The Calorimeter of the Mu2e experiment at Fermilab

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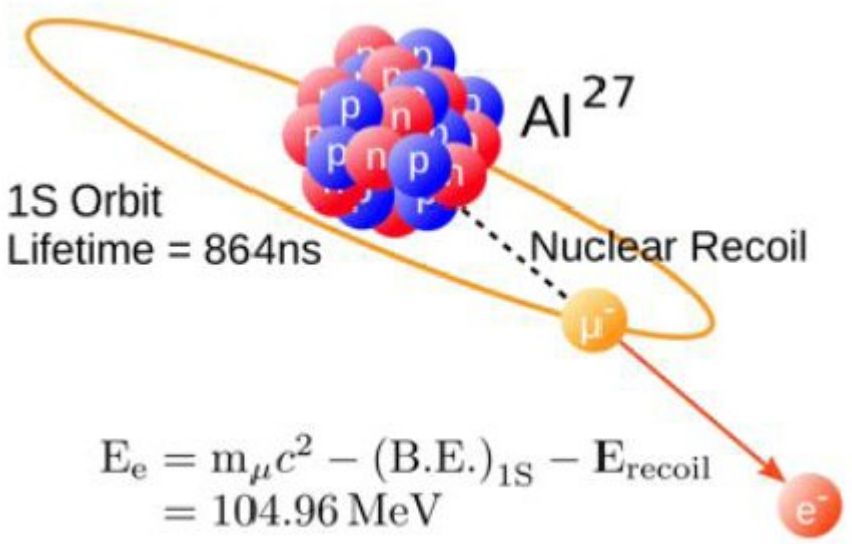
Mu2e Experiment at Fermilab: the goal

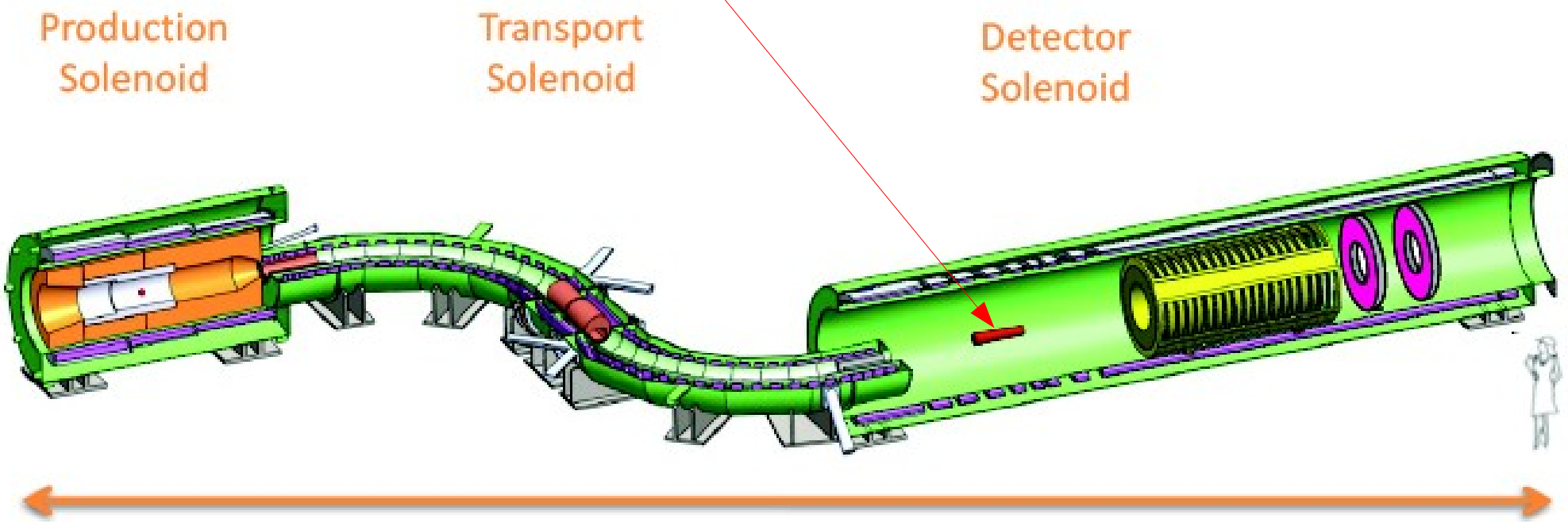


$$E_e = m_\mu c^2 - (B.E.)_{1S} - E_{recoil} = 104.96\,MeV$$

$$R_{\mu e} = \frac{\Gamma\left(\mu^- + N(A,Z)\right) \rightarrow e^- + N(A,Z)}{\Gamma\left(\mu^- + N(A,Z)\right) \rightarrow \text{all muon captures}}$$

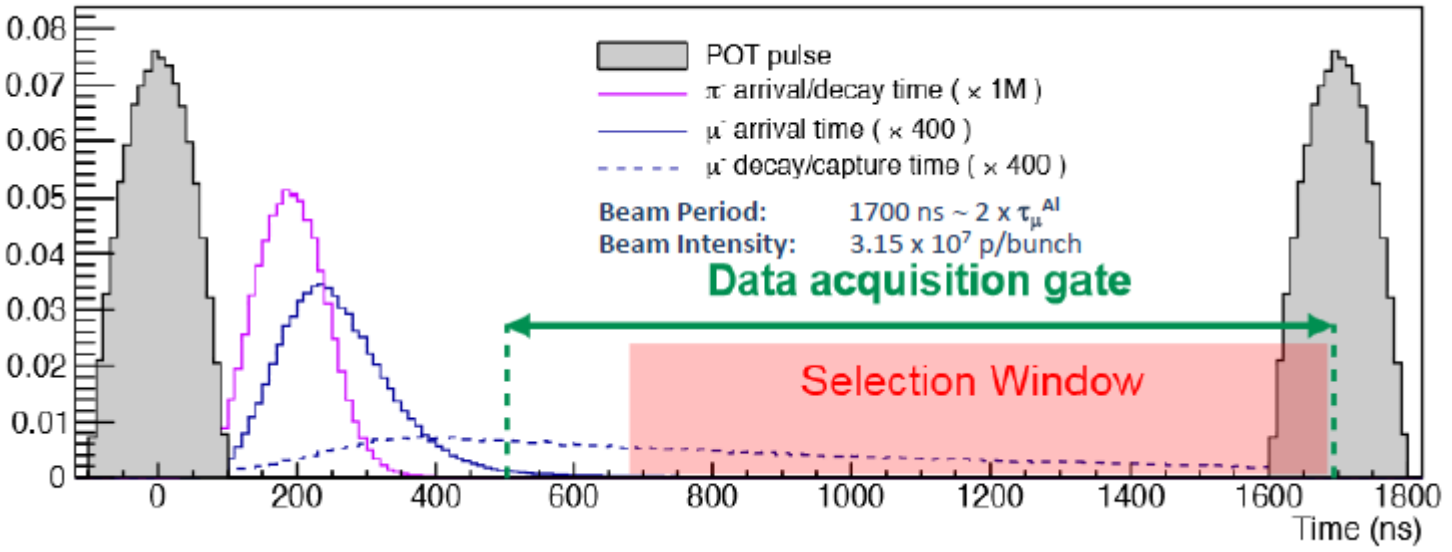
In 3 years:~10^{20} protons,~10^{18} stopped muons

→ A factor 10^4 improvement on sensitivity to $R_{\mu e}$: down to 6×10^{-17}



The Mu2e Experiment at Fermilab: the muon beam

Pulsed Proton Beam Structure



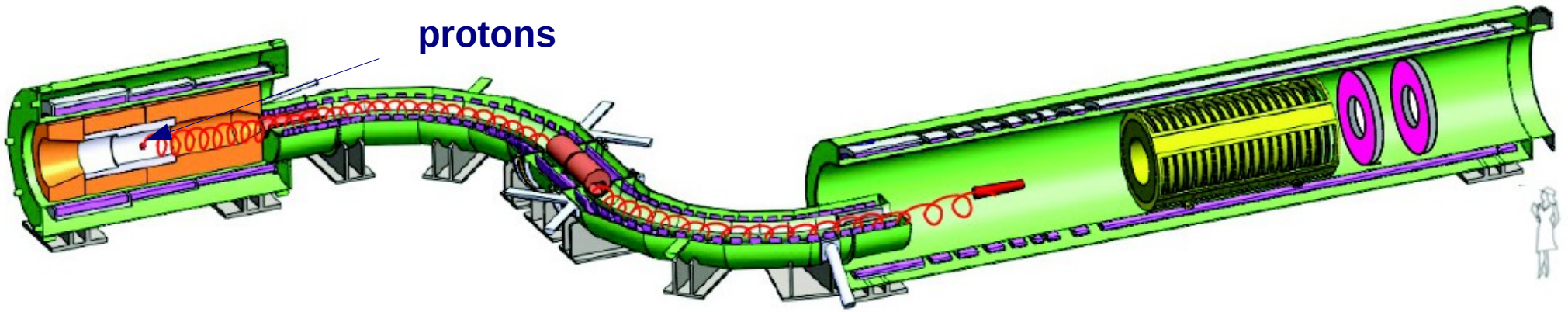
Extinction Factor $<10^{-10}$ (fraction of protons out of bunch)

Time window to avoid prompt background from beam flash

Production Solenoid

Transport Solenoid

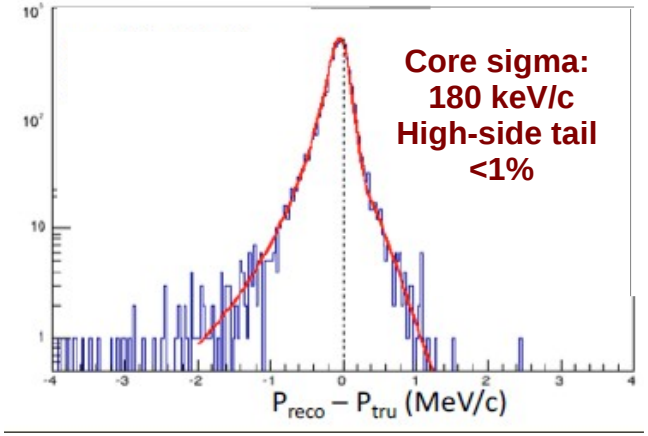
Detector Solenoid



Production Solenoid: 8 GeV *p* on tungsten, graded field channels π, K and μ from their decays
Transport Solenoid: transmit negative particles with the right momentum, antiproton absorber
Detector Solenoid: Al stopping target, proton absorber, graded field to direct to detectors

The Mu2e Experiment at Fermilab: tracker

Momentum resolution

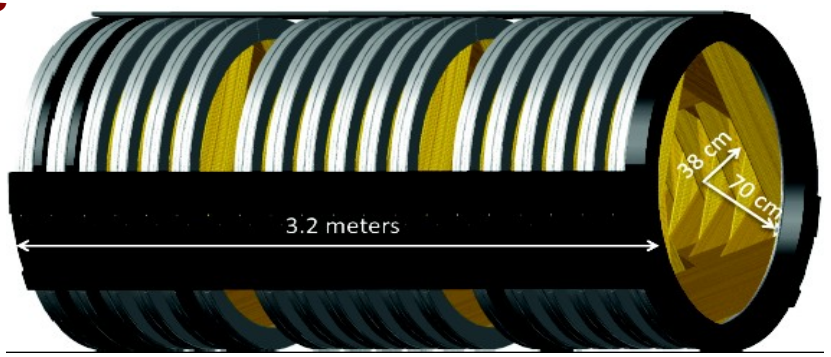


Tracker: >20k straw tubes each read by 2 ADCs and 2 TDCs

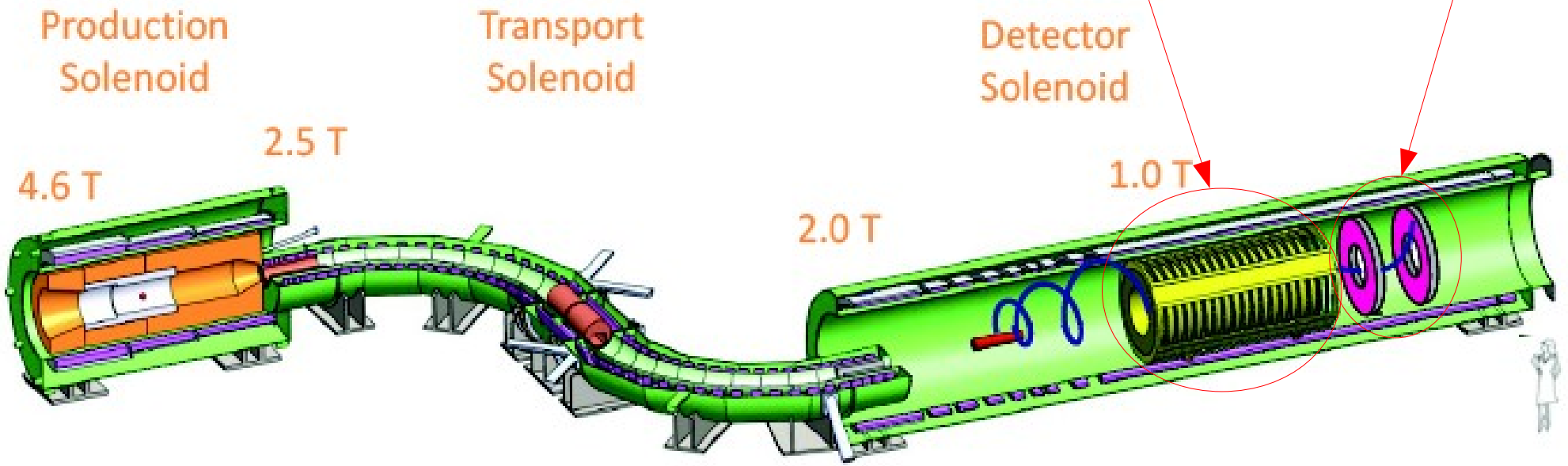
σ_p~180keV/c

σ_t~1 ns

Suppress DIO background

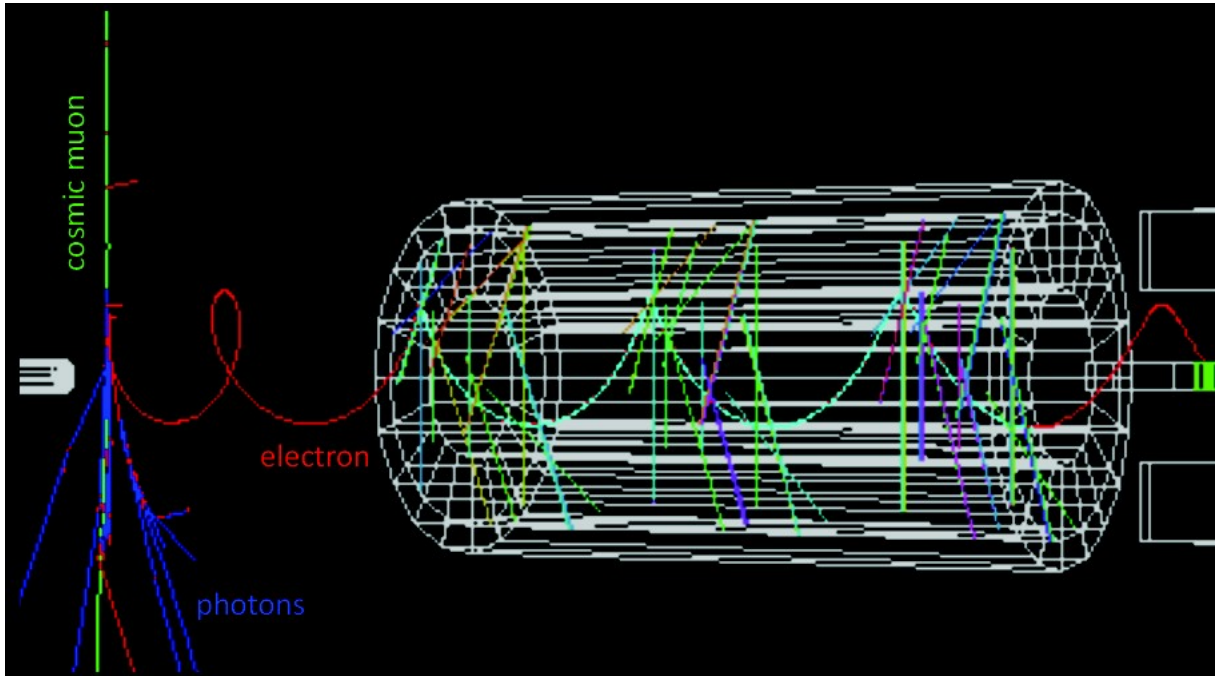


Calorimeter

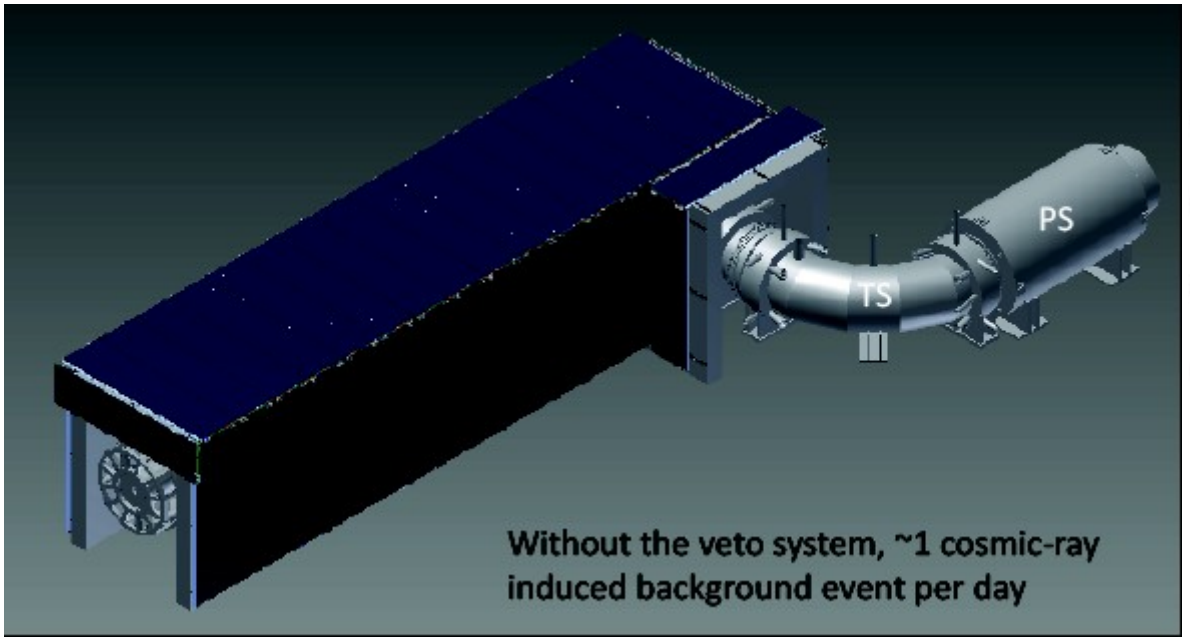


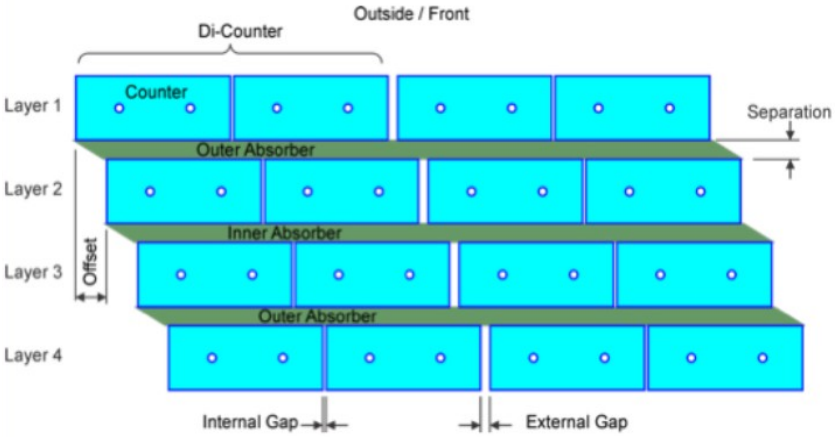
Graded fields:
suppress background, increase muon yield and improve geometrical acceptance

The Mu2e Experiment at Fermilab: cosmic veto



Cosmic ray induced events:
1 per day can mimic
a 105 MeV/c conversion
electron (CE)





Cosmic ray veto system:
inefficiency < 10^{-4}

Requirements for Mu2e calorimeter

The Mu2e electromagnetic calorimeter (ECAL) is **needed to:**

- **identify conversion electrons**

- **suppress cosmic muons** by an additional factor 100

- **provide a standalone trigger** to measure tracker trigger and track reconstruction efficiency

- (optional) **seed the tracker pattern recognition** to reduce hit combinations

ECAL must operate in an **harsh experimental environment**:

- **magnetic field**: 1 T

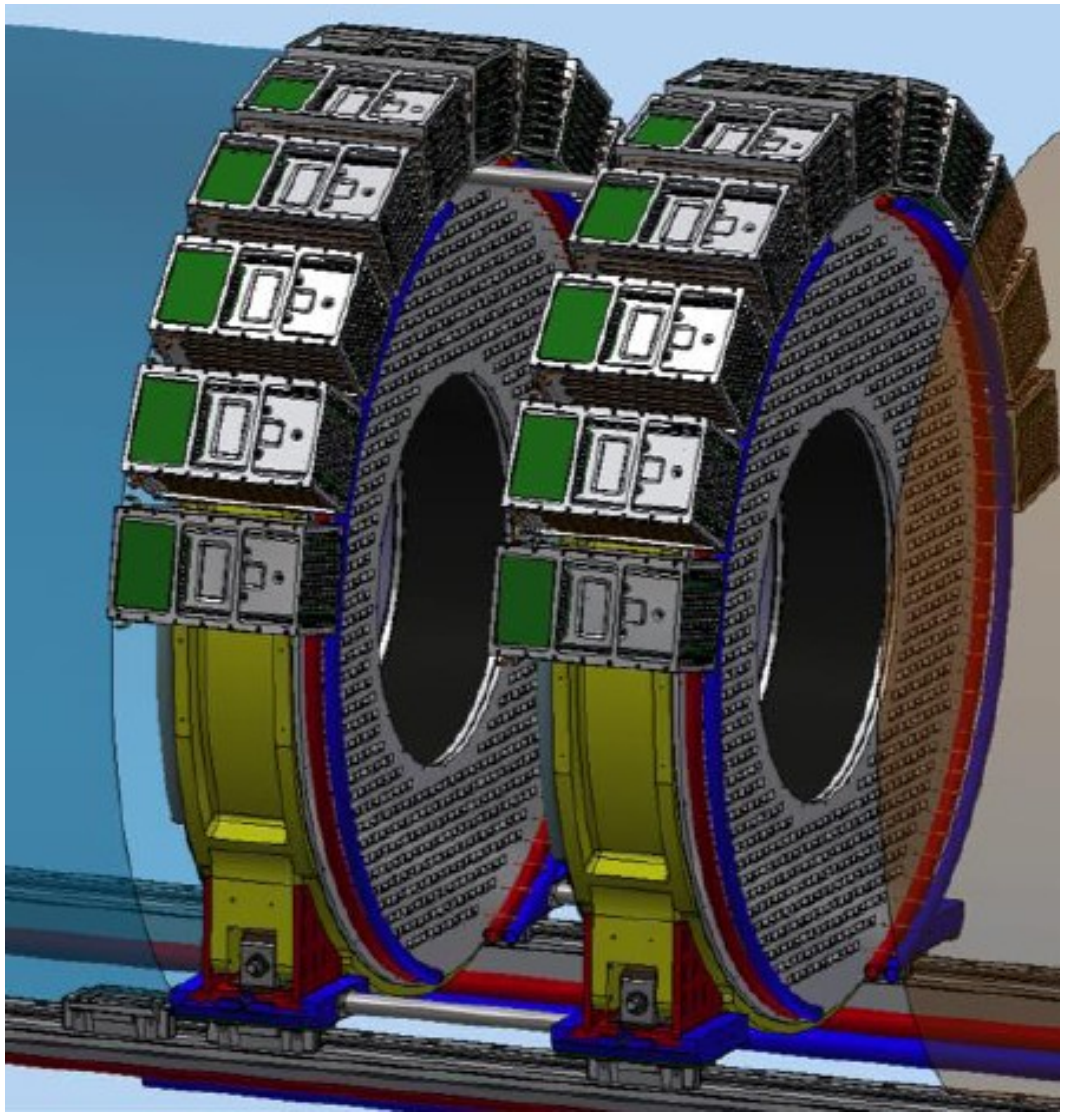
- **vacuum**: 10^{-4} Torr

- **max ionizing dose**: 100 krad (integrated in 3 years x safety factor 3)

- **max neutron fluence**: 10^{12} n/cm^2 (integrated in 3 years x safety factor 3)

- **high particle rate also in selection window → granularity in time and space**

The Mu2e calorimeter



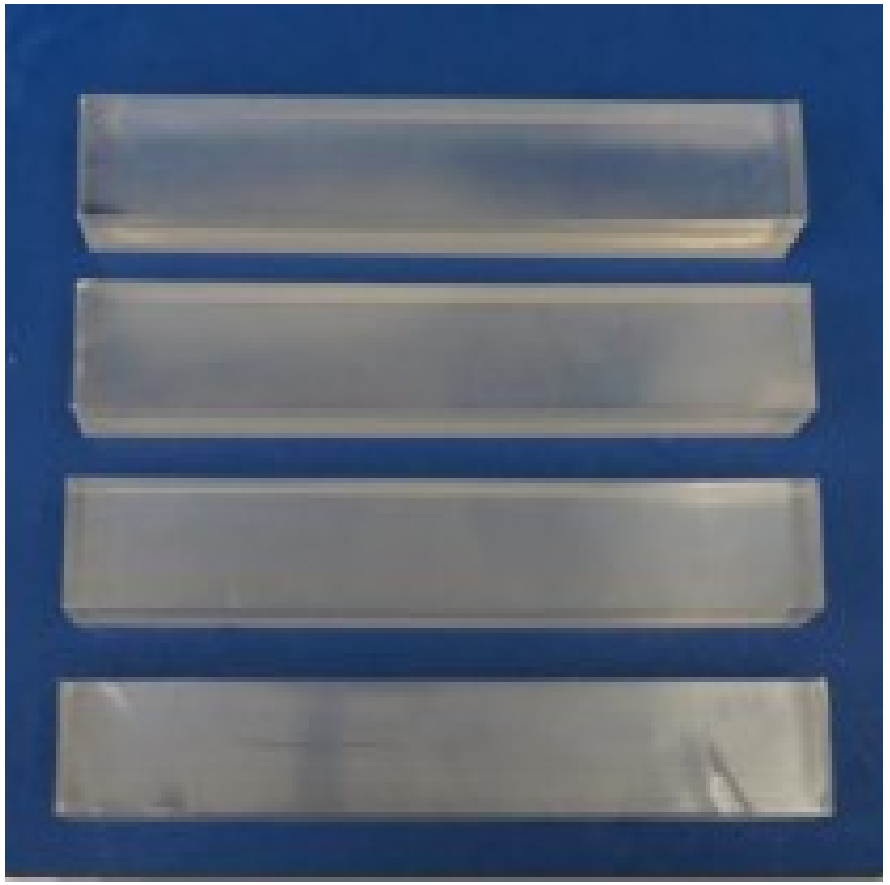
Geometry (acceptance optimized)
2 disks spaced by 70 cm
inner radius: 37.4 cm
outer radius: 66 cm

Active material:
pure CsI crystals
674 crystals/disk
3.4x3.4x20 cm^3

Sensors:
Arrays of 6 UV-extended of SiPMs
2 arrays/crystal
of 14x20 mm^2 each

Readout electronics:
Preamplifier close to the sensor
Voltage control and waveform
Digitizers in the electronic
crates around the disk

ECAL CsI crystals

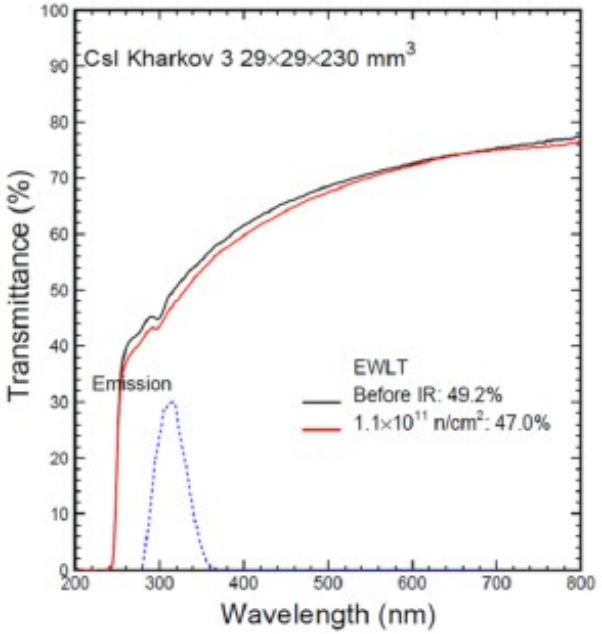


Wrapping: 150 μm of Tyvek

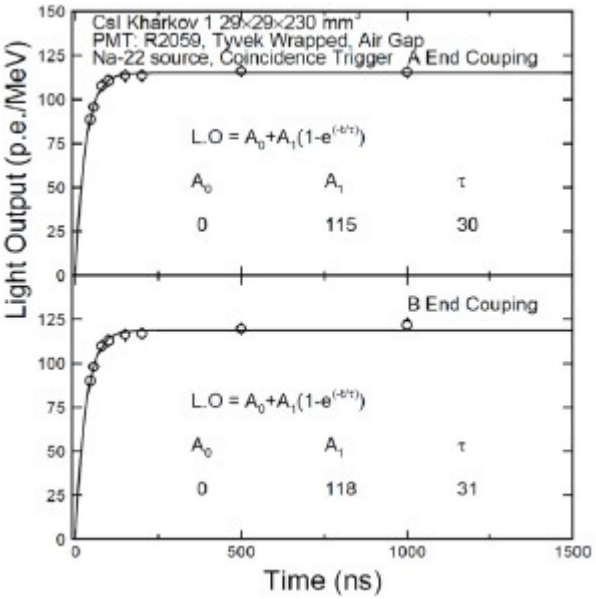
	CsI
Density (g/cm3)	4.51
Radiation length (cm)	1.86
Moliere Radius (cm)	3.57
Interaction length (cm)	39.3
dE/dX (MeV/cm)	5.56
Refractive index	1.95
Peak luminescence (nm)	310
Decay time (ns)	26
Light yield (rel. to NaI)	3.6%
Variation with temperature	-1.4% / deg-C

Quality tests in Caltech and Laboratori Nazionali di Frascati (LNF):
- light yield, light transmittance and light response uniformity
- time response
- hardness to ionizing and neutron radiation, induced emission

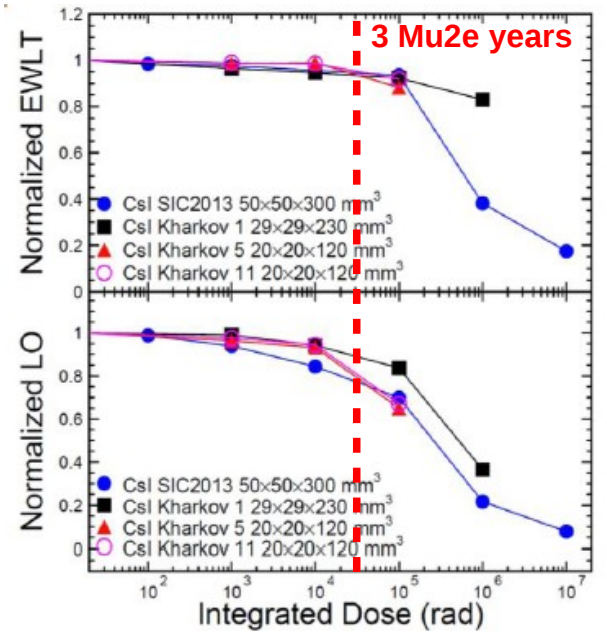
Tests on CsI crystals



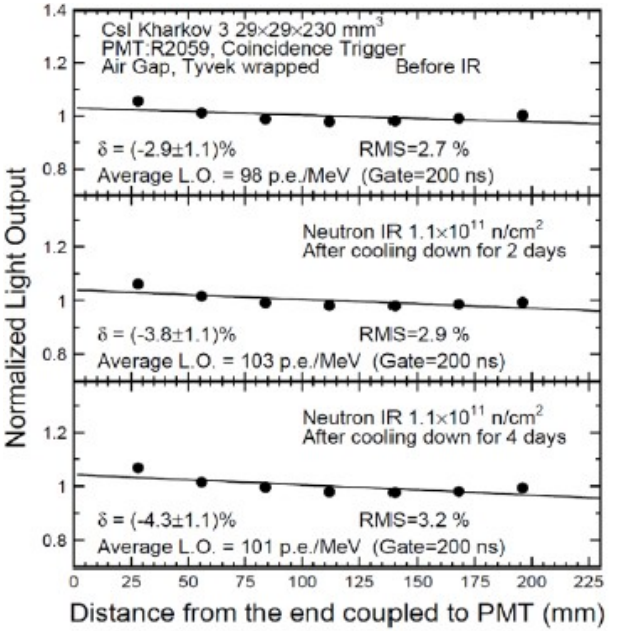
←
Emission Weighted Longitudinal Transmittance (EWLT) ~50%



→
Light output ~100 p.e./MeV
Decay time ~30 ns

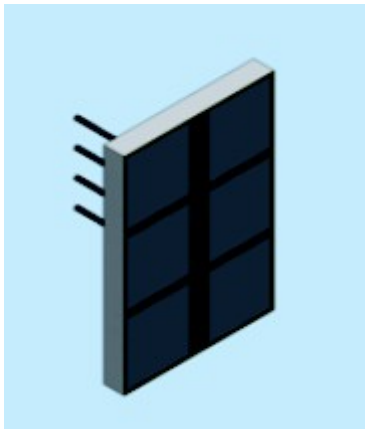


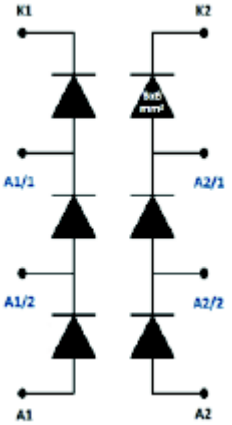
←
Ionizing dose irradiation



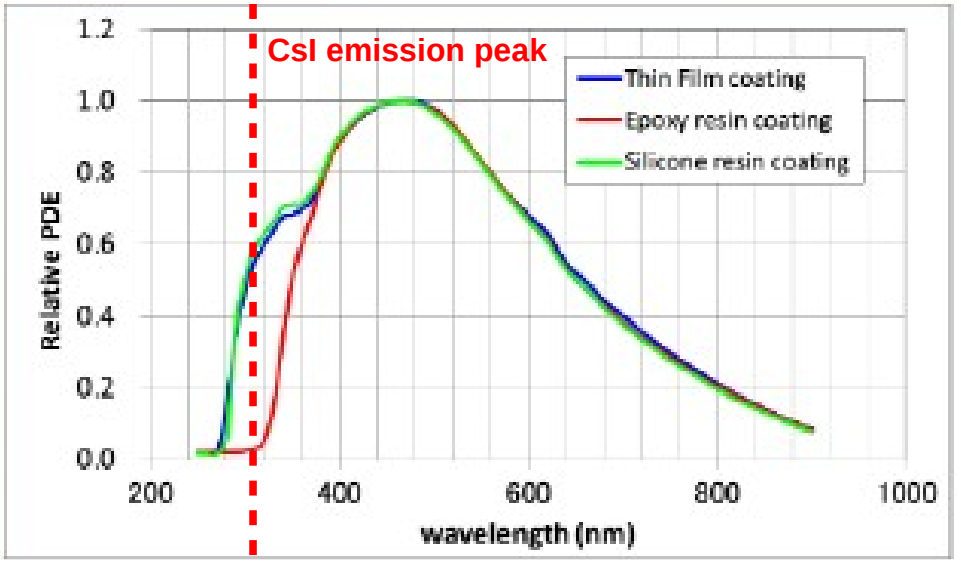
→
Light Response Uniformity
Neutron irradiation

UV extended SiPMs





6x6 mm^2 SiPM
Array:
Parallel of 2 series of 3 SiPMs each:
- signal decay time ~100 ns,
- redundancy x2

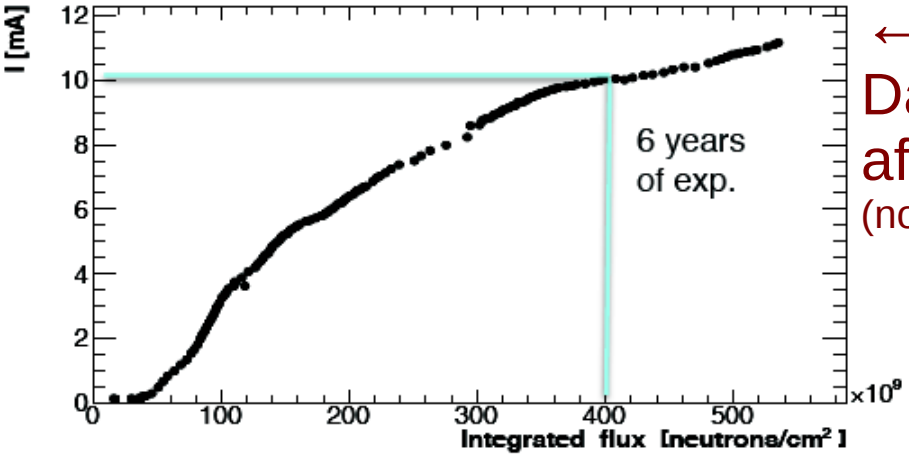


Monolithic UV extended SiPM
Particle Detection Efficiency (PDE):
~30% @ CsI emission peak

Gain at $V_{OP}=V_{BR}+3V > 10^6$

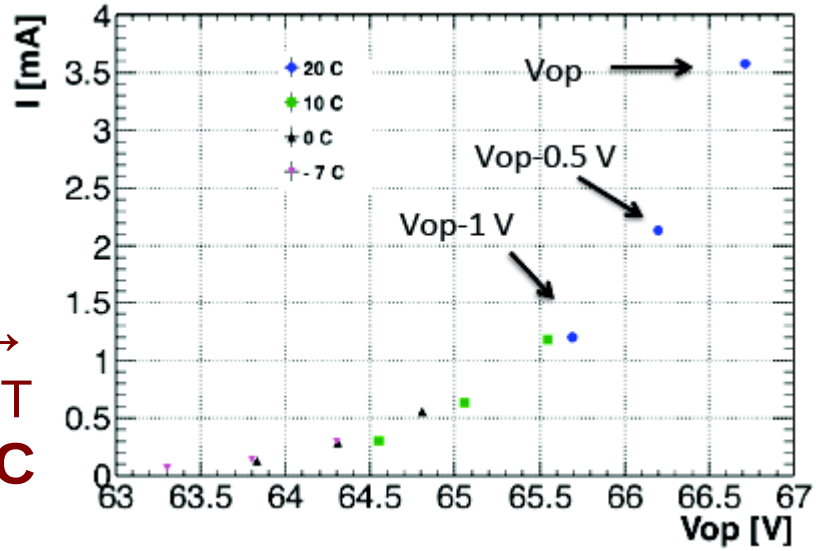
Quality tests in LNF, Pisa and Caltech for Hamamatsu, SENSL, FBK SiPM:
- dark current, breakdown voltage and gain vs Temperature
- time response
- hardness to ionizing and neutron radiation, mean time to failure (MTTF)

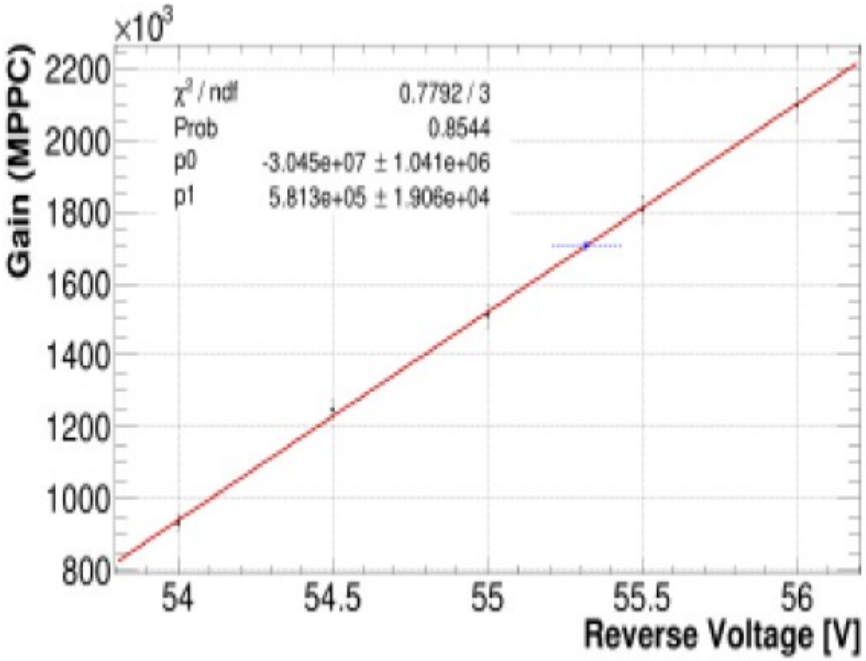
Tests on SiPMs



←
Dark current
after n radiation
(no damage from dose)

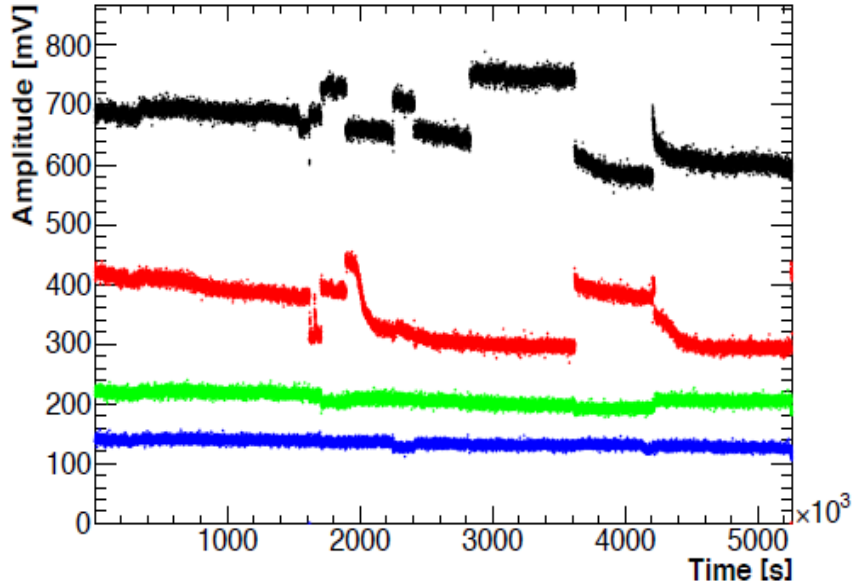
→
Dark current vs T
Operate at 0° C



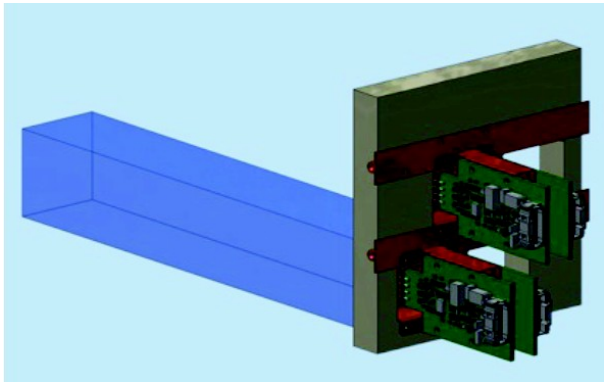


←
Gain vs V

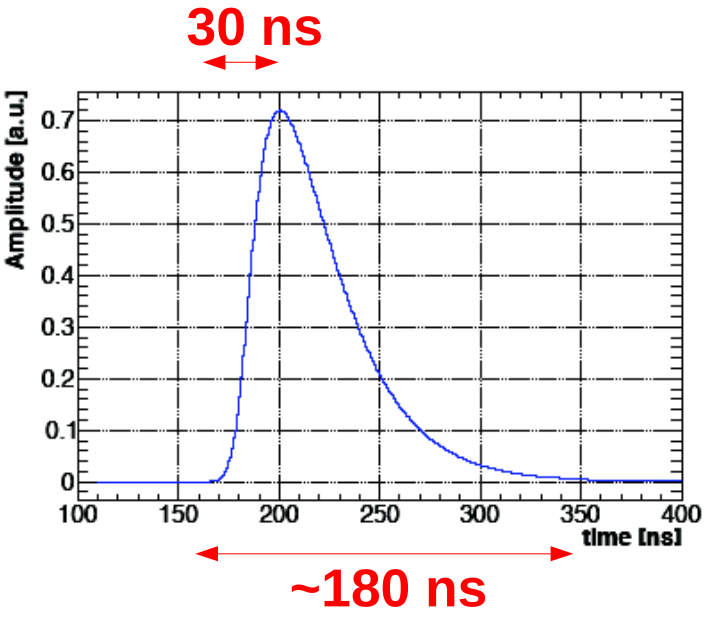
→
Accelerated
MTTF test
at 55° C

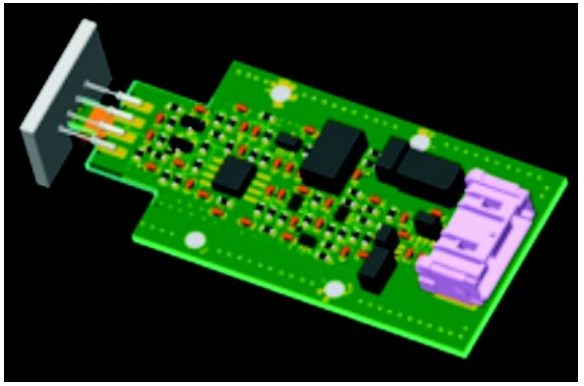


Readout electronics

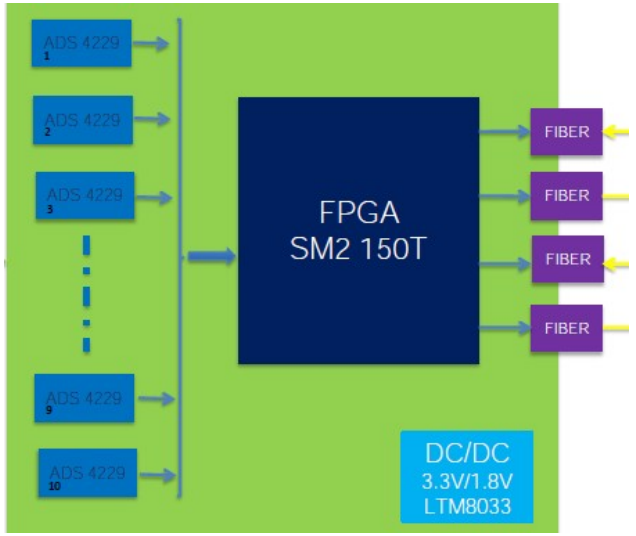


2 SiPM arrays/crystal
1 preamplifier/array
2 SiPM series/array
with indipendent bias

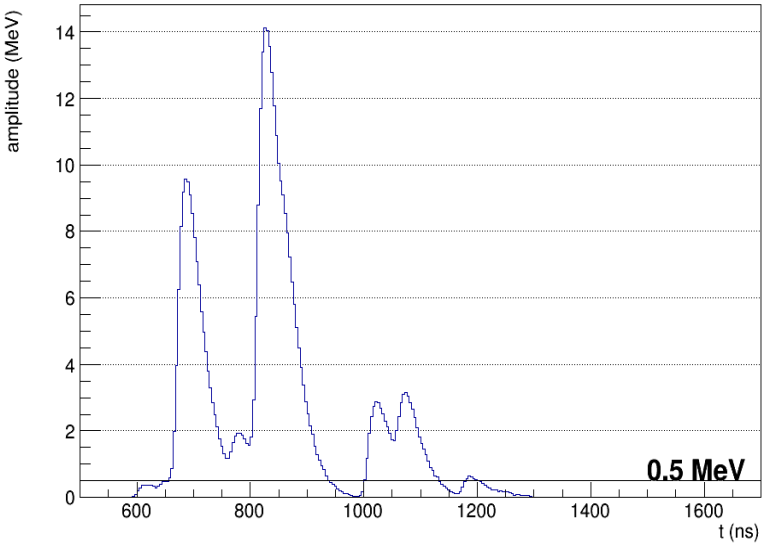




Preamplifier
also shapes
the signal



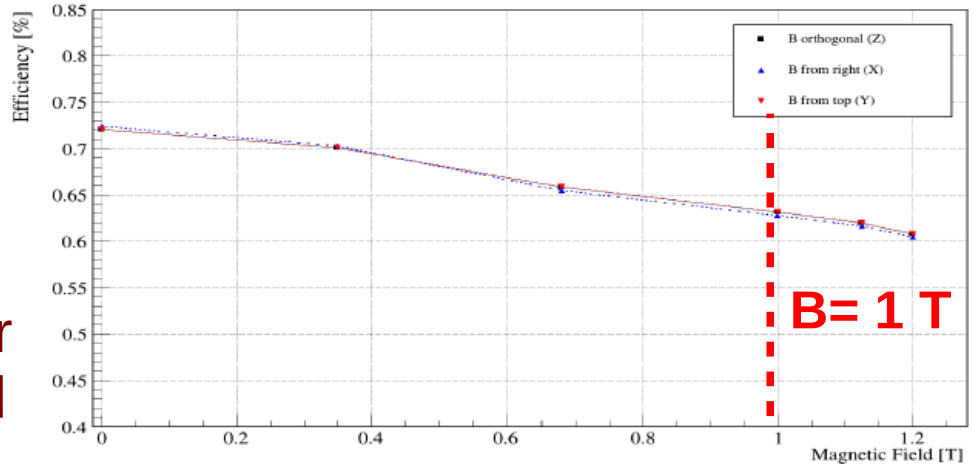
Waveform
Digitizer
reads 20
channels
at 200 Mhz
(1 sample
each 5 ns)



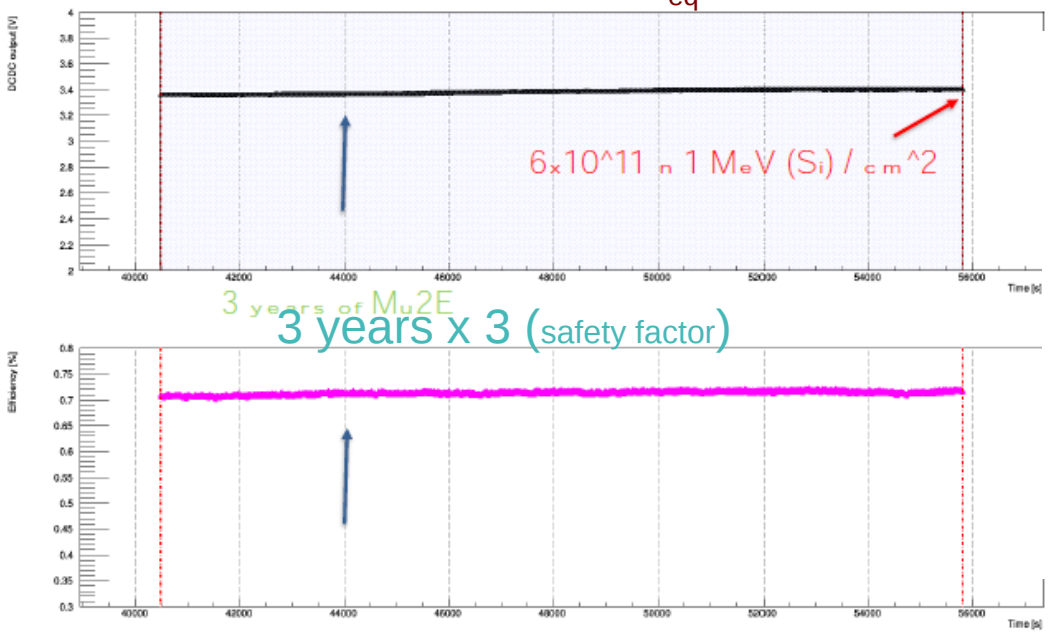
Qualification of electronic components

←
FPGA
SEL free
SEU free

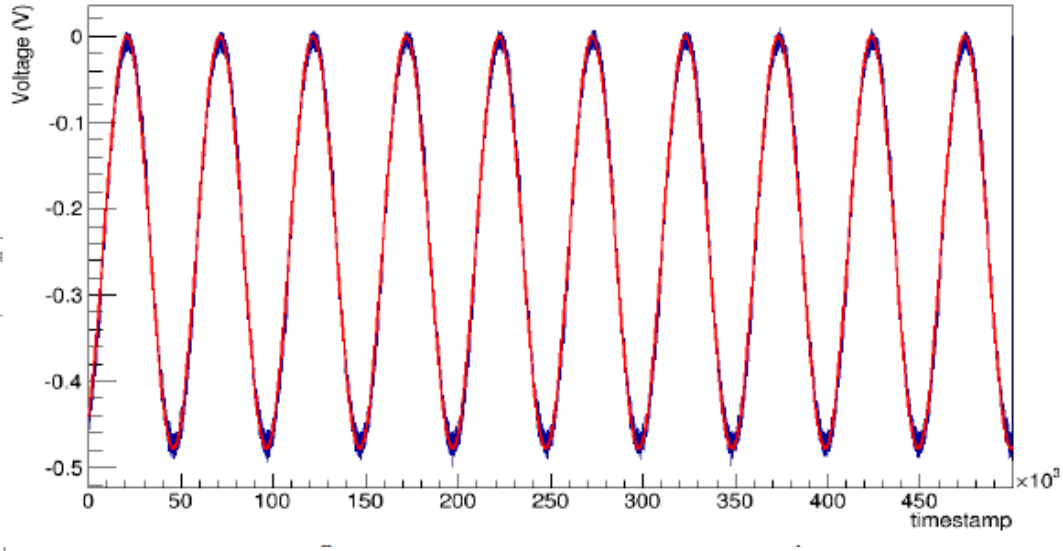
→
DCDC converter
in magnetic field



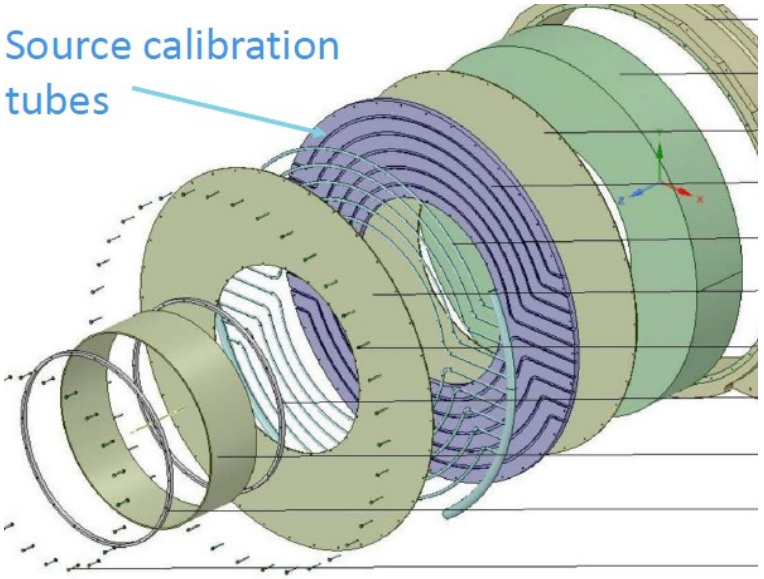
DCDC converter n irradiation
(1.5x10^{11} n/cm2 @ 1 MeV$_{eq}$ = 3 years)



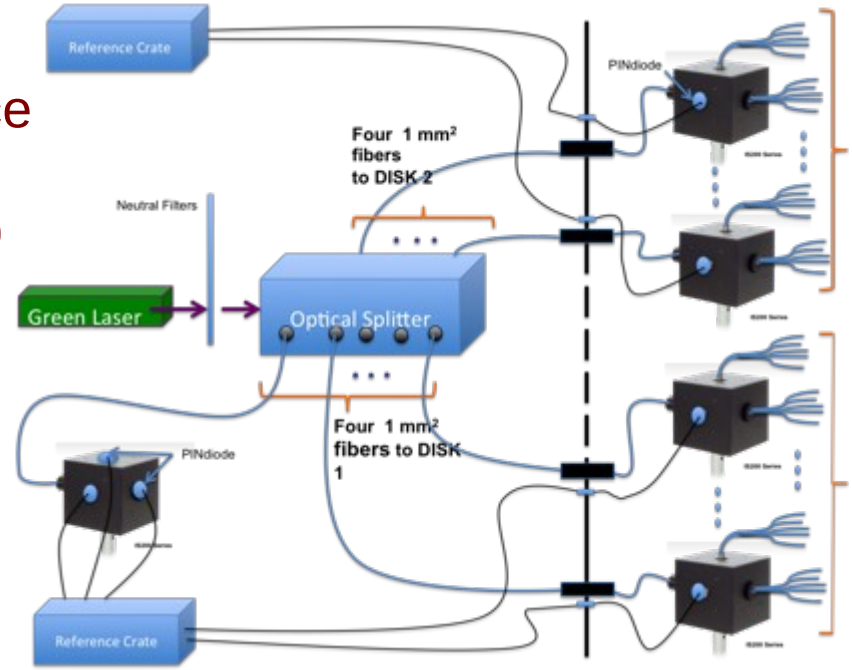
ADC after 20 krad
(1.5krad = 3 years)



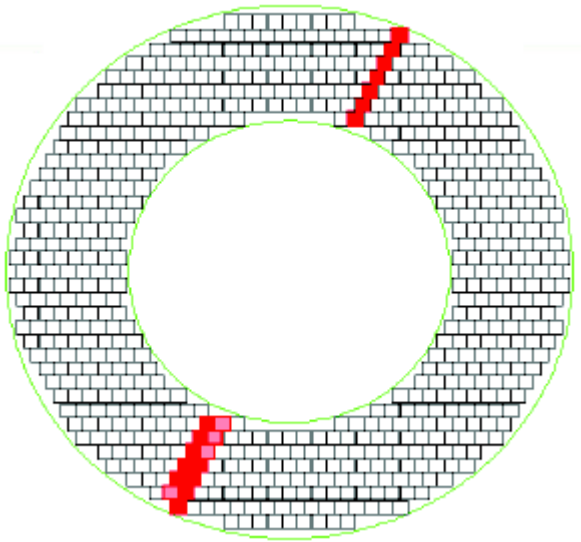
Calorimeter calibration



←
6 MeV liquid source in front of crystals (energy calibration)

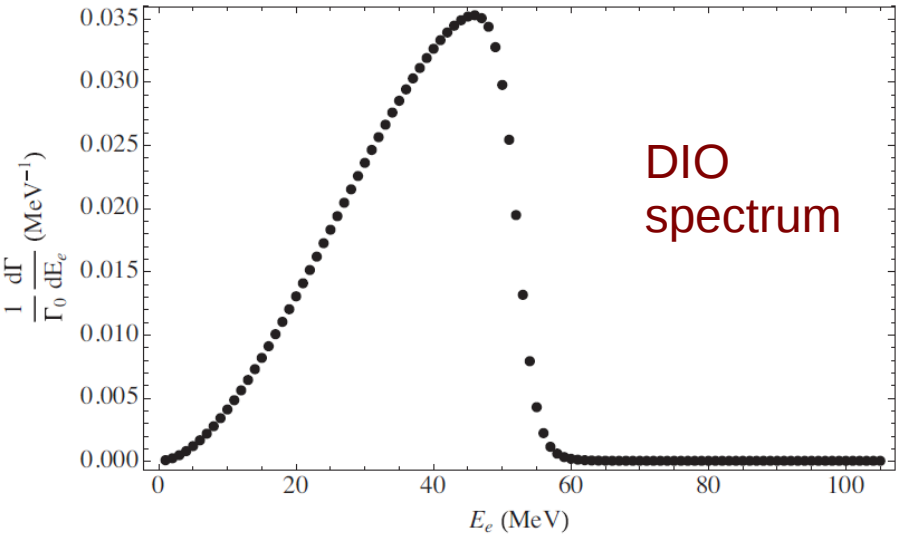


→
Laser pulses (energy and time Calibration)
FEE pulses



←
Cosmic muons (energy and time calibration)

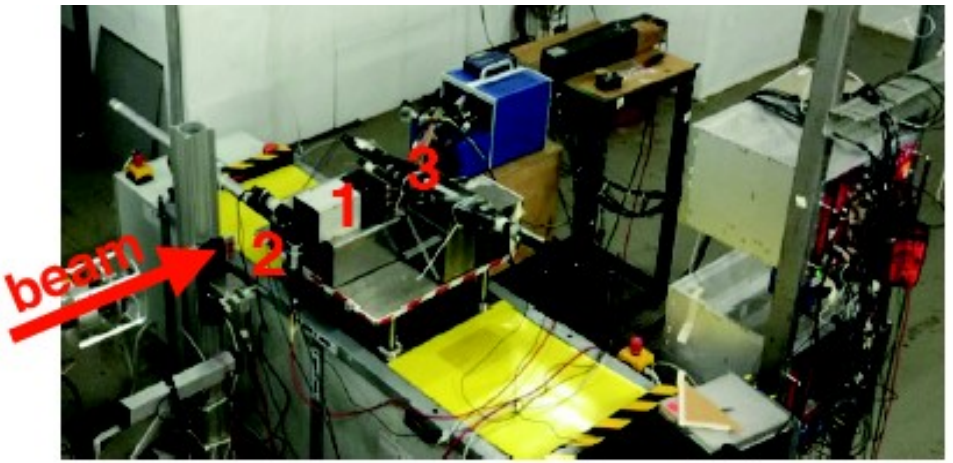
→
E/p and Δt from muon decays in orbit (DIO) and π→eν decays at reduced B field (energy and Tracker-ecal time)



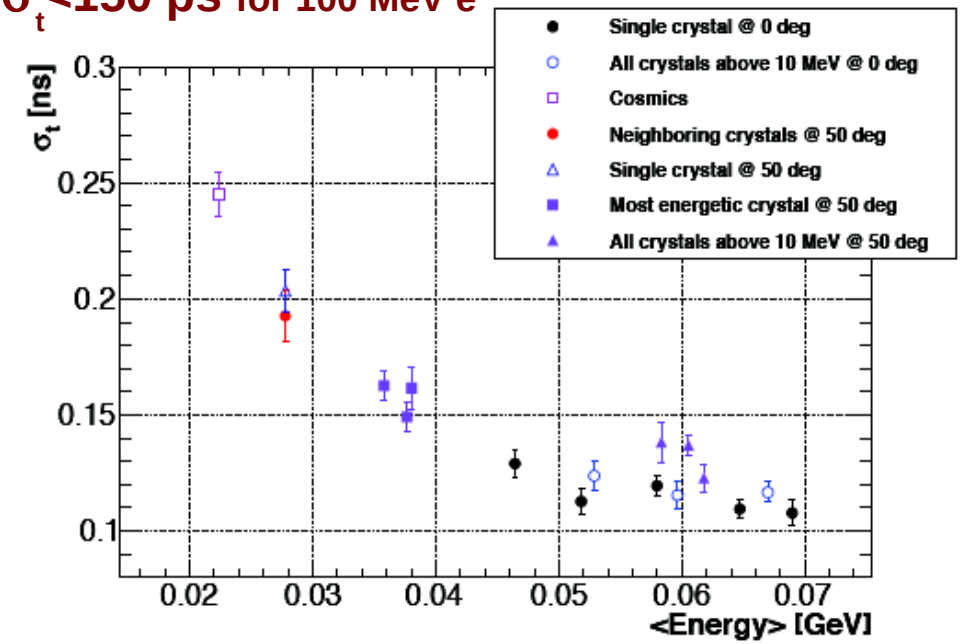
DIO spectrum

2015 Test beam results

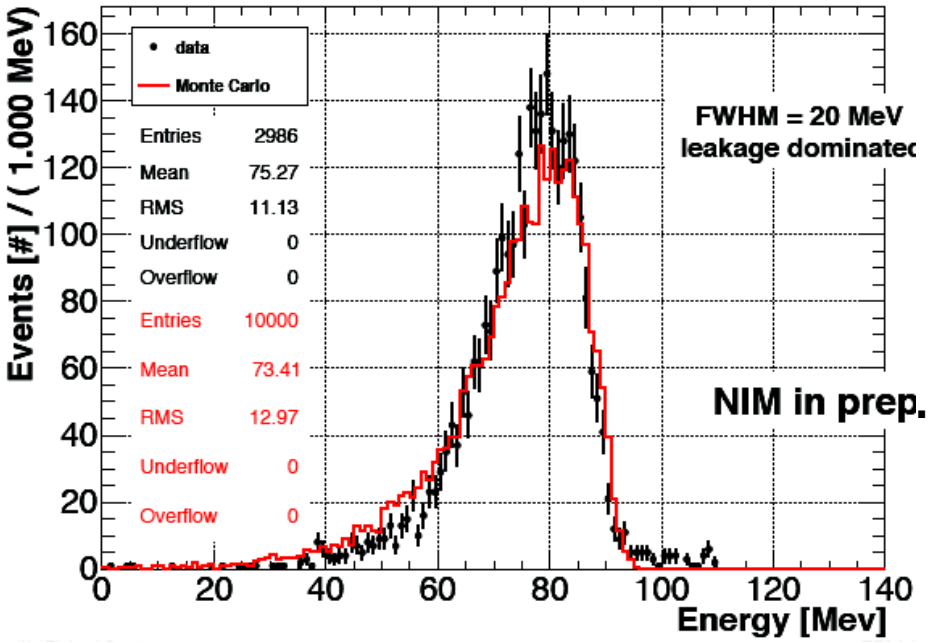
80->120 MeV electron beam at Beam Test Facility (BTF) in Frascati



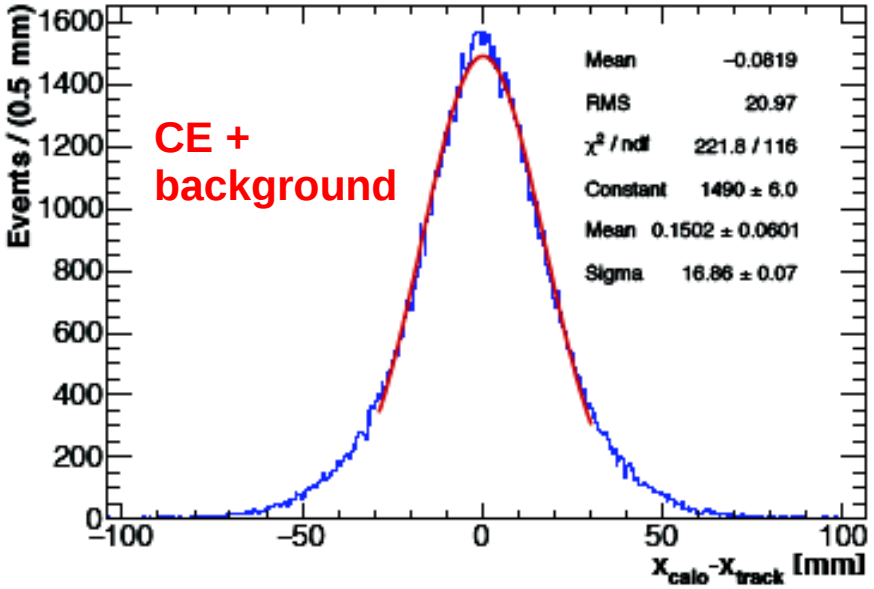
σ_t<150 ps for 100 MeV e-



σ_E/E~7% for 100 MeV e- at 50° (LEAKAGE dominated)



Expected performances from simulation: x,y,E,t

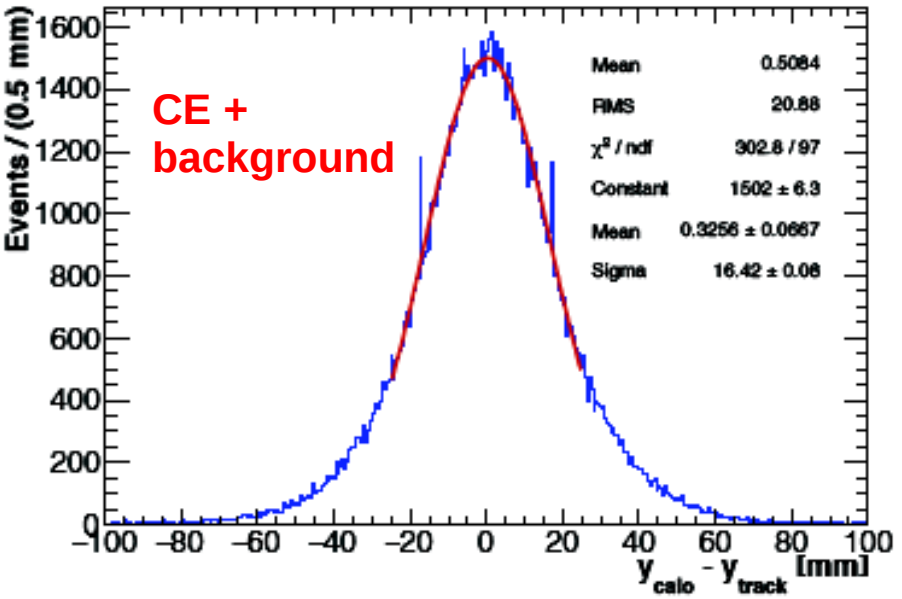


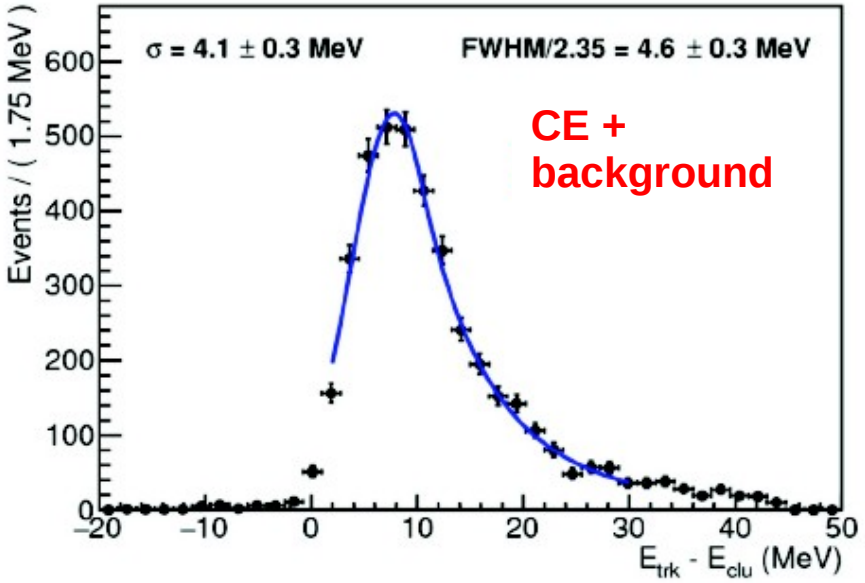
←

σ_x~16 mm

→

σ_y~16 mm



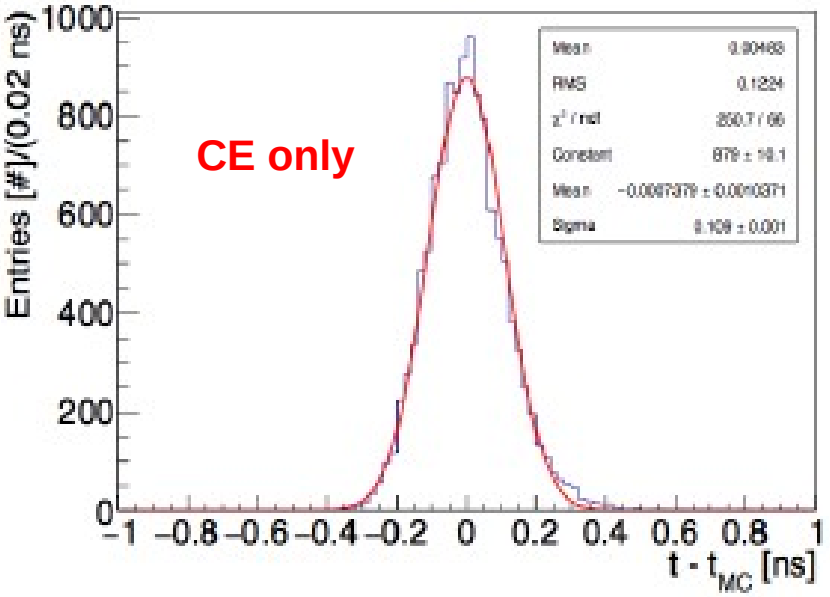


←

σ_E/E~4%

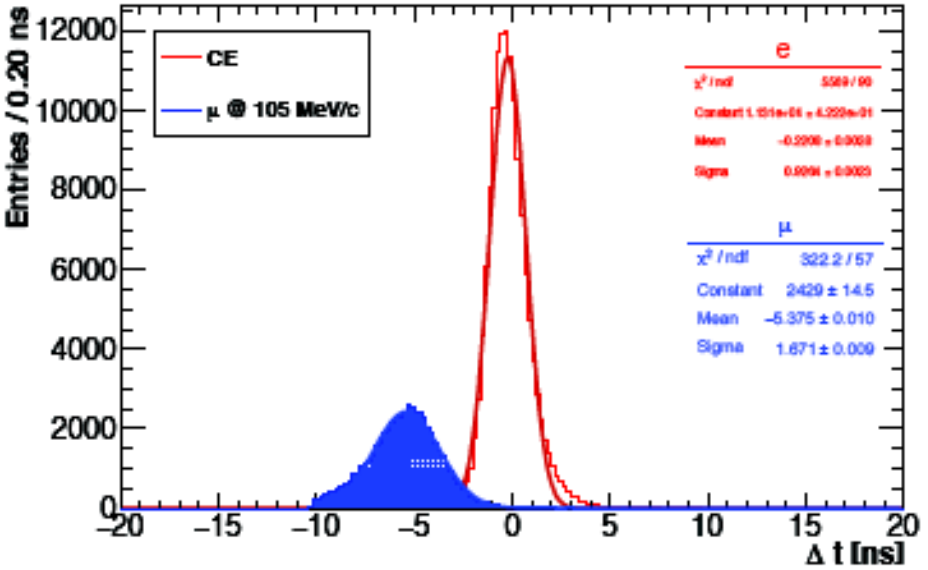
→

σ_t~110 ps

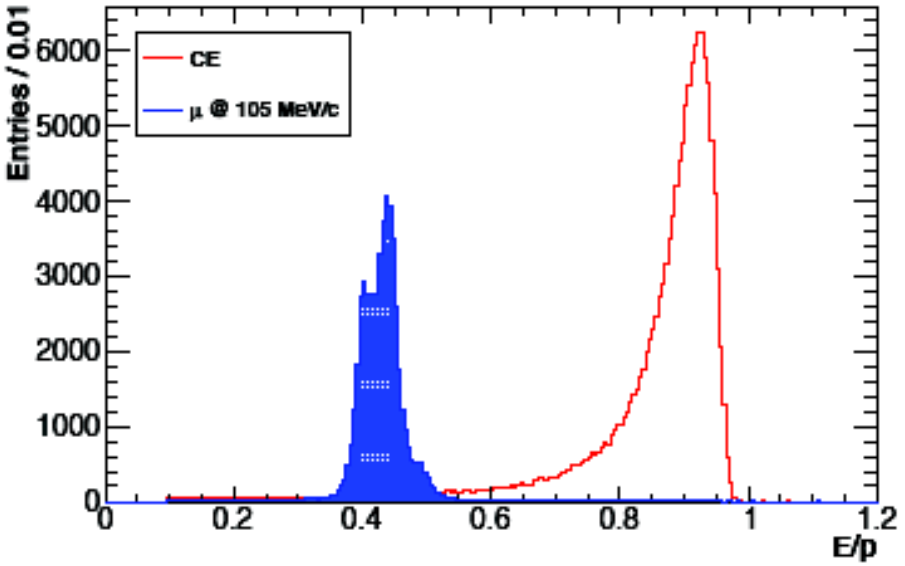


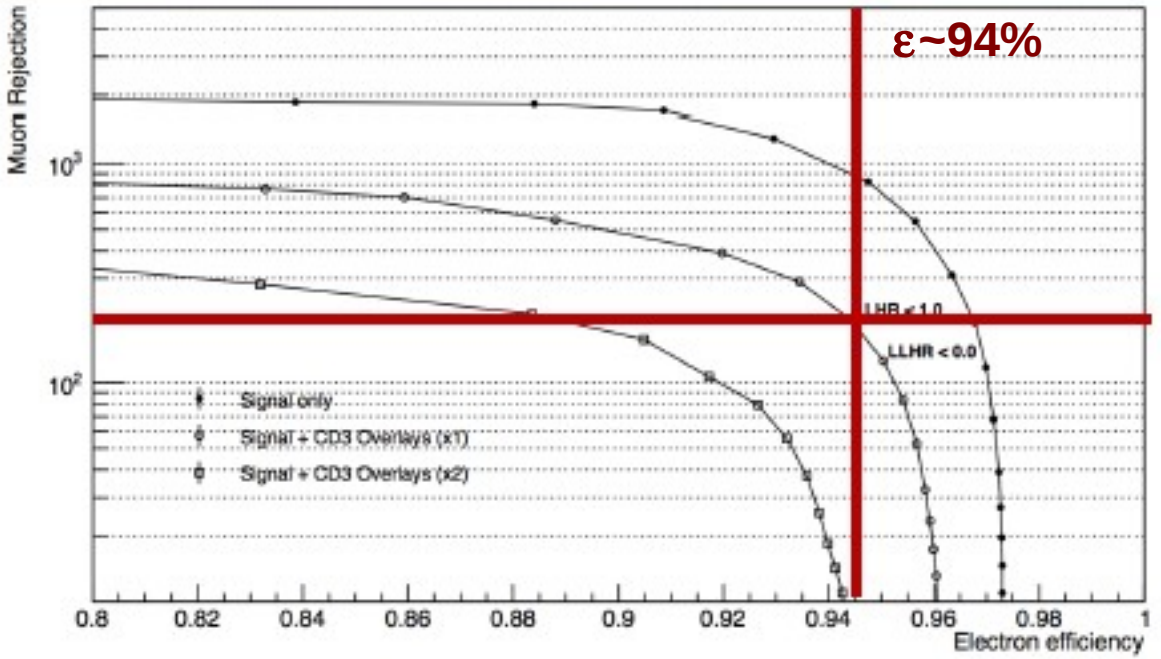
Expected performances from simulation: PID

Tracker-ECAL Time of Flight



Energy-momentum matching

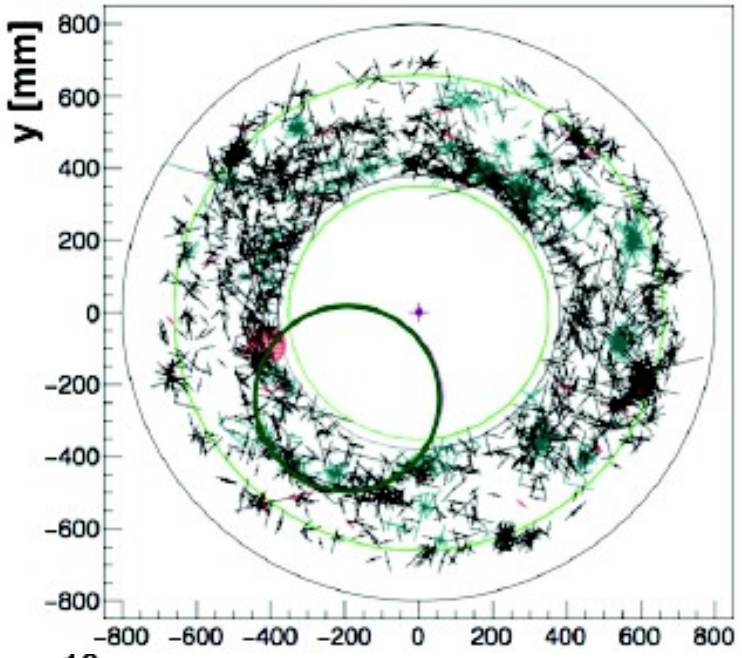




Rejection factor 200

Expected performances from simulation: tracker seeds

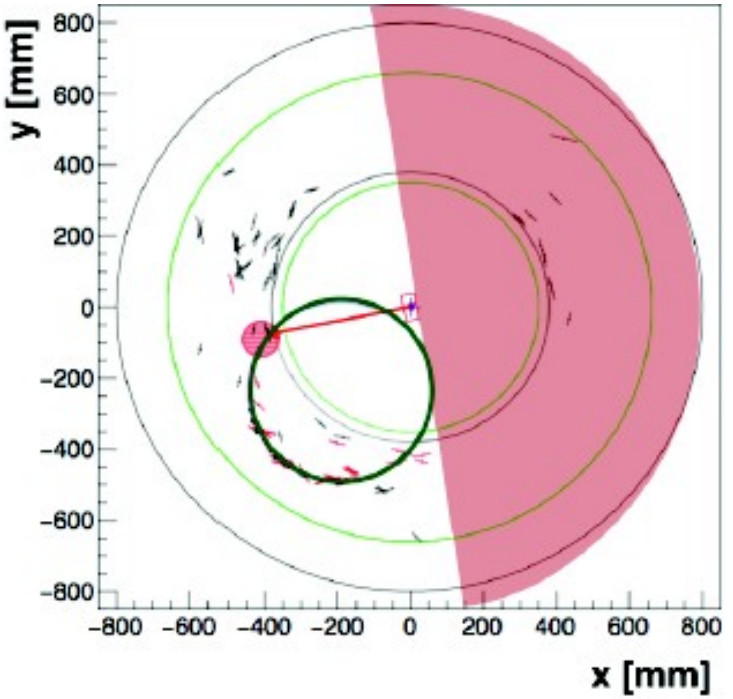
1.7 μs event (no hit selection)

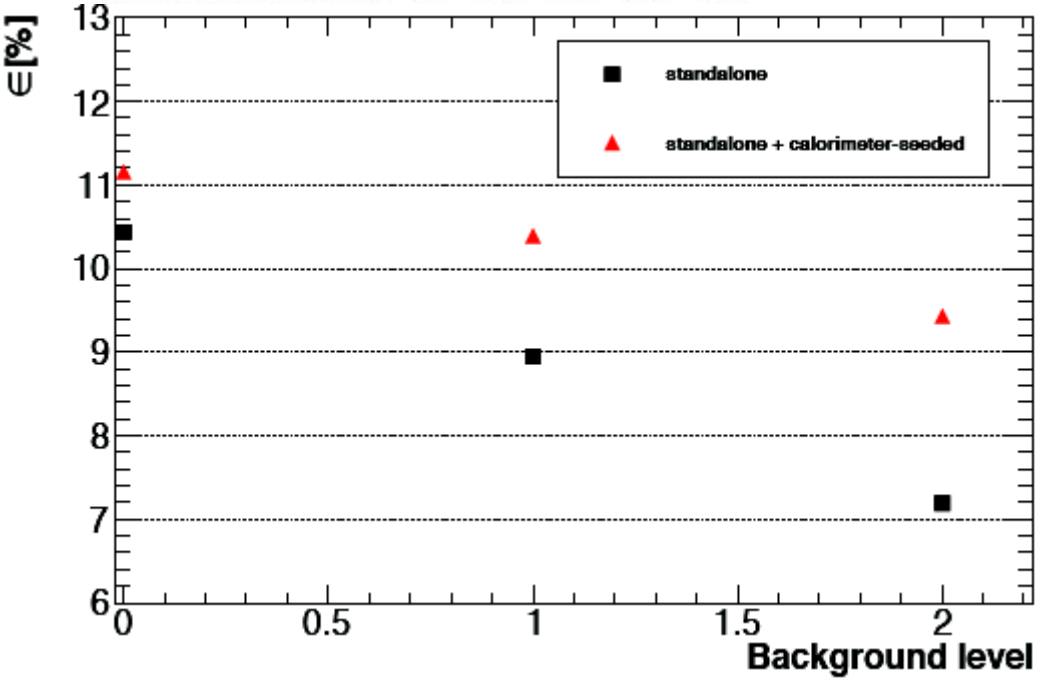


Select tracker hits matching time and position of ECAL cluster

→

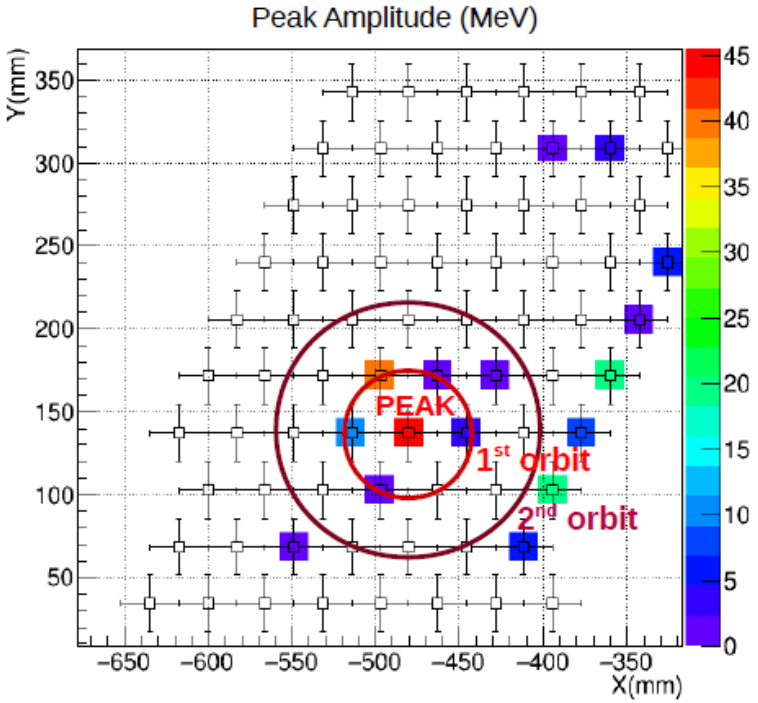
1.7 μs event (hit selection)





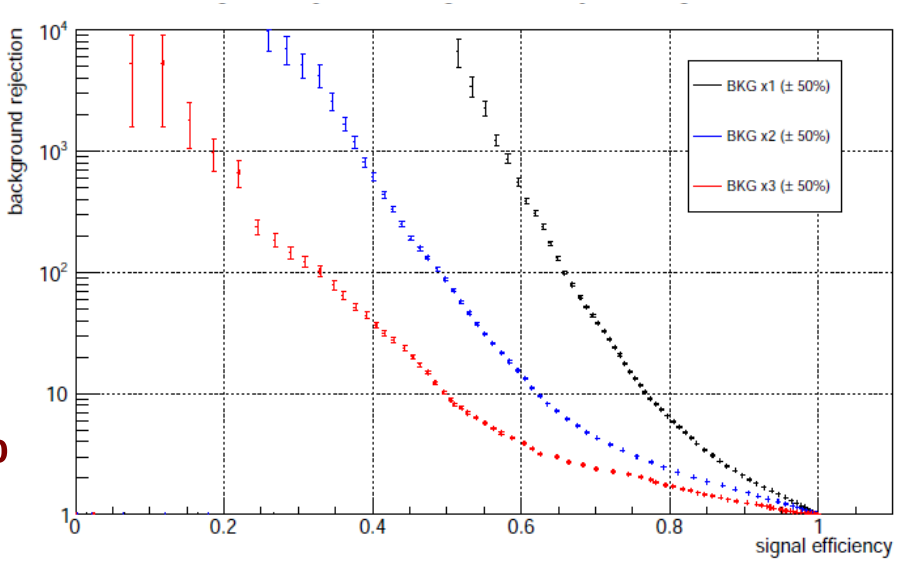
CE reconstruction efficiency improves and is more stable against background level

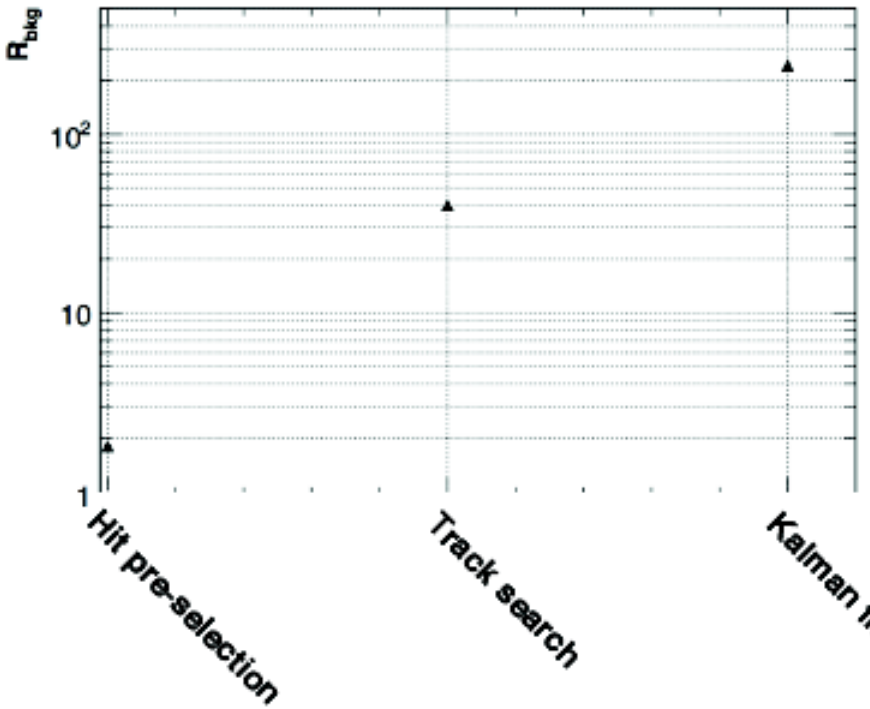
Expected performances from simulation: trigger



Stand-alone
Uses:
peak, time, position, surrounding crystals

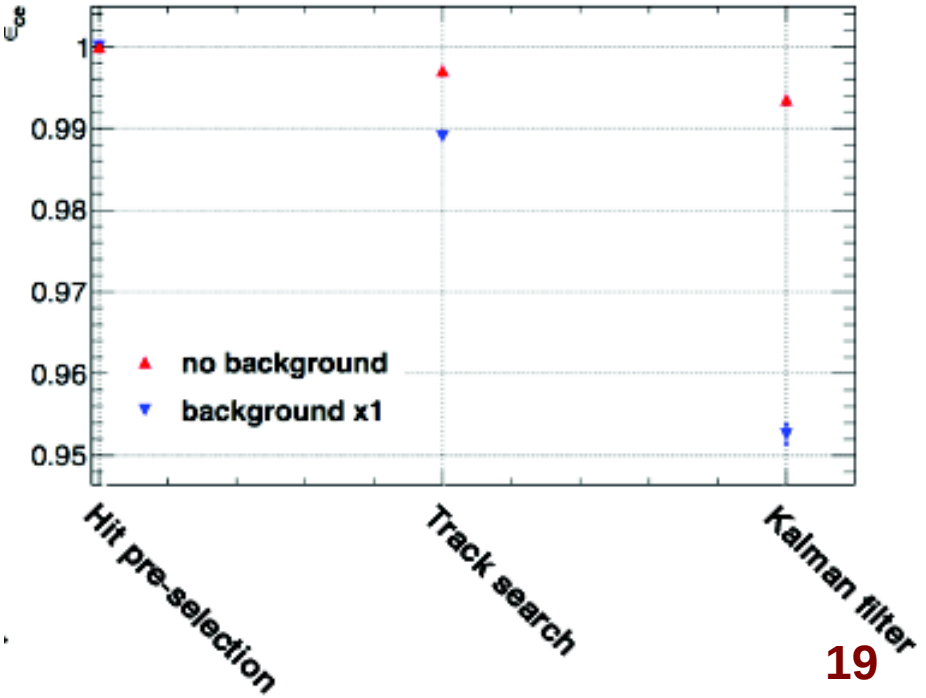
Efficiency 60%
Rejection 400



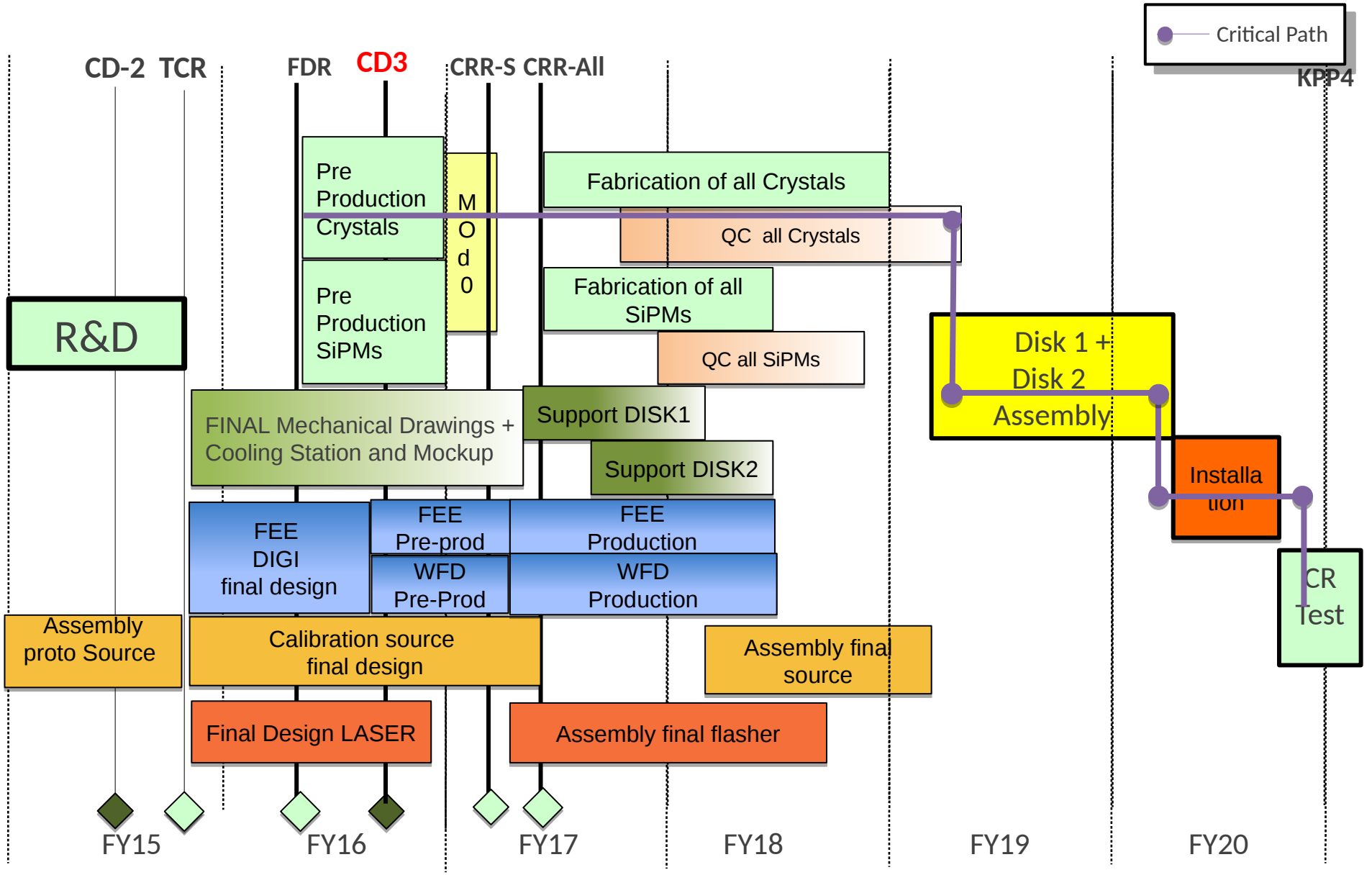


Combined
Uses tracks with ECAL seeds

Eff. 95%
Rej. 200



Calorimeter schedule



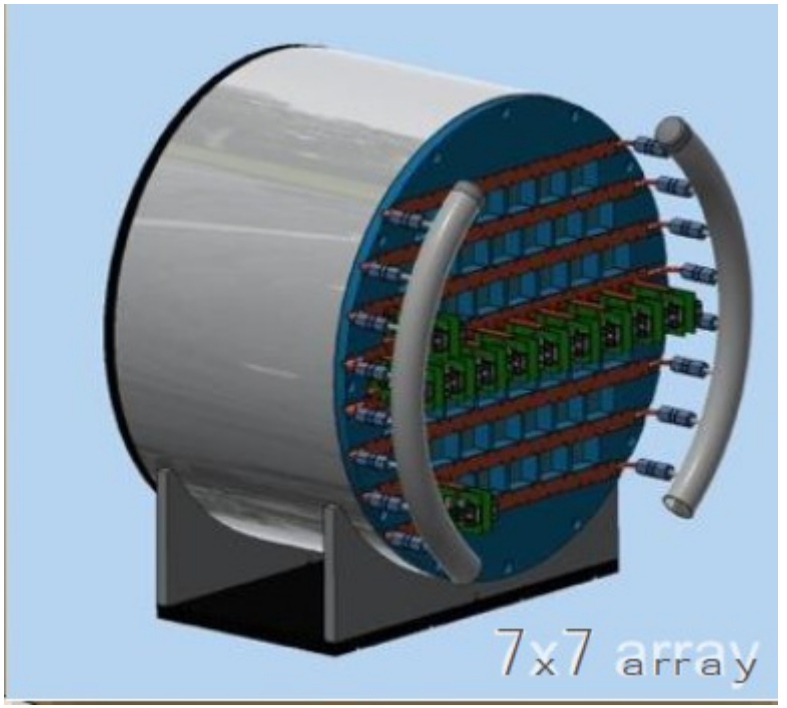
Summary and Outlook

- Mu2e calorimeter is a key component of the Mu2e experiment that will improve by a factor 10^4 the existing limit on charged lepton flavor violating conversion of muons to electrons in the atomic field

- Simulation supported by quality tests and test beam results confirms that the proposed ECAL design is able to operate in the Mu2e harsh environment performing muon identification, track seeding and trigger at the desired level

- Pre-production of crystals and photosensors has started and mass tests will be performed in the next months

- A small scale prototype with ~50 crystals will be tested with an electron beam at BTF in Frascati (Rome) at the end of 2016



Backup

Calorimeter cooling