GRAiNITA: A novel calorimeter design

The testbeam result and current status

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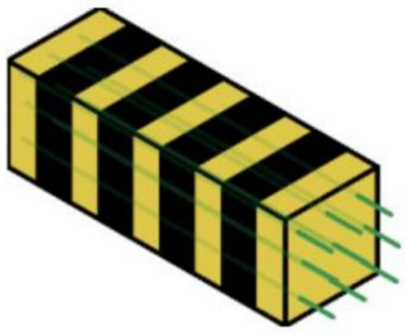
Outline

- The concept of GRAiNITA
- The energy resolution
- Future plans

The concept of GRAiNITA

- Shashlik-like sampling:
  - Energy resolution: (~$10\%/\sqrt{E}$)

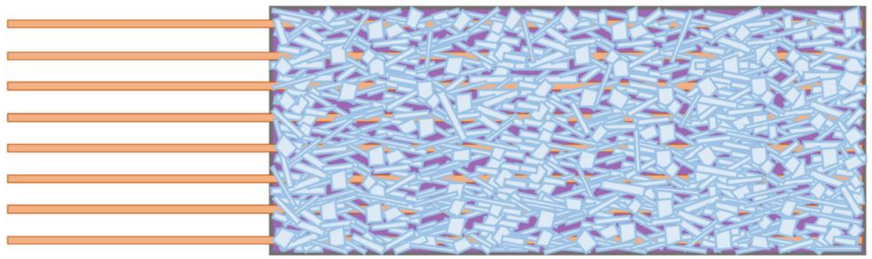


Better resolution

Lower cost (vs homogeneous)

- GRAiNITA:
  - Mixture of scintillator grains and heavy liquid
  - Extremely fine sampling

  \+ Energy resolution (~$2\%/\sqrt{E}$)



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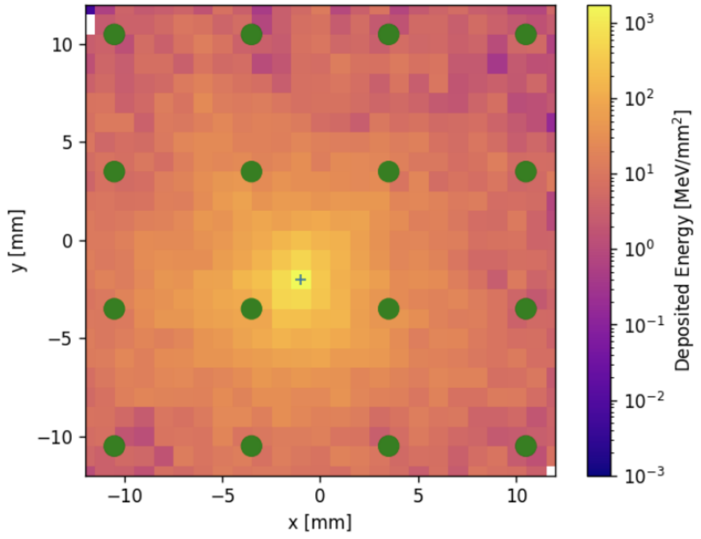
The concept of GRAiNITA

- The grains (produced by *ISMA)
  - Cadidates:
    - $ZnWO_4$ and BGO (reference)
  - Size:~1 mm
  - $ZnWO_4$: produced via flux method by ISMA
  - BGO: produced via mechanical crushing

	BGO	$ZnWO_4$
Effective Z	74	61
Density (g/cm^3)	7.13	7.87
Refractive index	2.15	2.0 - 2.3
Light yield (photons/MeV)	~ 9000	~ 9000
Peak emission wavelength (nm)	480	480
Decay time (μs)	0.3	20
Radiation length (cm)	1.12	1.20
Molière radius (cm)	2.26	1.98

*ISMA: Institute for Scintillation Materials, Kharkiv, Ukraine

To estimate the energy resolution



- The GRAiNITA prototype design
  - Size: 168 mm x 168 mm x 400 mm
  - Filled with $ZnWO_4$ grains (~1 mm) and heavy liquid*
  - Scintillating photons are read out by WLS fibers
- Simulation setup
  - Scintillators are simplified as virtual strips for now
    - $ZnWO_4$ (79.24%) + Heavy liquid (20.76%)
  - WLS fibers were simulated as cylinders (d=1 mm) and filled with carbon-hydrogen plastic
  - Scintillating process is not swtiched on and simulated for now

*a water-based sodium polytungstate solution

To estimate the energy resolution $\frac{\sigma_E}{E}$

- From deposited energy to measured energy

E_{Dep}	• Deposited energy
Y_{γ}	• Scintillating photons
$\epsilon_{Y(PE)}$	• Photo-electrons

⇩Take the deposited energy E_{Dep} from simulation

⇩Take $Y_{data} = Y_{\gamma} \cdot \epsilon_{Y(PE)}$ from beamtest data

⇩Get the measured energy as:

$$E_{Rec} \propto Y_{Rec} = E_{Dep} \cdot Y_{data}$$

⇩Get the resolution from Y_{Rec}

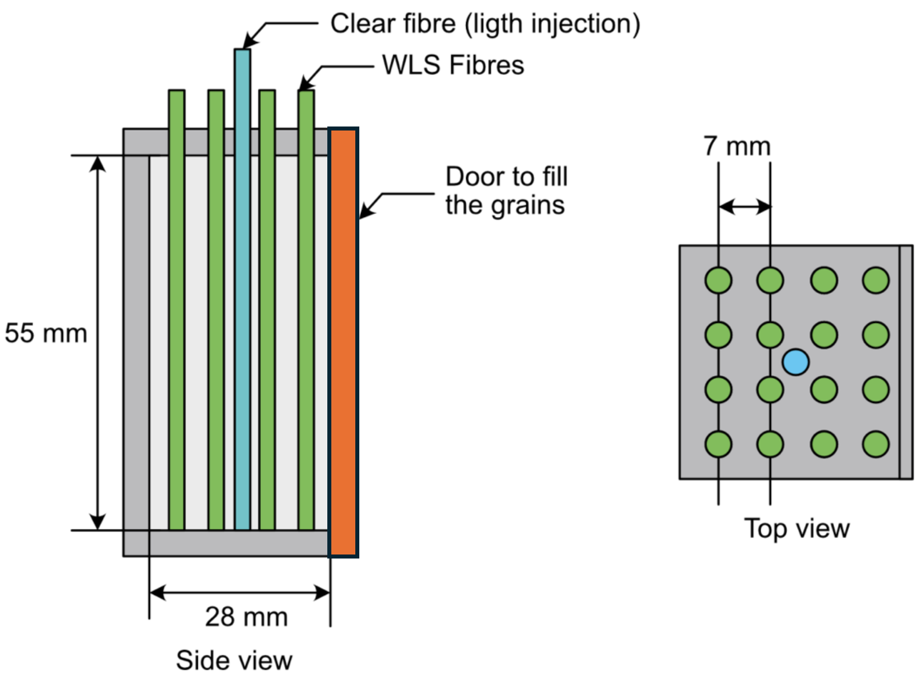
To estimate the energy resolution $\frac{\sigma_E}{E}$

$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus b$$

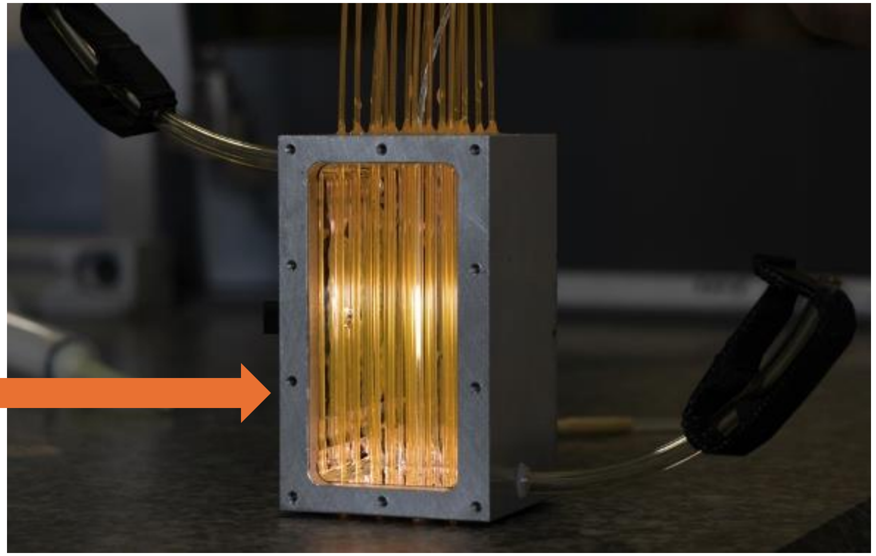
- The energy dependent stochastic term A:
  - Statistics of photo-electrons ⇒ a, estimated by simulation + testbeam
  - The scintillating difference between ZnWO4 and heavy liquid ⇒ $2\%/\sqrt{E}$
  - The statistics of scintillating photons generation
- The constant term b:
  - Non-uniformity of the detectors ⇒ addressed by testbeam data

A pre-prototype: Troll

- Size: 28 mm x 28 mm x 55 mm module
- Material: ~ 200 g ZnWO4 and heavy liquid (water, as reference)
- Readout by 16 WLS and SiPM
  - +1 clear fiber in the center for LED light injection

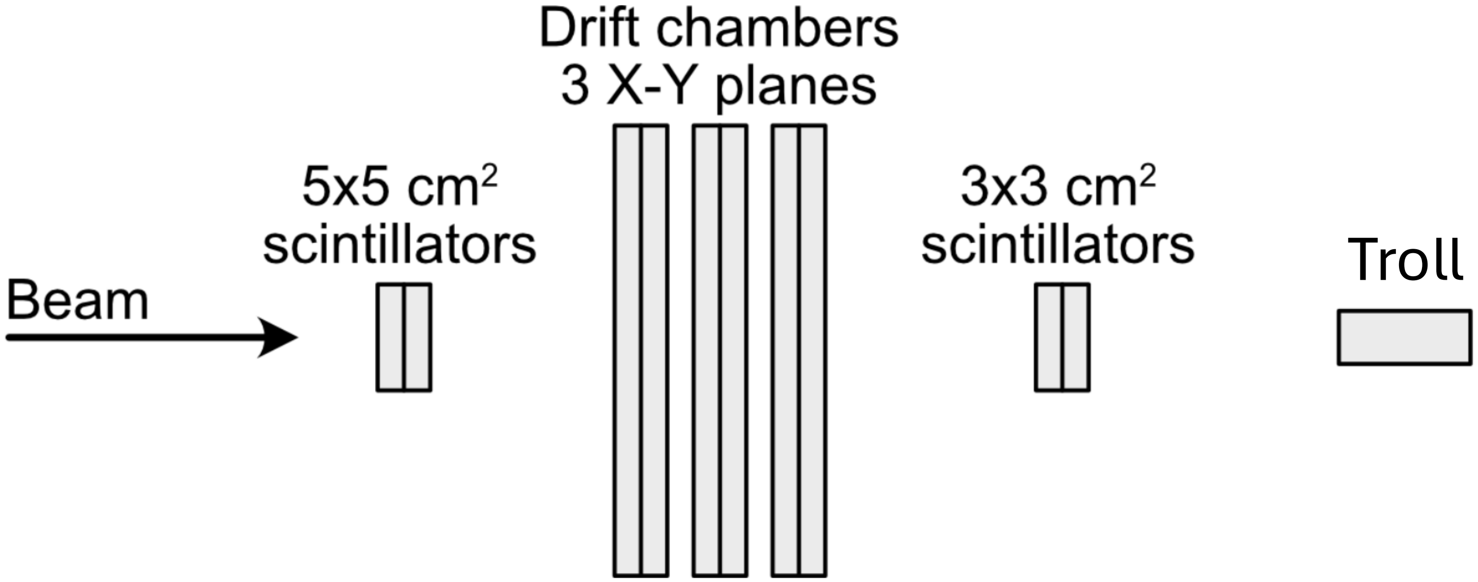


Grains and liquid injection side

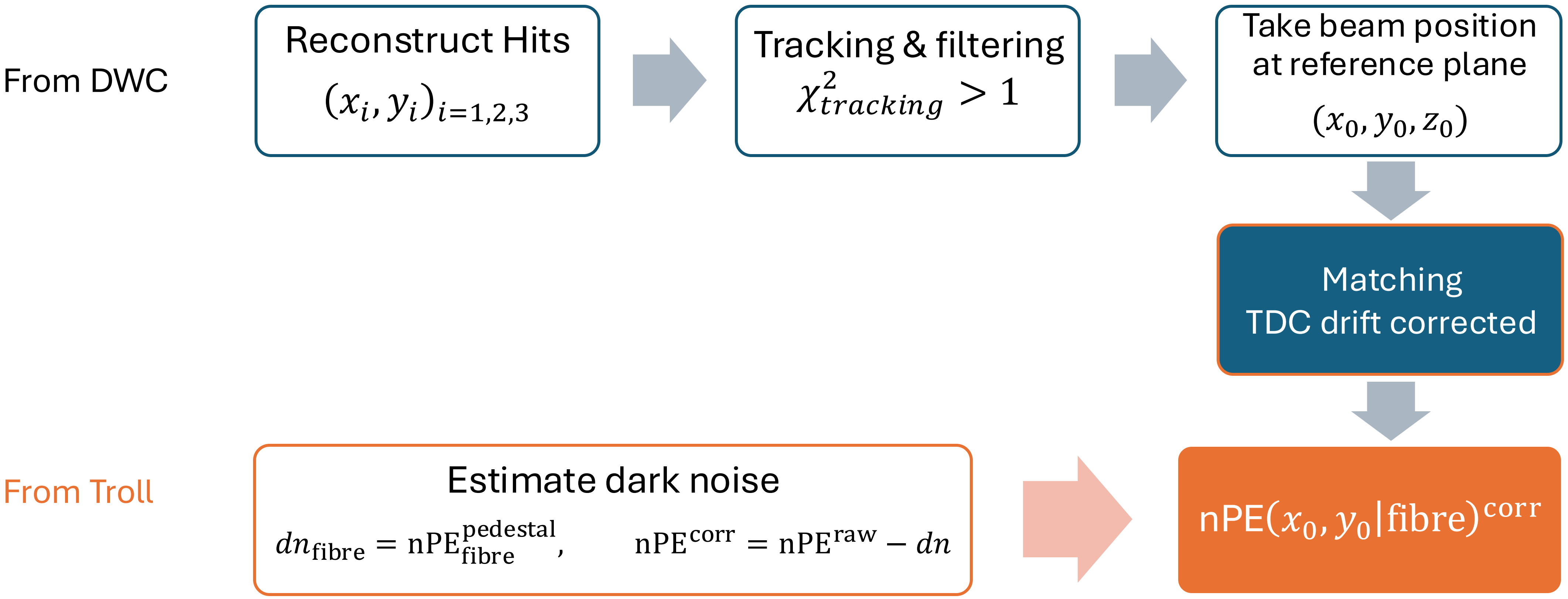


Testbeam setup

- Beam tracking: 3 layer wire drift chamber (DWC)
- Triggers: 2 dual scintillators, one next to Troll, one before DWC
- Beam: pion beam (more statistics) and muon beam

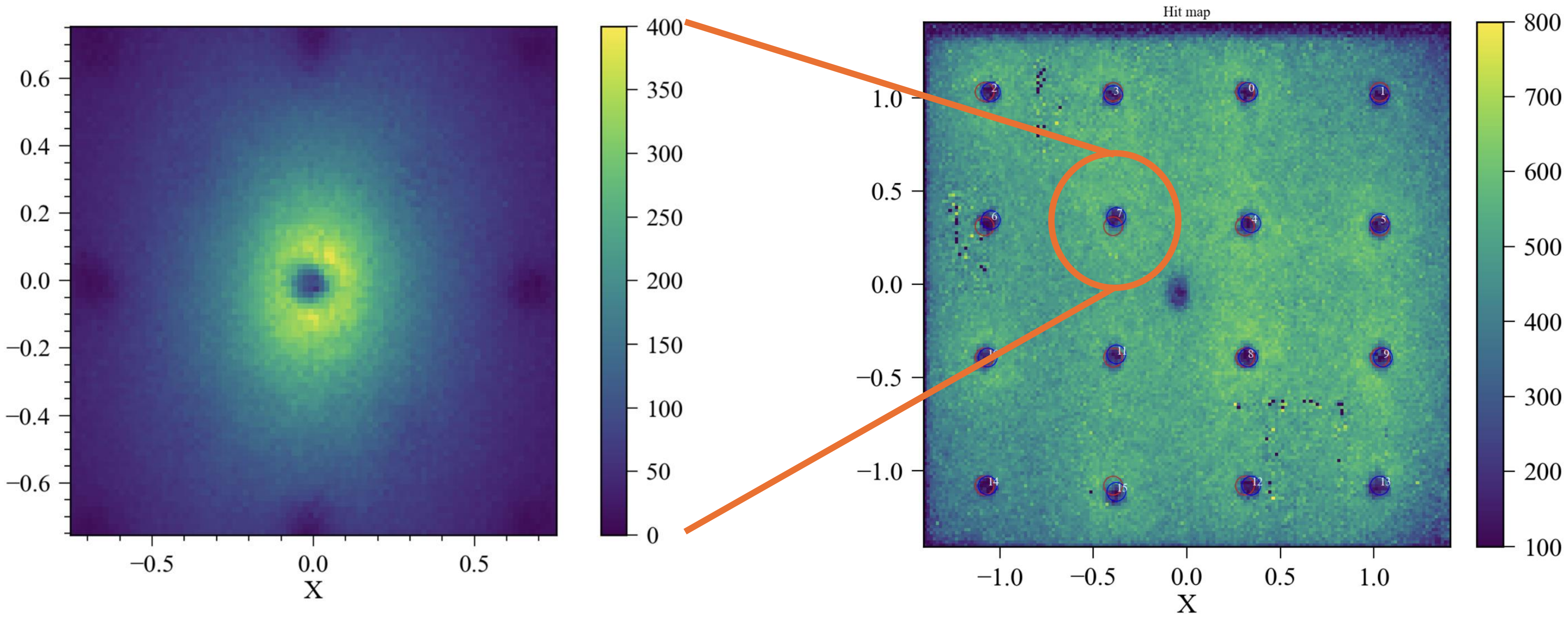


Roadmap to the nPE map



Roadmap to the nPE map

- Accurate fibre position: the minimum nPE bins in neighbour areas

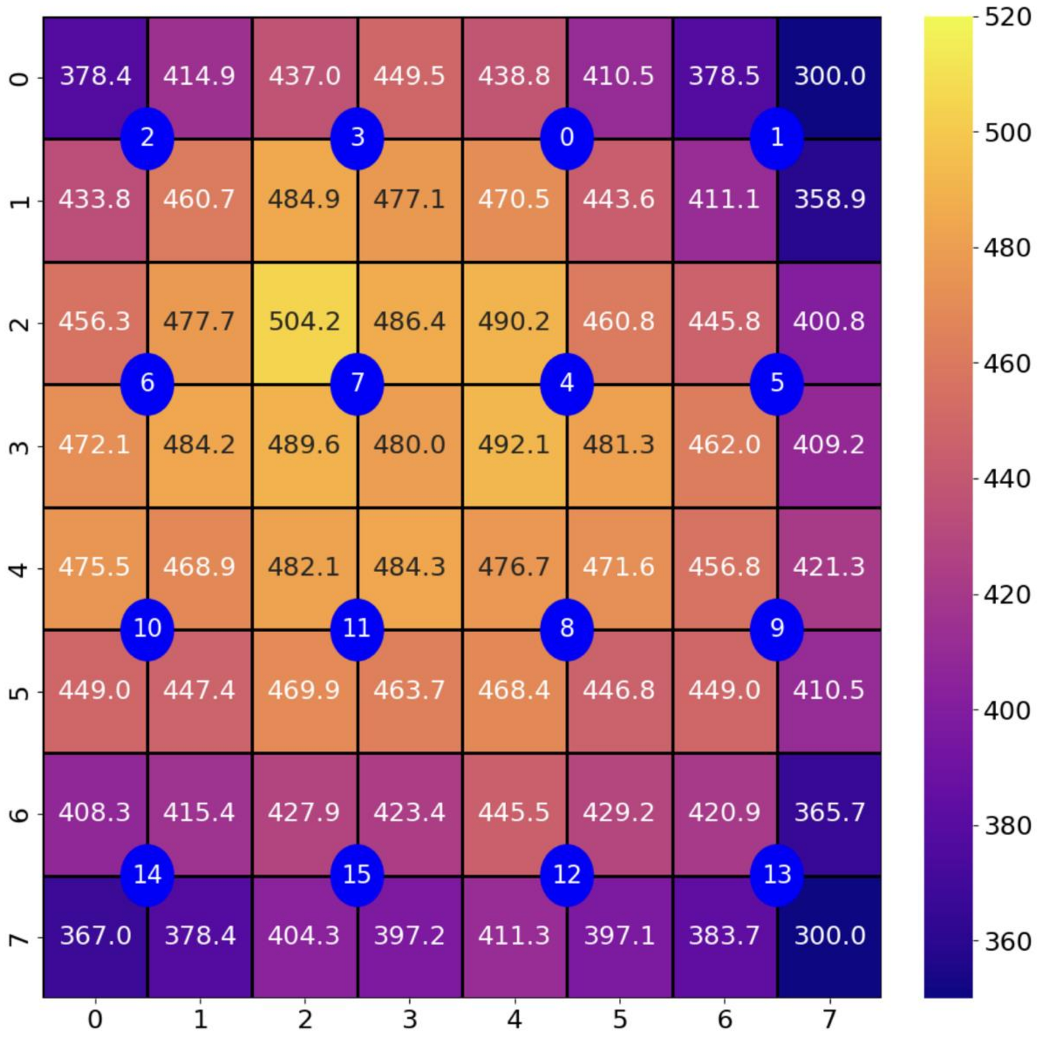


Roadmap to nPE map

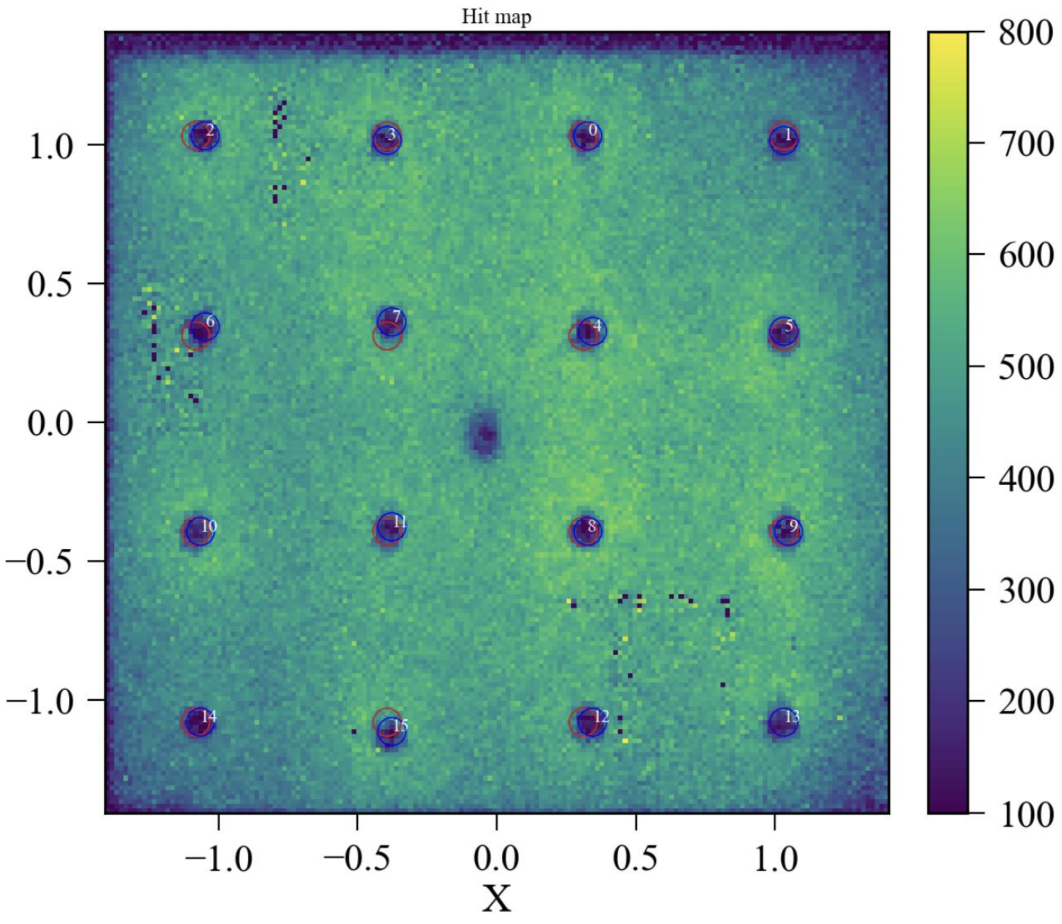
- Homogenisation of fibre responses
  - Take $\langle \mathrm{nPE}_{\mathrm{global}}^{\mathrm{corr}} \rangle$ as normalization number.
  - Get the homogenisation factor of fibre i.

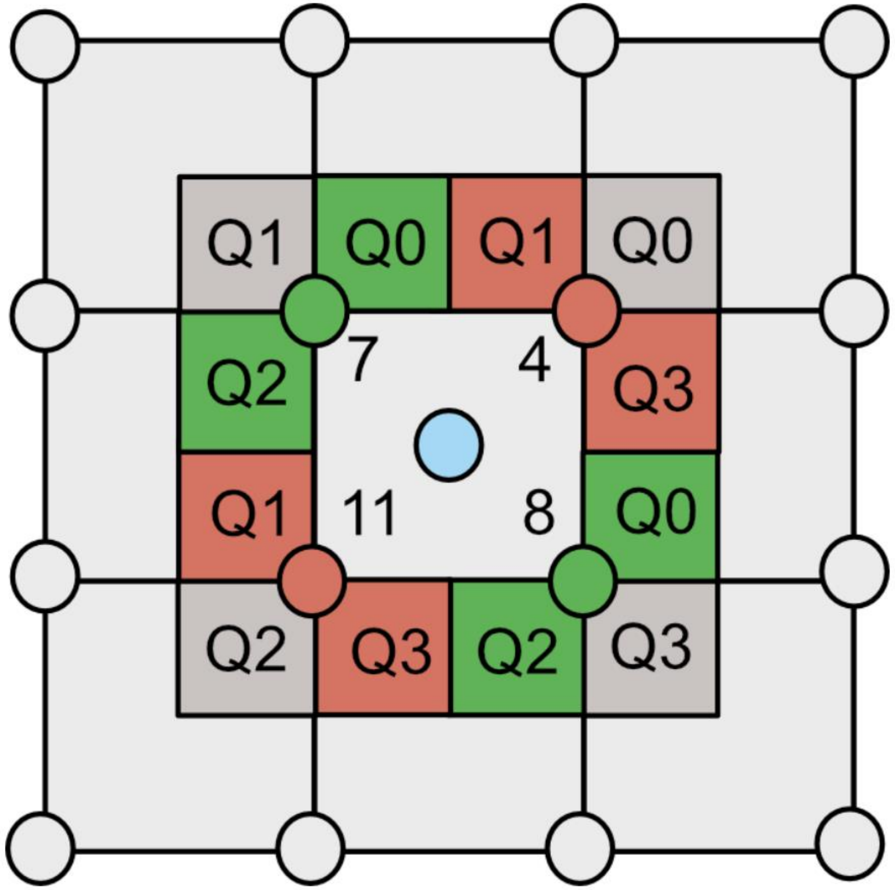
$$s_i = \frac{\langle \mathrm{nPE}_i^{\mathrm{corr}} \rangle}{\left\langle \mathrm{nPE}_{\mathrm{global}}^{\mathrm{corr}} \right\rangle}$$

  - $\mathrm{nPE}(x, y) = \sum \frac{\mathrm{nPE}_i^{\mathrm{corr}}(x,y)}{s_i}$.



Base units for uniformity maps





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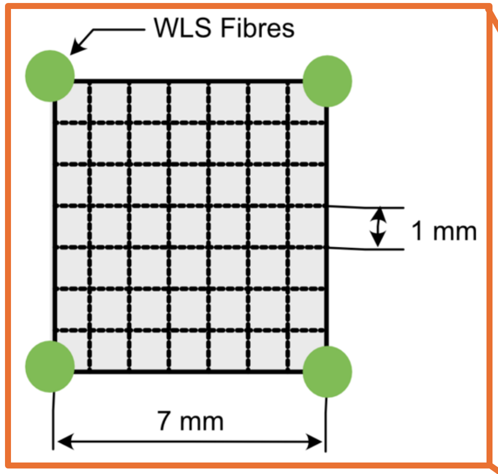
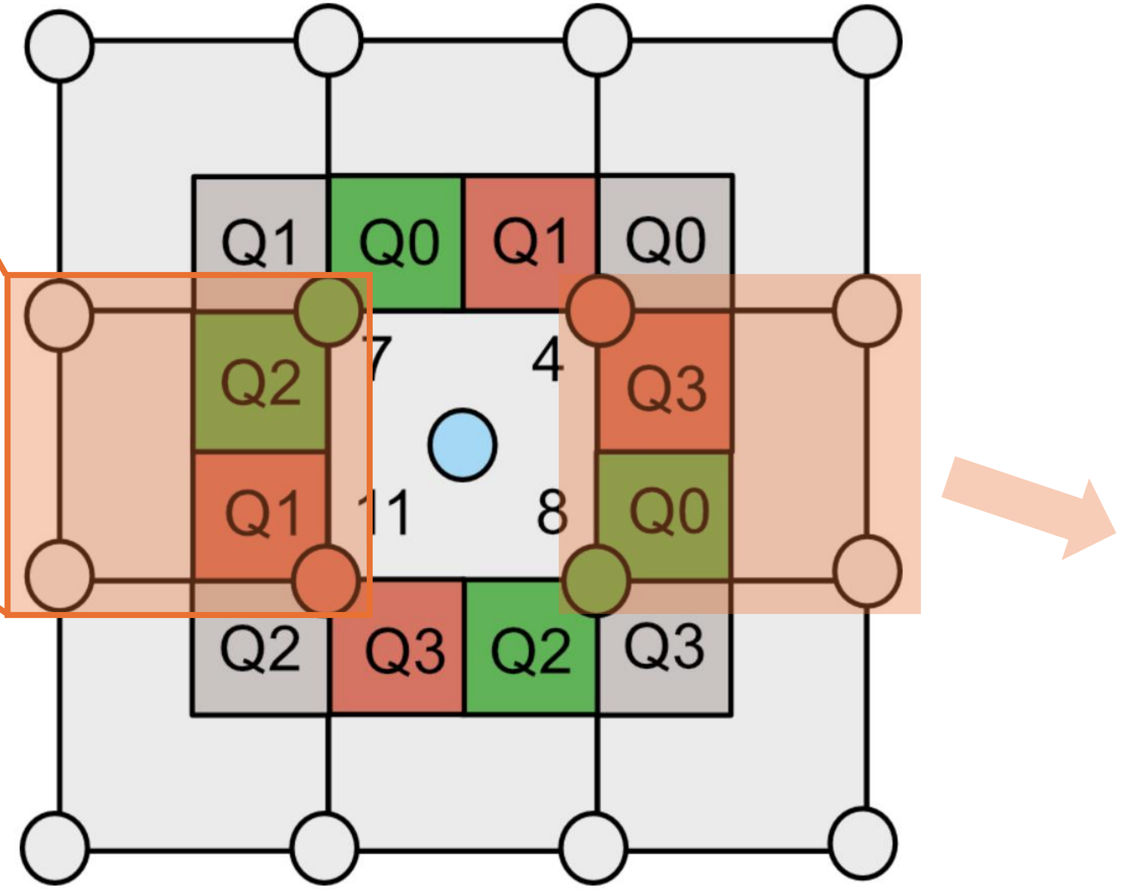
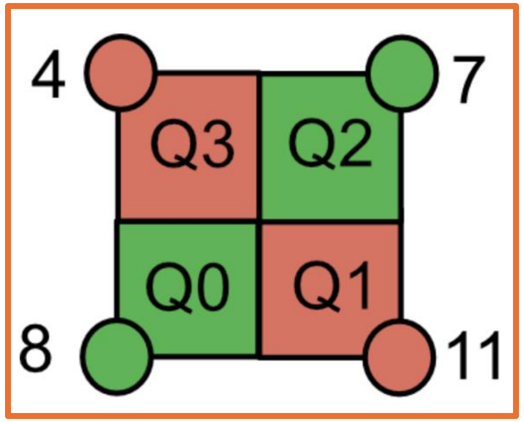
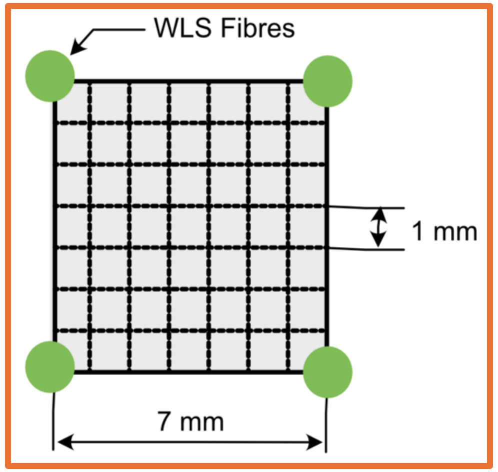


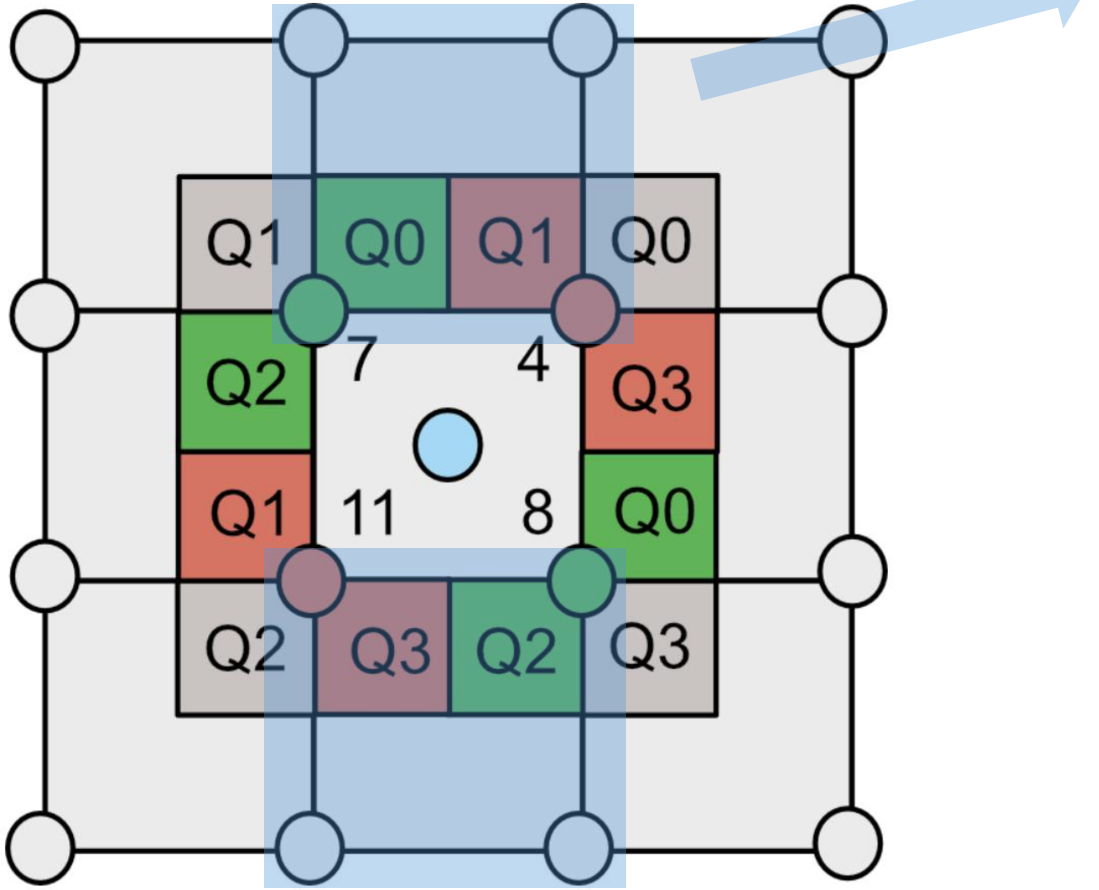


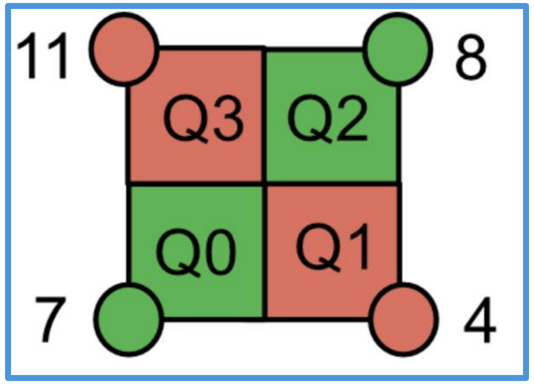


Map 1

Base units for uniformity maps







Map 2

Include uniformity map $C(x, y)$ in simulation

- The effected deposited energy:

$$E_{Dep}^{\text{eff}}(x, y) = E_{Dep}(x, y) \cdot C_{Dep}(x, y)$$

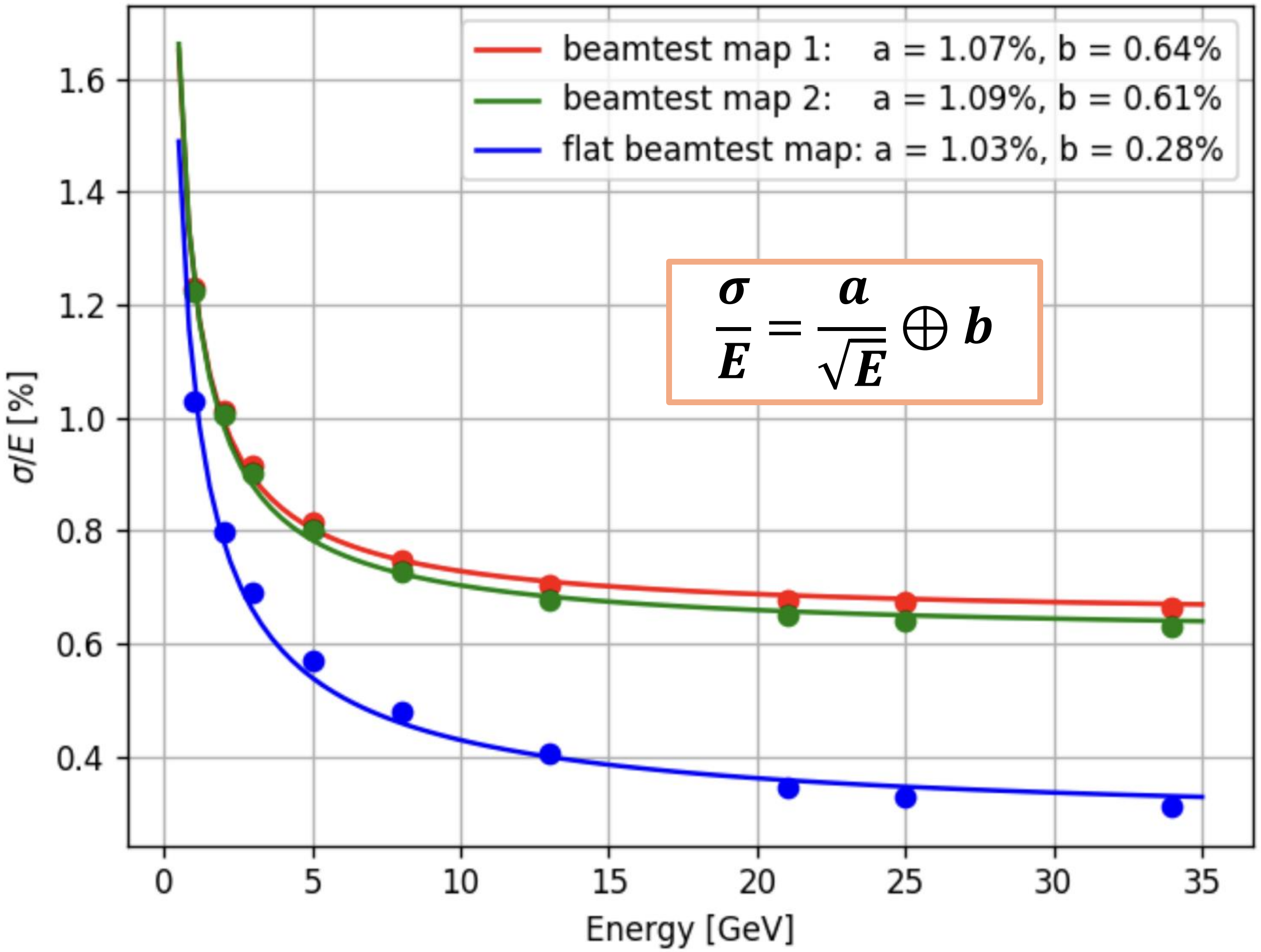
⇒ (x, y): The position of primary particles

⇒ E_{Dep}: Deposited energy from Geant4 simulation

⇒ C_{Dep}: Relative uniformity map of deposited energy, assuming it’s the same as nPE relative uniformity map

Energy resolution

- Consider map1, map2 and a flat map as reference
- The stochastic term a is map-independent, ~1% as priliminary result
- The constant term b < 1%, expectedly larger with non-flat maps than the flat map

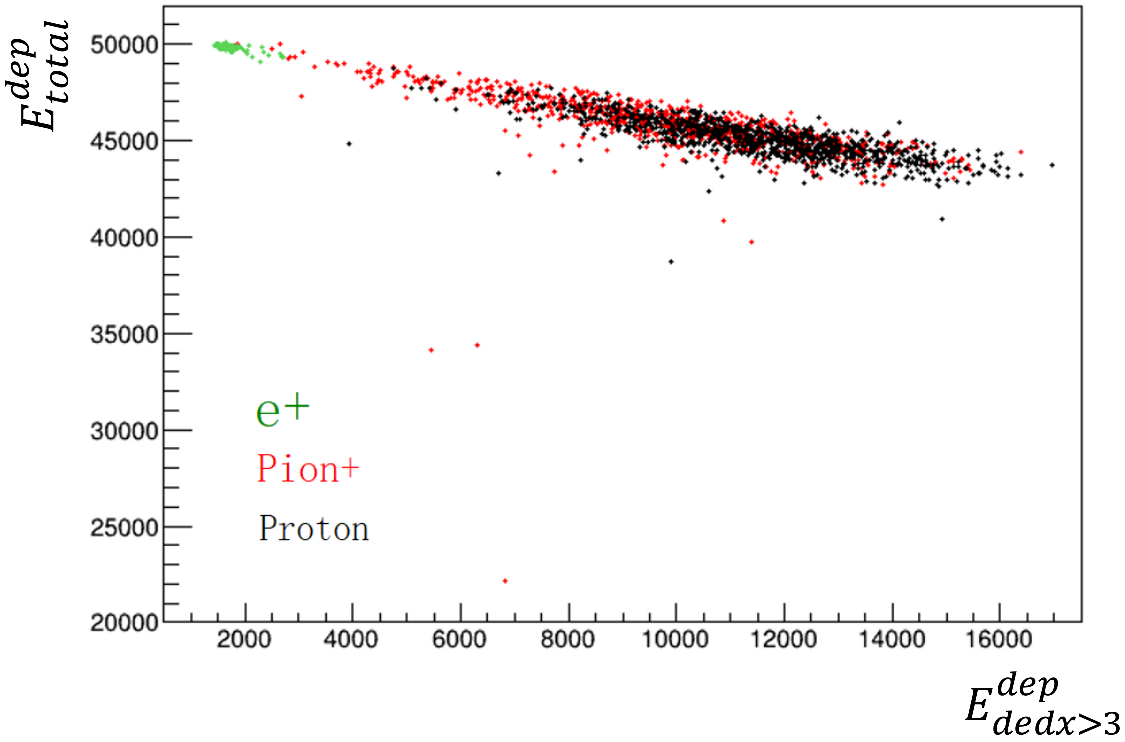


Summary

- An anlysis to testbeam data was done to extract uniformity map inside GRAiNITA prototype, then applying to the simplified simulation samples to determine the related energy resolution
- The statistics of detected nPE is measured in this test as $\sim 1\%/\sqrt{E}$
- The constant term due to non-uniformity is evaluated as <1%
- Other terms to the energy resolution
  - Deposited energy variation between ZnWO4 grains and heavy liquid
    - Studied with simulation of grain-size cube shows $\sim 2\%/\sqrt{E}$
  - The statistic of scintillating photon generation (on-going)

The potential of PSD approach

- Similarly idea as dual-readout calorimeter
  - Get the E_{EM} and E_h and correct the hadron shower energy
- Use scintillating time shape difference to extract f_{EM}
  - Need the time distribution of scintillating photons
  - Time shape templates can be extracted by measurements

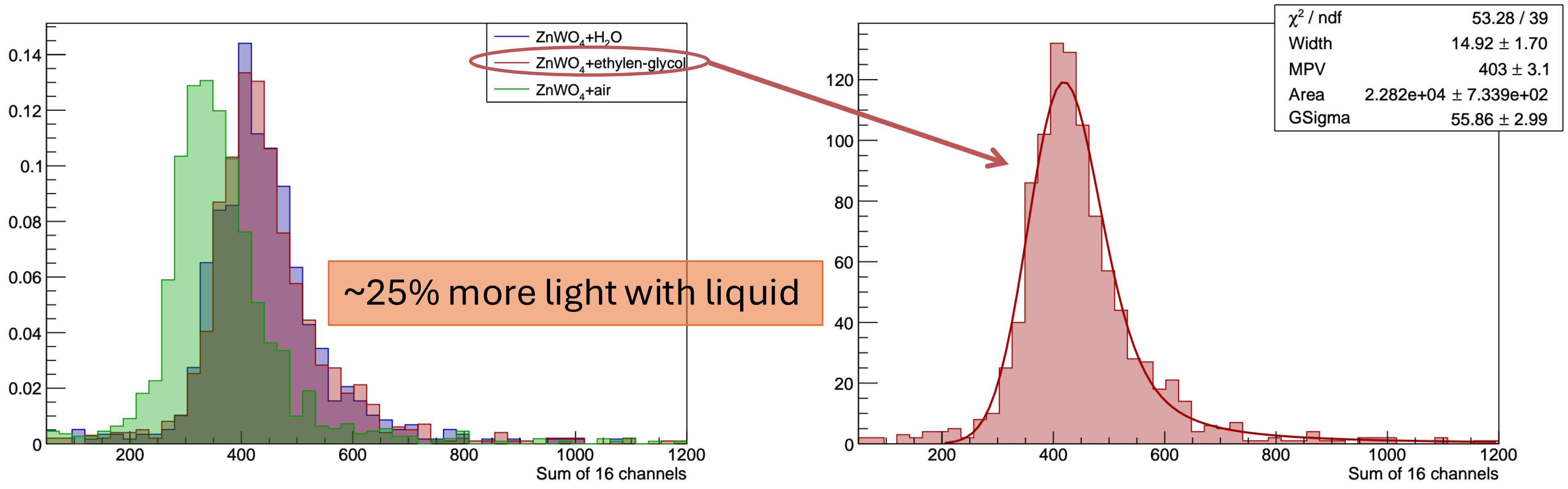


Outlook

- Got a grant to build a full-size module to address all the components of the resolution 🎉
  - 168 mm x 168 mm x 400 mm
  - 45 kg $ZnWO_4$ grains , heavy liquid, 576 fibres, 36 SiPMs
- A more detailed simulation is under development
  - Simulate the realistic grains: construct and fill in the geometry box
  - Including scintillating process
- Goal is to have module built in 2028
  - Tests with cosmics, beams, etc.

Backup

Cosmic ray test result



- The signal yield is larger when the medium refractive index is better matched with the grains.
- ~10000 PE/GeV is expected based on the result.
- Opens the road to a statistical fluctuation of $1\%/\sqrt{E}$ due to photon statistics

Definition of quarters

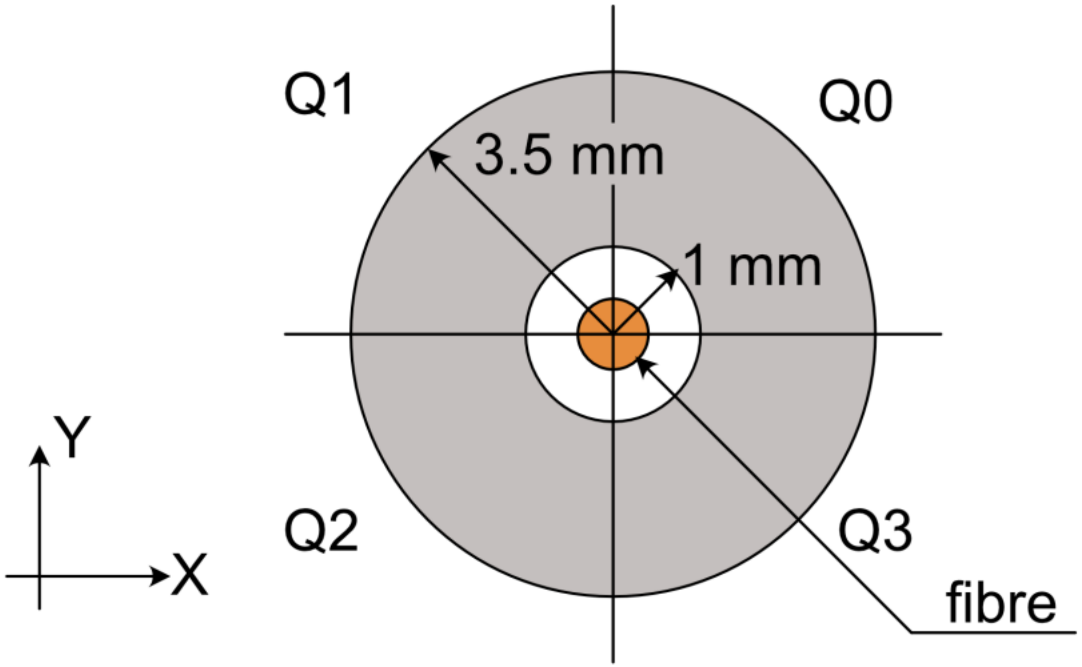


Figure 19: Quarter definition.

Fit to muon and pion nPE

- Muon: Landau ⊗ Gauss; Pion: Landau⊗ Gauss + CB