



Modeling of grain-based medium

for GRAiNITA detector

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FUTURE
CIRCULAR
COLLIDER



Currently LHCb uses Shashlik sampling calorimeters for ECAL, which have resolution of order

$$R \approx \frac{10\%}{\sqrt{E}}$$

GRAiNITA is a sampling electromagnetic calorimeter with a novel approach:

scintillating grains in the transparent absorber

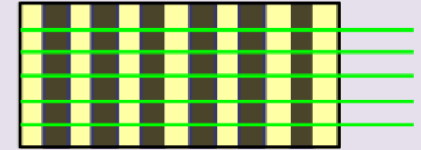
mix and confine the scintillation light,

giving us resolution of order

$$R \approx \frac{2\%}{\sqrt{E}}$$

- Concept is proposed for high precision calorimetry for FCC.
- The group is developing **168x168x400mm** demonstrator.
- The presentation is about modeling the prototype.

Shashlik calorimeter: alternating layers of scintillator and absorber

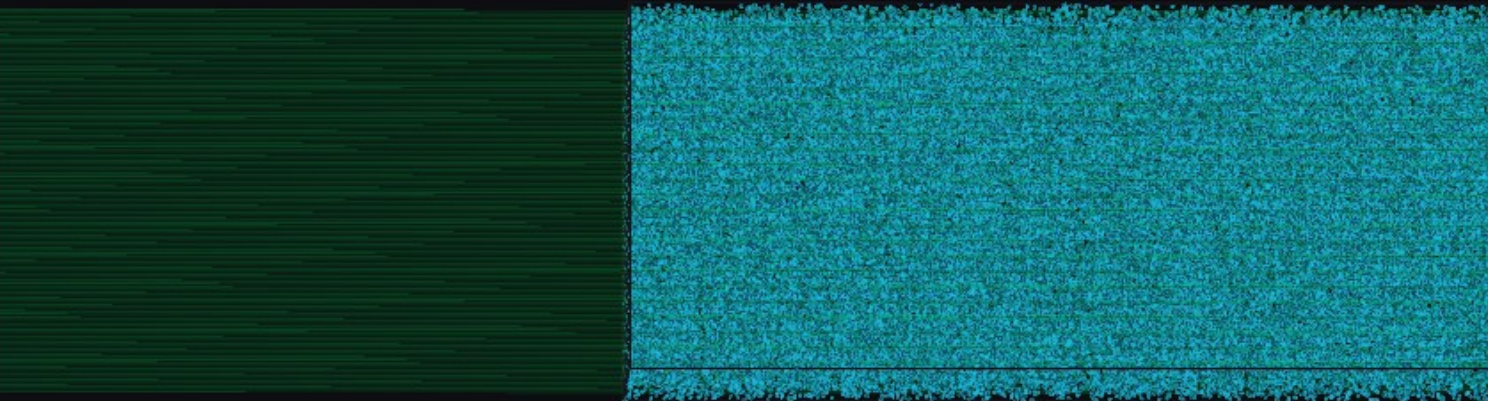


GRAiNITA: mix of scintillators grains and absorber in the same volume



Picture from D. Klekots

300mm fiber tails



Incoming particle

At each fiber end –
photon detector
 $24 \times 24 = 576$
sensors total

168x168x400 mm box with
grains and heavy liquid

There are 2 goals and difficulties we faced simulating the detector:

→ We want our geometry close to the actual detector.

We have to replicate: effective density of the detector $5,72 \text{ g/cm}^3$ and Volume fraction of grains 58%, elongated shapes, mixed placement.

Difficulty1:

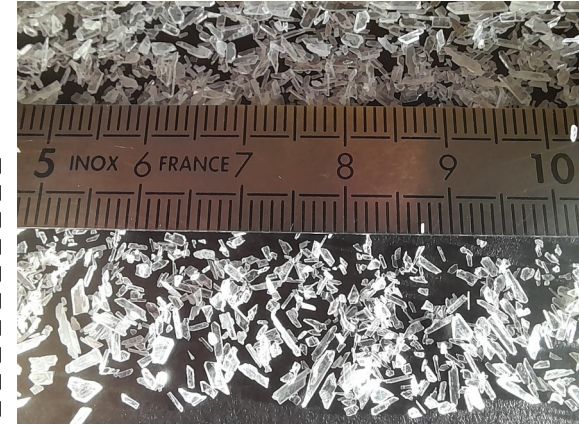
the larger the detector size and the denser the packing, the more the computing time and resources are needed for generating such geometry

→ We want our simulation to be fast.

We have to optimize simulation for optical events.

Difficulty2:

Geant4 has shortcomings for optical tracking.



Photos of grains:
thanks to Ianina Boyaryntseva

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Solution1:

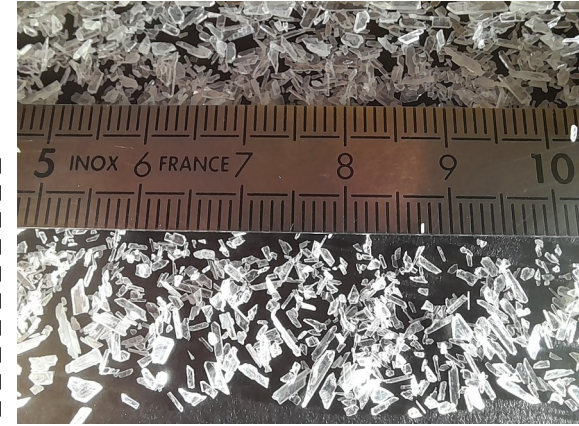
Produce a small volume with target parameters, and build full detector by stacking it.

→ We want our simulation to be fast.

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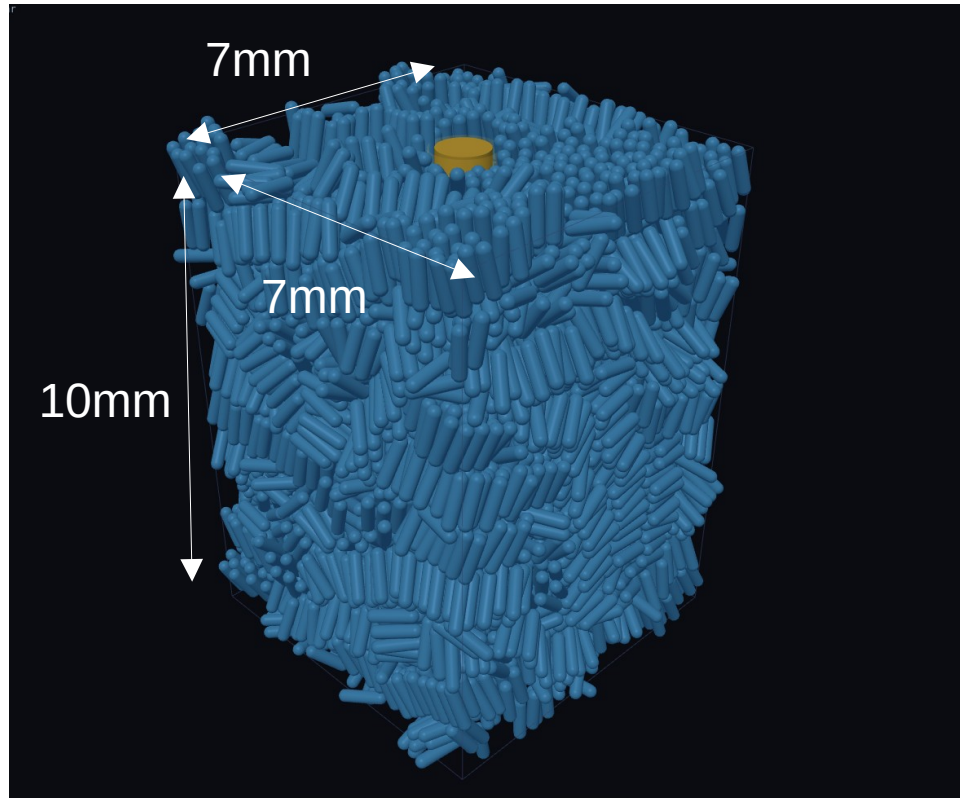
Solution2:

Use custom light propagation algorithm.

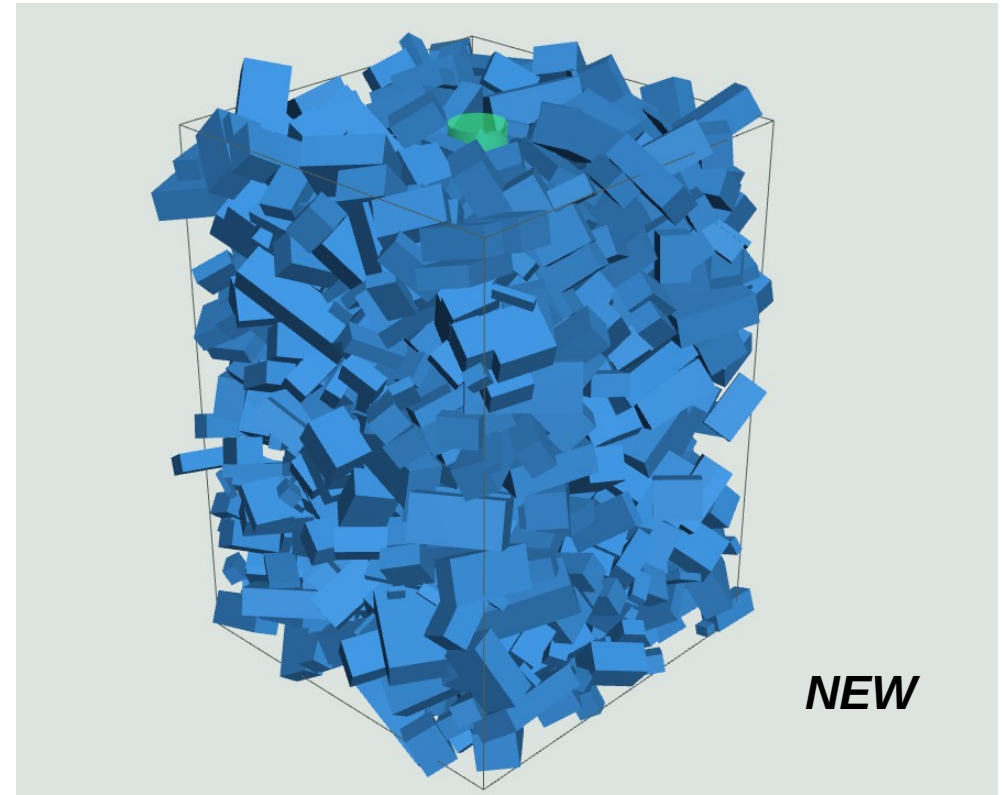


Photos of grains:
thanks to Ianina Boyaryntseva

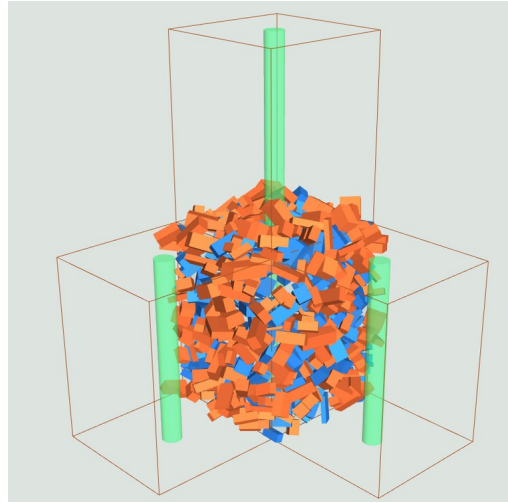
Generated 7x7x10 mm tiles. **Cell density=5.72 g/cm³ · No overlaps · Good mix · Fiber is accounted**



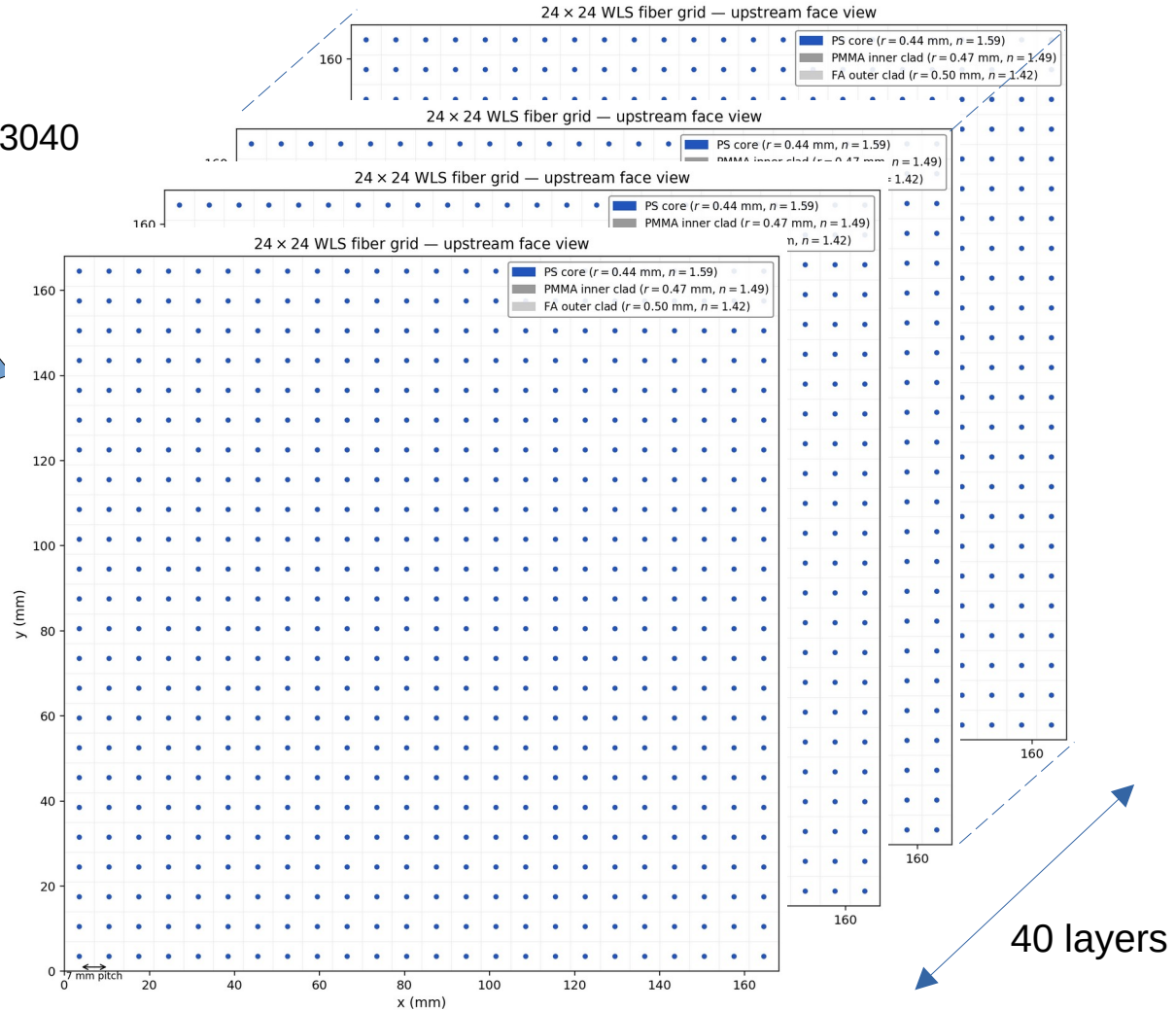
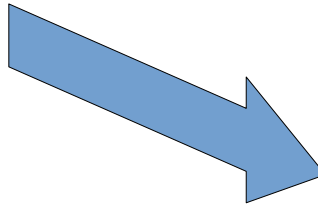
Left - contains **6237 identical capsule** grains packed using Stillinger algorithm using Vega-Lago overlap resolution.



Right - contains **1153 unique box** grains packed using physical drop simulation with friction.
From Hervé Chanal



Total cells:
 $24 \times 24 \times 40 = 23040$

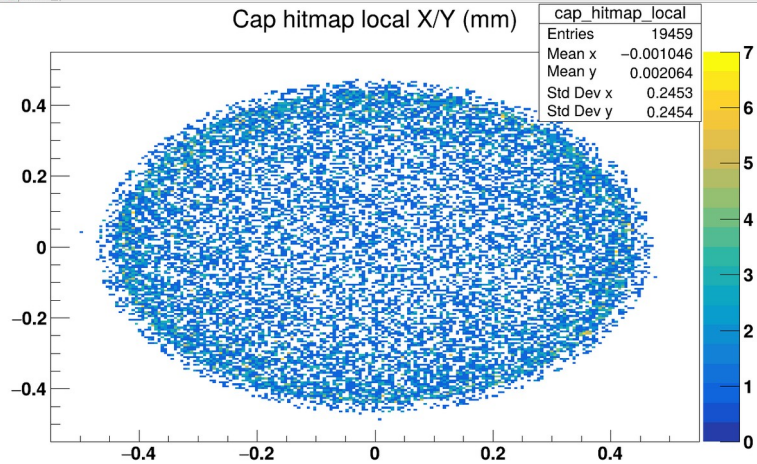
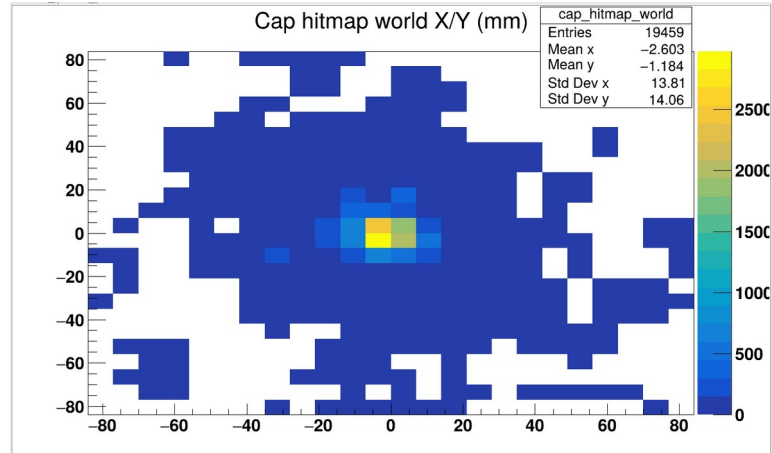


3 cells stacking in X-Y-Z plane (above)
 blue and orange – grains from different sides of the seam
 green - fibers
 Periodic border condition allows us to “click” the cells together without losing density at the seams (all 6 sides of the cell are periodic)

Positives:

- Needs generation only once
- Generating time is decreased (we generate 23040 times less volume)
- Saves us simulation time as the volume is highly repetitive

Optical readout signal for 1 simulated event:



GEANT 4:

~ **3 hours** optical tracking on CPU for 1 event
Reason: Geant4 tracks photons **one by one**, on 1 core.

$$\varepsilon = \frac{N_{\text{det}}}{N_{\text{total}}} = 2.44\%$$

Use GPU for parallel

GEANT 4 + GPU: (EIC-Opticks / Simphony)

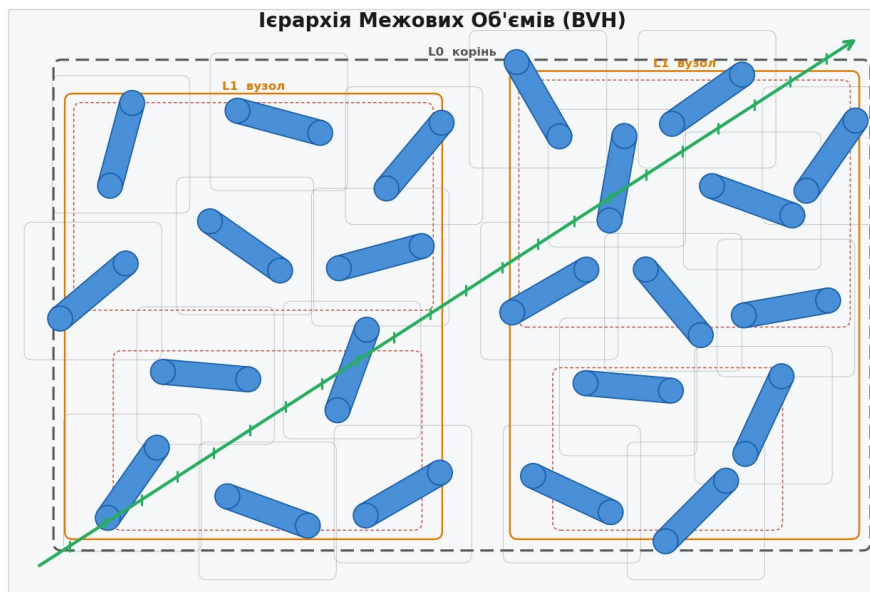
~ **3.5 hours** optical tracking on GPU for 1 event
Reason: not optimized for **large number of volumes**

$$\varepsilon = \frac{N_{\text{det}}}{N_{\text{total}}} = 2.35\%$$

Use DDA tracking for GPU

Next slides

Eic-Opticks(Simphony) GPU uses:

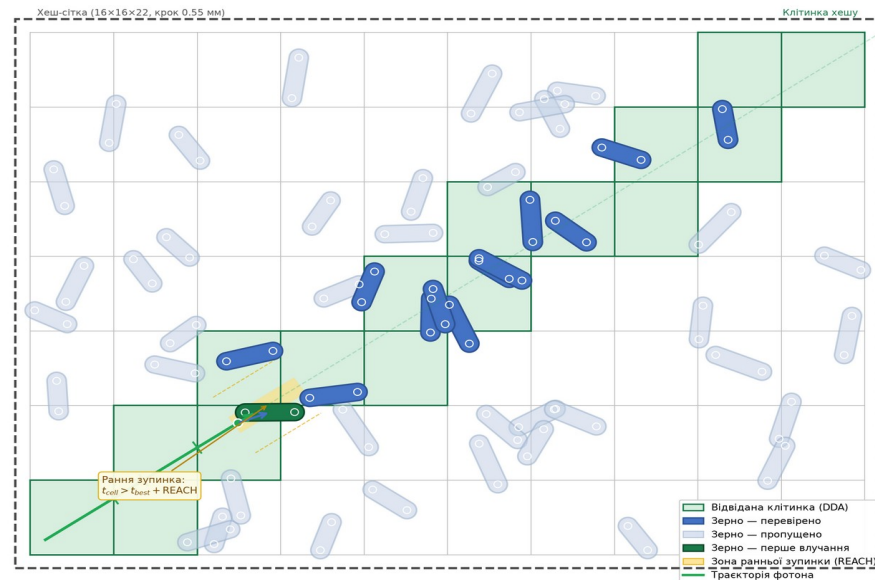


Bounding Volume Hierarchy.

- Geometry tree of all volumes
- Each volume gets bounding x, y, z
- During each step we perform AABB
- **Each step we traverse the full tree with grains**

GPU, our custom DDA + hash grid :

DDA + Просторовий Хеш



Digital Differential Analyzer.

- Cut the tile volume into x-y-z hash
- Assign grains to each hash cell
- Visit hash cells along the ray
- **During each step geometry and optical processes define minimum interaction distance.**

	Opticks (BVH)	DDA, capsules	DDA, boxes
Hardware	GPU H100 NVL	GPU H100 NVL	GPU A100
Algorithm	Bounding Volume Hierarchy (BVH)	Digital Differential Analyzer (DDA)	DDA, slab test on oriented boxes
GPU storage	~ 50 GB BVH for ~ 500,000 grains	~ 1.7 MB navigation data 6226 capsules per tile	~ 0.6 MB navigation data 1153 boxes per tile
GPU cache	Does not fit ($\gg$ L2 cache)	Fits entirely in L2 cache 1.7 MB $\ll$ 50 MB (H100)	Fits entirely in L2 cache 0.6 MB $\ll$ 40 MB (A100)
Operations / step	~ 25 AABB comparisons + capsule intersection	~ 1–5 cell checks capsule test: three quadratics	~ 3 cells, ~ 4 box tests slab test: no square root
Searches / photon	—	42	29
Time / photon	$\approx 1768 \mu\text{s}$	$\approx 221 \text{ ns}$	$\approx 135 \text{ ns}$
Photons / s	≈ 566	$\approx 4,500,000$	$\approx 7,400,000$
Speedup	reference	$\approx 8000\times$	$\approx 13\,000\times$

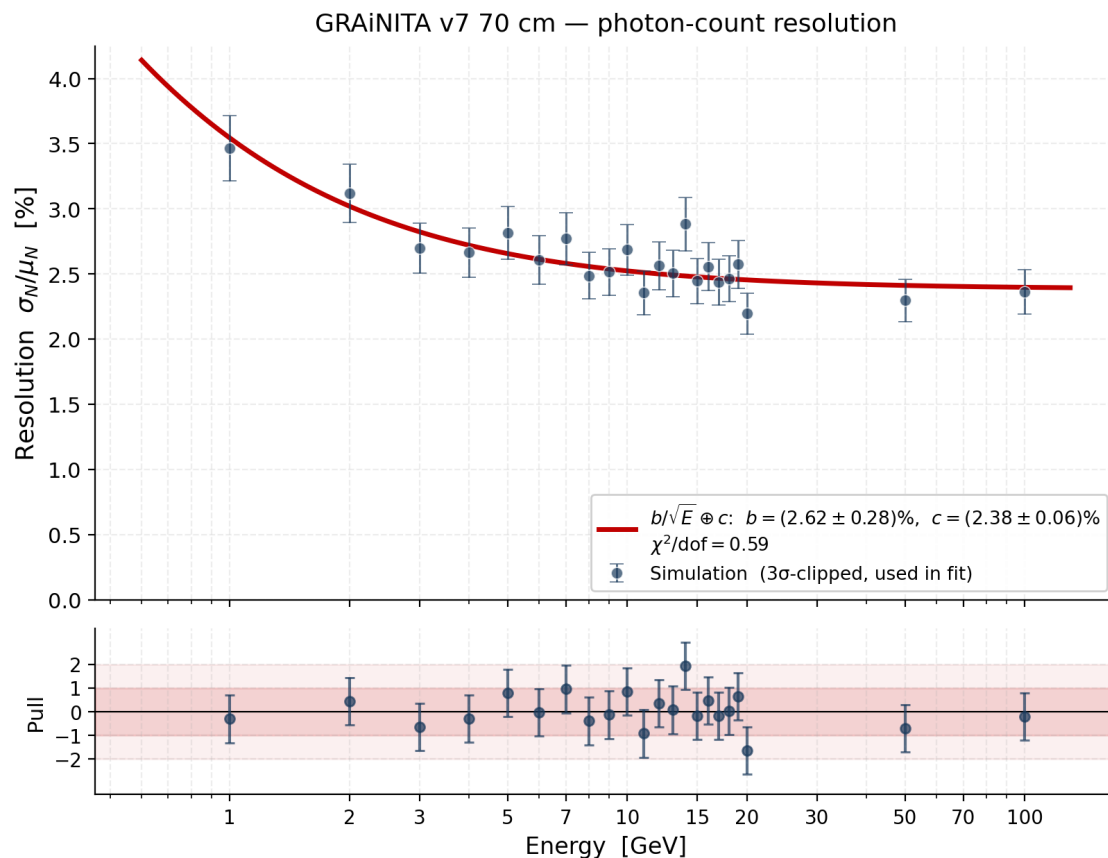
So for Energy resolution for calorimeter based on the 1-100 GeV energies we can approximate:

$$\frac{\sigma_E}{E} = \frac{a}{E} \oplus \frac{b}{\sqrt{E}} \oplus c,$$

After setting $a=0$ (no electronics noise) we get the stochastic parameter:

$$R(E) = \sqrt{\frac{(2.62\%)^2}{E/\text{GeV}} + (2.38\%)^2}$$

$$b = (2.62 \pm 0.28)\% \text{ GeV}^{1/2}, \quad c = (2.38 \pm 0.05)\%$$



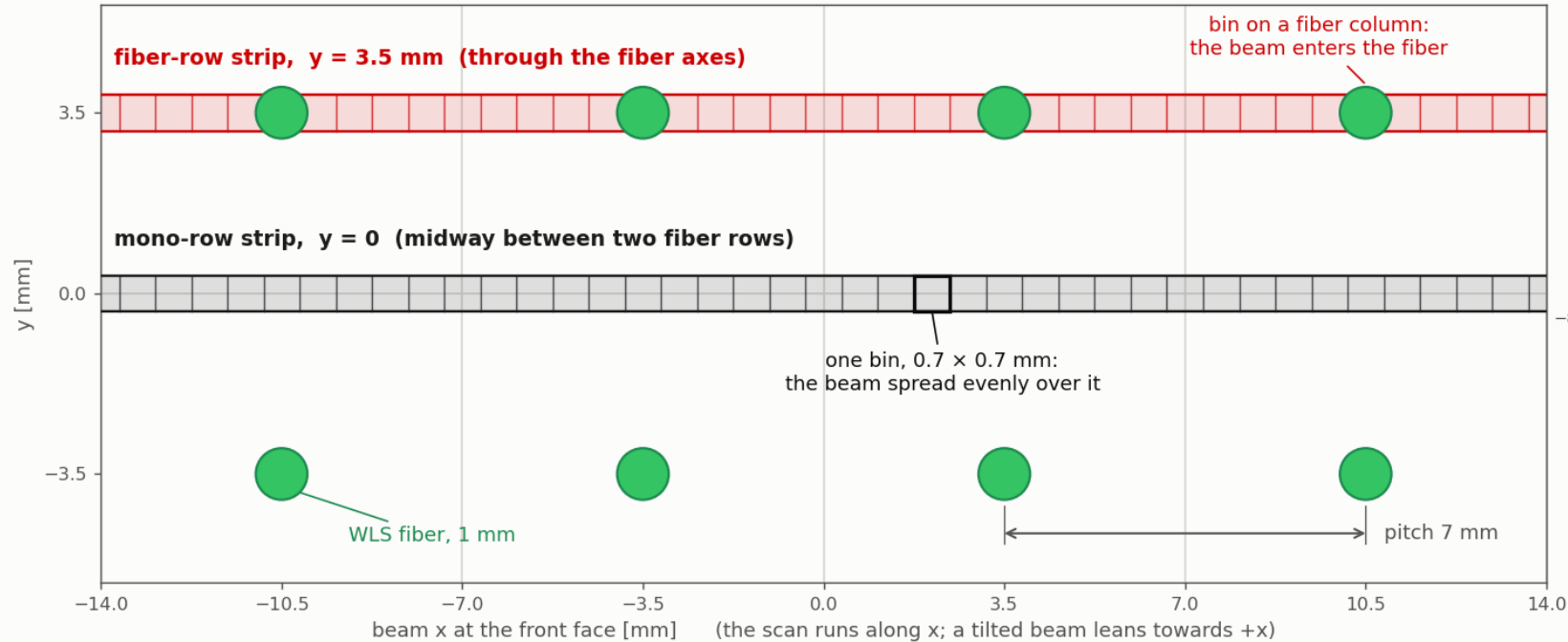
Results. Non-uniformity Strips

We shoot 5 GeV e^- along two strips in x axis on the detector face, reading the total photon number detected :

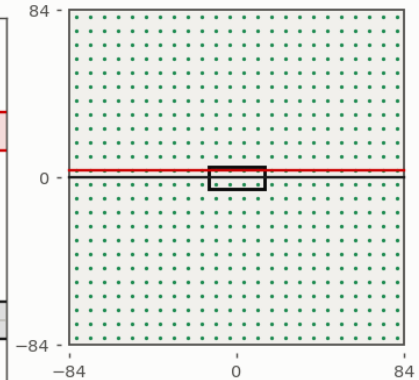
Fiber strip(**red**) – e^- pass through grains and fibers along the strip

Mono strip(**black**) – e^- pass trough grains only

Strip scans: where the beam enters the detector face (4 of the 24 fiber cells along x)



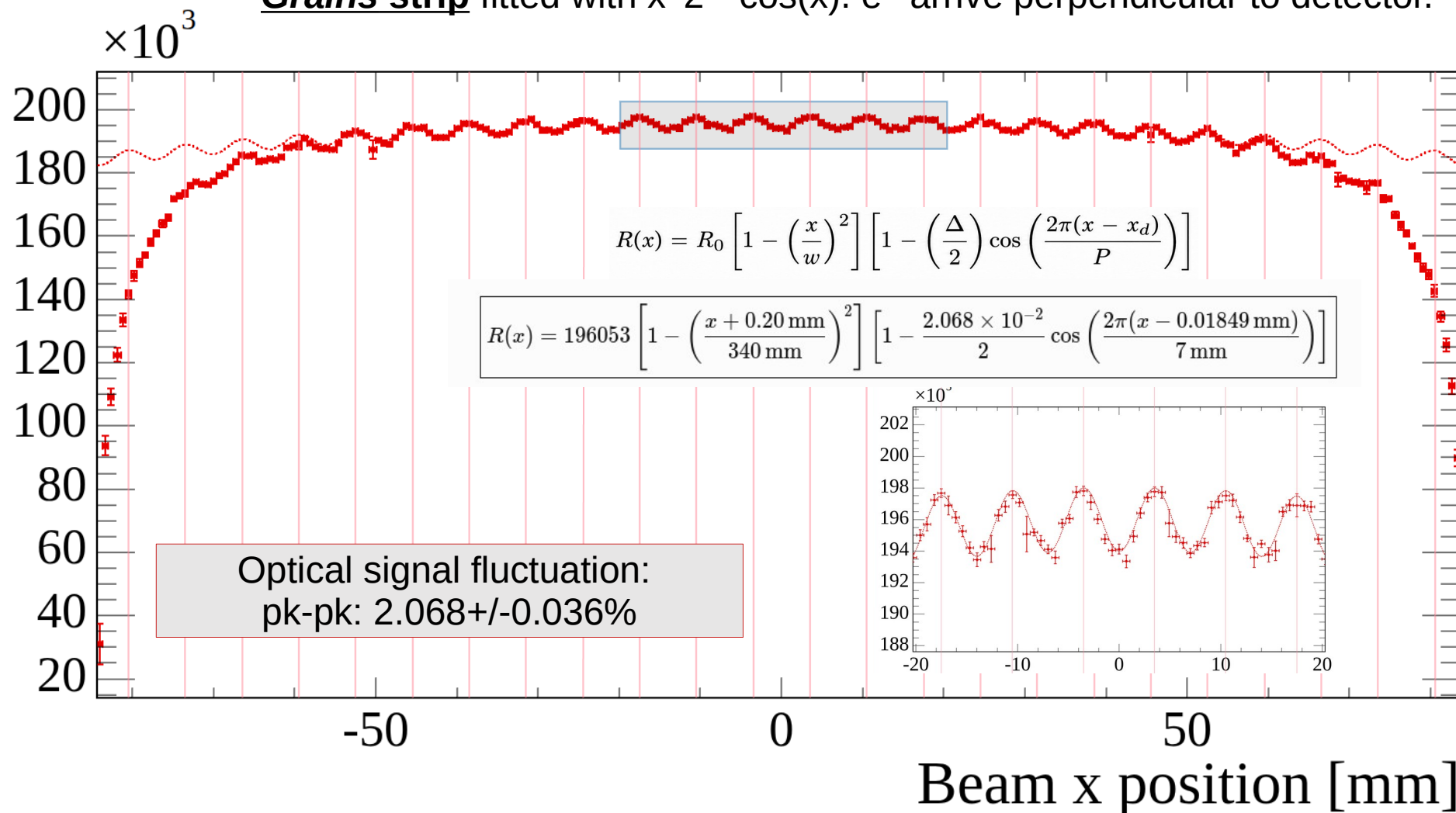
the whole face, 168 × 168 mm
24 × 24 fibers; the window in black



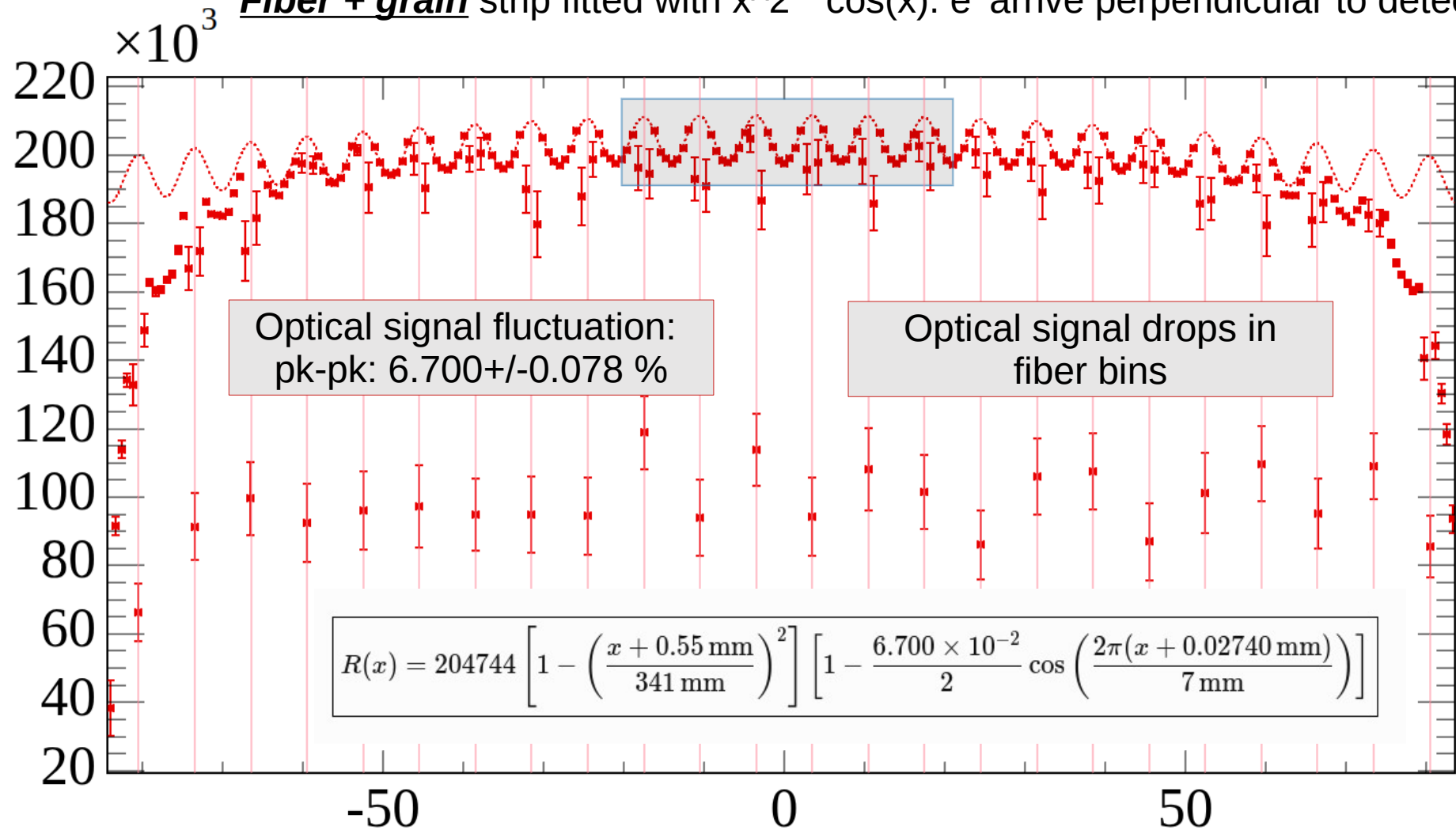
Each strip
240 bins of 0.7 mm across the face
10 bins per pitch, a fiber column
on a bin centre
 e^- of 5 GeV along z (the fibers);
tilted scans: 1° to 12° ,
in the x-z plane

Grains strip fitted with $x^2 \cdot \cos(x)$. e^- arrive perpendicular to detector.

Detected photons / event

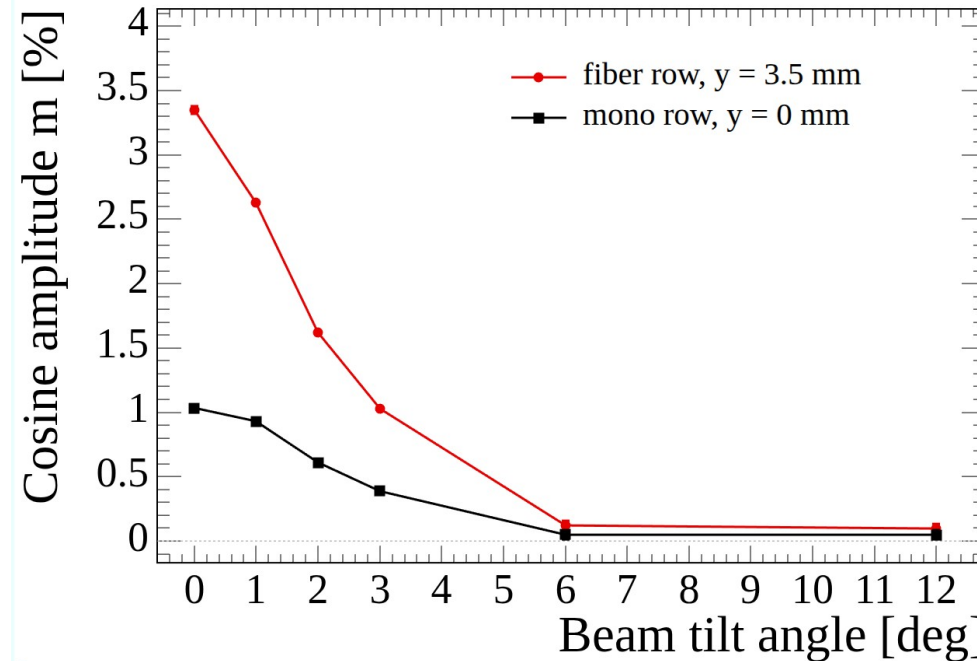
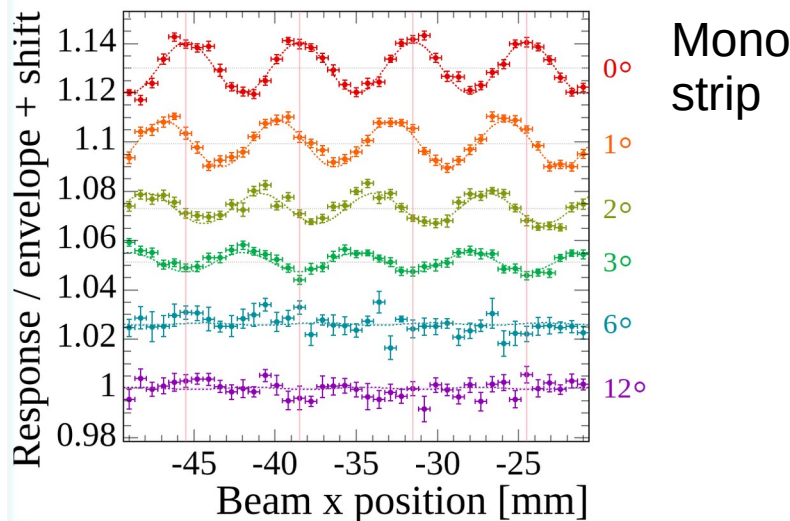
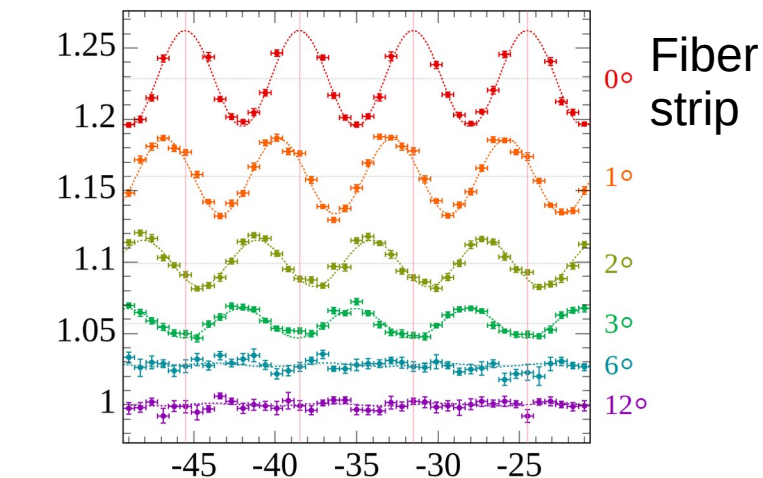


Fiber + grain strip fitted with $x^2 \cdot \cos(x)$. e^- arrive perpendicular to detector.



e^- has an *incident angle*:

Fluctuation amplitude is decreasing with tilt angle.
For tilt = 6° , cosine amplitude < 0.1%

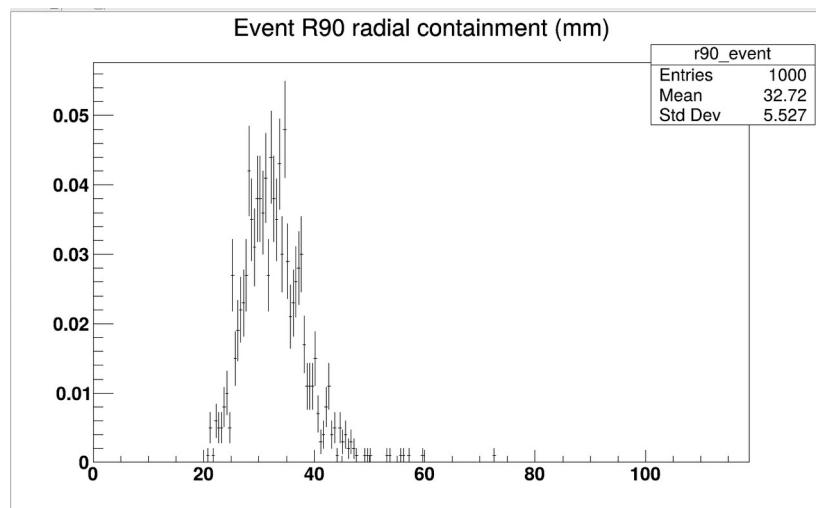


- Light response studies with **explicit geometry** for 168x168x400mm GRAiNITA demonstrator.
- Further optimization(**x13000**) reached with box-shape grains.
- Study performed:
 - 1-D non-uniformity shows cosine optical signal fluctuation.
 - Its amplitude decreases with increasing incoming particle tilt.

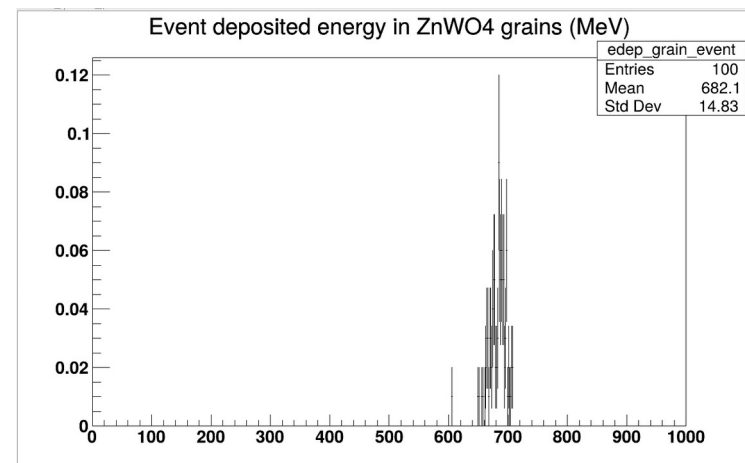
Conclusion:

The DDA + hash optical tracking, together with repeated geometry are useful tools for granular scintillating materials calorimetry.

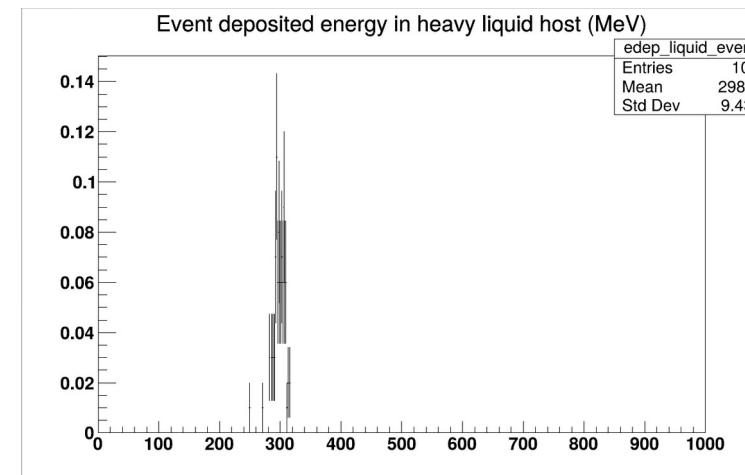
Thanks for attention!



1000 events,
Transverse radius of
deposition of 90%
 $R90 = 32.7 \pm 5.5$ mm



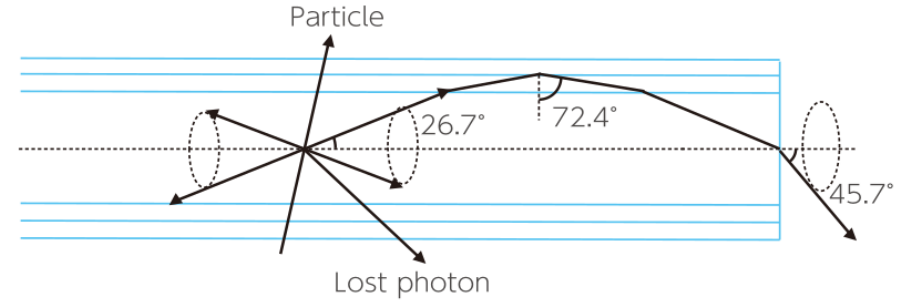
~ 68%
Energy lost
in grains



~ 30%
energy lost
in SMT

This is a big factor in optimization!

For optics BVH:
 fiber bounces took ~70% of optical tracking timing
 grain bounces took ~ 30% of optical tracking timing



We use a simple quadratic equation to check for the borders, as the fibers and the claddings are just coaxial cylinders:

$$x(t) = x + t d_x, \quad y(t) = y + t d_y.$$

$$(x + t d_x)^2 + (y + t d_y)^2 = R^2.$$

$$(d_x^2 + d_y^2)t^2 + 2(xd_x + yd_y)t + (x^2 + y^2 - R^2) = 0$$

