LYSO Crystal Calorimeter in Mu2e Experiment

Chih-hsiang Cheng
Caltech
For the Mu2e Collaboration

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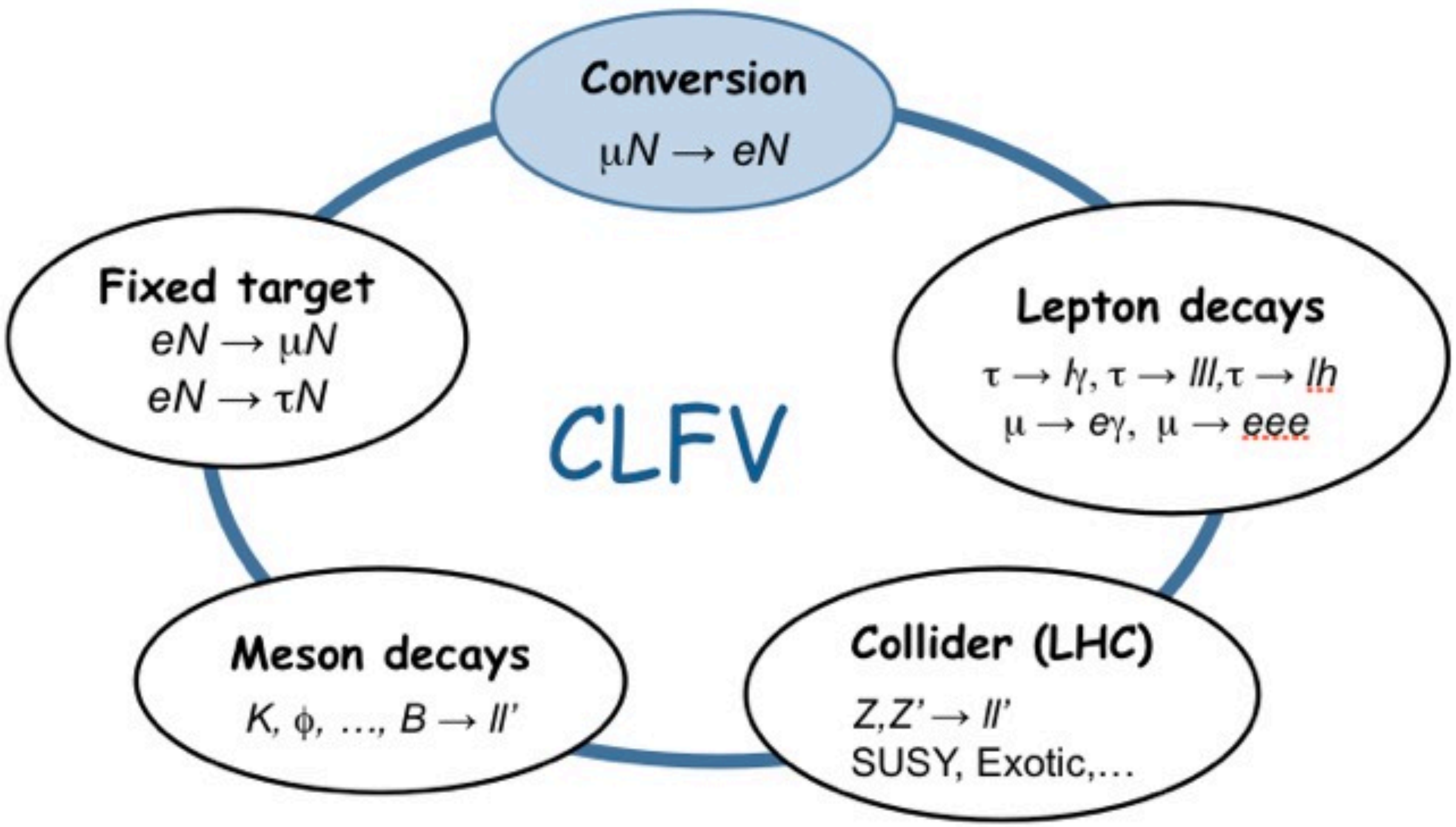
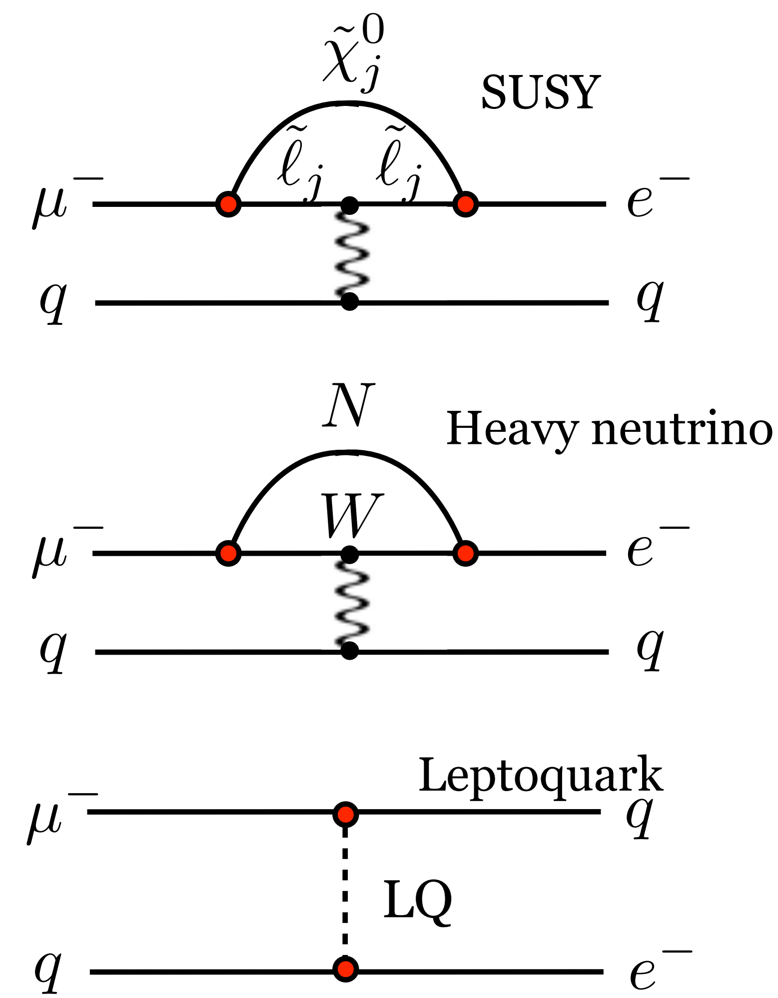
Charged lepton flavor violation

- Charged lepton flavor violation in the Standard Model is not detectable.
- Many new physics models could enhance the rate to detectable level. Observation of CLFV is a clear sign of new physics.





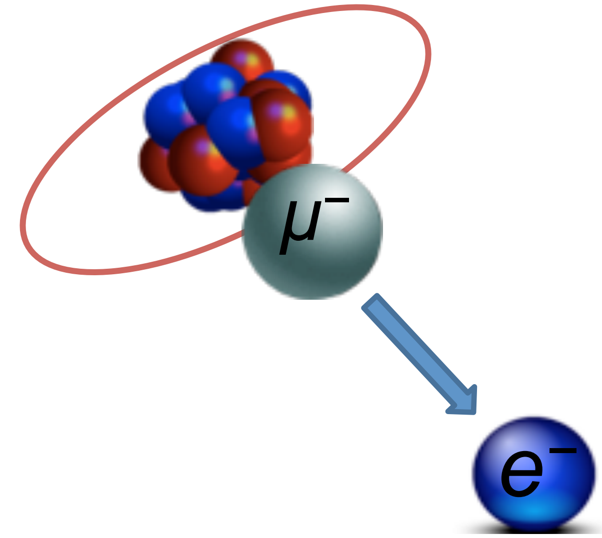
etc., etc.,

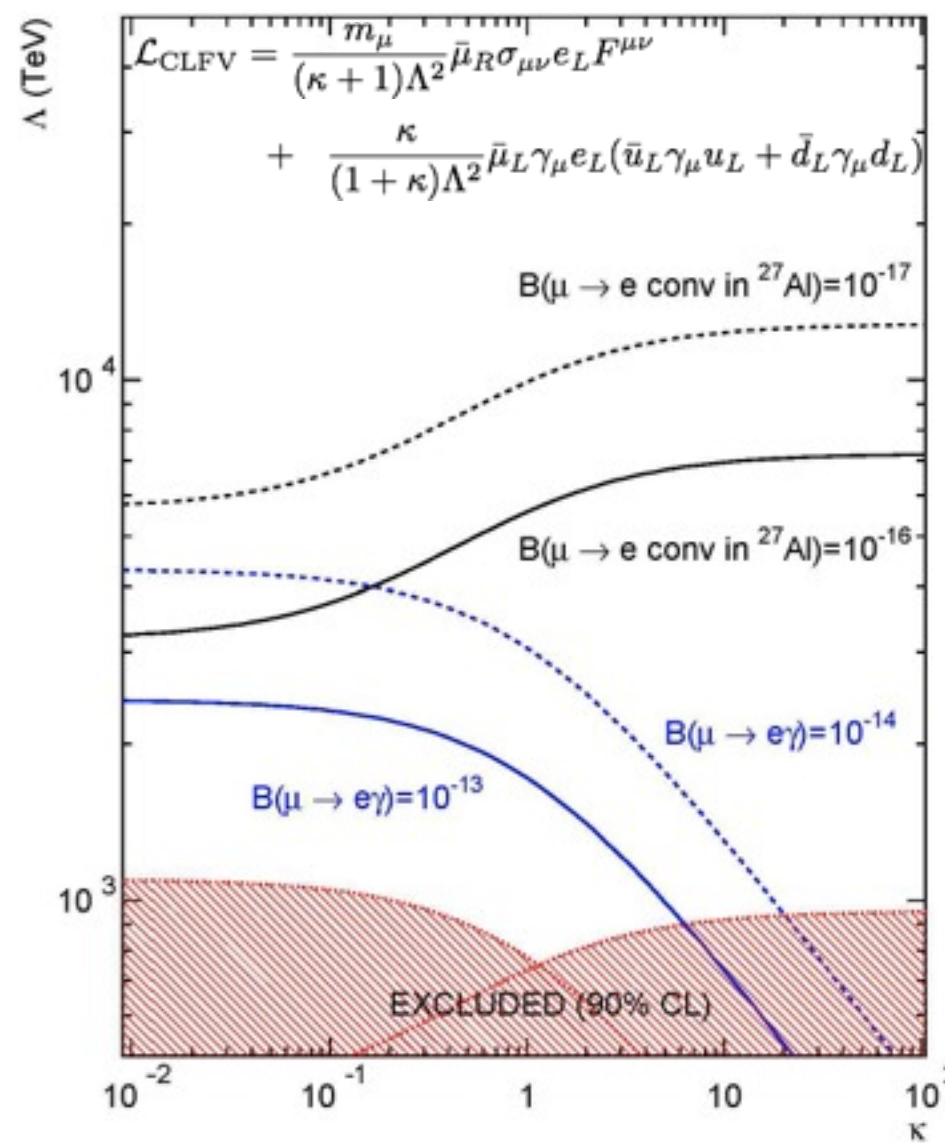
Muon to electron conversion

- Muon stopped and captured by a nucleus.
- Signal to search for: mono-energetic electron (neutrinoless) with $E_e = m_\mu - E_{\text{binding}} - E_{\text{recoil}}$.
- For Al^{27} target, E_e=104.96 MeV.
- Goal of Mu2e:

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

$< 6\times10^{-17}$ limit at 90% C.L.





A. De Gouvea, Prog.Part.Nucl.Phys. 71 (2013) 75-92

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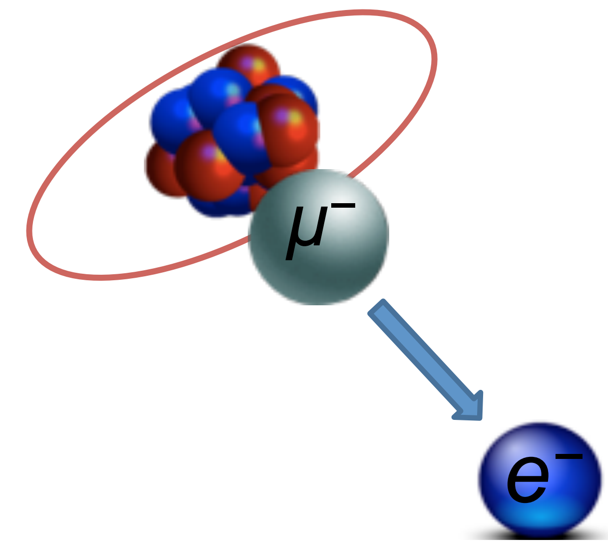
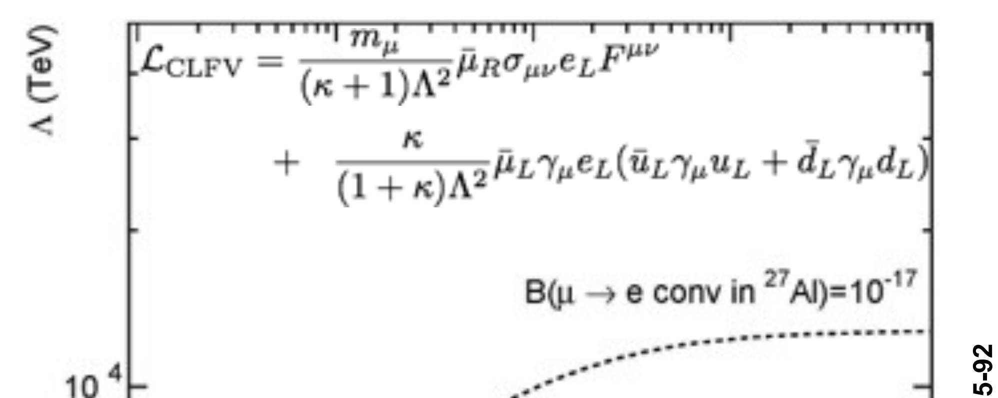
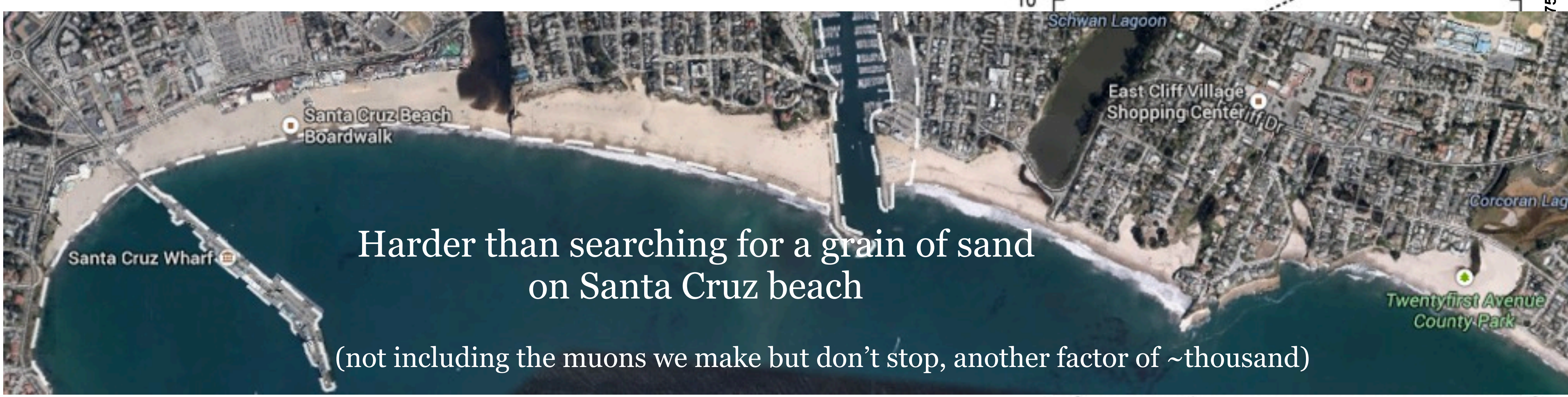


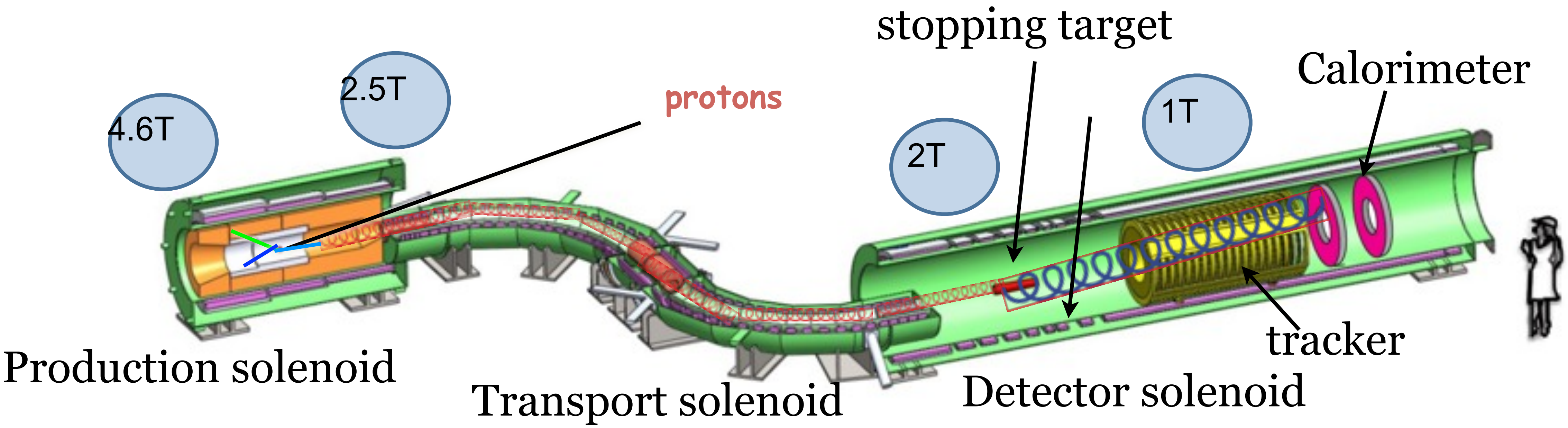


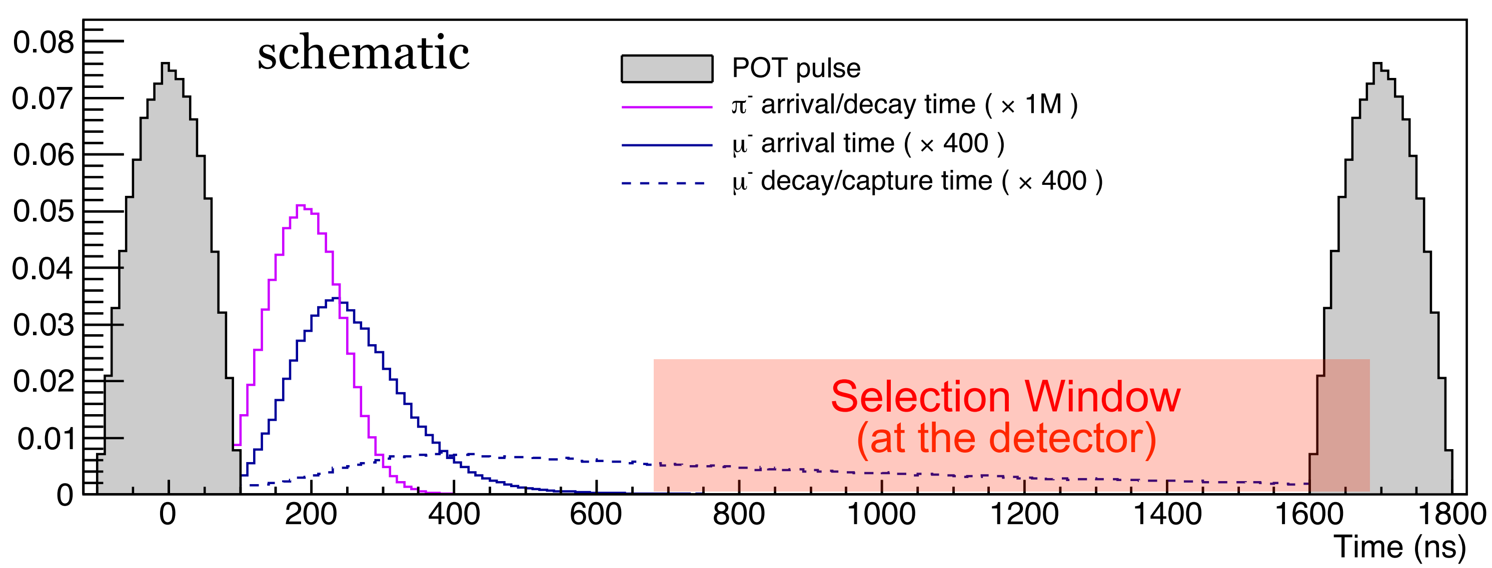


Harder than searching for a grain of sand on Santa Cruz beach

(not including the muons we make but don't stop, another factor of ~thousand)

Mu2e experiment

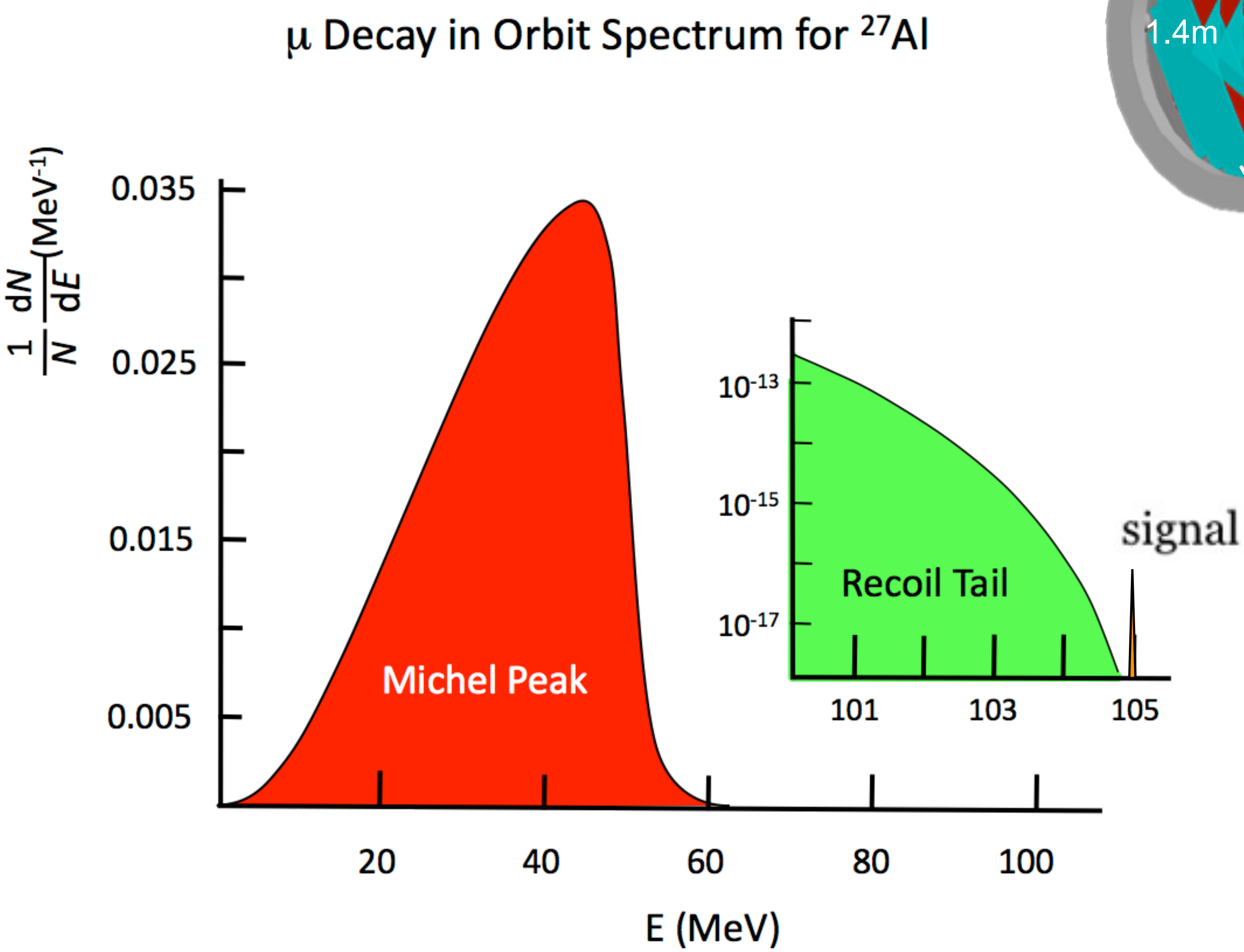


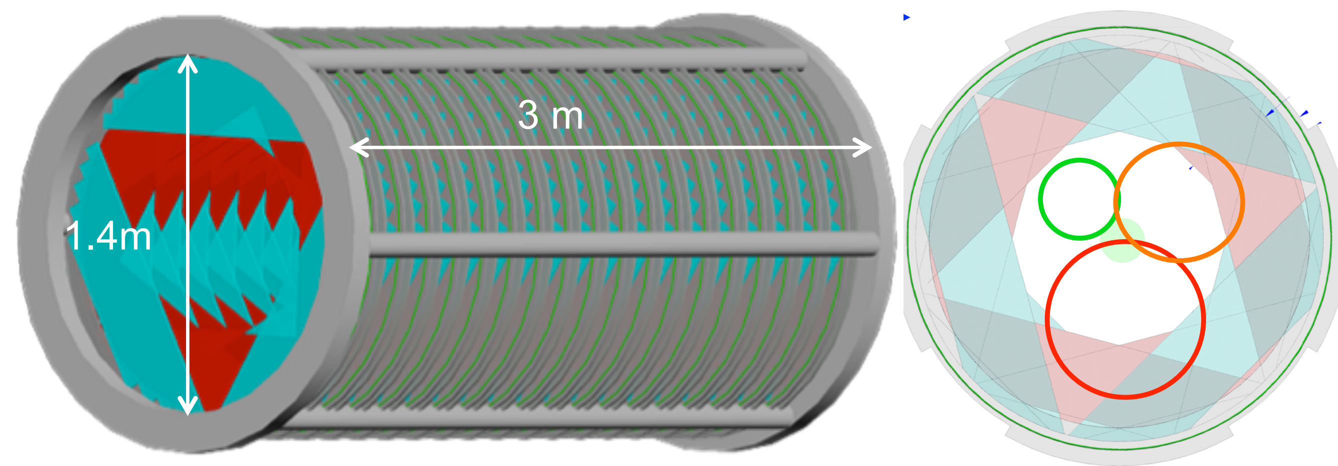


Detecting 1 out of $>10^{17}$

Major background:

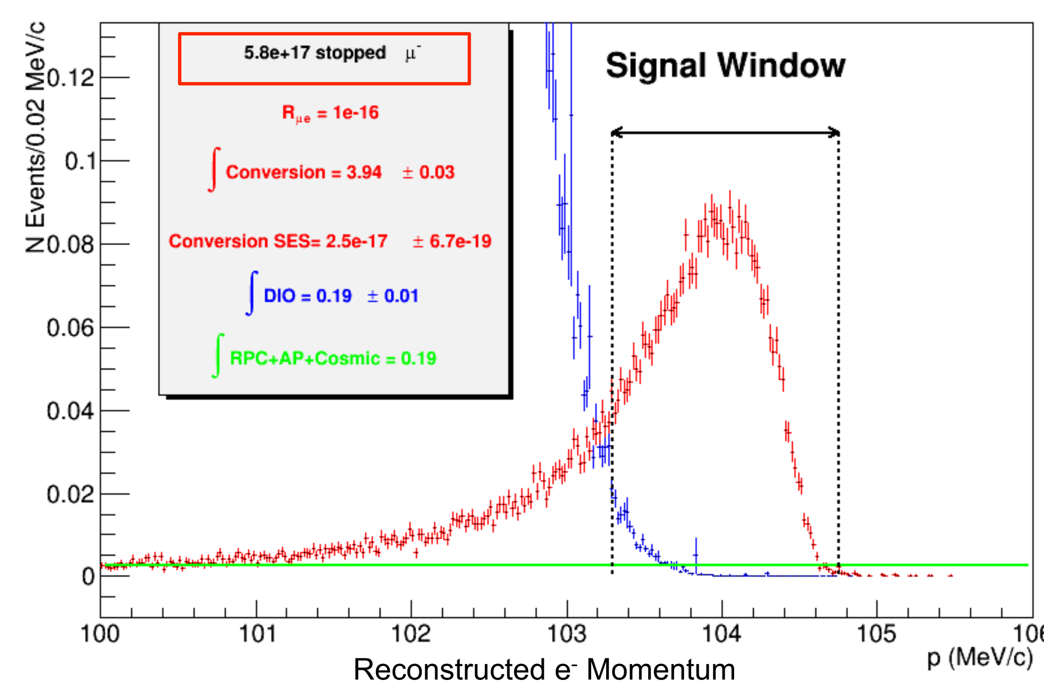
$$[\mu^- + A(N,Z)]^{1S}_{bound} \rightarrow A(N,Z) + e^- + \bar{\nu}_e + \nu_\mu$$





Light-weight straw tube tracker

excellent momentum resolution:
120 - 180 keV

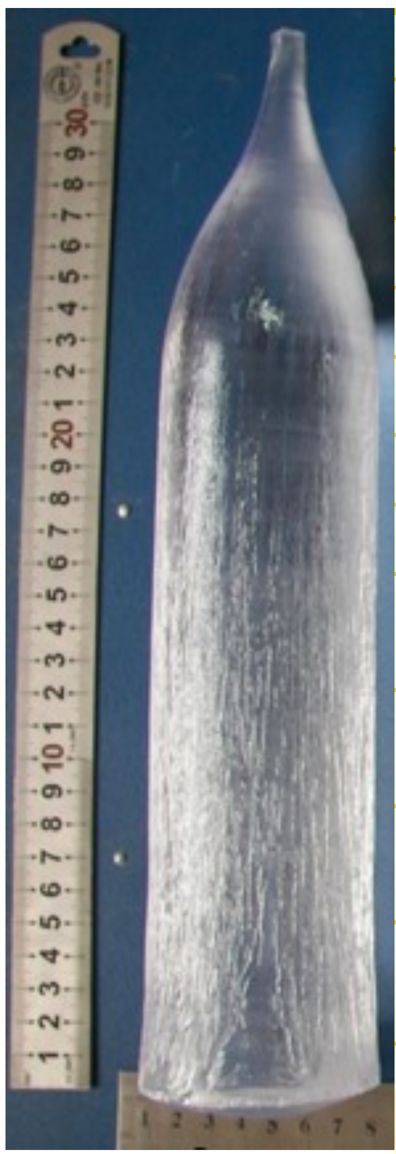


Role of calorimeter

- Confirm a reconstructed track is well measured.
- Capable of providing seeds for track reconstruction.
- Trigger capability.
- Particle identification.
- Requires:
    - Good energy resolution so that there's no significant decay-in-orbit background in the signal region.
    - Good timing (<1 ns) and spatial (≤ 1 cm) resolution.
    - Radiation hard (≃80 Gy/year).
    - Operable in 1-T magnetic field.
    - Efficient trigger/filter ability ~few kHz.

LYSO Crystal

- LYSO (lutetium-yttrium oxyorthosilicate [Cerium doped]) crystal is chosen in the baseline design.



Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	LYSO(Ce)	PWO	PbF_2
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	7.40	8.3	7.77
Melting Point (°C)	651	621	621	1280	1050	2050	1123	824
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89	0.93
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00	2.21
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.9	20.7	21.0
Refractive Index [a]	1.85	1.79	1.95	1.50	2.15	1.82	2.20	1.82
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Luminescence [b] (nm) (at peak)	410	550	420 310	300 220	480	402	425 420	?
Decay Time [b] (ns)	245	1220	30 6	650 0.9	300	40	30 10	?
Light Yield [b,c] (%)	100	165	3.6 1.1	36 4.1	21	85	0.3 0.1	?
d(LY)/dT [b] (%/ °C)	-0.2	0.4	-1.4	-1.9 0.1	-0.9	-0.2	-2.5	?
Experiment	Crystal Ball	BaBar BELLE BES III	KTeV	(L*) (GEM) TAPS	L3 BELLE	KLOE-2 SuperB SLHC?	CMS ALICE PANDA	HHCAL?

LYSO

high melting point

small Xo

~small Moliere Radius

non-hygroscopic

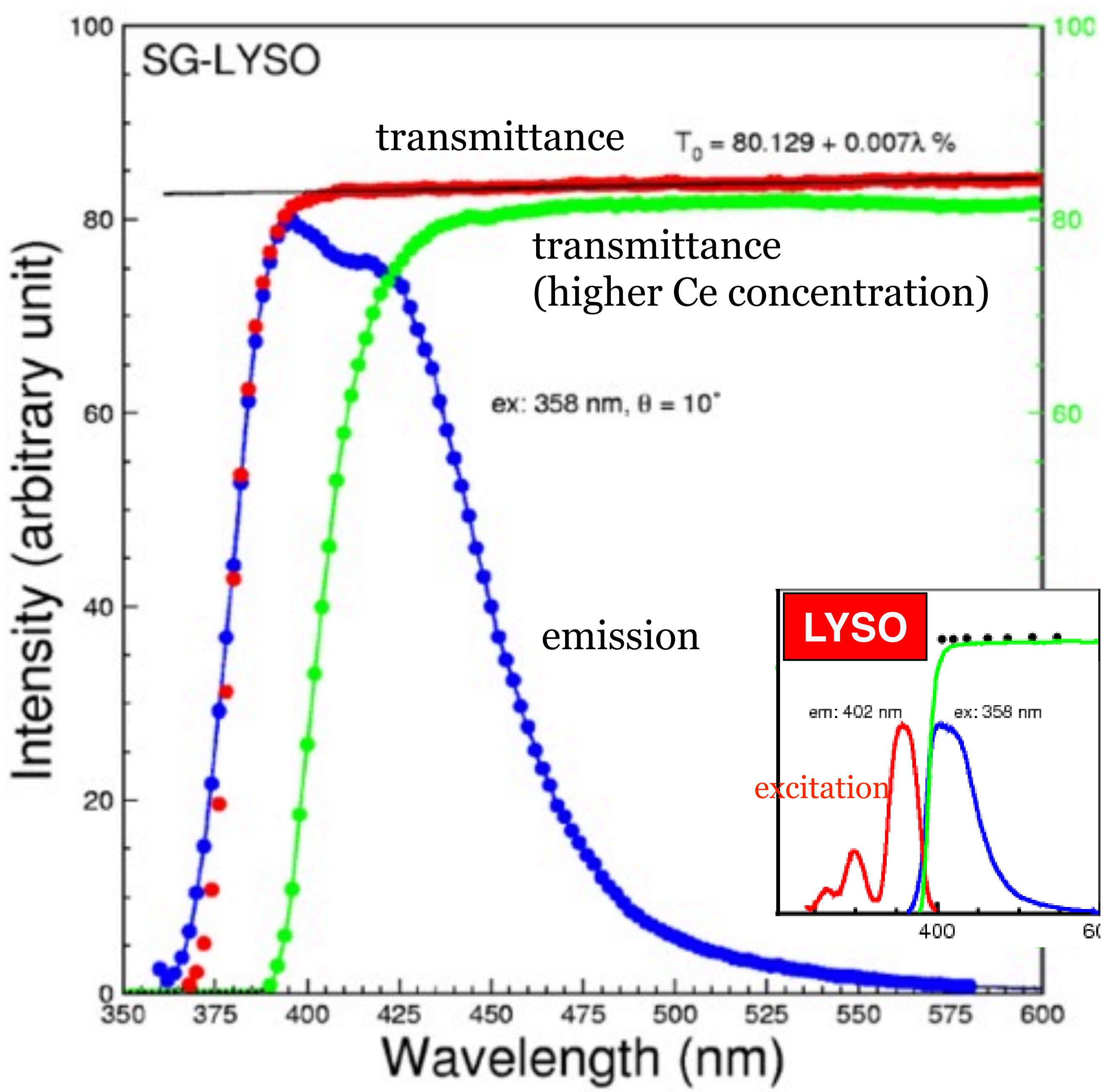
fast

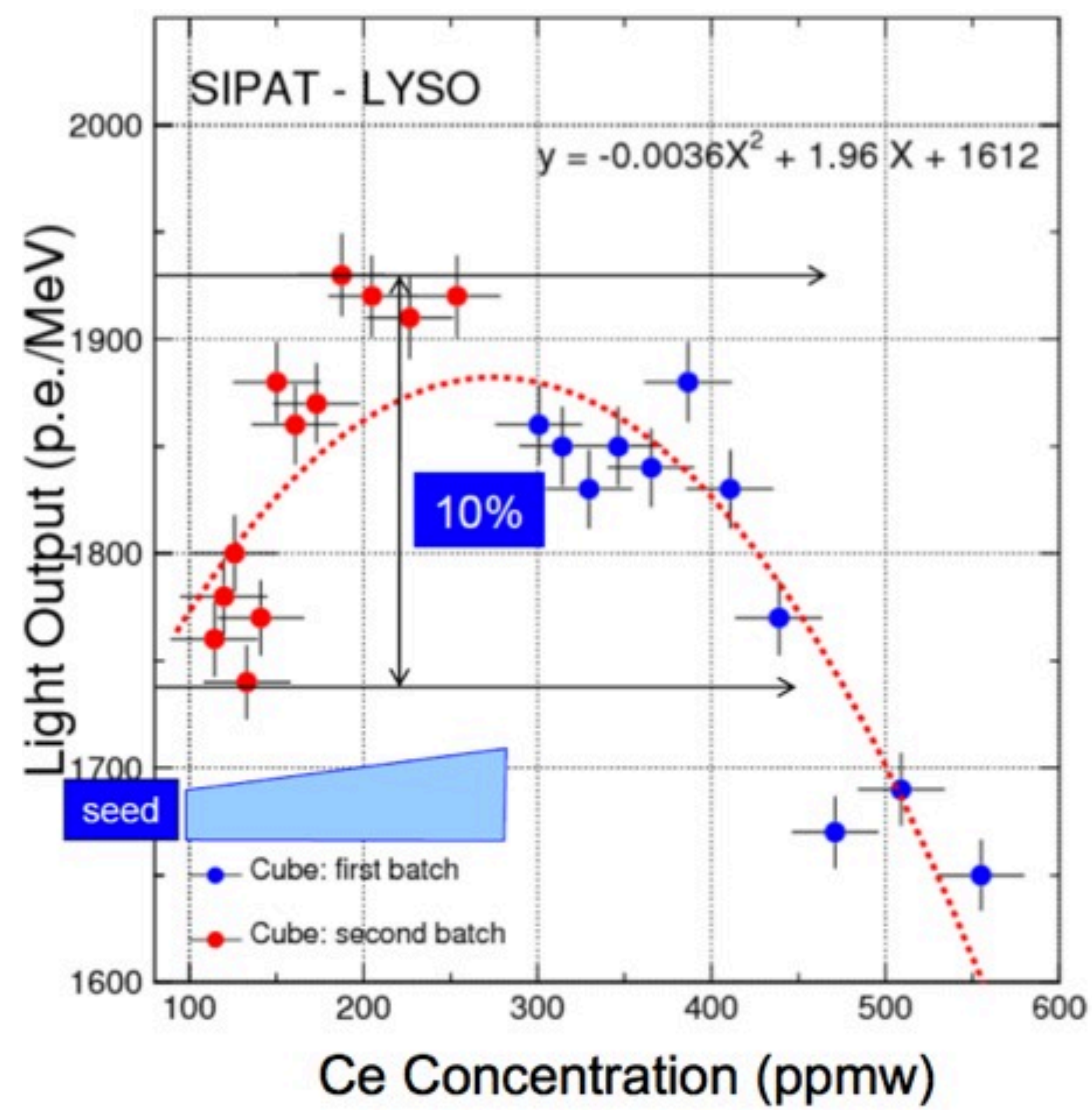
bright

radiation hard

NaI(Tl) light yield ~40000/MeV

LYSO scintillation property

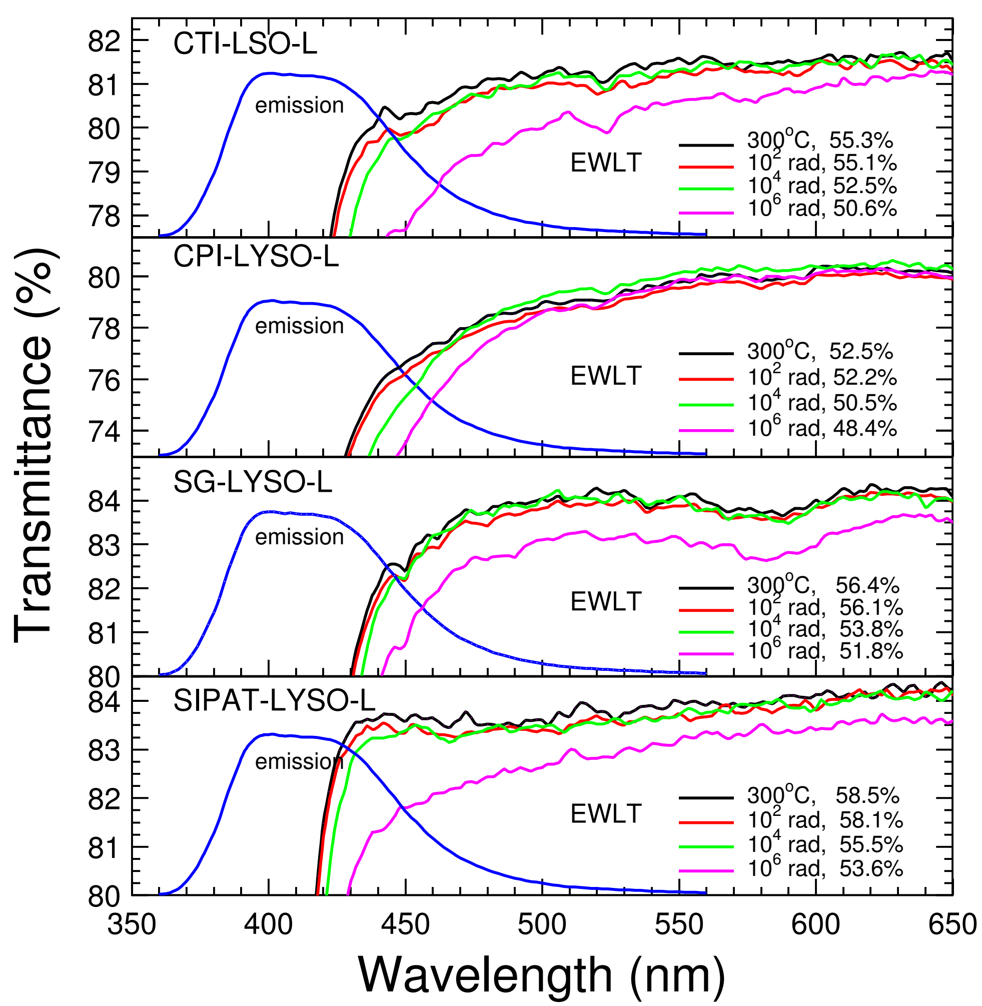


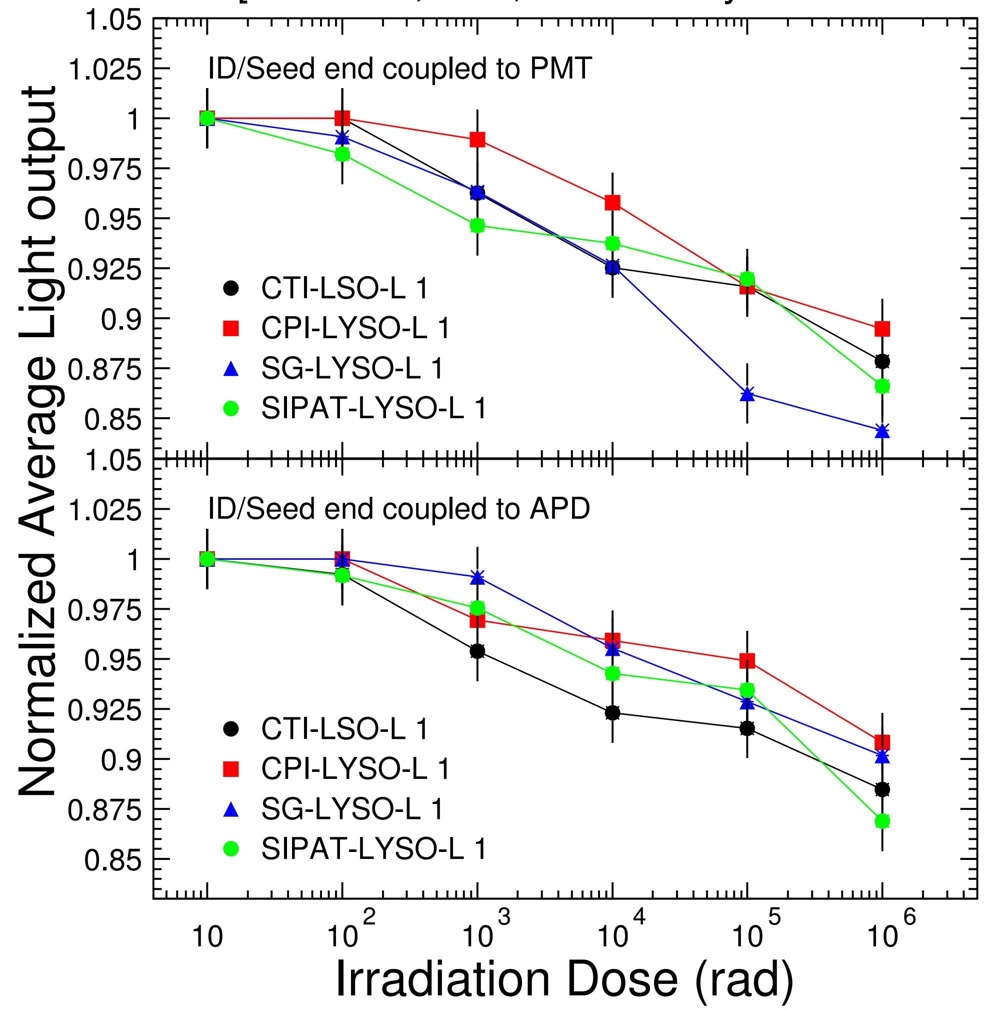


Radiation hardness

- ~10% loss of light after 1 Mrad (=10 kGy, ~50x expected dose in Mu2e) γ-ray irradiation.
  - ✦ slow recovery at room temperature;
  - ✦ can be cured by thermal annealing at 300°C for 10 hours.

[R.-Y. Zhu, et al, 2011 J. Phys.: Conf. Ser. 293 012004]

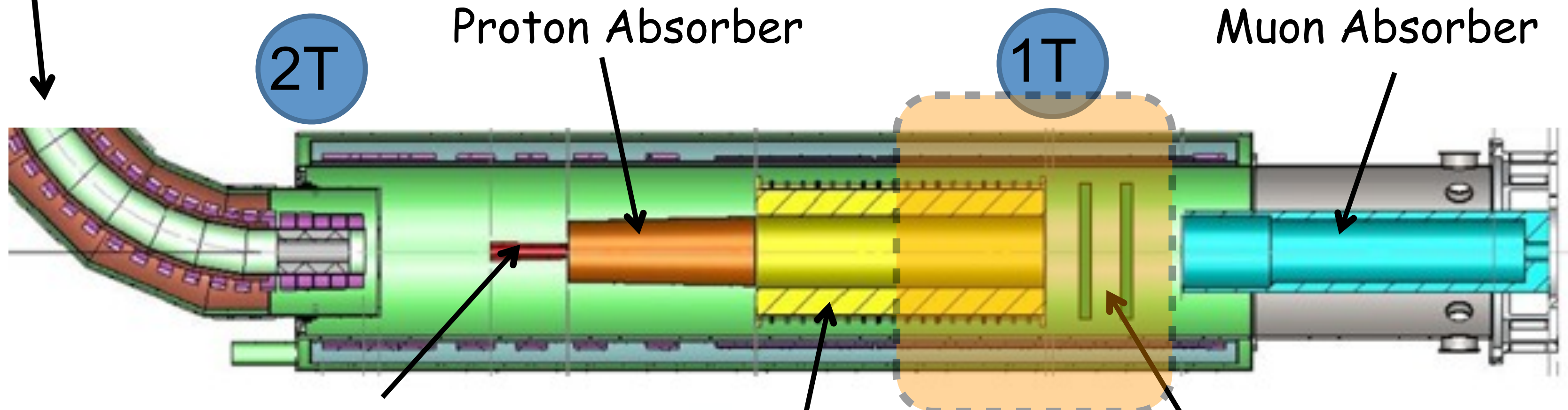


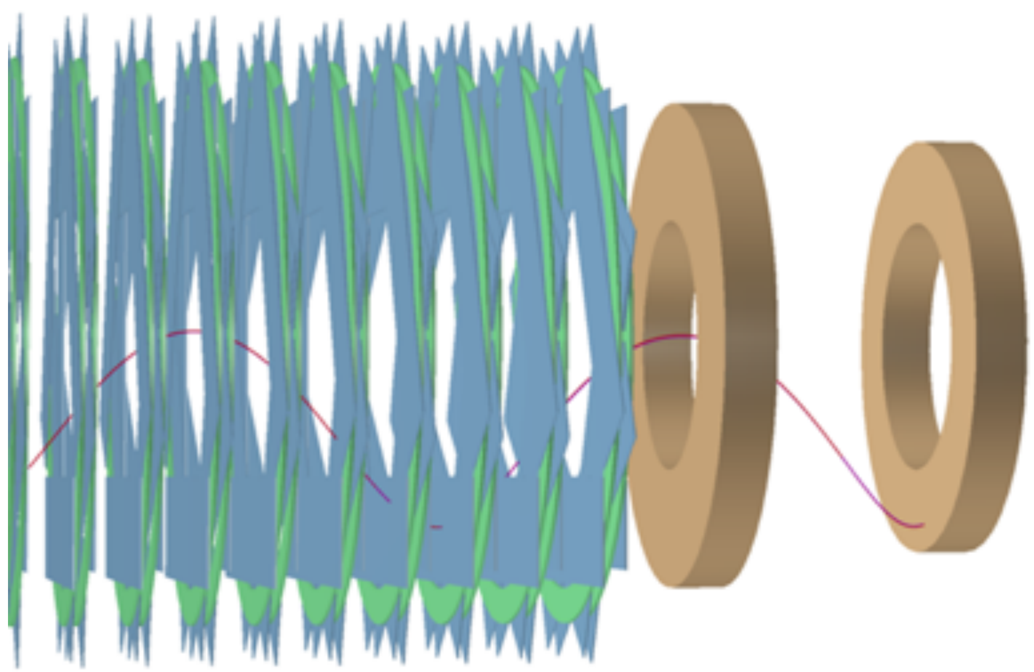


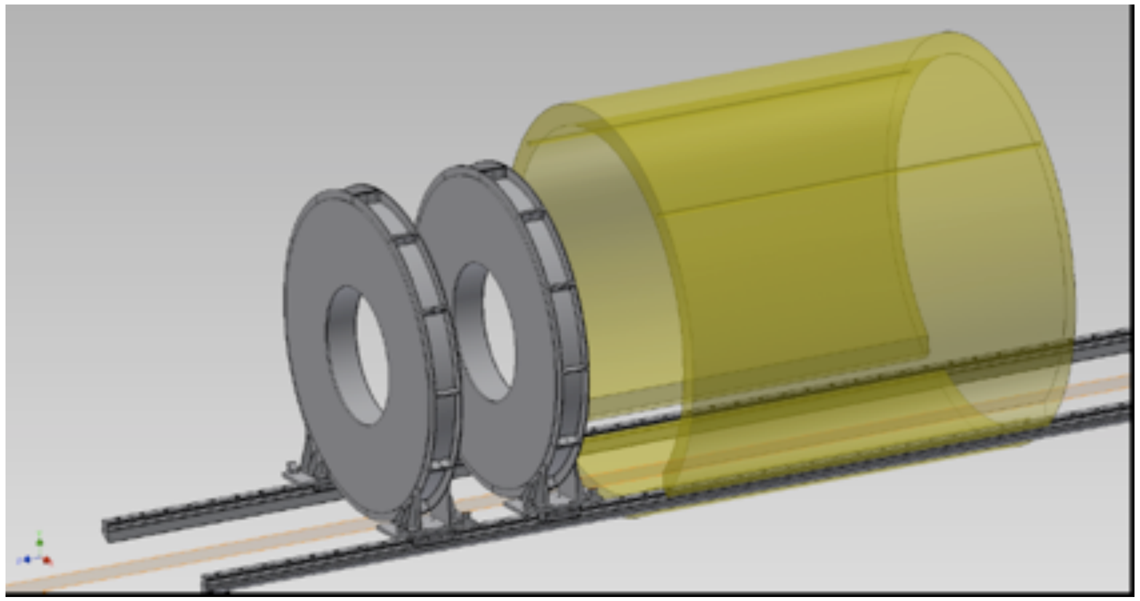
Tests on 25×25×200 mm³ crystals

Photo-luminescence weighted longitudinal transmittance $= \frac{\int LT(\lambda)Em(\lambda)d\lambda}{\int Em(\lambda)d\lambda}$

Detector layout

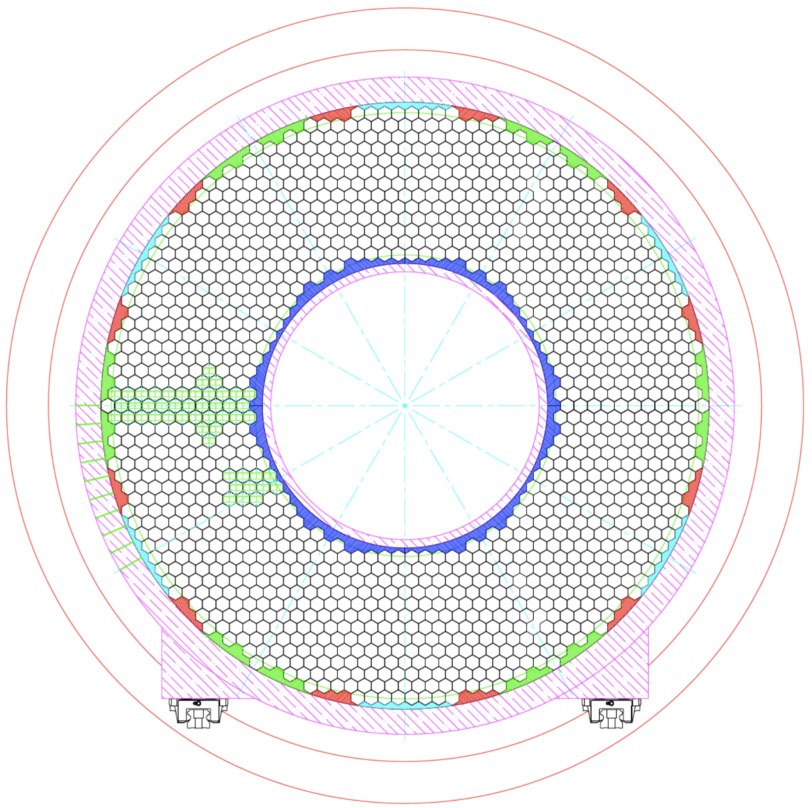




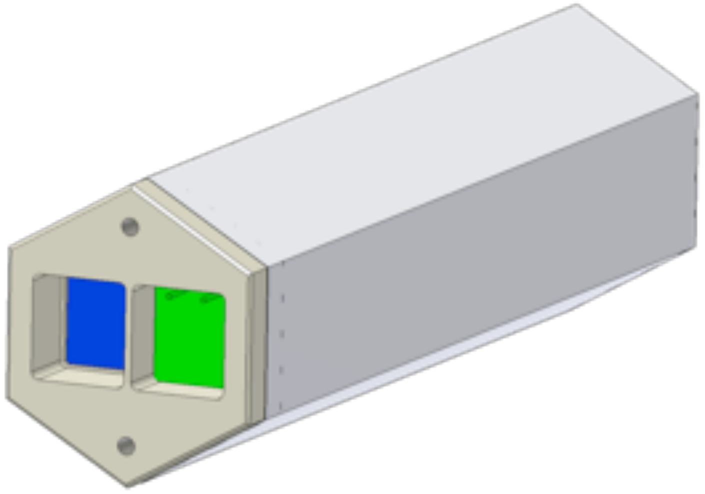


Baseline design

- Two disks consist of ~2000 haxagonal (or square) LYSO crystals.
  - ✦ Separation ~70 cm.
  - ✦ Inner/outer radii: 36-39/64-67 cm.
- $3\times3\times11$ cm^3 each crystal.
- Two 1×1 cm^2 APDs/crystal
- Many other issues to be resolved:
  - ✦ Wrapping, and structure (if any)
  - ✦ Linearization of response
  - ✦ Photosensor mounting
  - ✦ Preamp/HV config

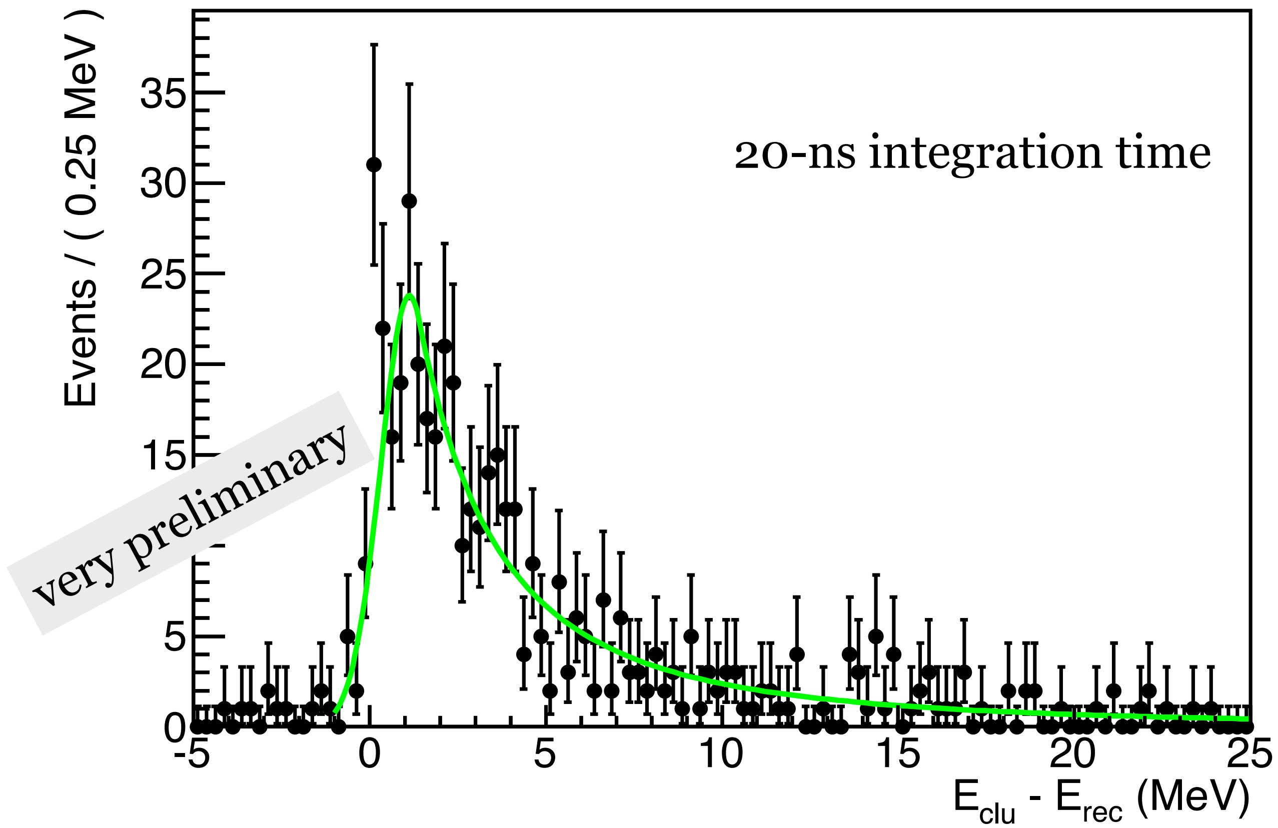


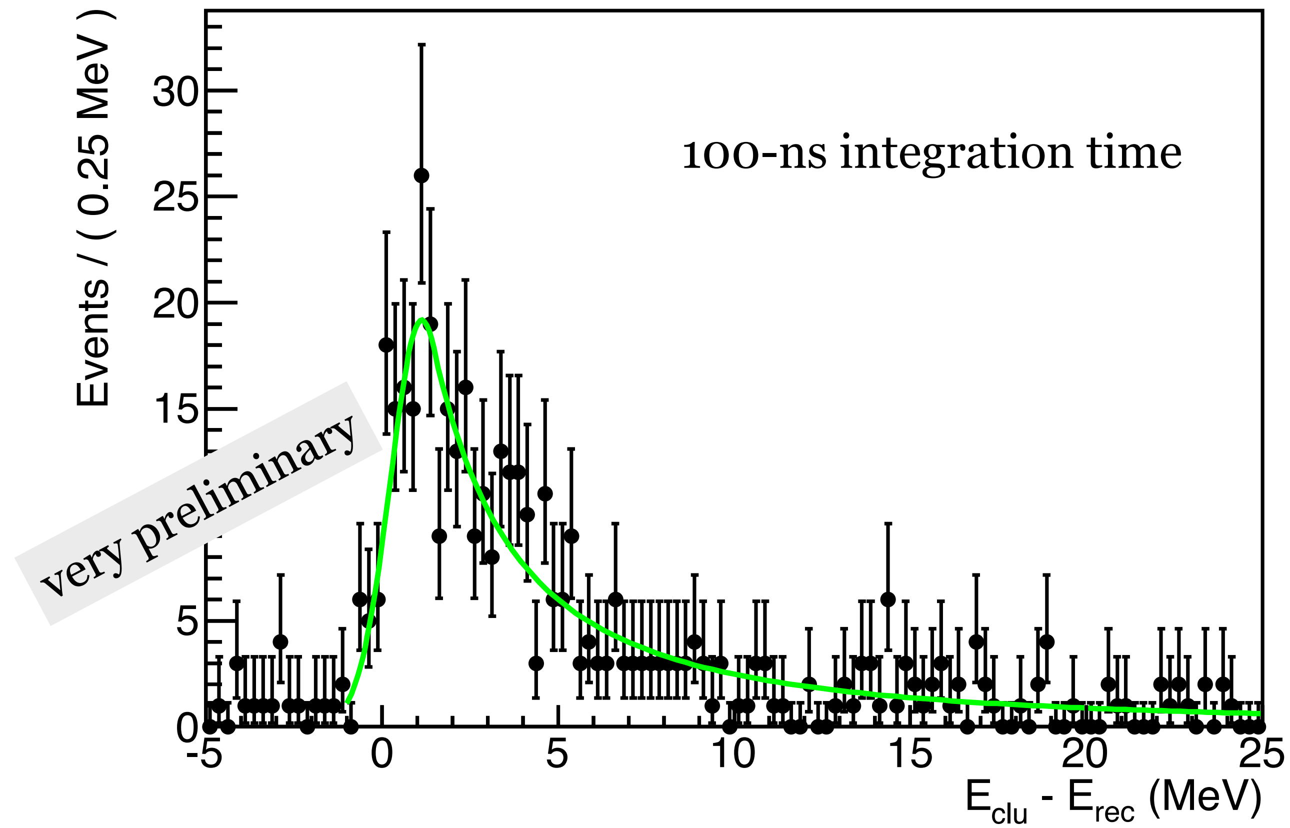
Detailed Geant4 simulation down to optical photon transport is underway



Energy resolution in simulation

- Geant4 simulation (signal electrons), including muon decay-in-orbit, neutron background, but *not* light collection, non-linearity, electronic noise, ...





(Energy loss (+pileup) in calorimeter alone)

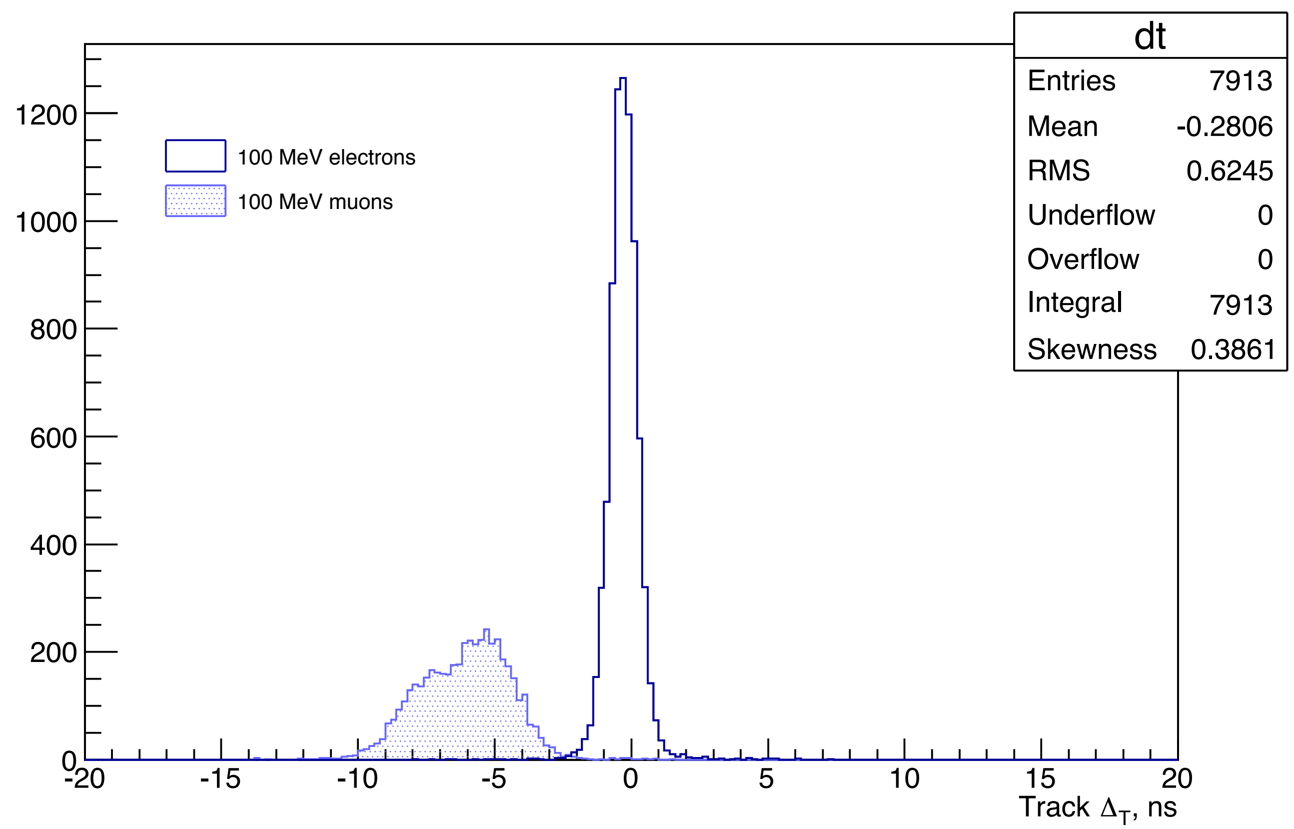
$\sigma \simeq 1.5$ MeV

FWHM/2.35 ≃ 1.7 MeV   Not very sensitive to background pile-up

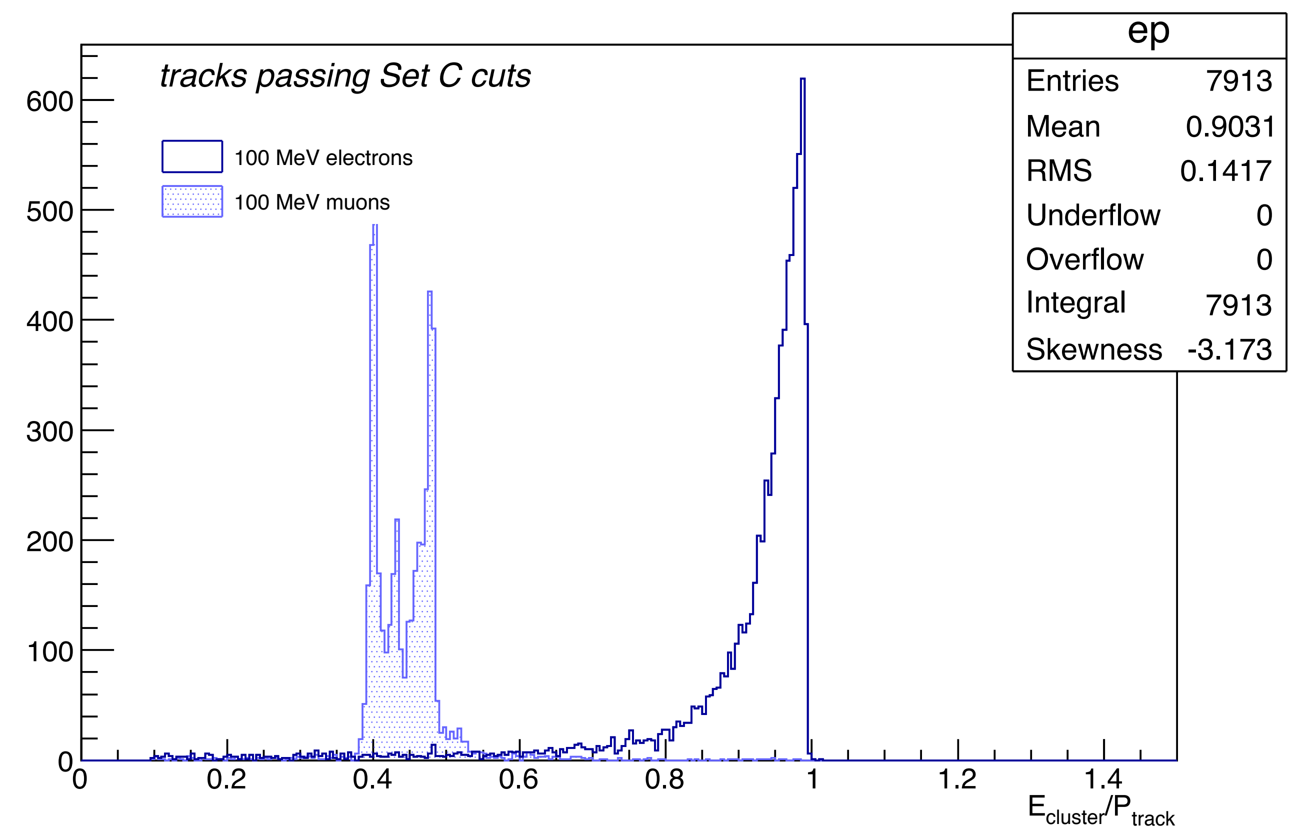
More studies with better estimated background and additional noise contributions are ongoing.

Particle identification

- Reject cosmic-induced background



Track Δt (ns)

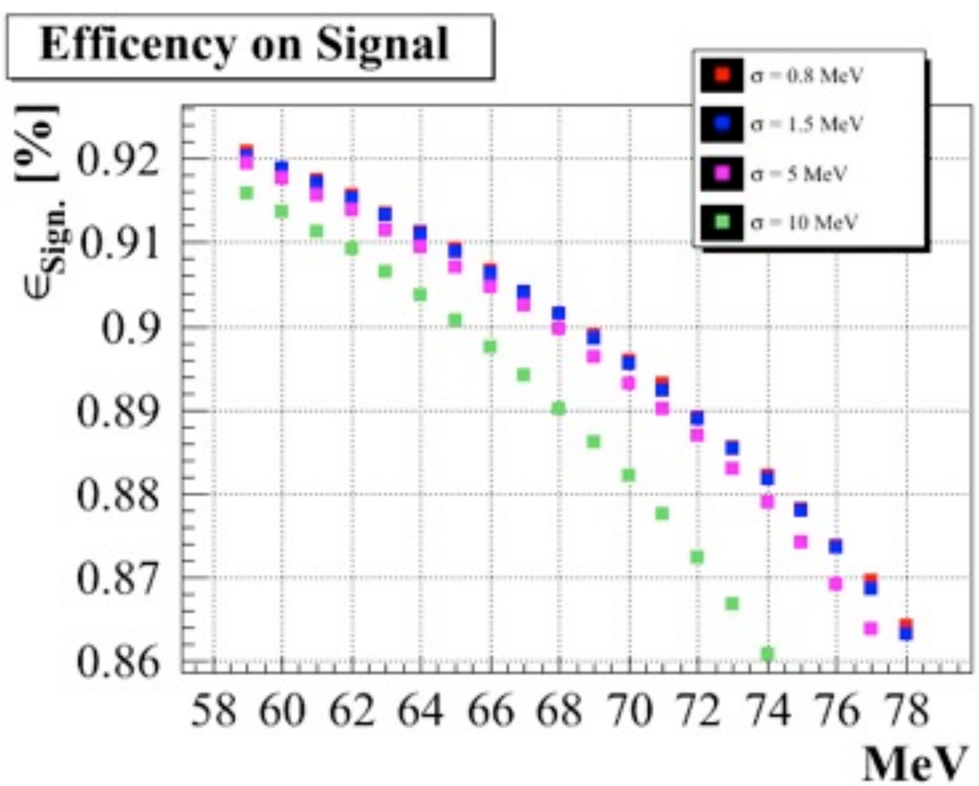


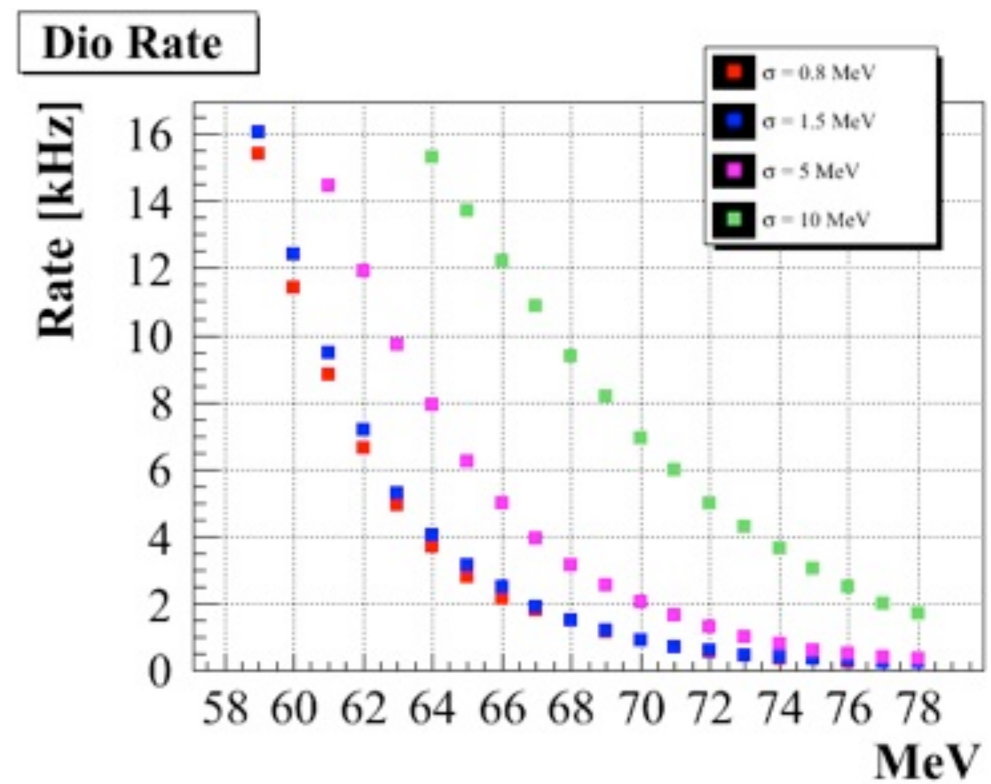
$E_{cluster}/P_{track}$

- Greatly improve muon rejection from tracker-only algorithm.
  - ✦ Tracker only: ϵ_e~92%, muon rejection ~5.
  - ✦ Calorimeter+Tracker: ϵ_e>99%, muon rejection ~10^2-10^3.

Calorimeter based trigger

- Trigger events with a cluster energy above a certain threshold.



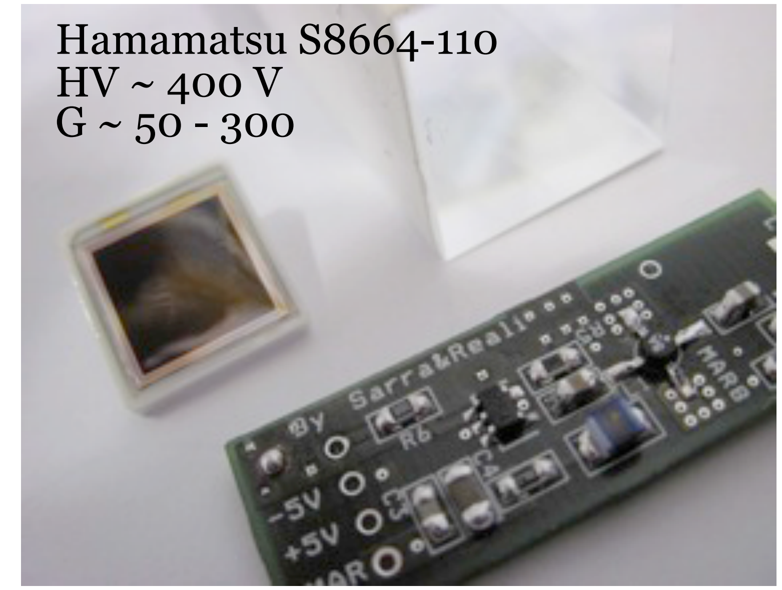


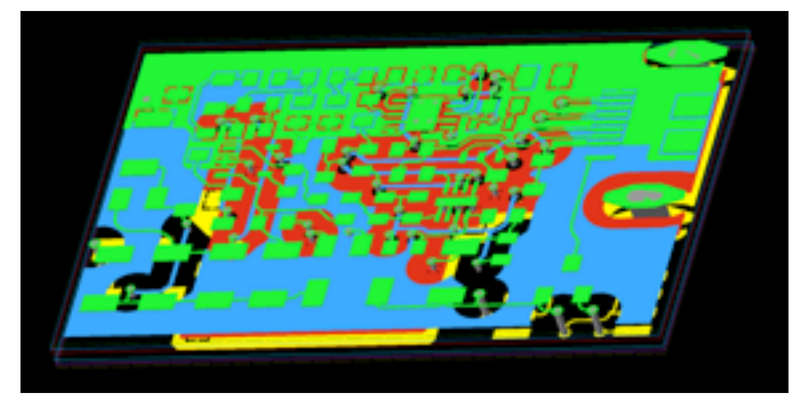
- @64 MeV (for example),
  - ✦ efficiency ~91%
  - ✦ reduce the DIO rate to <10 kHz.
- Efficiency/rejection depends on energy resolution.

Shown are simulations with "vanes" configuration.
Will repeat the study with "disks" configuration

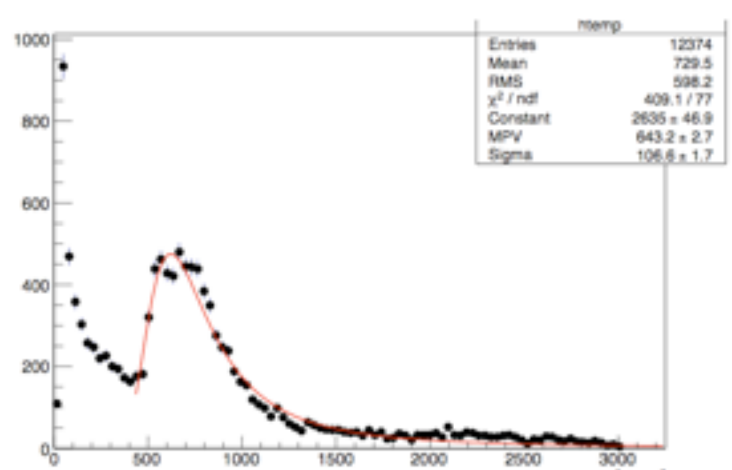
Photosensors

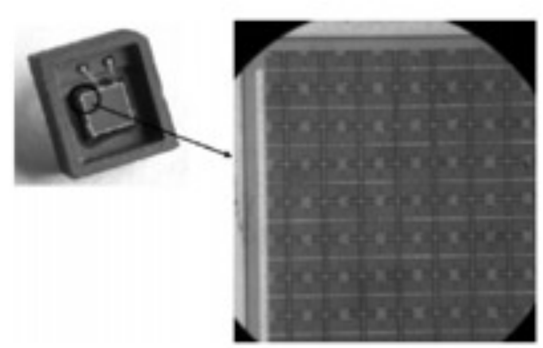
- Large area APD (10×10 mm²). Two/crystal.
  - ✦ functional in 1-T field
  - ✦ fast/proportional response
  - ✦ gain from 50 to 1000
  - ✦ large collection and quantum efficiencies.
- New preamplifier design, <50 keV noise, integrated HV linear regulator on board.

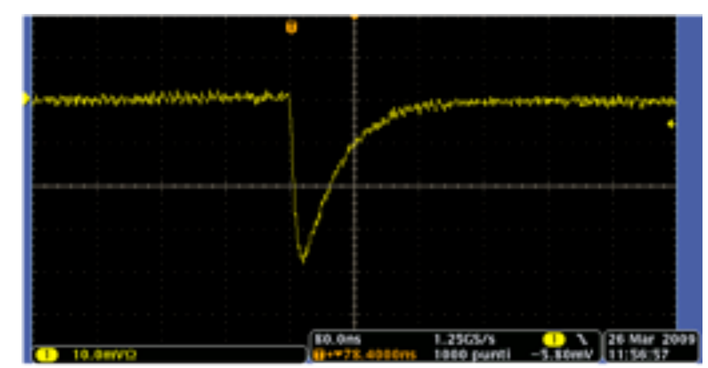




- Alternative: Large Area SIPM



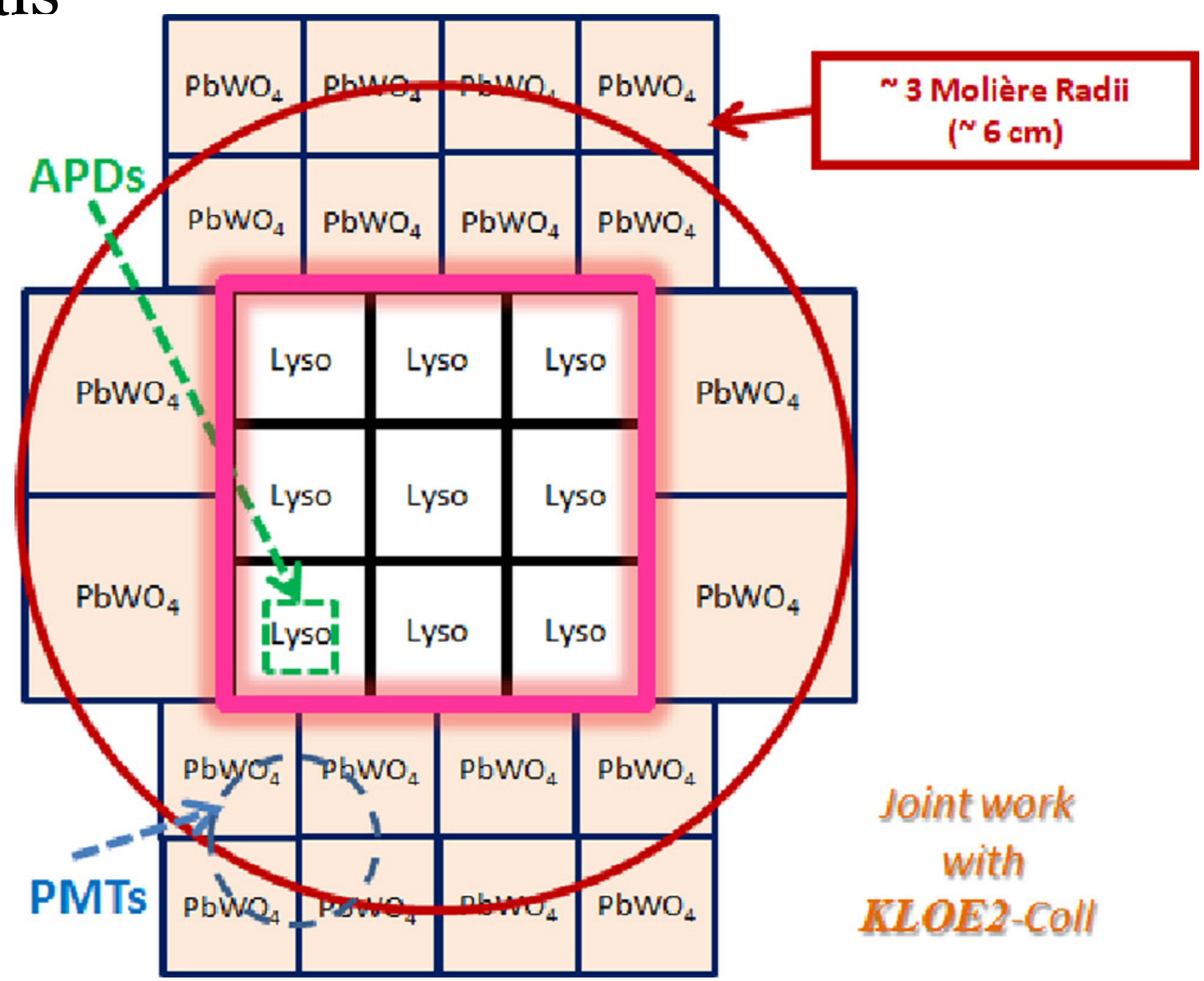




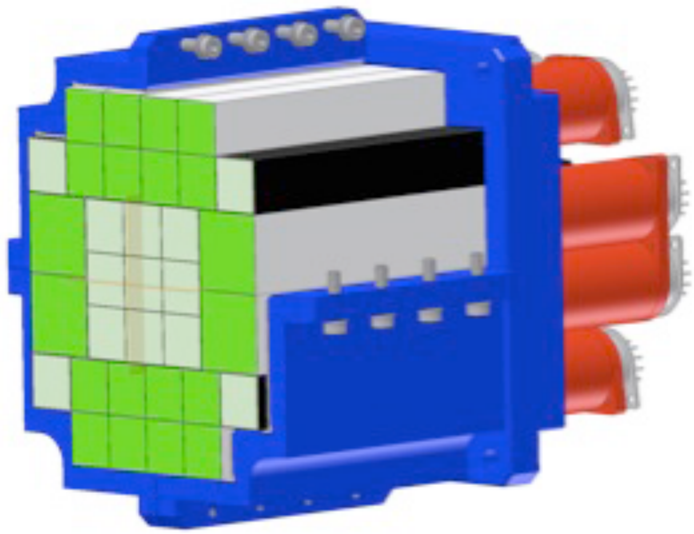
Beam test at MAMI

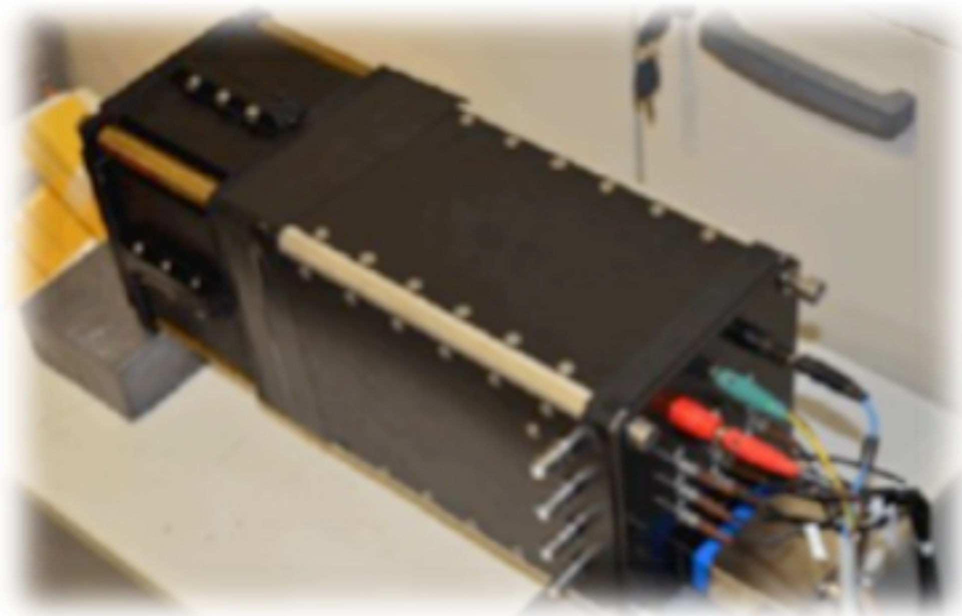
Test Beam (2011) at MAMI (Mainz Microtron, Germany) with a clean tagged photon.

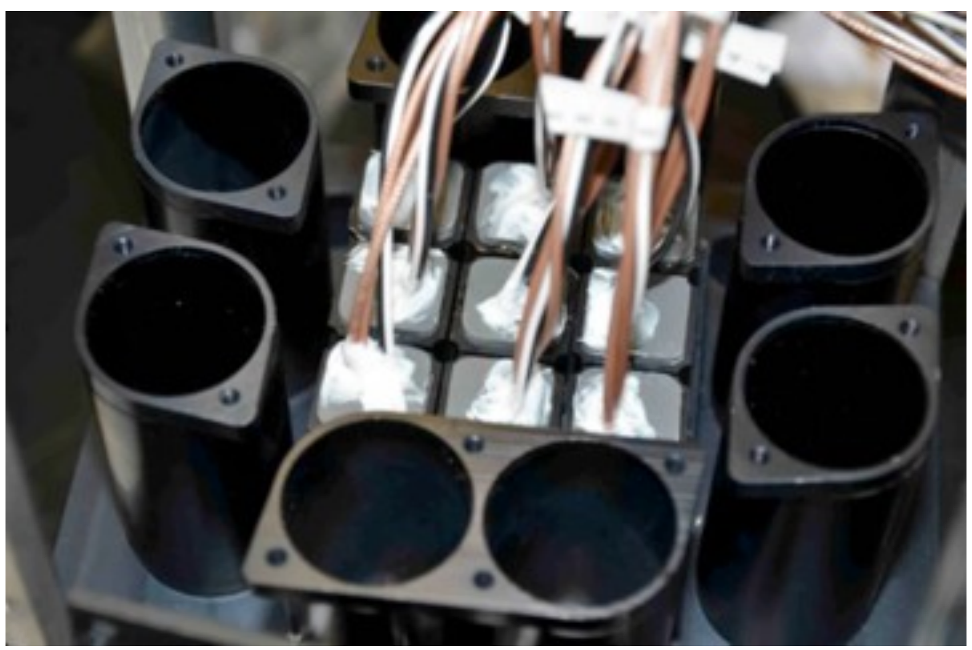
- An inner matrix of 9 LYSO crystals
  - LYSO from SICCAS High Technology Co. (Shanghai)
  - 20×20×150 mm^3
  - readout by 10×10 mm^2 APDs Hamamatsu S8664-1010
- An outer matrix of 8 PbWO4
  - for leakage recovery
  - 30×30 (or 40×40) ×130 mm^3
  - readout by 1 inch PMTs.
- Independently wrapped with 300 µm reflecting Tyvek + black tape.



Beam test prototype

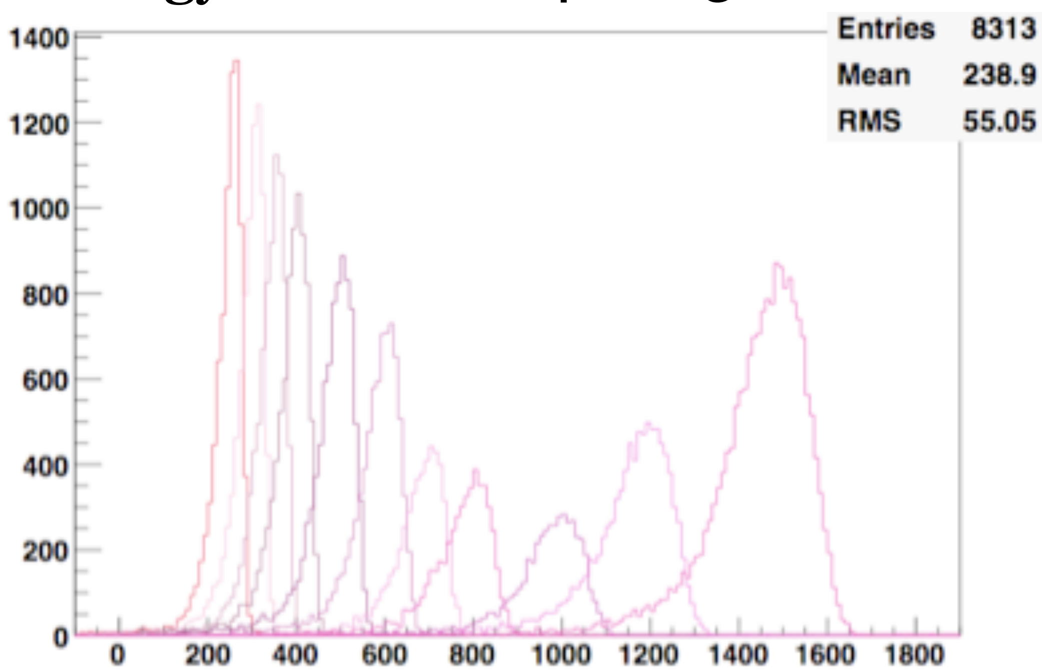


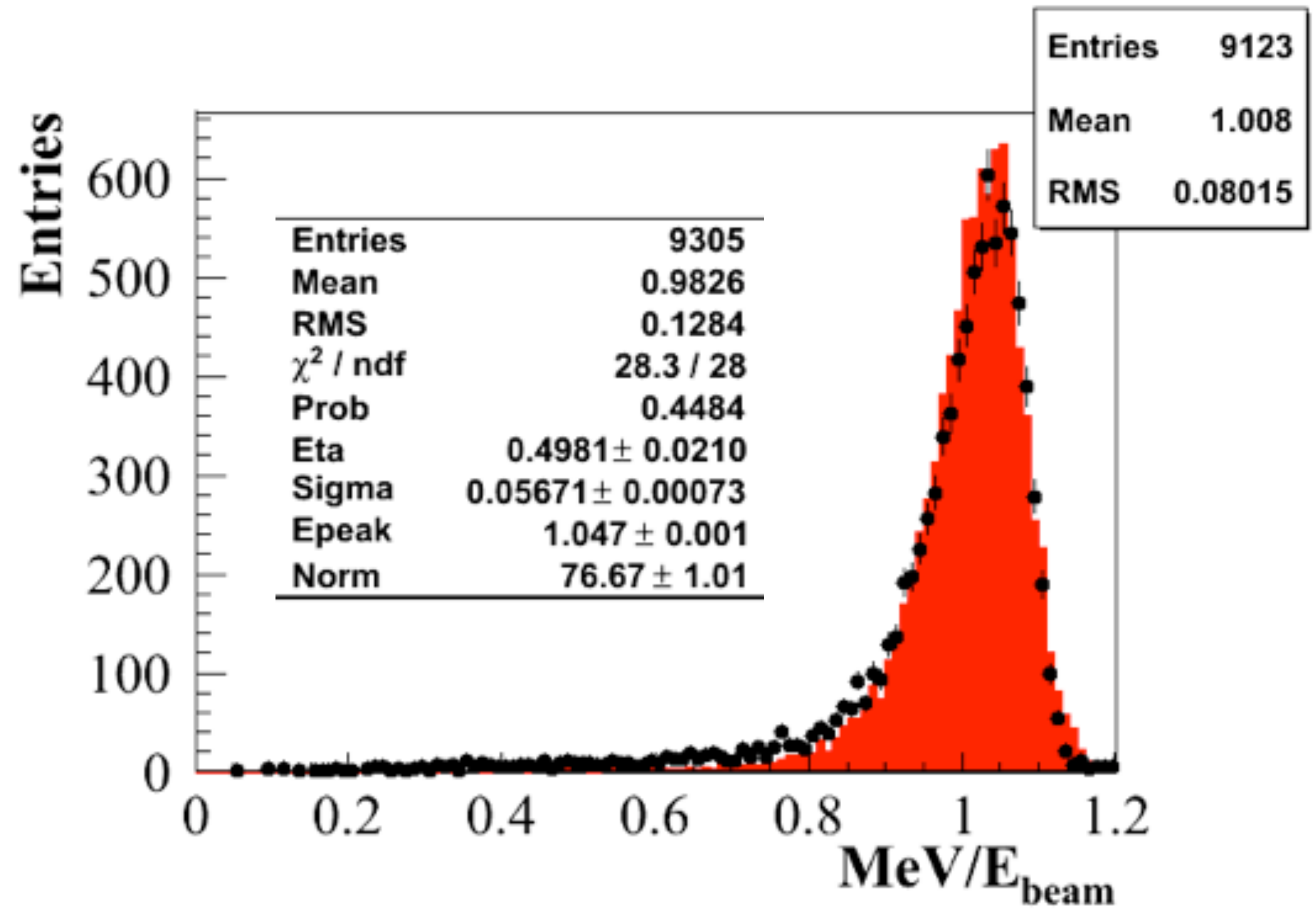


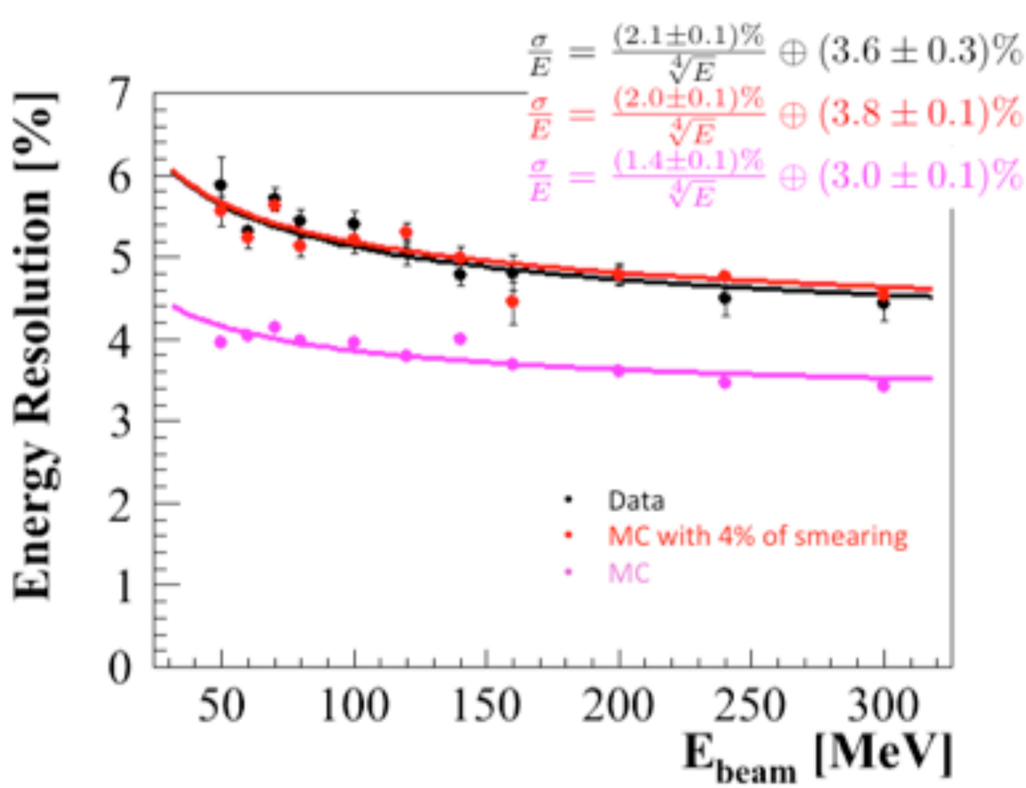


Beam test results

Energy scan from 40 to 300 MeV



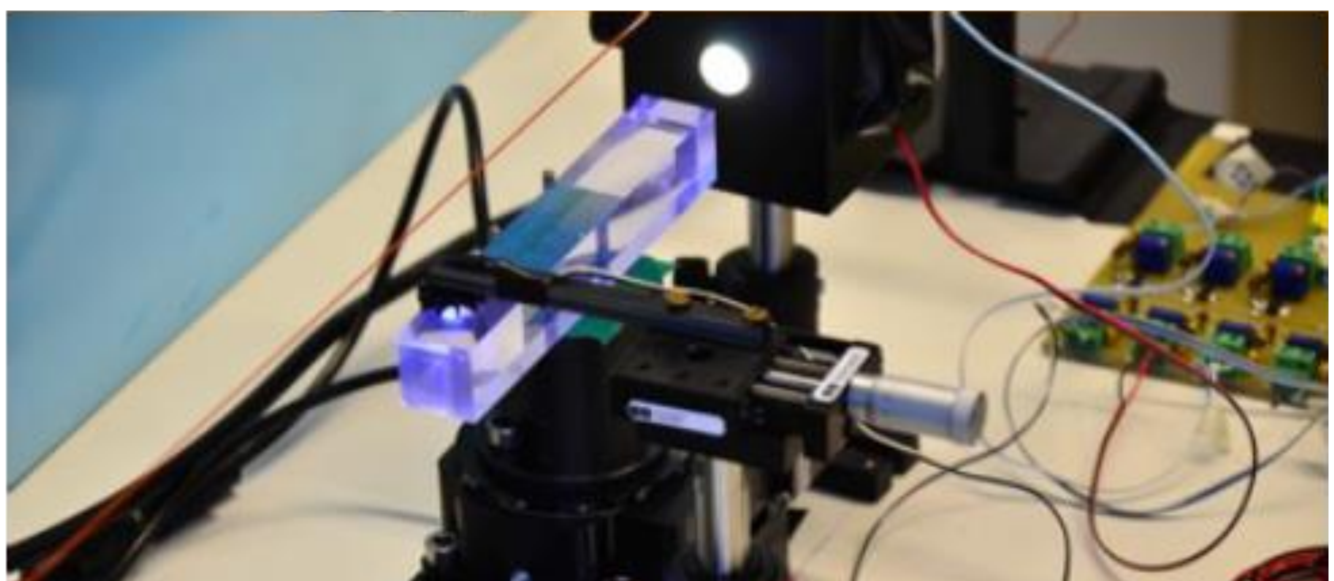




Large non-uniform response along the length of crystals causes the discrepancy between data and MC

[NIM A718, 56 (2013)]

Emission and transmission test stand



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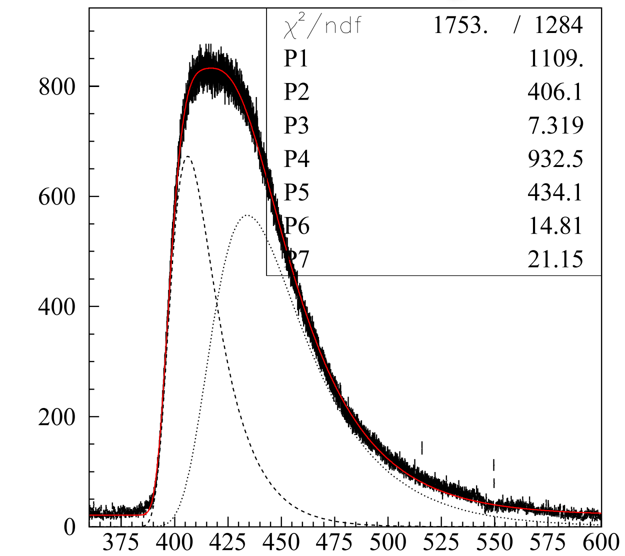
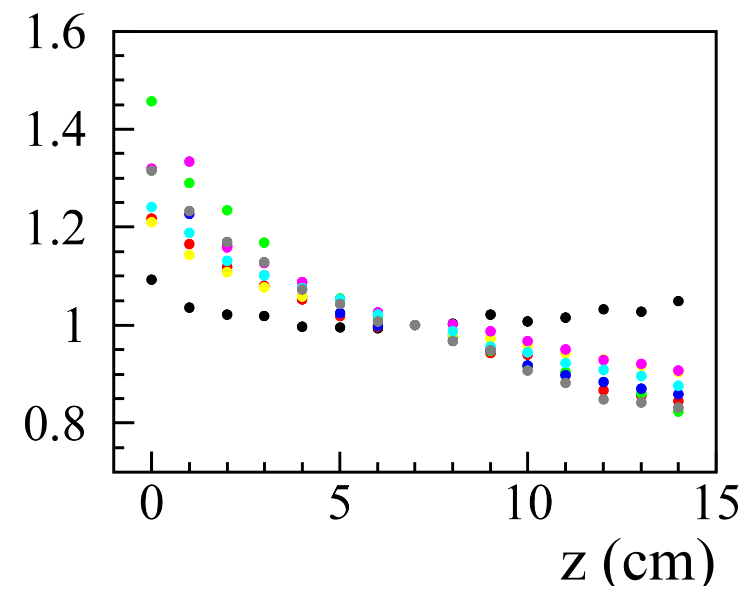
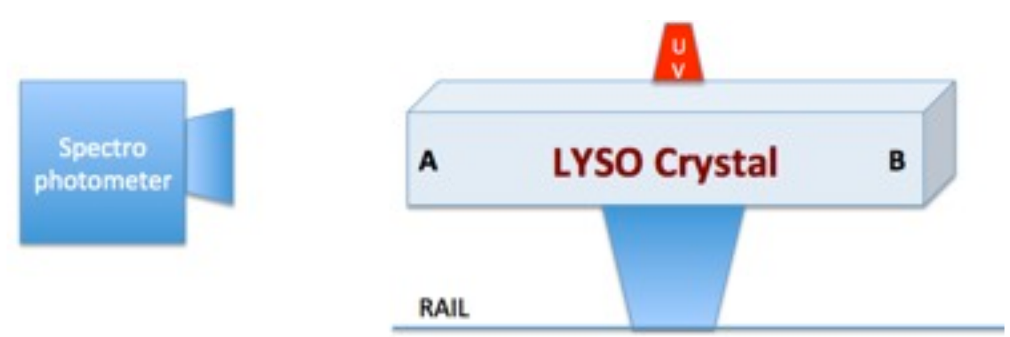
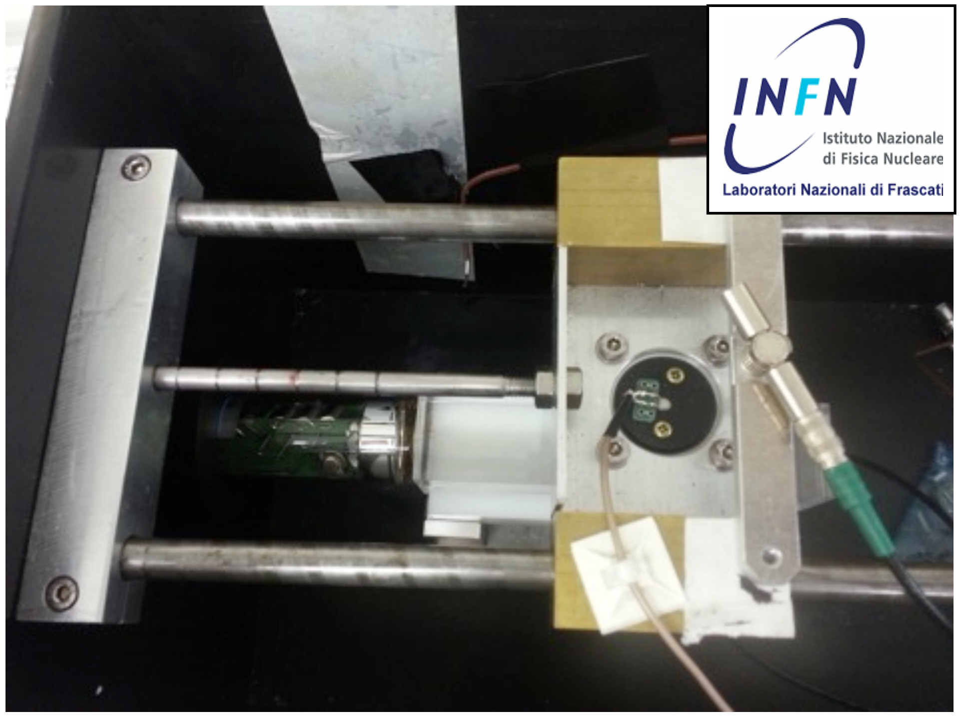
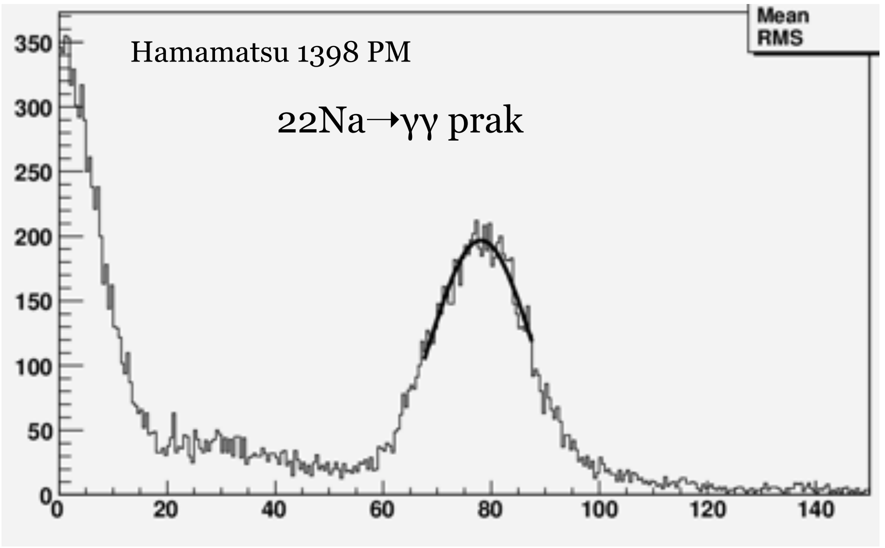


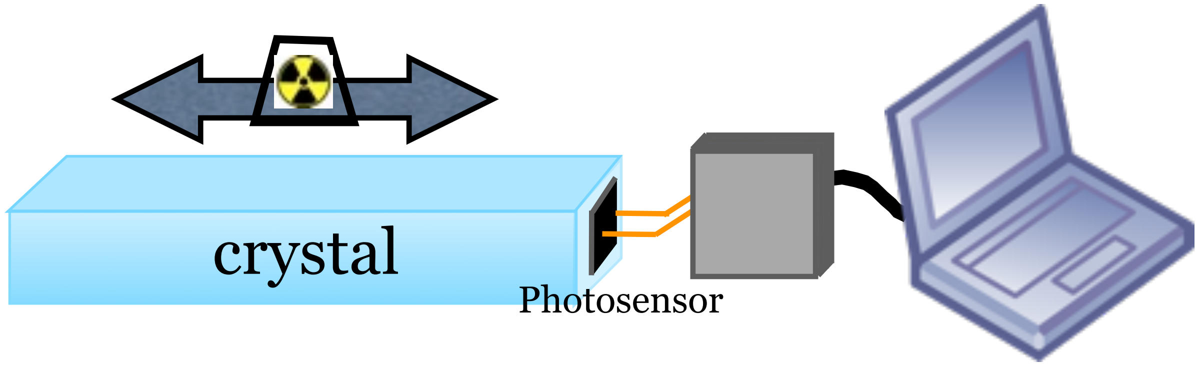




Source test stand







Will build an automatic system to scan each crystals, and devise a strategy to improve light response uniformity: Roughening surfaces, black paint, or tape...

Source calibration system

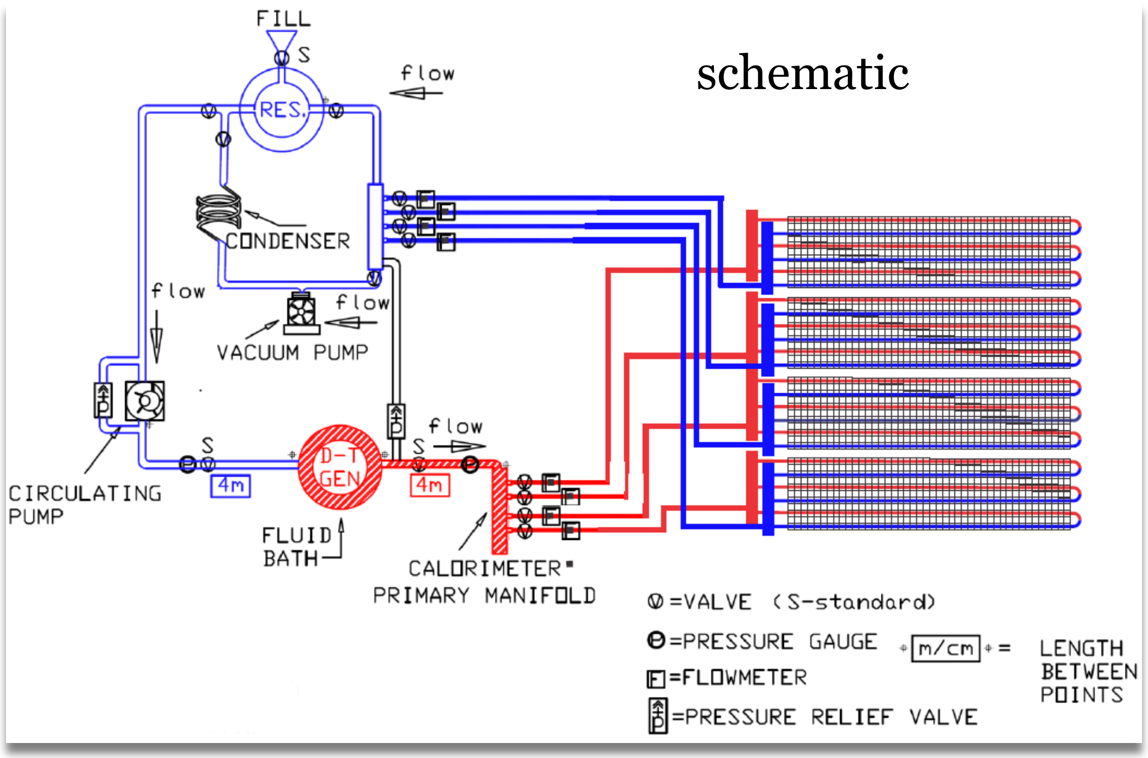
- Irradiated fluorine:

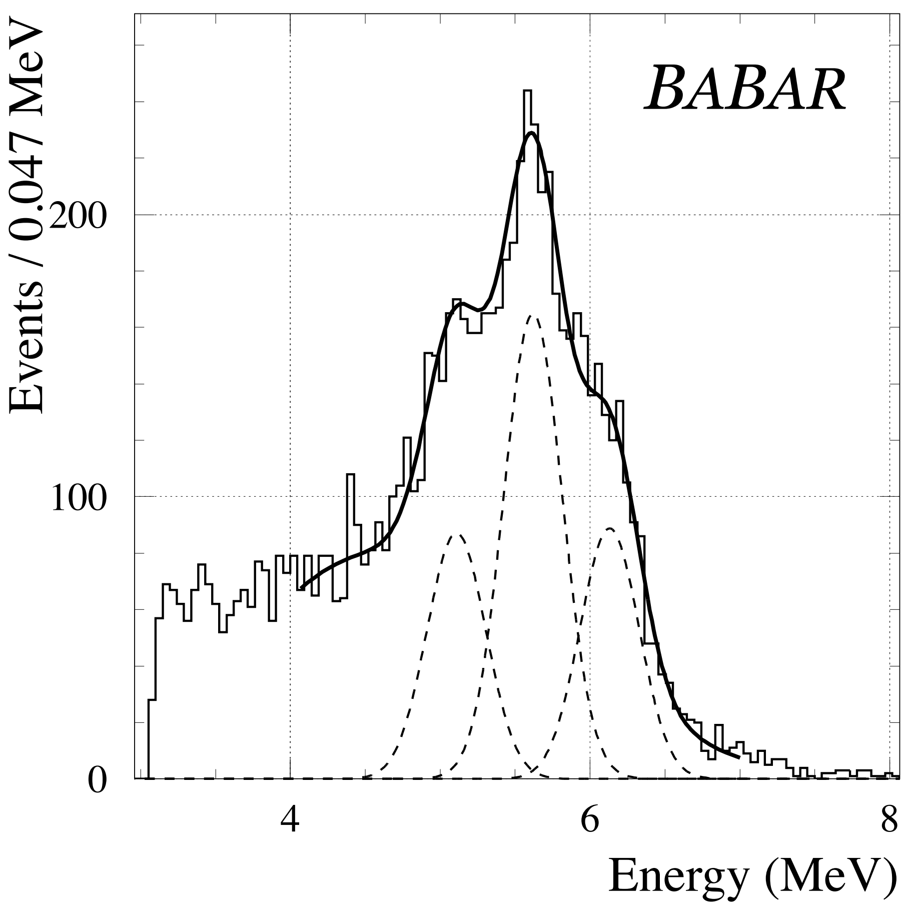
$$^{19}F + n \rightarrow {}^{16}N + \alpha$$

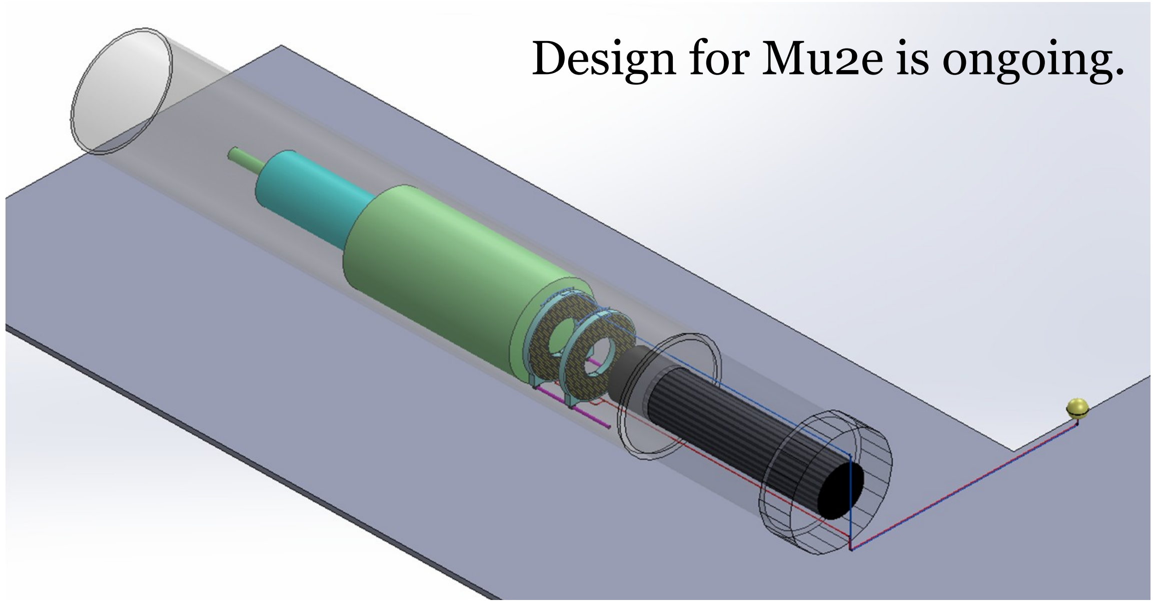
$$^{16}N \rightarrow {}^{16}O^* + \beta \quad (\tau_{1/2} = 7\ s)$$

$$^{16}O^* \rightarrow {}^{16}O + \gamma\ (6.13\,MeV)$$

  - ✦ crystal-by-crystal absolute calibration; performed once (~30 min.) per ~week.



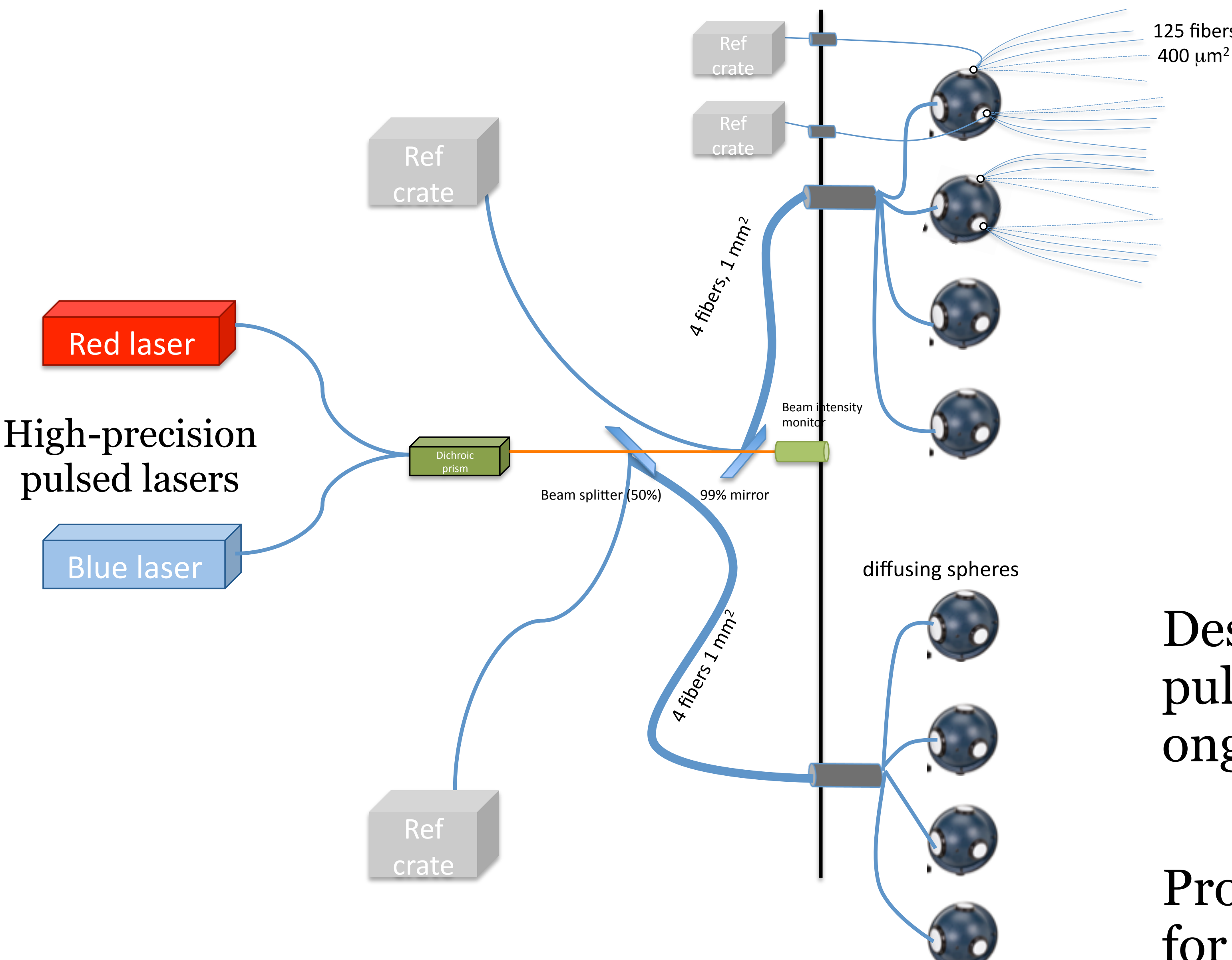


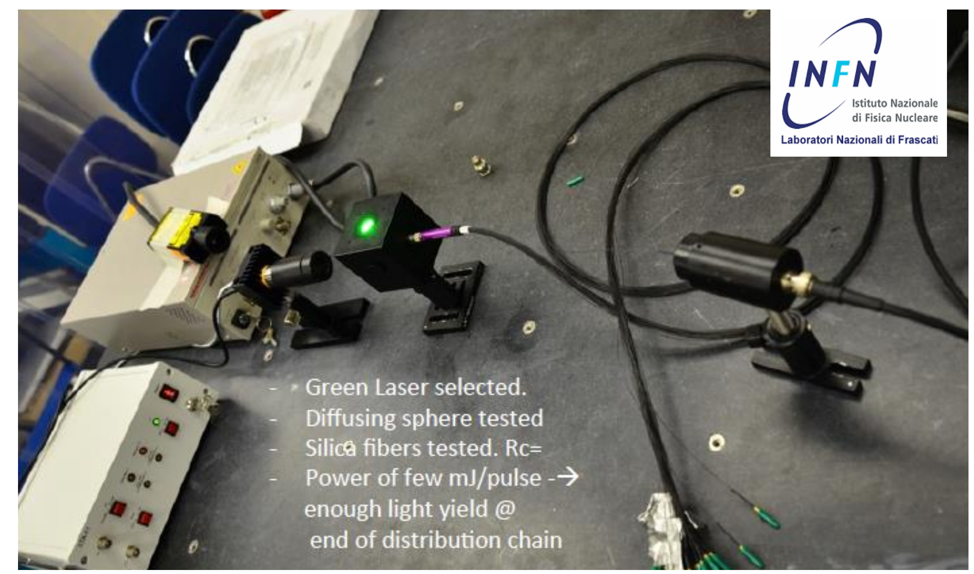


*In addition to calibrations using cosmic rays, DIO, Michel edge, and/or $\pi^+ \rightarrow e^+\nu$ mono-energetic positron.

Laser calibration system

- Monitor the variation of the crystal optical transmittance and APD gains. Similar to the one used for CMS.



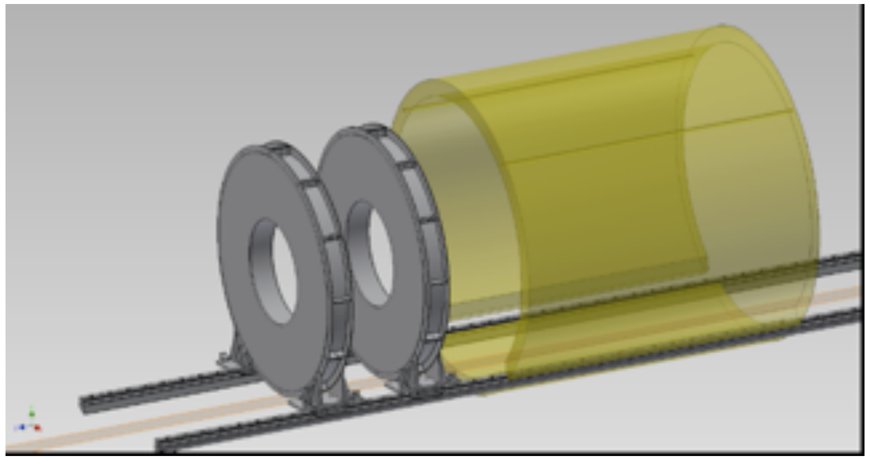


Design and tests of the system (light pulser, fibers, photosensors, etc.) are ongoing.

Prototype under development; will test for the next test beam.

Conclusions and future work

- We have established the baseline design of the Mu2e calorimeter:
  - ✦ Two disks of LYSO crystals + APD photosensors
  - ✦ Hexagonal cross-section crystals
- Exact geometry (radii, separation, location), mechanics, photosensors, readout, to be optimized.



- Next beam test with 5×5 array of $3\times3\times13$ cm^3 crystals (@LNF then @MAMI in 2014).
  - ✦ better shower containment;
  - ✦ reduce/eliminate structure between crystals;
  - ✦ better care of light response uniformity;
  - ✦ new electronics/digitizer.