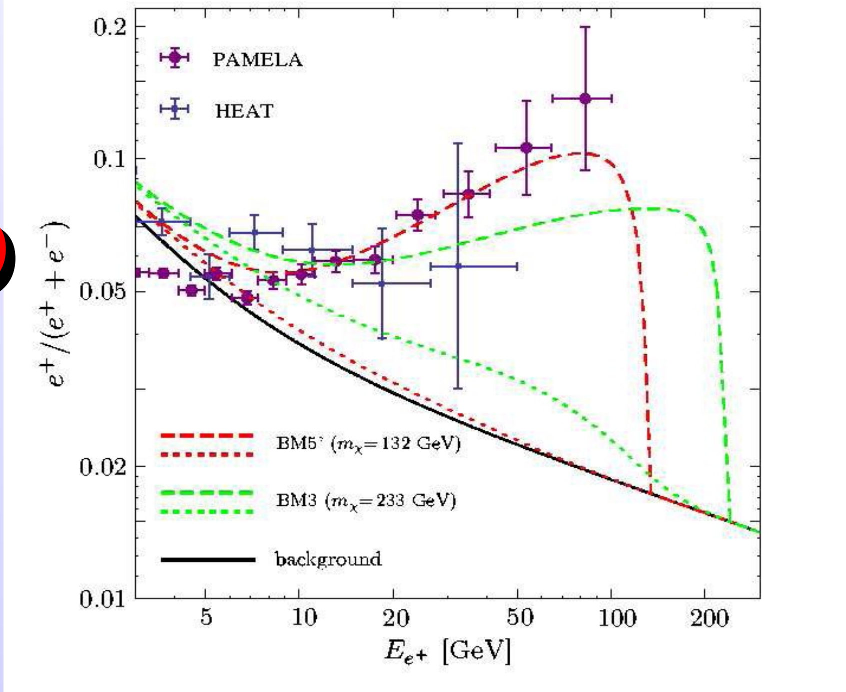
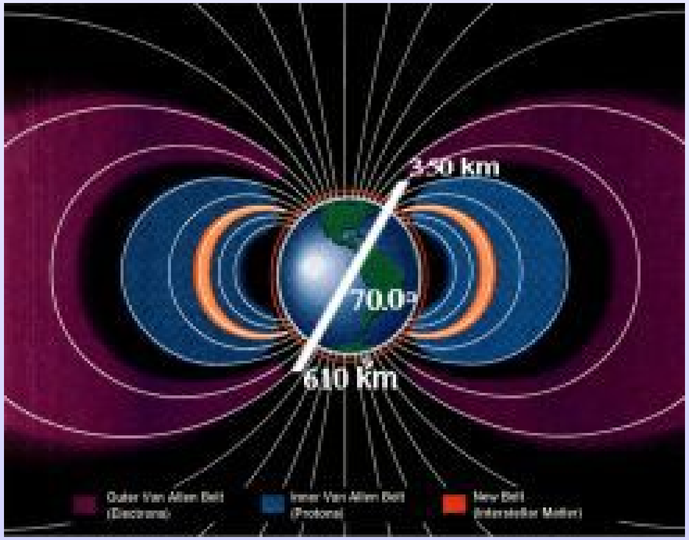
L. Bergström et al., 2008, Phys. Rev., D 78

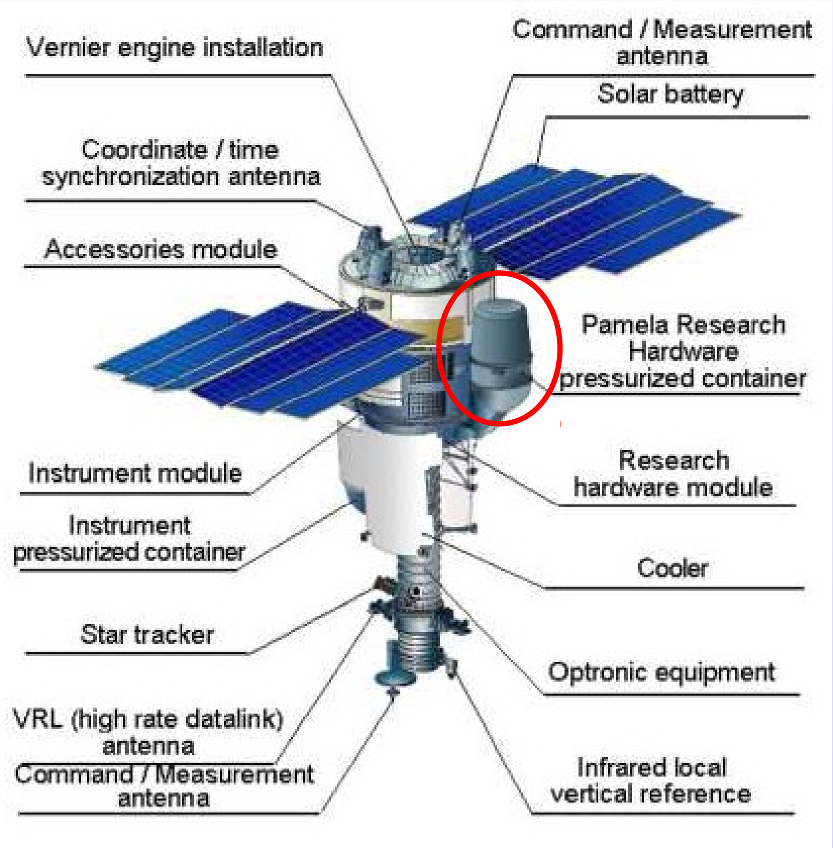


# The PAMELA experiment

- PAMELA is mounted on board of the Russian Resurs DK1 satellite
- the satellite was launched from the Baikonur cosmodrome in Kazakhstan on **June 15th 2006**
  → elliptical and semi-polar orbit
  → altitude between **350 – 600 km**
  → inclination angle of **70°**

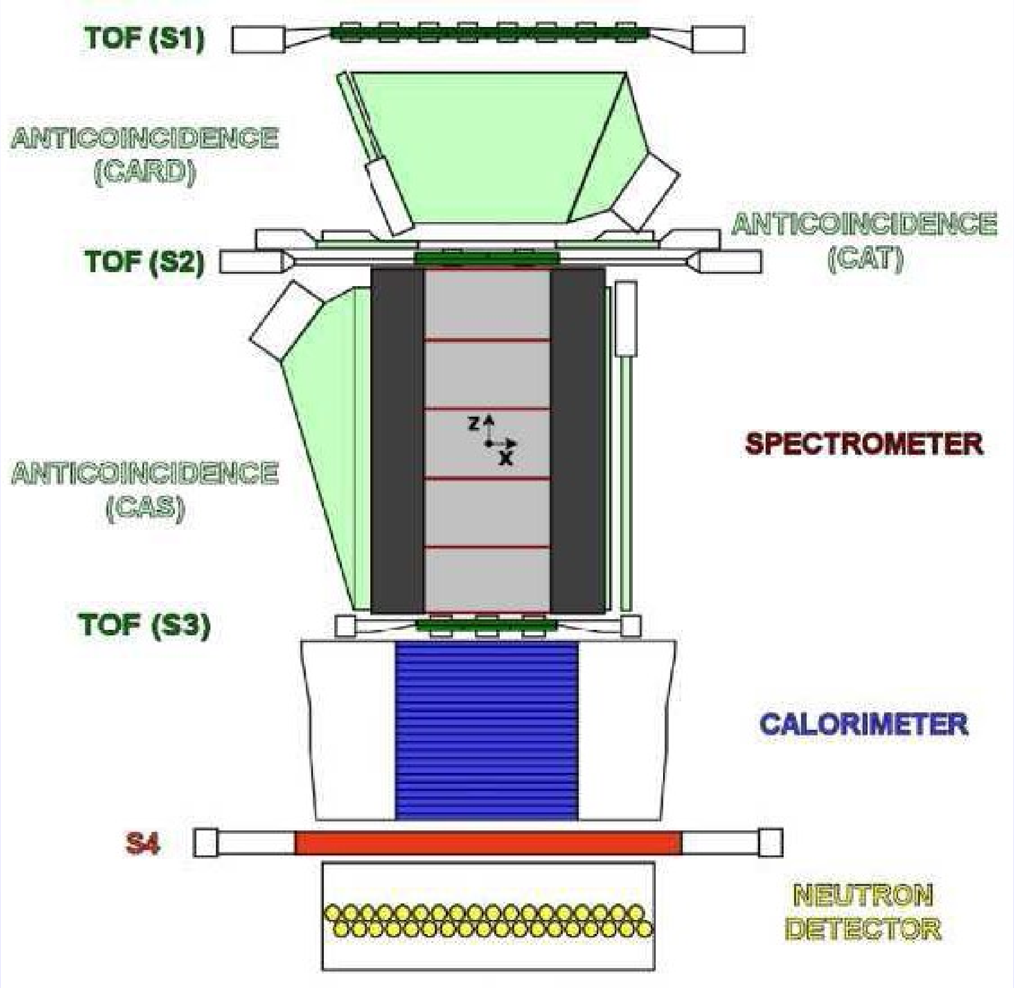



http://pamela.roma2.infn.it




P. Picozza et al., 2007, Astrop. Phys., 27

# The PAMELA experiment



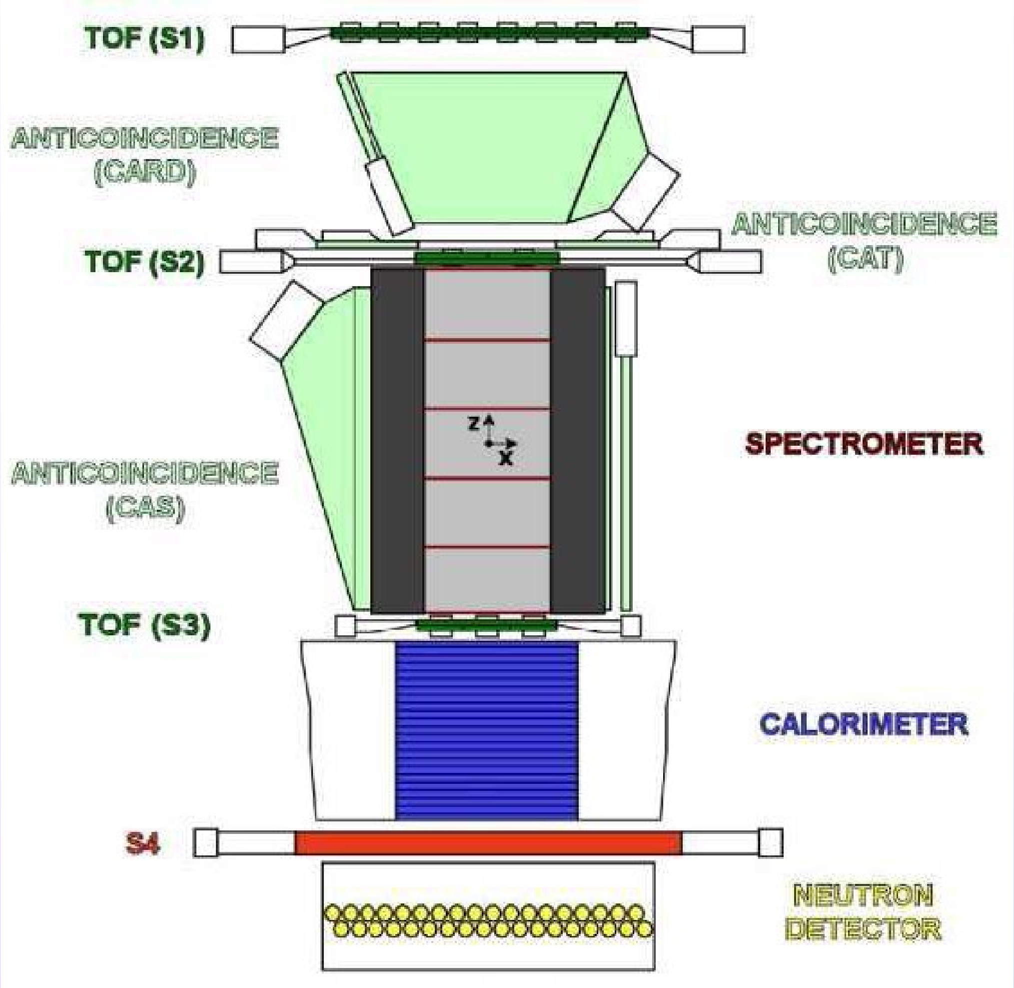

P. Picozza et al., 2007, Astrop. Phys., 27

- height of ~ 1.3 m
- mass of 470 kg
- power consuption of 355 W

- time-of-flight system
- magnetic spectrometer
- electromagnetic calorimeter
- neutron detector
- anticoincidence system

- geometrical acceptance
  21.5 $cm^2$ sr
  → determined by the geometry of the spectrometer cavity

# The PAMELA experiment

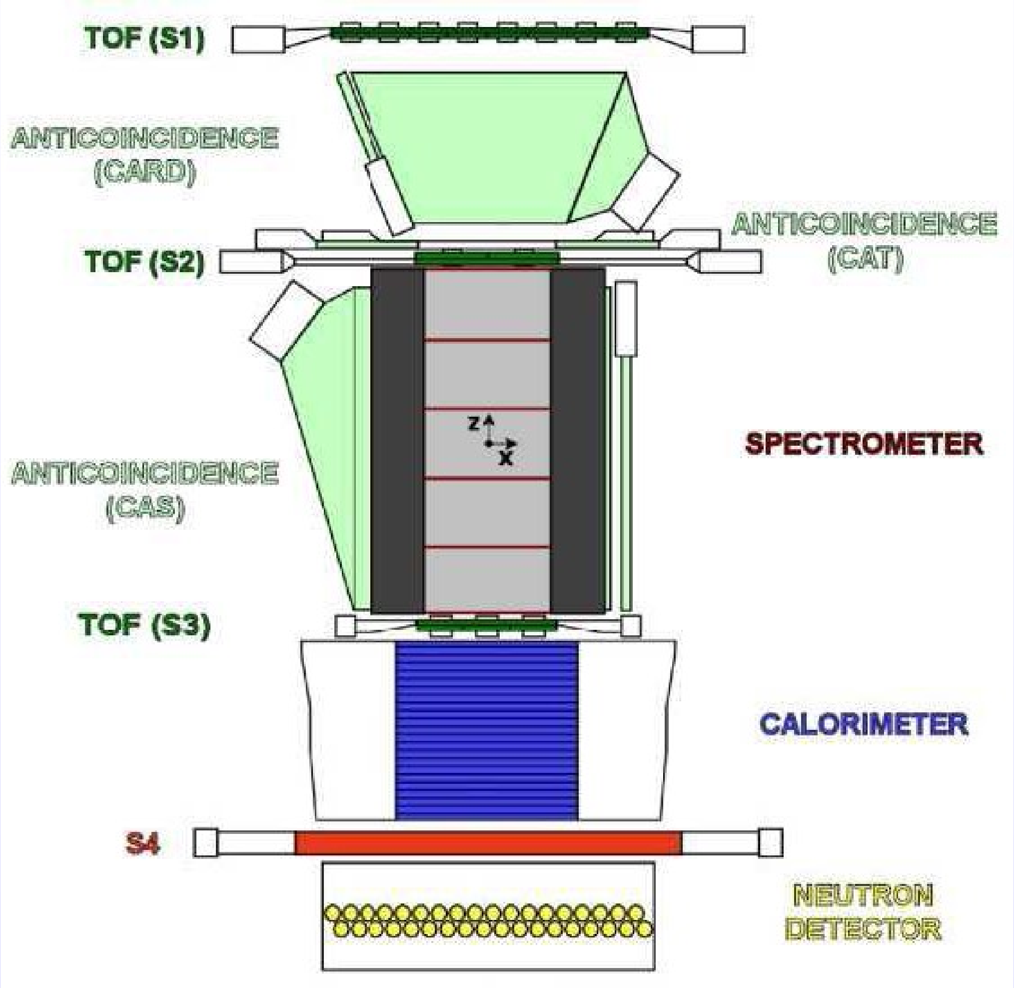



P. Picozza et al., 2007, Astrop. Phys., 27

- **time-of-flight system**
  - → 3 scintillator layers
  - → dE/dx, charge z
  - → flight time, velocity $\beta$
  - → time resolution ~ 250 ps
    lepton – hadron separation
    up to ~ 1 GeV/c

- **magnetic spectrometer**
  - → permanent magnet, B = 0.43 T
    along the y-direction
  - → 6 silicon detector planes
    300 μm thick
  - → deflection $\eta = 1 / R$
    $R = c \cdot p / Z \cdot e$

# The PAMELA experiment




P. Picozza et al., 2007, Astrop. Phys., 27

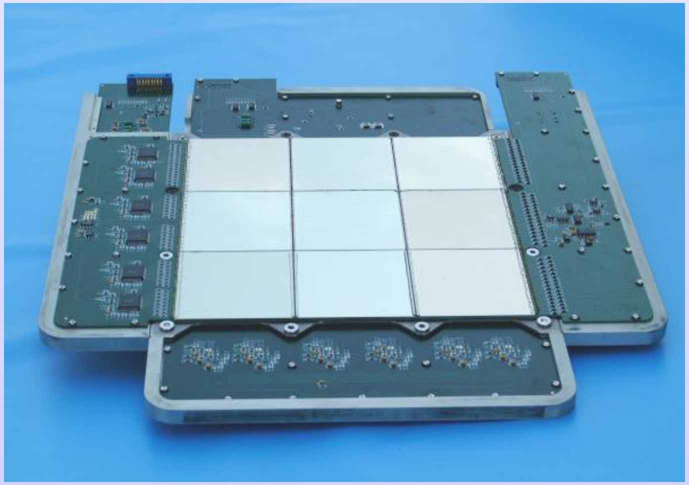
- **electromagnetic calorimeter**
  → 44 silicon sensor planes (x-y) interleaved with 22 W planes
  → total depth = 16.3 $X_0$ ~ 0.6 $\lambda$
  → lepton – hadron separation
- **neutron detector**
  → 36 counters filled with $^3$He in 2 planes
- **anticoincidence system**
  → 4 plastic scintillators (CAS)
  → 1 plastic scintillator (CAT)
  → 4 plastic scintillators (CARD)
  → identify false trigger events

# The PAMELA calorimeter

- 44 silicon sensor planes interleaved with 22 plates of tungsten absorbers
- silicon detectors total sensitive area ~ (24 × 24) cm$^2$ arranged in a 3 × 3 matrix
  → each silicon detector is segmented into 32 strips, 96 strips for each plane

- layout of one plane → Si – X / W / Si – Y

- the total depth is **16.3 $X_0$** → up to E ~ 1 TeV the maximum of the electromagnetic cascade is well contained
- the total depth is ~ **0.6 λ** → ~ 40% of hadronic particles do not interact

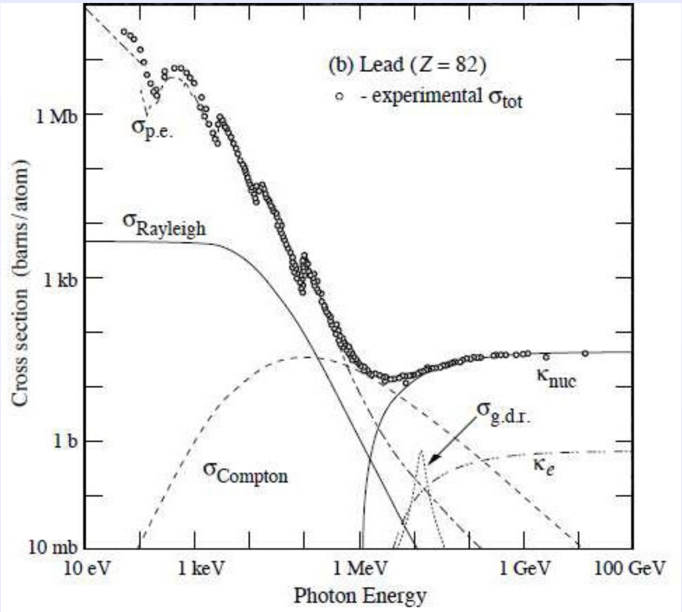


http://pamela.roma2.infn.it

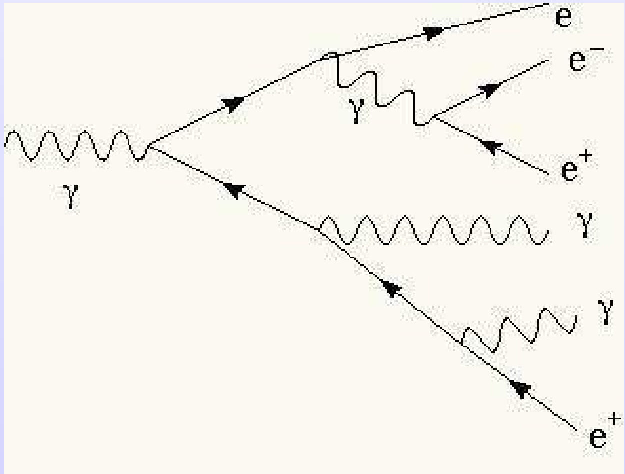
# Electromagnetic showers

- Electrons or positrons → Ionization, bremmstrahlung
- photons → photoelectric effect, Compton scattering, $e^{\pm}$ pair production

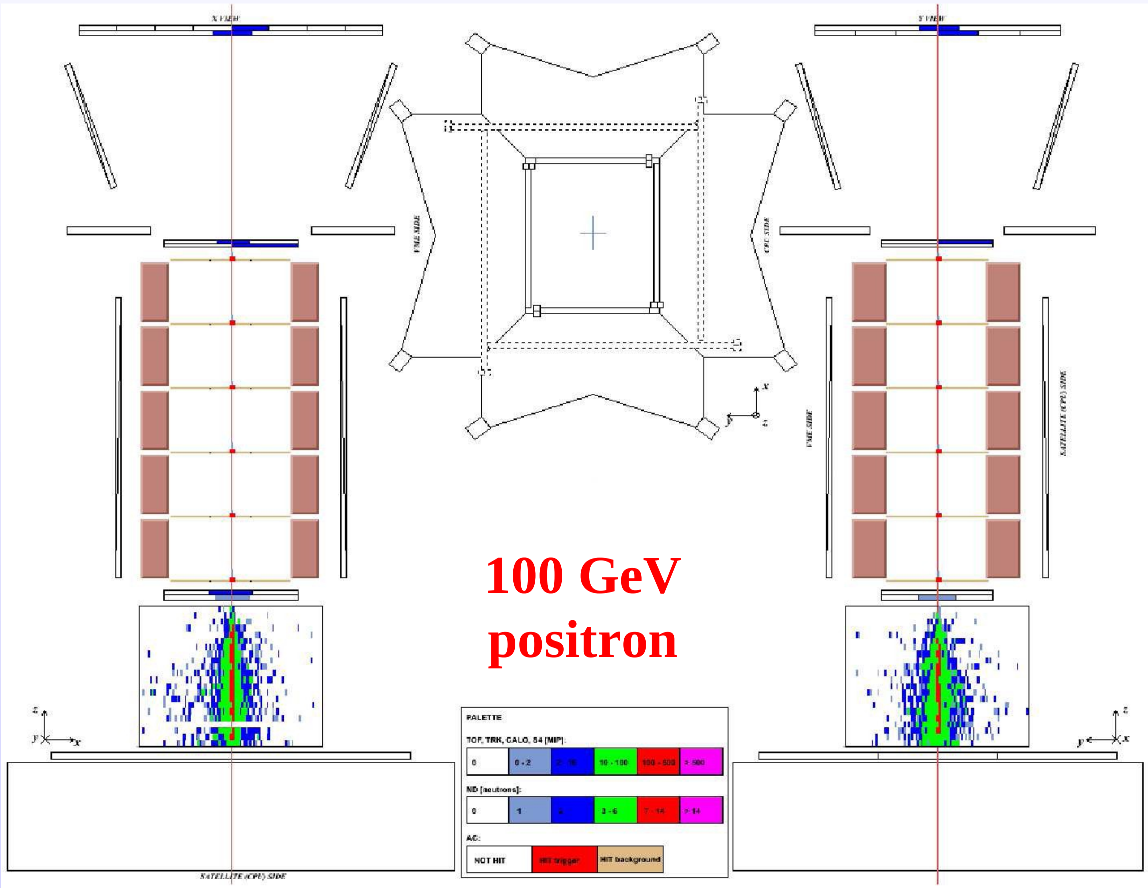
- **radiation length $X_0$** → distance over which an electron or positron loses 63.2% on average of its energy due to bremmstrahlung
- **Molière radius $\rho_M$** → about 90% of the energy is deposited in a cylinder with radius $\rho_M$ around the shower axis




Particle Data Group, 2008



# Electromagnetic showers




- **longitudinal profile**
  - → governed by the high-energy part of the cascade
  - → scales as $X_0$

- **transverse profile**
  - → characterised by a pronounced central core surrounded by a halo
  - → described in units of $\rho_M$

# Hadronic showers

- Hadronic interaction → strong interactions → more complicated shower development compared to the electromagnetic one

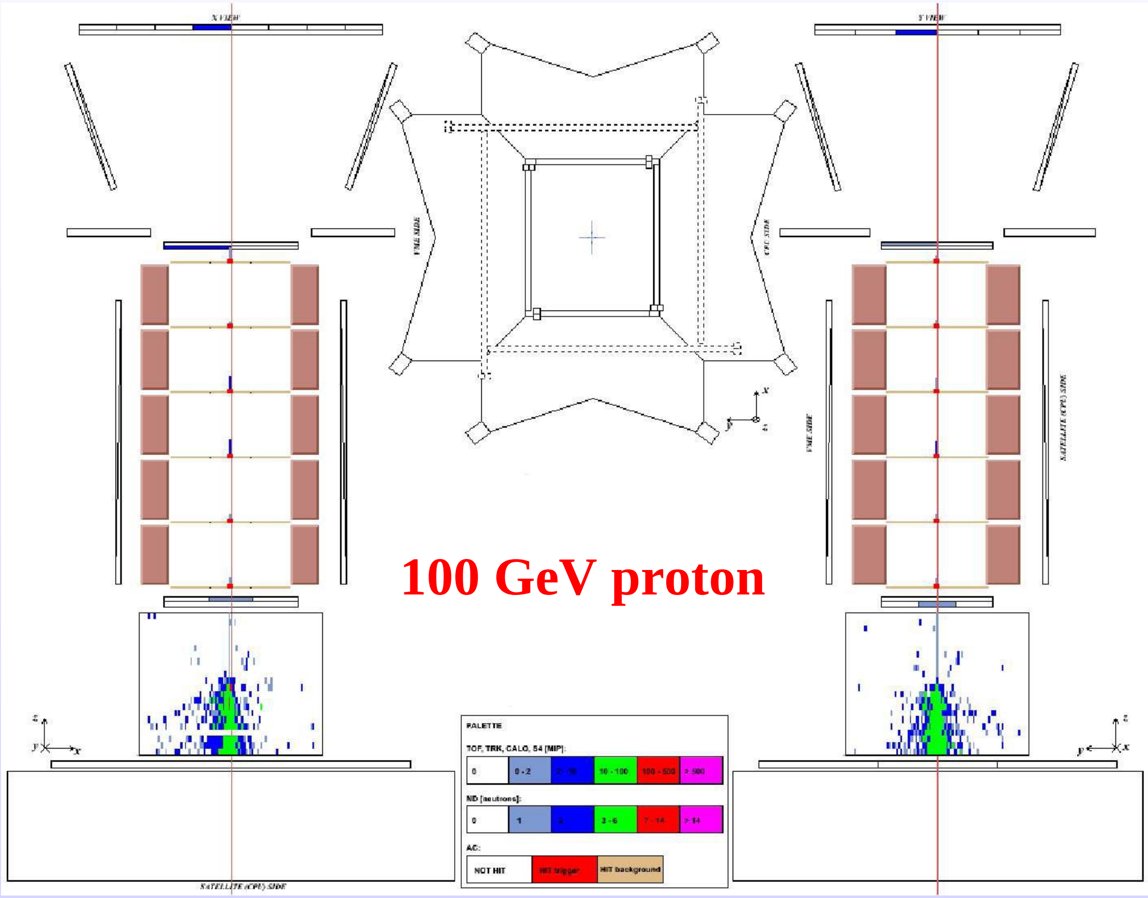
- **nuclear interaction length $\lambda_{int}$** → average distance a hadron has to travel inside an absorber medium before a nuclear interaction occurs

- secondary particles → mesons, nucleon, photons emitted in the forward direction of the primary hadron

- spallation fragments → emitted isotropically in the laboratory frame

→ longitudinal and transverse profile are very different from those of electromagnetic showers

# Hadronic showers




- **longitudinal profile**
  → any maximum lies deeper in the calorimeter for a given incident energy

- **transverse profile**
  → it is broader
  → composed by a narrow core (the electromagnetic component) and a halo (the non-electromagnetic component)

# $\pi^0$ contamination of hadronic showers

- Hadronic showers generally contain an **electromagnetic** component

$$p + N \rightarrow \pi^+, \pi^-, \pi^0 \qquad \pi^0 \rightarrow \gamma + \gamma \rightarrow e^+, e^-, \gamma\ldots$$

$\tau = 8.4 \cdot 10^{-17}$ s
probability ~ 99%

- ~ 1/3 of the mesons produced in the first interaction are $\pi^0$

$\rightarrow$ $\mathbf{f_{em} = 1 - (1 - f_{\pi^0})^n}$

n = number of generations
$(1 - f_{\pi^0})^n$ = non-electromagnetic content of the shower
$f_{\pi^0} \sim 1/3$

- the electromagnetic contamination of hadronic showers due to $\pi^0$ could affect the discrimination between positron and proton events
$\rightarrow$ it becomes extremely important within the context of the positron analysis

# Simulation studies of $\pi^0$ contamination

- Study the $\pi^0$ produced in hadronic showers within the context of the positron analysis

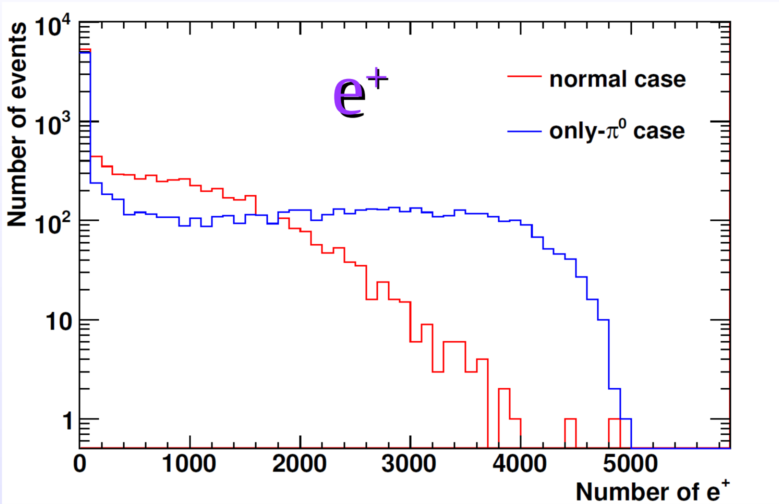
- Geant3 simulations → GPAMELA

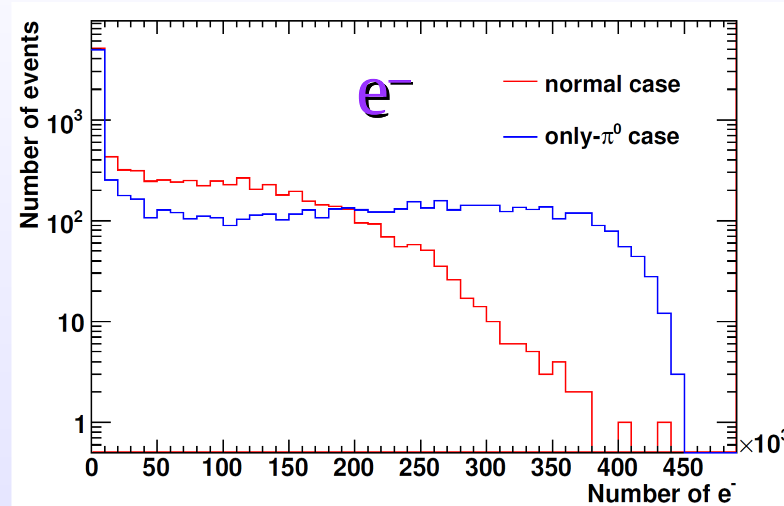
→ in the subroutine GUSTEP **every $\pi^{\pm}$** were changed into **$\pi^0$**, in order to increase the production of $\pi^0$ (without modifying the cross section of protons!!)

$p \longrightarrow N \rightarrow \pi^+, \pi^-, \pi^0$ ⇒ $p \longrightarrow N \rightarrow \pi^0, \pi^0, \pi^0$

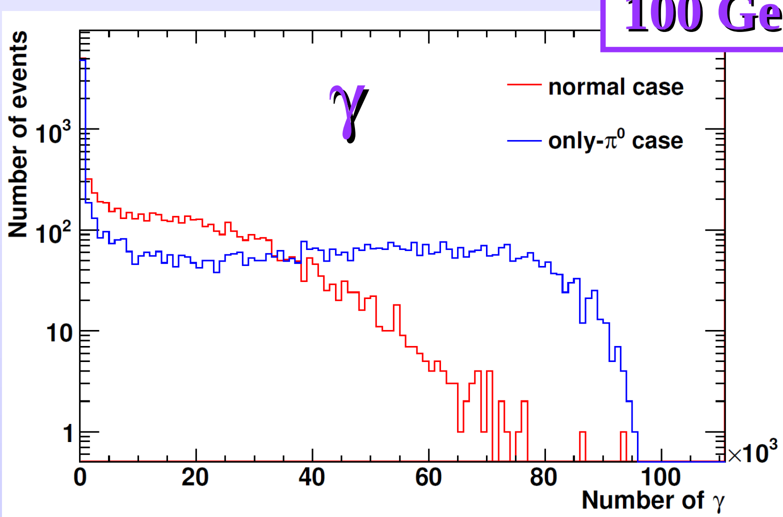
**normal case** **only–$\pi^0$ case**

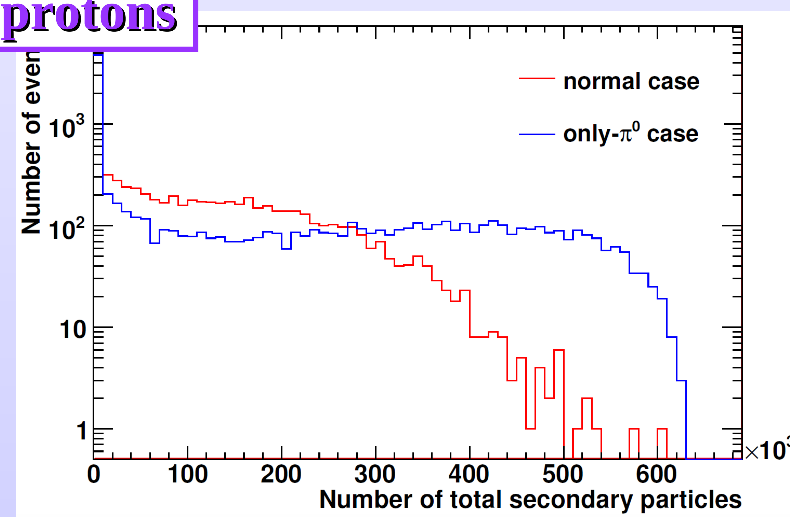
# Simulation studies of $\pi^0$ contamination




**100 GeV protons**



# Simulation studies of $\pi^0$ contamination

**E = 20 – 100 GeV**

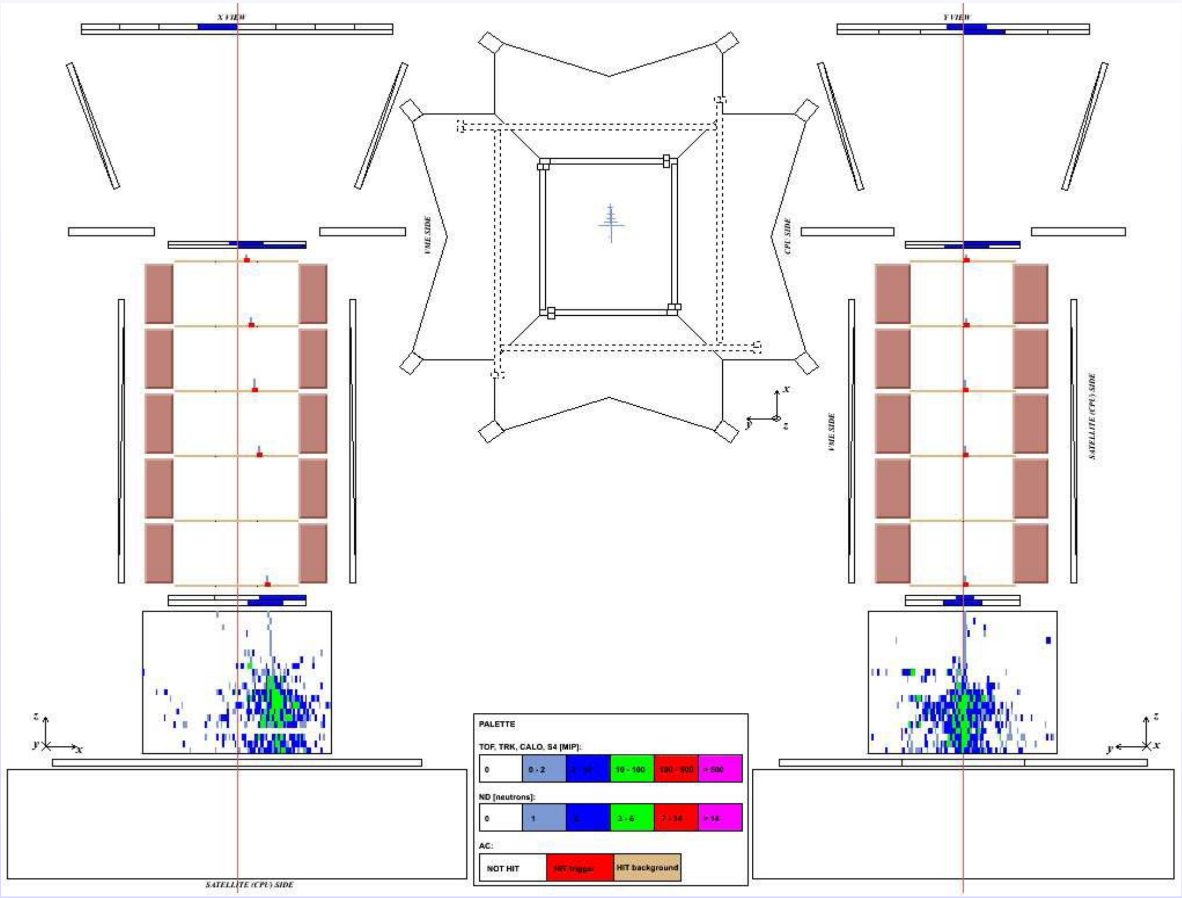
- $10^5$ protons (**normal case**)
- $5 \cdot 10^5$ protons (**only $\pi^0$ case**)

- $10^5$ positrons

power-law spectrum: $E^{-2.7}$ for protons
$E^{-3.0}$ for positrons

inclination angle: $\theta = (0 – 20)°$
azimuth angle: $\Phi = (0 – 359)°$

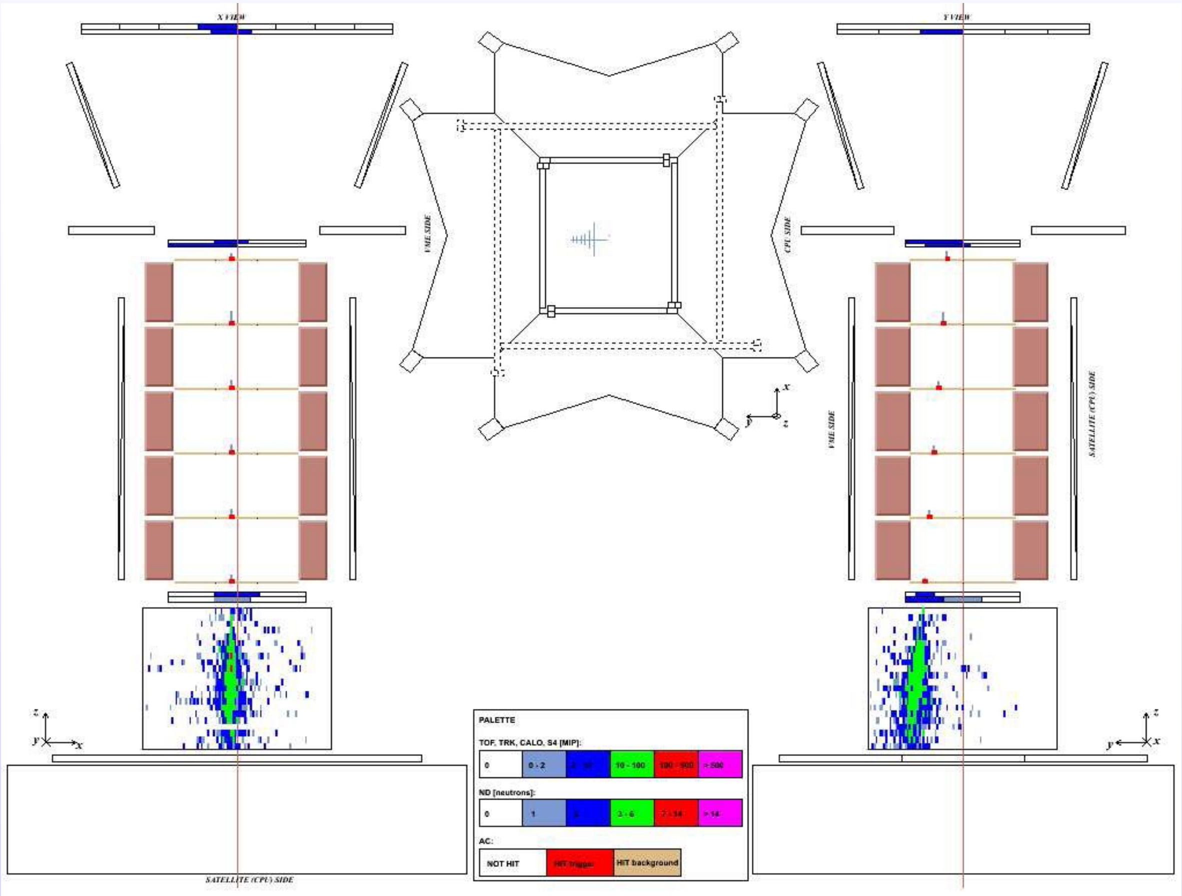
# Simulation studies of $\pi^0$ contamination



Hadronic shower development in the **only–$\pi^0$ case**

- tracker reconstructed rigidity $R = 47.6$ GV ($R = c \cdot p / Z \cdot e$)
- the shower development is similar to an **hadronic cascade**

# Simulation studies of $\pi^0$ contamination




Hadronic shower development in the **only–$\pi^0$ case**

- tracker reconstructed rigidity $R = 41.6$ GV $(R = c \cdot p / Z \cdot e)$
- the shower development is similar to an **electromagnetic cascade** → **problematic!!**

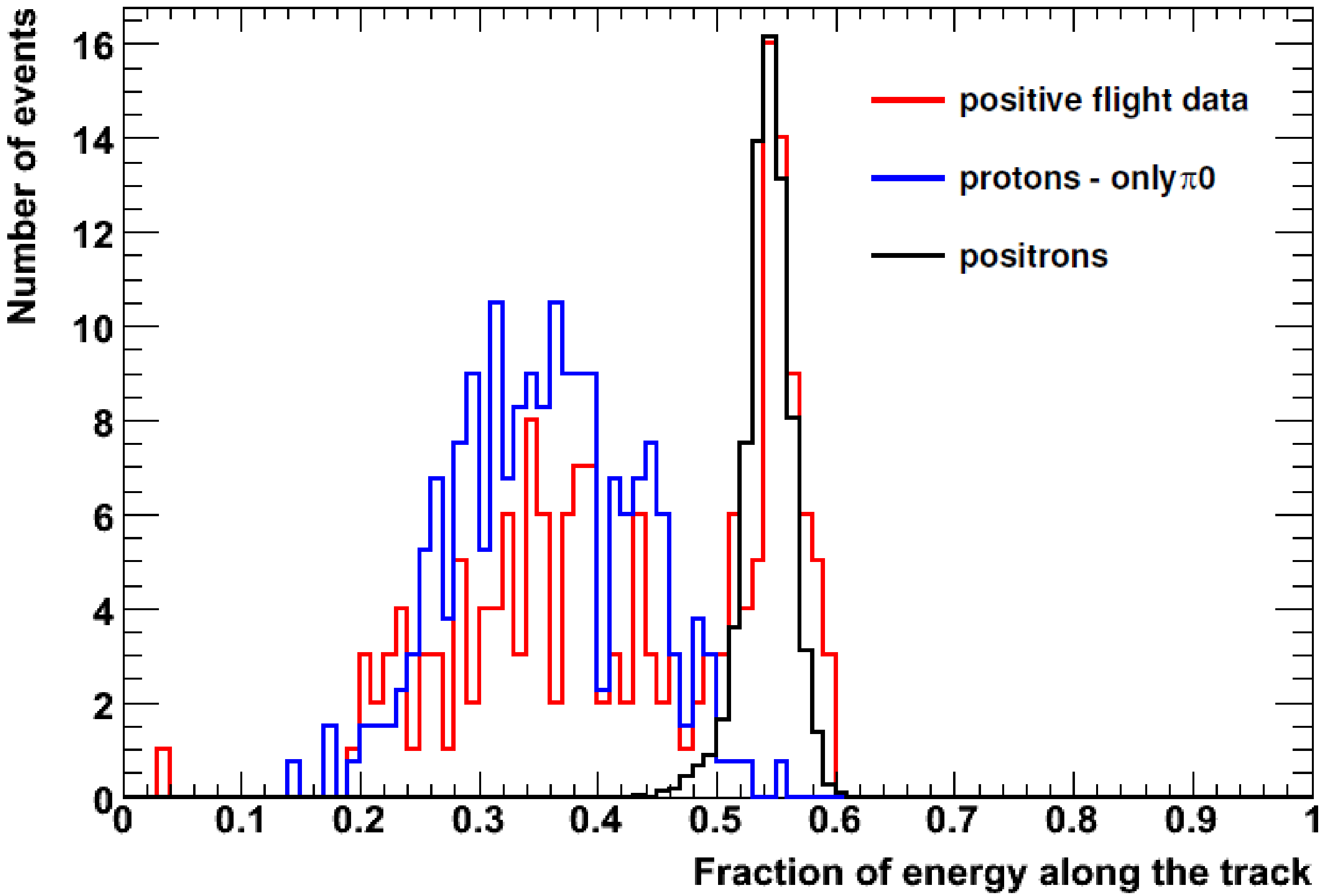
# I – The "Nature analysis" approach

- Evaluate the $\pi^0$ contamination in positron selection when following the "**Nature analysis**" approach

- the positron selection cuts used on Nature have been applied to positron and proton simulated samples

- distributions of the energy fraction (q3) have been compared with positively charged particles in flight data in order to investigate the $\pi^0$ contamination

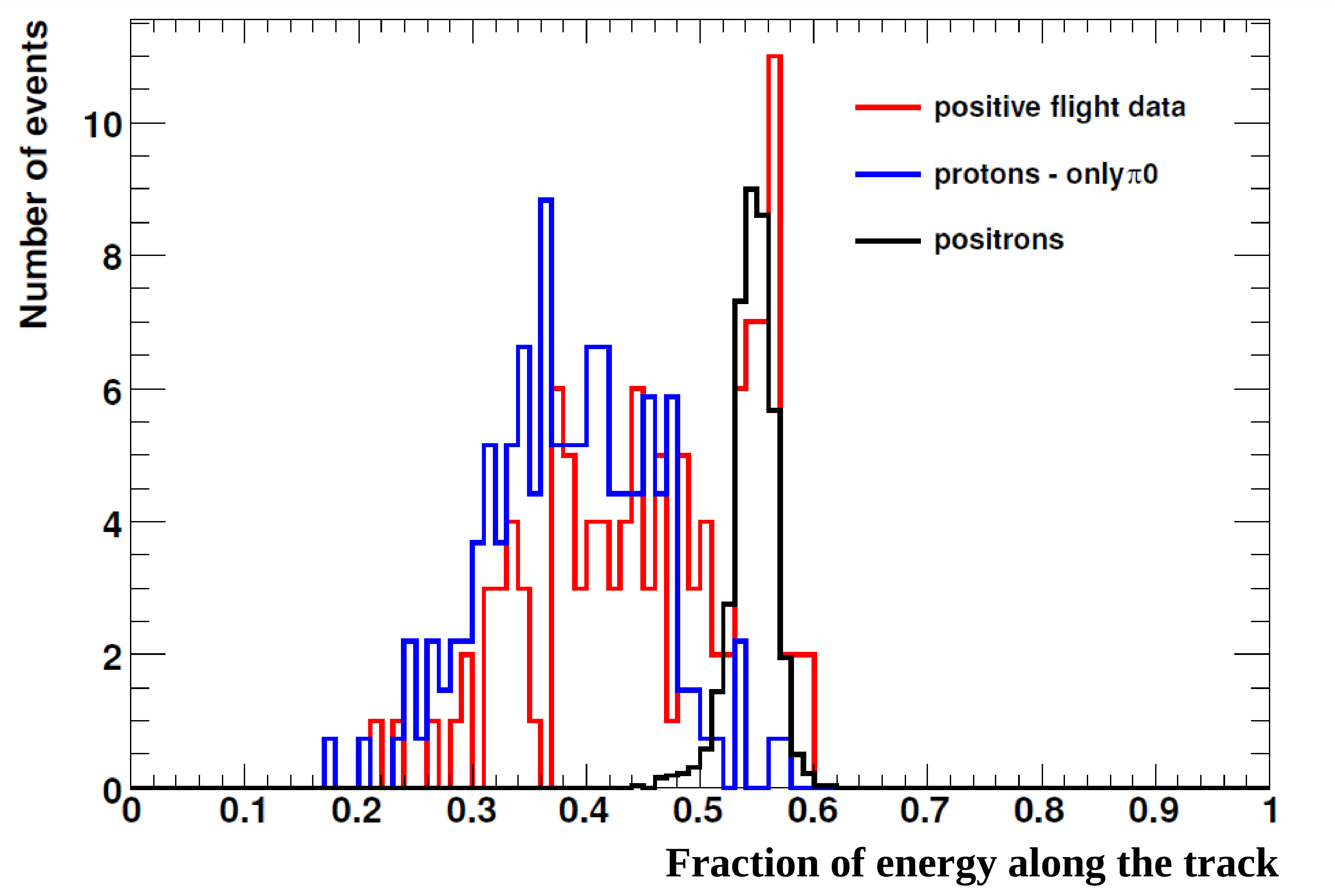
# 28 – 42 GV




q3 ≥ 0.5 selects → 3 protons – only-$\pi^0$ (simulations)

71 positive flight particles → 3/71 = 0.042

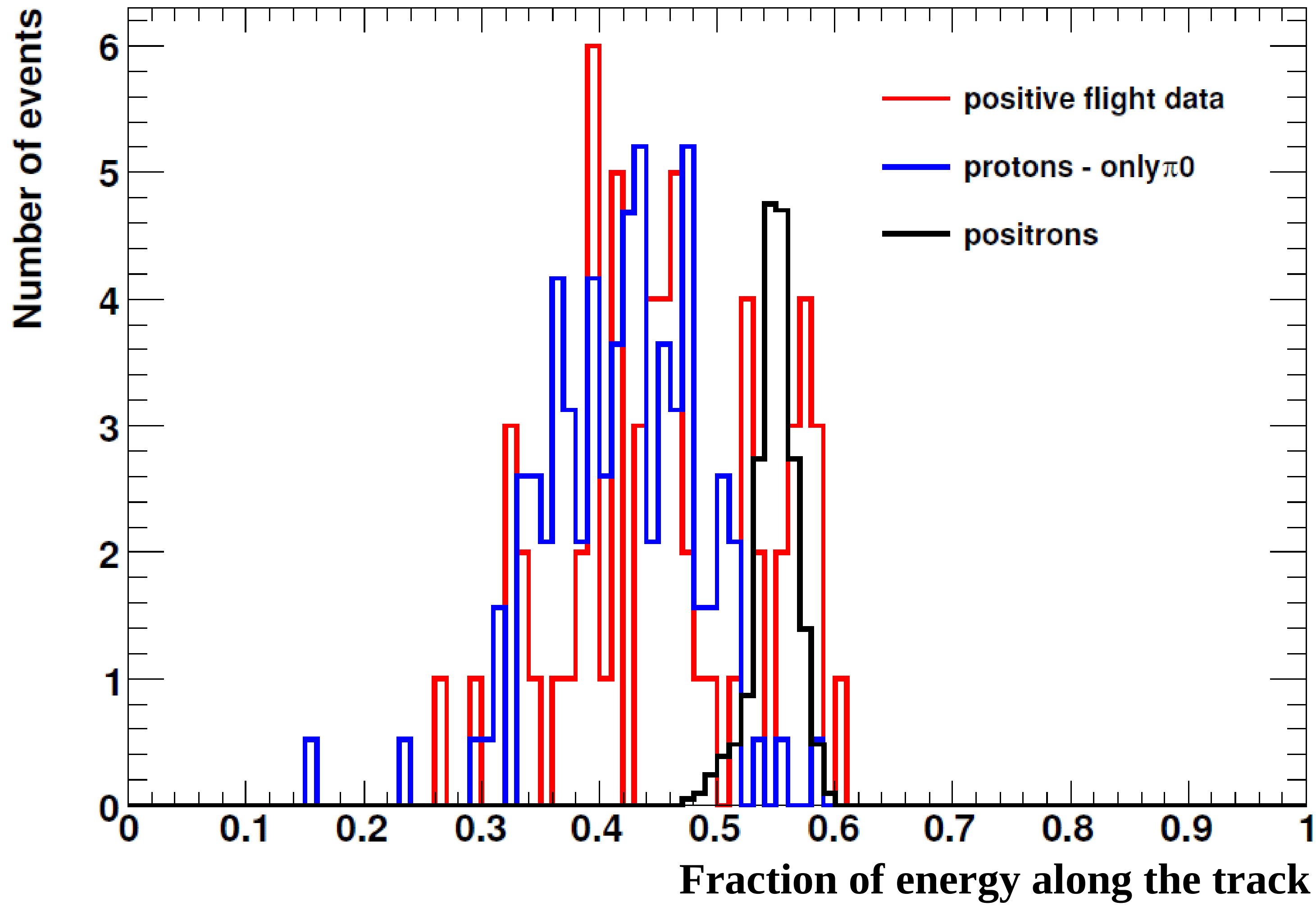
# 42 – 65 GV




q3 ≥ 0.52 selects → 4 protons – only-$\pi^0$ (simulations)

39 positive flight particles → 4/39 = 0.102

# 65 – 100 GV




q3 ≥ 0.52 selects → 2 protons – only-$\pi^0$ (simulations)

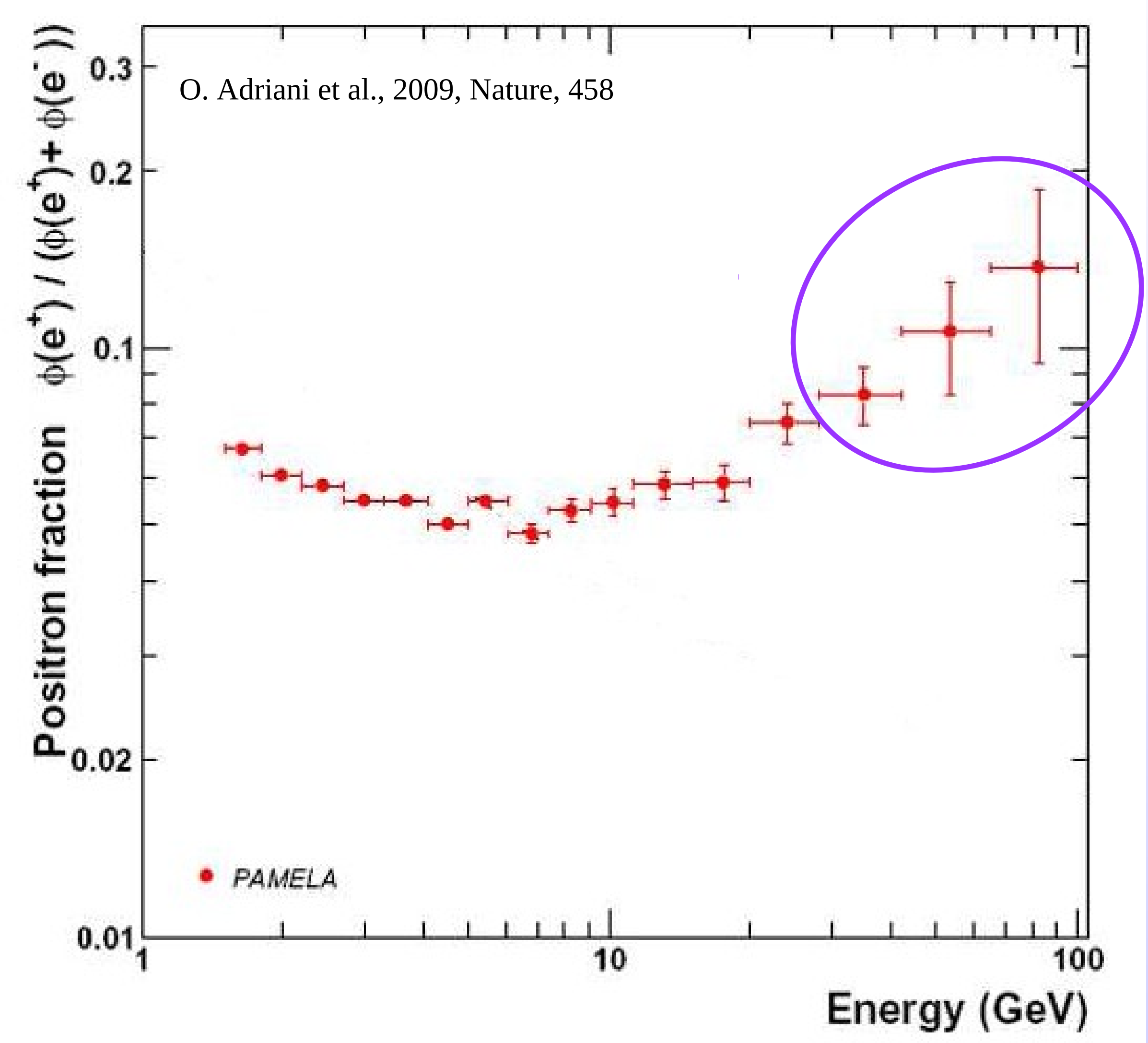
19 positive flight particles → 2/19 = 0.105

# I – Positron fraction

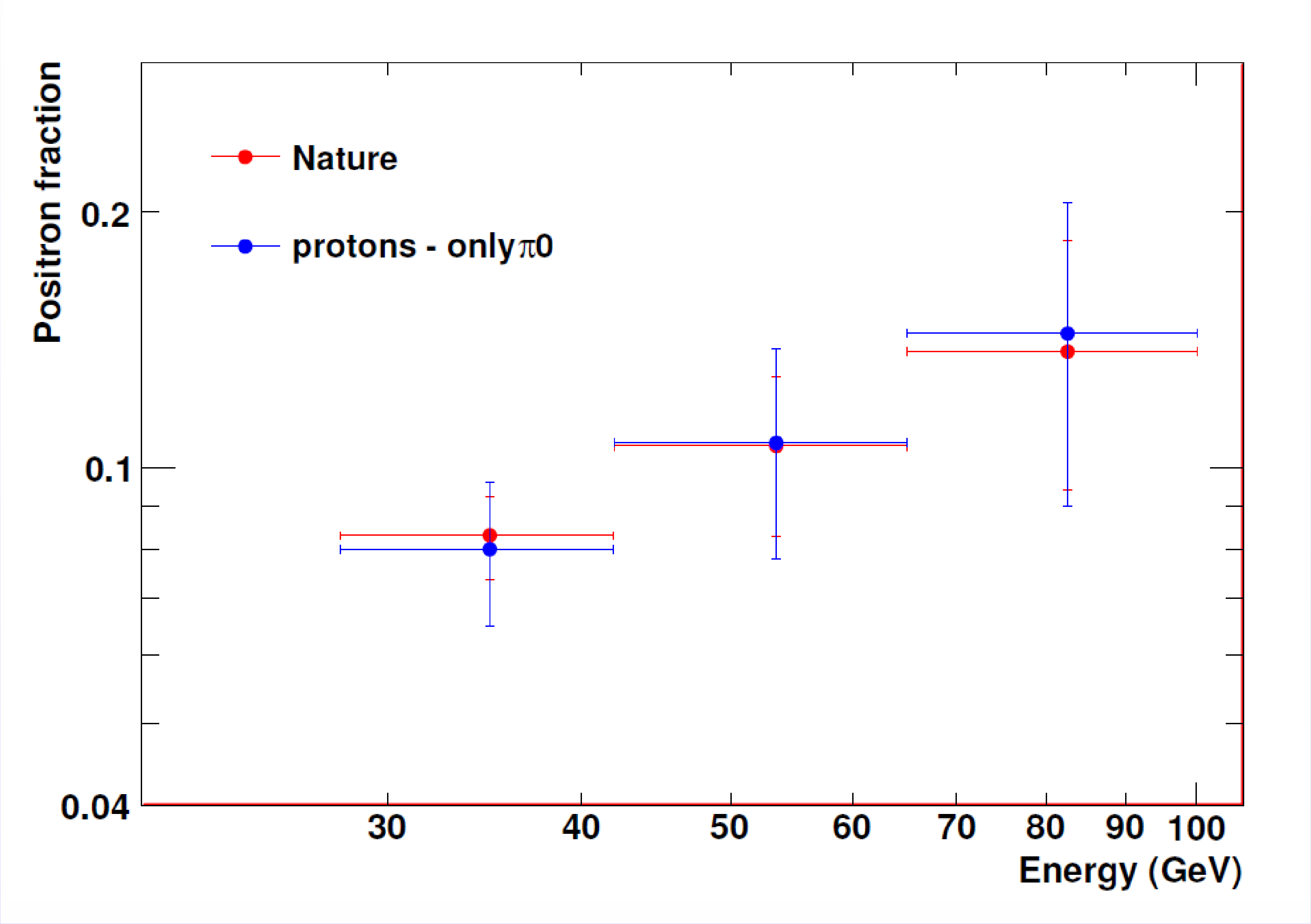
| | Rigidity (GV) | p *only*-$\pi^0$ | positive particles | p *only*-$\pi^0$ / positive particles |
|---|---|---|---|---|
| q3 ≥ 0.5 | 28 - 42 | $3^{+5}_{-2}$ | 71 | $0.042^{+0.066}_{-0.030}$ |
| q3 ≥ 0.52 | 42 - 65 | $4^{+5}_{-3}$ | 39 | $0.102^{+0.131}_{-0.067}$ |
| q3 ≥ 0.52 | 65 - 100 | $2^{+4}_{-2}$ | 19 | $0.105^{+0.226}_{-0.086}$ |

| Rigidity (GV) | $N_{e^+}$ | $N_{e^-}$ | simulations<br>$N_{e^+}$ / ($N_{e^+}$ + $N_{e^-}$) | Nature results<br>$N_{e^+}$ / ($N_{e^+}$ + $N_{e^-}$) |
|---|---|---|---|---|
| 28 - 42 | $68^{+14}_{-13}$ | 780 | $0.080^{+0.016}_{-0.015}$ | $0.0831 \pm 0.0093$ |
| 42 - 65 | $35^{+11}_{-10}$ | 292 | $0.107^{+0.031}_{-0.029}$ | $0.106^{+0.022}_{-0.023}$ |
| 65 - 100 | $17^{+8}_{-7}$ | 101 | $0.144^{+0.061}_{-0.054}$ | $0.137^{+0.048}_{-0.043}$ |

# I – Positron fraction



# I – Positron fraction



# I – Conclusions

- The q3 distribution of positively charged particles in flight data are well reproduced by two distributions of simulated events:

  → **protons – only-$\pi^0$ case** (q3 < 0.5)

  → **positrons** (q3 ~ 0.5 – 0.6)

- no double peak q3 distribution for simulated protons in the only-$\pi^0$ case

- the positron fraction evaluated from proton simulations in the only-$\pi^0$ case is compatible with the positron fraction values published in Nature

  → **it is unlikely that the rise in the positron fraction is due to $\pi^0$ contamination of hadronic showers**

# II – A new approach for positron identification

- $\pi^0$ contamination above 100 GeV ???

- study new positron selection cuts using **shower profile variables** in the calorimeter

- standard positron selection cuts have been applied to simulated positron and proton samples in the range **E = 20 – 100 GeV**

→ find out what shower profile variables in the calorimeter permit the most efficient positron selection

→ study positron selection efficiency and the related proton contamination

# II – Shower profile variables

**qtot** → total energy deposited in the calorimeter

**qtrack** → energy deposited in the strips along the track and in the neighbouring strips on each side

**qmax** → the maximum energy detected in a strip

**qcyl** → energy deposited in a cylinder of radius 8 strips around the shower axis ($2\rho_M$ = **8.5 strips**)

**qtr** → energy deposited in a cylinder of radius 4 strips around the shower axis

**qpresh** → energy deposited in a cylinder of radius 2 strips around the shower axis and only in the first 4 planes of the calorimeter

**qtotimp** = qtot / rigidity

**qm** = qmax / qtrack

**q1** = qcyl / qtot

**q2** = qtrack / qtr

**q3** = qtrack / qtot

**qt1** = qtrack / qcyl

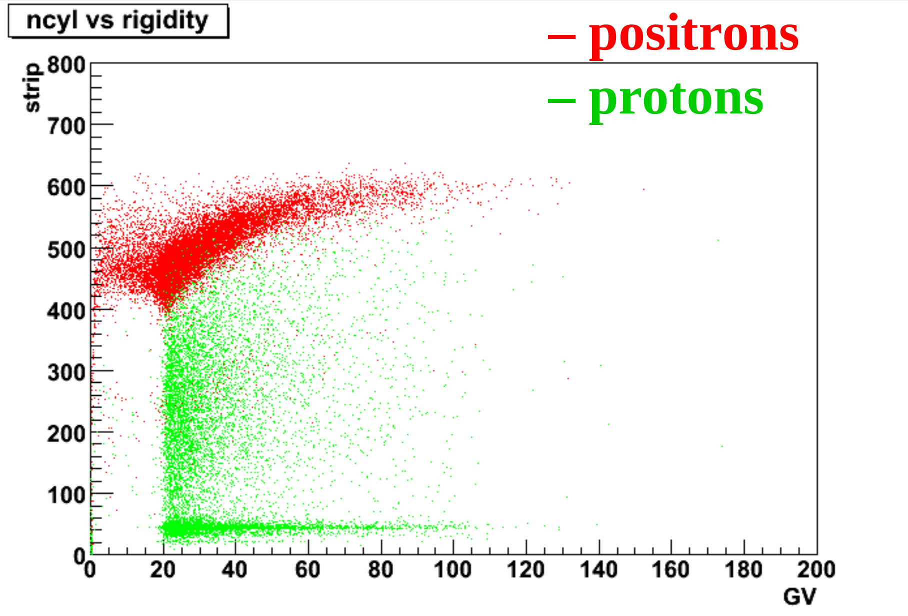
**nstrip** → total number of strips hit in the calorimeter

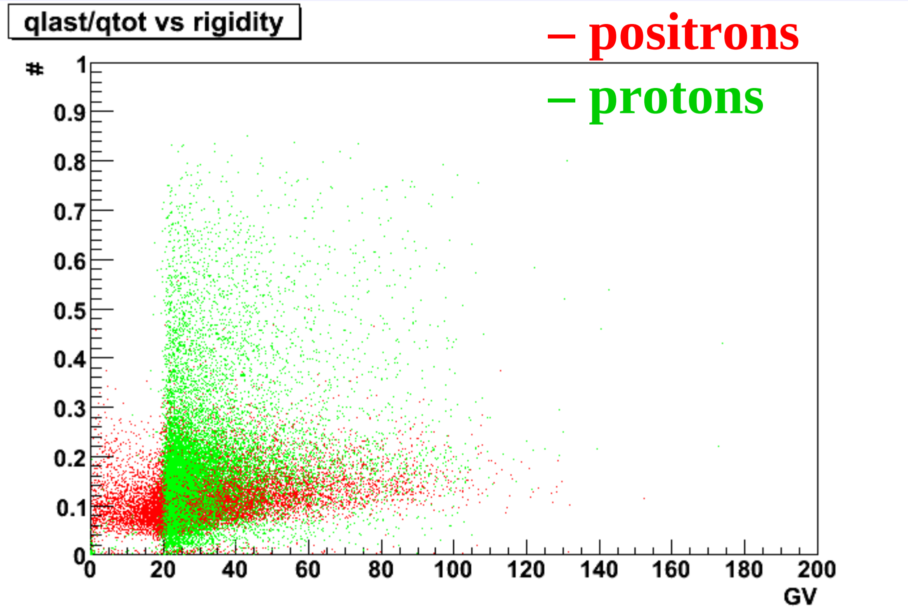
**ncyl** → number of strips hit in a cylinder of radius 8 strips around the shower axis

**ncore** → number of strips hit in a cylinder of radius $2\rho_M$ around the shower axis and up to the calculated electromagnetic shower maximum

# II – A new approach for positron identification

- study distributions of variables as function of the rigidity
  → identify what variables permit an efficient discrimination between positrons and protons




**ncyl** → number of strips hit in a cylinder of radius 8 strips around the shower axis

**qtot** → total energy deposited in the calorimeter
**qlast** → energy deposited in a cylinder of radius 4 strips around the shower axis and only in the last 4 planes of the calorimeter

# II – A new approach for positron identification

- study distributions of variables as function of the rigidity
  → identify what variables permit an efficient discrimination between positrons and protons

- construct the variable CALCHI

→ **CALCHI** $= \sum_i \chi^2_{\text{variable[i]}}$

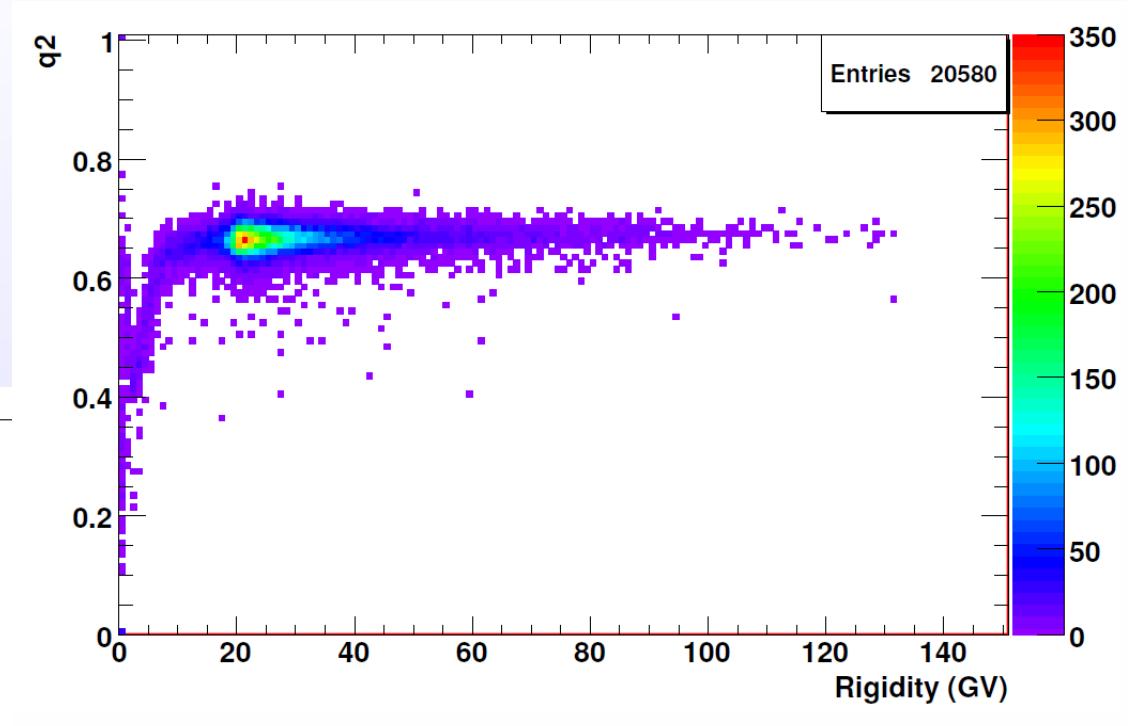
$$= \sum_i (\text{variable[i]} - \text{mean}_{\text{variable[i]}})^2 / \sigma^2_{\text{variable[i]}}$$

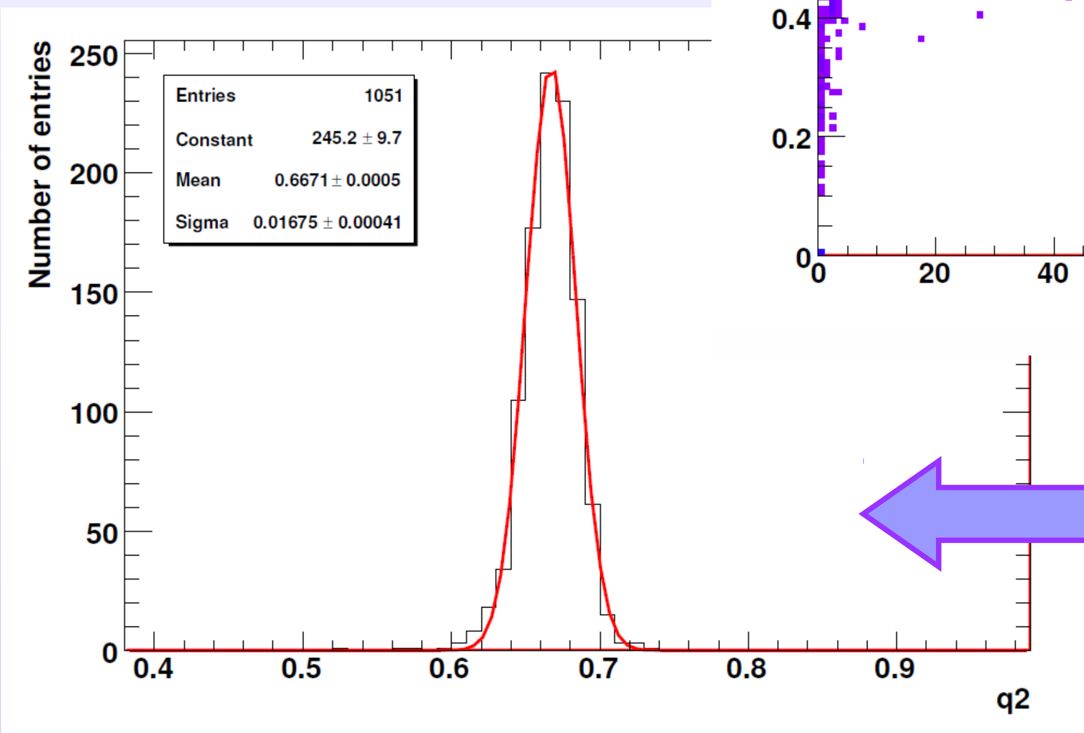
→ mean and standard deviation have been tuned on the simulated positron sample

# fit of mean and σ distributions as function of the rigidity

**20 – 100 GeV**

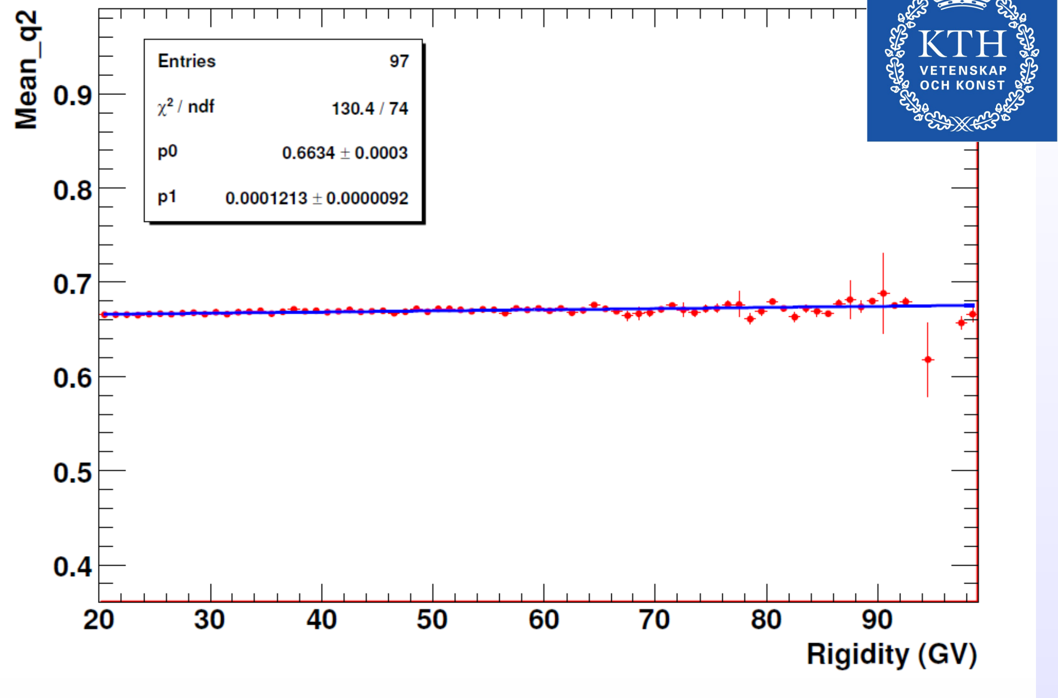
q2 = qtrack / qtr

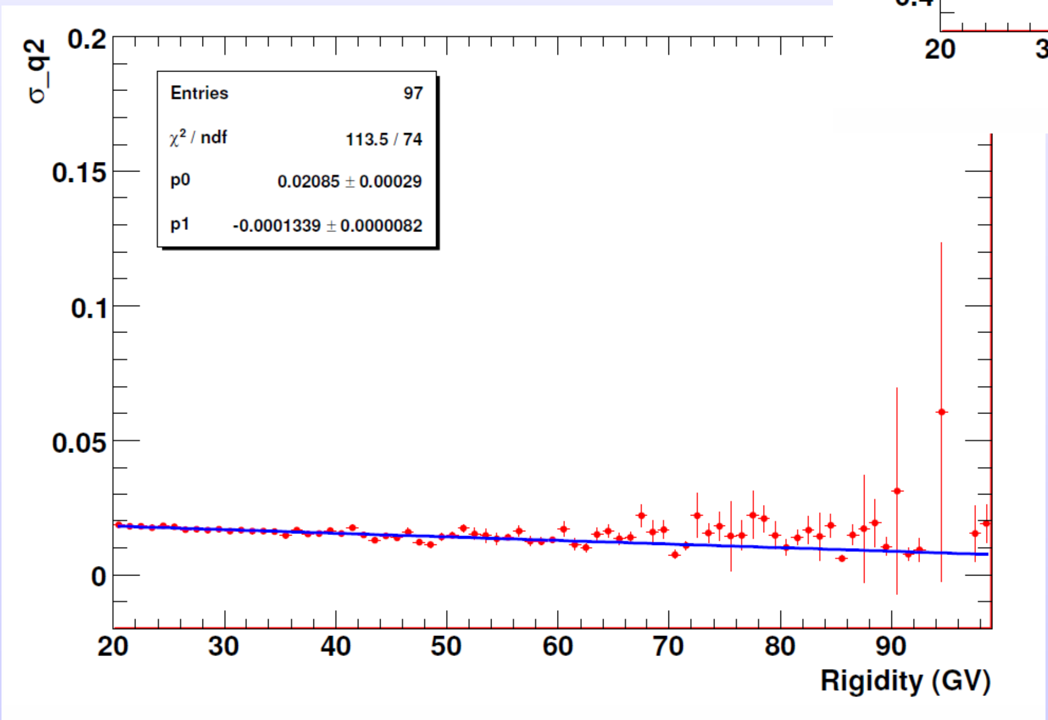



q2 distribution in the rigidity bin (30 – 31) GV

# 20 – 100 GeV




$$\text{mean}_{q2} = 0.6634 + 0.0001213 \cdot R$$

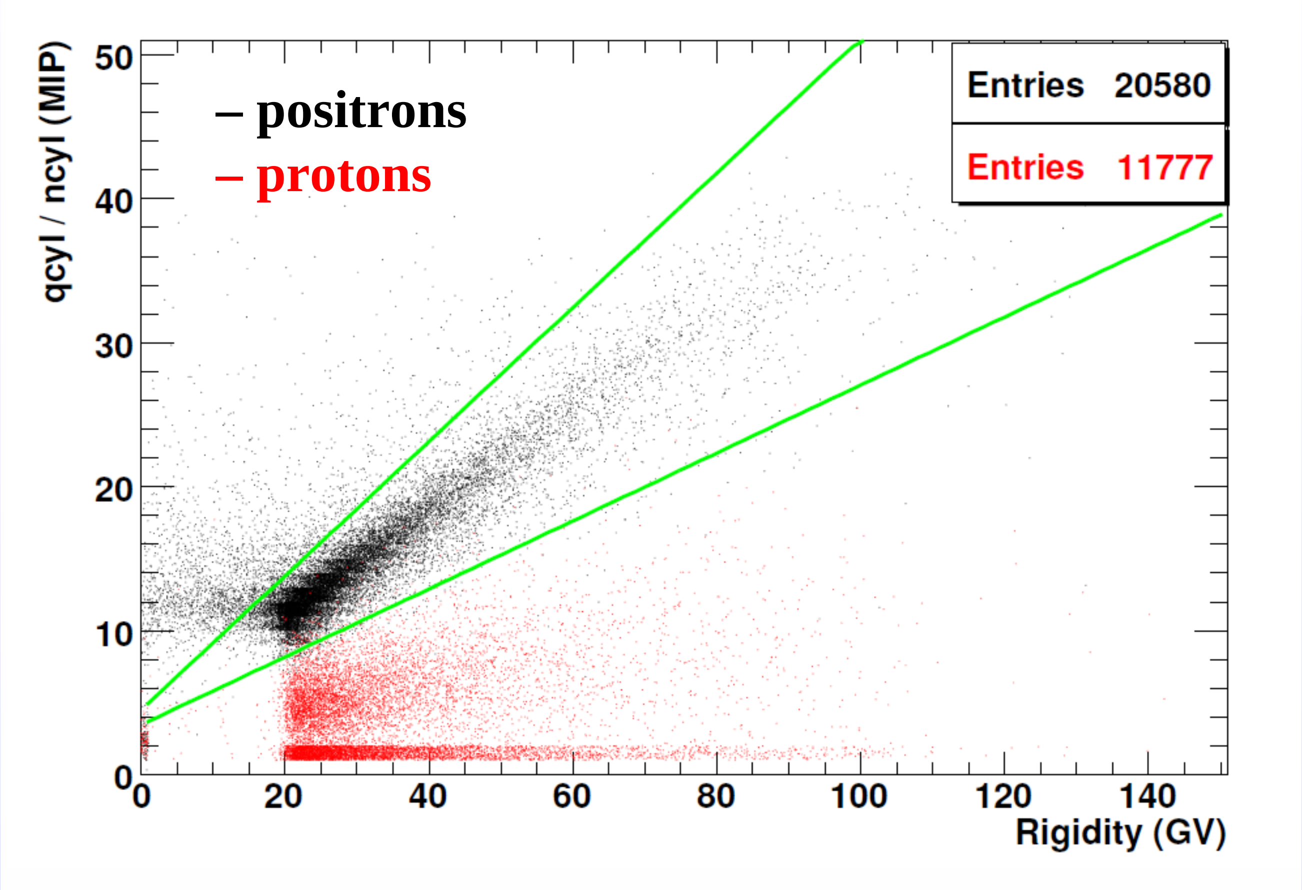
$$\sigma_{q2} = 0.02085 - 0.0001339 \cdot R$$

# II – Positron selection efficiency study

## Selections related to the transverse shower profile variables:

- $mean_{ncore} - 3 \cdot \sigma_{ncore} < ncore < mean_{ncore} + 3 \cdot \sigma_{ncore}$
- $ncyl > mean_{ncyl} - 3 \cdot \sigma_{ncyl}$
- $mean_{qcyl/ncyl} - 3 \cdot \sigma_{qcyl/ncyl} < qcyl/ncyl < mean_{qcyl/ncyl} + 3 \cdot \sigma_{qcyl/ncyl}$
- $qpresh > 50$
- $qtot/nstrip > 6$
- $CALCHI < CALCHI_{cut}$

# II – Positron selection efficiency study




$$\text{mean}_{qcyl/ncyl} - 3 \cdot \sigma_{qcyl/ncyl} < qcyl/ncyl < \text{mean}_{qcyl/ncyl} + 3 \cdot \sigma_{qcyl/ncyl}$$

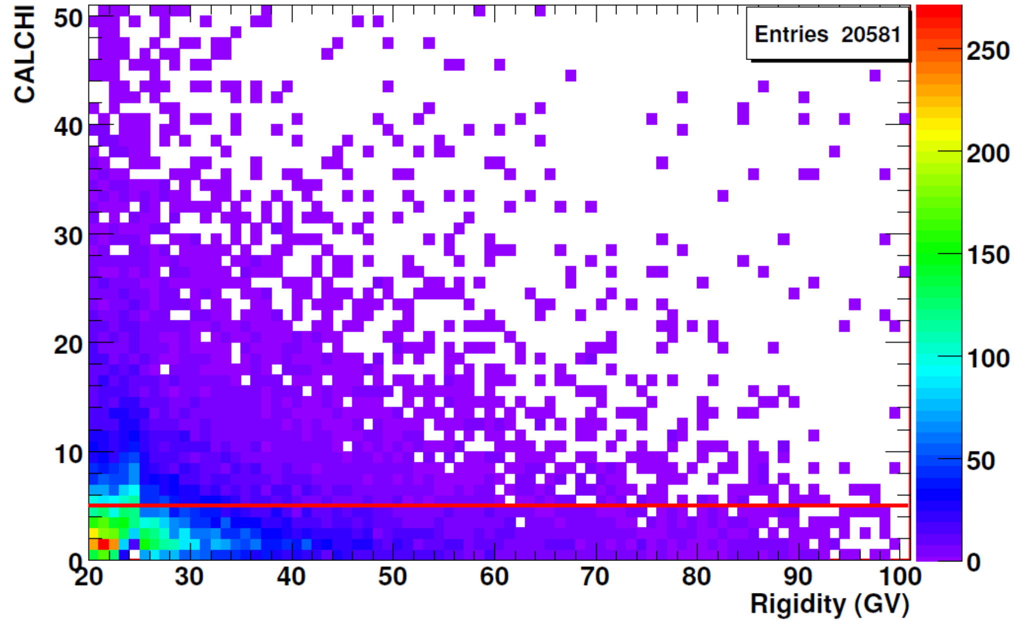
# II – Positron selection efficiency study

- Many combinations of different shower profile variables have been used in order to obtain the best positron selection efficiency with the smallest proton contamination

$$\mathbf{CALCHI} = \sum_i \chi^2_{\text{variable[i]}}$$

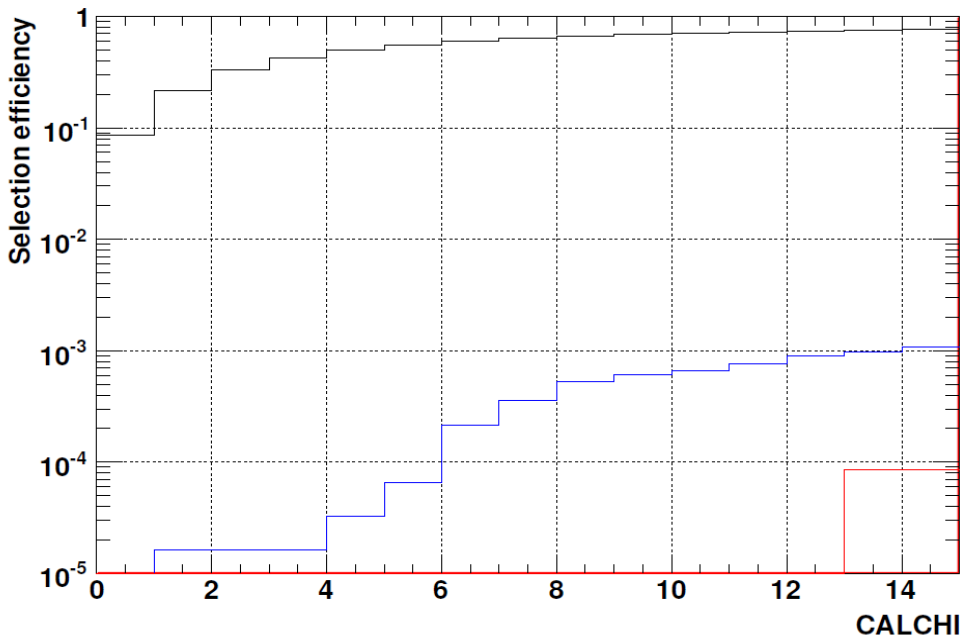
$$= \chi^2_{\text{ncore}} + \chi^2_{\text{q3}} + \chi^2_{\text{qpresh}} + \chi^2_{\text{ncyl}} + \chi^2_{\text{qcyl/ncyl}} + \chi^2_{\text{qtot/nstrip}}$$

- the selection efficiencies were studied for different values of $\text{CALCHI}_{\text{cut}}$




# 20 – 100 GeV

## CALCHI < 6
## selects 55.4% of positrons




**– positrons**
**– protons – only-$\pi^0$ case**
**– protons – normal case**

# II – Positron selection efficiency study

## Positron selection efficiencies for different CALCHI values and corresponding proton contamination

| *Only-$\pi^0$ case* | | | |
|---|---|---|---|
| $CALCHI_{cut}$ | $e^+$ efficiency | p efficiency | proton contamination |
| 3 | $0.328 \pm 0.006$ | $(1.6\ ^{+\,6.0}_{-\,1.5}) \cdot 10^{-5}$ | $(0.49\ ^{+\,1.84}_{-\,0.46}) \cdot 10^{-4}$ |
| 4 | $0.423 \pm 0.007$ | $(1.6\ ^{+\,6.0}_{-\,1.5}) \cdot 10^{-5}$ | $(0.49\ ^{+\,1.84}_{-\,0.46}) \cdot 10^{-4}$ |
| 5 | $0.497 \pm 0.008$ | $(3.3\ ^{+\,7.1}_{-\,2.7}) \cdot 10^{-5}$ | $(0.66\ ^{+\,1.42}_{-\,0.54}) \cdot 10^{-4}$ |
| 6 | $0.554 \pm 0.008$ | $(6.6\ ^{+\,8.5}_{-\,4.3}) \cdot 10^{-5}$ | $(1.19\ ^{+\,1.53}_{-\,0.77}) \cdot 10^{-4}$ |
| 7 | $0.600 \pm 0.009$ | $(2.1 \pm 1.0) \cdot 10^{-4}$ | $(3.50 \pm 1.67) \cdot 10^{-4}$ |
| 8 | $0.634 \pm 0.009$ | $(3.6 \pm 1.3) \cdot 10^{-4}$ | $(5.68 \pm 2.05) \cdot 10^{-4}$ |

proton contamination = p efficiency / $e^+$ efficiency

# II – Conclusions

- A new approach based on selections on shower profile variables was studied and tested on **simulations** in the energy range **20 – 100 GeV**

- a combination of six variables permit an efficient positron selection (e.g. **~ 0.50** considering CALCHI < 5)

- these selections yield no proton contamination in the **normal case** sample

- the proton contamination in the **only-$\pi^0$ case** sample is of order of **$10^{-5}$** (considering CALCHI < 5)

# Summary

- PAMELA calorimeter → discrimination between electromagnetic and hadronic showers induced by leptons and hadrons

- study the electromagnetic component in hadronic showers produced by $\pi^0$ using GEANT3 simulations
  → artificially boosted the number of $\pi^0$ produced in hadronic showers (**only-$\pi^0$ case** simulations)

I – the "Nature analysis" approach were applied to simulations
→ the positron fraction is in good agreement with the one published in Nature (O. Adriani et al., 2009, Nature, 458)
→ **it is unlikely that the rise in the positron fraction is due to $\pi^0$ contamination of hadronic showers**

II – a new approach based on selections on shower profile variables was studied and tested on **simulations** in the energy range **20 – 100 GeV**
→ a positron selection efficiency of ~ 0.50 was found with a proton contamination of order of $10^{-5}$

# Outlook

- Extend the PAMELA positron fraction to E > 100 GeV

- a new approach, based on selections on shower profile variables, was tested on simulations in the energy range **20 – 100 GeV**

- this new approach will be applied on positive charged particles in flight data
  → **reproduce the positron fraction**

- this method will be studied at **higher energies**, up to ~ 300 GeV
  → the shower profile variables will be optimised at higher energies

- measurement of the positron fraction for E > 100 GeV could solve the problem about primary positron production models a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

# Thank you!!!