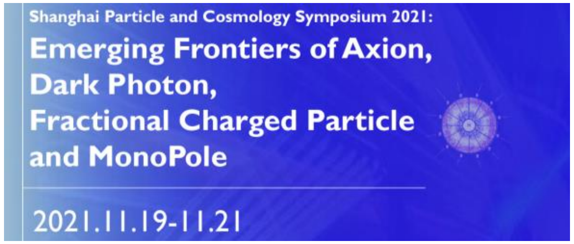
Searching for fractionally charged particles with DAMPE

Chengming Liu
On behalf of the DAMPE collaboration



State Key Laboratory of Particle Detection and Electronics
University of Science and Technology of China

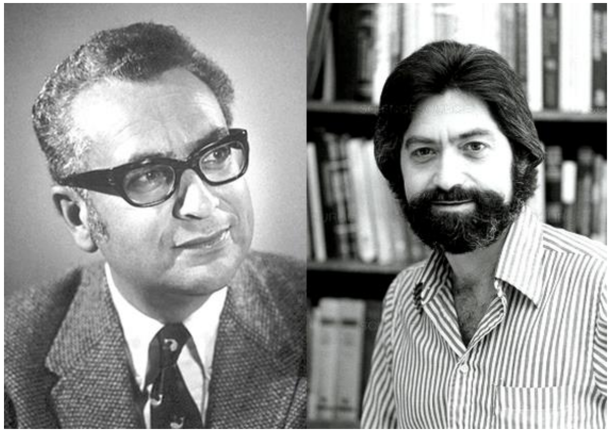
19 – 21 November 2021
Tsung-Dao Lee Institute @ SJTU, Shanghai, China
The 2021 Shanghai Particle Physics and Cosmology Symposium (SPCS2021)

Outline

- Motivation
- Previous searches of FCP
- DAMPE experiment
- Search for FCP with DAMPE
- Summary

Motivation

Oil Drop Experiment



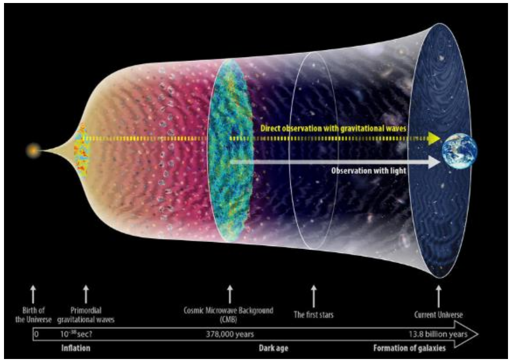
Quark Model

QCD Theory

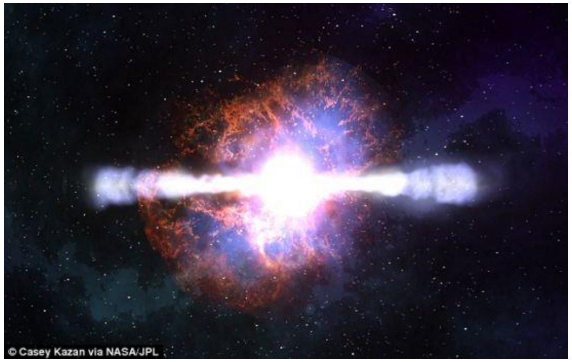
- Since the oil drop experiment performed in 1909, all particles are measured as having charges of multiples of electron charge.
- In 1964, quark model for hadrons was proposed by Gell-man and Zweig.
- Due to the QCD theory, the quarks will not exist freely.
- Fractionally Charged Particle (FCP) is supposed to carry any non-integer charge.

The possible origins of FCP

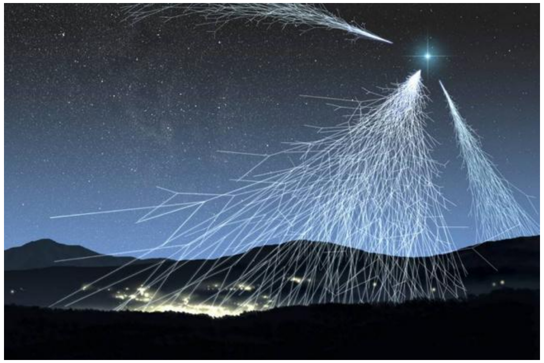
The basic assumption: FCP is a kind of heavy lepton



Early universe



Supernova explosion



Extensive air shower

There are three possible sources of FCP in cosmic rays:

- **First,** it may be produced at the early Universe after the Big Bang.
- **Second,** it may be produced through high-energy astrophysical processes.
- **Third,** it may be produced in the extensive air shower of cosmic-rays.

Outline

- Motivation
- Previous searches of FCP
- DAMPE experiment
- Search for FCP with DAMPE
- Summary

The previous experiments of large volume

For searches of underground, the target FCP should have energy above hundreds GeV to penetrate the rocks

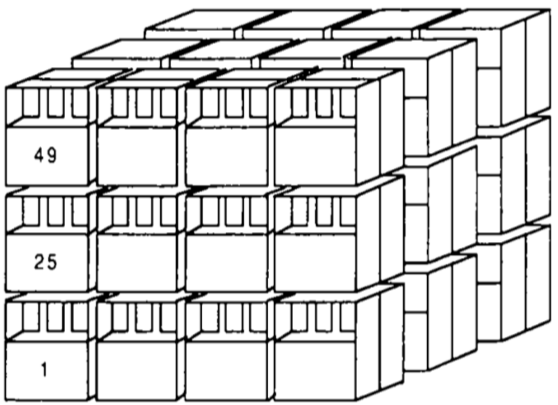
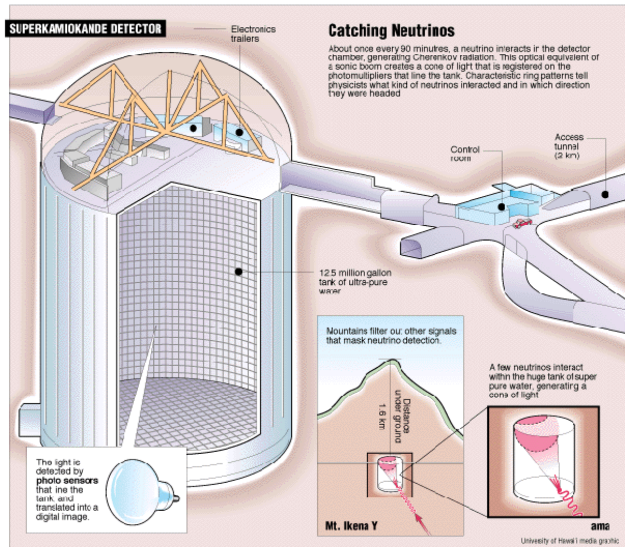
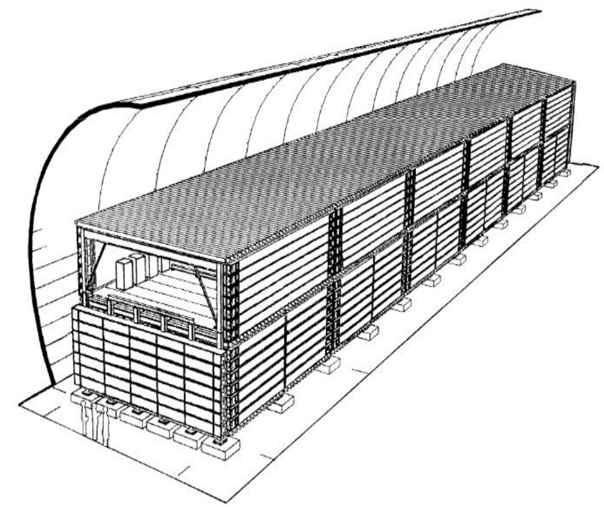


Fig. 1. The LSD experimental detector. The 72 tanks are considered as divided into 24 vertical columns (e.g. tanks 1–25–49 form the first telescope).





LSD 1800 m

Kamiokande II 1000 m

MARCO 1400 m

$$\Phi\left(\frac{1}{3}\right) = 2.3 \times 10^{-13}\ \mathrm{cm^{-2}sr^{-1}s^{-1}}$$

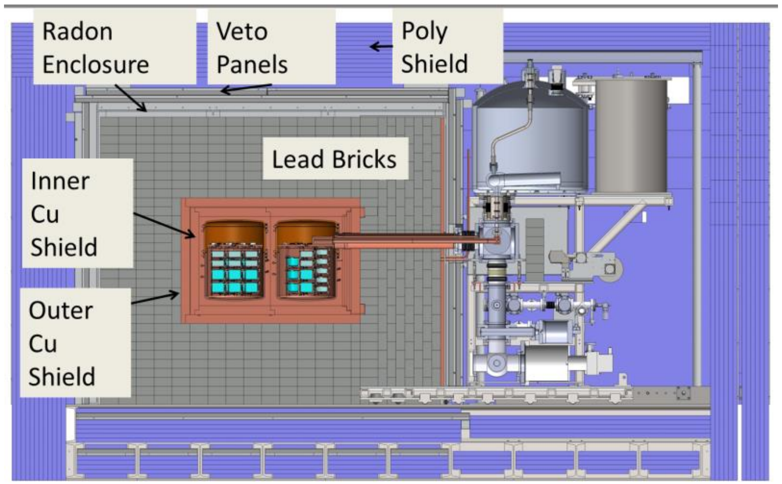
$$\Phi\left(\frac{2}{3}\right) = 2.7 \times 10^{-13}\ \mathrm{cm^{-2}sr^{-1}s^{-1}}$$

$$\Phi\left(\frac{1}{3}\right) = 2.1 \times 10^{-15}\ \mathrm{cm^{-2}sr^{-1}s^{-1}}$$

$$\Phi\left(\frac{2}{3}\right) = 2.3 \times 10^{-15}\ \mathrm{cm^{-2}sr^{-1}s^{-1}}$$

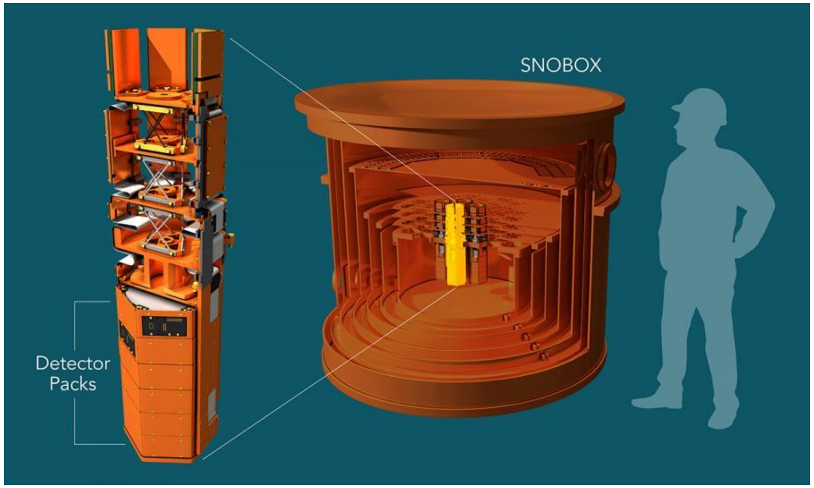
$$\Phi\left(\frac{1}{4} \sim \frac{2}{3}\right) = 6.1 \times 10^{-16}\ \mathrm{cm^{-2}sr^{-1}s^{-1}}$$

The previous experiments of charge sensitivity



MAJORANA 1600 m

$$\frac{1}{1000} < Q < \frac{1}{6}$$
$$\Phi\left(\frac{1}{6} \sim \frac{1}{30}\right) = 2 \times 10^{-9}\ \mathrm{cm^{-2}s^{-1}sr^{-1}}$$



CDMS II 700 m

$$\frac{1}{200} < Q < \frac{1}{6}$$
$$\Phi\left(\frac{1}{160}\right) = 1.36 \times 10^{-7}\ \mathrm{cm^{-2}s^{-1}sr^{-1}}$$

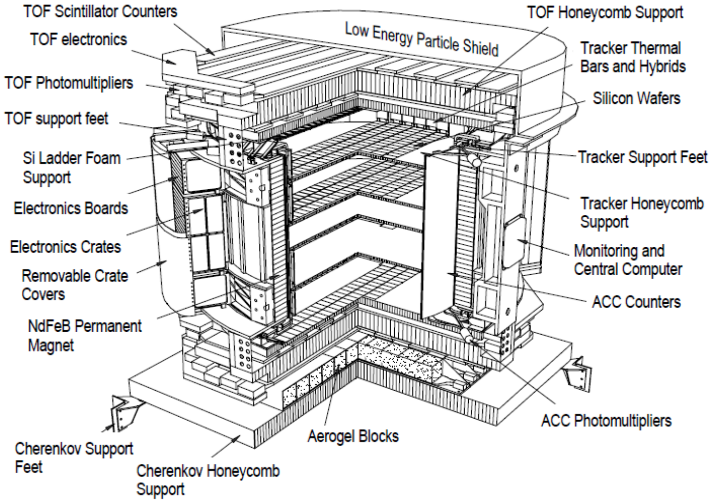
Searches for Millicharge, these experiments have very good capability of charge measurement

CDMSlite: $\frac{1}{1000} < Q < \frac{1}{6}$

TEXONO: $10^{-6} < Q < 10^{-3}$

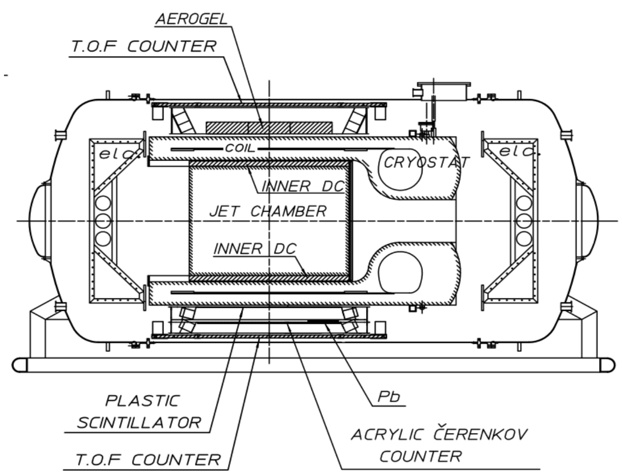
The previous experiments in space

For searches in space, the target FCP need not to penetrate the rocks, it can have energy as low as ~GeV level (the geomagnetic cutoff)



AMS01 space shuttle

$$\Phi\left(\frac{2}{3}\right) = 3.0 \times 10^{-7}\ \mathrm{cm^{-2}sr^{-1}s^{-1}}$$

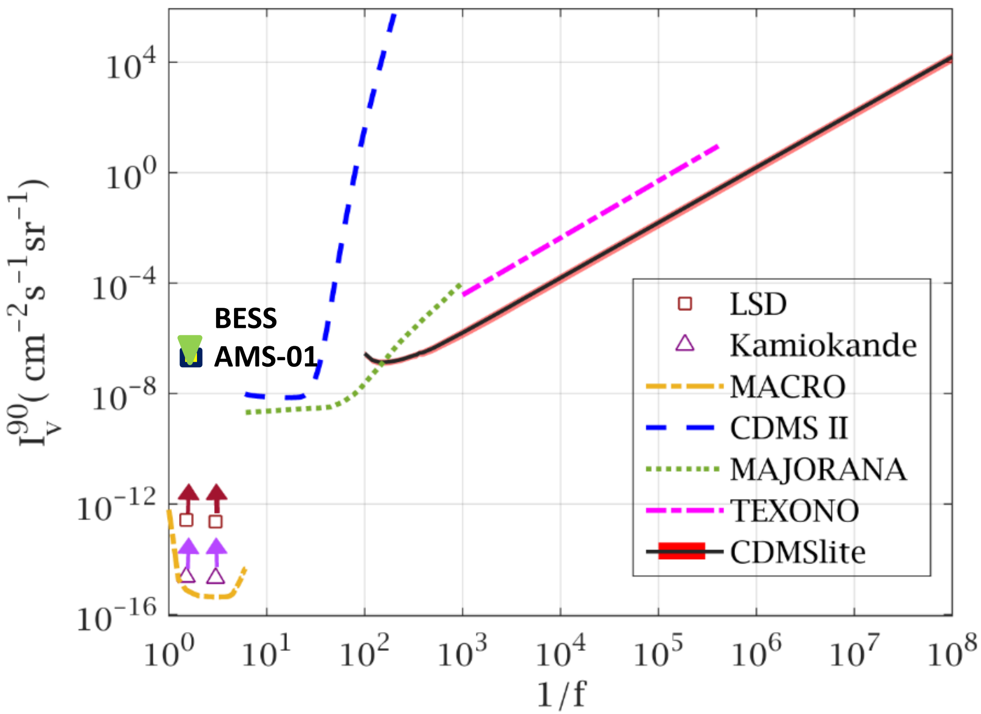


BESS balloon

$$\Phi\left(\frac{2}{3}\right) = 4.5 \times 10^{-7}\ \mathrm{cm^{-2}sr^{-1}s^{-1}}$$

The previous experiments

The flux upper limit versus the inverse charge value

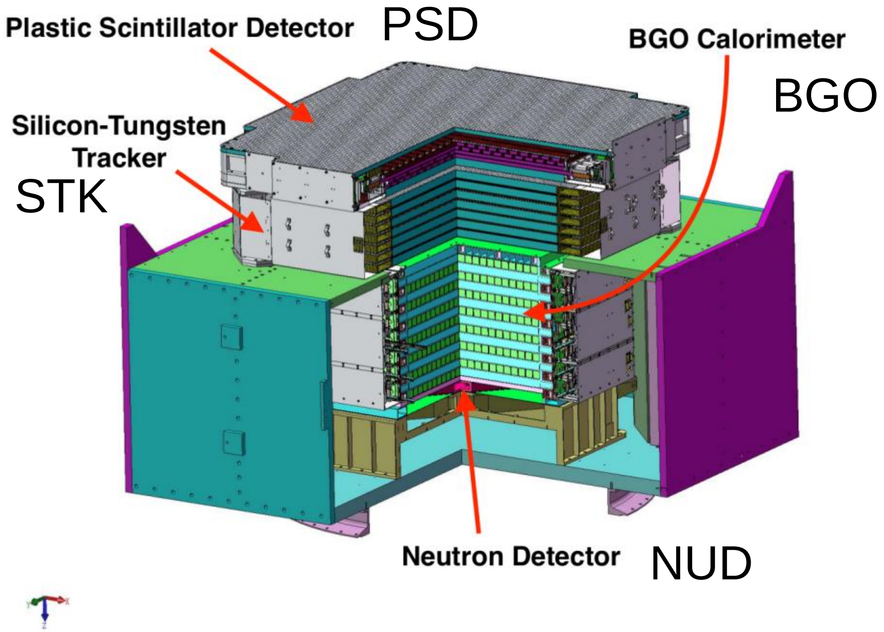


- DAMPE has been working stably on orbit for nearly six years.
- A lot of scientific data was accumulated.
- We hope to do something in searching for FCP as an on-orbit apparatus.

Outline

- Motivation
- Previous searches of FCP
- DAMPE experiment
- Search for FCP with DAMPE
- Summary

DAMPE experiment



Charge measurement (**PSD, STK**)
Precise tracking (**STK + BGO**)
Precise energy measurement (**BGO**)
Particle identification (**BGO + NUD**)

DArk Matter Particle Explorer(**DAMPE**)

Main Scientific Goals:

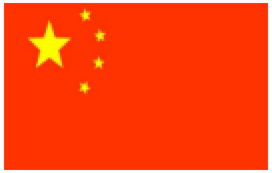
- Origin and Propagation of Cosmic-Rays
- Dark Matter Indirect Detection
- Gamma-ray Astronomy

- Orbit: sun-synchronous
- Altitudes: 500 km
- Period: about 90 minutes
- 5 million events/day
- 16 GB/day downlink
- Launched on Dec.17^{th} 2015
- Life time > 5 years

DAMPE collaboration

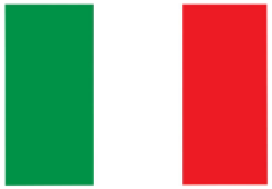
CHINA

- Purple Mountain Observatory, CAS, Nanjing
- University of Science and Technology of China, Hefei
- Institute of High Energy Physics, CAS, Beijing
- National Space Science Center, CAS, Beijing
- Institute of Modern Physics, CAS, Lanzhou



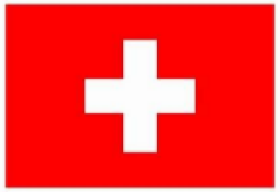
ITALY

- INFN Perugia and University of Perugia
- INFN Bari and University of Bari
- INFN Lecce and University of Salento
- INFN LNGS and Gran Sasso Science Institute

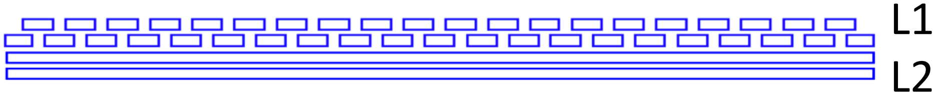


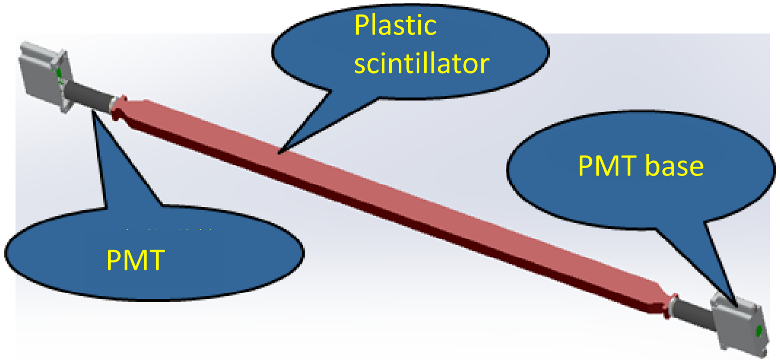
SWITZERLAND

- University of Geneva



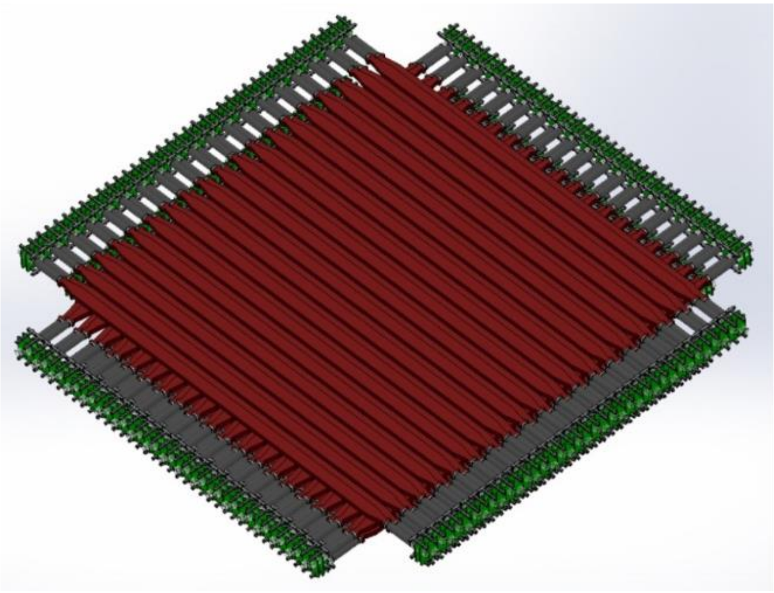
Plastic Scintillator Detector (PSD)



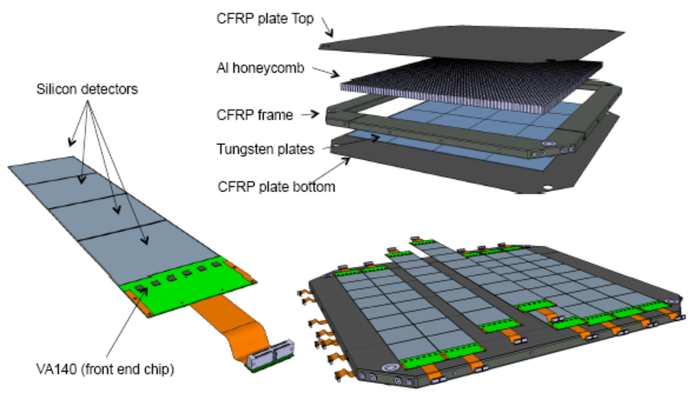


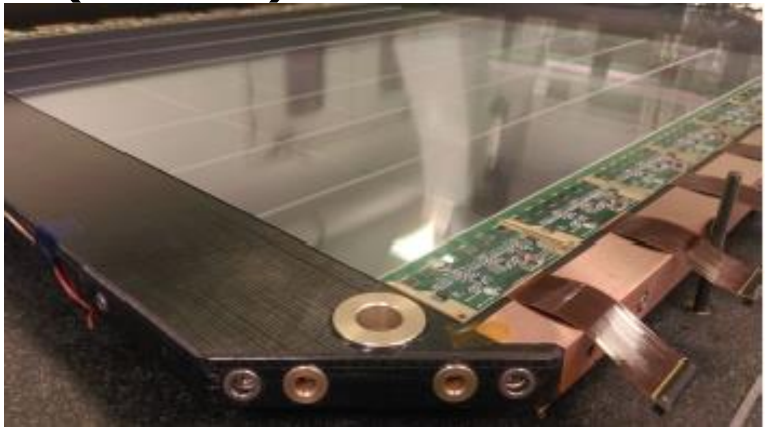
PSD is located on the top of the payload

- Active area: 82 cm × 82 cm
- Number of layers: 2
- 41 modules each layer
- A PMT at each end of strip
- Each PMT provides two signals (from Dy5 and Dy8 for large dynamic range)
- Charge resolution: 6% for Z = 1



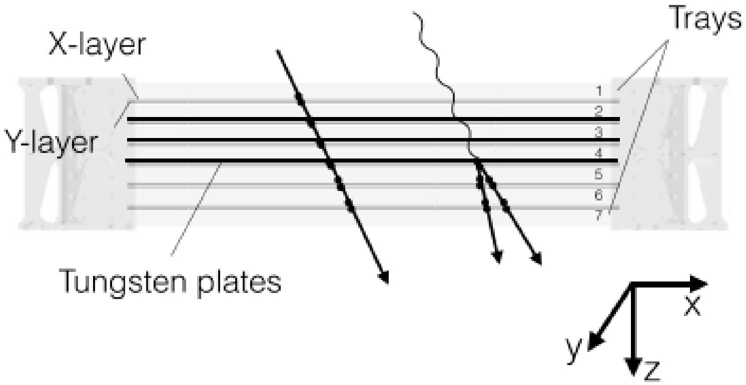
Silicon Tungsten tracKer (STK)





STK is composed by:

- Active area: 758 mm × 758 mm
- 7 CERP trays, 3 with tungsten plates for photon conversion
- Number of layers: 6
- 192 Si ladders. 16 on each sensitive face(12)
- each tray is orthogonal to the previous one to allow 3D tracking



BGO calorimeter

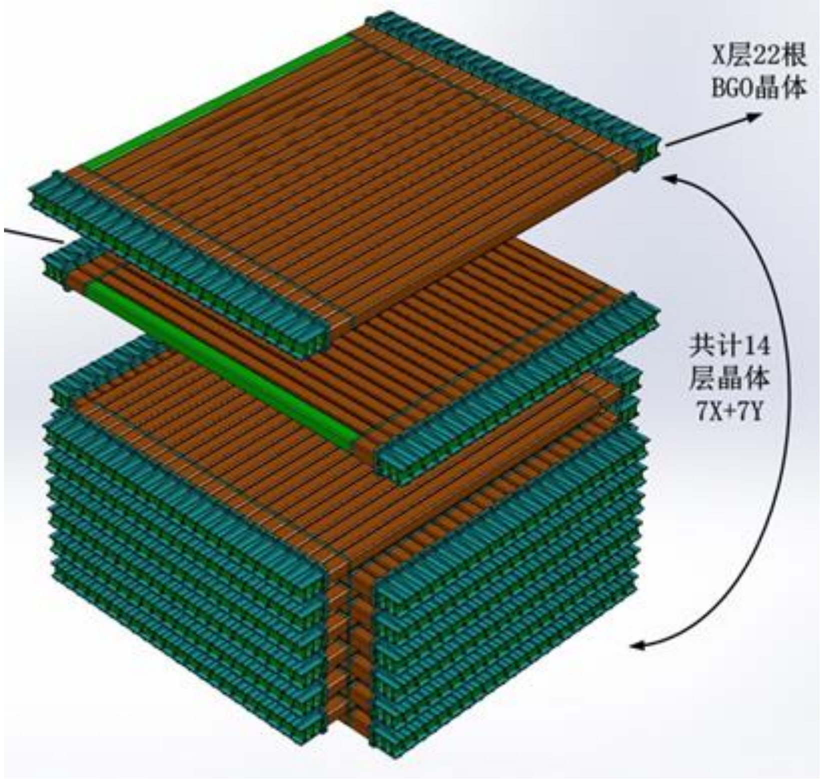
BGO structure:

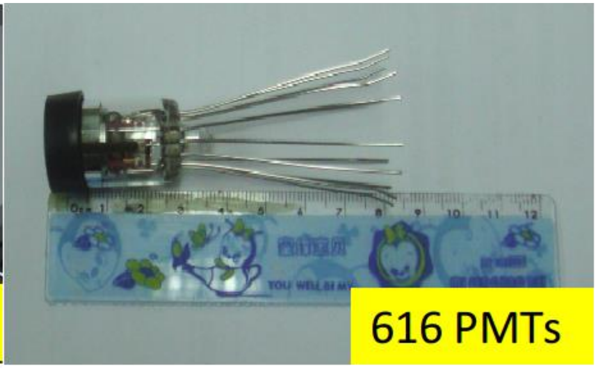
- 14 layers of 22 BGO crystals

- Dimension of BGO bar: $2.5 \times 2.5 \times 60\ \mathrm{cm}^3$
- Hodoscopic stacking alternating orthogonal layers
- r.l: 32X0, NIL:1.6

- Two PMTs coupled with each BGO crystal bar in two ends

- Electronics boards attached to each side of module



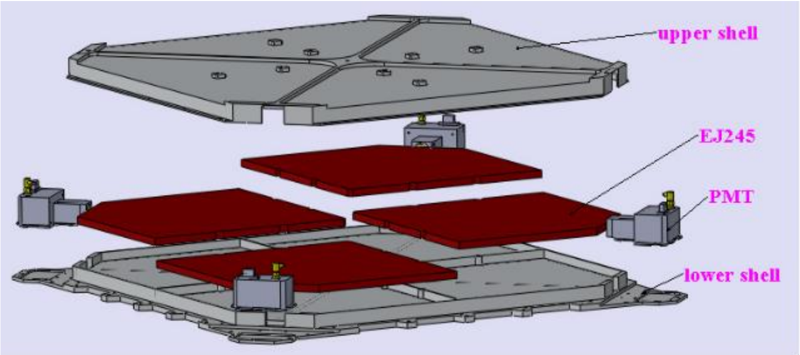


Neutron Detector

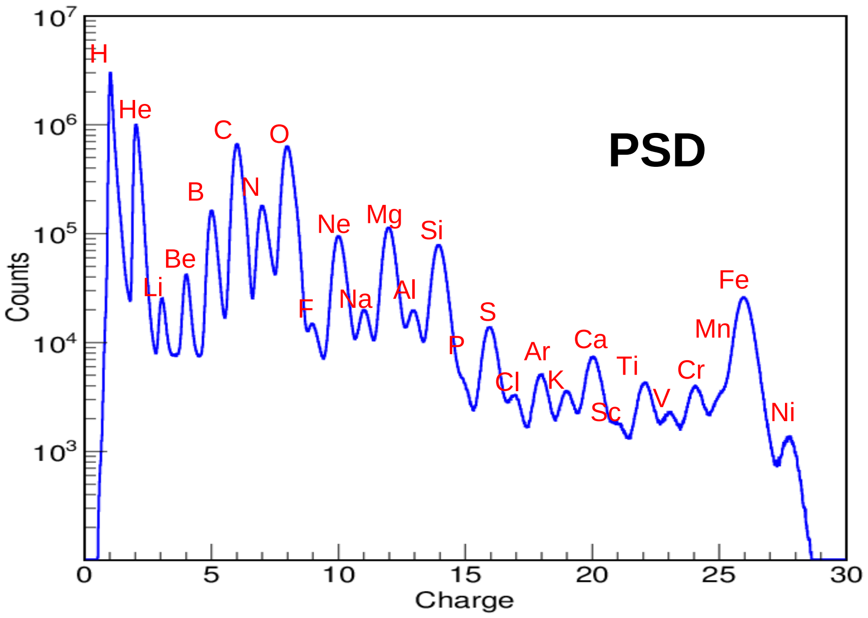
$$n +^{10} B \rightarrow \alpha +^{7} Li + \gamma$$

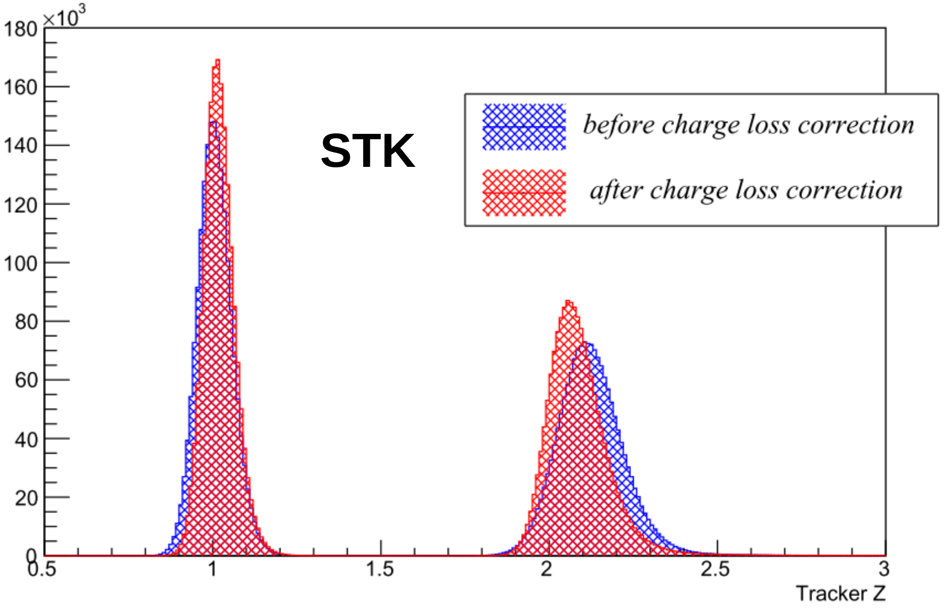
NUD designed parameter:

- 4 boron-doped plastic scintillators (30 cm × 30 cm × 1 cm)
- Active area: 61 × 61 cm^2
- Energy range: 2 - 60 MeV for single detector
- Energy resolution: ≤ 10% at 30 MeV



Performance of charge measurement





Left: The charge discrimination of PSD in Z from 1 to 28

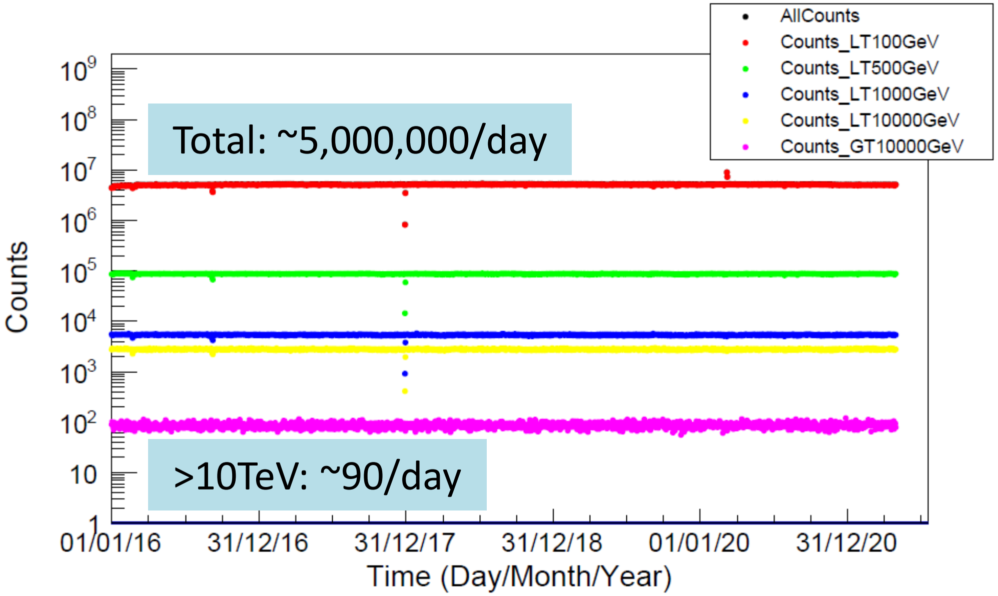
Right: The charge discrimination of STK between proton and helium

Charge resolution for singly charged particles:

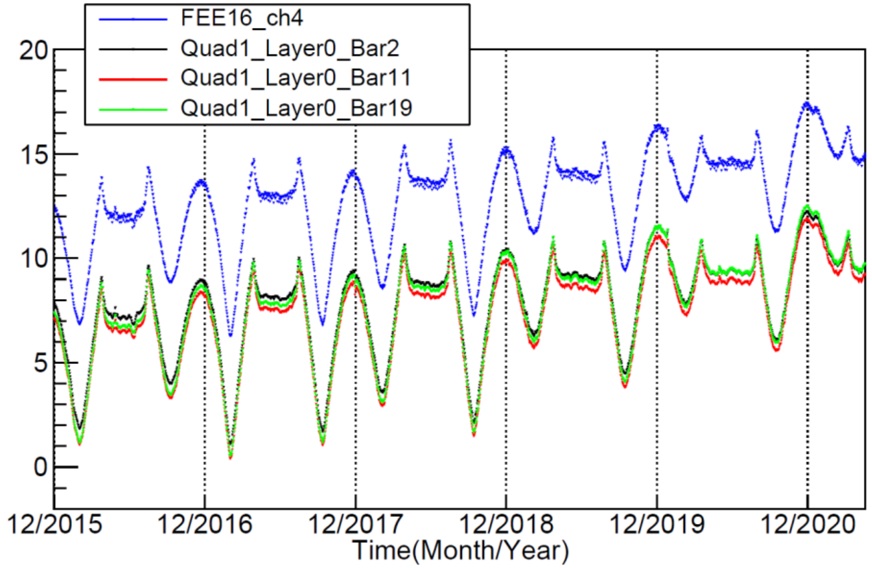
PSD: 0.06e STK: 0.04e

DAMPE status

Trigger rate per day



Daily temperature variation of BGO

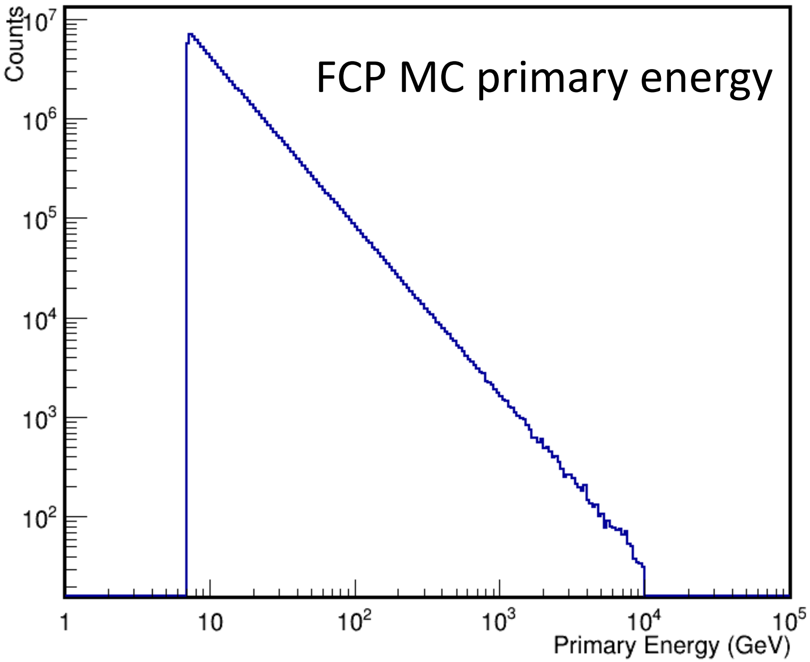


Outline

- Motivation
- Previous searches of FCP
- DAMPE experiment
- Search for FCP with DAMPE
- Summary

Data samples

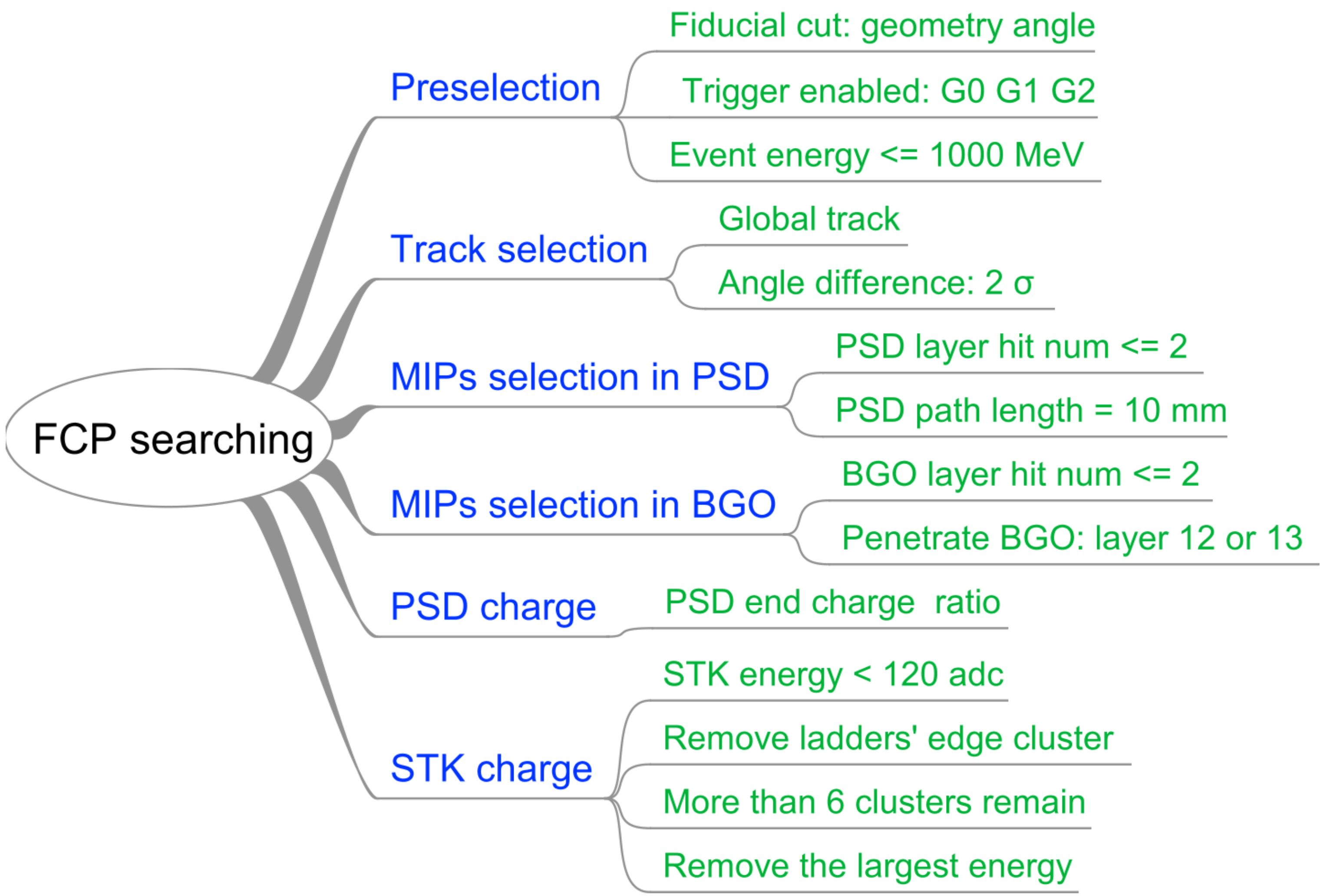
- Five years on-orbit data
- Proton simulation based on Geant4 in DAMPE software 10 GeV - 100 TeV
- FCP simulation based on Geant4 in DAMPE software 7 GeV – 10 TeV



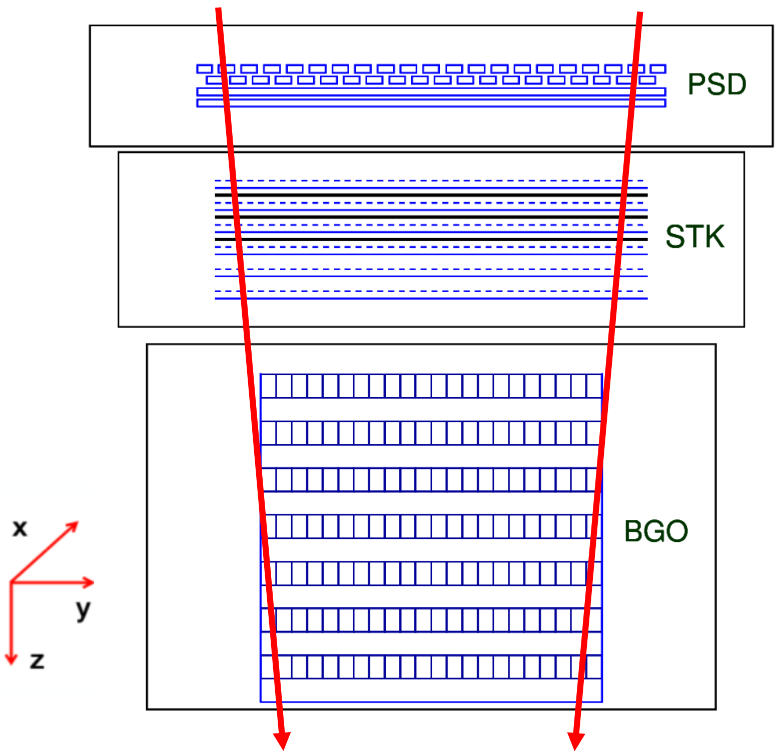
FCP simulation:

- Created a virtual particle
- Charge with $\frac{2}{3}\mathrm{e}$
- Mass with 1.2 GeV
- Add ionization and multi scattering process
- Energy spectrum obey the E^{-3}
- Spheric particle source

Searching FCP with DAMPE

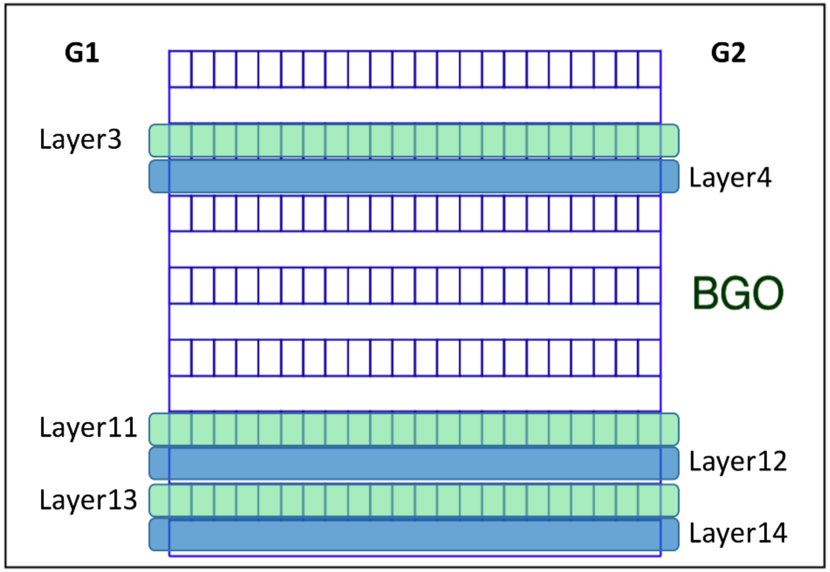


Pre-selection



Fiducial cut:
Constrain the positions of injection and ejection to maintain the event in the whole detector

MIPs Trigger: G1||G2 trigger enabled
-20° < latitude < 20°



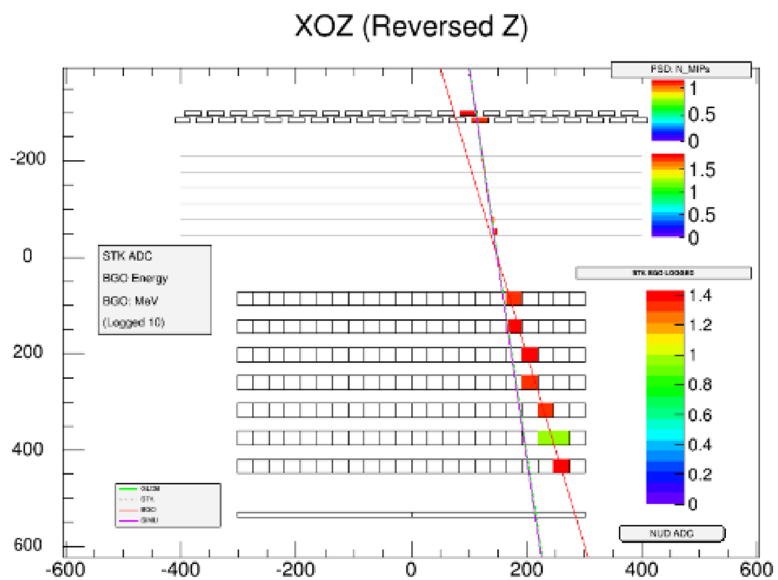
Since the calibrated trigger threshold of G1 G2 is ~0.2 MIPs, higher than the 1/3 charged particles(1/9 MIPs), we aim to search the 2/3 charged particles.

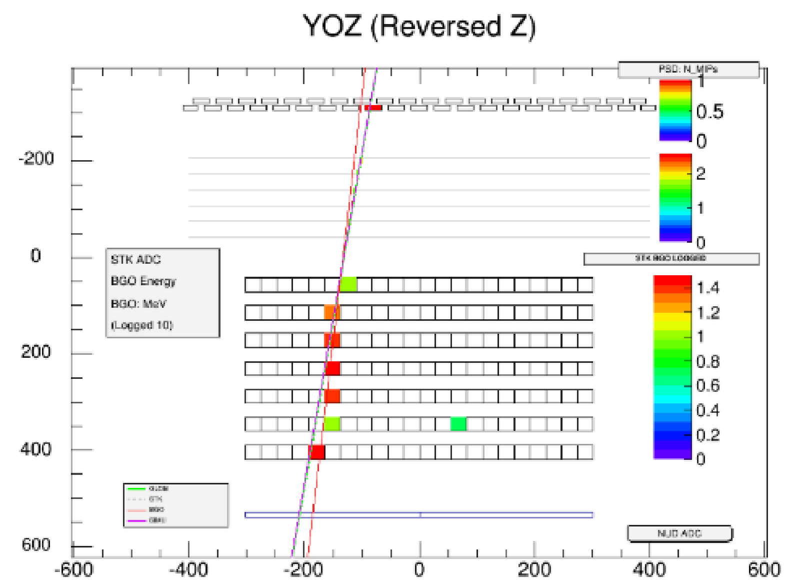
Mips energy:
1000 MeV loose cut since singly charged particle depositing energy is about 700 MeV

Track selection

Global track:
should be reconstructed in STK.

Angle difference between Global Track and BGO Track:
The hits in BGO calorimeter can be used to reconstruct a BGO track. If global track deflects too much from BGO track, there may be scatters happened





MC_Proton event Angle > 6°

MIPs selection

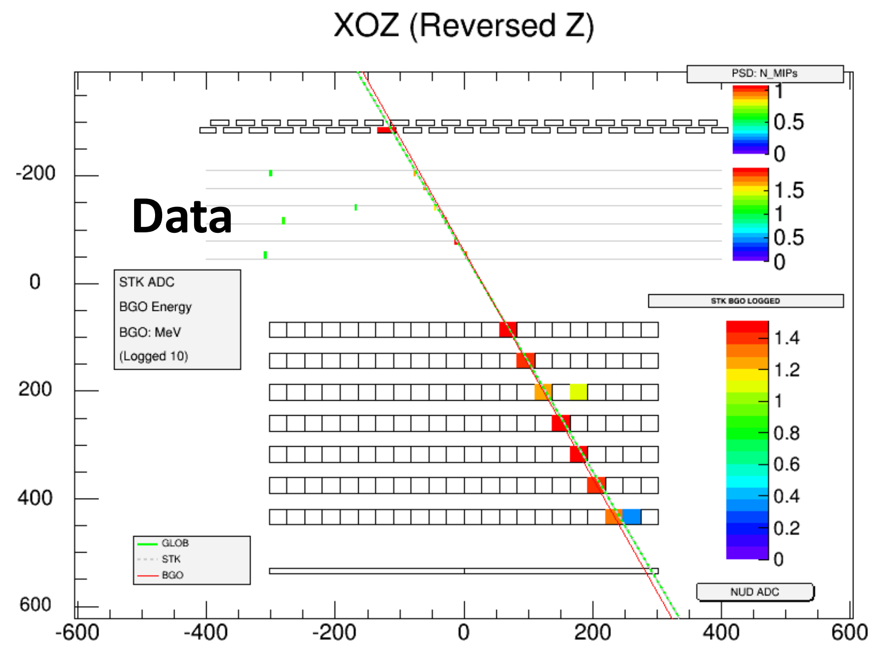
MIP in PSD:

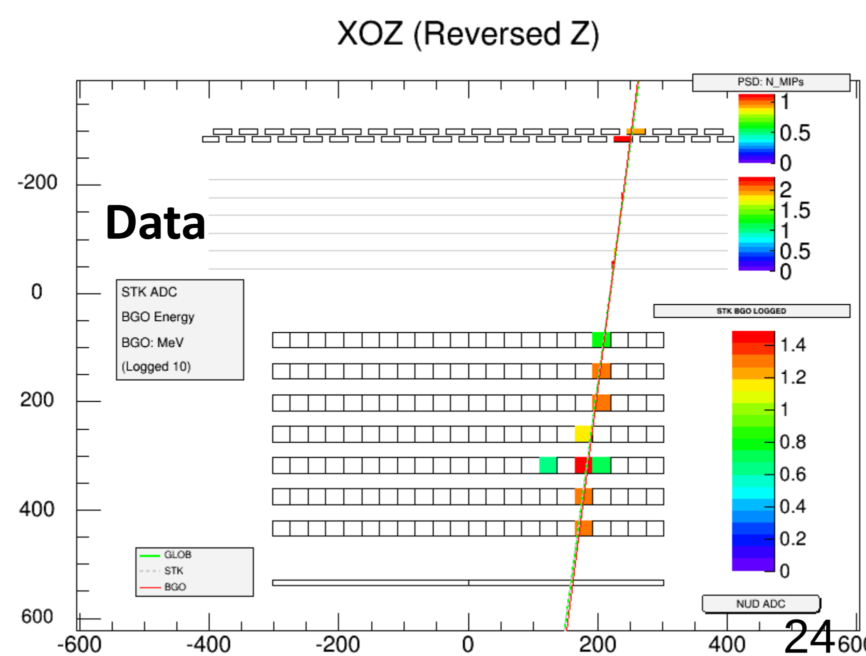
- Every Layer hit bars <= 2
- Path length = 10 mm

MIP in BGO:

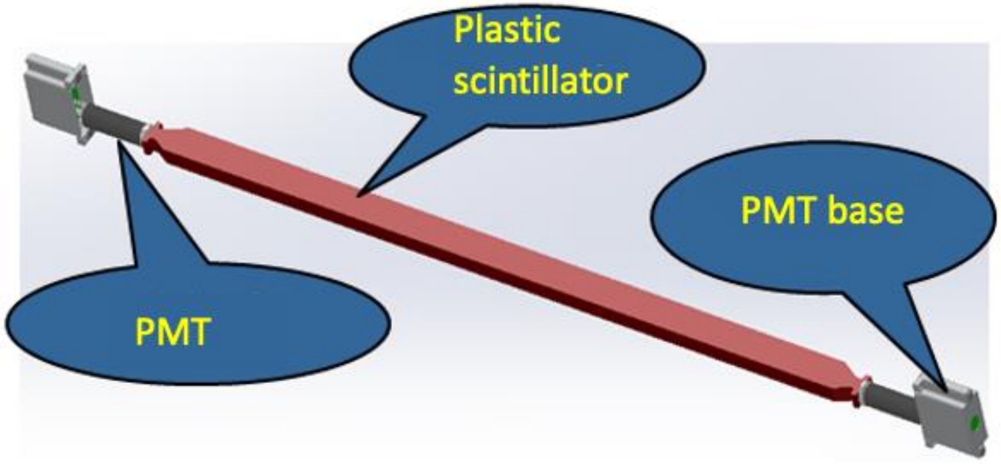
- Over-threshold(2 MeV) hits no more than 2 in one layer along the track and no more than <u>28</u> in the whole calorimeter

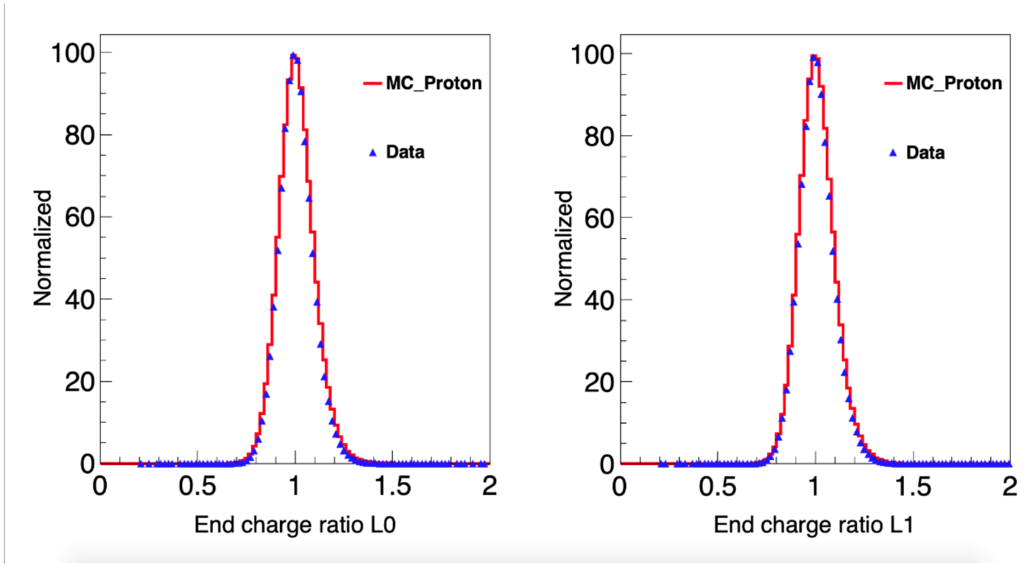
- Hit layers > 5 in both YOZ and XOZ, **one of last two layers** should be fired





PSD charge

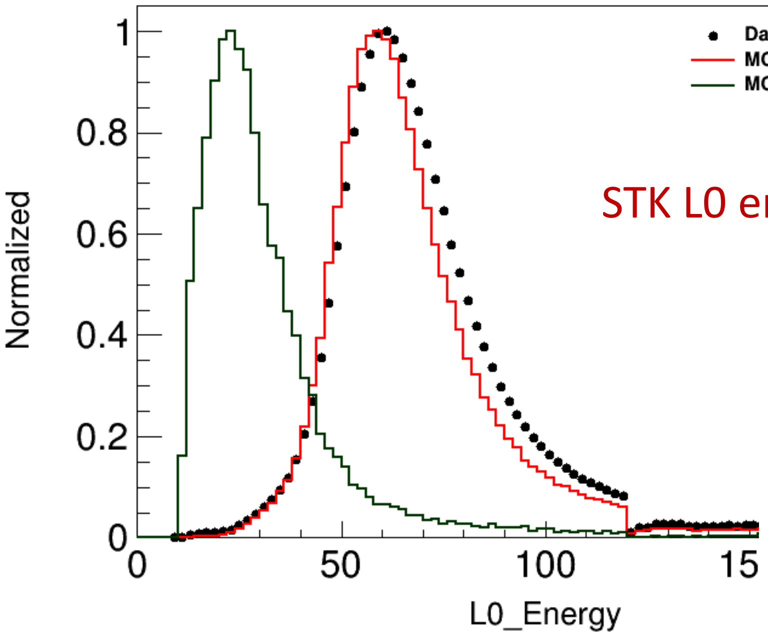


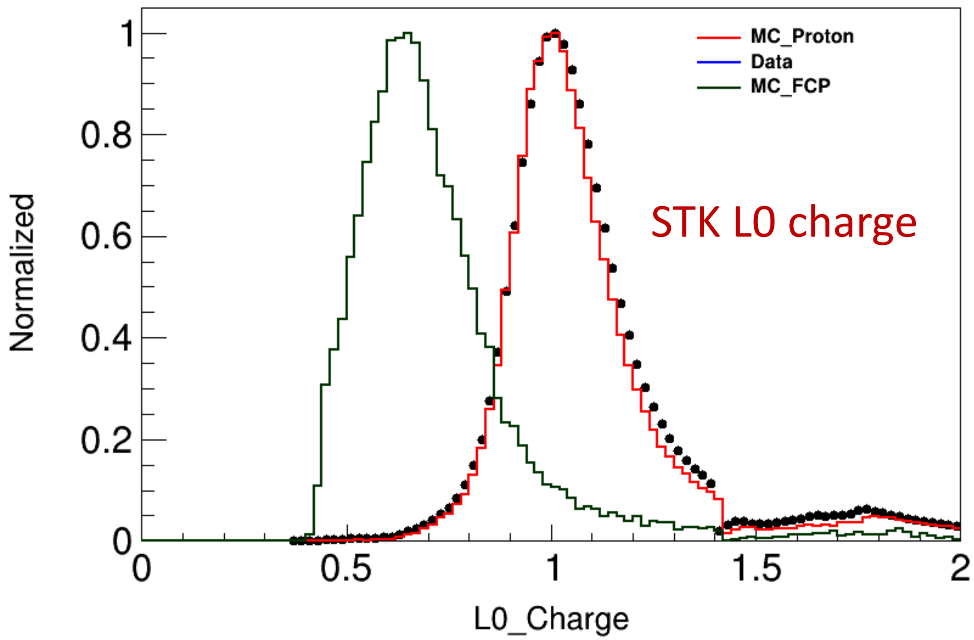


To ensure the reliability of charge reconstruction, the ratio of two ends of one strip should be consistent

STK sub-layer energy and charge

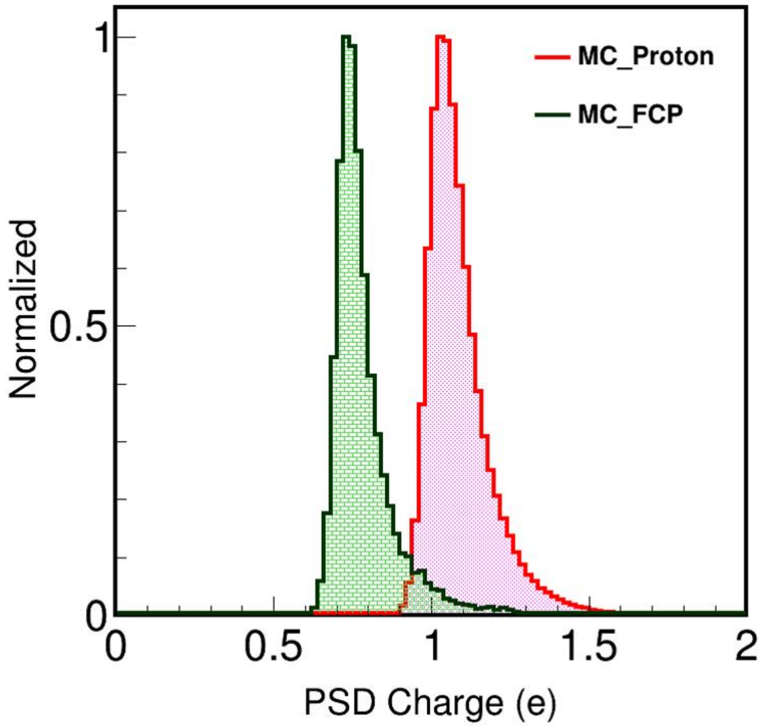
- Take layer 1 for example

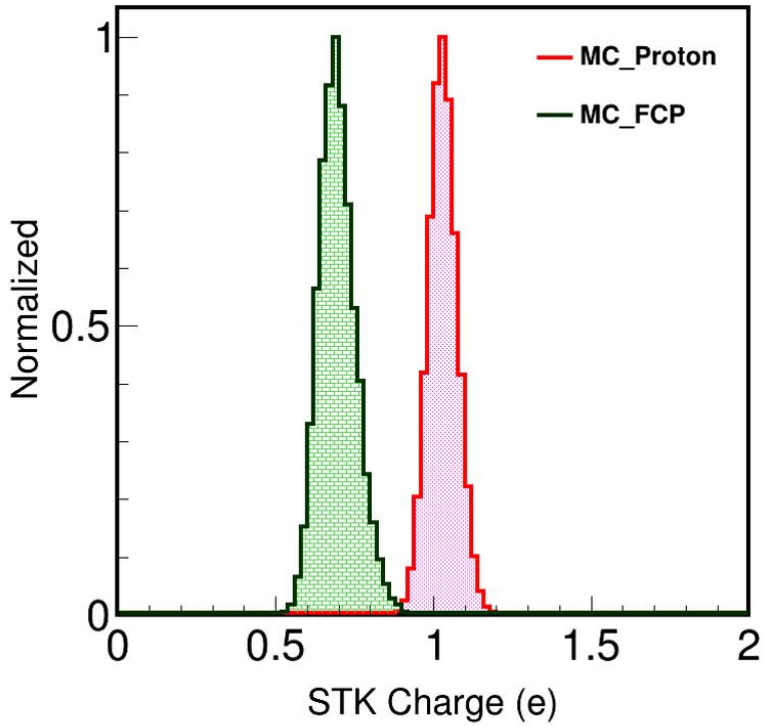




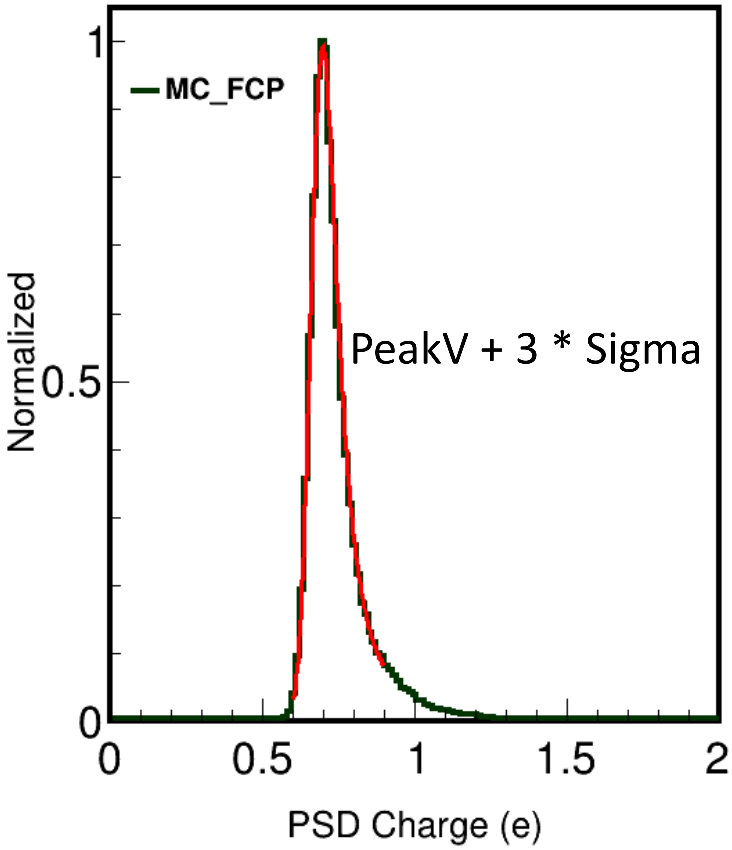
Charge reconstruction

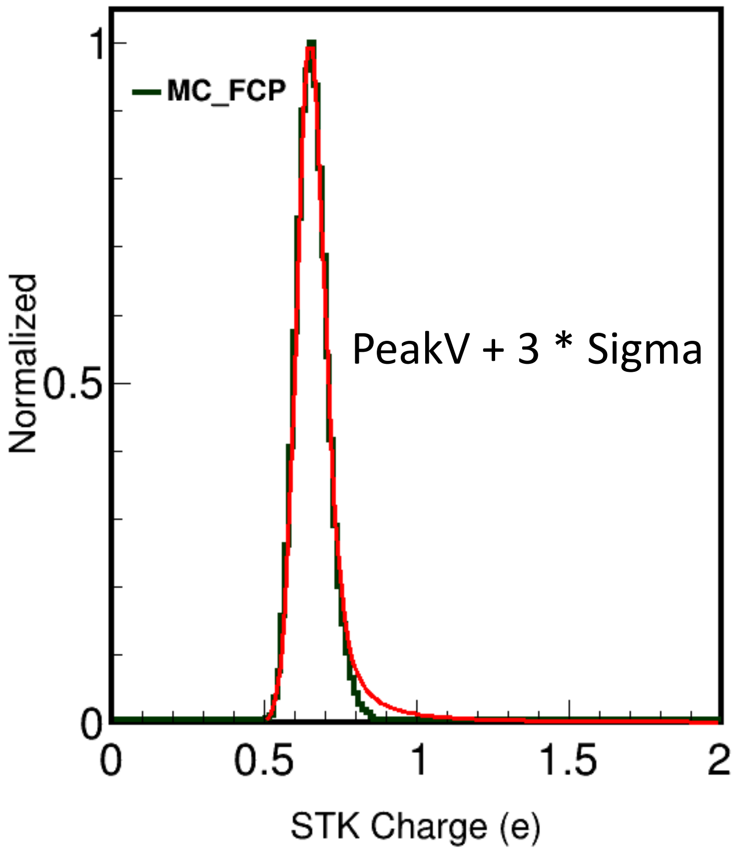
$$Q_{PSD} = \frac{Q_0 + Q_1}{2} \qquad Q_{STK} = \frac{\sum_{i=1}^{N} Q_i}{N}$$





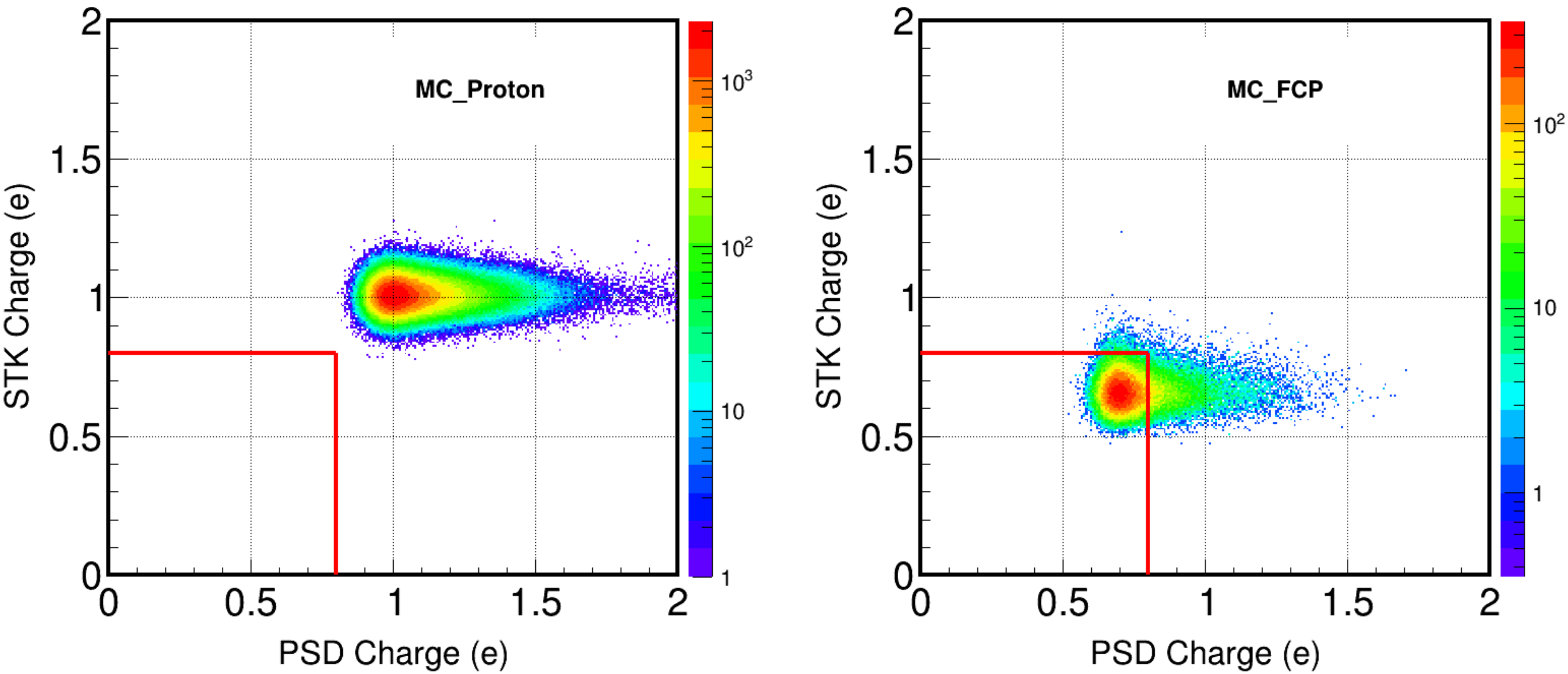
Signal region definition





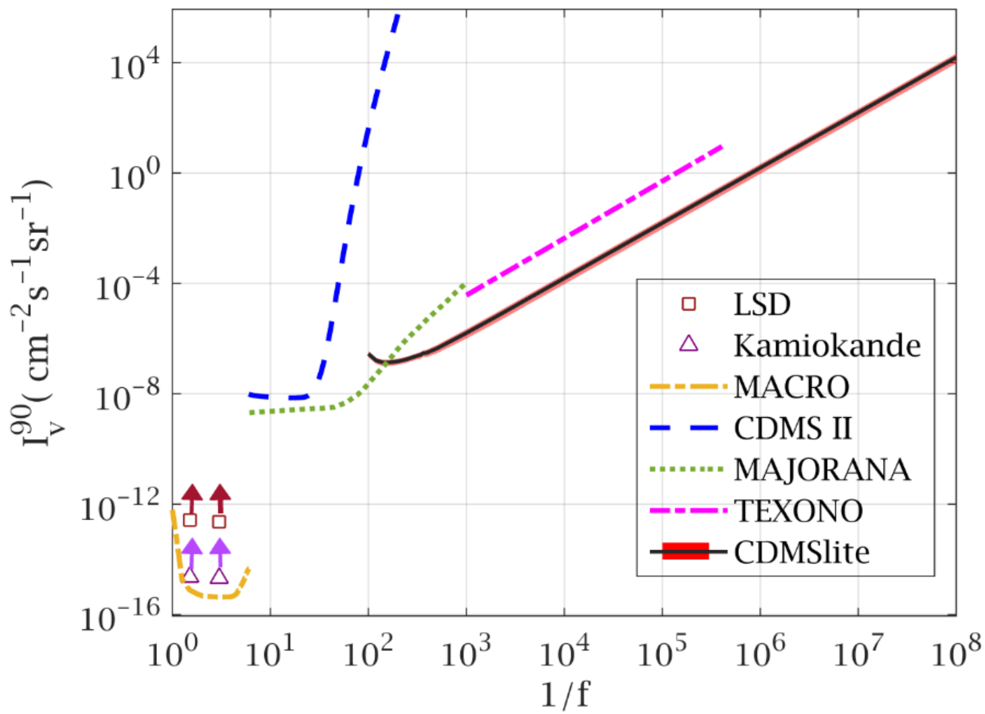
The charge distributions are fitted with the convoluted Landau and Gaussian function, the sigma is token with FWHM/2.35.

Signal region application



A signal region can be defined by PSD and STK MC as the red lines shows, the charge of two lines are set to around 0.8e. The signal region is effective to exclude the background and has a 86% efficiency of covering the FCP.

Results from underground experiments



With the large volume and long exposure time, The MACRO released the most stringent upper limit; with high degree of charge sensitivity, the CDMS and others could measure very small charge.

Comparison with same type experiments

Experiments	Geometry acceptance $(\mathrm{cm}^2\mathrm{sr})$	Exposure time (s)	Upper limit $\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$
AMS-01	3000	3.6×10^4	3.0×10^{-7}
BESS	1500	3.2×10^5	4.5×10^{-7}
DAMPE	3000	2.4×10^7	To be released

- AMS-01 has a large acceptance, but short of the exposure time
- BESS integrates four times of flights to achieve a longer exposure time
- DAMPE has a relatively larger acceptance and the longest exposure time. We hope to release a lower upper limit in the near future.

Summary

- The history of FCP has been reviewed briefly.
- The DAMPE experiment has been introduced.
- The selection criteria to search FCP with DAMPE have been studied.
- A MC simulation has been performed and an evaluation of the detection efficiency has been carried out.
- A comparison between DAMPE and other equipment has been done. DAMPE is hopeful to release a lower upper limit in space.

Summary

- The history of FCP has been reviewed briefly.
- The DAMPE experiment has been introduced.
- The selection criteria to search FCP with DAMPE have been studied.
- A MC simulation has been performed and an evaluation of the detection efficiency has been carried out.
- A comparison between DAMPE and other equipment has been done. DAMPE is hopeful to release a lower upper limit in space.

Thank you!