Development of fine-sampling calorimeters with nanocomposite scintillating materials

NanoCal Status Report

INFN
Istituto Nazionale di Fisica Nucleare

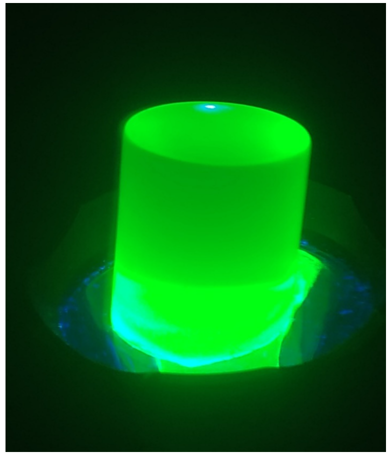
GLASS to POWER

AIDA innova

Matthew Moulson, INFN Frascati

Prospective and Technology-Driven Detector R&D
AIDAinnova 2nd Annual Meeting, 25 April 2023

Nanomaterial composites (NCs)

Semiconductor nanostructures can be used as sensitizers/emitters for ultrafast, robust scintillators:

- Perovskite (ABX_3) or chalcogenide (oxide, sulfide) nanocrystals
- Cast with polymer or glass matrix
- Decay times down to O(100 ps)
- Radiation hard to O(1 MGy)

Nanocrystals and composite can be **engineered** to obtain performance requirements

- **Nanocrystal:** emission wavelength, decay time, etc.
- **Composite:** concentration of nanocrystals and/or additional fluors, e.g. very high concentration of nanocrystals to obtain shorter radiation length

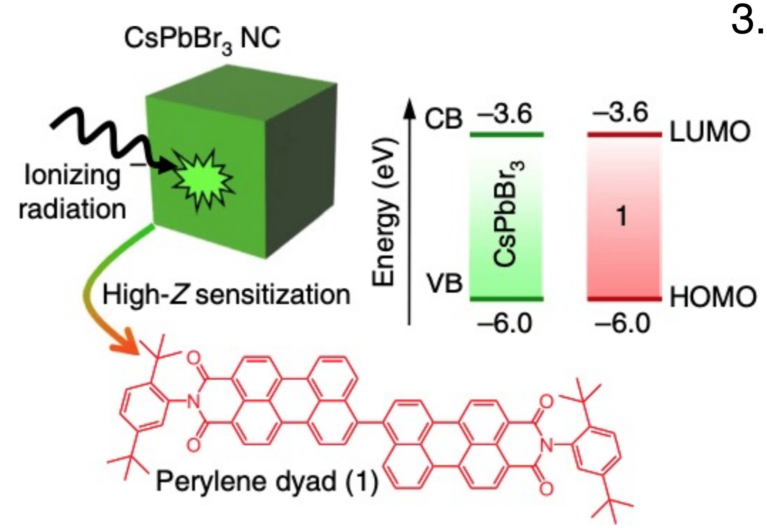
Can realize thin nanocrystal films to realize **fast timing layers**

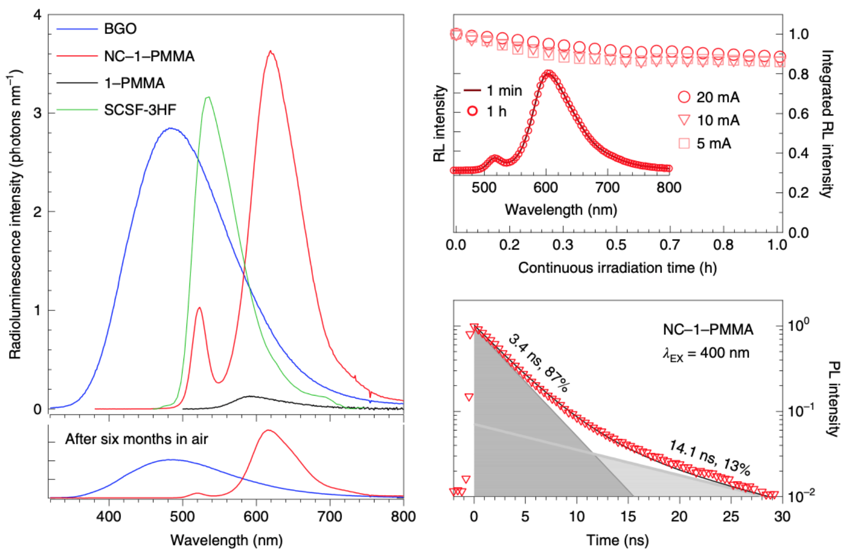
Nanocrystal composites could make **very fast WLS devices** to efficiently couple light from fast scintillators to SiPMs

Nanomaterial composites: State of the art

nature nanotechnology
ARTICLES
https://doi.org/10.1038/s41565-020-0683-8
Check for updates

Efficient, fast and reabsorption-free perovskite nanocrystal-based sensitized plastic scintillators

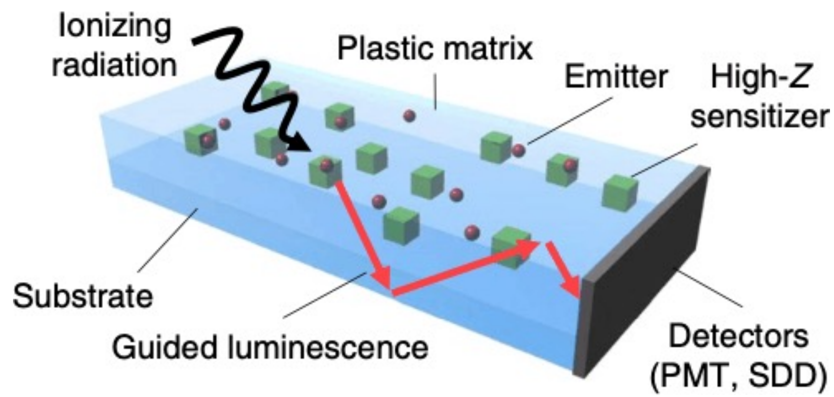




R&D on practical scintillators for HEP:

1. Perovskite sensitizer ($CsPbBr_3$, 2% wt)
2. Non-radiative transfer to fluor (perylene dyad, 0.15% wt)
3. Light propagation and readout via PMMA matrix

M. Gandini et al., *Nat. Nanotechnol.* 15 (2020) 462



Tests with perovskite composite:

$CsPbBr_3$ NC + perylene dyad + PMMA

- **Peak emission ~ 620 nm**
- **BGO-like light yield at peak**
- **τ_{decay}(fast) = 3.4 ns (87%)**
- **τ_{decay}(slow) = 14.1 ns (13%)**
- **No degradation up to 800 Gy**

From test bench to detector

Nanocomposite scintillators have received much attention in the materials-science community

- Many studies of photoluminescence for E_γ **< 10 eV**
- However, **almost no studies** have been done on the response of NC scintillators to **high-energy particles**

So far, **applications in HEP have received little attention**

No attempt yet to build a **real calorimeter with NC scintillator** and **test it with high-energy beams**

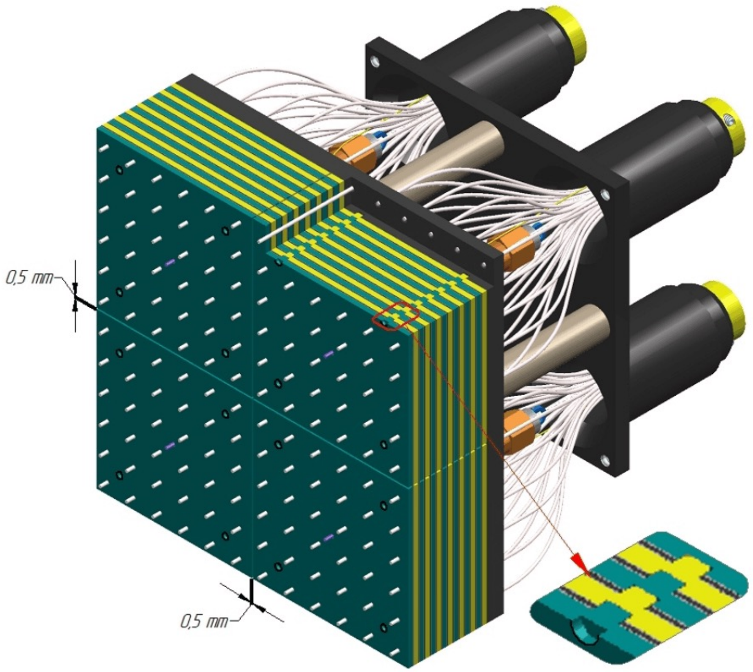
Shashlyk design naturally ideal as a test platform

- Easy to construct a shashlyk calorimeter with very fine sampling
- Primary scintillator and WLS materials required: both can be optimized using NC technology

NCs have high potential for innovative, high-performance HEP calorimetry

The NanoCal project will demonstrate this by creating the missing link

Baseline: Prototype/test platform



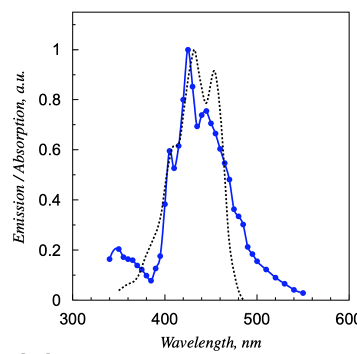
Fine-sampling shashlyk based on PANDA forward EM calorimeter produced at Protvino

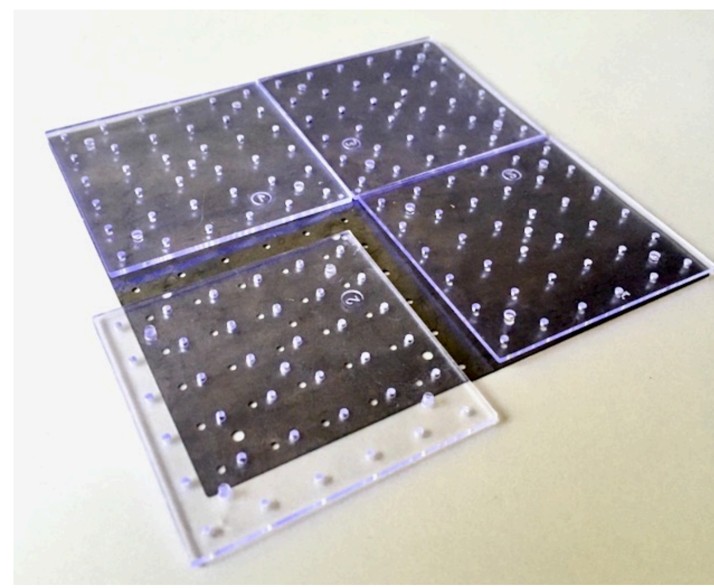
Original design for KOPIO experiment at BNL
0.275 mm Pb + 1.5 mm scintillator

KOPIO prototypes:

- $\boldsymbol{\sigma_E/\sqrt{E}}$ **~ 3%** $/\sqrt{E}$ (GeV)
- $\boldsymbol{\sigma_t}$ **~ 72 ps** $/\sqrt{E}$ (GeV)
- $\boldsymbol{\sigma_x}$ **~ 13 mm** $/\sqrt{E}$ (GeV)

Tiles and lead absorber plates obtained from IHEP Protvino





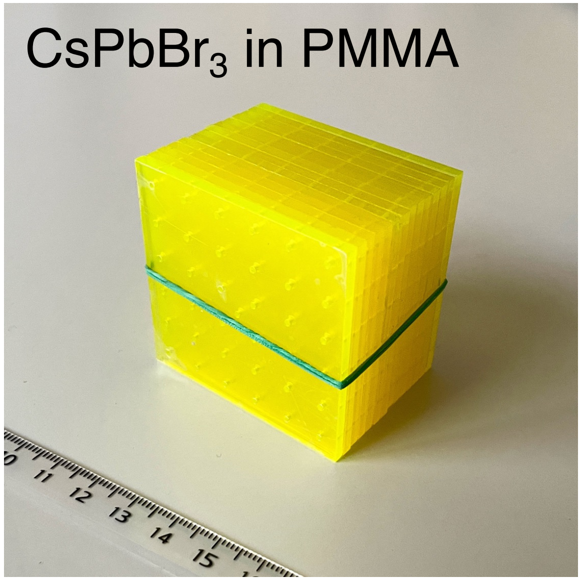
Scintillator:

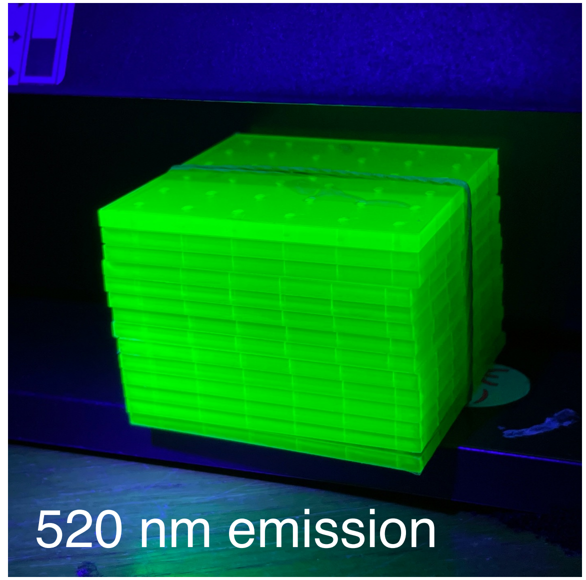
- Extrusion molded polystyrene
- 1.5% PTP + 0.04% POPOP

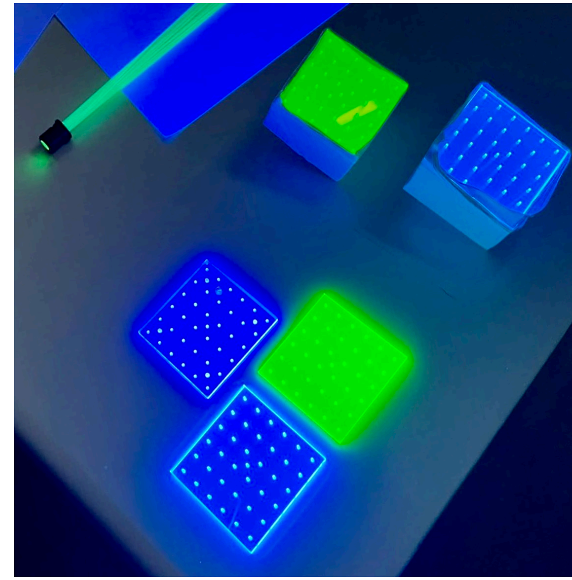
WLS fibers

- Kuraray Y-11(200), 1 mm ⌀
- λ_{att} ~ 3.5 m; τ_{decay} ~ 7.5 ns

Baseline: Nanocomposite scintillator







Quick-start using known NC scintillator formulation

$CsPbBr_3$, 0.2% w/w in UV-cured PMMA

- Light yield O(few k) photons/MeV deposit
- 50% of light emitted in components with $\tau < 0.5$ ns
- Radiation hard to O(1 MGy)

Trial production of tiles in Protvino format

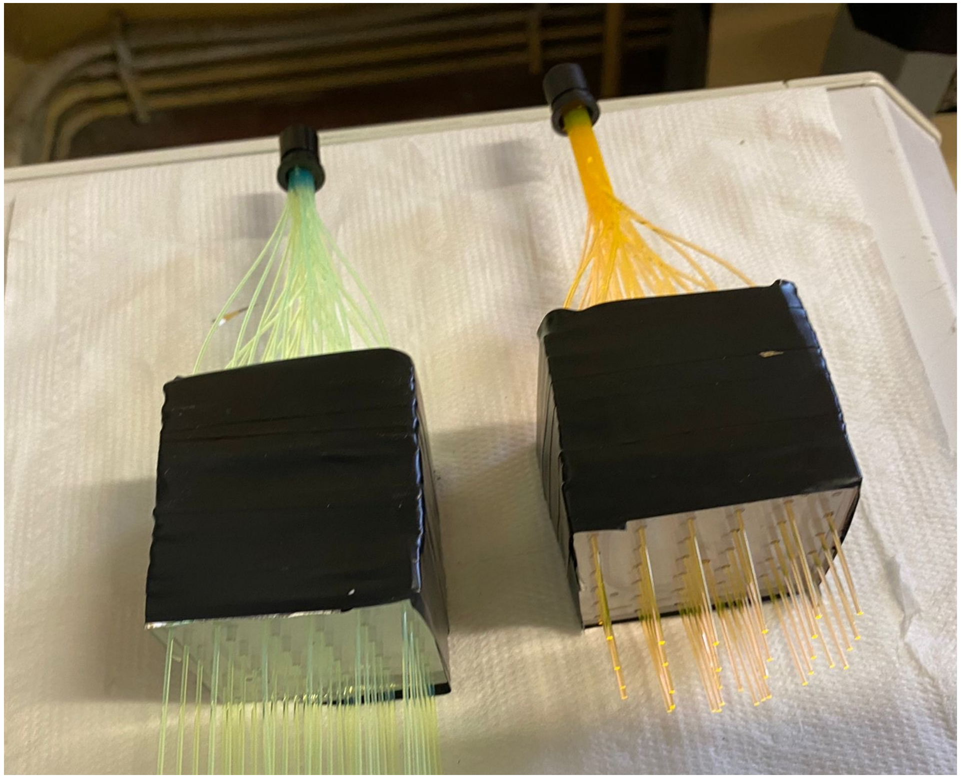
55 x 55 mm^2

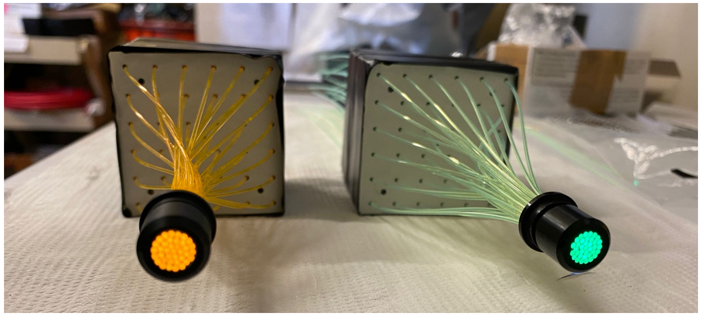
Progress:

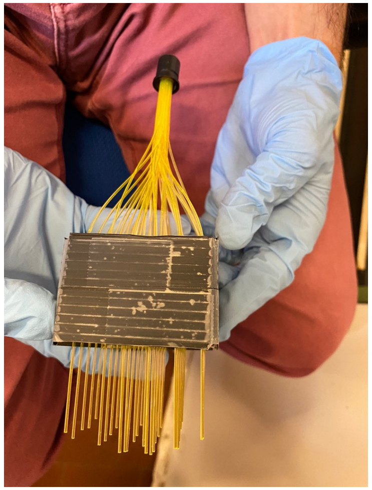
- **Oct 2022: First component test at CERN: fibers/tiles/SiPMs**
- **2023**: Further iterations to improve performance of NC scintillator prototype
- **2024:** Construction of full-scale prototype modules; performance comparison

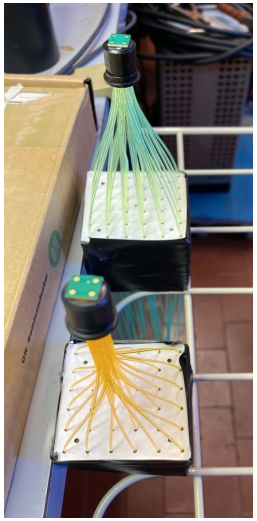
Prototype construction for 2022

- Two prototypes with 12 fine sampling layers: 0.6 mm Pb + 3 mm scintillator
- Each 1.3X_0 in depth: expected MIP energy deposit = 10 MeV
- Each read out with a single Hamamatsu 13360-6050 SiPM









Protvino scintillator

Polystyrene
1.5% PTP/0.04% POPOP
Kuraray Y-11(200) fibers

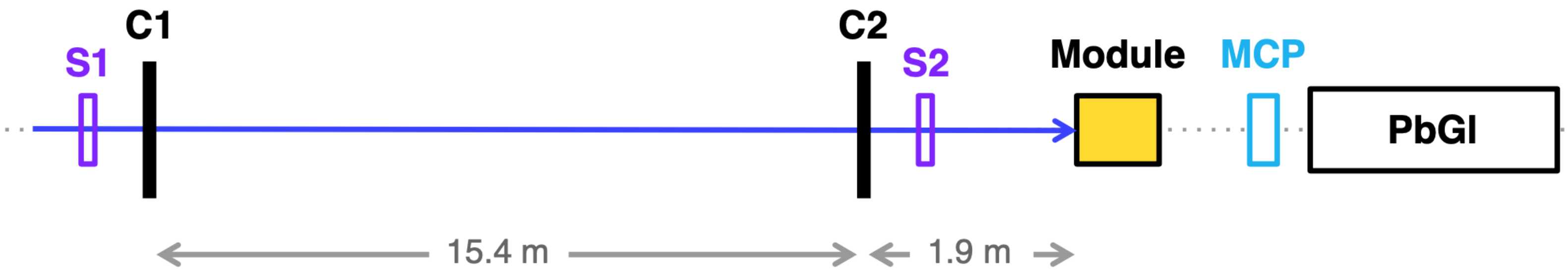
NanoCal scintillator

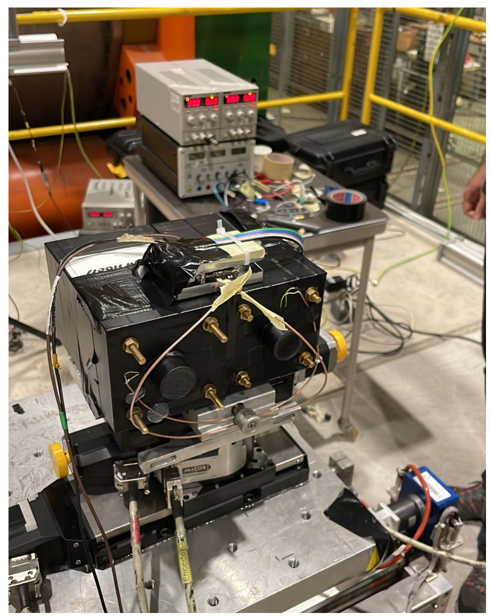
PMMA
0.2% $CsPbBr_3$
Kuraray O-2(100) fibers

2022 beam test of shashlyk prototypes

Tested at H2 beamline with 80 GeV e^- and 150 GeV π^+ (MIPs), Oct 2022

- Beam tracked with 5 μrad, 50 μm precision using C1, C2 Si-strip detectors
- 30 ps timing reference from MCP module





Nearly identical prototypes side by side on beamline

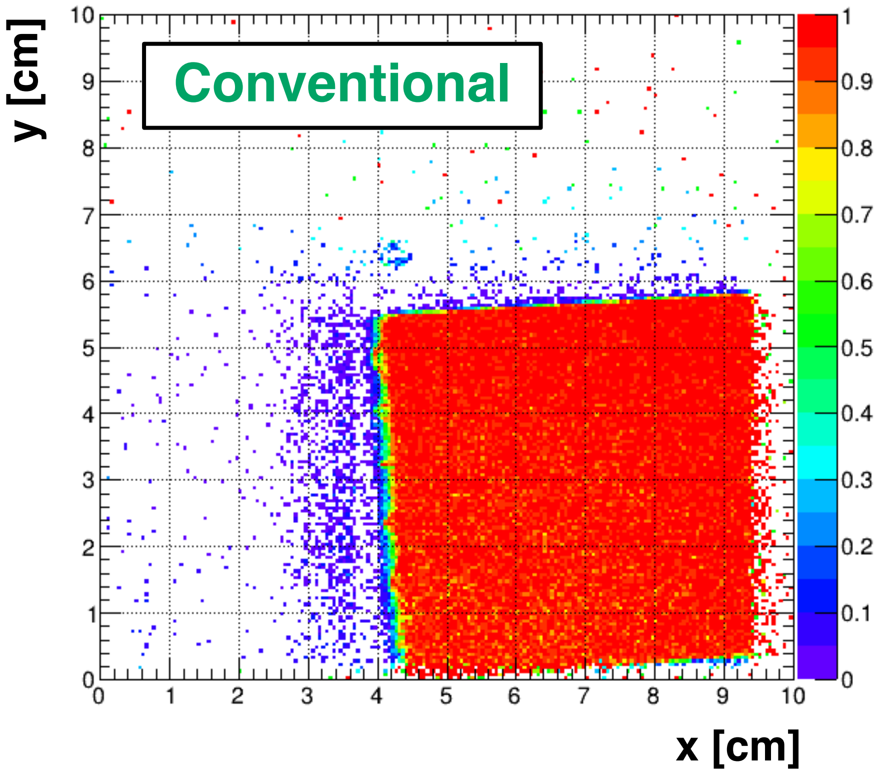
CRILIN readout electronics

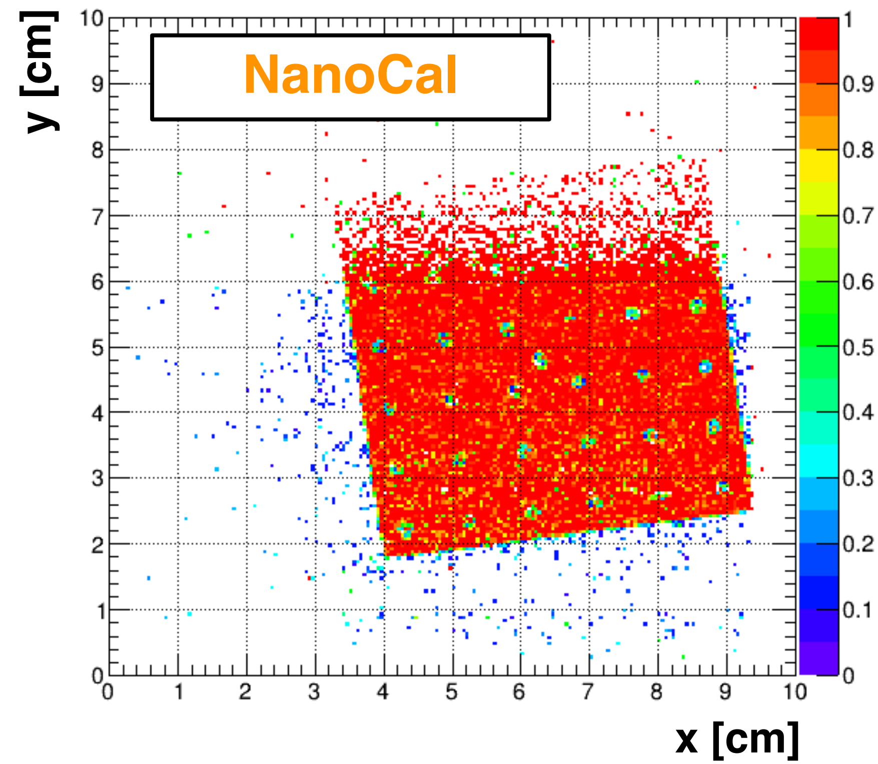
- 4x gain
- 2 ns rise time
- 70 ns fall time

Signals digitized at 5GS/s with CAEN 1742 FADC

Response to MIPs

Track impact point on shashlyk prototype extrapolated with silicon-strip trackers to calorimeter front plane ($\sigma_{xy} \sim 50$ μm)





Overall efficiency high and uniform in both cases

- Possibly somewhat lower for NanoCal prototype

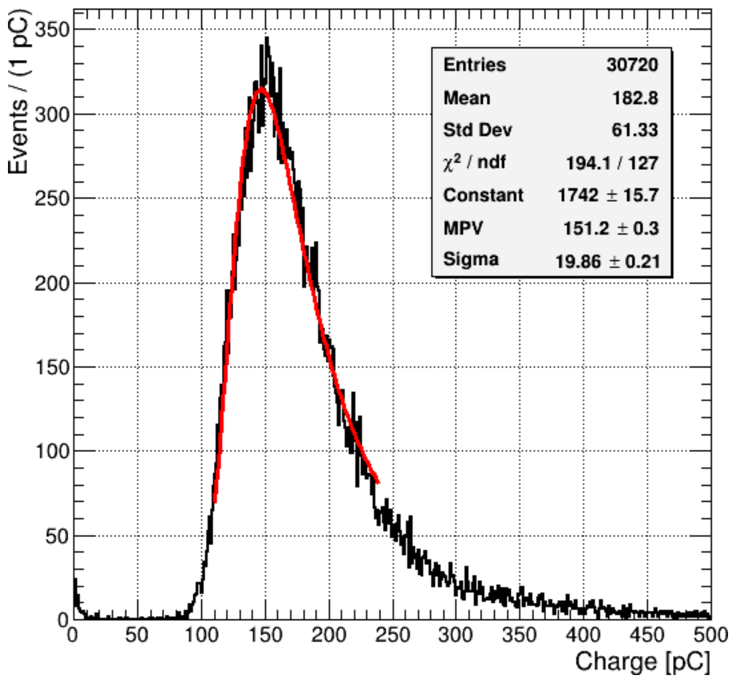
Holes more visible in NanoCal prototype → better alignment?

- Error in hole size for NanoCal module (2 mm instead of 1.3 mm)

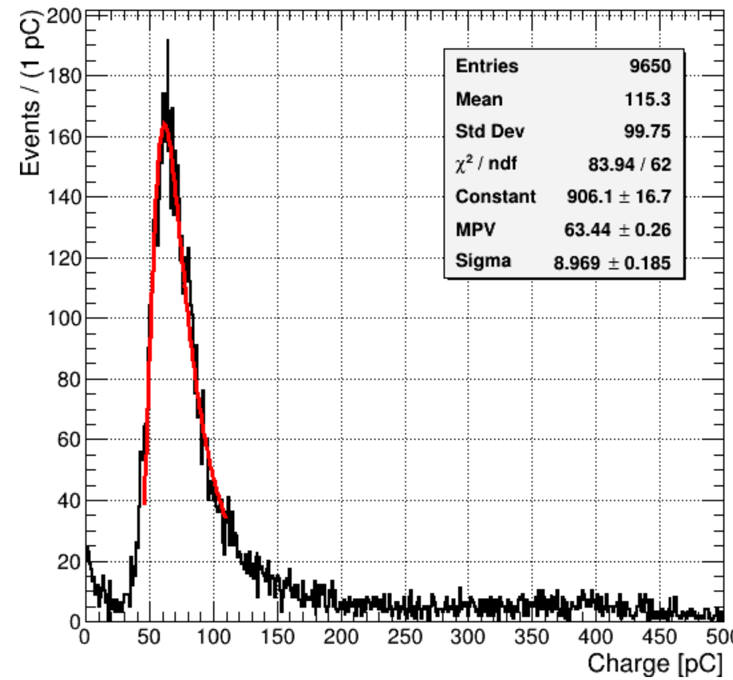
Response to MIPs

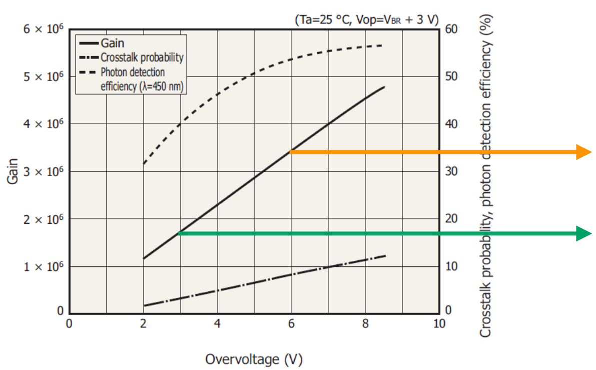
MIP peak obtained with fiducial cuts and fit with Landau distribution

Conventional



NanoCal





Hamamatsu 13360-6050 SiPM

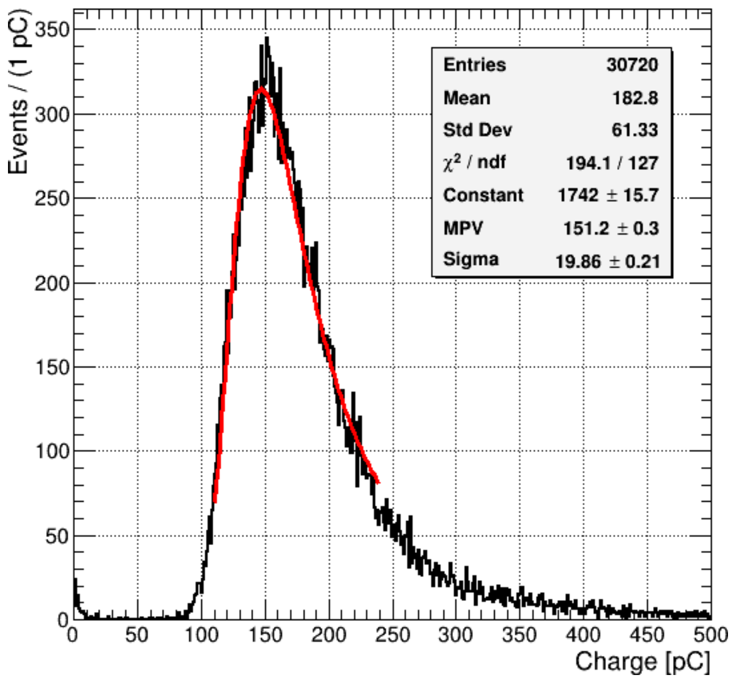
NanoCal operated at V_{op} + 3V: $G = 3.4 \times 10^6$

Conventional operated at V_{op}: $G = 1.7 \times 10^6$

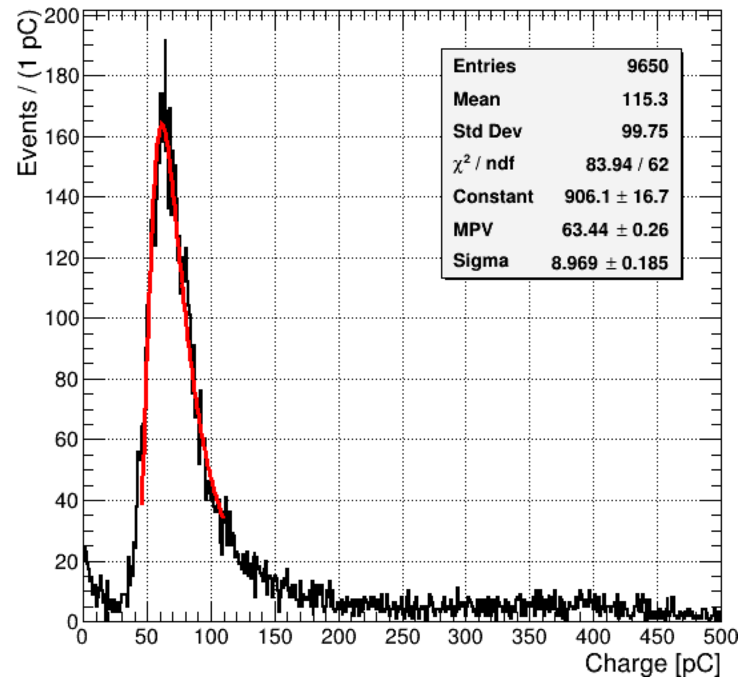
Response to MIPs

MIP peak obtained with fiducial cuts and fit with Landau distribution

Conventional



NanoCal



$$N_{\mathrm{pe}} = \mathrm{MPV}_Q / (G_{\text{front-end}}\, G_{\text{SiPM}}\, e)$$

138.8 pe/10 MeV

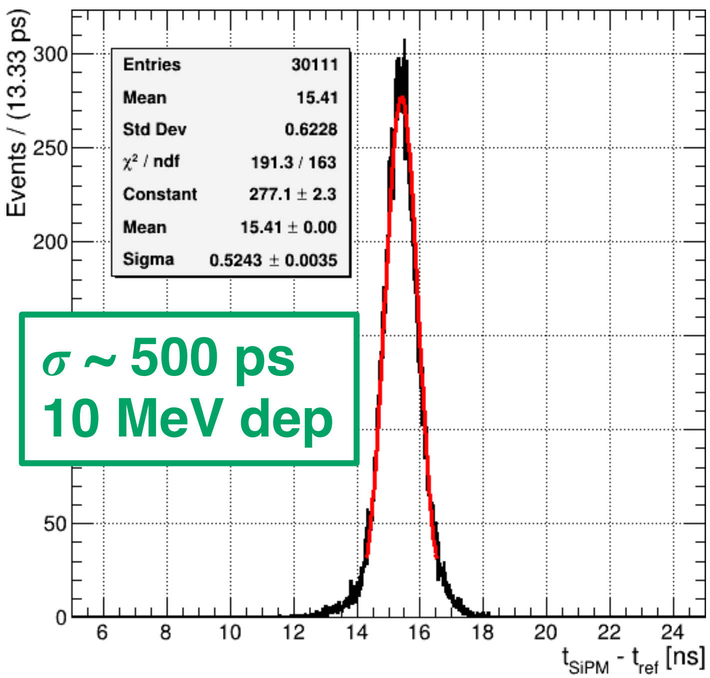
28.9 pe/10 MeV

Conventional prototype gives 4.8x charge of first NanoCal prototype
However, many confounding factors…

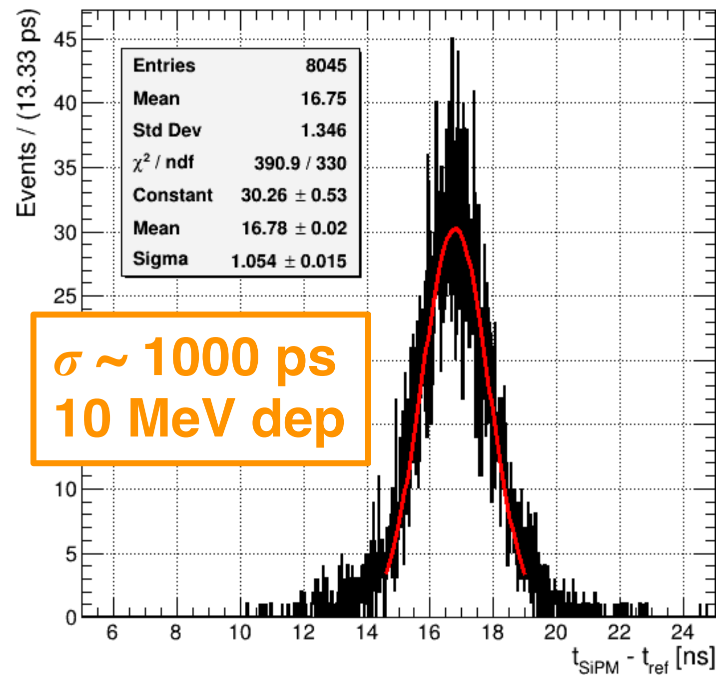
Time resolution with MIPs

Time reference $\sigma \sim 37$ ps from 2x MCP-PMT with Cerenkov radiators
CF threshold at 25% on signals digitized at 5 GS/s

Conventional



NanoCal



- Encouraging results for small energy deposit ($\sigma_t \sim$ 50-100 ps at 1 GeV)
- Better resolution for conventional prototype attributable to ~4x higher light yield
- NanoCal has faster scintillator (~50% with $\tau < 0.5$ ns) and fibers (5.3 ns vs 7.5 ns)
- However, some indication of longer 10-90% rise time for NanoCal (18 ns vs 16 ns)
  Possible effect of small Stokes shift in WLS fibers: multiple re-emissions

Factors affecting light yield measurement

Intrinsic light yield of scintillator

- Direct measurements in progress
- Dependence on concentration
  - First test with 0.2% w/w $CsPbBr_3$ – good dispersal in matrix
  - Next tests to be done with $\gtrsim$ 1% $CsPbBr_3$

Minor construction error for NC prototype

- Diameter of shashlyk holes 2.0 mm instead of 1.3 mm
- Poor light coupling – to be corrected!

Additional optimizations to be implemented for both prototypes

- Finer sampling (1.5 mm scintillator + 0.3 mm lead)
- Better reflective layers between scintillator and lead
- Reflector around edges of scintillator
- Ends of fibers to be mirrored

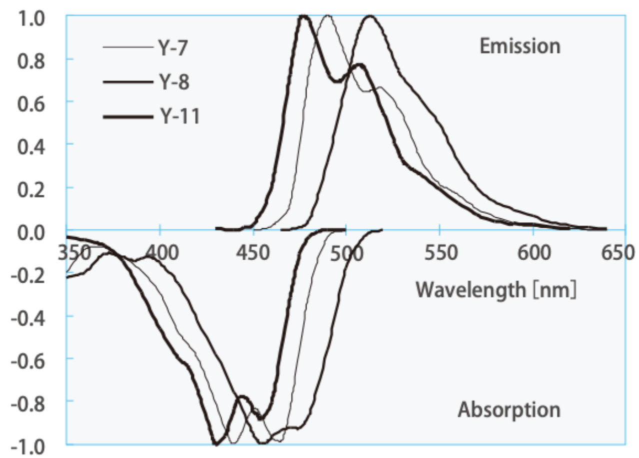
Role of WLS fibers

Potentially invalidating construction error for both prototypes!

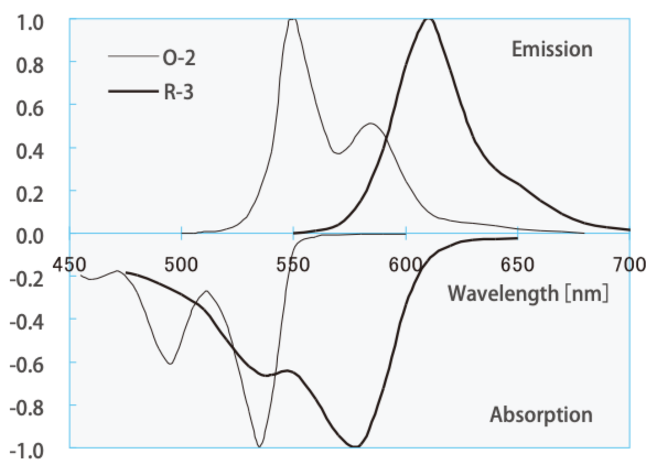
Role of WLS fibers

Emission/Absorption Kuraray data sheet:

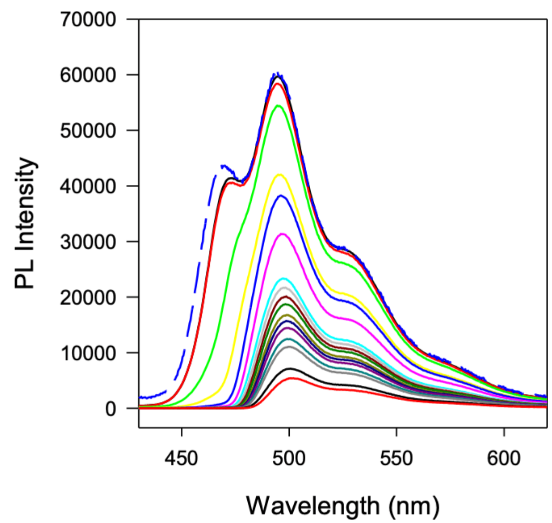
Y-7, Y-8, Y-11

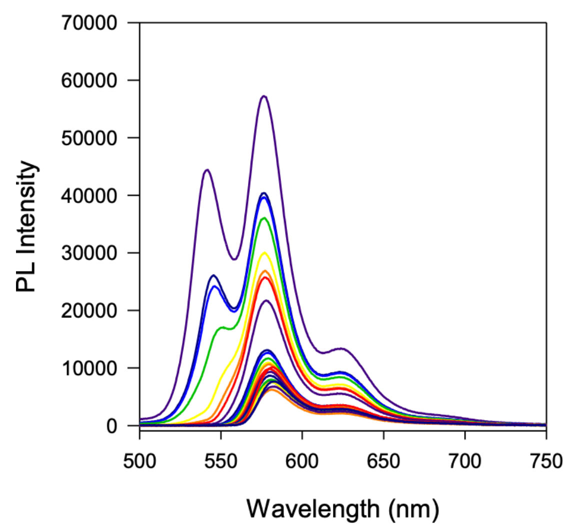


O-2, R-3



Our emission spectra Length = 0-20 cm





Summary After 20 cm:

Conventional Y-11 fibers

$\lambda \sim 495$ nm

Intensity ~ 4000

$L_{att} = 3.5$ m from data sheet

NanoCal O-2 fibers

$\lambda \sim 580$ nm

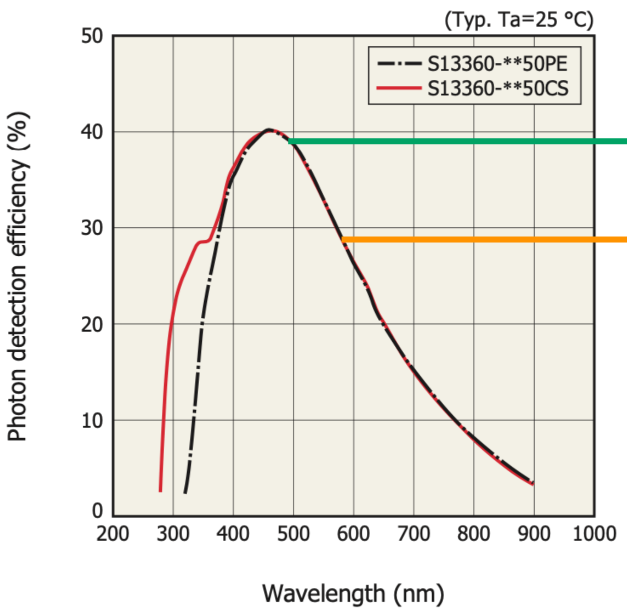
Intensity ~ 5000

$L_{att} = 1.5$ m from data sheet

Role of WLS fibers

O-2 fiber has more attenuation than Y-11 due to smaller Stokes shift

- We do not necessarily see less peak light output
- We definitely see the emissions peak shifted further to red than expected
- Leads to decreased efficiency of SiPM



Hamamatsu 13360-6050 data sheet

QE ~ 38.5% at 495 nm

QE ~ 29.0% at 580 nm

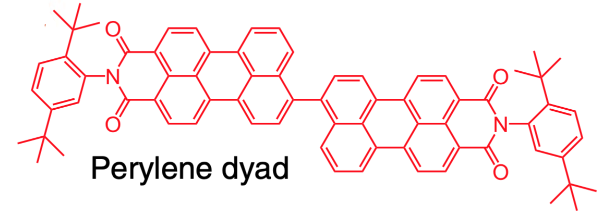
Expect 25% less response due to spectral mismatch?

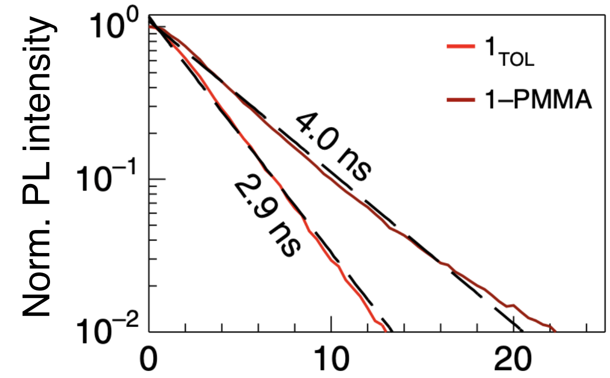
Needs verification

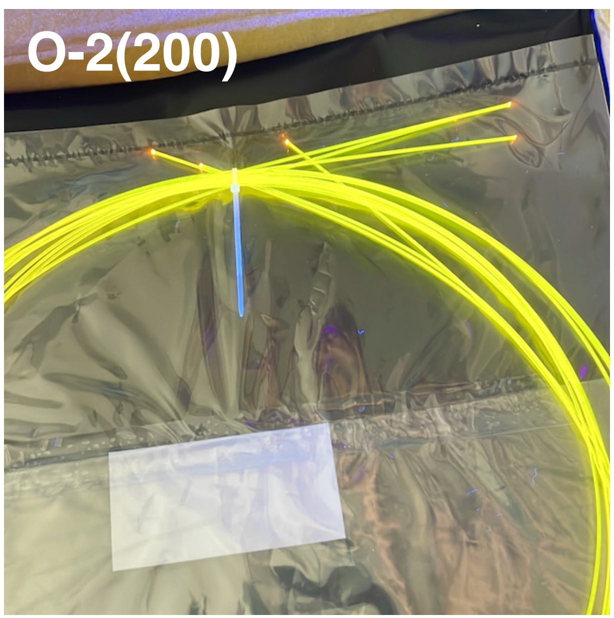
Custom WLS fibers for NanoCal

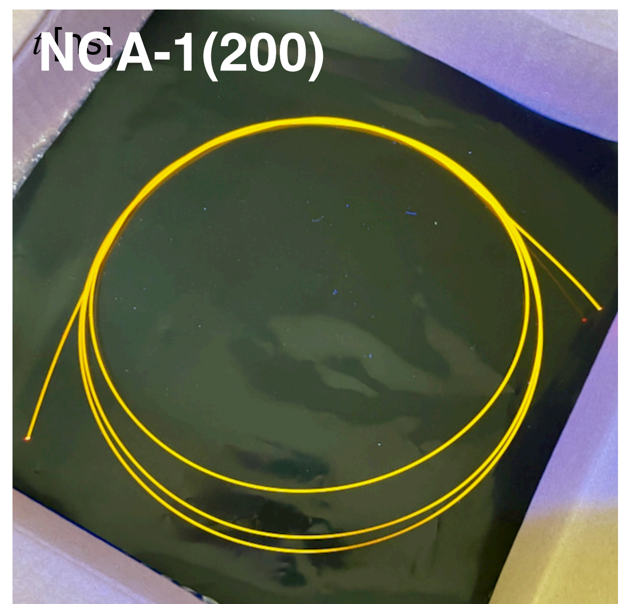
Commissioned production of custom fiber from Kuraray (NCA-1)

- Absorption peak well matched to $CsPbBr_3$ emission (520 nm)
- Emission peak at 580 nm (like O-2):
  60 nm Stokes shift
- Expected τ_{decay} **~ 3 ns**
  Compare to 5.3 ns for O-2, 7.5 ns for Y-11

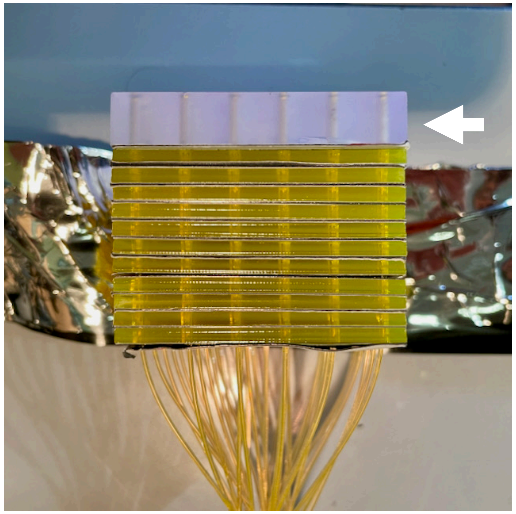


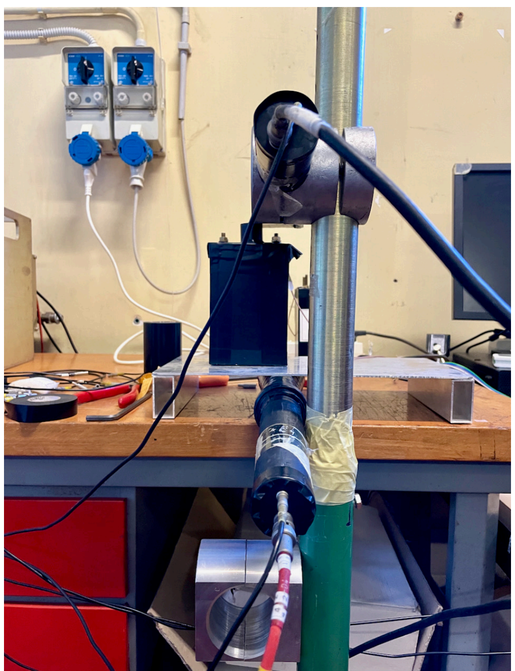






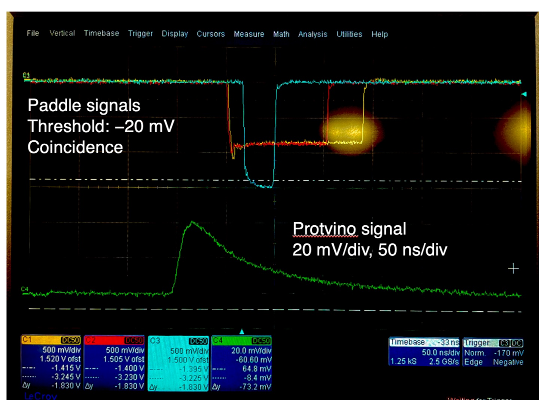
Assembly error for 2022 prototypes

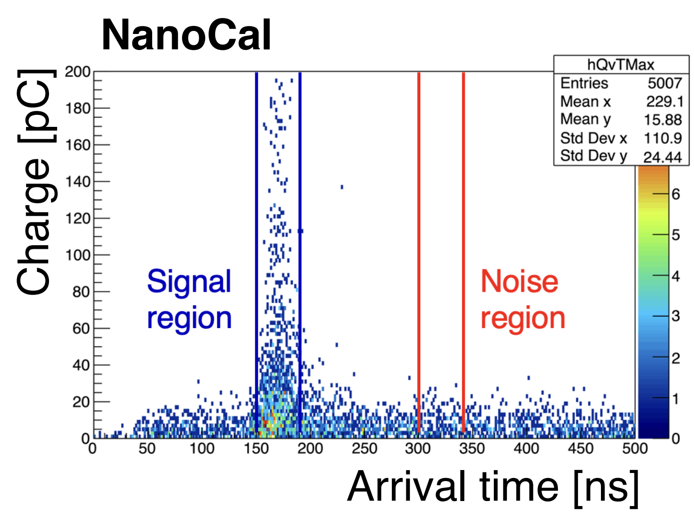




A piece of scintillator from an earlier Protvino prototype instrument was inadvertently included in the shashlyk stack for both Protvino and NC modules!

- Discovered during disassembly for measurement
- 1/3 thickness of scintillator in test stack
- Poor wavelength coupling to O-2 fibers
  - ε = 30% relative to coupling to Y-11 fibers
  - From this, estimate N_{pe}(NanoCal/Protvino) = **12%**
- Attempt to verify with cosmic ray-tests without extra piece
  - Find **N_{pe}(NanoCal/Protvino) = 5%**





Further investigations into light yield

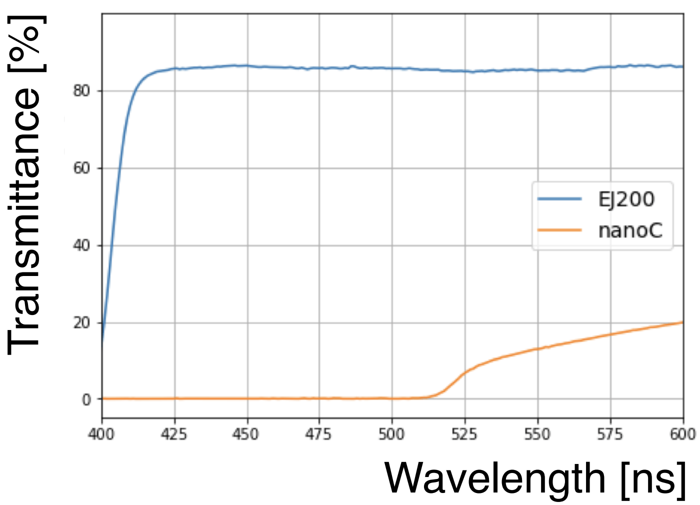
Try to exclude possibility that all signal is from WLS fibers

Easy to do in test beam: fibers can be imaged with Si-strip trackers

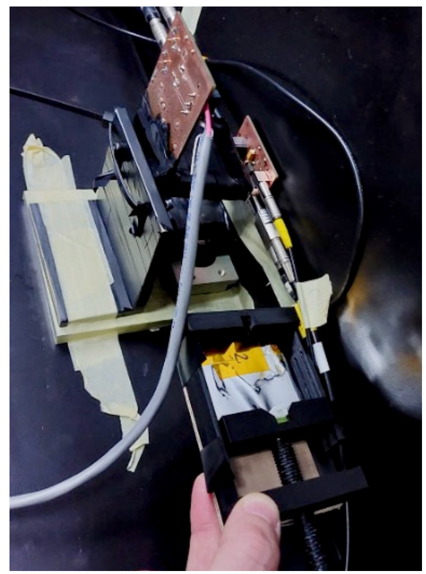
Harder to do in laboratory with cosmic rays: insufficient rate

Measure light yield in laboratory for scintillator alone

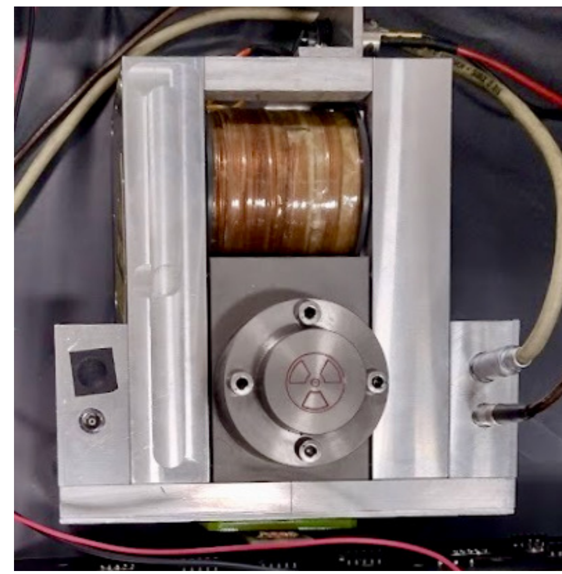
Results qualitatively consistent with cosmic-ray tests



Test rig for cosmic rays at Napoli



Test rig with triggered ^{90}Sr source at CERN



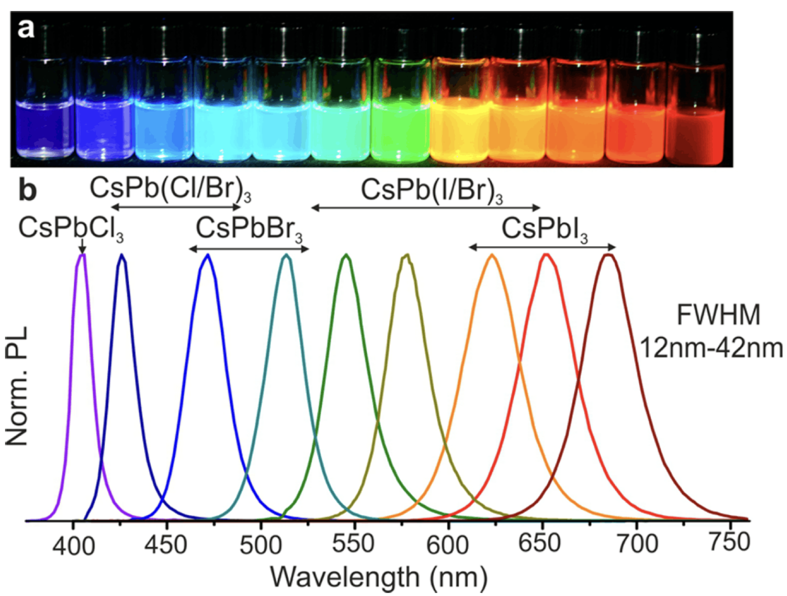
In process of laboratory testing NC scintillator transmittance seen to be low:

Is low light yield from self absorption?

Next steps for NC scintillator optimization

Continue to optimize NC scintillator via additional tests with small modules before constructing full-scale prototypes

- 1 week of beam time in CERN PS T9 beamline approved (14-21 June 2023)
- New NanoCal prototypes to be tested:
  - O-2 fibers and 0.2% $CsPbBr_3$ with corrected hole size → **new baseline**
  - NCA-1 (custom) fibers and 0.2% $CsPbBr_3$ size → **optimization of fibers**
  - NCA-1 fibers and ~1% $CsPbBr_3$ → expect increase in light yield from **higher concentration**
- New ideas for NC scintillators with **longer absorption length**



- Use co-dopant as internal WLS, like conventional scintillator
  - Many fast (1-2 ns) candidates
- Use blue-emitting $CsPbCl_3$ to obtain primary emission at shorter wavelength
  - Tricky interface chemistry needed to stabilize $CsPbCl_3$ against non-emitting phases, but possible
  - Can tune emission by admixture of different halides

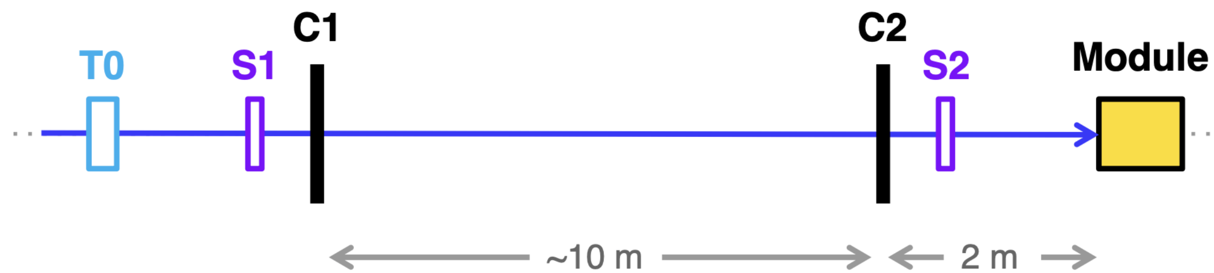
NanoCal setup and 2023 T9 test program

Electron beam, 1-10 GeV
MIP beam (μ^- or π^-), ~4 GeV
Cerenkov detectors to allow verification of beam ID $e/\mu\pi/p$

T0	Time reference detector
S1, S2	Trigger scintillator paddles
C1, C2	Si strip tracking chambers, 10×10 cm^2
Module	Module to be tested

For each prototype:

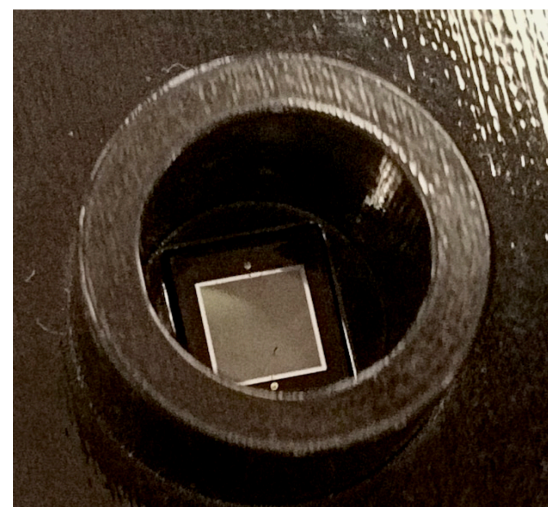
- MIP response
- MIP efficiency map
- $e-$ response
- Time resolution



New mechanics to allow rapid construction of test modules


External mock-up


3d-printed internals


Fiber/SiPM coupling

Final observations

First test of NanoCal prototype only 6 months after start of project!

Current formulation of NanoCal scintillator works but needs improvement

- Light yield ~ 10x less than conventional scintillator, accounting for decrease in SiPM quantum efficiency at longer wavelength
- Time resolution approximately same as or better than for conventional scintillator, accounting for difference in light yield

Optimization of NanoCal scintillator continuing, supported by analysis and laboratory measurements

Additional tests with small modules planned before constructing full-scale prototypes

- Test beam scheduled for 14-21 June
- New NanoCal prototypes under construction

NanoCal project making significant progress and starting to produce interesting results!