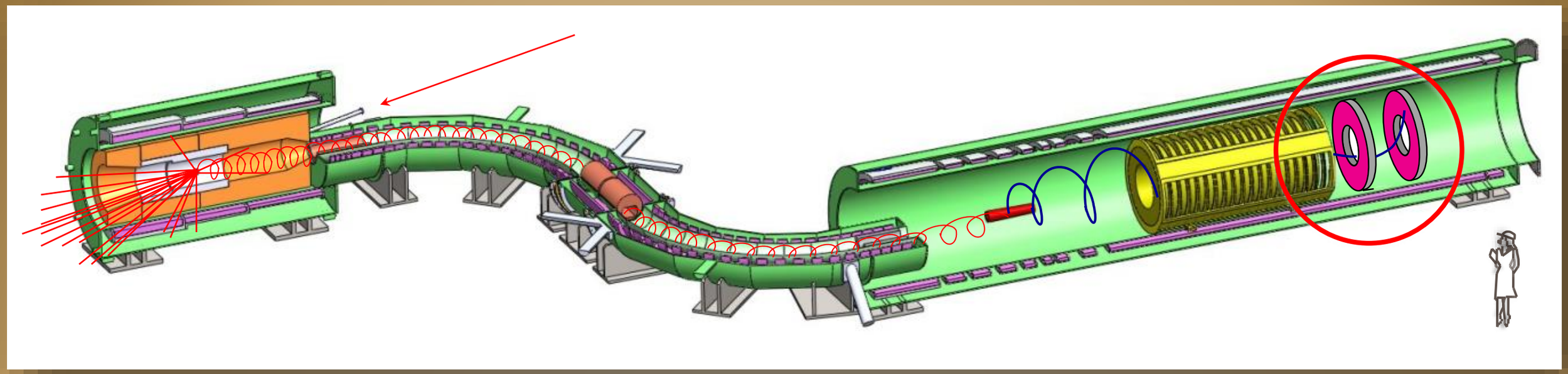


The Mu2e Calorimeter

Design, status and test results

David Hitlin On behalf of the Mu2e Collaboration[1]

Caltech

ICHEP

August 4, 2016

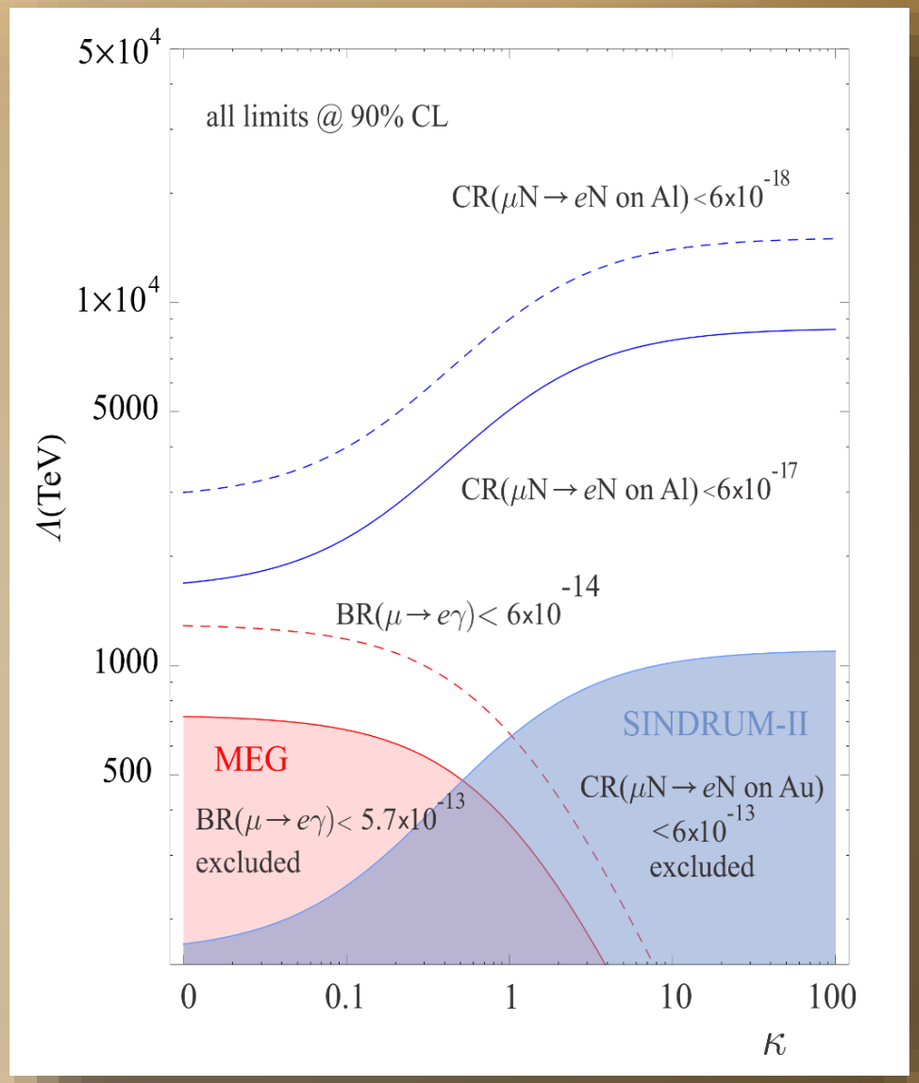
[1] The full Mu2e Collaboration is listed at http://mu2e.fnal.gov/collaboration.shtml.)

Mu2e is a search for $\mu \rightarrow e$ conversion on Al

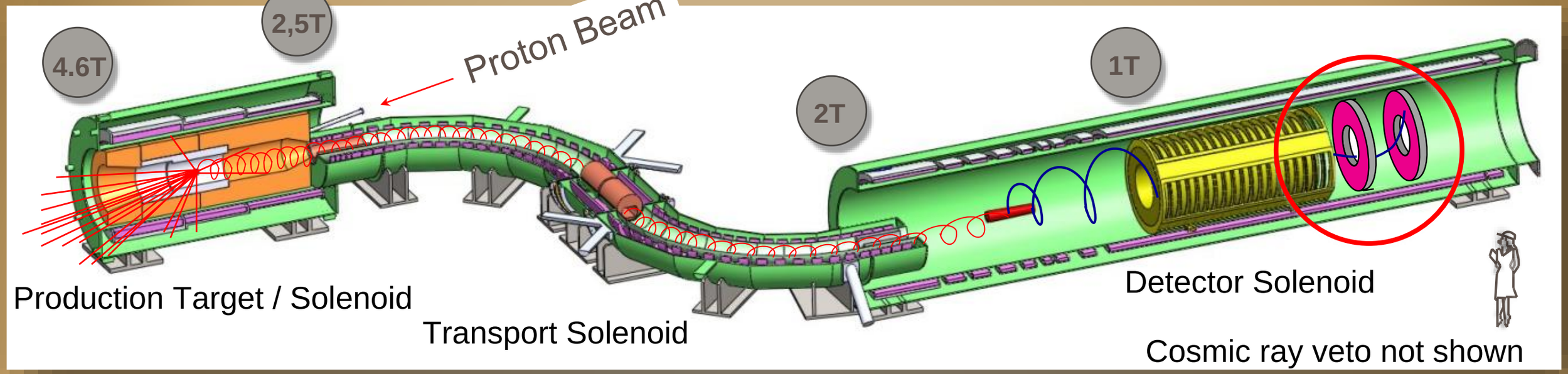
- Mu2e will provide the most sensitive search for charged lepton flavor violation
  - Sensitivity improvement of four orders of magnitude
- The conversion signal is an electron with a momentum corresponding to

  $$m_\mu - E_{\text{binding}} - E_{\text{recoil}} \ (104.97 \text{ MeV}/c)$$

  - The electron momentum is measured by a low mass straw tube tracker in a solenoidal magnetic field
  - The calorimeter provides confirmation (require E/p =1) (at lower precision) and several other crucial functions:
    - Shower cluster-based seeding of the track-finding algorithm imporves efficiency
    - Online software trigger capability
  - The calorimeter is also crucial for background rejection:
    - μ decay in orbit (DIO)
    - Radiative capture (RPC): $\pi^- N \rightarrow \gamma N'$, $\gamma \rightarrow e^+e^-$ and $\pi^- N \rightarrow e^+e^- N'$
    - Pions produced by slow antiprotons in the target
    - π/μ decay in flight
    - Electrons in the beam
    - Cosmic rays



The Mu2e experiment

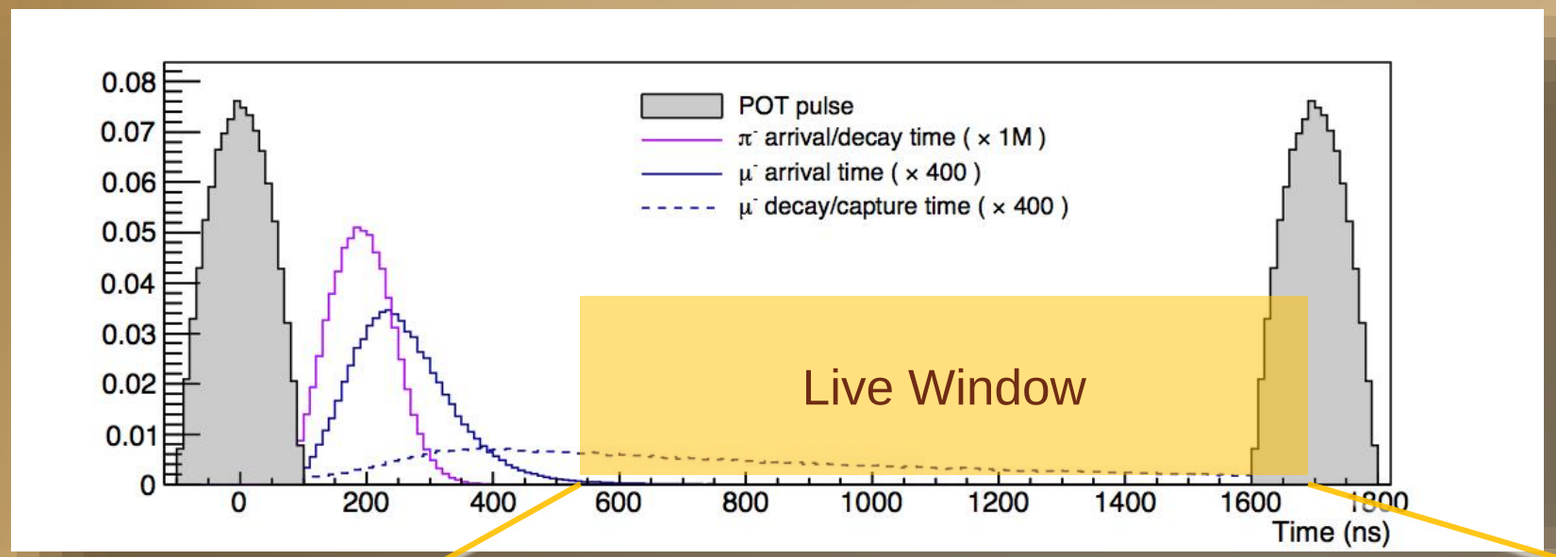


The sensitivity goal demands a total of ~ 6×10^{17} stopped muons in a 3 year run of ~ 6×10^{7} sec
This requires a muon stopping rate of 10^{10}/sec, placing demands on the detector technologies

Resulting calorimeter requirements:

- Energy resolution $\sigma_E/E \sim \mathcal{O}(5\%)$ at 105 MeV
- Time resolution $\sigma(t) < 500$ ps
- Position resolution < 1 cm
- Adequate rate capability
- Operate in 1T magnetic field in a 10^{-4} Torr vacuum
- Reliability through redundant photosensors and DAQ
- Survive in the neutron (10^{12} n/cm^2) and gamma (100 krad) radiation environment of Mu2e (includes a safety factor of 3)
- Provide close to full acceptance for conversion electron at 105 MeV

A microbunch event

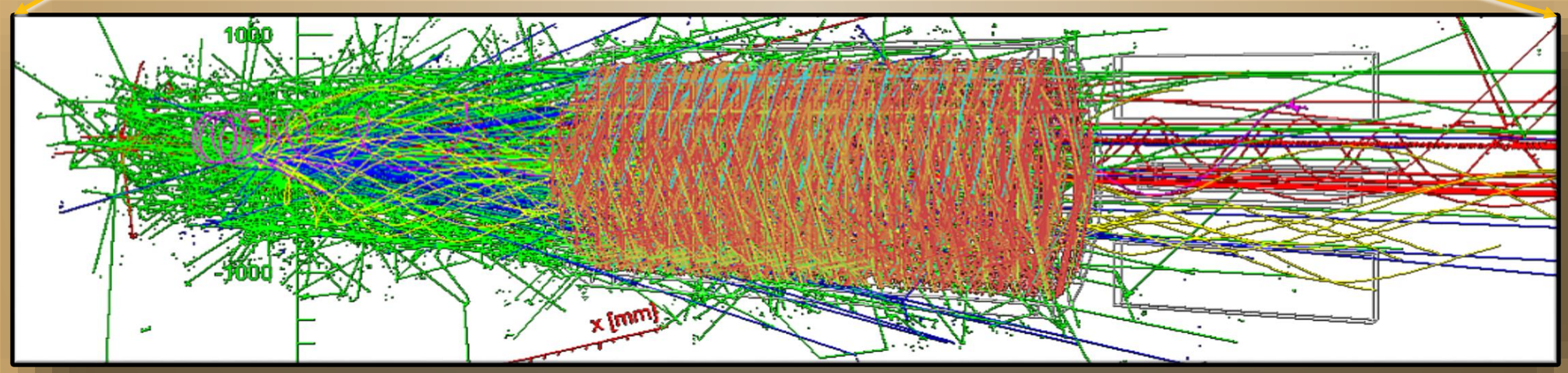


Use of pulsed proton beam and a delayed live gate allows suppression of prompt backgrounds by many orders of magnitude

Proton pulses must be narrow

Out-of-time protons must be suppressed by $\mathcal{O}(10^{10})$

Stopping Target ↔ *Straw Tracker* ↔ *Crystal Calorimeter*

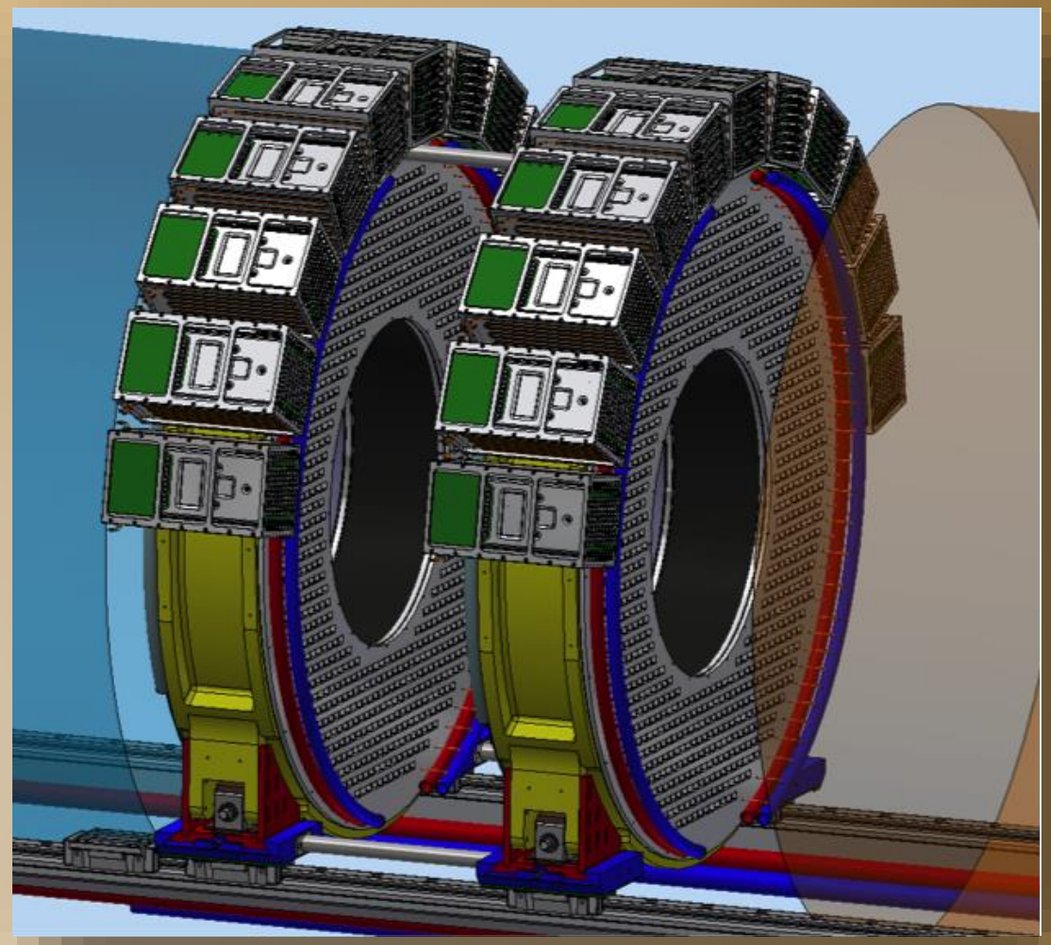


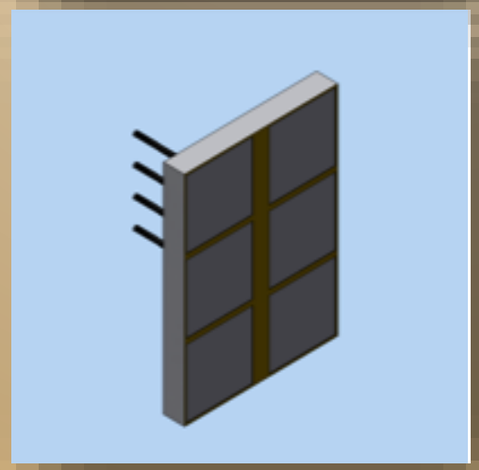
- Simulations encompass a full ~1μs, including all the background overlays from the beam flash, μ capture products, neutrons, *etc*. and properly account for contributions from previous bunches.

Calorimeter design

- The central hole region in the tracker and calorimeter allows us to be largely insensitive to DIO and beam flash backgrounds
- The calorimeter consists of two identical annuli, spaced apart by 700 mm (½ λ of the helical trajectory of the conversion electron)
- r_{inner} = 374 mm
  r_{outer} = 660 mm
  depth = 10 X_0 (200 mm)
- Each annulus contains 674 square CsI crystals with dimensions 34x34x200 mm^3
- Each crystal is read out by two large area (14x20 mm^2) six element UV-extended SiPMs

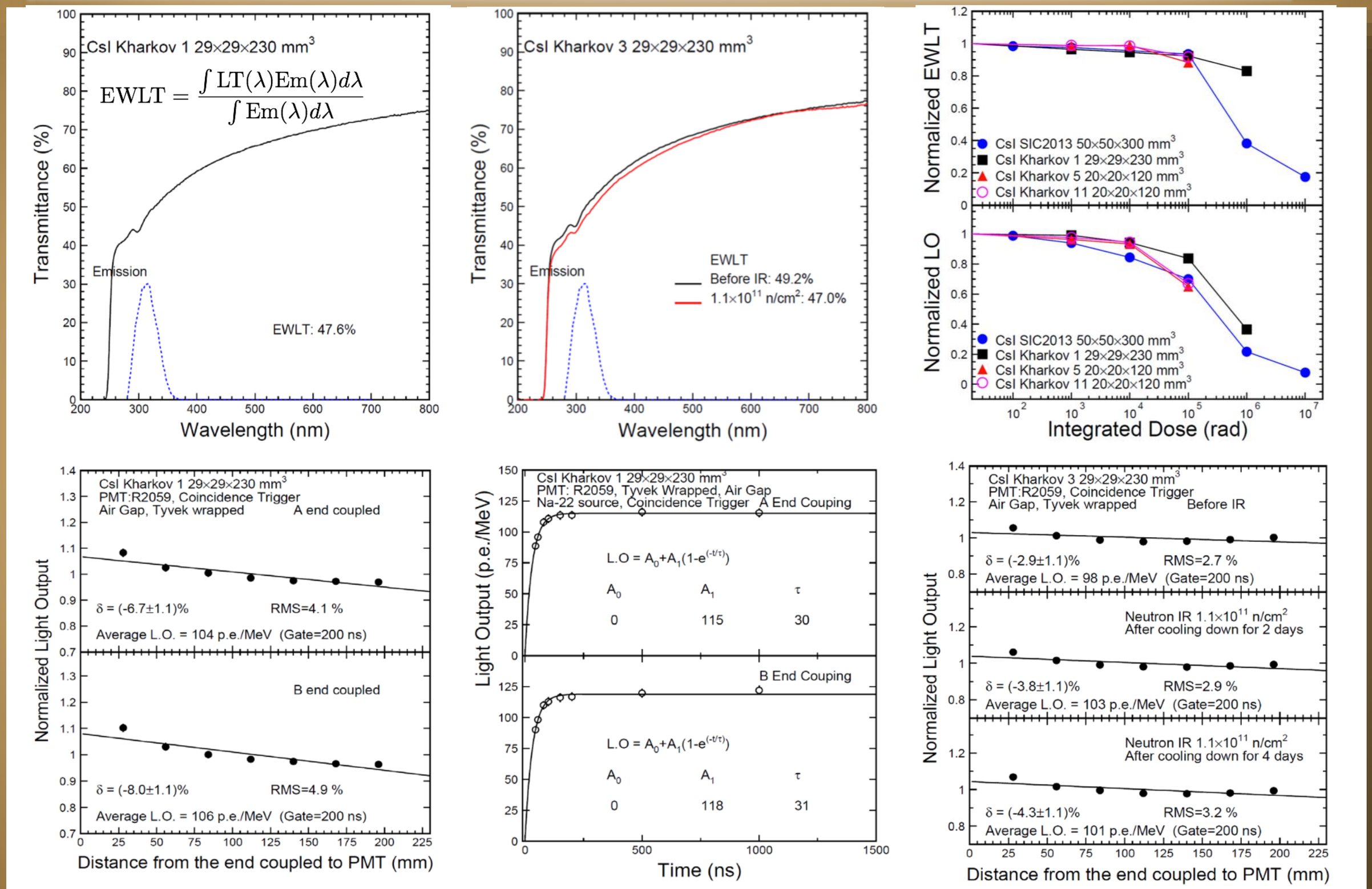
  The analog front end electronics is directly mounted on the SiPM





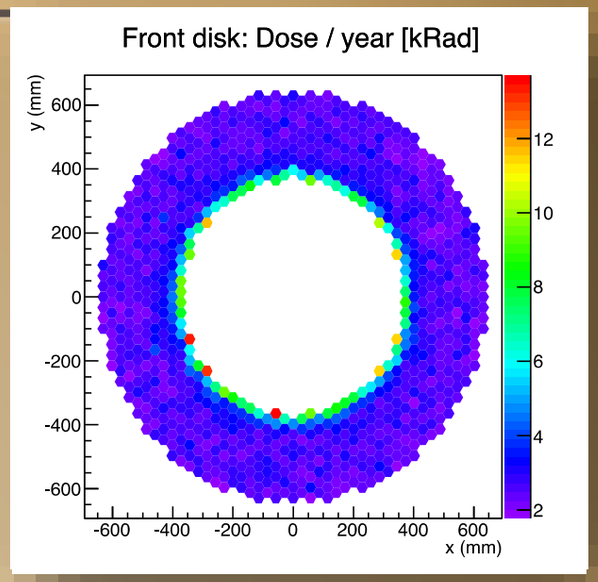
- The digital electronics and voltage regulators are located in electronics crates mounted on the periphery
- Calibration and monitoring are provided by a 6 MeV radioactive source and a laser system

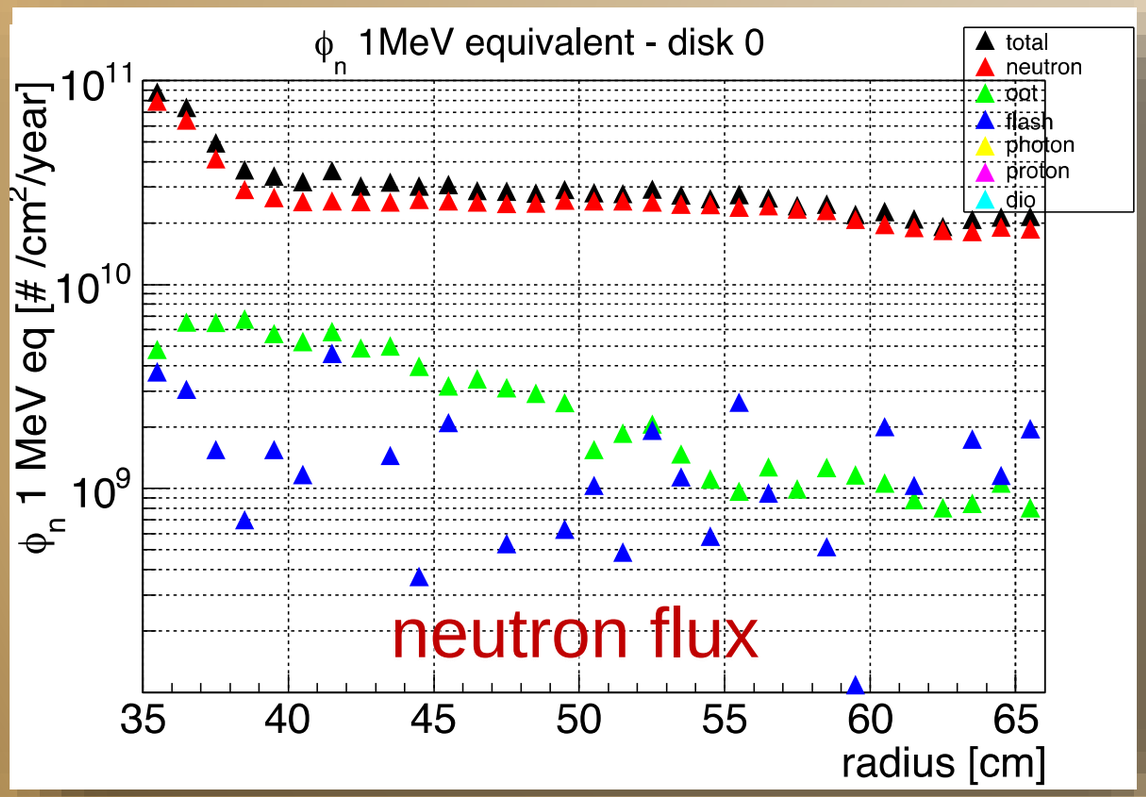
Measured CsI crystal properties

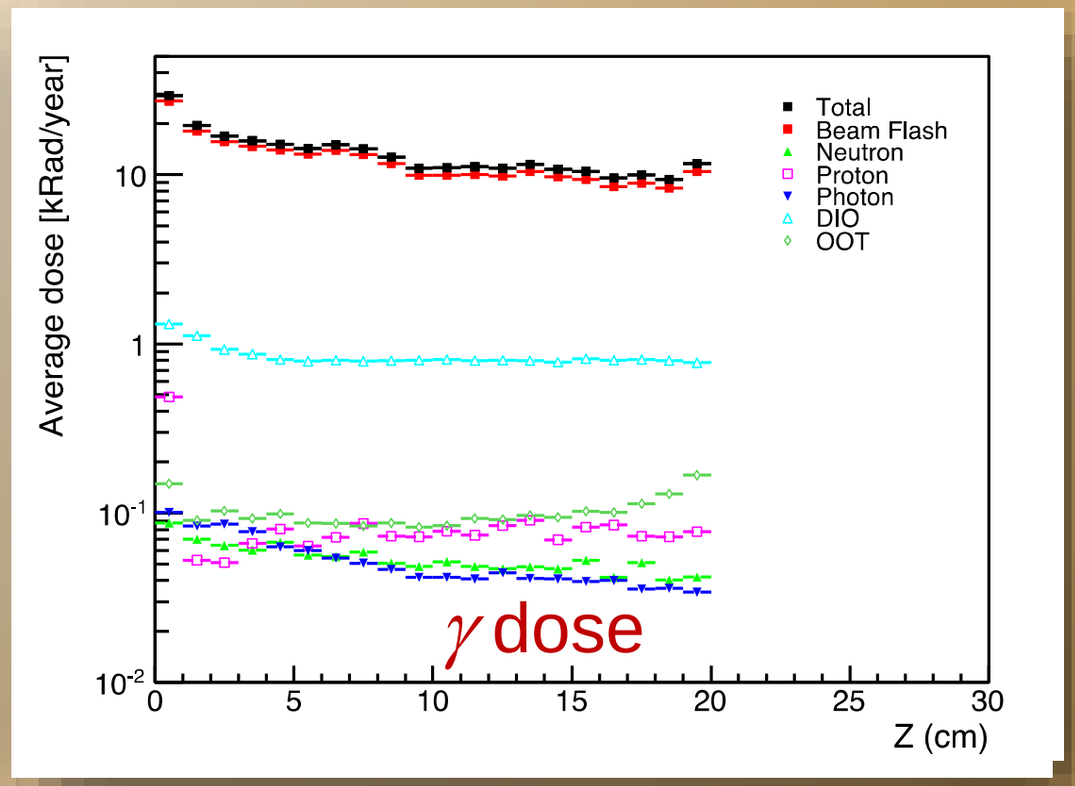


The radiation environment

- The calorimeter radiation dose is driven by the beam flash (the interaction of the proton beam on target).
- The dose from muon capture is 10x smaller
- Dose is mainly to the inner radius (up to 400 mm)
- Highest dose/year ~ 10 krad
- Highest *n* flux/year on crys. ~ 2×10^{11} *n*/cm^2
- Highest dose/year on SIPM ~ 6×10^{10} *n*_1Mev eq/cm^2



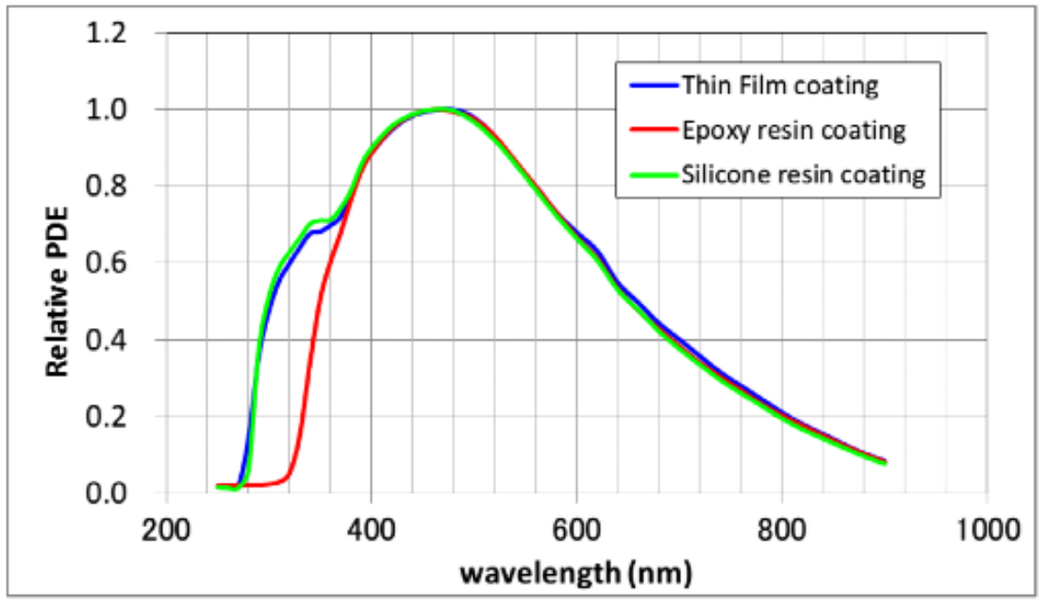


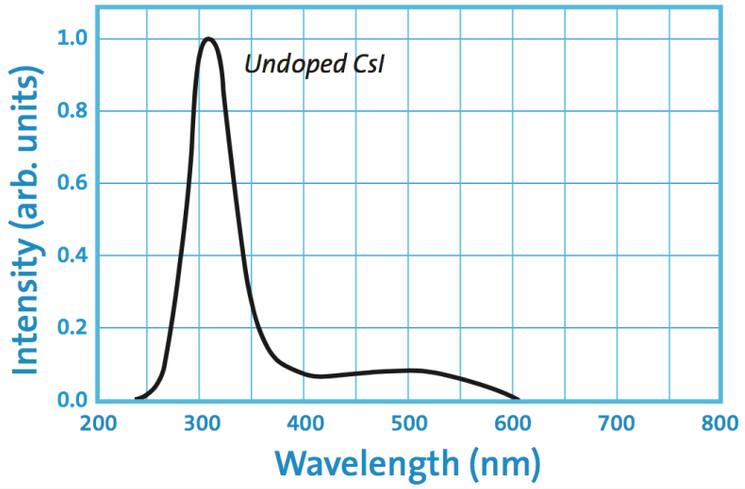


- Qualify crystals up to 100 krad, 10^{12} *n*/cm^2
- Qualify photo-sensors up to 3×10^{11} *n*_1MeV/cm^2

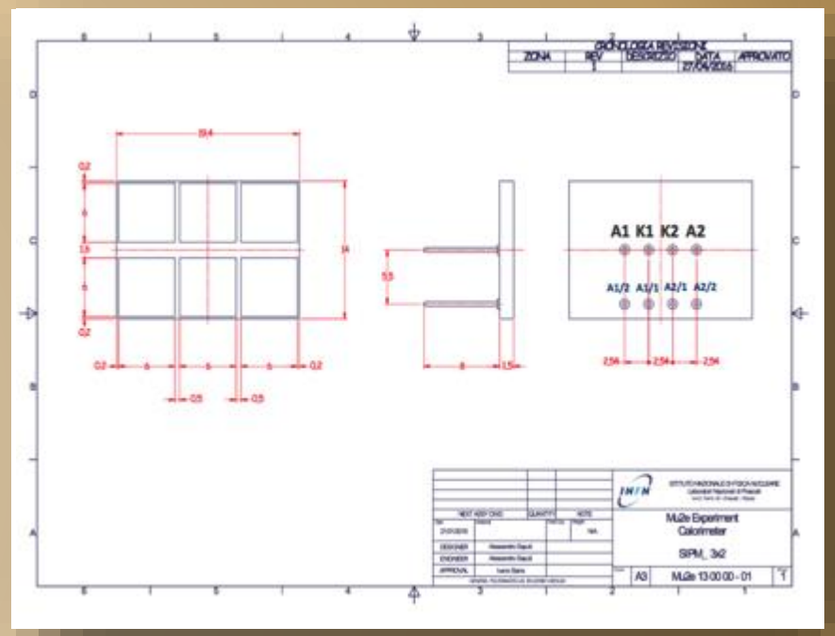
Includes a safety factor of 3 for a 3 year run

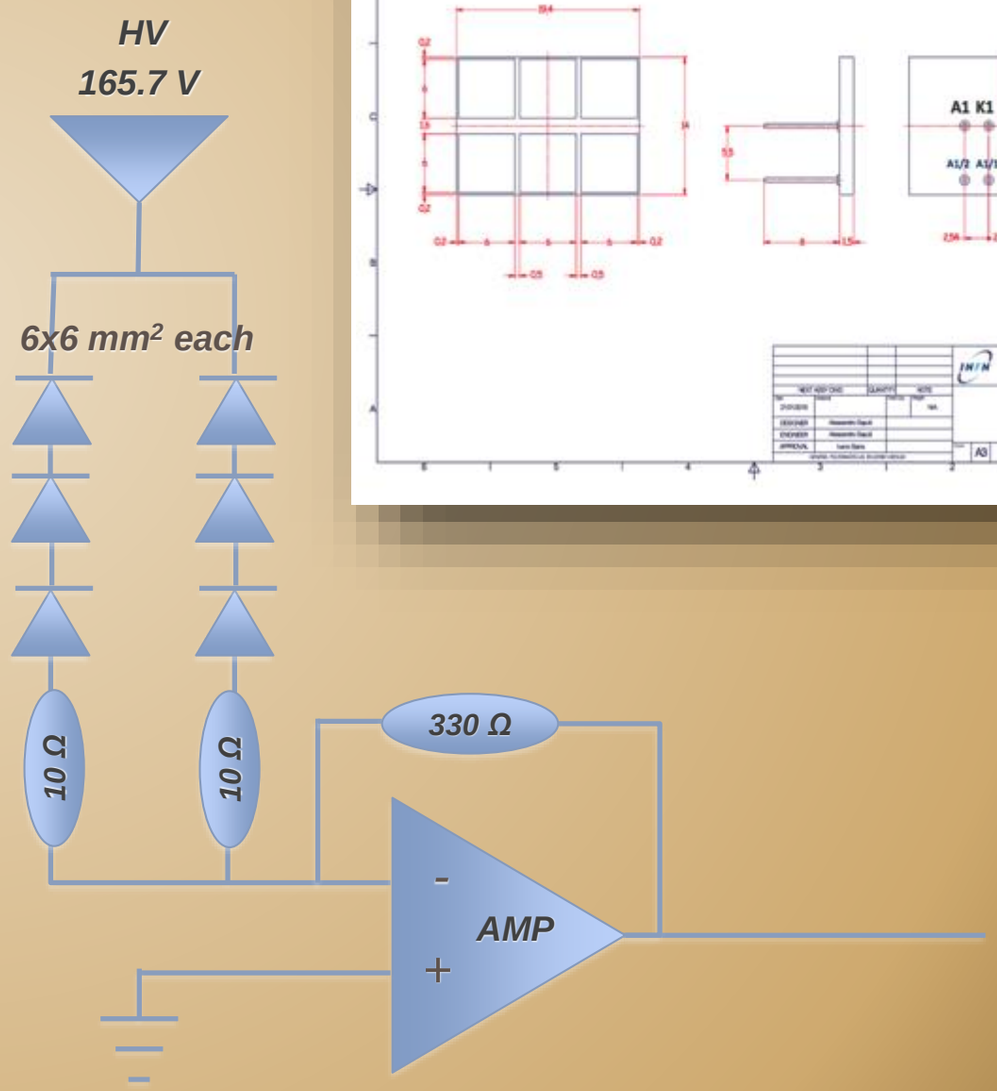
Extended response SiPMs match CsI spectrum





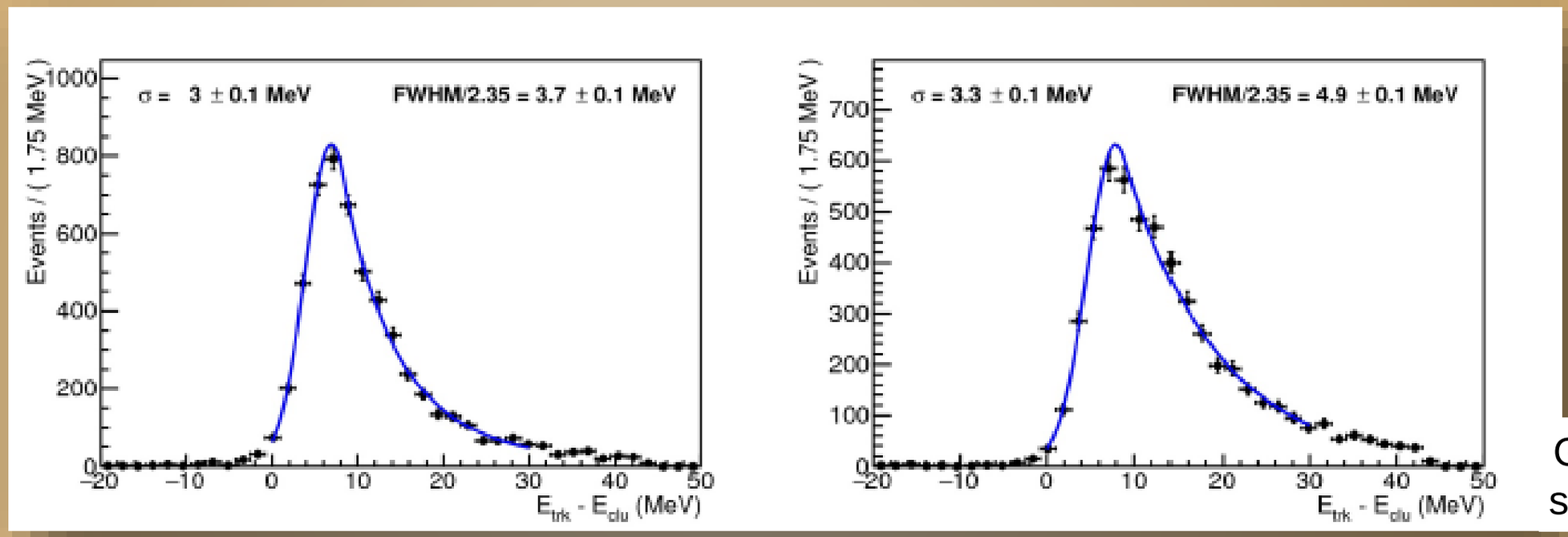
- Six 6x6mm cells in a 2x3 array
  - 50 mm pixels
  - Biased in series/parallel





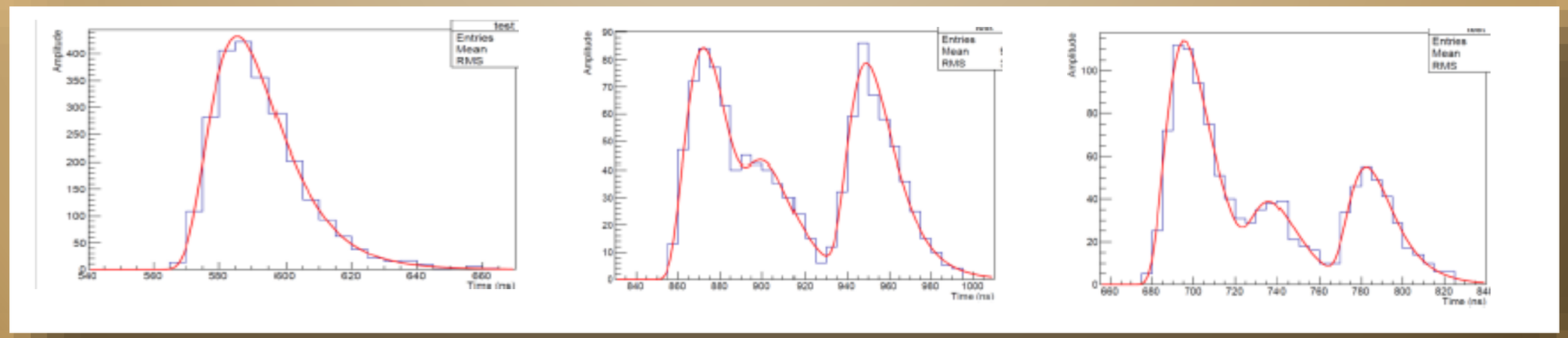
Energy resolution

- Achieving best possible energy resolution requires efficient shower clustering algorithm with detached cluster recovery and pile-up rejection
  - Cluster algorithm with and without detached cluster recovery



GEANT4 simulation

  - Pile-up rejection using waveform digitization



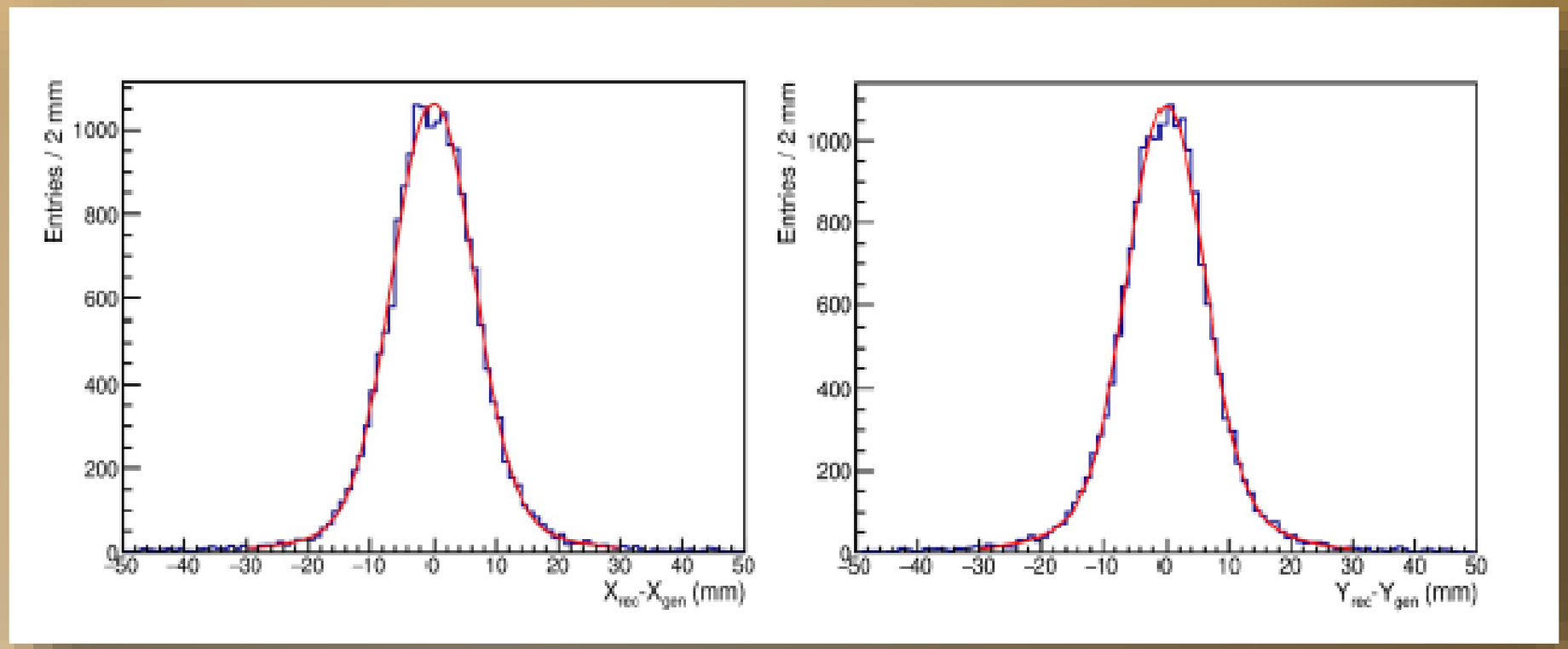
Spatial, time resolution

Spatial resolution

Compare predicted and Monte Carlo positions with signal events

$\sigma_x = 6.3 \pm 0.2$ mm

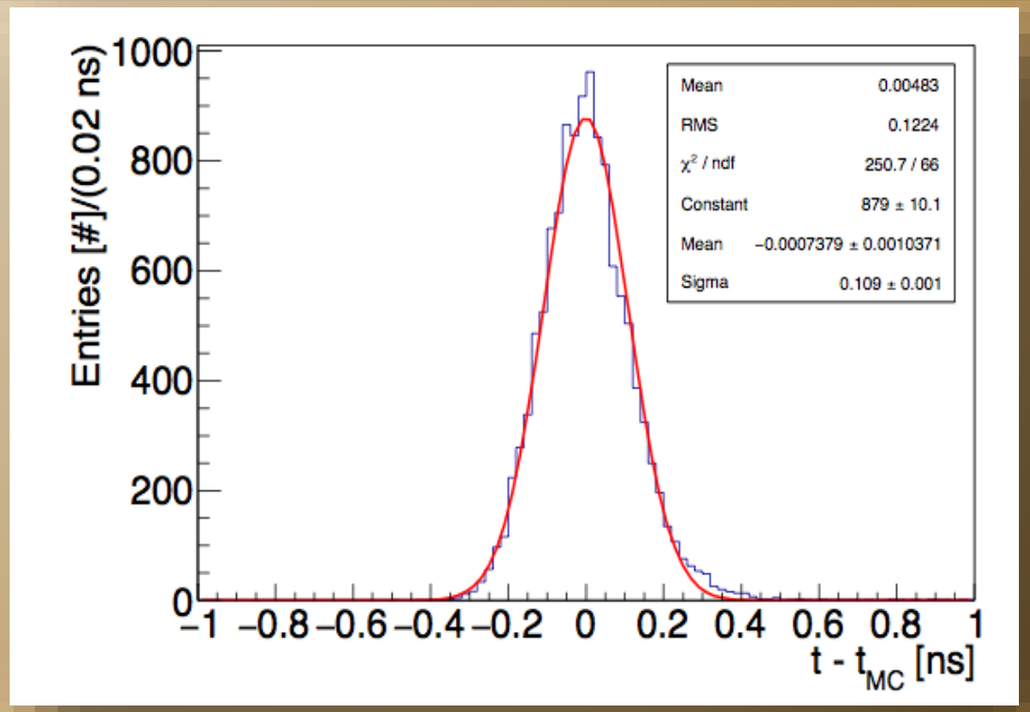
$\sigma_y = 5.8 \pm 0.2$ mm



Time resolution

Cluster time defined using the energy-weighted crystal times

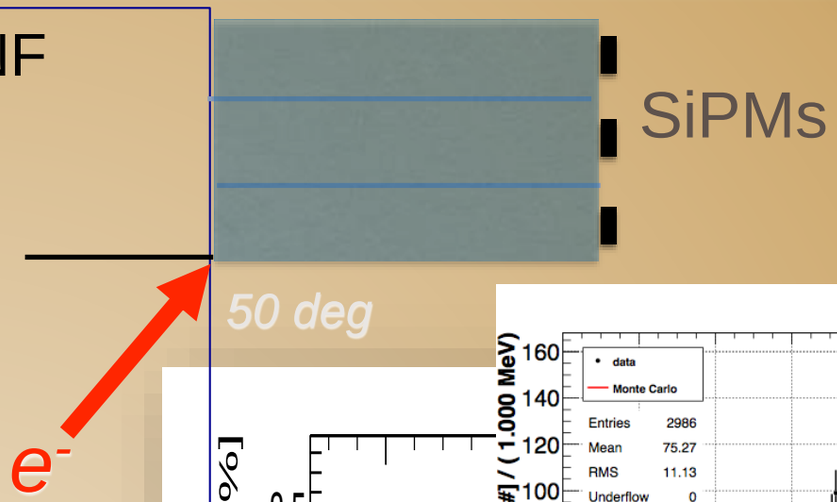
$\sigma_t = 109 \pm 1$ ps

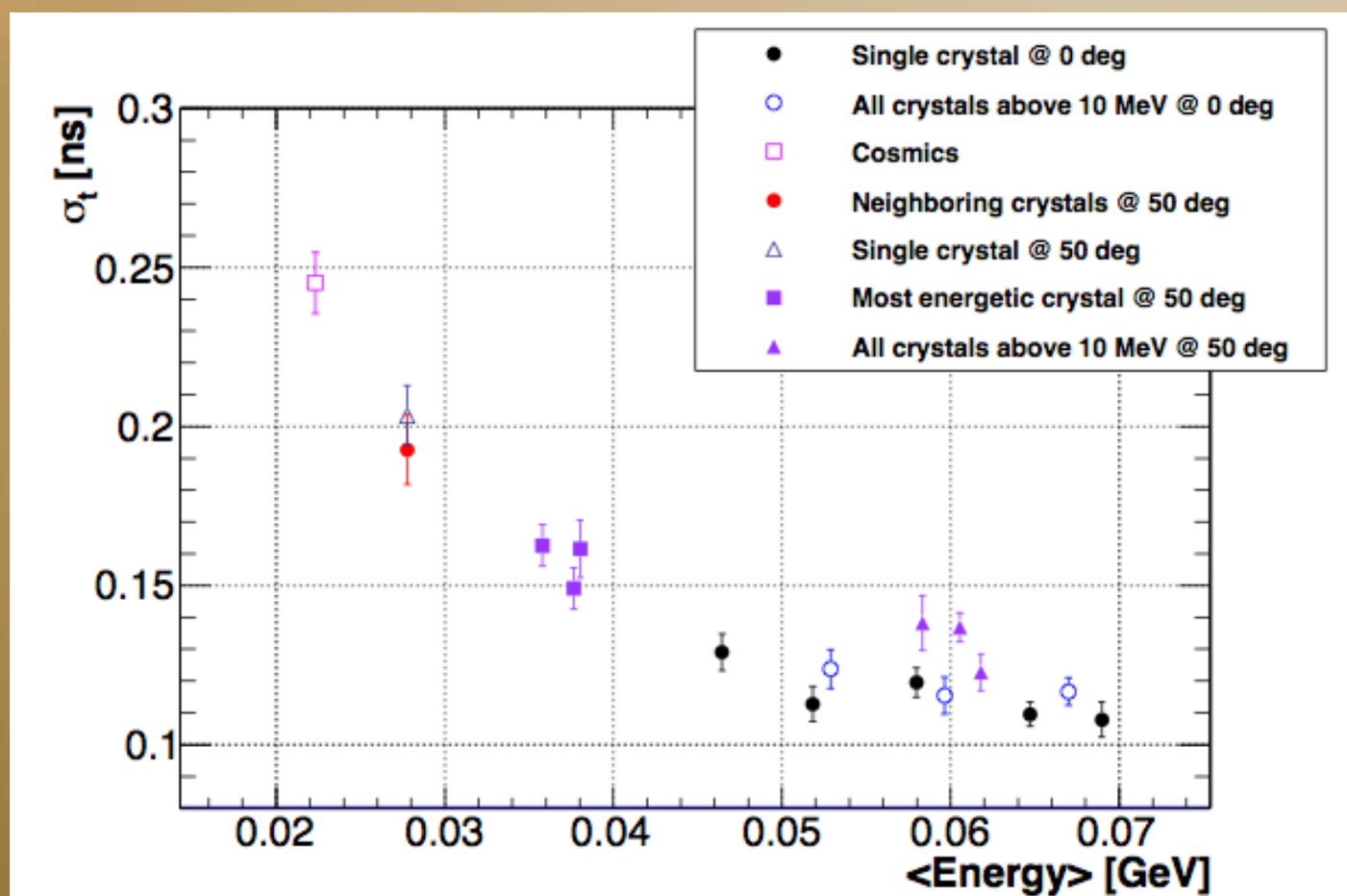


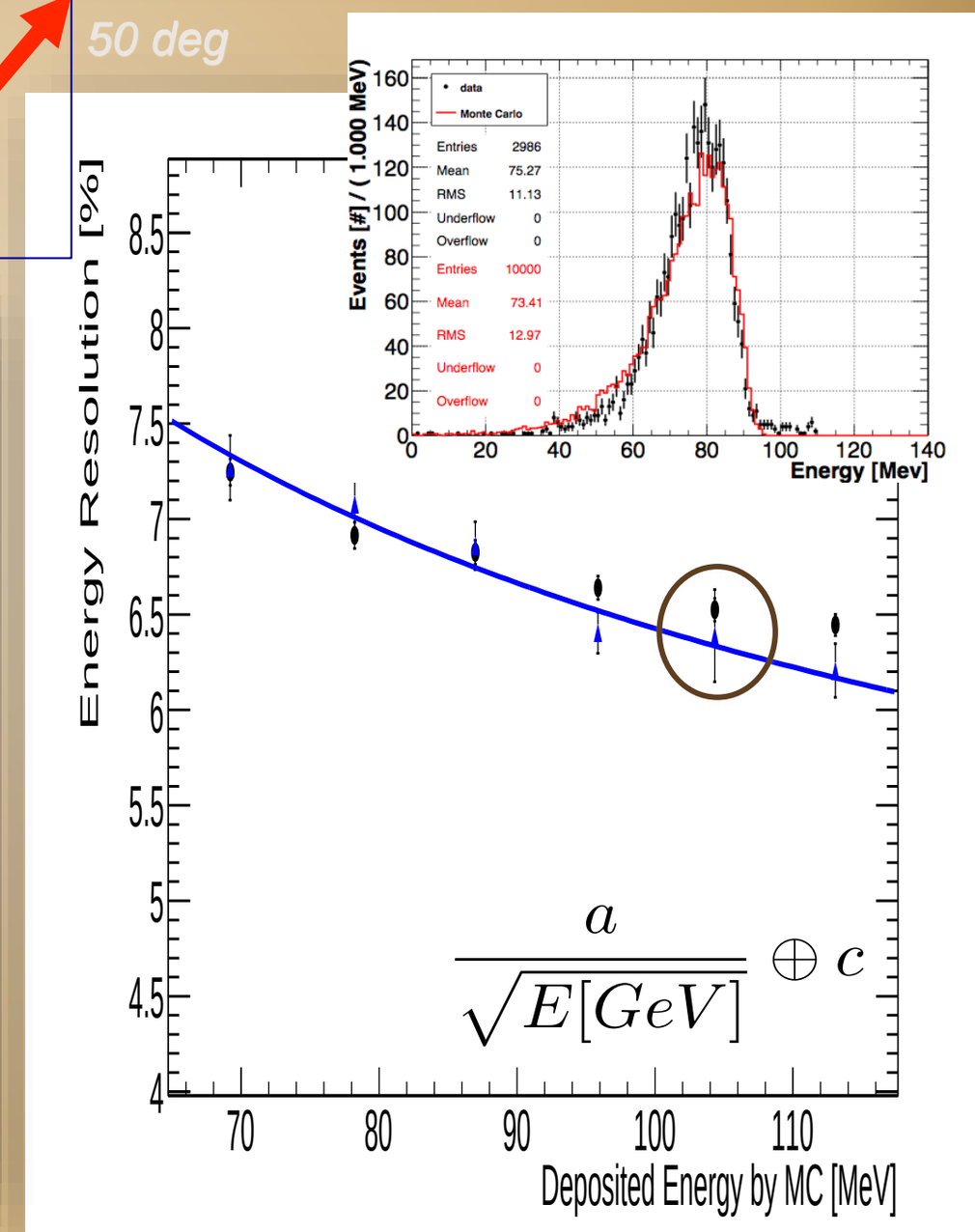
GEANT4 simulation

Test beam results: CsI + SiPM

- Test beam with 70-115 MeV electrons @ LNF
- 3x3 array of 30x30x200 mm³ CsI crystals
- Readout: SPL MPPCs
- Results
- Energy resolution σ_E/E =7% dominated by shower leakage and beam energy spread
- Time resolution $\sigma(t)$=110 ps.

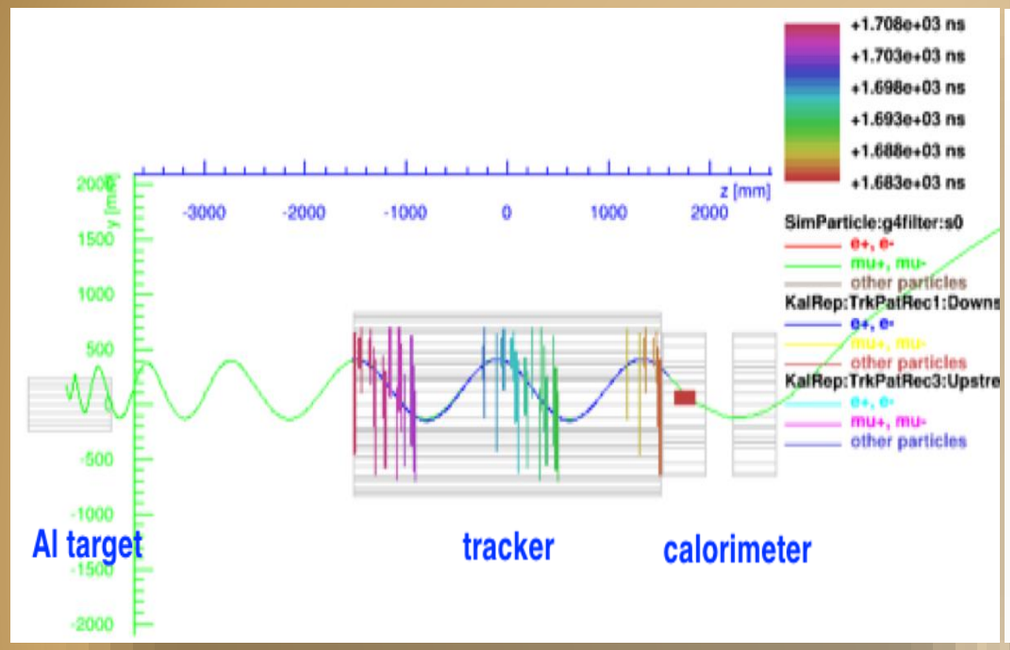


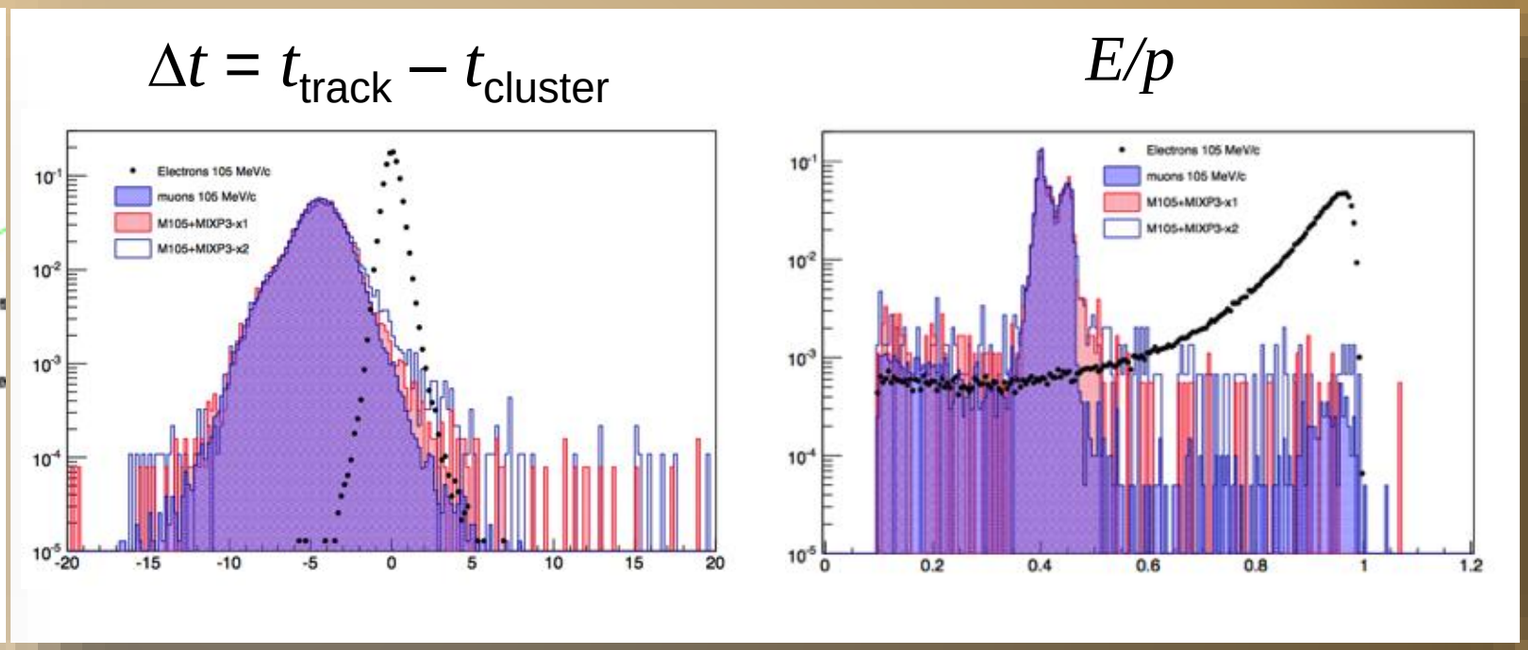




PID: e/μ separation by TOF, E/p

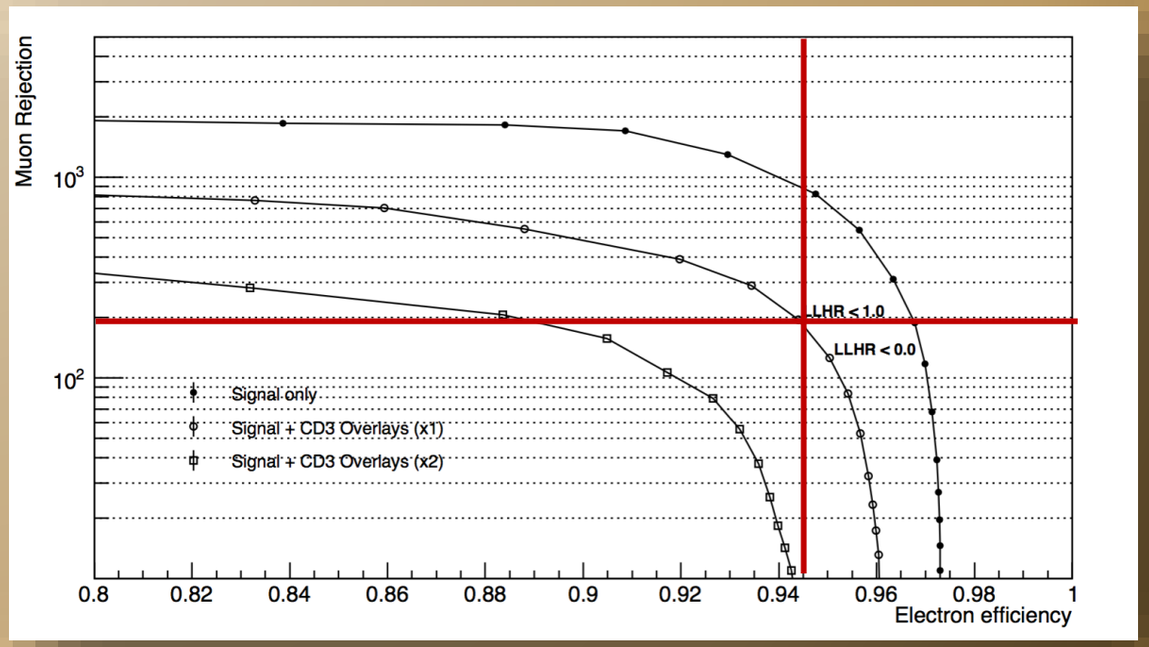
CRV studies show that with a CRV inefficiency of 10^{-4}, an additional rejection factor of ~200 is needed in order to have < 0.1 fake events from cosmics in the signal window





a cosmic ray muon event can mimic a conversion electron signal event

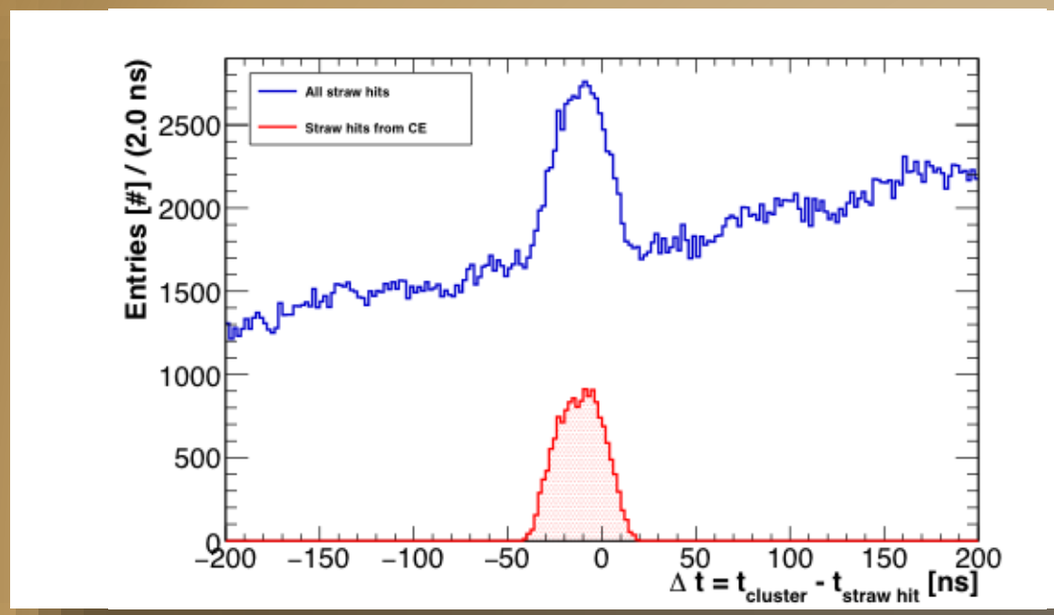
events of this type can be vetoed using the timing information from the calorimeter

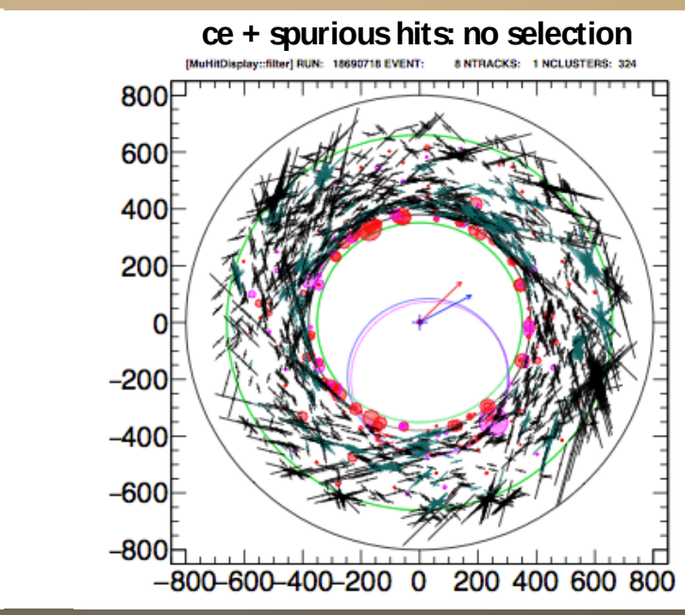


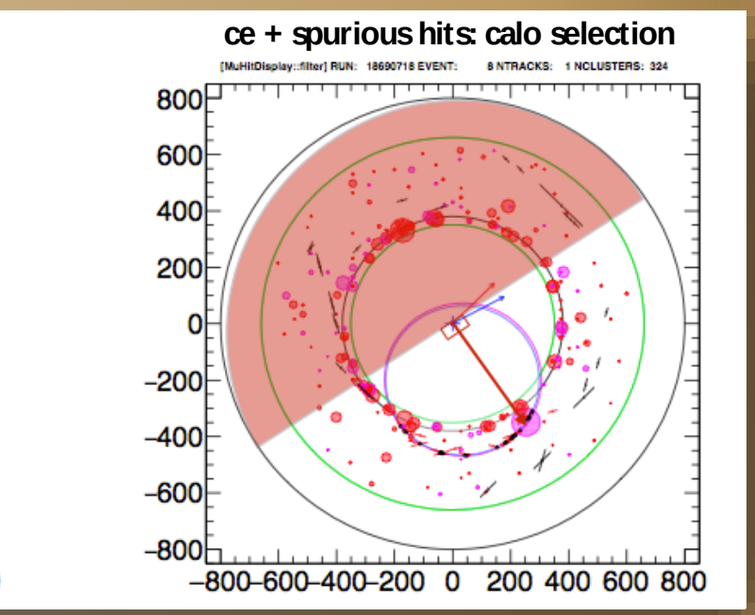
A rejection factor of 200 can be achieved with ~95% conversion electron efficiency

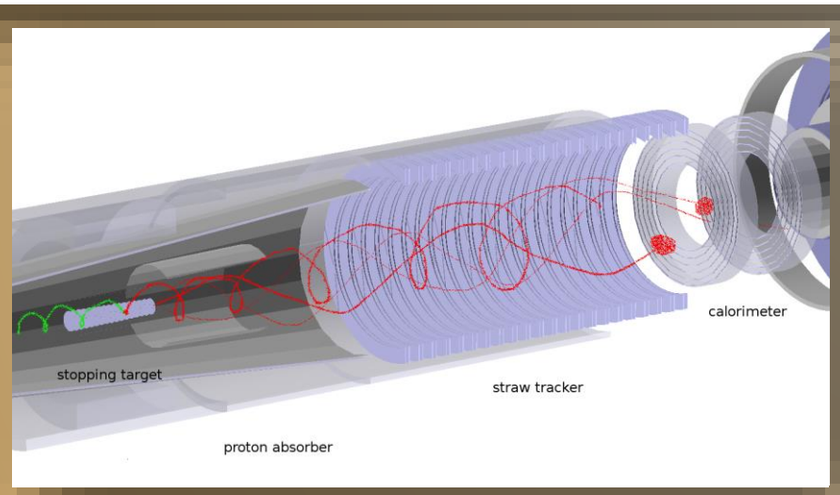
Calorimeter cluster-seeded track finding

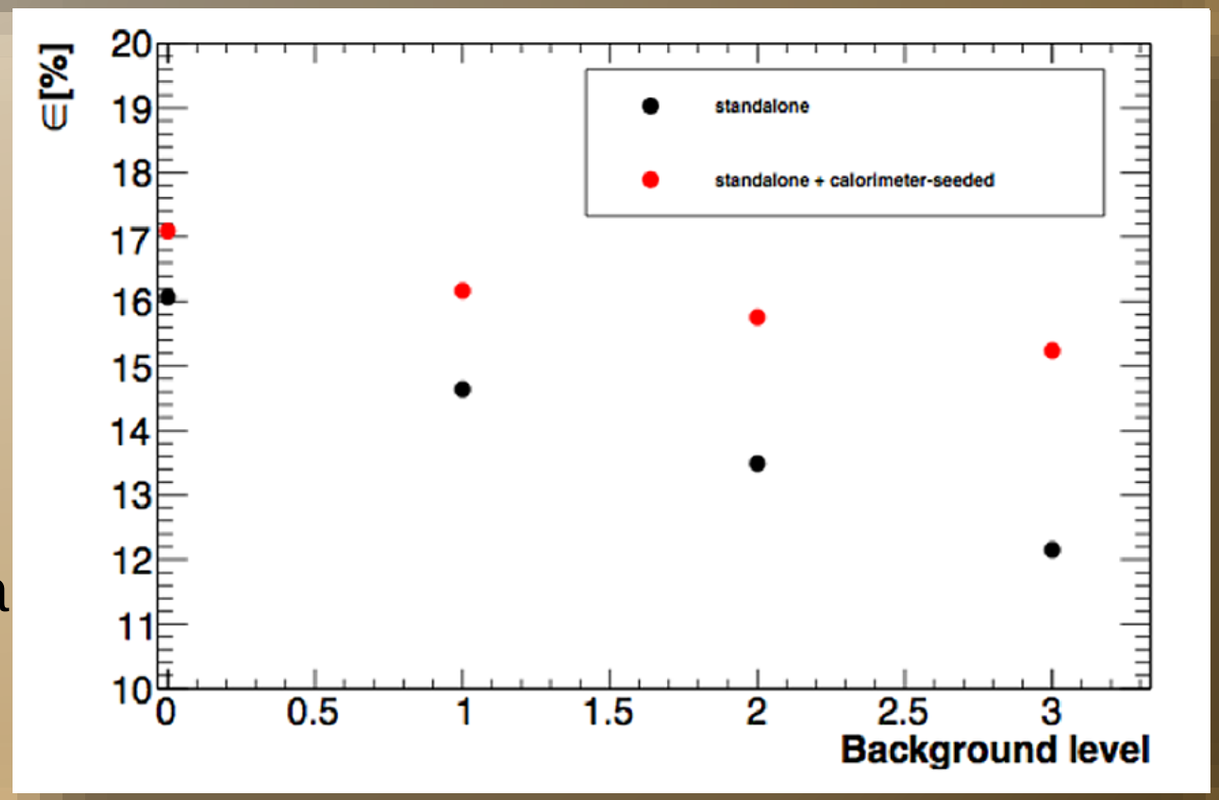
The speed and efficiency of track reconstruction is improved by selecting tracker hits compatible with the time ($|\Delta t| < 50$ ns) and azimuthal angle of calorimeter clusters







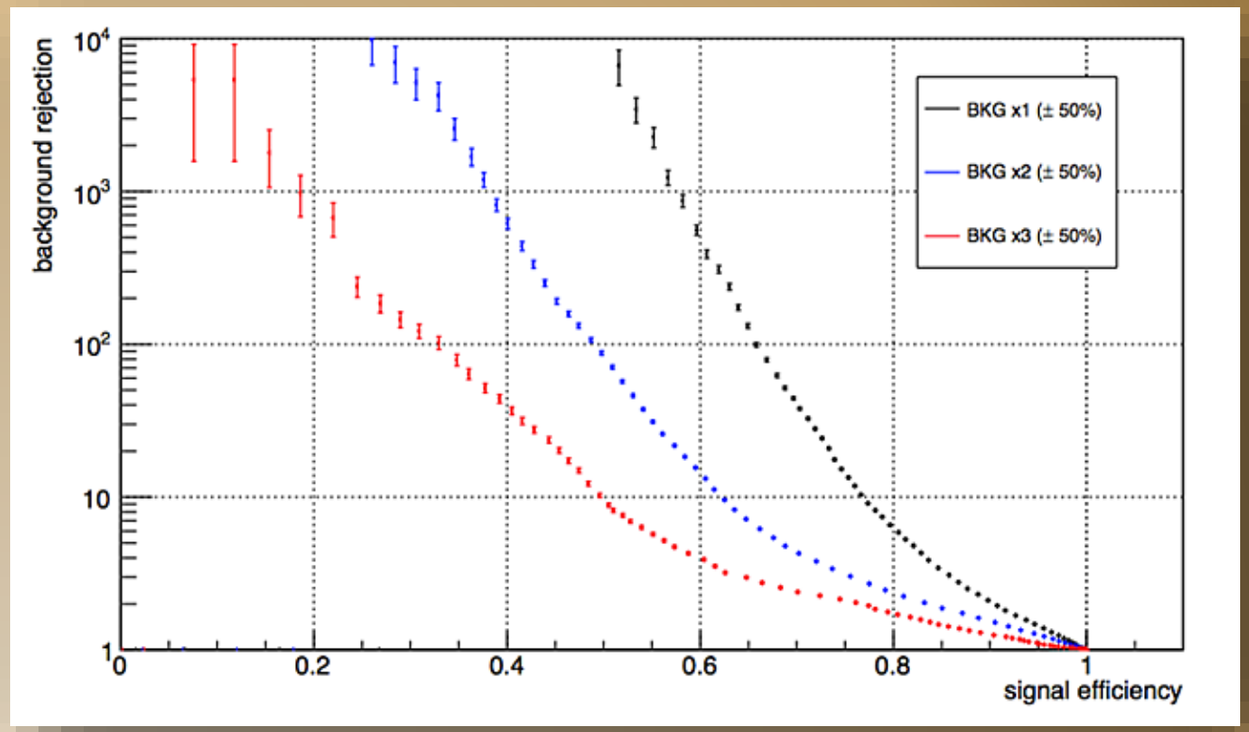




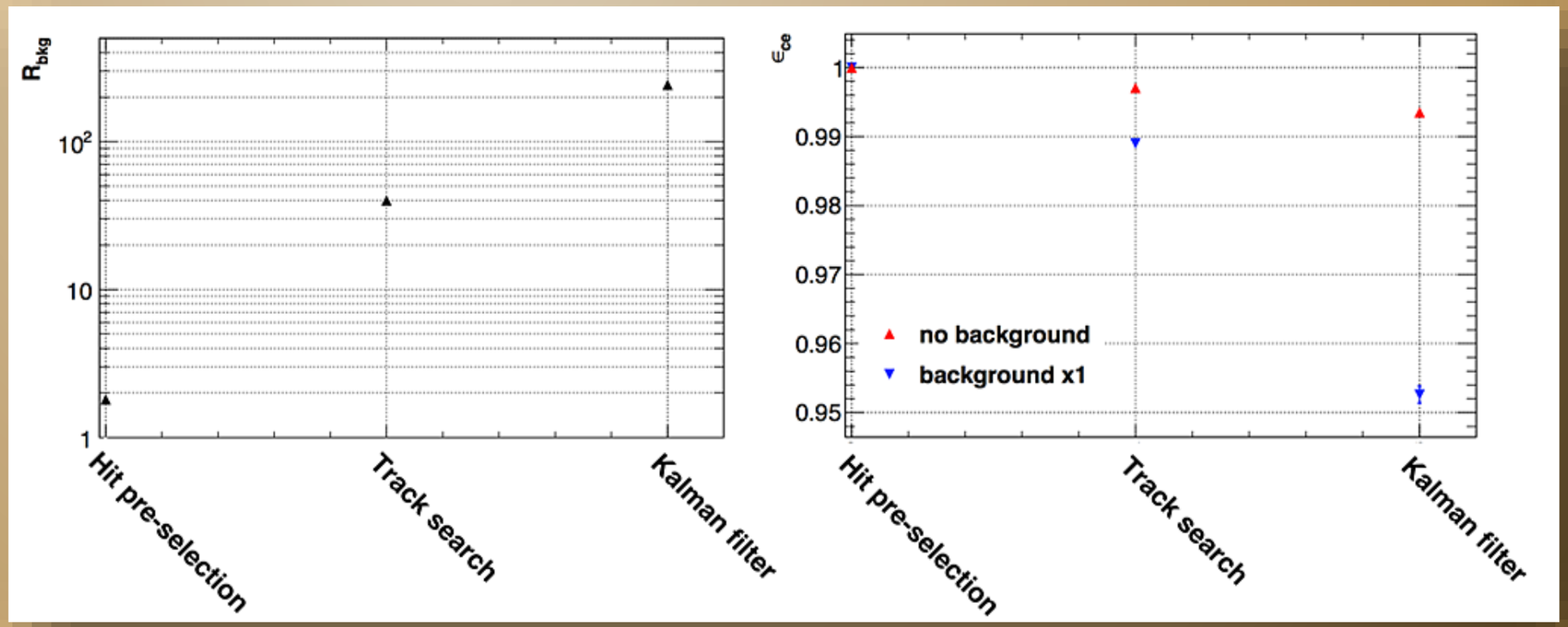
Calorimeter-seeded track finding improves the relative efficiency for tracks in the signa region (103.5 < p <105 MeV/*c*) by ~11% and is more robust against background

Calorimeter trigger options

Standalone trigger:
65% efficiency for
background rejection of 200



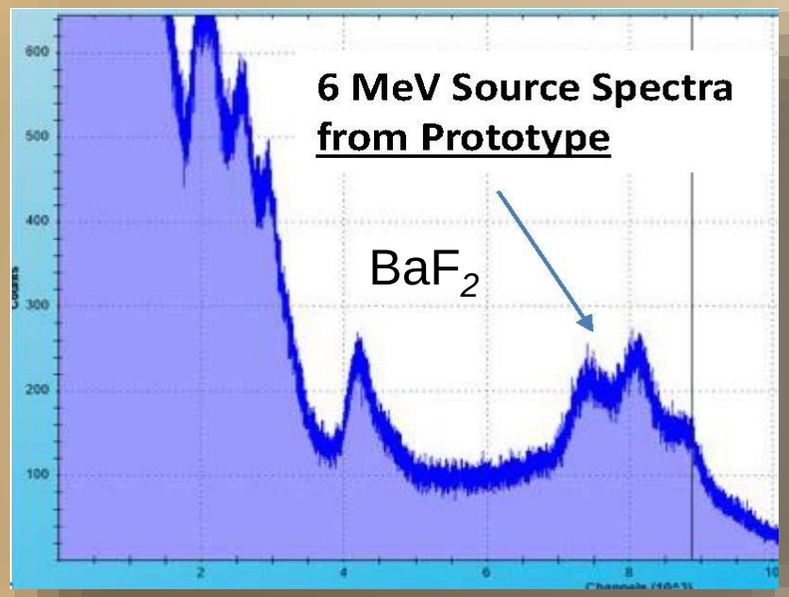
Calorimeter-seeded track
trigger can increase
conversion electron
acceptance by
10%, to 95%,
for background
rejection > 200

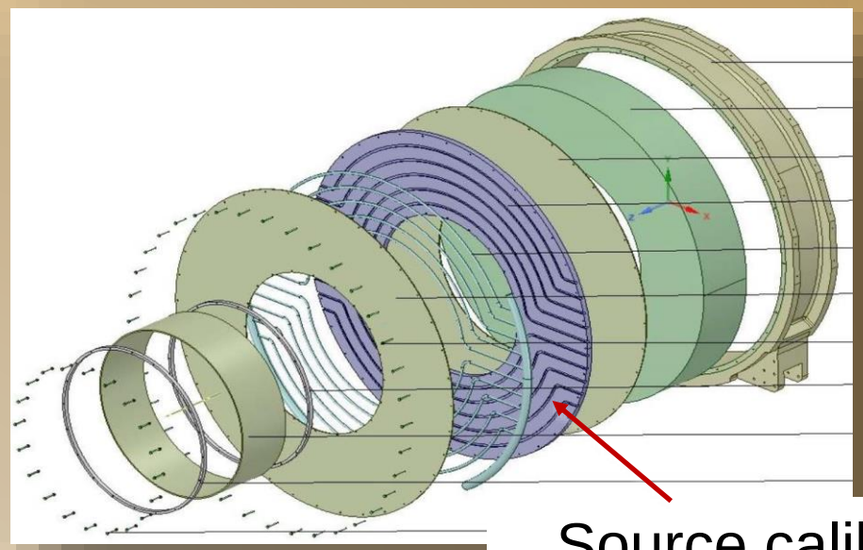


Calibration and monitoring

1) The *BABAR* calibration source has been rebuilt to provide 6.13 MeV γs on demand

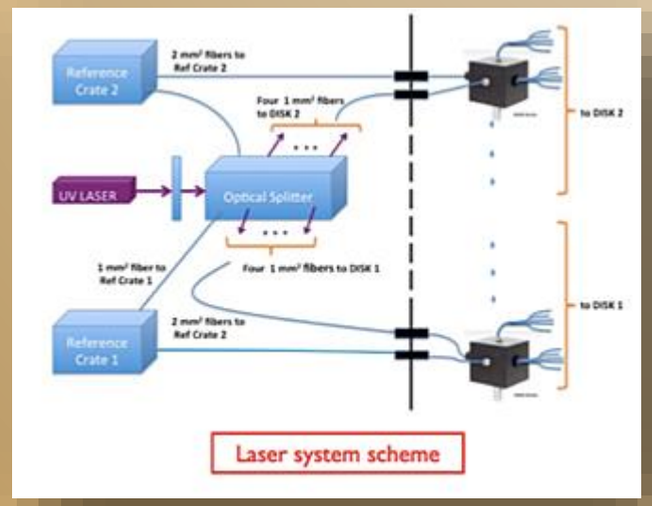
$$^{19}F + n \rightarrow {}^{16}N + \alpha$$
$$^{16}N \rightarrow {}^{16}O^* + \beta \quad t_{1/2} = 7\ \mathrm{s}$$
$$^{16}O^* \rightarrow {}^{16}O + \gamma(6.13\ \mathrm{MeV})$$



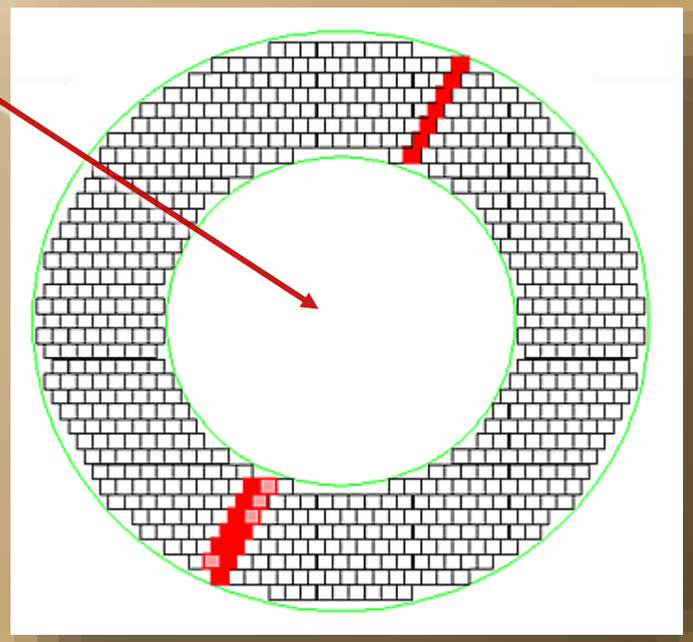


Source calibration tubes

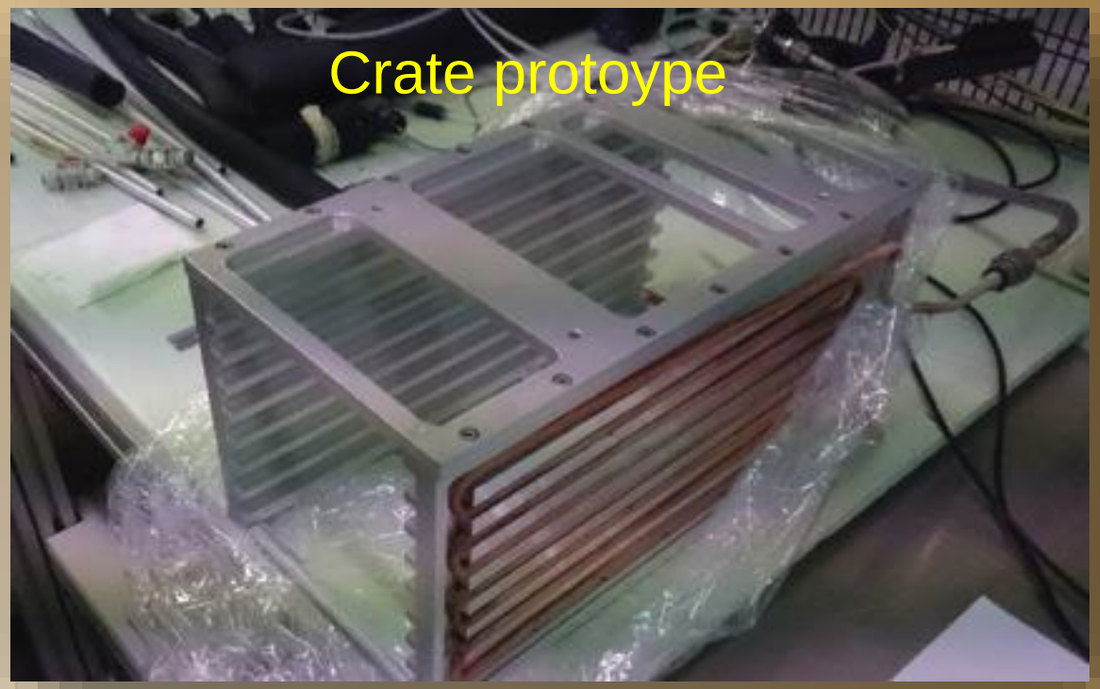
2) Laser system to monitor SiPM performance

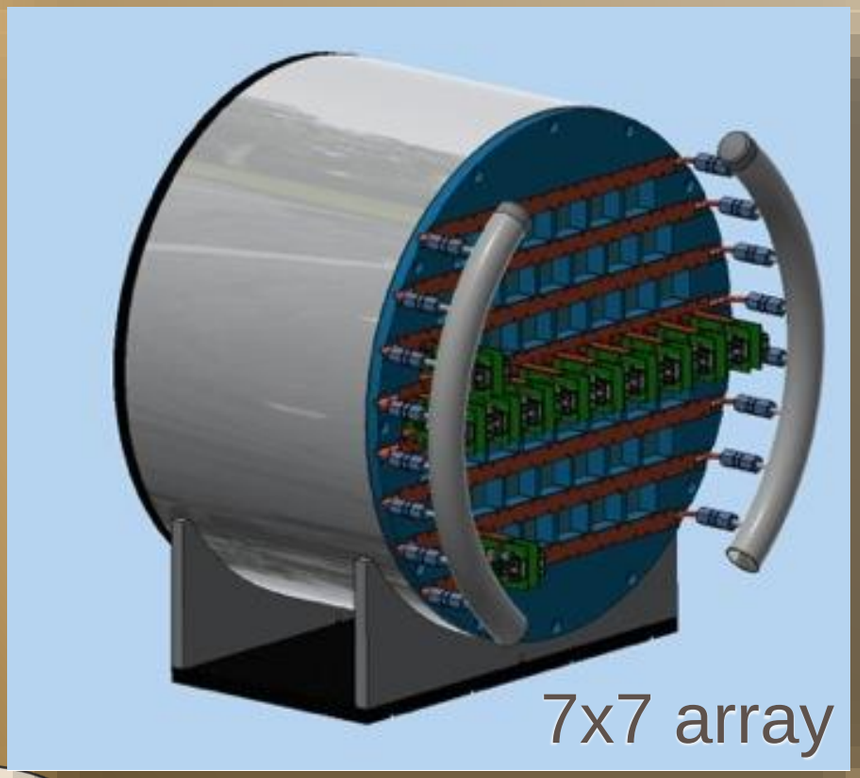


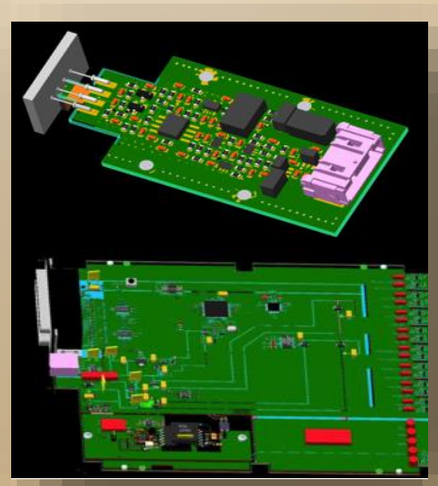
3) Cosmics + E/p for DIOs at reduced B field



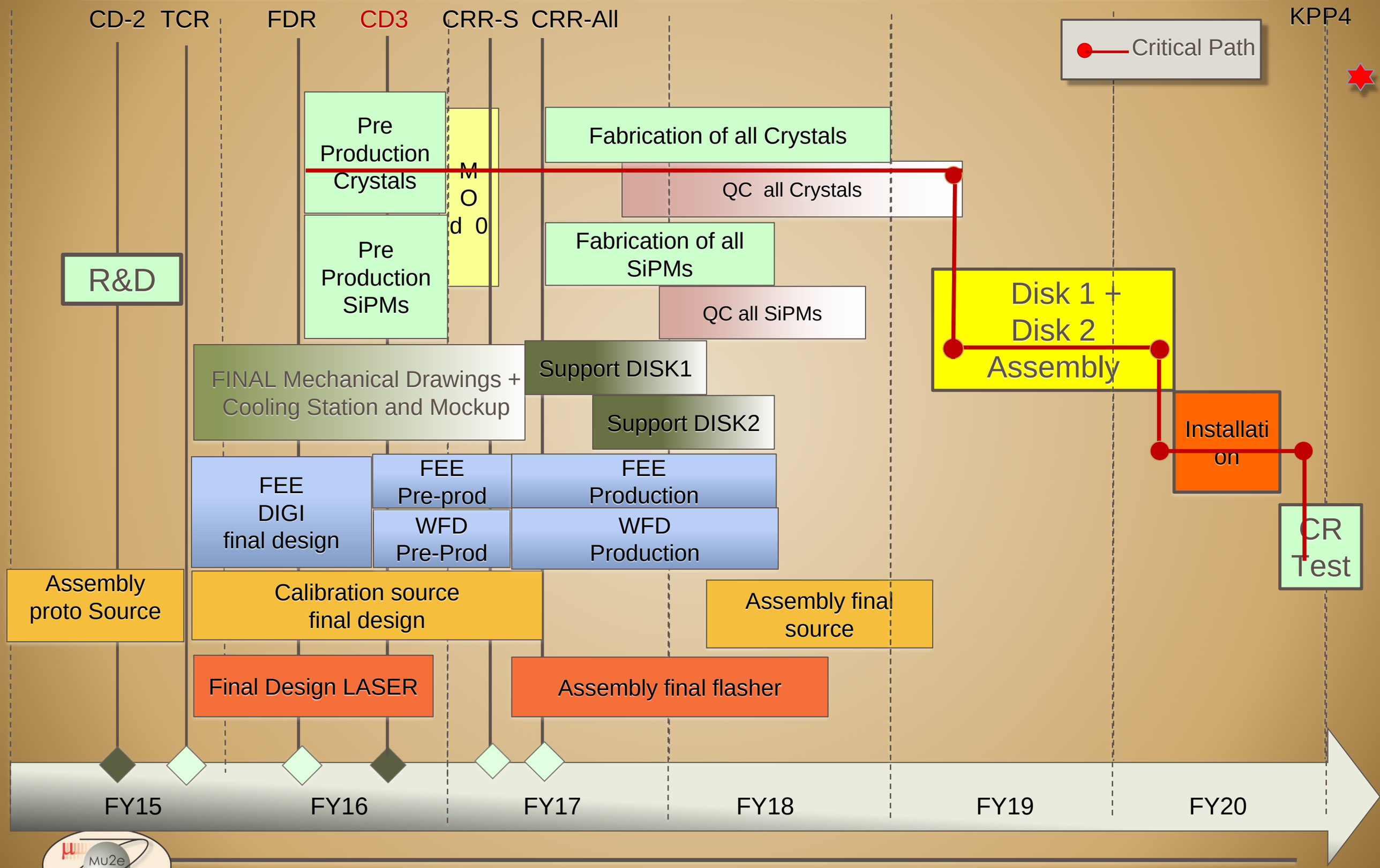
Prototyping/testing







Calorimeter schedule



Conclusions

A CsI-crystal-based calorimeter with SiPM readout meets the physics requirements for the Mu2e experiment

Its energy, time and position resolution allow the calorimeter to perform its main functions of

- Electron identification
- e/μ separation to reject rare cosmic ray-induced background
- Cluster-seeded track finding and triggering

Full scale construction begins in 2017, commissioning begins at the end of this decade