Workshop on Multi-front Exotic phenomena in Particle and Astrophysics (MEPA 2023)

Searching for Fractionally Charged Particles with DAMPE

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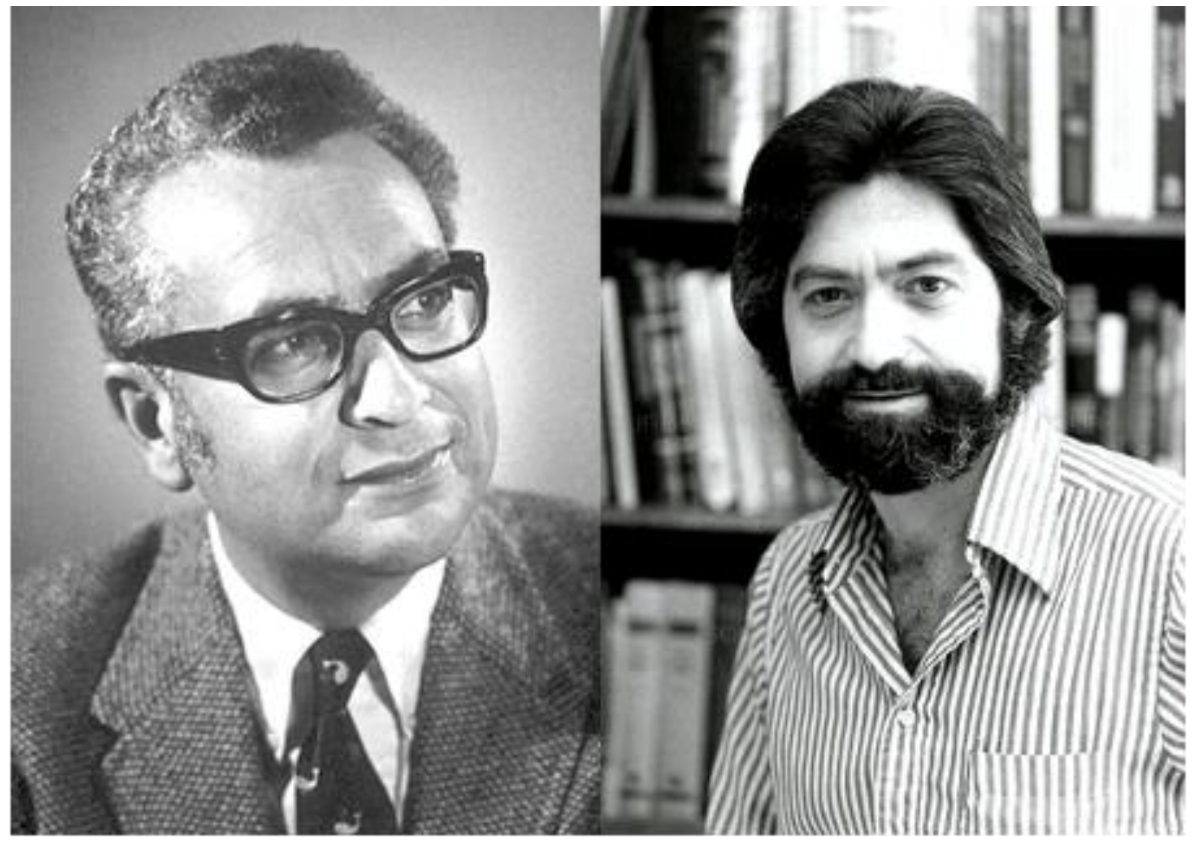
Outline

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

Motivation

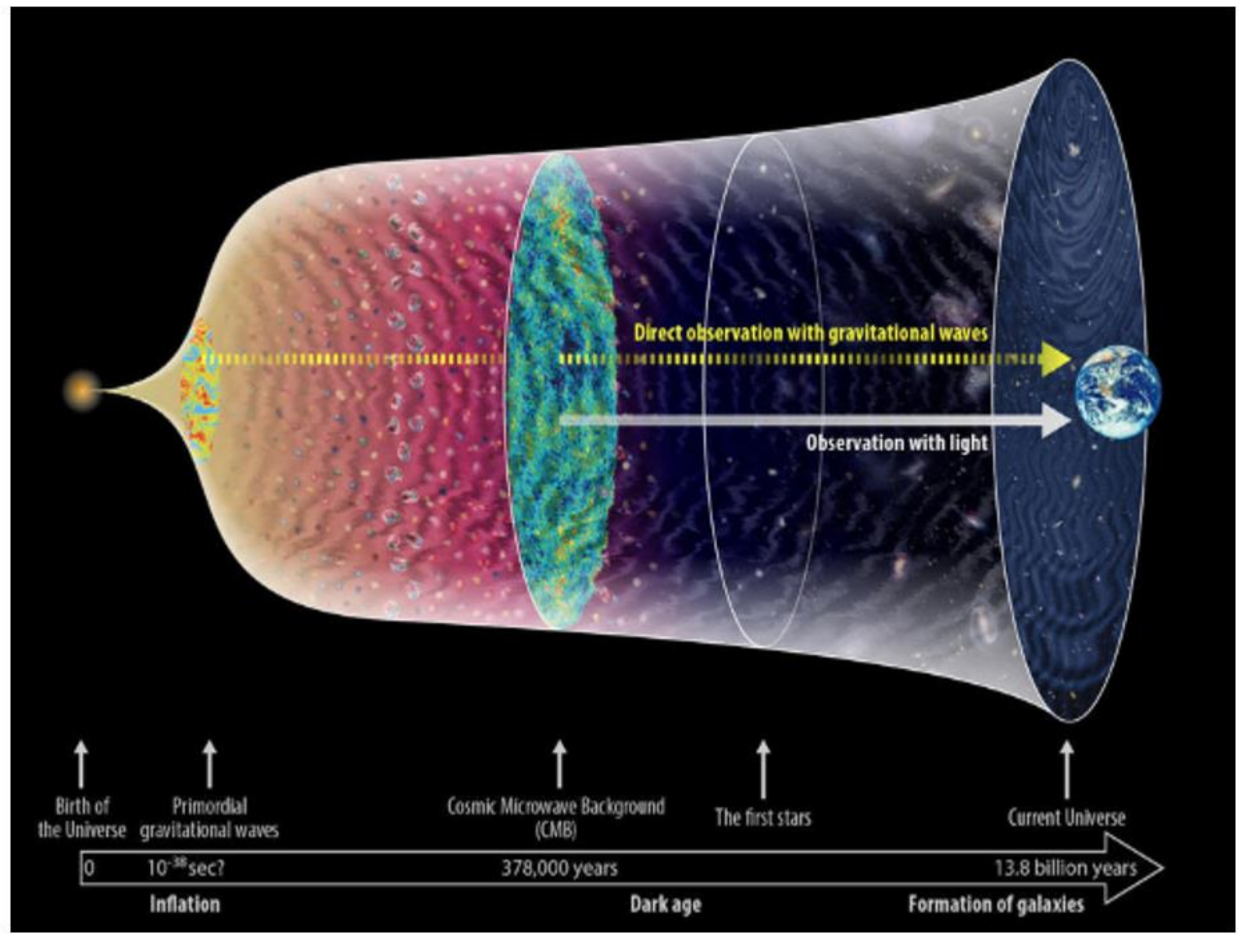
- Since the oil drop experiment performed in 1909, all particles are measured as having charges of multiples of electron charge.
- In 1964, quark model for hadrons was proposed by Gell-mann and Zweig.
- Due to the QCD theory, the quarks will not exist freely.
- Fractionally Charged Particle (FCP) is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

R. A. Millikan

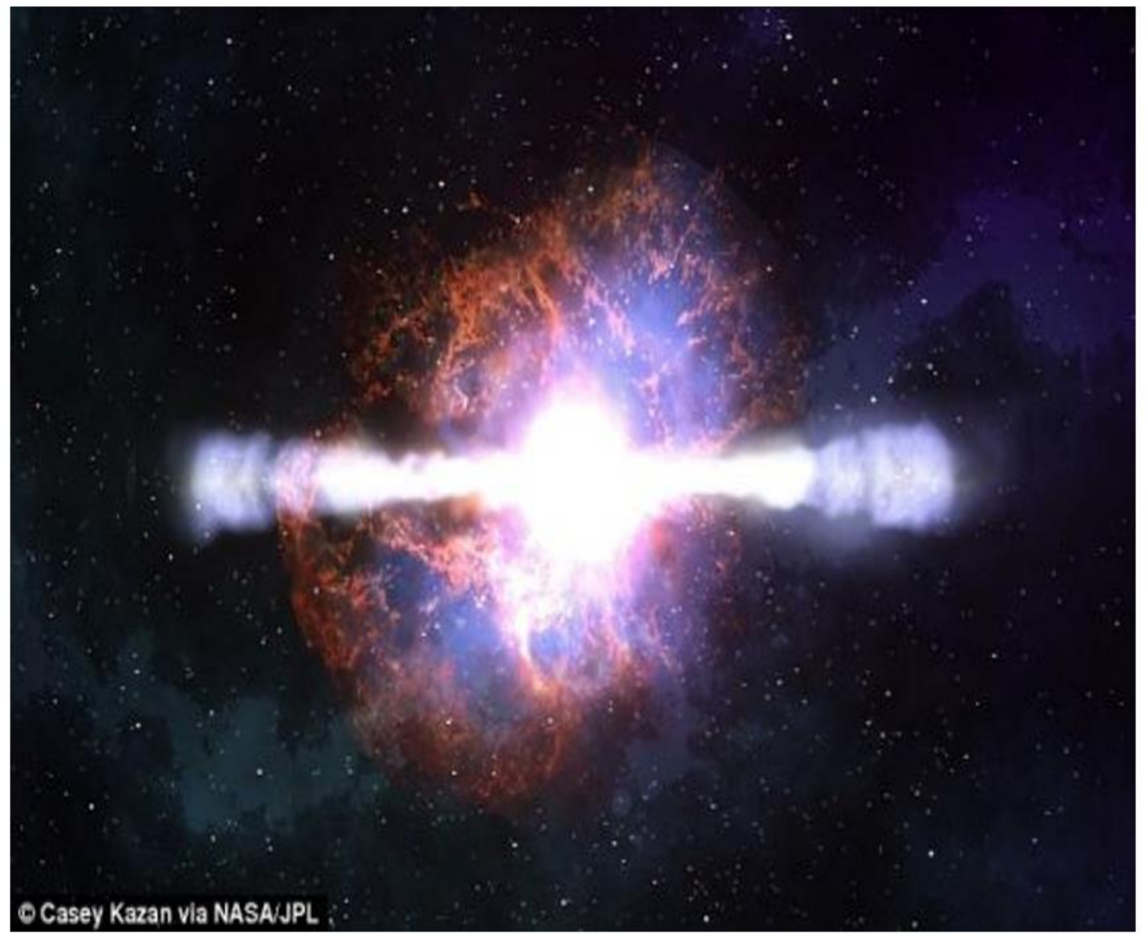


Gell-mann and Zweig

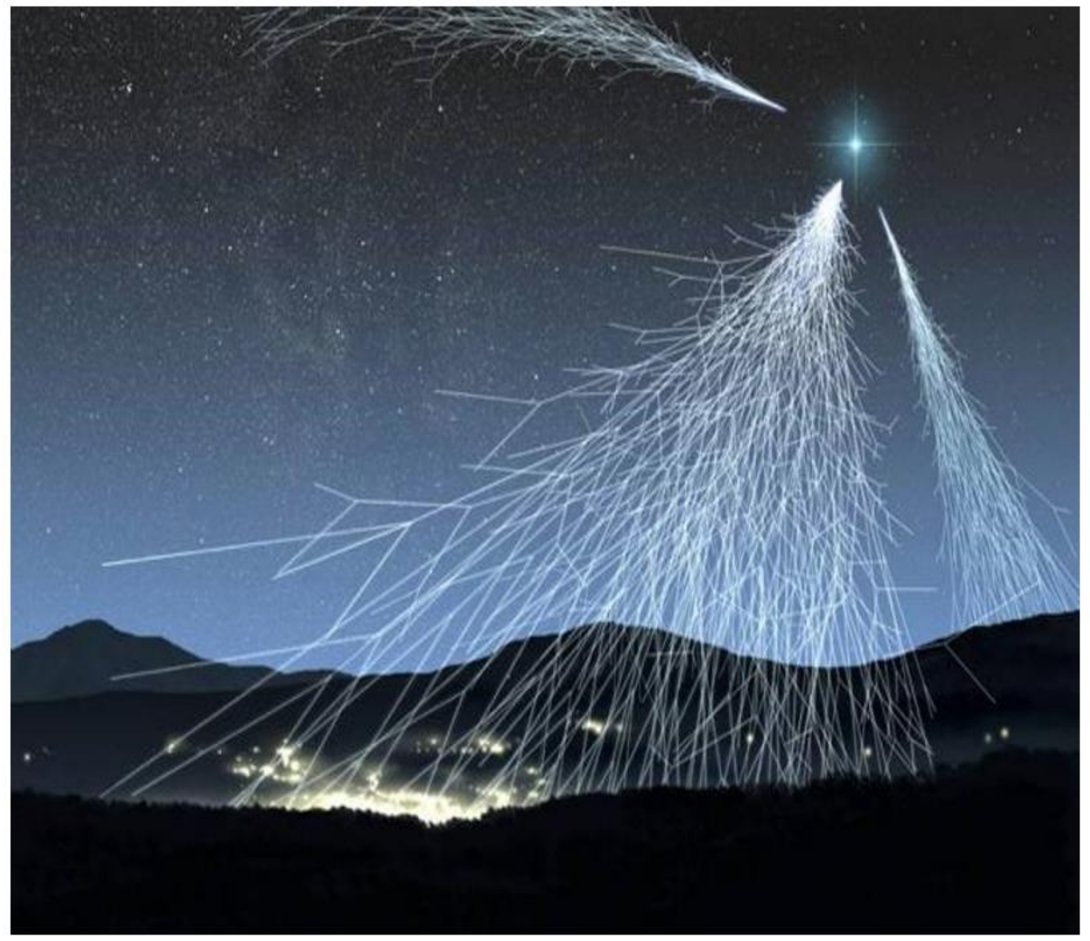
The possible origins of FCP



Early universe



Supernova explosion

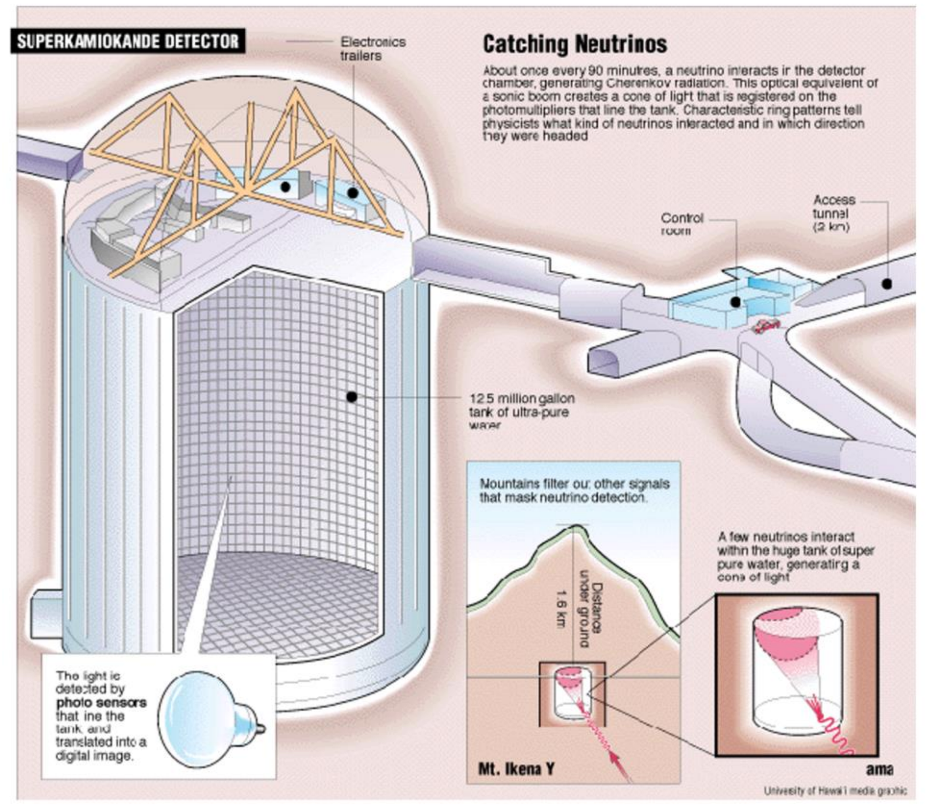


Extensive air shower

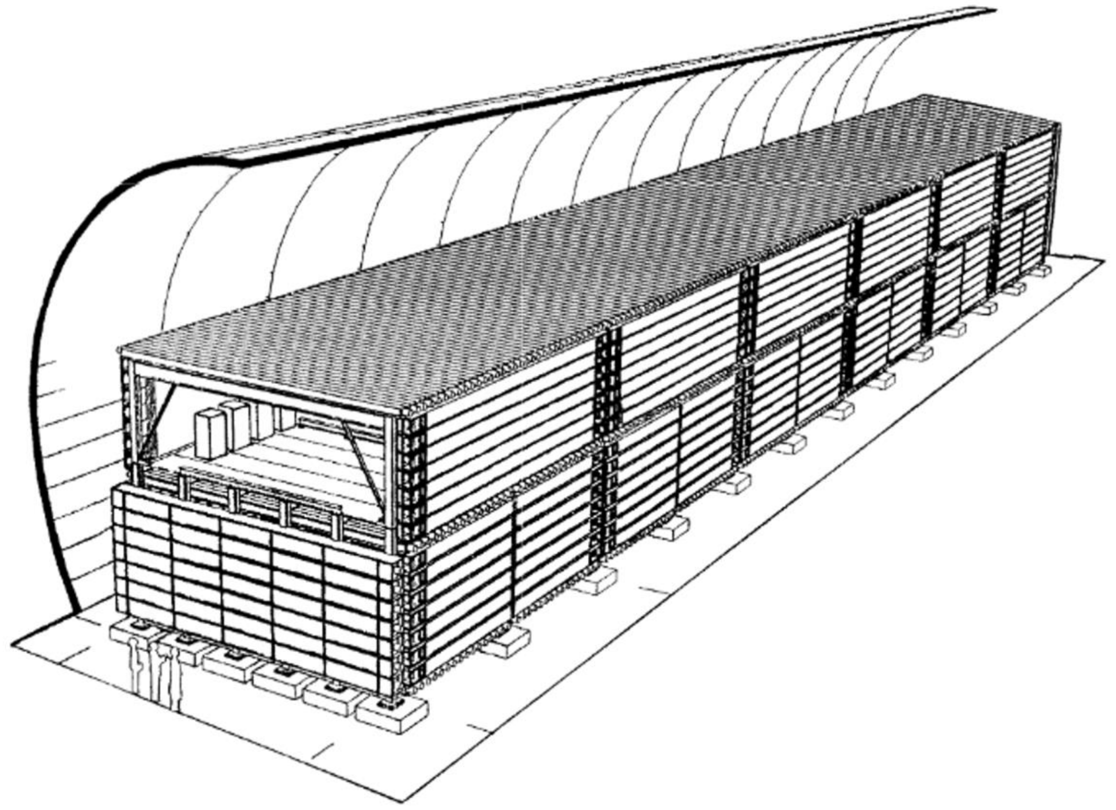
- There are three possible sources of FCP in cosmic rays:
  - It may be produced at the early Universe after the Big Bang
  - It may be produced through high-energy astrophysical processes
  - It may be produced in the extensive air shower of cosmic-rays

Searching for FCP with Underground Experiment

Kamiokande II
depth: 1000 m



MACRO
depth: 1400 m



LSD
depth: 1800 m

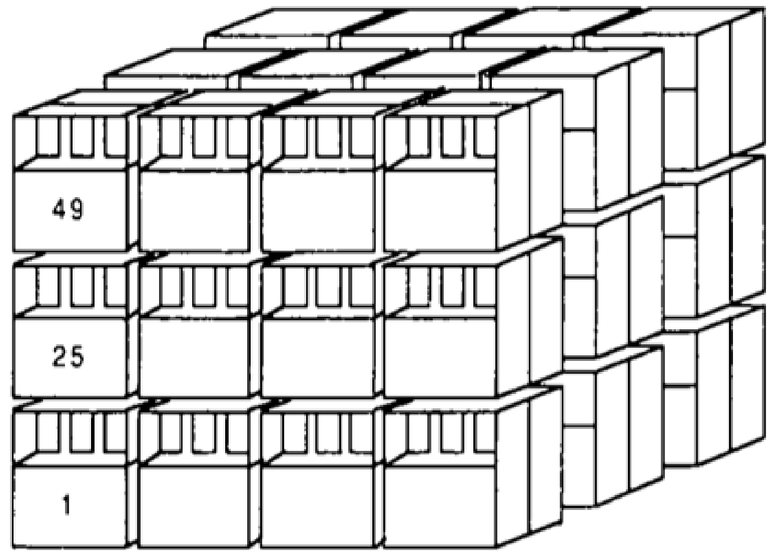
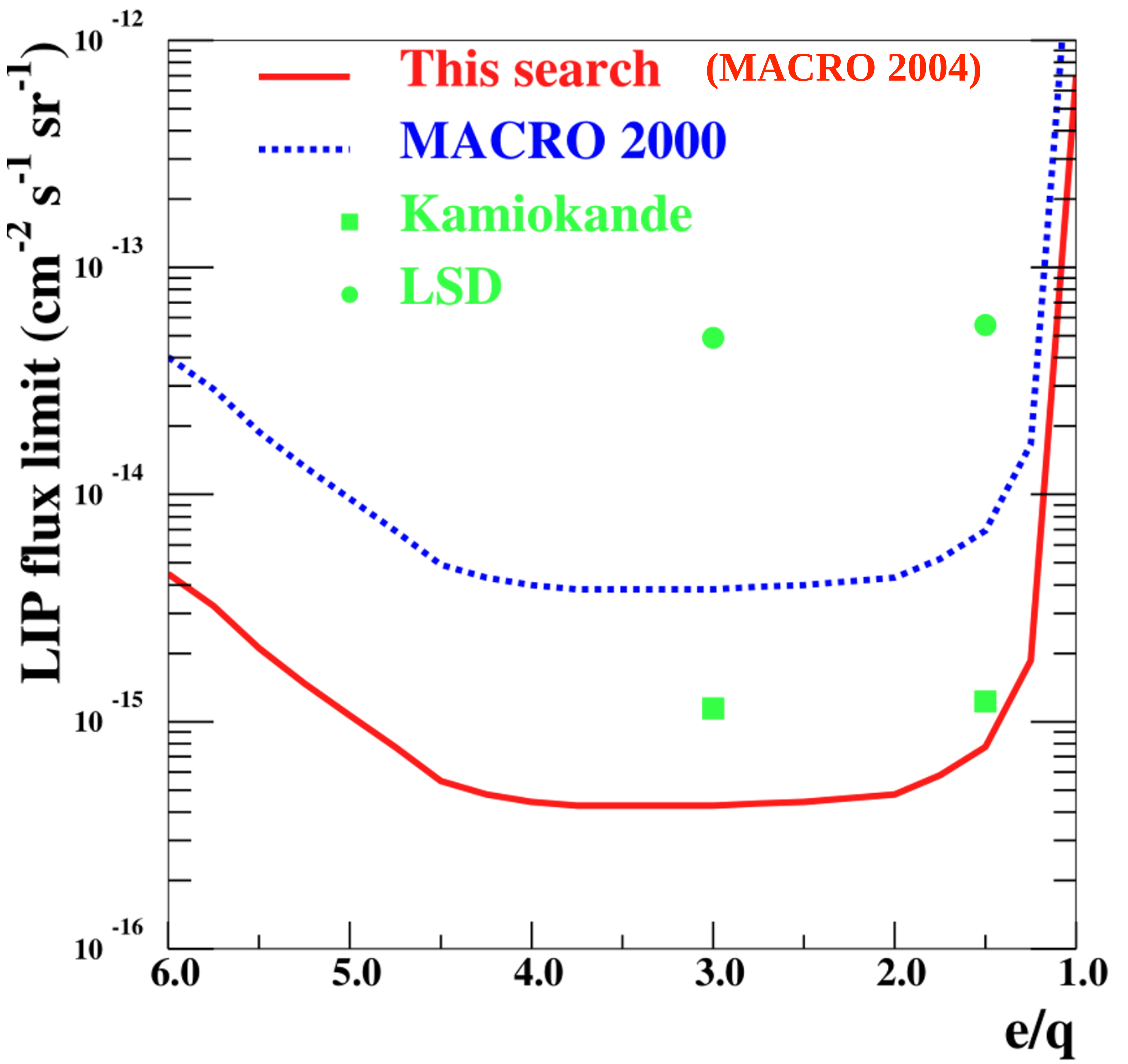


Fig. 1. The LSD experimental detector. The 72 tanks are considered as divided into 24 vertical columns (e.g. tanks 1–25–49 form the first telescope).

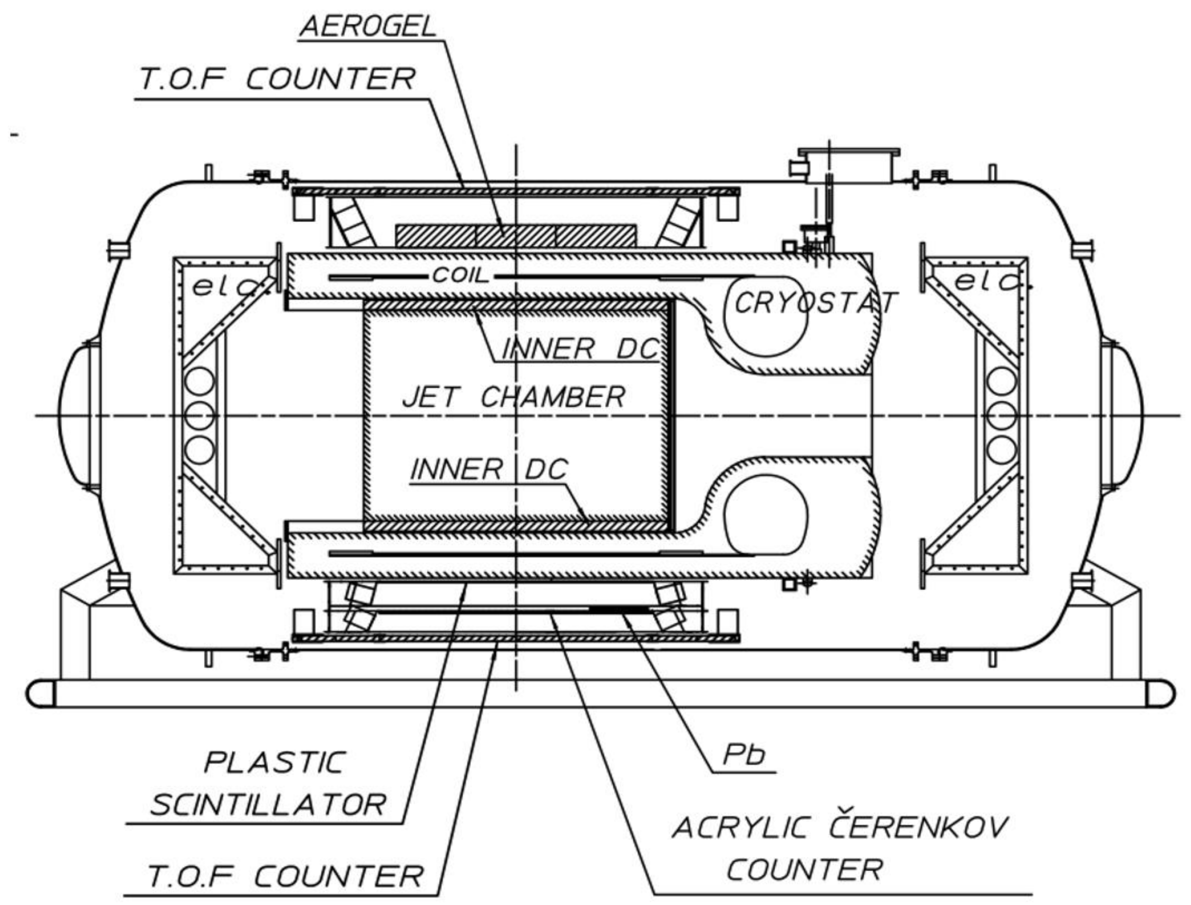


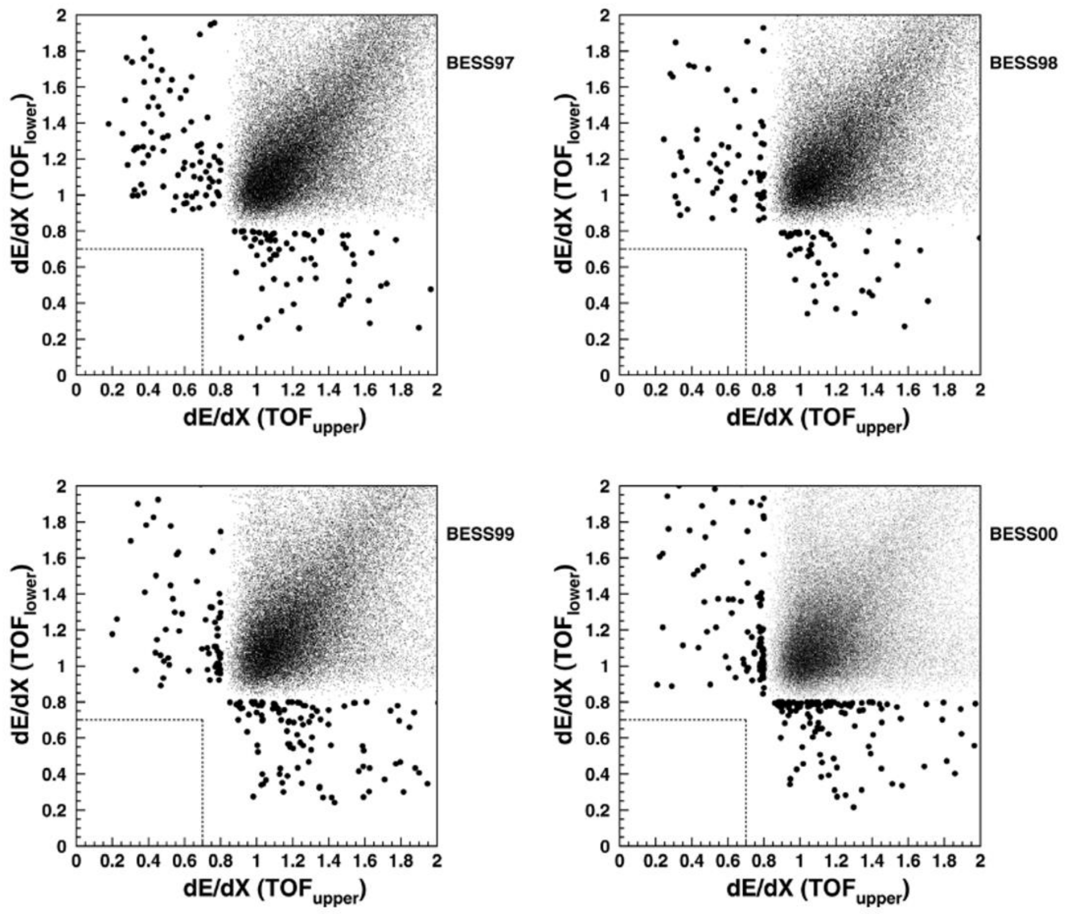
Current strictest upper limit given by MACRO (2004):

$$\Phi\left(\frac{1}{4}\sim\frac{2}{3}\right) = 6.1\times10^{-16}\ \mathrm{cm^{-2}sr^{-1}s^{-1}}$$

Searching for FCP with Space Experiment

BESS

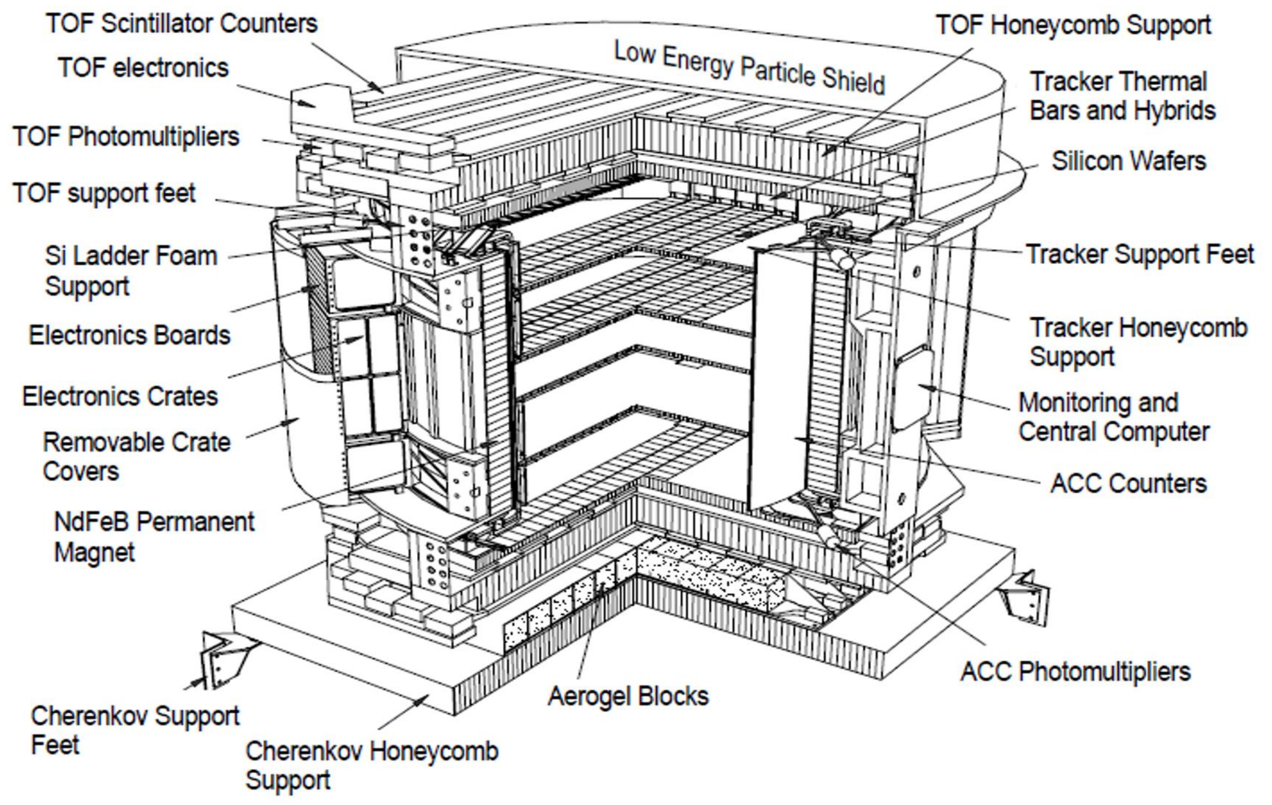


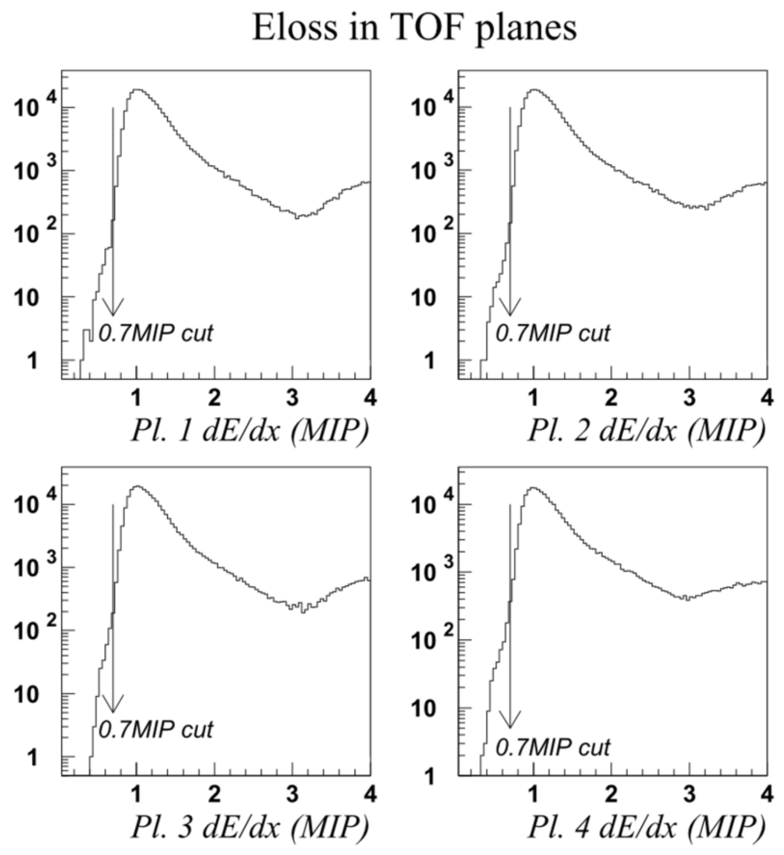


Upper limit (90% C.L.):

$$\Phi\left(\frac{2}{3}\right) = 4.5\times10^{-7}\ \mathrm{cm^{-2}sr^{-1}s^{-1}}$$

AMS01

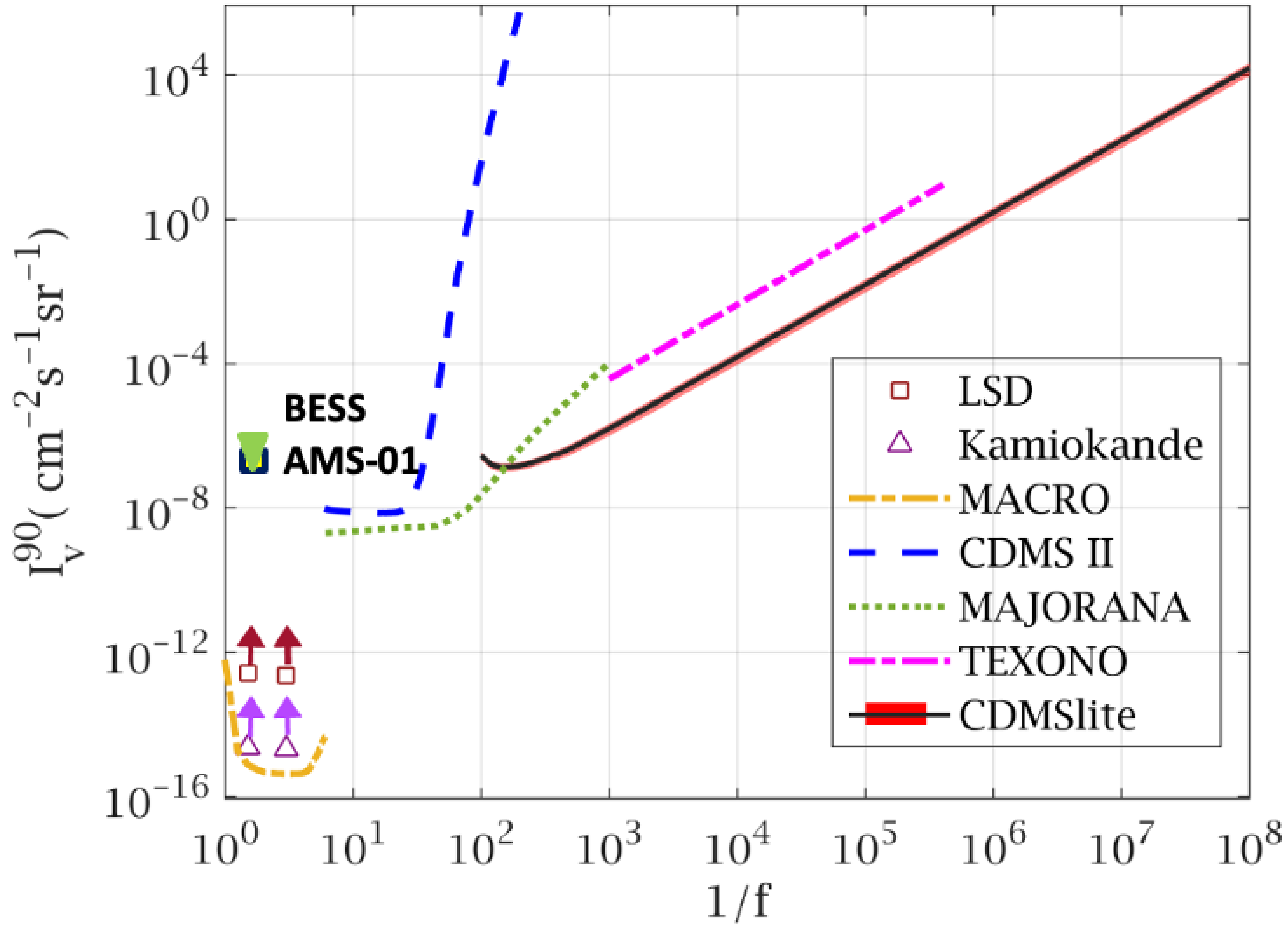




Upper limit (95% C.L.):

$$\Phi\left(\frac{2}{3}\right) = 3.0\times10^{-7}\ \mathrm{cm^{-2}sr^{-1}s^{-1}}$$

The results of previous experiments



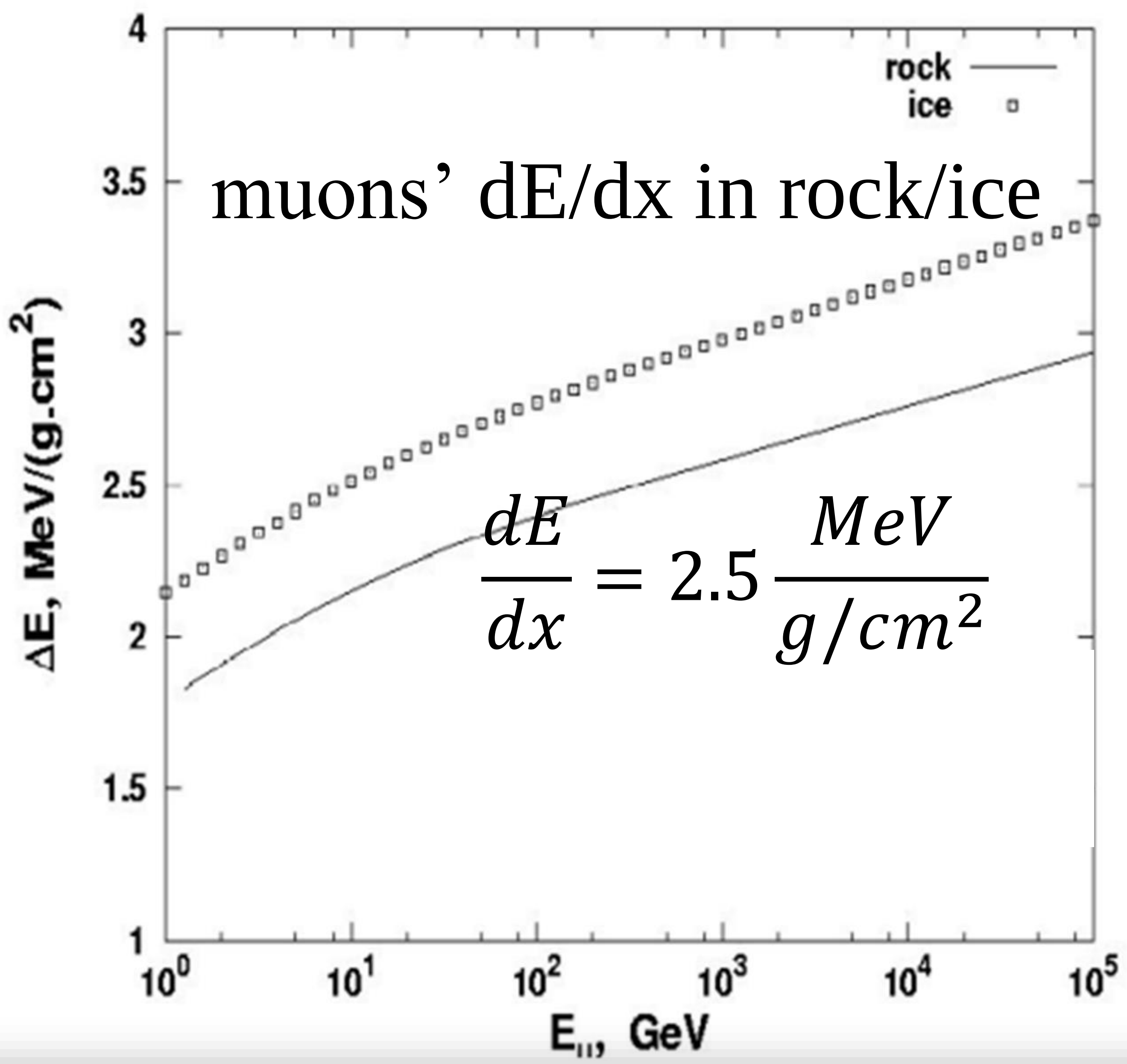
The flux upper limit versus the inverse charge value

Comparison between experiments

Underground Experiment

Energy loss when a particle passes through the 1000m depth rock

- for muon： ~ 663 GeV
- for 2/3e FCP： ~ 300 GeV



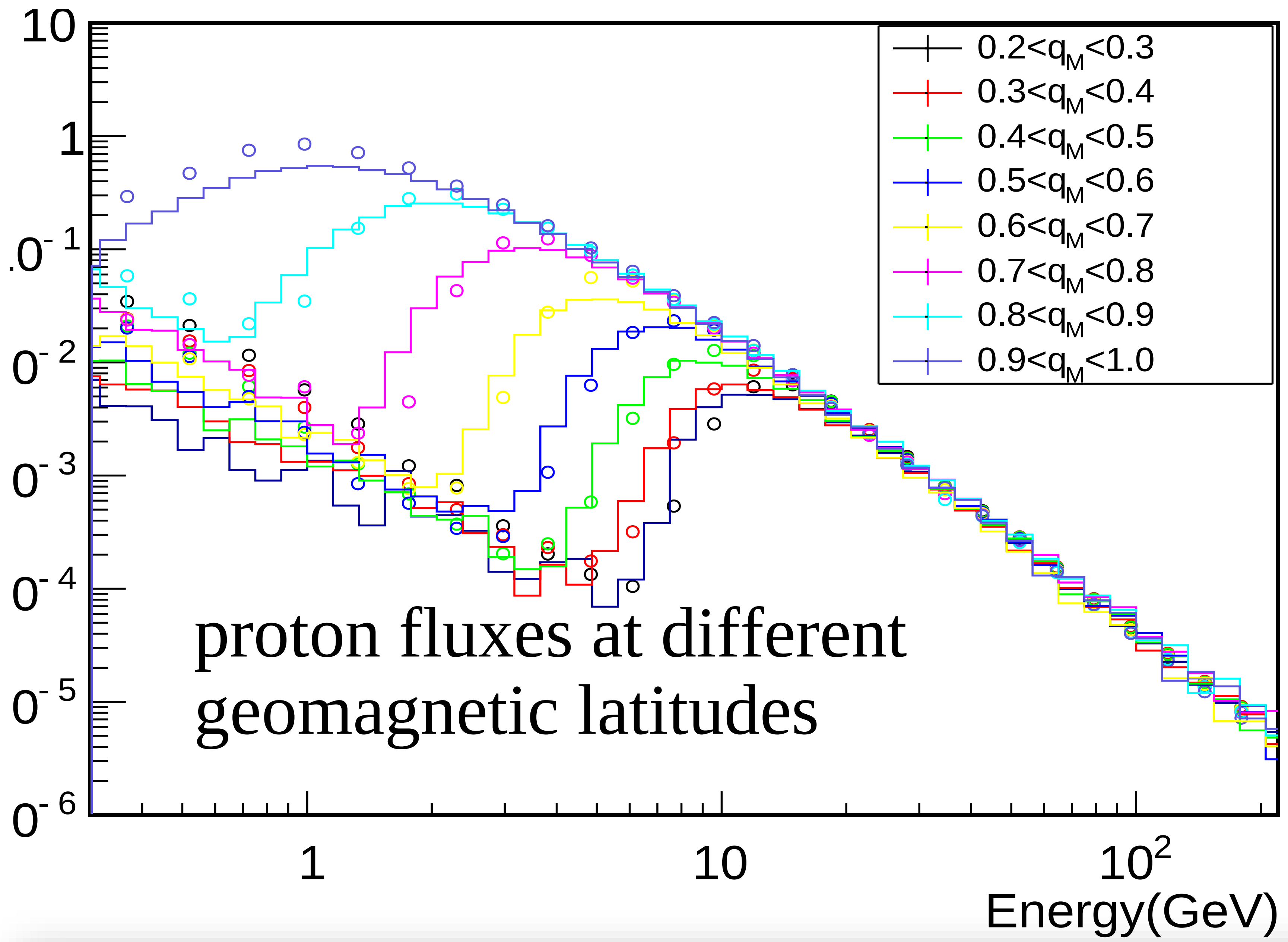
FCP should be with a high kinetic energy (> hundreds of GeV)

Space Experiment

A cutoff structure is caused by the earth's magnetic field

Near the equator, proton flux cutoff ~ 10 GeV

2/3e FCP flux cutoff: 6 ~ 7 GeV



FCP could be detected at a lower kinetic energy (tens of GeV)

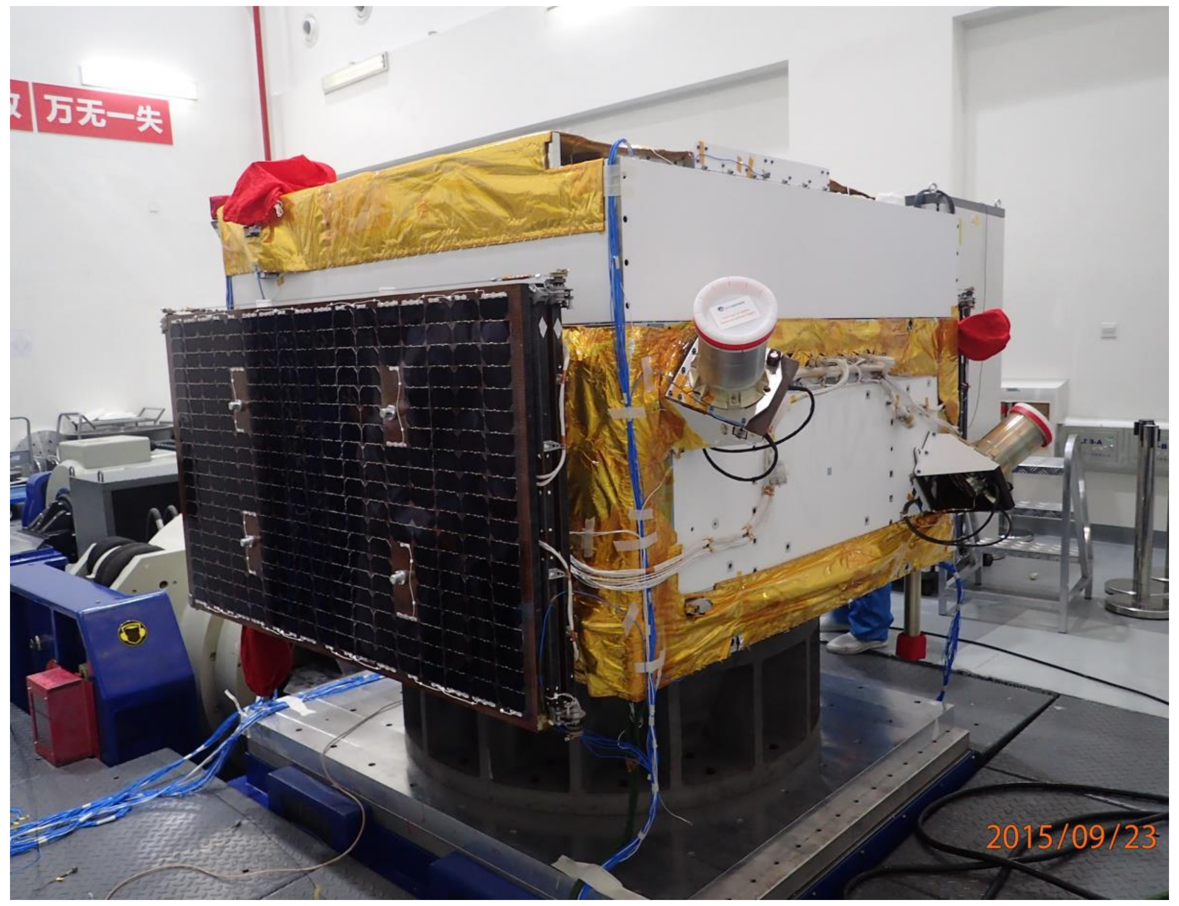
What can DAMPE do ?

- Advantages of DAMPE compared with other FCP experiments
  - Observe FCPs with significantly lower energy (a few GeV)
  - Relatively large acceptance
  - Long exposure time

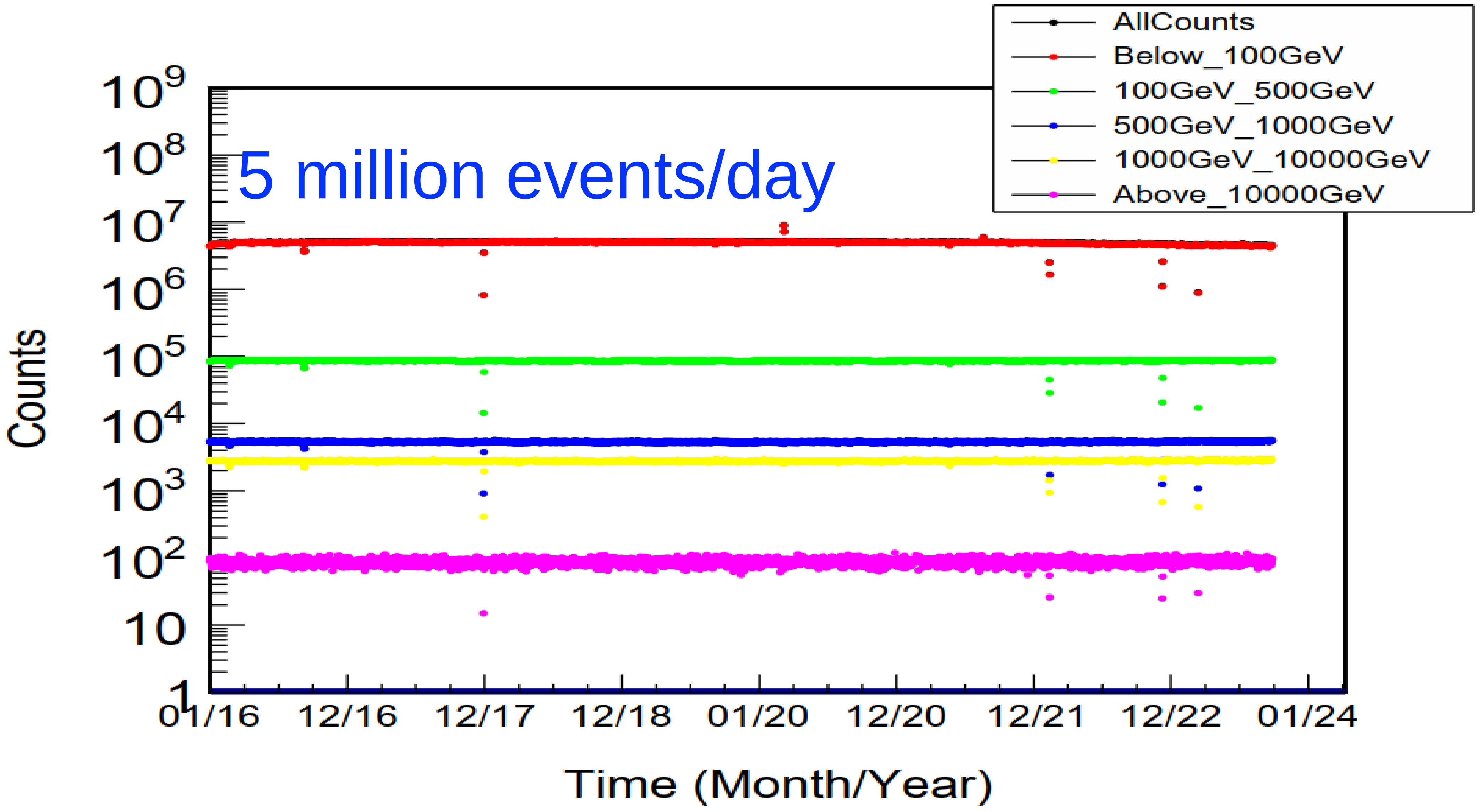
Experiment	Geometrical acceptance (cm^2Sr)	Exposure time (s)	Upper limit ($cm^{-2}Sr^{-1}s^{-1}$)
AMS01	3000	3.6×10^4	3.0×10^{-7} (95% C.L.)
BESS	1500	3.6×10^5	4.5×10^{-7} (90% C.L.)
DAMPE	3000	2.3×10^7	?

DArk Matter Explorer (DAMPE)

- DArk Matter Particle Explorer (DAMPE) is a space experiment for detecting high energy cosmic rays



- Orbit: sun-synchronous
- Altitude: 500 km
- Period: 94 minutes
- 5 million events/day
- 16 GB/day downlink

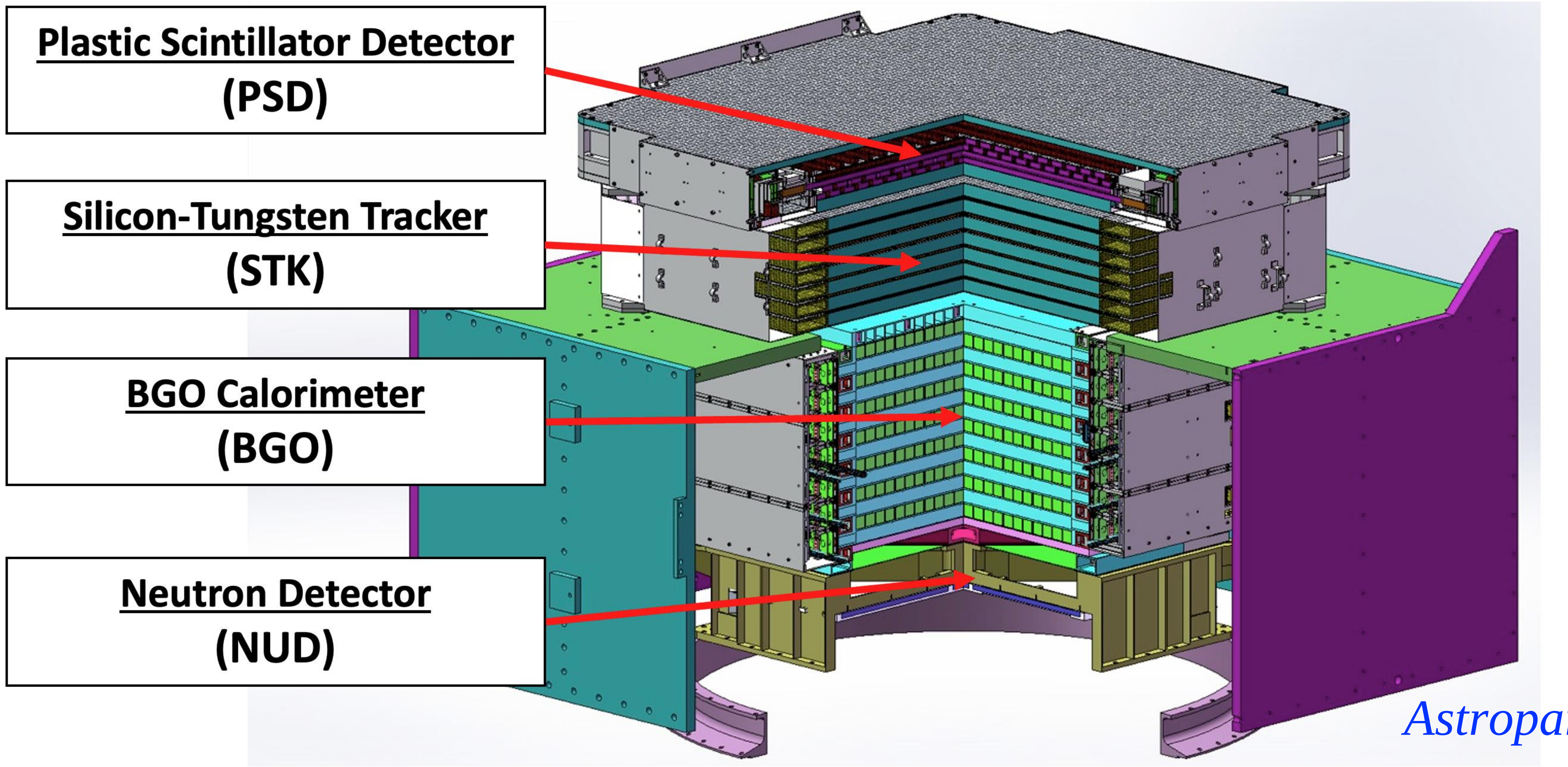


CNINA
- Purple Mountain Observatory, CAS
- University of Science and Technology of China
- Institute of High Energy Physics, CAS
- Institute of Modern Physics, CAS
- National Space Science Center, CAS

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

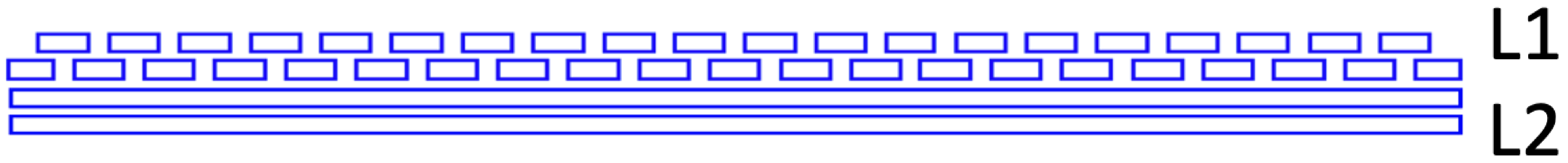
DArk Matter Explorer (DAMPE)

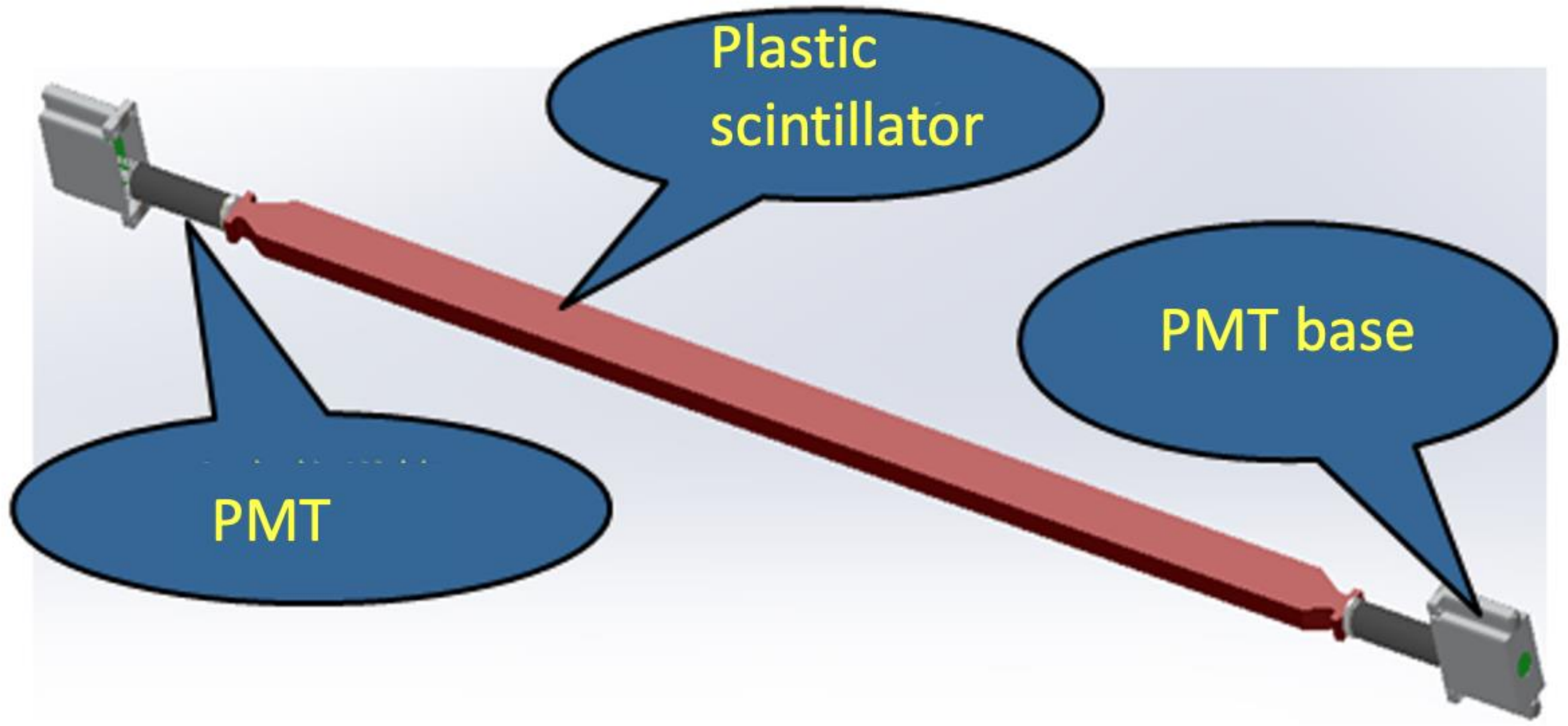


Astropart. Phys. 95 (2017) 6–24

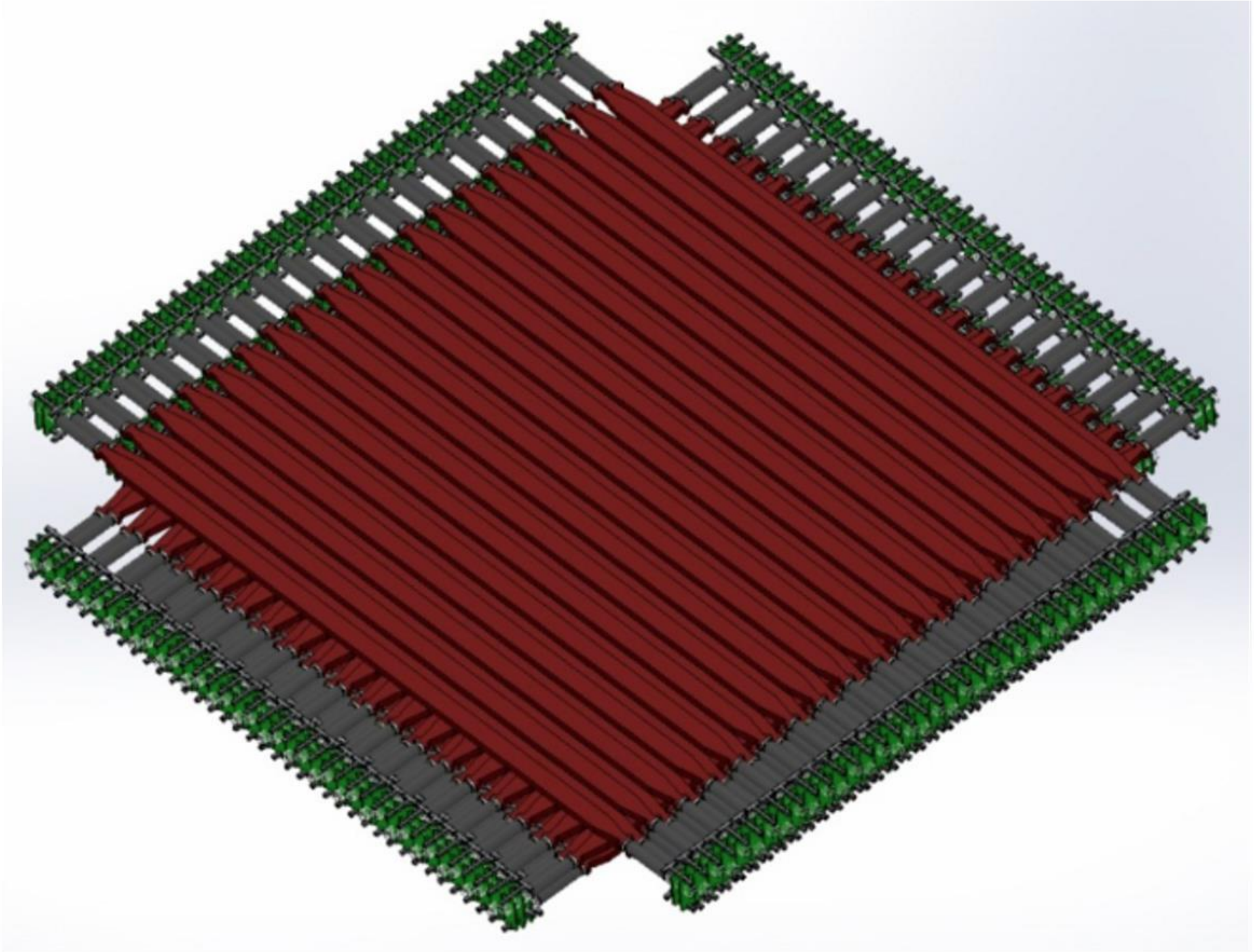
- Charge measurement (dE/dx in PSD, STK)
- Gamma-ray converting and tracking (STK + BGO)
- Precise energy measurement (BGO)
- Hadron rejection (BGO + NUD)

Plastic Scintillator Detector (PSD)



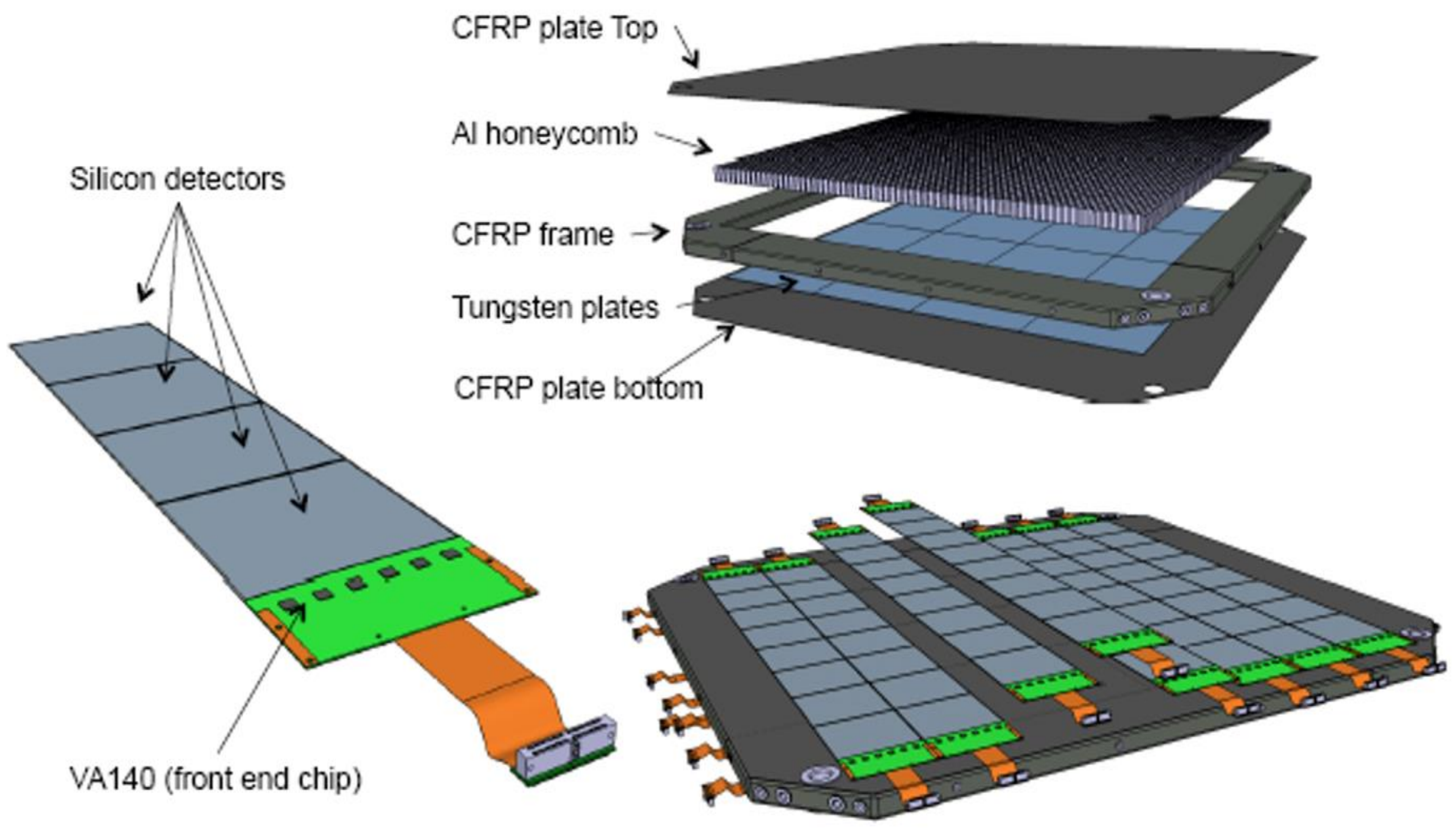


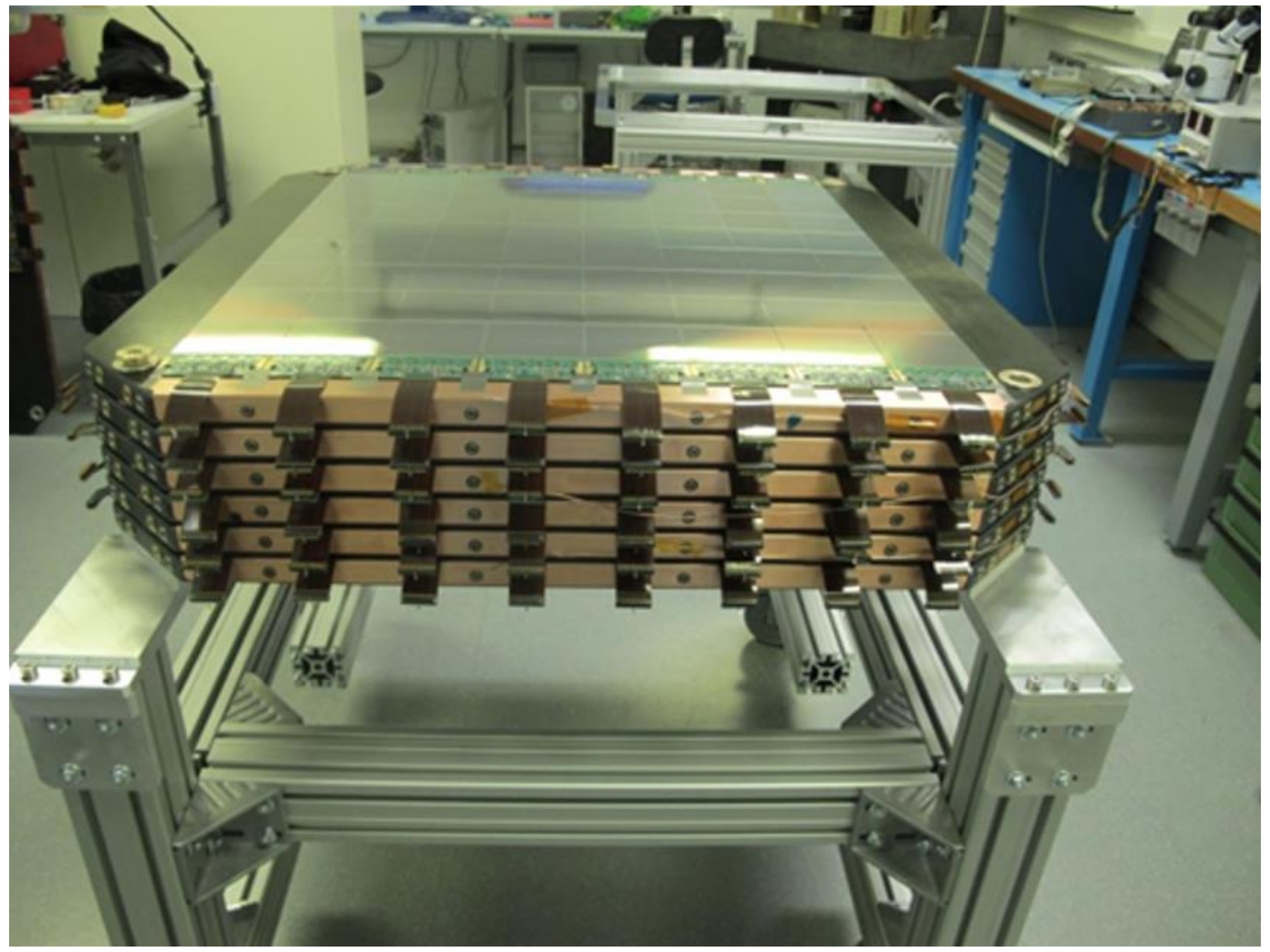
- PSD is located on the top of the payload
  - Active area: 82 cm × 82 cm
  - Number of planes: 2
  - 41 strips each layer
  - Overall efficiency ≥0.9975 for charged particles

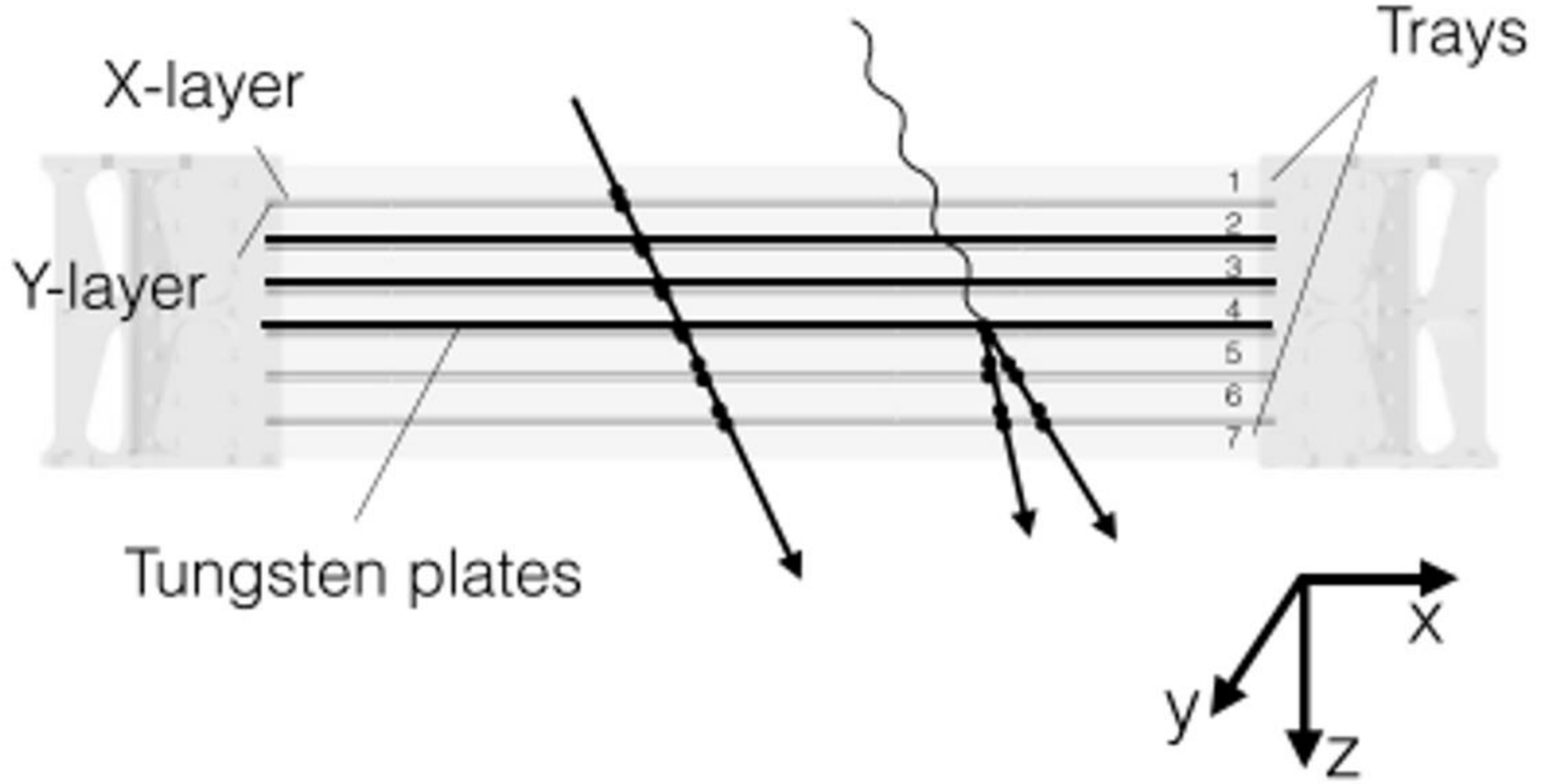


Silicon Tungsten tracKet (STK)

- Structure of STK
  - Pitch of silicon micro-strip: 121 μm
  - Active area: 75.8 × 75.8 cm^2
  - 6 Planes （6X + 6Y）
  - Three 1 mm thickness tungsten layers embed in the STK



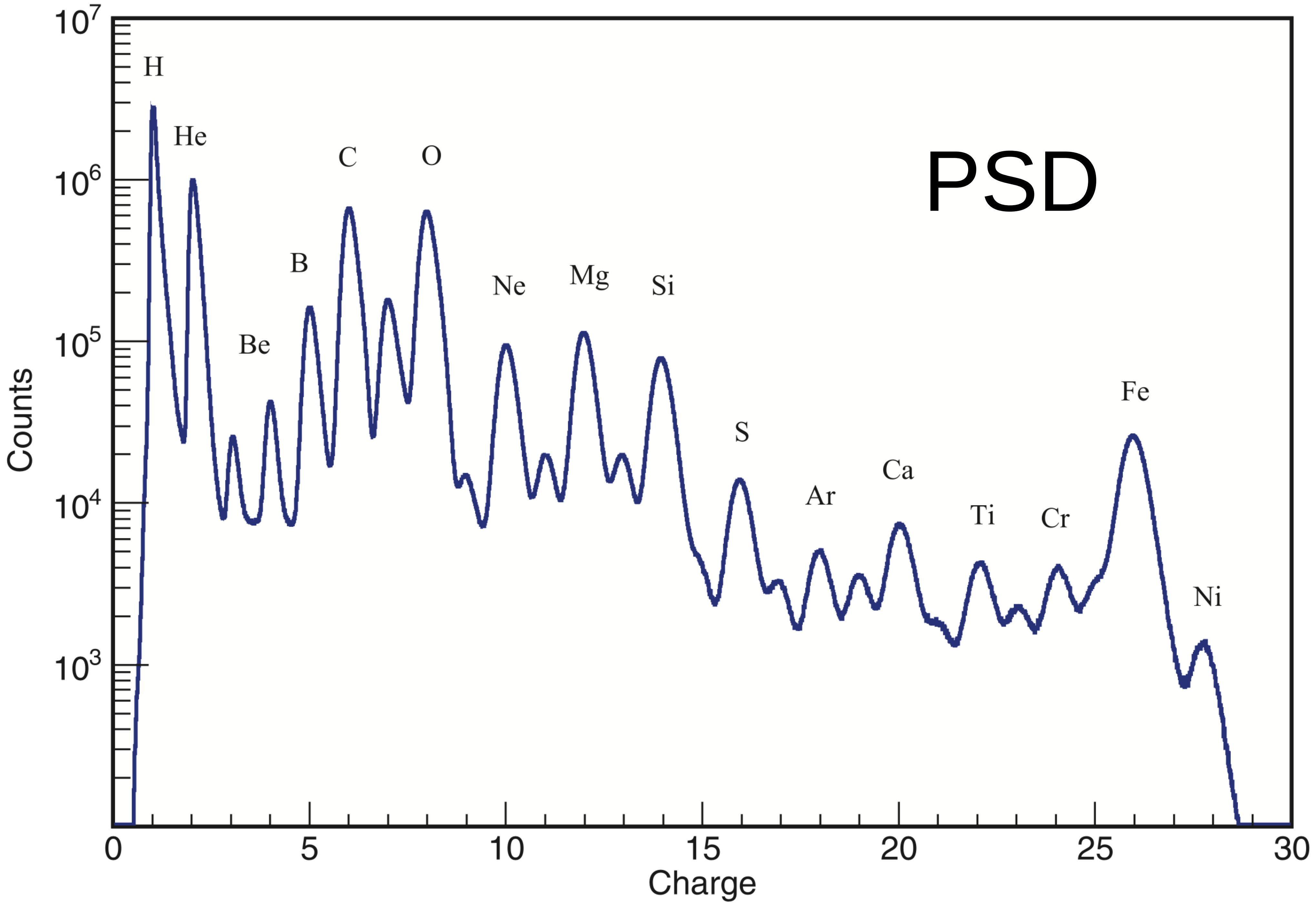


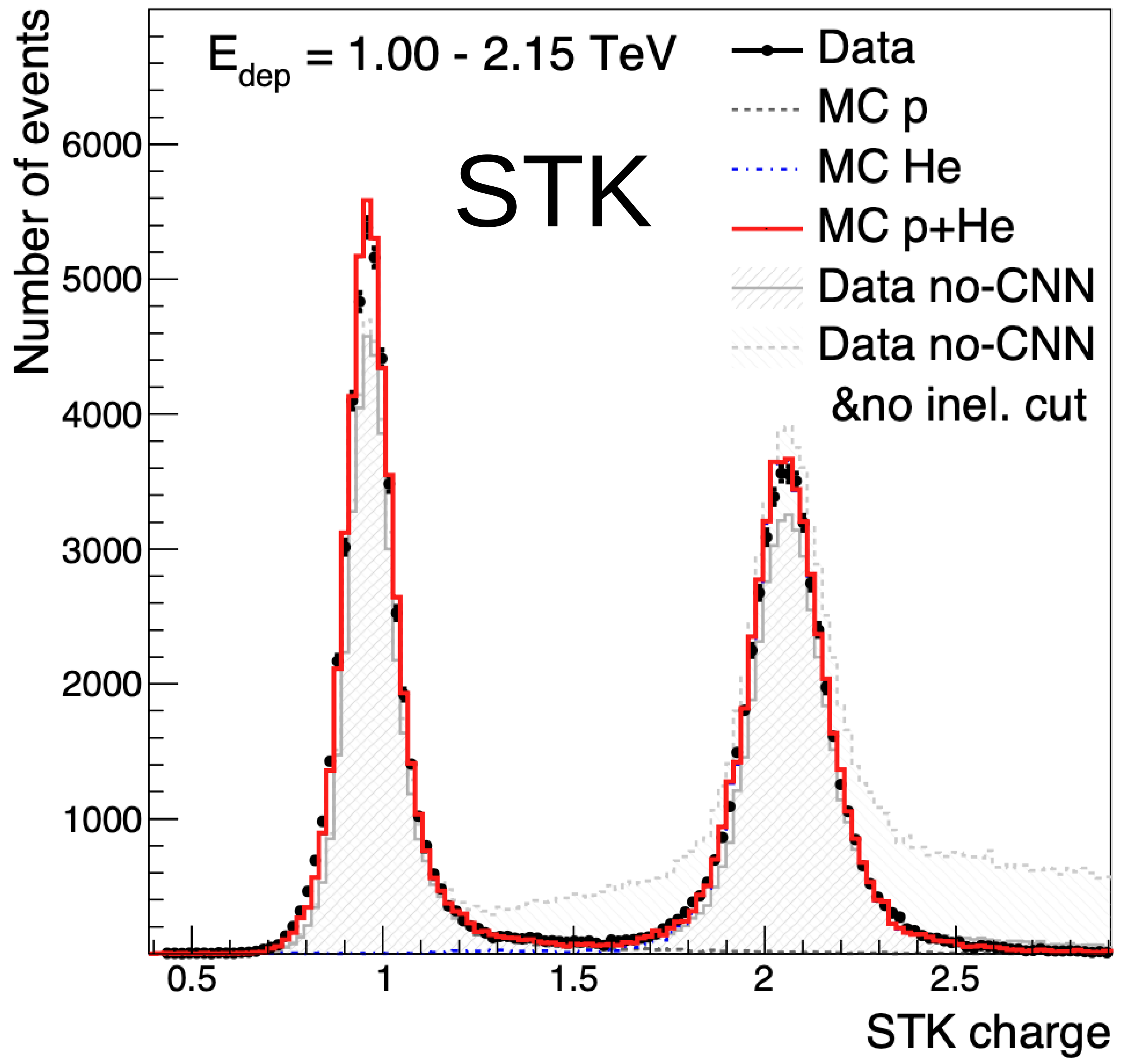


Charge Measurement

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

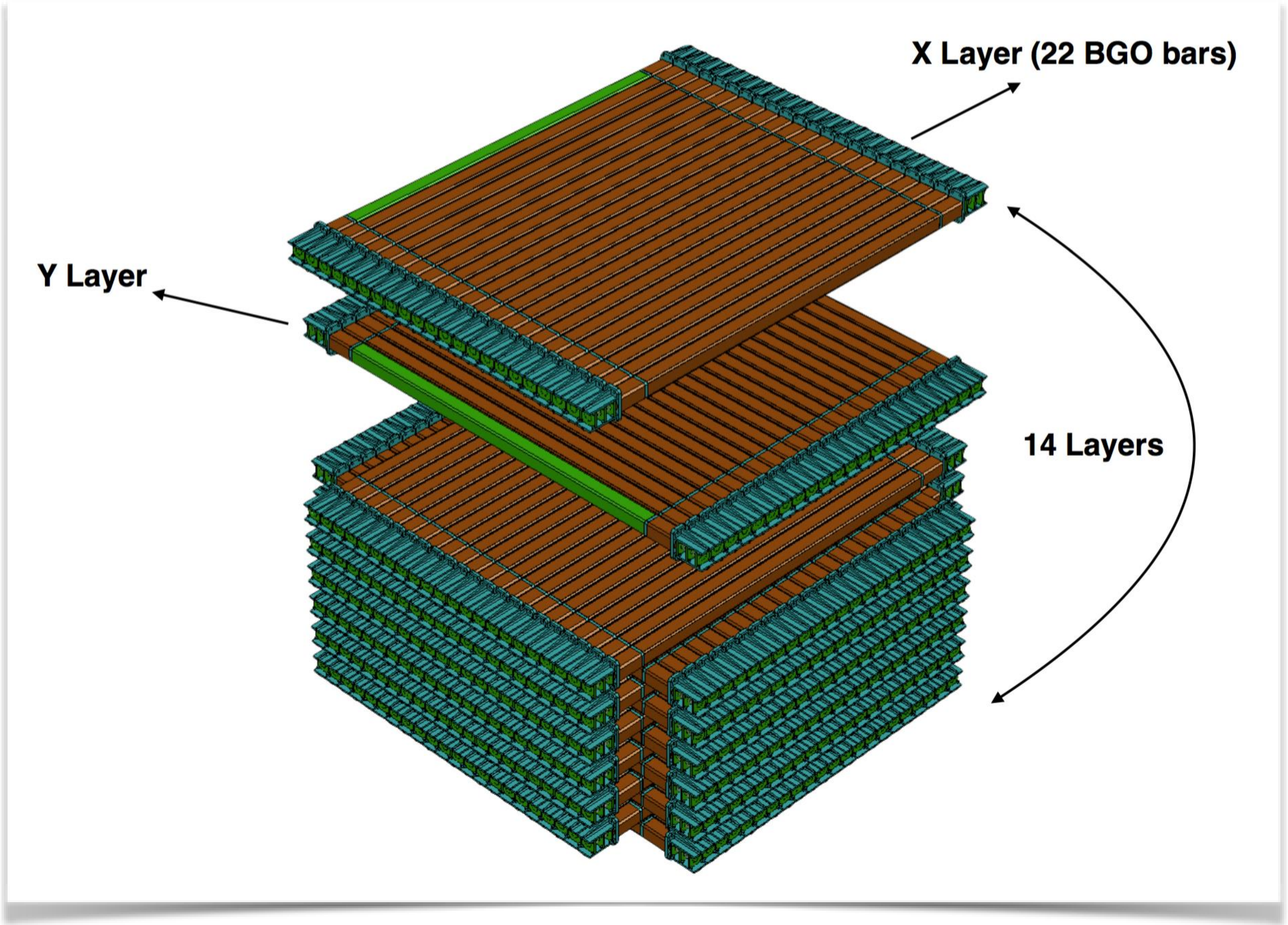
	PSD Charge resolution (Charge unit, c.u.)	STK Charge resolution (Charge unit, c.u.)
Proton	0.06	0.04
Helium	0.10	0.07

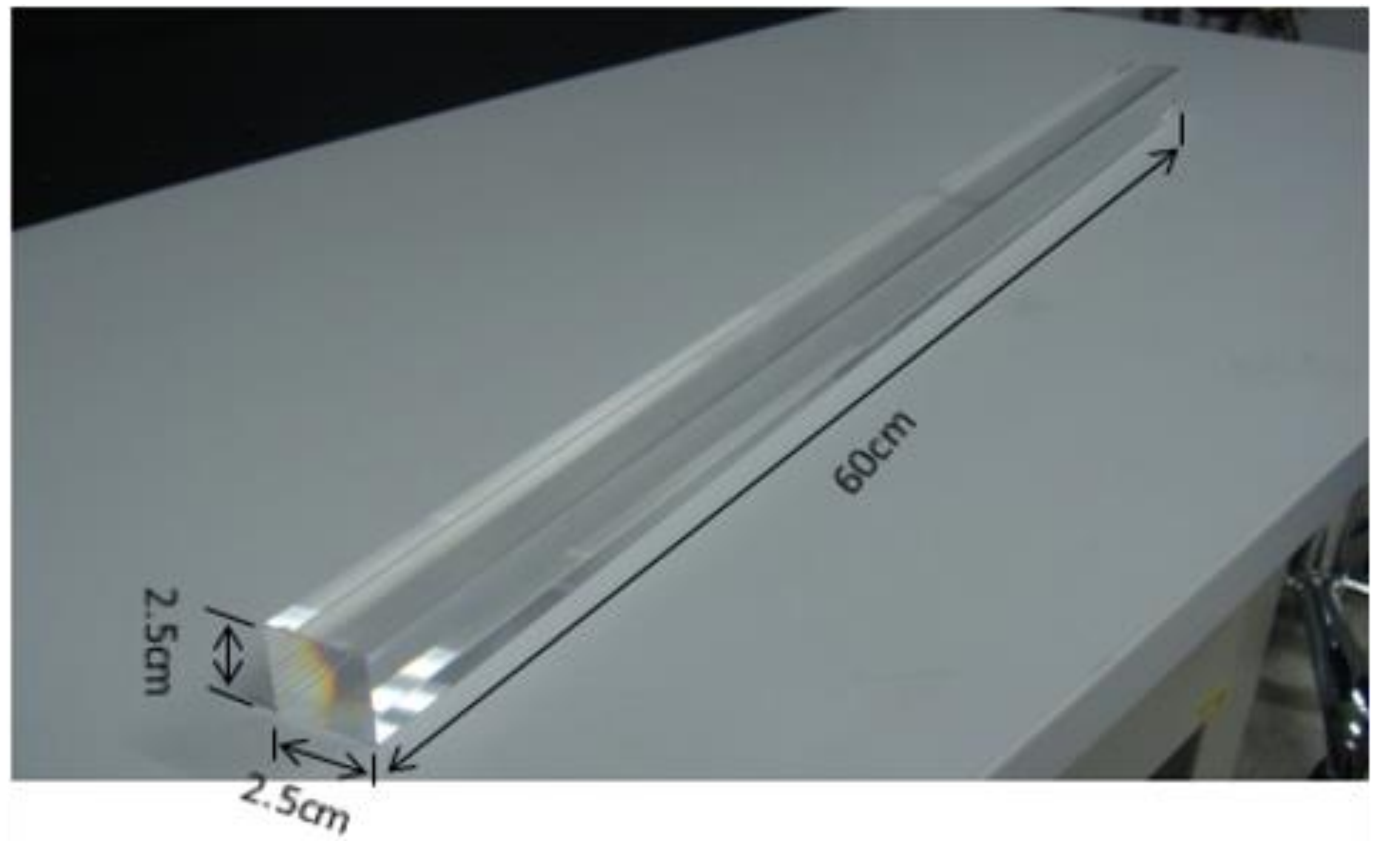


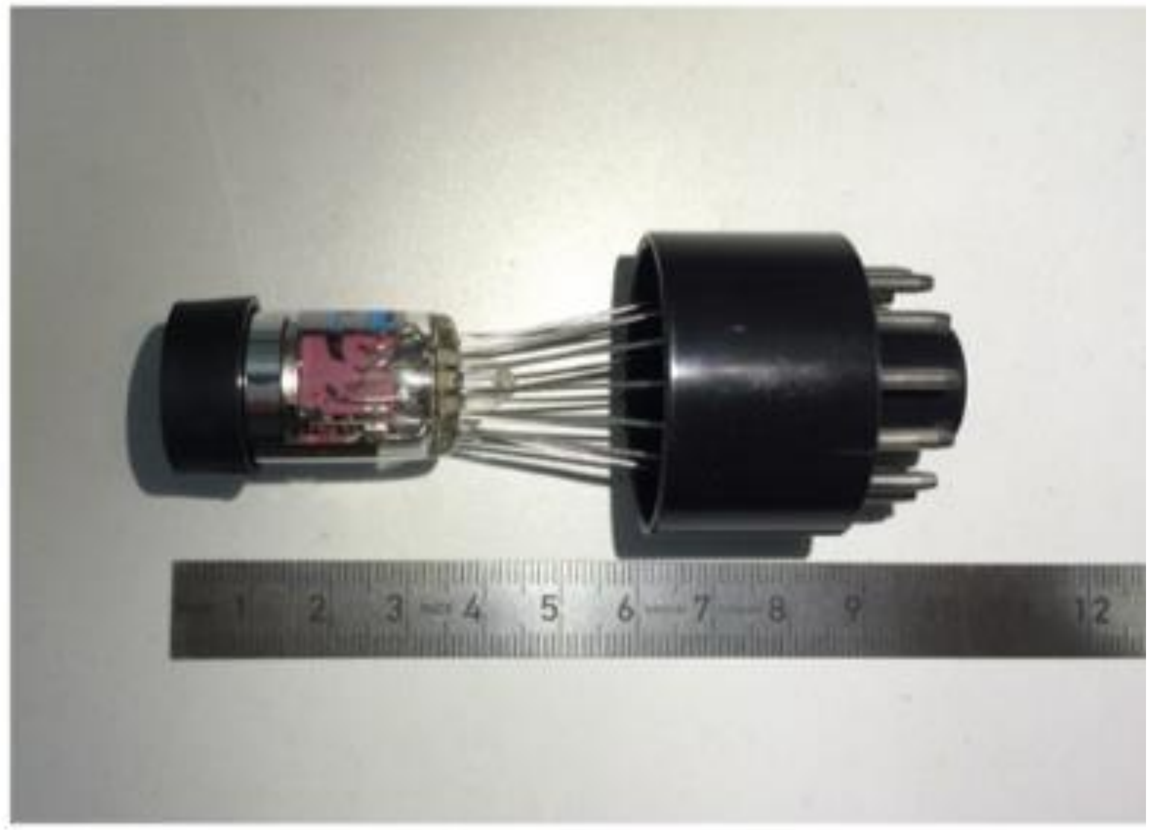


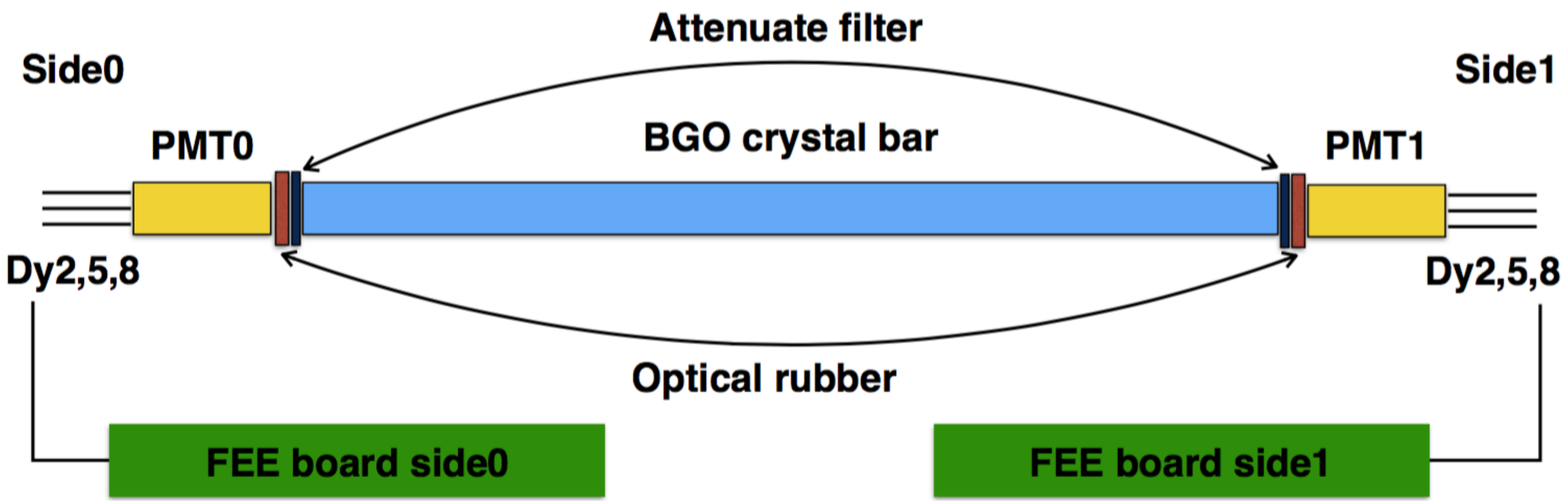
BGO calorimeter

- 14 × 22 BGO crystal array
  - Dimension of a BGO bar： $2.5\times2.5\times60cm^3$
  - Layers are alternated in an orthogonal way
- Thickness： $32X_0, 1.6\lambda_I$
- Each end of BGO bar is coupled to a PMT



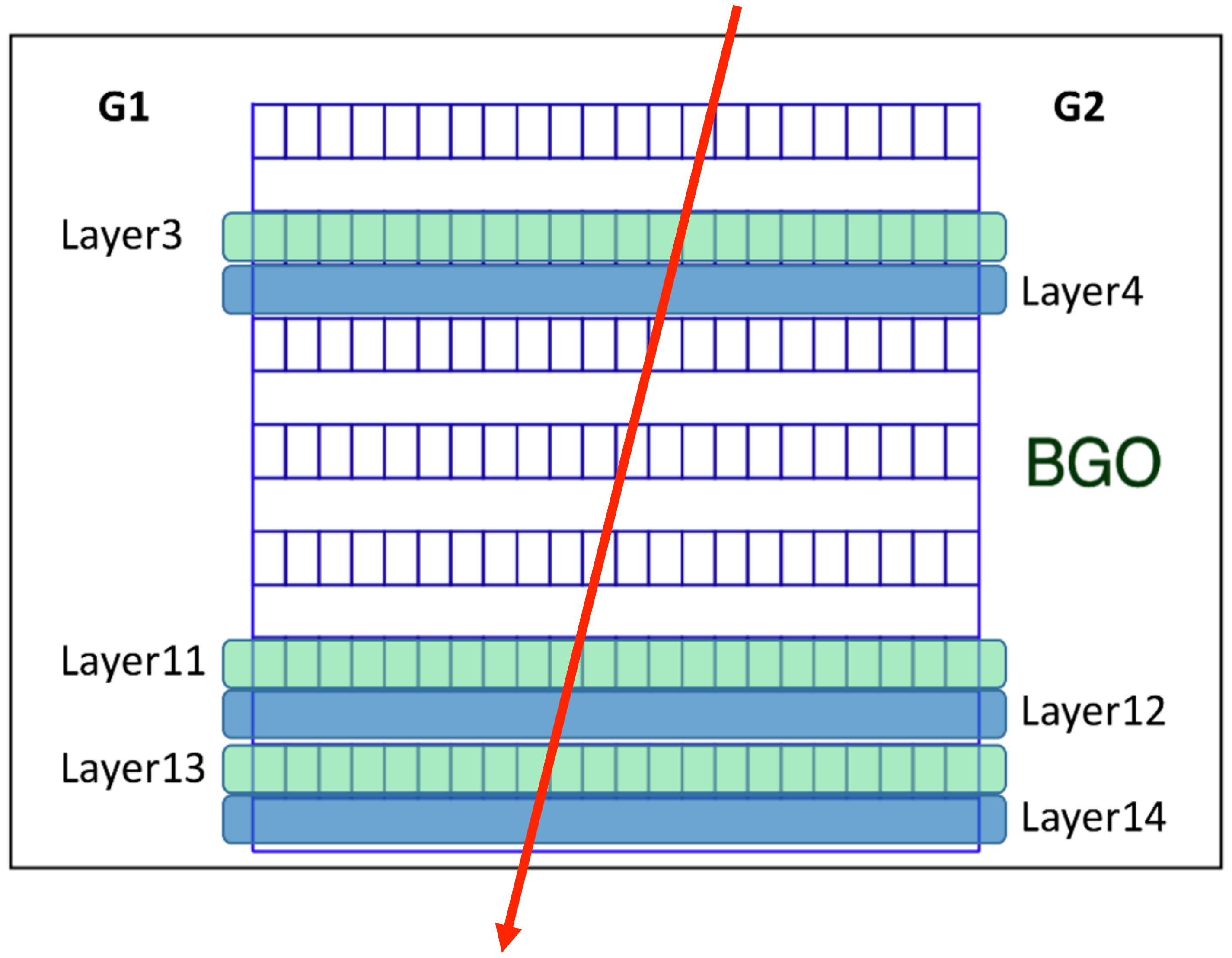






Assuming the nature of FCP

- Assuming the nature of FCP：
  - Massive
  - With electromagnetic interaction
  - W/O hadronic interaction
  - The charge would be 1/3e or 2/3e
  - like a massive lepton (e.g. muon)

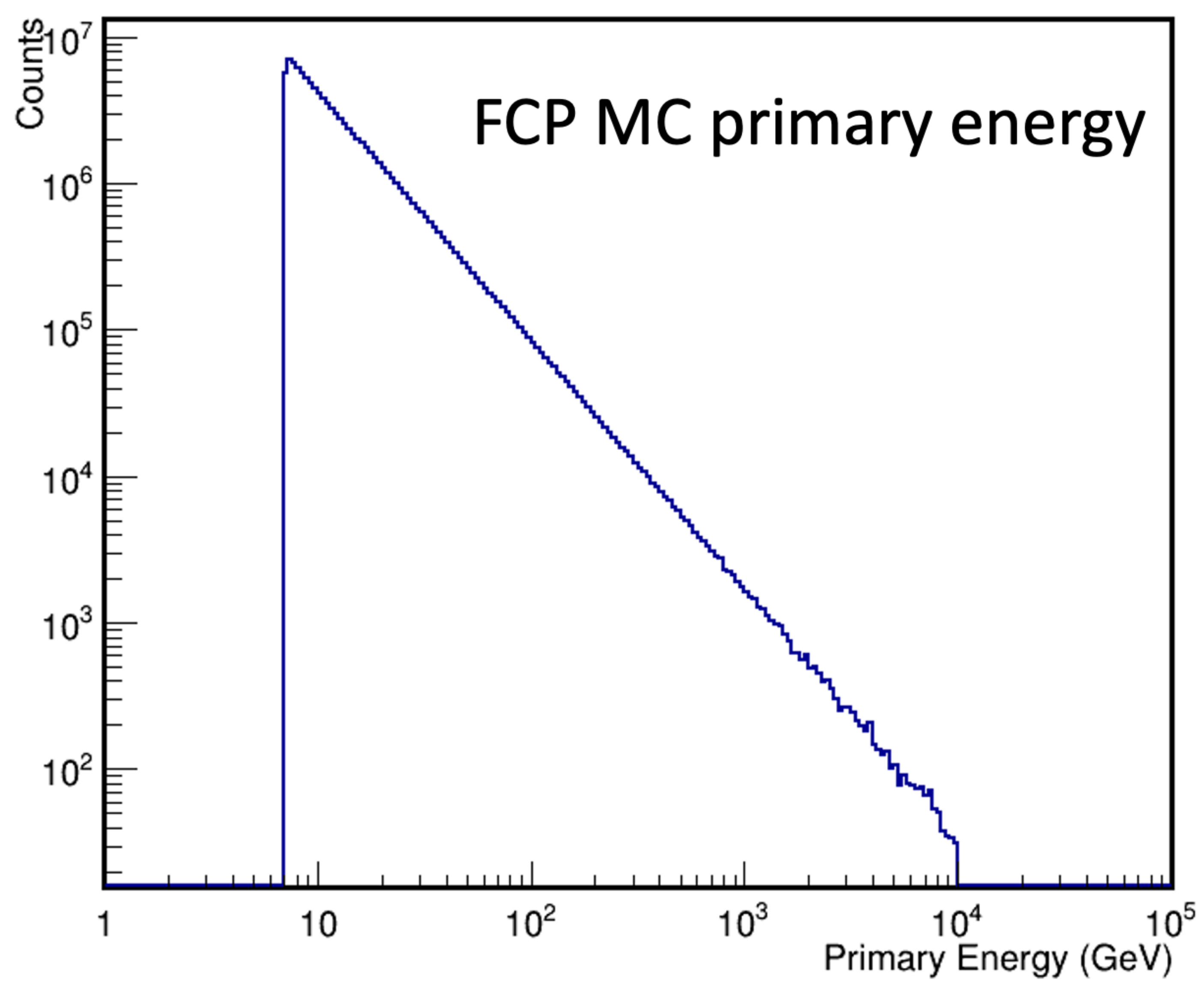


- DAMPE MIPs trigger
- Trigger threshold: 0.2 proton MIP
- Ionization energy loss for 1/3 e FCP ≈ 1/9 MIP，Not Pass Trigger
- Ionization energy loss for 2/3e FCP ≈ 4/9 MIP，Pass Trigger

Our target

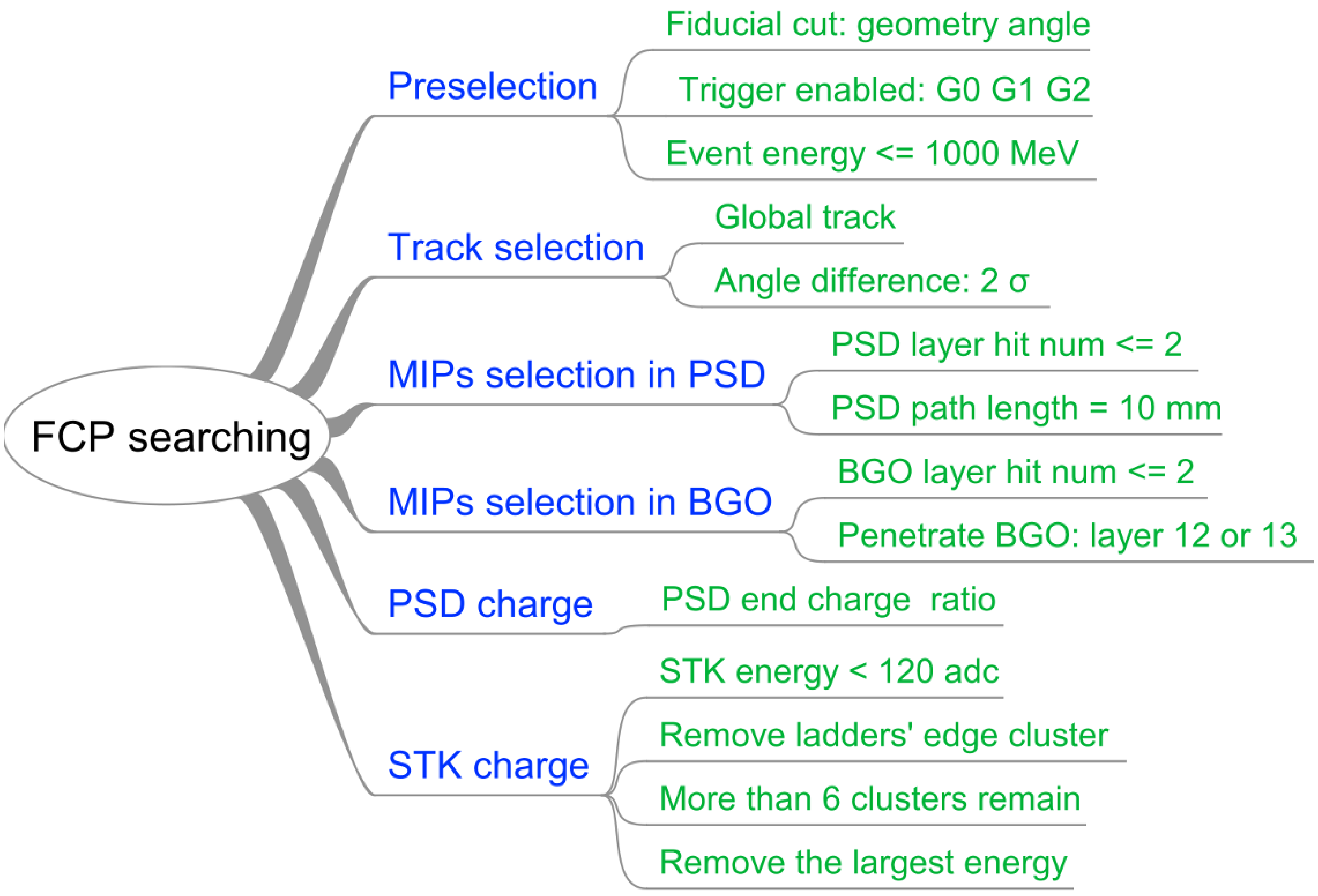
Data Sample

- Flight data： 2016.01.01 ~ 2020.12.30
- Simulation：
  - proton 10 GeV ~ 100 TeV
  - FCP 7 GeV ~ 10 TeV



- FCP simulation
  - Created a virtual particle in Geant4
  - Charge with 2/3 e
  - Add ionization and multi scattering process
  - Energy spectrum obey the $E^{-2.7}$
  - Spheric particle source

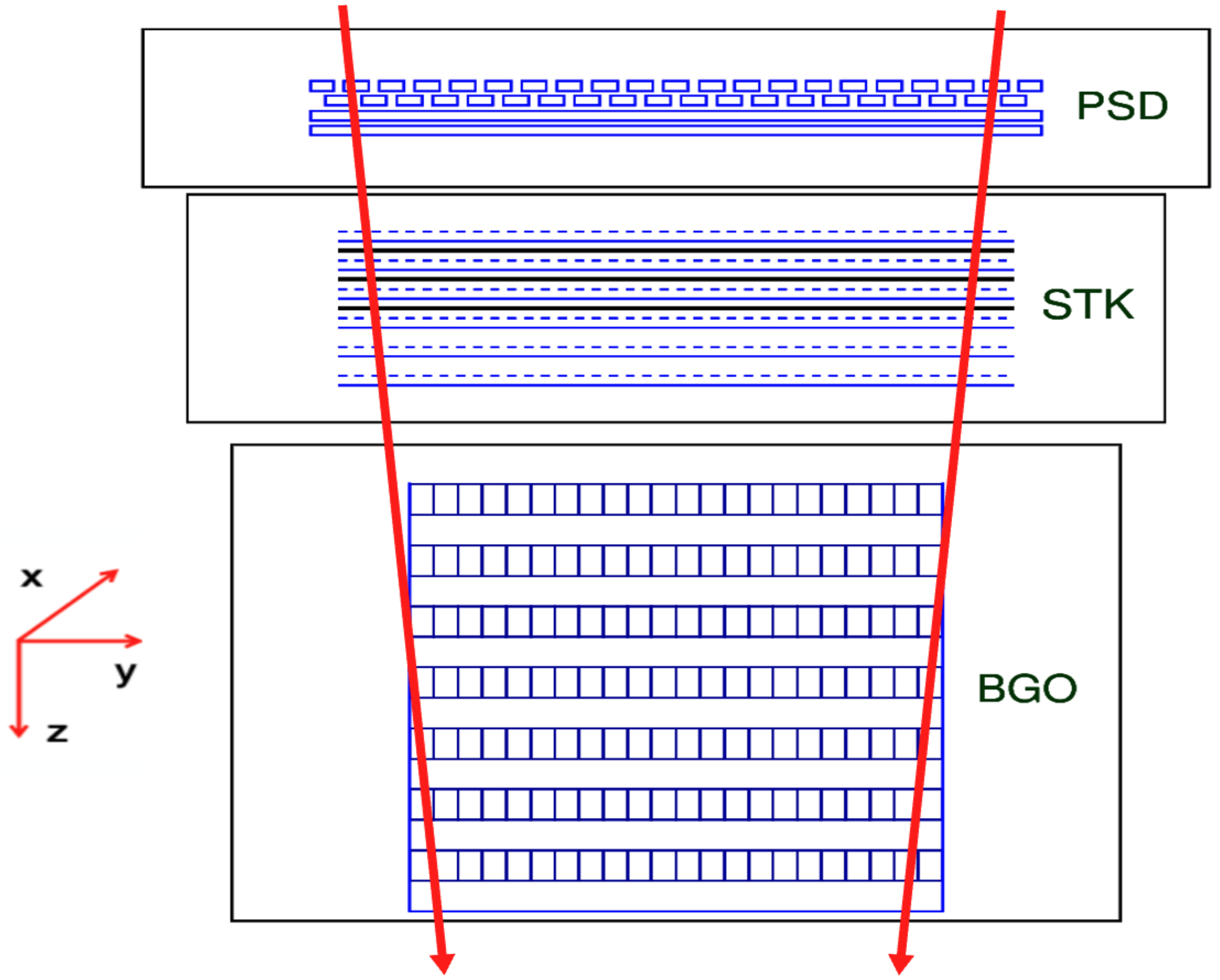
Selections

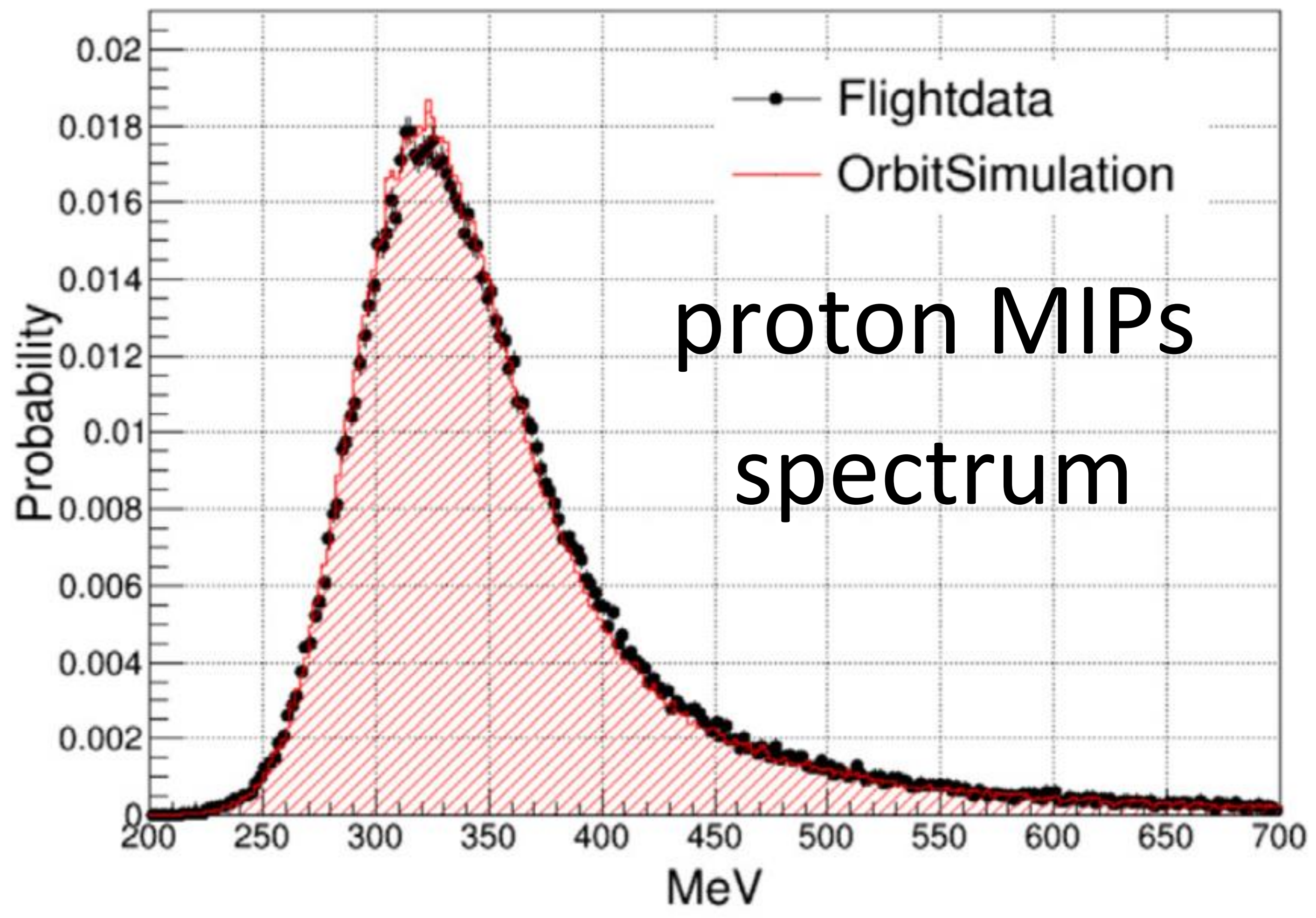


FCP searching
Preselection
Fiducial cut: geometry angle
Trigger enabled: G0 G1 G2
Event energy <= 1000 MeV
Track selection
Global track
Angle difference: 2 σ
MIPs selection in PSD
PSD layer hit num <= 2
PSD path length = 10 mm
MIPs selection in BGO
BGO layer hit num <= 2
Penetrate BGO: layer 12 or 13
PSD charge
PSD end charge ratio
STK charge
STK energy < 120 adc
Remove ladders' edge cluster
More than 6 clusters remain
Remove the largest energy

Pre-Selection

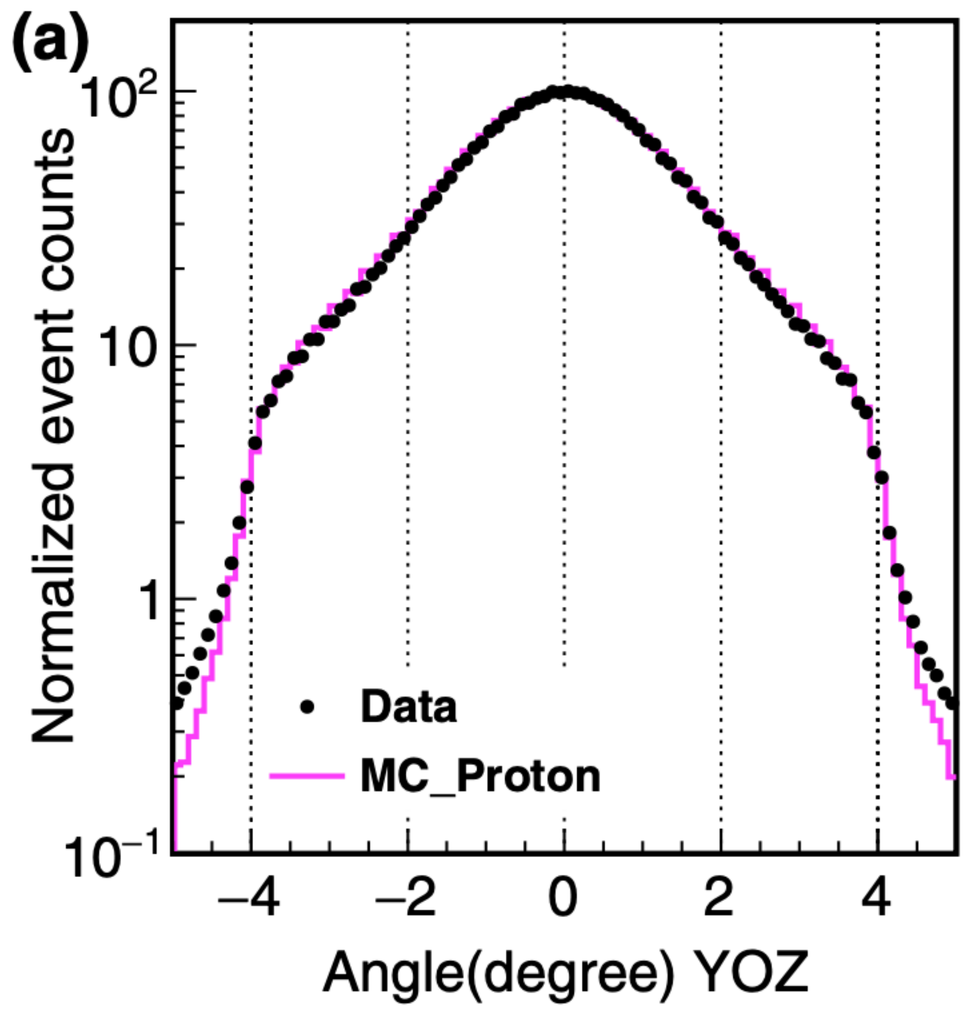
- Pass MIPs trigger
- Fiducial selection: Constrain the positions of injection and ejection to maintain the event in the whole detector
- Total energy selection:
  - Energy deposition in ECAL < 1 GeV
  - Reject particles with charges higher than proton



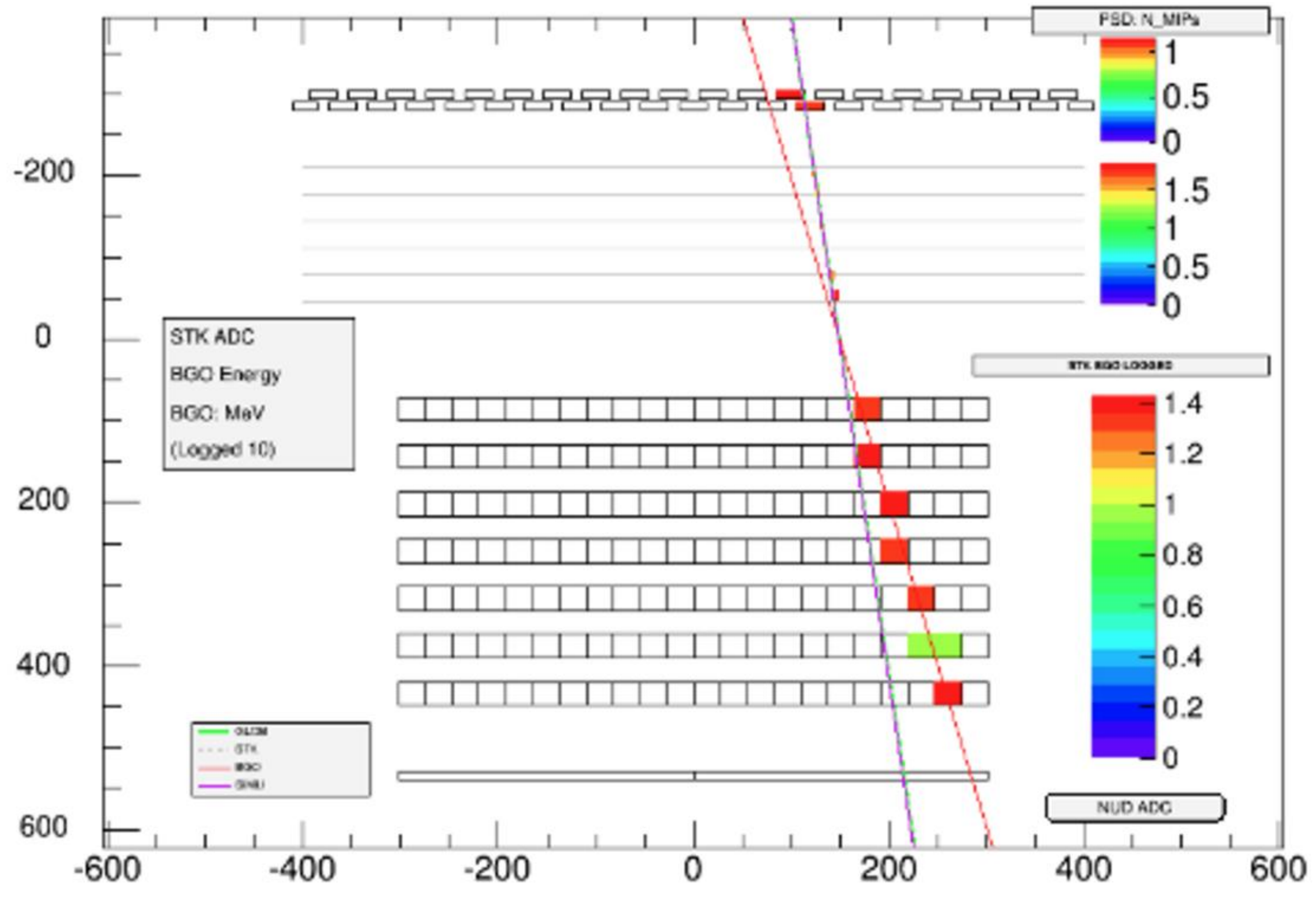


Track Selection

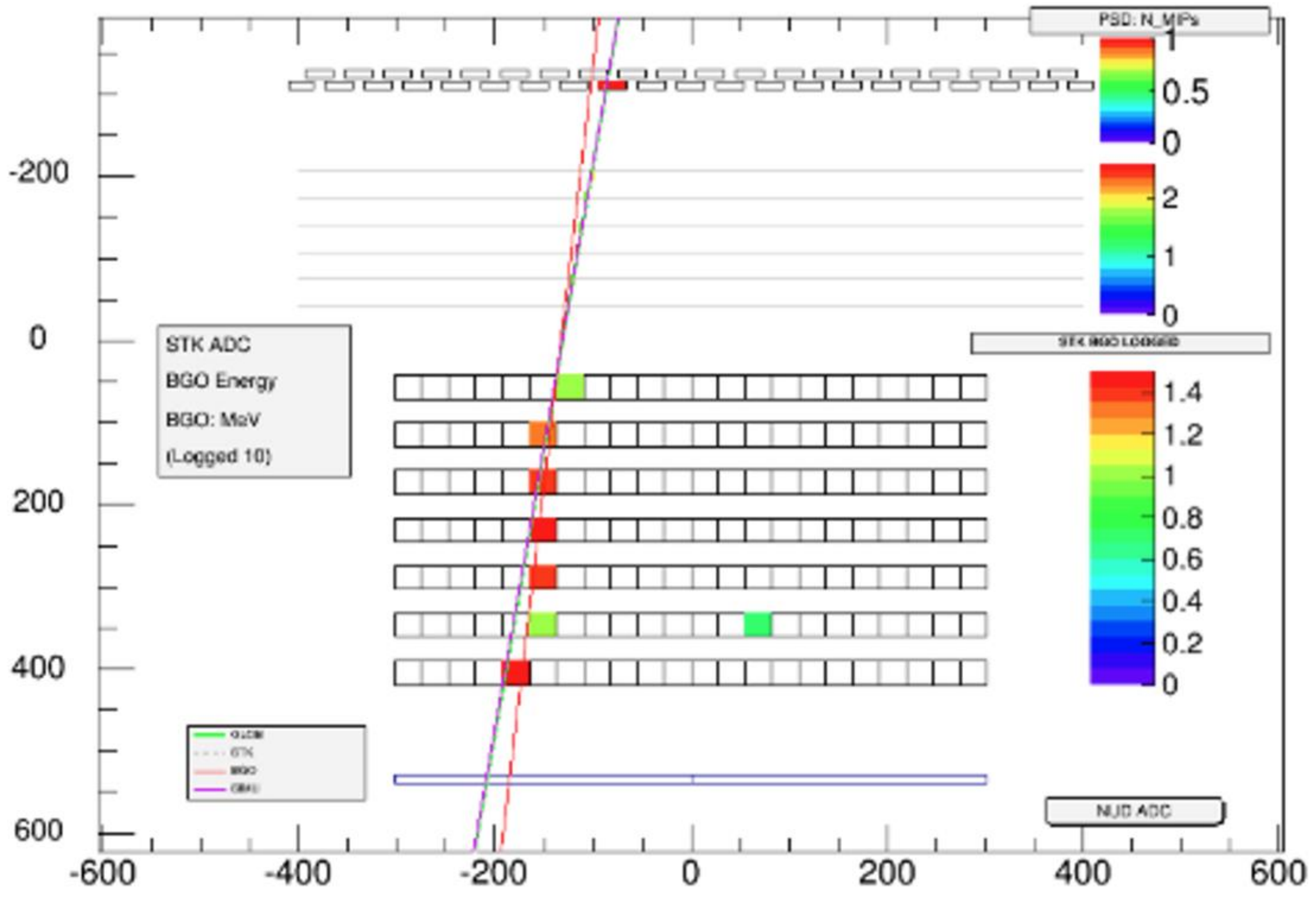
- Select STK tracks with good qualities
- Constrain the angle difference between STK Track and BGO Track
  - Angle difference < 4°
  - Reject the scattering events

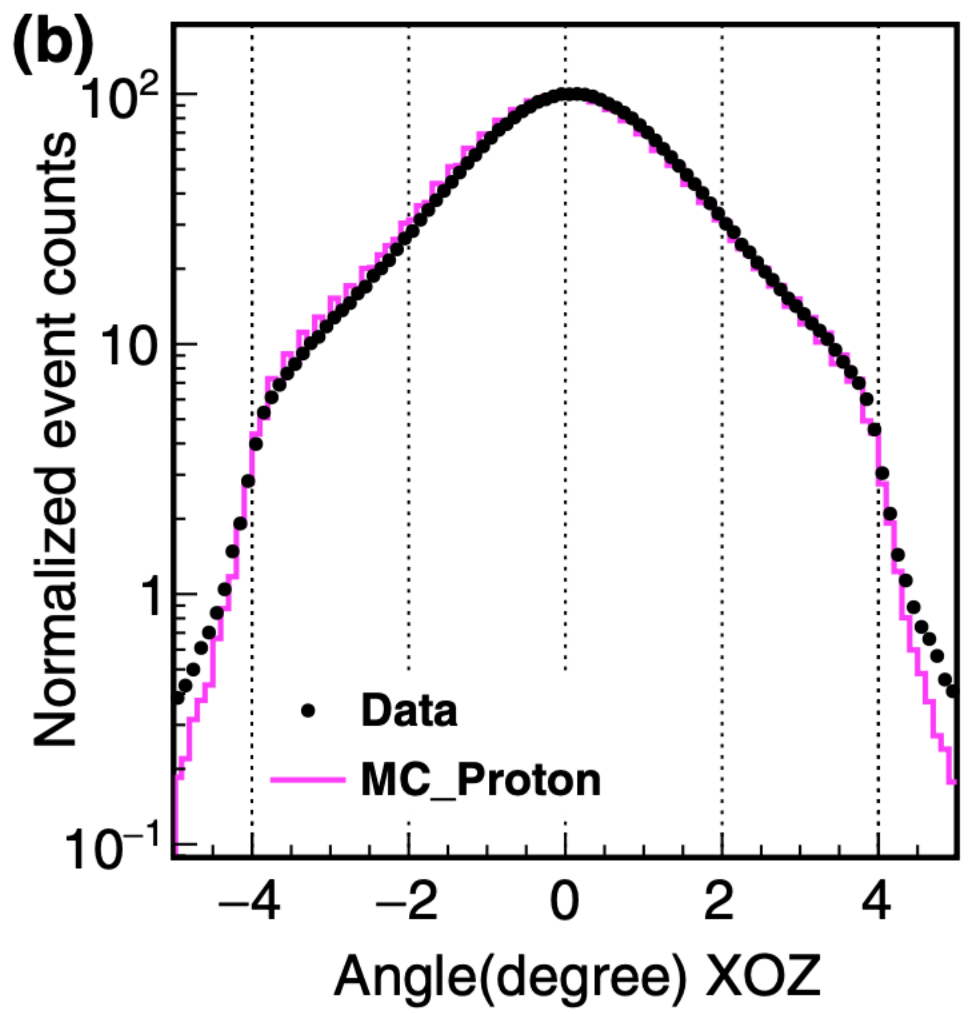


XOZ (Reversed Z)



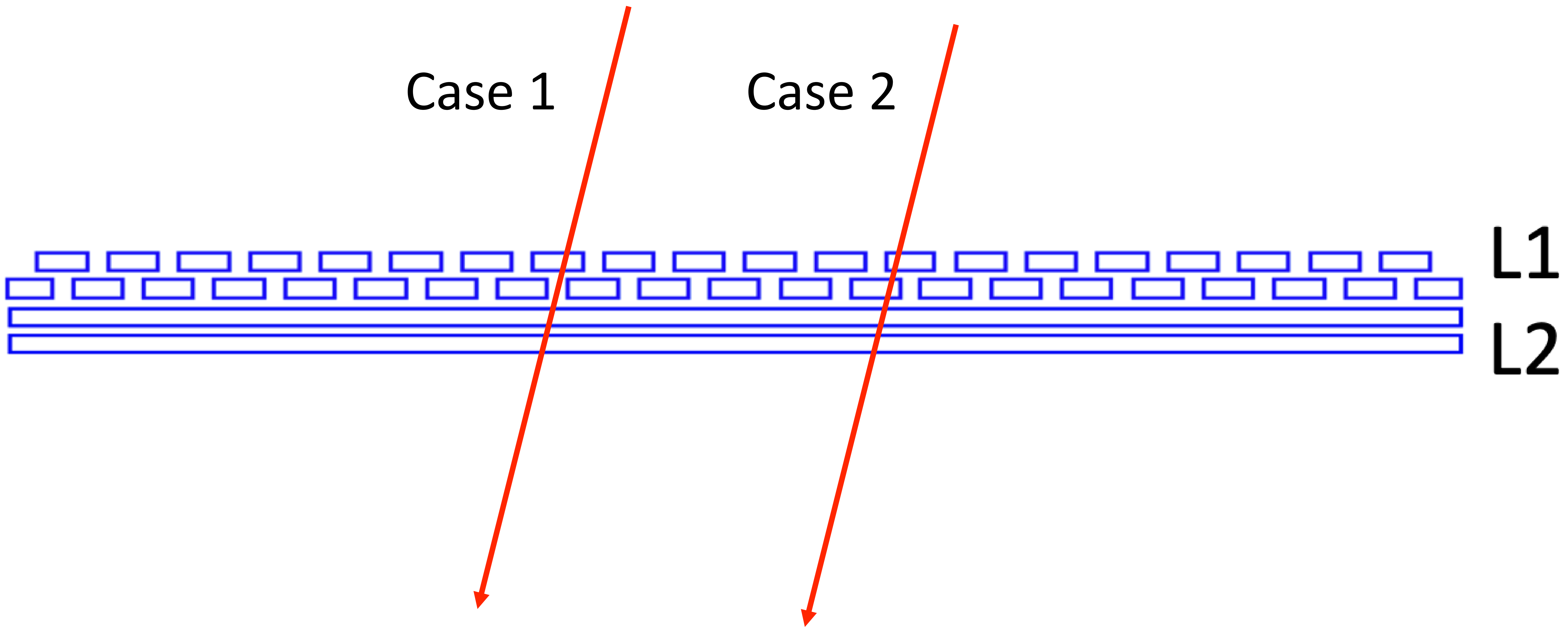
YOZ (Reversed Z)





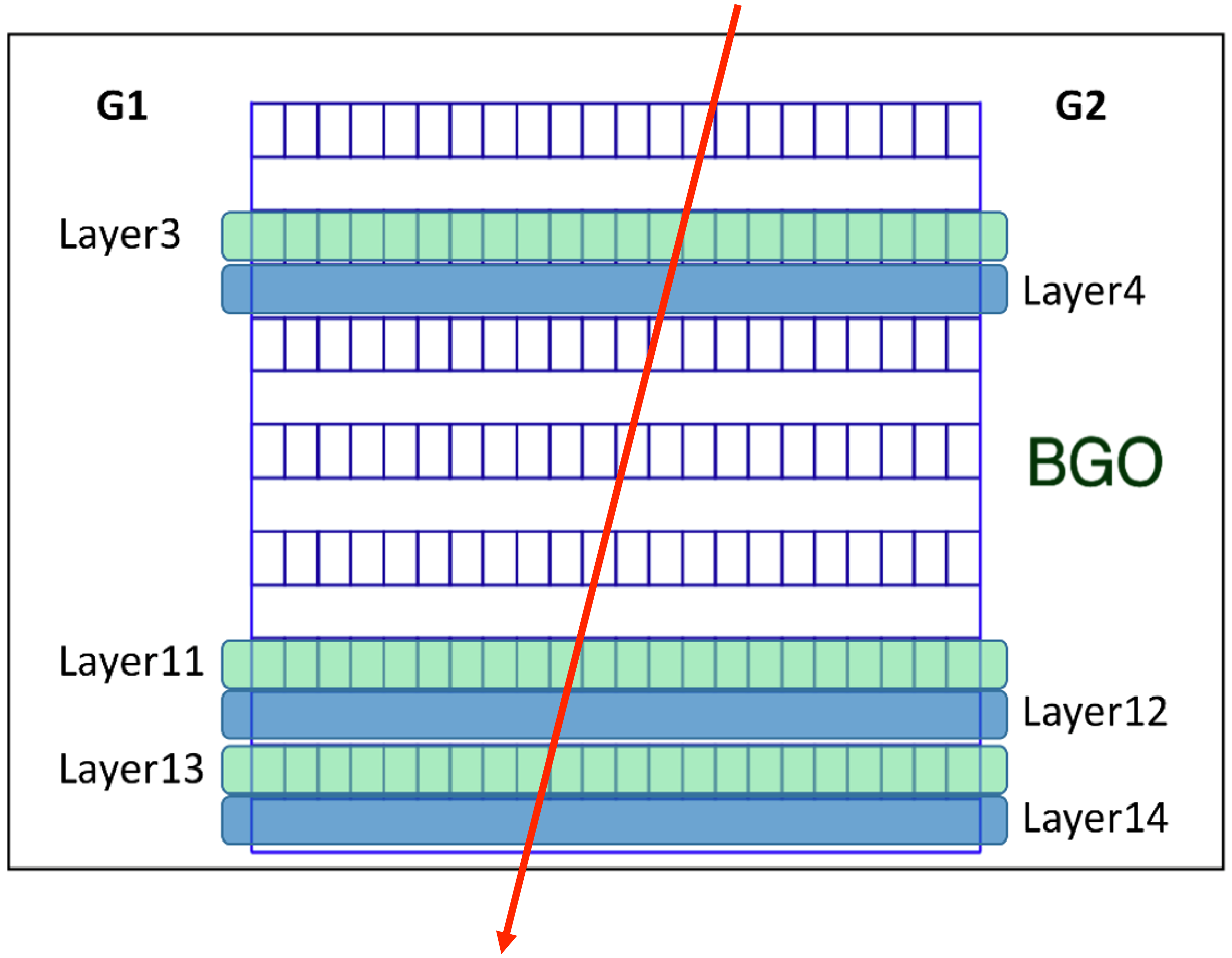
MIP-like Event Selection

- MIPs in PSD:
  - The number of fired strip in one layer ≤ 2
  - The selected track should cross the strip with maximum energy

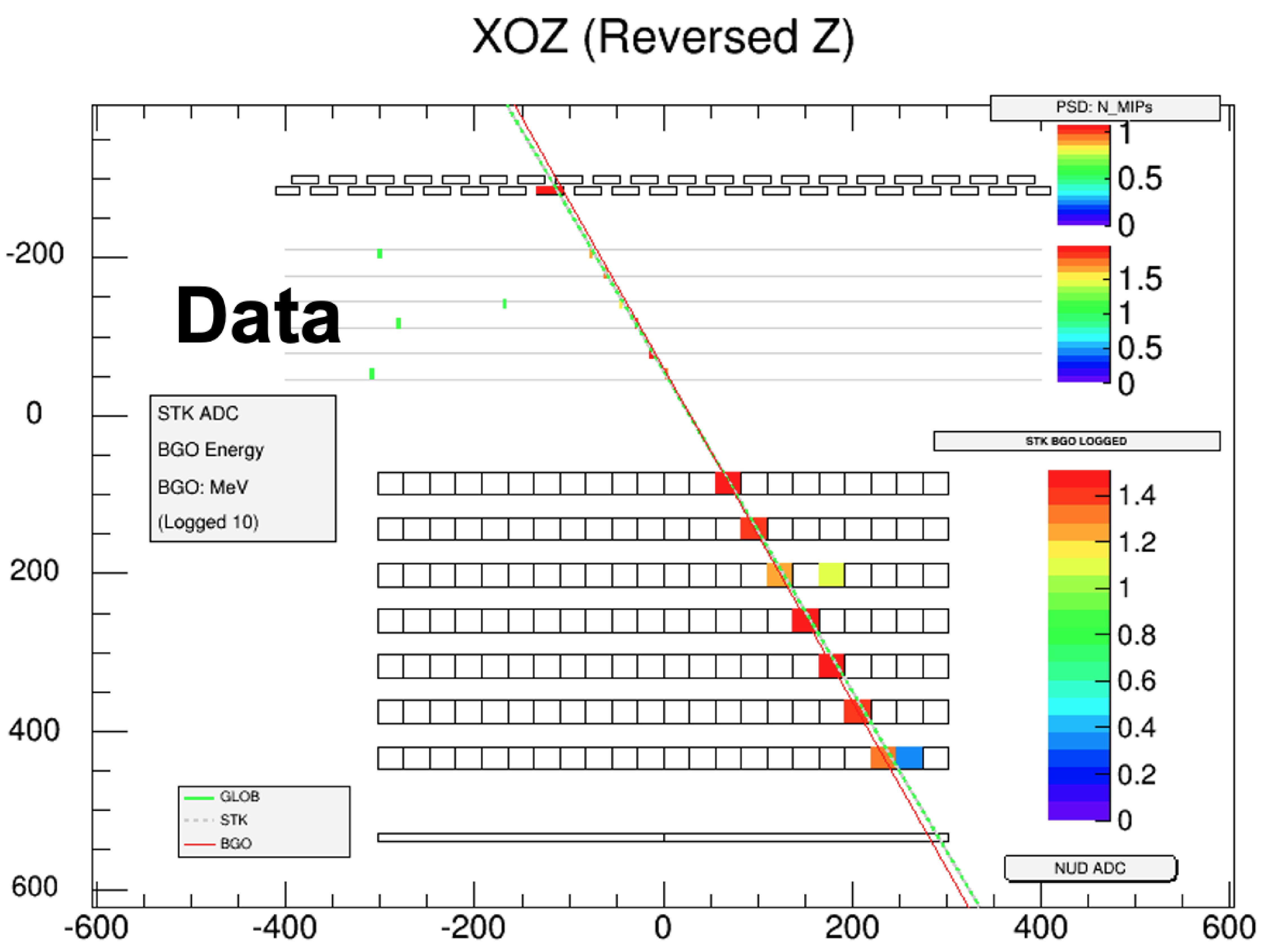


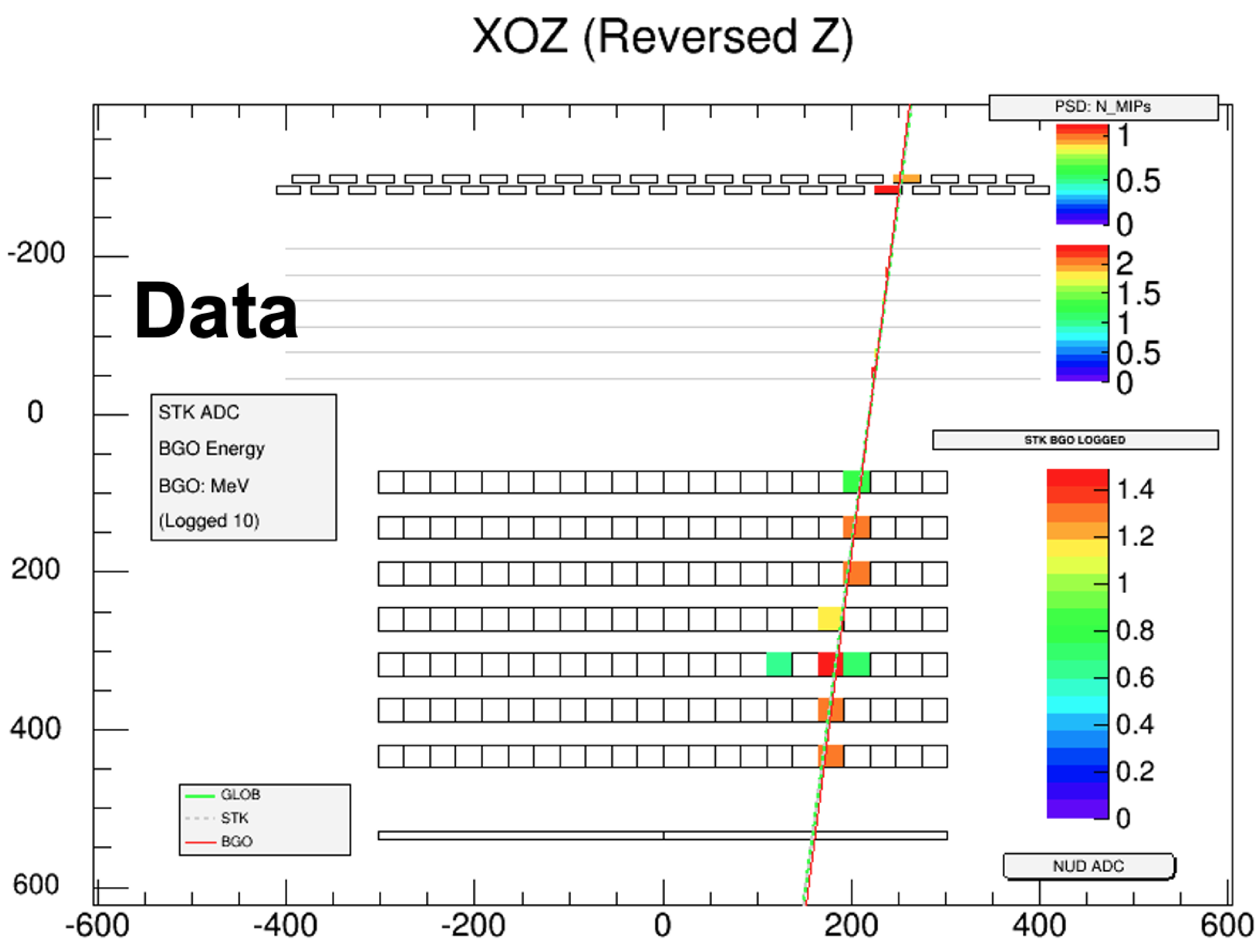
MIP-like Event Selection

- MIPs in BGO:
  - Over-threshold(2 MeV) hits no more than 2 in one layer along the track
  - More than 10 layers are required to have signals
  - One of last two layers should be fired



MIP-like Event Selection

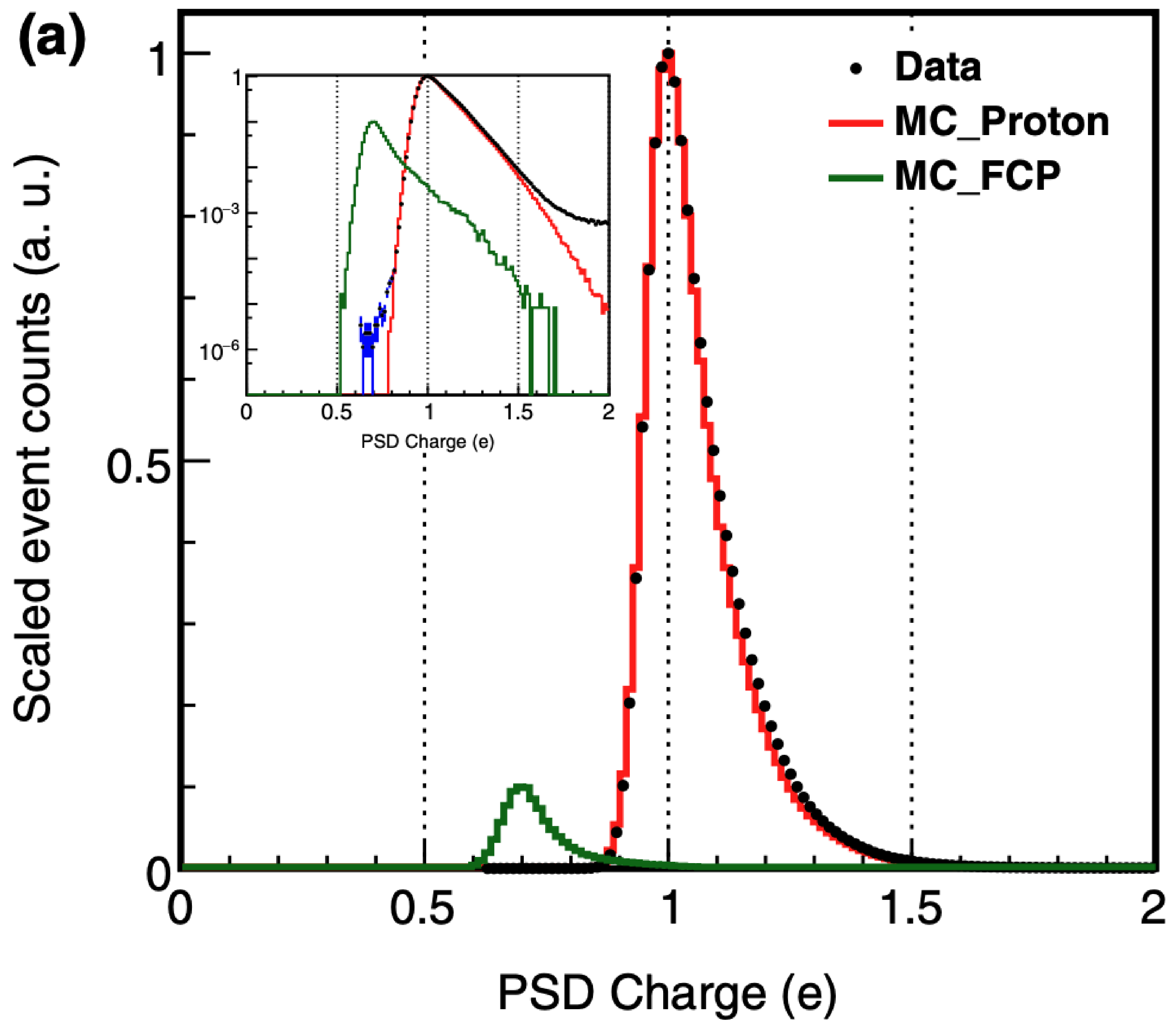


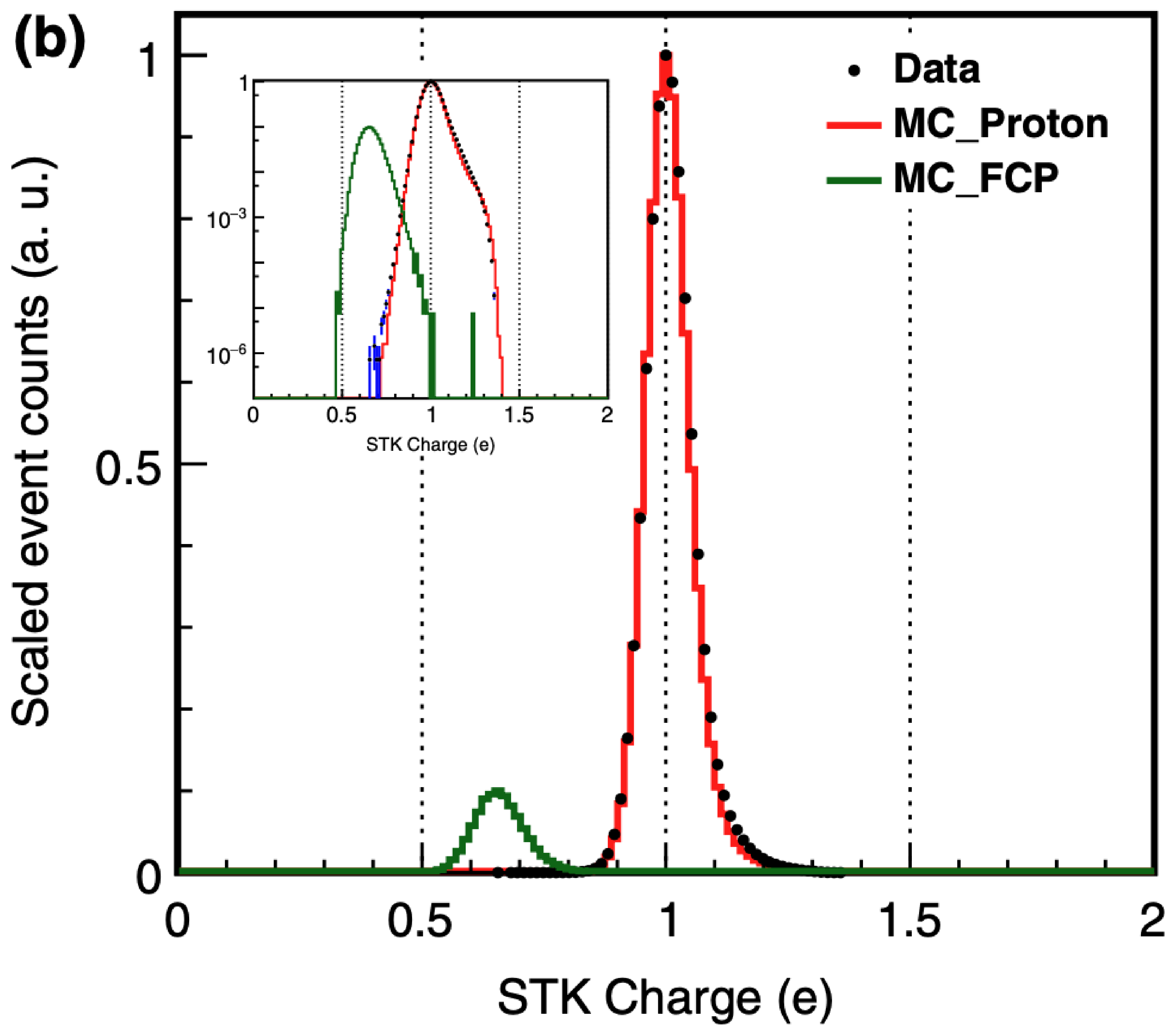


Charge Reconstruction

$$Q_{PSD} = \frac{Q_0 + Q_1}{2}$$

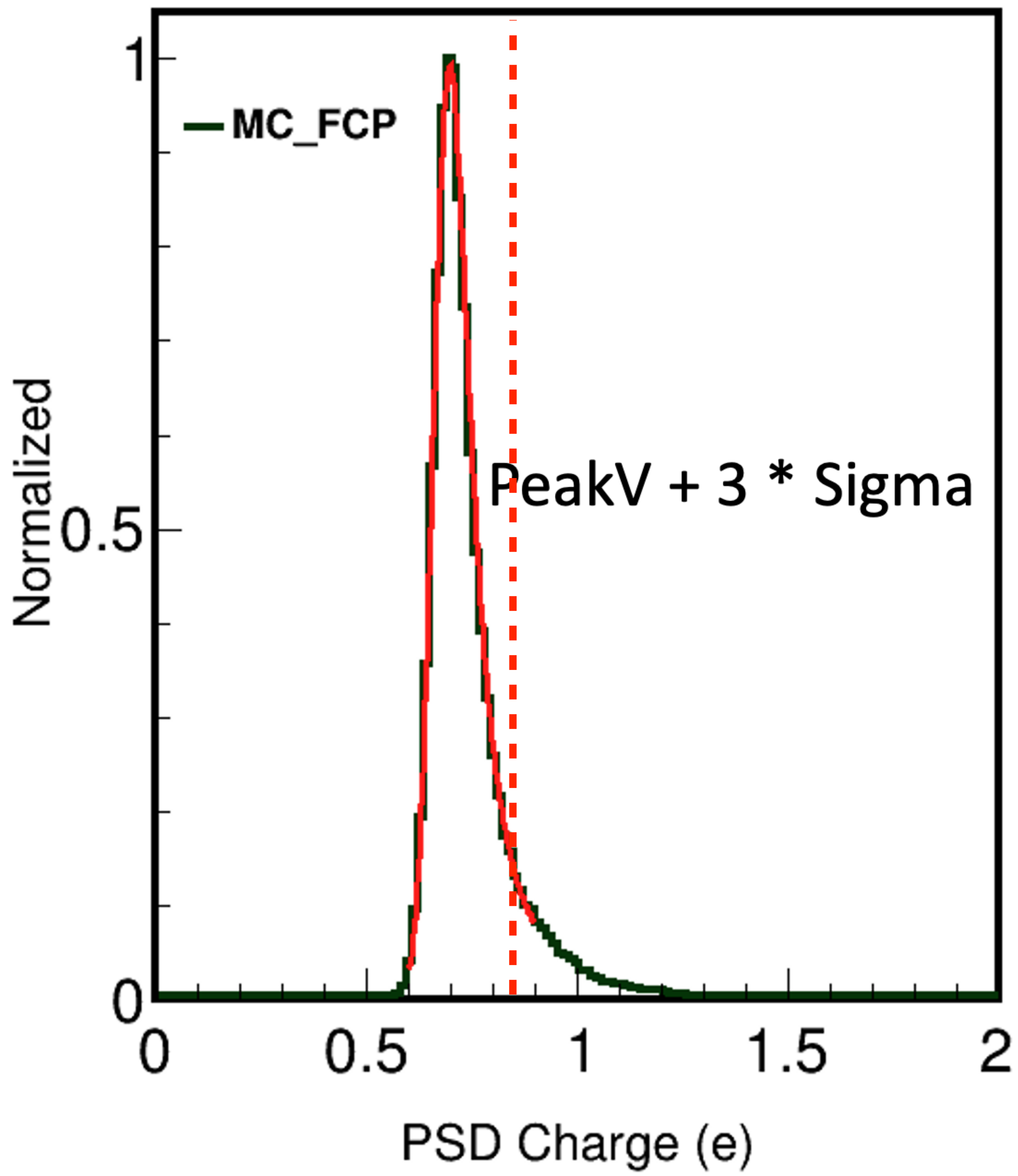
$$Q_{STK} = \frac{\sum_{i=1}^{N} Q_i}{N}$$



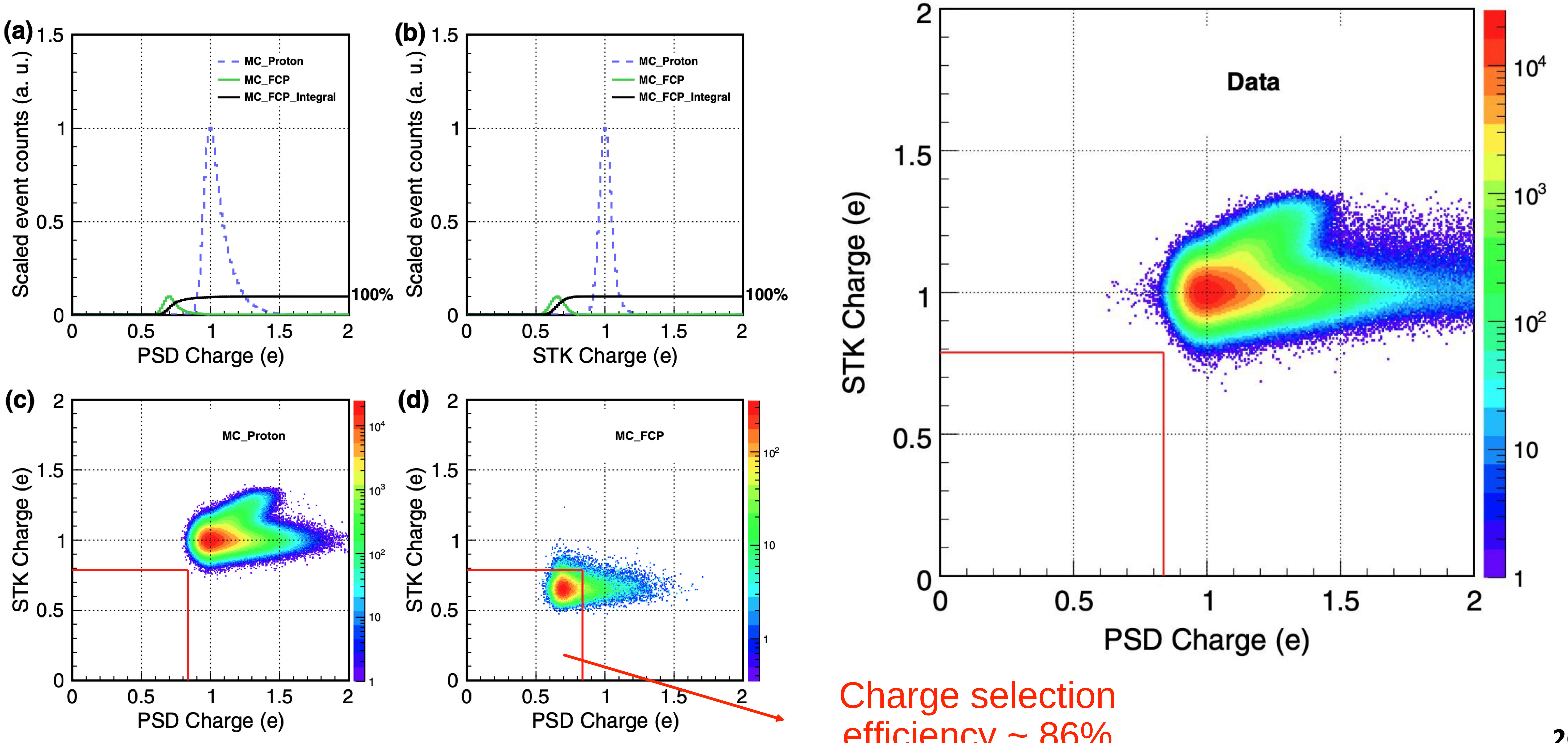


Signal Region Definition

- Signal region: Peak of MC FCP + 3sigma
  - Signal region on PSD：Z < 0.84e
  - Signal region on STK：Z < 0.79e



Signal Region



Charge selection efficiency ~ 86%

Upper Limit Calculation

$$\Phi = \frac{N_{\text{obs}}}{T_{\text{exp}}\epsilon_{\text{scale}}\epsilon_{\text{trig}}A_{\text{eff}}\epsilon_{\text{region}}},$$

Φ : Flux or flux upper limit (cm^{-2}sr^{-1}s^{-1})

N_{obs} : Number of observed FCP

no candidate is observed, N_{obs} is taken to be 2.44 at the 90% C.L.

T_{exp} : Exposure time 2.34×10^7s

ϵ_{trig} : trigger efficiency, 85.5%, given by MC

ϵ_{scale} : pre-scaler factor 1/4

A_{eff} : effective acceptance 940 cm^{2}sr

ϵ_{region} : signal region efficiency 86%

Upper Limit Calculation

$$\Phi = \frac{N_{\rm obs}}{T_{\rm exp}\epsilon_{\rm scale}\epsilon_{\rm trig}A_{\rm eff}\epsilon_{\rm region}},$$

Φ : Flux or flux upper limit (cm^{-2}sr^{-1}s^{-1})

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no candidate is observed,
N_{obs} is taken to be 2.44 at
the 90% C.L

$T_{\rm exp}$: Exposu

$\epsilon_{\rm trig}$: trigger efficiency,

85.5%, given by MC

$\epsilon_{\rm scale}$: pre-scaler factor 1/4

$A_{\rm eff}$: effective acceptance

sr

gion efficiency

$$\delta = \sqrt{\delta^2_{\rm trigger} + \delta^2_{\rm track} + \delta^2_{\rm charge}} = 3.1\,\%$$

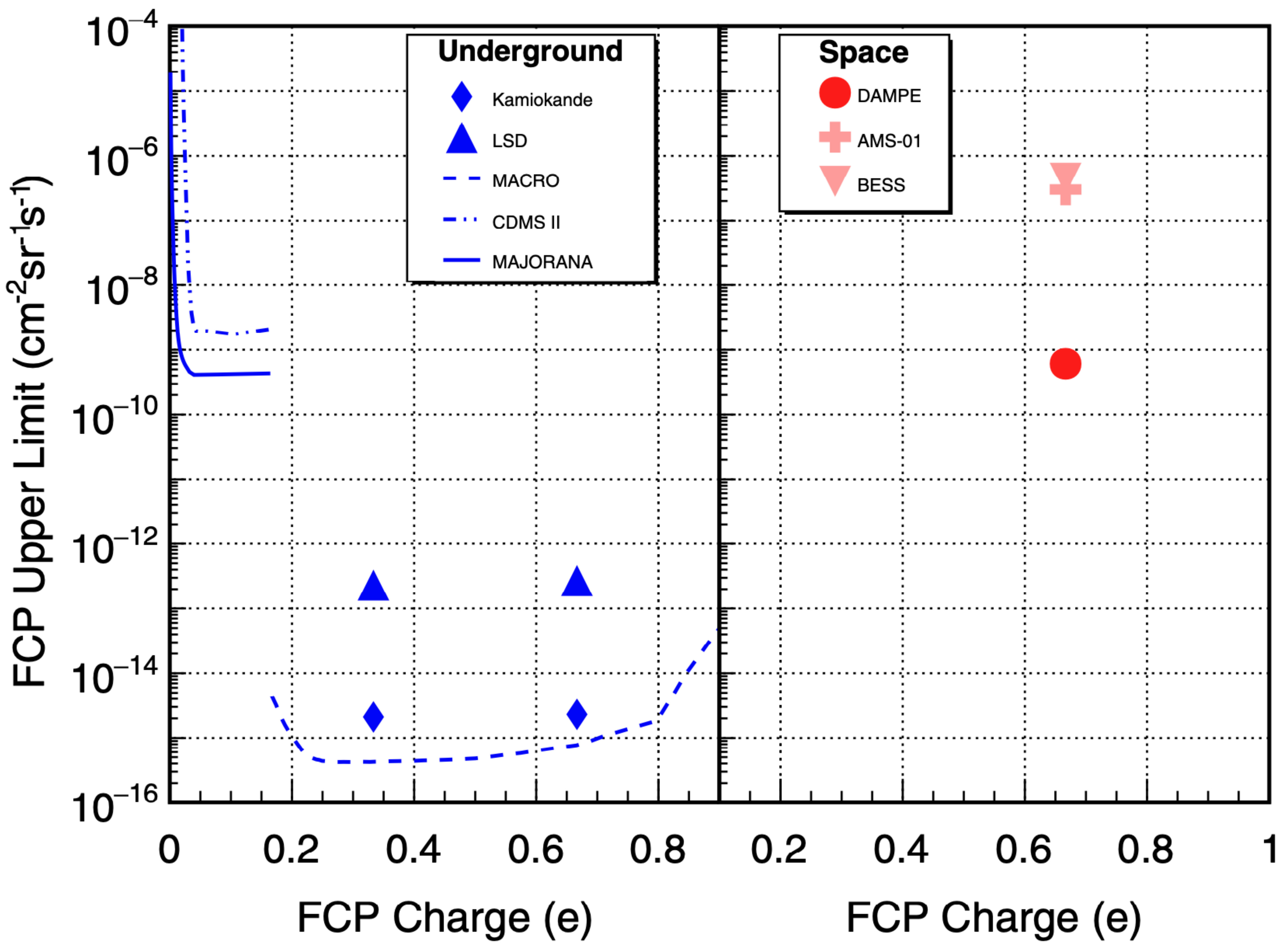
where $\delta_{\rm trigger} = 1.1\%$, $\delta_{\rm track} = 2.9\%$, and $\delta_{\rm charge} = 0.5\%$

Upper Limit of 2/3e FCP

TABLE I. The comparison between DAMPE and other similar types experiments.

Experiments	Geometric acceptance(cm^{-2} sr)	Exposure time (s)	Upper limit (cm^{-2} sr^{-1} s^{-1})
AMS-01	3000	3.6×10^4	3.0×10^{-7} (95% CL)
BESS	1500	3.2×10^5	4.5×10^{-7} (90% CL)
DAMPE	3000	2.3×10^7	6.2×10^{-10} (90% CL)

$$\Phi < 6.2 \times 10^{-10} cm^{-2}\, sr^{-1}\, s^{-1}$$



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Prospects for Searching for Light FCP

FCP should not be constrained to be heavy lepton

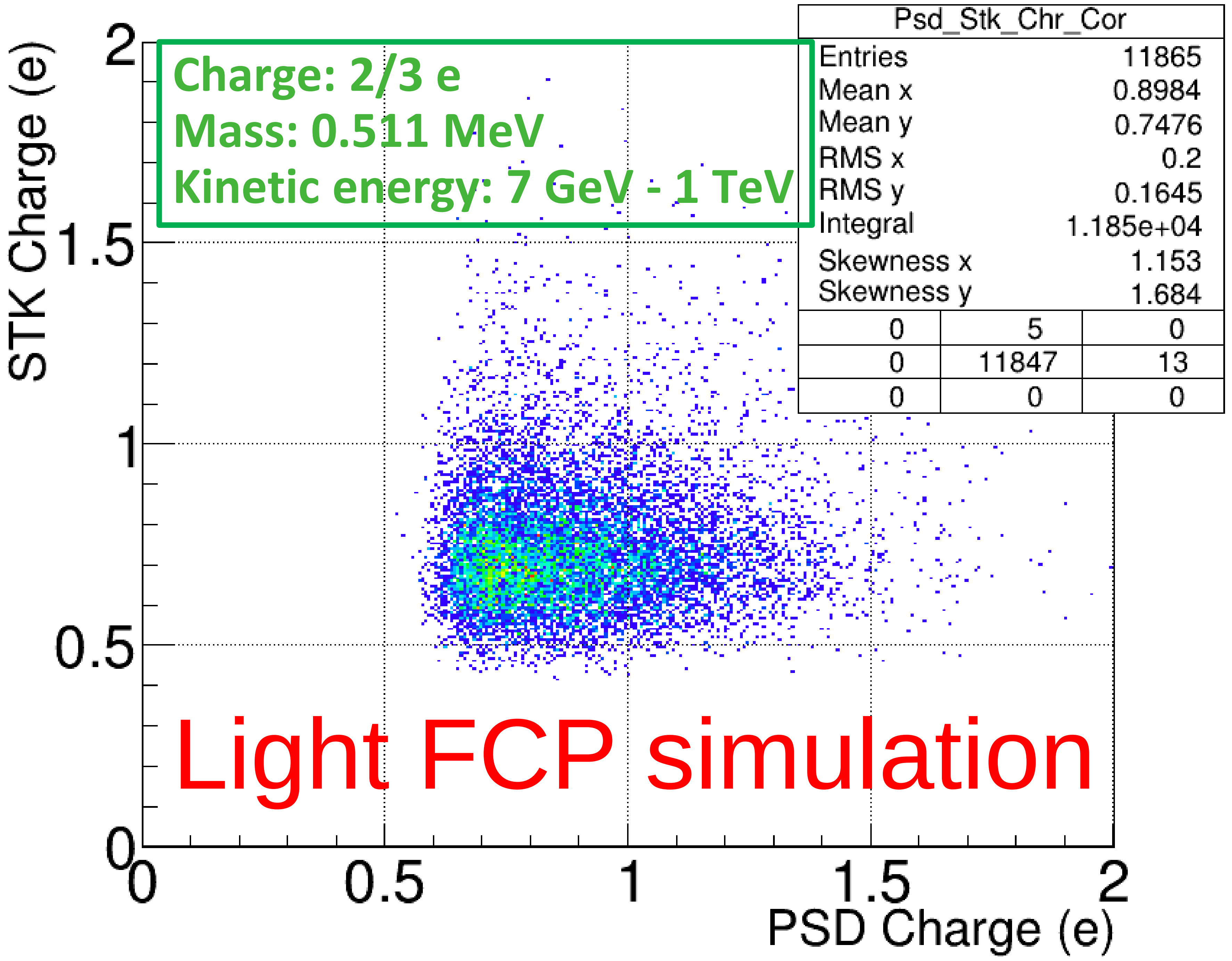
- Shower can happen
- Mass may be light
- Electron-like light-mass particle

Origin: nearby stars

Energy loss: Bremsstrahlung

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = 4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{1}{4\pi\epsilon_0}\frac{e^2}{mc^2}\right)^2 E\ln\frac{183}{Z^{1/3}}$$

Based on the dataset accumulated by DAMPE, the mass-, energy-dependent spectrum are supposed to be observed.



Next step

- Light-mass FCP simulation.
- Evaluate the background contamination (electron, proton, gamma).
- Evaluate the selection efficiency and effective acceptance.

Summary

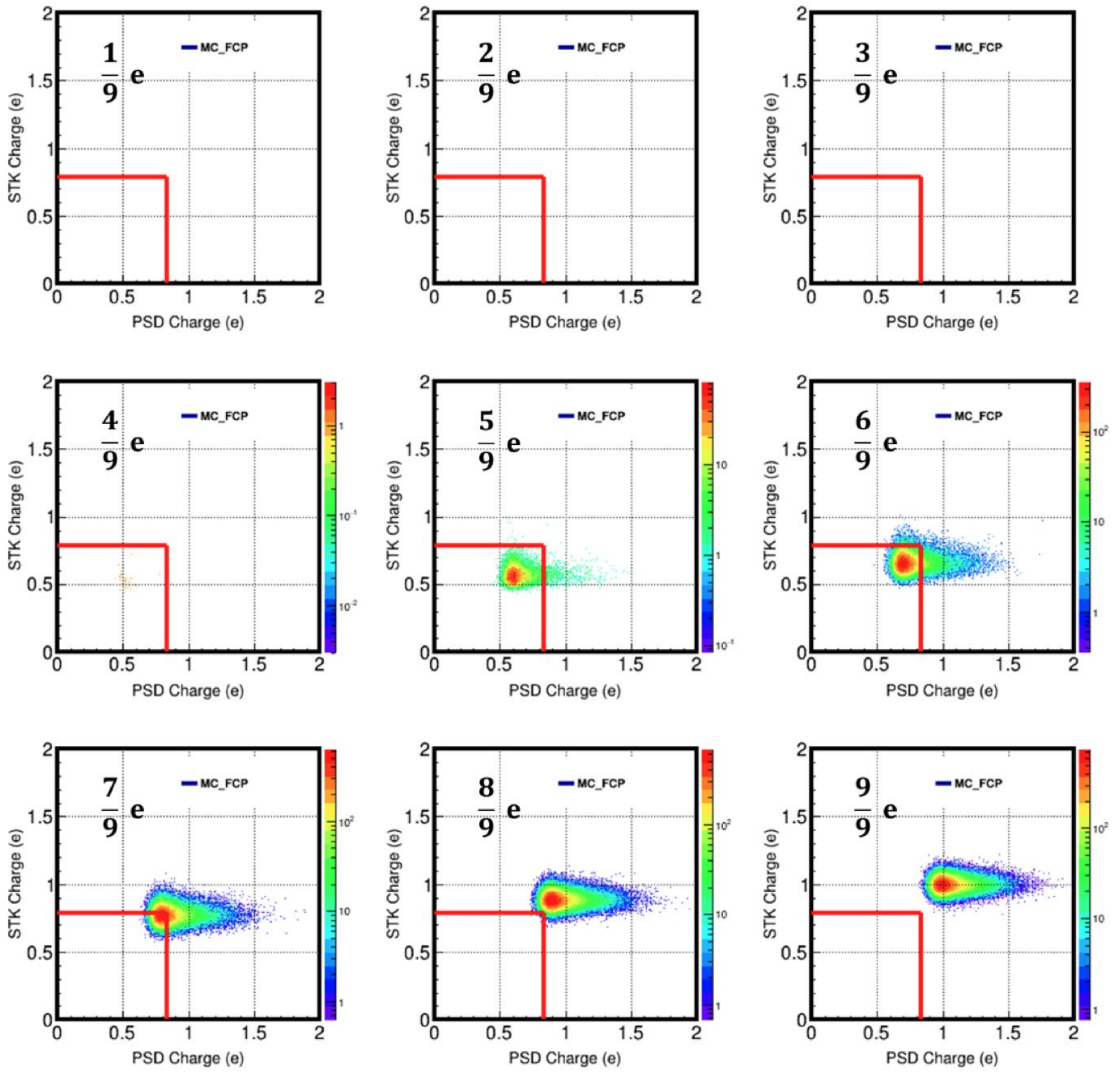
- We search for 2/3e FCP with DAMPE experiment
- Space experiments can detect FCPs with energy as low as a few GeV
- FCPs are assumed to be a type of heavy lepton
- No FCP signals are observed and a flux upper limit of $\Phi < 6.2 \times 10^{-10} cm^{-2} sr^{-1} s^{-1}$ is established at the 90% C.L..
- Result is published in *Phys. Rev. D 106, 063026 (2022)*
- A prospect for Searching for Light FCP is proposed.

Thank you!

Backup

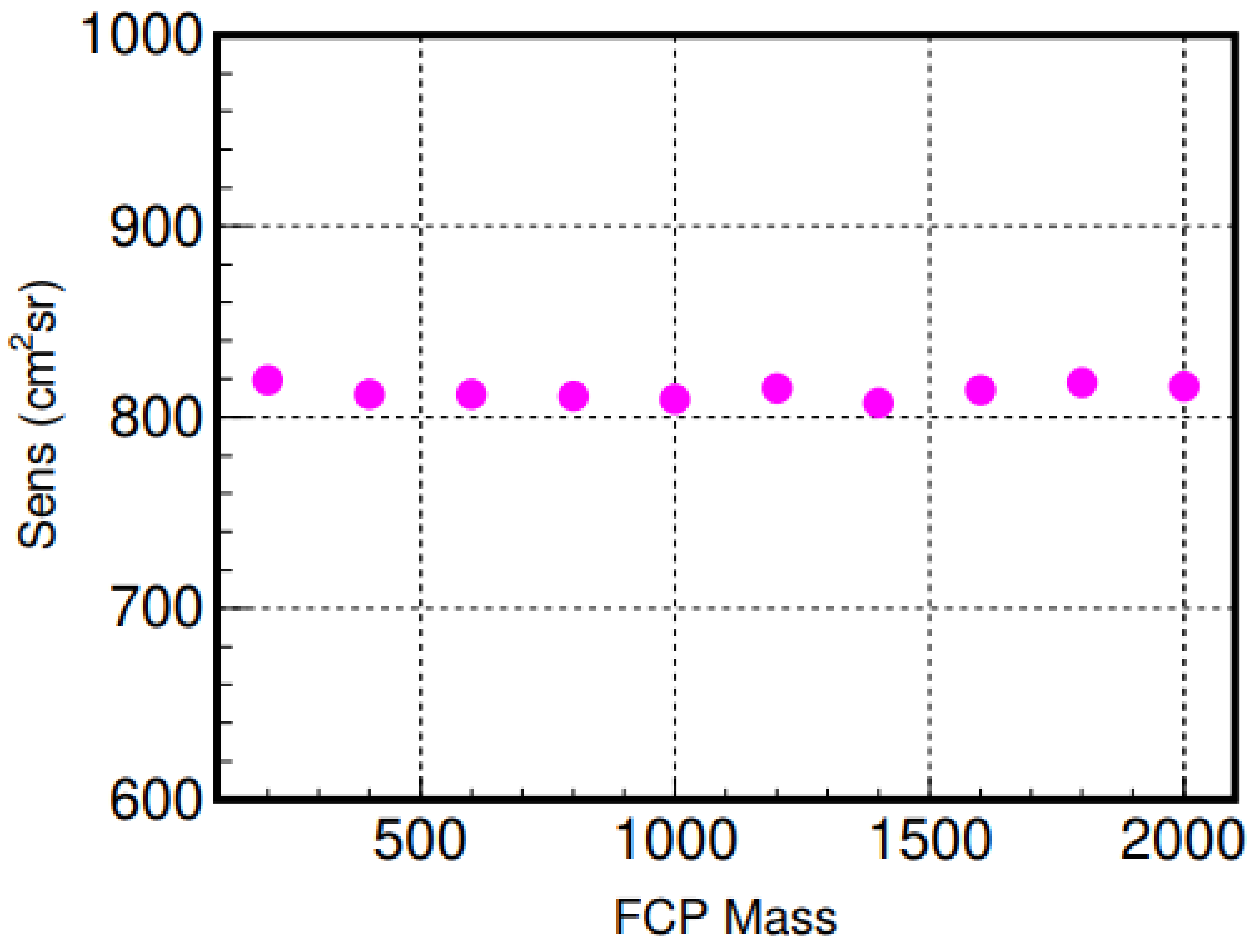
Charge scan

Low charge:
No response from detector
High charge:
Difficult to distinguish from the background

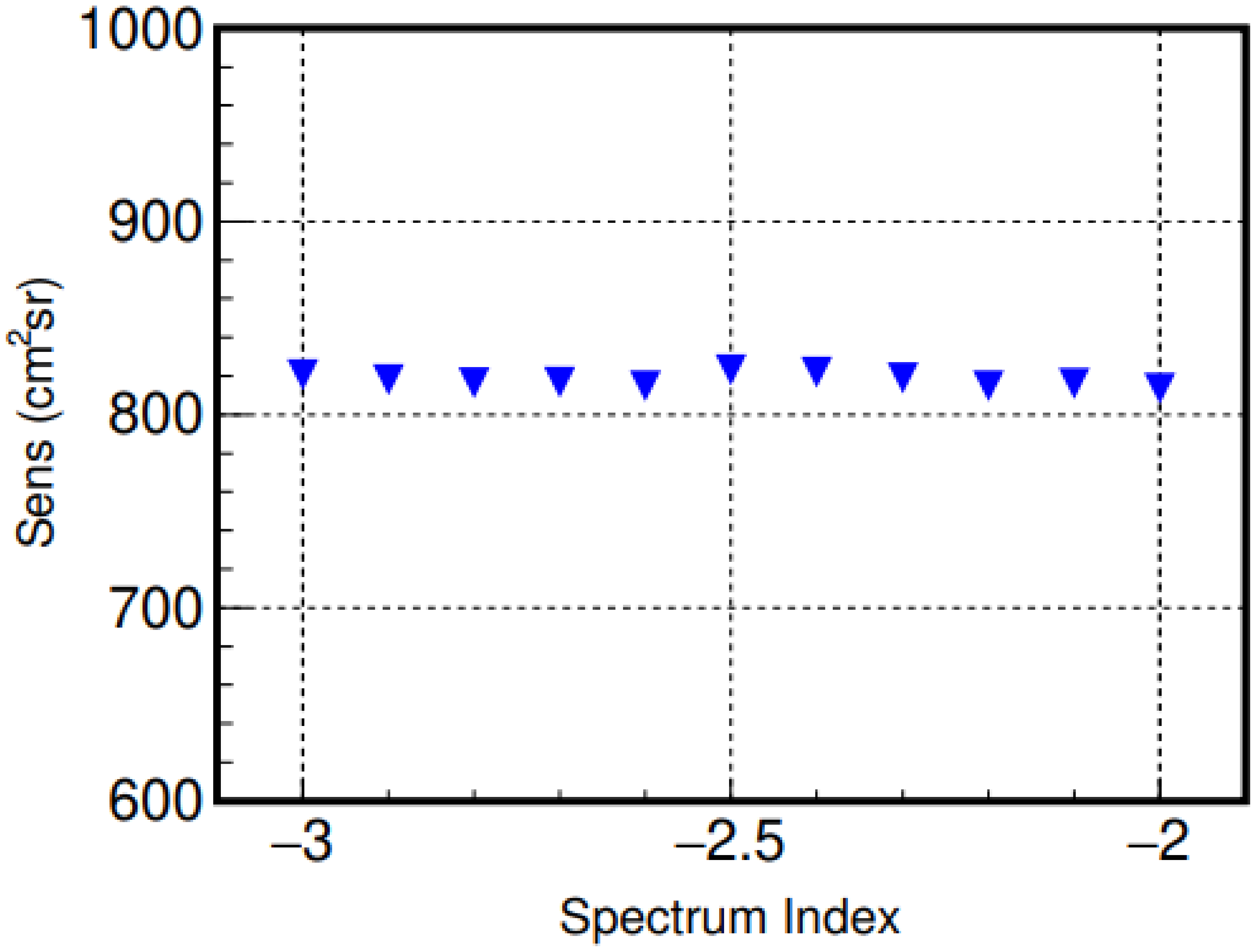


Mass and Spectrum index scan

$$\text{Sens} = A_{eff} \times \epsilon_{region}$$



The mass varies from 200 MeV to 2000 MeV with a step of 200 MeV is applied to the simulation.

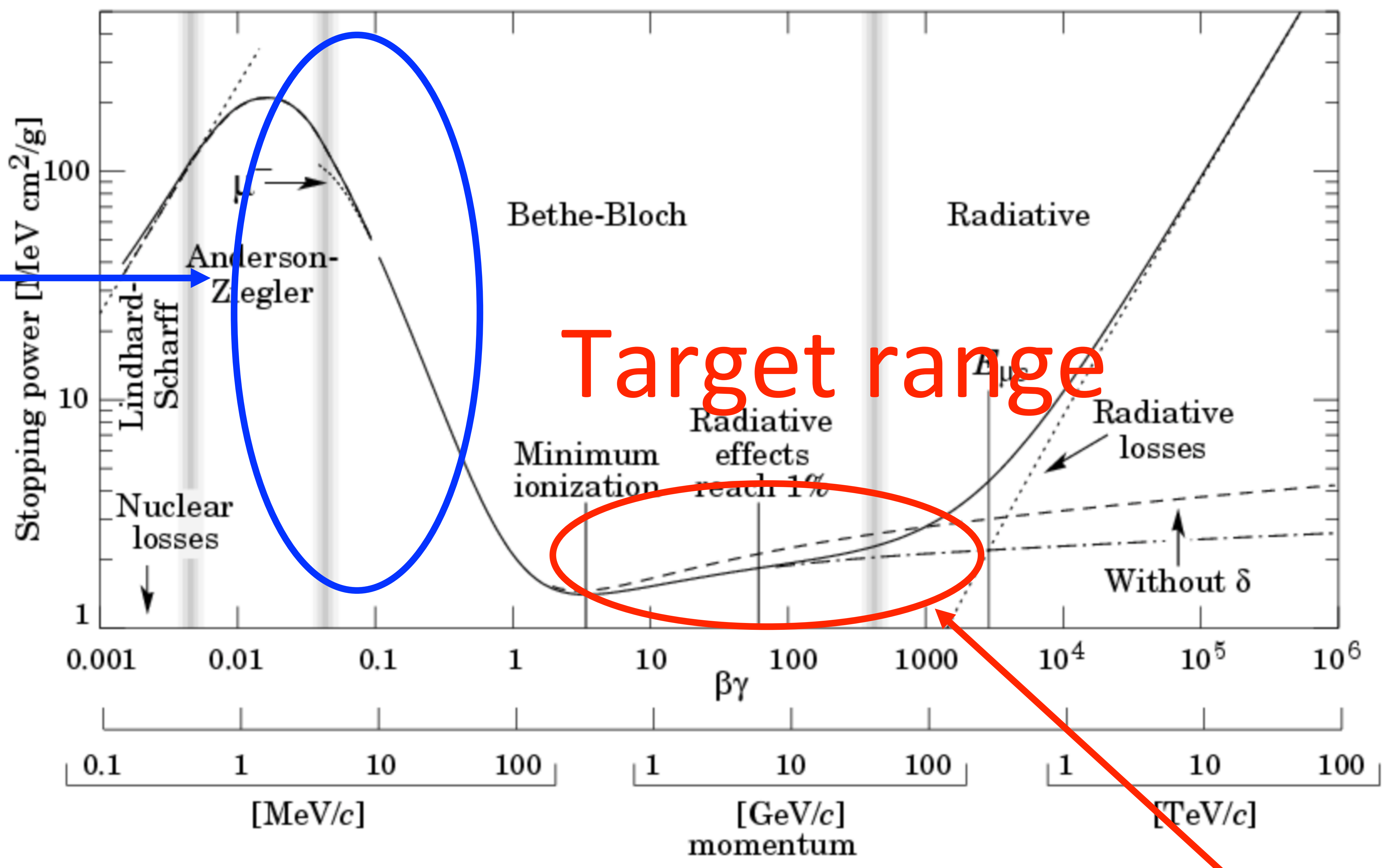


The spectrum index varies from -3 to -2 with a step of 0.1 is applied to the simulation.

Kinetic Energy Control

- Energy of MIP-like events cannot be measured by a calorimeter
- Kinetic energy should be constrained

Non-relativistic region
dE/dx change sharply



dE/dx is stable

Why did N_{obs} choose 2.44?

According to the Feldman-Cousins method, the observed small signal events *n* obeys the Poisson distribution $p(n|s) = e^{-(s+b)}\frac{(s+b)^n}{n!}$, the real signal events *s* and background events *n* obey the Poisson distribution as well. Since *n* and *b* are zero, the *s* takes 2.44 for the calculation of upper limit within 90% confidence level.

90% C. L.

$n_0 \backslash b$	0.0	0.5
0	0.00, 2.44	0.00, 1.94
1	0.11, 4.36	0.00, 3.86
2	0.53, 5.91	0.03, 5.41
3	1.10, 7.42	0.60, 6.92
4	1.47, 8.60	1.17, 8.10

95% C. L.

$n_0 \backslash b$	0.0	0.5
0	0.00, 3.09	0.00, 2.63
1	0.05, 5.14	0.00, 4.64
2	0.36, 6.72	0.00, 6.22
3	0.82, 8.25	0.32, 7.75
4	1.37, 9.76	0.87, 9.26