



European Research Council
Established by the European Commission



Looking for light dark matter with POKER/NA64 experiment

Anna Marini, INFN-Genova



Milan, October 26th 2023

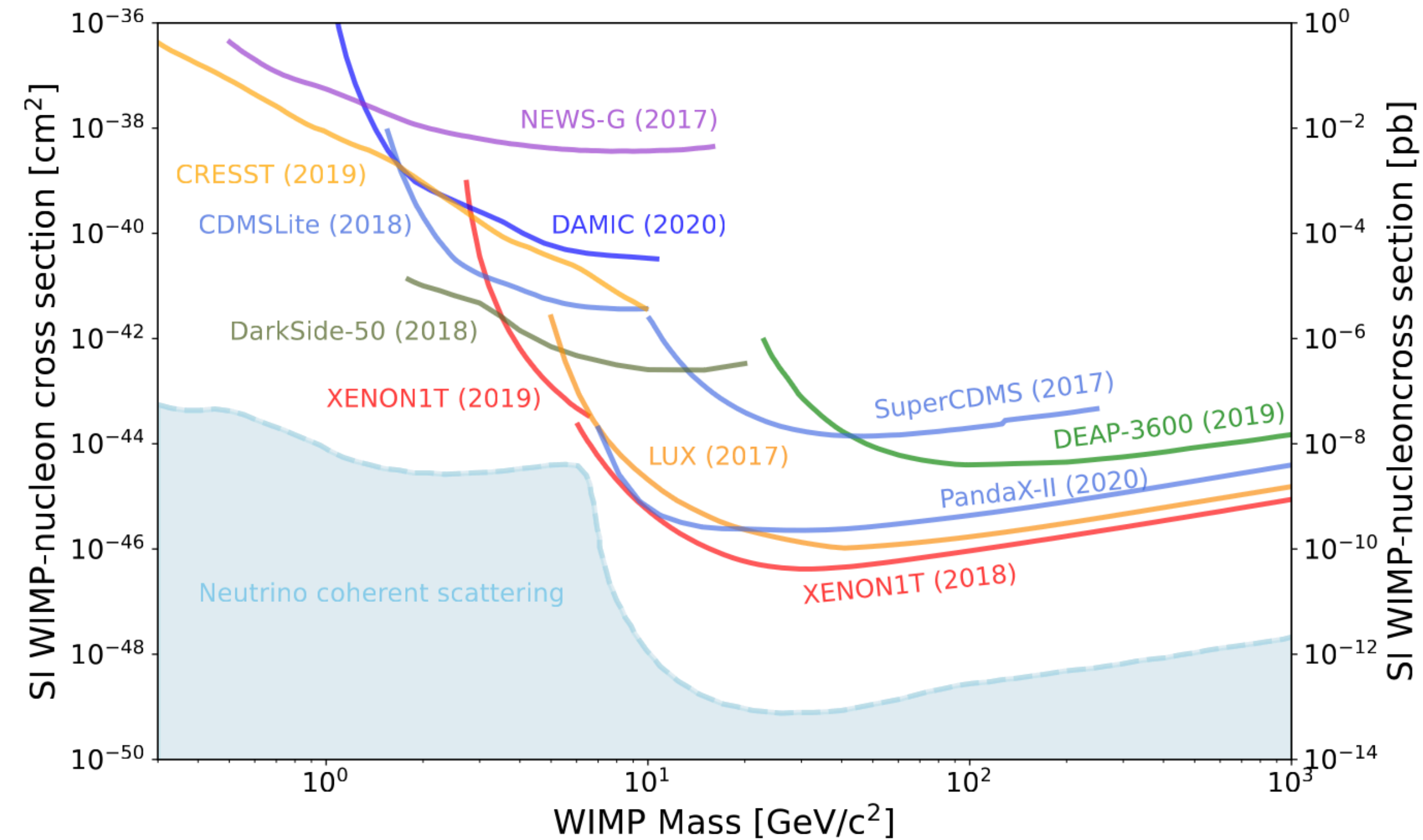
Outline

- Introduction to light dark matter
- NA64 experiment at CERN
- POKER project
- POKER R&D activities

Introduction

Dark matter puzzle

- One of the open questions of the physics beyond the standard model
- Focus: particle signature
- Complementarity is necessary at low masses

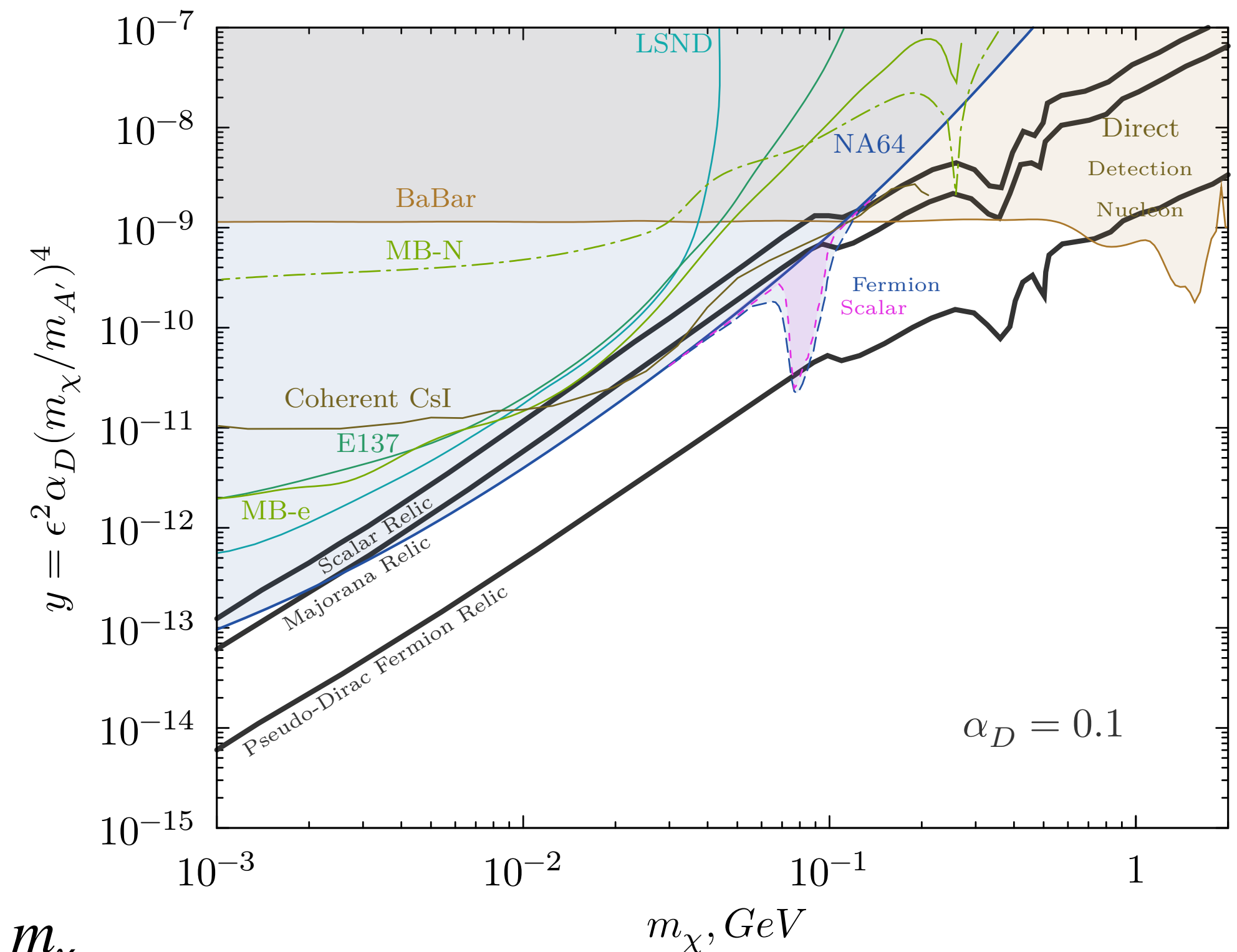


PDG 2023

Introduction

Light dark matter

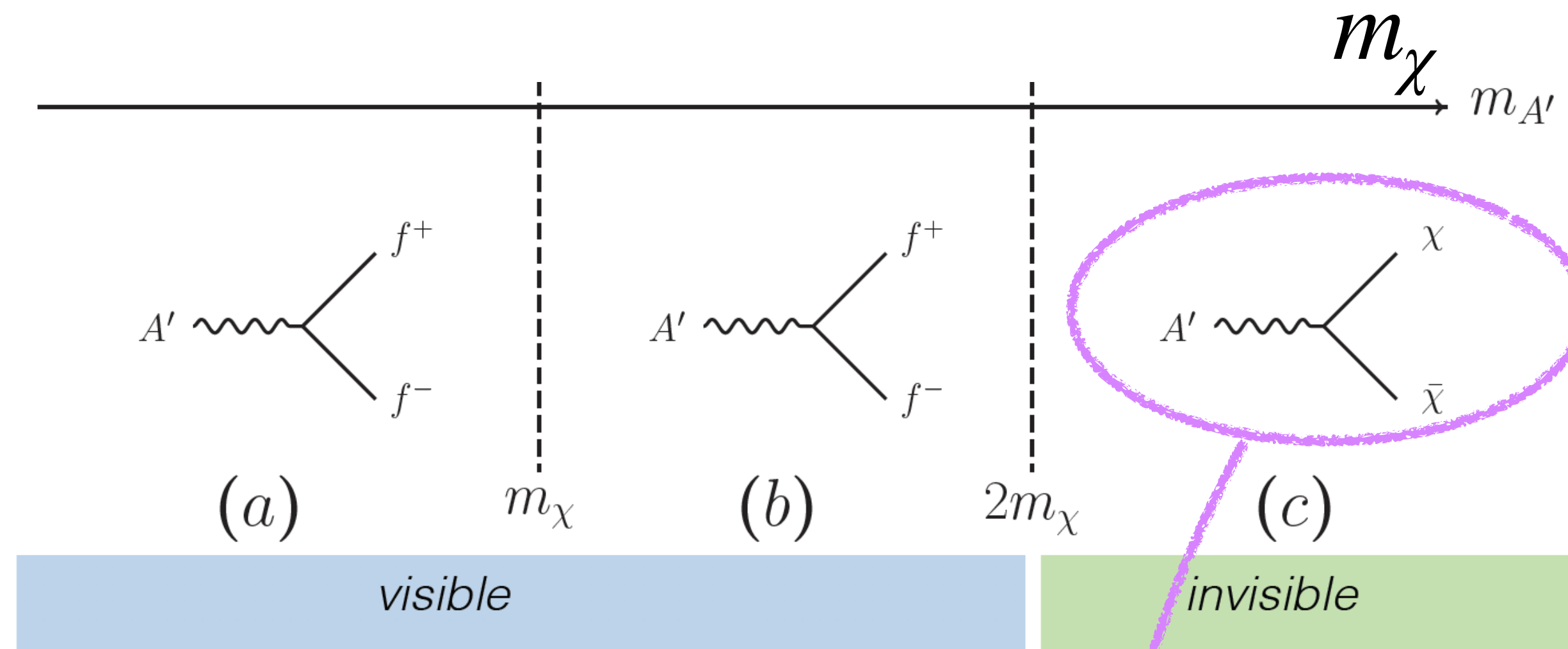
- Light dark matter (LDM) hypothesis: can predict the observed DM relic abundance
- $1 \text{ MeV} < m_\chi < 1 \text{ GeV}$
- Introduction of a new a new U(1) gauge-boson ("dark-photon", A'). This model includes 4 parameters:
 1. $m_{A'}$
 2. m_χ
 3. Coupling constant α_D (A' - χ)
 4. Kinetic mixing of A' with SM ϵ ($\ll 1$).



$$y = \left(\frac{m_\chi}{m_{A'}}\right)^4 \alpha_D \epsilon^2$$

Dark photon Phenomenology

Possible A' decays (depending on $\frac{m_{A'}}{m_\chi}$)



$$m_{A'} > 2m_\chi$$

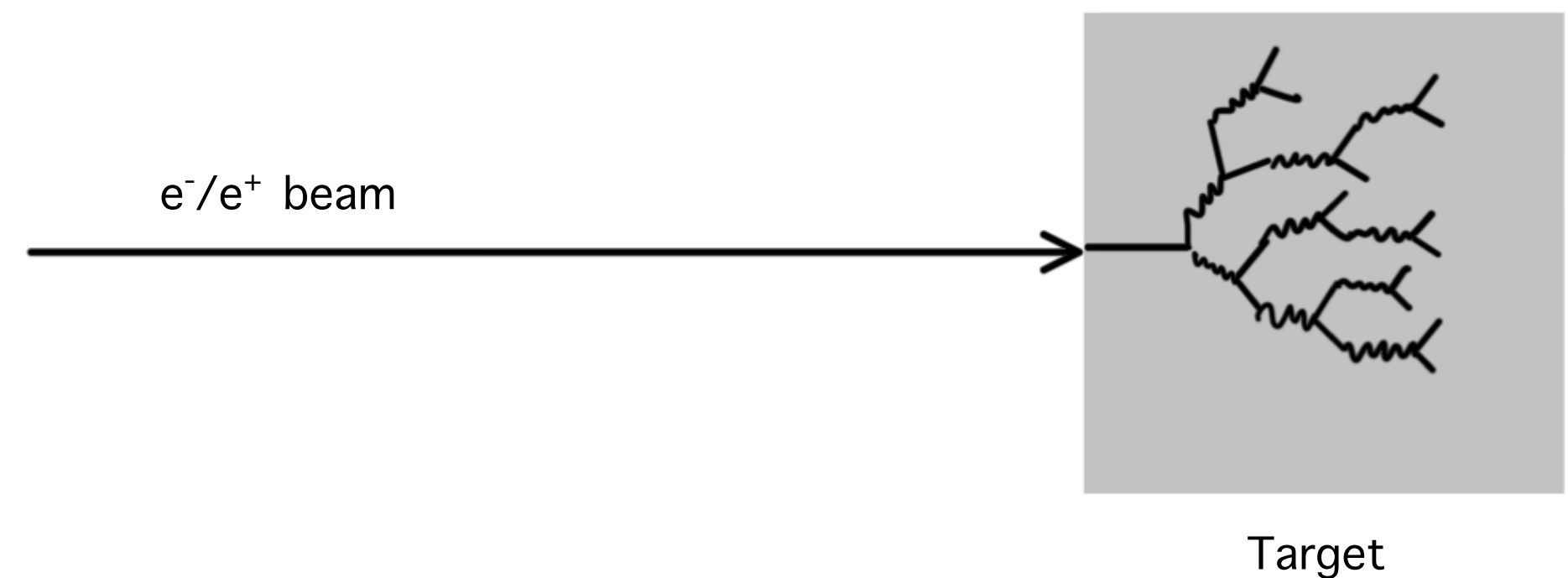


$$m_{A'} = 3m_\chi$$

“Missing energy” approach

Active thick targets

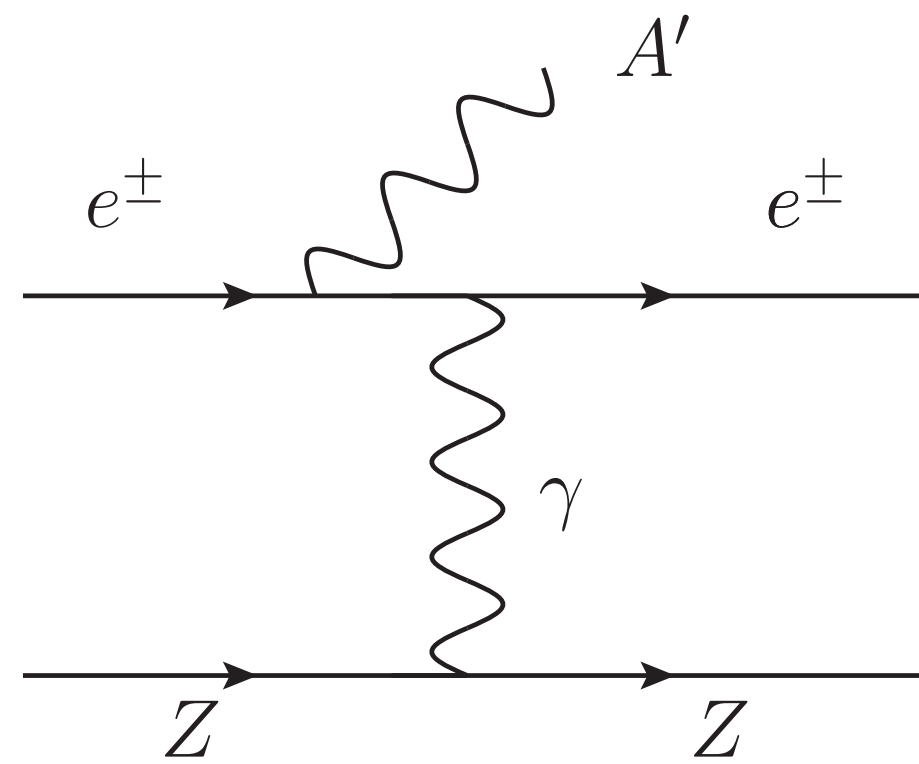
- The target is the detector
- Beam particles hit the target one at a time to avoid pile-up
- LDM particles produced in the target following an electromagnetic shower
- Signal in the form of a missing energy, as: $E_{miss} = E_{beam} - E_{dep} > \approx n \cdot 10 \text{ GeV}$
- Possible background sources:
 - Particles escaping the target
 - Beam contaminations



LDM production

With e^+/e^- beams

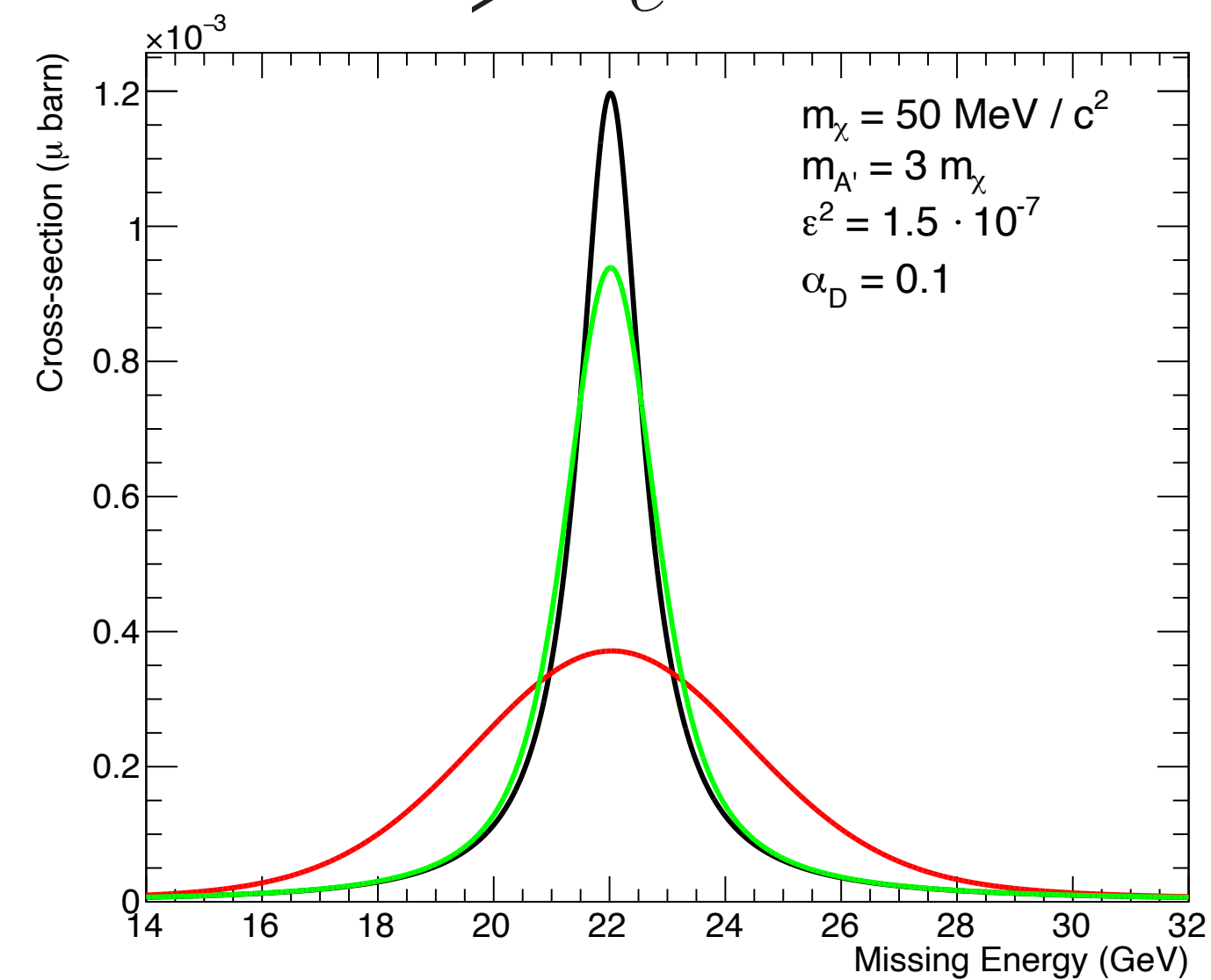
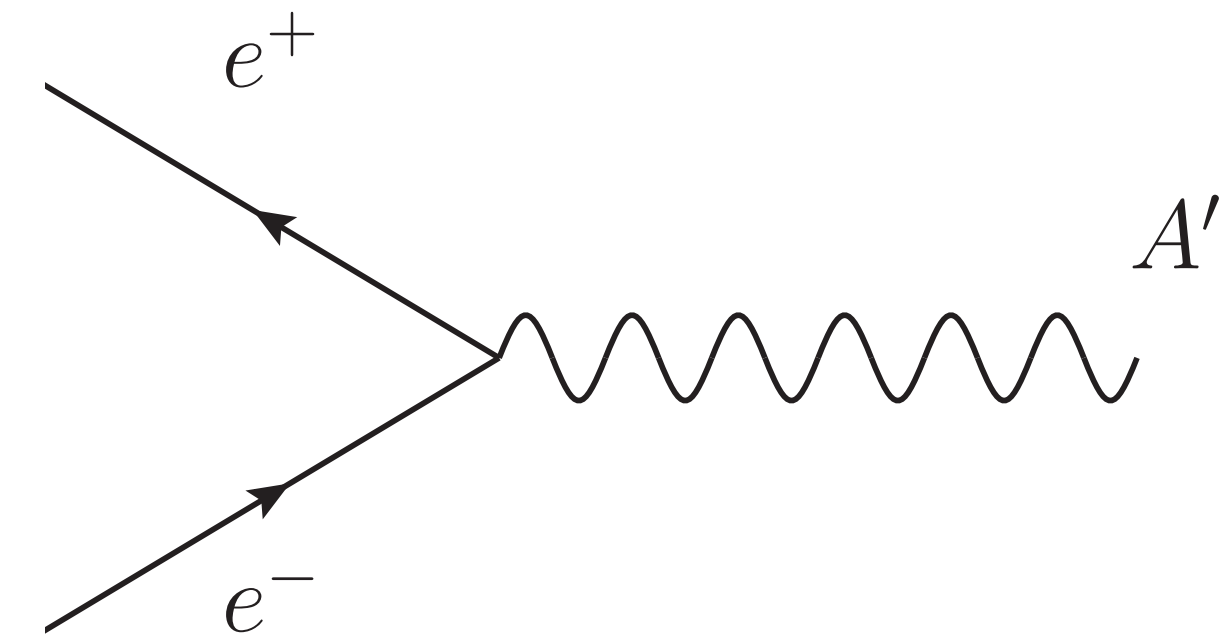
A' -strahlung



$$\sigma \propto \alpha_{EM}^3 Z^2$$

Forward-peaked A' emission

A' resonant production

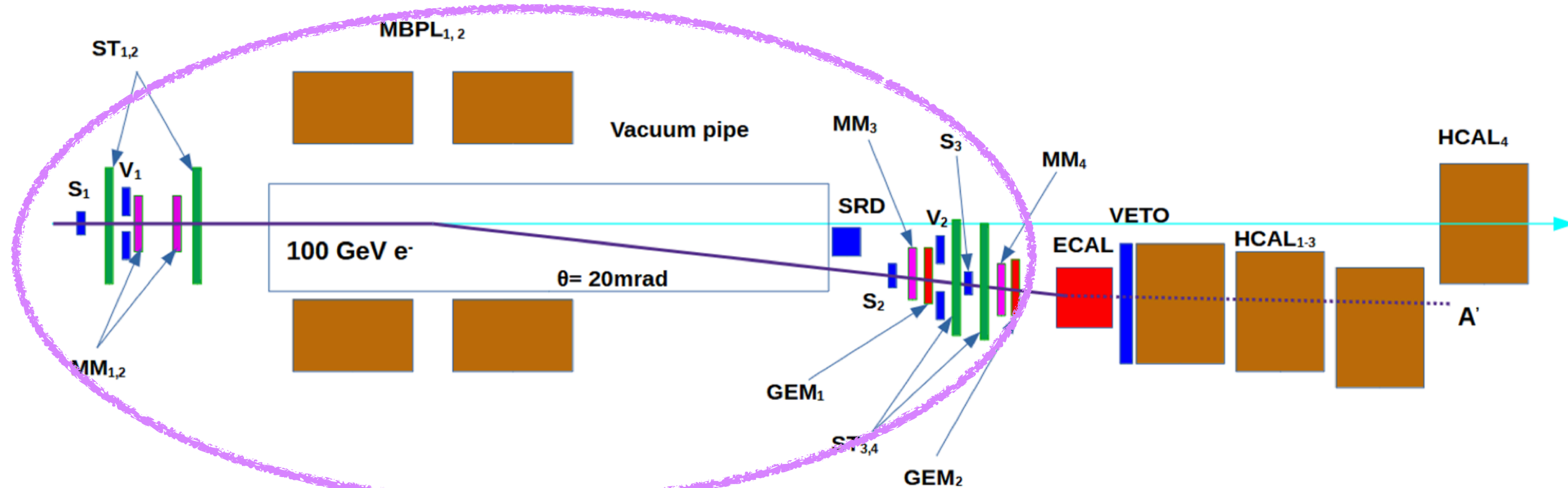
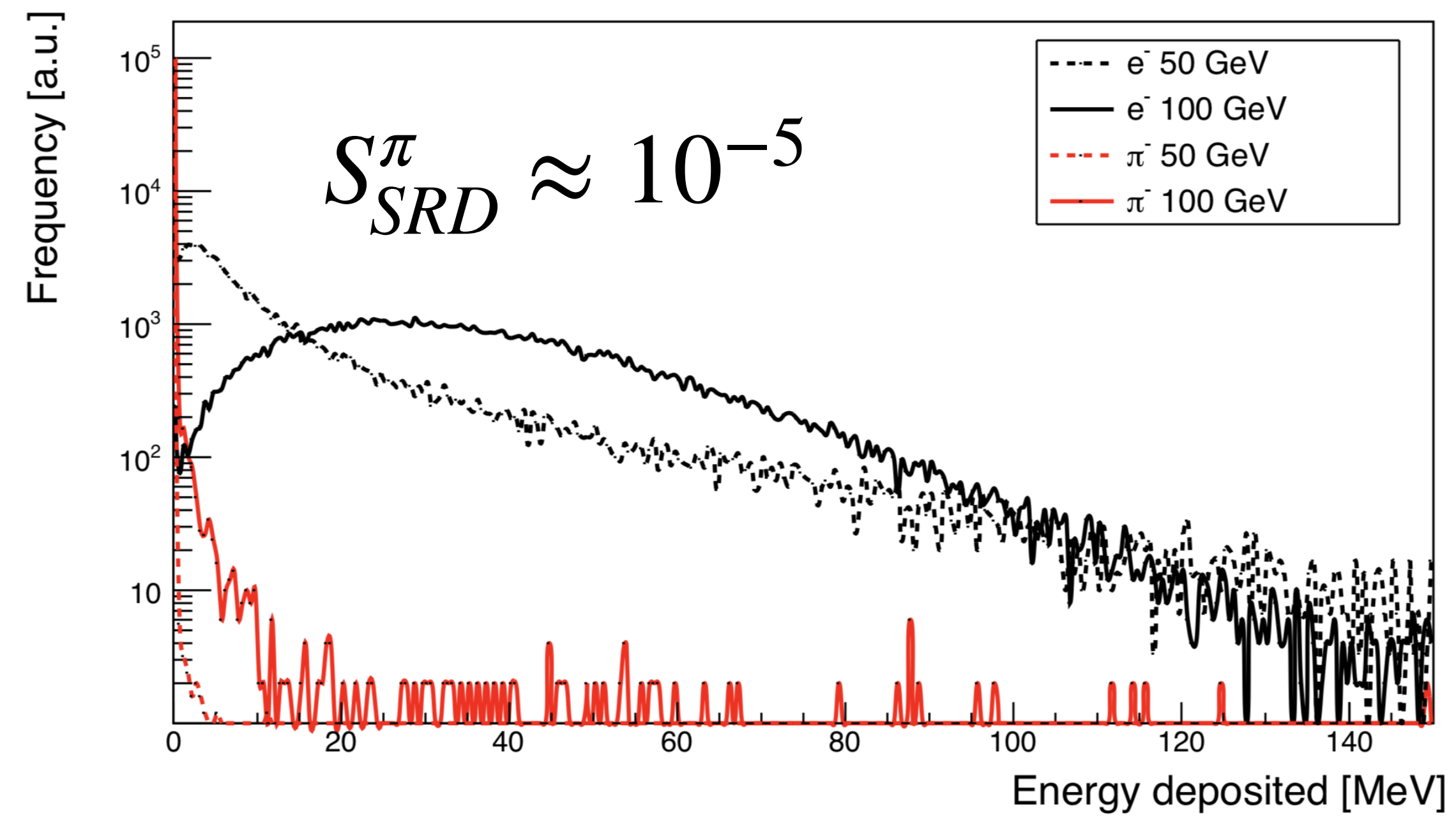


$$\sigma \propto \alpha_{EM} Z$$

$$E_R = \frac{m_{A'}^2}{2m_e}$$

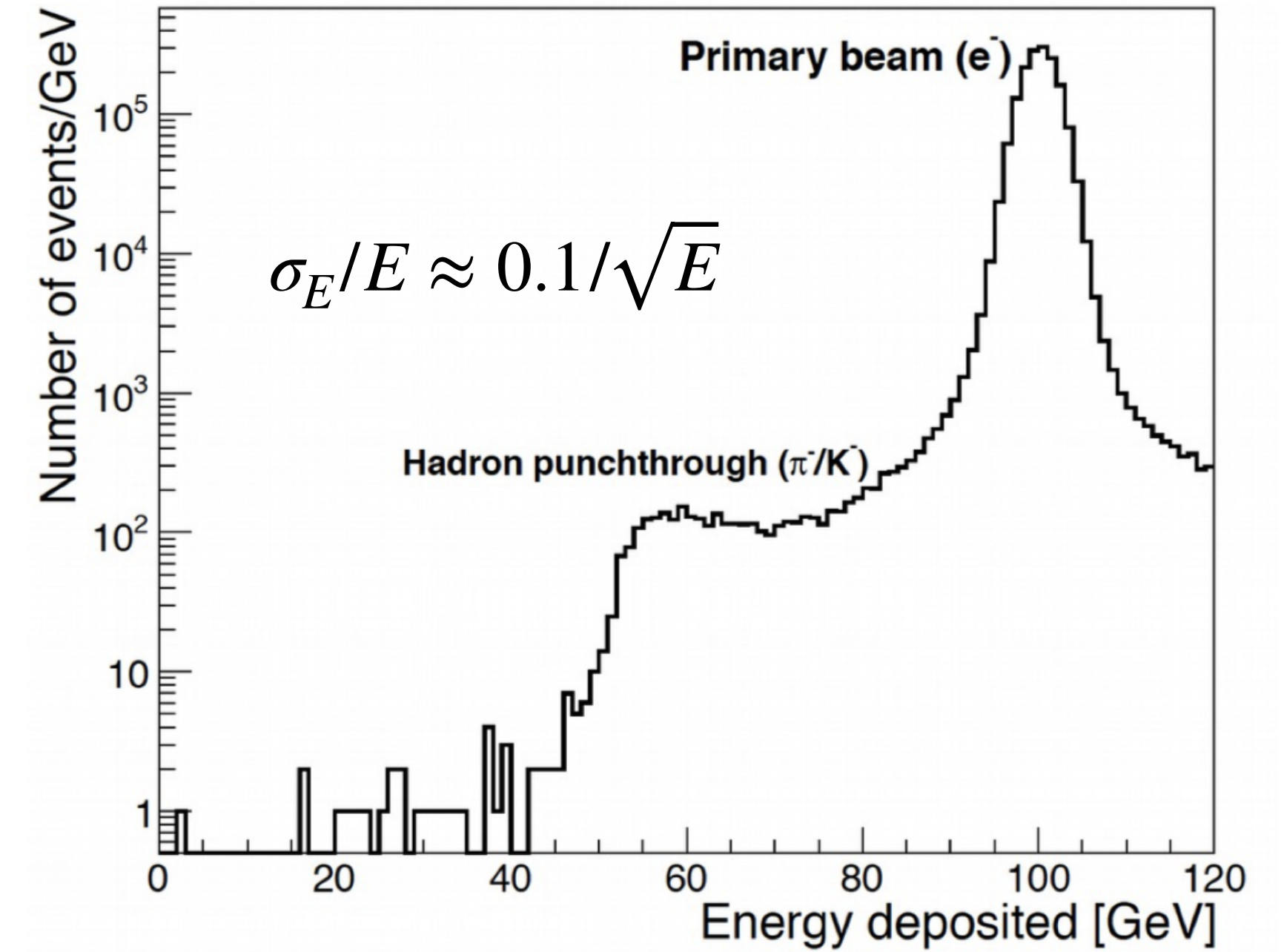
NA64 Experiment

- Located in the CERN's North Area (NA)
- Operates at line H4 of CERN SPS
- Uses a 100 GeV electron beam
- $R_{e^-} \approx 1 \text{ MHz}$
- $\sigma_{E_{beam}}/E_{beam} \approx 1 \%$
- $h/e^- \approx 0.005$

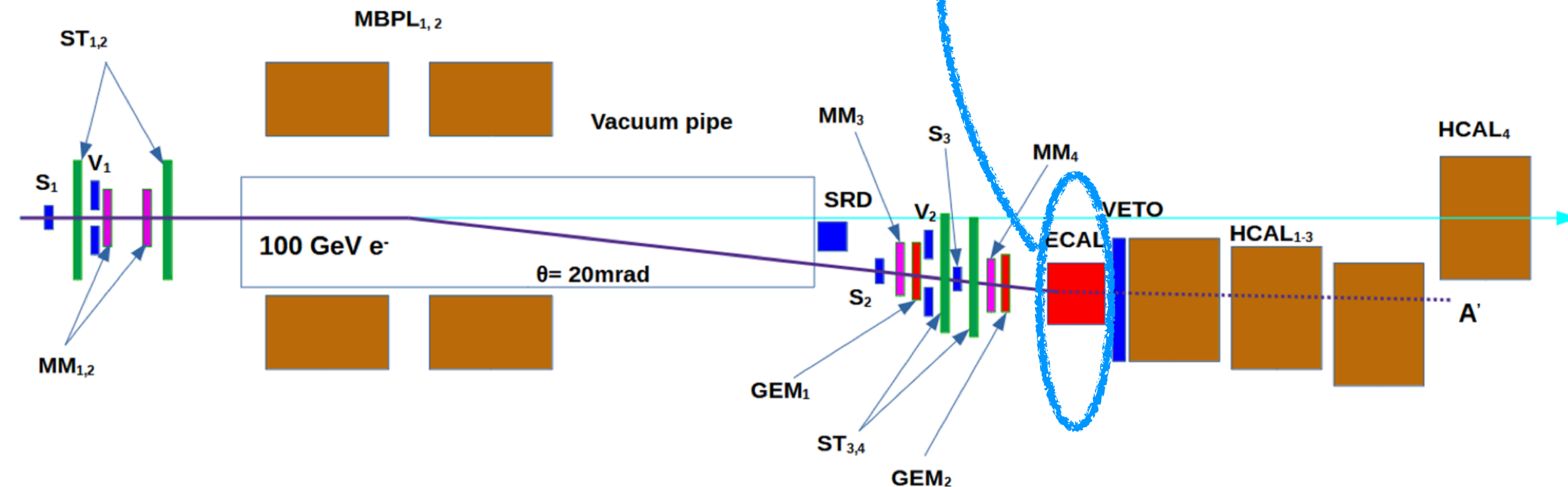


NA64 Experiment

- Located in the CERN's North Area (NA)
- Operates at line H4 of CERN SPS
- Uses a 100 GeV electron beam
- $R_{e^-} \approx 1$ MHz
- $\sigma_{E_{beam}}/E_{beam} \approx 1\%$
- $h/e^- \approx 0.005$

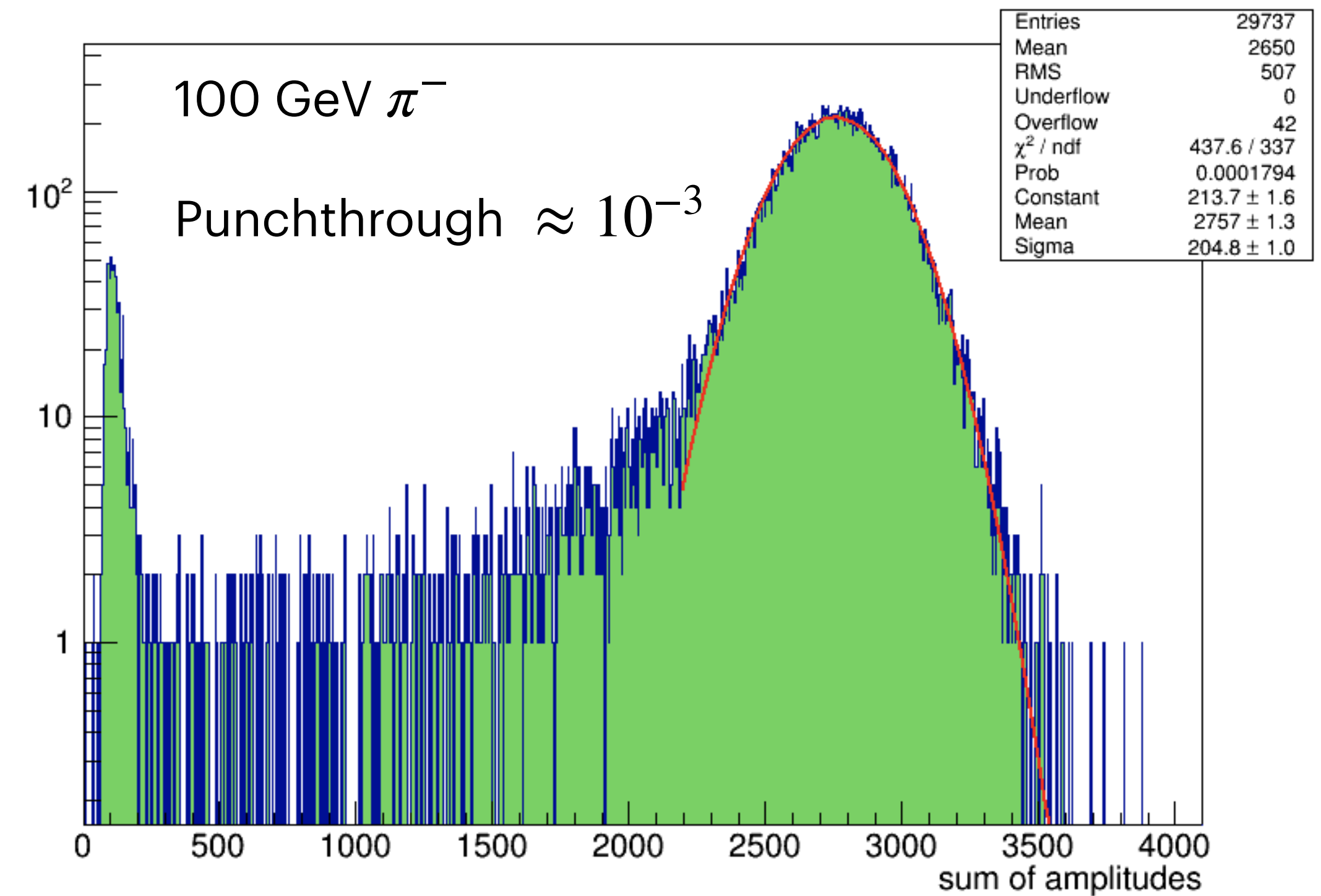


Pb-Scintillator. 40 radiation lengths

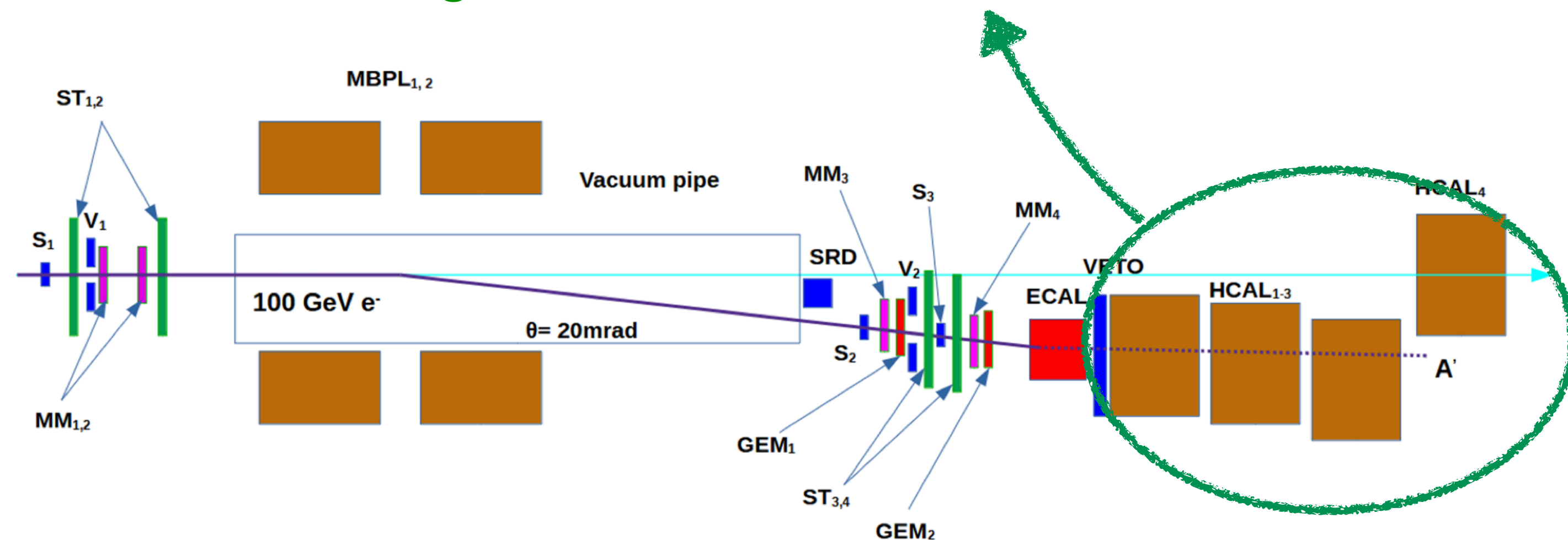


NA64 Experiment

- Located in the CERN's North Area (NA)
- Operates at line H4 of CERN SPS
- Uses a 100 GeV electron beam
- $R_{e^-} \approx 1$ MHz
- $\sigma_{E_{beam}}/E_{beam} \approx 1\%$
- $h/e^- \approx 0.005$



Pb-Scintillator. 30 nuclear interaction lengths



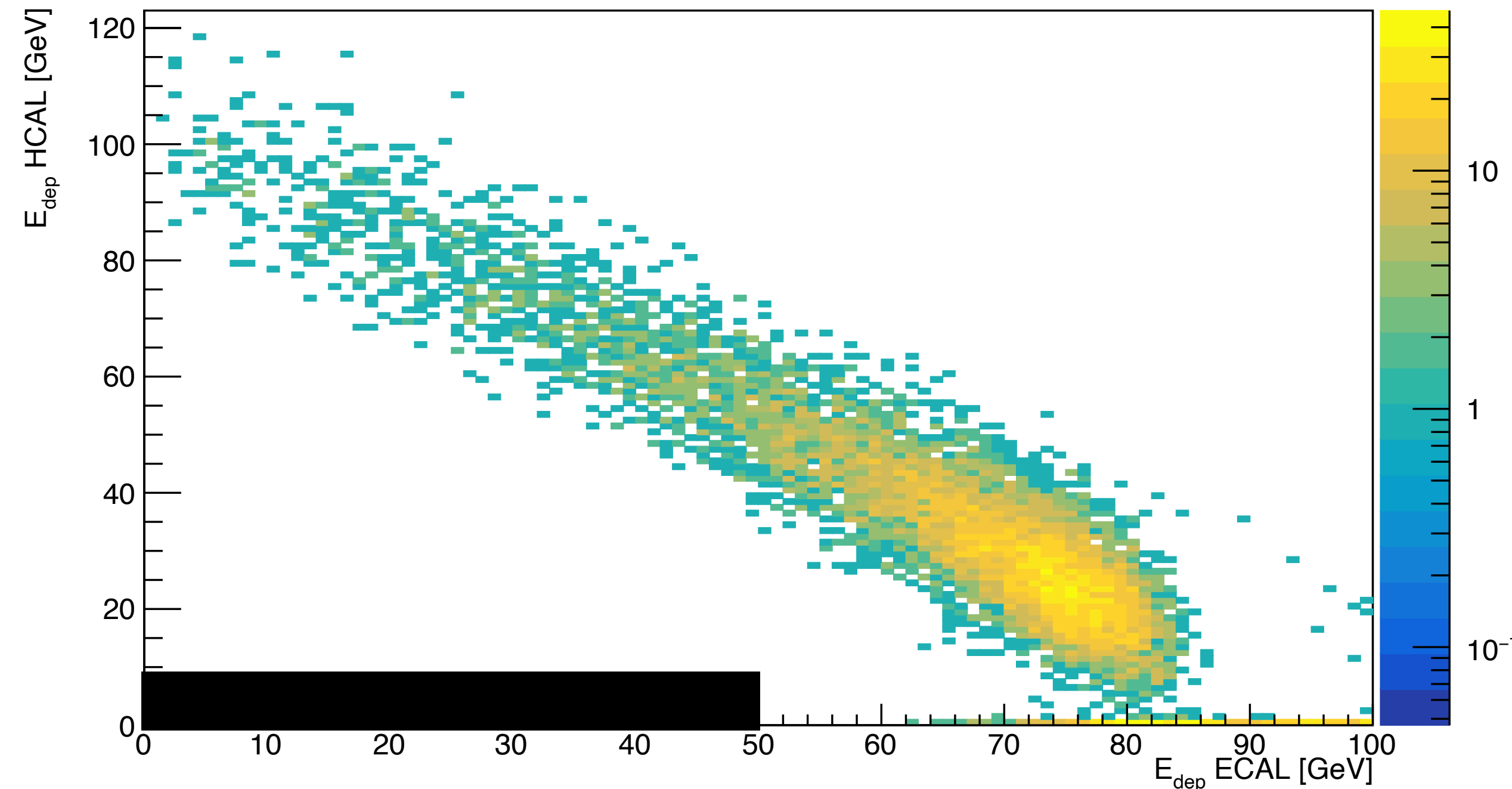
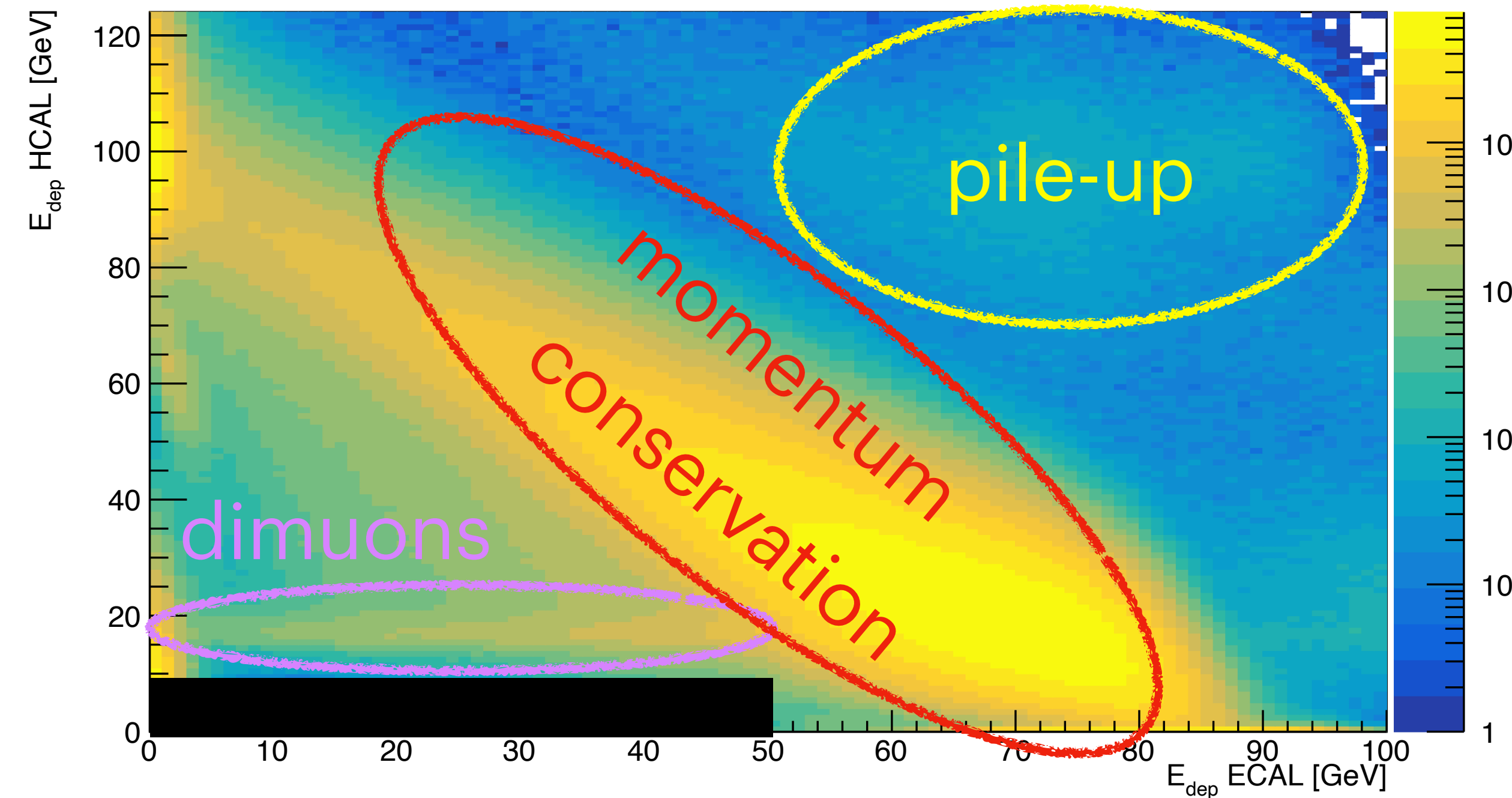
NA64

Hermeticity plot

Trigger: plastic scintillators + $E_{miss} > \sim 20$ GeV

Cuts:

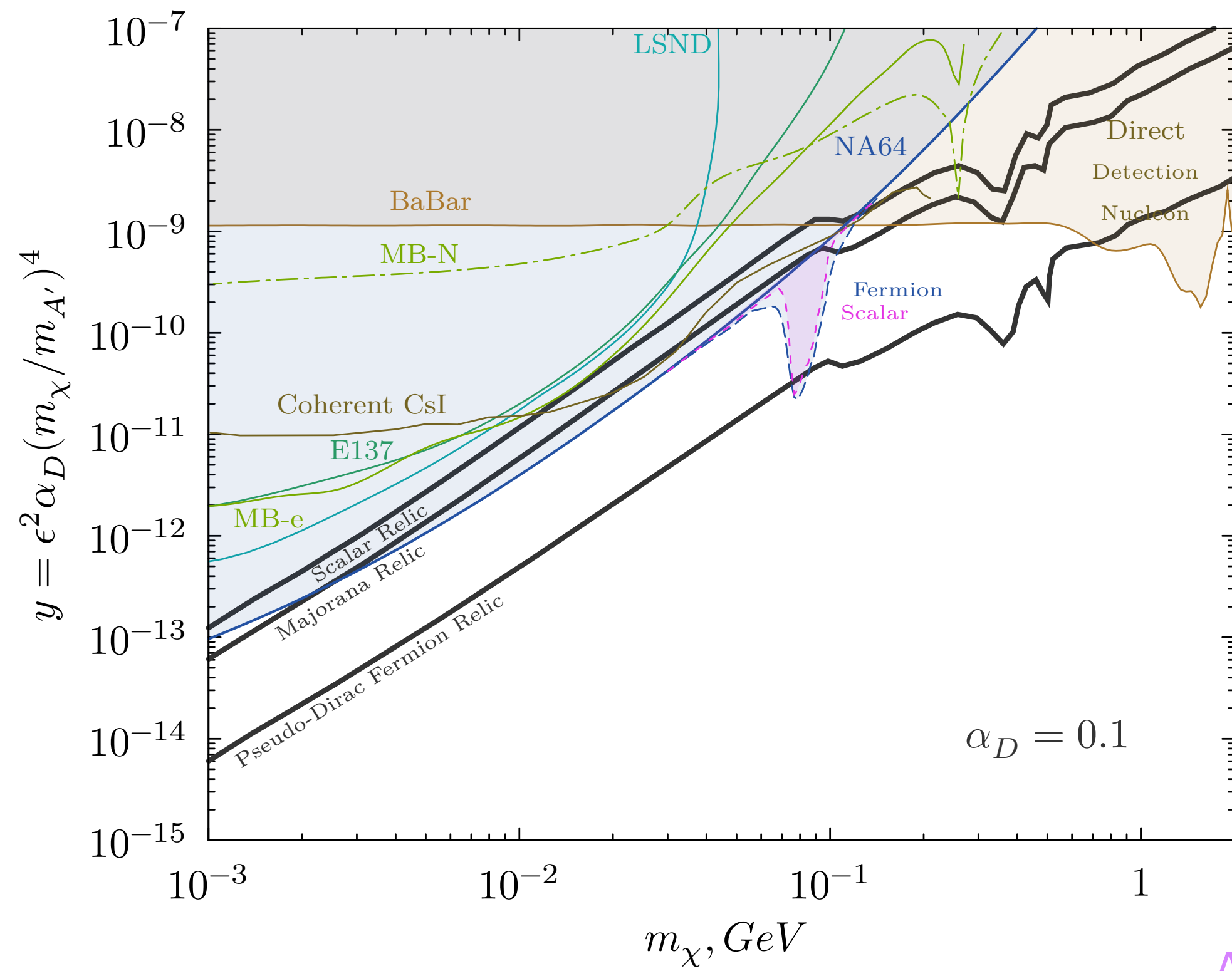
- Well-identified 100 GeV particles (SRD, track)
- No activity in Veto and HCAL



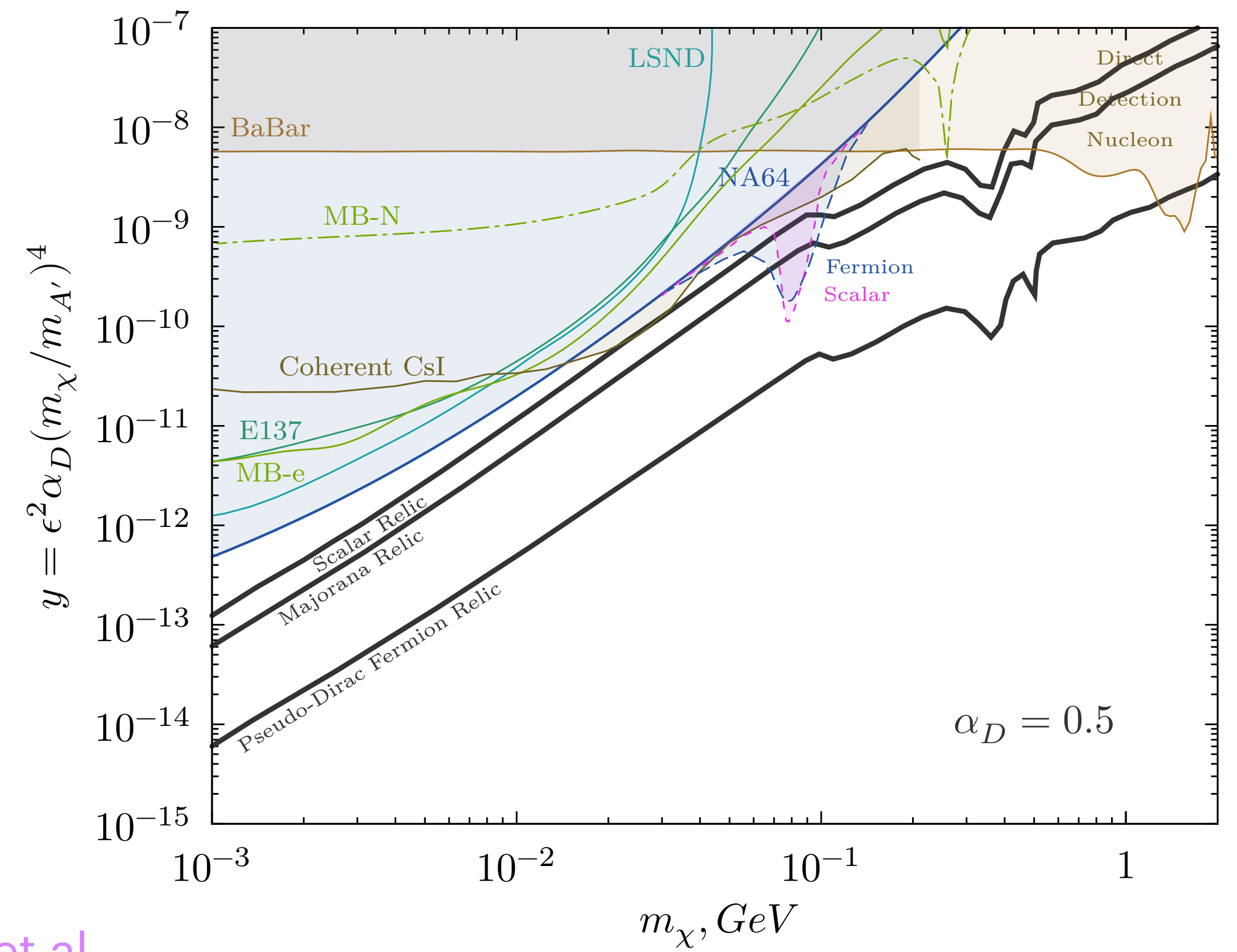
$$E_{ECAL} < 50 \text{ GeV and } E_{HCAL} < 1 \text{ GeV}$$

NA64 Limits

$9.37 \cdot 10^{11}$ electrons on target collected during 2016–2022 runs



$$m_{A'} = 3m_\chi$$



$$m_{A'} = 3m_\chi$$

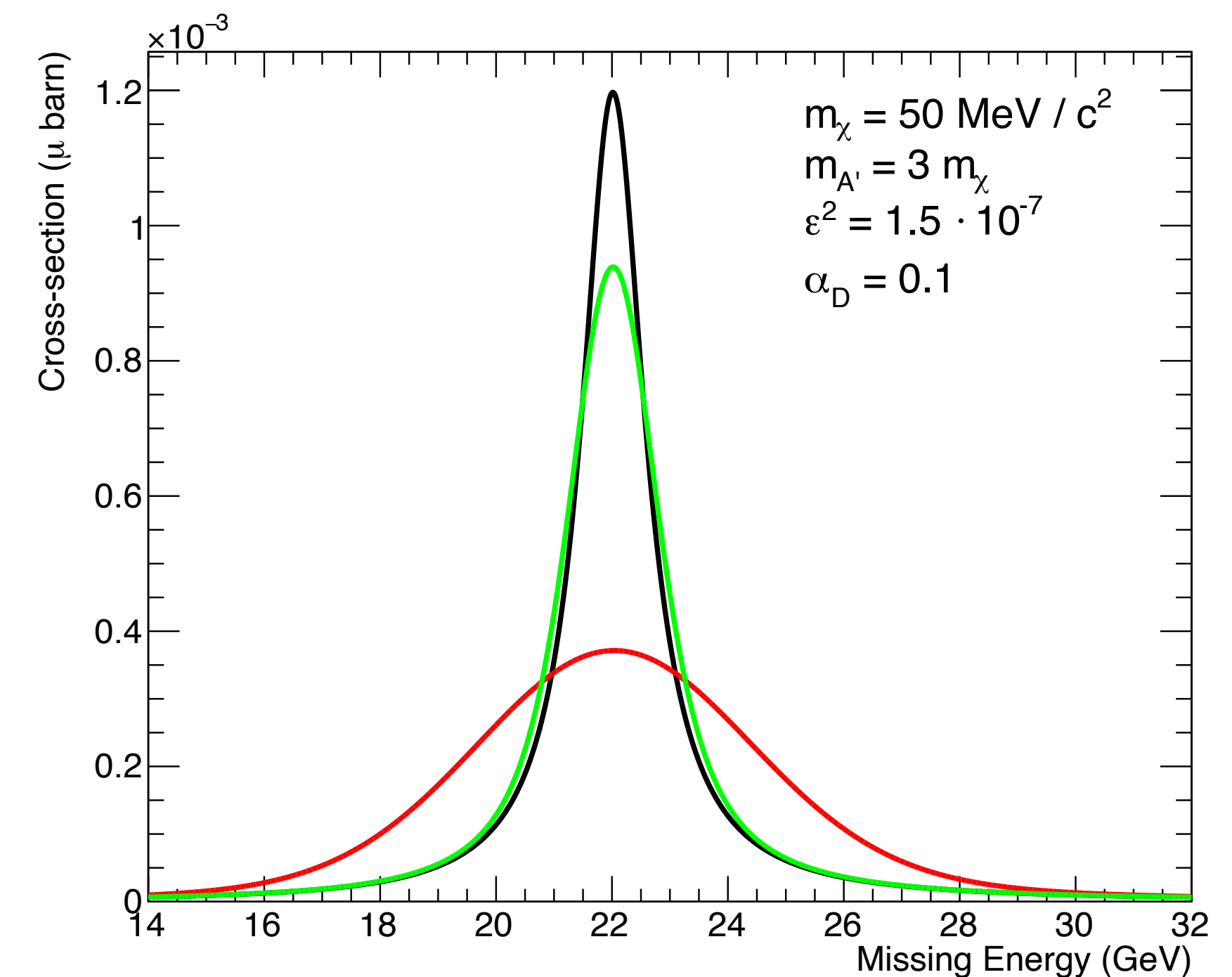
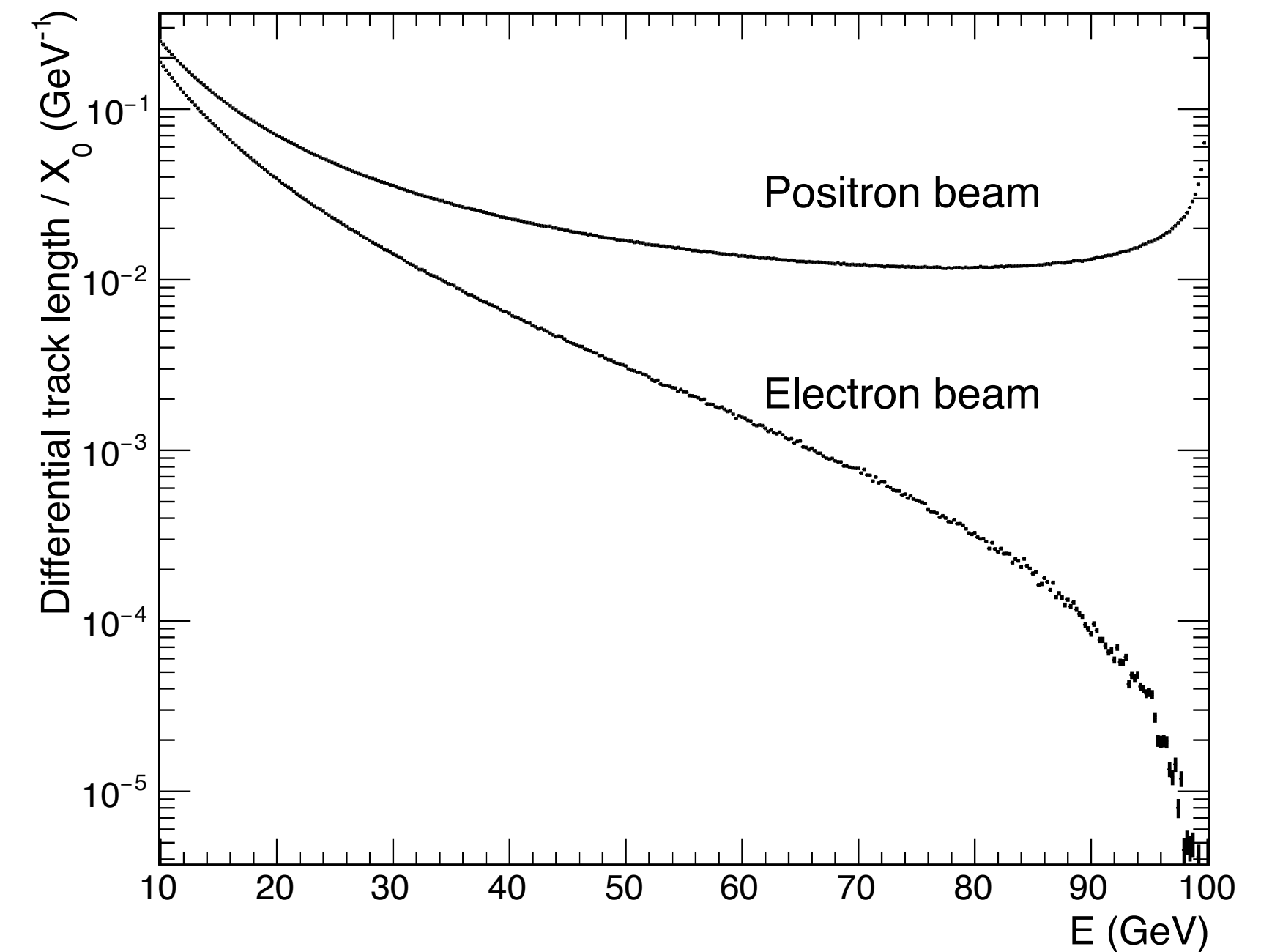
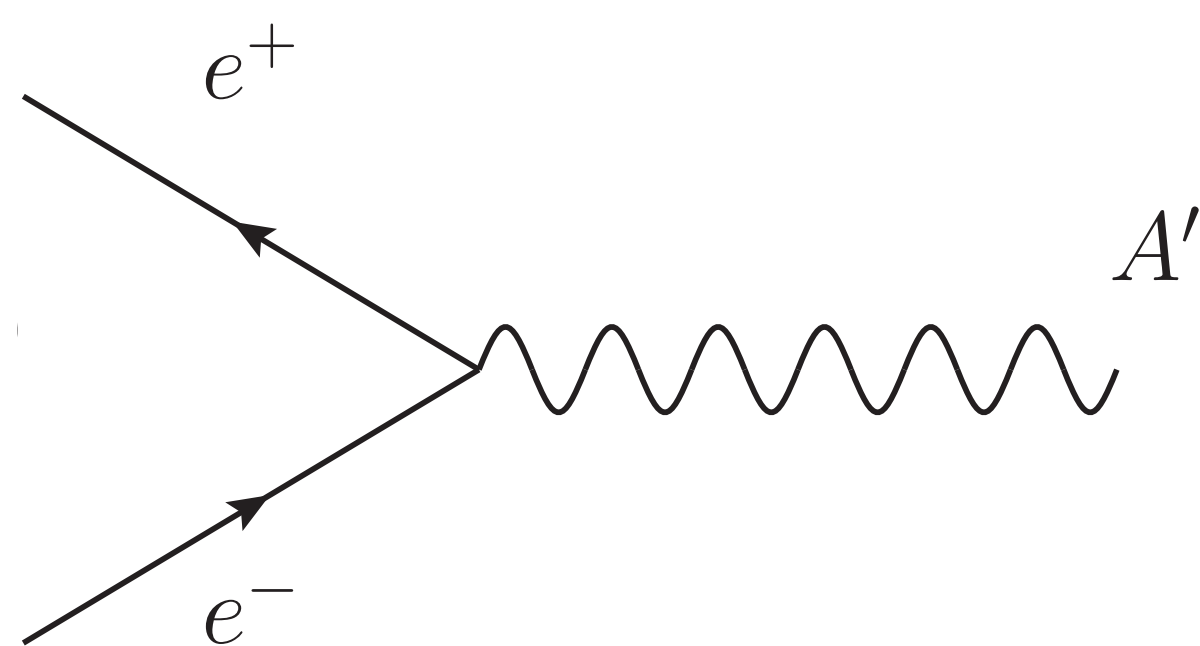
Andreev, Yu. M. et al.

P.R.L. 131.161801

Light dark matter

Resonant annihilation

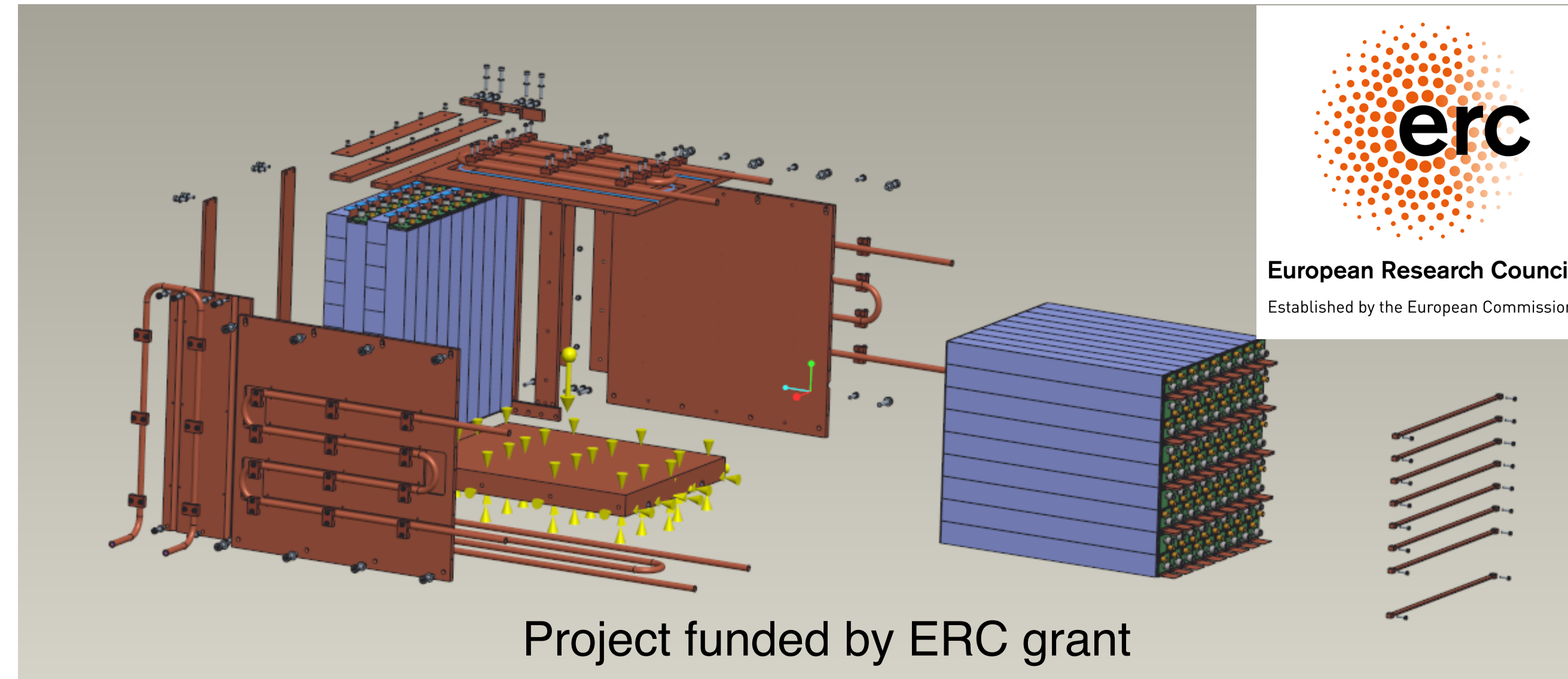
- Higher ECAL energy resolution allows to exploit the resonant signature of the process.
- Detector upgrades: SRD and ECAL



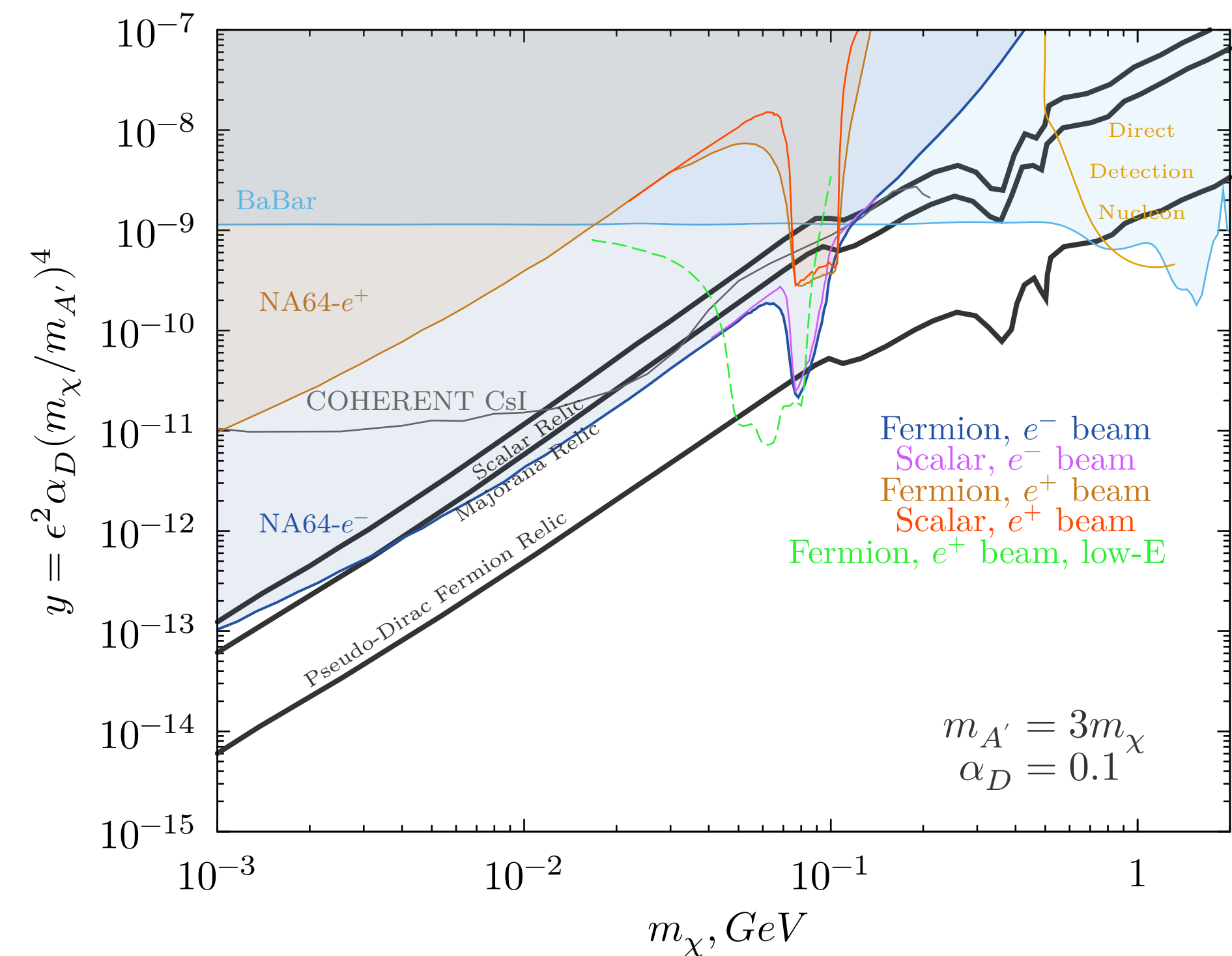
POKER

POsitron resonant annihilation into dark mattER

- $E_{beam} = 40-60$ GeV
- New ECAL based on 130 $PbWO_4$ crystals ($20 \times 20 \times 220$ mm³) assembled in a 9x9 matrix (+ pre-shower)
- 34 radiation lengths
- Light readout with SiPMs (Hamamatsu S14160-6010)
- SiPMs are kept at a constant temperature with a cooling system



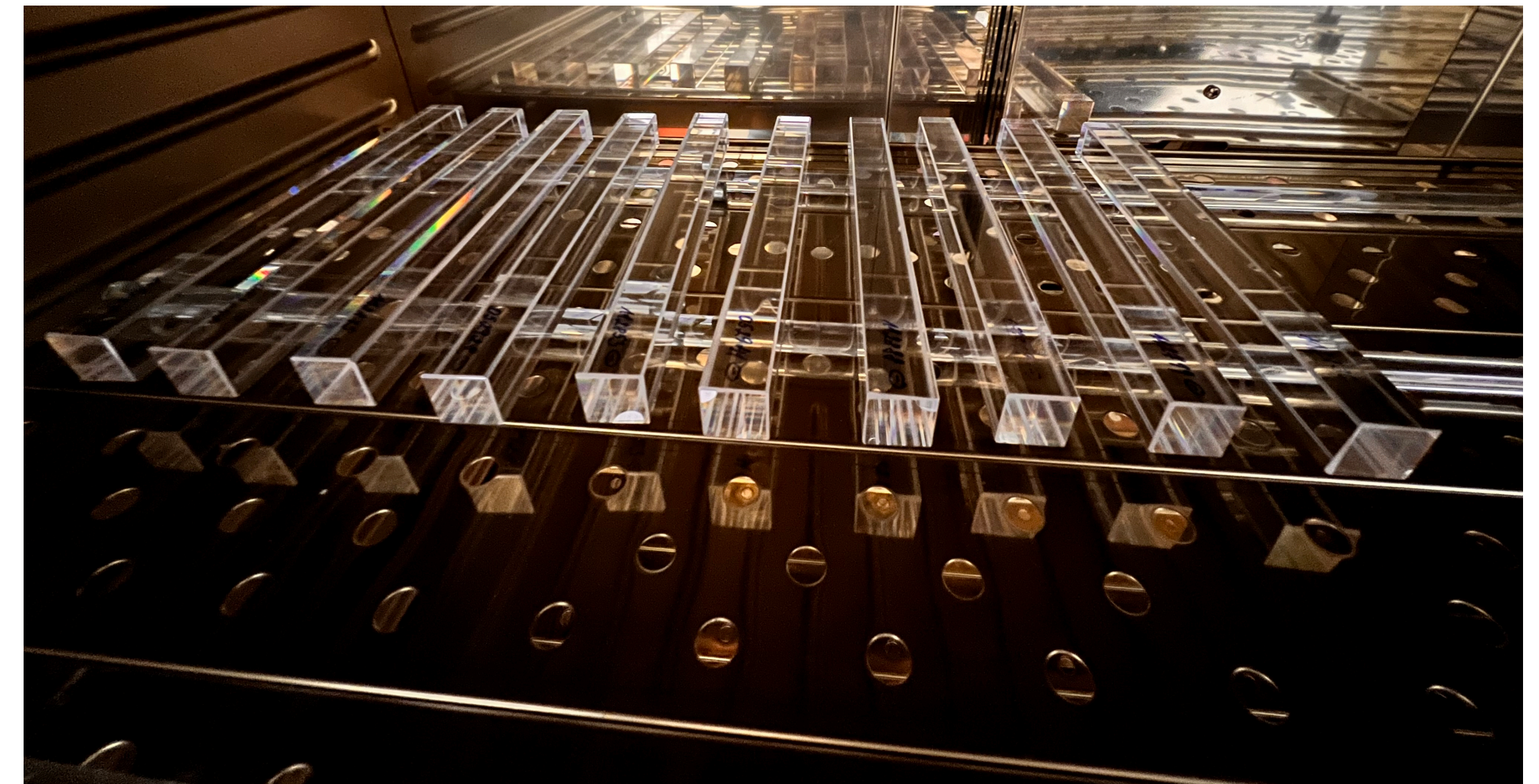
European Research Council
Established by the European Commission



POKER ECAL

PbWO₄ crystals

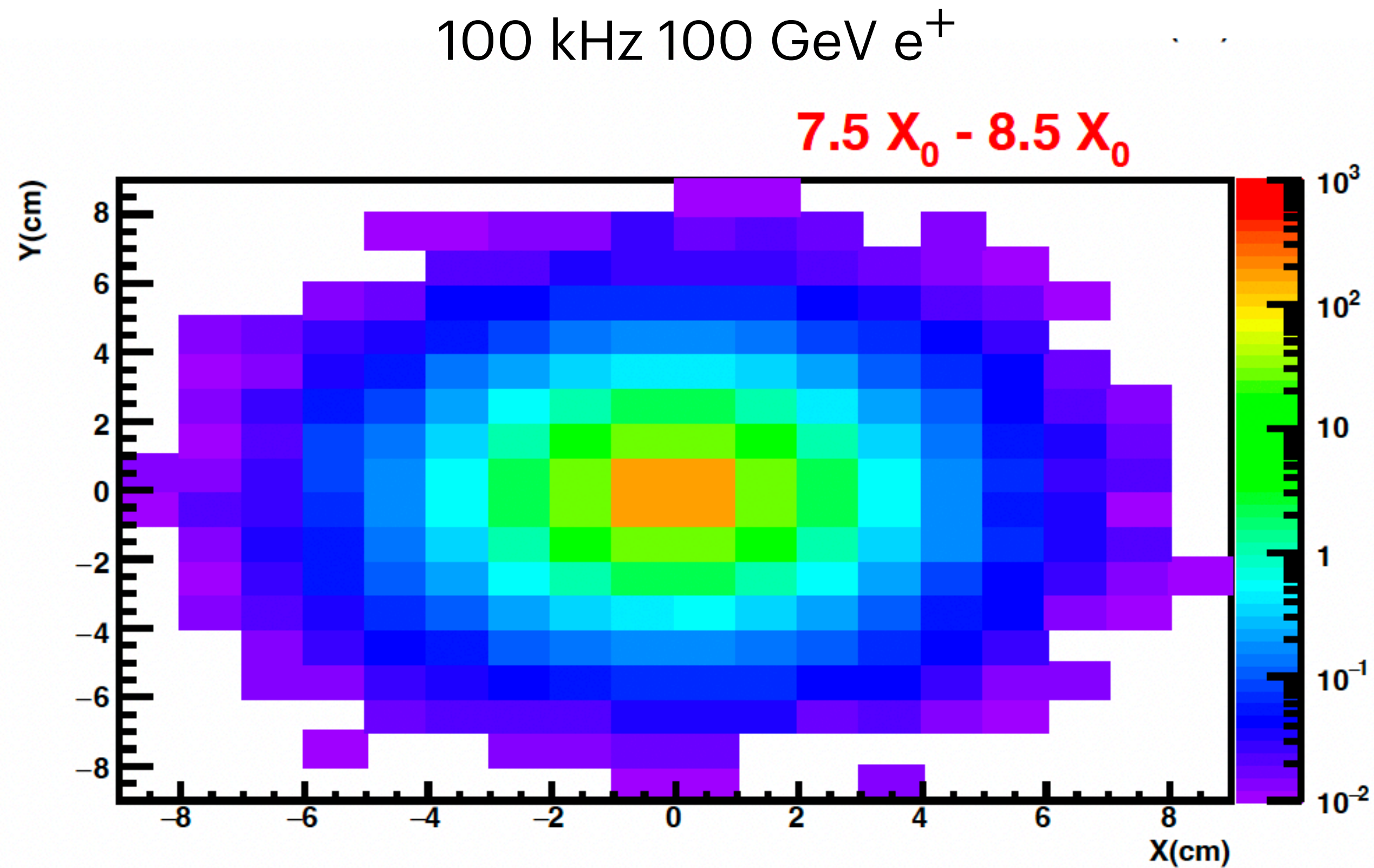
- High density $\approx 8.3 \text{ g}\cdot\text{cm}^{-3}$
- Fast decay time (5-15 ns)
- Measured light yield $\approx 3 \text{ phe}\cdot\text{MeV}^{-1}$ (4x SiPM $6\times 6 \text{ mm}^2$, cell size $10 \mu\text{m}$ to avoid non-linearity effects)
- Maximum emission wavelength = 420 nm



POKER ECAL

Crystals characterisation

- LY and dynamics of PbWO_4 crystals are not affected by radiations, but the impurities could lead to the formation of “colour centres”, reducing the transparency
- It was fundamental to characterise the optical Transmittance
- The simulations show absorbed doses compatible with CMS PbWO_4 calorimeter.

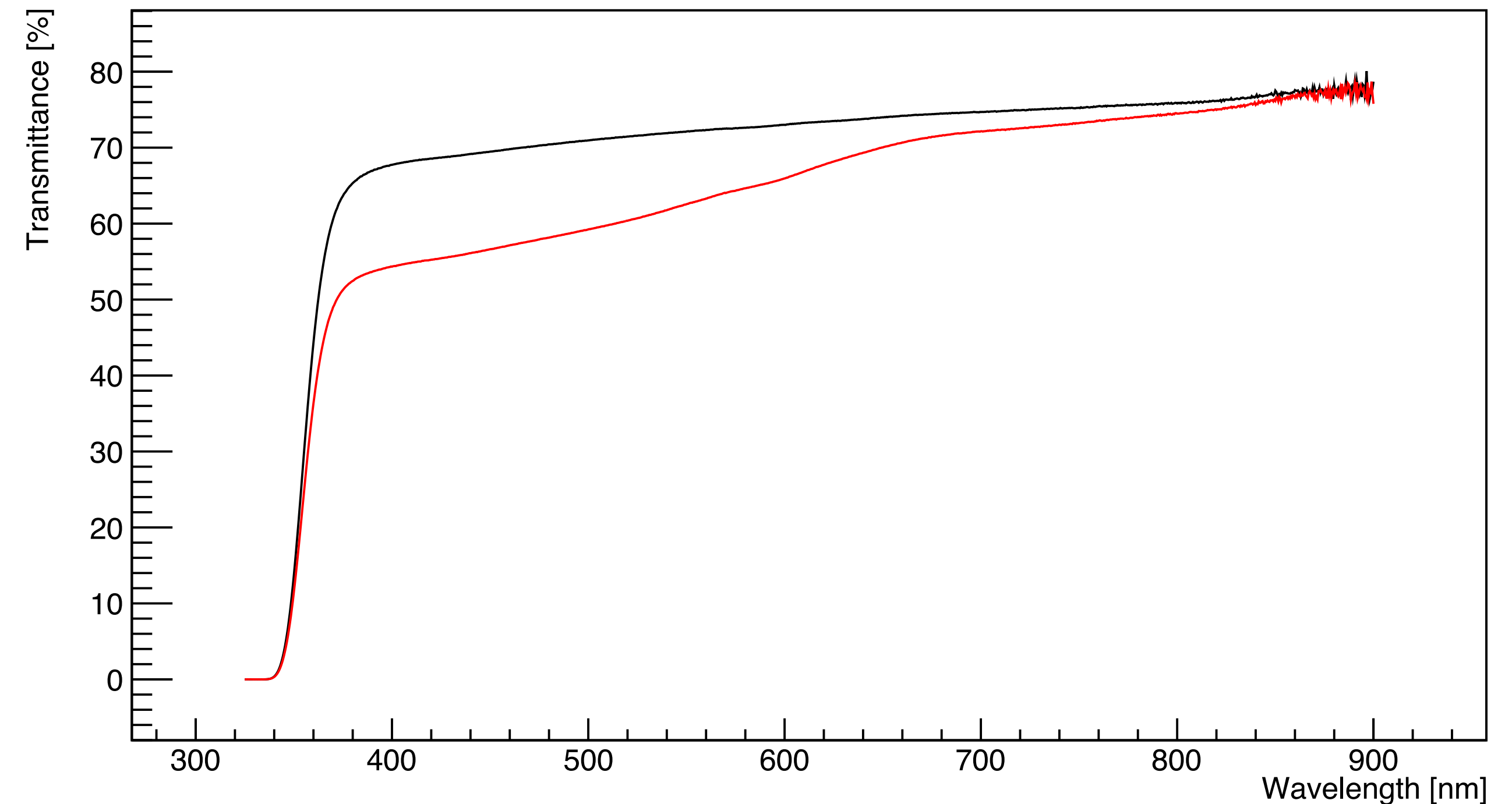


POKER ECAL

Crystals characterisation



- Measurements campaign at Strahlenzentrum (Gießen, Germany)
- Intense ^{60}Co source
- Dose ≈ 30 Gy (== maximum dose absorbed by the centermost crystal in few days)
- Measured longitudinal optical transmittance before and after the exposure



POKER ECAL

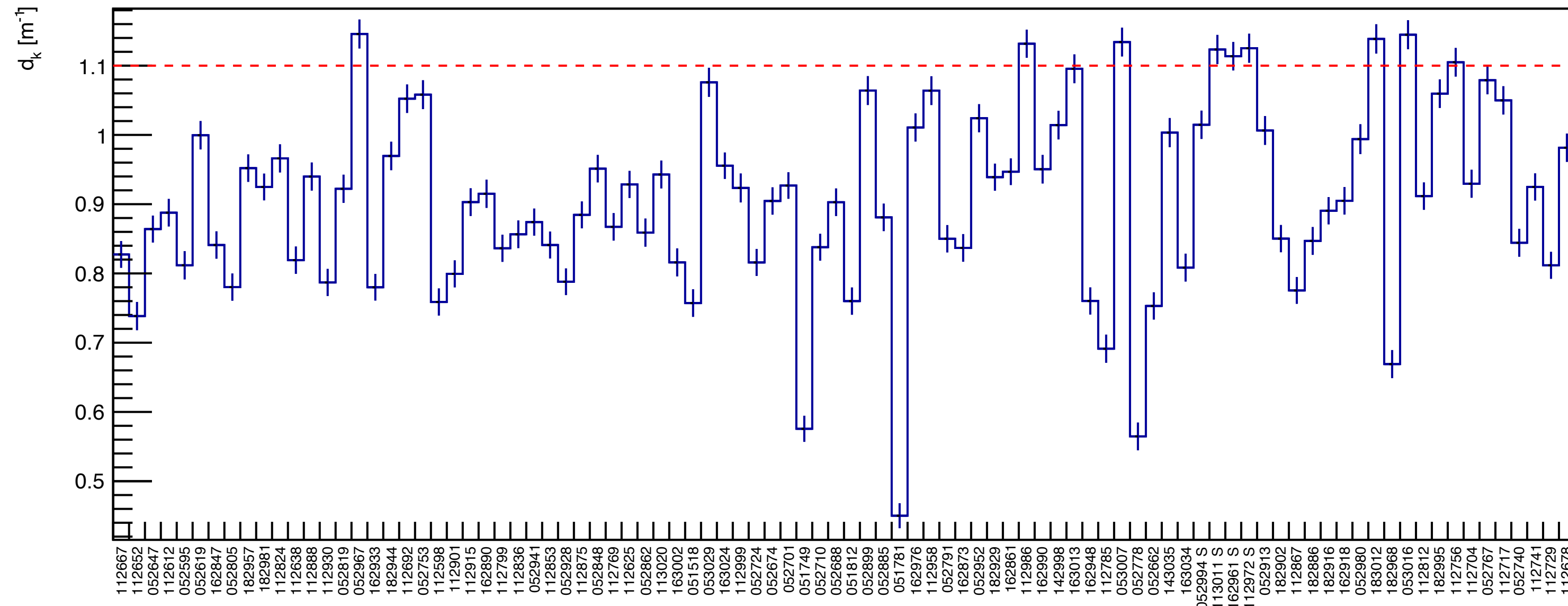
Crystals characterisation

- The radiation damage was evaluated in terms of a parameter, called d_k

- $$d_k = \frac{1}{L} \ln\left(\frac{T_{before}(\lambda_i)}{T_{after}(\lambda_i)}\right), \text{ where}$$

- $$\lambda_i = 420 \text{ nm}$$

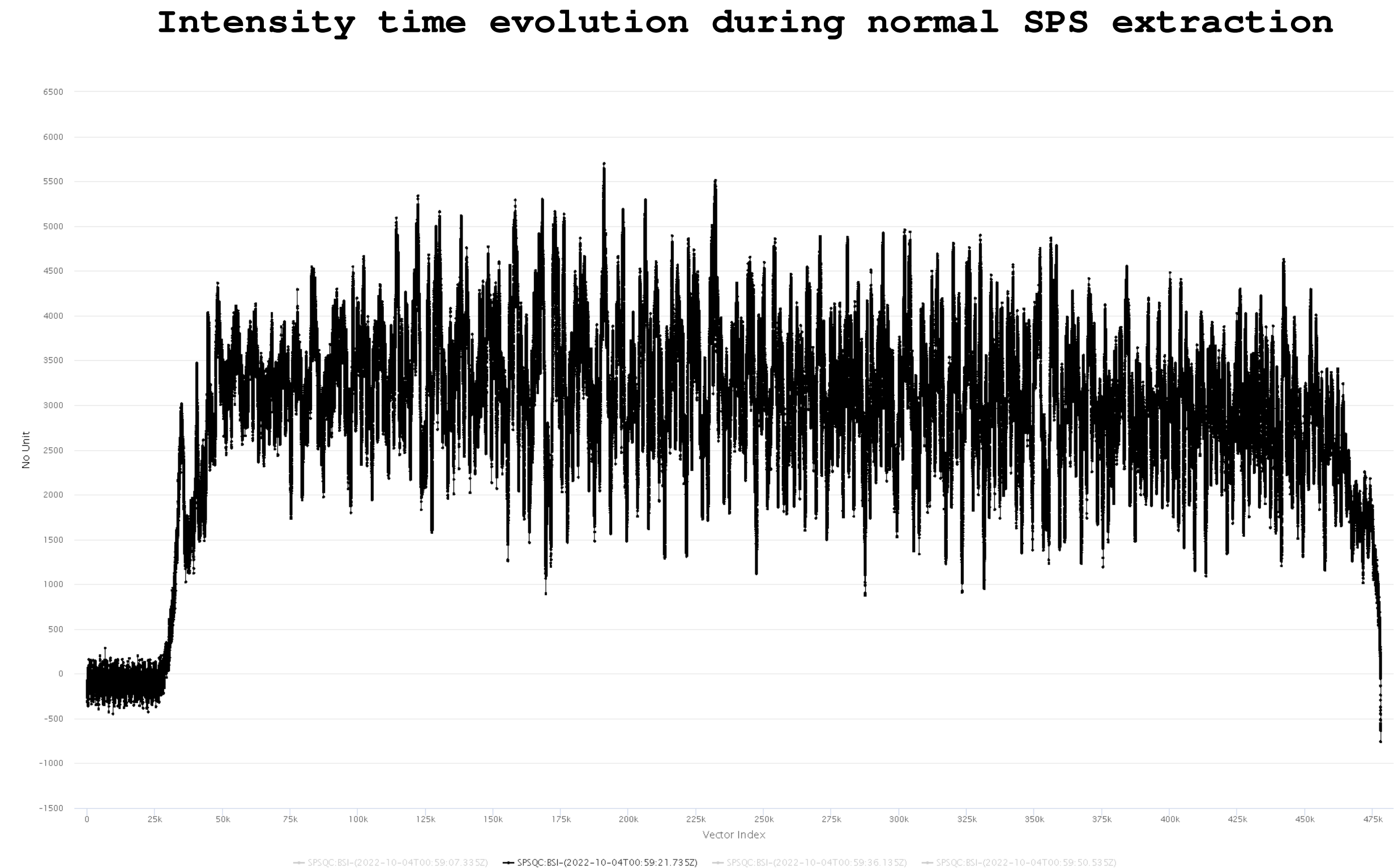
- The best crystals will be placed in the center of the calorimeter
- The extent of radiation damage is kept under control during calibrations



SPS beam

Temporal structure

- Secondary electrons from the H4 beamline impinge on the target with a stochastic time distribution during 4.8-s long time periods (“spills”), interleaved by no-beam periods.
- The number of spills per minute ranges between 2 and 4



Courtesy of Dmitry Shchukin

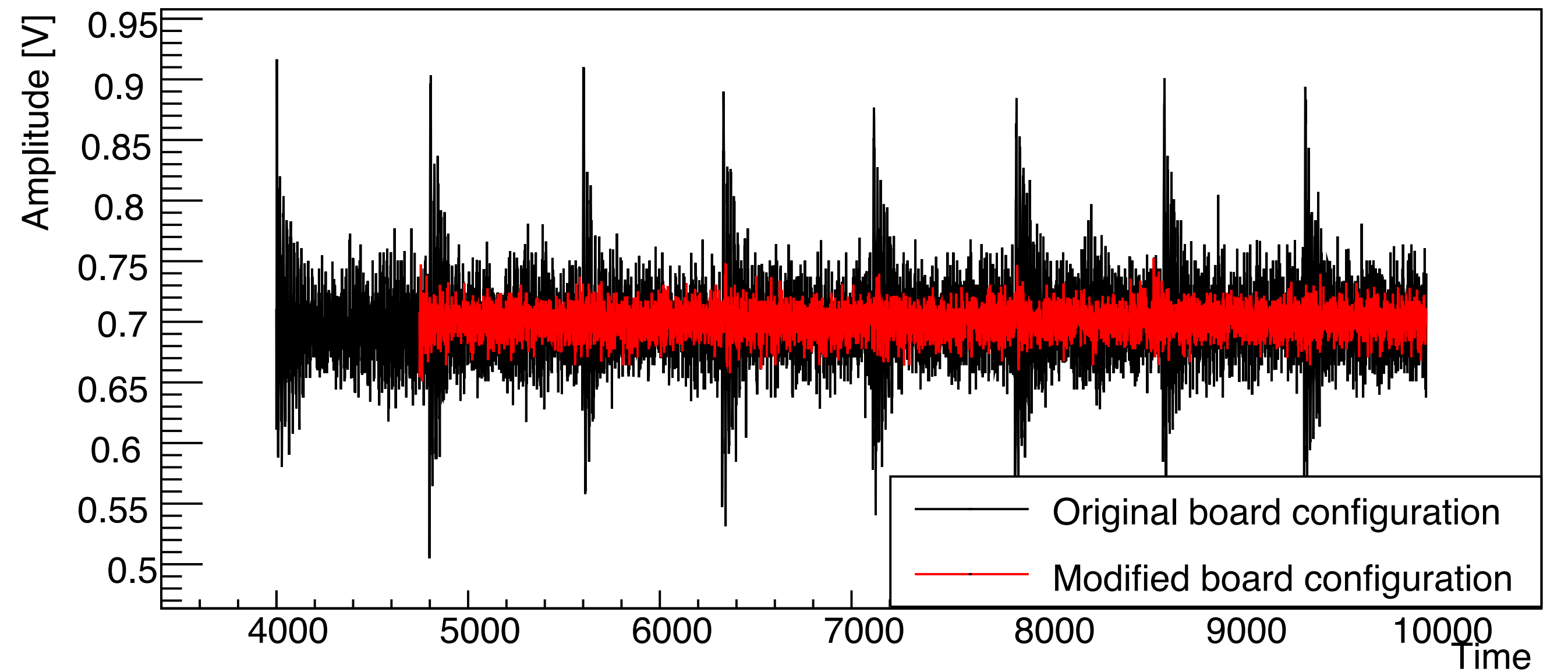
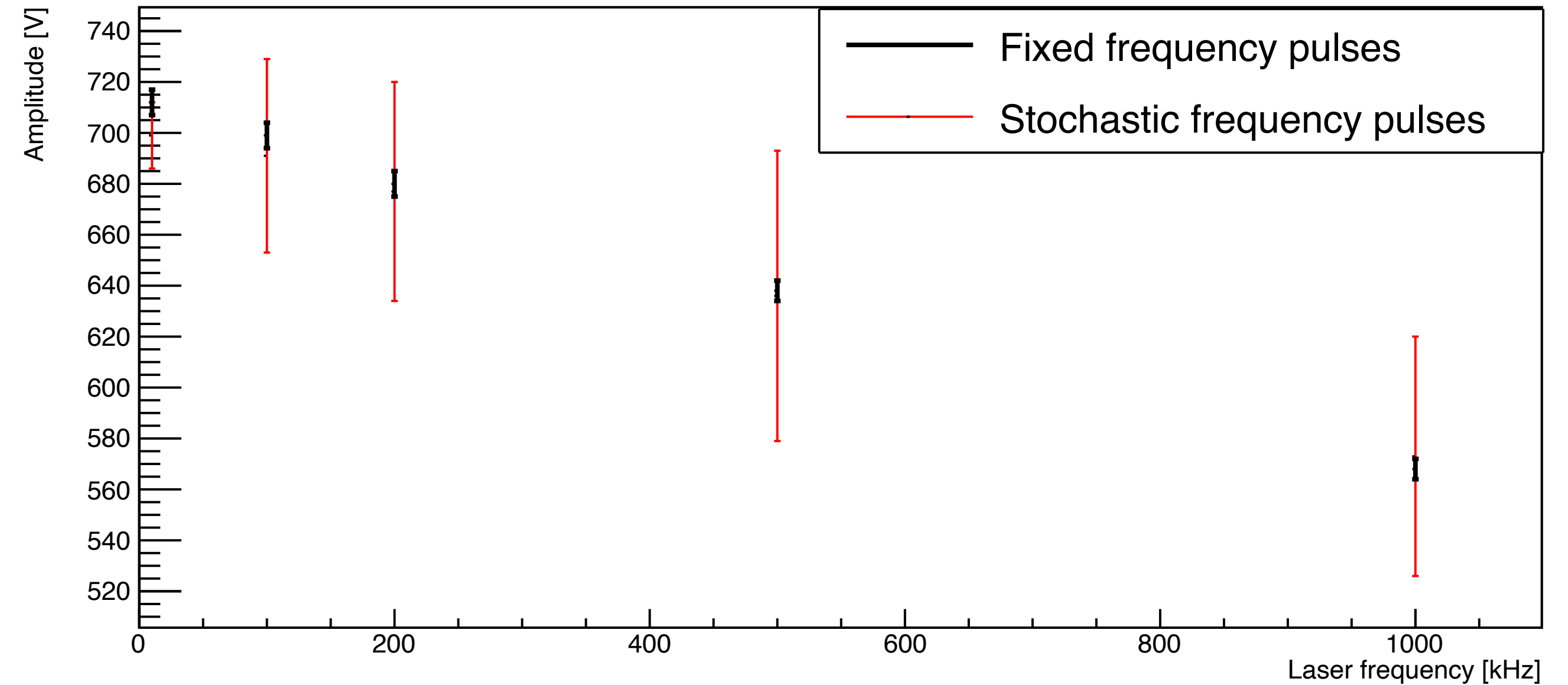
POKER readout

HV board

- The SPS beam is not continuous
- The POKER SiPMs gain scales as $G = g_0(V_{OV} - V_{break})$ and the relative gain variation is of about $\frac{\Delta G}{G} \simeq \frac{\Delta V_{OV}}{V_{OV} - V_{break}} < 1\%$.
- To avoid V variations following we use inductive couplings.
- We plan to use four 32-channel CAEN A1539 boards, with 10 mA maximum output current.

POKER readout HV board

- Fluctuations due to high output impedance
- CAEN reduced this impedance on a channel, which was again characterized with the same experimental setup



σ_V/V from 8% to 5% at 1 MHz

Prototype runs

POKERINO

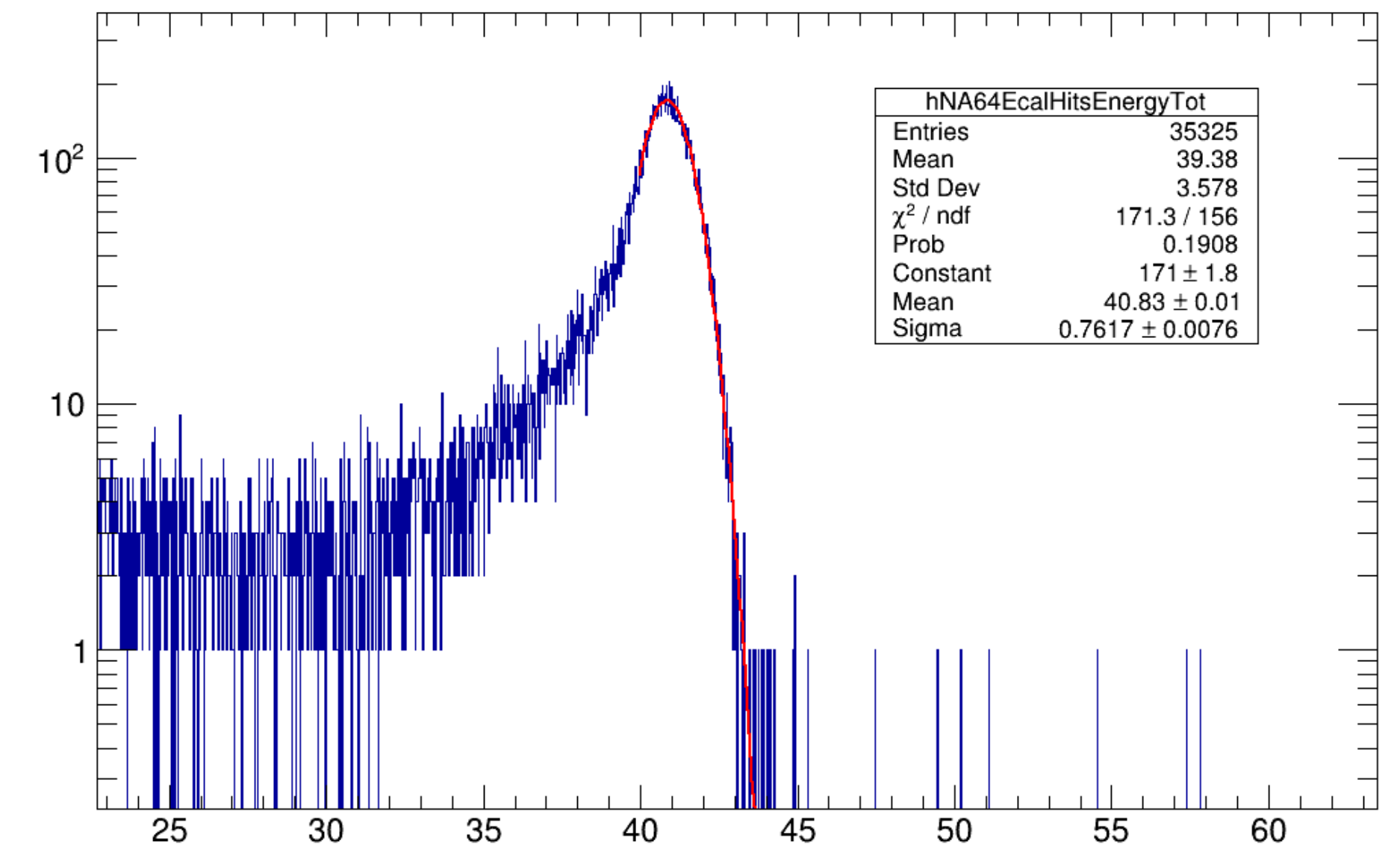
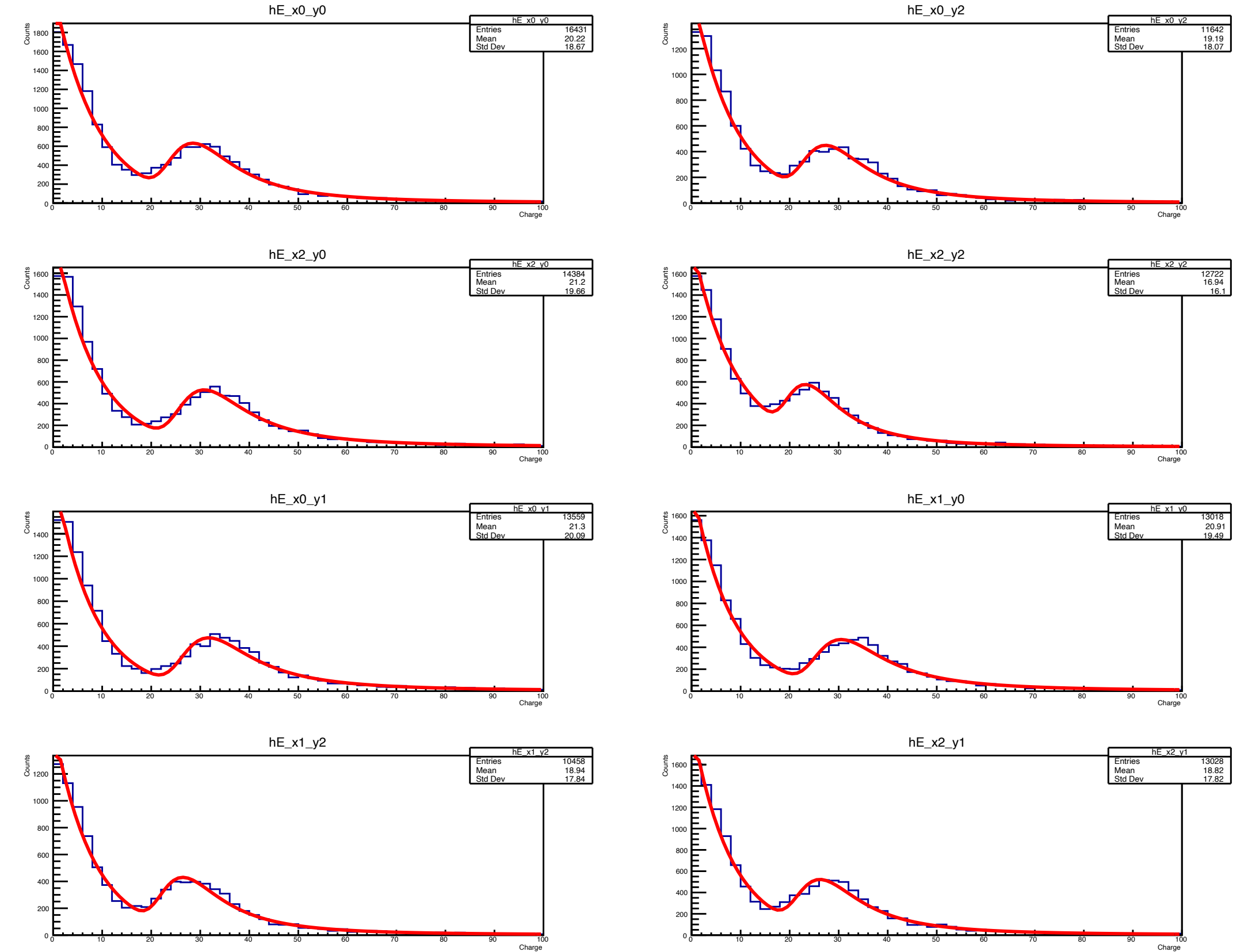
- 3x3 PbWO₄ crystals matrix
- POKERINO's temperature is kept at 20°C.
- Characterization run at H8 SPS beam line (North Area), during Summer 2023
- Test aimed to investigate the energy-time resolution, linearity...



Prototype runs

POKERINO

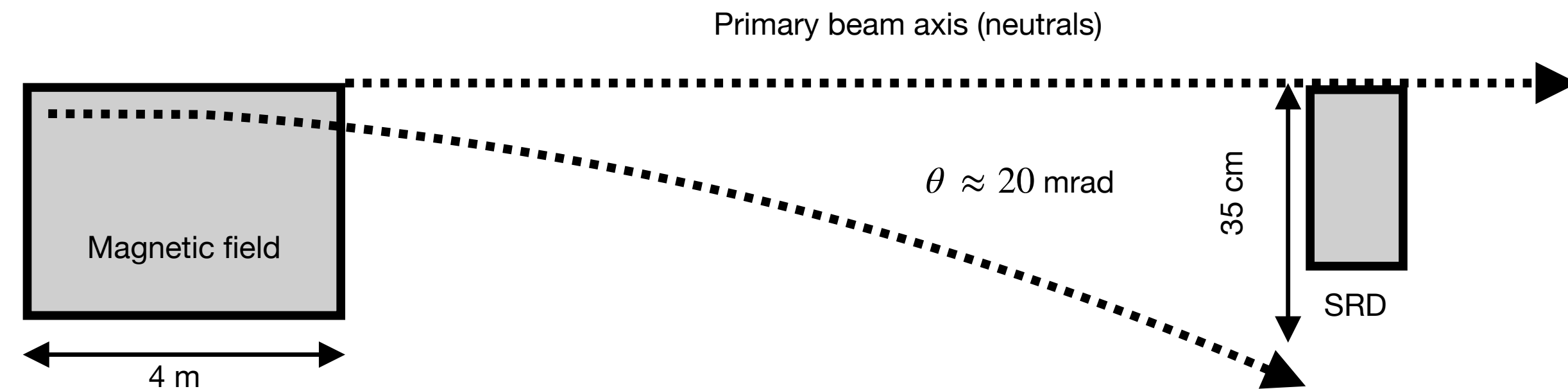
- Preliminary calibration run with 160 GeV muon beam
- Crystals scan with [10-120] GeV e^+ and hadrons beam
- The results look very promising



POKER

Upgrades to NA64

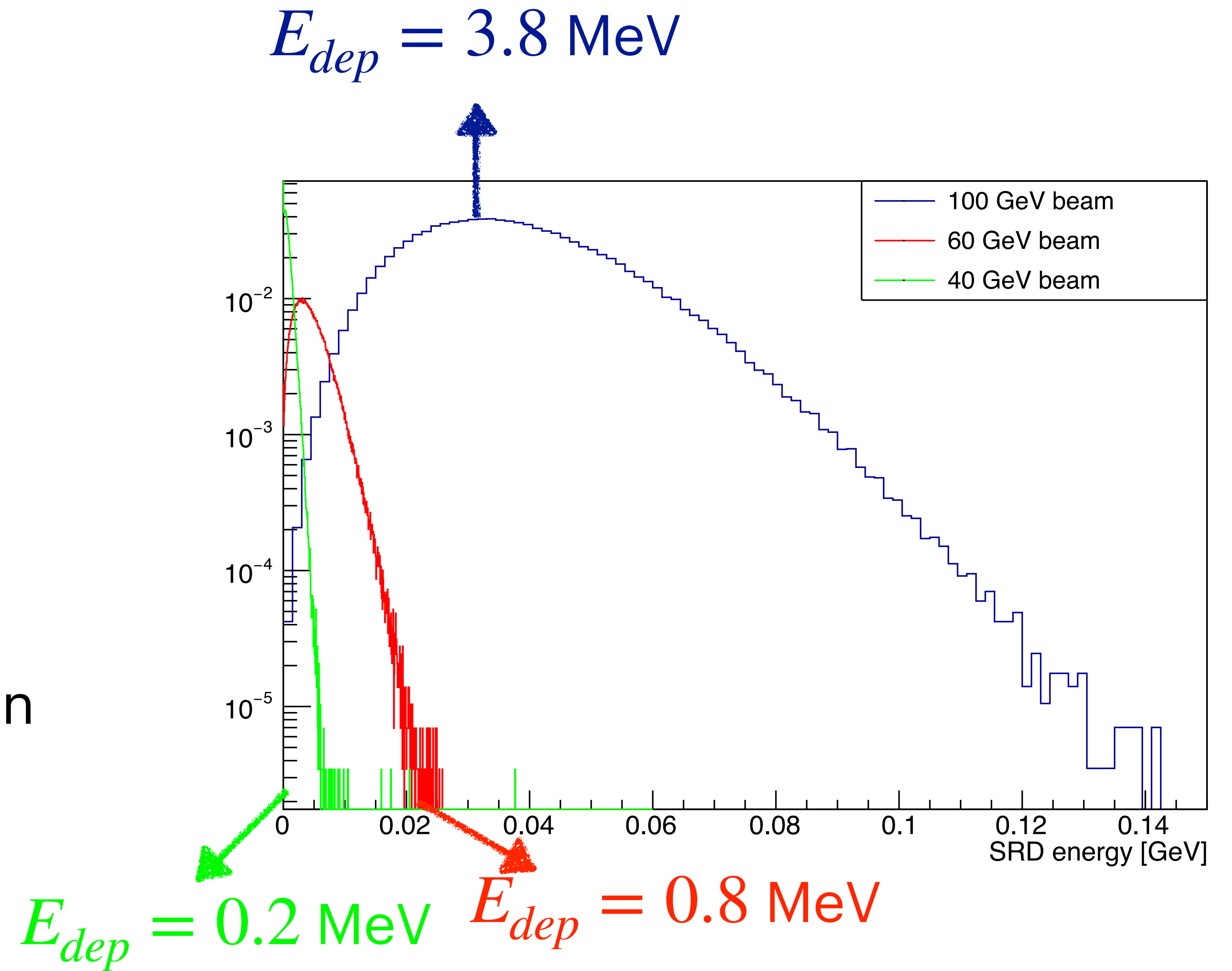
- A Synchrotron Radiation Detector is used to identify impinging e^+/e^-
- The NA64 magnet has a total magnetic field of $\approx 7 \text{ T}\cdot\text{m}$
- The current NA64 SRD is optimised for $E_{beam} = 100 \text{ GeV}$ and consists of Pb-plastic scintillator layers



POKER

Upgrades to NA64

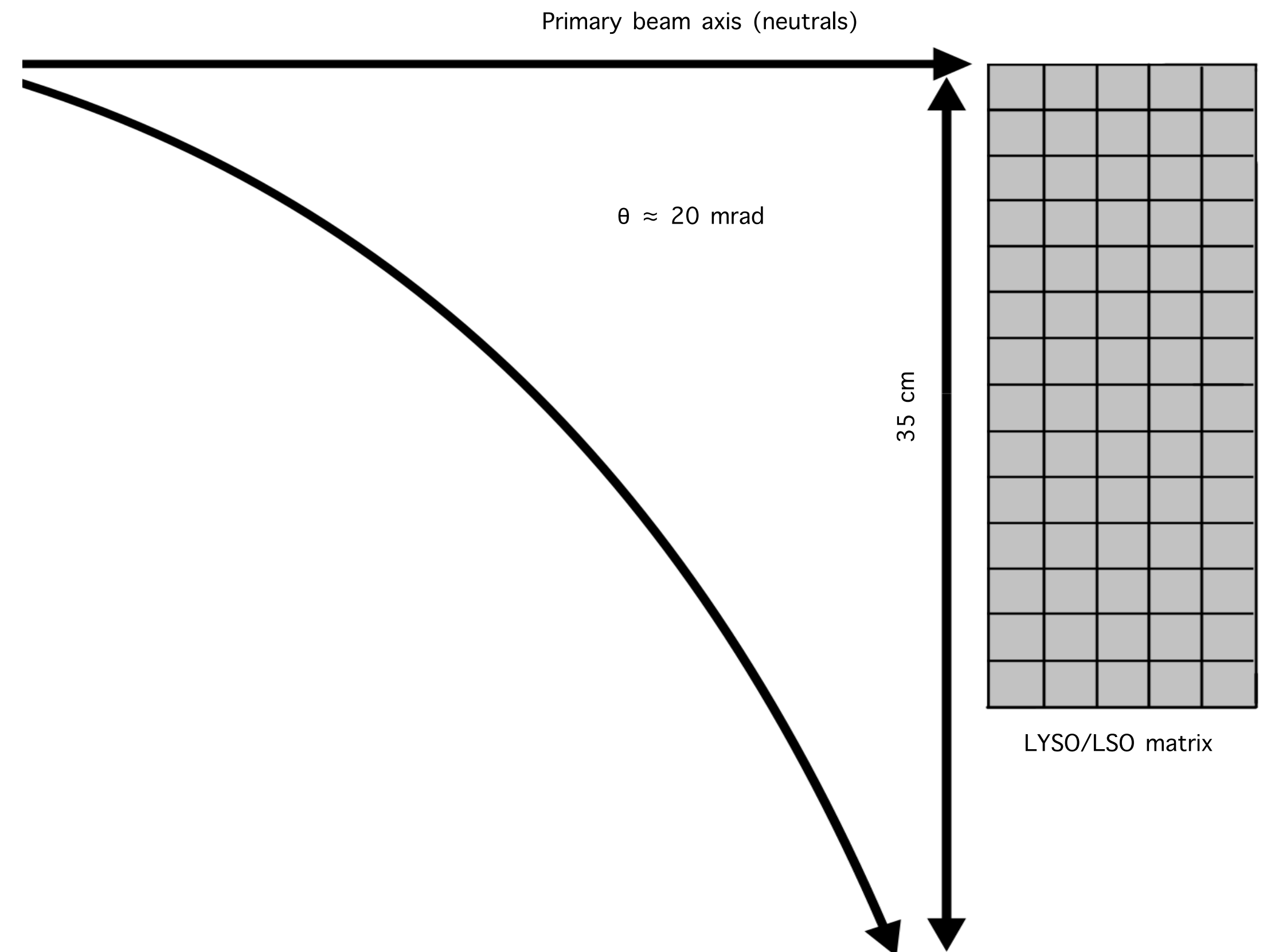
- $E_{beam} = 40-60$ GeV
- In NA64 $E_{synch} \propto E_{beam}^4$
- For lower beam energy, this results in low energy deposition and poor detection efficiency of the SRD
- We proposed an upgrade, based on LYSO crystals



POKER

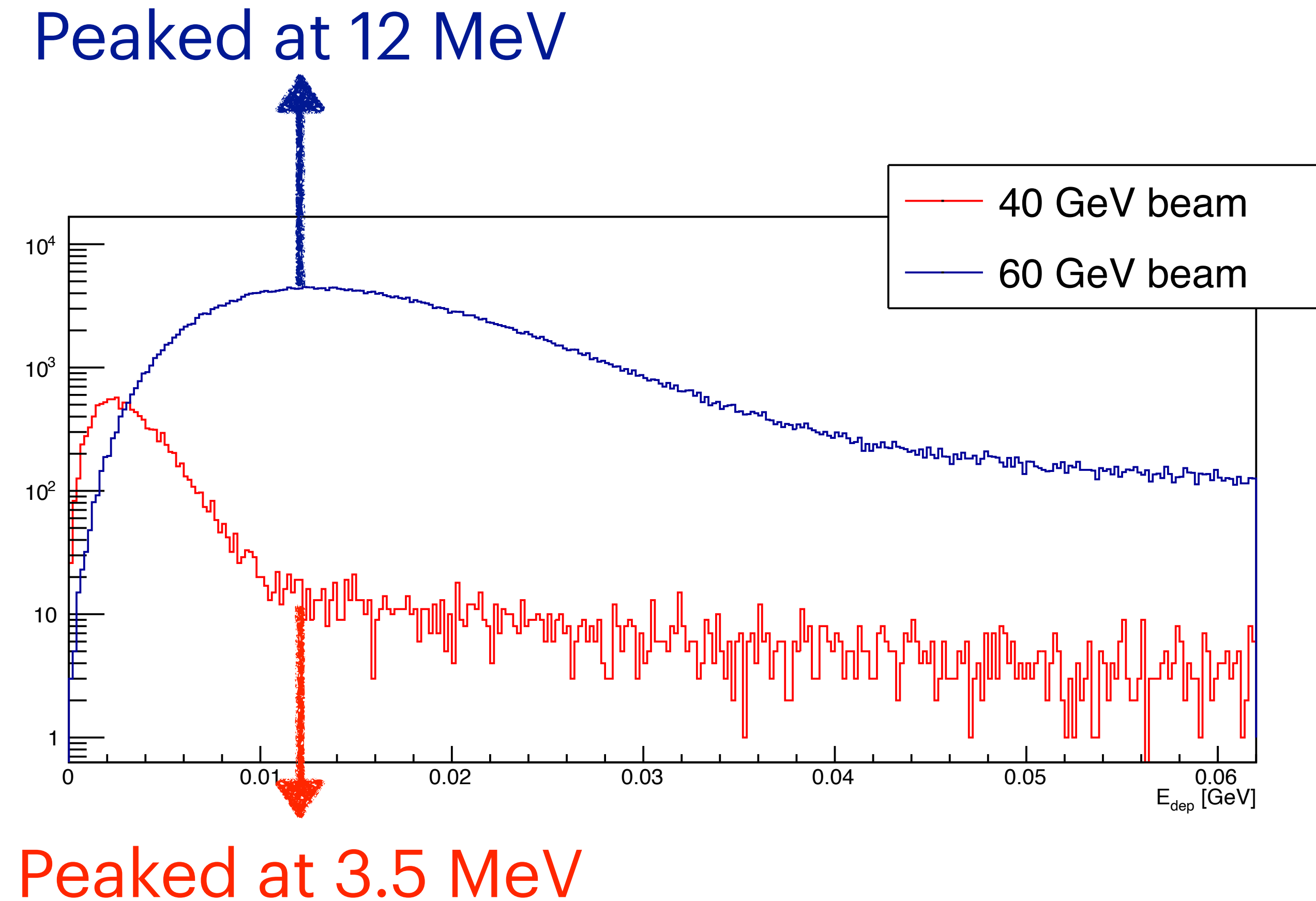
New SRD

- $LY \approx 3 \cdot 10^2 \text{ phe} \cdot \text{MeV}^{-1}$ ($LY_{PbWO_4} \approx 3 \text{ phe} \cdot \text{MeV}^{-1}$)
- Decay time: order of tens of nanoseconds
- Density $\approx 7 \text{ g} \cdot \text{cm}^{-3}$
- Preliminary proposed geometry: 14x5 matrix (signals read by Hamamatsu MPPC S13360 $6 \times 6 \text{ mm}^2$, $25 \mu\text{m}$ pixel size)
- Crystals dimensions: $2 \times 2 \times 5 \text{ cm}^3$ (length perpendicular to the bending plane)



New SRD MC simulations

- MC simulations were carried out implementing the proposed detector in the NA64 simulation framework.
- Simulations performed with $E_{beam} = 40$ GeV and 60 GeV.
- The positron detection efficiency was then evaluated through some thresholds



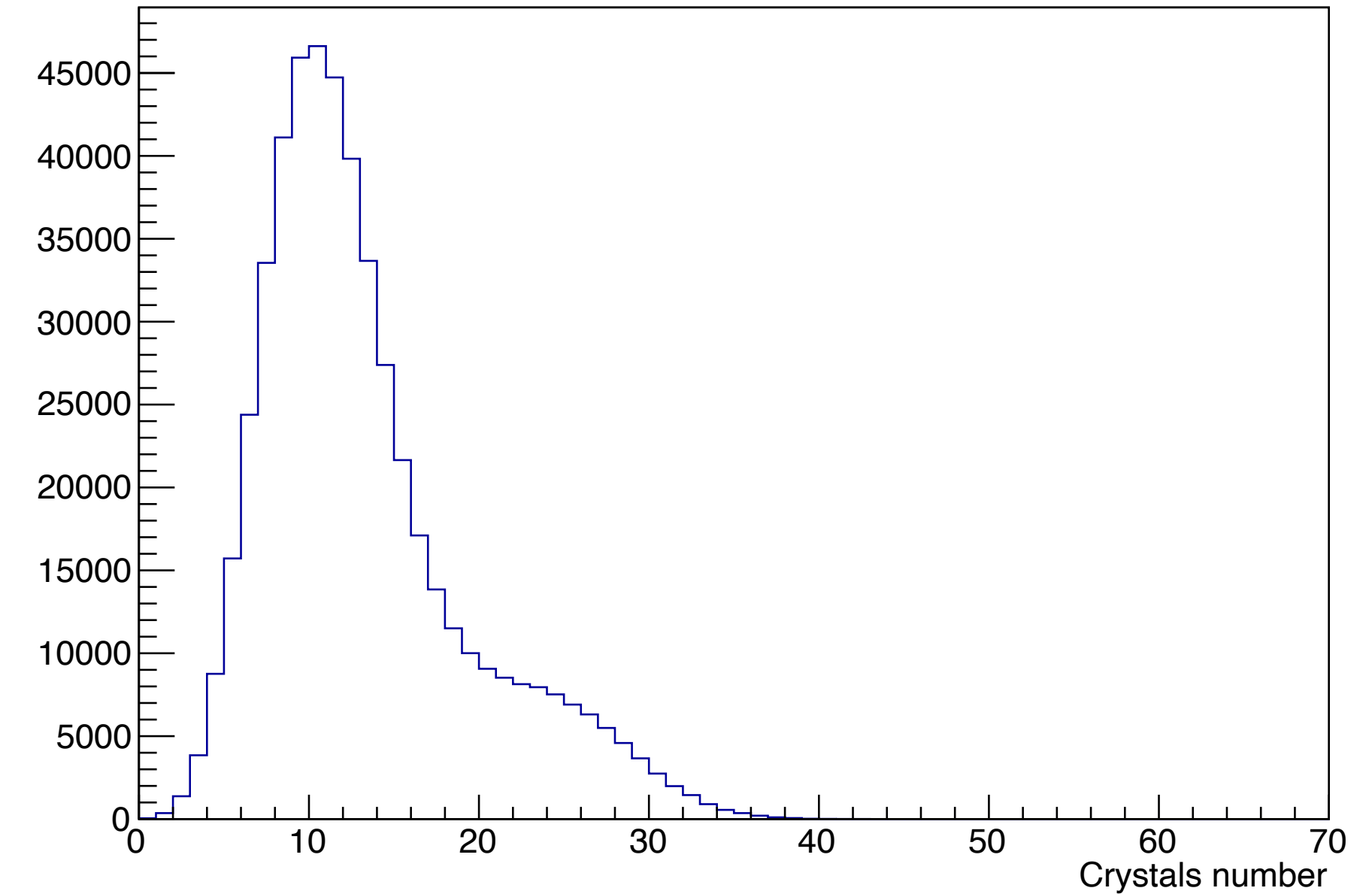
New SRD Efficiency

- Threshold on the deposited energy on single crystals for each event (> 100 phe \Rightarrow 330 keV)
- “Multiplicity” threshold (n° of crystals exceeding the energy threshold for each event) (>2)

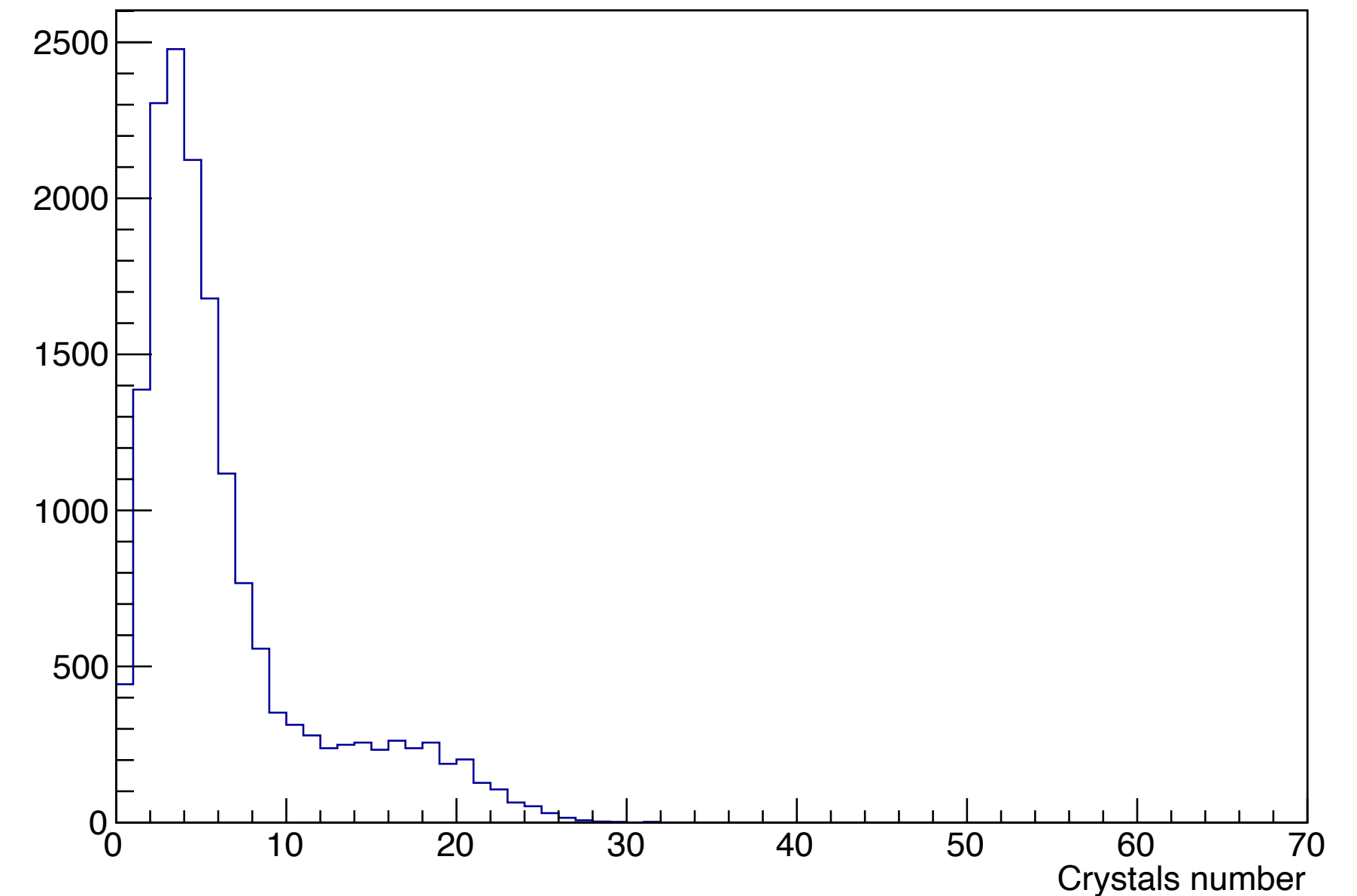


$$\eta_{40\text{GeV}} = 0.888, \eta_{60\text{GeV}} = 0.999$$

60 GeV



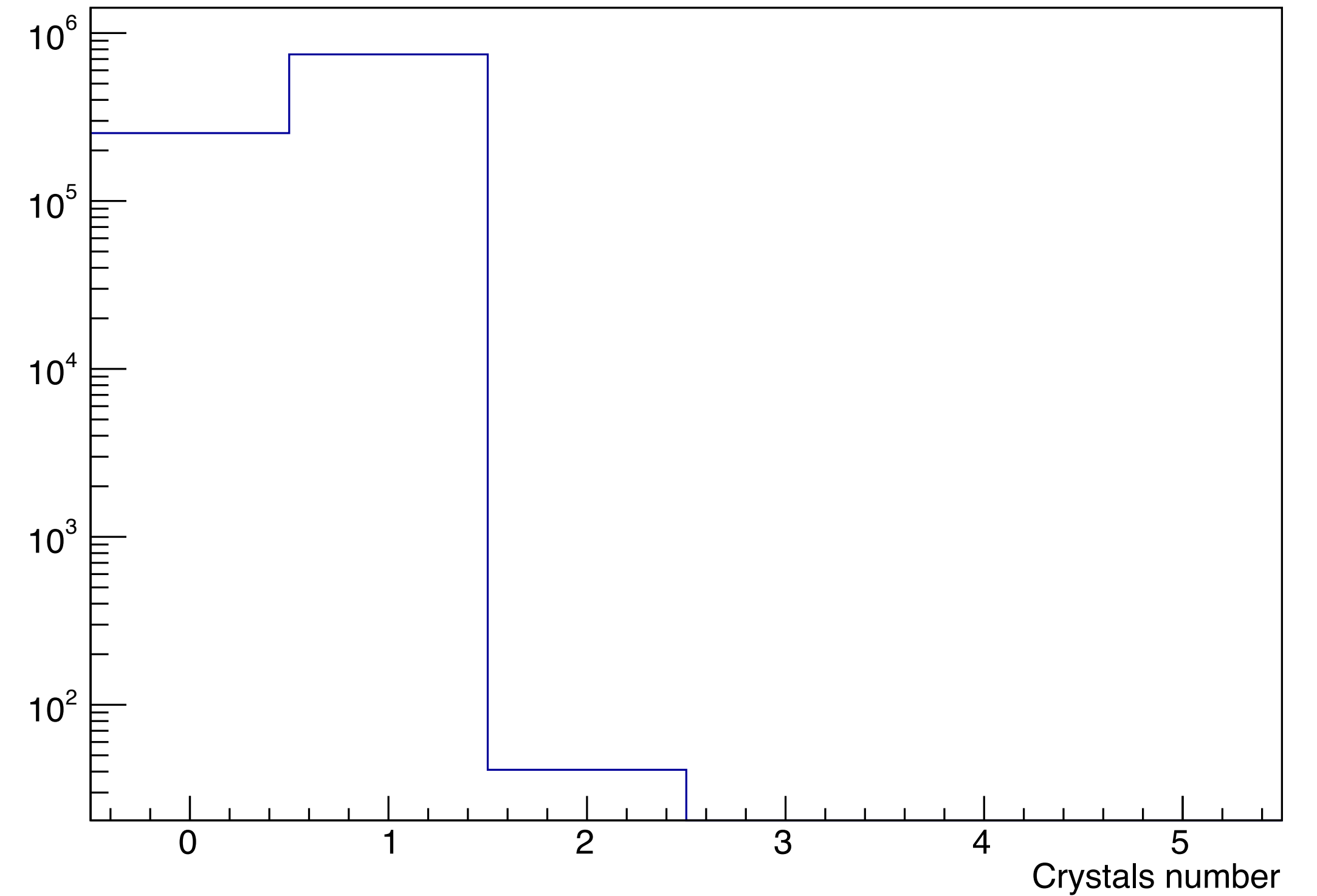
40 GeV



New SRD

Intrinsic radioactivity

- MC simulation on the ^{176}Lu decays
- The same cuts were applied on these results

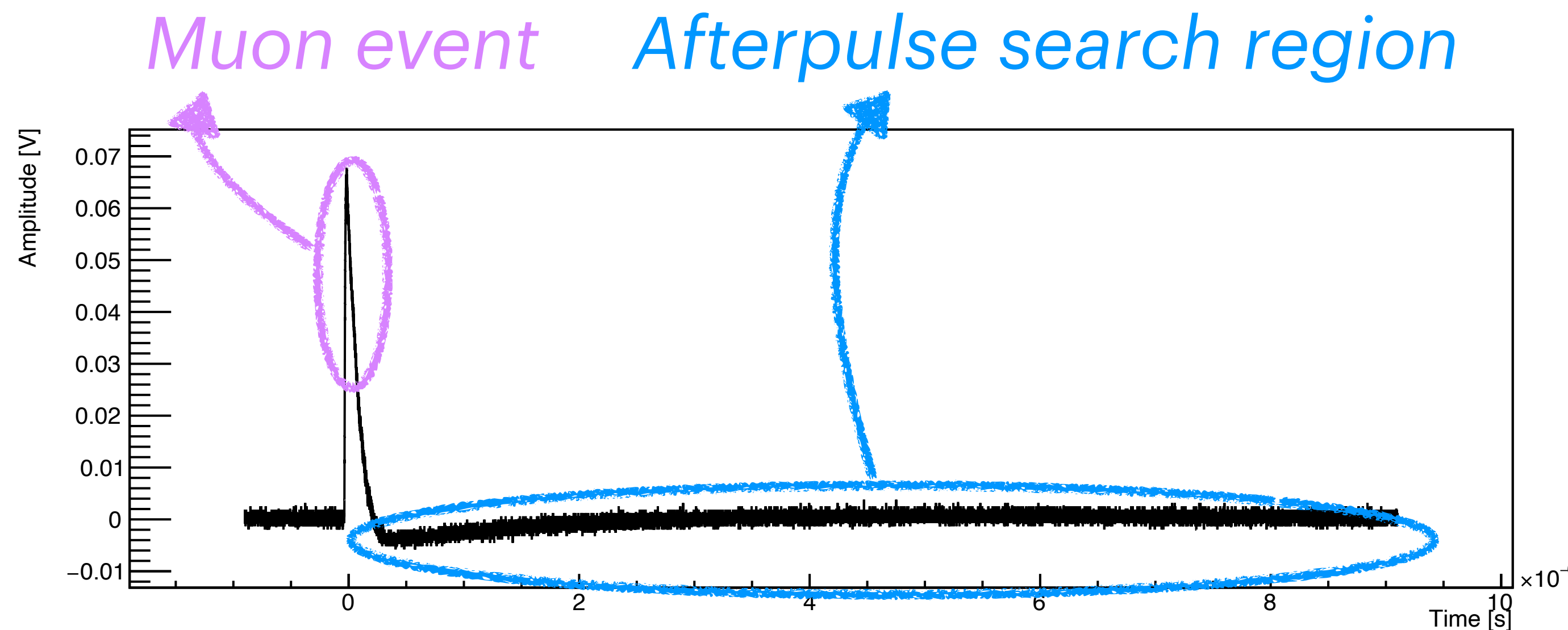
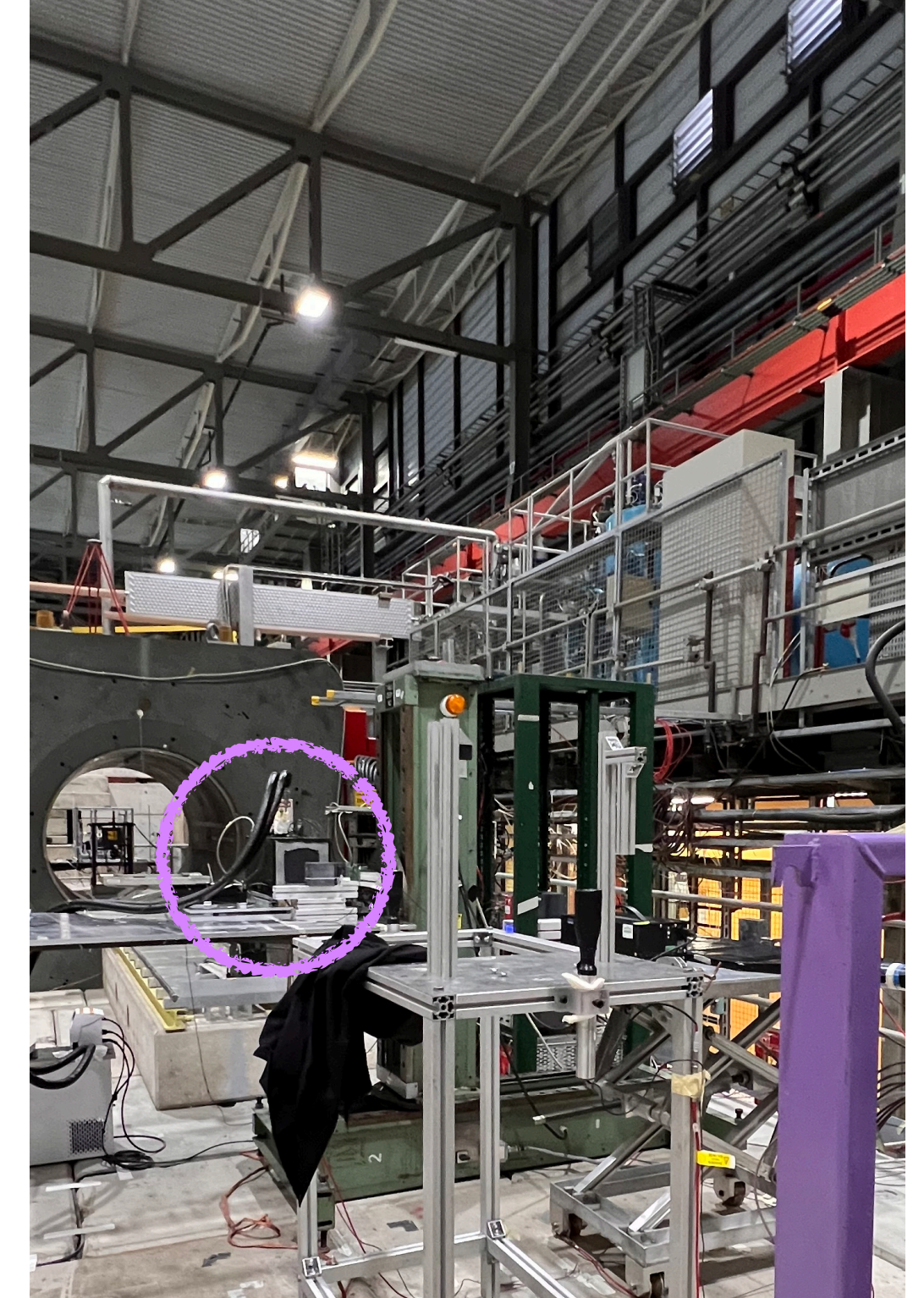


Matrix geometry	Rh @ 40 GeV [Hz]	Rh @ 60 GeV [Hz]
14x5	4,31	10,78
14x3	1,60	3,99

New SRD

Preliminary test

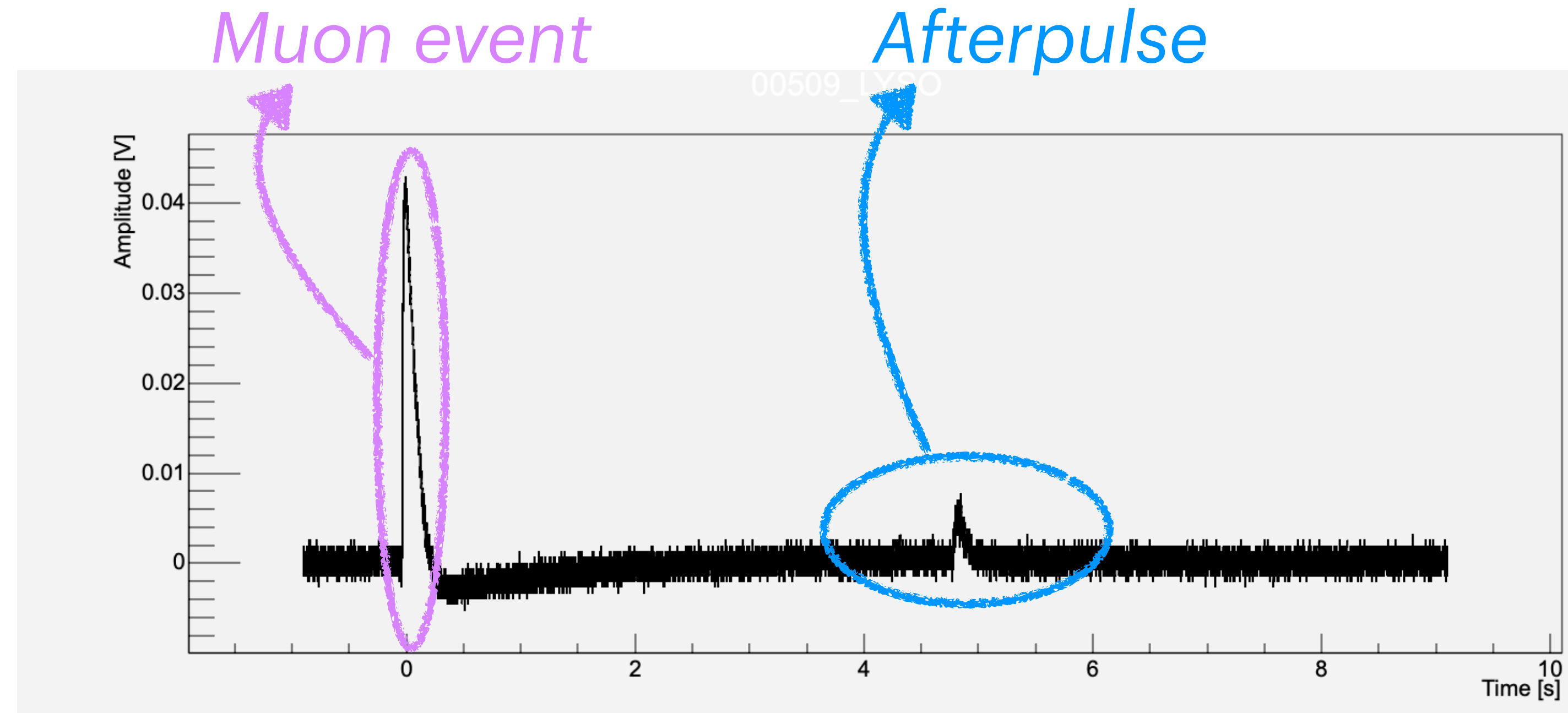
- Afterglow effect: presence of lesser scintillating components with larger decay times
- Test conducted at SPS line H8 in CERN's North Area with a 160 GeV muons beam
- The test required a triple coincidence with two plastic scintillators
- 10 microseconds time window



New SRD

Preliminary test

- We collected 7743 muon events
- We developed an algorithm to look for afterpulse events, based on a template fit
- Of those muon events, just **0.17%** showed afterpulse

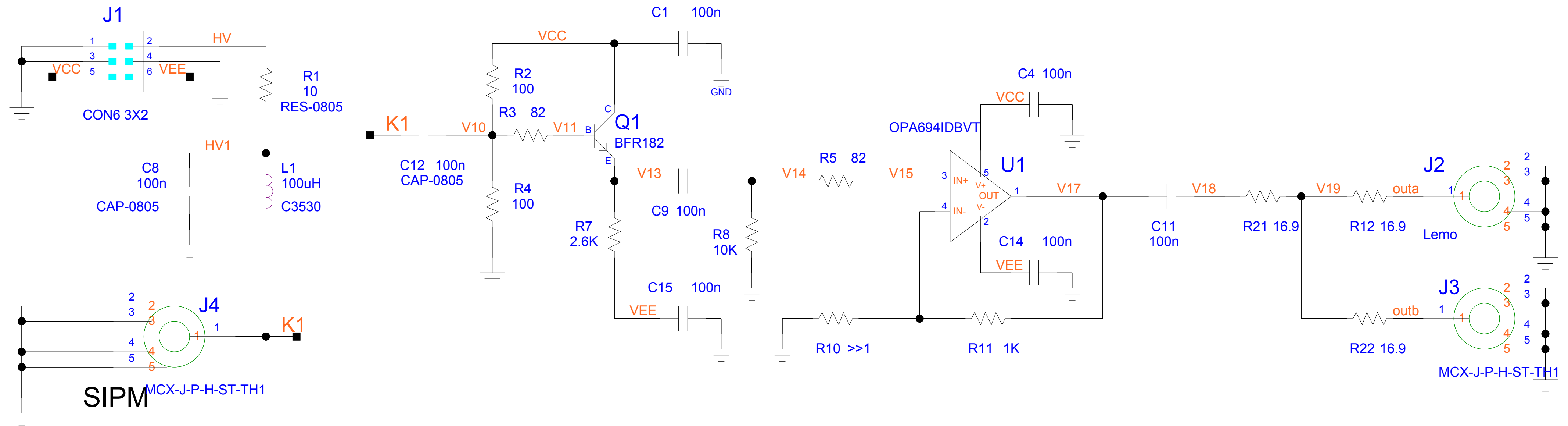


The fraction of afterpulse events doesn't seem significantly high to potentially affect our measurements

Conclusions

- NA64 is an experiment that searches for DS particles at SPS line H4, CERN
- NA64 2023 data taking concluded, the analysis is currently ongoing.
- Statistics brought to $\approx 1 \cdot 10^{12}$ electrons on target
- The results set the most competitive limits at 1-100 MeV
- POKER is an ERC winning project which aims to exploit the resonant production channel for A' for [40-60] GeV positron beams
- The SRD activity is ongoing
- POKERINO data currently being analyzed
- The assembly of the final calorimeter has started
- POKER data-taking will take place in 2025
- Any collaborator is welcome!

POKER Amplifier



NA64 ECAL

Summer 2023 run

54 FEU-84-3 PMTs to be integrated into the NA64 ECAL for the run were characterised

2023. For these tests, a setup was used that reproduces the conditions of the SPS beam at CERN. The characterization aims to determine:

- The charging trend of the signal as a function of frequency (over a frequency range between 10 kHz and 1.2 MHz);
- The behavior of PMTs in response to a "spill": emission of random signals at a given average frequency. Each spill lasts 5 seconds, interspersed with 10-25 seconds of darkness;
- The stability of PMTs on times comparable to the run. The best-performing PMTs were identified and selected

