The High Energy cosmic-Radiation Detection facility: goals, design and performances

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on behalf of the ***HERD Collaboration***

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Overview

The **High Energy cosmic-Radiation Detection** (HERD) facility is a China-led international space mission that will start operation around 2026.

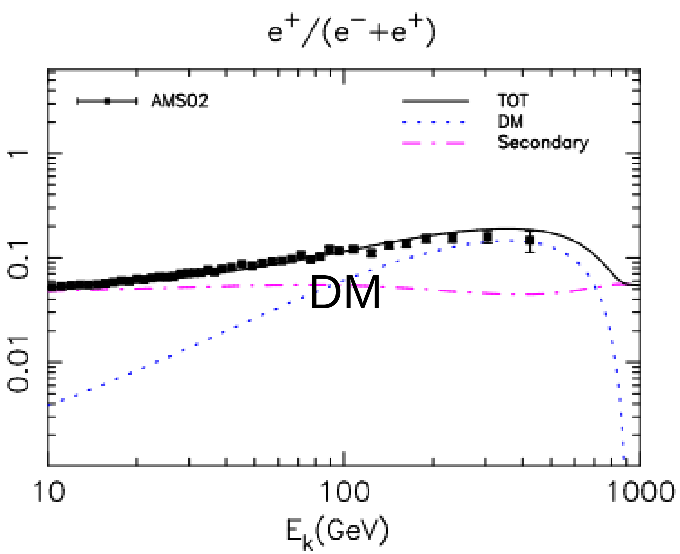
The experiment is based on a **3D, homogeneous, isotropic and finely-segmented calorimeter** that fulfills the following requirements and goals:

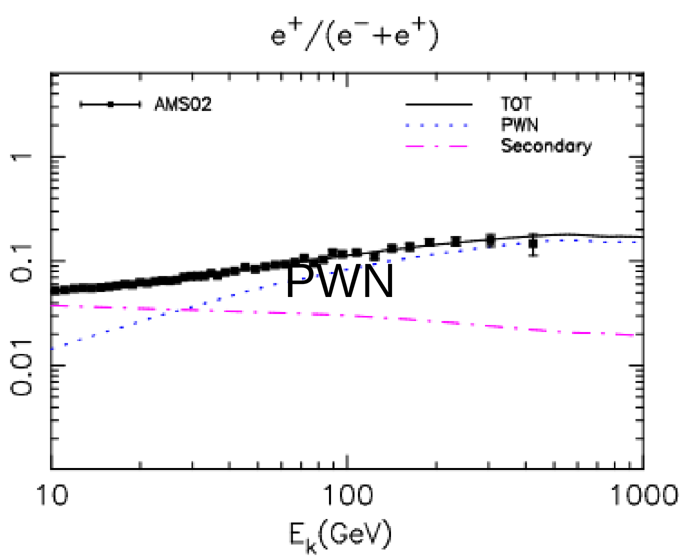
Main requirements			
	γ	e	p, nuclei
Energy Range	0.5 GeV - 100 TeV	10 GeV - 100 TeV	30 GeV - 3 PeV
Energy resolution	1% @ 200 GeV	1% @ 200 GeV	20% @ 100 GeV -1 PeV
Effective GF		> 3 m^2sr @ 200 GeV	> 2 m^2sr @ 100 TeV

Main Scientific goals
Direct measurement of cosmic rays flux and composition up to the knee region
Gamma-ray monitoring and full sky survey
Indirect dark matter search (e^++e^-, γ,...)

Why is HERD needed?

Electrons and Positrons
PAMELA and AMS-02



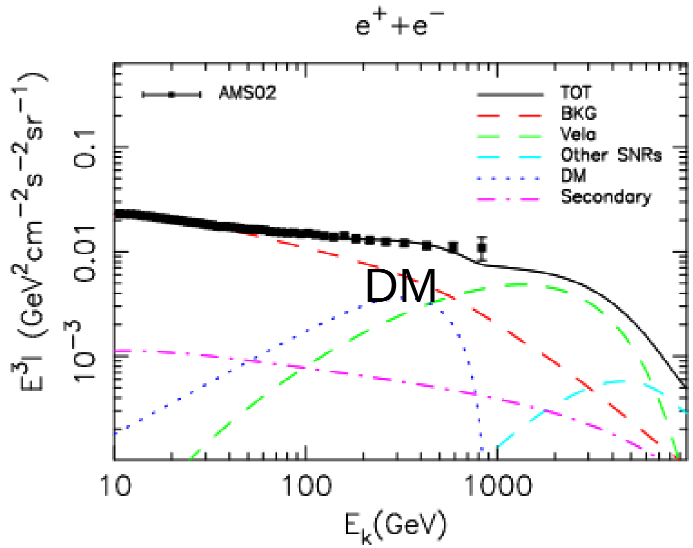


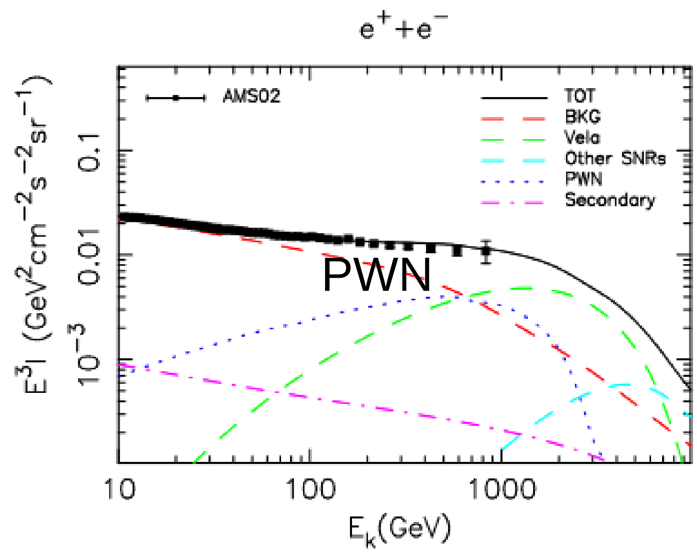
Positron excess respect to pure secondary production (PAMELA, AMS-02)

Two hypotheses

- Dark Matter (DM) annihilation
- Nearby Pulsar Wind Nebulae (PWN)

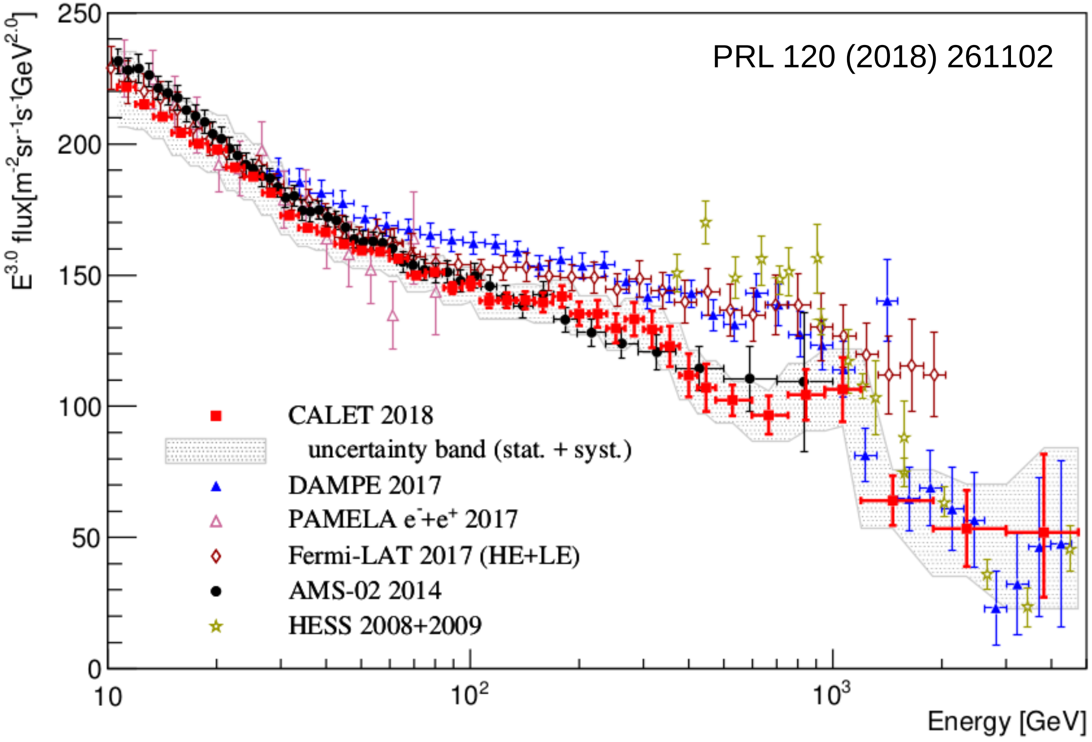
How to distinguish among them?





An important contribution to our understanding can be obtained by **high energy (calorimetric) measurement of the e^++e^- flux**

Electrons and Positrons
Fermi-LAT, CALET and DAMPE



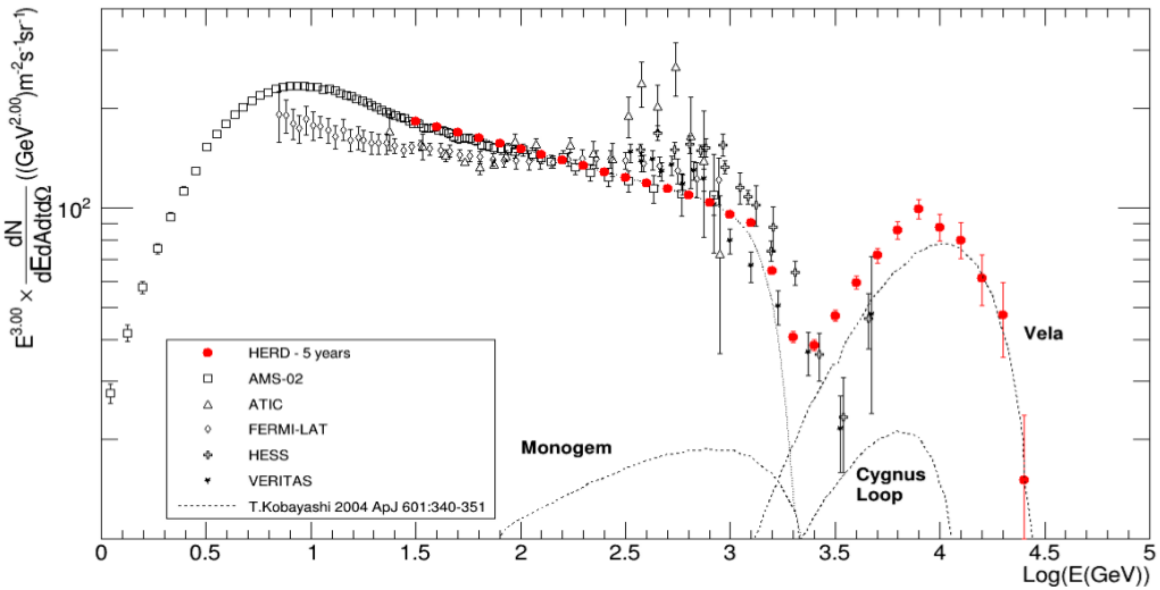
Recent calorimetric measurement of the e^++e^- flux (Fermi-LAT, CALET, DAMPE) lead to **very different results** and **no clear conclusion**

For example:
- CALET data are consistent with a single power law without cutoff
- DAMPE data shows a cutoff at 1 TeV and a “sharp peak” at 1.4 TeV

HERD will test the validity of the spectral features observed by DAMPE:
- improving the precision of the measurement
- extending the measurement to higher energy

Electrons and Positrons
HERD

Expected e^++e^- flux in 5 years

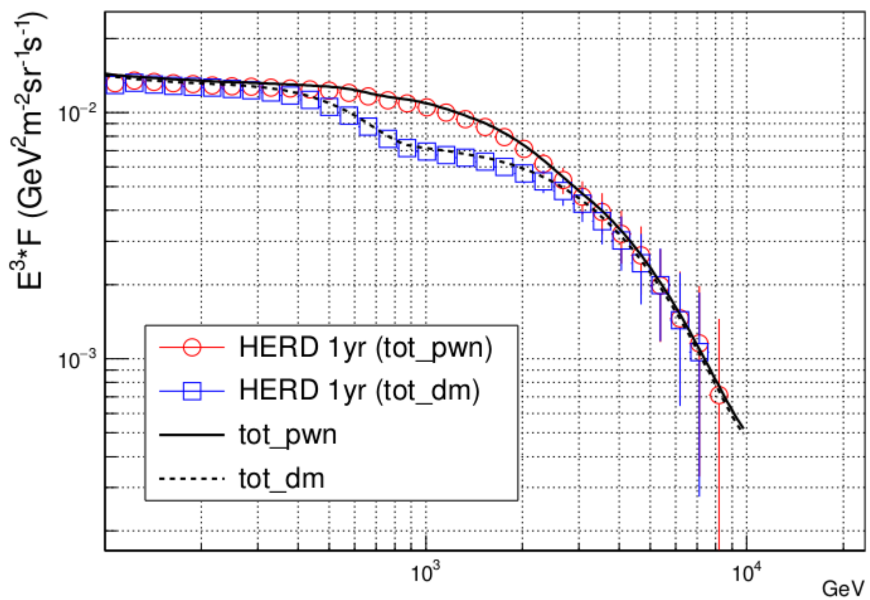


HERD will measure the flux up to several tens of TeV in order to detect:

- spectral cutoff at high energy
- local SNR sources of very high energy e^-

... and additional information from anisotropy measurement!

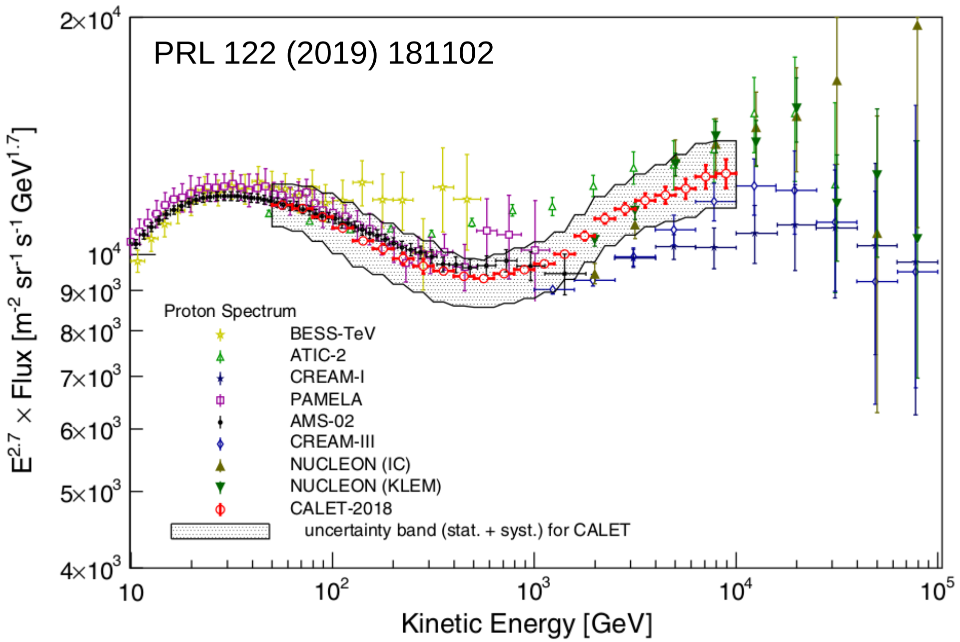
Expected e^++e^- flux in 1 year with PWN or DM sources

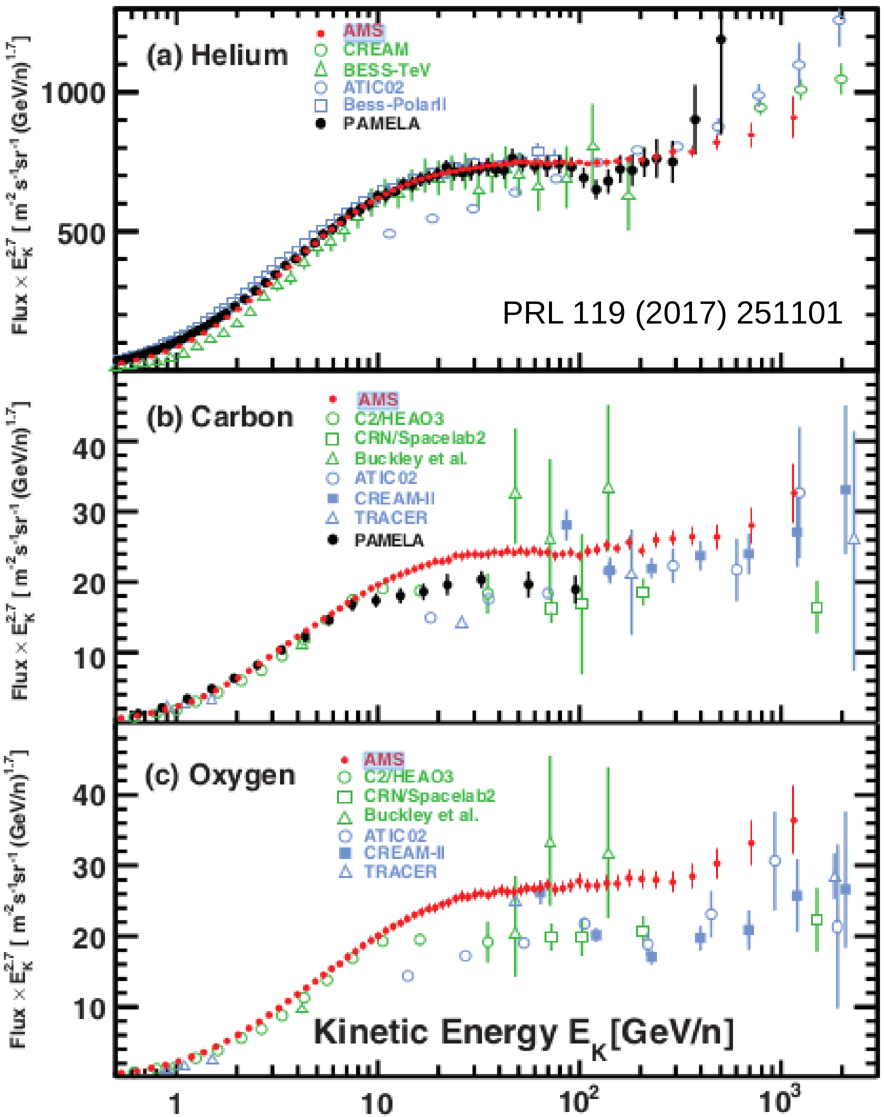


In case of additional PWN or DM production, **HERD** will give important indications on the two hypothesis thanks to precise measurement of the different spectral shape

Protons and Nuclei

Present status





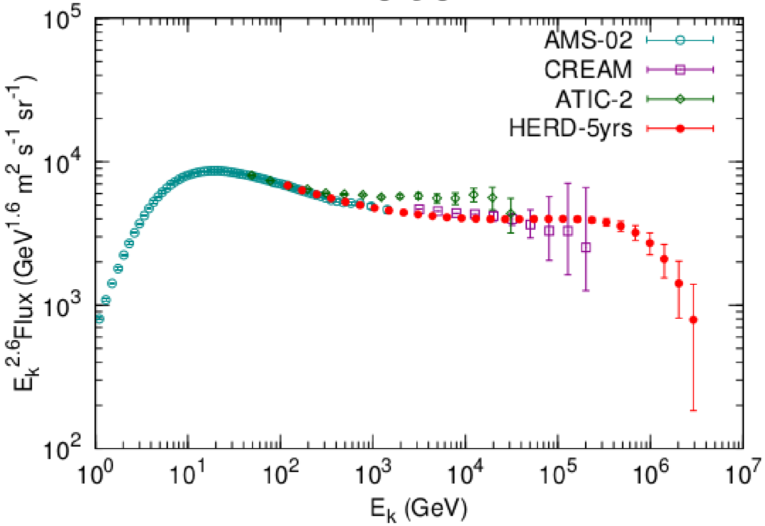
Proton flux measured up to 100 TeV but with large uncertainties:

- spectral hardening at 200 GeV
- spectral softening above 10 TeV?

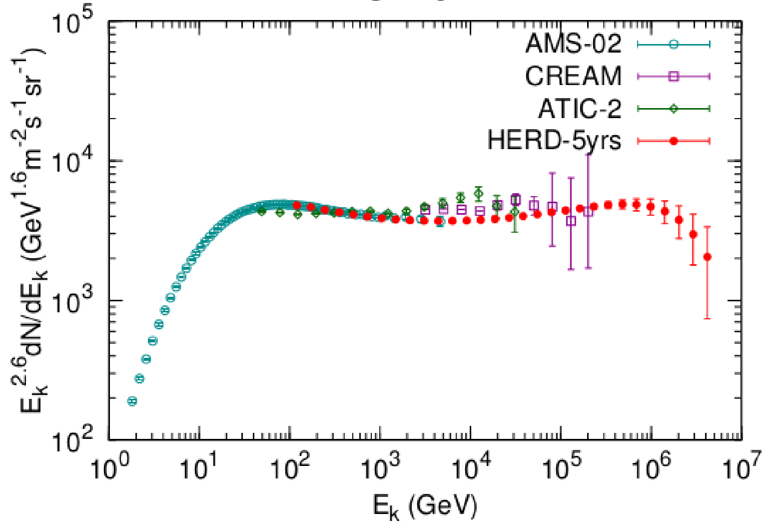
Still no direct measurement of proton and helium knee

Protons and Nuclei
HERD

Proton

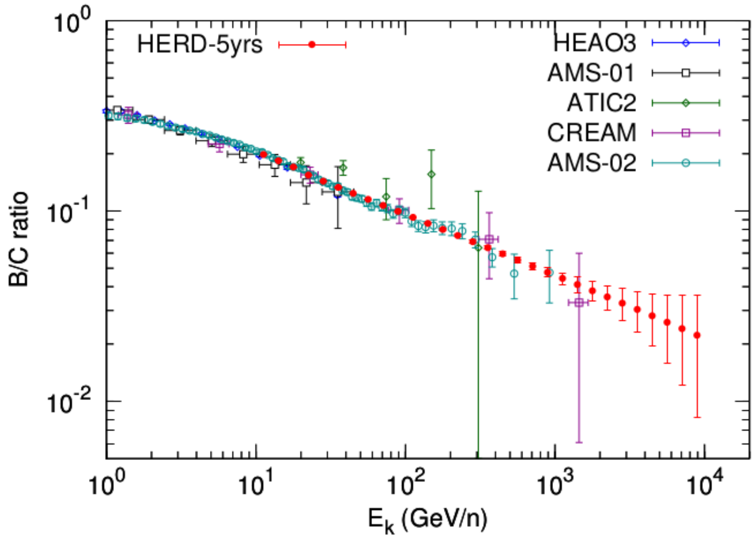


Helium



Expected flux in 5 years

B/C



HERD will measure the flux of nuclei:

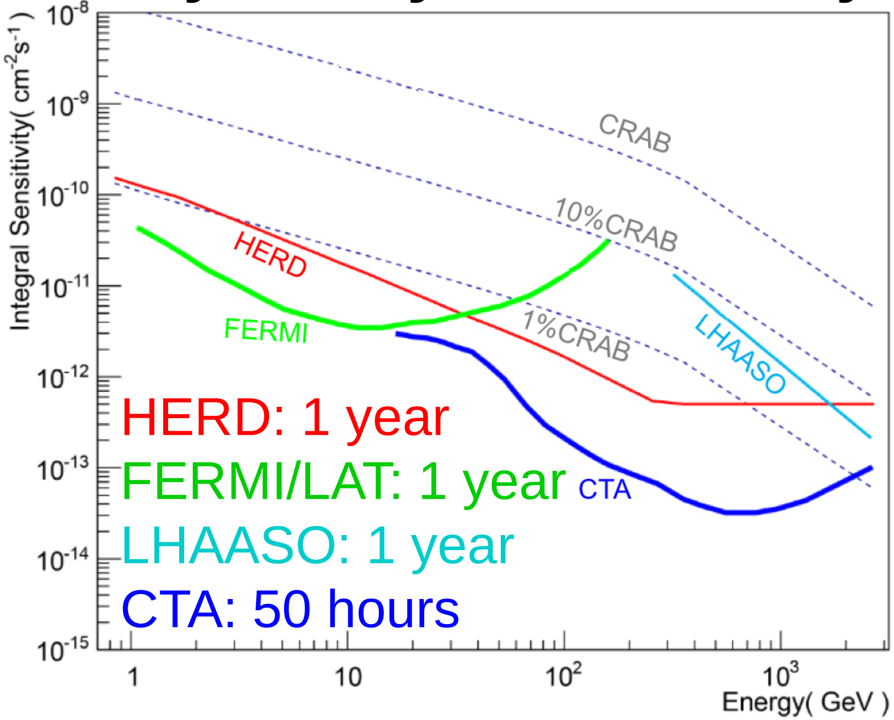
- p and He up to a few PeV
- nuclei up to a few hundreds of TeV/n

First direct measurement of p and He knees will provide a strong evidence for the knee structure as due to acceleration limit

Extension of the B/C ratio to high energy will provide further test for the propagation mechanisms of cosmic rays

Gamma-Ray Sky Survey
HERD

Sky survey 5σ sensitivity



Multi-messenger astronomy
Possible synergy with other experiments designed for Gamma-Ray (CTA), Neutrino (IceCube), Gravitational Waves (LIGO)

Thanks to its large acceptance and good sensitivity, **HERD** will be able to:

- improve Fermi-LAT measurements between 10 and 100 GeV
- <u>extend Fermi-LAT catalog to higher energy</u> (between 0.1 and 100 TeV)
- increase the <u>chances to detect of very rare Gamma-Ray activities</u>

Targets of Gamma-Ray Sky Survey:

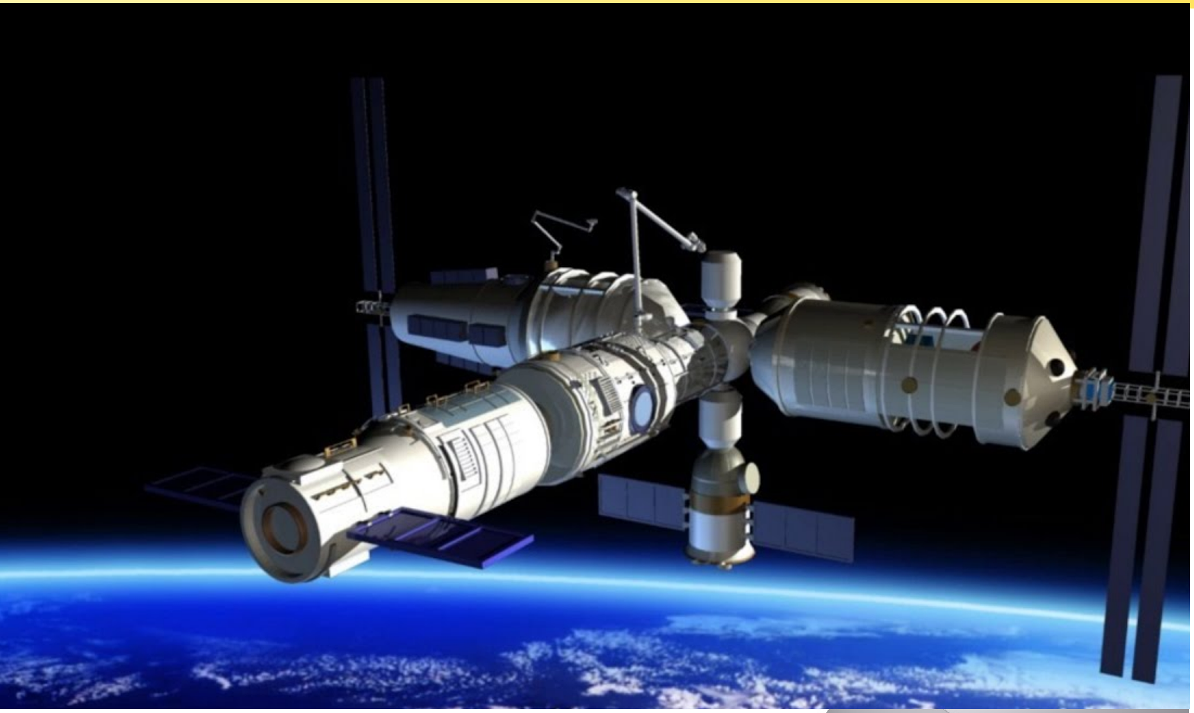
- search for dark matter signatures
- study of galactic and extragalactic Gamma-Ray sources
- study of galactic and extragalactic Gamma-Ray diffuse emission
- detection of Gamma-Ray Burst

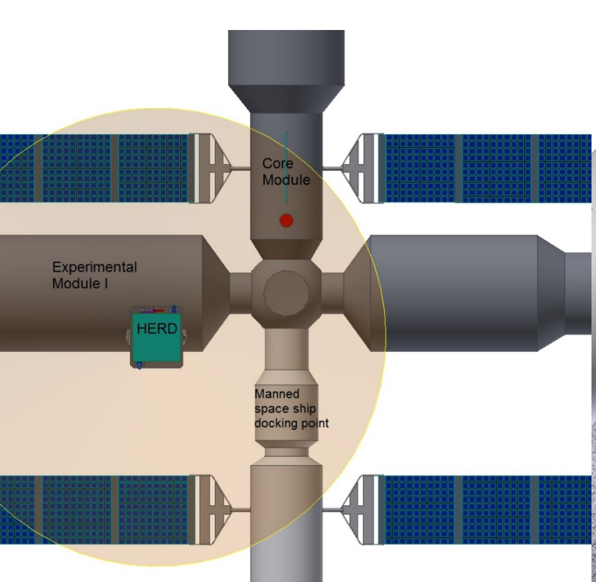
The HERD experiment

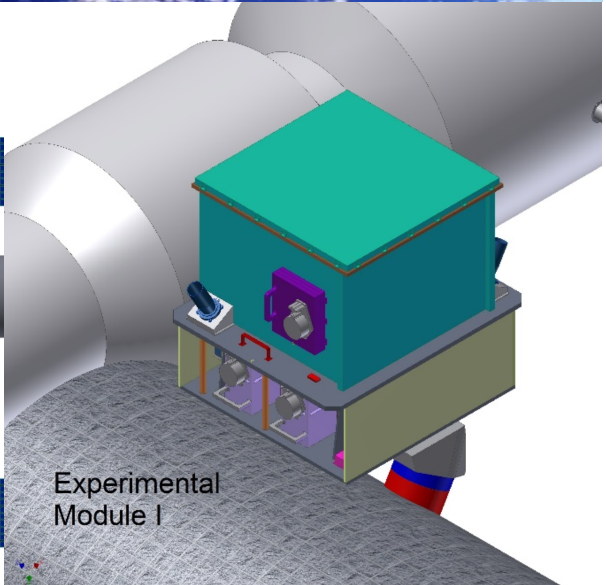
HERD International Collaboration

- China: CSU, IHEP, XIOPM, PMO, USTC, IGG, XAO, NAOC, TSU, GXU, PKU, NJU, YNU, NBU, SYSU, University of Hong Kong (HKU), National Central University (NCU)
- Italy ： INFN Perugia, University & INFN Firenze, University & INFN Bari, University & INFN Pisa, University & INFN Trento, University of Salento and INFN Lecce, IAPS/INAF, University & INFN Catania, University & INFN Napoli, University & INFN Trieste, GSSI
- Switzerland: University of Geneva ； Sweden: KTH ； Spain: CIEMAT
- Germany: KIT ； Russia: Lebedev Physical Institute
- Japan: University of Tokyo

HERD on board CSS







CSS expected to be completed in 2022

Life time	> 10y
Orbit	Circular LEO
Altitude	340-450 km
Inclination	42°

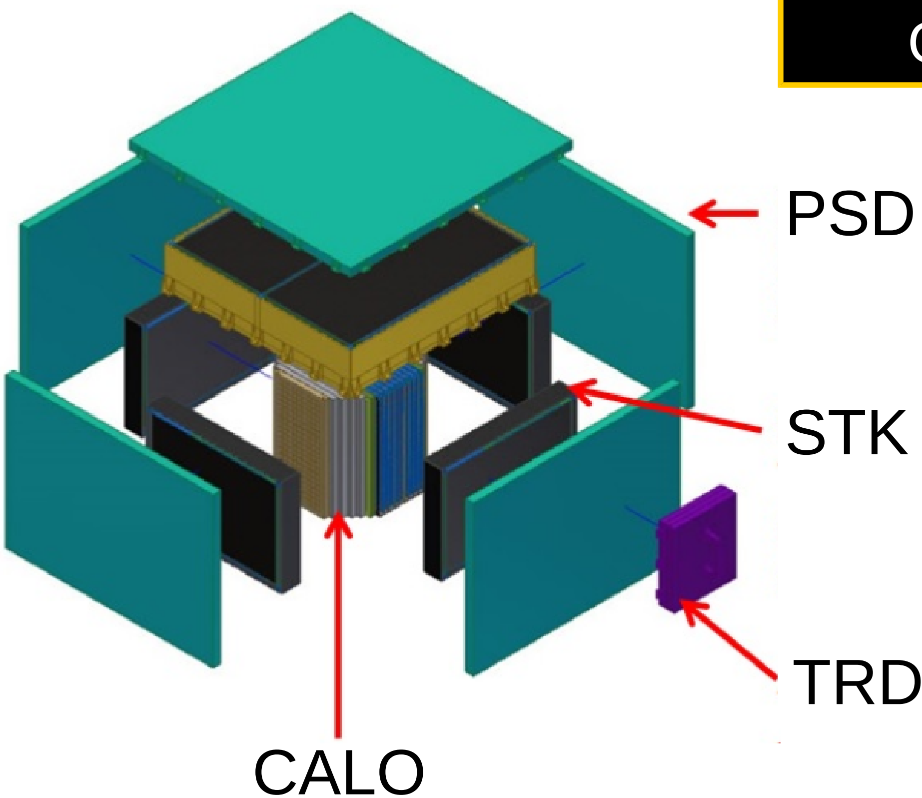
HERD expected to be installed around 2026

Life time	> 10y
FOV	+/- 70°
Power	< 1.5 kW
Mass	< 4 t

HERD detector and requirements

$\sigma_\theta(\gamma)$	0.1° @ 10 GeV
Z	1 - 26
σ_z	0.1 - 0.15 e
e/p	10^6

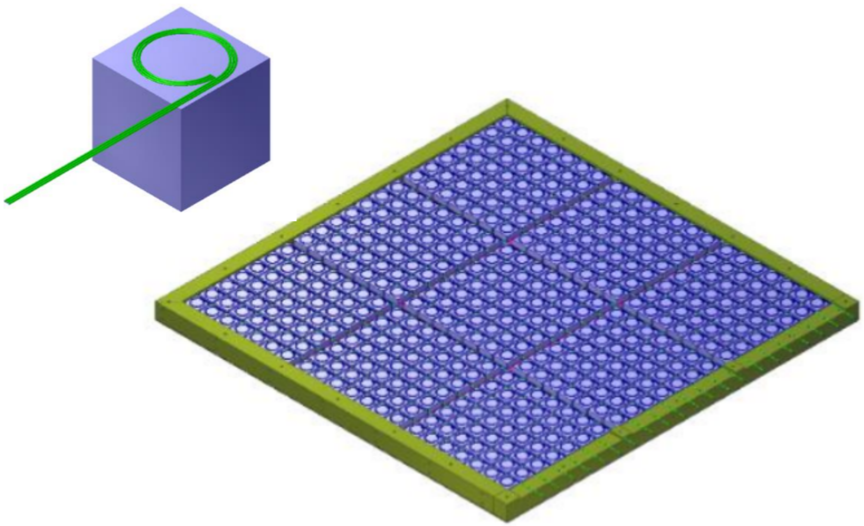
	e	p, nuclei
Energy Range	10 GeV - 100 TeV	30 GeV - 3 PeV
Energy resolution	1% @ 200 GeV	20% @ 100 GeV -1 PeV
Effective GF	> 3 m^2sr @ 200 GeV	> 2 m^2sr @ 100 TeV

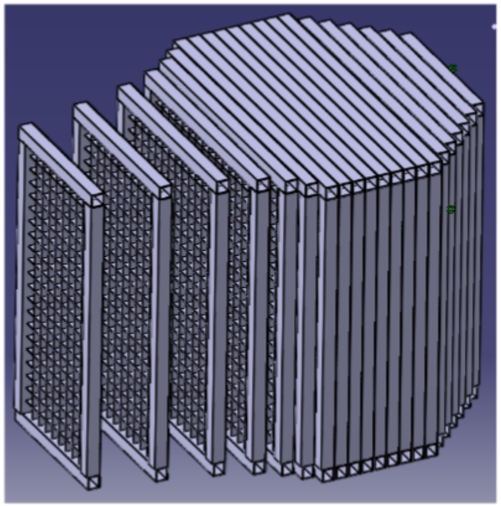


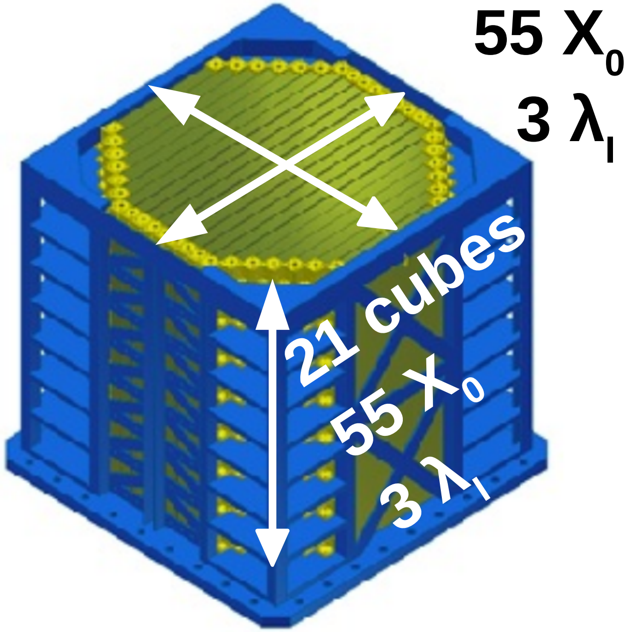
CALO	Energy Reconstruction e/p Discrimination
STK	Trajectory Reconstruction Charge Identification
PSD	Charge Reconstruction LE γ Identification
TRD	Calibration of CALO response for TeV proton

HERD CALOrimeter (CALO)

Octagonal Prism made of about 7500 LYSO cubic crystals:
each crystal has 3 cm side and 4-8 mm spacing from other crystals





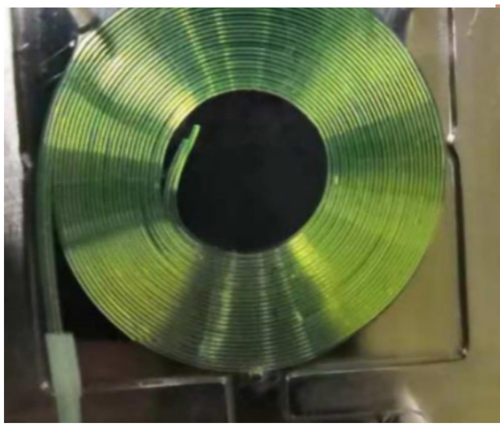


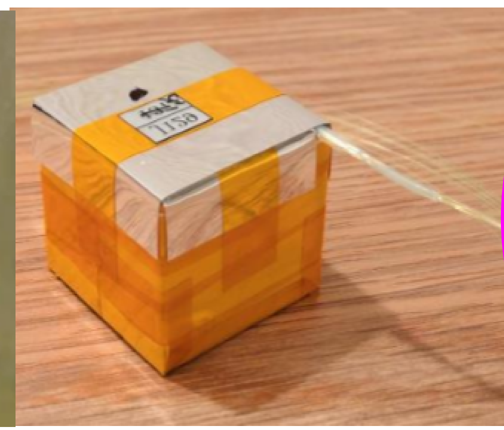
Innovative design

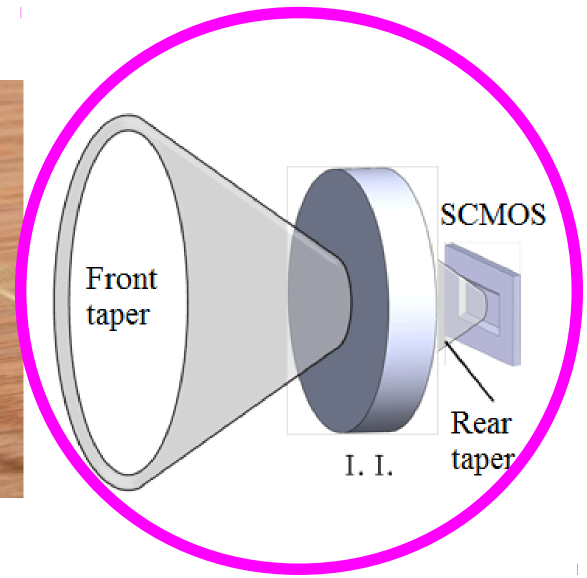
Deep homogeneous calorimeter	→	Good energy resolution
Isotropic 3D geometry	→	Large geometric factor (top + lateral faces)
Shower imaging with 3D segmentation	→	Good e/p discrimination, identification of shower axis and of shower starting point

HERD CALOrimeter (CALO)
Wavelength shifting fibers readout

Dynamic range of 10^7 needed to detect deposit in a single crystal going from a fraction of MIP (~10 MeV) to the release of a PeV proton (~20 TeV)







IsCMOS
(I.I. and sCMOS)
developed by
CAS Xi'an
Institute of Optics
and Precision
Mechanics

Three **WLS**
- Fiber 1
- Fiber 2
- Fiber 3

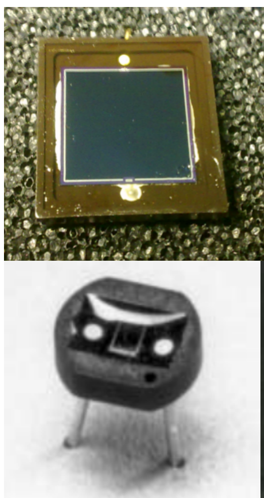
Image Intensifier (I.I)
- High gain
- Low gain

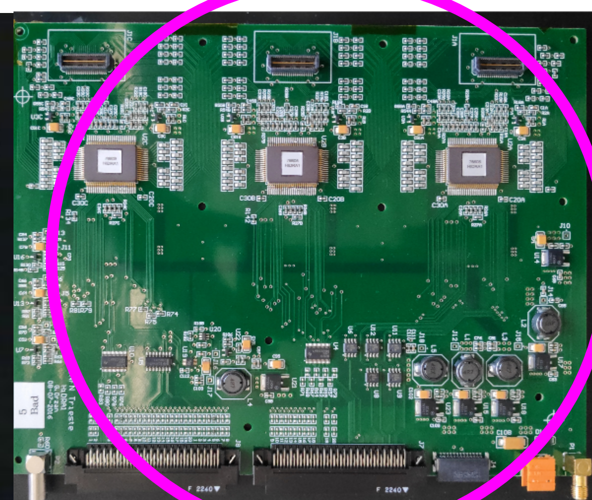
scientific CMOS (sCMOS)
- sCMOS 1 (20x20 pixels/fiber)
- sCMOS 2 (20x20 pixels/fiber)

PMT (Trigger system)

HERD CALOrimeter (CALO)
Photodiodes readout

Dynamic range of 10^7 needed to detect deposit in a single crystal going from a fraction of MIP (~10 MeV) to the release of a PeV proton (~20 TeV)





CASIS read-out chip (based on a CSA + CDS) developed by INFN Section of Trieste

Two **PD**
- Large
- Small

(1:100 Area ratio)

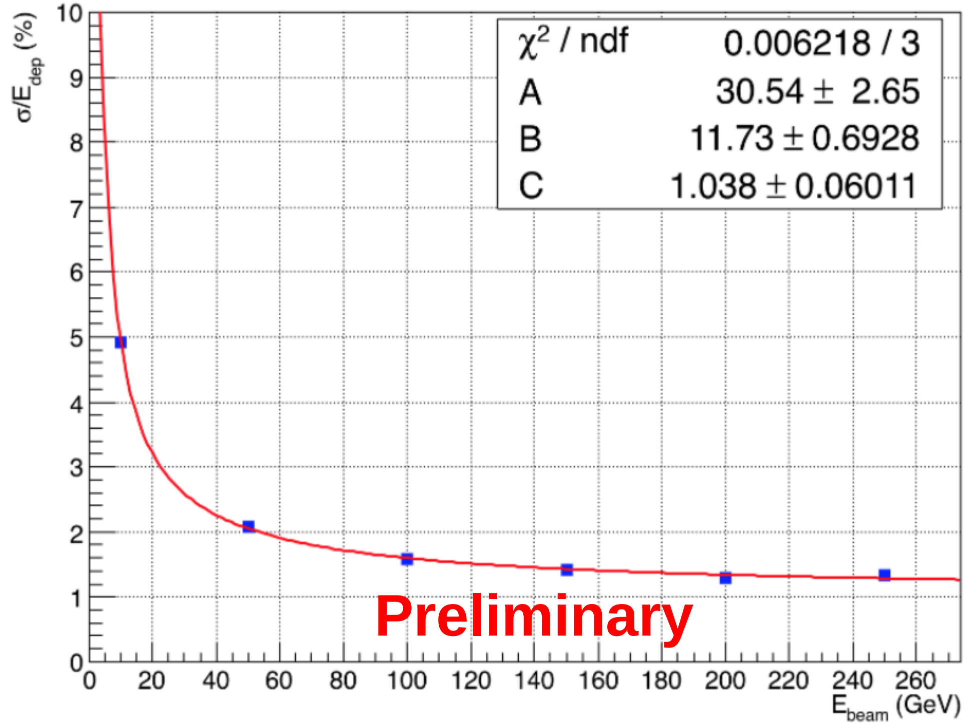
CASIS chip
- double gain (1:20)
- 52.6 pC dynamic range
- 2280e$^-$ + 7.6e$^-$/pF ENC
- Auto trigger system capability

In order to improve **redundancy** and **cross calibration**, LYSO crystals will be equipped:
- <u>all with WLS</u>
- <u>fraction or all with PD</u>

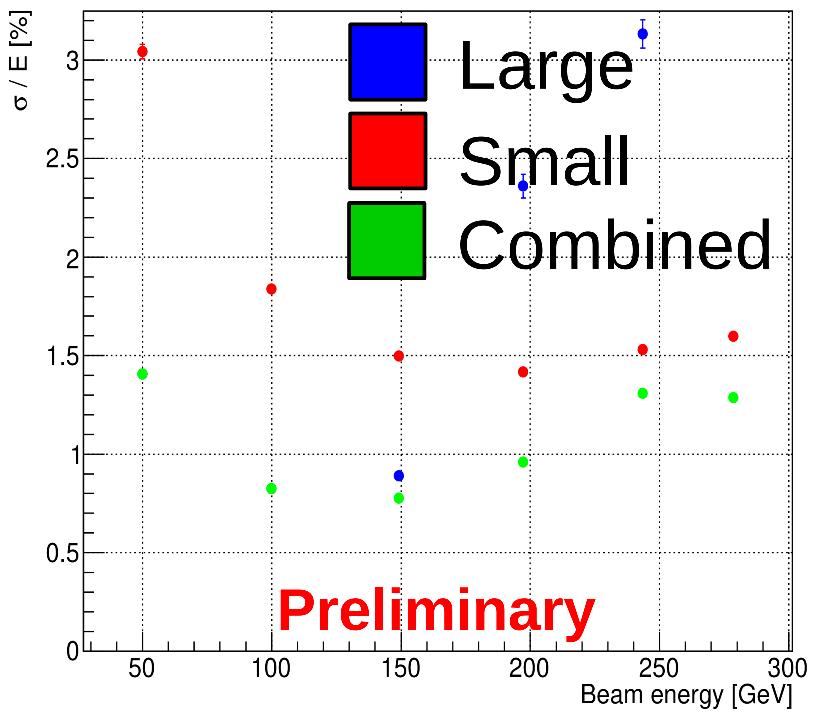
HERD CALOrimeter (CALO)
Prototype performances

Energy resolution for high energy electrons

LYSO prototype
readout using WLS



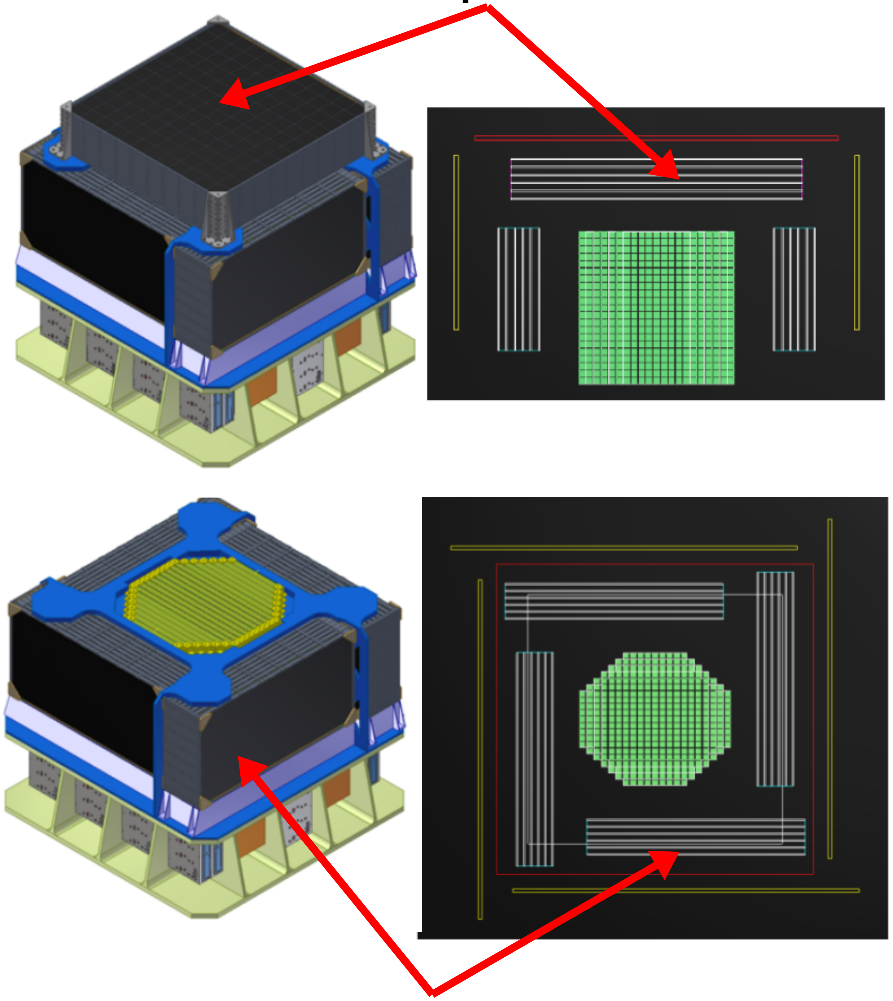
CSI:Tl prototype
readout using PD



Good and similar performances among the two readout systems.
The performances will be improved in next versions of the prototype.

HERD Silicon TracKer (STK)

1 Top STK



4 Lateral STK

1 Top STK

- 6 Layers of XY SSD
  with LYSO as **active converter** →
- Active Area 133 cm x 133 cm

4 Lateral STK

- 3 Layers of XZ or YZ SSD
- Active Area 95 cm x 66.5 cm

Strip pitch

- $d_{Implantation}$ = 121 μm
- $d_{Readout}$ = 242 μm

Expected resolution

σ = 40 μm

Innovative geometry: **Tracker in Calorimeter**

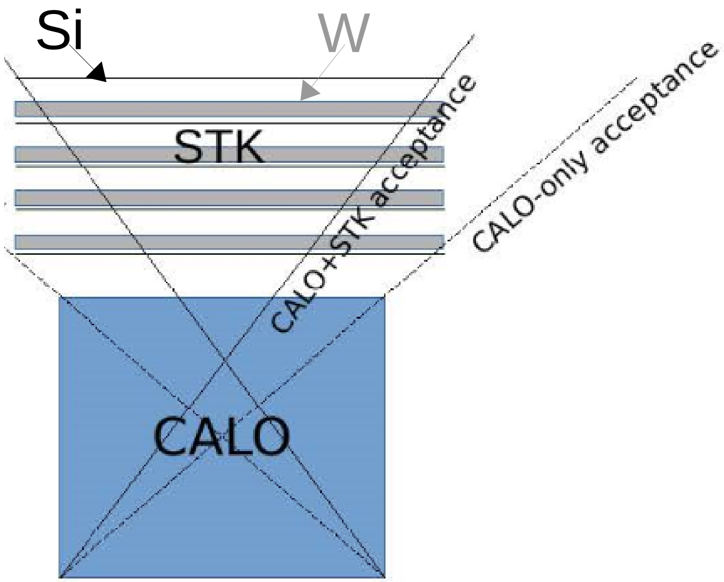
Alternative design: **FIber Tracker** instead of **Silicon TracKer**

HERD Tracker in Calorimeter (TIC)

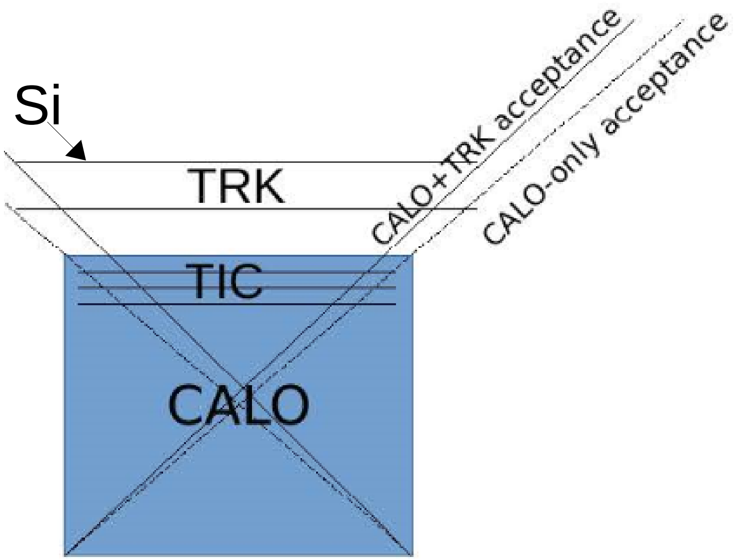
Idea

Under study: **Novel approach to trajectory reconstruction**

Standard approach that exploits the conversion of γ->e^+e^- in W



TIC approach that exploits the transverse profile of the shower



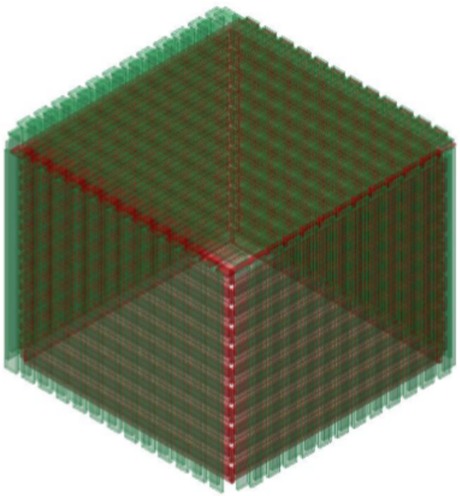
Advantages of TIC design

• decrease the amount of mass used for passive material (W)

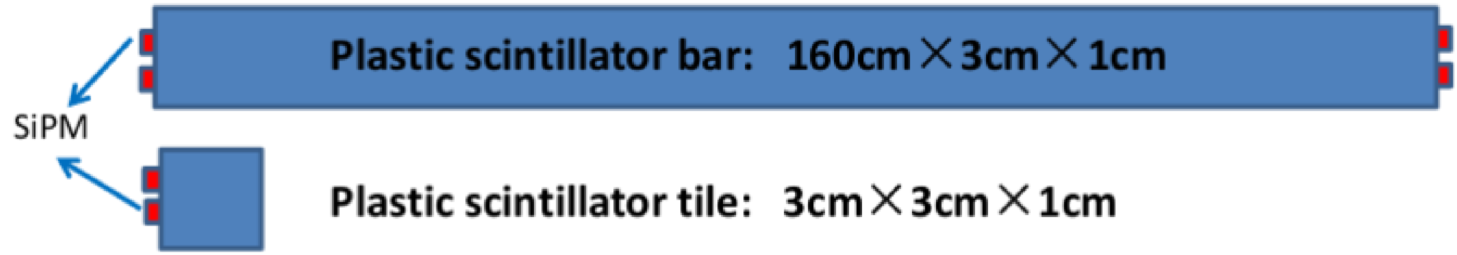
• reduce hadron fragmentation in passive material

• increase the geometric acceptance

HERD Plastic Scintillator Detector (PSD)

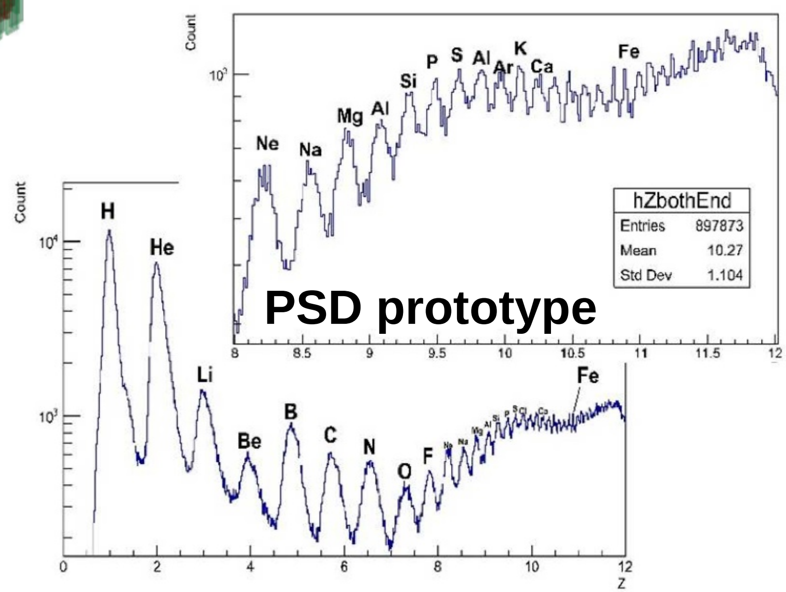


Bars or Tiles readout by SiPM



PSD Layers

- 1 Top XY
- 4 Lateral XY
- 1 Bottom X



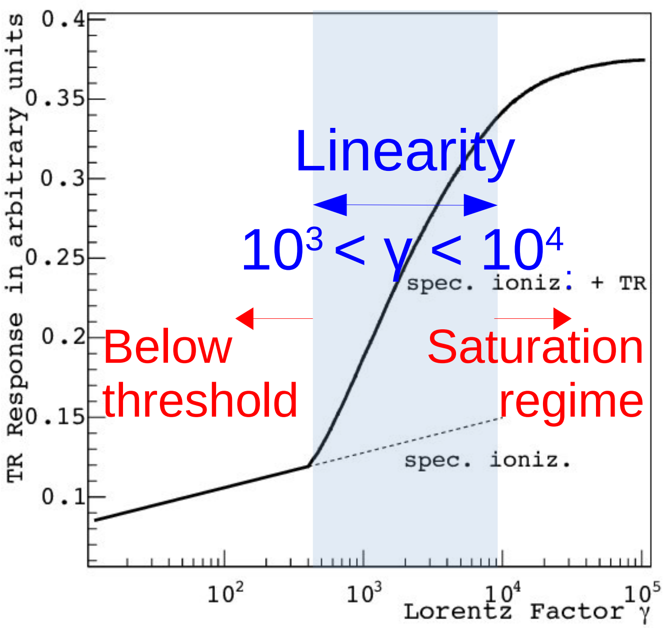
	Advantages
Bars	Lower number of readout channels
Tiles	Better identification of backscattered particles

The correct identification of backscattered particles is crucial to avoid:

- charge misreconstruction in case of incident charged particles
- self veto in case of incident γ

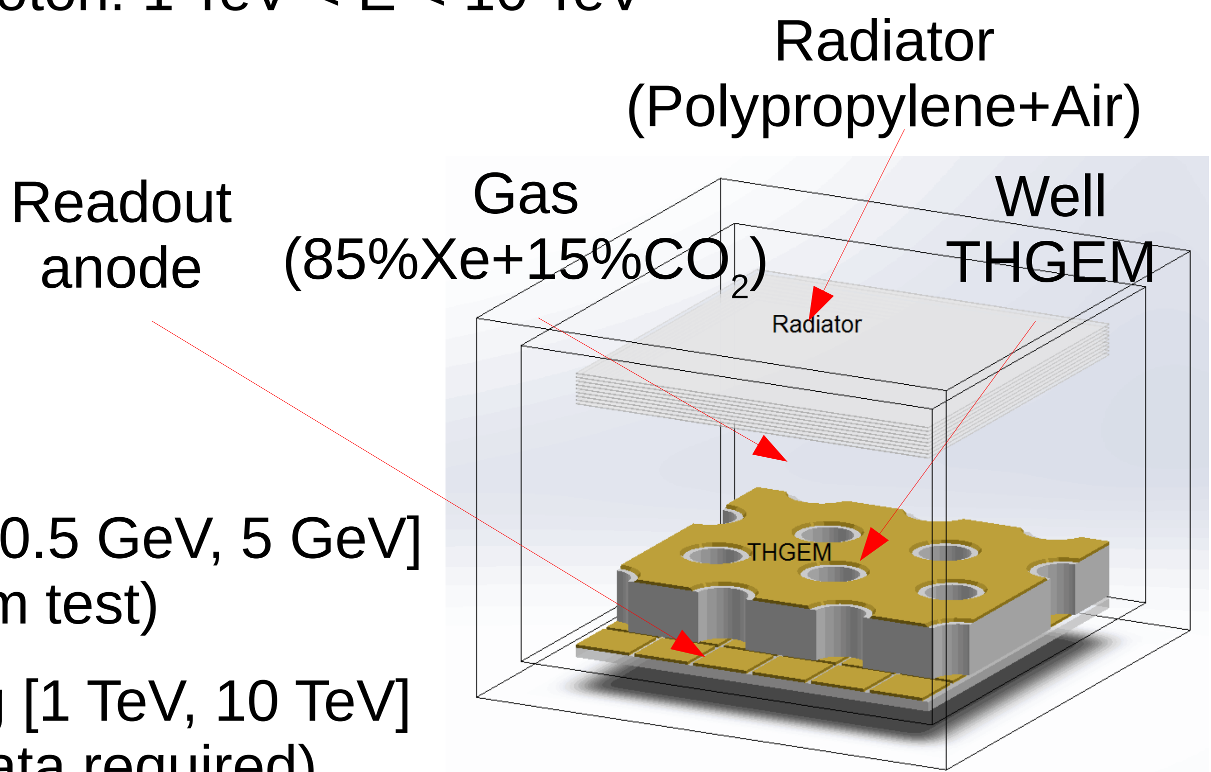
HERD Transition Radiation Detector (TRD)

The TRD, installed on a lateral face of the detector, is needed to calibrate the response of the calorimeter to high energy hadronic showers



Linearity for $10^3 < \gamma < 10^4$

- Electron 0.5 GeV < E < 5 GeV
- Proton: 1 TeV < E < 10 TeV



Calibration procedure

- calibrate TRD response using [0.5 GeV, 5 GeV] electrons in space (and at beam test)
- calibrate CALO response using [1 TeV, 10 TeV] protons from TRD (3 months data required)

Summary

The **High Energy cosmic-Radiation Detection** facility is a China-led international space mission that will start its operation around 2026 on board the future China's Space Station.

Thanks to its **novel design**, based on a 3D, homogeneous, isotropic and finely-segmented calorimeter, HERD is expected to accomplish **important and frontier goals** relative to DM search, CR observations and Gamma-Ray astronomy:

A) extend the measurement of e^{+}+e^{-} flux up to several tens of TeV

* testing the hypothesis of the expected cutoff at high energy
* distinguishing between DM or astrophysical origin of positron excess

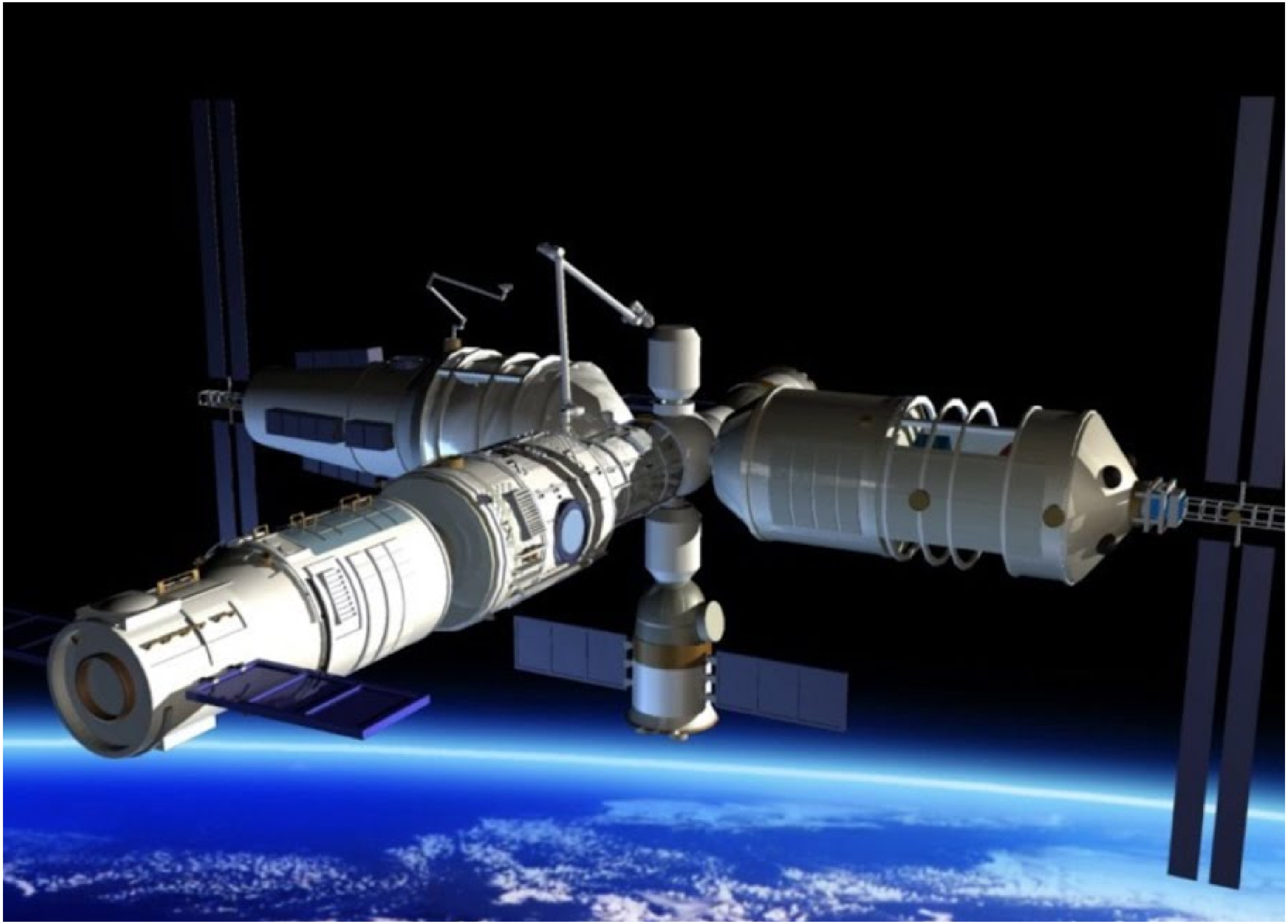
B) extend the measurement of p and He flux up to a few PeV

* testing the theory of the knee structure as due to acceleration limit

C) large acceptance, high sensitivity to γ up to several tens of TeV

* searching for Gamma-Ray Line associated to DM annihilation
* accomplishing a Gamma-Ray sky survey up to very high energy

Thank You!

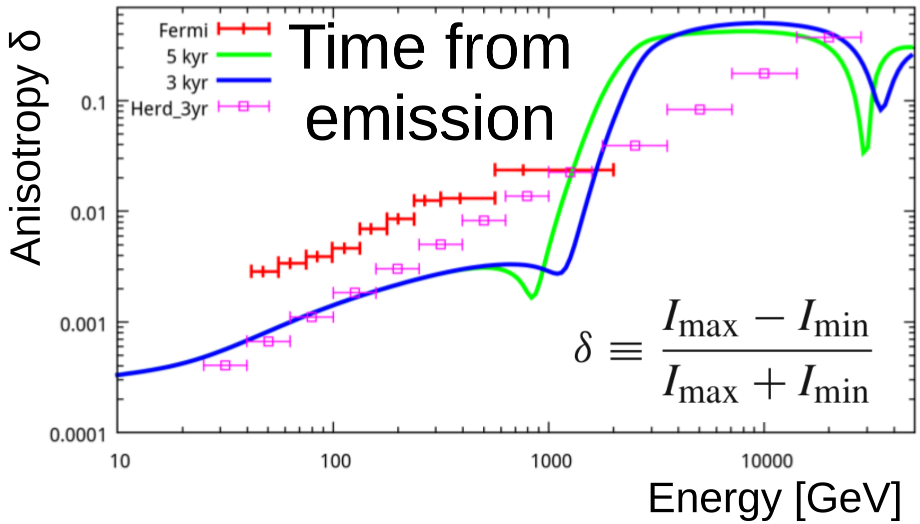


Back Up

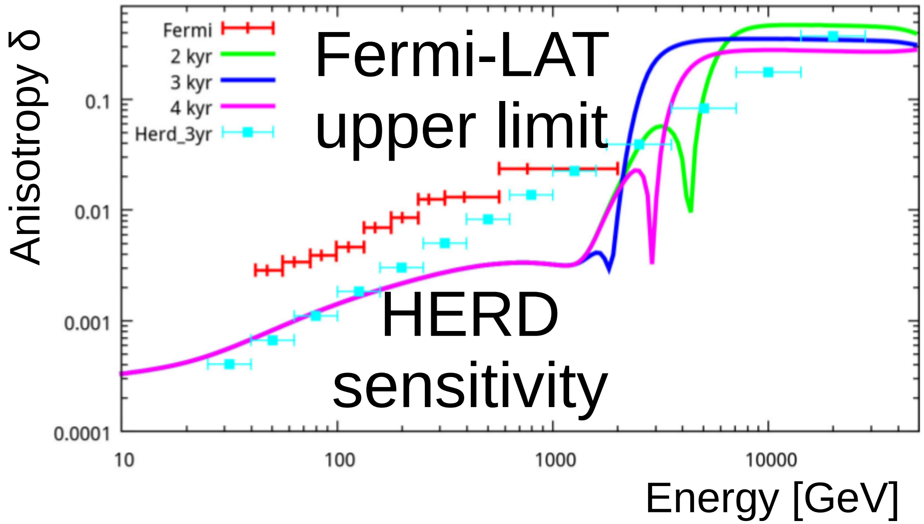
Electrons and Positrons

e^++e^- Anisotropy

Contribution to e^++e^- anisotropy from Cygnus-Loop



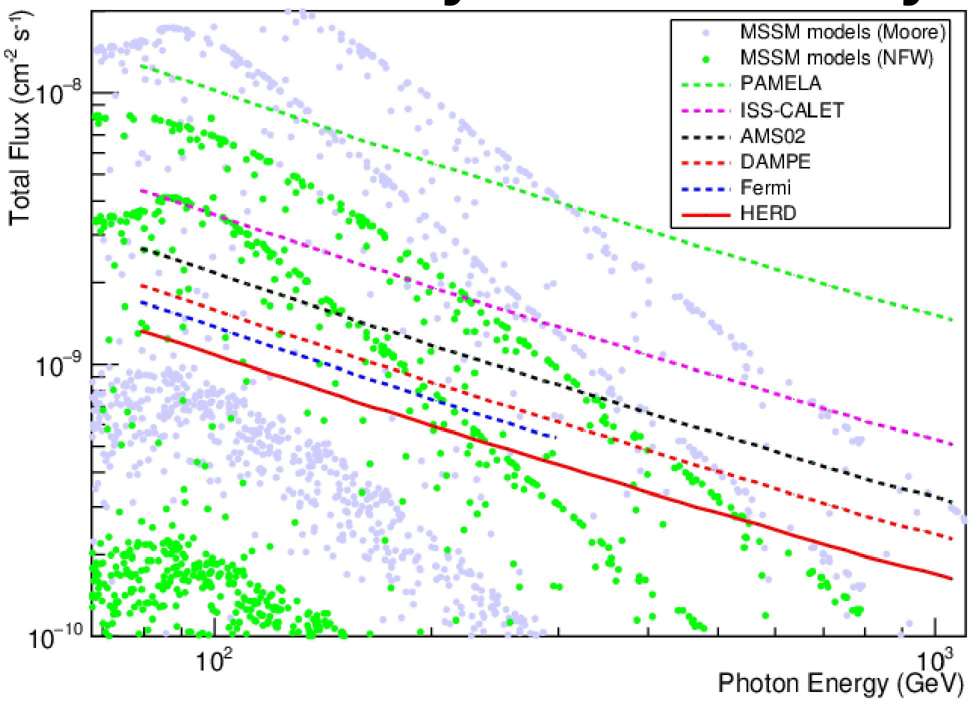
Contribution to e^++e^- anisotropy from Vela X



Thanks to the good sensitivity to e^++e^- anisotropy, HERD will be able to better discriminate between source (high anisotropy) or DM (low anisotropy) origin

Gamma-Ray
HERD

Gamma-Ray line sensitivity



PAMELA: 2006-2016

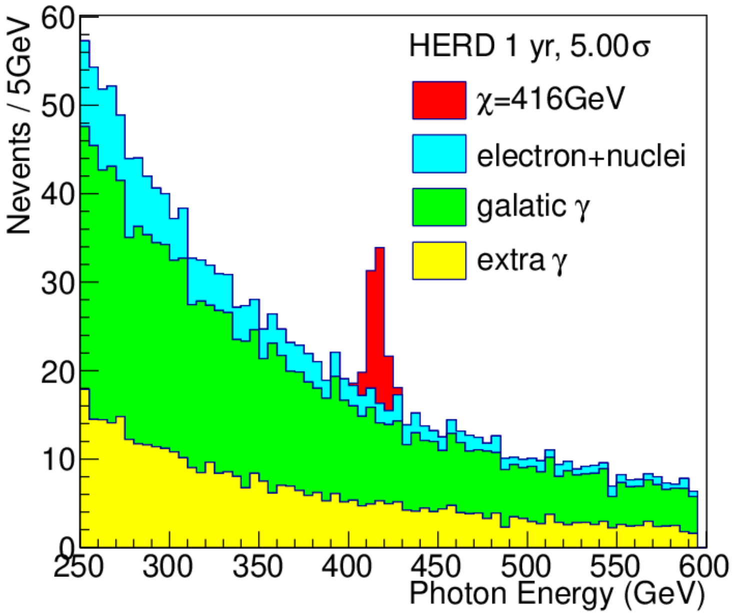
CALET: 2015-2020

AMS: 2011-2024

DAMPE: 2015-2020

Fermi: 2008-2018

HERD: 1 year



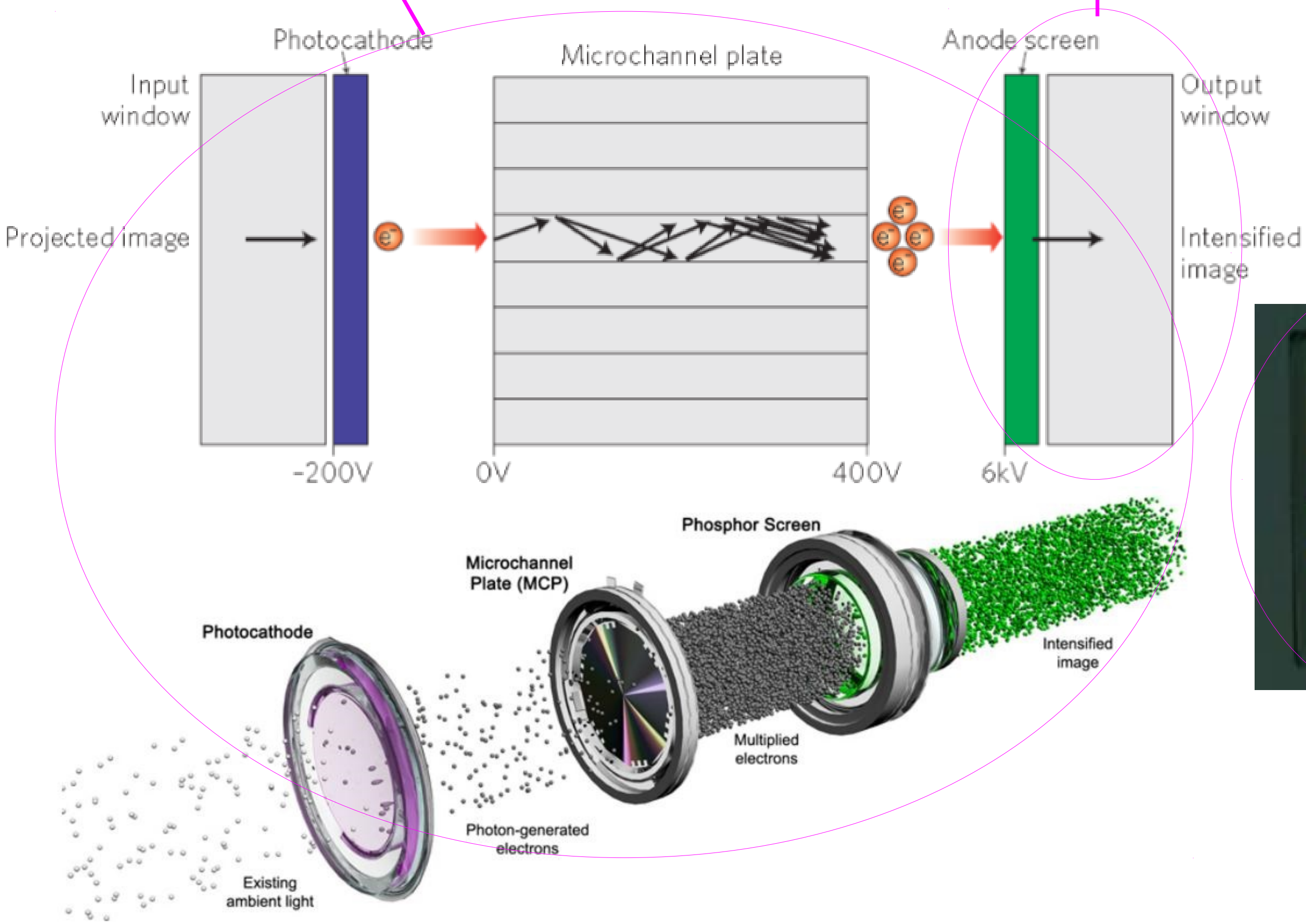
Thanks to its large acceptance and good sensitivity, **HERD** <u>will offer an unprecedented capability for the search of gamma-ray line from dark matter annihilation</u> (galactic center, dwarf spheroidal galaxies,...)

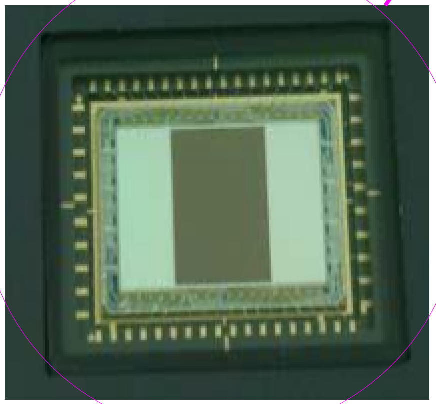
IsCMOS

Image Intensifier

Phosphor screen
840 μs decay time

sCMOS
High sensitivity
Low Noise
Global shutter
500 fps Frame rate
10^3 Dynamic Range



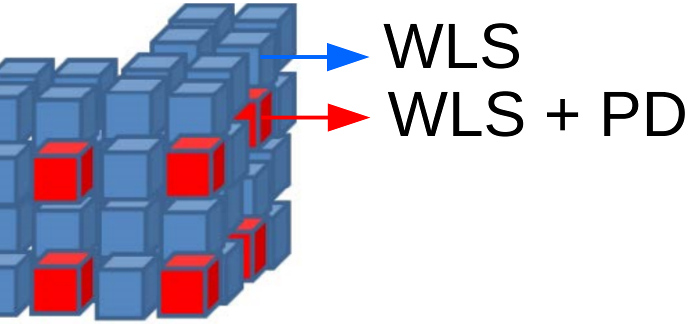


1 MIP in LYSO generates about 200 photoelectrons on IsCMOS

HERD CALOrimeter (CALO)

Dual readout

	Advantages	Disadvantages
WLS	Compact system with external power consumption (no thermal effect due to the sensors)	Cross Talk among fibers on sCMOS and degradation of IsCMOS (substitution required after 3 years)
PD	Compact and simple system	Direct ionization in sensor



Being the calorimeter the main detector of HERD, we decided to **instrument all crystals with WLS and a fraction** (*i.e.* 1/8) **or all of them with PD** .

With a 1/8 fraction, PD can independently measure the energy without strong loss in performances (σ_E/E from 20% to 25% for 1 TeV p)

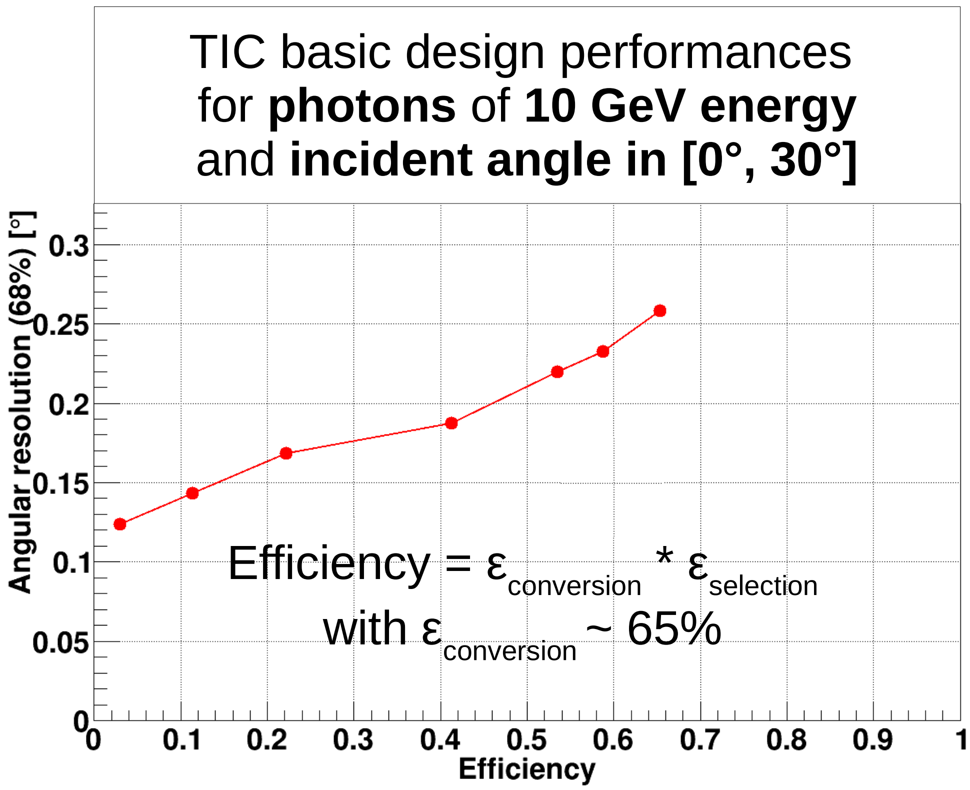
<u>Decrease uncertainty on the calibration of the energy scale:</u>

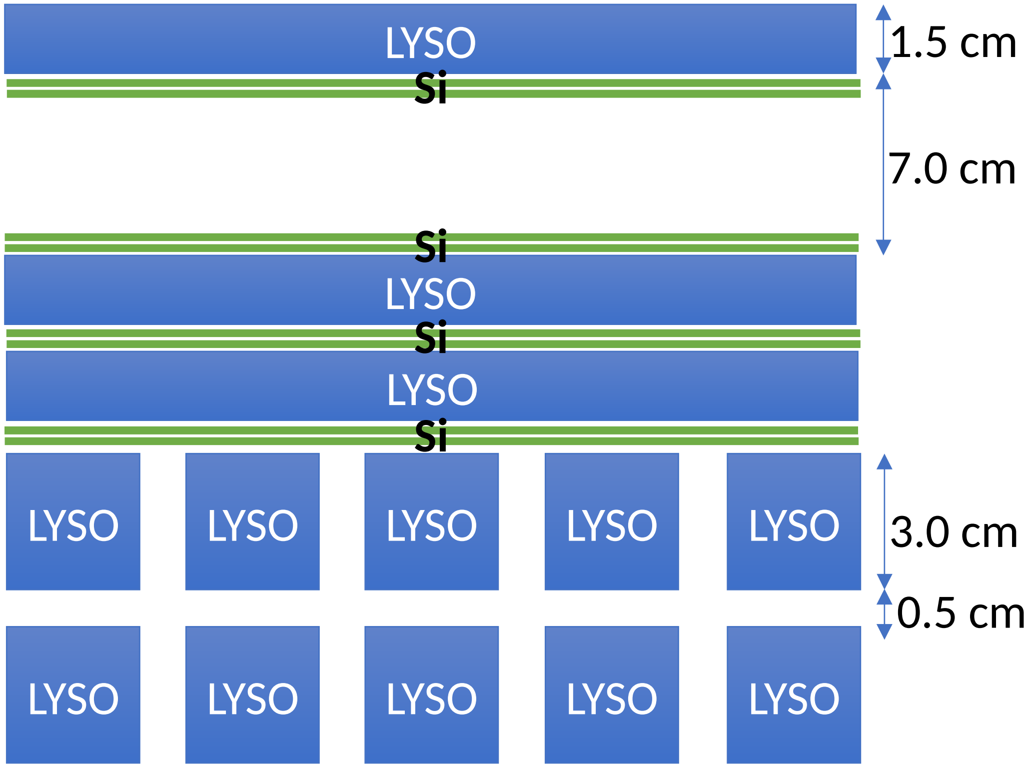
- cross calibration of different sensors in different ranges
- monitoring of the stability of sensors gains

<u>Increase the redundancy of the system:</u>

- independent energy measurement
- independent trigger system

HERD Tracker in Calorimeter (TIC)
Simulated performances





Basic TIC design: it will be optimized in the future
Current performances: **$\Delta\theta$ = 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 $\Delta\theta$ and ε</u>

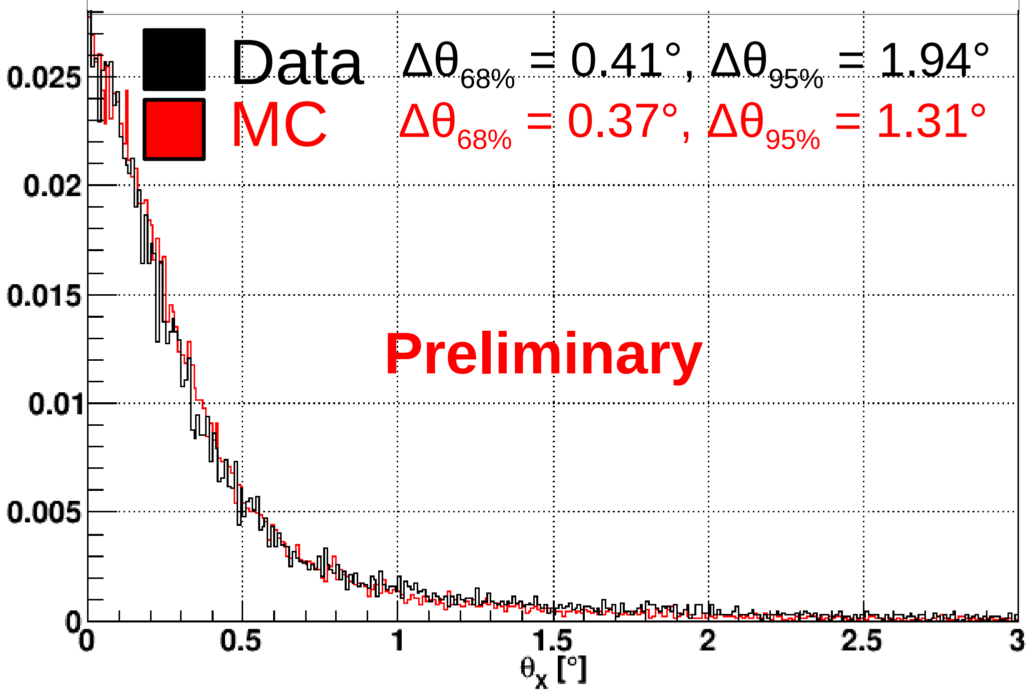
HERD Tracker in Calorimeter (TIC)

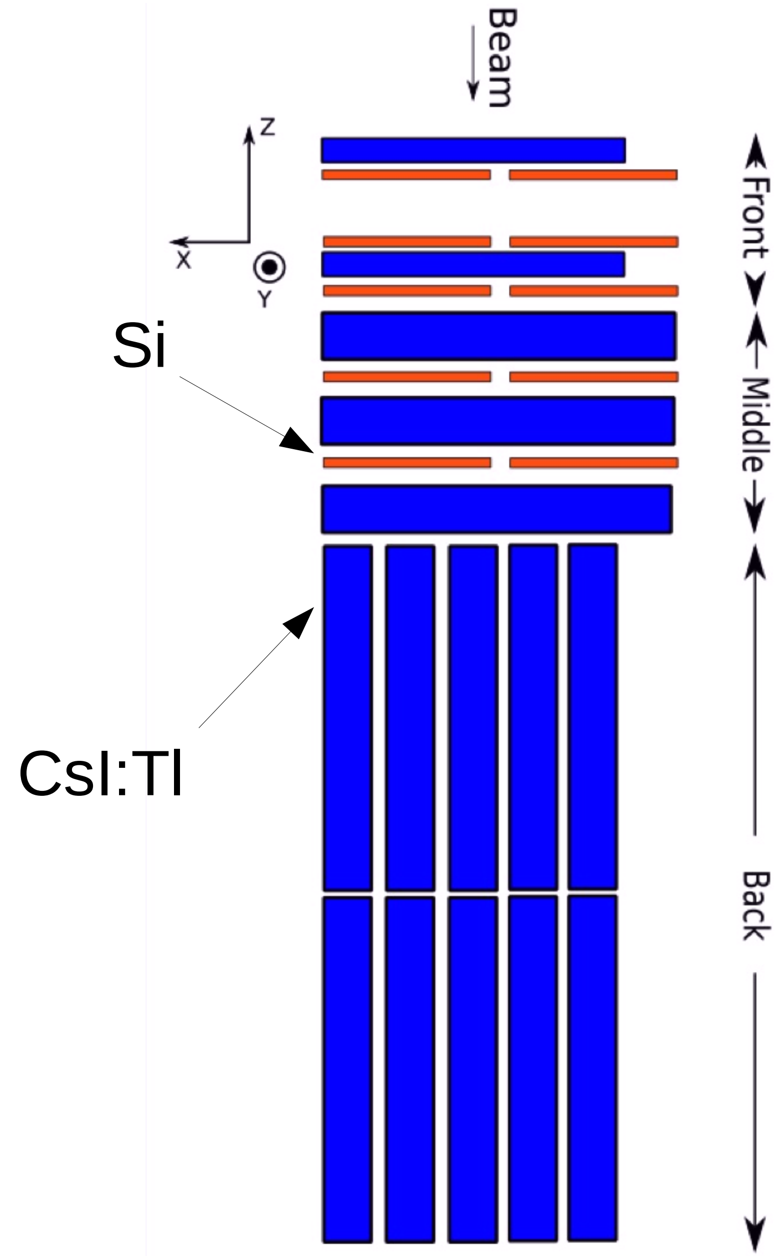
Prototype Performances

$\Delta\theta_x$ of a TIC prototype
for 10 GeV incident electrons

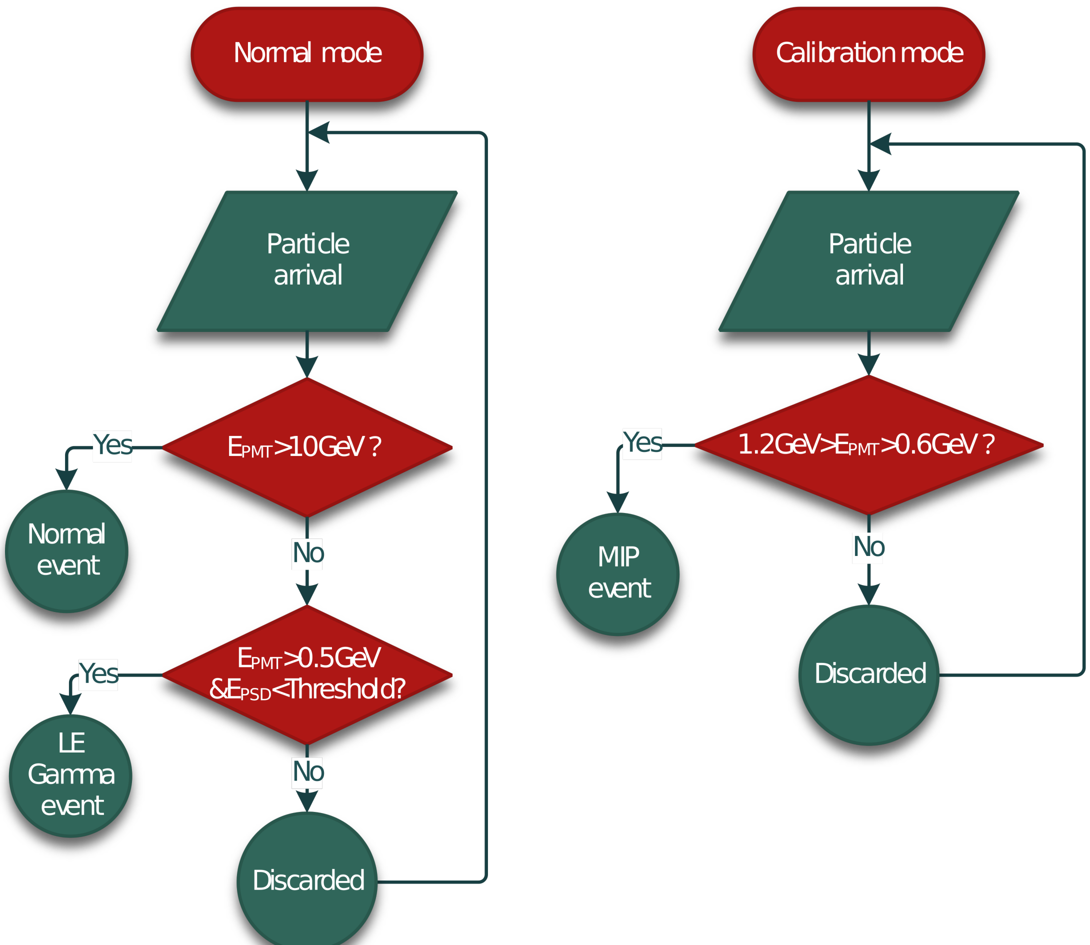
<u>Good agreement</u>
<u>between data and MC</u>

(Beam condition
and Si microstrip capacitive coupling
were taken into account)





Trigger system
Wavelength shifting fibers trigger



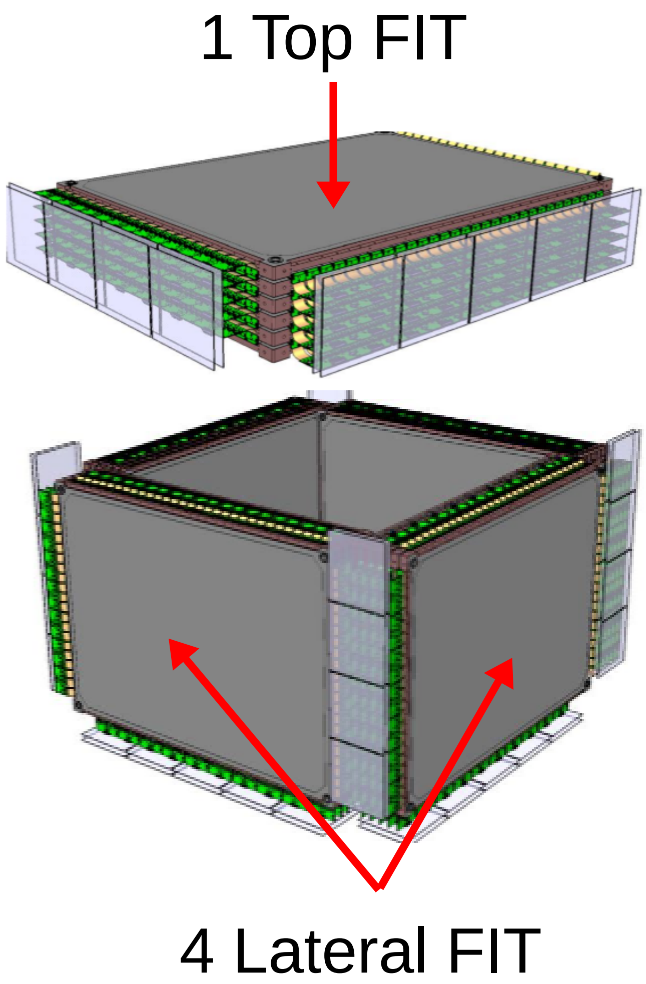
Trigger is generated grouping fiber 3 of each crystal in N different groups, each one read by a PMT

The groups are conveniently defined in order to represent the core and the different shells of CALO

Different working mode:

- Normal mode (150 cps)
  - HE trigger
  - LE electron
  - LE photon
  - Unbiased trigger
- Calibration mode (350 cps)
  - MIP trigger

HERD FIber Tracker (FIT)



1 Top FIT

- from 5 to 10 Layers of XY fibers mats

4 Lateral FIT

- 5 Layers of XZ or YZ fibers mats

Fiber pitch

- d = 250 μm

Expected resolution

- σ = 65 μm

Read-out

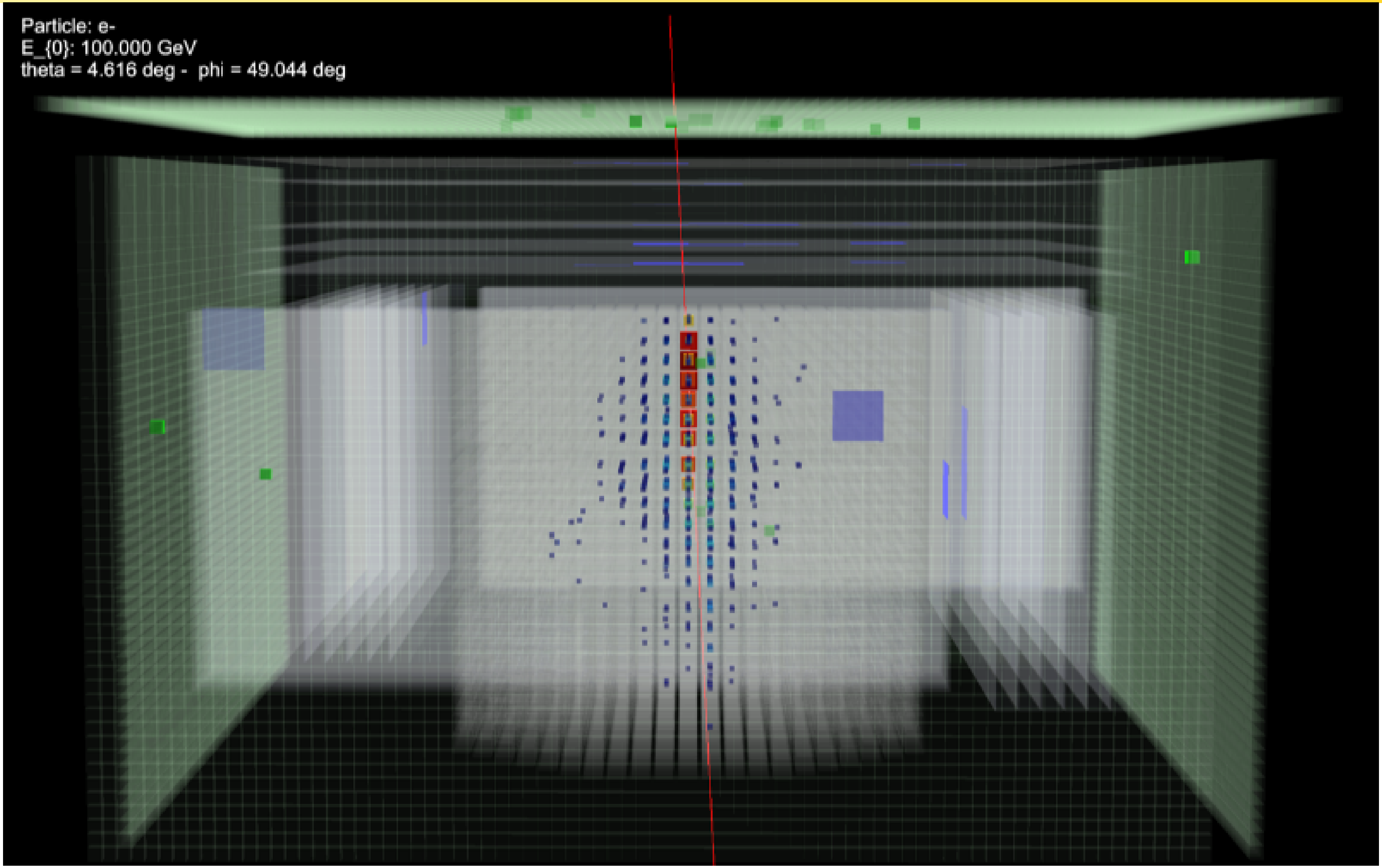
- SiPM array

Being fibers light and no mechanical support needed, the mass and volume budget of FIT is much lower than STK and it allows a higher number of layers for track and charge reconstruction

Advantages of FIT design

- better track and charge reconstruction
- high precision for sub-GeV γ

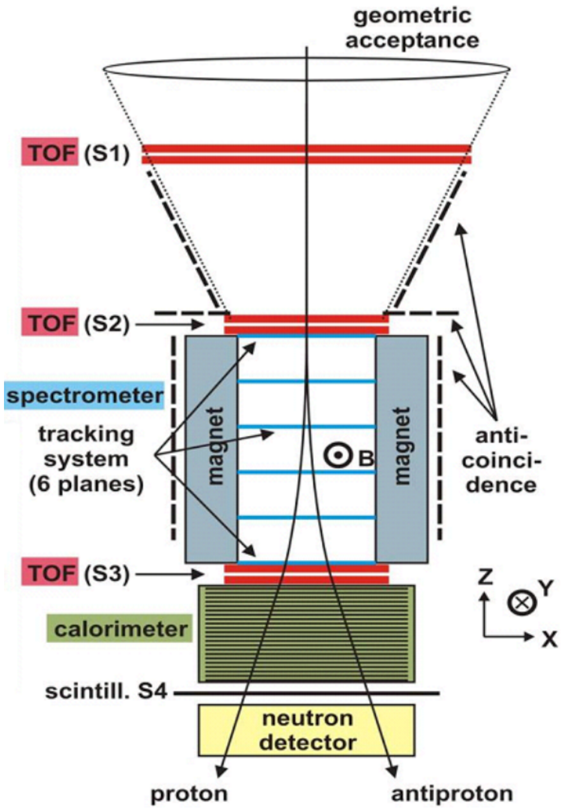
HERD
100 GeV Electron simulation



Past vs Future experiments

Past experiments

based on *magnetic spectrometer*



better resolution at high energy

$$\sigma_E/E \propto E$$

$$\sigma_E/E \propto 1/\sqrt{E}$$

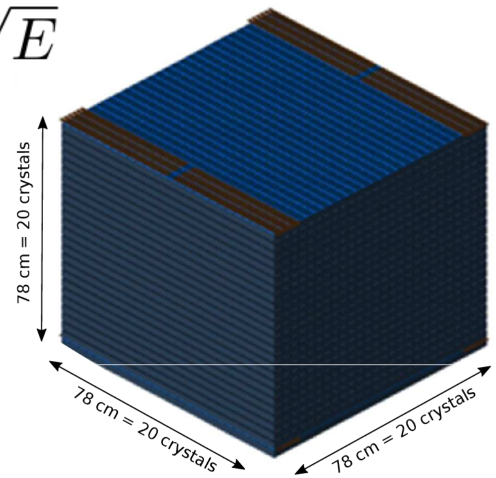
better geometrical acceptance

because of rigid geometry
it measures only particles from one direction

For example in the case of PAMELA
$G = 20.5\ \mathrm{cm}^2\ \mathrm{sr}$
$\sigma_p/p \sim 15\%$ for 100 GeV p
MDR = 740 GV/c

Future experiments

based on *calorimeter*



because of flexible geometry
it can detect particles from more faces

Satellite experiments

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

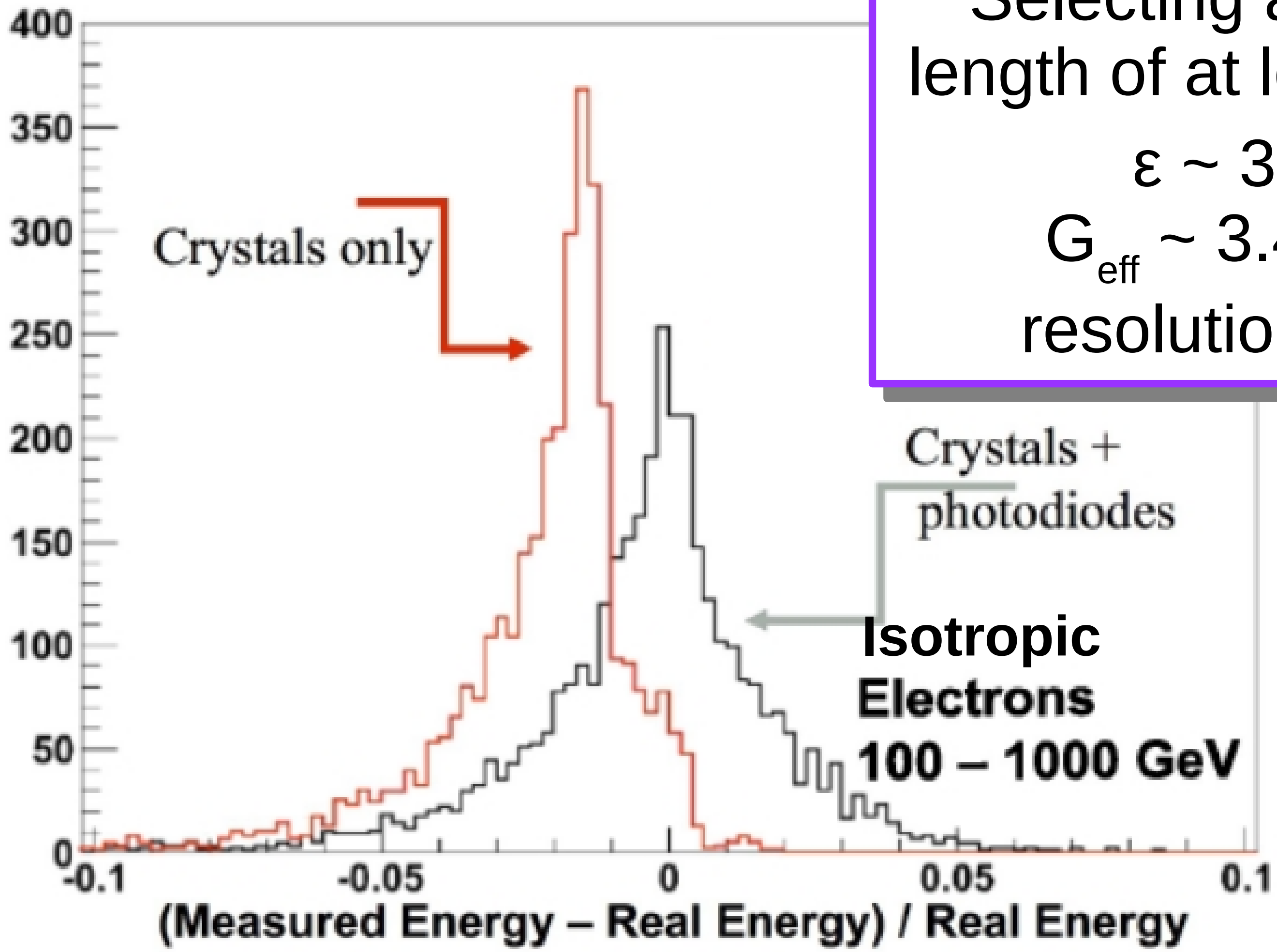
Effective geometric factor

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

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

Electron performances

Calocube Simulation



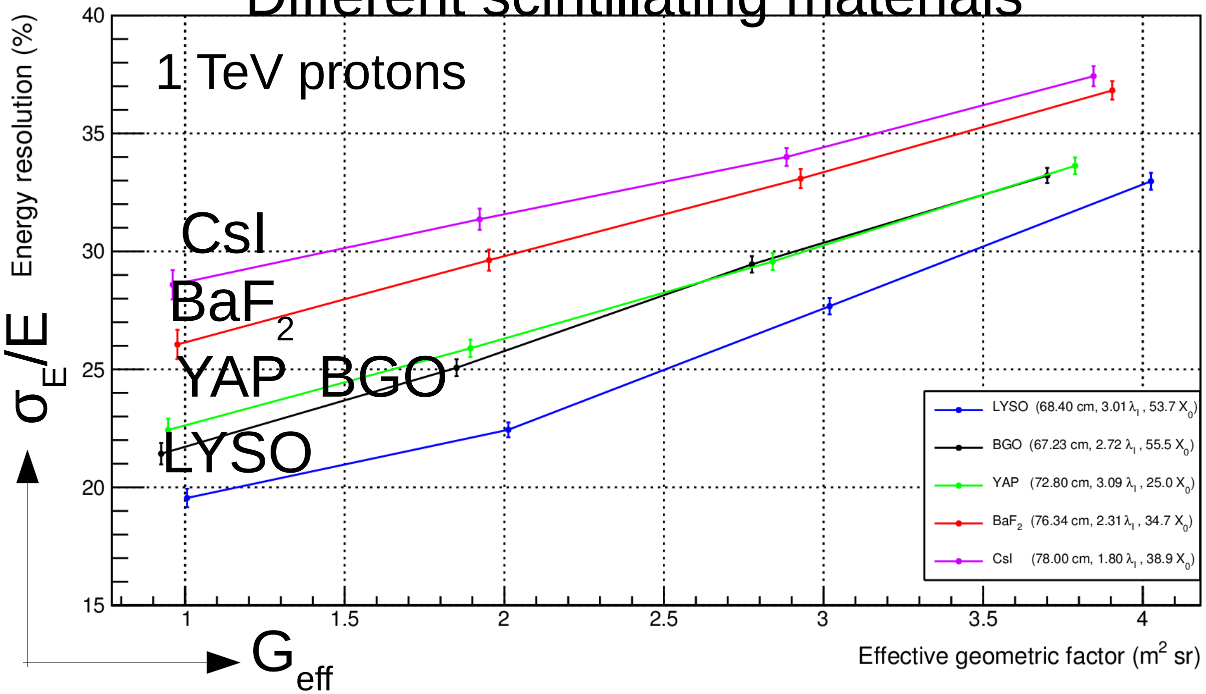
Selecting a shower length of at least 22 X_0:
$\varepsilon \sim 36\%$
$G_{eff} \sim 3.4\ m^2 sr$
resolution ~ 2%

Direct ionization in photodiodes is about 1.7% of the total signal

Proton performances

Calocube Simulation

Different scintillating materials



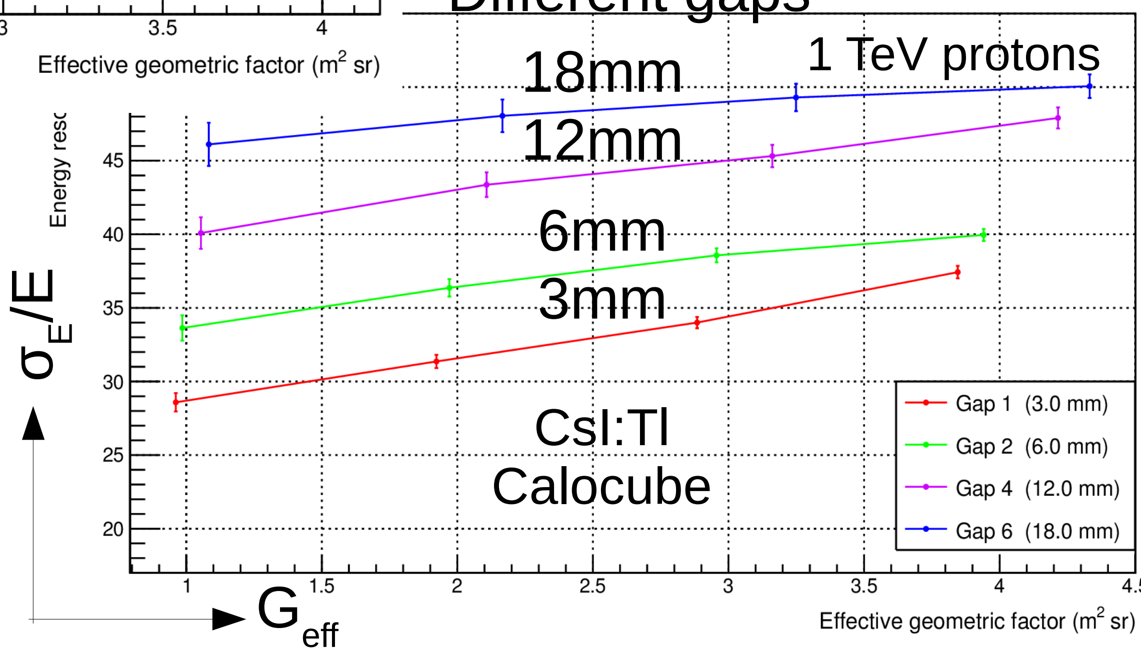
The best value of σ_E/E is obtained using low λ_I crystals. The maximum G_{eff} has a small dependence on the material.

LYSO is the best candidate.

Larger gap increases G_{eff},
Smaller gap improves σ_E/E

A compromise is needed.

Different gaps



The points corresponds to different selection efficiency

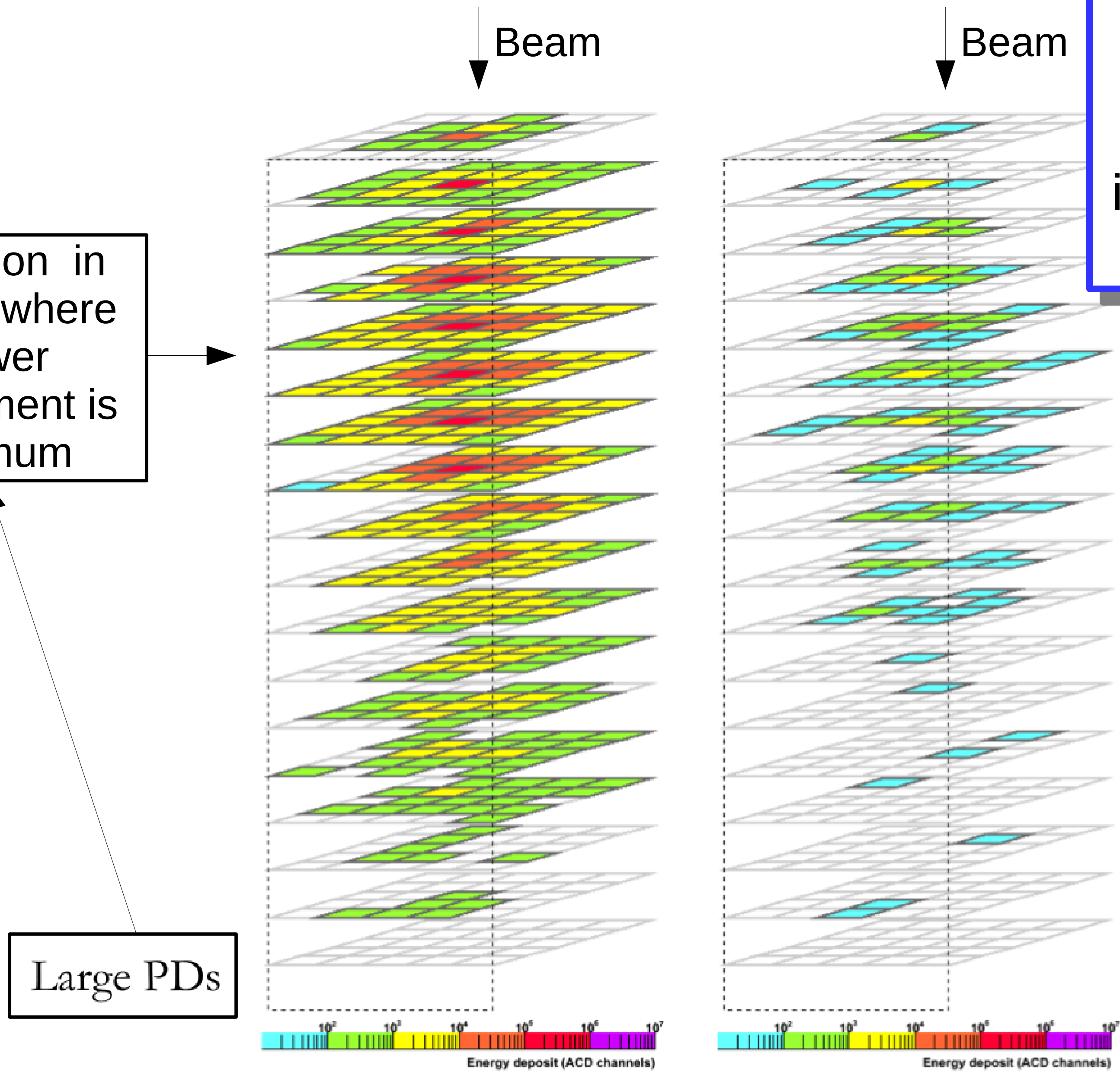
Event view
200 GeV electron

Calocube Prototype

Combining the Large and Small PDs we can improve the linearity and resolution

Saturation in crystals where shower development is maximum

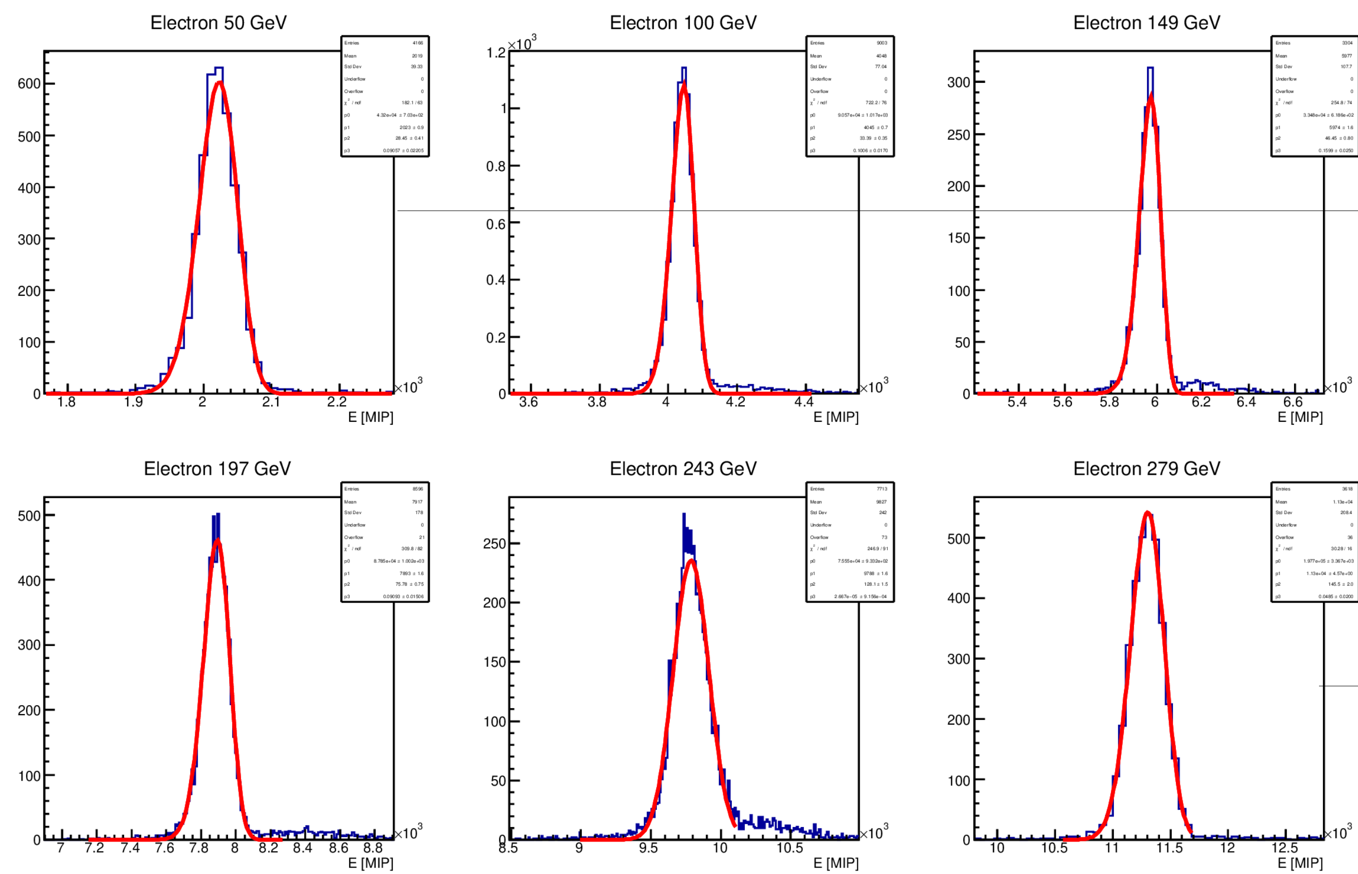
The information of Large PDs saturated channels can be recovered using Small PDs



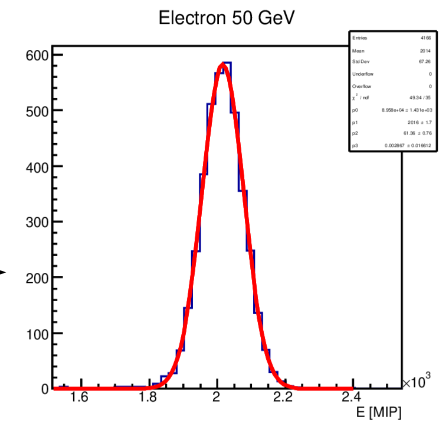
Electron deposit

Calocube Prototype

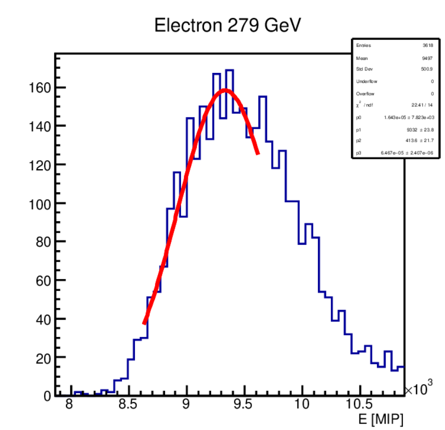
Combined PDs



Small PDs



Large PDs



Crystal linearity

Tarlé model

$$\frac{dL}{dx} = K\left\{\frac{(1-F_s)dE/dx}{1+B(1-F_s)dE/dx} + F_s\frac{dE}{dx}\right\}$$

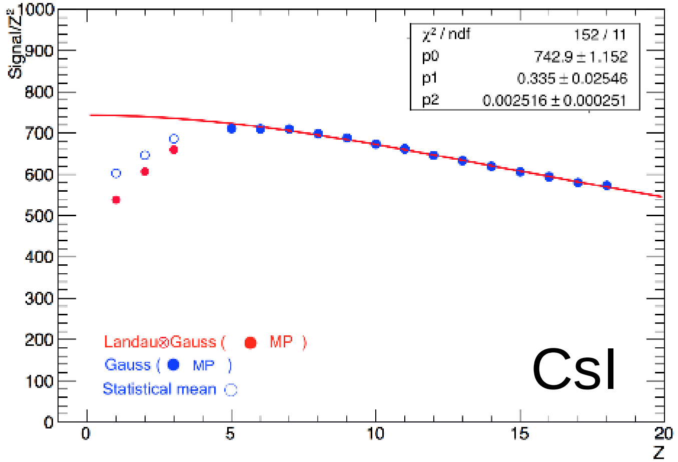
Fit function

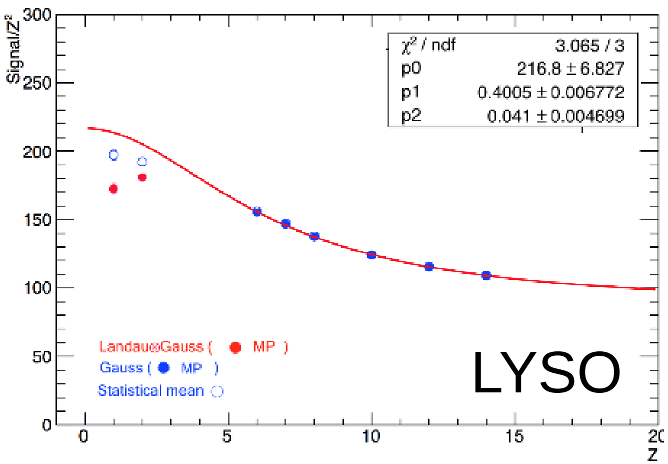
$$\frac{S}{Z^2} = p_0\left\{\frac{(1-p_1)}{1+p_2(1-p_1)Z^2} + p_1\right\}$$

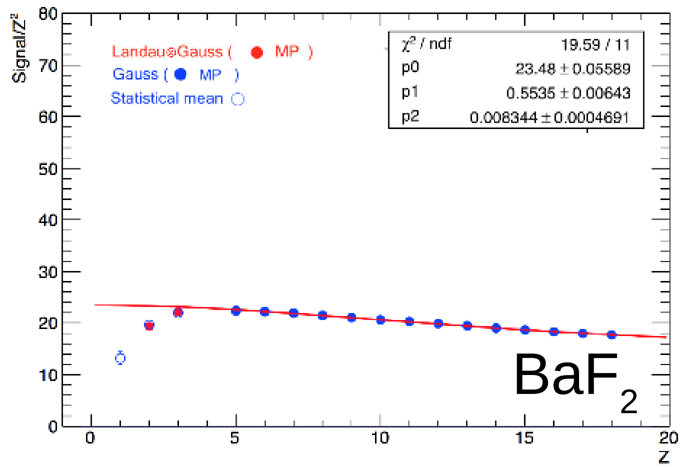
The non linear regime starts for $Z^2 = p_2 = 1/Z_0^2$

CsI:Tl has the largest Z_0

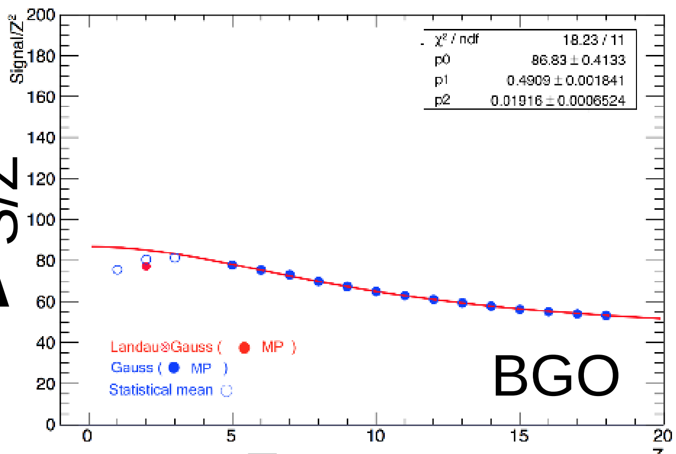
LYSO has the smallest Z_0

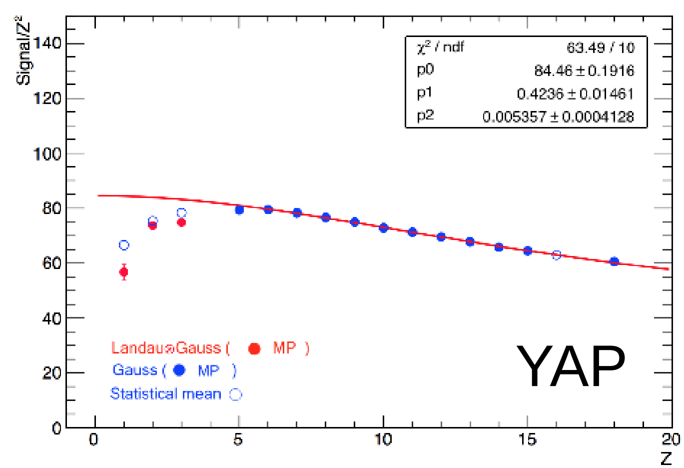






S/Z2





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