HERD Tracker Simulation for γ-rays and Some General Issues on the Tracker

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HERD Workshop
2-3 December, 2013, Beijing

HERD Gamma-Ray Detection

- **Stated goal of HERD**
  - **"HERD must have the capability of accurate electron and gamma-ray energy and direction measurement (tens of GeV – few TeV)"**
- **However there is great interest to detect gamma-rays sources in the "medium energy", ie. hundreds of MeV to tens of GeV range (see relevant talks earlier)**
  - **Large number of interesting extragalactic sources**
  - **Fermi will likely be decommissioned when HERD will be in operation**
  - **HERD can overlap and extend to the lower side of the sensitivity of CTA (>tens of GeV)**
  - **Potential long operation time (~10 years) makes gamma-ray astronomy specially suitable for HERD**
    - **Detecting new sources and continuously monitoring known sources**
    - **Serve a large astronomy community**

Challenges of Gamma-Ray Detection

- It is challenging to detect medium energy gamma-rays because of the conflicting requirements with the photon conversion technique
  - Higher detection efficiency ⟹ thicker tungsten converter plates
  - Better angular resolution ⟹ thinner tungsten converter plates
- Solution: many thin tungsten layers
  - limited by cost of silicon detector and acceptance (Field of View)
- Useful to have good energy resolution for spectral measurements
  - Calorimeter with good energy resolution (<10% at 1 GeV?)
    - But limited to conversions that deposited large fraction of energy in the calorimeter
- Trigger issue
  - Using calorimeter for trigger
    - only sensitive to gamma-rays above a few hundred MeV
  - Using tracker trigger
    - complex electronics and trigger algorithms

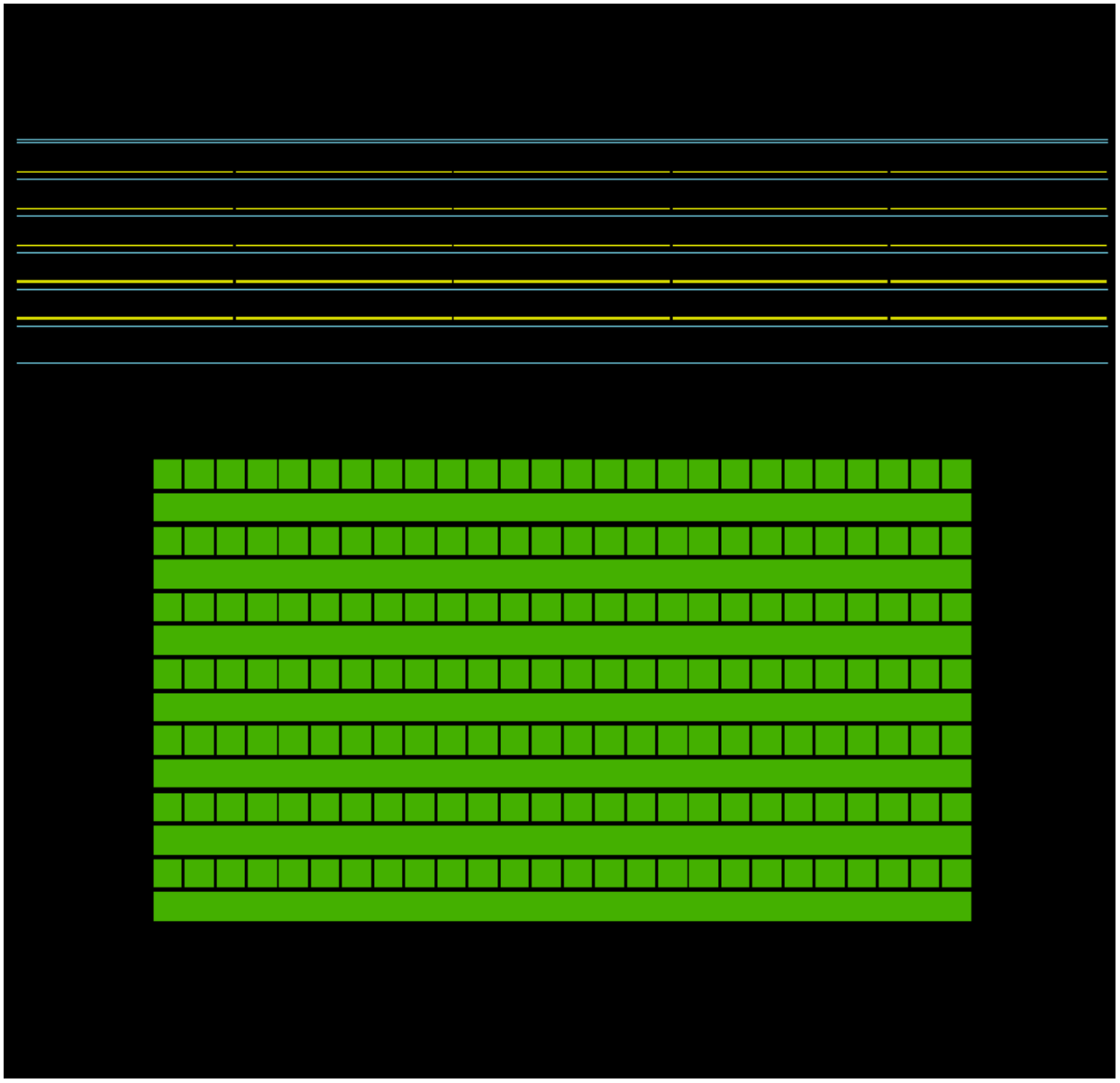
Tracker Layout Optimization for γ-Ray

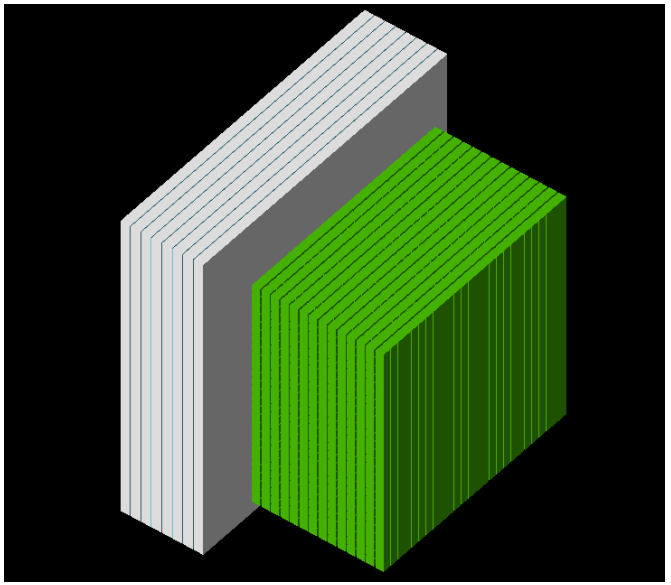
- Concentrate on the "central" part
- Original "high energy" layout
  - 7 double-layers of Si + 5 layers of W (3x1mm + 2x2mm)
  - Total 5mm = $2X_0$, high conversion probability
    - But too thick for GeV photons and below
- Compare total thickness vs number of layers with several thinner layouts
  - 8 double-layers of Si + 5 layers of W (3x0.5mm + 2x1mm, total $1X_0$)
  - 8 double-layers of Si + 5 layers of W (5x0.5mm, total $0.71X_0$)
  - 8 double-layers of Si + 5 layers of W (5x0.3mm, total $0.43X_0$)
  - 11 double-layers of Si + 8 layers of W (8x0.4mm, total $0.91X_0$)
  - 11 double-layers of Si + 8 layers of W (8x0.3mm, total $0.68X_0$)
- Note: Fermi $1.044X_0$ in 16 layers(12x0.095mm + 4x0.72mm, ~4mm total)

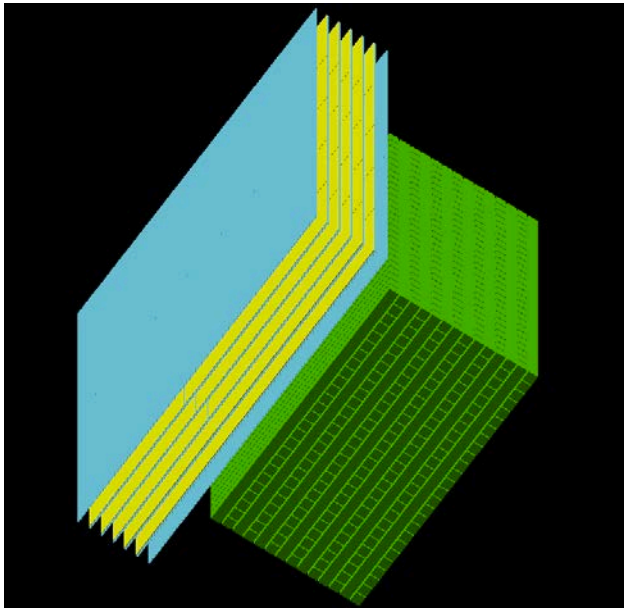
Calorimeter in the Simulation

- **Simply scale up the DAMPE BGO calorimeter**
  - **BGO bar dimensions: 2.5x2.5x71.25 cm^3**
  - **7 double layers, each layer with 26 bars**
  - **Distance between bars in a layer: 4mm**
  - **Distance between 2 layers: 2.5mm**

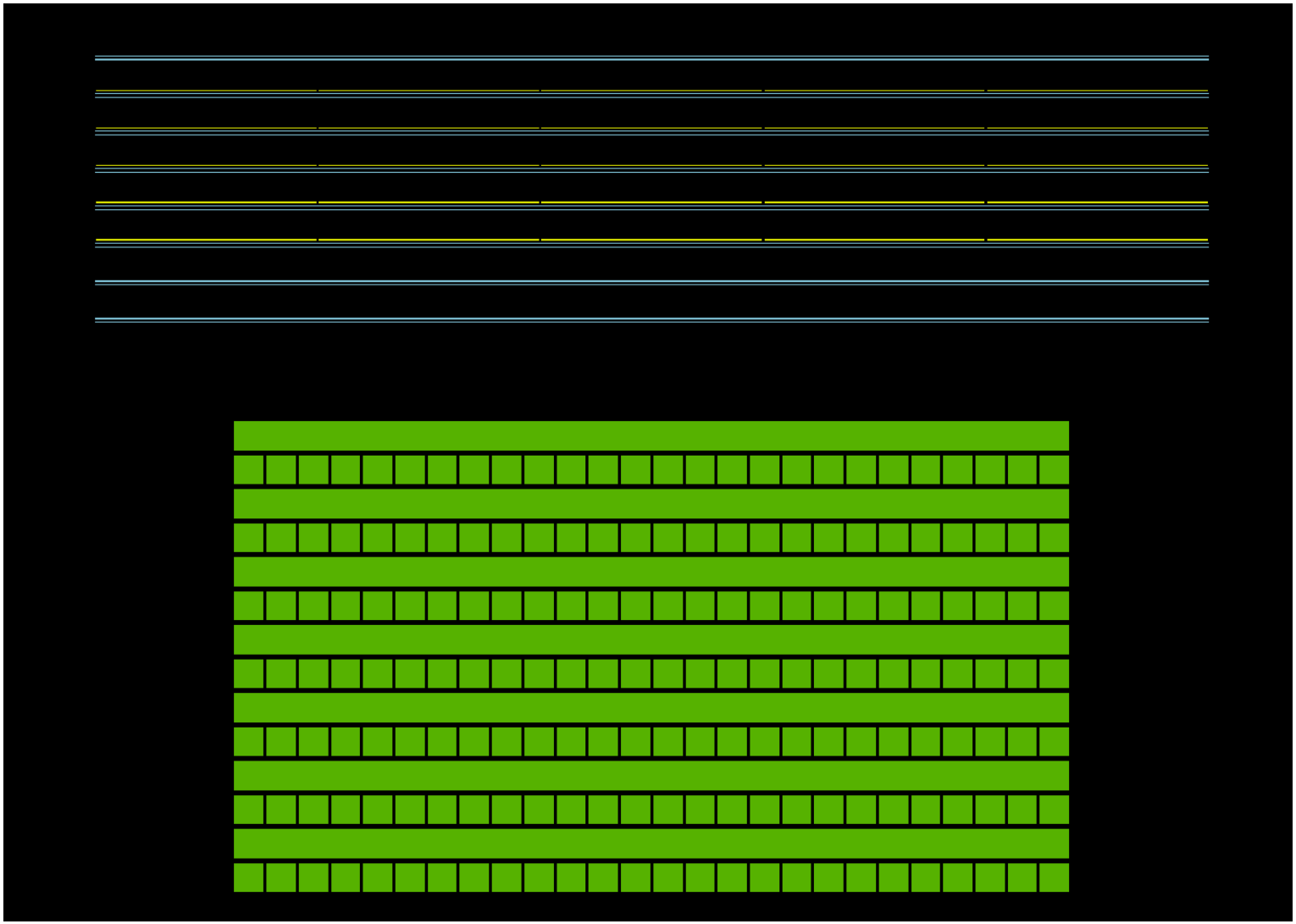
“High Energy 5/7” Layout



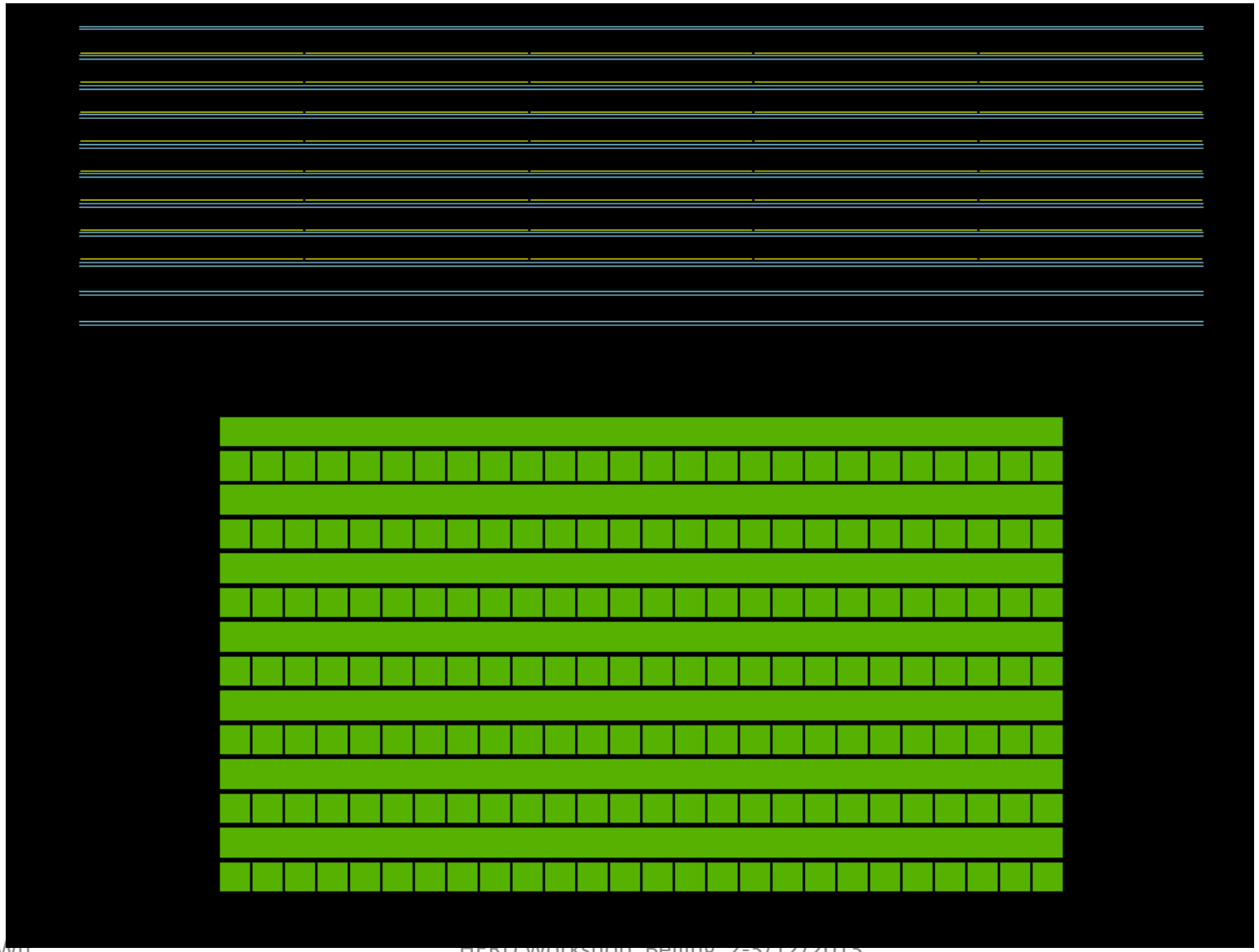




“5/8” Layouts



“8/11” Layouts



Detailed Tracker Layout

- A ladder is made of 5 DAMPE silicon strip detector (SSD)
  - SSD size 9.5x9.5cm^2, sensitive area 92.928x92.928cm^2, 320μm thick
  - Distance between SSD on a ladder: 80μm
- A silicon layer has 20 ladders, in 2 columns
  - Distance between ladders (lateral and head-to-head): 80μm
  - One silicon layer has 100 SSD, ~0.9m^2 silicon area (0.86m^2 sensitive)
- Size of W plate = 18.808x18.808cm^2, covering 2x2 SSDs
- Distance between x- and y-view tracking layers: 2mm
- Distance between W plate and next Si layer: 1.6mm
- Distance between two double-layers
  - 32 mm for 5 W-layer configurations
  - 25 mm for 8 W-layer configurations

Details of Simulation

- Use the DAMPE software framework (DmpSoftware)
- Use Geant4.9.6
  - Default physics list QGSP_BIC
  - Range cut 10 μm in Si and W, 700μm in other material
- Digitization of STK floating strip readout
  - Simple charge sharing using AGILE coefficient, very similar to those obtained from Spice RC network simulation of DAMPE SSD
- BGO simulation: only energy deposit simulated, no digitization
- No material on support structure structure
  - Results shown here are preliminary

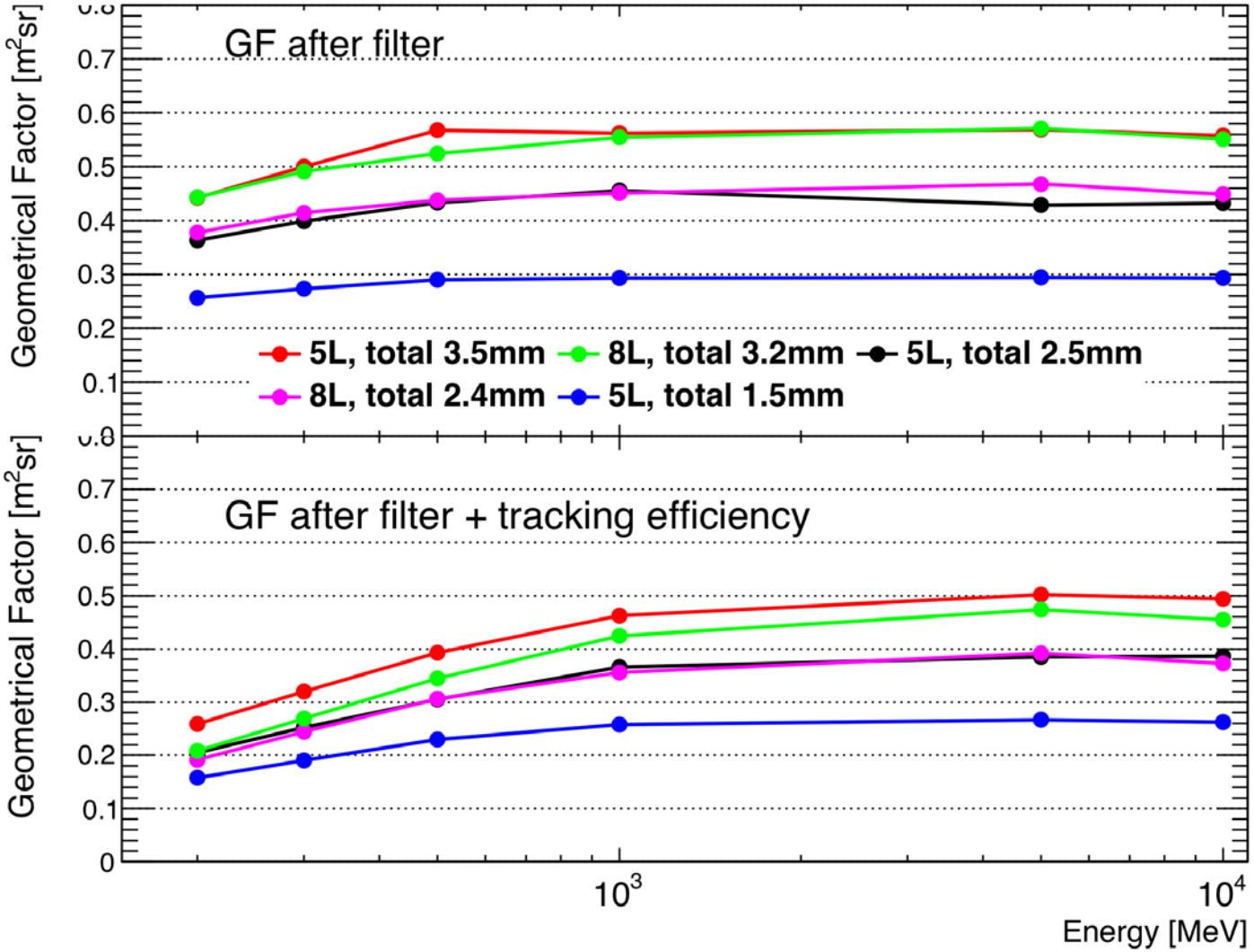
Photon Generation and Filter

- **Generate inward photons of fixed energy from a sphere englobing the payload**
- **Filter to ensure photon is roughly with the acceptance**
  - **Require photon theta >100 deg (+z pointing upward)**
  - **Reject photon starting below the top surface of BGO**
  - **Photon should extrapolate to within the top surface of BGO**
  - **Total energy deposited in the BGO > 100 MeV**
  - **Total energy deposited in the BGO > 70% of the photon energy**
  - **At least 1 x- and 1 y BGO layer has energy**
  - **At least 1 hit found in the tracker**
  - **Photon should convert above the bottom of the lowest W plate**

Track Reconstruction

- Cluster finding
  - Special care needed to for breaking up long clusters
- Track finding
  - Seeded by direction reconstructed in the calorimeter
    - Energy deposited in the BGO > 100 MeV
    - Reconstructed position at each layer: center of gravity of energy
    - At lease 1 x- and 1 y-layer has energy
  - Use Kalman filter, taking into account tungsten material crossed by the track
- Algorithms can be further refined so results are very preliminary
  - Pattern recognition can be improved
  - Detector condition can be worse (dead channels, noise, truncation, …)

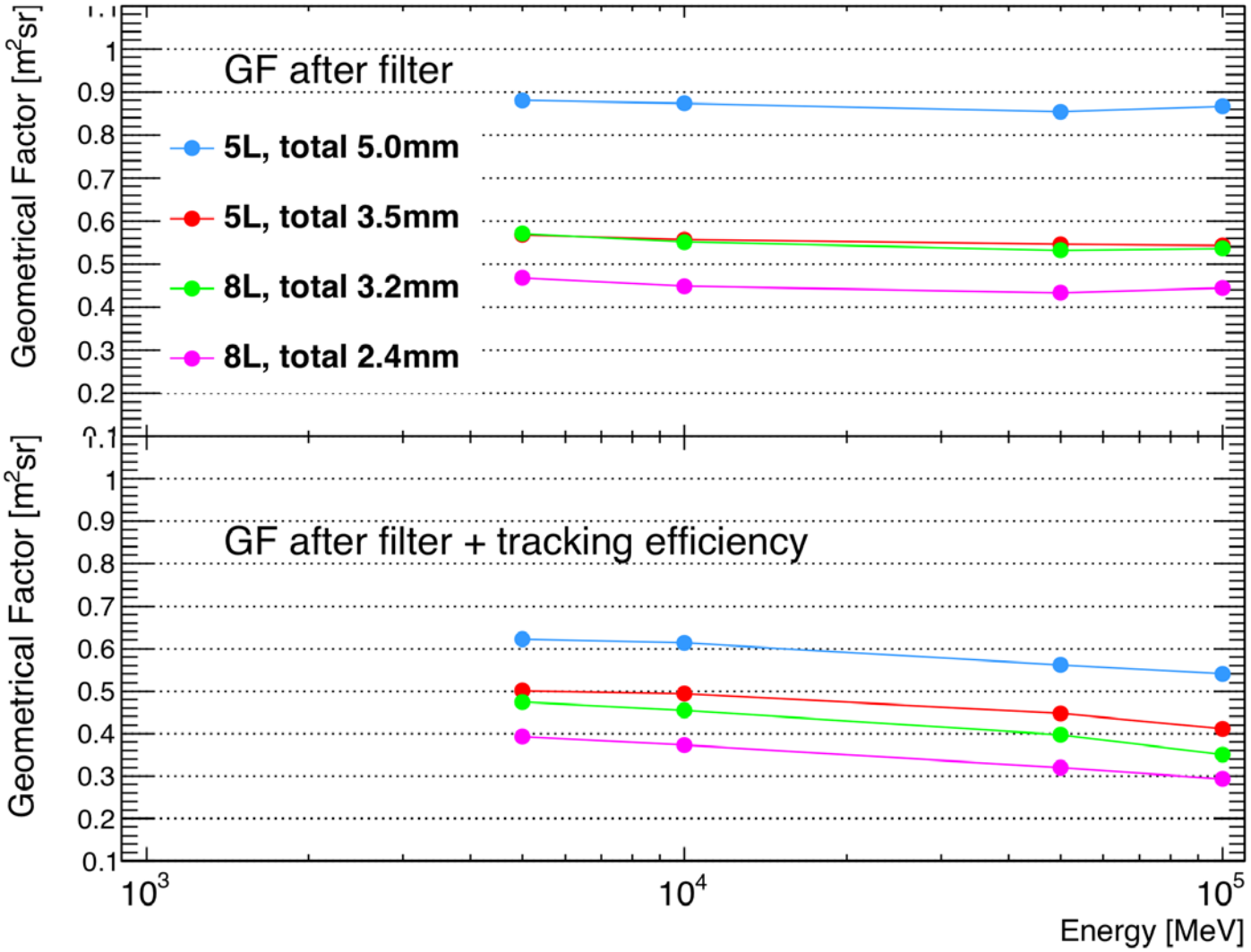
GF of Converted γ–Ray, Low Energy



GF scales with total W thickness

Tracking efficiency drops significantly below 1GeV because of MS

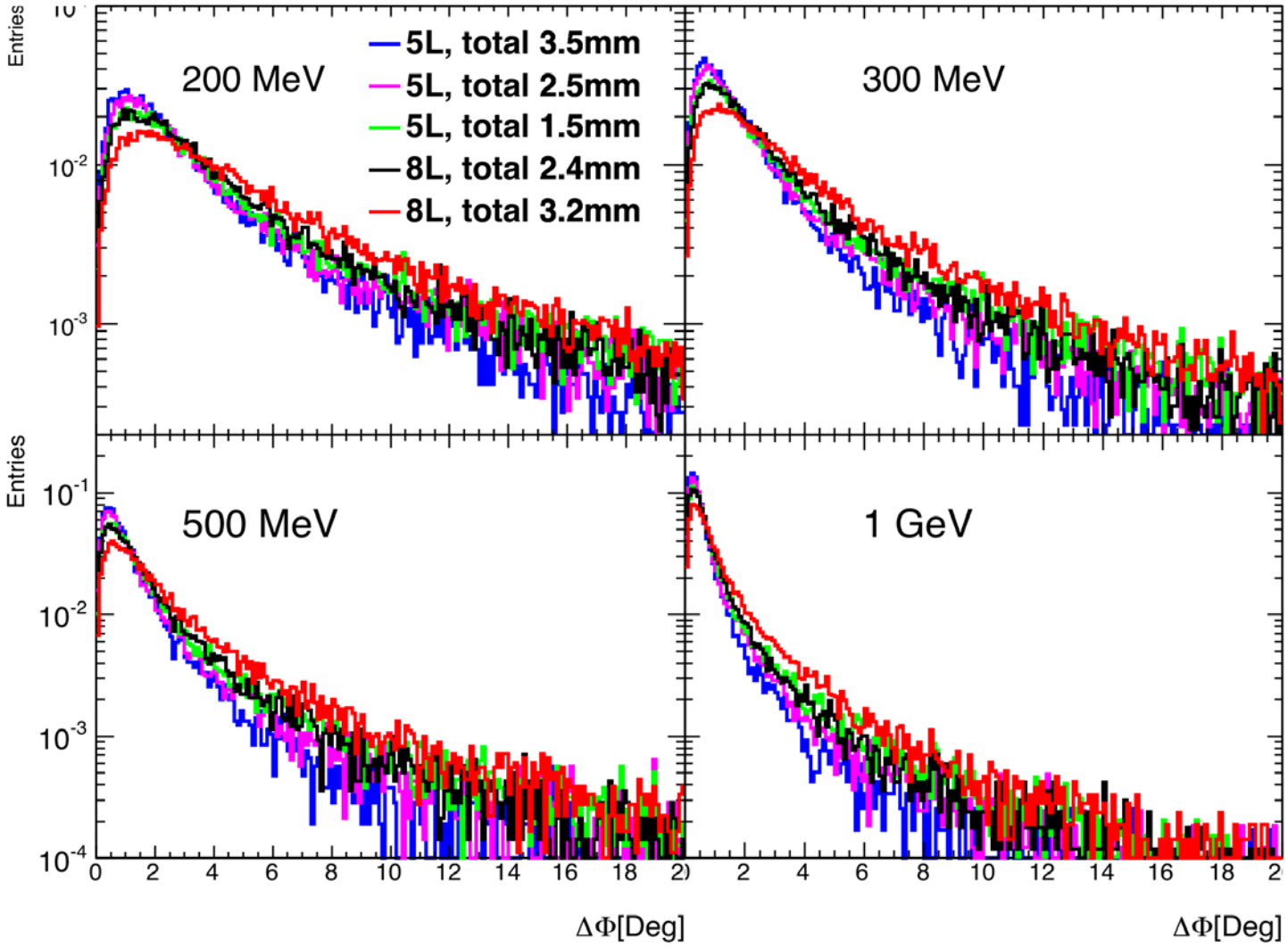
GF of Converted γ-Ray, High Energy



GF scales with total W thickness

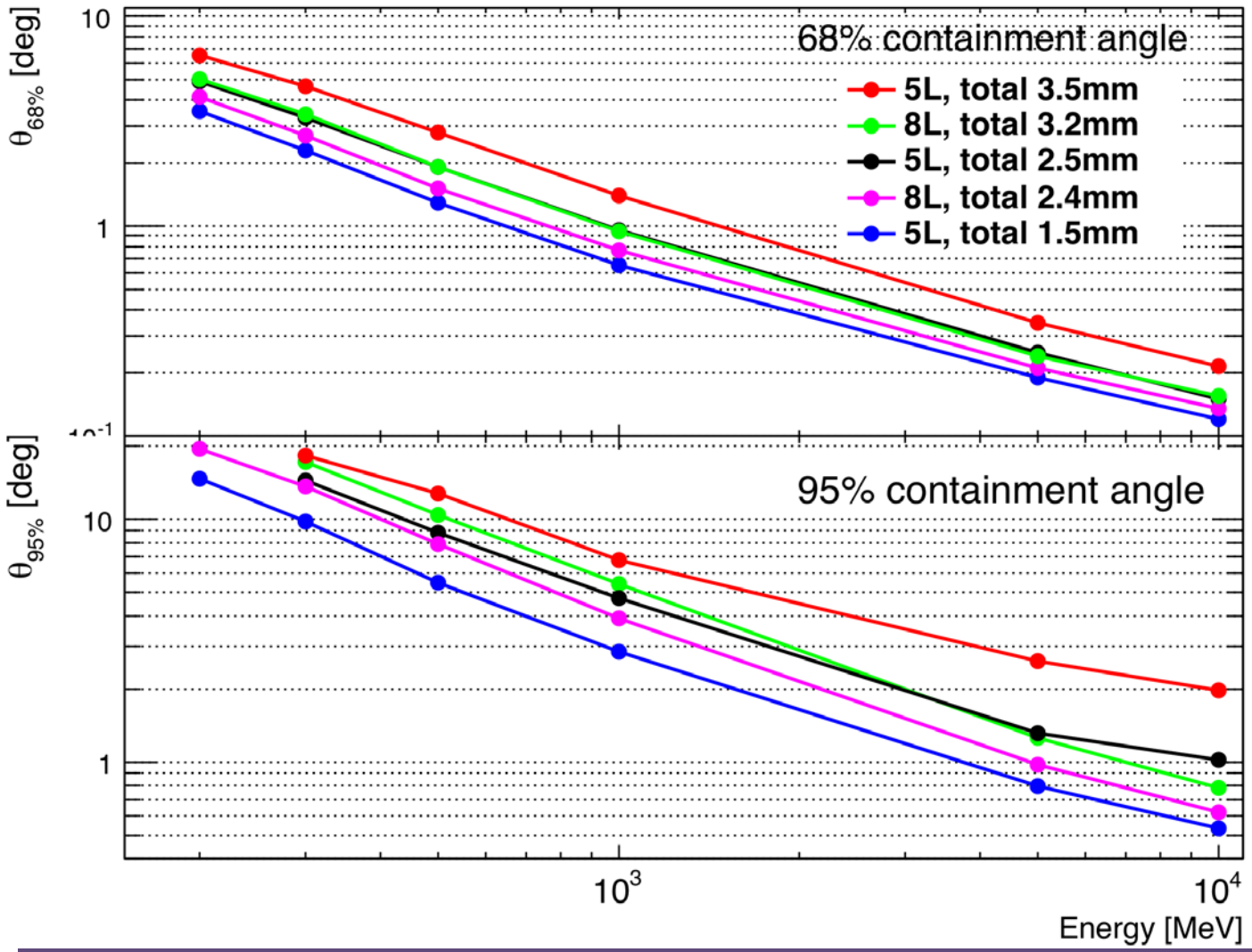
Tracking efficiency drops at high energy because of pattern recognition

Angular Resolution, Low Energy



Angular resolution defined mainly by W-thickness of single layer

68% & 95% Containment Angle, Low E

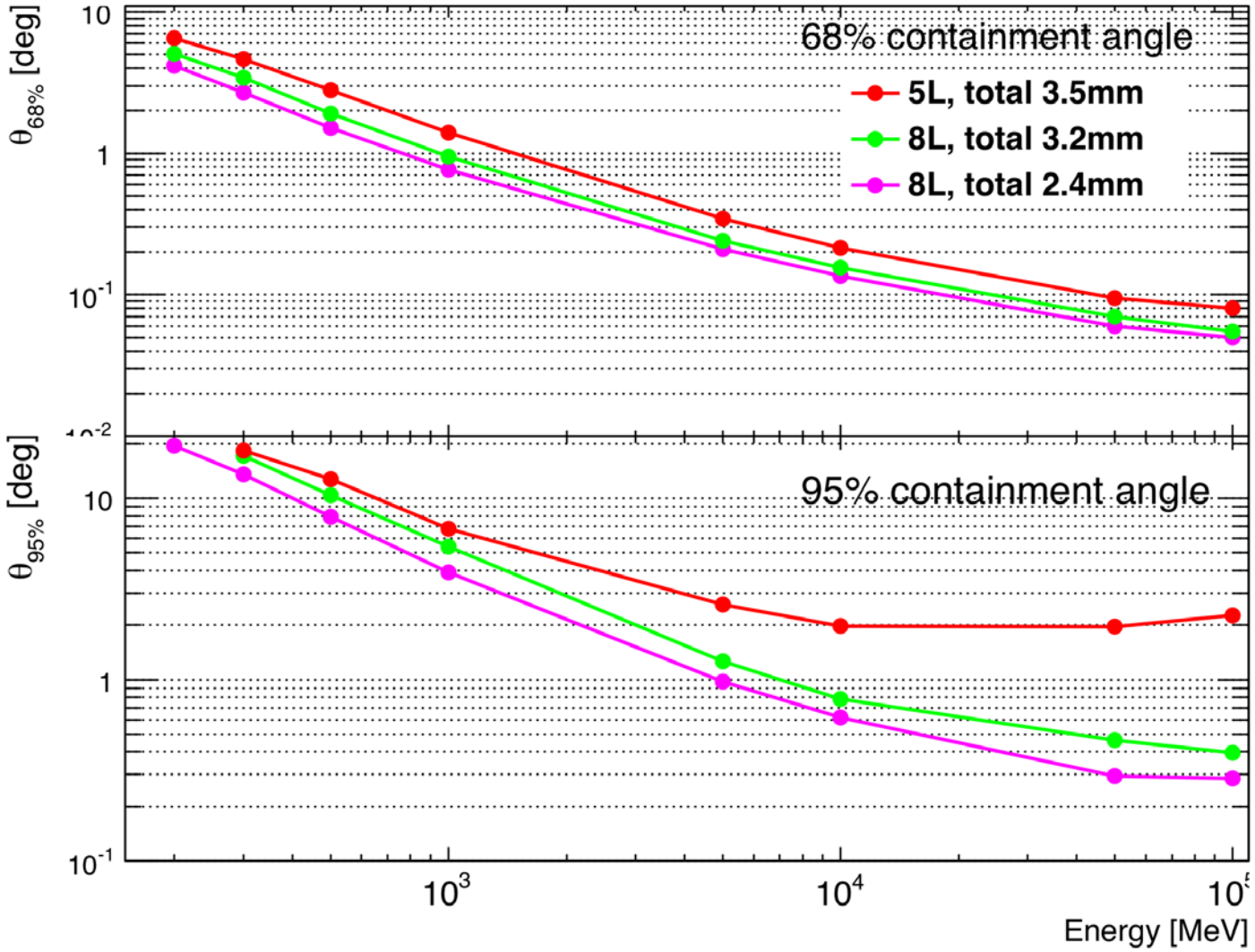


Core resolution depends mainly on MS before the first Si hit, ie. W-thickness of a single layer

Tail mainly due to "bad" track (wrong hit or wrong track), so also affected by number of layers

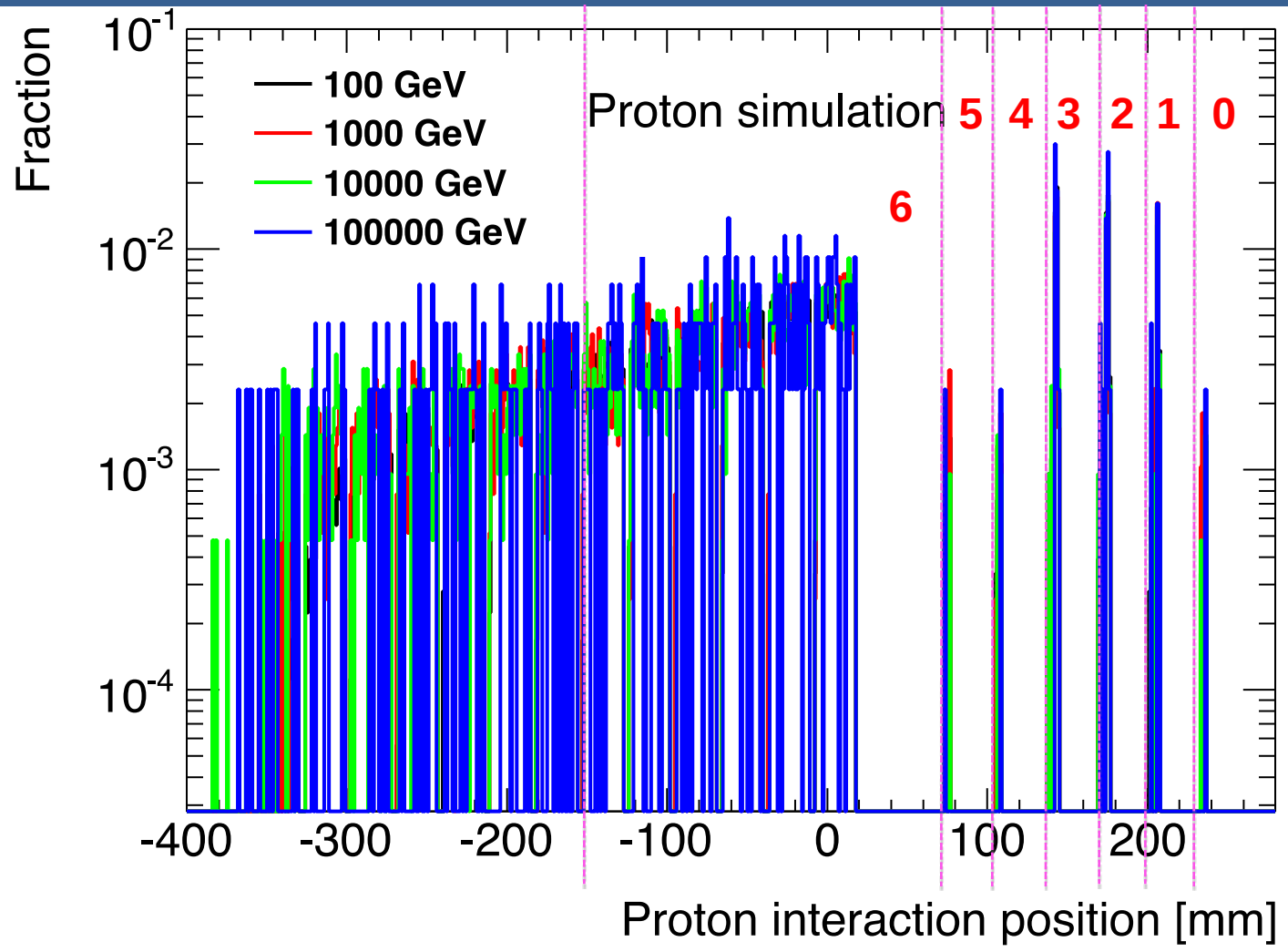
Tail can be improved by better pattern recognition and tighter cut, but will impact on efficiency

68% & 95% Containment Angle, High E



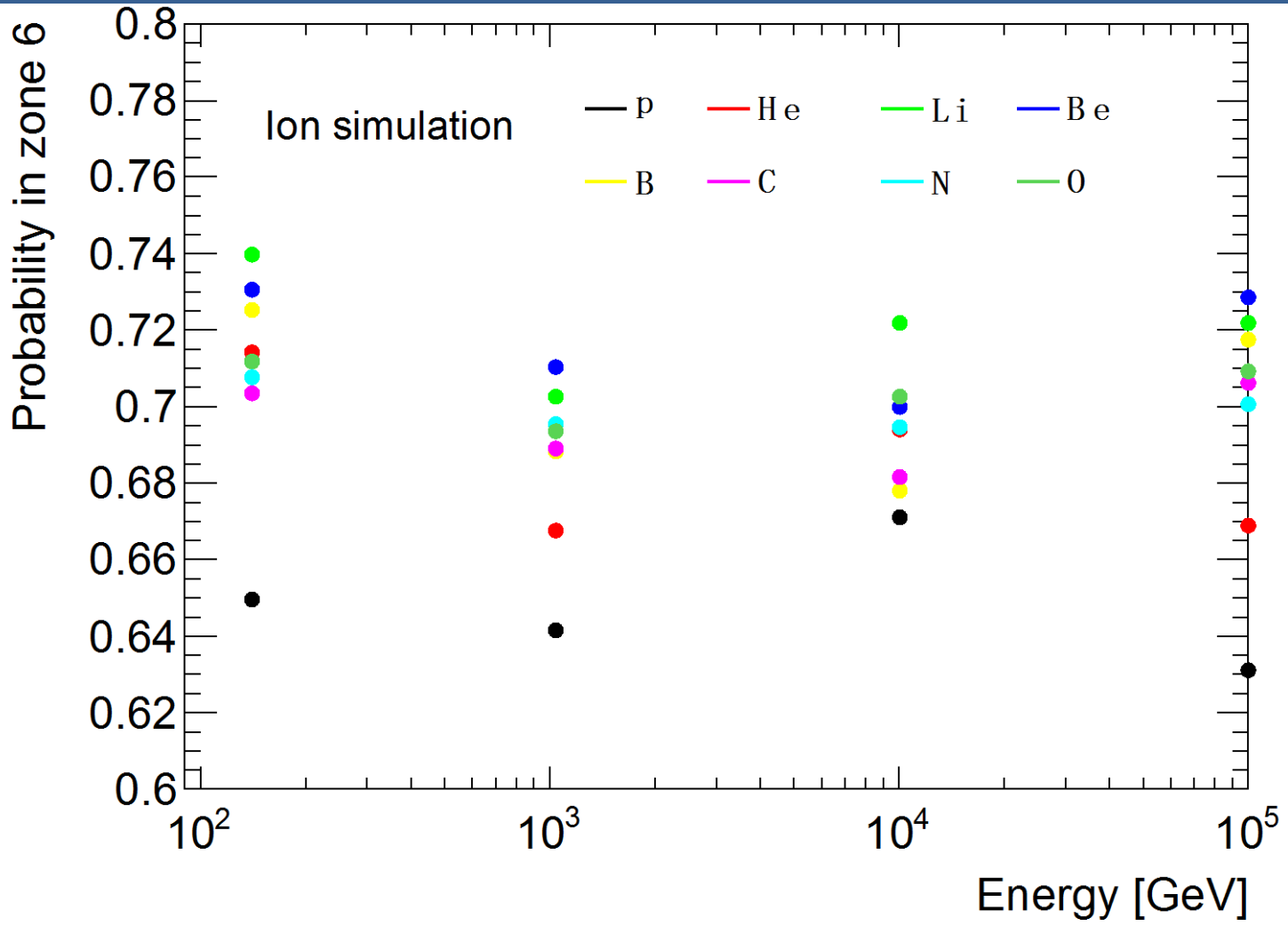
Pattern recognition gets more difficult at high energy for thick converters. Note unconverted γ-ray at high energy can be used

DAMPE: Proton Interaction Position



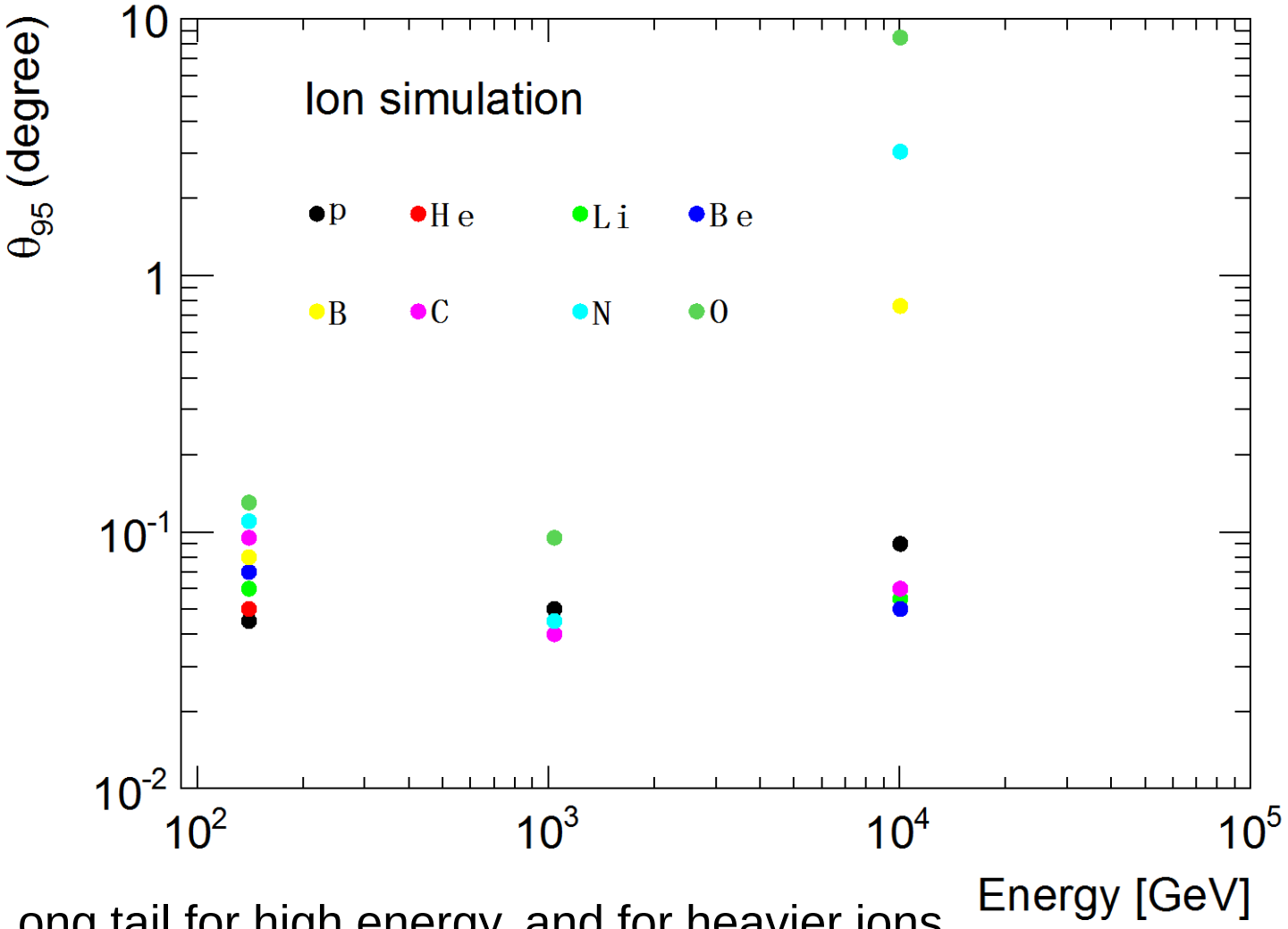
Interaction position influence the tracking precision and the number of charge measurements

DAMPE: Ion Interaction Prob. in Zone 6



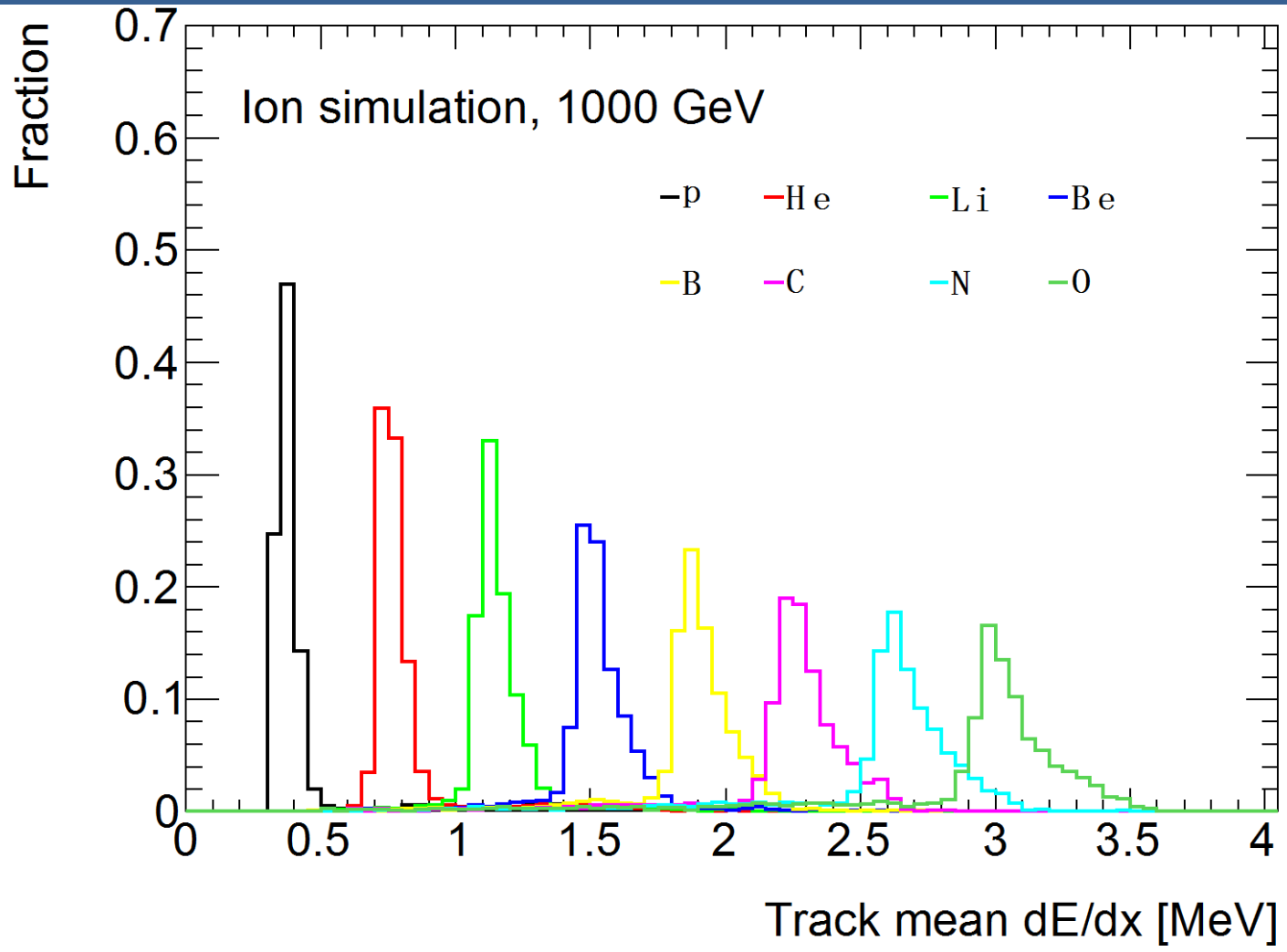
~ 60-75% interaction probability in first 6 layers of BGO

DAMPE: θ_{95} of Ions in zone 6



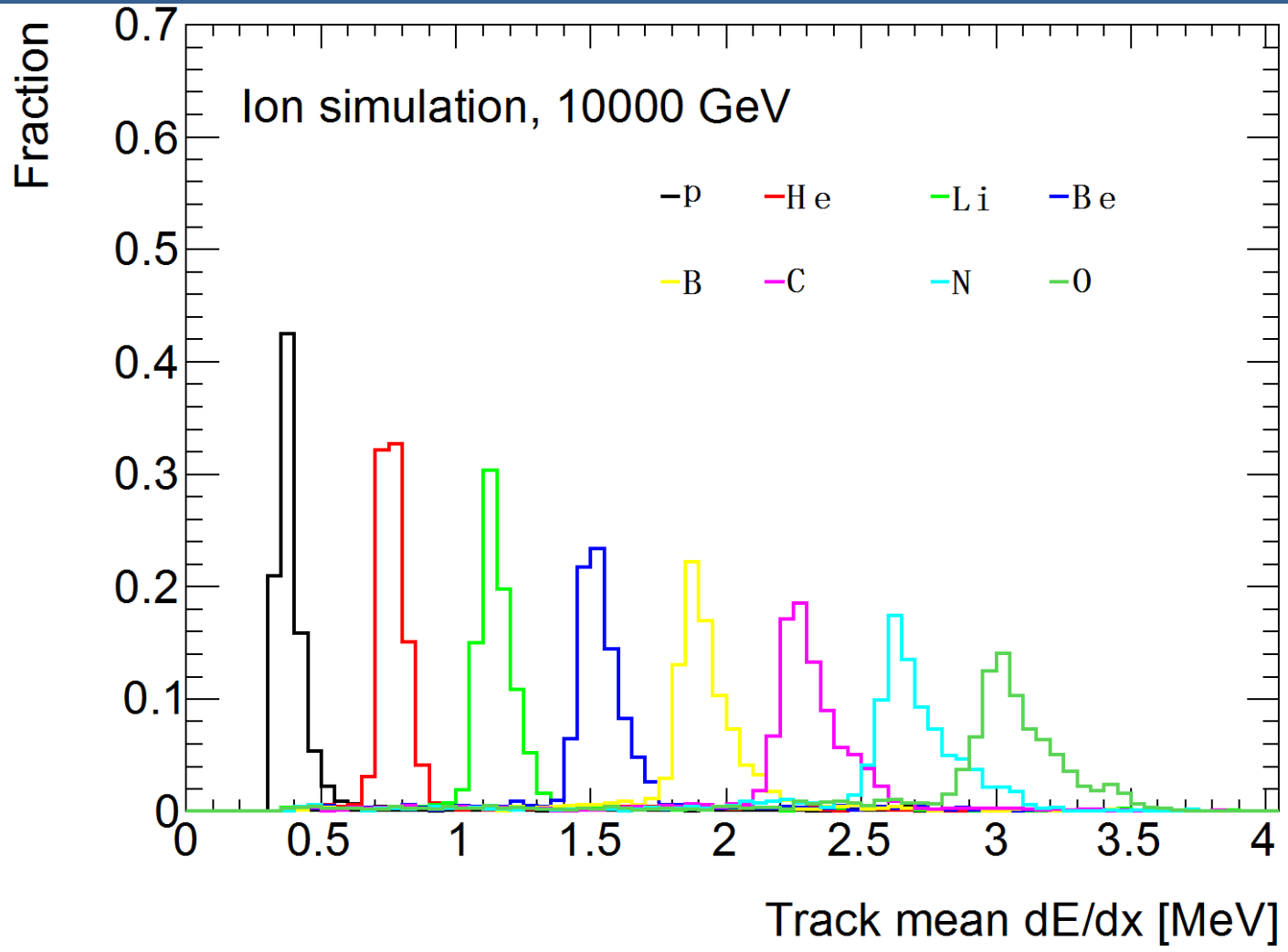
- Long tail for high energy, and for heavier ions
  - Pattern recognition becomes difficult

Mean dE/dx of Ions in zone 6, 1 TeV



Need to be folded with ASIC response (saturation at ~5 MeV)

Mean dE/dx of Ions in zone 6, 10 TeV



General Issues of HERD Tracker

- I think it is time to focus the effort on a few tracker key issues
- Requirements related issues
  - Requirement on γ-ray detection
    - Energy range, GF, angular resolution, energy resolution
    - The γ-ray requirements will drive the design of the tracker layout, and will affect to a large extent the overall design of HERD
      - If the interest is only for γ-ray of very high energy (>50GeV), the necessity of of W converters can be questioned, if the calorimeter provides sufficient angular resolution
      - Or add converters to the side detectors if GeV γ-rays are important
  - Requirement on charge measurement
    - Precision and range of charge measurement
    - This requirement will drive the FE chip design (dynamic range), as well as number of tracker layer (number of measurement points)

Mechanical Structure

- The base line calls for ~1m^2 support trays
  - DAMPE is developing support trays for 8x8 SSDs, including those with 1mm W-plates
    - Can be extrapolate to 10x10 SSDs with 5-SSD per ladder
    - 56% larger, but not heavier when using 0.3-0.5mmW
- Option to go beyond 1m^2 (Fermi is 1.5mx1.5m)
  - Towers: 3x3 SSD/tower, 4x4 towers -> 12x12 SSDs per layer
    - Advantage: modular approach
    - challenge: routing the readout cable, integration with calorimeter
  - 6-SSD long ladder: is back splash a problem? FE noise?
- Integration of "top tracker" and "side tracker"
  - Layout and routing of readout electronics
  - Do we need silicon for "side tracker"? Or add converters to it?
  - Overall optimization together with calorimeter based on scientific objectives

Silicon Sensor and FE

- **Silicon sensor**
  - **For the required precision (~70μm) AGILE/DAMPE or Fermi type SSD is sufficient**
  - **Cost scales with Si surface, DAMPE ones ~1000 euro/pcs, any cheaper, but reliable alternatives?**
  - **Floating strip readout or not? Pitch 121 μm vs 242 μm**
  - **Double-sided detector? Pixel detector (cost!)?**
- **Readout electronics**
  - **Integration of the ADC into the ASIC**
  - **Larger dynamic range for charge measurement**
  - **Fast discriminators in the ASIC for trigger?**
  - **How much event processing in the readout board (related to the trigger issue)**

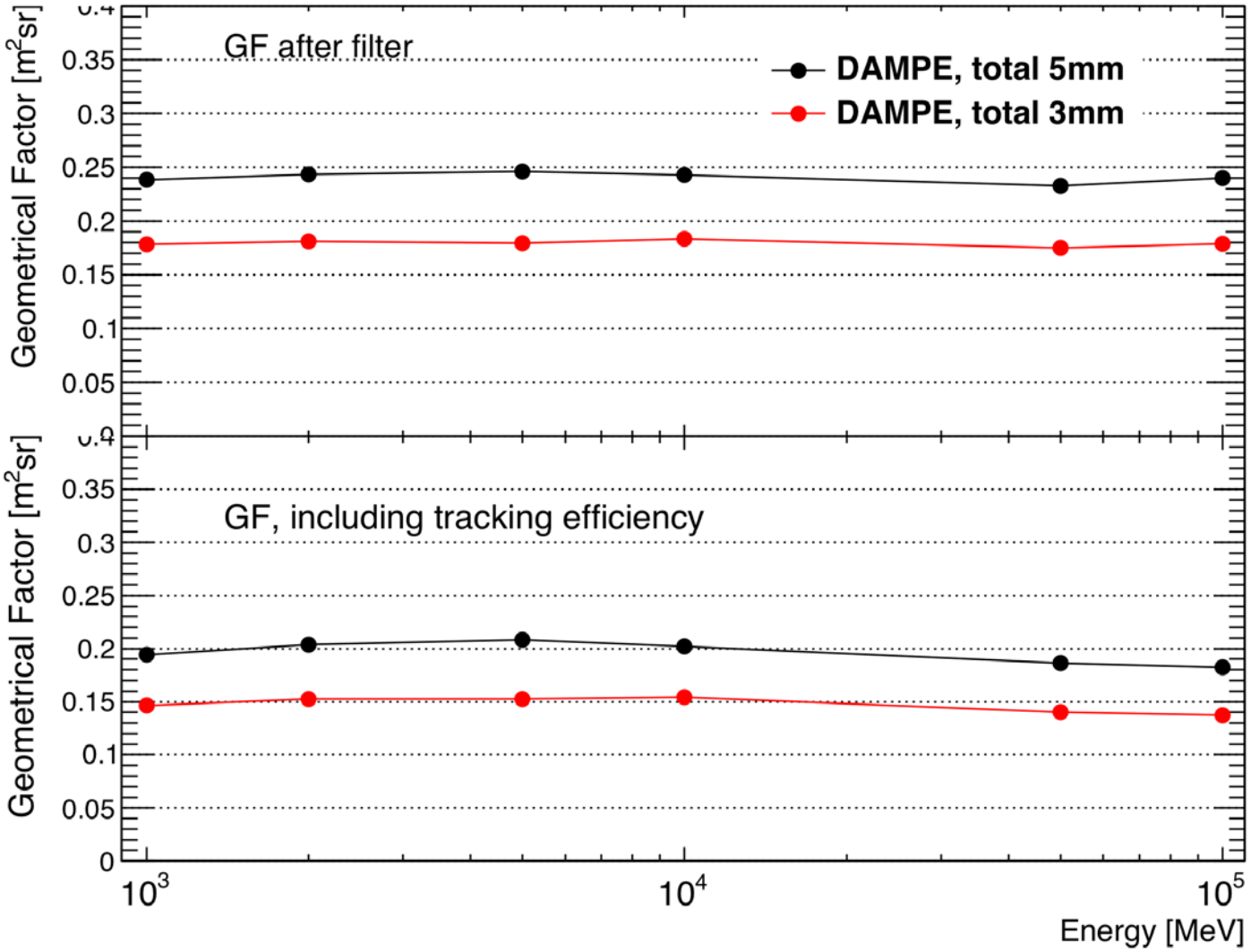
Trigger and DAQ

- **Trigger**
  - **Does the tracker participate in the first level trigger**
    - **Need fast discriminator in ASIC?**
  - **Does the tracker participate in the higher level trigger?**
    - **Need more complex readout board for fast track finding and trigger buffering**
- **DAQ**
  - **What is the requirement on dead time for observing transient (γ-ray) events?**
  - **What are the limit on resources: CPU, power, data storage**

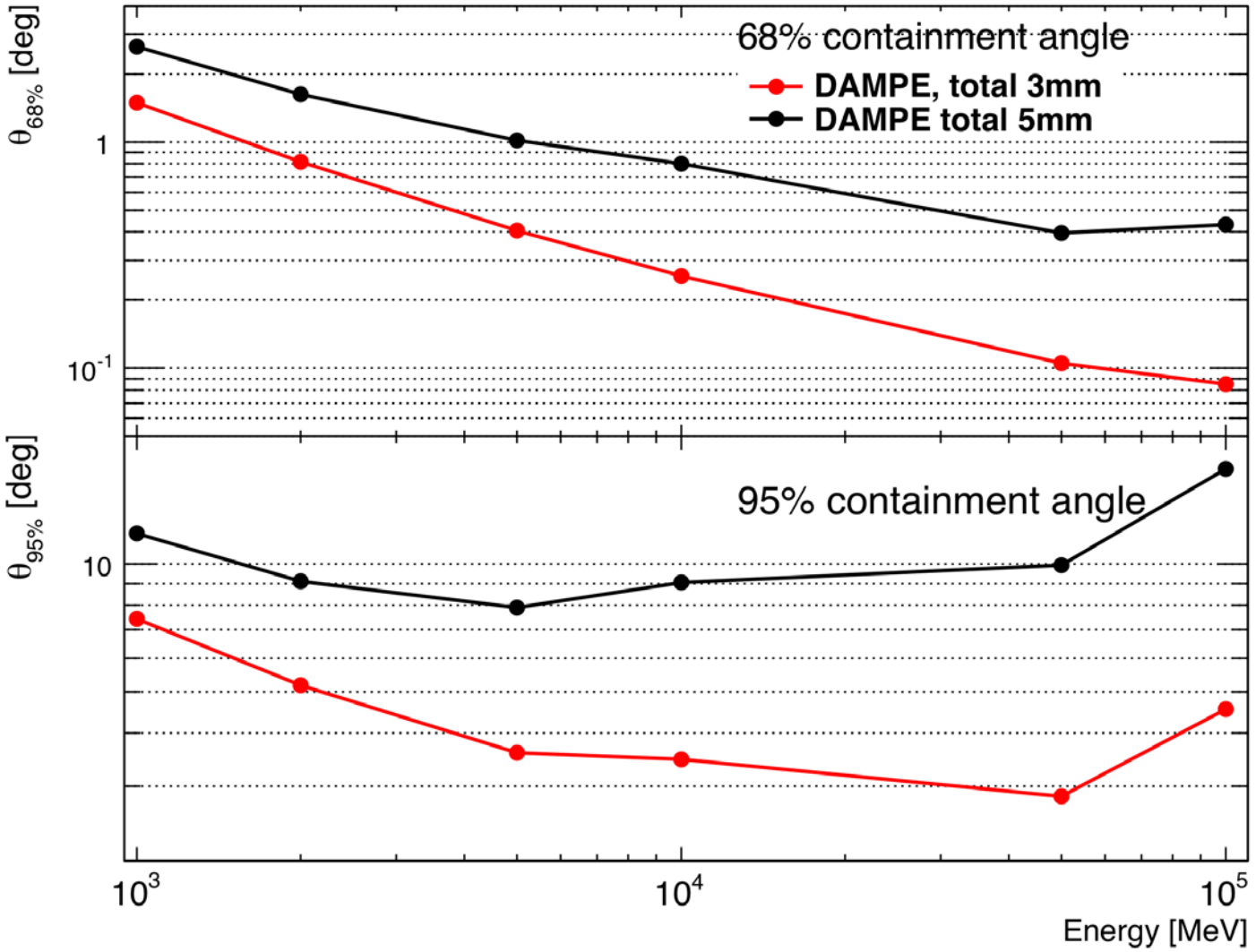
Conclusions

- **To improve the sensitivity to GeV γ-rays optimization on tungsten plate thickness and number of layers is needed**
  - **Need to consider together GF, tracking efficiency, angular resolution (core and tail), and cost and size**
  - **Optimization can only be done with detailed simulation and track reconstruction**
  - **The science goal on γ-rays astronomy will have a big impact on the tracker design**
- **We should start to discuss tracker design issues concerning layout, mechanics, sensors, electronics, trigger and DAQ and to plan R&D effort**
  - **Coupled to the definition of the science goals of the project and the design of the calorimeter.**

DMAPE Converted γ-Ray GF



68% & 95% Containment Angle, DAMPE



DAMPE is discussing to use 3mm W instead of 5mm
Note unconverted γ-ray at high energy can add to efficiency.