

A compact particle detector for Space-Based applications: Development of the Low Energy Module (LEM) for the NUSES space mission



Riccardo Nicolaidis, Francesco Nozzoli
On behalf of the NUSES collaboration

ASAPP 2023 – Perugia – 22/06/2023

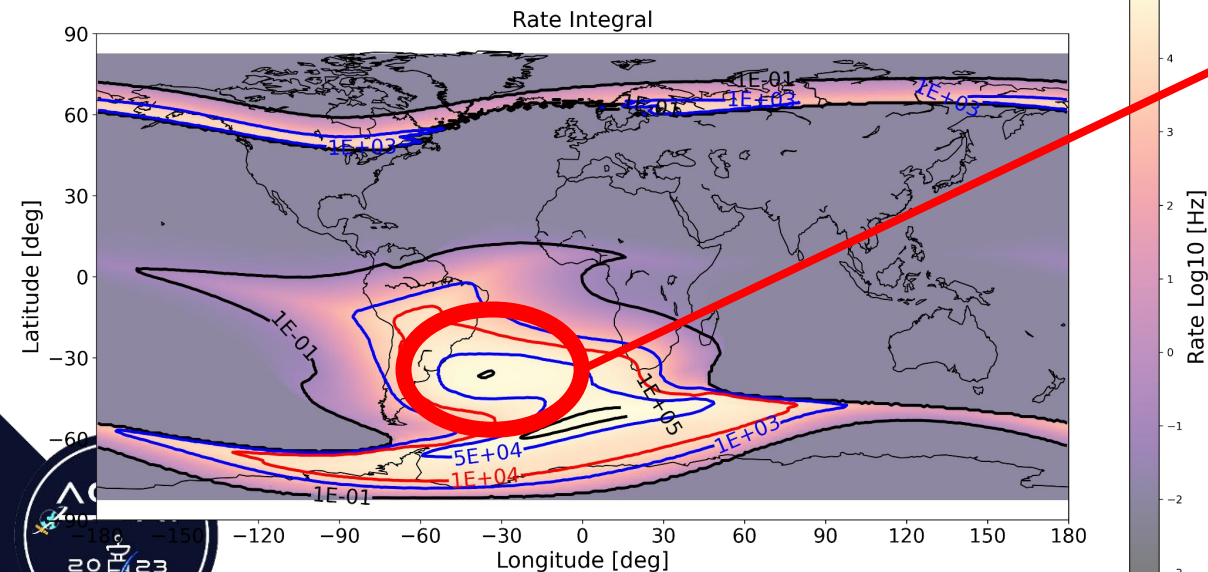
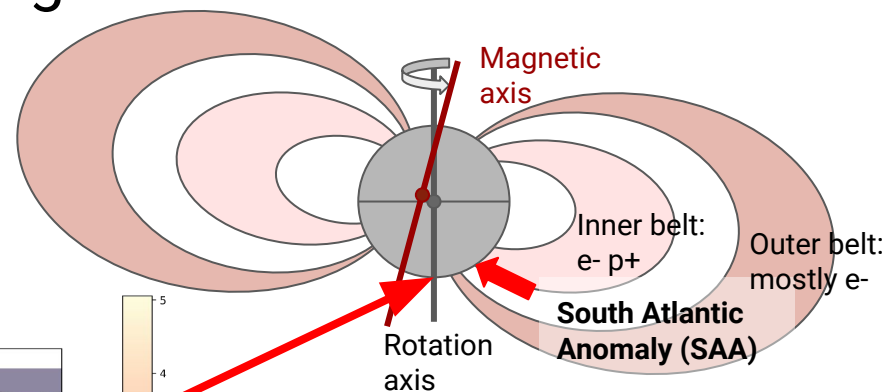


UNIVERSITÀ
DI TRENTO



Trapped particles: 7 orders of magnitude

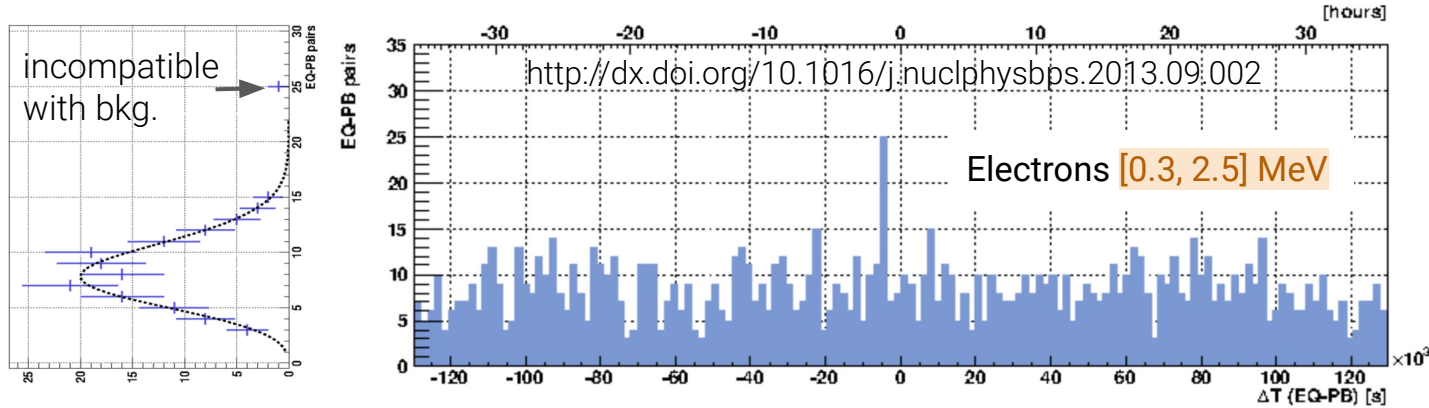
- Earth's magnetic field is approx. dipolar
- Shifted and tilted dipole
- **SAA**: Furthest place from dipole (B weaker)
- **Van Allen radiation belts**: from 1000 km above surface up to 6 Earth's radii



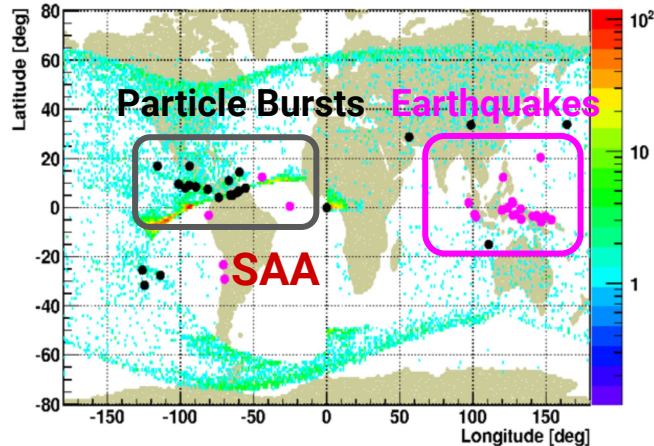
There is the need to design a detector for harsh environment



Statistical correlation between PBs and seismic events



Particle Bursts
(PBs) Earthquake
(EQs) $M > 5$
Time correlation

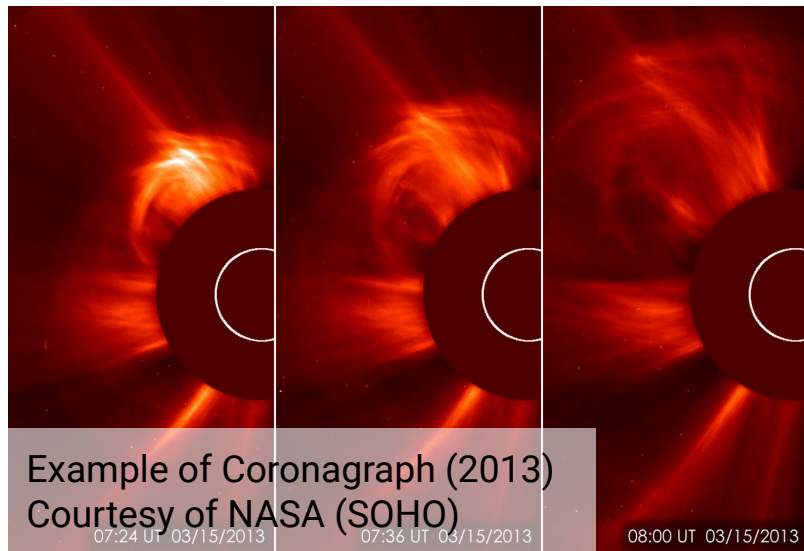


Correlation found with channel:
electrons [0.3, 2.5] MeV (NOAA MEPED)

PBs mostly generated by Indonesian earthquakes but detected near SAA

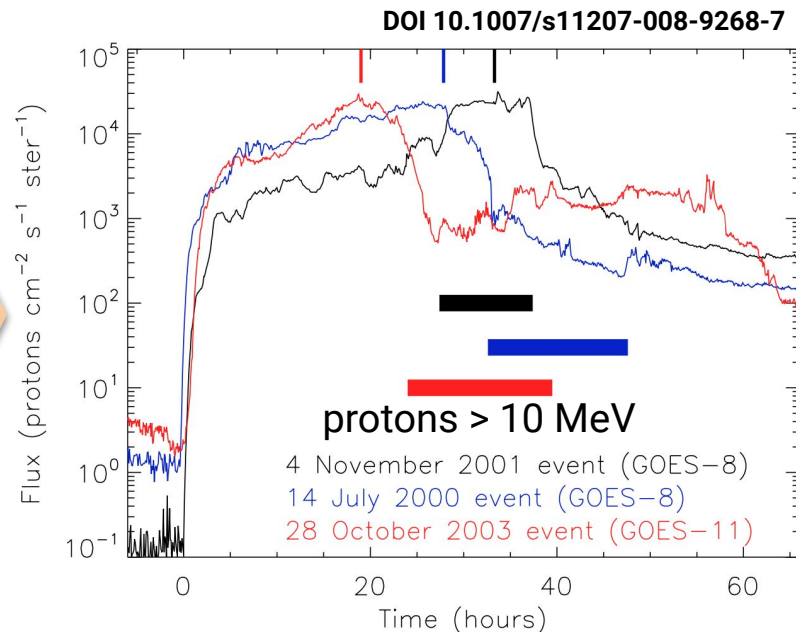


Investigation of the Space Weather



Example of Coronagraph (2013)
Courtesy of NASA (SOHO)

Example
of CME
effects



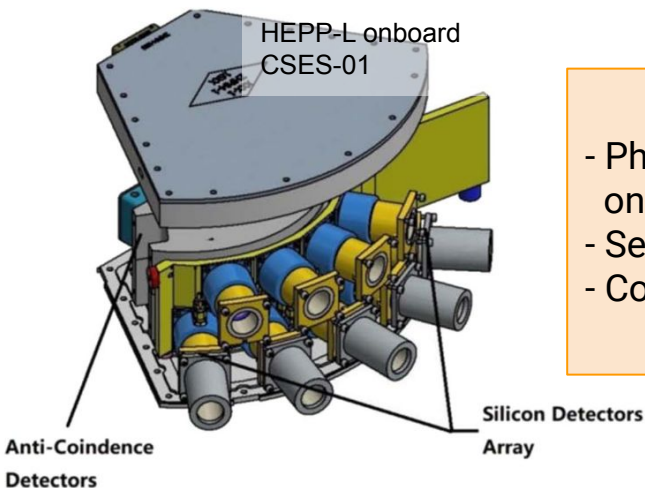
- Space weather:

- variable conditions of the Sun activity
- Solar wind takes 1-2 days to reach Earth

- Magnetic storms can produce strong EM fields
- **Observations needed** to train predictive models

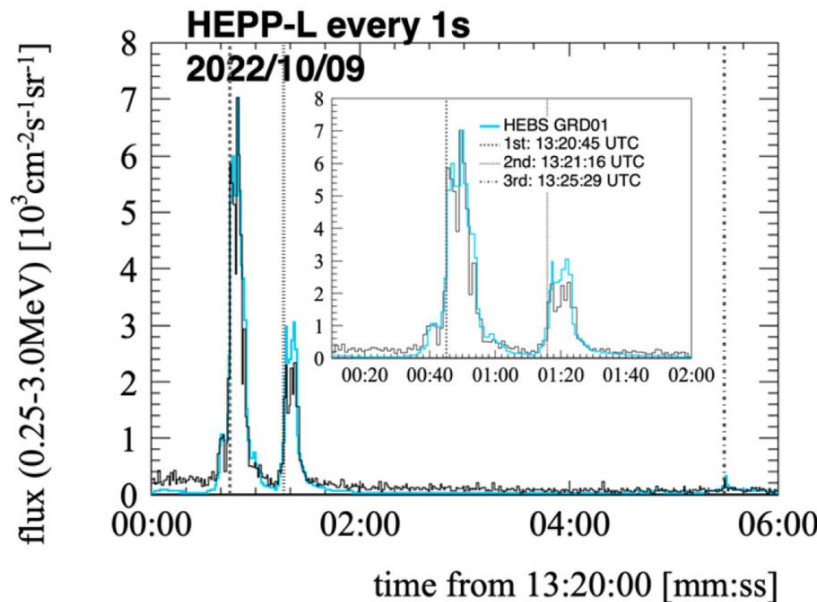


State of art: HEPP-L detector



- Photons impinge on **collimators**
- Secondary electrons
- Counting rate increase

- **H**igh **E**nergy **P**article **P**ackage (**L**ow energy version) detector (CSES-01)
- 9 channels: Silicon detector hodoscope + CsI(Tl) calorimeter
 - $\Delta E - E$ technique (as in the **LEM**)
 - Target: low energy particles (e^- , protons)



DOI 10.3847/2041-8213/acc247



Riccardo Nicolaidis

The NUSES space mission



UNIVERSITÀ
DI TRENTO



NUSES mission: two payloads...

Gran Sasso Science Institute
Thales Alenia Space Italy (TAS-I)
INFN

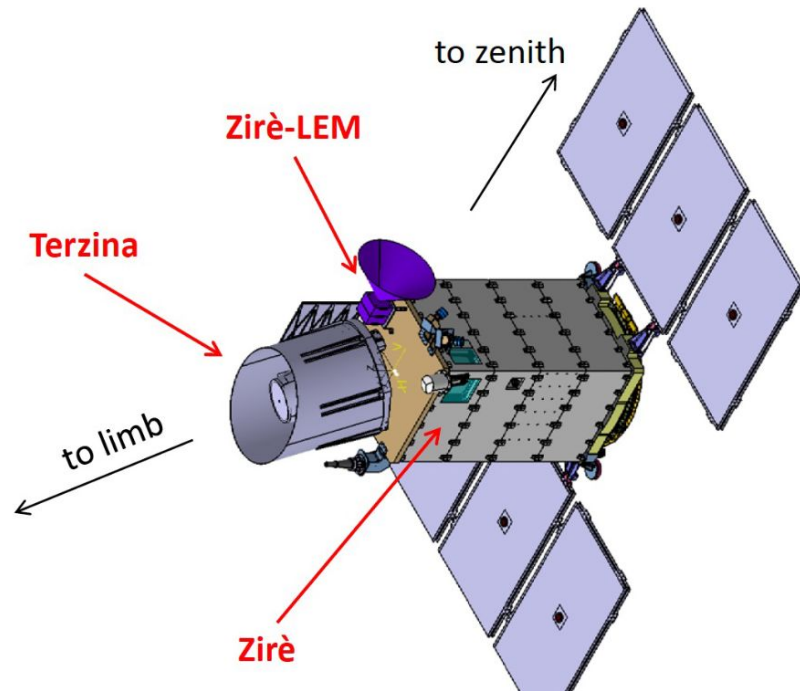
ASAPP 2023 Talk about NUSES:

Ivan De Mitri "The **Zirè** instrument on board the NUSES space mission"

Roberta Pillera "The fiber tracker of the **Zirè** instrument on board NUSES"

Roberto Aloisio "The **Terzina** instrument onboard the NUSES satellite"

Leonid Burmistrov "A SiPM based camera for the **Terzina** telescope on board the NUSES space mission"



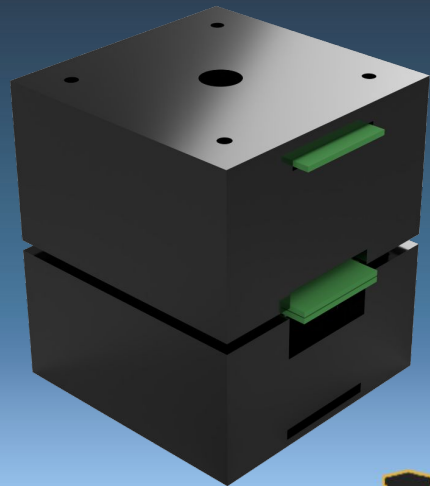
LEM: extending ZIRE observed energy window down to 0.1 MeV (e⁻)



Riccardo Nicolaidis

The Low Energy Module

A compact particle spectrometer for time resolved measurement of differential flux distribution of low-energy charged particles



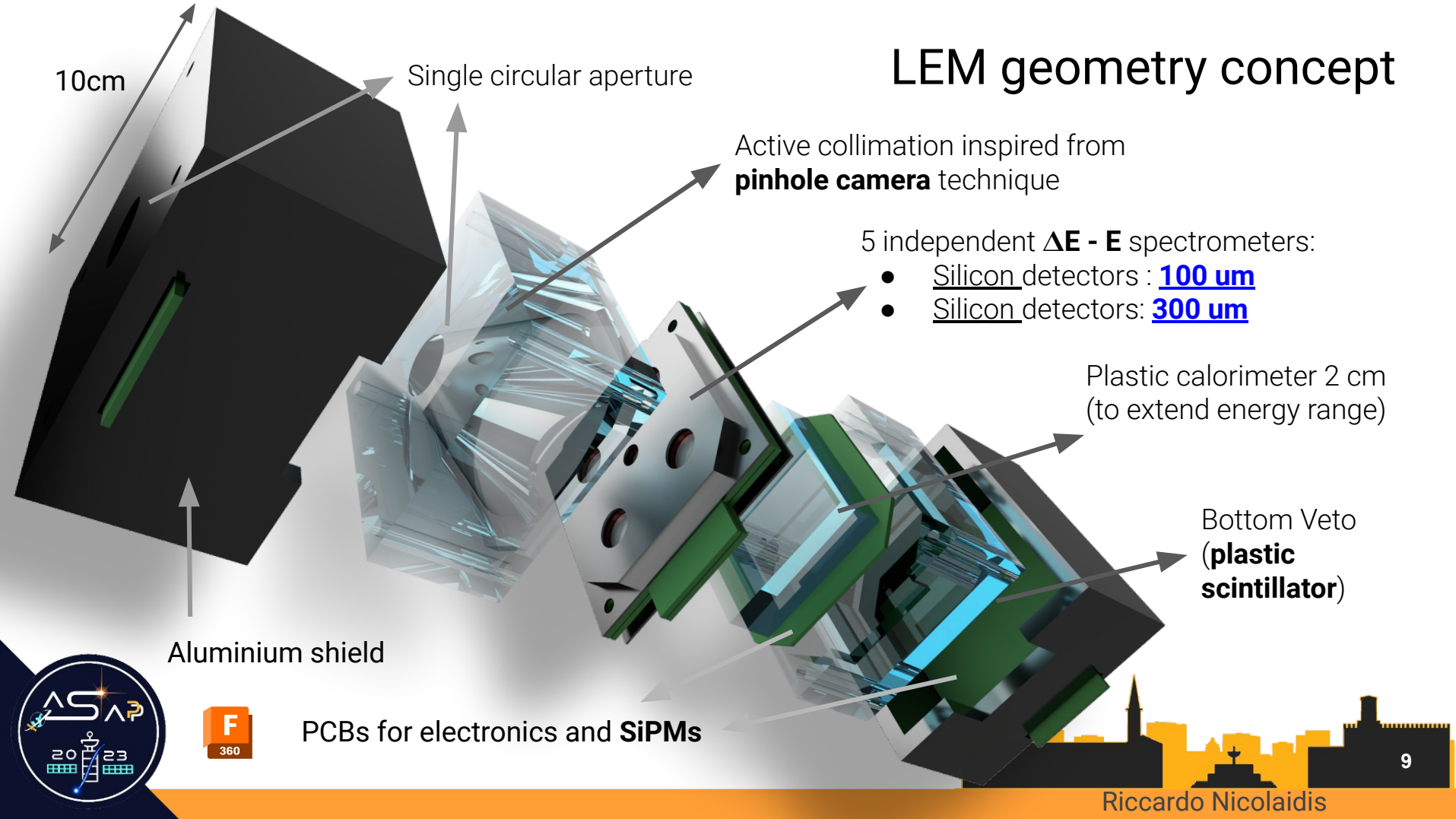
10 cm



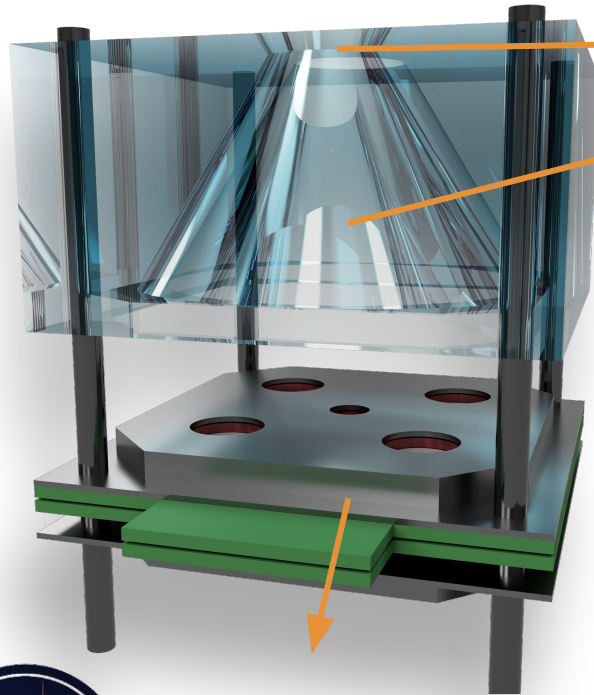
UNIVERSITÀ
DI TRENTO



LEM geometry concept



LEM geometry concept

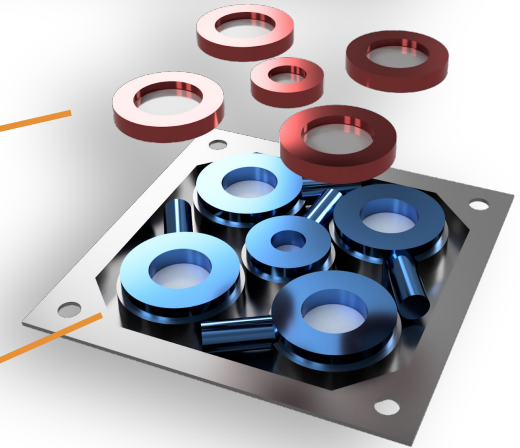
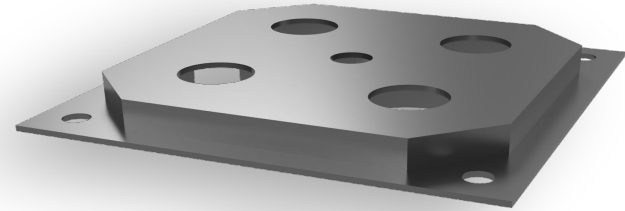


- Central circular aperture at the top
- Conical expansion volume

Pinhole camera technique for direction selection

ΔE detectors: Ametek
100 μm thick fully depleted silicon detectors
 $150\text{ mm}^2 - 55\text{ mm}^2$

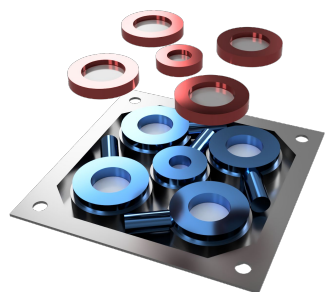
E detectors: Mirion
300 μm thick PIPS
 $150\text{ mm}^2 - 55\text{ mm}^2$



Silicon $\Delta E - E$
spectrometer assembly

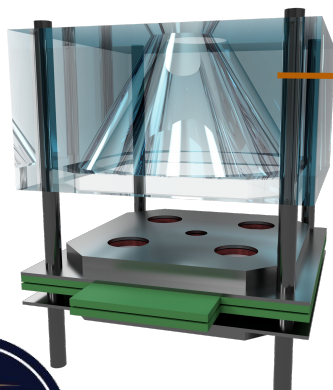


LEM geometry concept

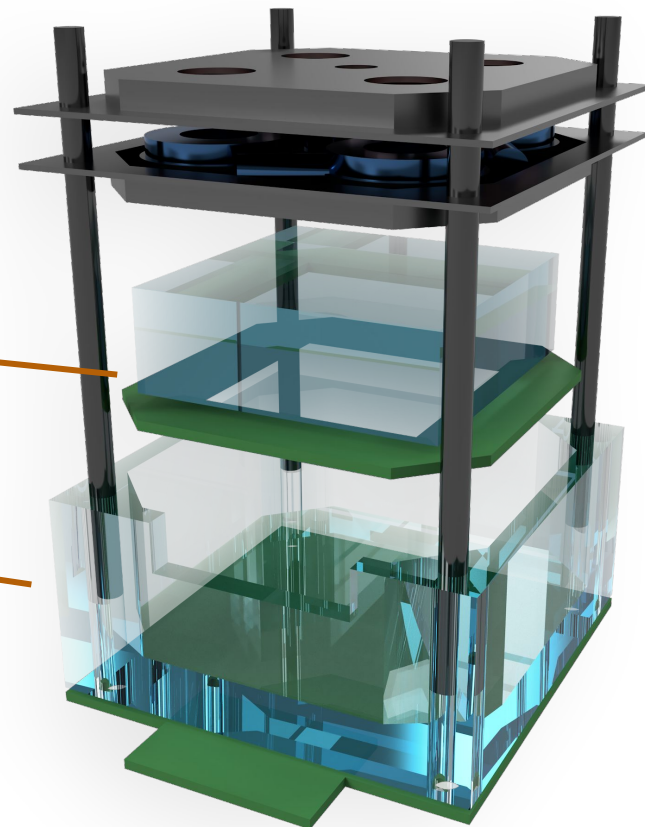


Silicon ΔE - E
spectrometer assembly

Plastic calorimeter
SiPM readout
For higher energies



**Anti-Coincidence
Detector (ACD)**
- Veto top
- Veto bottom
SiPM readout



Partners



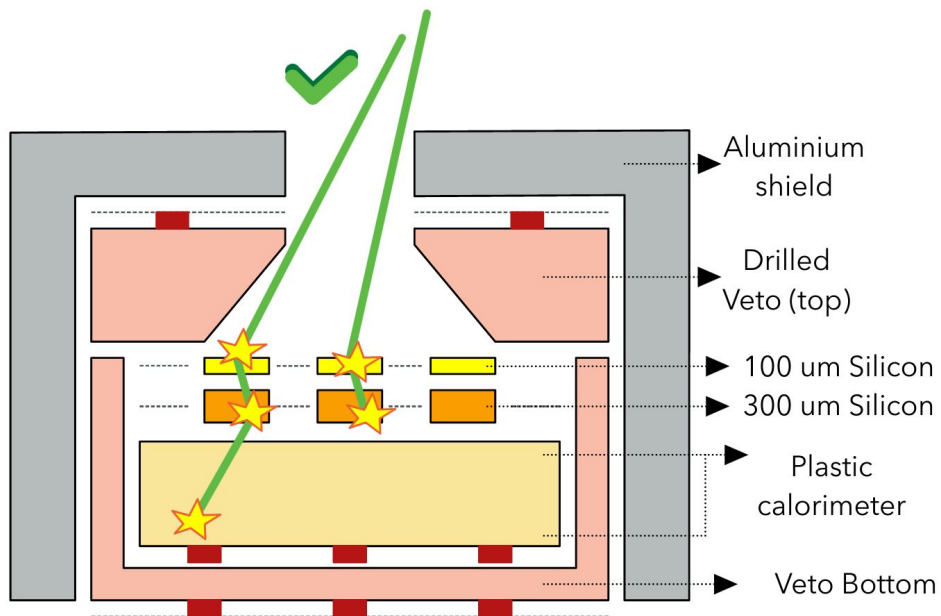
Firmware & DAQ



Front-End



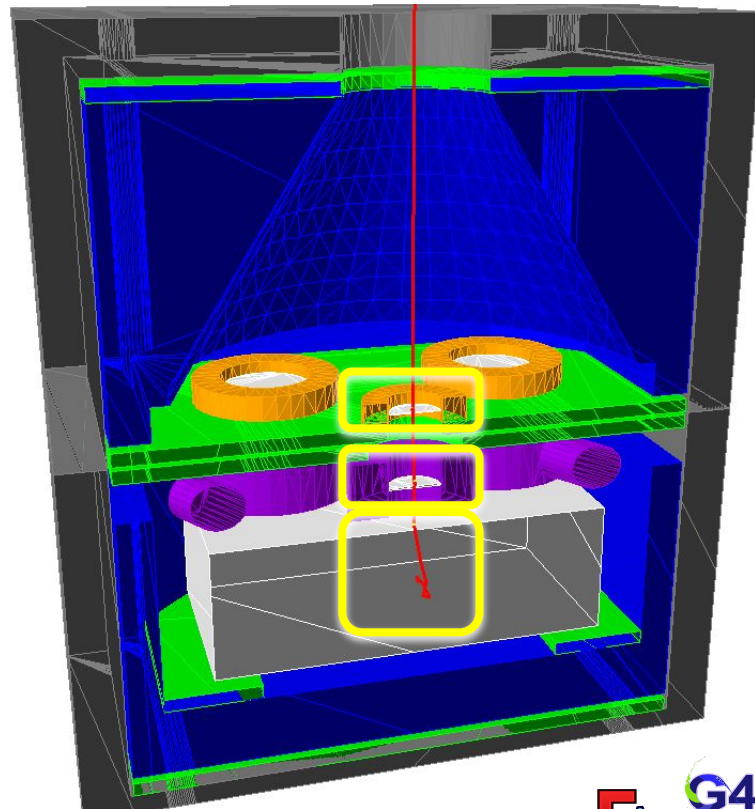
The detection concept



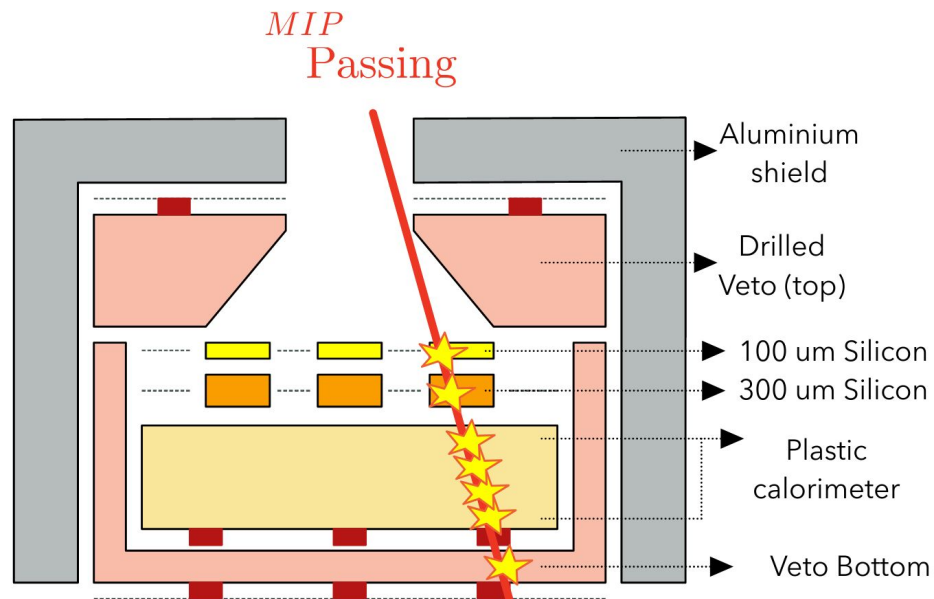
- Particle **confined** within the thin detector and the veto
- **Event-based PID**



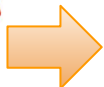
Good events



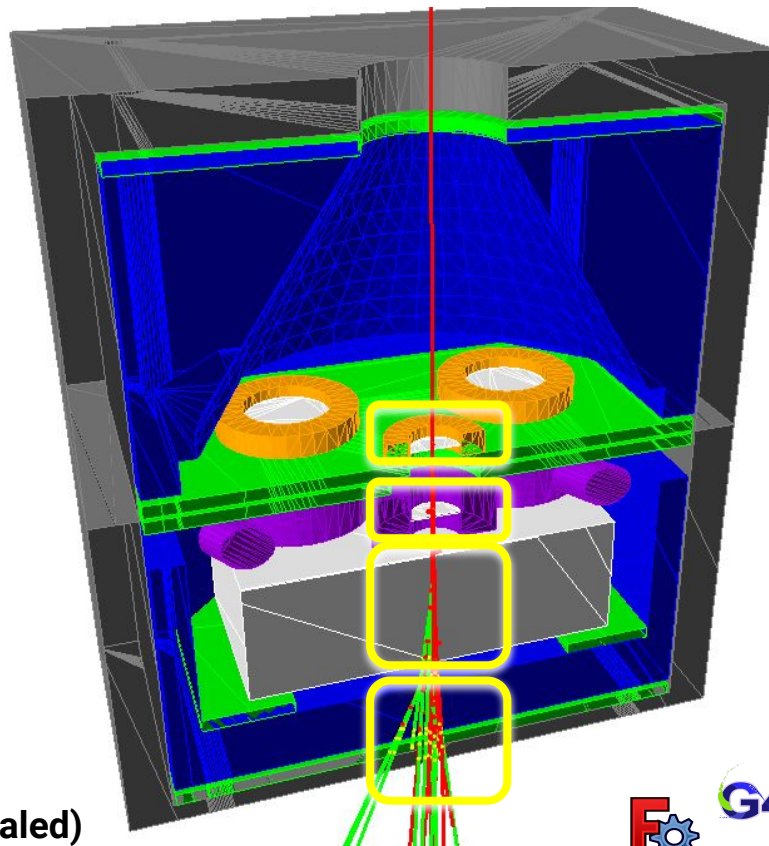
The detection concept



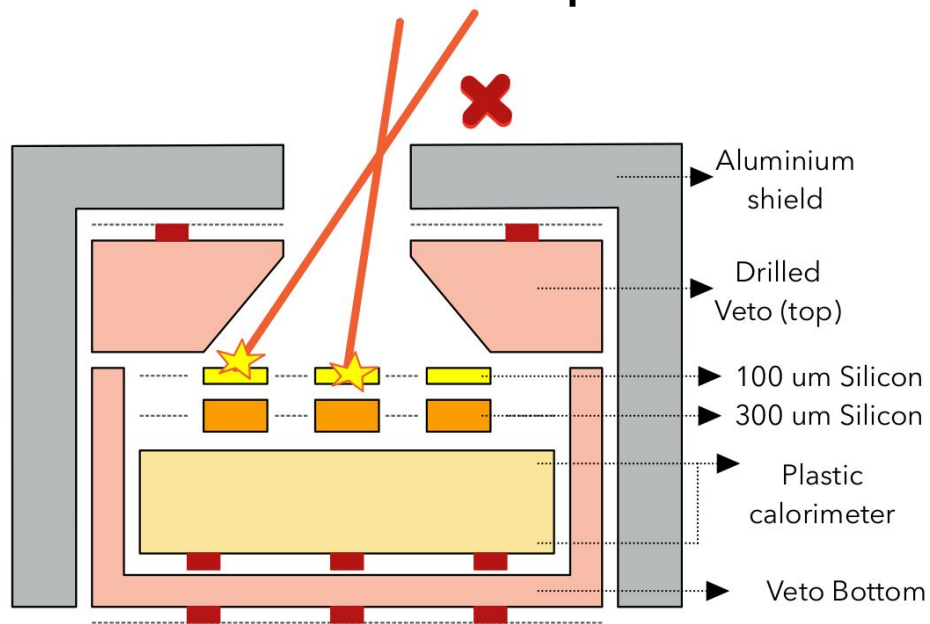
- Energy too large
- Very difficult PID
- MIP particles
- Veto activated



Rejected (or prescaled)
MIP used for
calibrations



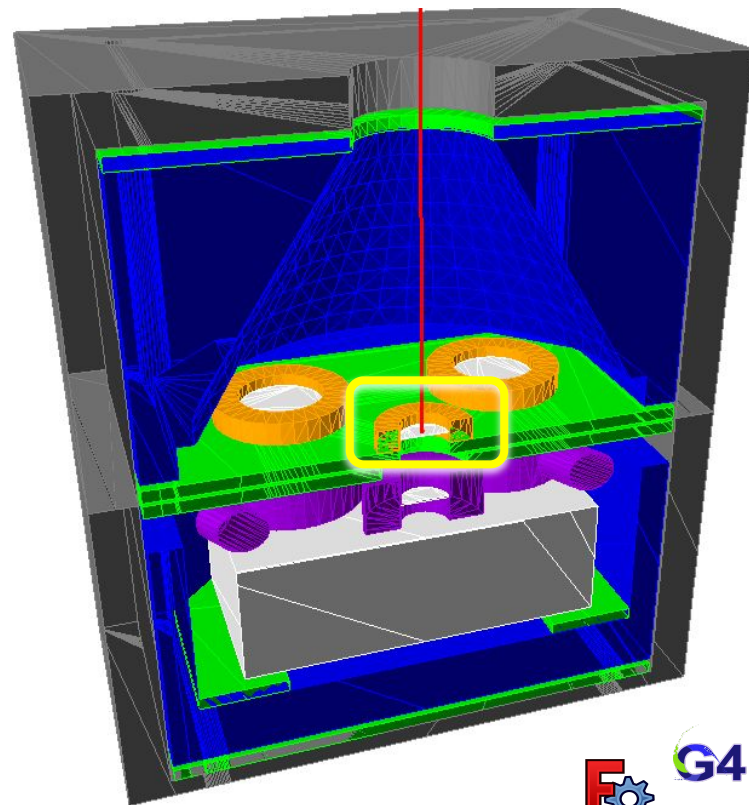
The detection concept



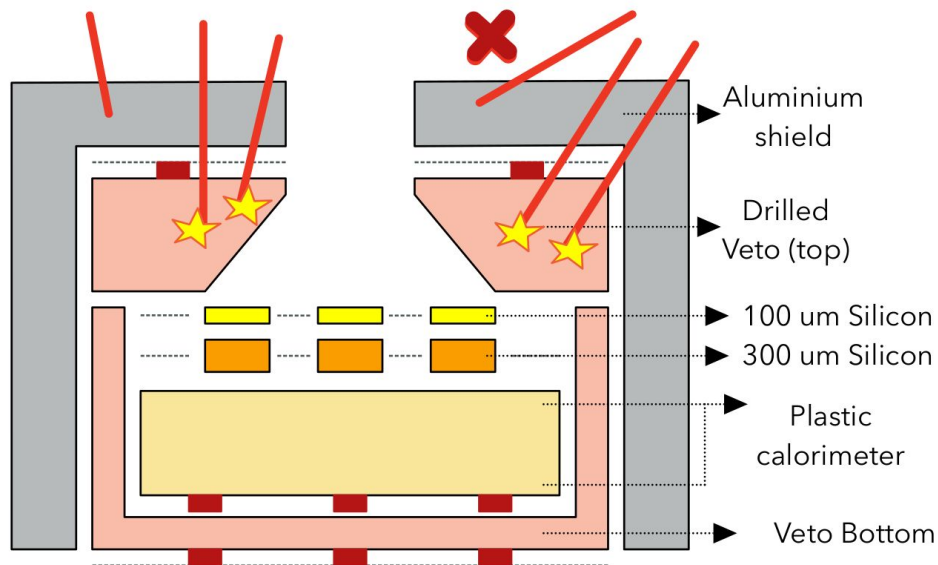
- Energy too low
- No PID
- Direction OK



**Single silicon spectra
Rate meter**



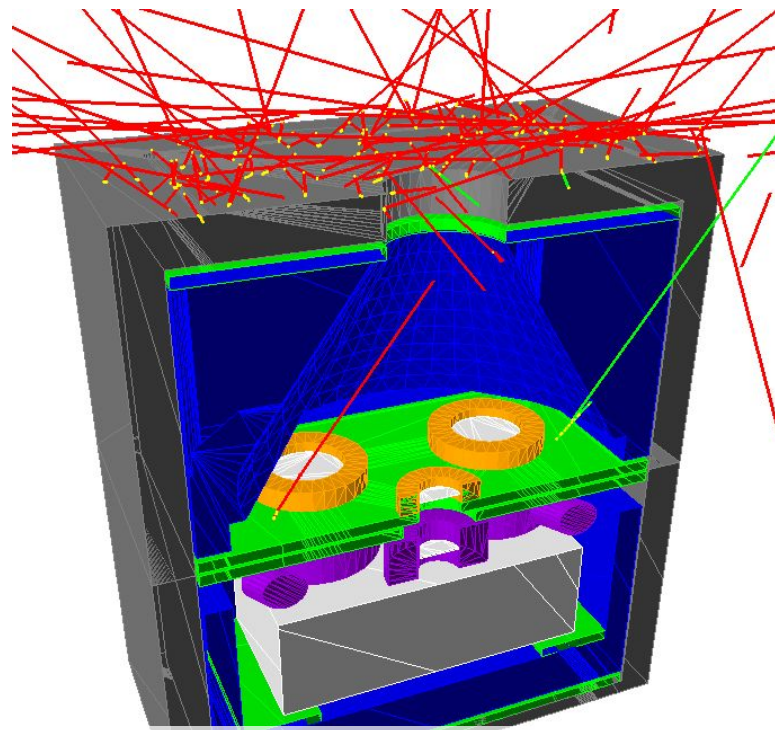
The detection concept



- Shielded by Aluminium
- Undefined direction
- Veto top activated



Rejected



Geometry imported in Geant4
with FreeCad GDML Workbench



Particle Identification

Some definitions:

ΔE Energy in 100 μm Si (Thin)

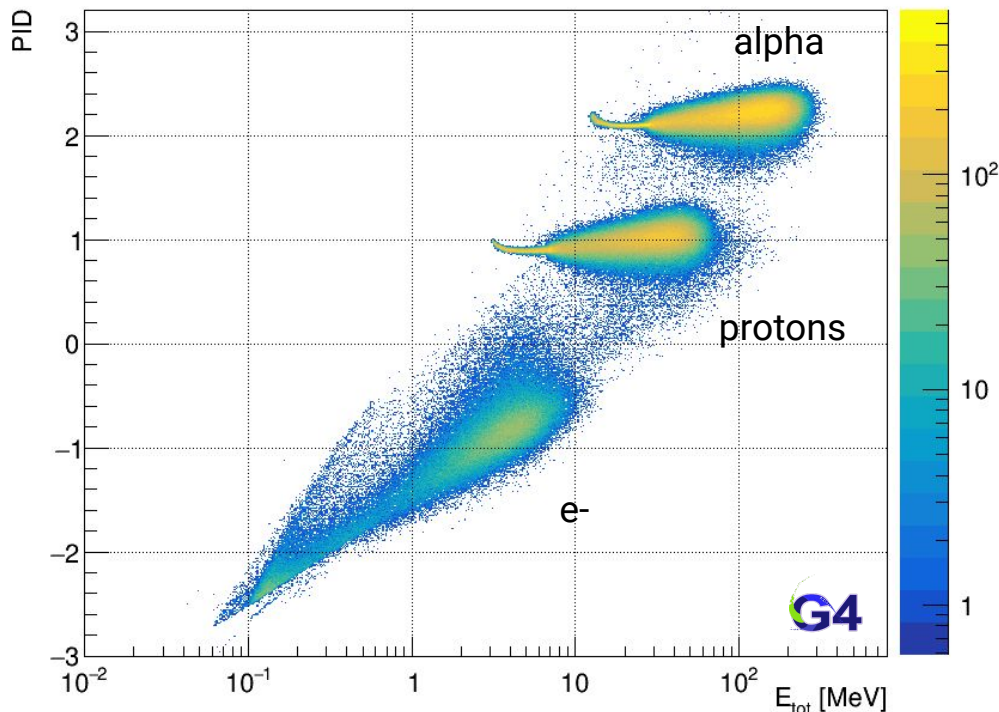
E Energy in 500 μm Si
(or eventually in PS)

$$\Delta E \propto \frac{z^2}{\beta^2} \quad \Downarrow \quad E_{tot} \simeq \frac{1}{2} m \beta^2$$

$$E_{tot} = E + \Delta E$$

$$PID_{\text{proxy}} = \log_{10} \left(\frac{\Delta E}{1 \text{ MeV}} \frac{E_{tot}}{1 \text{ MeV}} \right)$$

$$\simeq \log_{10} \frac{z^2 \cancel{\beta^2} m}{\cancel{\beta^2} 2} = \boxed{\log_{10} z^2 m} + \text{const.}$$



- $\Delta PID (e^-, p^+) \sim \text{Log}_{10}(938/0.511) \sim \mathbf{3}$
- $\Delta PID (p^+, \text{alpha}) \sim \text{Log}_{10}(2^2 * 4) \sim \mathbf{1.2}$



Particle Identification

Some definitions:

ΔE Energy in 100 μm Si (Thin)

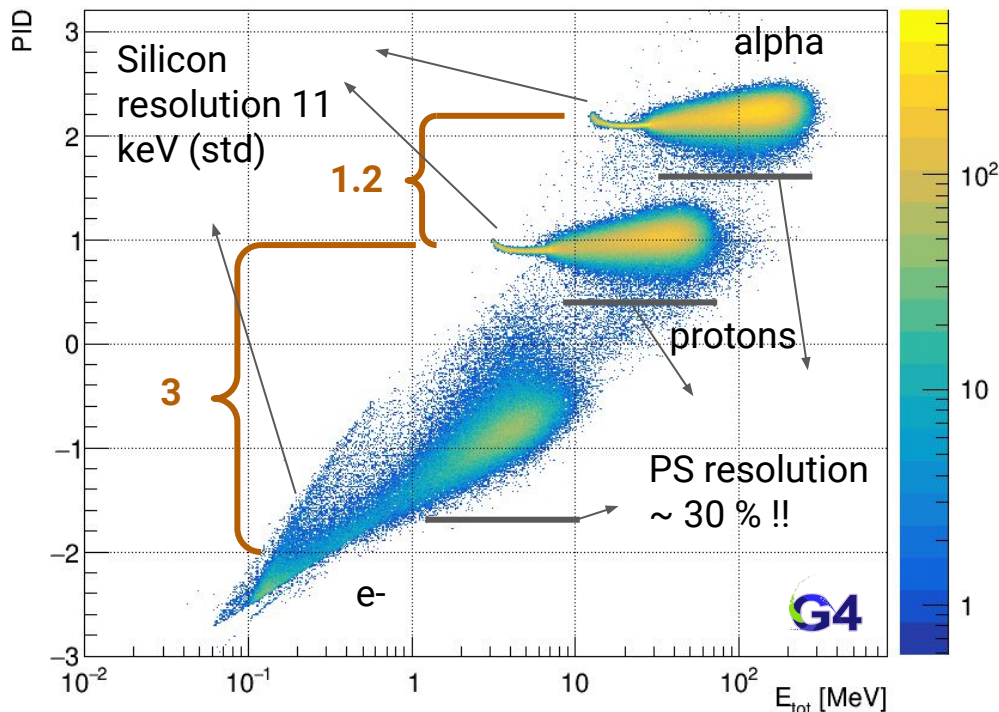
E Energy in 500 μm Si
(or eventually in PS)

$$\Delta E \propto \frac{z^2}{\beta^2} \quad \Downarrow \quad E_{tot} \simeq \frac{1}{2} m \beta^2$$

$$E_{tot} = E + \Delta E$$

$$PID_{\text{proxy}} = \log_{10} \left(\frac{\Delta E}{1 \text{ MeV}} \frac{E_{tot}}{1 \text{ MeV}} \right)$$

$$\simeq \log_{10} \frac{z^2 \cancel{\beta^2} m}{\cancel{\beta^2} 2} = \boxed{\log_{10} z^2 m} + \text{const.}$$



- $\Delta PID (e^-, p^+) \sim \text{Log}_{10}(938/0.511) \sim 3$
- $\Delta PID (p^+, \alpha) \sim \text{Log}_{10}(2^2 * 4) \sim 1.2$



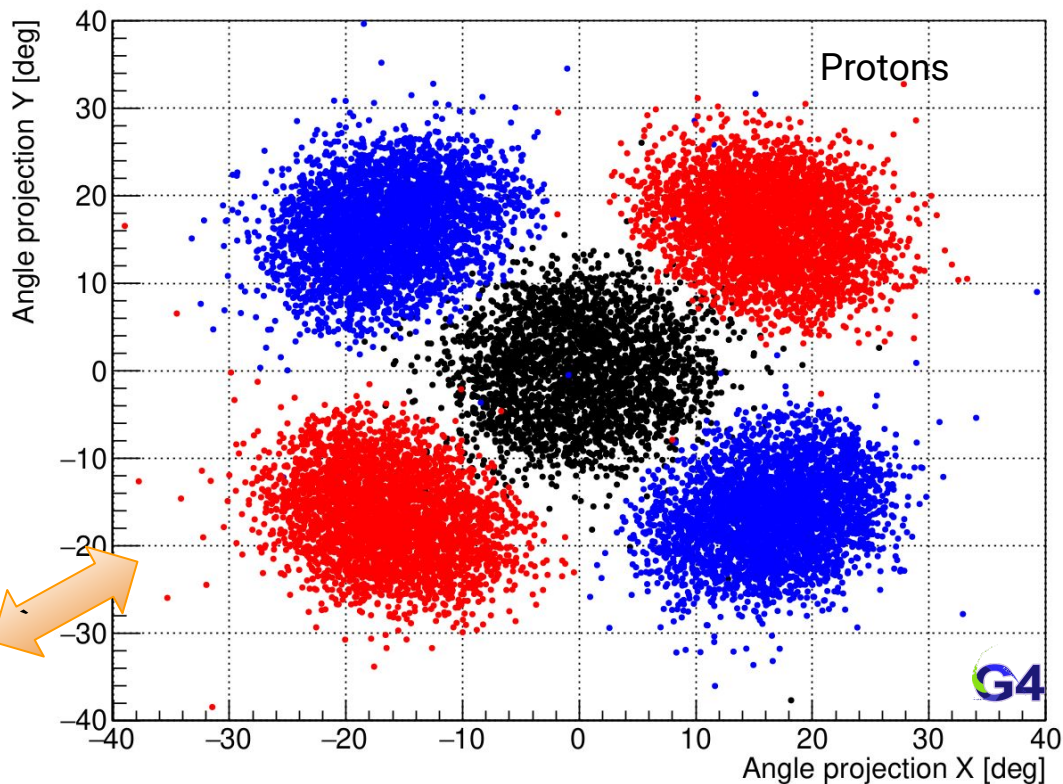
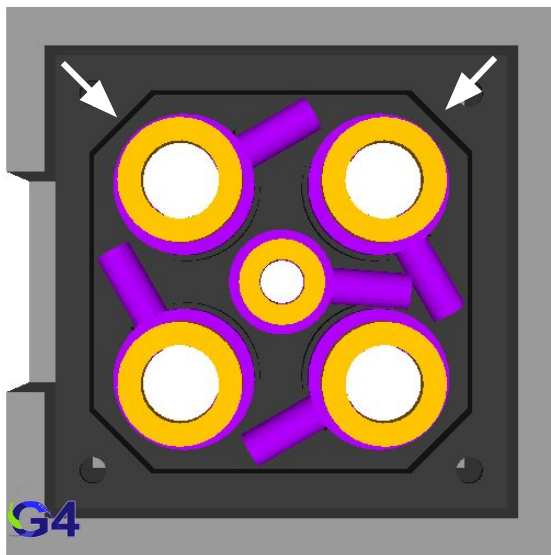
Angular resolution

- 12 degs std. resolution for electrons (multiple scattering)
- 5-6 degs std. resolution for protons and alpha particles

5 Distinct channels



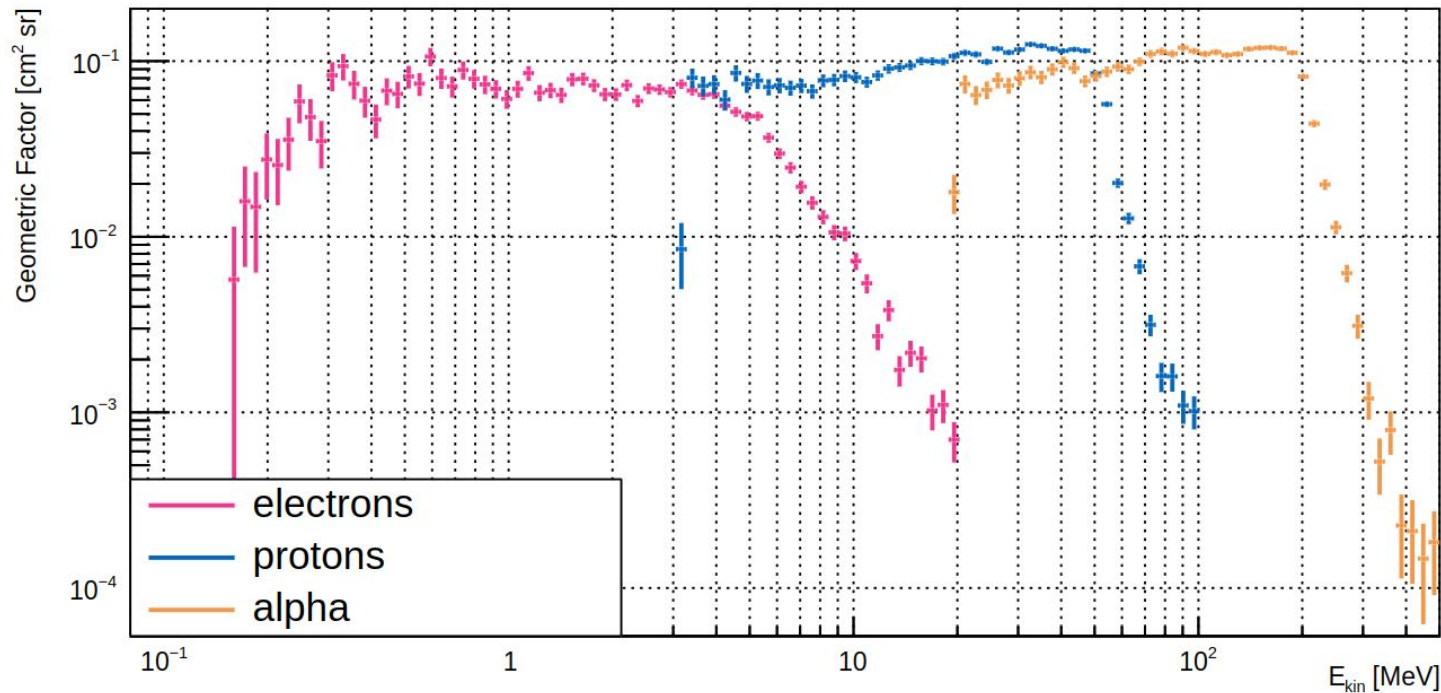
5 different sold angles



Central channel is smaller to limit its geometric factor



Geometric Factors



Geometric factor:
 $\sim 0.1 \text{ cm}^2 \text{ sr}$

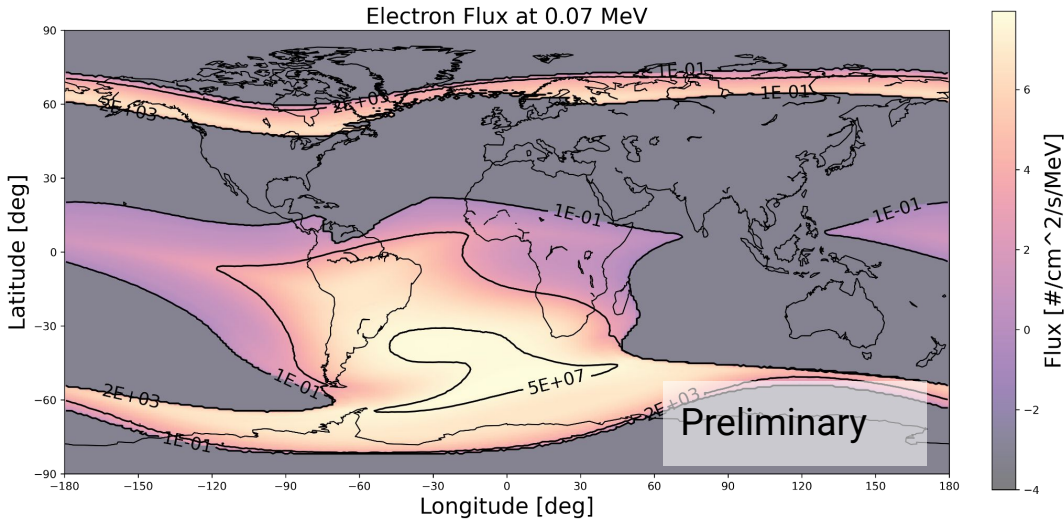
Electrons
[0.2 - 5] MeV

Protons
[3 - 50] MeV

Alpha
[20 - 200] MeV

Used for the estimation of the expected rates





IRENE-AE9/AP9 for radiation environment:

- LEO orbit
- Sun-synchronous 95 degs
- 550 Km altitude

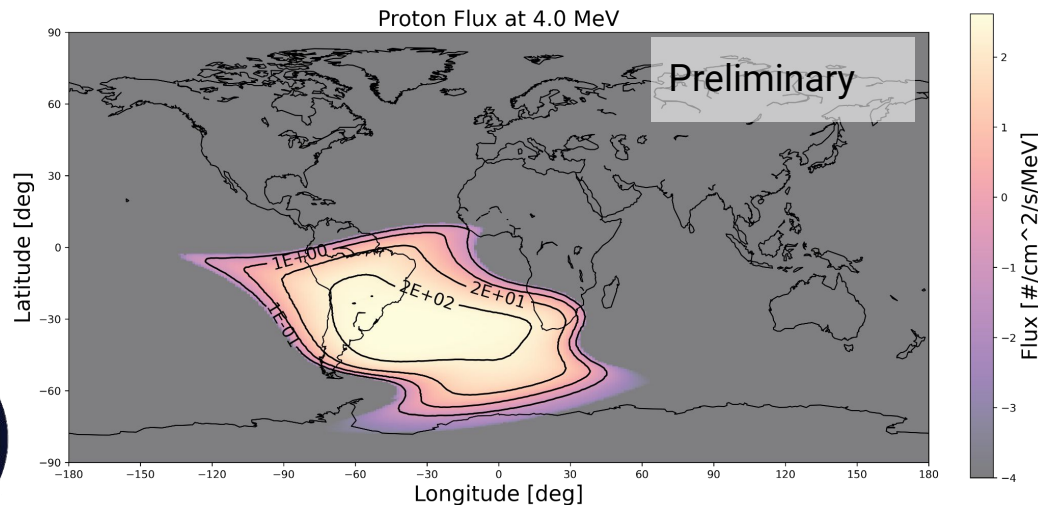


Isotropic fluxes differential in energy [$\text{cm}^{-2}\text{s}^{-1}\text{MeV}^{-1}$]



Expected rates

electrons

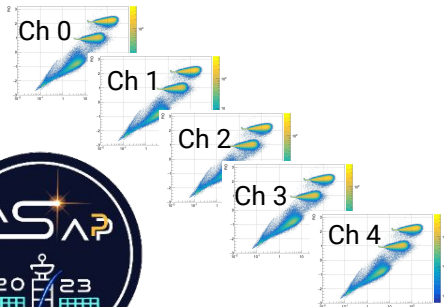
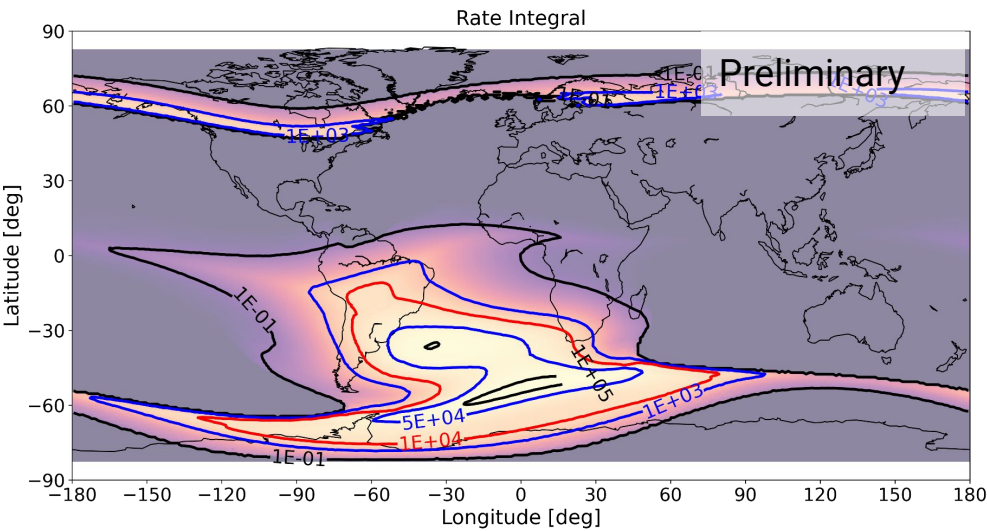


protons



Riccardo Nicolaidis

Expected rates

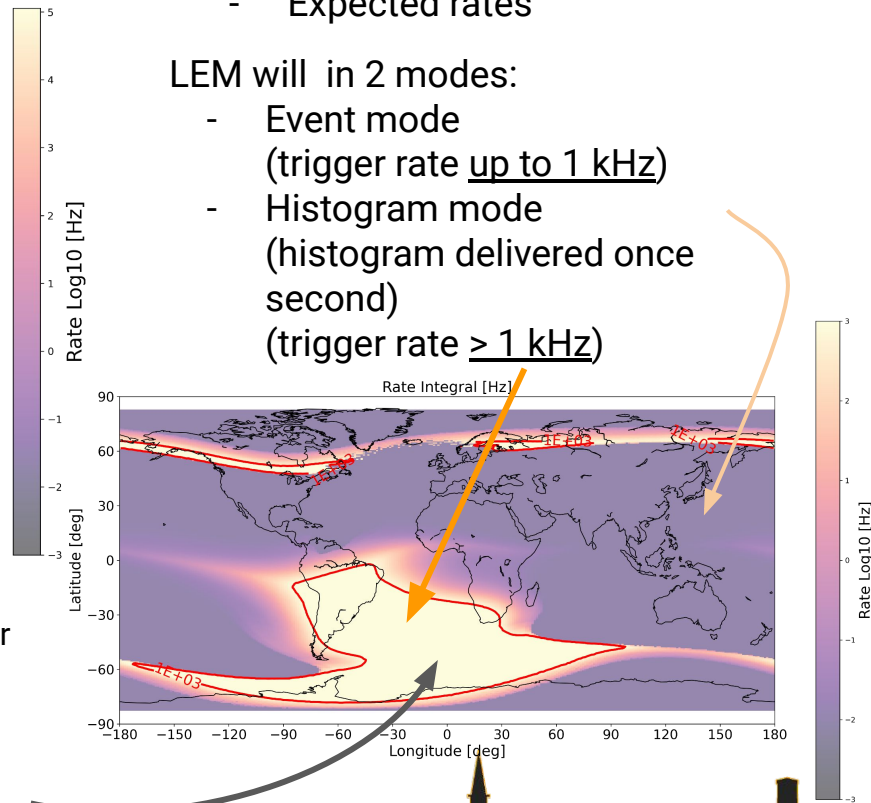


1 PID - Energy histogram per
channel every second
+
Single channel spectra
+
Calibration (MIP) spectra

- Geometric factor $\sim 0.1 \text{ cm}^2 \text{ sr}$
- Expected rates

LEM will in 2 modes:

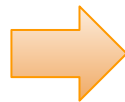
- Event mode
(trigger rate up to 1 kHz)
- Histogram mode
(histogram delivered once
second)
(trigger rate $\geq 1 \text{ kHz}$)



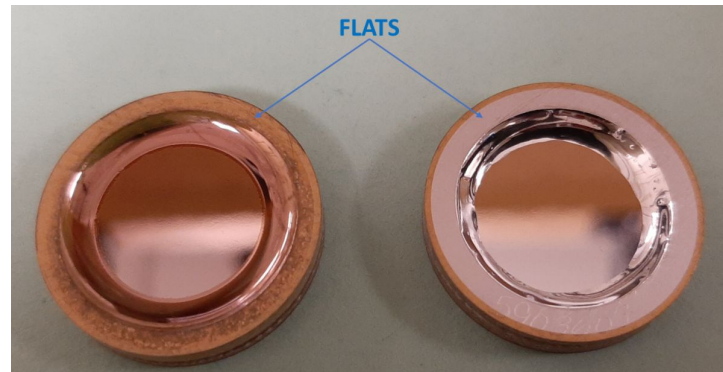
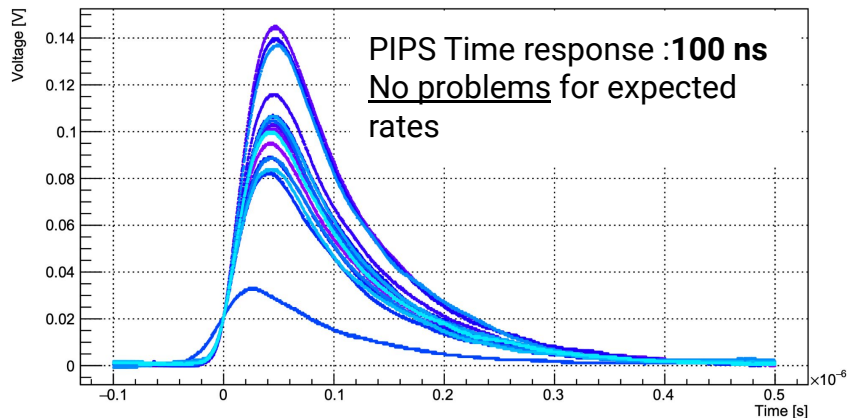
Development and test

Passivated Implanted Planar Silicon (PIPS)

- 100 μm thick silicon detectors
- Light tight and ruggedized
- 50 $\mu\text{g cm}^{-2}$ dead layer material

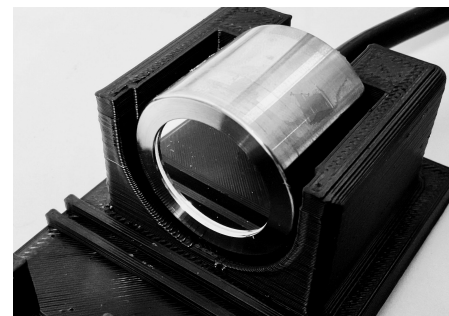


100 μm thick fully depleted Silicon
AMETEK



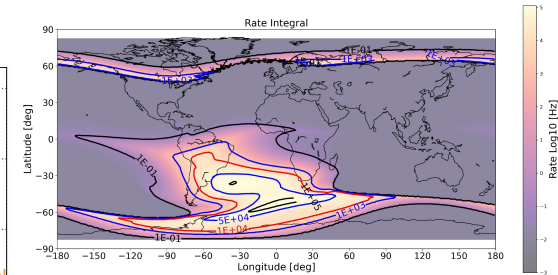
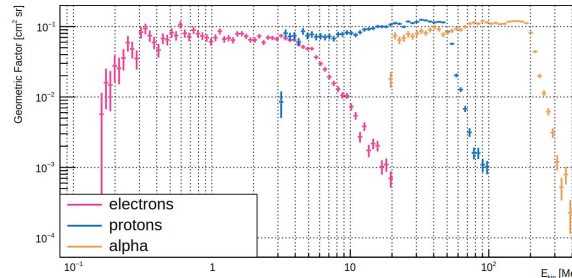
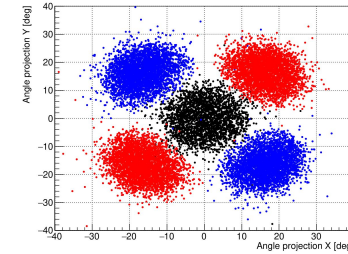
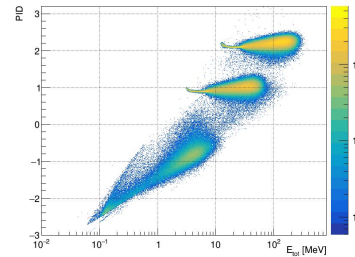
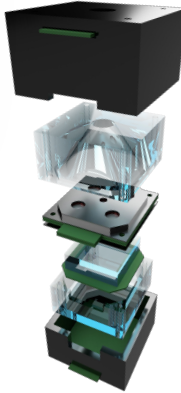
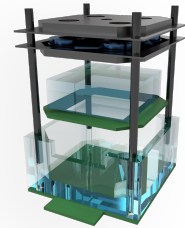
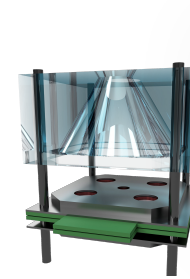
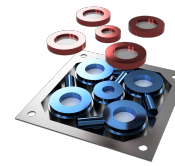
300 μm thick
Silicon MIRION

Induced
waveform
 ^{241}Am alpha
particle



Conclusions

- LEM: Compact particle spectrometer ($10 \times 10 \times 10 \text{ cm}^3$)
- Active collimation
standard tracking spoils direction (**multiple scattering**)
- $\Delta E - E$ technique: Energy - PID
 - e- [0.1 - 7] MeV
 - proton [3 - 15] MeV
 - alpha [20 - 200] MeV
- Angle res:
 - ~12 degs e-
 - ~6 degs protons/alpha
- Geometric factor $\sim 0.1 \text{ cm}^2\text{sr}$
- Two operation modes:
 - List mode (below 1 kHz)
 - Histo mode (trig rate > 1 kHz)



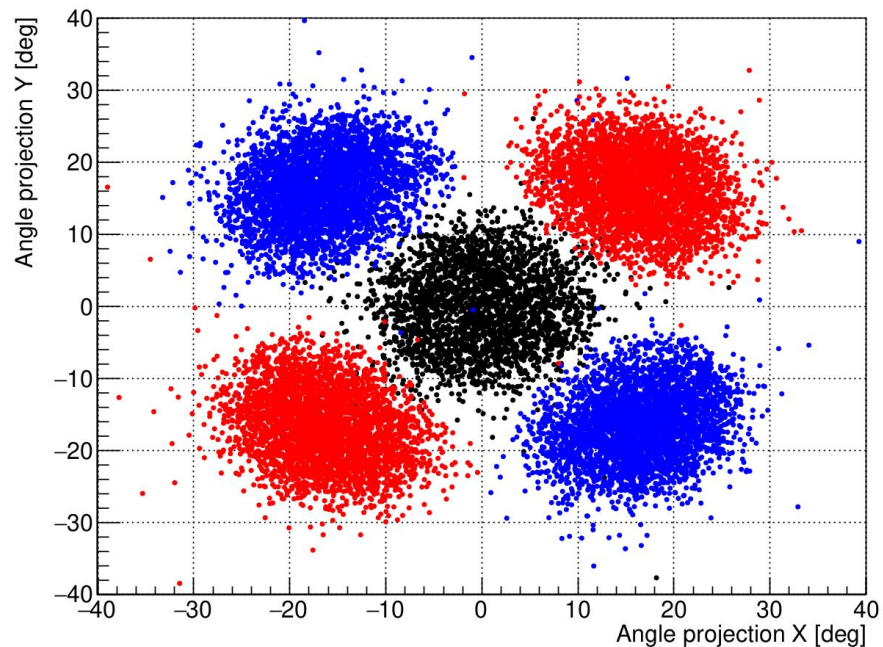
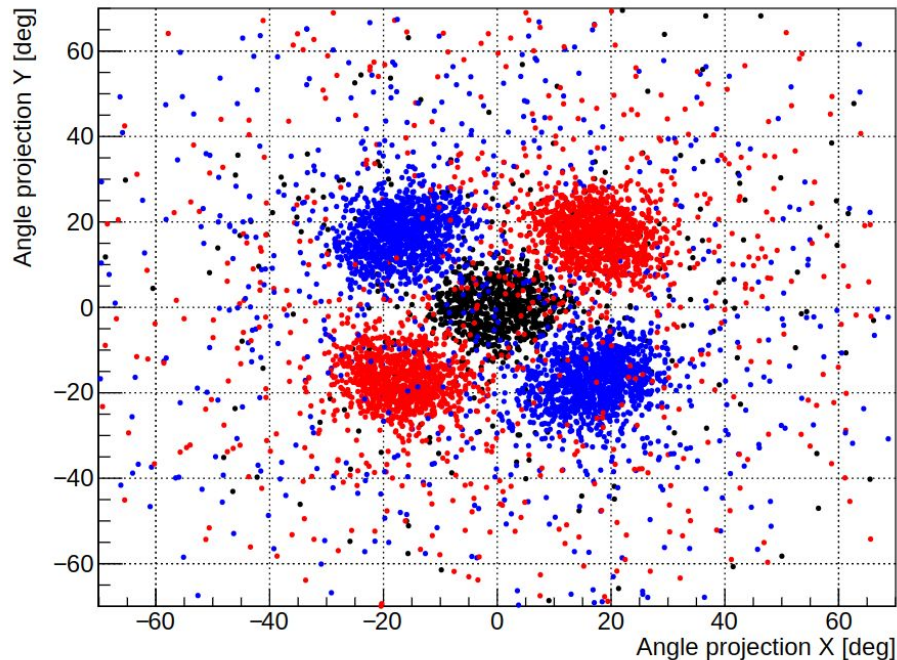
Backup



UNIVERSITÀ
DI TRENTO



Angular resolution



- Electrons: ~ 12 degs
- Protons/alpha: \sim

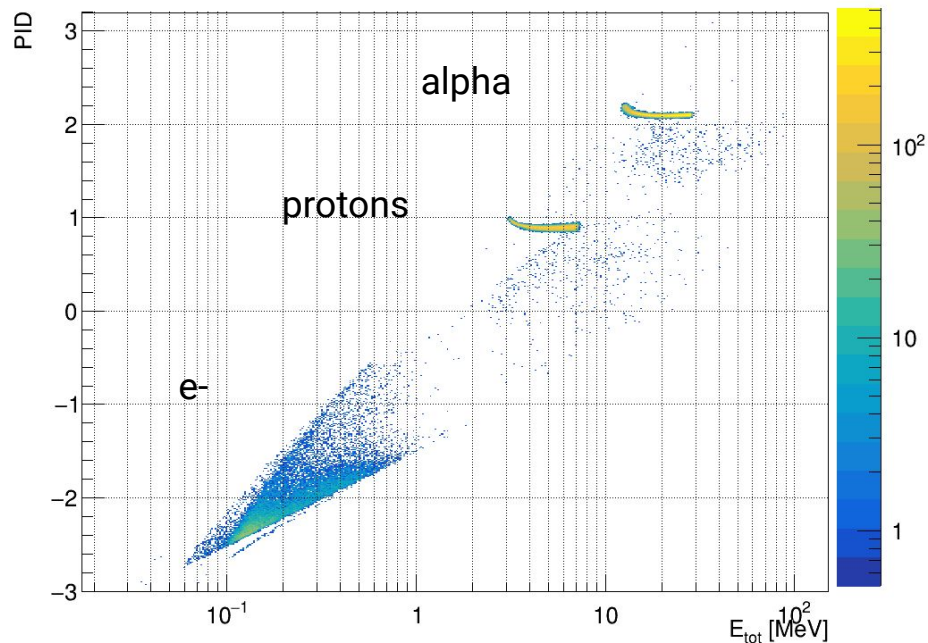


Details on the electronics

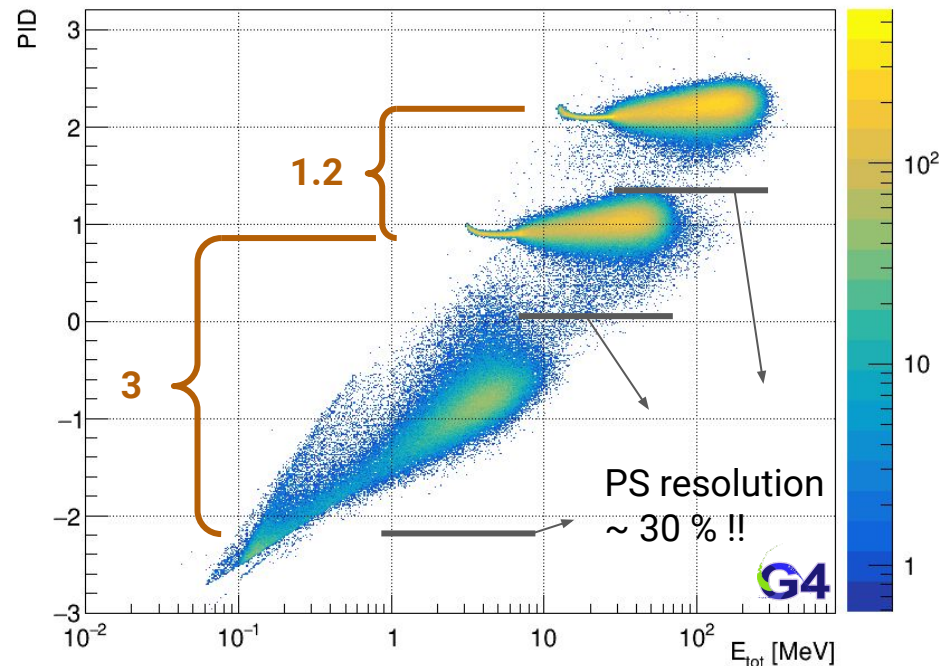
- Charge sensitive preamplifier + Shaper (100 ns time constant)
- Artix7 UltraScale+ FPGA for the firmware
 - Upgradable firmware during flight (bootloaders on concentrator)
 - Configurable settings
 - Firmware redundancy
- Data budget: 4.2 Gbit/day
- Weight: 1.6 kg
- Power budget: 5 W
- Size: $\sim 10 \times 10 \times 10 \text{ cm}^3$



Si 100 μm - Si 300 μm (**No PS**)



Si 100 μm - Si 300 μm **+ 2 cm PS**

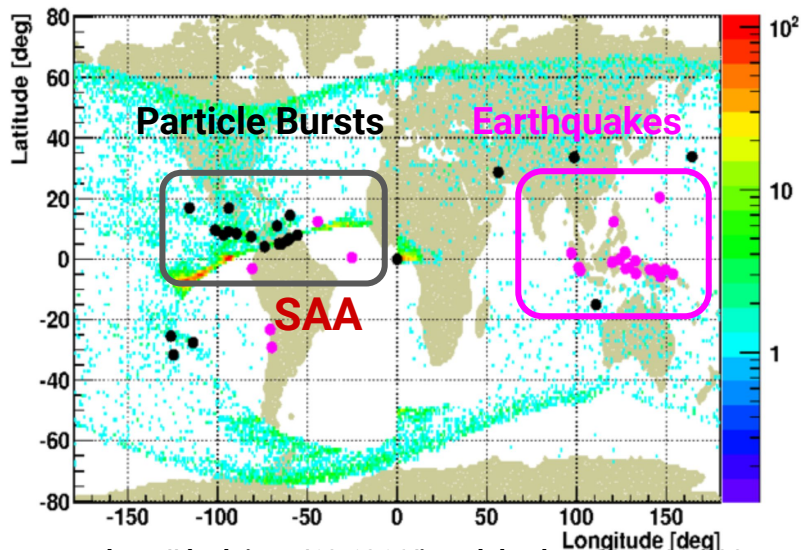


$$\text{PID}_{\text{proxy}} \simeq \log_{10} m z^2 + \text{const.}$$

- $\Delta \text{PID} (e^-, p^+) \sim \text{Log}_{10}(938/0.511) \sim \mathbf{3}$
- $\Delta \text{PID} (p^+, \alpha) \sim \text{Log}_{10}(2^2 * 4) \sim \mathbf{1.2}$



Different observations suggest common phenomenology



<http://dx.doi.org/10.1016/j.nuclphysbps.2013.09.002>

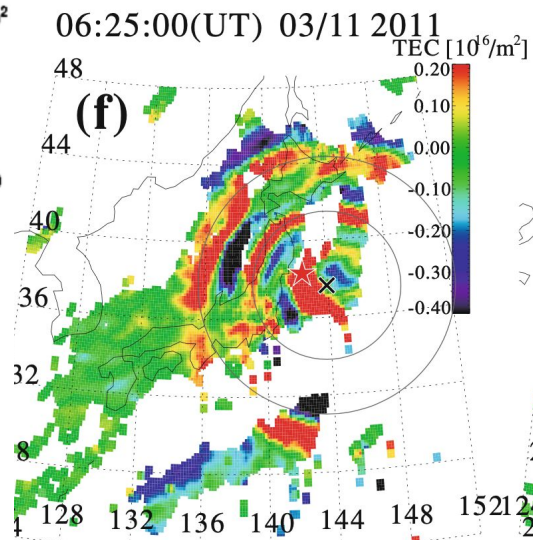
Earthquakes mostly indonesian

PBs mostly detected near SAA:

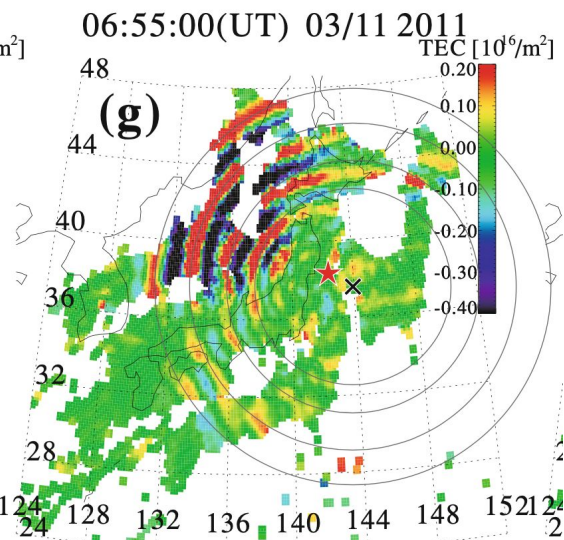
→ B weaker

→ radiation belts lower altitudes

→ LEO satellites intersects
PBs/perturbations



[doi:10.5047/eps.2011.06.035](https://doi.org/10.5047/eps.2011.06.035)



Other hints for MILC? e.g. Total Electron Content monitoring after Tohoku Earthquake in Japan.



Riccardo Nicolaidis