# Mu2e CD3c Review
# Calorimeter simulation

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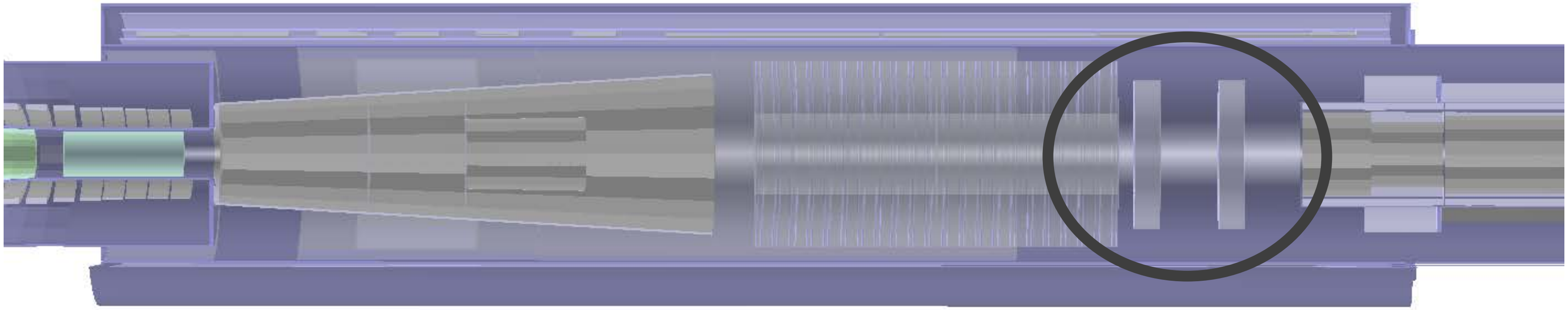
4/19/16

# Mu2e calorimeter

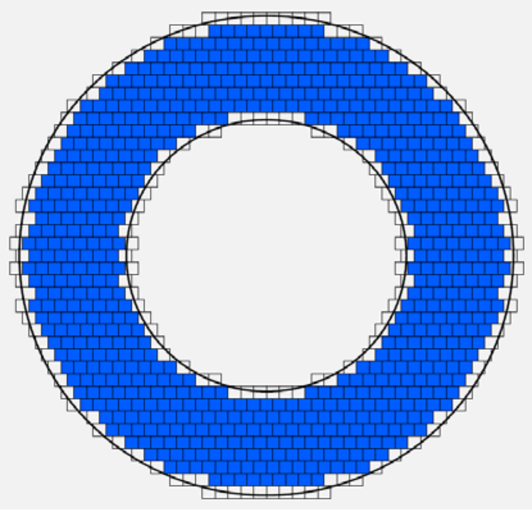
**Disk calorimeter:** 2 disks separated by ~1/2 wavelength



**Disk dimensions**
- inner / outer radii: 374 – 660 mm
- separated by 700 mm (face to face)

**Crystal**
- CsI square shape
- 3.4 cm across flats x 20 cm
- 2 readouts per crystal
- 150 μm wrapping

Disk



# Mu2e calorimeter

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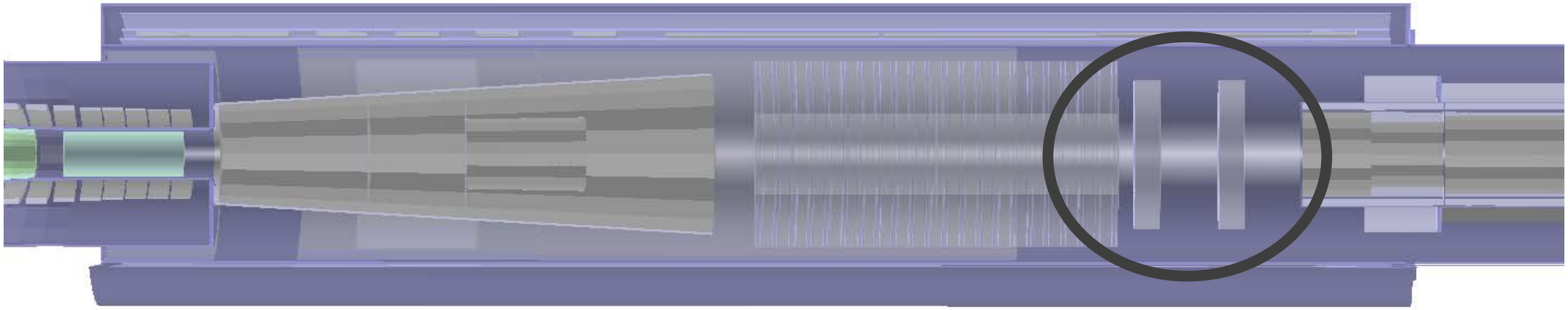


Detailed simulation with Geant 4 to characterize the energy, time and position resolution, include the estimates of backgrounds performed for cd3.

**Backgrounds:**

**Beam flash** coming from particles produced at production target (peaking at T ~ 300 ns) **Photon, neutron, protons and few DIOs,** products of muon capture on target, muon decays in orbit (DIO), antiprotons,…

**People:** B. Echenard, G. Pezzullo, P. Murat

# Summary of calorimeter requirements

- Provide high electron reconstruction efficiency for muon rejection of 200
- Provide online trigger capability
- Provide cluster-based track seeds for track finding
- In order to do so it should:
  - → provide energy resolution $\sigma(E)/E \sim O(5\%)$ monitored at a level of < 0.5%
  - → provide timing resolution $\sigma(t) < 0.5$ ns
  - → provide position resolution < 1 cm

These requirements should be met in a radiation environment of

Front face of the inner ring of crystals:

photons: 100 krad/crystal

neutrons: $10^{12}$ n/cm$^2$

Inner ring of photosensors

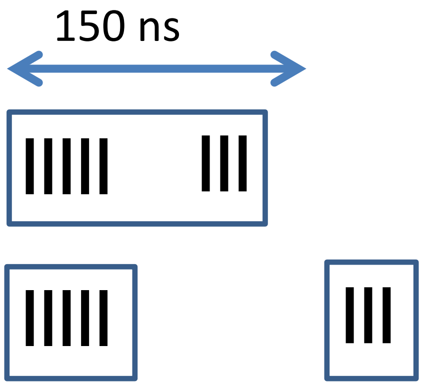
neutrons: $3 \times 10^{11}$ n_1MeV/cm$^2$

# Hit creation

## Hit creation

1) Collect energy left in CsI crystal from Geant 4 energy deposits within a 150 ns window from the first hit to include effect from pile-up.

   Set the hit time to most energetic energy deposit to approximate waveform extraction.




2) Include corrections for
   - longitudinal response uniformity (LRU)
   - photo-statistics
   - electronic noise

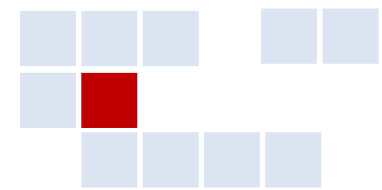
**Improved simulation of readout in progress:** waveform simulation and fitting, better pile-up rejection and timing performance.

**Refinement of some corrections in progress**

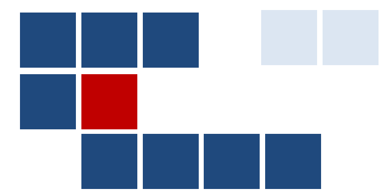
# Clustering

## Cluster finding algorithm

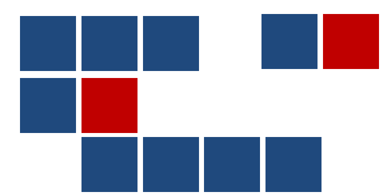
1) Start with seed, crystal with largest energy deposit



2) Add all crystals simply connected to the seed in a 2 ns time window around the seed time and with an energy above 1 MeV (limit  imposed by DAQ bandwidth). The 2 ns window is larger that the typical hit time resolution (< 0.5 ns)



3) Repeat steps 1 and 2 until there are no more crystal left



4) Apply split-off recovery algorithm. Low-energy split-off less than two crystals apart from the main cluster and within 2 ns are reattached.



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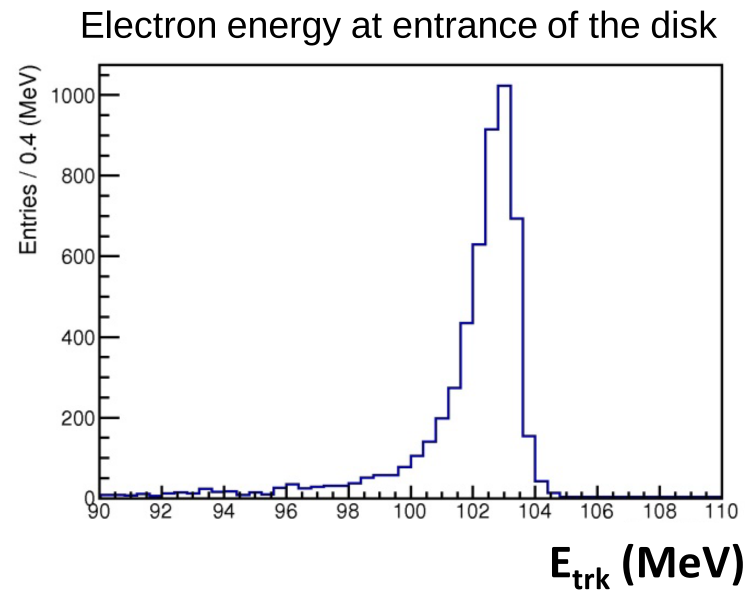
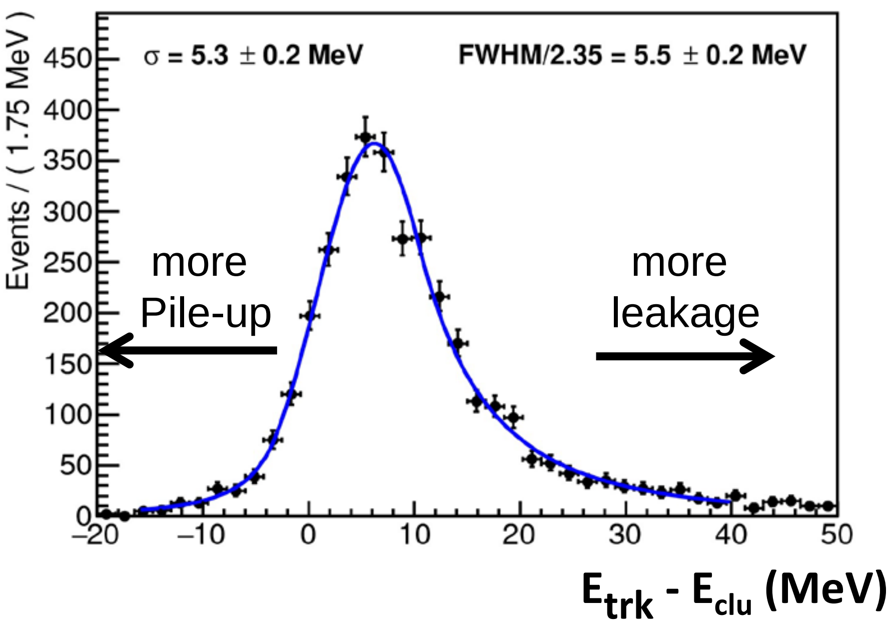
# Energy resolution

Resolution given by the difference between the cluster energy and the energy of the electron at the entrance of the calorimeter.

Fit the energy resolution with a double-sided Crystal Ball function, quote both core resolution ($\sigma$) and FHWM/2.35. The core resolution is more sensitive to the pile-up, while the FHWM is more representative of the "total" resolution



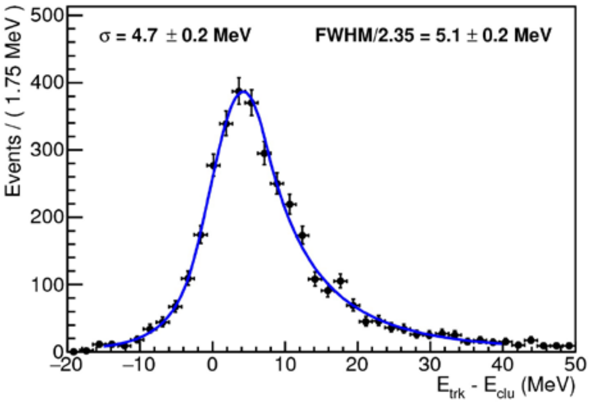




**FWHM / 2.35 = 5.5 ± 0.2 MeV**

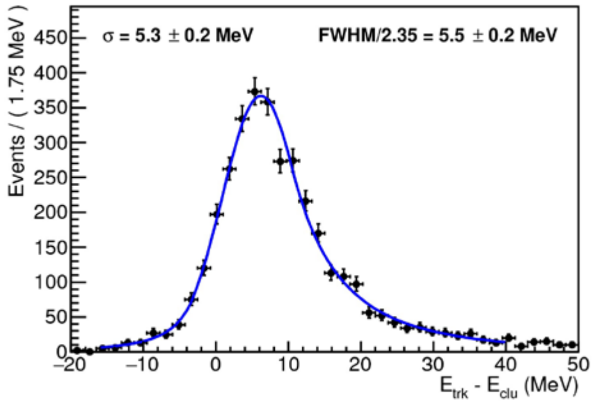
# Dependence on clustering parameters

**Effect of energy threshold for clustering algorithm**

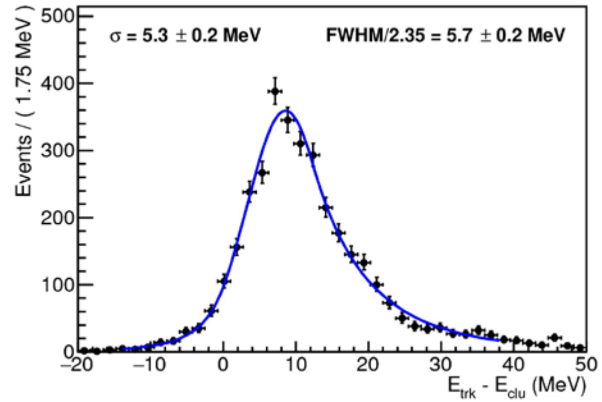
Ecut = 0.5 MeV




Ecut = 1.0 MeV




Ecut = 2.0 MeV

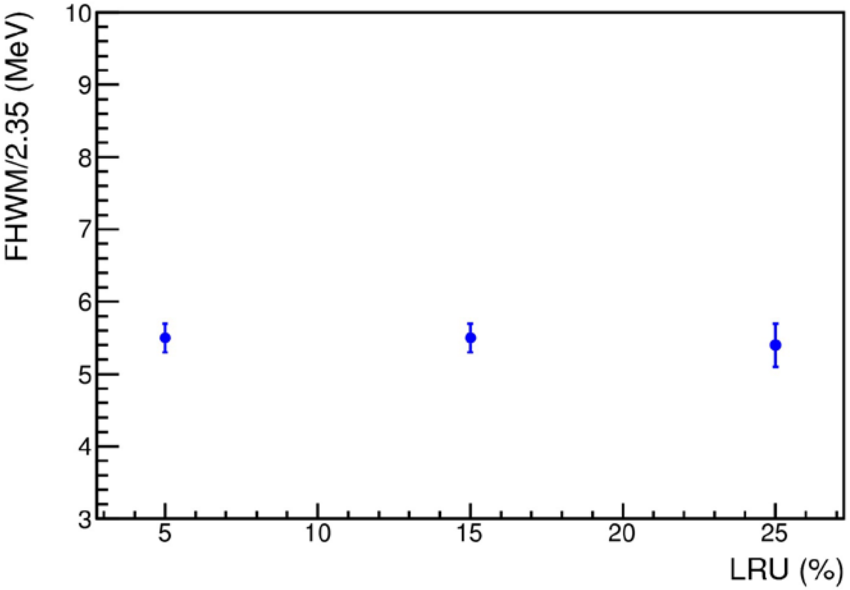


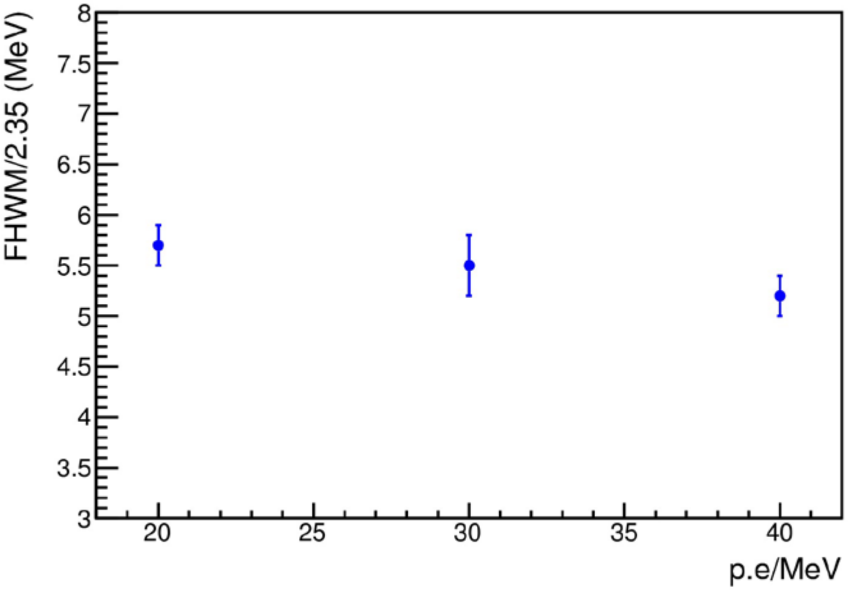

| Ecut = 0.5 MeV | Ecut = 1.0 MeV | Ecut = 2.0 MeV |
|---|---|---|
| σ = 4.7 ± 0.2 MeV | σ = 5.3 ± 0.2 MeV | σ = 5.3 ± 0.2 MeV |
| FWHM / 2.35 = 5.1 ± 0.2 MeV | FWHM / 2.35 = 5.5 ± 0.2 MeV | FWHM / 2.35 = 5.7 ± 0.2 MeV |

Resolution mildly sensitive to cut value, though it would be desirable to keep it as low as possible.

# Dependence on simulation parameters

**Dependence on the photo-statistics and LRU**

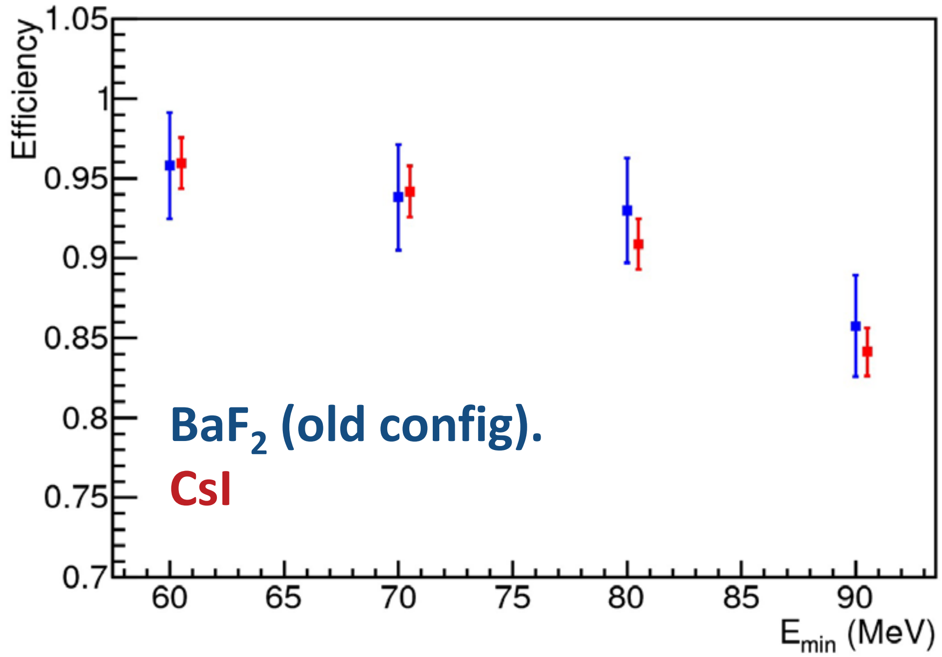



The impact of the LRU and the number of p.e/MeV seems limited

# Signal acceptance

**Efficiency = # cluster E> $E_{min}$ with a good track / # good tracks**



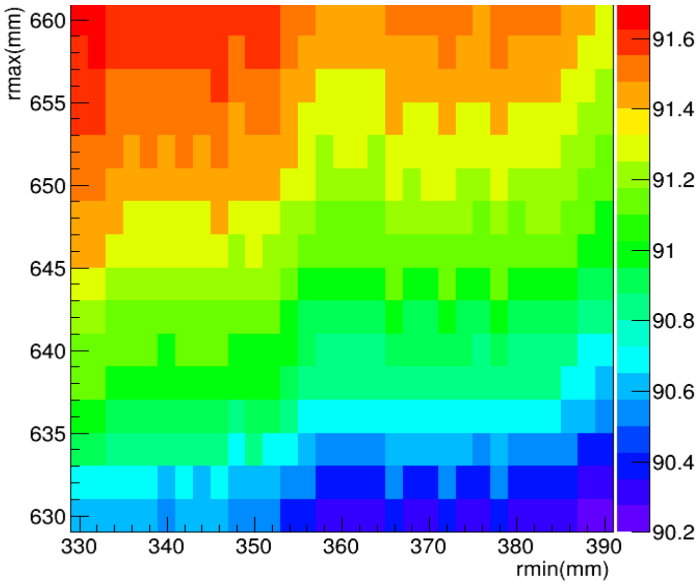

Efficiency above 95% for $E_{min}$ > 60 MeV, inefficiency mainly due to tracks hitting the inner side of disks or missing both disks.

Calorimeter helps finding tracks by providing seed for tracking algorithm

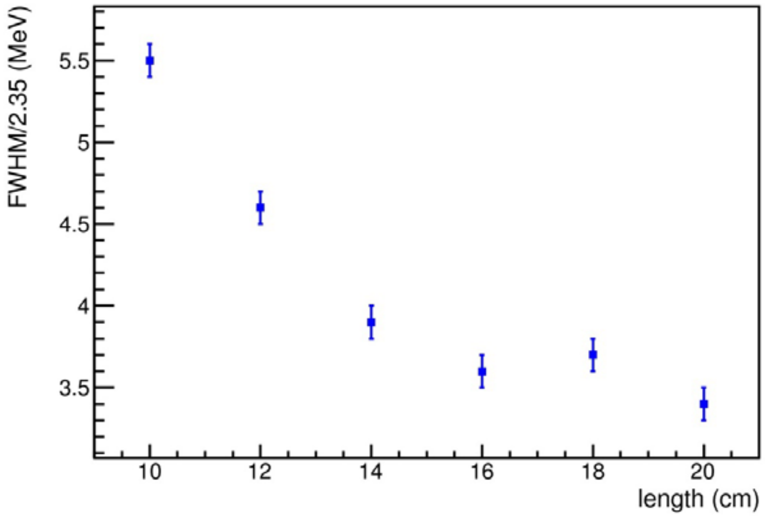
# Dimensions optimization

Simplified algorithm to estimate the efficiency *vs.* disk dimensions within constraints on calorimeter envelope, crystal and readout sizes, radiation dose and efficiency

Acceptance (E > 60 MeV)




Resolution *vs* crystal length



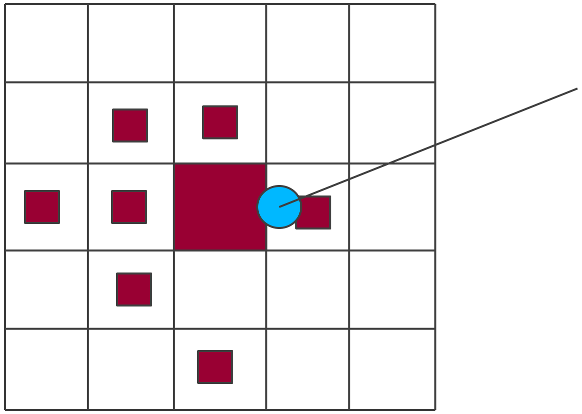

Select promising configurations and run full signal simulation to confirm results

Final configuration robust against small perturbations:

Rin=374 mm, Rout = 660 mm, crystal size = 34 mm, crystal length = 200 mm

# Position resolution

Train multivariate regressor to reconstruct the track position given the position / energy of the 10 most energetic hits forming the cluster, and together with the incident angles and momentum of the incoming track.

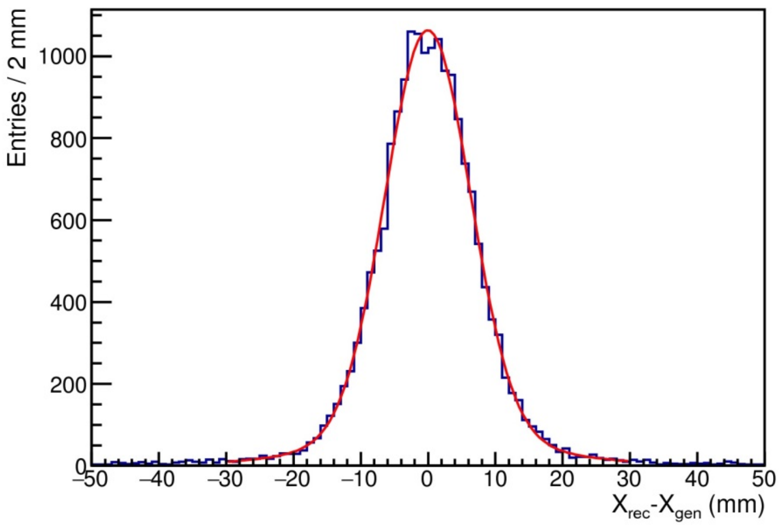


Center the matrix around the largest energy deposit and input the pattern in the ML algorithm

# Position resolution

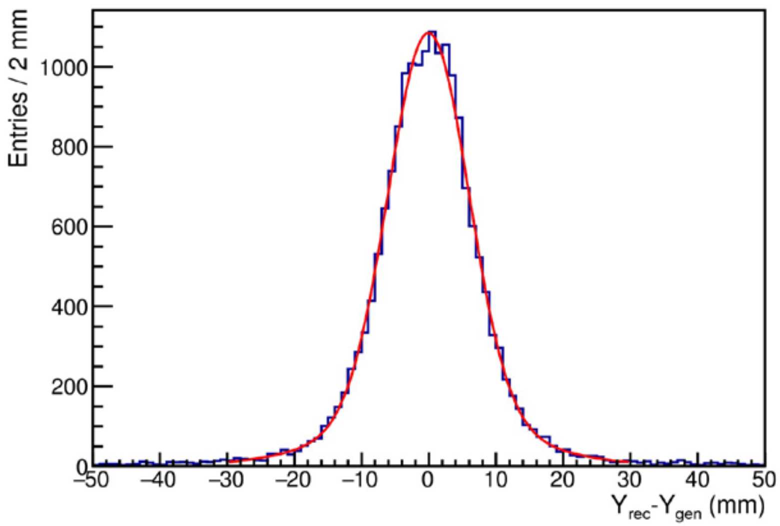
Compare the predicted and Monte Carlo positions with pure signal events.

X predicted – X MC




$\sigma = 6.3 \pm 0.2$ mm

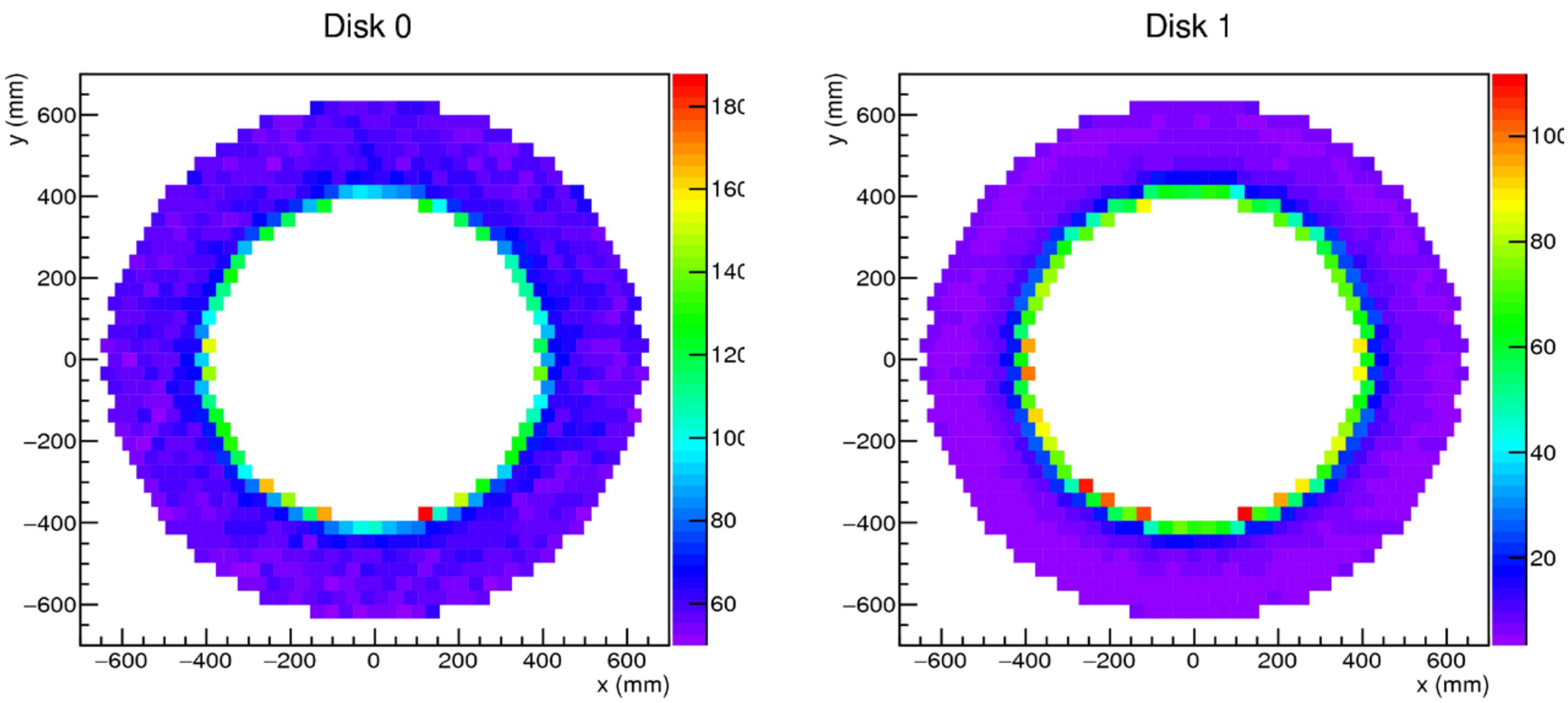
Y predicted – Y MC




$\sigma = 5.8 \pm 0.2$ mm

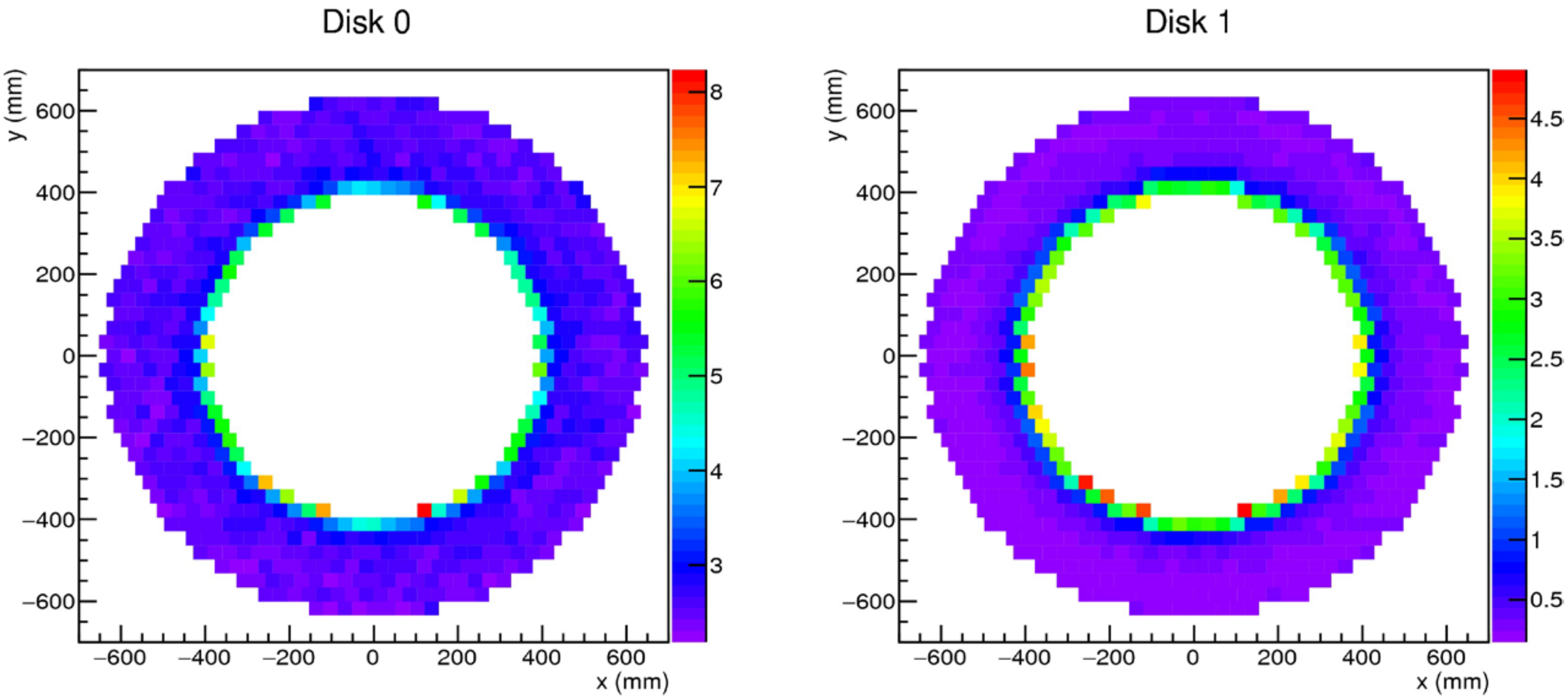
Almost Gaussian distributions, resolution at the level of 6.0 mm in X and Y coordinates, well within requirements

# Energy deposited in crystals




Average energy deposited / microbunch is ~130 (70) MeV in inner ring of first (second) disk, 60 (10) MeV in the rest of the first (second) disk.

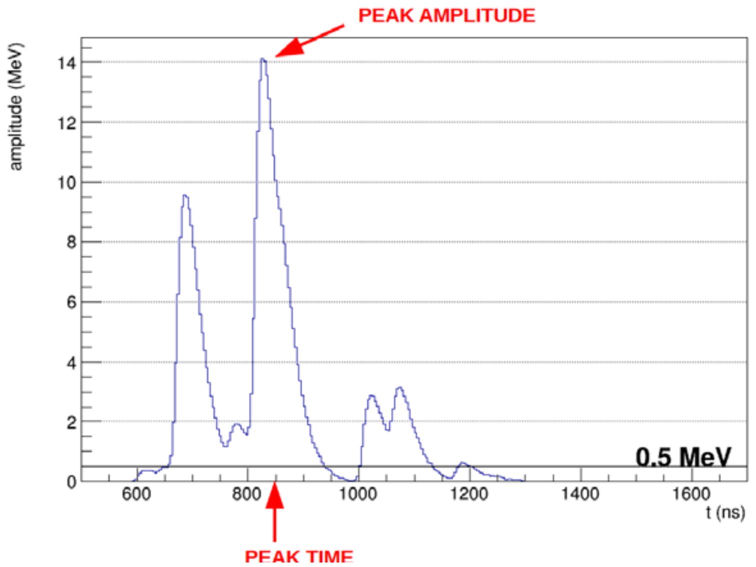
# Radiation dose kRad / year

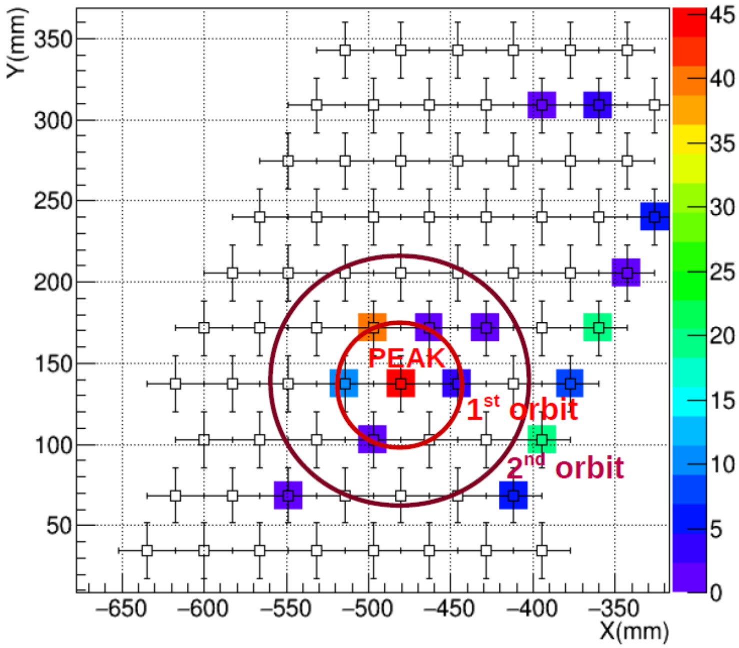



The average dose is around 3 (0.5) kRad / year for the front (back) disk, spiking up to 8 (4) kRad / year for the innermost crystals in the front (back) disks

# Calorimeter trigger

Standalone trigger based on the digitized information for each crystal to select conversion electrons

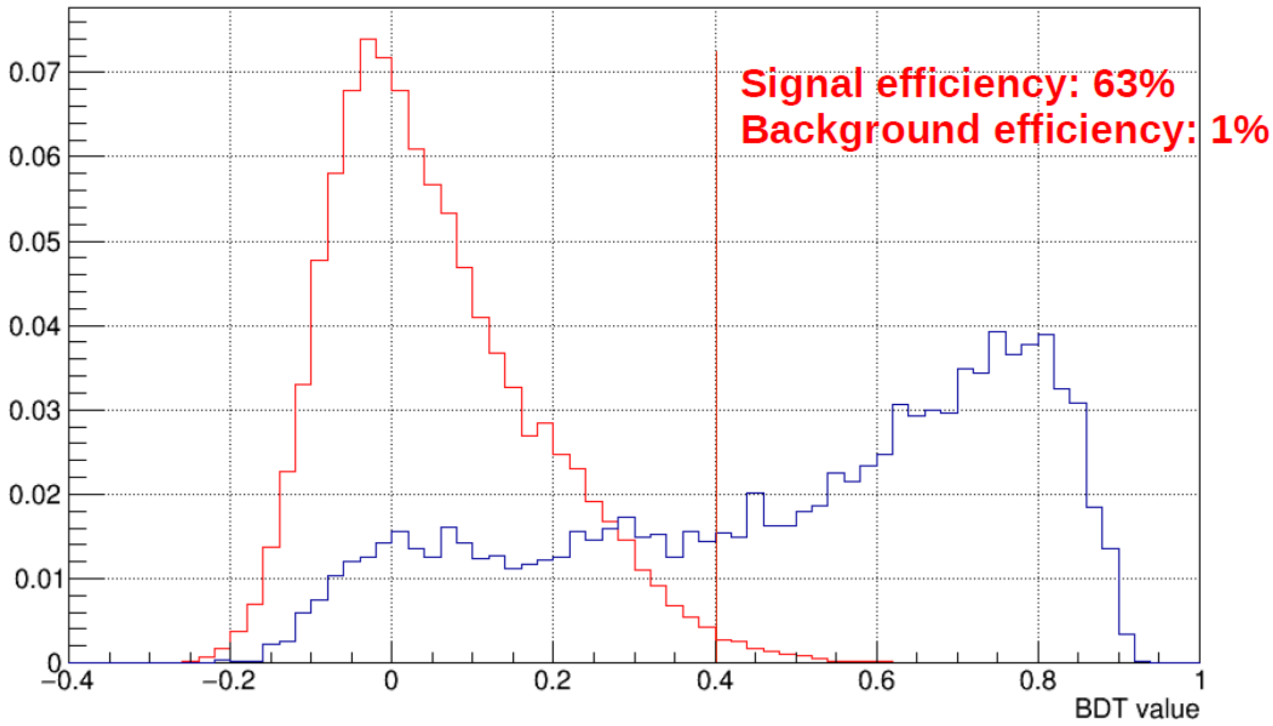



Use peak amplitude, position, time and cluster structure to identify signal electrons

# Calorimeter trigger

Train multivariate classifier to identify signal events

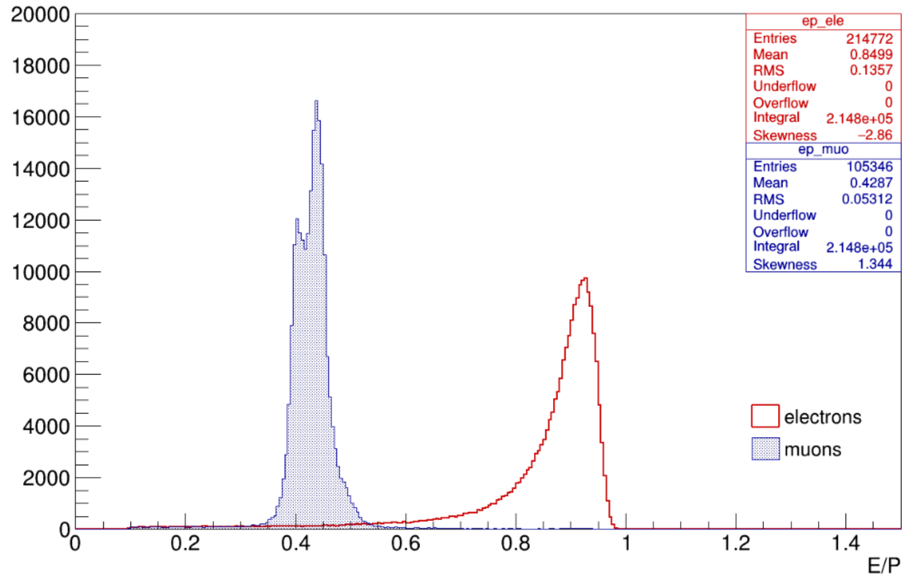



Work in progress, but already achieve a signal efficiency around 60% for 1% background level

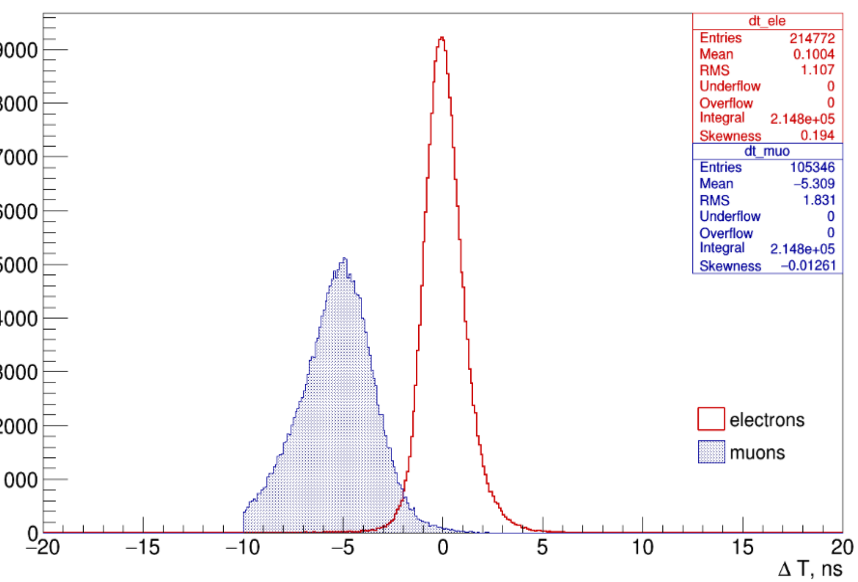
# Particle identification

Selector based on the ratio energy/momentum (E/p) and the time difference between the center of the tracker and the calorimeter (ΔT)

E/p: electrons vs muons

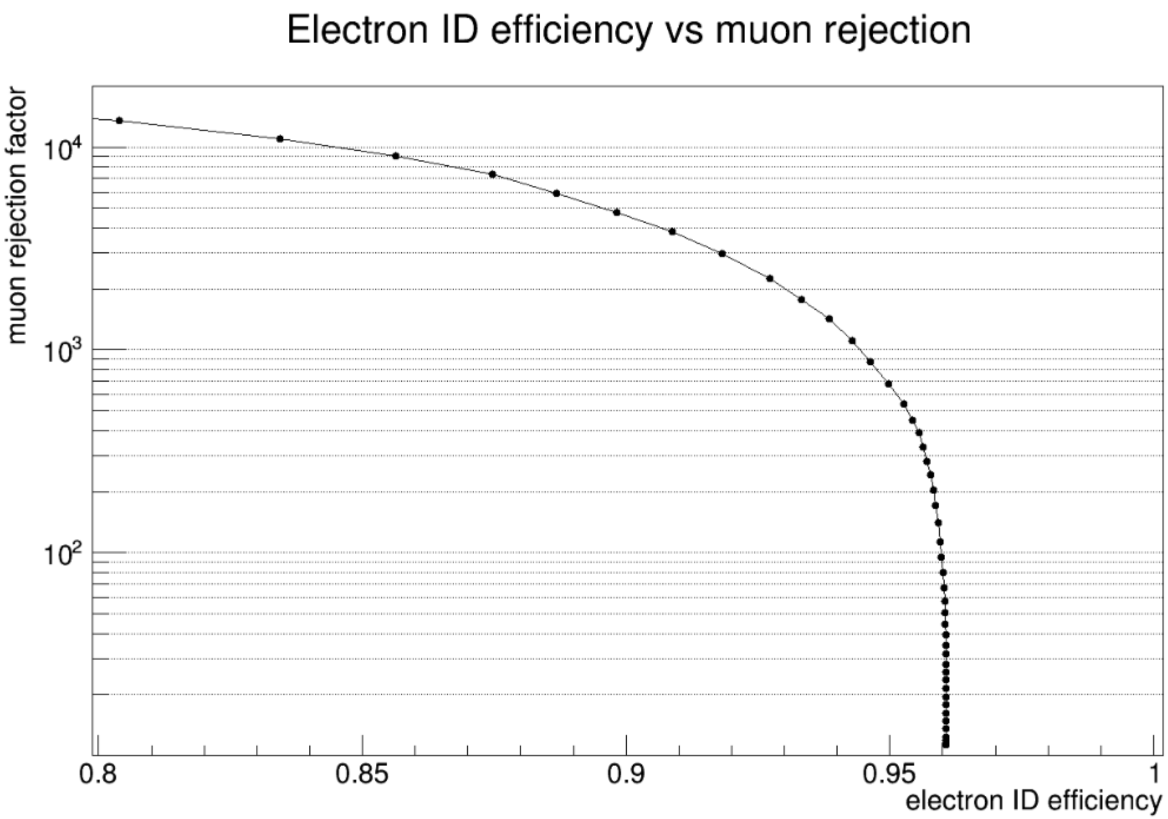



ΔT: electrons vs muons




Build a PID selector (likelihood ratio) based on these two variables

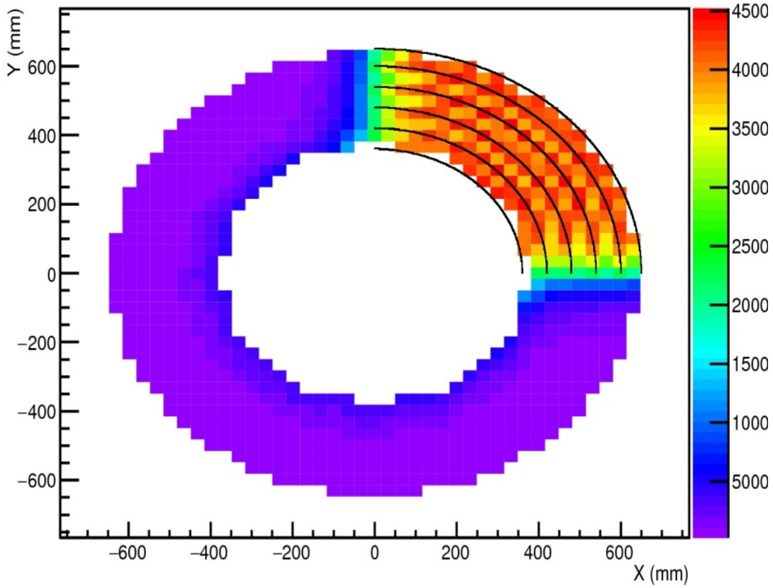
# Particle identification

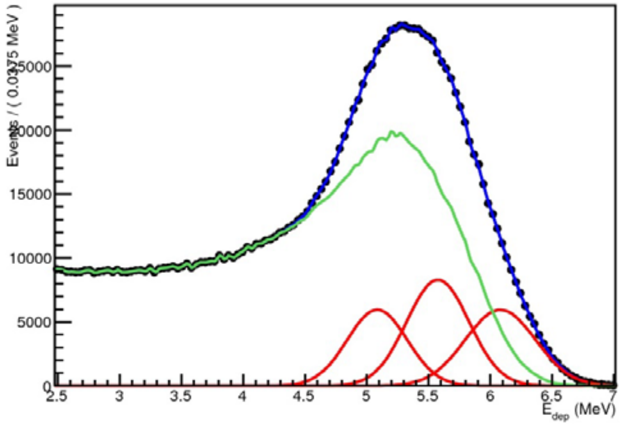


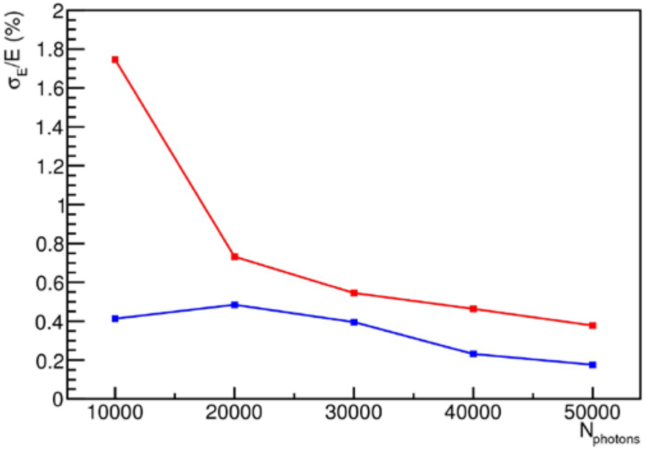

Rejection factor of the order of 1000 for a 95% signal efficiency

# Calibration source

Simulate fraction of disk




Started simulation work on calibration system

See F. Porter talk



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# Conclusion

Extensive simulation campaign to explore the parameter space for the CsI calorimeter

The nominal resolution is FHWM/2.35 = 5.5 $\pm$ 0.2 MeV, and varies mildly when the simulation parameters are altered

The geometry has a  signal efficiency above 95% for E> 60 MeV.

The position resolution is around 6 mm, within requirements

The core simulation tools are available, on-going work to refine the geometry description, digitization and clustering. We expect to have the full digitization soon.