Development of nanocomposite scintillators for high-energy physics: **NanoCal Final Report**

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For the NanoCal Project

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Nanomaterial composites (NCs)

Next-generation detectors for experiments at the intensity frontier demand scintillators with

- faster response (τ < 1 ns)
- higher radiation resistance (> 50 kGy)
- better light output (> 10k ph/MeV)

than currently available

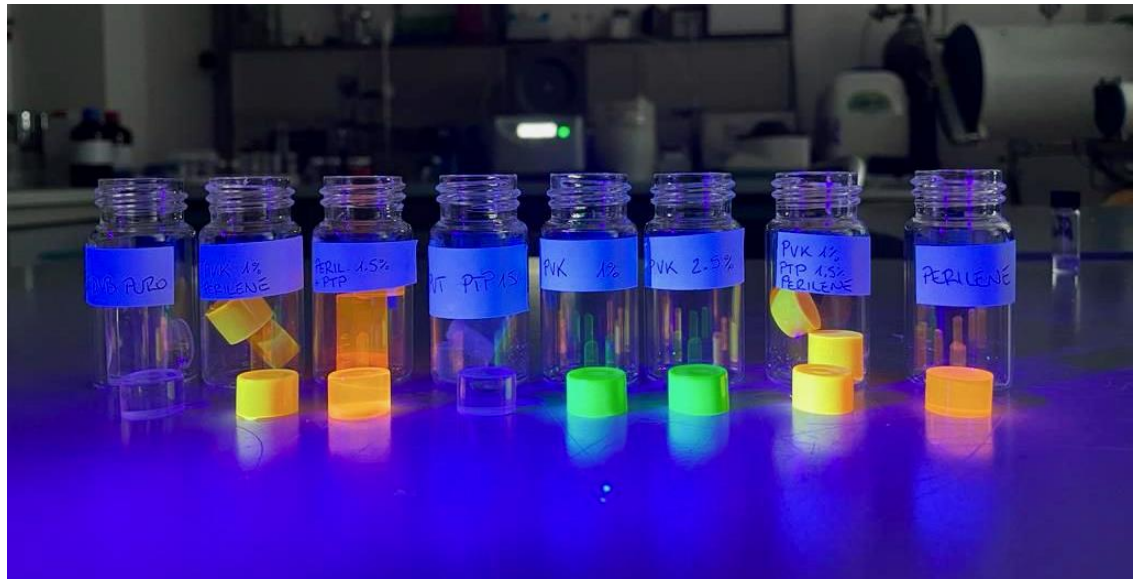
Semiconductor nanostructures can be used as sensitizers/emitters for ultrafast, robust scintillators:

- Perovskite (ABX_3) or chalcogenide (oxide, sulfide) nanocrystals, typically 5-10 nm in size
- 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 meet 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



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

NCs have high potential for innovative, high-performance calorimeters

NanoCal: From test bench to detector

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

- Many studies with photoluminescence (PL) and radioluminescence (RL)
- However, **almost no studies** 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**

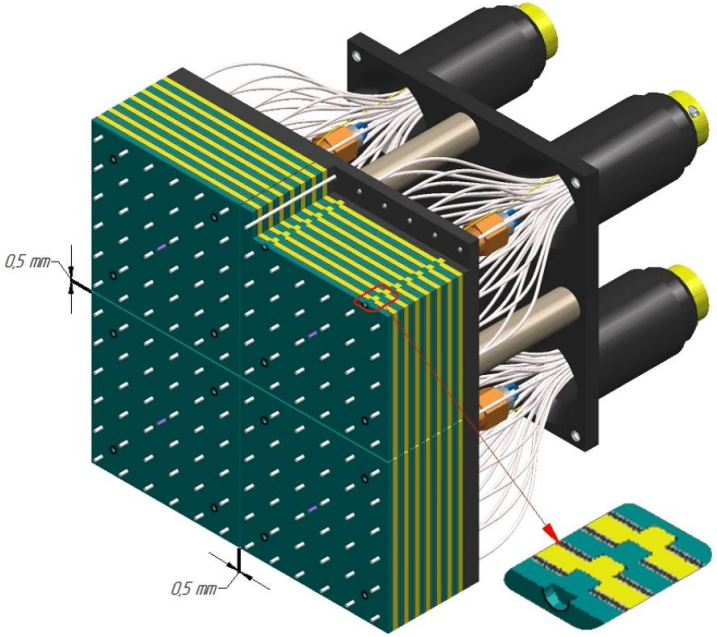
NanoCal project: Construct a calorimeter prototype with NC scintillator and test with high-energy beams

Shashlyk design naturally ideal as a test platform:

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

In context of research on NC scintillators, also explore:

- **New dyes** for optimized conventional scintillators
- Fast, bright **long-wavelength (green, orange) scintillators** for additional radiation hardness

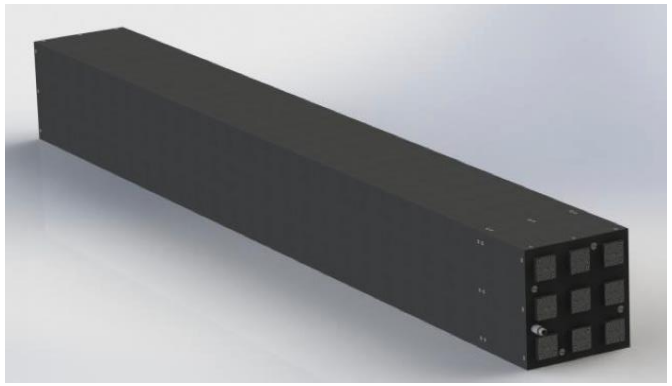


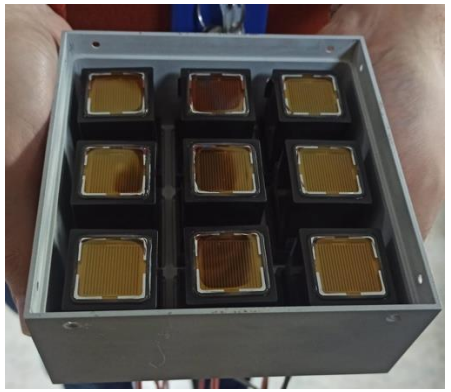
KOPIO/PANDA design
Fine-sampling shashlyk

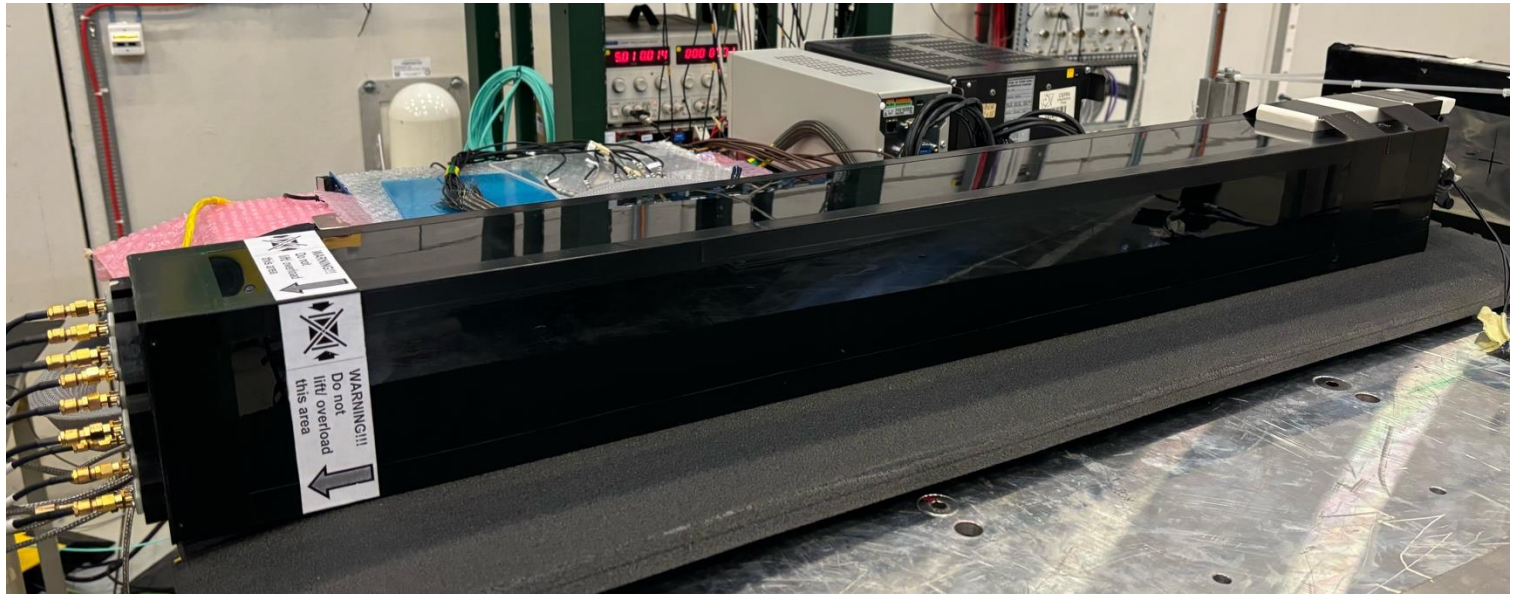
NC scintillators and shashlyk calorimetry

NanoCal shashlyk platform adapted from PANDA forward EM calorimeter:

- Very fine sampling
  0.3 mm Pb/1.6 mm scintillator
- ISMA UPS-923A scintillator
  2% PTP + 0.03% POPOP
- BCF-92XL WLS, 1.2 mm dia.
- 500-layer depth = $27X_0$
  Can be reconfigured
- Fine granularity
  3x3 cells, 4x4 cm^2 each
- Alternatives for light readout
  - SiPM: Hamamatsu S13360-6025
  - PMT: R7600-300 (green extended)
- **Use as platform for studies with innovative scintillator**
- **First perform exploratory tests with $1X_0$ shashlyk towers**



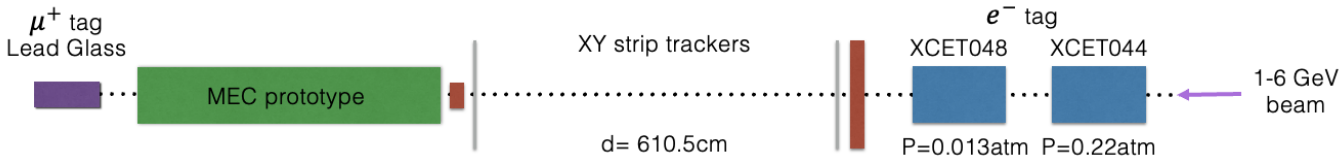


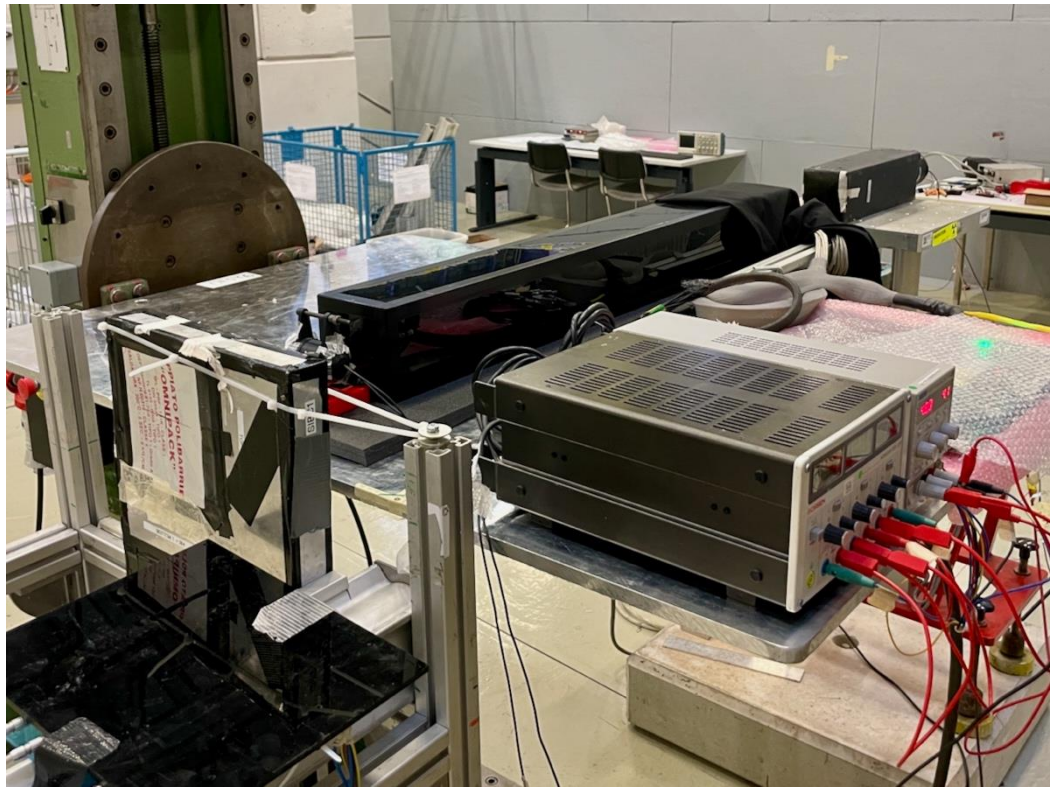


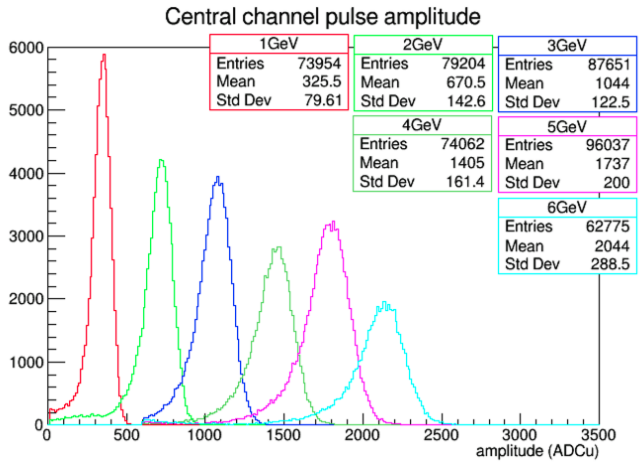
Prototype developed in synergy with HIKE
Parts & main assembly at ISMA Ukraine

Test beam studies of shashlyk prototype

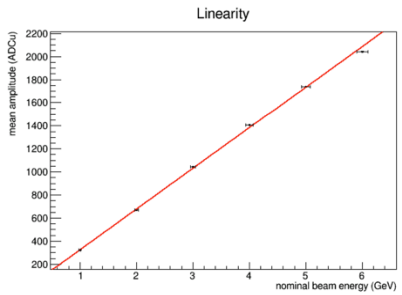
Tests with 1-6 GeV e^- T9 beamline, Oct 2024

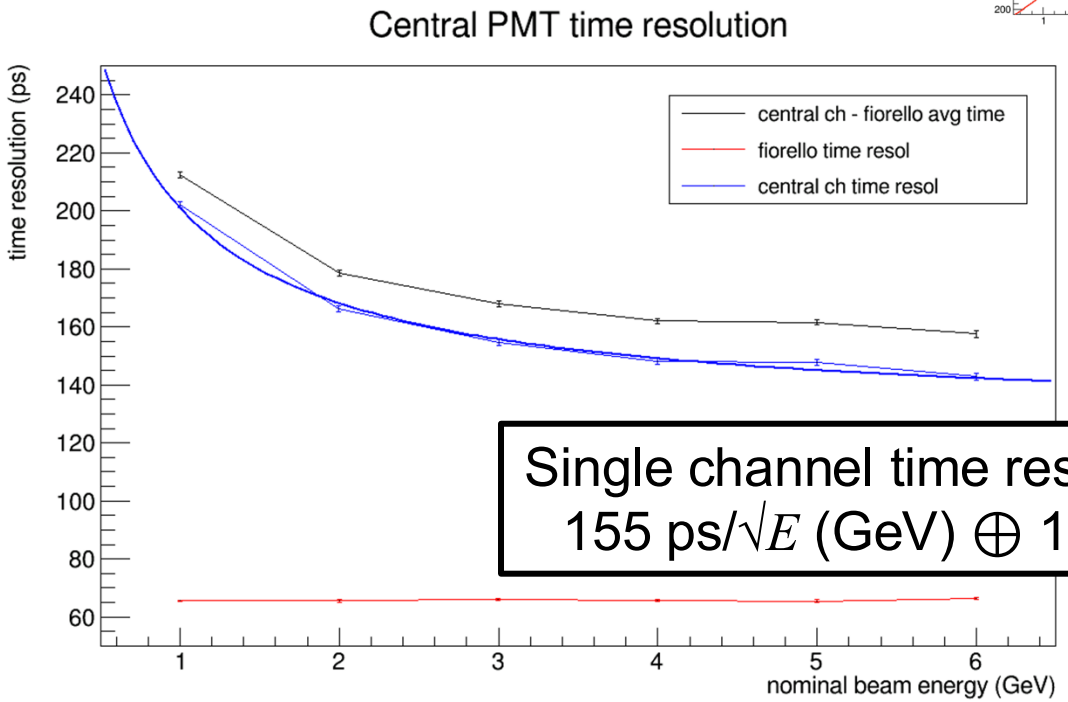






- Good amplitude linearity for single channels
- Intercalibration in progress

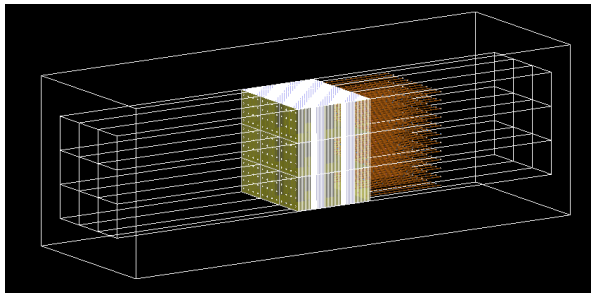


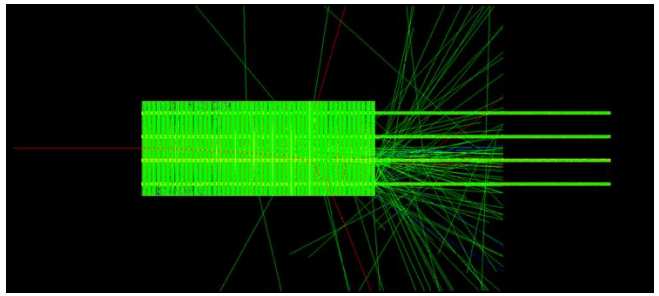


Single channel time resolution
155 ps/$\sqrt{E}$ (GeV) $\oplus$ 127 ps

Next beam test scheduled Sep 2025
Dual side readout, faster fibers (YS-4) and PMTs (R9880)

Simulation of baseline shashlyk prototype



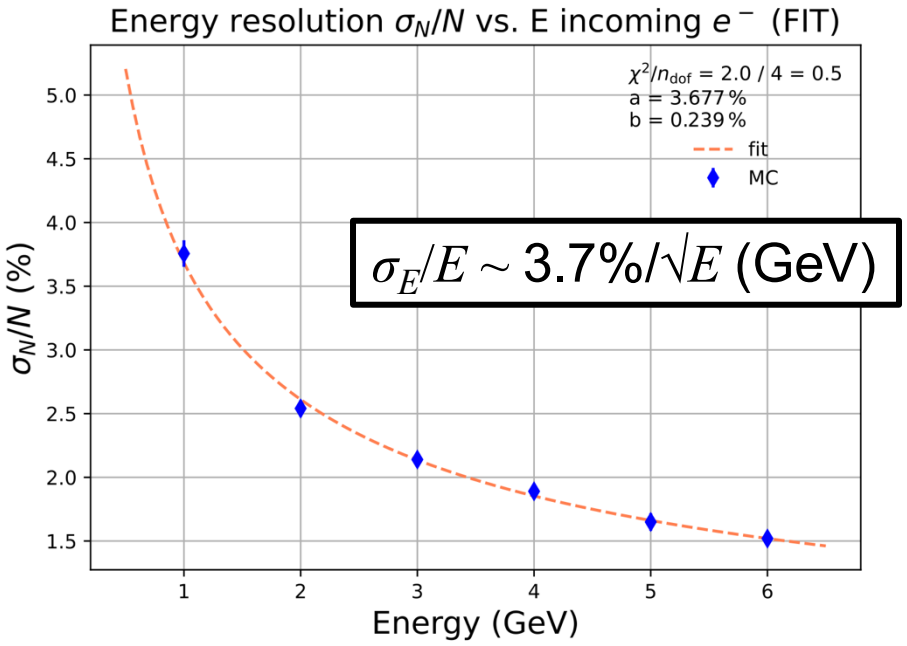


Geant4 simulation:

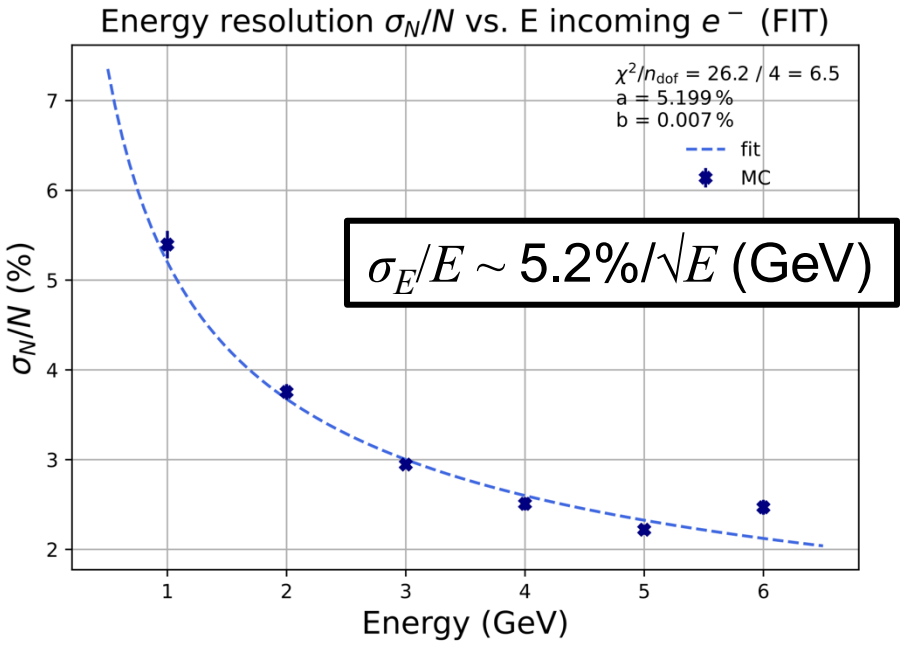
- Detailed simulation of structure, material properties, optical surfaces
- Energy resolution from number of photons at photodetector (photodetector response not simulated)

Energy resolution of prototype limited by **transverse leakage** and **beam energy spread:**

5x5 cell prototype, **no** beam energy spread



3x3 cell prototype, beam energy spread



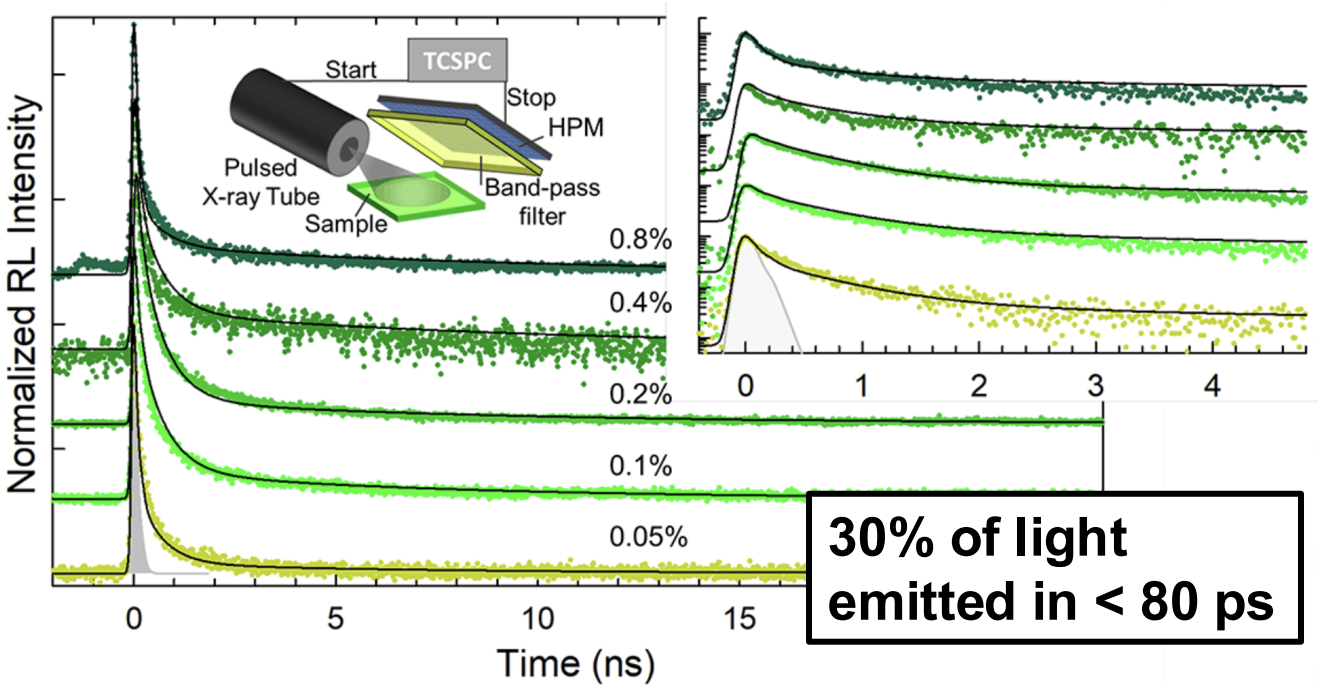
The promise of lead halide perovskite NCs

ACS Energy Letters
http://pubs.acs.org/journal/aelccp

A. Erroi et al. 2023
ACS Energy Lett 8 3883

Ultrafast and Radiation-Hard Lead Halide Perovskite Nanocomposite Scintillators

$CsPbBr_3$ nanocrystals (~10 nm)
0.05 to 0.8% w/w in UV-cured polyacrylate matrix, measured with **radio- and photoluminescence**



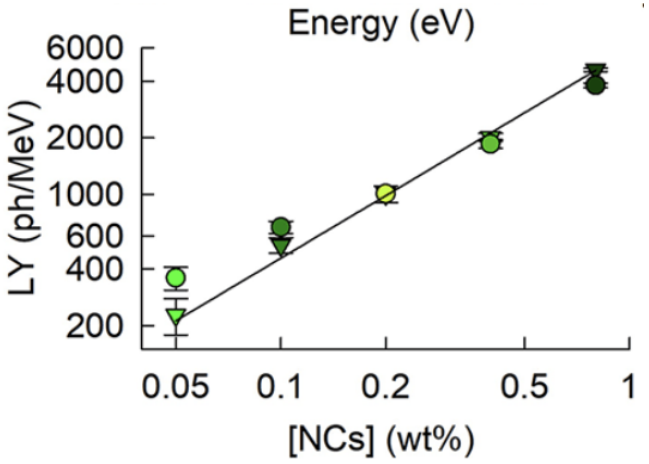
30% of light emitted in < 80 ps

3-component fit to pulse shape for 0.2% sample:

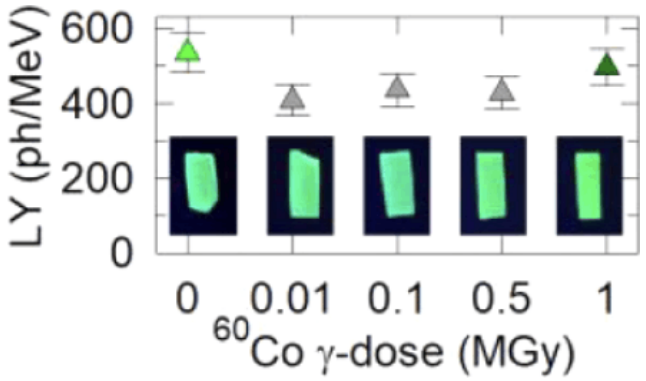
- 34% prompt (Gaussian, 160 ps IRF)
- 22% with τ_{decay} ~ 600 ps (R_1)
- 44% with τ_{decay} ~ 10 ns (R_2)

R_2 increases with concentration, prompt component maintained

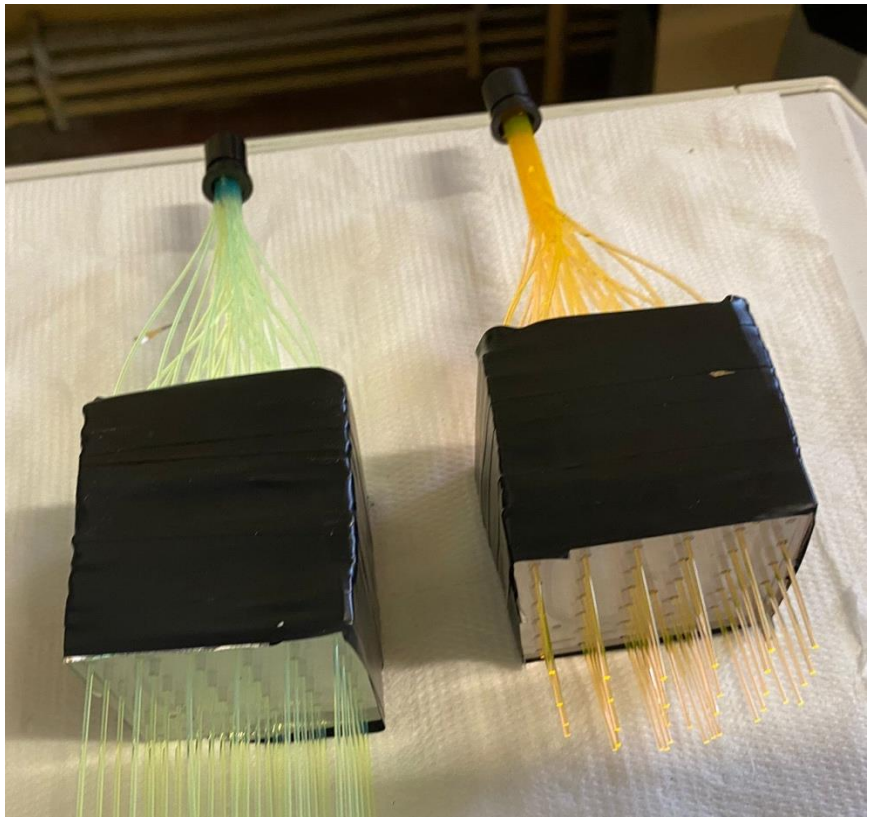
4800 ph/MeV at 0.8% w/w



No decrease in LY up to 1 MGy



Early tests of NC shashlyk towers



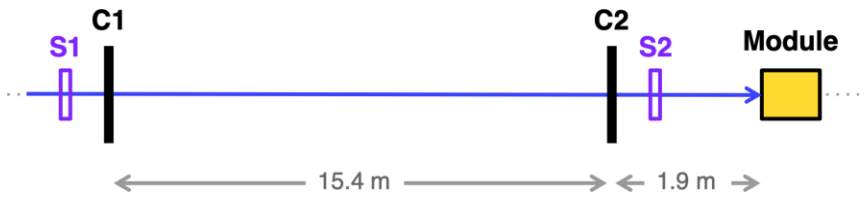
Conventional
Protvino scintillator
Polystyrene
1.5% PTP
0.04% POPOP
Y-11(200) WLS

NanoCal
PMMA
0.2% $CsPbBr_3$
O-2(100) WLS

First test of NanoCal prototype, fall 2002

Comparison of light yield from
- Protvino shashlyk tower
- NanoCal prototype

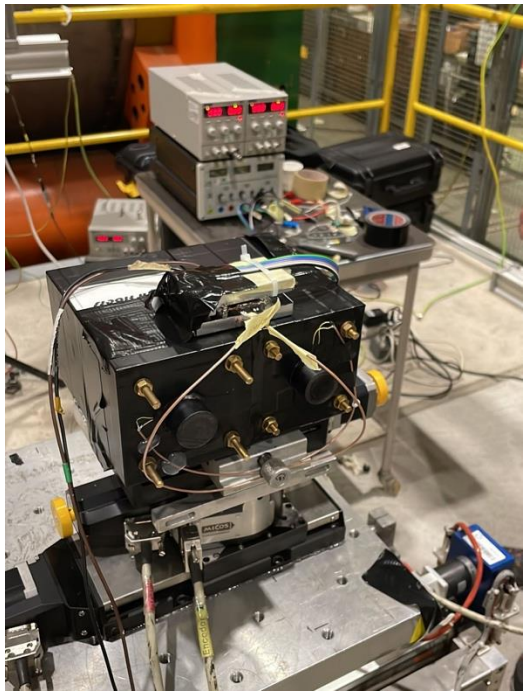
SPS H2 beamline:
- 80 GeV e^-, 150 GeV π^+



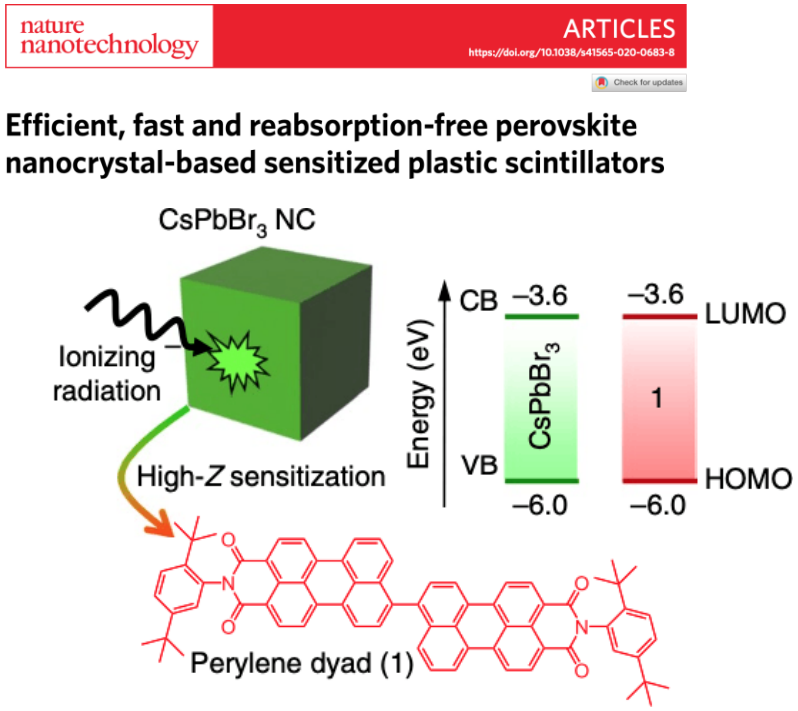
LY_{mip}(NanoCal/Protvino) ~ 5%

Possible issues:

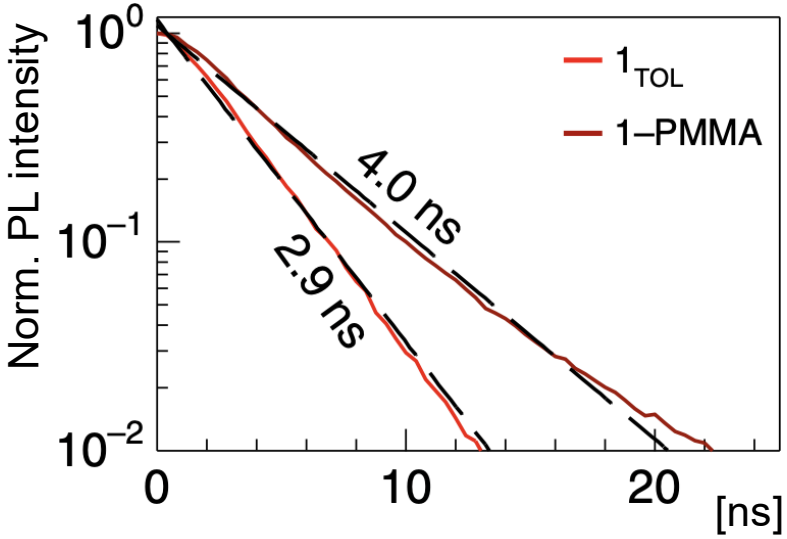
1. NCs have too much self-absorption?
2. Inefficient excitation of nanoparticles: concentration too low, no energy transfer from matrix?

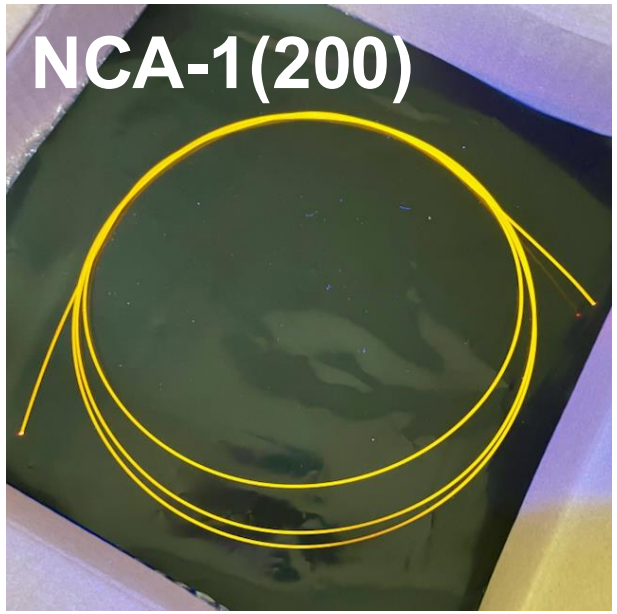


Perylene-based WLS fibers for NanoCal



Perylene dyad in toluene and PMMA





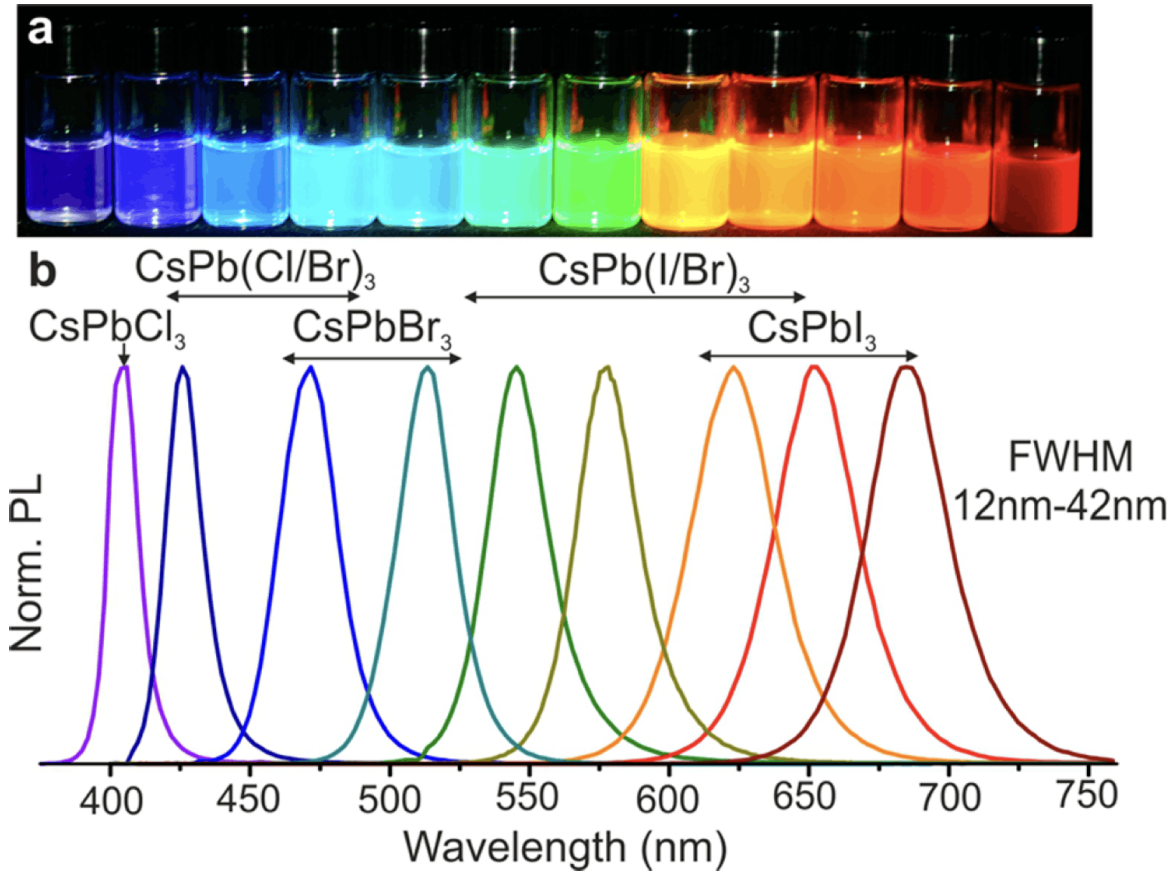
Commissioned production of custom fiber from Kuraray (NCA-1)

- 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} **~ 4 ns**
  Compare to 5.3 ns for O-2, 7.5 ns for Y-11

First ideas for NC scintillator optimization

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

- Explore new ideas for NC scintillators with longer absorption length



- Use co-dopant as internal WLS, like conventional fiber
  - 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

WL-shifted NC scintillators for shashlyk applications

$CsPbBr_3$ in PMMA (green emission) → **inconvenient to shift to red**

A promising idea:

1. Use $CsPb(Br,Cl)_3$: Substitution of some Br with Cl shifts emission to blue
2. Add coumarin-6 as a high-Stokes-shift WLS → shifts emission back to green

Synthesis of $CsPbBr_3$

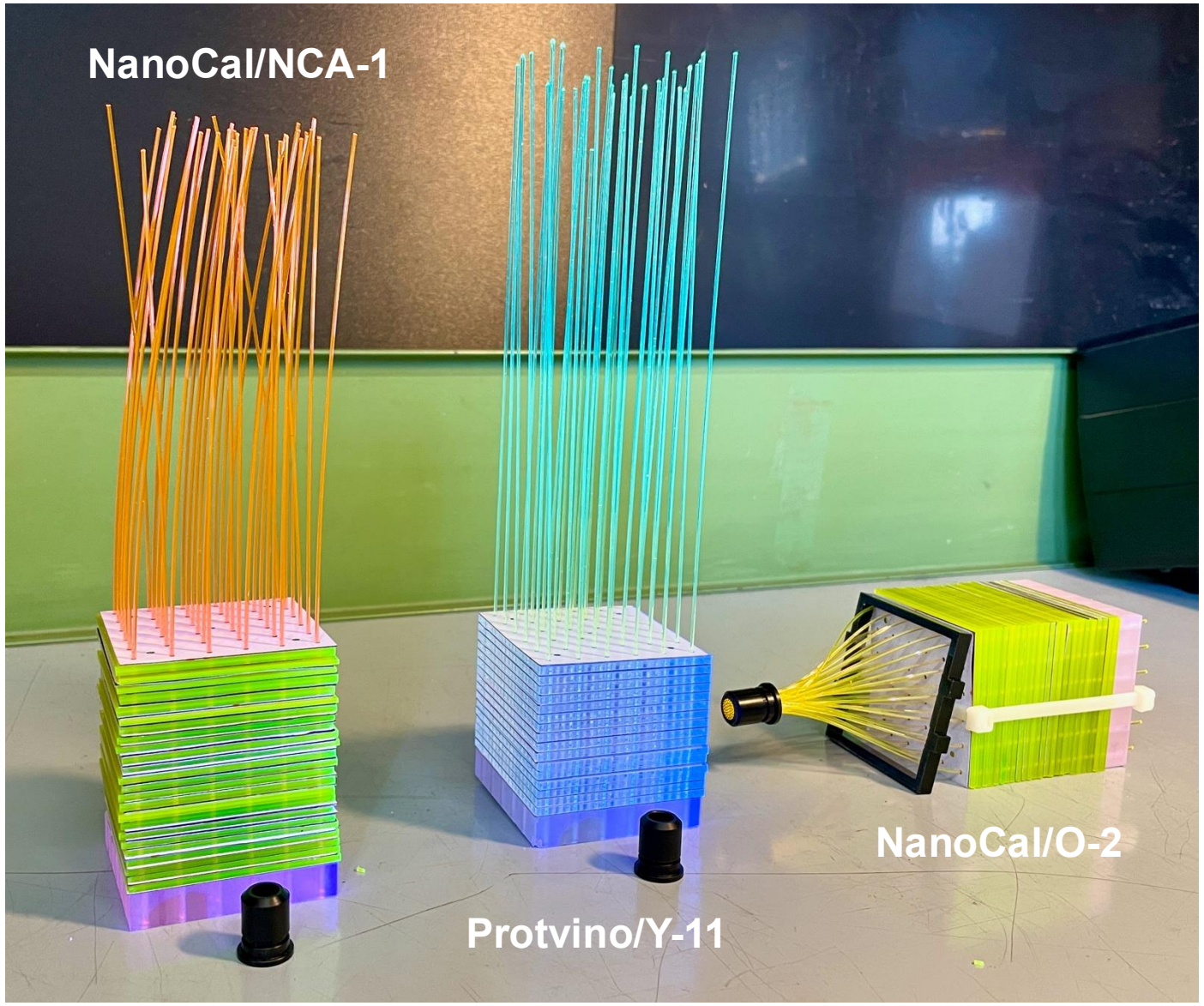
Substitution of 50% of Br with Cl

Addition of coumarin-6

However, surface passivation of nanocrystals destroyed during substitution reaction, leading to aggregation (milky appearance, poor transparency)

First prototype tested anyway with custom (NCA-1) fibers at CERN in June 2023

Second-generation shashlyk test modules

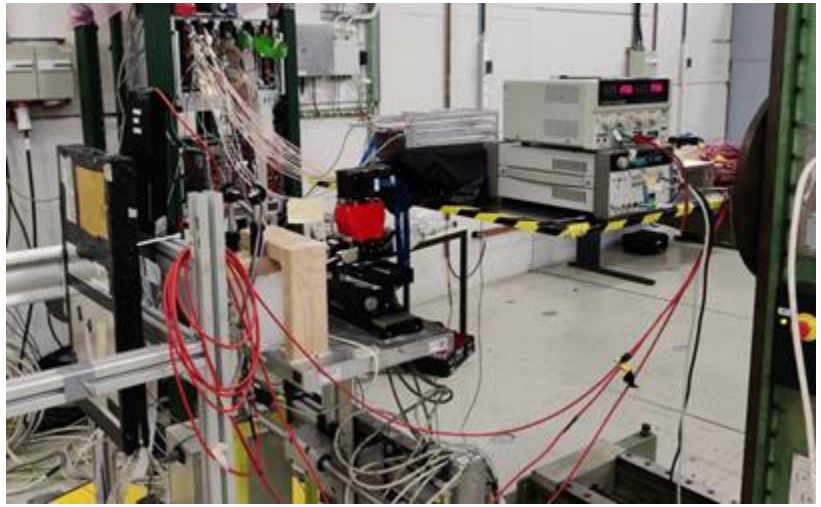


Prototypes tested in PS T9, June 2023:

- Conventional scintillator (Protvino), Y-11 fibers
- Conventional scintillator (PVT + BTP 0.02%), Y-11 fibers
- PMMA + $CsPbBr_3$ 0.2%, O-2 fibers
- PMMA + $CsPbBr_3$ 0.2%, custom NCA-1 fibers*
- PMMA + $CsPb(Br,Cl)_3$ + coumarin-6, NCA-1 fibers

*NCA-1 fibers
Custom produced by Kuraray
Perylene dyad 200 ppm in PS

Tests with second-generation modules



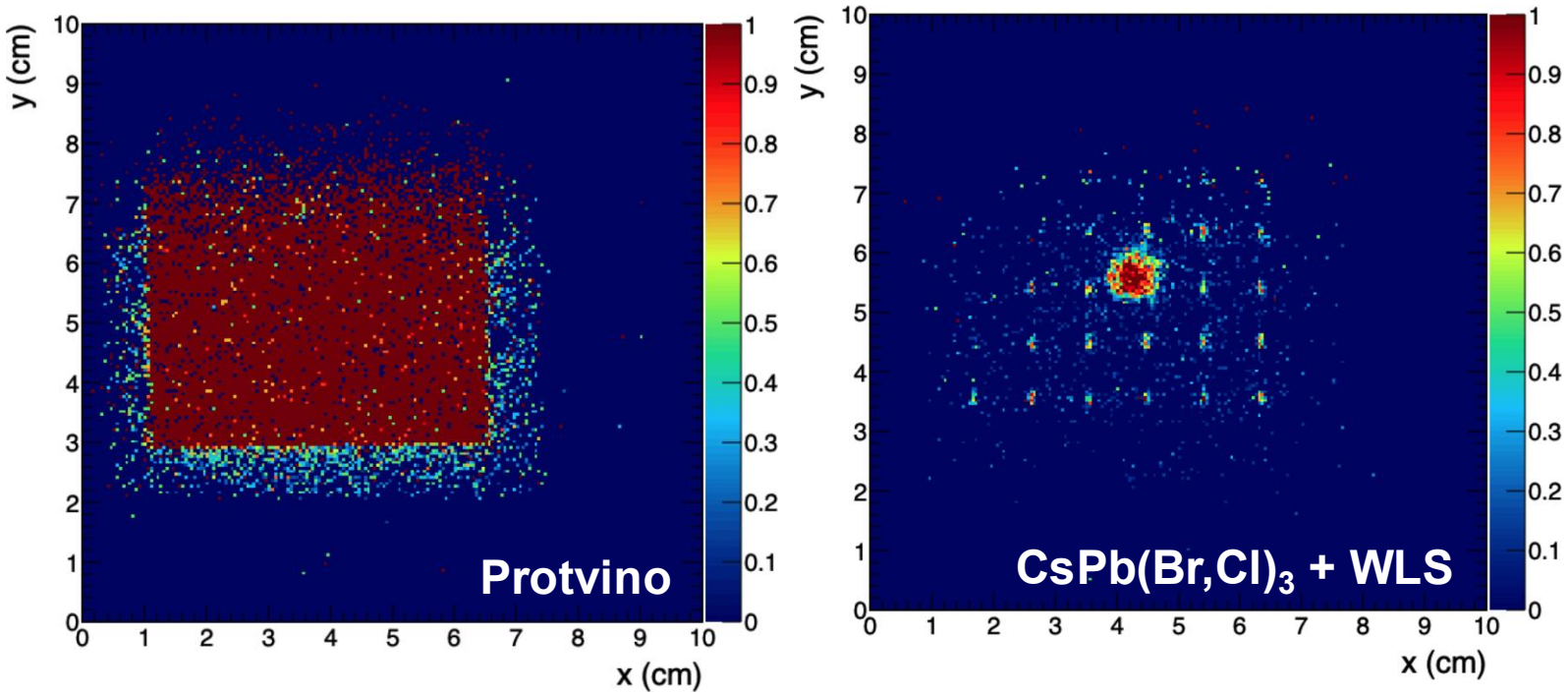
PS T9 beamline, Jun 2023

- Electron beam, 1, 2, 4 GeV
- MIP beam (μ^- or π^-), 10 GeV
- Cerenkov ID for $e/\mu\pi/p$

For each prototype:

- MIP response, efficiency
- e^- response
- Time resolution

Efficiency maps with 10 GeV μ, threshold = $5\sigma_{noise}$



- Reliable combination of Protvino scintillator and Y-11 fibers shows good performance
- **Signal from the NC-based modules entirely from the fibers:**
  - Reabsorption, in part because WL-shifted NC scintillator not working because of (resolvable) quality problems
  - Inefficient nanocrystal excitation: low concentration, inert matrix

One step back: First focus on NC scintillator alone

Explore WL-shifted NC scintillators to overcome self absorption

- Direct synthesis of $CsPb(Br,Cl)_3$ to preserve surface passivation is possible
  - Needed for green scintillators (e.g. shahslyk applications)
- For direct tests of NC scintillators, can use green-to-orange WLS: makes synthesis easier

Use aromatic matrix materials to transfer energy to nanocrystals

- First formulations use PMMA
  - UV polymerized to preserve nanocrystal surface passivation
  - Gives no primary scintillation contribution
- New protocol developed to allow use of perovskites in thermally polymerized matrix (e.g. PS, PVT)
- Surface passivation with fluorine allows higher nanocrystal concentrations

Complete set of new samples synthesized and tested:

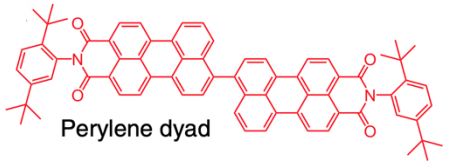
- Beam tests at CERN PS T9 in Oct 2023 and at Frascati BTF in Nov 2023 and Apr 2024
- Molecular (organic) scintillators included for comparison and study
- Complete set of control samples to isolate contributions from components

NC scintillator samples for direct testing

$PVT/DVB_{90/10\%}$ + PTP_{α} + γ^{*}:$CsPbBr3_{\beta}$ + perylene $dyad_{\delta}^{\dagger}$

*Surface passivation

†Green-to-orange WLS dye



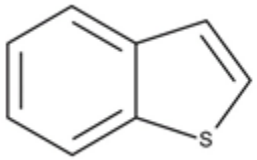
Sample	α	β	γ	δ	Appearance
Blank_0	0	0	-	0	transparent, colorless
Blank_1	1.5%	0	-	0	transparent, colorless
Blank_2	0	0	-	0.05%	transparent, orange
Blank_3	1.5%	0	-	0.05%	transparent, orange
NC23_2	1.5%	1.5%	Yb	0	hazy, green
NC23_4	1.5%	1.5%	Yb	0.05%	hazy, orange
NC24_0	0	1.5%	F	0	opaque, green
NC24_1	0	2.5%	F	0	very opaque, **green**
NC24_2	1.5%	1.5%	F	0	opaque, green
NC24_3	0	1.5%	F	0.05%	very opaque, orange
NC24_4	1.5%	1.5%	F	0.05%	very opaque, orange

Molecular scintillator samples for testing and comparison

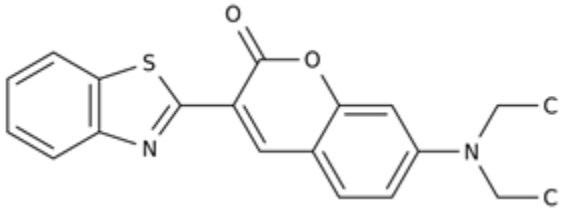
$PVT/DVB_{90/10\%}$ + PTP_{α} + $(BBT^{*}\text{ or }POPOP)_{\beta}$ + $coumarin\text{-}6_{\gamma}^{\dagger}$

Sample	α	β	γ	Appearance
Mol_0 Protvino-*like* PVT instead of PS	1.5%	POPOP 0.04%	0	transparent colorless, **blue** under UV
Mol_1	1.5%	BBT 0.04%	0	transparent colorless, **blue** under UV
Mol_2	1.5%	0	0.04%	transparent, green
Mol_3	1.5%	BBT 0.04%	0.04%	transparent, green

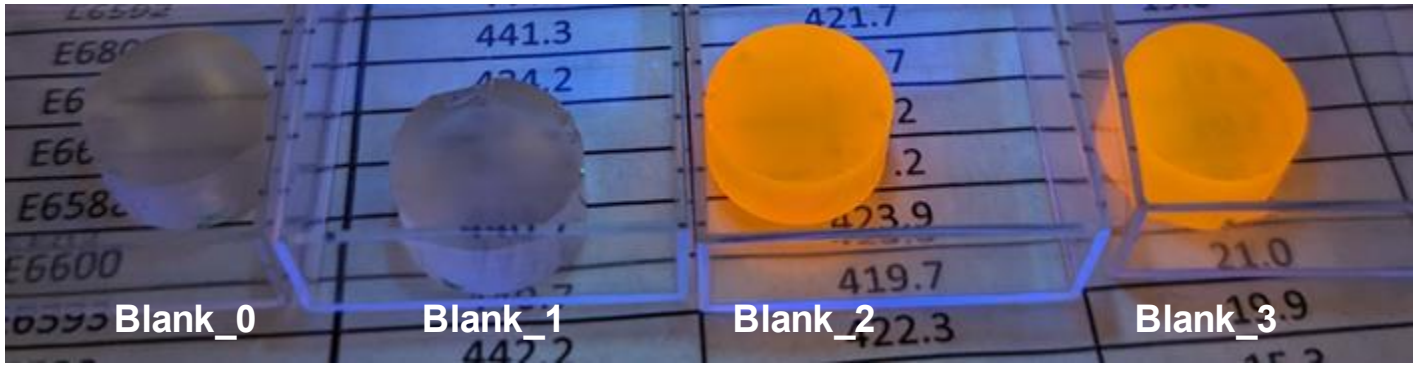
*BBT = benzo(b)thiophene
near-UV to blue WLS dye

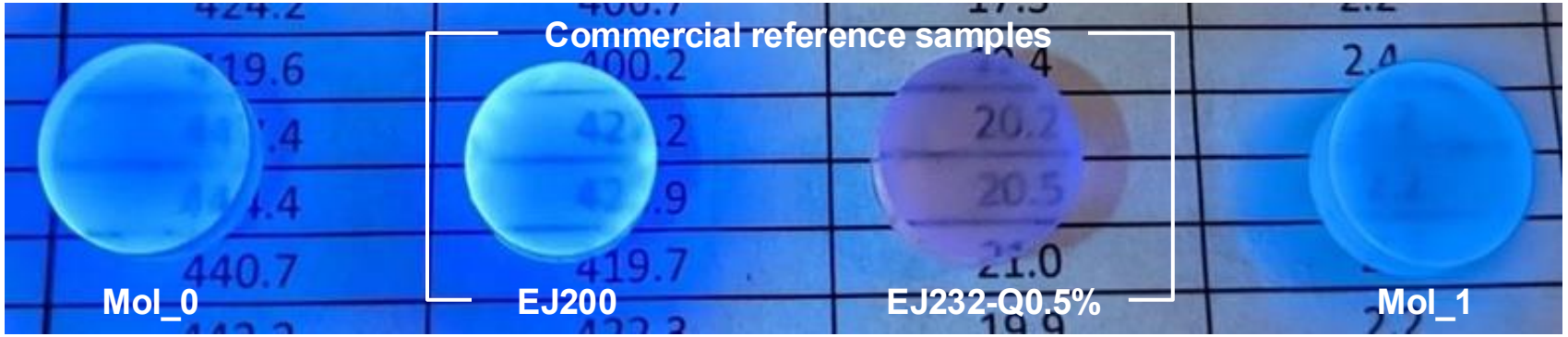


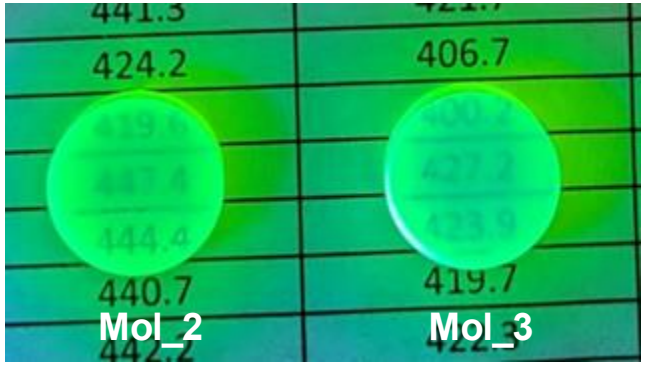
coumarin-6
blue-to-green WLS dye

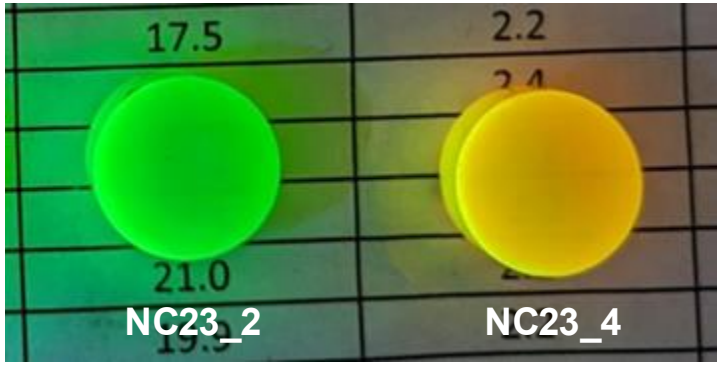


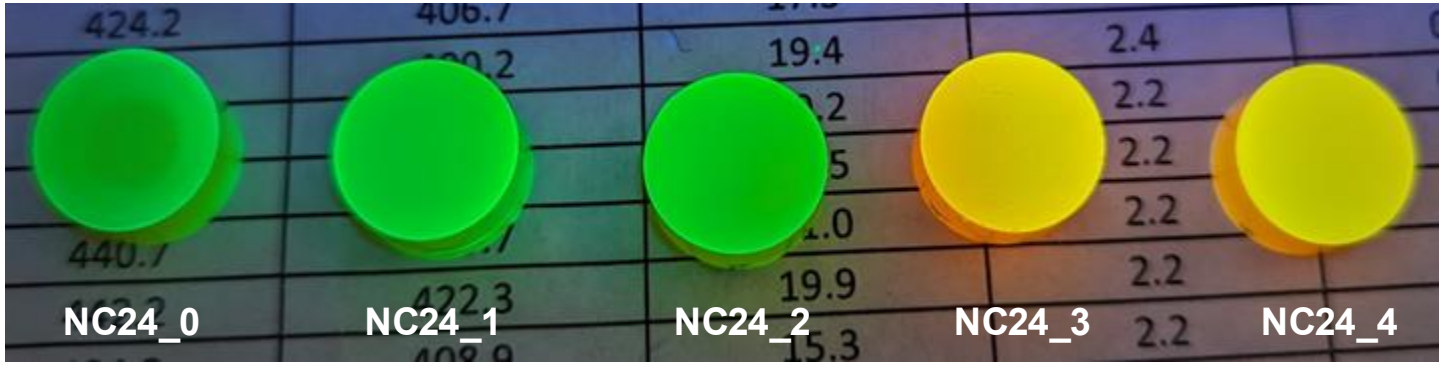
Samples under UV light











Light-yield measurements at the Frascati BTF

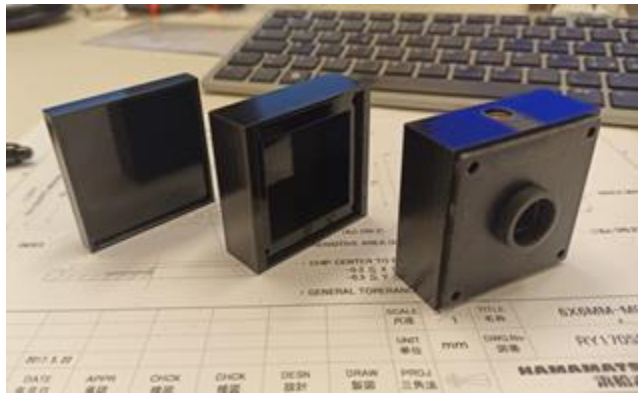
Frascati Beam-Test Facility (BTF)

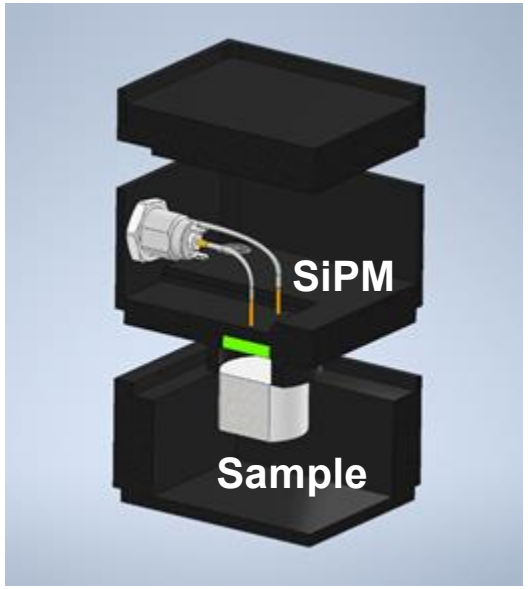
- Single 450 MeV e^- at 25 Hz, spot size ~400 μm: Similar dE/dx to mips
- FitPix unit and Pb glass block to measure electron multiplicity for single-particle selection

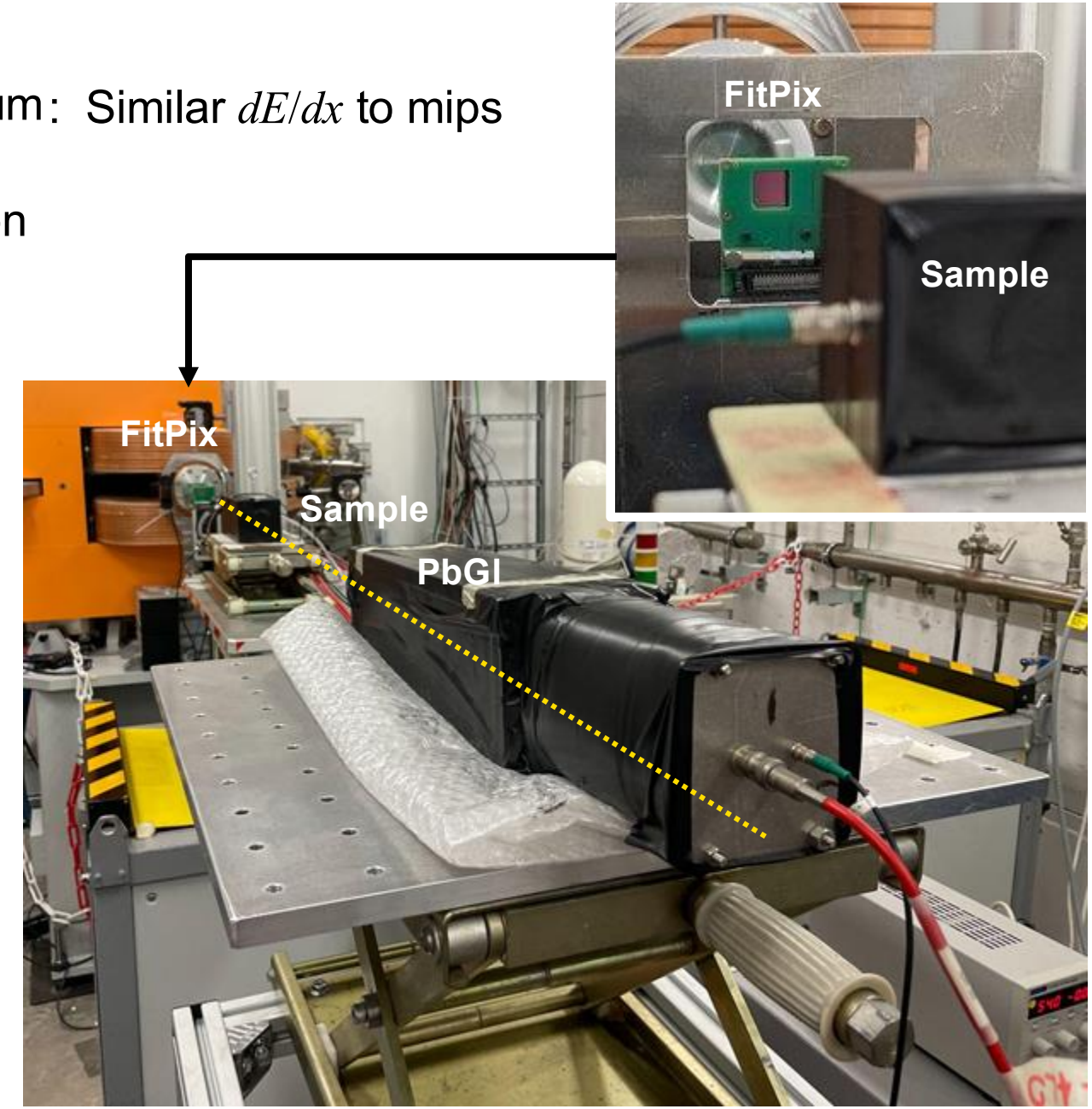
Test device

- Sample cell: 14.5 mm diameter x 7 mm deep
- SiPM: Hamamatsu S13360-6050CS
- Surface index matching with silicone grease
- Amplifier: 300 MHz BW, TIA gain = 4.87

$$Q = \frac{1}{Z_{\text{in}} G} \int V_{\text{out}}(t) \mathrm{d}t$$

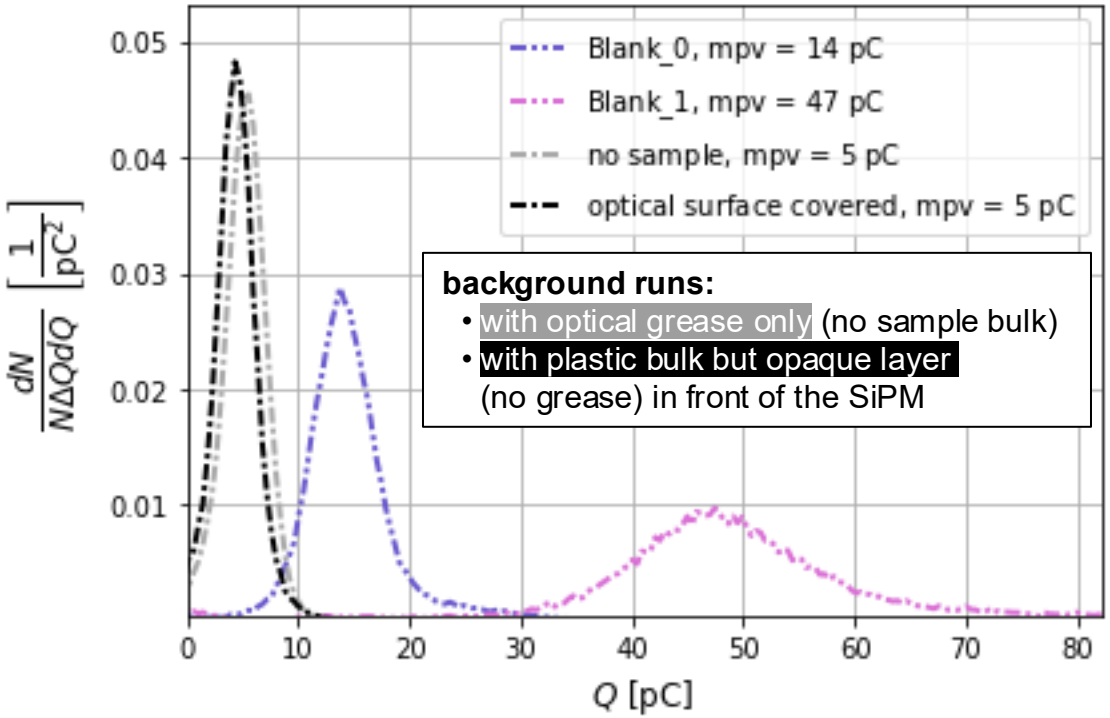






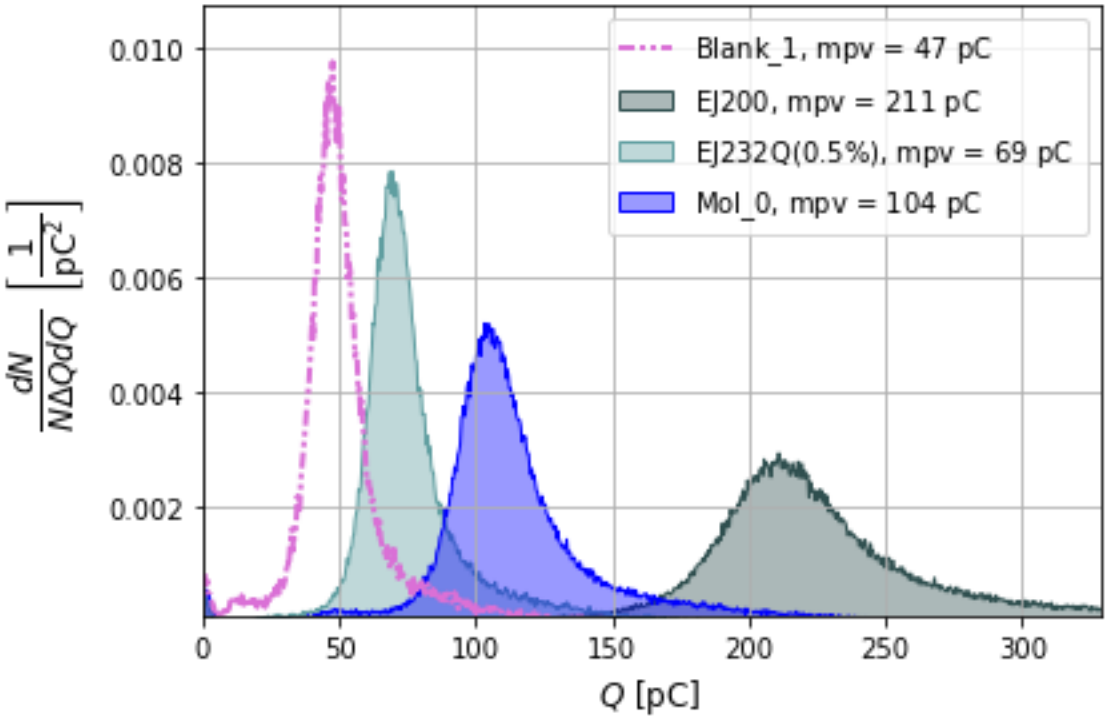
Single-electron spectra: Control samples

background & matrix



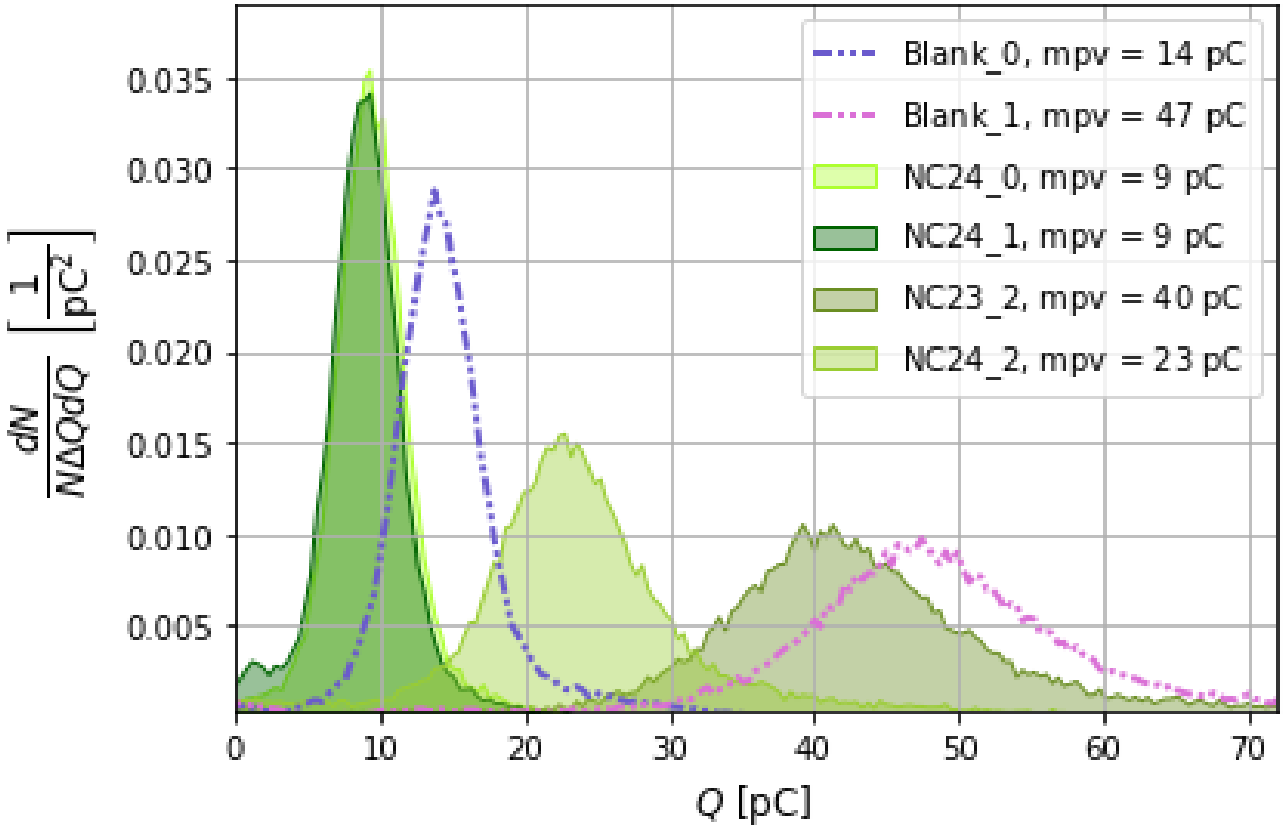
- Some signal from **PVT alone** in excess of charge signal from background runs
  - SiPM sensitive to long-λ tail of PVT emission
  - Cherenkov component
- LY for **PTP-doped matrix** > 300% LY for **PVT alone**

reference



- LY ratio between **EJ200** (datasheet: 10k ph/MeV) and **EJ232Q** (datasheet: 2.9k ph/MeV) correctly reproduced
- **Mol_0 (Protvino-like sample)** has 50% light-yield of **EJ200**: roughly consistent with expectation

Single-electron spectra: Unshifted NC samples



NC24_0, NC24_1 (perovskite only):

- LY significantly below that of **PVT-only**
- Independent of nanocrystal concentration (**1.5%** vs **2.5%**)
- PTP critical for transferring energy from matrix to perovskite

NC23_2, NC24_2 (perovskite+PTP):

- LY is lower than for **Blank_1**
- Perovskite seems to block part of the light emitted by the PTP-doped matrix

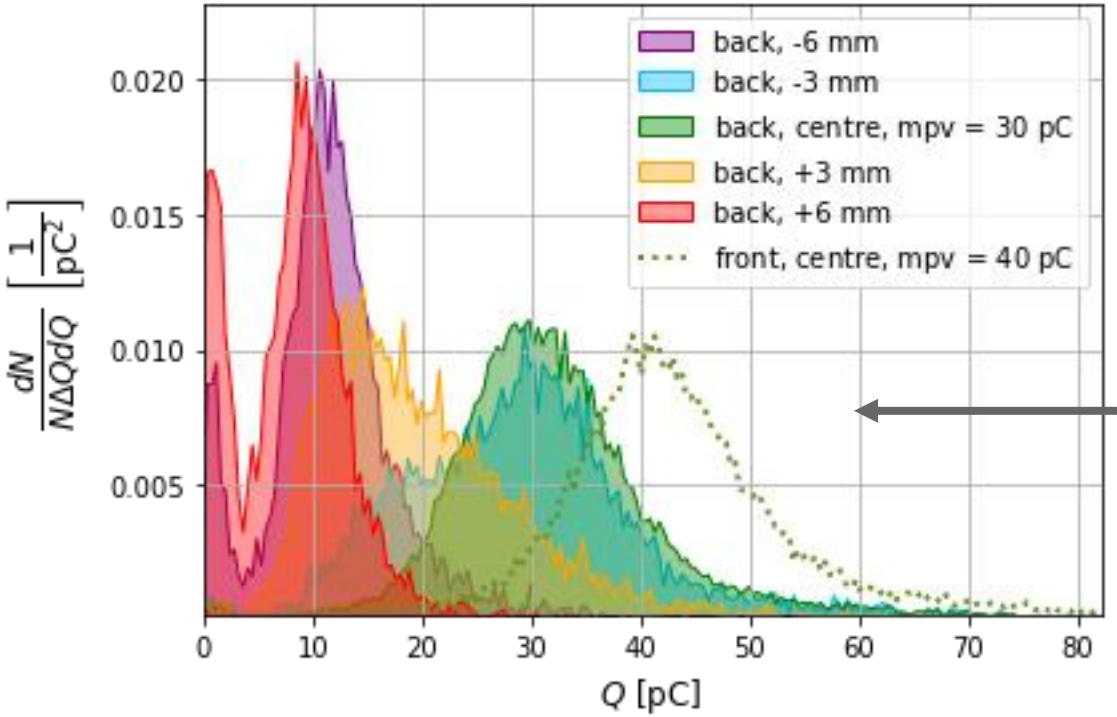
NC24_2 performs worse than **NC23_2:**

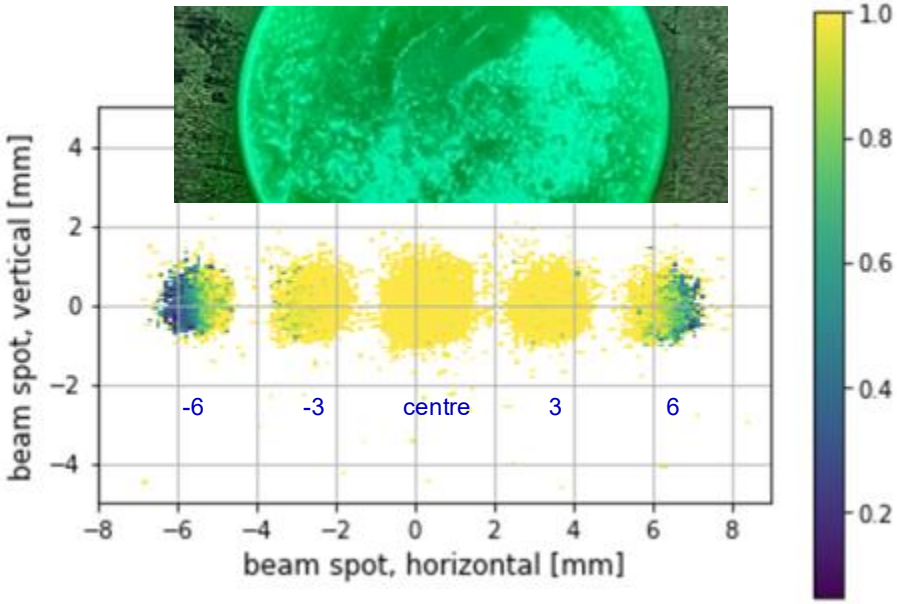
- **NC23_2** appears to be overall more transparent, albeit non uniformly

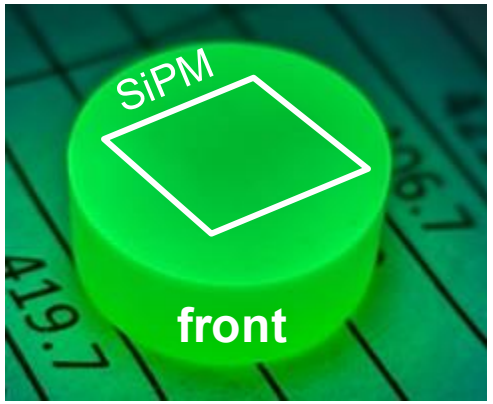
NC23_2 and **NC24_2** share same formula, but are produced in different batches, with different protocols for quantum dot passivation

Quality issues with NC samples

NC23_2: PTP + perovskite



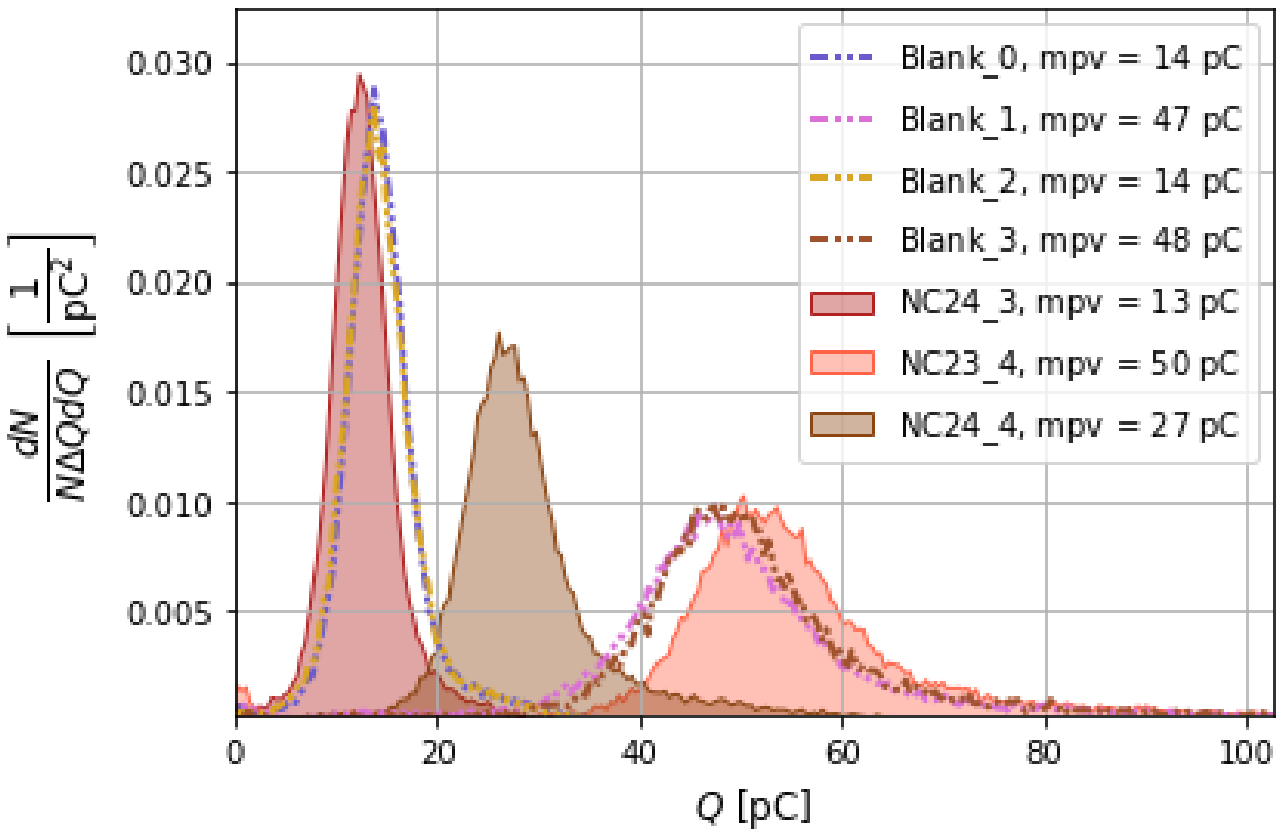




Non-uniform optical properties due to precipitation of nanocrystals on one face: Hint of self absorption?

- LY smaller when precipitate between sample bulk and photodetector
- LY larger where less precipitate

Single-electron spectra: WL-shifted NC samples



NC23_4 and **NC24_4** share same formula, but are produced in different batches, with different protocols for quantum dot passivation

In absence of perovskite, adding perylene does not seem to affect the total light output:

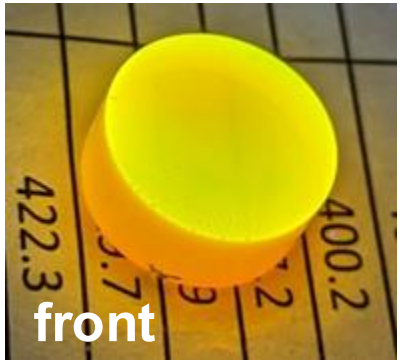
- LY **Blank_2** (perlyene) = LY **Blank_0** (PS only)
- LY **Blank_3** (perlyene+PTP) = LY **Blank_1** (PTP)
- Perylene **inefficient** to convert light from PS/PTP

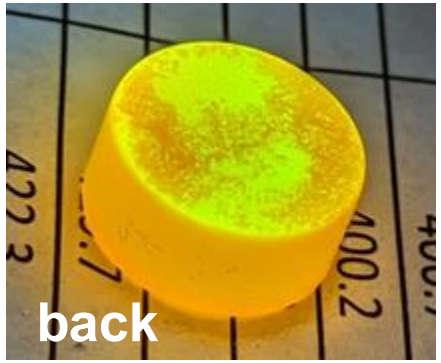
Perovskite + perylene together (**NC23_4**) give slightly higher LY:

- Marginally higher than **Blank_1, Blank_3**
- **25% higher LY** than **NC23_2** **(unshifted)**

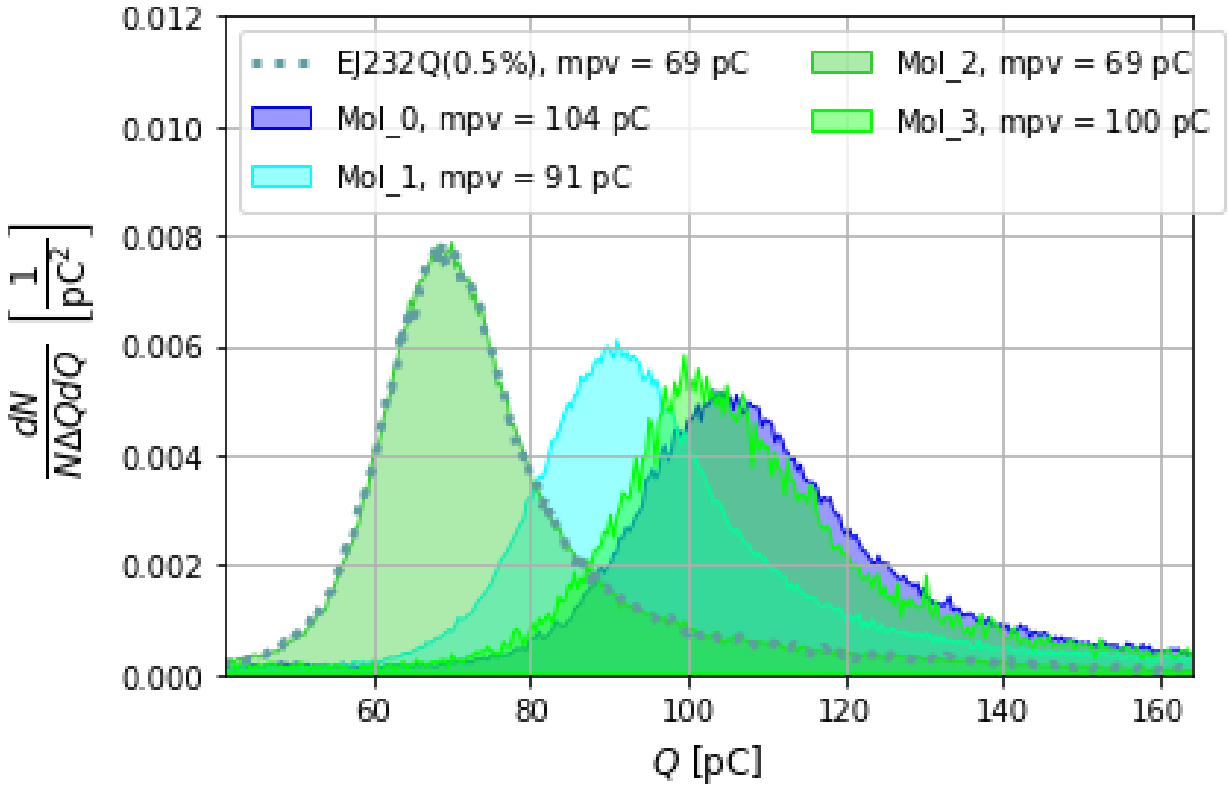
NC24_4 with perylene has same issues as **NC24_2:** In both cases, **LY 2024 ~ 50% LY2023**

- **NC23_4** has precipitate on one side, few % front-back asymmetry in response





Single-electron spectra: Molecular samples



Mol_1 (matrix+PTP+BBT) gives > **30% more light** than **EJ232Q**

Mol_2 (matrix+PTP+coumarin-6) gives the least light among our fully molecular samples: exactly **same** signal distribution as **EJ232Q**

- Inefficient spectrum matching

Mol_3 (matrix+PTP+BBT+coumarin-6) has approximately **same** LY as **Mol_0** (Protvino-like):

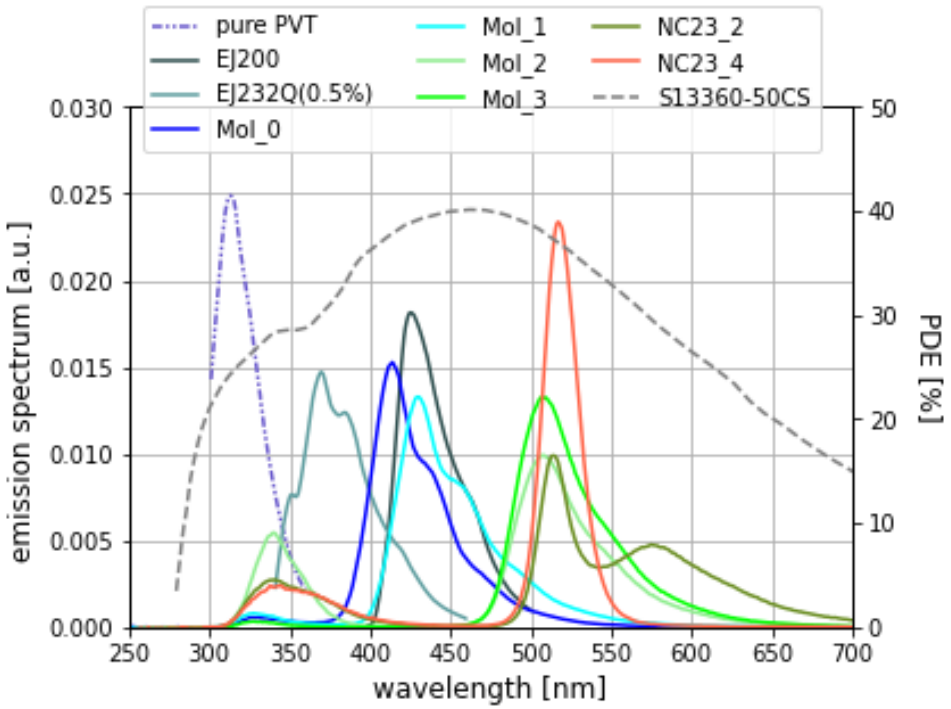
- **~ 150% EJ232Q, ~ 50% EJ200**
- Promising candidate for green scintillator pending evaluation of timing performance and radiation hardness

Overall comparisons with spectral corrections

Spectral corrections needed for meaningful quantitative comparisons of light yield between samples

Corrections obtained from integration of product of:

- **emission spectra**
- **SiPM PDE**



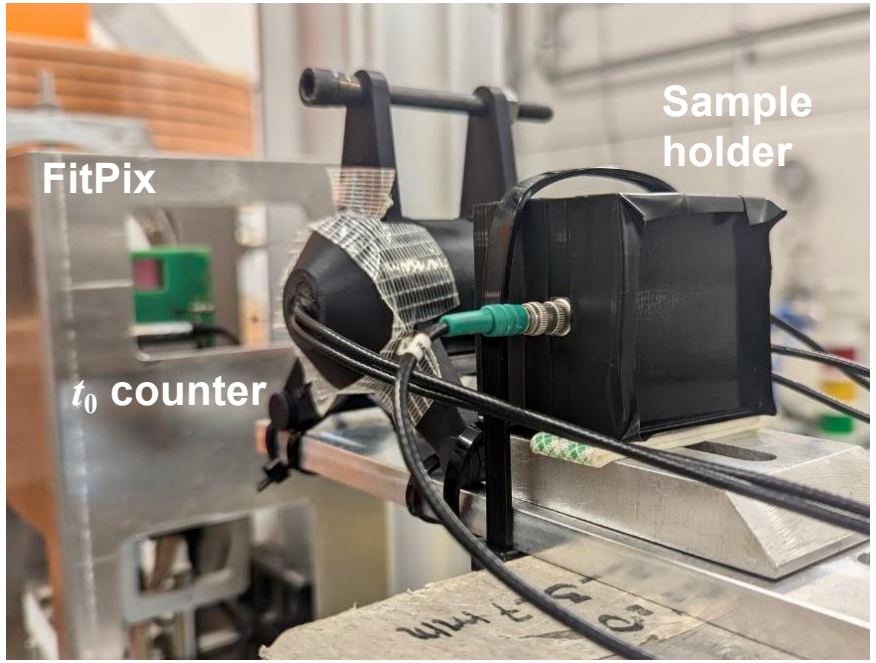
sample	charge MPV [pC]	corr. Mol_0 = 100	charge MPV [pC Mol_0 eq]	relative LY Mol_0 = 100
Mol_0 Protvino-like	104	100	104	100
EJ200	211	96.5	203.6	194.3
EJ232Q 0.5%	69	115.3	79.6	75.9
Mol_1	91	97.9	89.1	85.2
Mol_2	69	111.0	76.6	73.0
Mol_3	100	103.1	103.1	99.0
NC23_2	40	106.2	42.5	40.1
NC23_4	50	121.0	60.5	58.0

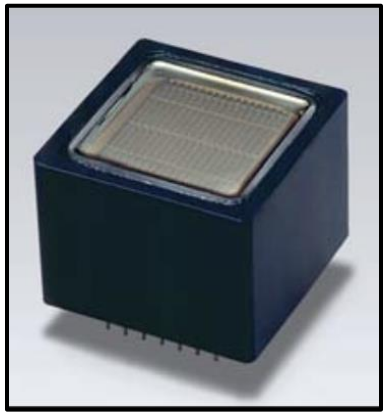
Relative to EJ200:

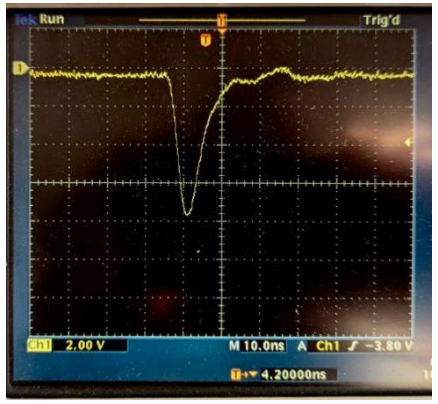
- **Our molecular samples have 40-50% of LY**
- **Our best NC samples have 20-30% of LY**

Timing characterization with beams

First measurements of scintillator rise times
Frascati BTF, July 2024: single 450 MeV e^-

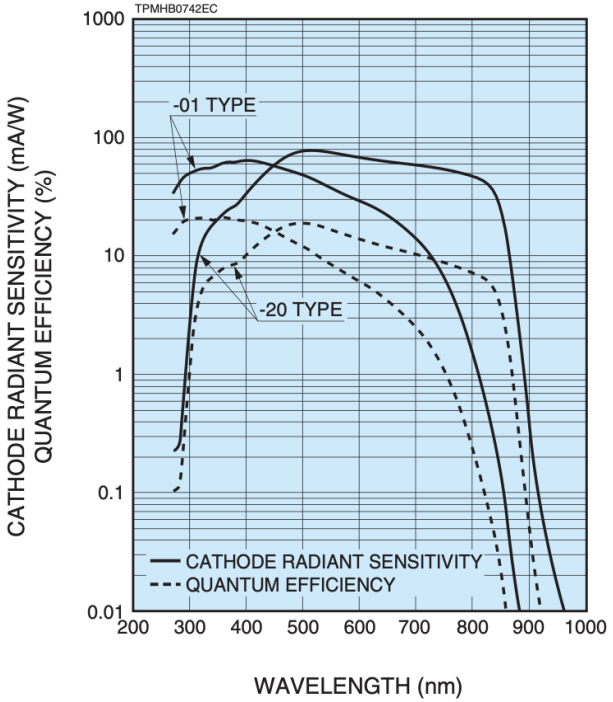






Sample holder
R7600-20 PMT

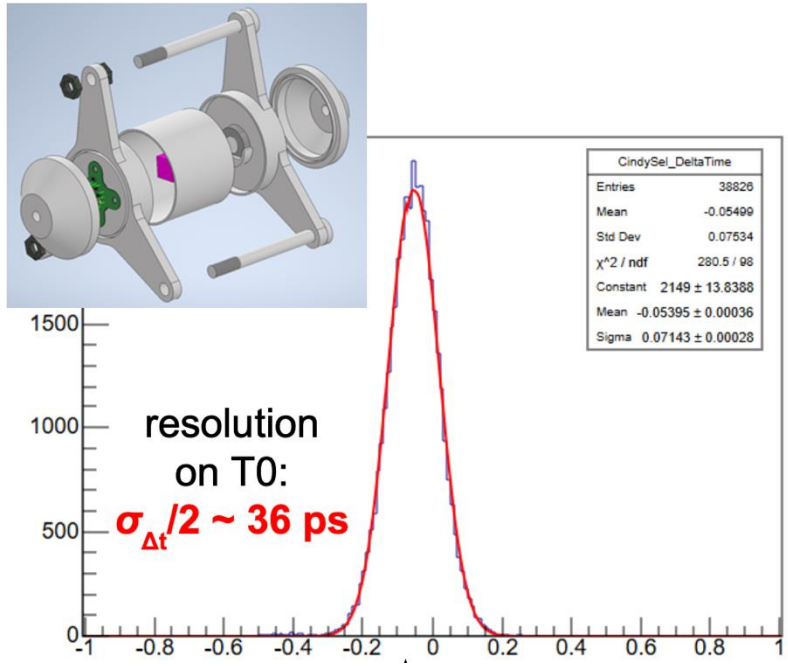
- 1.6/2.7 ns rise/fall
- ERMA photocathode



t_0 counter

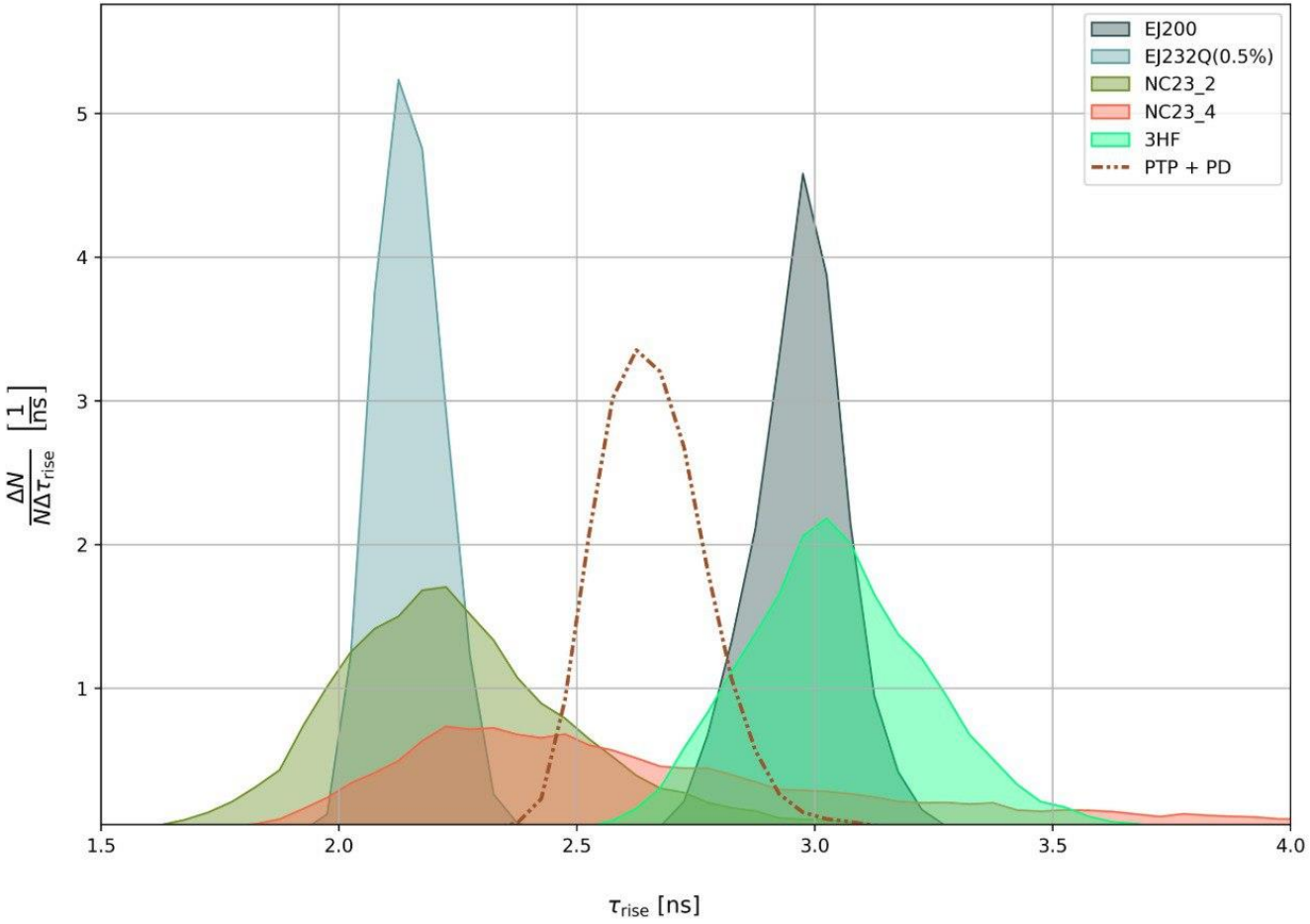
1 cm^3 EJ232Q 0.5%
2x R14755U-100 PMT

- 0.40/0.42 ns rise/fall
- $\sigma_{\Delta t}$ ~ 72 ps → σ_{t0} **~ 36 ps**



Timing characterization with beams

Signal rise times



Measurements with R7600 PMT also provide comparison with measurements with SiPMs

Preliminary results indicate that fast kinetics for NCs seen in RL also are obtained with beams

Rise time differences visible by eye

- NC23_2: **2.2 ns rise time**
  - Faster than **EJ200** (0.9/2.1 ns rise/fall)
  - Not quite as fast as EJ232Q (0.11/0.70 ns rise/fall)
- NC23_4: **2.3 ns rise time**
- Spread in RT distribution evidence of effects from different spectral components (possible inefficiencies in spectral coupling)
- Need measurements with band selection (filters)

Fast organic scintillators with long-wavelength emission

Long-wavelength scintillators generally more radiation resistant than blue scintillators

- Radiation-induced color centers absorb more strongly at short wavlengths
- Standard for green scintillators: **3HF** (~7 ns emission)
- Modern photocathodes and SiPMs → possible to consider orange scintillators as well

Development of shashlyk prototypes has required work with long-wavelength organic scintillators, e.g., coumarins (green) and perylene dyes (orange), mainly as WLS agents

- **MoI_3** high light yield (~50% **EJ200**), with faster emission than **3HF**
- Perylene dyes (**Blank_3**, **NC23_4**, **NC24_4**) also known to be fast and bright

Synergy with LHCb PicoCal project to develop fast, radiation hard scintillating fibers

- Current best candidate for PicoCal is **3HF** but a faster scintillator would be advantageous
- In collaboration with CERN and Milano Bicocca Materials Science, manufacture, characterize, and test samples of perylene orange scintillator
- Irradiate samples at IRRAD
- Work towards construction and test of prototype

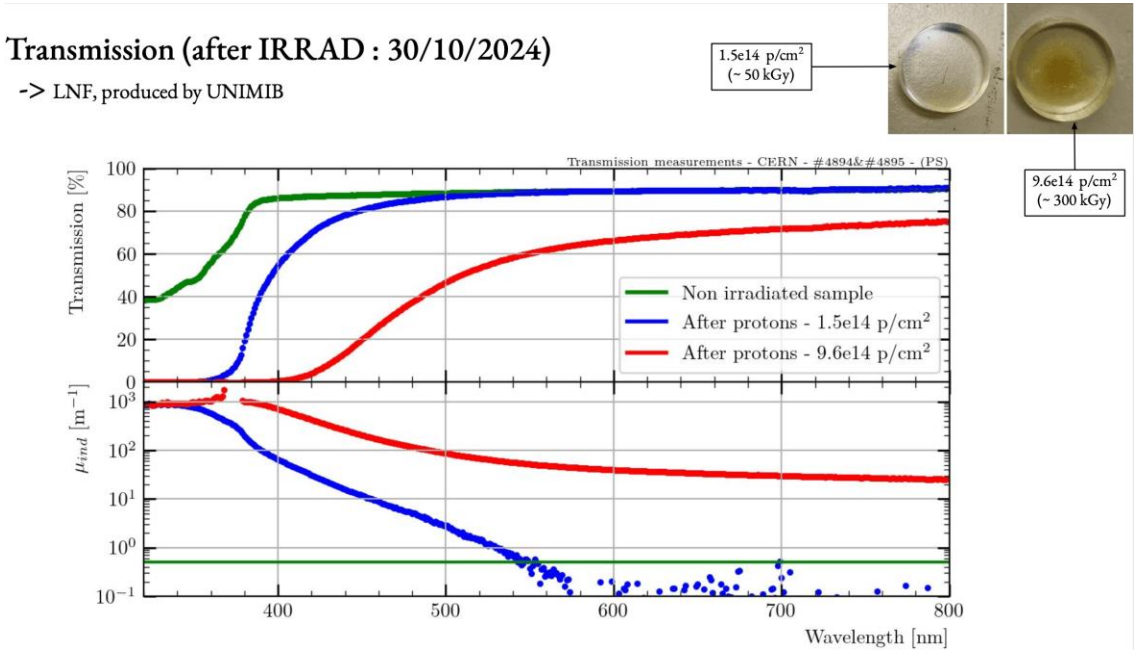
Perylene-based orange fibers for LHCb PicoCal

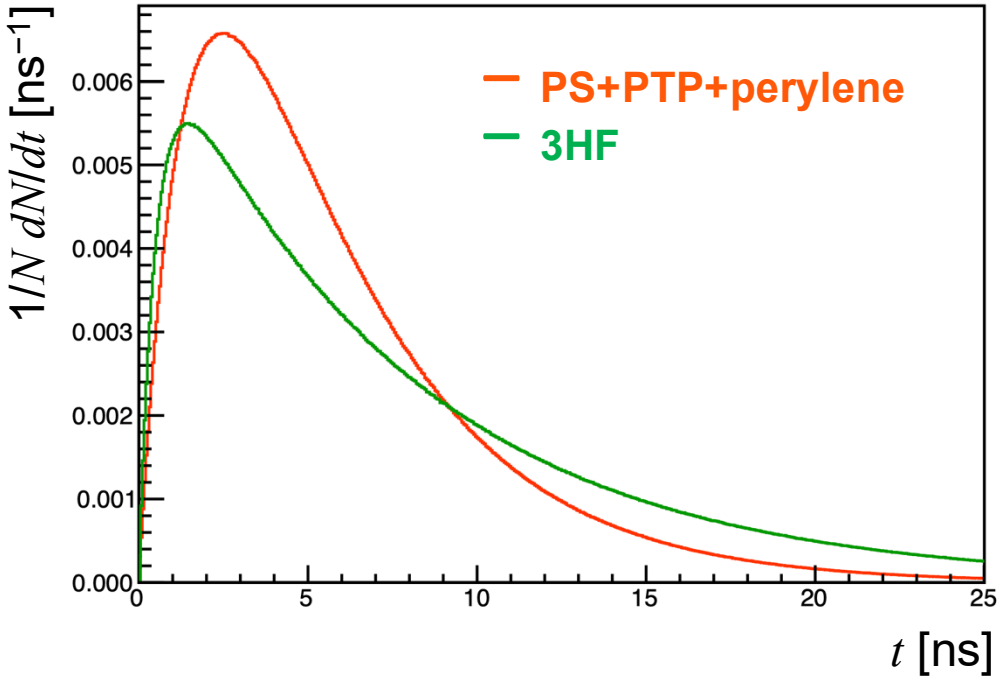
Radiation hardness:

- Radiation-induced color centers absorb at short wavelength
- Orange better than green for propagation through discolored fiber

Faster light emission:

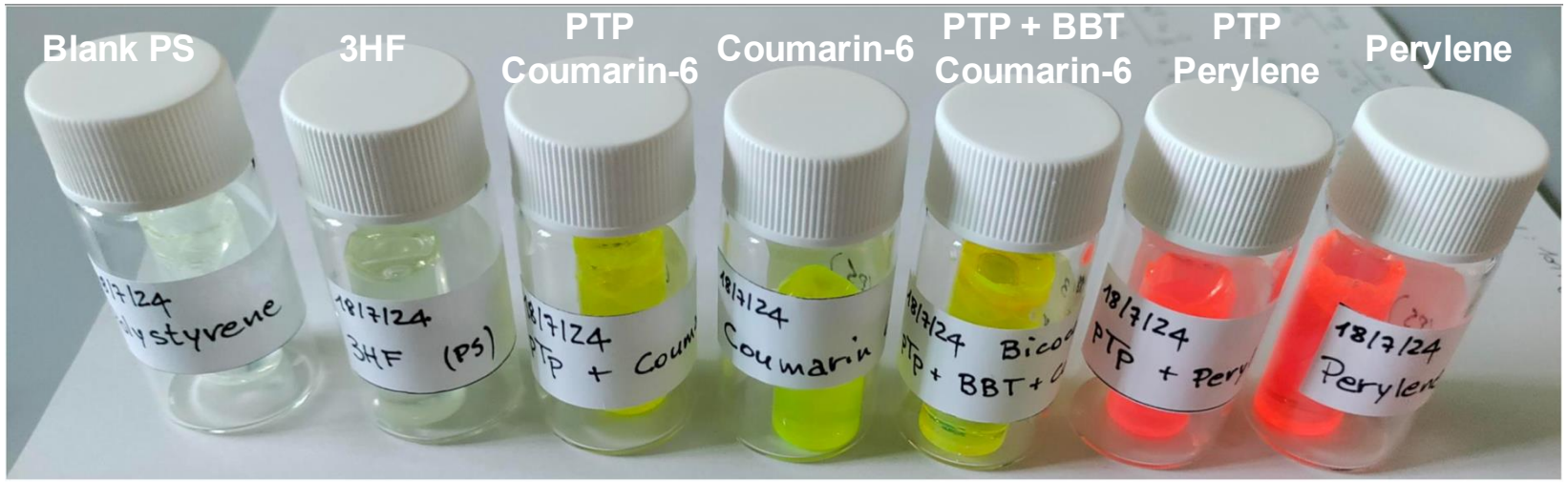
- Perylene τ_{decay} ~ 4 ns < 3HF τ_{decay} ~ 7.5 ns
- Fewer problems with pile-up events
- Better light collection in time gate < 25 ns:
  Better energy resolution





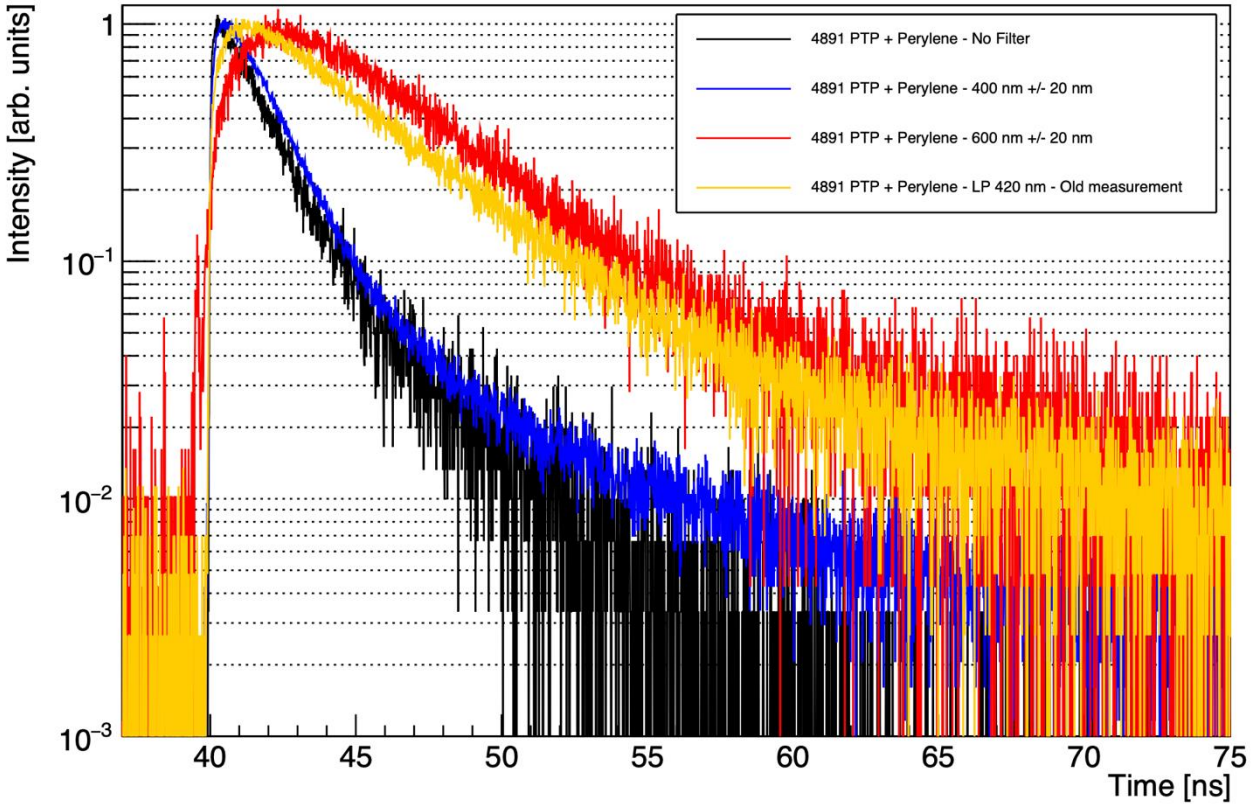
Organic scintillator samples tested in autumn 2024

- Prepared at Milano Bicocca
- All samples PS based
- 2 samples of each type to allow comparison with/without irradiation
- 14.5 mm dia x 7 mm thick



Sample additives	Description
Blank (PS only)	control
Coumarin-6 (0.04%)	blue → green WLS
Perylene (0.0025%)	green → orange WLS
PTP (1.5%) + coumarin-6 (0.04%)	green scintillator
PTP (1.5%) + BBT (0.04%) + coumarin-6 (0.04%)	green scintillator
PTP (1.5%) + perylene (0.0025%)	orange scintillator
3HF (1%)	green scintillator (comparison)

Radioluminesce decay kinetics with band selection



PTP + perylene: Measurements at CERN

3 component fit to decay distribution, **no filter**

- τ_1 **= 1.67 ns** (66%, PTP)
- τ_2 **= 4.2 ns** (22%, perylene)
- τ_3 = 28 ns (12%, PS fluorescence)

τ_1, τ_2, τ_3 fixed in fits to distributions with filters: **400±20 nm** and **600±20 nm**

Compare to fit with **low-pass filter**

Substantial residual blue component (although RL measurements in reflection)

Meas	Rise time [ps]	Decay time 1[ns]	Abundance 1 [%]	Decay time 2 [ns]	Abundance 2 [%]	Decay time 3 [ns]	Abundance 3 [%]
No Filter	83	**1.67**	66.12	**4.2**	22.27	**28**	11.61
400 nm	214	**1.67**	78.04	**4.2**	10.44	**28**	11.52
600 nm	1620	**1.67**	0.00	**4.2**	87.80	**28**	12.17

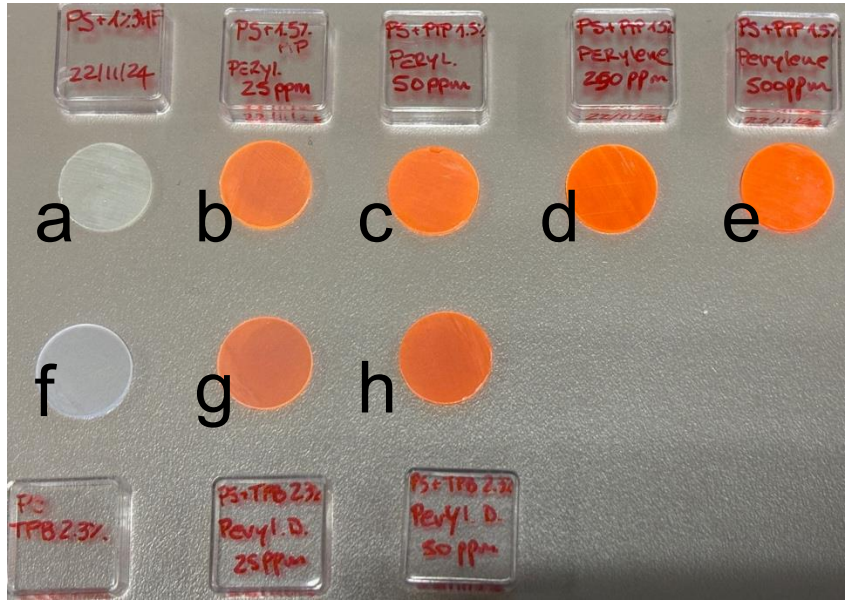
Optimization of scintillation coupling and LY at MIB

TPB (tetraphenyl butadiene) is a common fluor with emission peak at 430 nm, which is matched better to perylene absorption than PTP (broad emission peaking at 340 nm)

New samples produced and tested with different concentrations of perylene dyad coupled to PTP and TPB

List of samples:

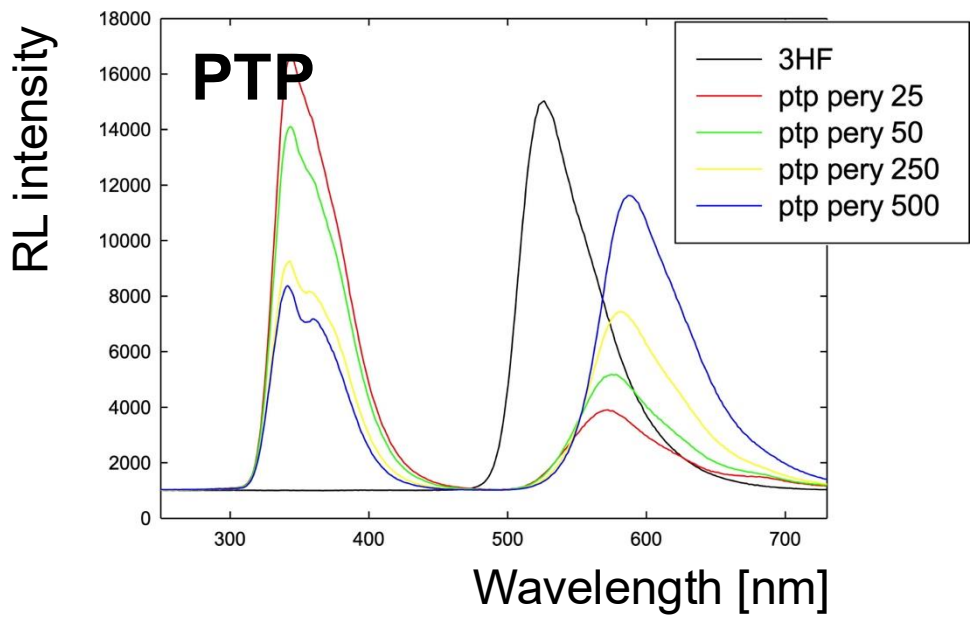
a) PS + 3HF (1%) — Reference
b) PS + PTP (1.5%) + perylene 25 ppm
c) PS + PTP (1.5%) + perylene 50 ppm
d) PS + PTP (1.5%) + perylene 250 ppm
e) PS + PTP (1.5%) + perylene 500 ppm
f) PS + TPB (2.3%) — Same molar conc. as PTP
g) PS + TPB (2.3%) + perylene 25 ppm
h) PS + TPB (2.3%) + perylene 50 ppm

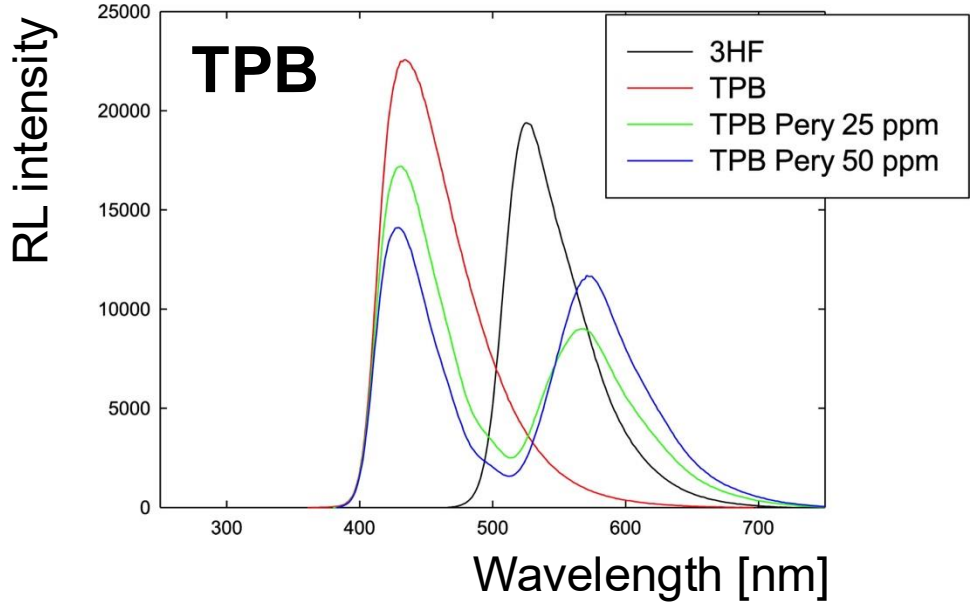


All samples 1.5 mm thick, unpolished

NB: Synthesis of perylene problematic for large-scale production if concentration > 200 ppm

Radioluminescence LY for new samples at MIB





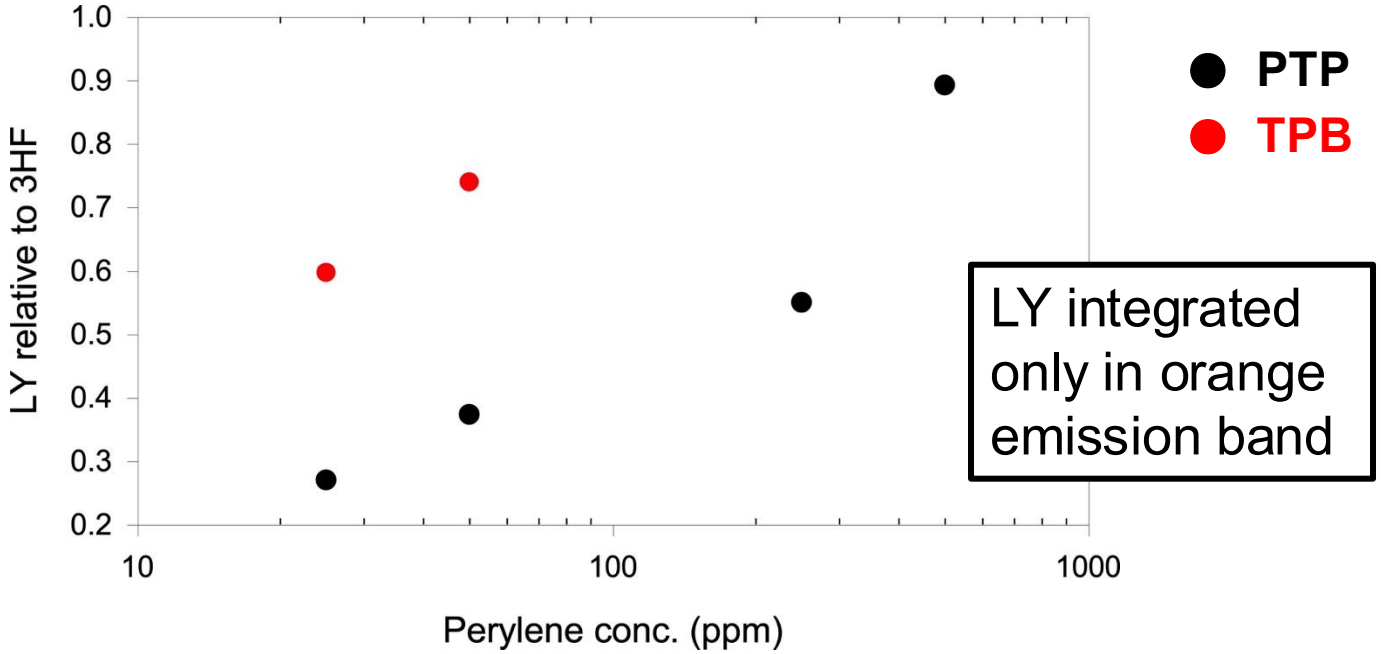
Increased transfer of light from primary (PTP/TPB) to perylene with increasing concentration

Coupling more efficient for TPB:

- LY (1.5% **PTP** + 50 ppm perylene) ~ **0.35 LY 3HF**
- LY (2.3% **TPB** + 50 ppm perylene) ~ **0.75 LY 3HF**

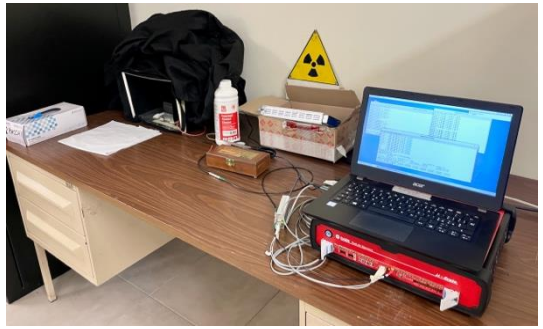
Blue-orange conversion enhanced along fiber length:

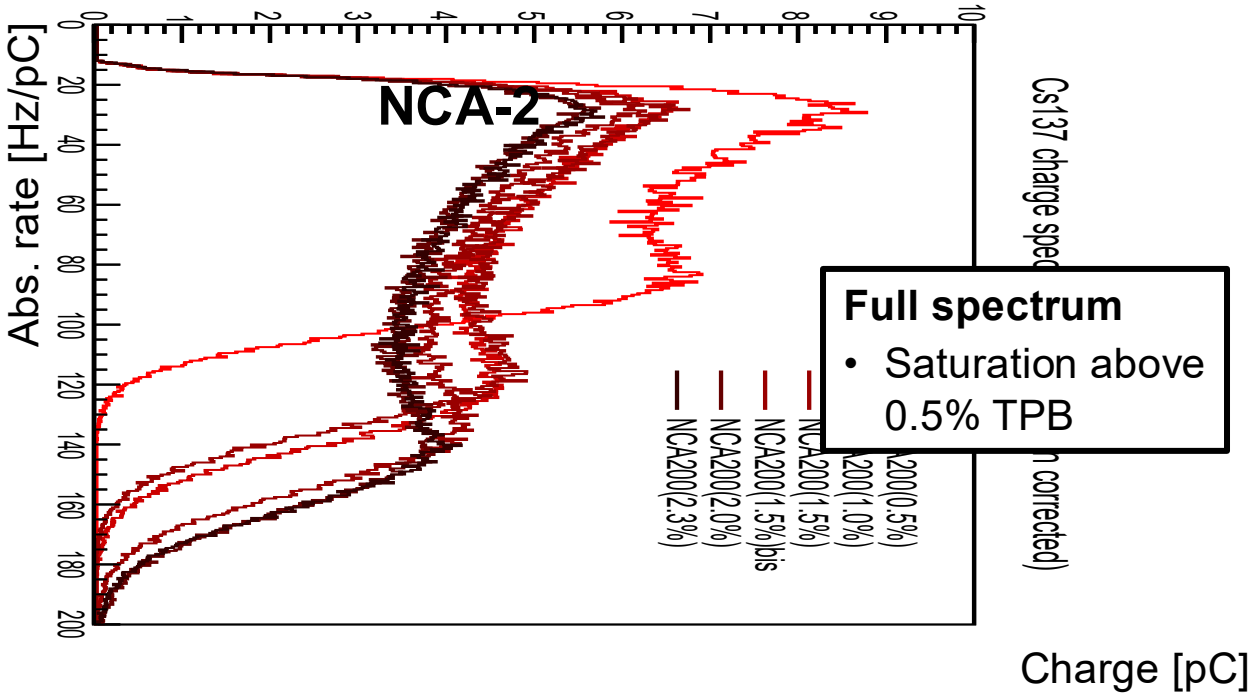
- Optimization of perylene concentration to ensure blue-orange conversion dominates over blue absorption from radiation damage suggests **200 ppm**

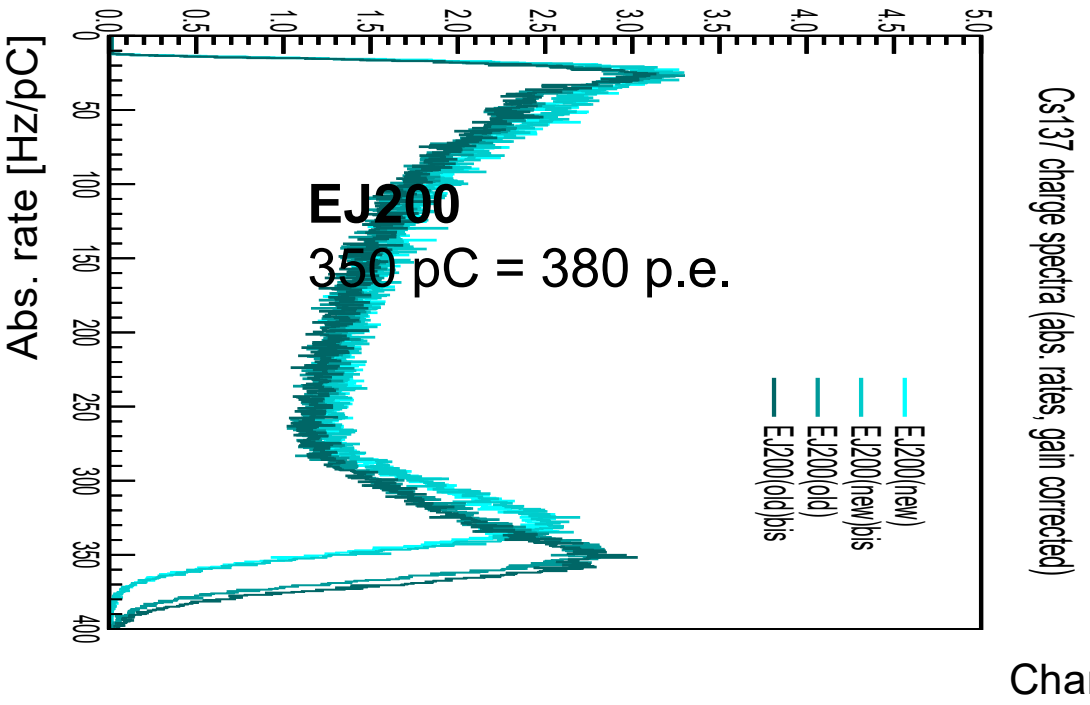


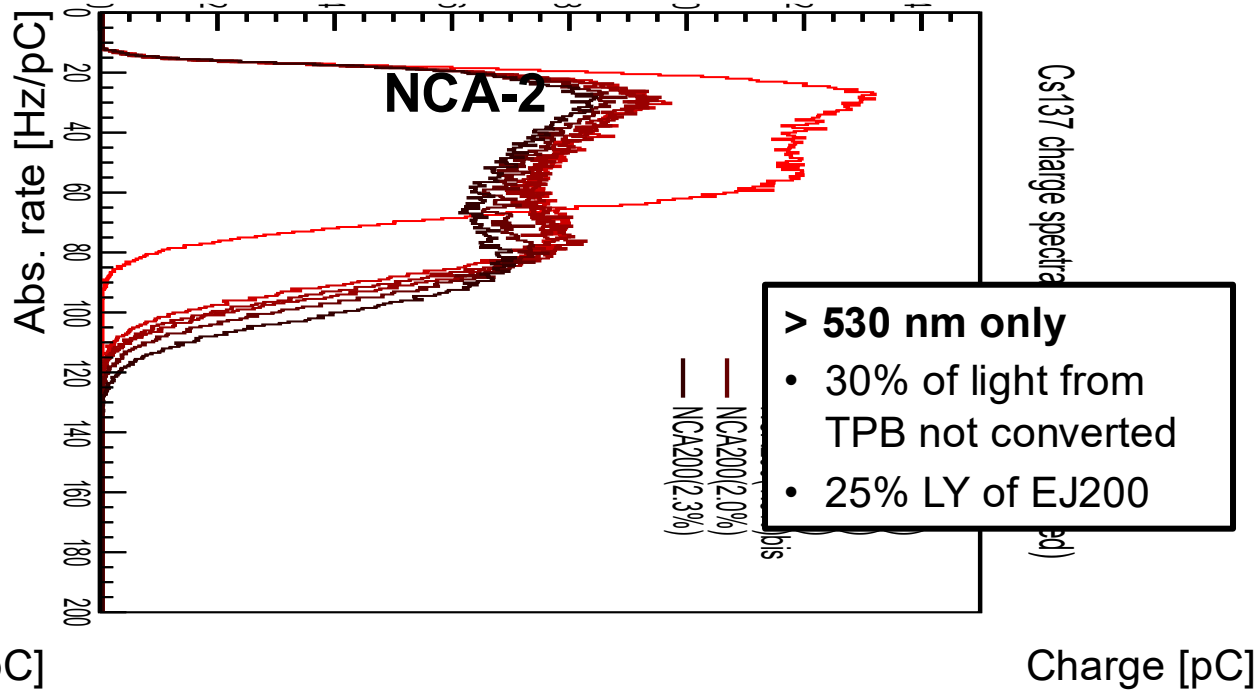
LY from Compton edge

Test bench with Cs-137 source (662 keV γ)
Compton edge = 482 keV









Summary and outlook

Realization of the promise of perovskite nanocomposites as **fast, bright, and radiation-tolerant** scintillators for HEP will require efforts to **increase the light output**, which is currently limited by various factors:

- **Number concentration** of nanocrystals **too small for direct excitation** by single quanta
- **Inefficient energy transfer from matrix** compared to conventional scintillators

  Number concentration of nanocrystals O(10^5) smaller than for organic dye molecules at same weight concentration
- **Self-absorption of light** emitted by nanocrystals

Energy deposition mechanism in **radioluminescence** measurements is **very different from the interaction of a mip or shower particle:**

- **RL:** Many simultaneous low-energy quanta (10 keV x-ray) can directly excite nanoparticles?
- **MIP:** Single quanta depositing 2 MeV/cm in matrix, which has to be transferred to the nanoparticle

Collaboration with the HEP community is essential for NC scintillator development!

NanoCal accomplishments

NanoCal project focus has shifted from rapid prototyping to **sample characterization** to **drive the development of better NC scintillators for HEP:**

- NCs with WLS shifting dyes
- Thermally polymerized NCs with aromatic matrix materials
- NC scintillators with higher concentrations of nanocrystals
- Longer term: Possibility to continue studies of novel nanostructures & hybrid materials

NanoCal has also given rise to side projects to evaluate **novel compositions for organic scintillators** that respond to specific needs in HEP, such as **fast, long-wavelength (radiation tolerant) scintillators**

NanoCal has developed experience and **infrastructure for the experimental qualification of novel scintillators,** both organic and nanocomposite

- Test beam detectors for reproducible light yield measurements with fast timing detectors and optical band selection
- Compton edge LY measurements with radioactive sources
- A working shashlyk module as a test platform for future prototyping

NanoCal project: Final steps

Comprehensive reanalysis and final synthesis of all data collected from all samples:

- Light yields and timing measurements from cosmic rays, radioactive sources, beam tests
- Still collecting data from last few samples with radioactive sources
- 5 days of beam time scheduled at CERN PS in Nov 2025 in case we need to perform systematic checks (otherwise use to test new ideas!)
- Intercalibration of photodetectors from different measurements done
- Obtain remaining spectral corrections

Final publication by AIDAinnova end date (Sep 2025)

We would be very interested in proposing a new project for the development of novel scintillators in next iteration of AIDAinnova

In any case, we will continue to leverage the infrastructure and experience developed in NanoCal for future projects!

The NanoCal Project: Contributors

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The NanoCal Project: Publications and talks

- S. Carsi, “Development of nanocomposite scintillators for use in high-energy physics” (poster), 16th Pisa Meeting on Advanced Detectors, La Biodola, Italy, 26 May-1 Jun 2024. Proceedings: *Nucl. Instrum. Meth. A* 1069 (2024) 169877
- M. Soldani, “Innovative nanocrystal-based scintillators for next-generation sampling calorimeters”, 20th International Conference on Calorimetry in Particle Physics (CALOR 2024), Tsukuba, Japan, 19-24 May 2024. Proceedings: *EPJ Web Conf.* 320 (2025) 00020
- M. Moulson, “Development of nanocomposite scintillators for high-energy physics”, Kaons at J-PARC Workshop, Tokai, Japan, 27-29 July 2024

The NanoCal Project: Synergies

The NA62 and HIKE experiments

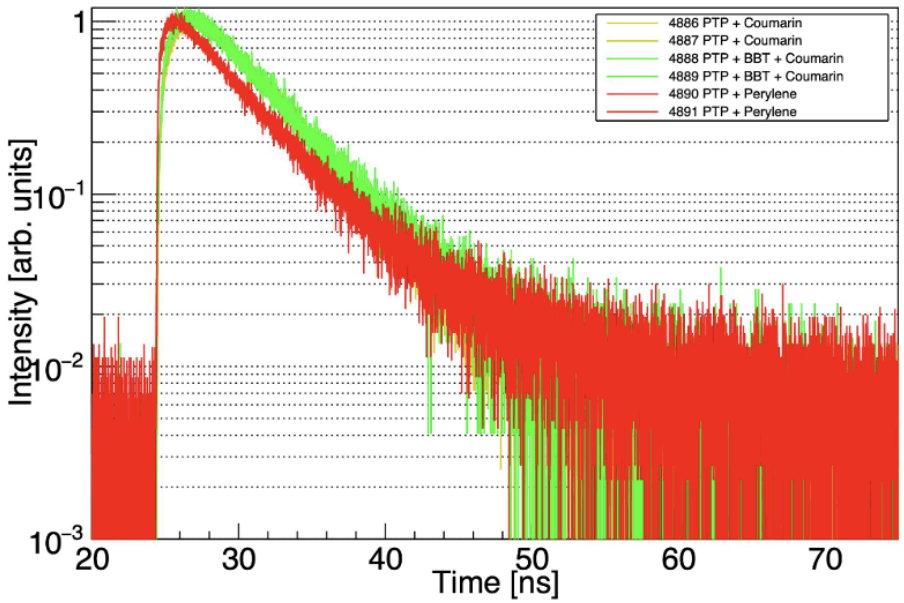
HetCal (PRIN – Italian Ministry of Research)

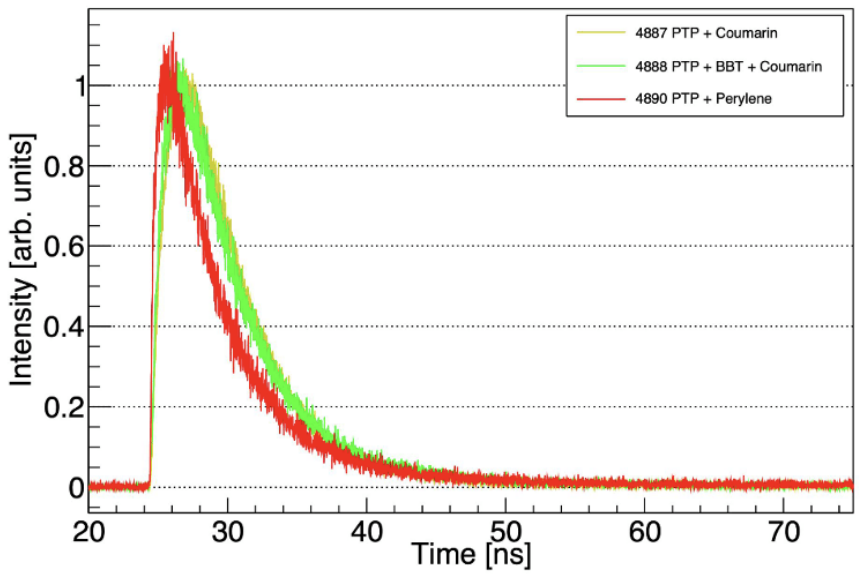
The LHCb experiment

AIDAinnova WP 8.3.1

UNICORN (EIC Pathfinder)

Radioluminesce studies of decay kinetics at CERN





Low-pass filter:
λ > 420 nm

3HF:

- Rise time 560 ps
- Decay time 7.6 ns
- **Eff. decay 8.2 ns**

PTP+perylene:

- Rise time 500 ps
- Decay time 4.4 ns
- **Eff. decay 4.9 ns**

Sample	CCC #	Rise time [ps]	Decay time 1[ns]	Abundancy 1 [%]	Decay time 2 [ns]	Abundancy 2 [%]	Effective Decay Time [ns]
Kuraray SCSF78*	-	533	**3.04**	88.98	**38.3**	11.02	**3.4**
Kuraray 3HF*	-	561	**7.58**	91.63	**120.9**	8.37	**8.2**
PTP Coumarin	4886	1509	**3.96**	93.66	**46.1**	6.34	**4.2**
PTP Coumarin	4887	1479	**3.95**	93.77	**44.8**	6.23	**4.2**
PTP BBT Coumarin	4888	1065	**4.44**	91.03	**32.2**	8.97	**4.8**
PTP BBT Coumarin	4889	1116	**4.41**	91.39	**38.6**	8.61	**4.8**
PTP Perylene	4890	507	**4.36**	88.91	**31.8**	11.09	**4.8**
PTP Perylene	4891	495	**4.42**	89.44	**31.4**	10.56	**4.9**

* 2 mm diam x 5 mm piece cut from multi-cladded fibre