Beam tests of a BGO matrix calorimeter at a BSRF station

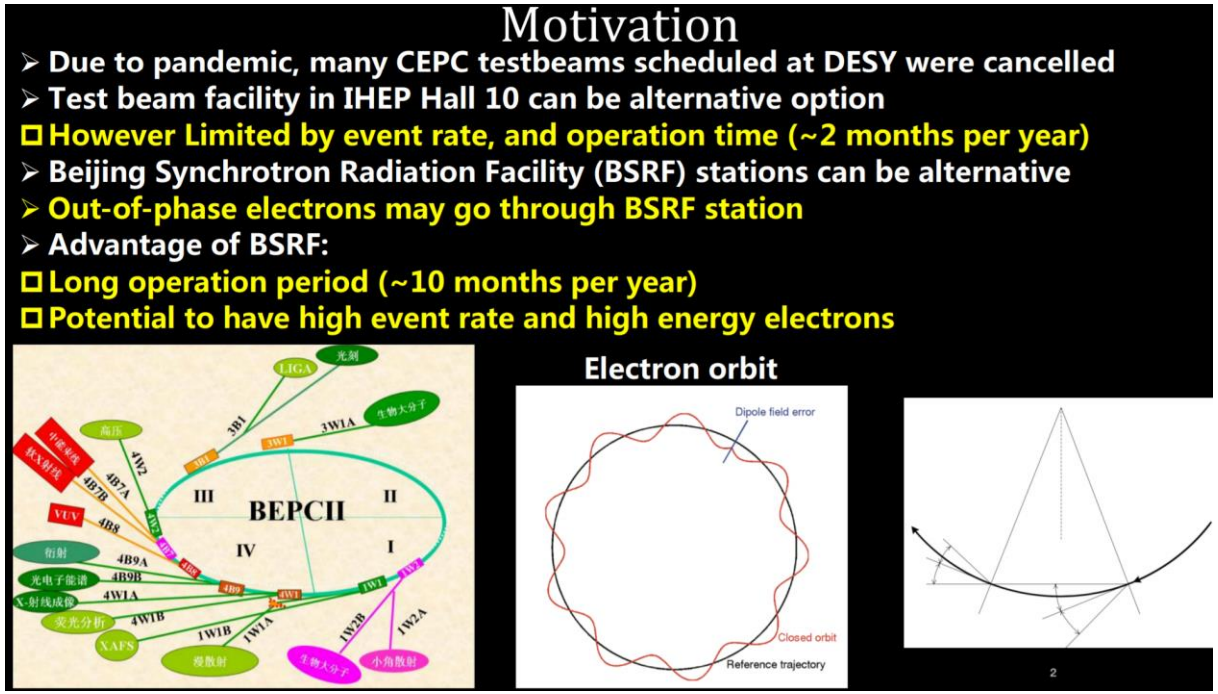
Yong Liu, Baohua Qi, Zhiyu Zhao (IHEP)

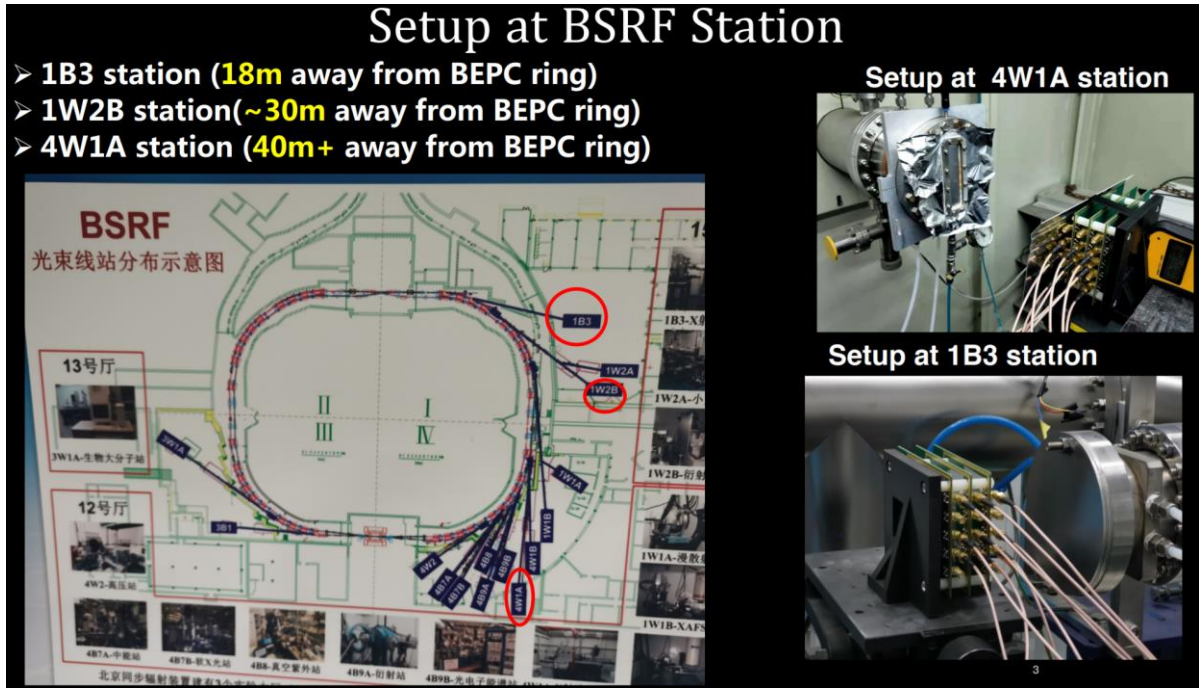
July 28, 2021

Reminder: a possible option for beam tests

- Beijing Synchrotron Radiation Facility (BSRF) at IHEP
  - Reported by IHEP colleagues at CEPC Day (Dec. 28, 2020):
    - https://indico.ihep.ac.cn/event/13393/session/2/contribution/9/material/slides/1.pdf
  - Measured at two BSRF stations with 3 LGAD detectors
    - Coincidence events, time intervals, pulse shape, etc.

Slides from Zhijun Liang, etc.

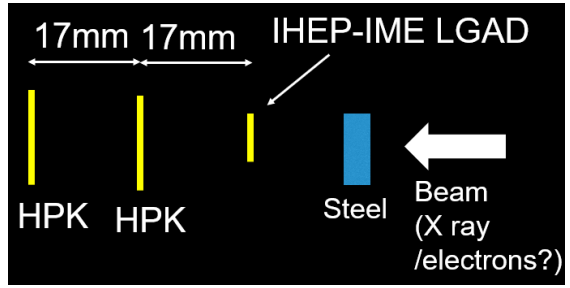




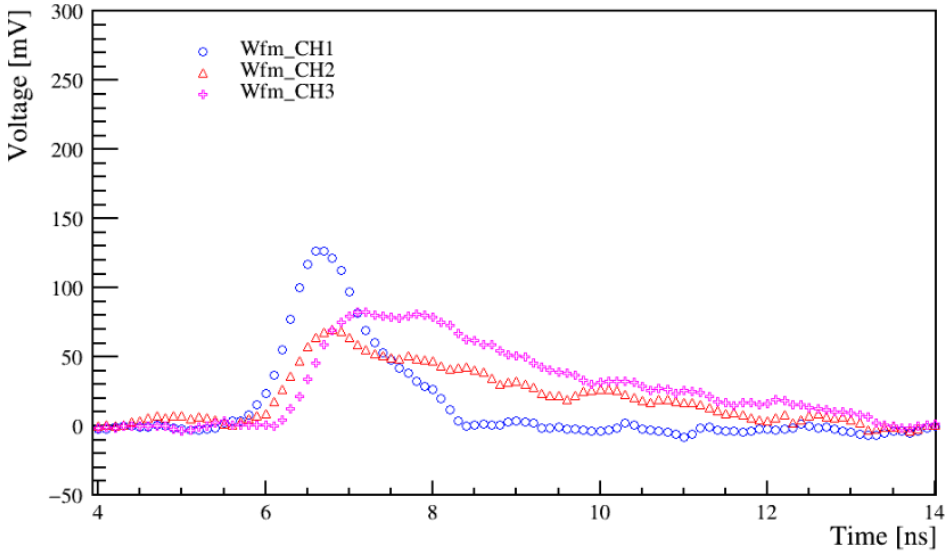
Reminder: a possible option for beam tests

- Beijing Synchrotron Radiation Facility (BSRF) at IHEP
  - Two BSRF stations: (different) trigger rates measured
    - 1.5 Hz/cm² and 50 Hz/cm² (depending on the distance to the storage ring)
  - Observed high-energy particles penetrating up to 20mm thick steel
  - Could be “out-of-phase” electrons from the BEPC-II Storage Ring
  - Need to verify this assumption: beam energy measurements

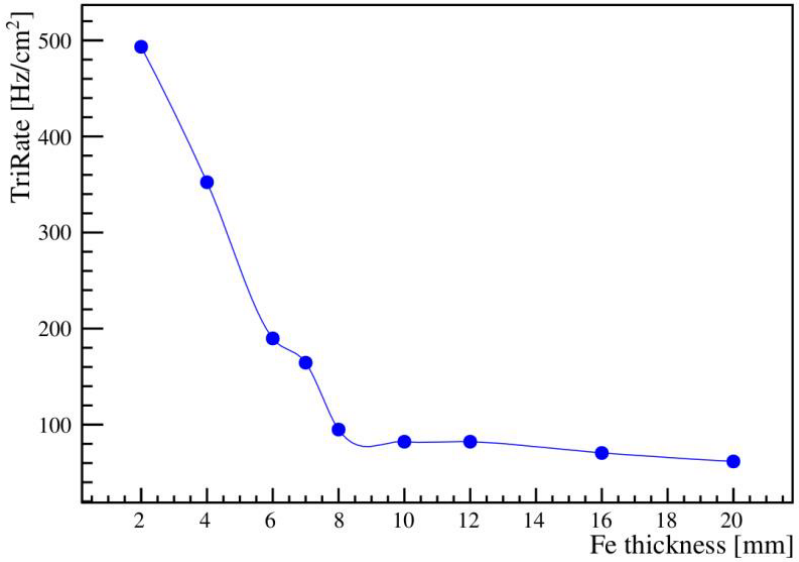
Zhijun Liang et al., Test Beam opportunity on Beijing Synchrotron Radiation Facility (BSRF)



Typical Coincidence Event



Trigger Rate vs. Steel Thickness

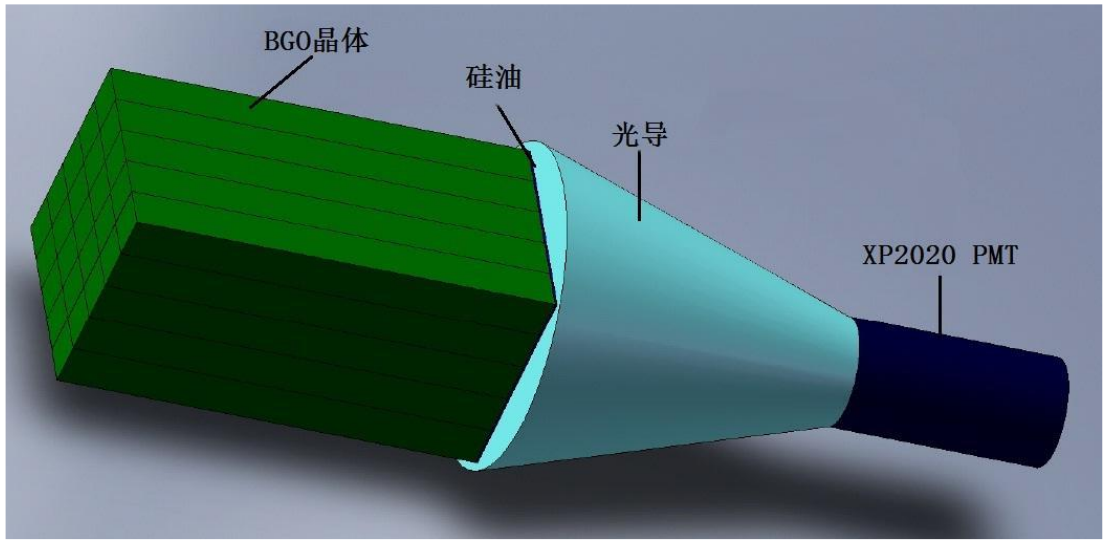


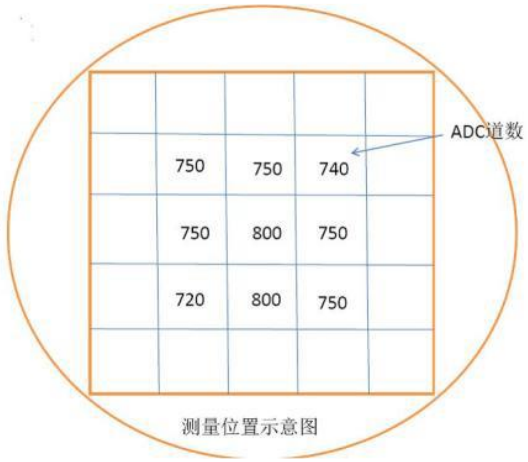
Event Rates at 2 BSRF stations

BSRF Station	1B3	4W1A
Coincidence events rate (Hz/cm²)	~50	~1.5 Hz/cm²
Distance to BEPC ring (meter)	18	~43

BGO matrix calorimeter for beam tests

- Need to measure the energy of high-energy particles at BSRF: GeV-level electrons or not?
- Use the existing BGO matrix calorimeter (at Hall-10 for BEPC-TBF)
- 5×5 matrix of BGO crystal bars
  - Each BGO bar: $20 \times 20 \times 200$ mm^3
  - Replaced malfunctioning PMTs with a 2-inch PMT and a light guide (in ~2010)
  - Response uniformity scanned in the central 3x3 matrix





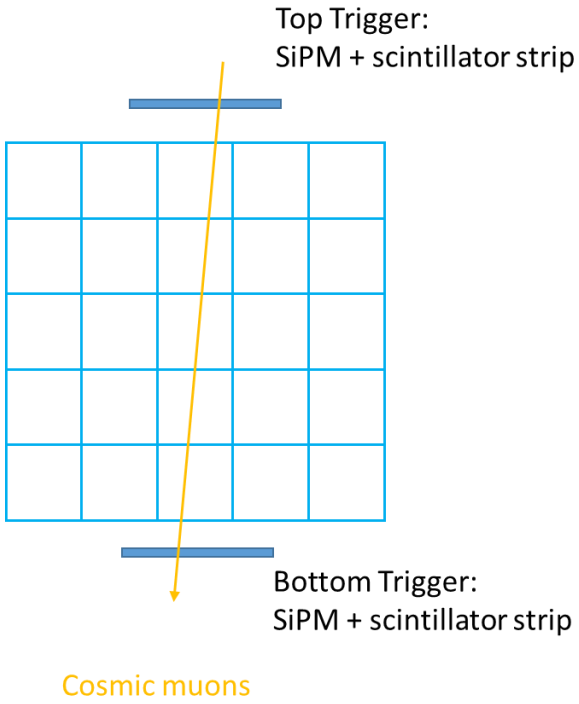
Pictures taken from the PhD thesis of Boxiang Yu (2010), Graduate University of Chinese Academy of Sciences

Tests for the BGO calorimeter: outline

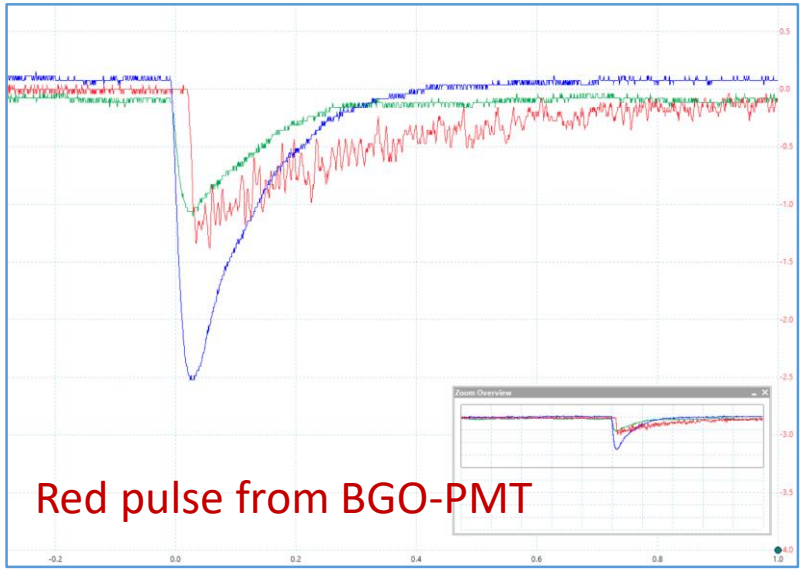
- Cosmic ray tests for energy (MIP response) calibration
  - Rely on the MIP energy deposition for the energy calibration of BGO matrix
- Geant4 simulation studies with incident muons
  - Estimate the impact from different muon momenta
- Beam tests with the BGO matrix at a BSRF station (3W1)

Efforts to revive the BGO calorimeter

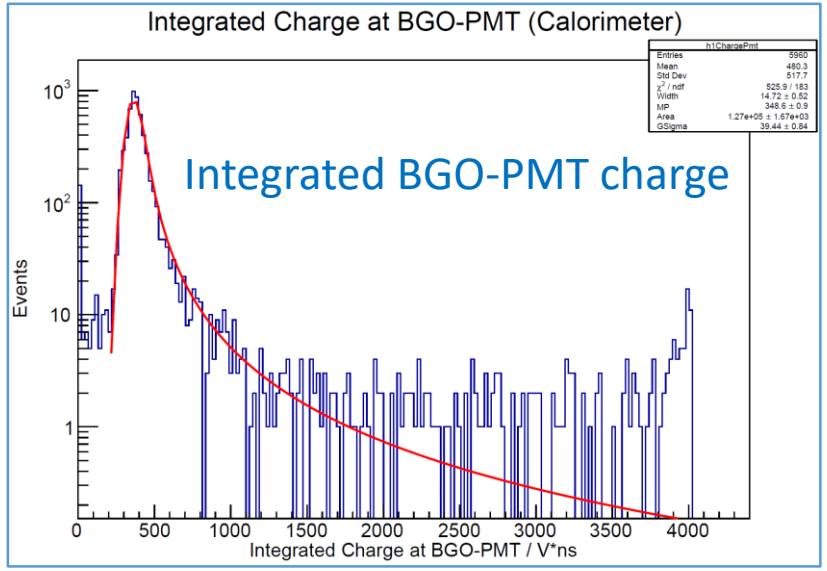
- BGO matrix calorimeter with cosmic muons
  - BGO calorimeter successfully revived (at #10 hall)
  - Stable data taking: MIP energy calibration (vs. hit positions, PMT HV, etc.)
  - Done during February and March 2021



A typical cosmic event
(coincidence with trigger SiPMs)

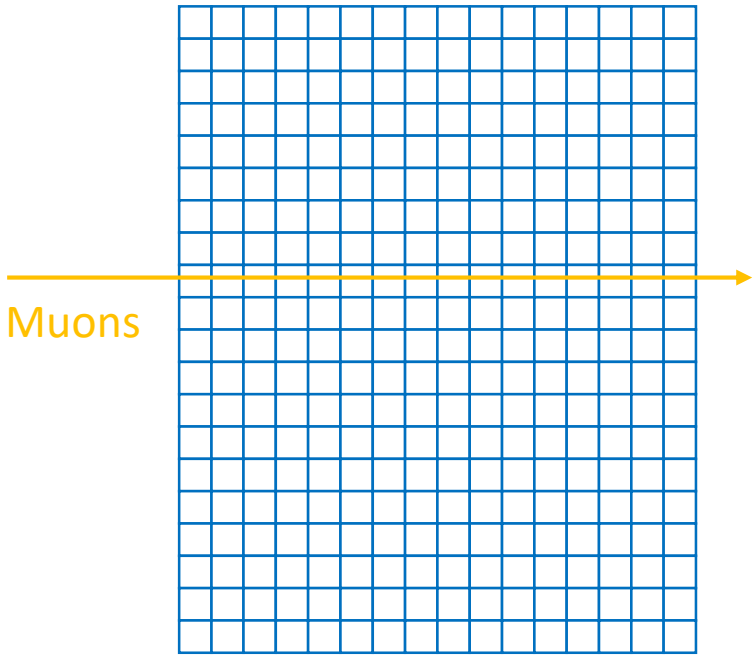


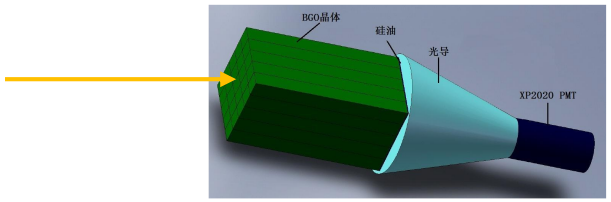
BGO MIP response: ~6k cosmic events



PMT-HV: 1750 V (for good S/N ratio)

Geant4 simulation studies with muons

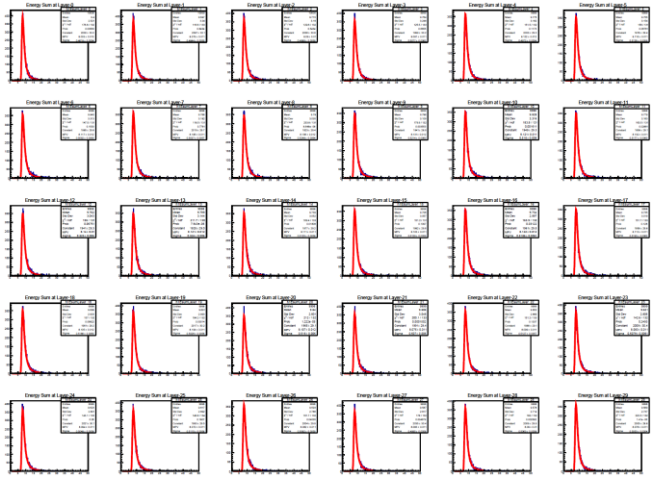


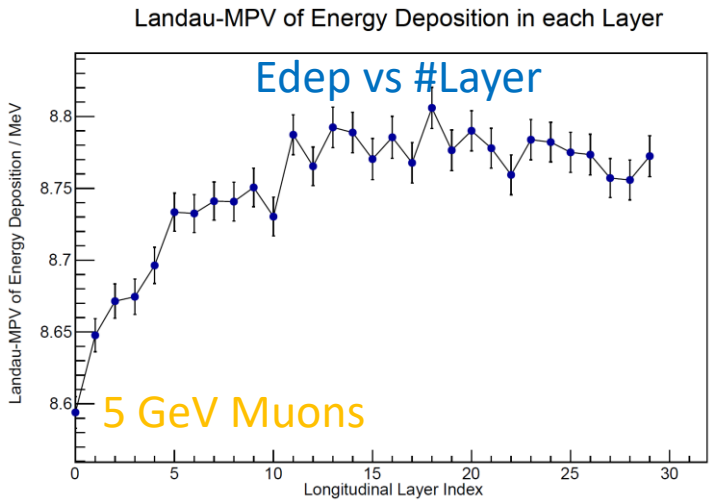


Muons along crystal bar length direction (20cm): ~180 MeV/MIP expected

- Highly granular BGO calorimeter in the G4 simulation
  - Crystal cubes: exactly 1cm thick
- Muons: perpendicular incidence
  - Varying momenta: 1, 5, 10, 120 GeV
- Energy deposition (Edep) in each crystal cube
  - Landau fit for the Most Probable Value (MPV): ~9MeV/cm
  - Edep per cm: 0.1-0.4 MeV difference observed in the muon momentum range of 1-120 GeV (~1-4% relative difference)

Landau Fit for Edep per BGO layer

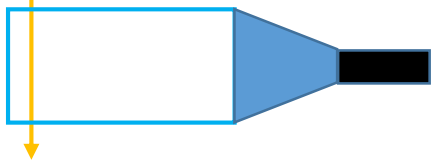


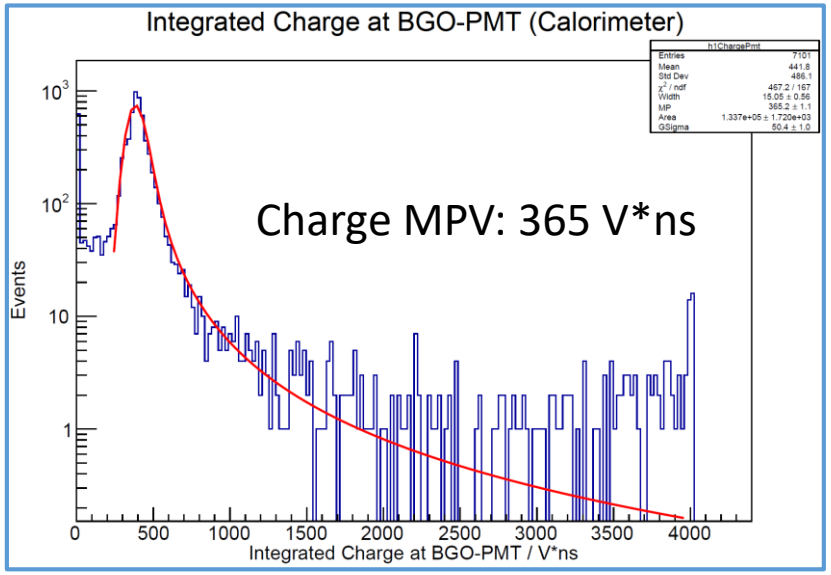


Cosmic tests: MIP response vs. hitting positions

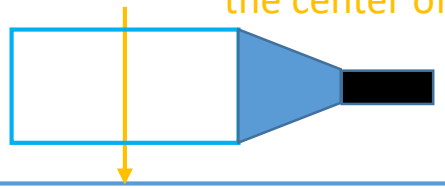
- MIP response: varying scintillator-trigger positions
  - ~15% response difference observed along bar length direction
  - Temperature effects: long runs of data taking within several weeks

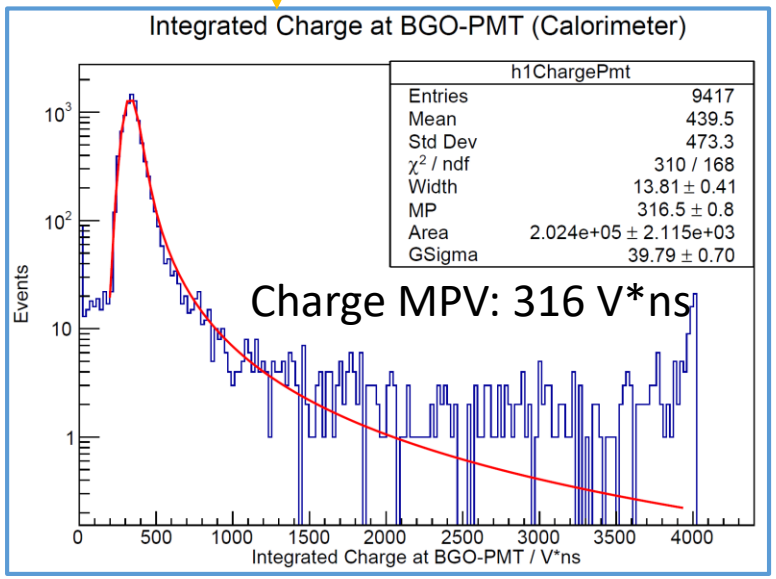
Muons hitting around the far end of BGO bars



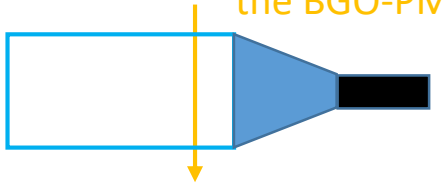


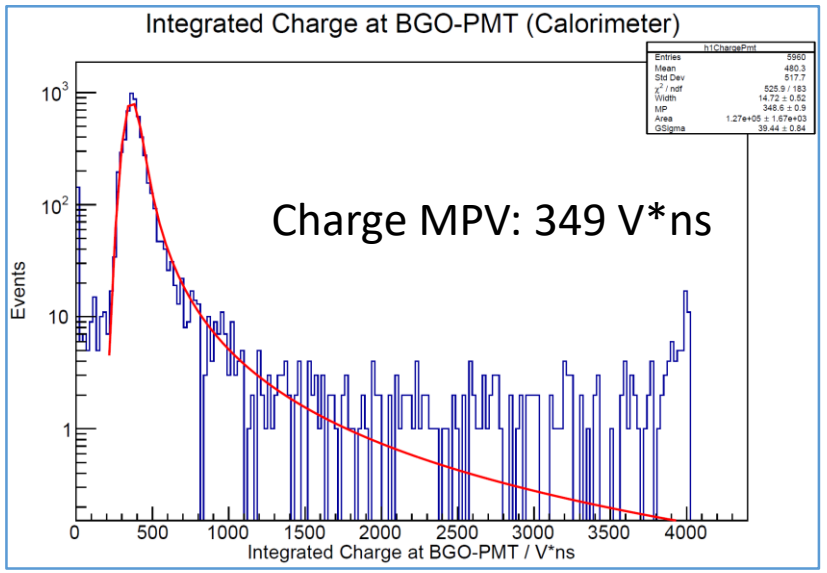
Muons hitting around the center of BGO bars





Muons hitting near the BGO-PMT

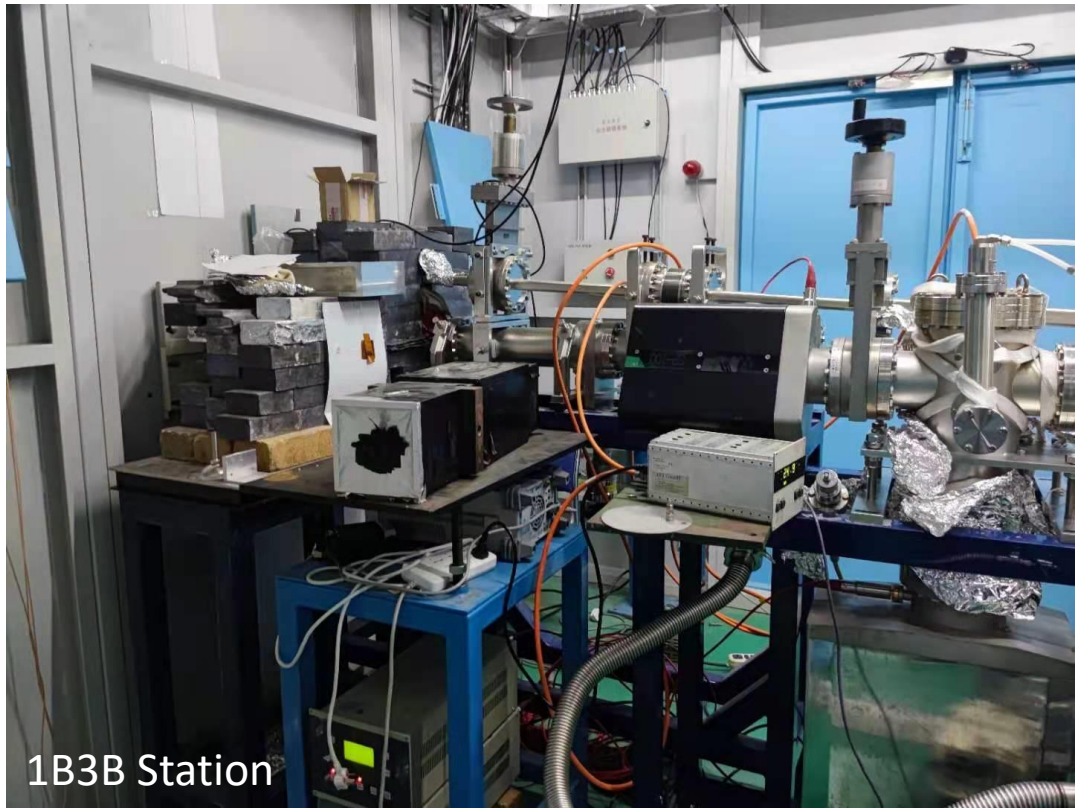


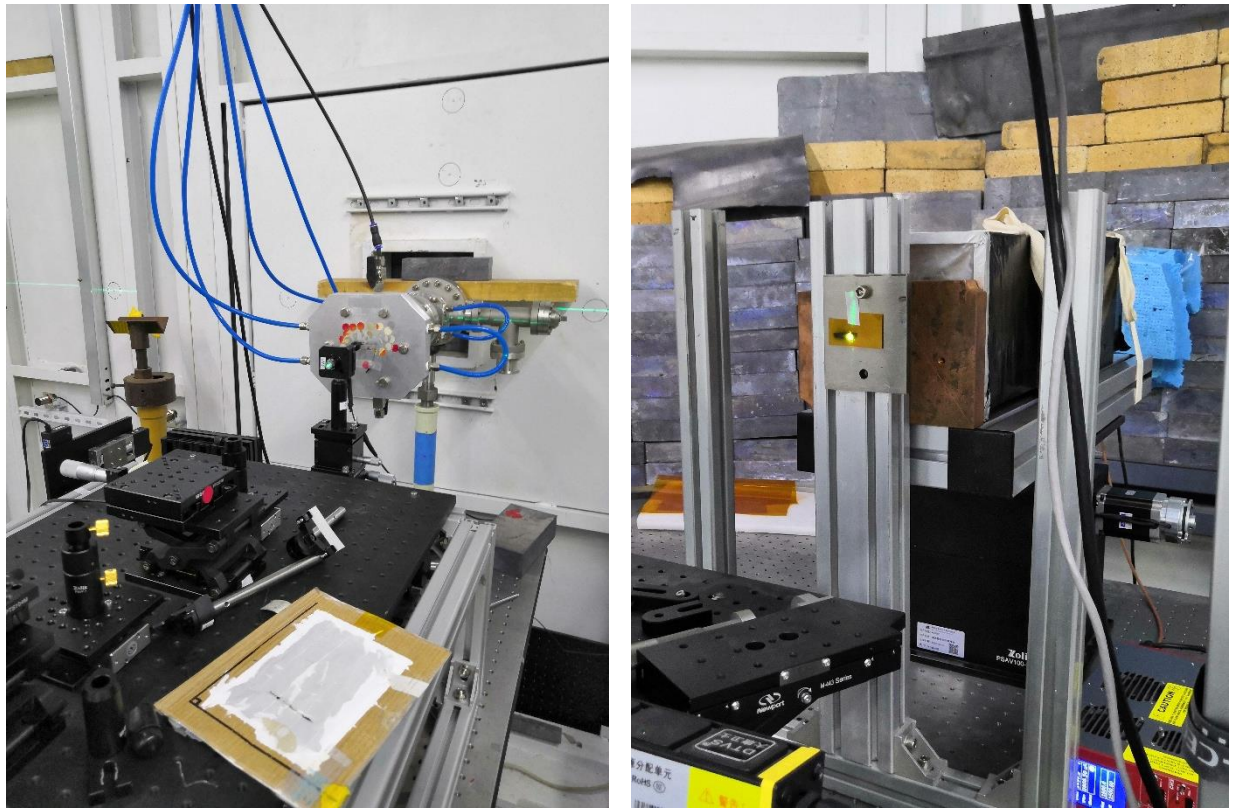


PMT-HV: 1750 V

Preparations for beam tests at BSRF

- BGO calorimeter moved to the BSRF stations: first to 1B3B and later to 3W1
  - Final beam tests done at 3W1, before the BEPC-II summer shutdown; unfortunately time conflicts at 1B3B
- Preparations: mechanical stage for vertical height adjustment, power cabling, etc.

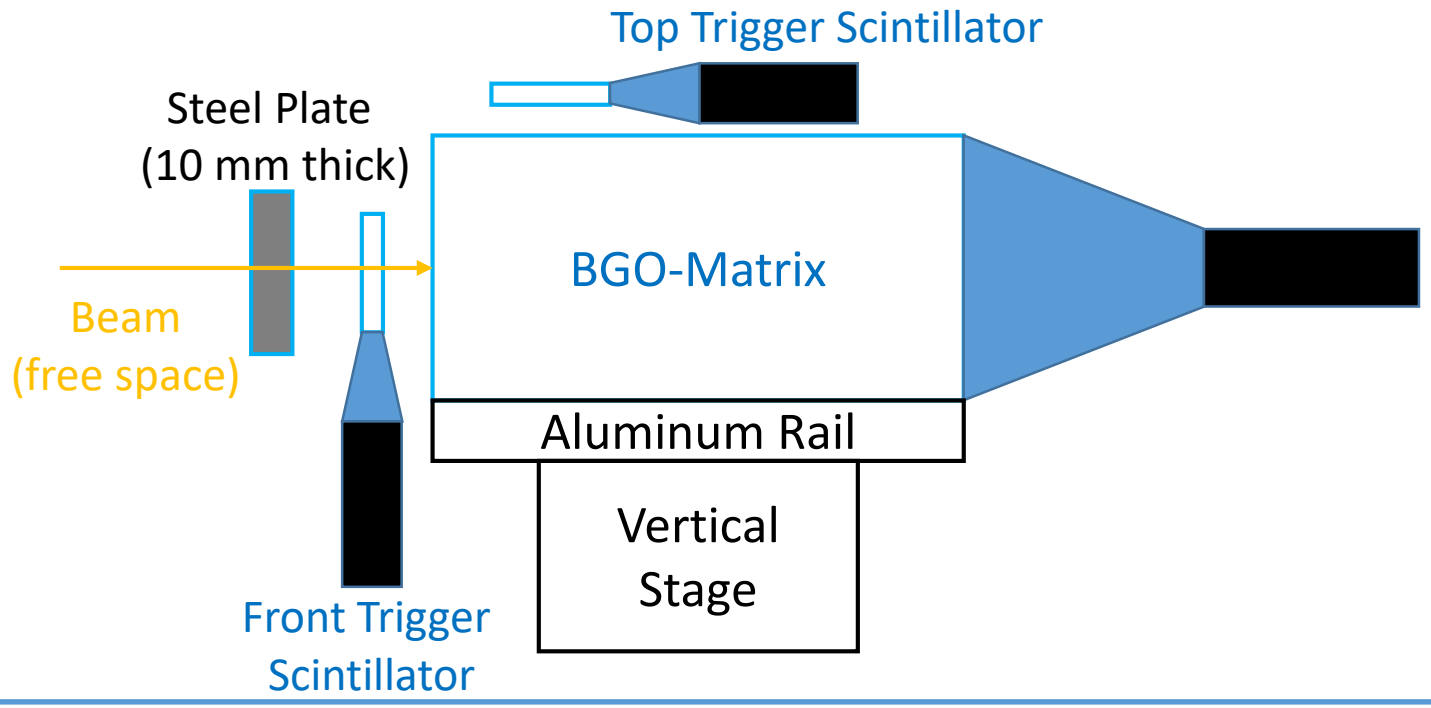




3W1 Station: with more free space and a small crane

Beam tests at BSRF-3W1 station

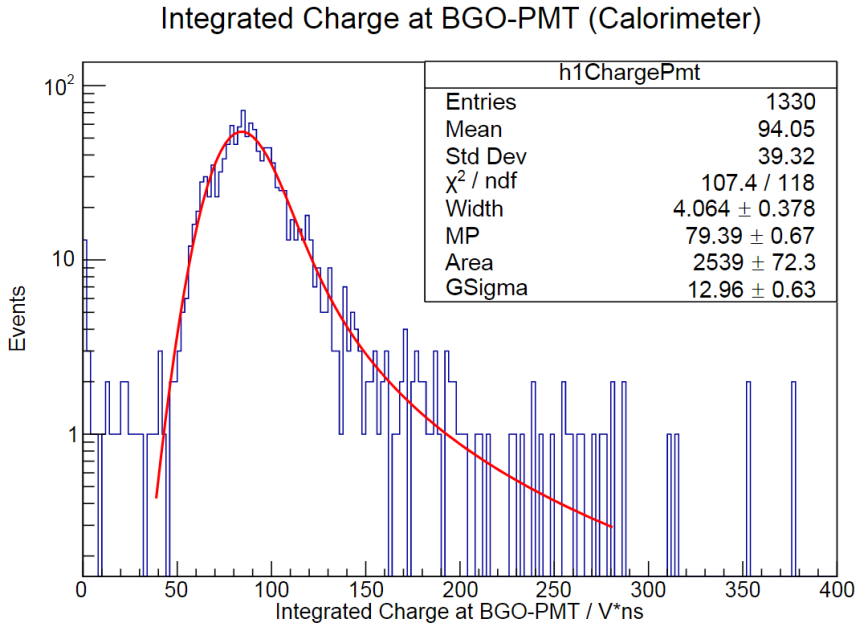
- Test stand mounted on an optical table downstream near the beam dump
  - Steel plate: stop X-rays, passive cooling (high power X-ray)
  - Front (upstream) trigger scintillator + PMT: provide coincidence signals for BGO
  - Top trigger scintillator + PMT: upstream showers, cosmic muons, beam halo (?)
- Materials in the upstream: e.g. aluminum mechanics of X-ray users



Beam tests at BSRF-3W1 station

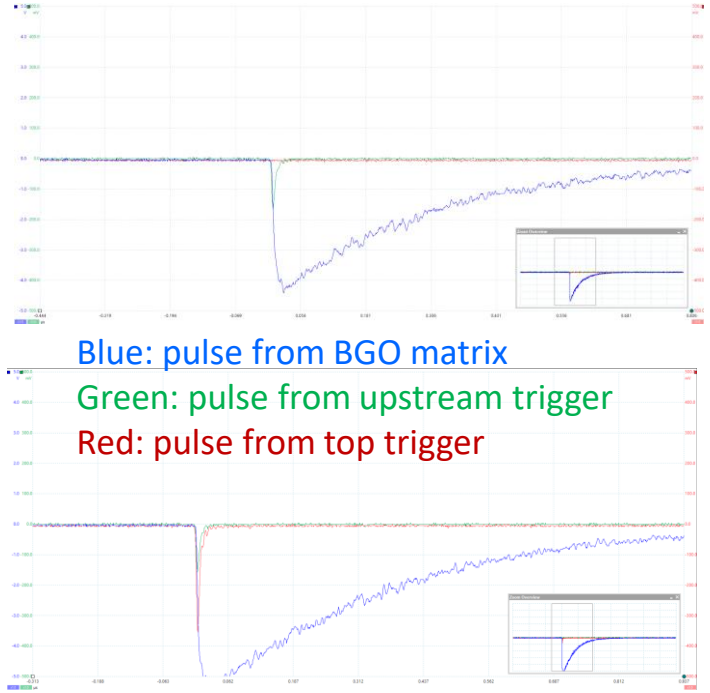
- Data taking during July 15-21, 2021: beam time shared with X-ray users
- Dedicated synchrotron radiation runs: 2.5GeV electrons in the BEPC-II storage ring
- PMT voltage tuning for S/N ratio (1-MIP response) and dynamic range (EM showers)

Single MIP response: MPV corresponds to ~90 MeV



BGO-PMT at an optimized HV (1550 V)

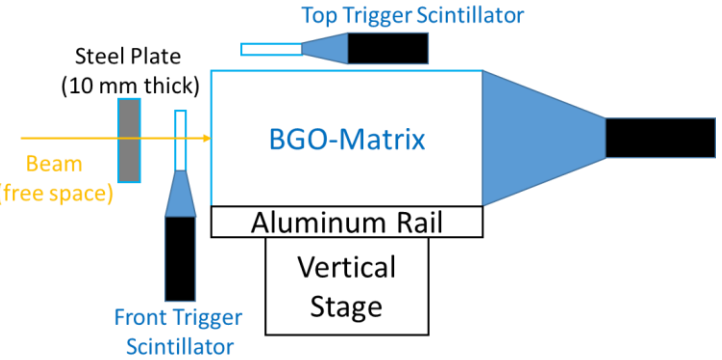
Typical events at the beam line



Blue: pulse from BGO matrix

Green: pulse from upstream trigger

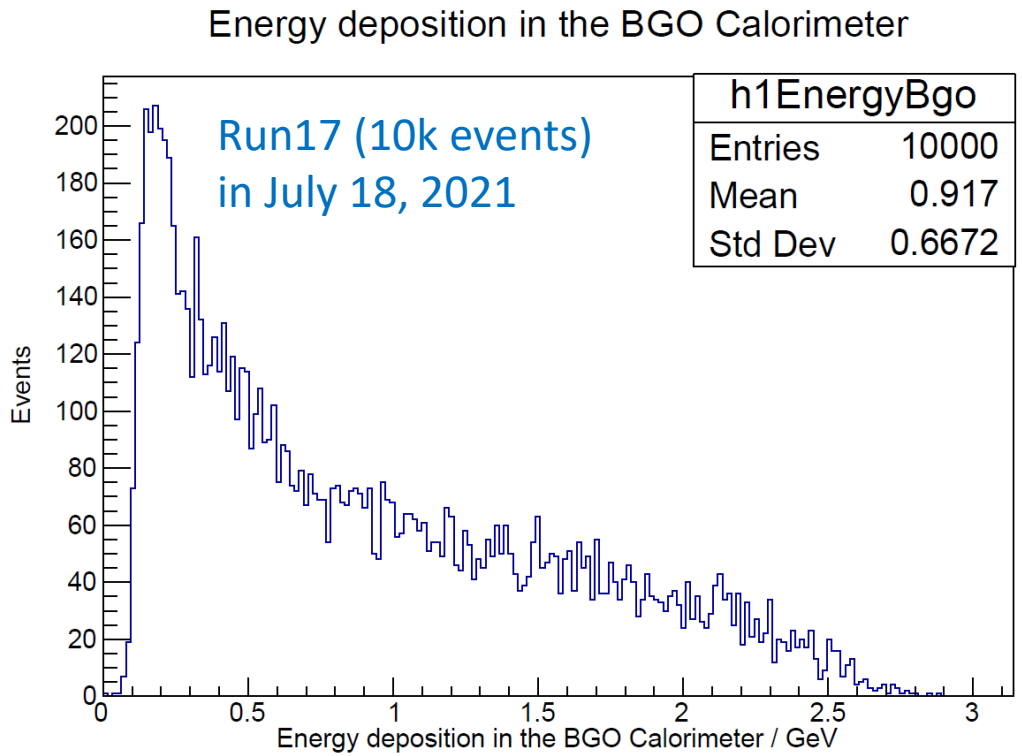
Red: pulse from top trigger

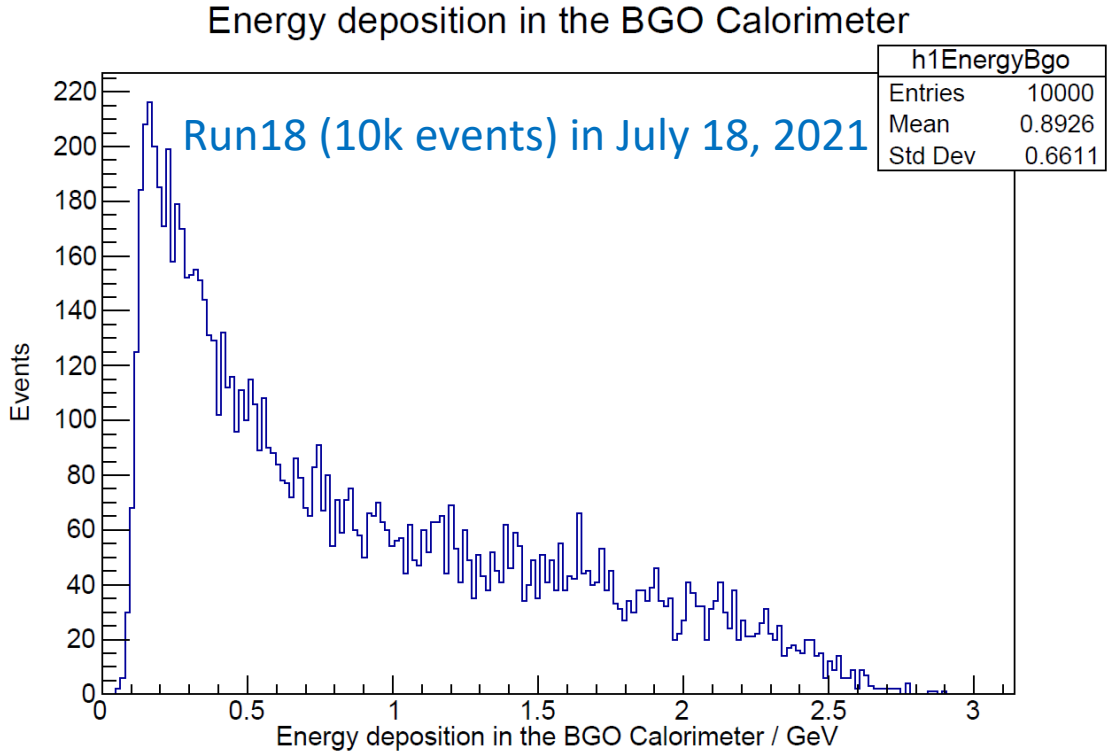


First results of beam tests: energy spectrum

- Energy deposition in BGO calorimeter (after MIP calibration)
- Measured continuous energy distributions
  - Peak at around 0.2 GeV
  - Event rate decreases with beam energy

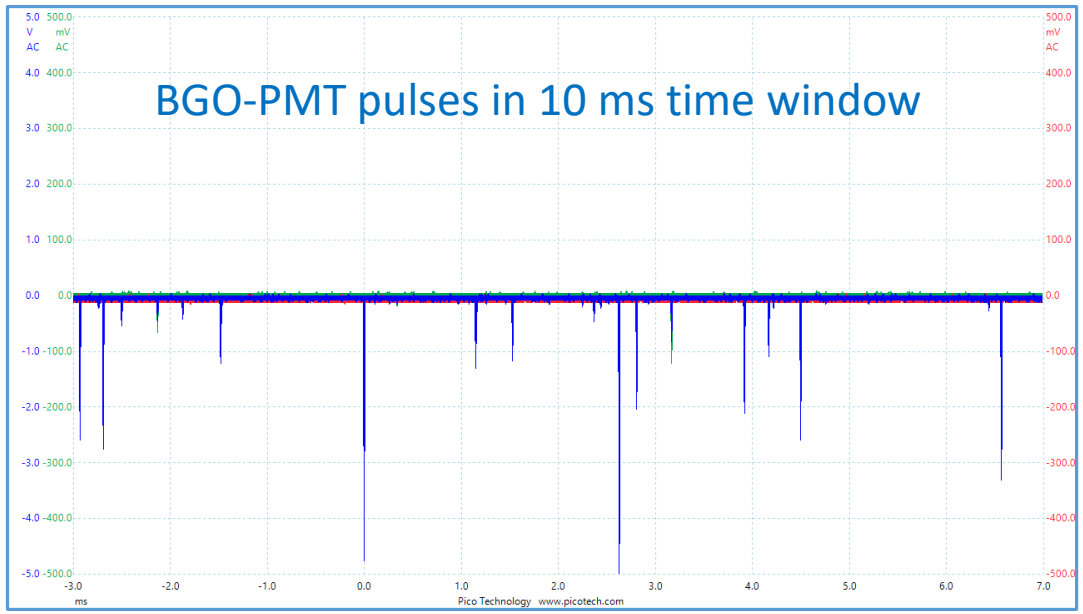
Maximum energy ~2.9 GeV, higher than nominal 2.5GeV, can be due to the limited precision of MIP calibration in the cosmic setup

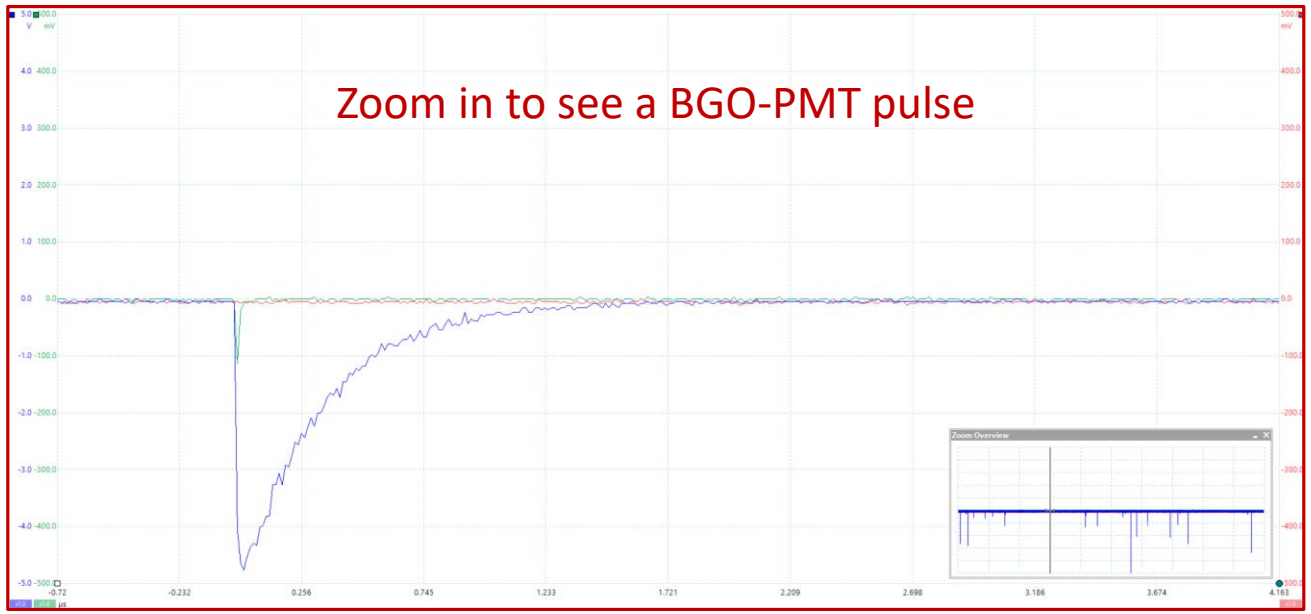




First results of beam tests: beam rate

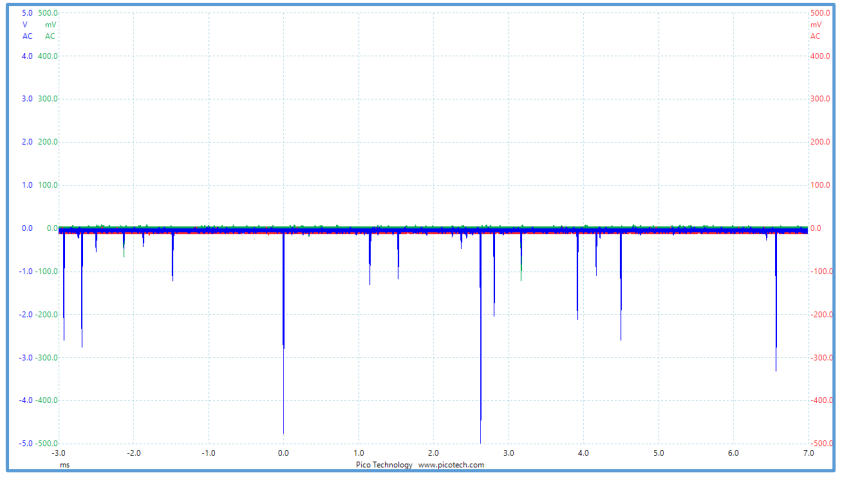
- Measurements of beam rate: pulses within a wider time window (10ms)
  - First locate multiple peaks (BGO-PMT pulses)
    - Algorithm searching for local extrema
    - Time stamps corresponding to the extrema
  - Then determine the time interval between two near-by peaks

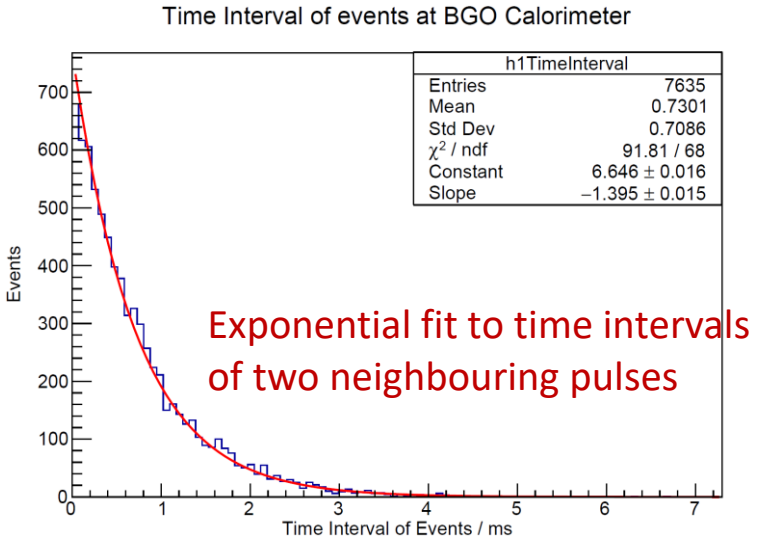


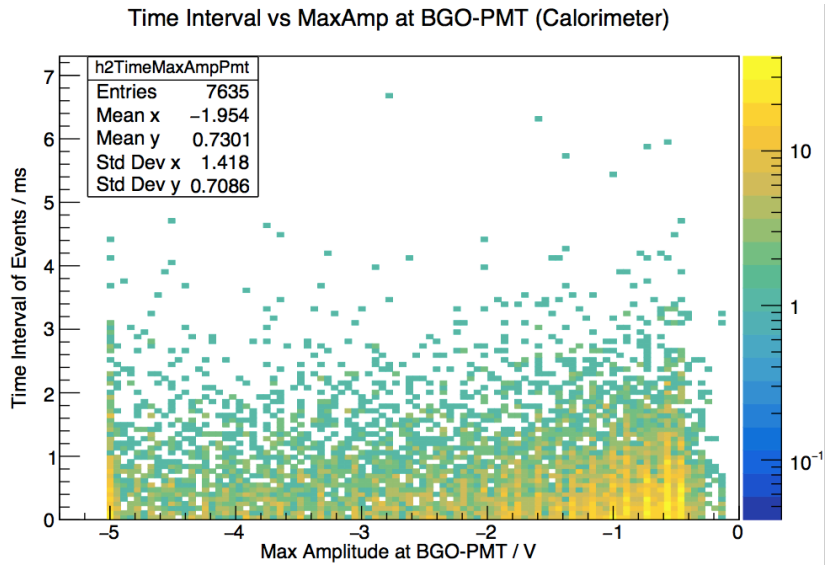


First results of beam tests: beam rate

- Measurements of beam rate: data taking within a wider time window
  - First locate multiple peaks (BGO-PMT pulses)
  - Then determine the time interval between two near-by peaks
- Time intervals: average of an exponential fit around 1.4 ms
  - All BGO-PMT pulses above threshold (200mV)
  - Also looked at its correlation with maximum pulse height (~energy deposition)

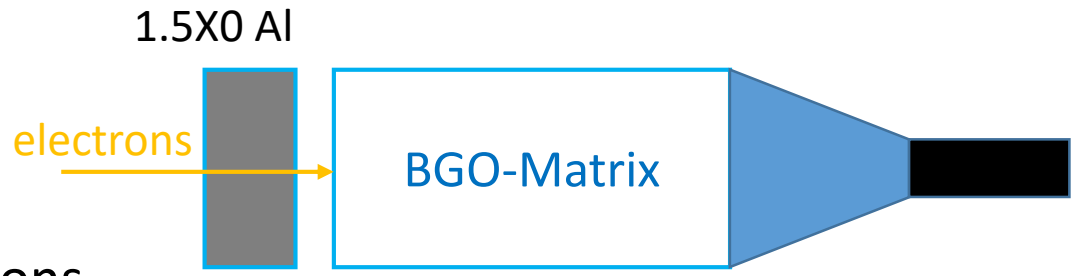




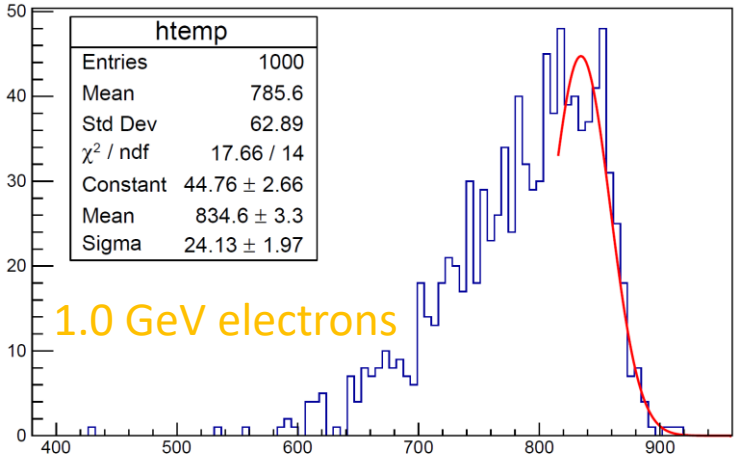


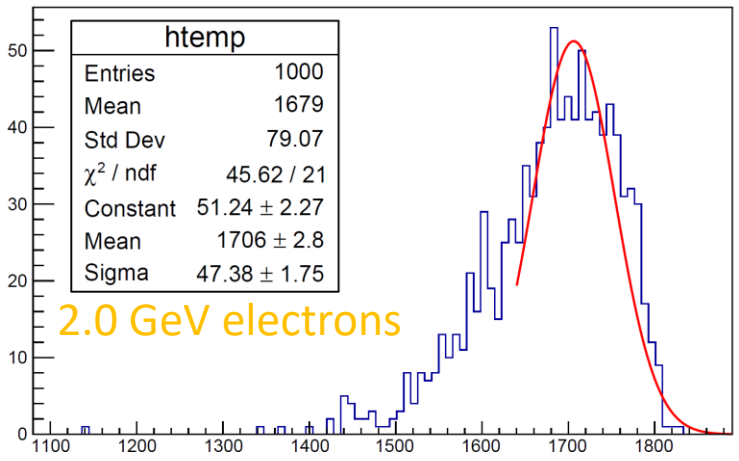
Impacts of upstream materials: Geant4 simulation

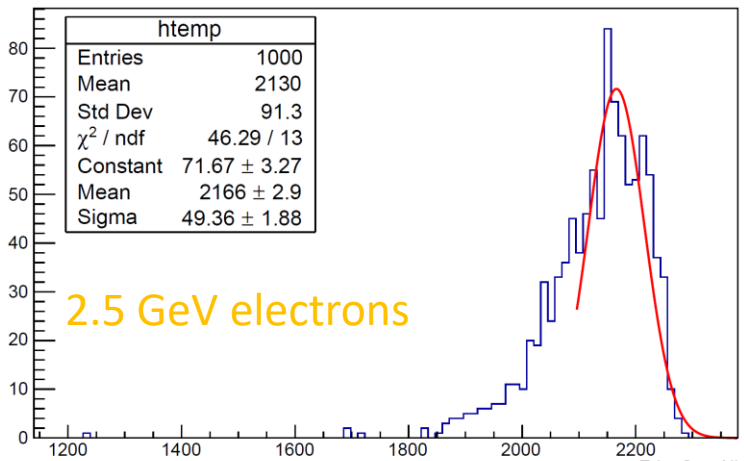
- Calorimeter setup in simulation
  - Upstream material: 1.5X0 thick aluminum plate
  - Electron beams
    - Each run at a fixed energy point, up to 2.5 GeV
  - BGO calorimeter response: sum of energy depositions
- Simulation results
  - Peak structure in BGO response; only resolution degrades



It can be inferred that the upstream electrons may already have a continuous energy distribution

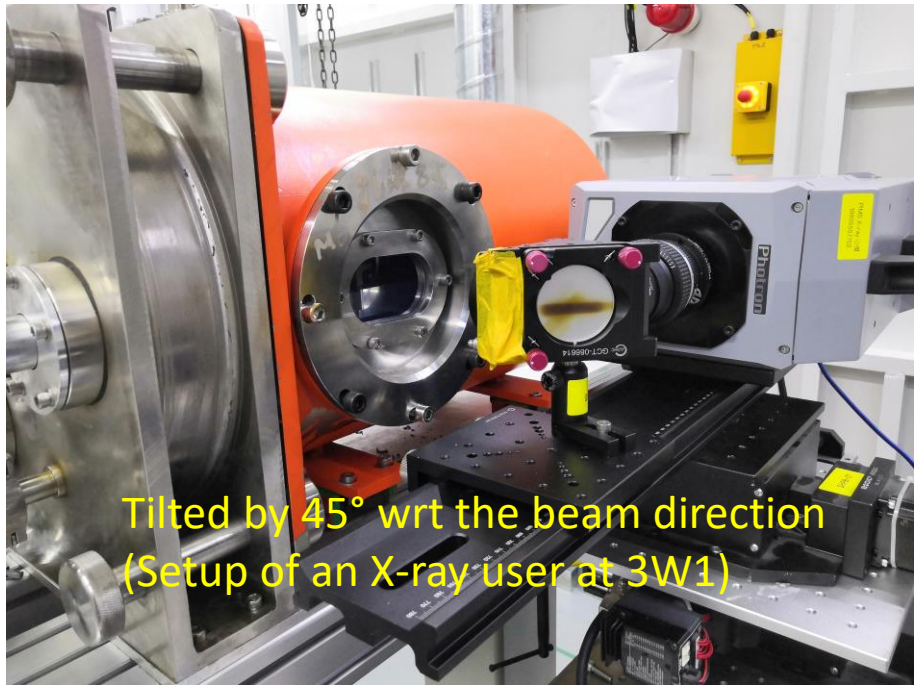


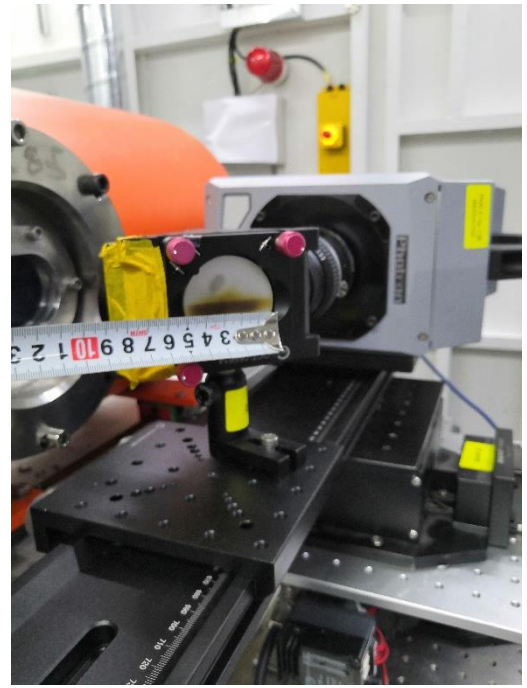




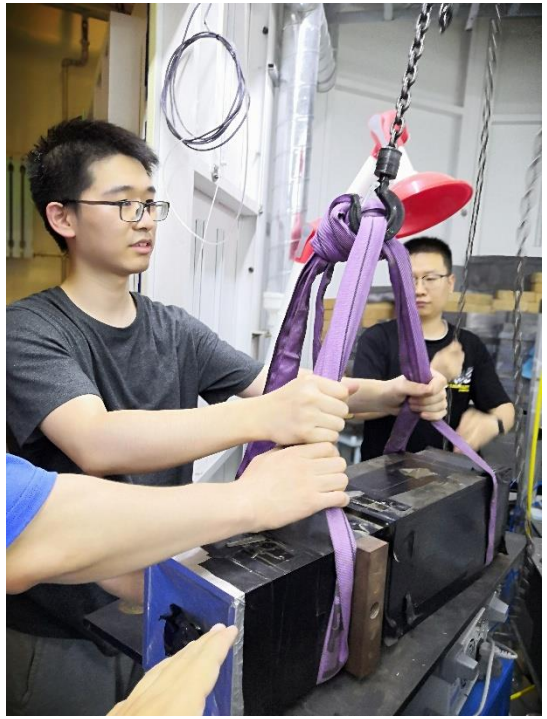
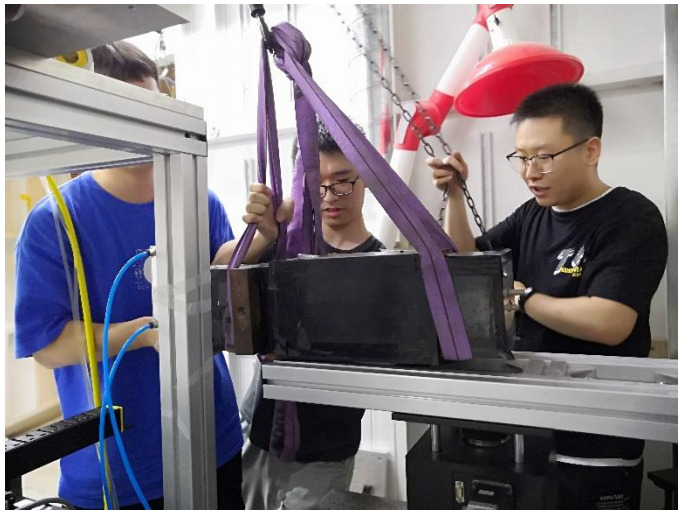
Further information on the 3W1 station

- BSRF X-ray beam profile
  - ~3cm horizontally and ~6mm vertically
  - First measured with a film: for positioning alignment
  - Also measured by a CMOS camera (of a BSRF user)





Photos and acknowledgements

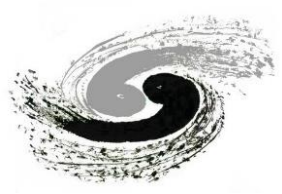




Experiences of compact dense crystals: impressive gravity

- Thanks to Baohua and Zhiyu for working together till late nights
- A big thank you to IHEP colleagues at 3W1 for their kind help and discussions
  - Xiaodong Li, Hong Shi, Yiming Yang, etc.

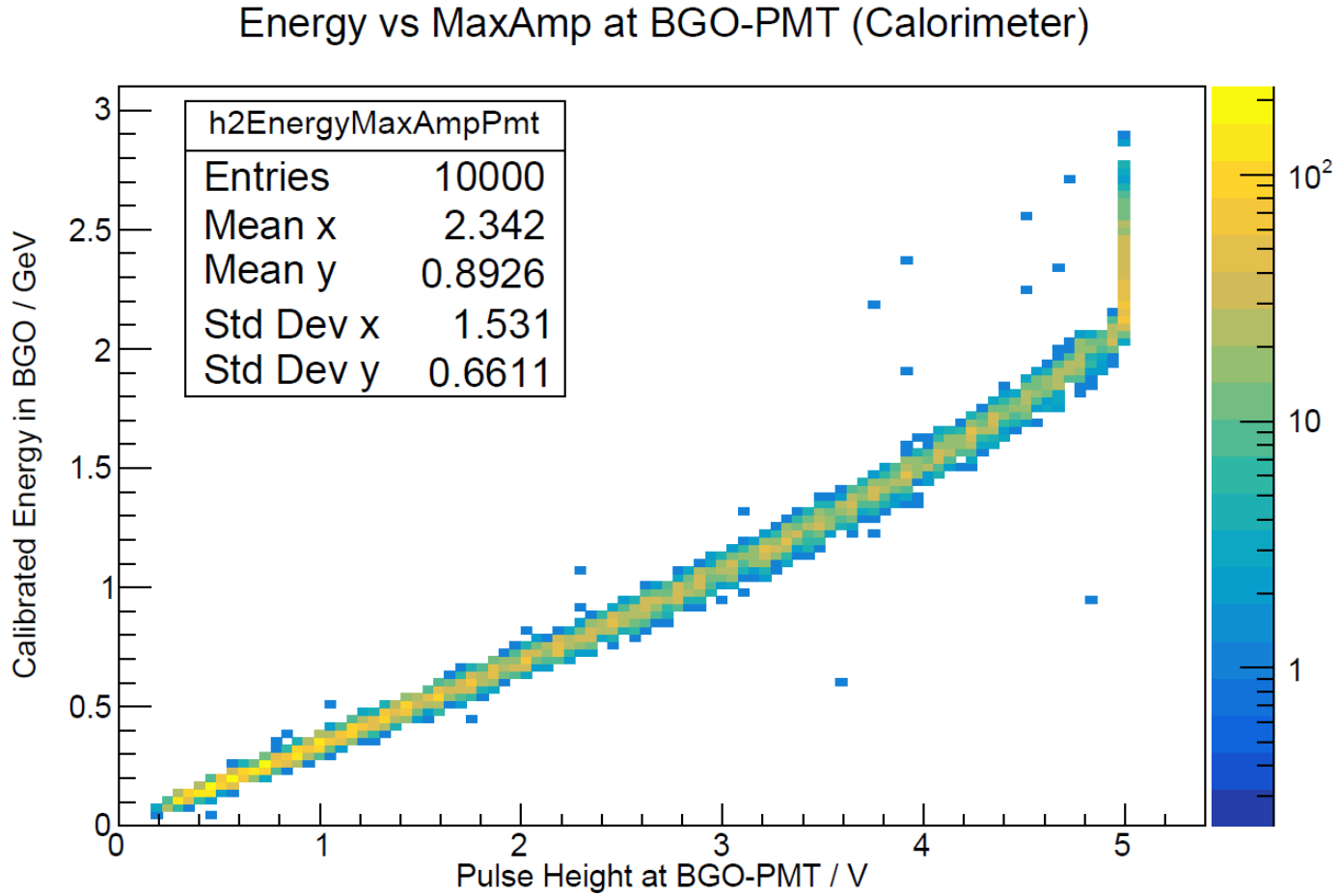
Summary

- Long data taking runs for BGO calorimeter
  - Successfully revived and showed robust operation
  - Finished MIP response calibration
- Beam tests of BGO calorimeter at a BSRF station
  - First results obtained in short time: generally preliminary
  - Measured beam energy spectrum
    - Continuous distribution: to be understood
    - Abundant in lower energy region: around ~0.2GeV
    - Still significant in high energy: e.g. above 1 GeV
  - Measured time intervals of beam particles: ~1.4ms on average
- More discussions needed
  - How to make/use it as a good testbeam option for detector prototypes



Spare Slides

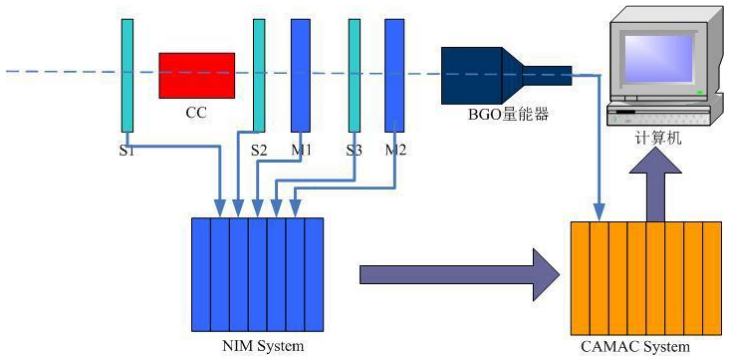
Beam energy vs. BGO-PMT pulse height

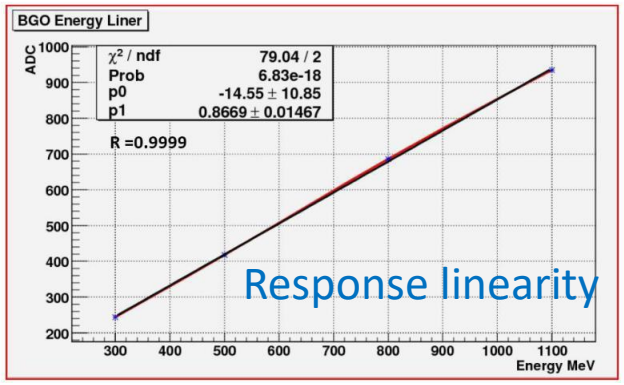


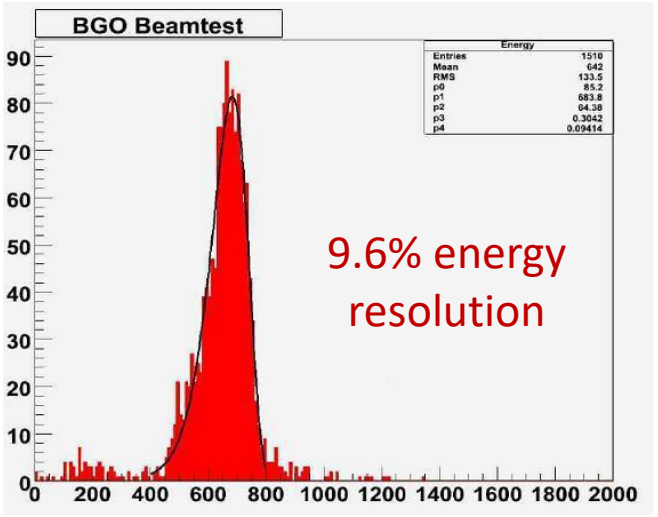
- Beam energy was already calibrated based on the cosmic ray data
- Noticeable saturation effect when BGO-PMT pulse height is around 5V

BGO calorimeter in the past beam tests

- Performance studies: response linearity and energy resolution
  - Combined tests at the IHEP BEPCII-TBF with
    - A Cherenkov Counter (CC), Multi-wire Chambers (M1,M2), Scintillator Counters (S1,S2,S3)

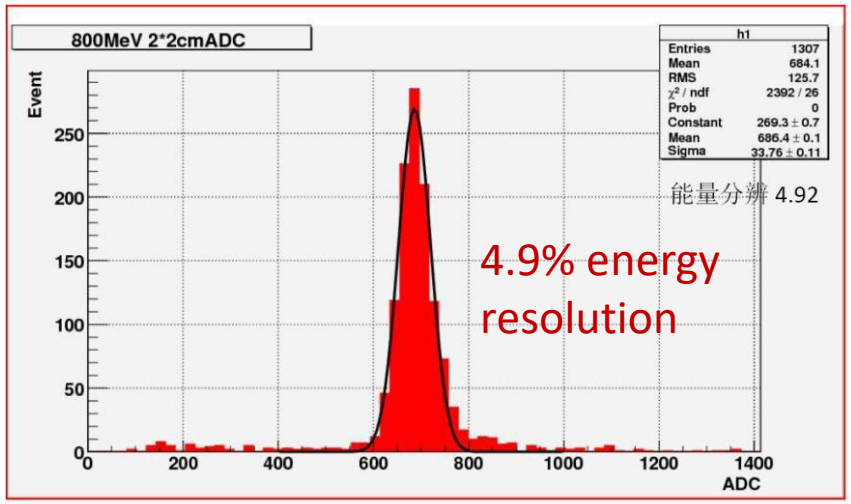






800 MeV electrons within 6x6 cm² around the calorimeter center

Energy resolution: suffered from the lateral shower leakage

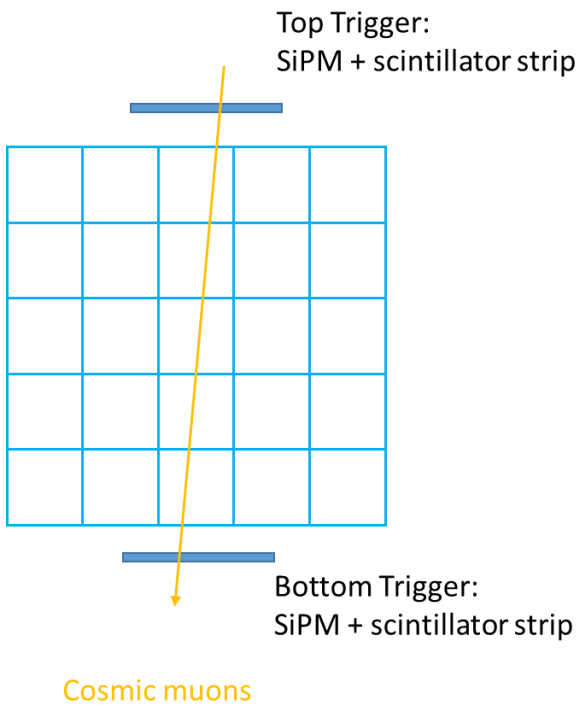


800 MeV electrons within 1x1 cm² around the calorimeter center

Plots taken from the PhD thesis of Boxiang Yu (2010), Graduate University of Chinese Academy of Sciences

Efforts to revive the BGO calorimeter

- BGO calorimeter: MIP calibration with cosmic rays
  - Done during February and March 2021



- Cosmic muons as Minimum Ionizing Particles
  - Energy deposition in BGO: 8.918 $\mathrm{MeV} \cdot \mathrm{cm}^{-1}$ on average (PDG value)
- Muons pass through 5 crystals in a row (10cm)
  - ~90 MeV: mean energy deposition for the ideal perpendicular incidence
- Cosmic-ray setup
  - Desktop HV module and PMT for BGO
  - Trigger scintillators and SiPMs
    - Power suppliers and preamps for 2 SiPMs
  - 4-channel oscilloscope (bandwidth 350MHz)
    - Trigger scheme: coincidence of 3 channels