Tracker-In-Calorimeter (TIC) project:
a calorimetric new solution to tracking gamma rays in space experiments

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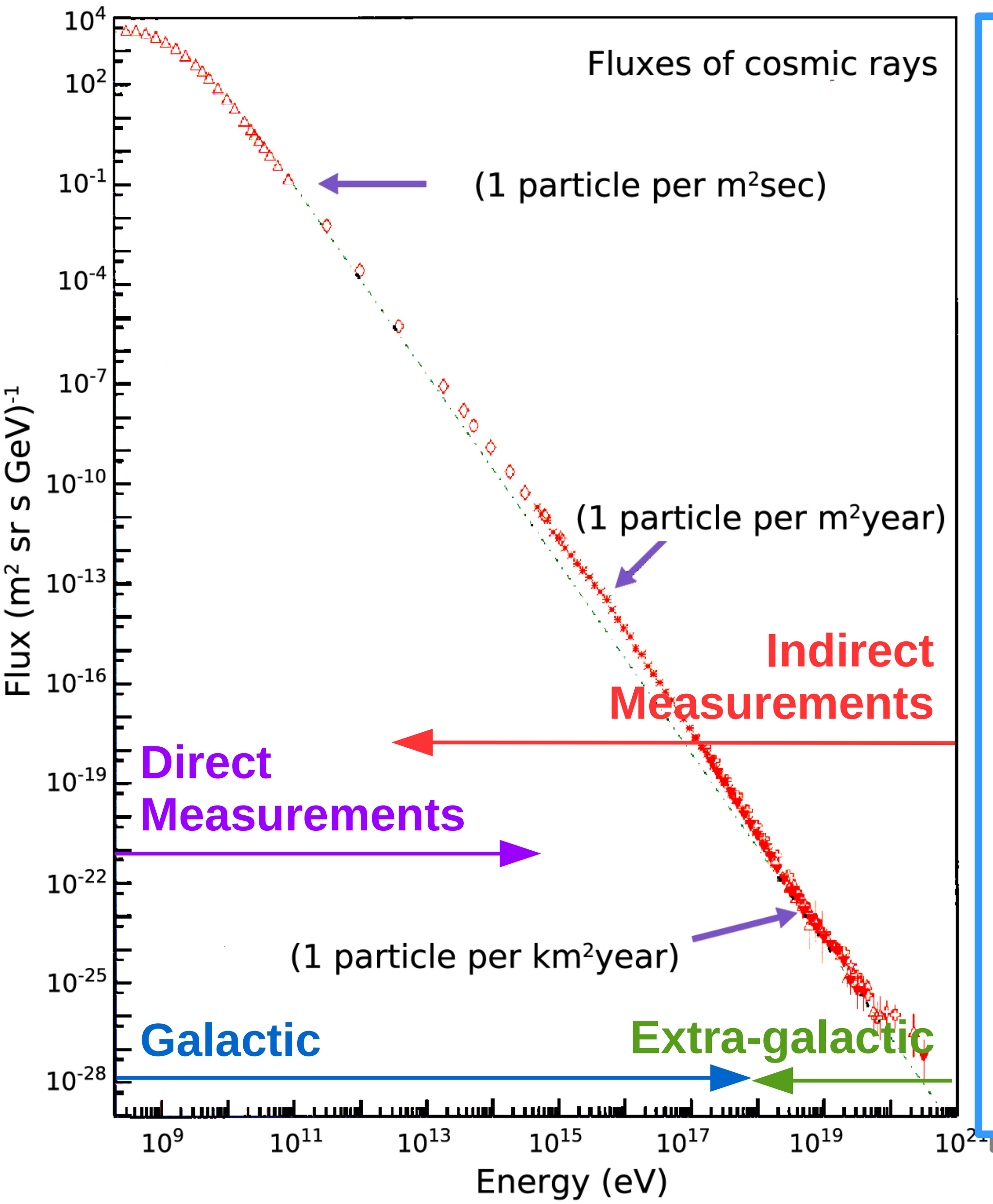
Reference: **arXiv:2008.01390**

Outline

- Cosmic rays
- Space-based cosmic ray experiments
- The TIC project:
  - Simulations
  - Prototype
  - Beam test results

Cosmic rays



Open problems

- Identification of astrophysical sources responsible for acceleration
- Understanding of acceleration, propagation and interaction mechanisms
- Location of the transition region between galactic and extra-galactic origin
- Search for dark matter sources

Direct Measurements

Advantage

Individual particle identification

Disadvantage

Payload limitation ⇒small statistics

Indirect Measurements

Advantage

Large arrays ⇒large statistics

Disadvantage

Large model systematics

Space-based experiments

charge particle physics

In order to improve past measurements and extend them to higher energy, future space experiments must fulfill several requirements

Protons and Nuclei up to 3 PeV/n

$\sigma_E/E < 40\%$

$G_{eff} \times T > 2.5\ m^2\ sr \times 5yr$

Dynamic Range $> 10^7$

$\sigma_Z < 0.2\text{-}0.3\ e$

Electrons and positrons up to 30 TeV

$\sigma_E/E < 2\%$

$G_{eff} \times T > 3.6\ m^2\ sr \times 5yr$

Dynamic Range $> 10^5$

e/p separation $> 10^6$

Geometric factor

$$G = \frac{dN_{detected}}{dt} / I$$

Typical limitations

Mass ~10^3 Kg

Power ~10^3 W

Down link ~10^2 Gb/d

Volume ~ 1 m^3

Effective geometric factor

$$G_{eff} = \epsilon_{sel}\, x\, G$$

Need to find new design for future experiments in order to fulfill requests

The TIC project

In a large space satellite experiment, we are interested in collecting signals from **different channels**: electron, proton, nuclei and **also γ-rays**.

Need a good compromise between

good angular resolution for γ-rays

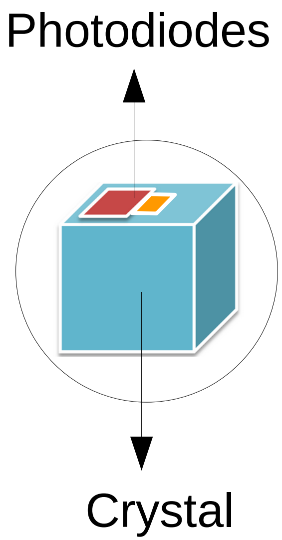
large acceptance for charged particles

A possible approach could be the **TIC** project, an R&D project financed by INFN in Italy

The aim of the project is the design and optimization of a ***tracker integrated inside a calorimeter (Tracker In Calorimeter)***

The Calocube idea:

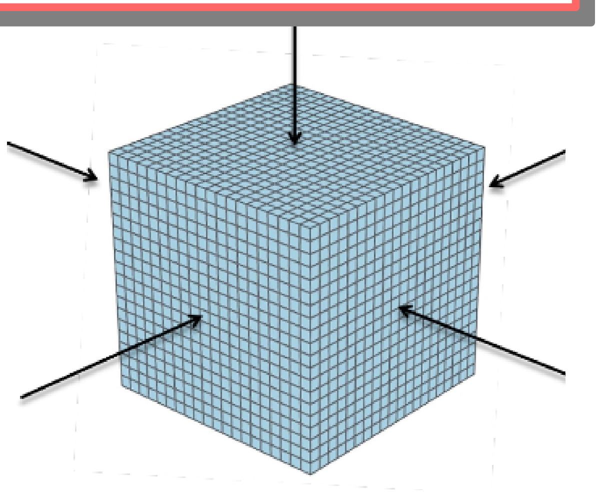
an innovative proposal for a homogeneous and isotropic calorimeter [4]



NxNxN cubic crystals with 1 Moliere radius side

Signal read by two PDs and double gain electronics

In case of CsI, N=20, side=3.6 cm, $L=39X_0$ ($1.8\ \lambda_I$)



Deep homogeneous isotropic calorimeter → Good energy resolution

Cubic geometry with 5 face detection → Large geometrical acceptance

Shower imaging with 3D segmentation → Good e/p rejection, identification of shower axis and of shower starting point

This design has been chosen with some modifications for the future HERD experiment [5]

Gamma-Ray physics:
tracking reference tecnique

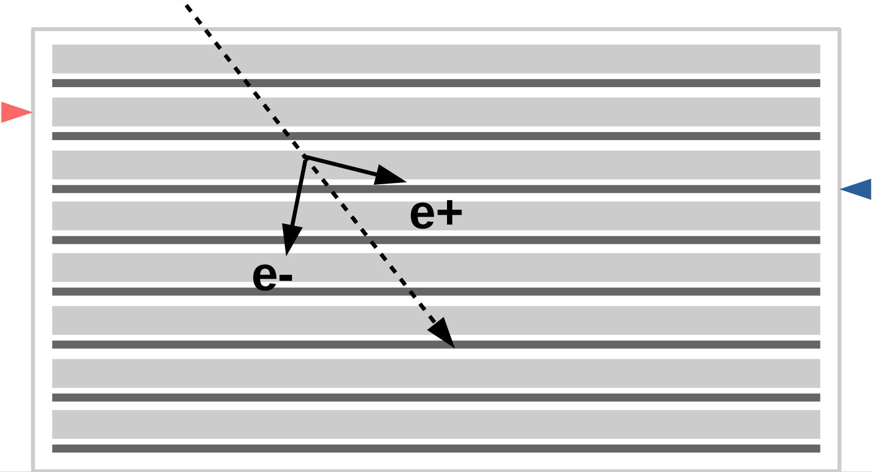
Performed using a **pair-conversion telescope**:
composed by several planes, each one composed by

a layer of **passive material** (e.g. tungsten)
→ to convert the primary photon into an e+/e- pair

coupled with

a **sensitive layer**
(e.g. silicon microstrip detector)
→ to measure the impact position of the electron and the positron

- the planes are stacked
  - → to increase the photon conversion probability
  - → to provide multiple position measurements along the e+/e- trajectory
    - → from these measurements the track of the incident photon is reconstructed
- and suitably spaced apart from each other
  - → lever arm and spatial resolution of the position measurements provide the required tracking resolution

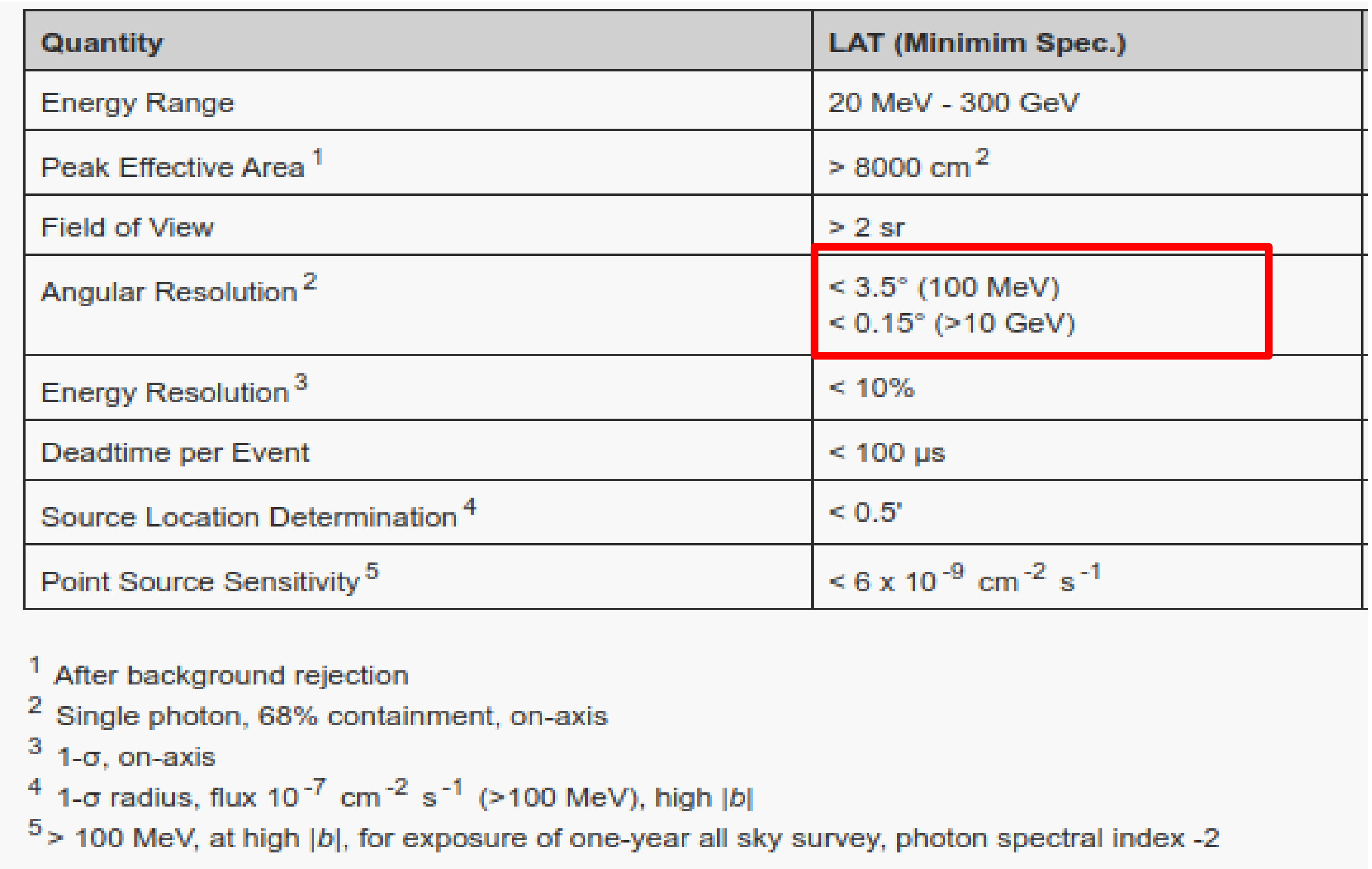


This concept has been successfully implemented in recent space-borne gamma-ray detectors: Fermi [2] and AGILE [3]

Space-based experiments

Gamma-Ray physics

Fermi LAT performances



Quantity	LAT (Minimim Spec.)
Energy Range	20 MeV - 300 GeV
Peak Effective Area [1]	> 8000 cm^{2}
Field of View	> 2 sr
Angular Resolution [2]	< 3.5° (100 MeV) < 0.15° (>10 GeV)
Energy Resolution [3]	< 10%
Deadtime per Event	< 100 μs
Source Location Determination [4]	< 0.5'
Point Source Sensitivity [5]	< 6 x 10^{-9} cm^{-2} s^{-1}

[1] After background rejection

[2] Single photon, 68% containment, on-axis

[3] 1-σ, on-axis

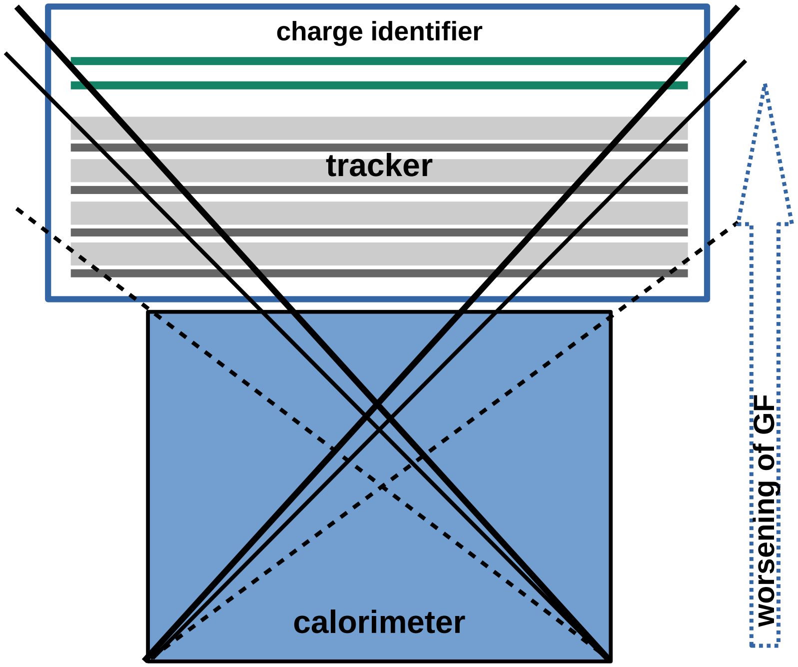
[4] 1-σ radius, flux 10^{-7} cm^{-2} s^{-1} (>100 MeV), high |*b*|

[5] > 100 MeV, at high |*b*|, for exposure of one-year all sky survey, photon spectral index -2

Charge particle physics:
accurate measurement of the charge is mandatory

a pair-conversion telescope is in principle also <u>able to track charged primary particles</u>
It is actually used in detectors for charged particles **<u>(e.g. DAMPE [4])</u>**

charge of a relativistic particle can be **measured by exploiting the Z^2** scaling of the energy deposited by ionization on the sensitive layers



a non-negligible amount of passive material increases the fragmentation probability of the nucleus

worsening of the charge identification performance

Simplest solution:
a dedicated charge identifier externally to the telescope
(e.g. a set of silicon detectors with a minimal amount of passive material)

Charge detector+tracker geometry:
- **degradation of the geometric factor**
- **limit on the energy range covered by the instrument**

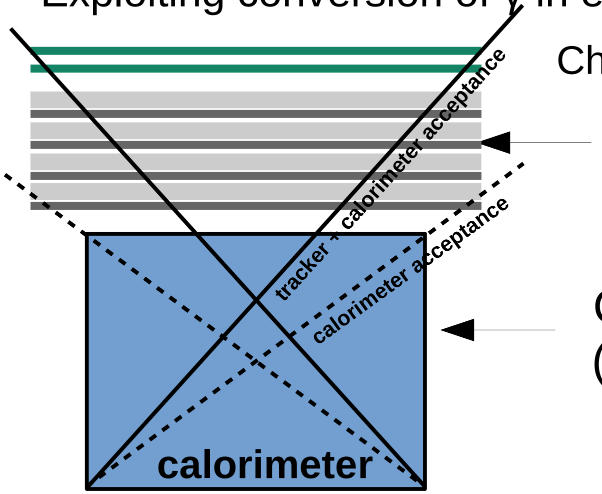
The mass budget of a space experiment is severely constrained:
- **limit on the maximum weight and dimension of the calorimeter**
- **allocating a significant fraction of the budget to the tracker reduces the instrument performance.**

TIC Tracker design

The angle can be measures using two different approaches

Standard approach

Exploiting conversion of γ in e^+e^- pair in W

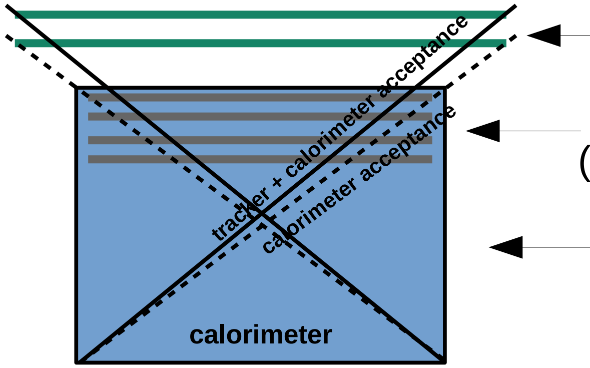


Charge identifier
+
Tracker
(Si + W)

Calorimeter
(e.g. LYSO)

TIC approach

Exploiting transverse profile of shower



Charge identifier
(e.g. Si only)

Tracker
(e.g. Si + LYSO)

Calorimeter
(e.g. LYSO)

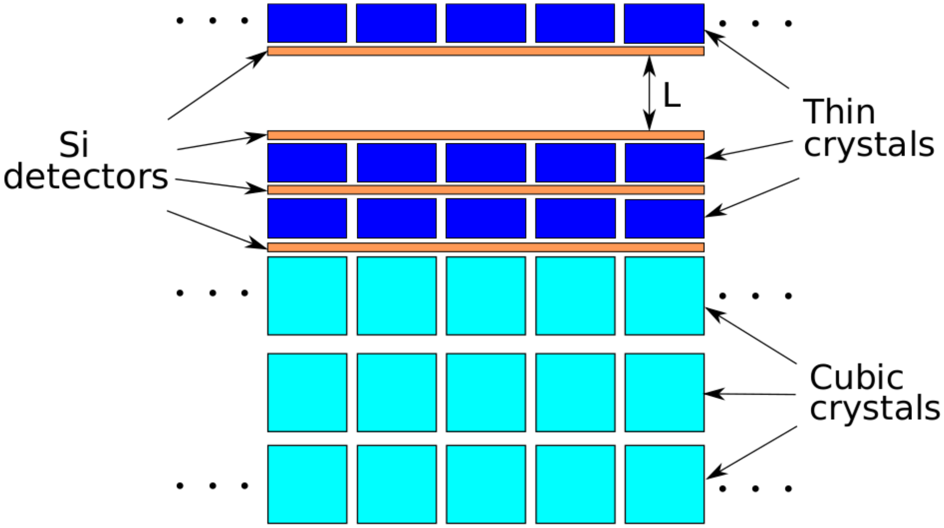
Advantages of TIC design are to

- decrease the amount of mass used for passive material (W)
- reduce hadron fragmentation in passive material
- increase the geometric acceptance

Detector Geometry

Starting from a tracking calorimeter (e.g. CaloCube or HERD design):
- **provides sizeable information about the development of the electromagnetic shower**

that can be further enhanced by instrumenting one side with silicon microstrip detectors interleaved with the first layers of scintillating crystals



The simulated geometry:
- 21x21x21 mesh of **LYSO** cubic crystals (3/1.5 cm)
- gap between the first two Si detectors 7 cm
- inter-crystal gaps 5 mm
- total depth along the up-down direction ∼3.2 λ_I and ∼58 X_0
- thickness and pitch for Si detectors set to 300 μm and 50 μm
- gaps between the cubes filled with carbon fiber
  to mimic the presence of a support structure

From top to bottom:
1. the upper layers made of thin crystals
2. gap between the first two silicon detectors.
   - ➔ to reduce the material traversed by the e+/e- pair
   - ➔ two consecutive silicon detectors without material in between
     - ➔ to mitigate the impact of multiple scattering on the tracking performance
3. two subsequent layers of crystals made of thin elements and silicon detectors
   - ➔ to limit the amount of material between other precise position measurements
4. the basic calorimeter design made of cubic scintillators is restored.

A similar approach has been adopted in other detector design, e.g. silicon detectors interleaved with tungsten plates to build a sampling calorimeter with tracking capabilities. The novelty is the use of an active material as gamma-ray converter to maximize the energy resolution.

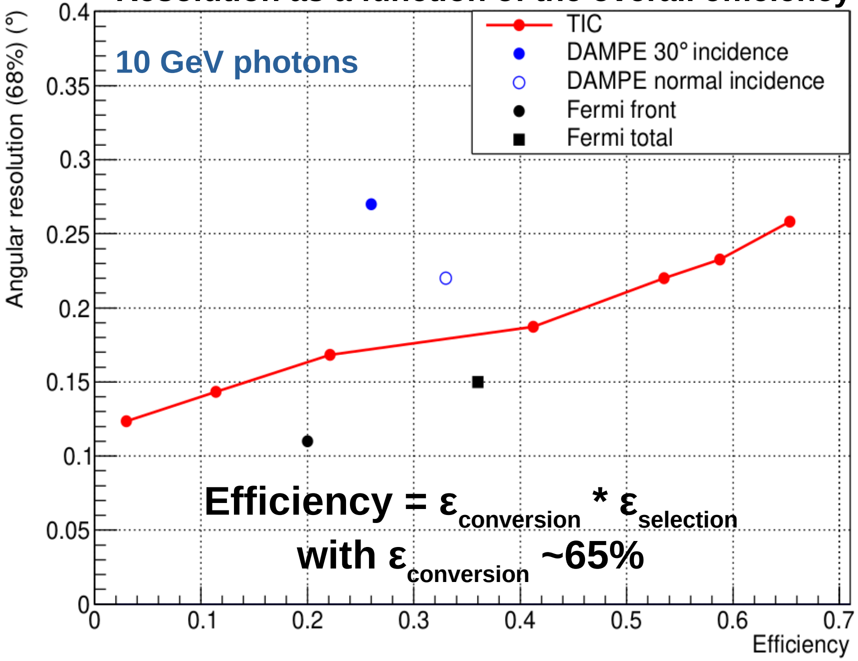
TIC Simulated performances

a FLUKA Monte Carlo simulation has been set up.

Simulated input spectra:

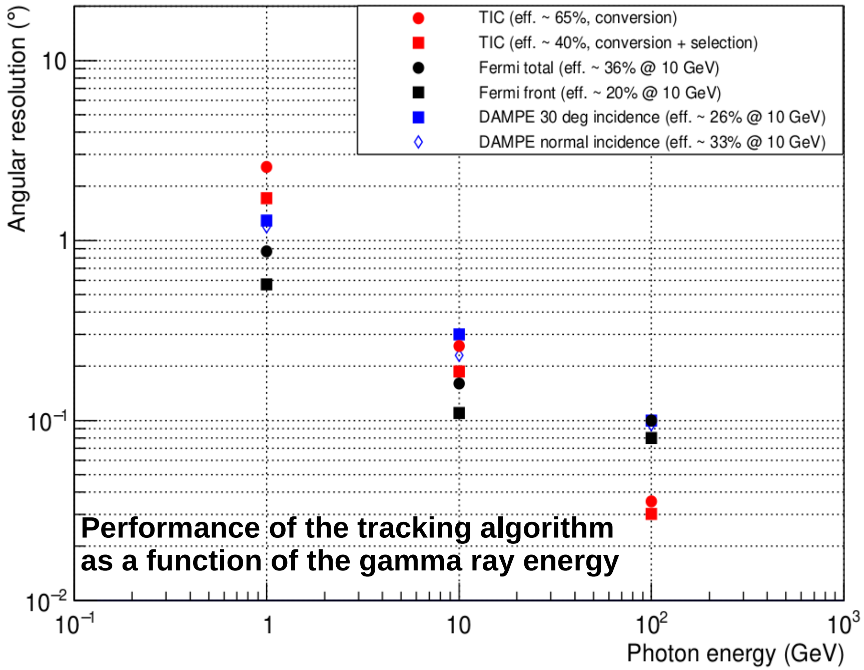
- ➔ **monochromatic gamma rays at different energies (1, 10 and 100 GeV)**
- ➔ **isotropic angular distribution**
- ➔ **initial direction limited in the ± 30 ◦ region around the zenith direction**
- ➔ **the whole top face is uniformly illuminated by incoming photons.**

Resolution as a function of the overall efficiency



Efficiency = $\varepsilon_{conversion}$ * $\varepsilon_{selection}$

with $\varepsilon_{conversion}$ ~65%



Performance of the tracking algorithm as a function of the gamma ray energy

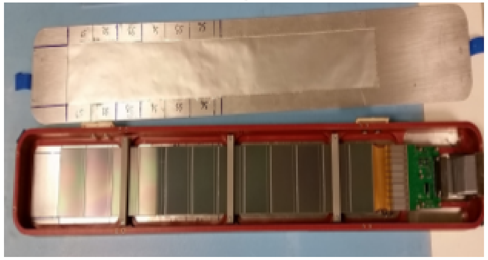
- resolution worse than Fermi (efficiency of ∼36%)
- It can match Fermi by reducing the efficiency to ∼14%
- It is generally better than DAMPE.

- performance improves with increasing energy
- at 100 GeV the performance is better than Fermi and DAMPE
  ➔ (with comparable or better efficiency)

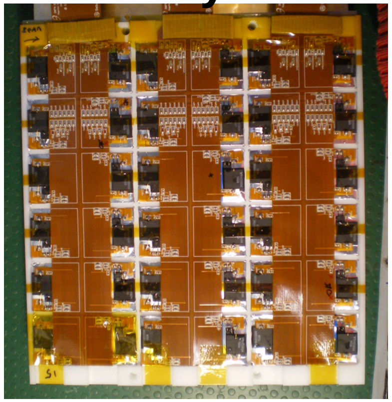
Basic TIC design will be optimized in the future
Current performances: **Δθ = 0.12-0.26° for ε = 2-65%**
Changing the event selection, <u>the analysis of a given data sample can be optimized according to desired requirements on Δθ and ε</u>

TIC Prototype

Si layers

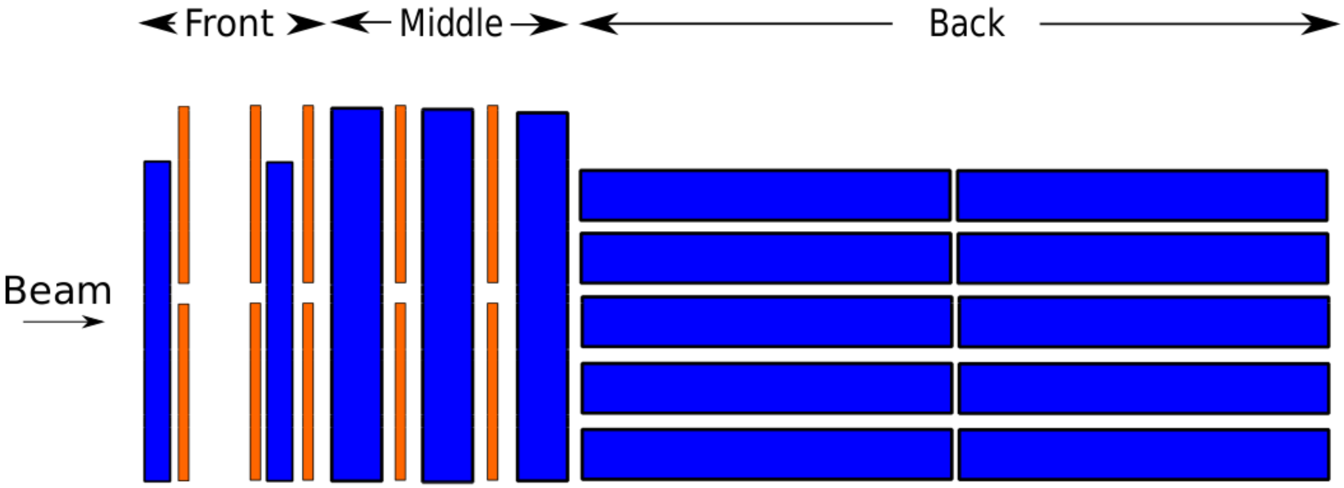


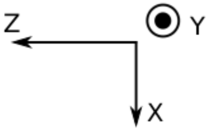
CsI layers



detector was built:

- by refurbishing the CaloCube prototype
  - ➔ layers of thin crystals obtained by **sawing some spare CaloCube cubic scintillators**
- spare one-sided **silicon microstrip detectors from the DAMPE experiment**





CaloCube crystals made of CsI(Tl):

- ➔ different sizes wrt full-scale detector
- ➔ dedicated simulation of the prototype detector

Front part:

- two trays of thin crystals (25 detectors per tray with 1.7 cm thickness)
- three layers of silicon microstrip detectors.

Middle part:

- three trays of 6x5 cubic elements
- interleaved by two silicon layers

Back part:

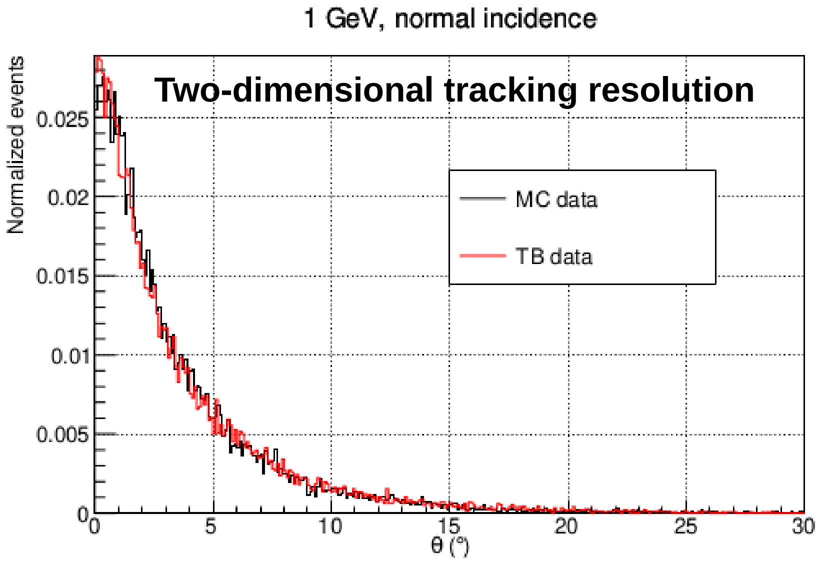
- made of 10 trays of cubes
  - ➔ arranged longitudinally with respect to the beam
    - two blocks of 5 trays each.

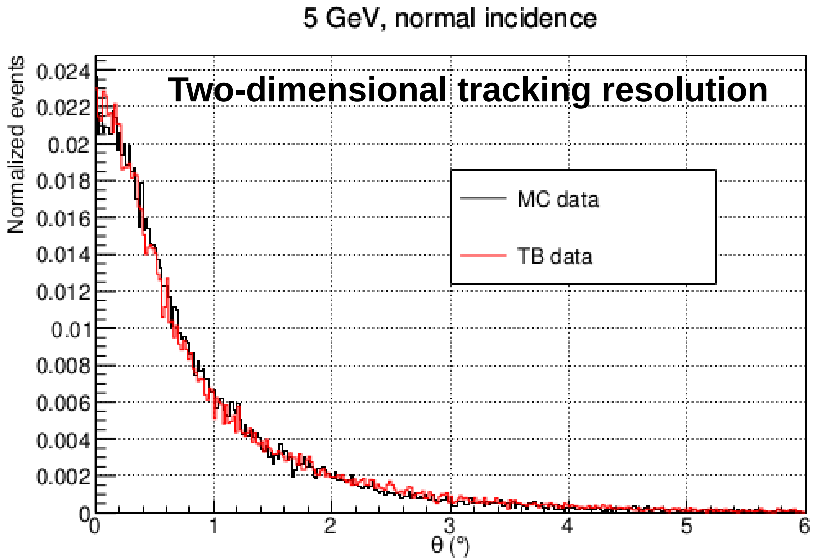
The prototype have been tested **at the CERN PS+SPS with 1-100 GeV electrons** at different incident angles

TIC Prototype Performances:

1 GeV & 10 GeV electrons with normal incidence

accurate simulation of the experimental setup realized using FLUKA (detector geometry + experimental effects)





⬛ **Data: $\Delta\theta_{68\%} = 3.72°$, $\Delta\theta_{95\%} = 10.63°$**

🟥 **MC: $\Delta\theta_{68\%} = 3.87°$, $\Delta\theta_{95\%} = 11.44°$**

⬛ **Data: $\Delta\theta_{68\%} = 0.985°$, $\Delta\theta_{95\%} = 3.3°$**

🟥 **MC: $\Delta\theta_{68\%} = 0.955°$, $\Delta\theta_{95\%} = 3.28°$**

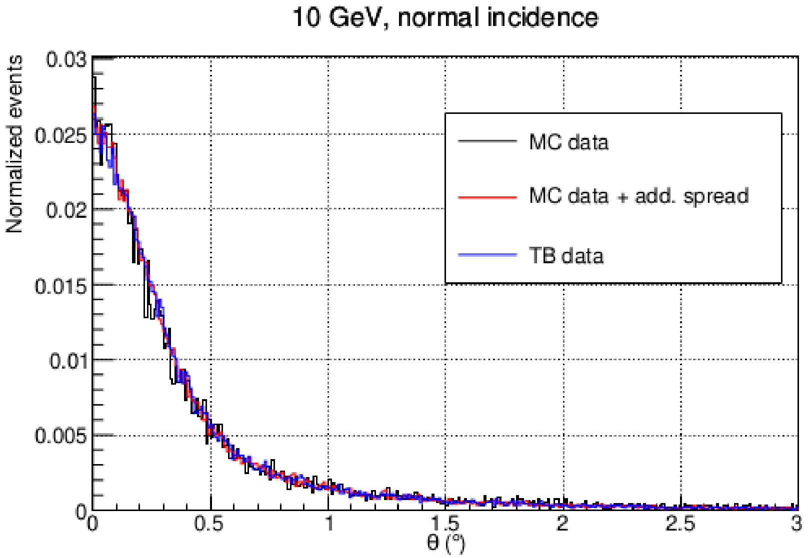
Experimental effects due to:

- segmented beam pipe + air + trigger scintillators
- angular and spatial distribution of the real beam
- capacitive couplings between the silicon microstrips
- spread induced by residual rotation misalignment of the silicon sensors

Good agreement between data and MC

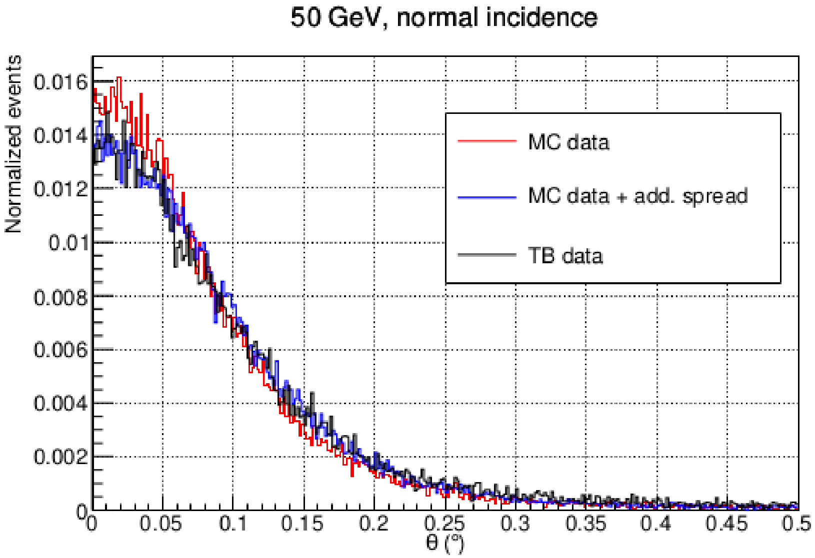
Track reconstruction algorithm explained in a spare slide

TIC Prototype Performances: 10 GeV, 50 GeV, 100 GeV electrons with normal incidence



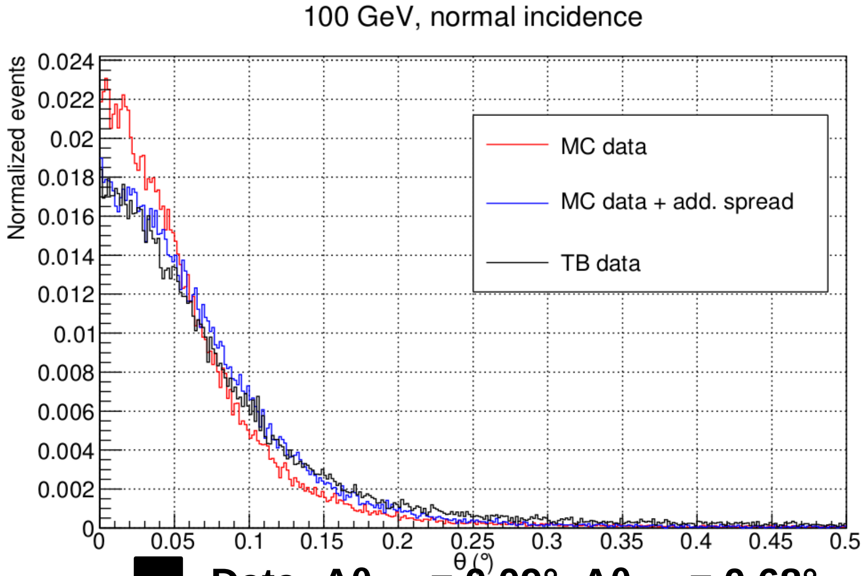
⬛ **Data: $\Delta\theta_{68\%}$ =0.41°, $\Delta\theta_{95\%}$ = 1.95°**

🟥 **MC: $\Delta\theta_{68\%}$ = 0.40°, $\Delta\theta_{95\%}$ = 1.79°**



⬛ **Data: $\Delta\theta_{68\%}$ = 0.12°, $\Delta\theta_{95\%}$ = 0.92°**

🟥 **MC: $\Delta\theta_{68\%}$ = 0.10°, $\Delta\theta_{95\%}$ = 0.71°**



⬛ **Data: $\Delta\theta_{68\%}$ = 0.09°, $\Delta\theta_{95\%}$ = 0.68°**

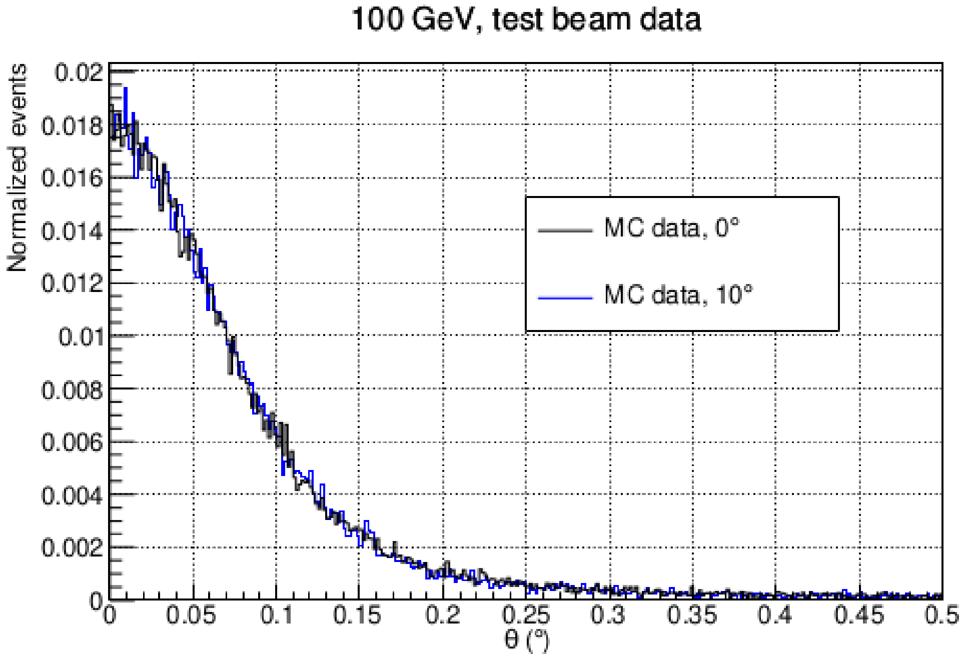
🟥 **MC: $\Delta\theta_{68\%}$ = 0.07°, $\Delta\theta_{95\%}$ = 0.31°**

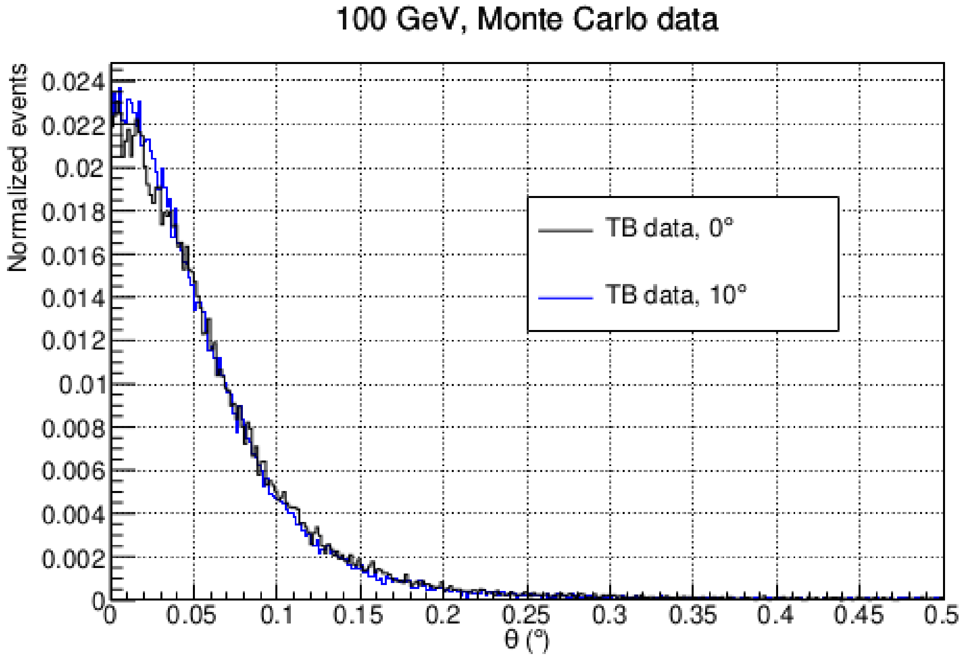
➔ to fully reconcile test beam and Monte Carlo data at higher energies
  - ➔ additional spread of about 0.04° added to the nominal spread of the simulated beam
  - ➔ this correction accounts for unknown residual systematic effects at all energies
  - ➔ the residual BT-MC resolution difference taken as a systematic error.

TIC Prototype Performances:

angular resolution @ different angles

The tracker performances have been tested at different incident angles: 0, 10, 30 degrees





The angular resolution seems not depending on incidence angle:

- ➔ **by comparing the resolution plots for 0° and 10° incidence angles no sizeable difference was found;**
- ➔ **this was confirmed by Monte Carlo simulations**

TIC Prototype Performances: result summary

Energy (GeV)	Angle (deg)	Res. 68% (deg) - TB	Res. 68% (deg) - MC
1	0	3.72 ± 0.11	3.87 ± 0.12
5	0	0.985 ± 0.016	0.955 ± 0.014
10	0	0.4095 ± 0.0087	0.3971 ± 0.0050
50	0	0.1205 ± 0.0023	0.0995 ± 0.0050
100	0	0.0897 ± 0.0010	0.0680 ± 0.0008
100	10	0.0884 ± 0.0013	0.0646 ± 0.0004

The agreement between test beam and Monte Carlo data is quite satisfactory, especially at lower energies for 68% containment of the two-dimensional Point Spread Function (PSF).

Energy (GeV)	Angle (deg)	Res. 95% (deg) - TB	Res. 95% (deg) - MC
1	0	10.63 ± 0.15	11.44 ± 0.33
5	0	3.300 ± 0.063	3.282 ± 0.054
10	0	1.946 ± 0.062	1.790 ± 0.068
50	0	0.921 ± 0.029	0.710 ± 0.058
100	0	0.678 ± 0.033	0.3077 ± 0.0099
100	10	0.662 ± 0.036	0.259 ± 0.019

At 95% PSF the agreement gets worse:

➔ likely due to residual instrumental effects

  ➔ not-so-good modeling of the tails of the distribution by the Monte Carlo

Summary

The **TIC R&D project** is a proposal for a new instrument design for tracking gamma rays in cosmic-ray space experiments

A prototype made of CsI(Tl) crystals and Si micro-strips have been built and tested, good angular resolutions, as expected from simulations

- **Δθ = 1.94° with 10 GeV electrons**
- **Δθ = 0.68° with 100 GeV electrons**

The TIC tracking calorimeter has comparable tracking performance with respect to the current generation of gamma-ray experiments (Fermi, DAMPE) for energies from 1 GeV to ~50 GeV, and better performance above 50 GeV, while allowing for important design optimizations for multi-particle detection.

Data acquired with a detector prototype at CERN test beam facilities showed a reasonable agreement with the Monte Carlo simulation, providing a deep insight on the relevant instrumental effects and a robust validation of the measurement principle.

References

- [1] O. Adriani et al., *CaloCube: An isotropic spaceborne calorimeter for high-energy cosmic rays. Optimization of the detector performance for protons and nuclei*, Astropart.Phys. 96 (2017) pg. 1-17
- [2] W.B. Atwood et al., *Design and initial tests of the Tracker-converter of the Gamma-ray Large Area Space Telescope*, Astropart. Phys. 28 (2007) pg. 422-434
- [3] A. Bulgarelli et al., *The AGILE silicon tracker: Pre-launch and in-flight configuration*, Nucl. Inst. and Meth. in Phys. A 614 (2010) pg. 213-226
- [4] J. Chang et al., *The DArk Matter Particle Explorer mission*, Astropart. Phys. 95 (2017) pg.6-24
- [5] S. Zhang et al., Introduction to the High Energy cosmic-RadiationDetection (HERD) Facility onboard ChinaâĂŹs FutureSpace Station, Proc. of Sc. 301 (2017)

Thank you!

Spare slides

Track reconstruction algorithm

Iterative algorithm based on all the information obtained by the calorimeter signals (both crystals and Si detectors).
The Principal Component Analysis method (PCA) has been used.

First step based on the crystal signals only: building of the **3D covariance matrix of the crystal coordinates**

$$M_{ij}^{CAL} = \frac{1}{\sum_{n=1}^{N} W_{CAL}^{(n)}} \sum_{n=1}^{N} W_{CAL}^{(n)} (c_i^{(n)} - C_i)(c_j^{(n)} - C_j) \rightarrow C_i = \frac{\sum_{n=1}^{N} W_{CAL}^{(n)} c_i^{(n)}}{\sum_{n=1}^{N} W_{CAL}^{(n)}}$$

C_i is the center of the distribution of the signals

- N crystals with signal above a given threshold
- $c_i^{(n)}$ crystal coordinates
- $W^{(n)}_{CAL}$ weight = equal to the signal $S^{(n)}_{CAL}$ on nth crystal

the eigenvector with the largest eigenvalue is considered as estimator of the primary track

Second step based on the Si signals: building of the **3D covariance matrix of the Si strip coordinates**

$$M_{ij}^{SIL} = \frac{1}{\sum_{k=1}^{J} W_{SIL}^{(k)}} \sum_{k=1}^{J} W_{SIL}^{(k)} (d_i^{(k)} - D_i)(d_j^{(k)} - D_j) \rightarrow D_i = \frac{\sum_{k=1}^{J} W_{SIL}^{(k)} d_i^{(k)}}{\sum_{k=1}^{J} W_{SIL}^{(k)}}$$

D_i is the center of the distribution of the signals

- i/j = X-Z or Y-Z view
- J strips with signal above a given threshold
- $d_i^{(k)}$ strip coordinates
- $W^{(k)}_{SIL}$ weight for the kth silicon channel

the spatial dispersion of the CAL track intersection in the P^{th} plane can be approximated by a Gaussian function. Then the weight is defined by:

$$W_{SIL}^{(k)} = \boxed{\frac{S^{(k)}}{S_P}} \times \frac{1}{\sqrt{2\pi}\sigma_P} \exp\left[-\frac{1}{2}\left(\frac{d_{X/Y}^{(k)} - X_P}{\sigma_P}\right)^2\right]$$

$S^{(k)}/S_P$ ratio takes into account the increasing angular dispersion of the electromagnetic shower

- X_P intersection on the P^{th} plane from of CAL track
- σ_P STD estimated by simulation
- S_P total signal from P^{th} plane
- $S^{(k)}_{SIL}$ dignal of the kth strip (part of P^{th} plane)

the eigenvector with the largest eigenvalue is considered as best estimator of the primary track. Since this new estimate depends on the previous one, the procedure can be repeated by using the new estimate as the previous one until convergence.