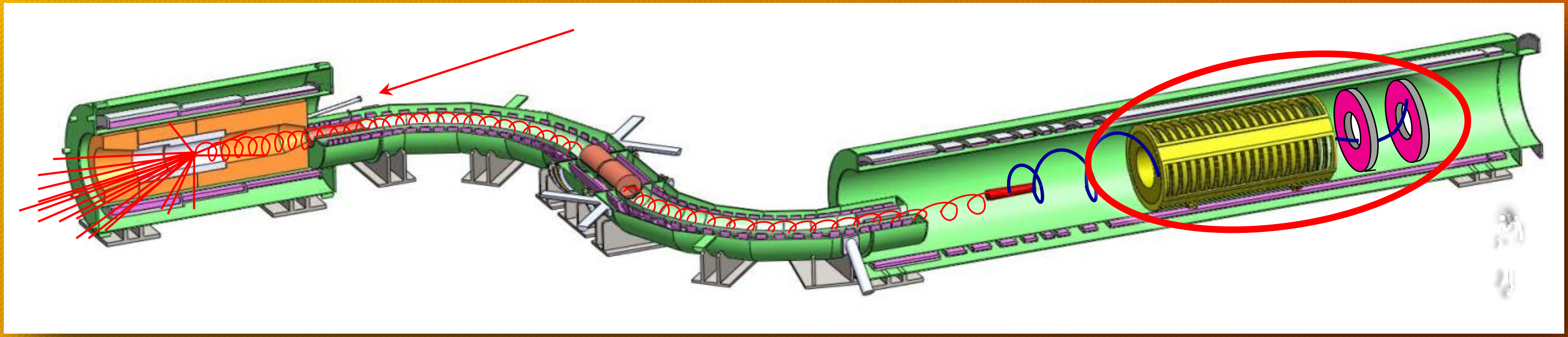


The Tracking and Calorimeter Systems of the Mu2e Detector

David Hitlin
Caltech

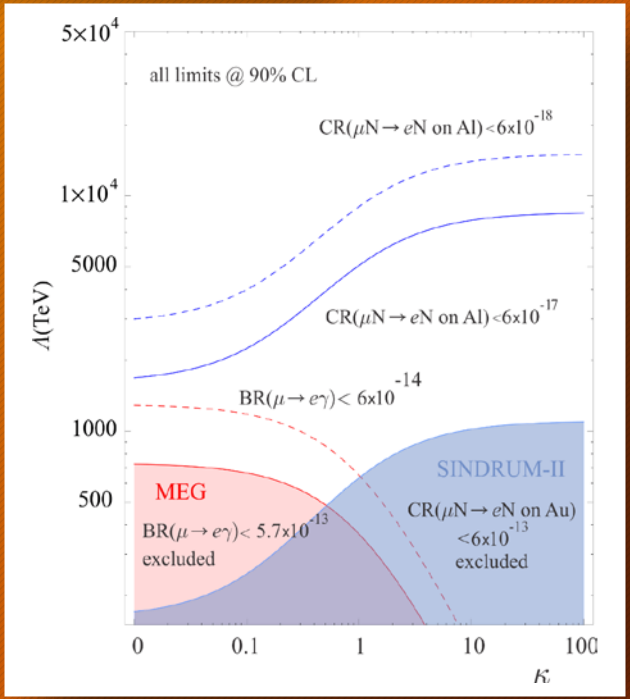
On behalf of the Mu2e Collaboration[1]

INSTR17
February 28, 2017

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

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

- Mu2e will provide the most sensitive search for charged lepton flavor violation
  - Sensitivity improvement of four orders of magnitude
    SES = 2.5×10^{-17}
- The signal of conversion is an electron with a momentum corresponding to
  $m_\mu - E_{\text{binding}} - E_{\text{recoil}}$ (104.97 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 improves 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

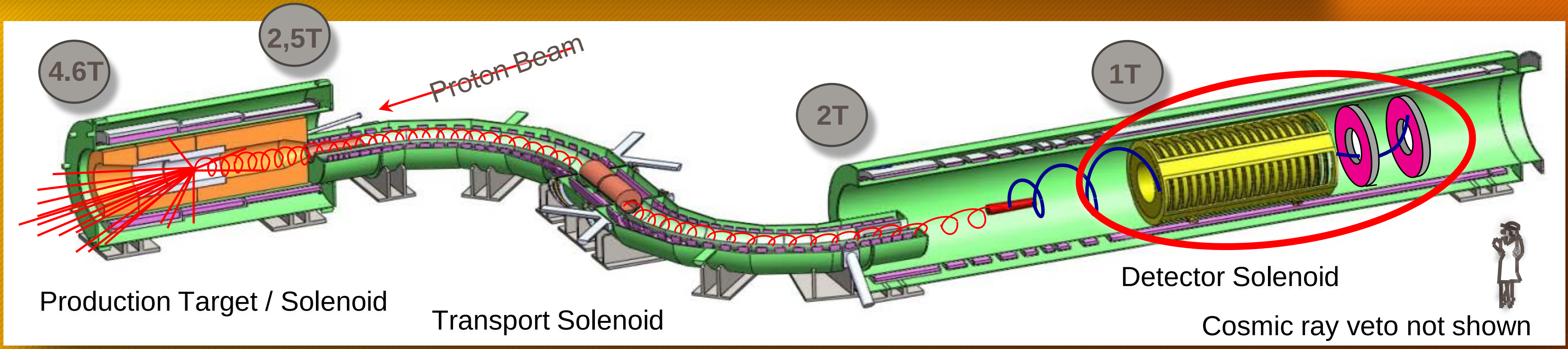


$$L_{\text{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L)$$

The Muon Campus at Fermilab

The Collaboration in the Mu2e hall

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

Tracker requirements:

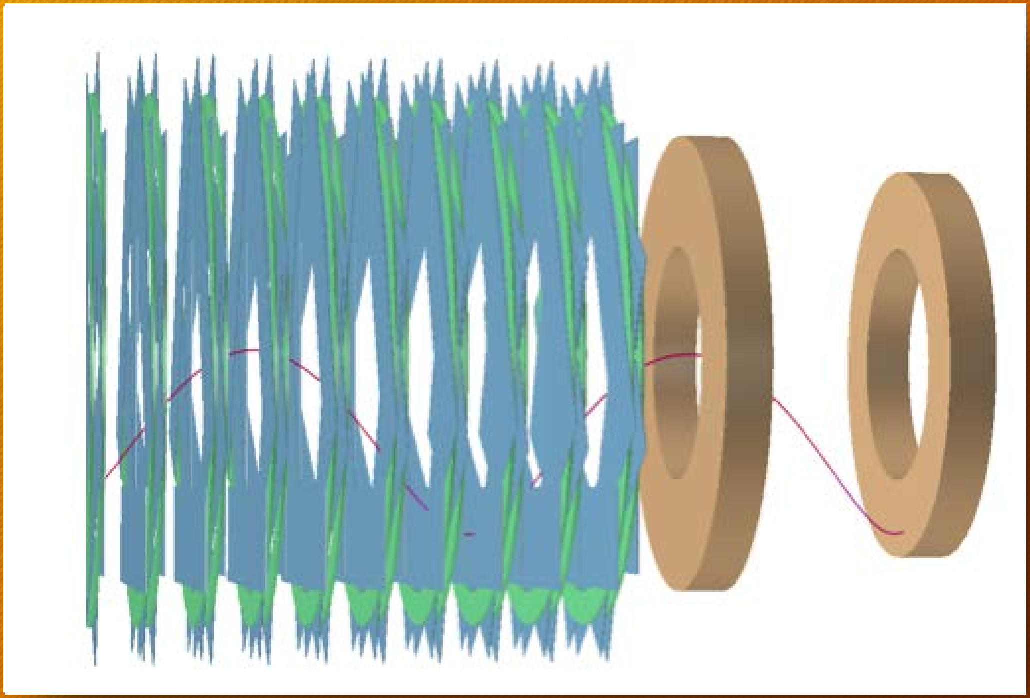
Momentum resolution σ_p/p < 180 keV/*c* at 105 MeV
Adequate rate capability:
20 kHz/cm^2 in live window
Tolerate beam flash rate of 3 MHz/cm^2
Have dE/dx capability to distinguish electrons from protons
Operate in a 1T magnetic field in a 10^{-4} Torr vacuum
Provide maximum acceptance for conversion electrons at 105 MeV

Calorimeter requirements:

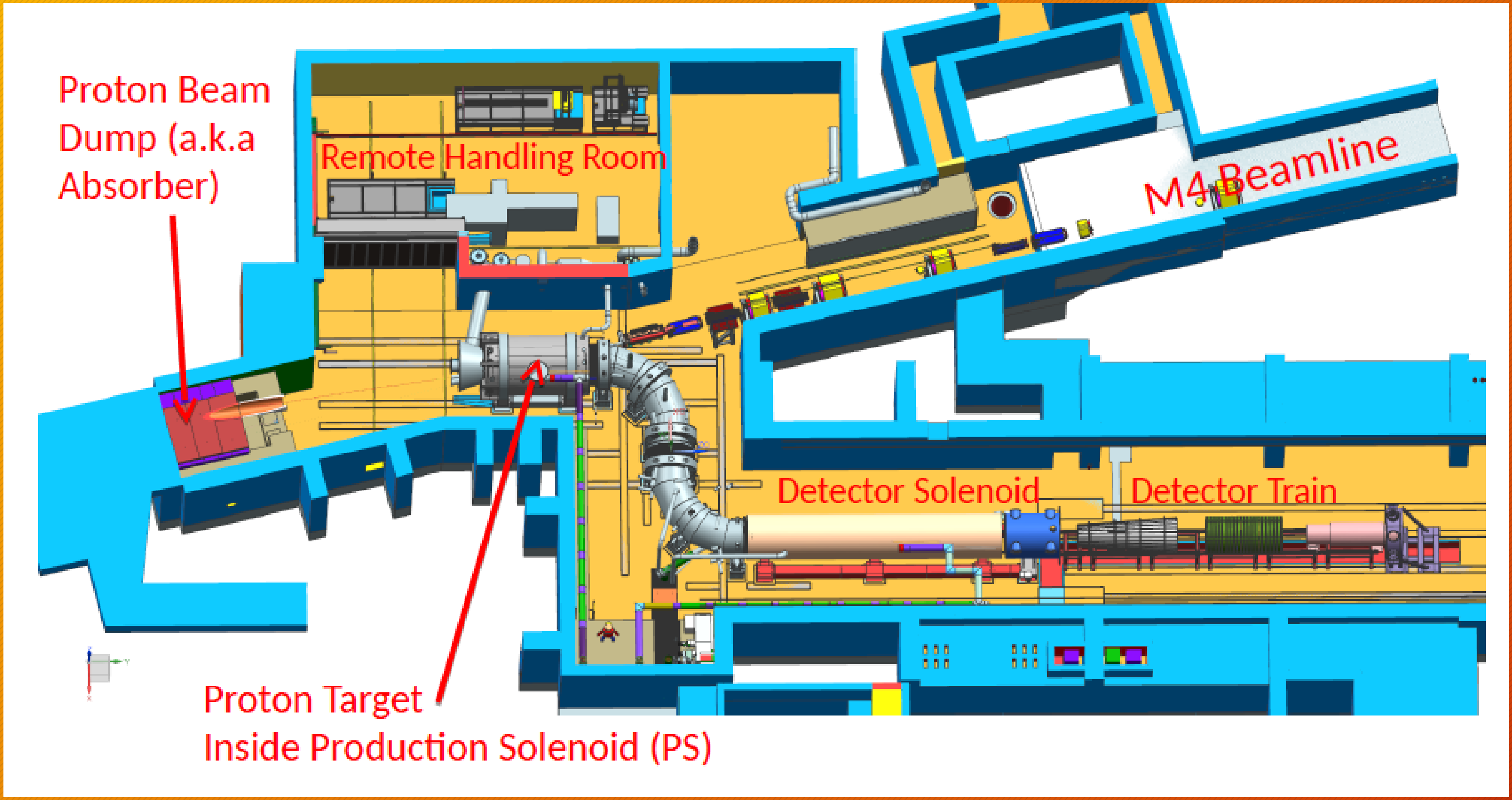
Energy resolution $\sigma_E/E \sim \mathcal{O}(5\%)$ at 105 MeV
Time resolution σ(t) < 500 ps
Position resolution < 1 cm
Adequate rate capability
Operate in a 1T magnetic field in a 10^{-4} Torr vacuum
Redundant photosensors and DAQ
Survive in the neutron (10^{12} n/cm^2) and gamma (100 krad) radiation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

The calorimeter is composed of annular disks

- Calorimeter disks are spaced apart by ½ wavelength of the pitch of a 105 MeV/*c* helical track



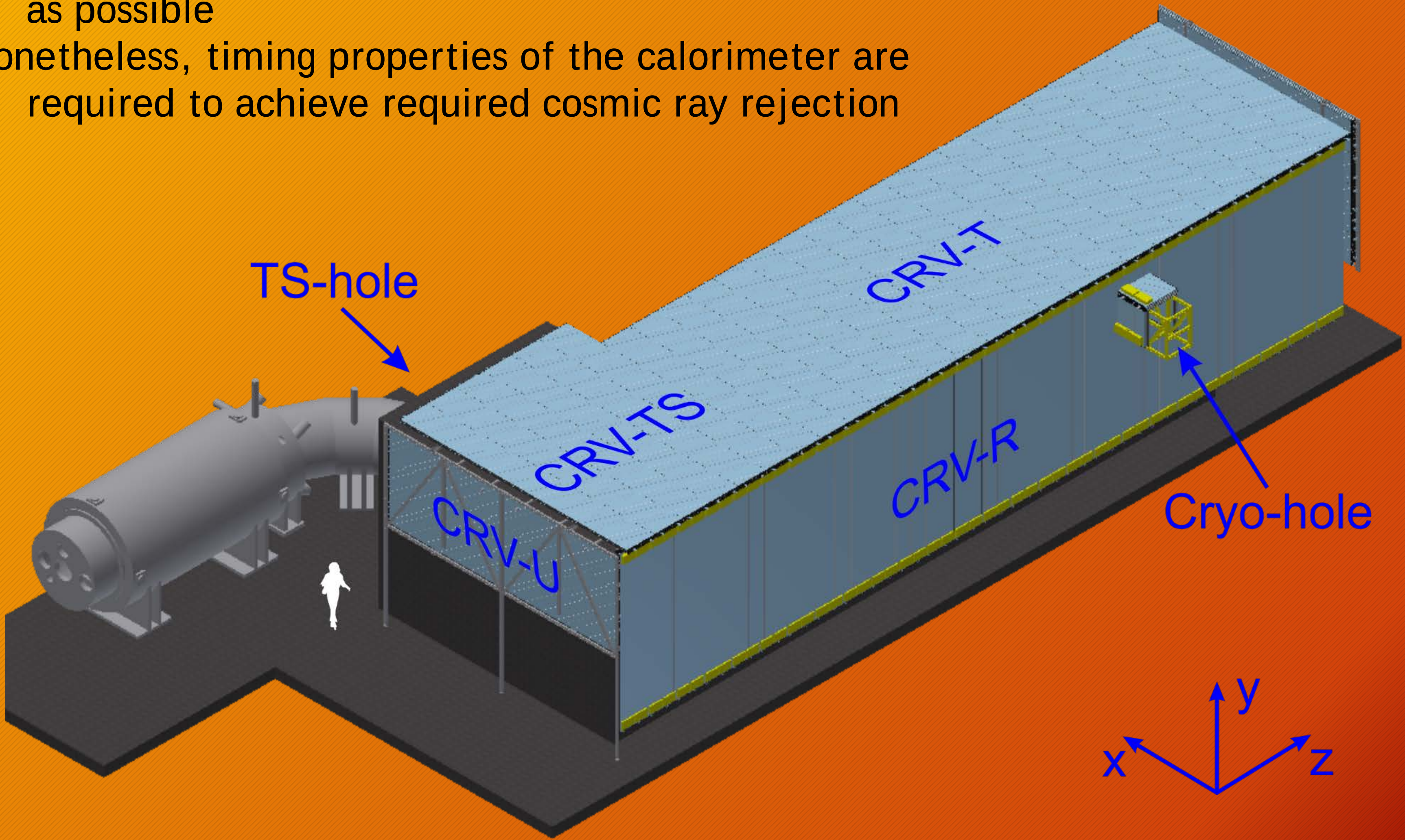
Beamline + detector layout



Cosmic ray veto (four layers)

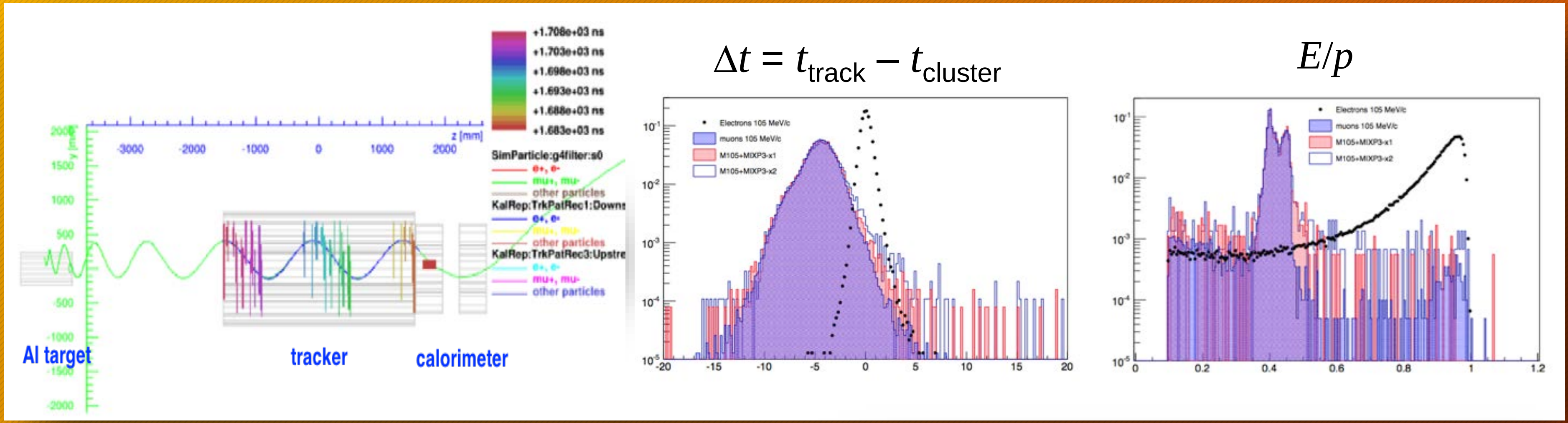
Covers as much of the transport and detector solenoids as possible

Nonetheless, timing properties of the calorimeter are required to achieve required cosmic ray rejection



PID: e/μ separation by TOF, E/p

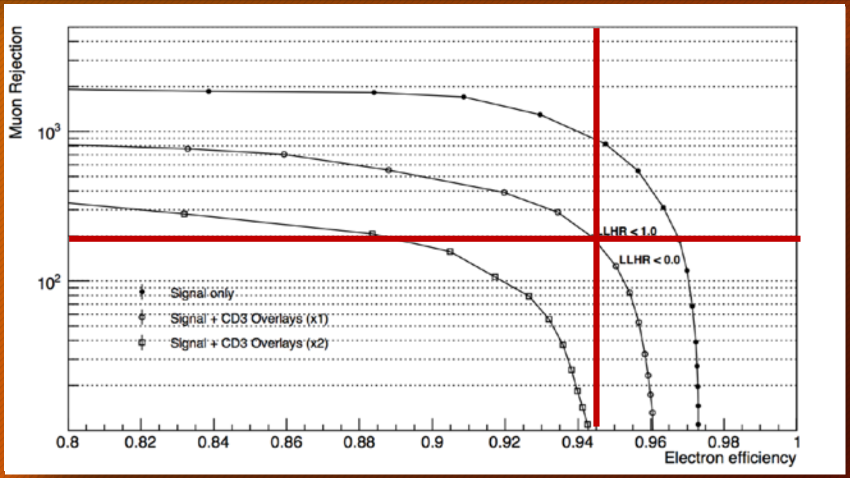
CRV studies show that with a CRV inefficiency of 10^{-4}, an additional rejection factor of ~200 is needed in order to have < 0.1 fake events from cosmics in the signal window



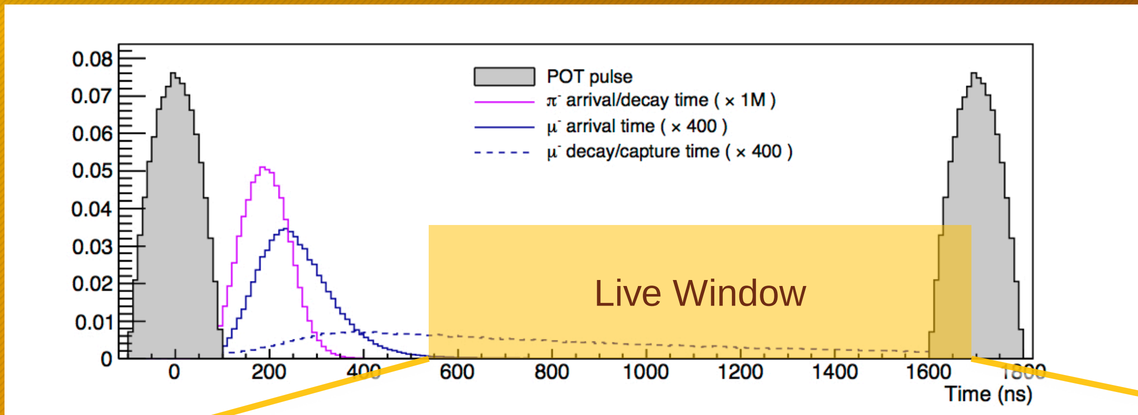
Rare cosmic ray muon events can mimic a conversion electron signal event

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



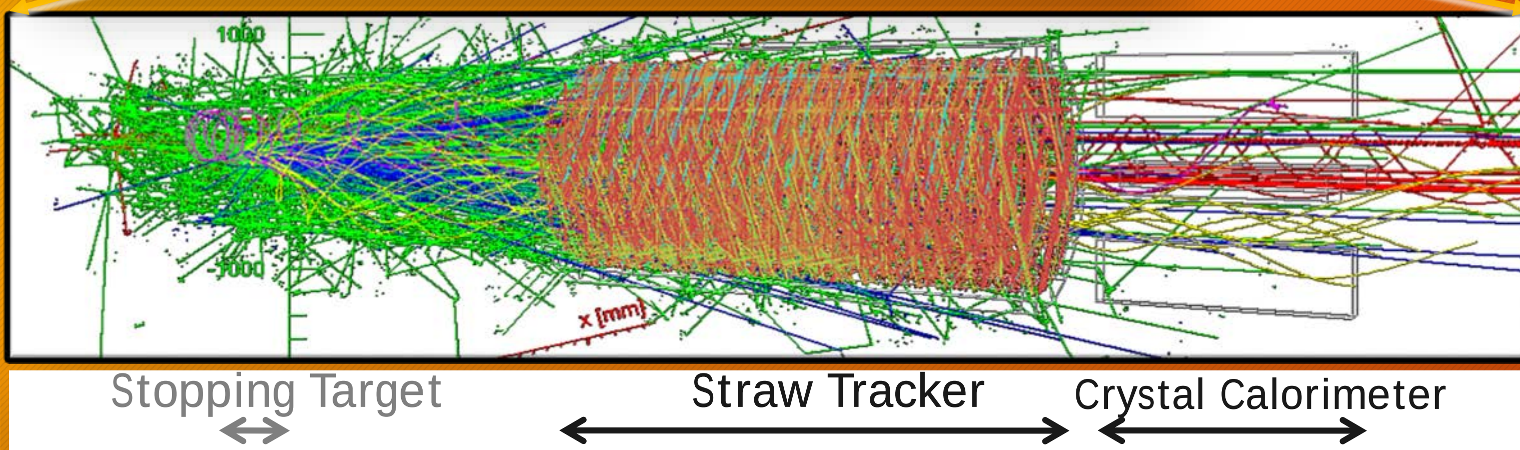
What happens in a microbunch ?



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

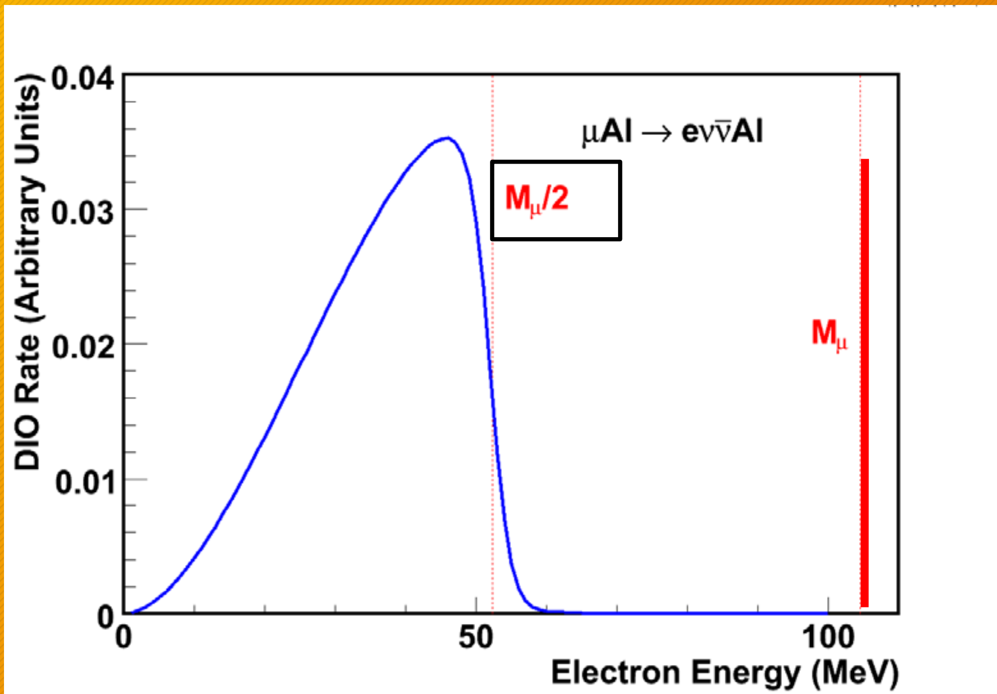
Proton pulses must be narrow

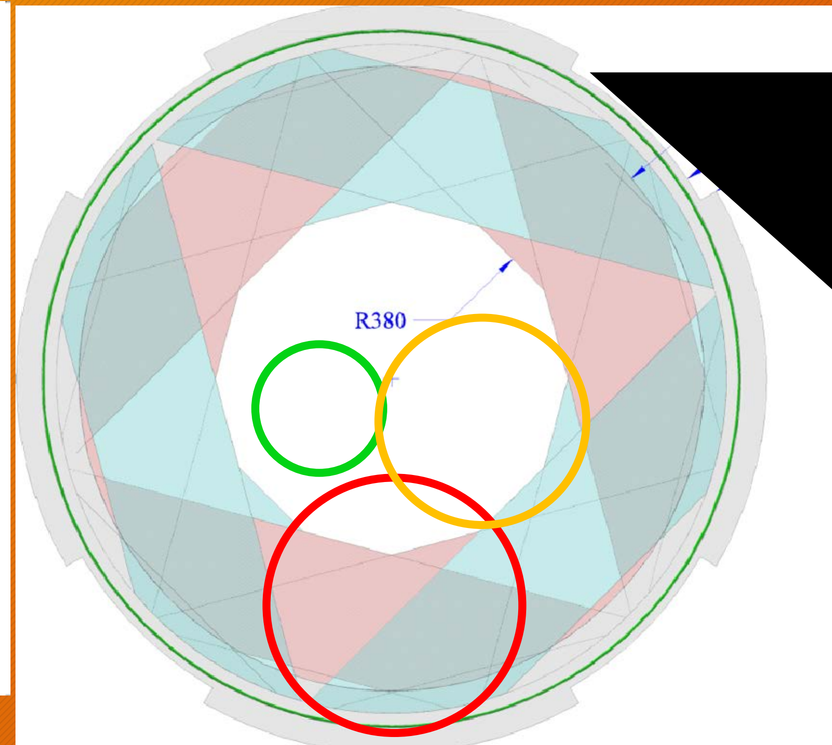
Out-of-time protons must be suppressed by $\mathcal{O}(10^{10})$



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

Tracker and calorimeter are designed to avoid DIOs and beam flash events



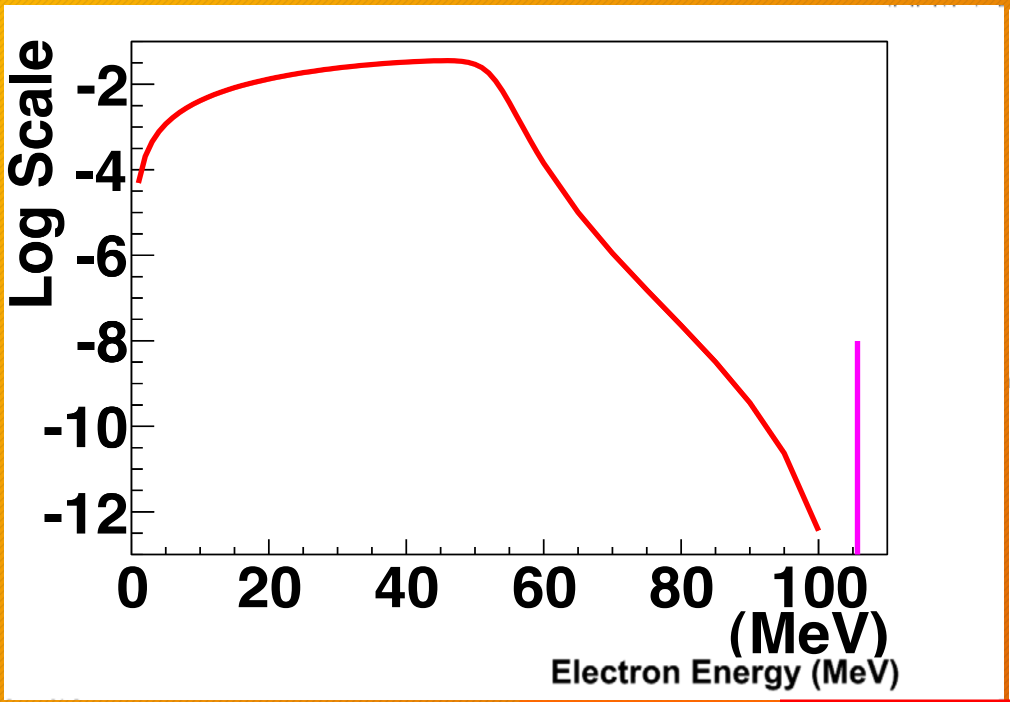


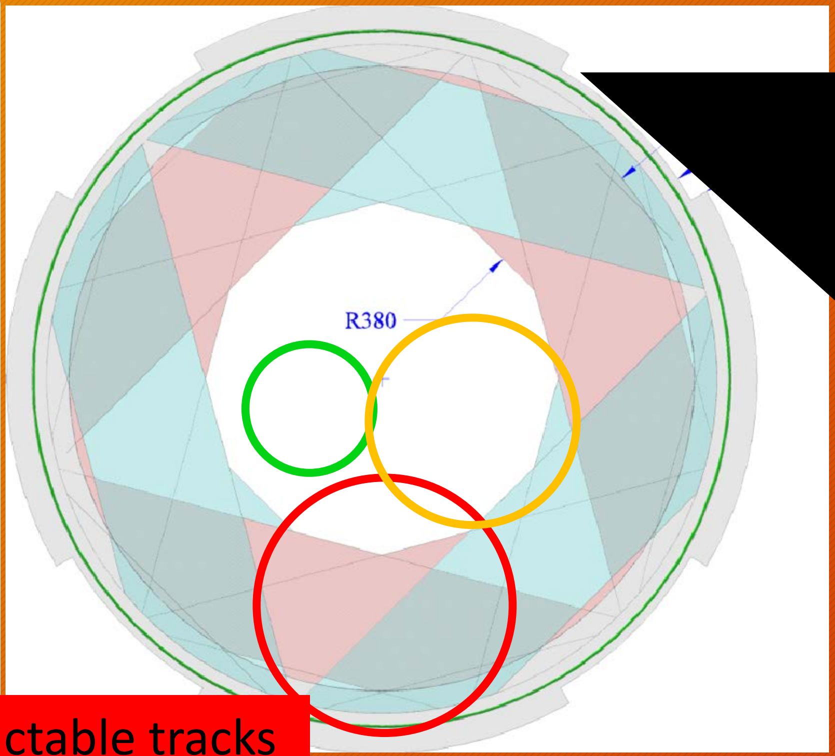
no hits in tracker

some hits in tracker, tracks not reconstructable

reconstructable tracks

Tracker and calorimeter are designed to avoid DIOs and beam flash events





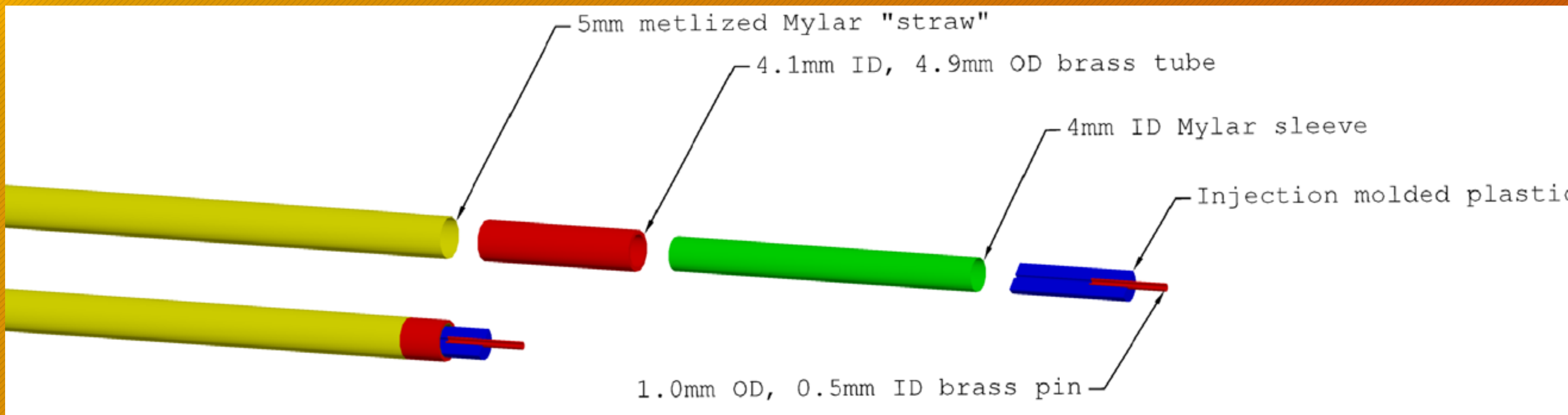
no hits in tracker

some hits in tracker, tracks not reconstructable

reconstructable tracks

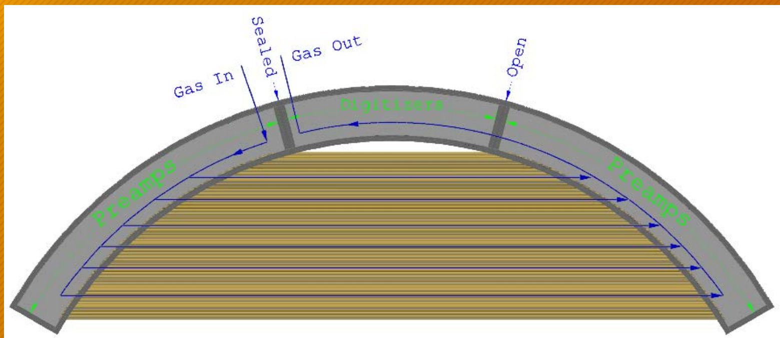
Tracker : straws ⇨ panels ⇨ planes

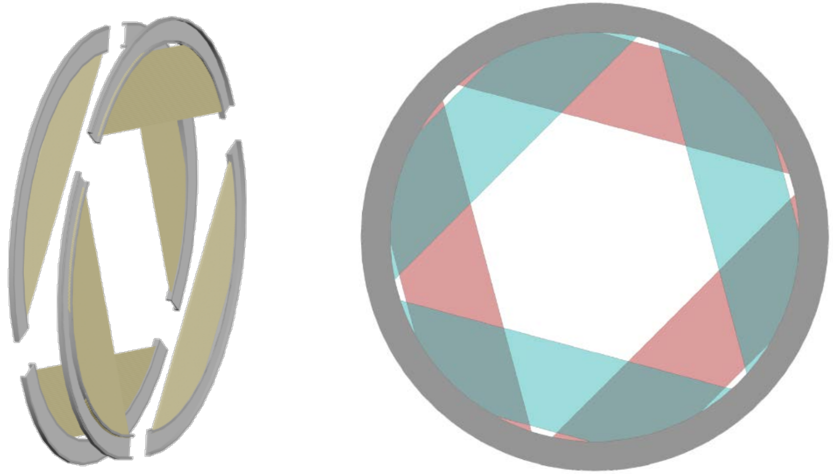
Straws: 5 mm OD; 15 μm metalized mylar wall



Panel: 2 layers, 48 straws each

Plane: 6 self supporting panels

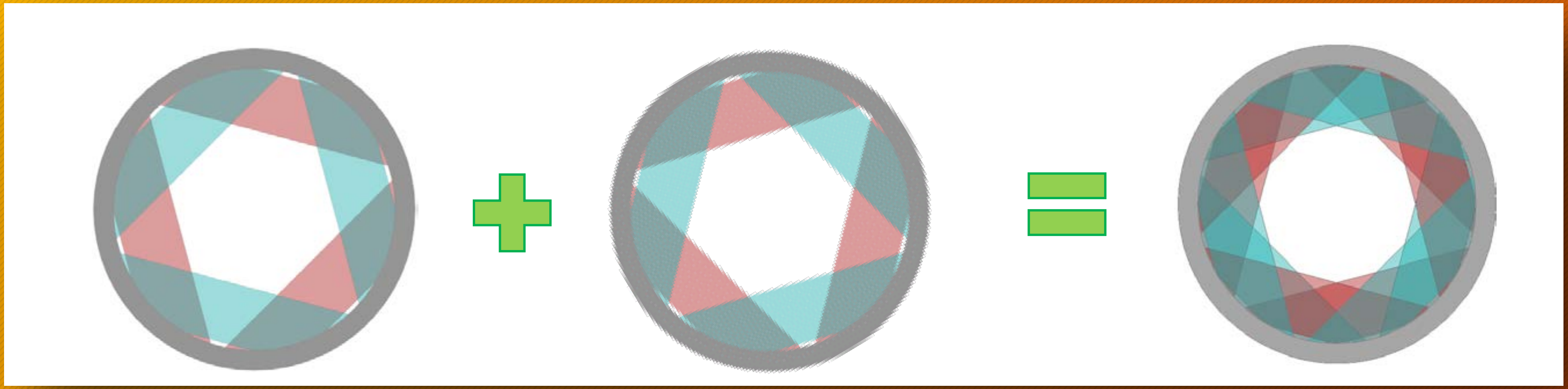




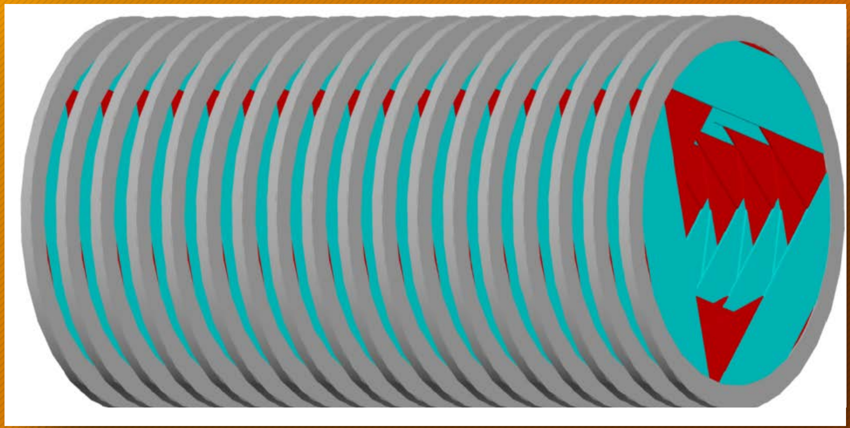
Custom ASIC for time division:
$\int \approx$ 5 mm at straw center

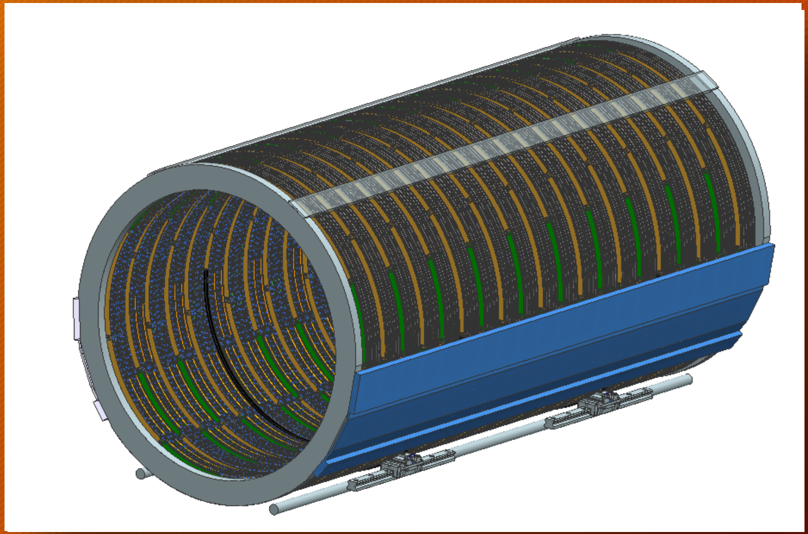
⇨ Stations ⇨ Tracker

Station: 2 planes

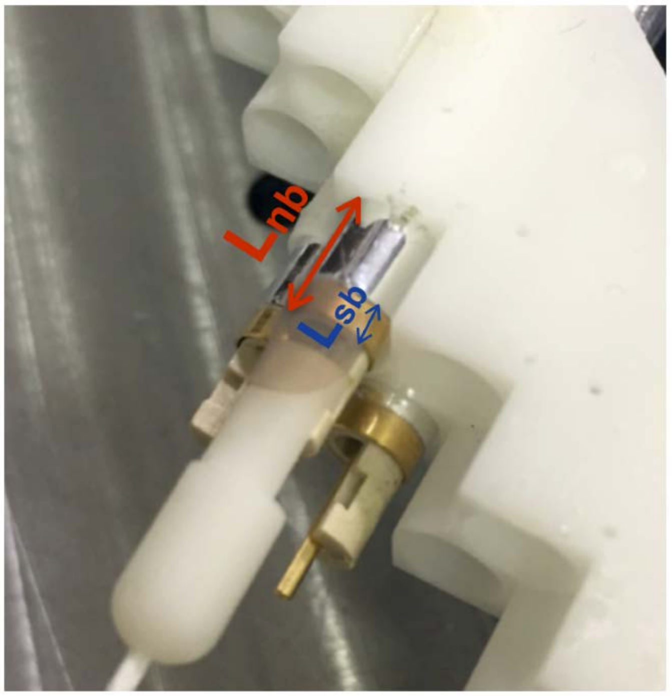


Tracker: 18 stations

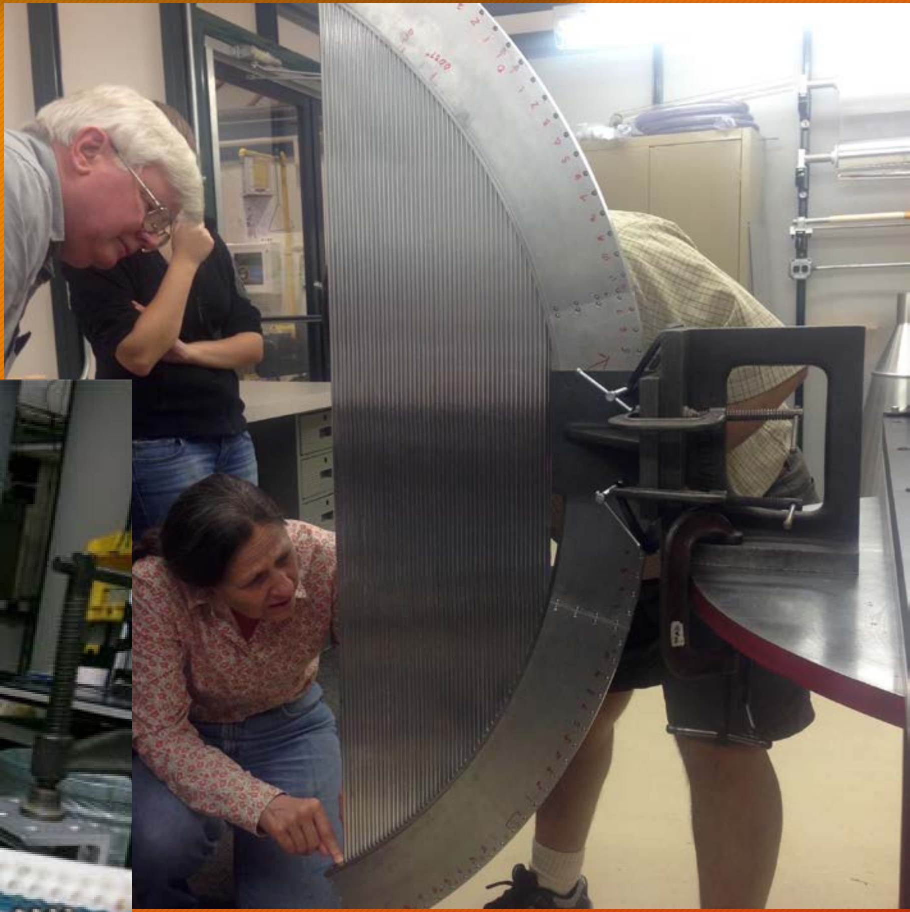




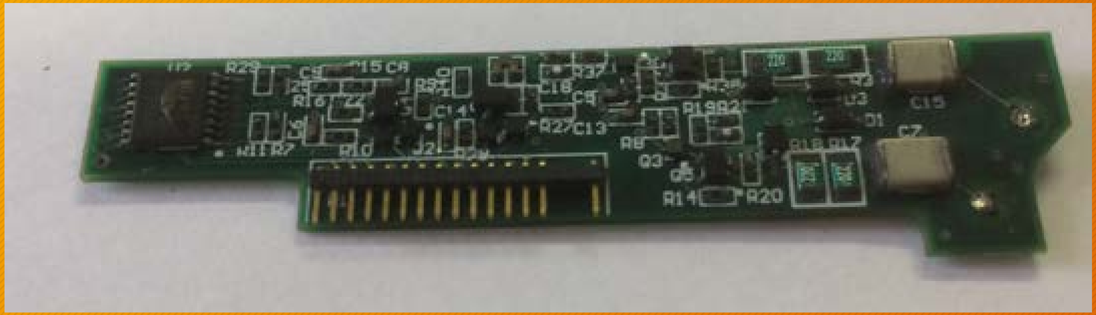
Straws: laser cutting and termination



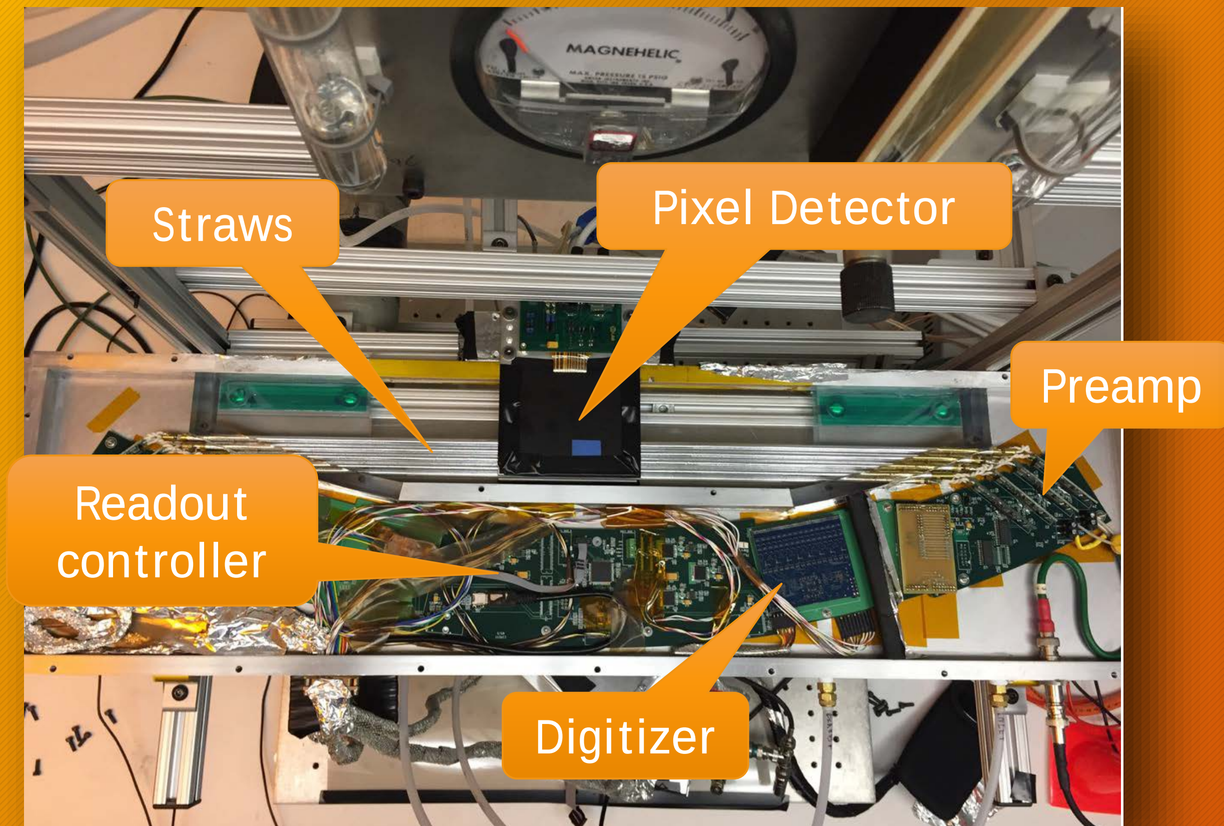
Panel assembly and straw tensioning

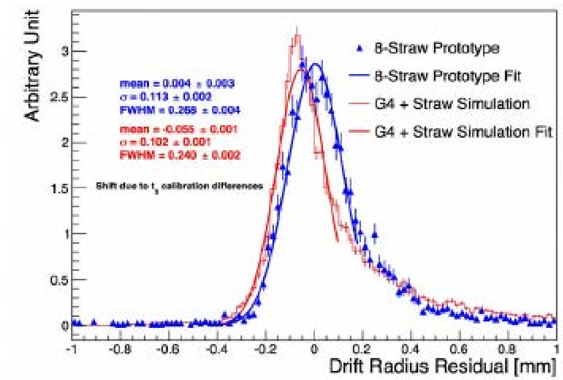


Preamp and digitizer prototypes



Prototype test with cosmics

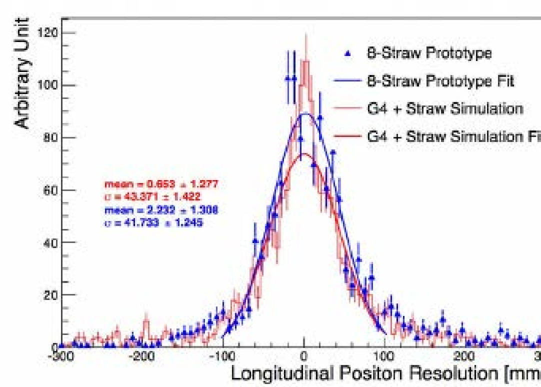




Transverse Resolution
(Data vs MC)

$\sigma_{data} = 0.113 \pm 0.002$ mm

$\sigma_{MC} = 0.102 \pm 0.001$ mm

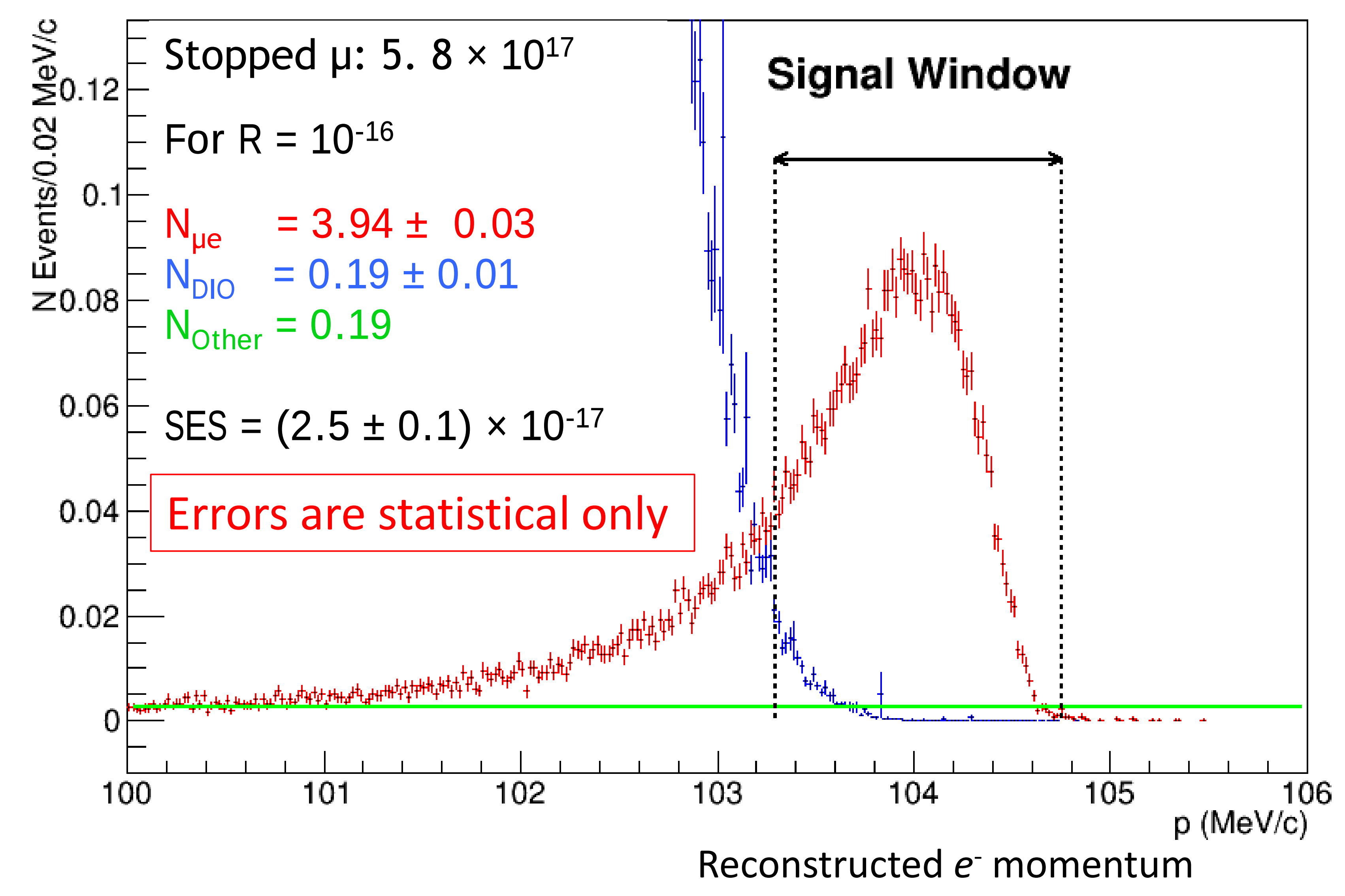


Longitudinal Resolution
(Data vs MC)

$\sigma_{data} = 42 \pm 1$ mm

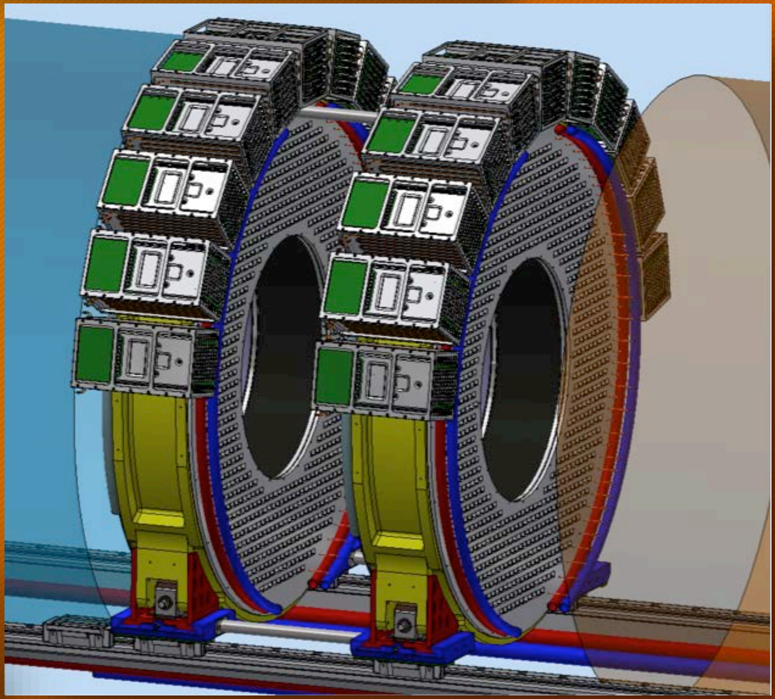
$\sigma_{MC} = 43 \pm 1$ mm

Signal sensitivity for a three year run



Calorimeter design

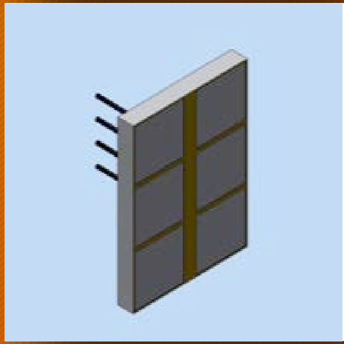
- The central hole region in the tracker and calorimeter allows us to be largely insensitive to DIO and beam flash backgrounds
- The calorimeter has two identical annuli, spaced apart by 700 mm (½ λ of the helical trajectory of the conversion electron)
- r_{inner} = 374 mm
  r_{outer} = 660 mm
  depth = 10 X_0 (200 mm)



- Each annulus contains 674 square CsI crystals with dimensions 34 x 34 x 200 mm^3

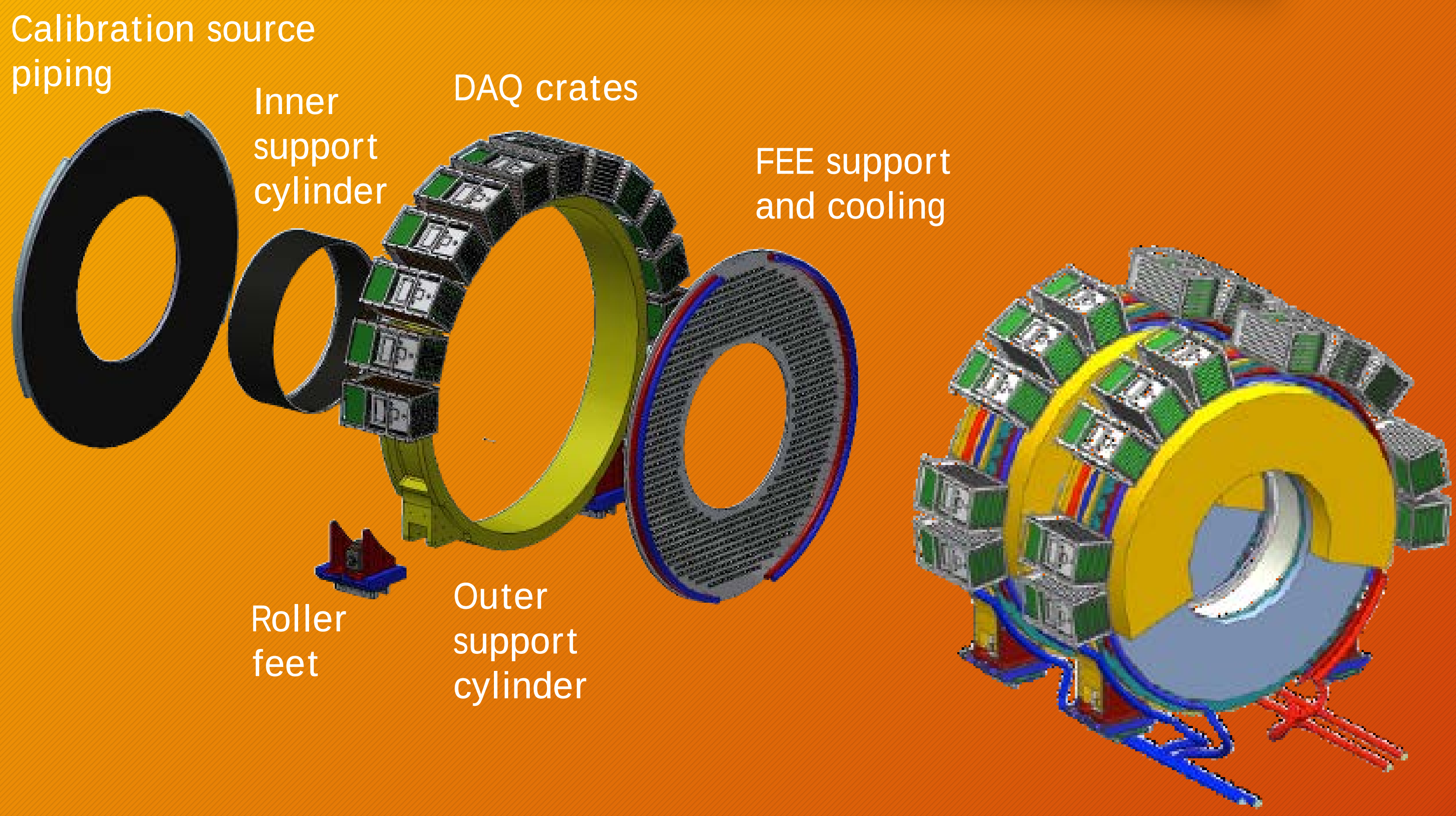
- Each crystal is read out by two large area (14x20 mm^2) six element UV-extended SiPMs

  The analog front end electronics is directly mounted on the SiPM

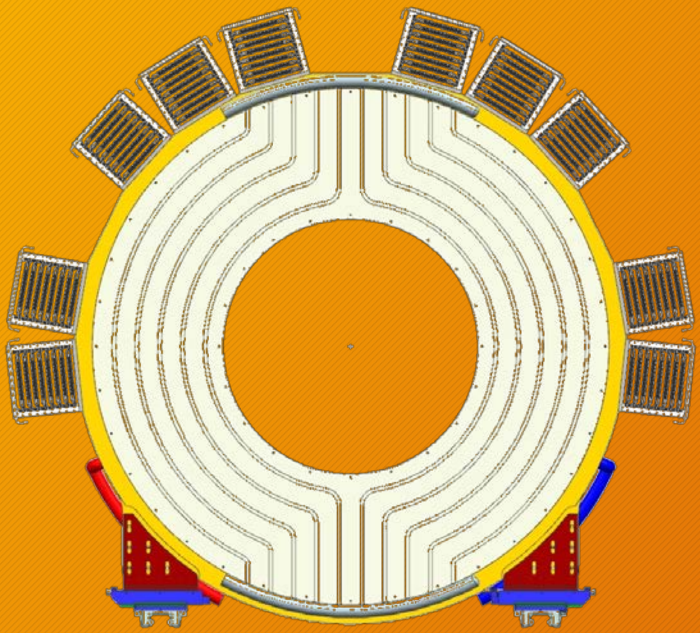


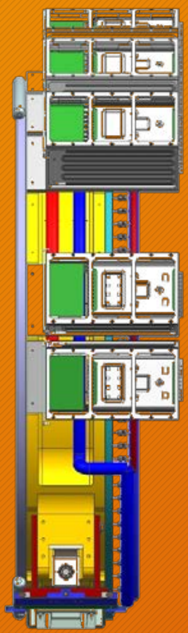
- The digital electronics and voltage regulators are located in electronics crates mounted on the periphery
- Calibration and monitoring are provided by a 6 MeV radioactive source and a laser system

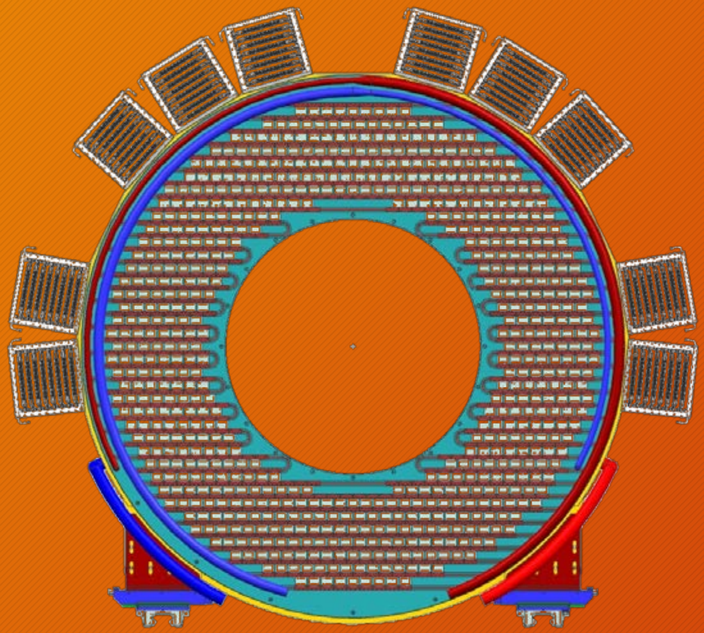
Calorimeter structure exploded view



Three views





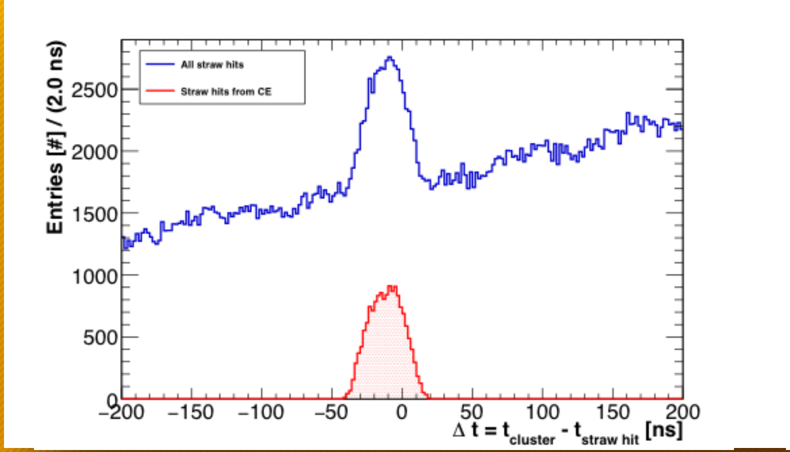


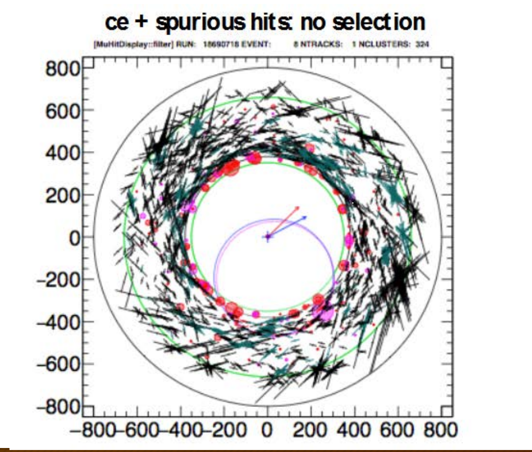
The front faces of the disk include thin Al tubing through which we flow irradiated fluorinert to provide a 6.13 MeV calibration γ

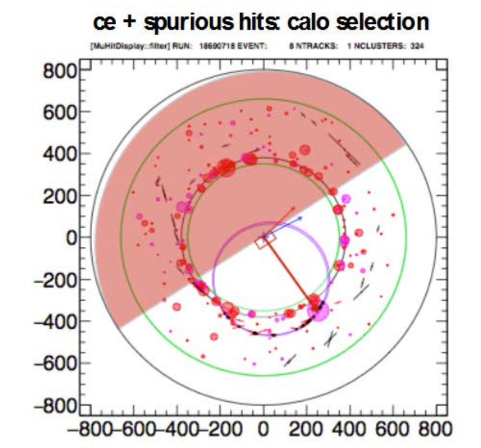
There is no internal crystal support structure: Tyvek-wrapped crystals are chosen by dimension, leveled and shimmed to minimize placement error

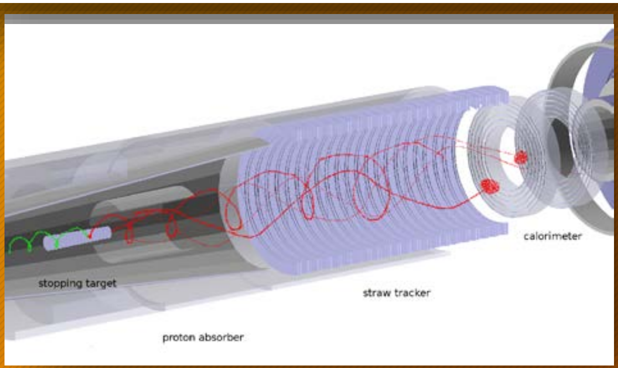
Calorimeter cluster-seeded track finding

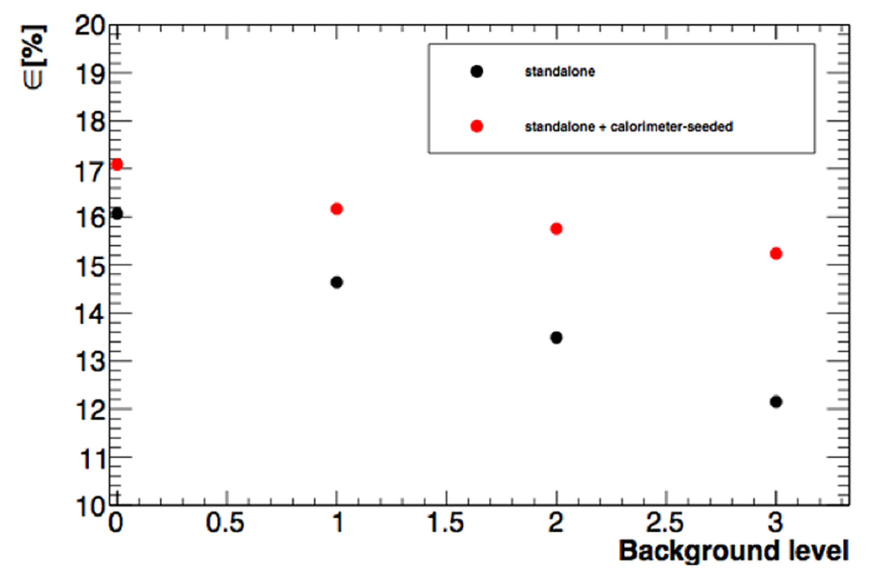
The speed and efficiency of track reconstruction is improved by selecting tracker hits compatible with the time (|Δt| < 50 ns) and azimuthal angle of calorimeter clusters







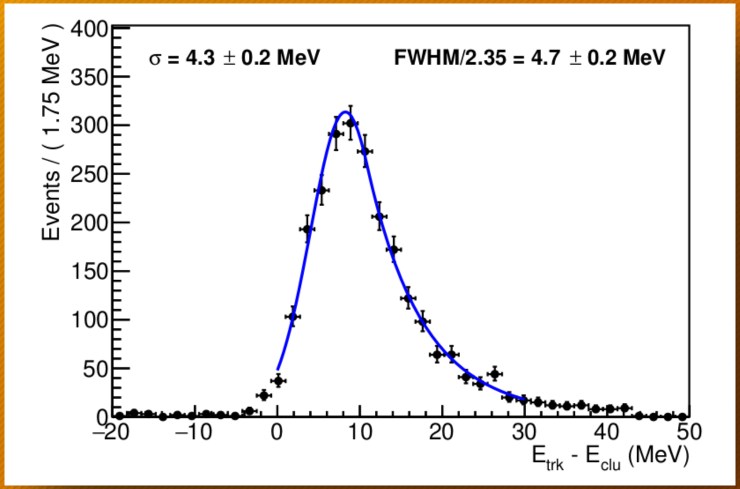




Calorimeter-seeded track finding improves the relative efficiency for tracks in the signal region (103.5 < p <105 MeV/c) by ~11% and is more robust against background

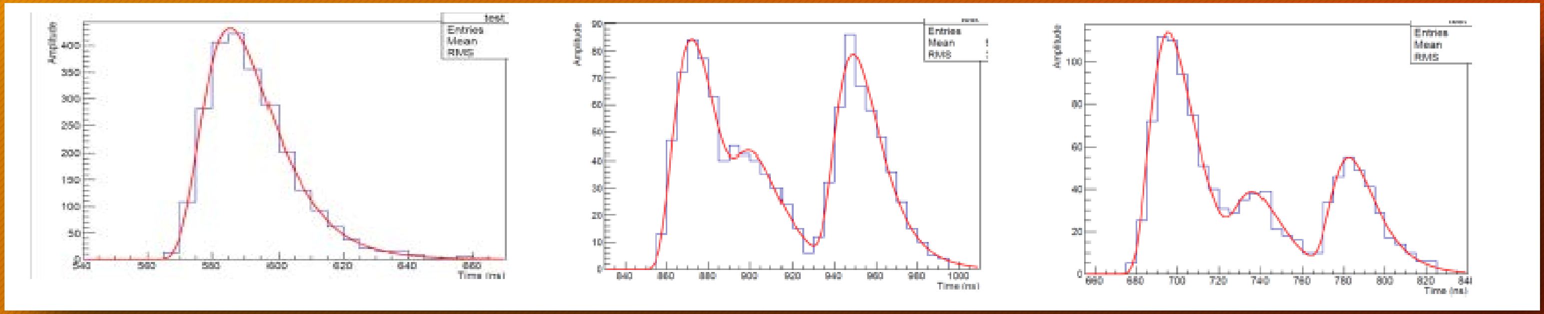
Calorimeter energy resolution

- Achieving best possible energy resolution requires efficient shower clustering algorithm with detached cluster recovery and pile-up rejection
    - Cluster algorithm with detached cluster recovery



GEANT4 simulation

- Pile-up rejection using waveform digitization



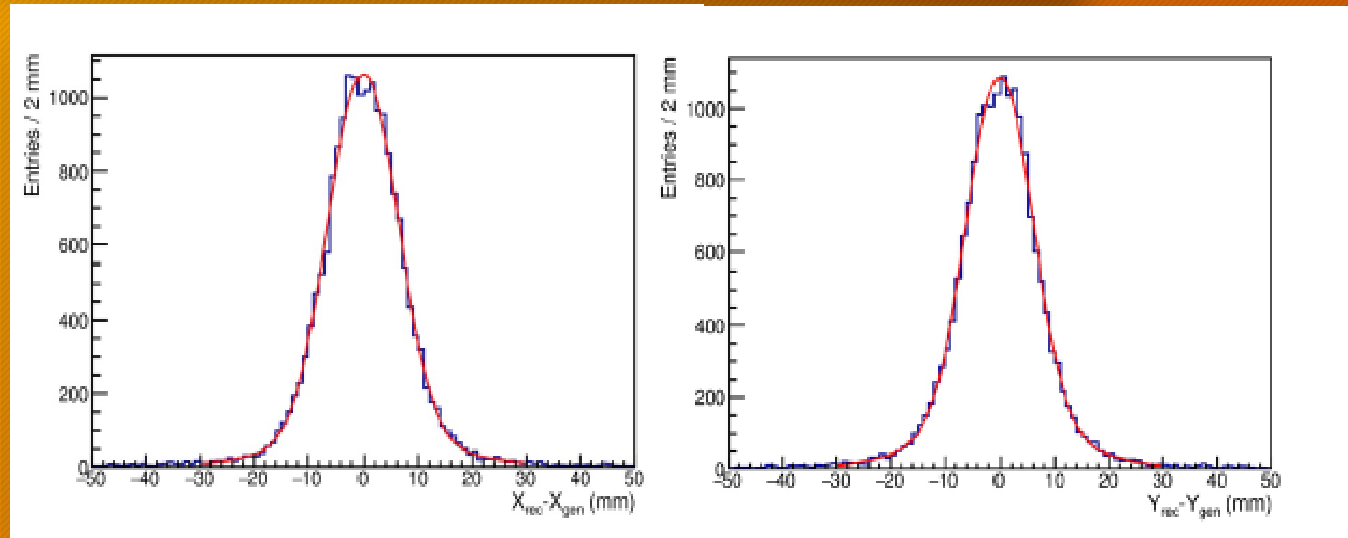
Calorimeter spatial, time resolution

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

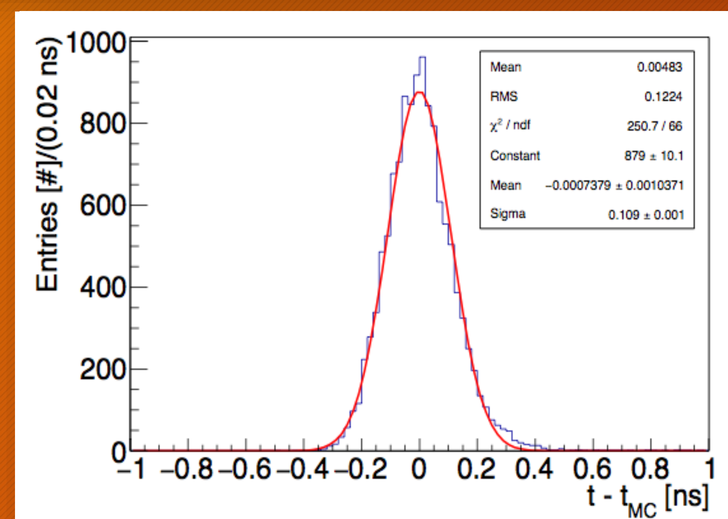


Time resolution

Cluster time defined using the energy-weighted crystal times

$\sigma_t = 109 \pm 1$ ps

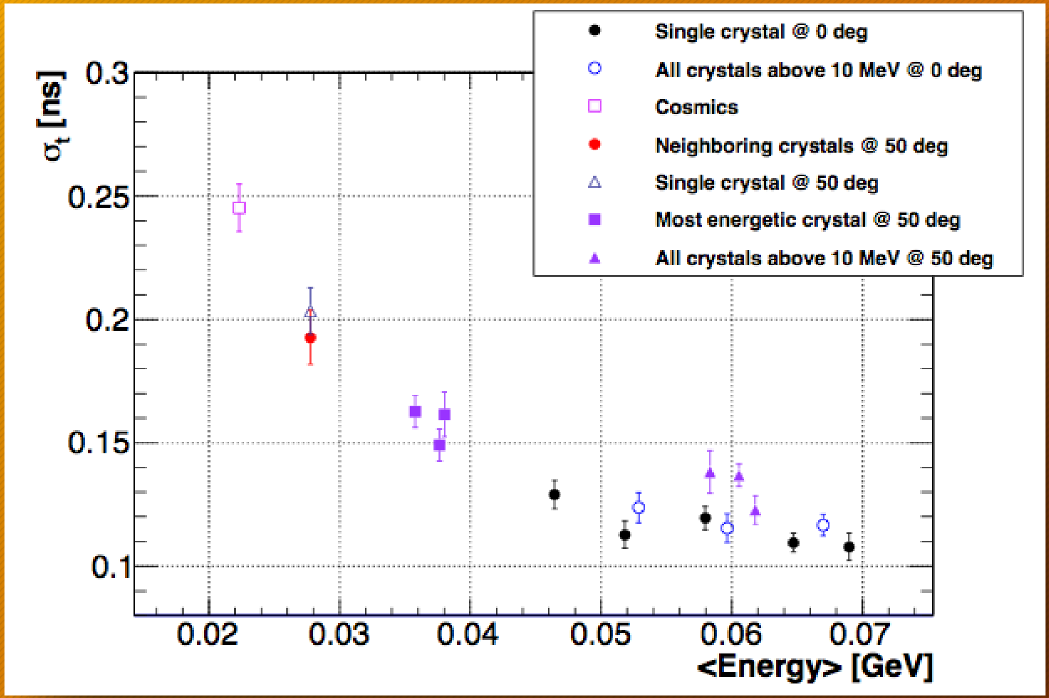
GEANT4 simulation

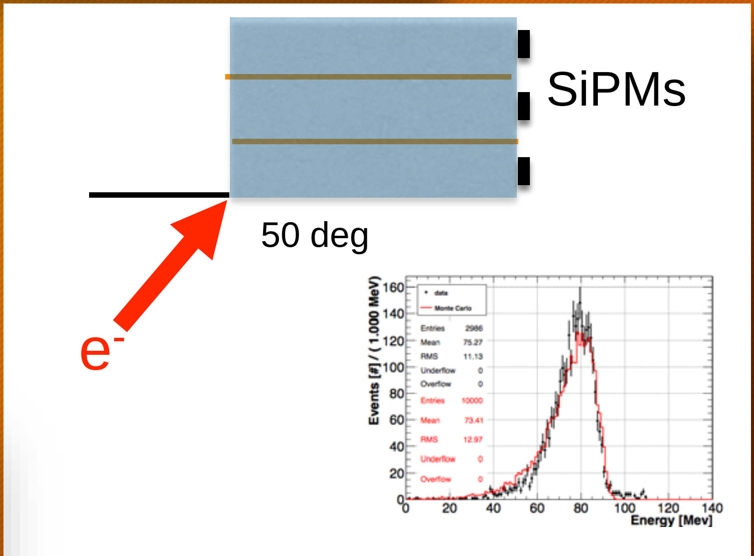


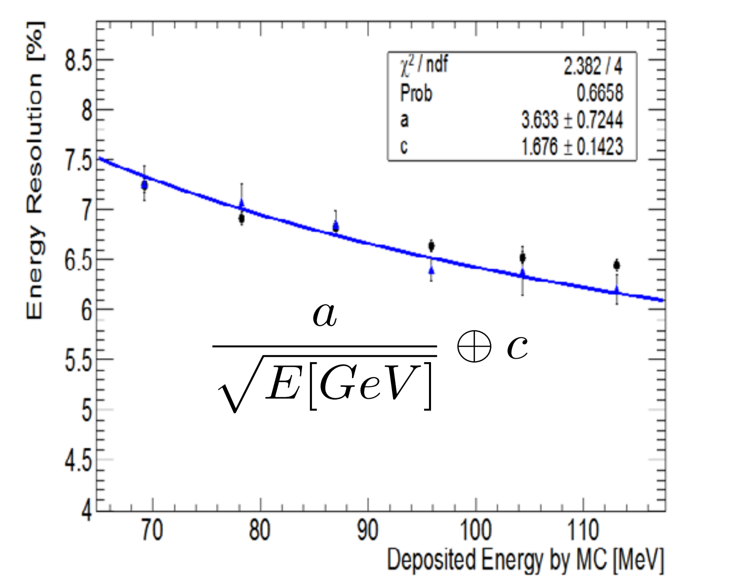
7

Frascati test beam results: CsI array + SiPM

- Test beam with 70-115 MeV electrons @ LNF
- 3x3 array of 30x30x200 mm^3 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.



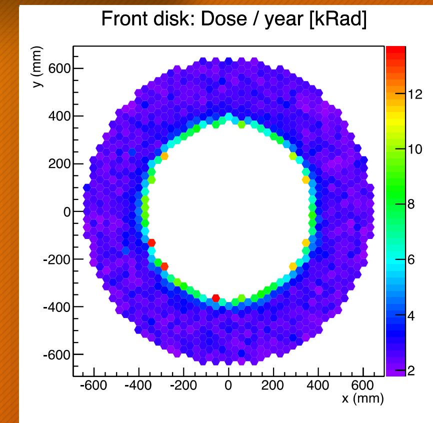


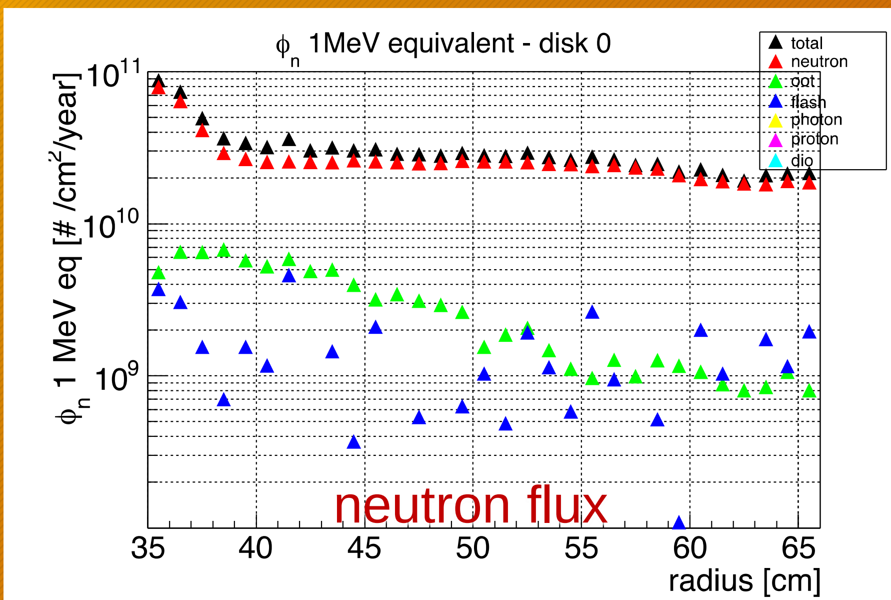


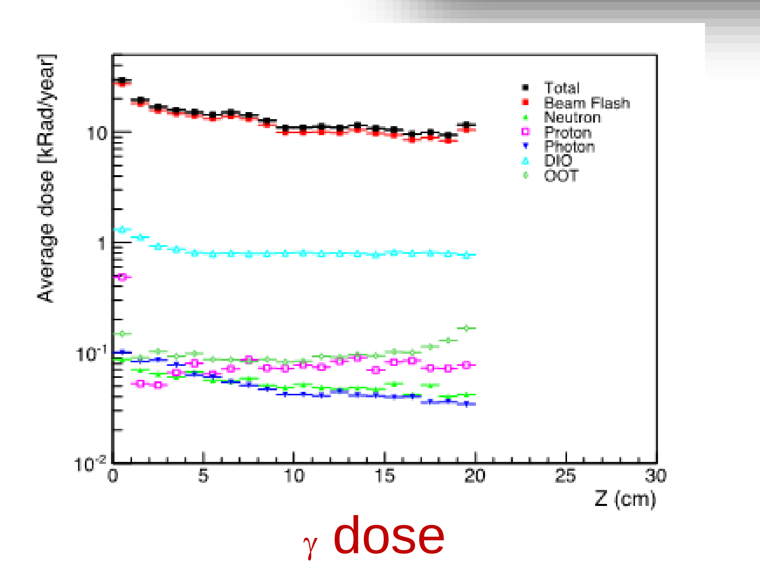
$$\frac{a}{\sqrt{E[GeV]}} \oplus c$$

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



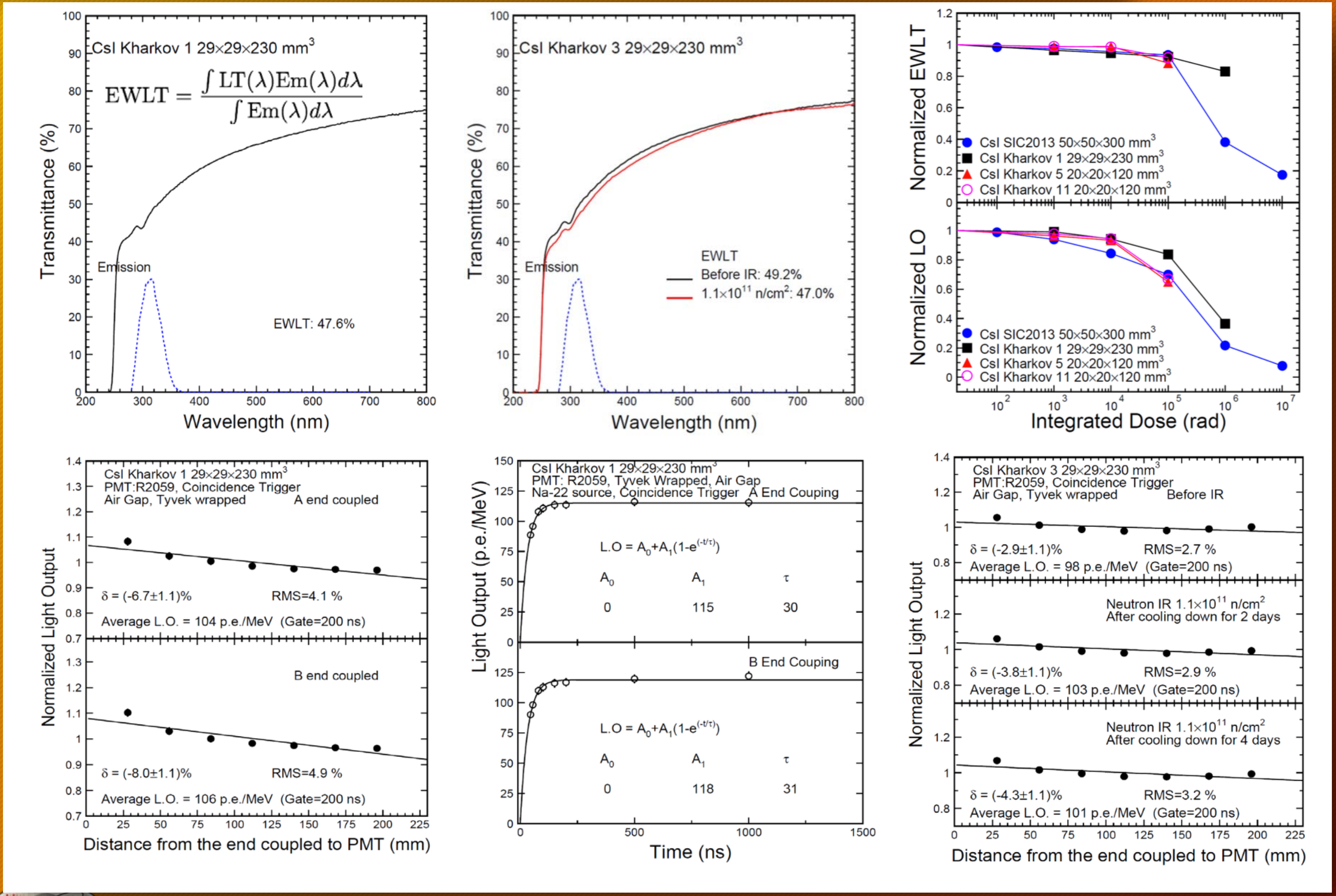




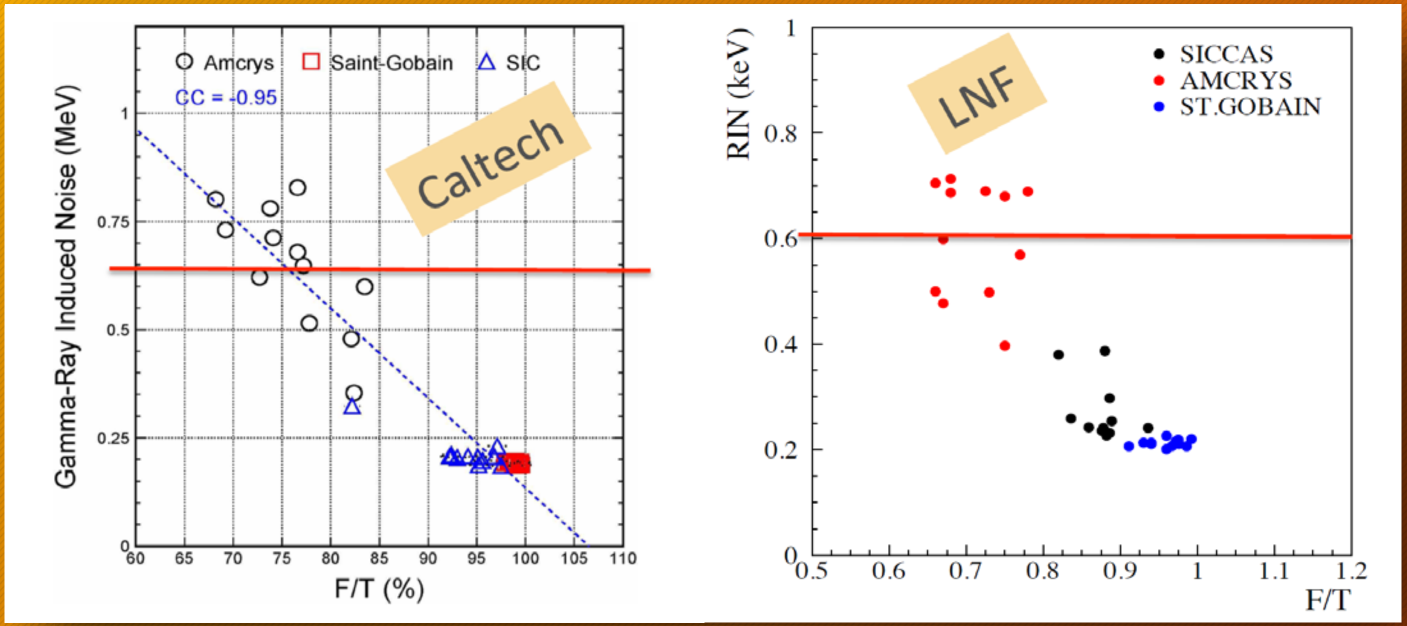
- Qualify crystals up to 100 krad, 10^{12} n/cm^2
- Qualify photo-sensors up to 3×10^{11} n_1MeV/cm^2

Includes a safety factor of 3 for a 3 year run

Measured CsI crystal properties



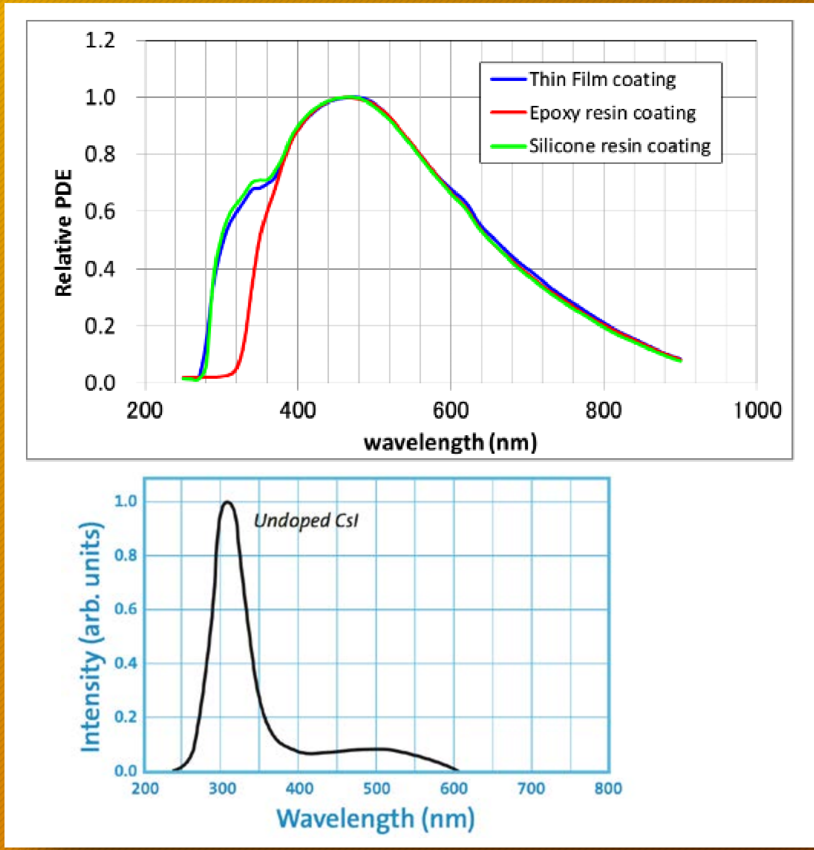
Radiation-induced noise (PMT+SiPM)



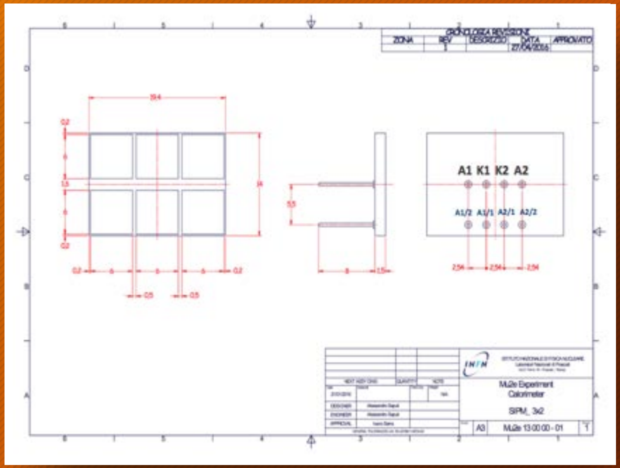
- RIN measurements of preproduction crystals from three manufacturers at Caltech and LNF are in agreement
- RIN and fast/slow component ratio are correlated
  This will be useful in developing final acceptance criteria

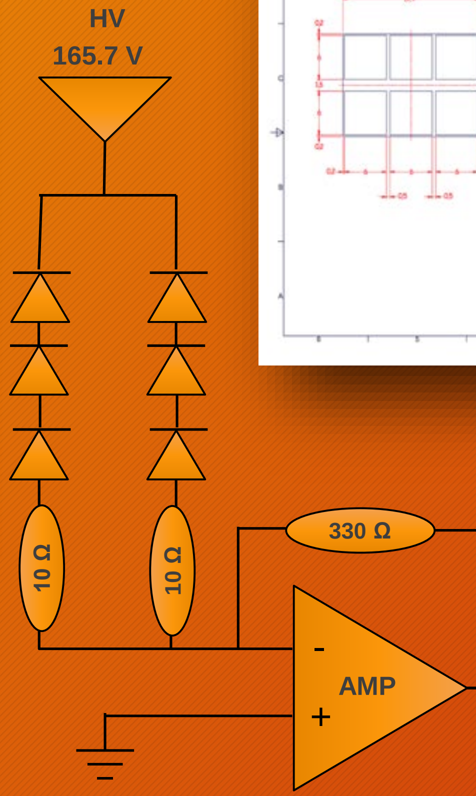
Side A	RIN PMT (KeV)	RIN SIPM (KeV)
C0011 - S	629	718
C0020 - A	713	1299
C0053 - SG	226	385

Extended response SiPMs match CsI spectrum

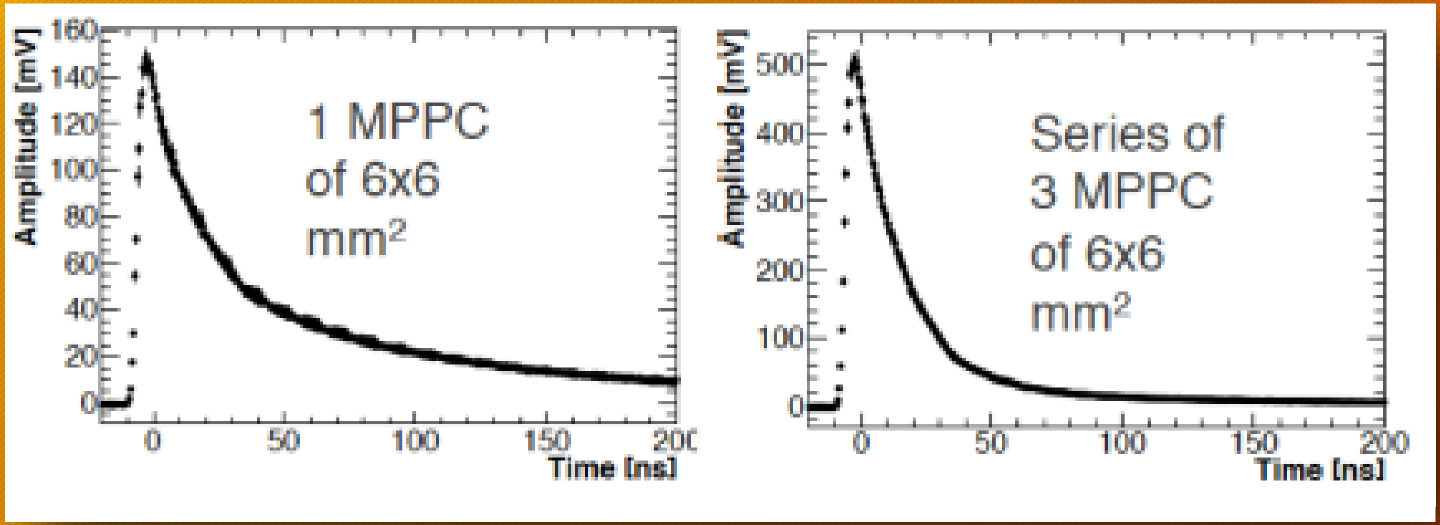


- Six 6x6mm cells in a 2x3 array
  - 50 mm pixels
  - Biased in series/parallel

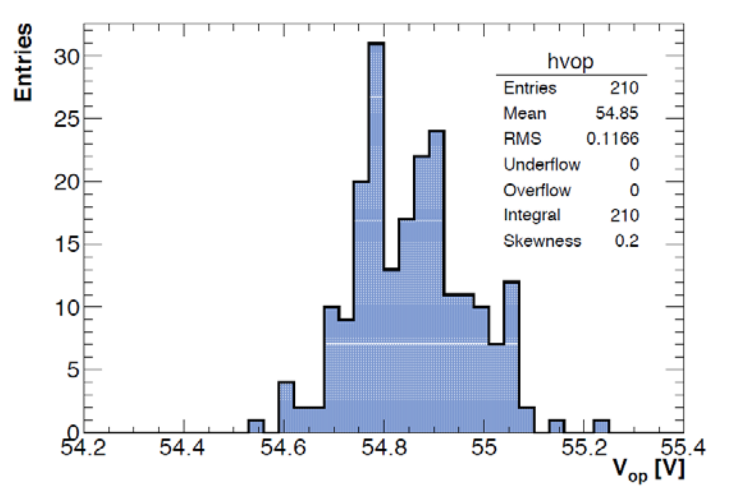




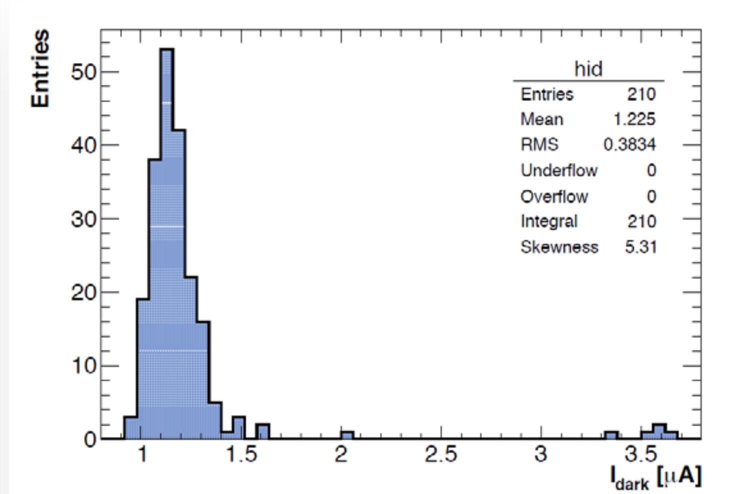
Series coupling improves decay time



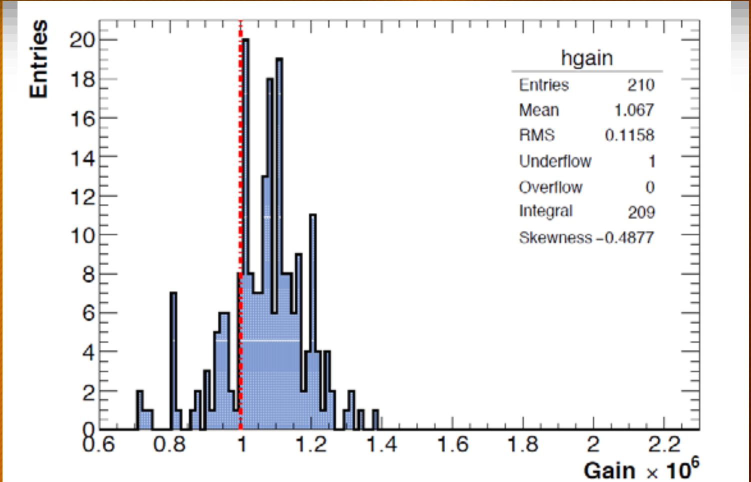
35 SiPM samples from each of 3 suppliers tested



Operating voltage - Hamamatsu



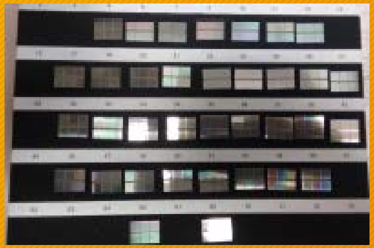
Dark current - SensL



Gain - Advancid

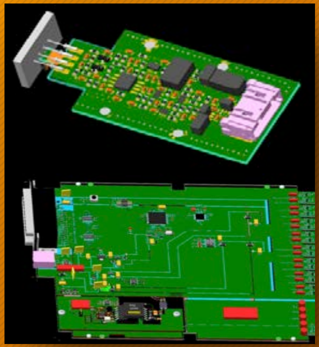
SiPM preproduction articles

Hamamatsu



SENSL

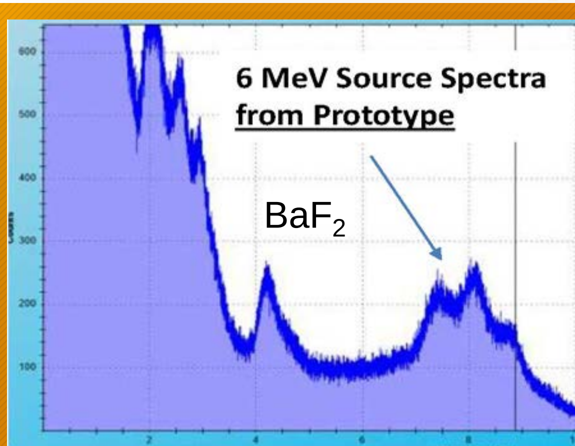
Advansid

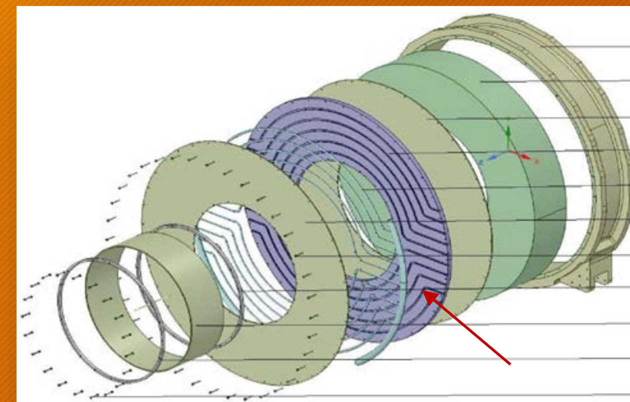


Calibration and monitoring

1) The *BaBar* calibration source has been rebuilt to provide 6.129266 MeV γ s on demand

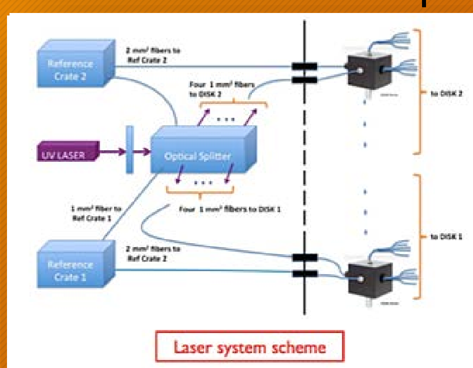
$$
\begin{aligned}
{}^{19}F + n \rightarrow\ & {}^{16}N + \alpha \\
& {}^{16}N \rightarrow {}^{16}O^{*} + \beta \quad t_{1/2} = 7\ \mathrm{s} \\
& \quad {}^{16}O^{*} \rightarrow {}^{16}O + \gamma(6.13\ \mathrm{MeV})
\end{aligned}
$$



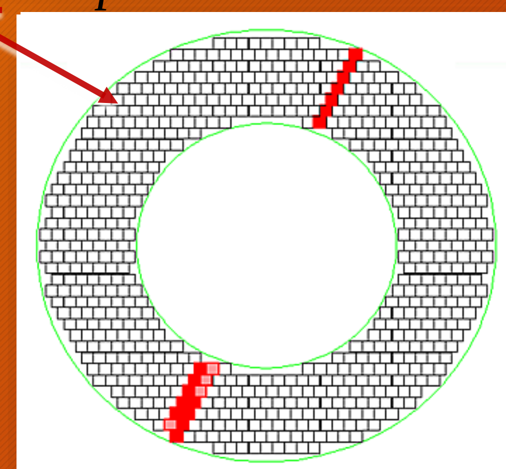


Source calibration tubes

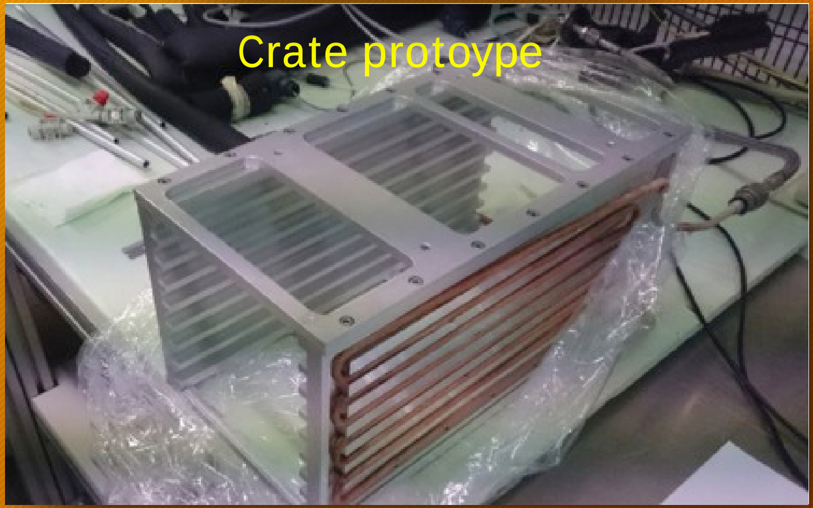
2) Laser system to monitor SiPM performance

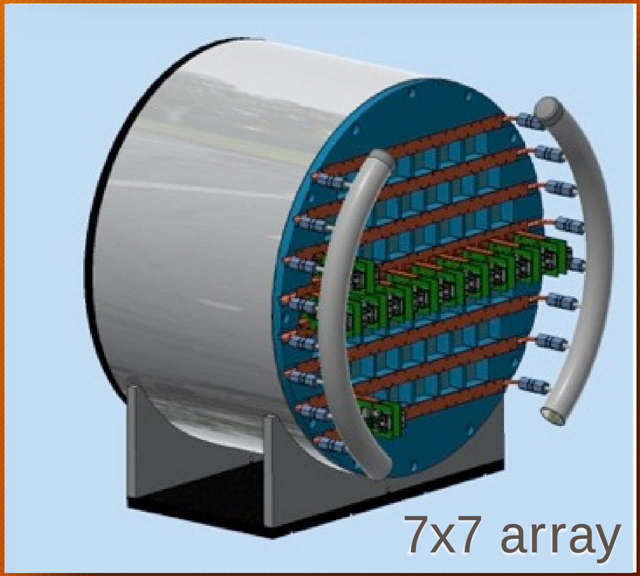


3) Cosmics + E/p for DIOs at reduced B field

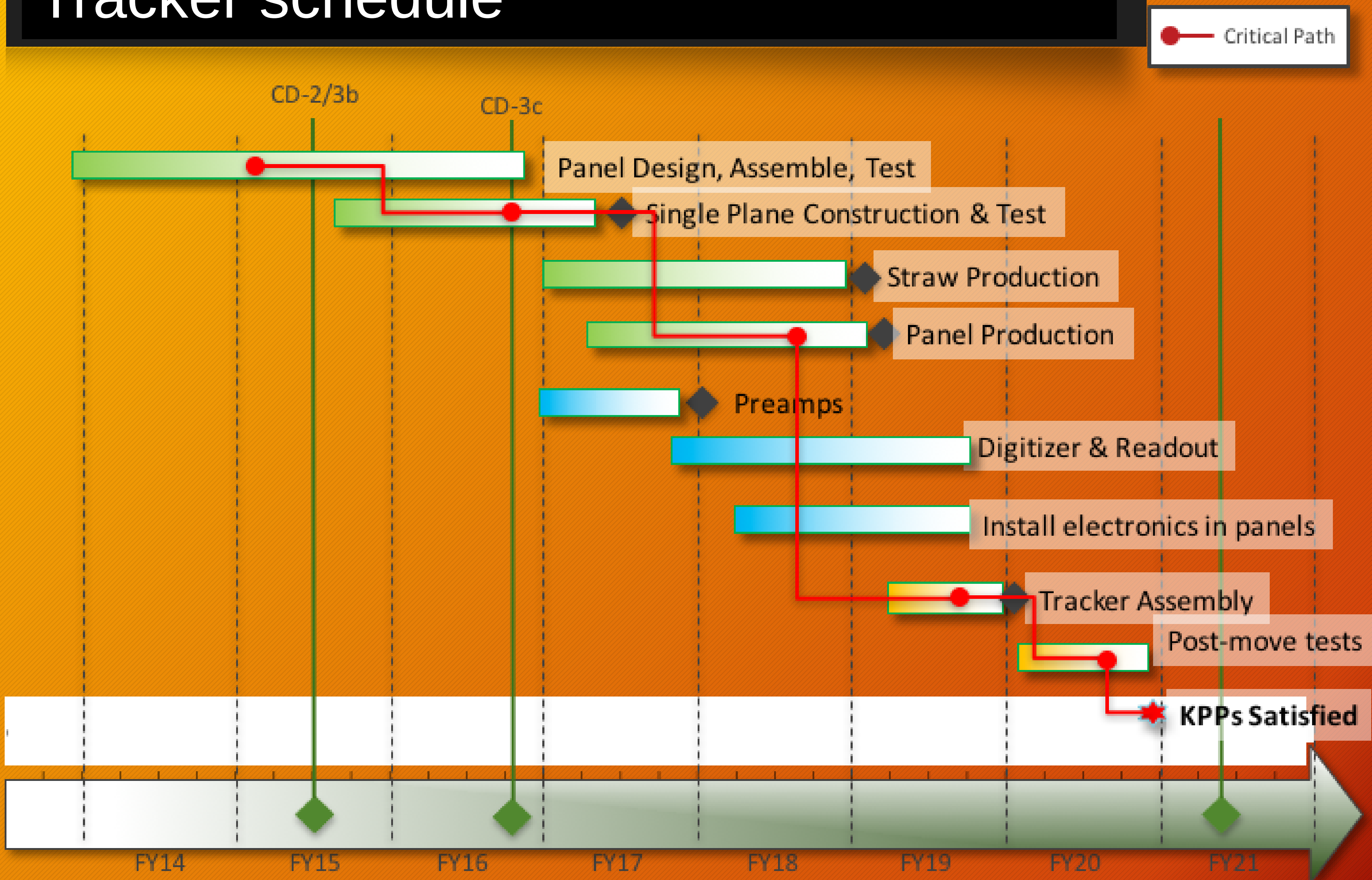


Prototyping/testing

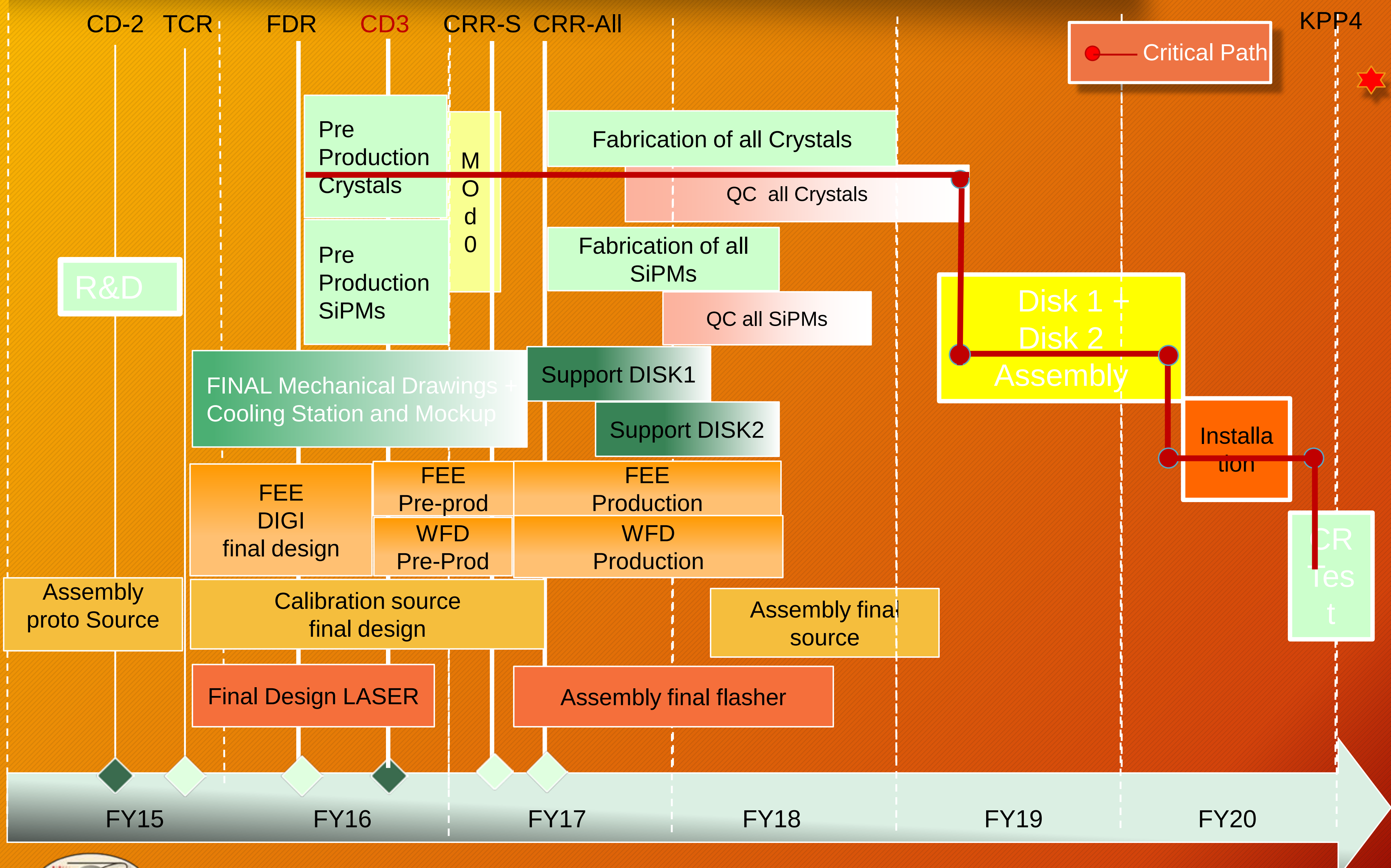




Tracker schedule



Calorimeter schedule



Conclusions

- A straw tube tracker and a CsI-crystal-based calorimeter with SiPM readout form the heart of the Mu2e experiment, meeting the demanding physics requirements
- Operating in vacuum, they together provide conversion electron measurement, electron identification and background rejection in a high rate, high background environment adequate to give Mu2e a single event sensitivity of $\sim 2.5 \times 10^{-17}$ in a three year run
- Both systems areat the end of their prototyping phase and are about to enter production on schedule