Development of nanocomposite scintillators for use in high-energy Physics

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Abstract

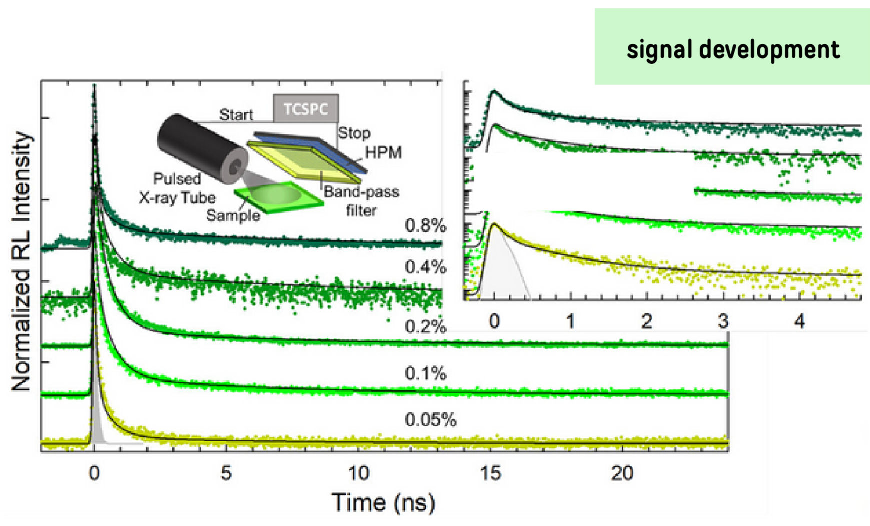
Semiconductor nanocrystals ("**quantum dots**") are light emitters with high quantum yield that are relatively easy to manufacture.
There is therefore much interest in their possible application for the development of **high-performance scintillators** for use in **high-energy physics**. Nanocomposite scintillators can be obtained by casting nanocrystals into a transparent polymer matrix, to obtain materials functionally similar to conventional plastic scintillators. Since inorganic nanocrystals can potentially have O(100 ps) light decay times and O(1 MGy) radiation resistance, **nanocomposite scintillators** could prove to be ideal for the construction of **high-performance detectors** that are **economical enough** to be used for **large-volume applications**. However, **few previous studies** have focused on the **response** of these materials to **high-energy particles**.
To evaluate the potential for the use of nanocomposite scintillators in calorimetry, we are performing side-by-side tests of fine-sampling **shashlyk calorimeter prototypes** with both **conventional** and **nanocomposite scintillators** using electron and minimum-ionizing particle beams, allowing the performance gains obtained from the use of NC scintillators to be directly measured.

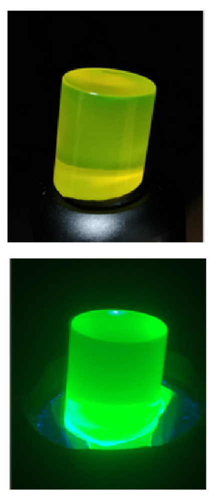
1. NanoComposites(NC) crystals

Semiconductor nanostructures can be used as sensitizers/emitters for **ultrafast**, **robust scintillators**.
- **Nanocrystal**: can be engineered to decide **emission parameters**, such as the **wavelength** or the **decay time**
- **Composite**: control over concentration of nanocrystals: very **high concentration** to obtain **shorter radiation length.**

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.**

Lead halide **Perovskite** (ABX3):
- **Ultrafast**: 30% of the light emitted in 80 ns
- **Radiation hard**: no decrease in Light Yield up to 1 MGy





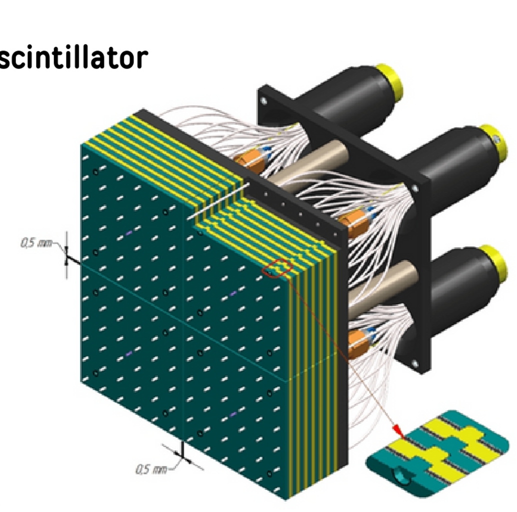
2. The NANOCAL project

NanoComposites (NC) scintillators have received much attention in the materials-science community:
- Many studies of **photoluminescence** for **E < 10 eV** ⟶ Promising results
- Almost **no studies** have been done on the **response** of NC scintillators to **high-energy particles**

NanoCal goals:
- **Construct** a **calorimeter** prototype with **NC scintillator**
- **Test** with high-energy beams

Shashlyk design chosen as a test platform:
- **Easy to construct** with very fine sampling
- **Primary scintillator** and **WLS** materials required: both **can be** independently **optimized** using NC technology

Additionally exploring:
- New dyes for **optimized conventional scintillators**
- Fast, bright green scintillators for additional **radiation hardness**

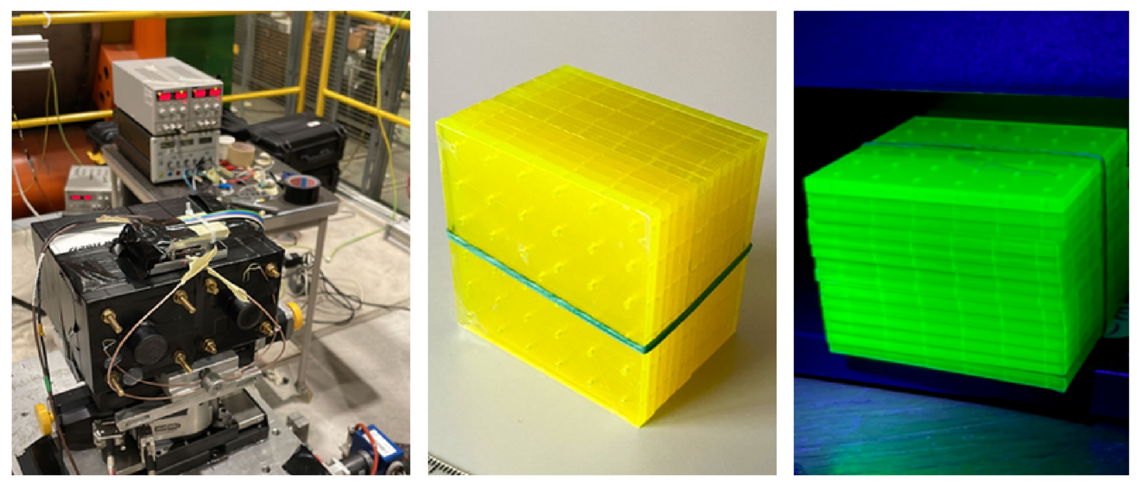


3. First shashlik prototypes tests

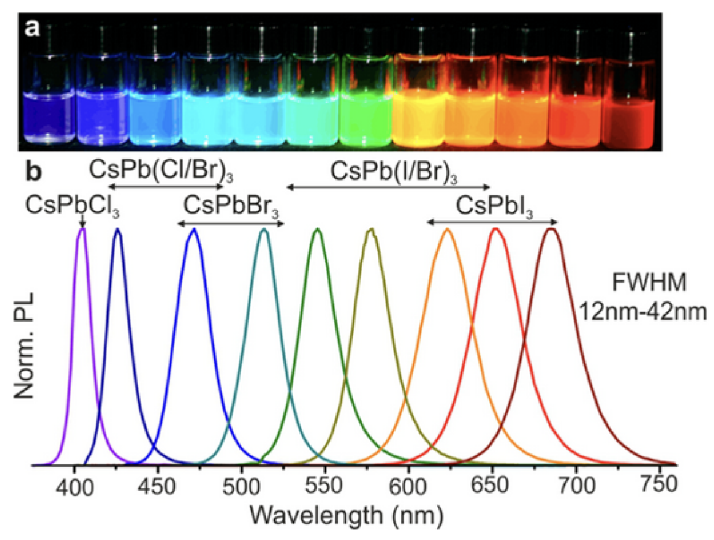
- Beamtest @ CERN H2 beamline (october 2022)
- **Lab test** with **cosmic rays** (spring 2023)

The **light yield** for **MIPs** with respect to conventional scintillators was of the order of **5%.**

Possible problems:
- Nanoparticles exhibit **too much self-absorption**?
- Inefficient excitation of nanoparticles: maybe concentration too low

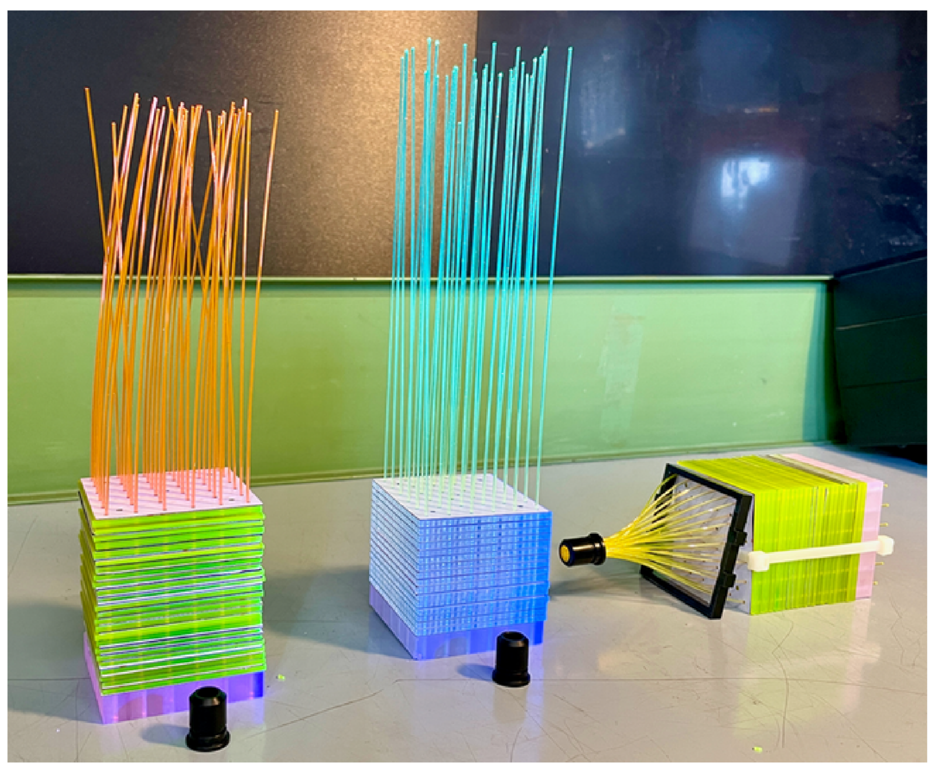


4. NC scintillator optimization



- Optimization of NC scintillator before constructing full-scale prototypes
- Test of new **scintillators with longer absorption length**

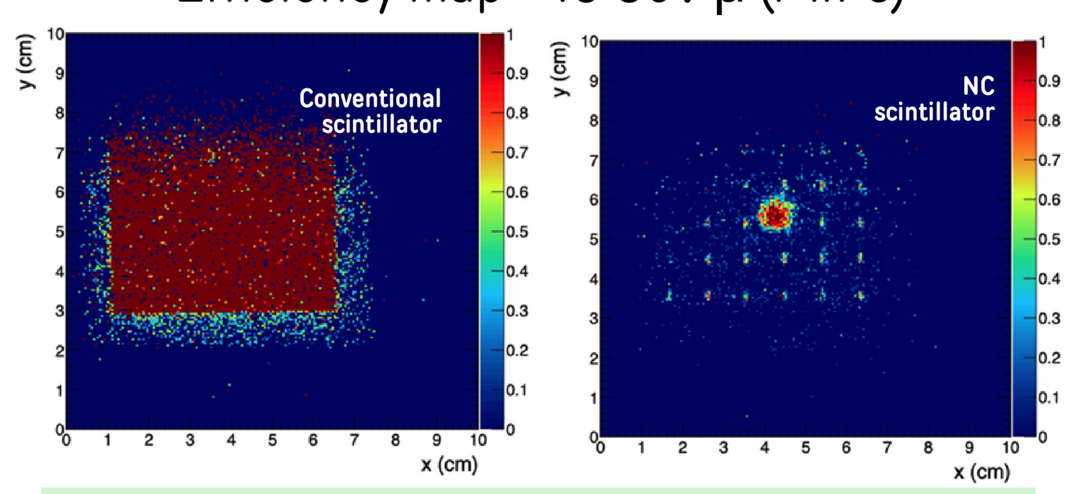
5. Test of new shashlik prototypes



Beamtest @ CERN T9 beamline (June 2023), with
- **Electron** beam, 1, 2, 4 GeV
- **MIP** beam (μ− or π−), 10 GeV

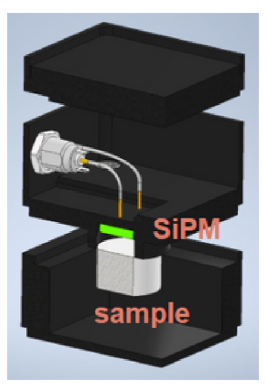
Benchmark parameters tested:
- MIP response, efficiency
- *e−* response
- Time resolution

Efficiency map – 10 GeV μ (MIPs)



Disappointing result from new nanocomposite: the only light is from readout fibers!

6. New nanocomposite samples



A **full** shashlik **calorimeter** is a **complex system** ⟶
Difficult to **understand** where the **problem** is

It might be:
- in the **fibers**
- in the **photosensor** or the **optical coupling**,
- in the **energy deposit** in the material itself
- in the **energy exchange** inside the material

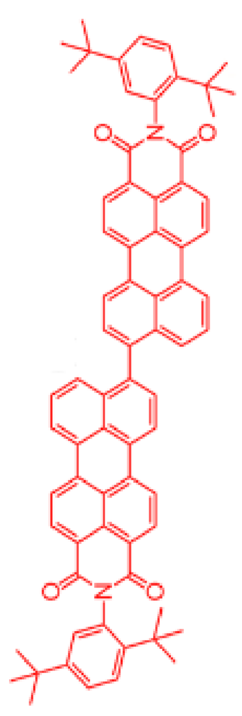
NanoCal main aim moves to the **study of the nanocomposite materials themselves**, directly coupled with a SiPM, to measure the light output

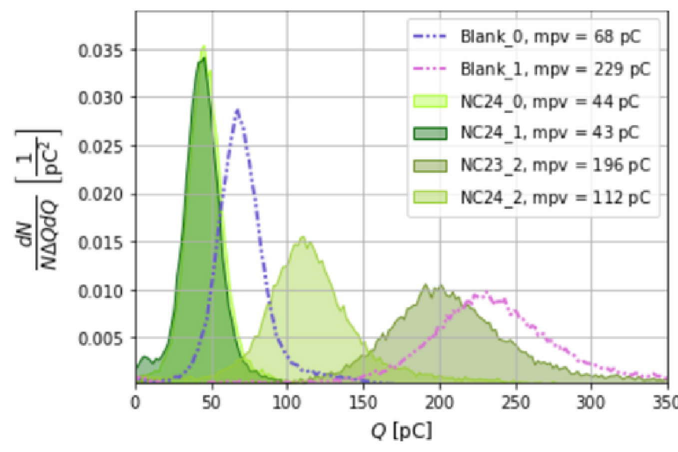
Need to **investigate** why very good light output in photoluminescence studies but almost **no output with MIPs**

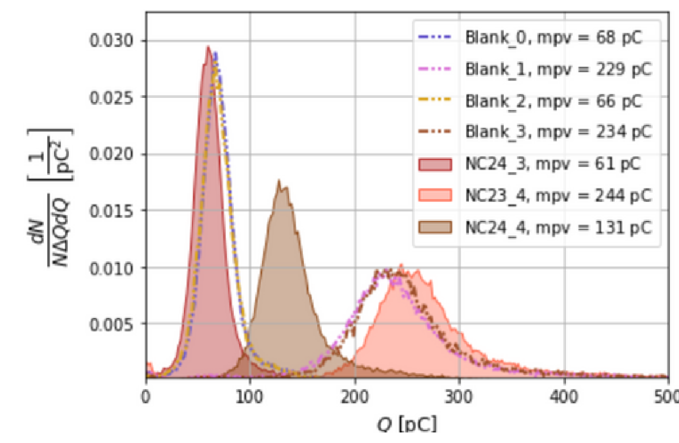
PVT/DVB$_{90/10\%}$ + PTP$_{\alpha}$ + γ*:$CsPbBr_3$$_{\beta}$ + perylene dyad$_{\delta}$†

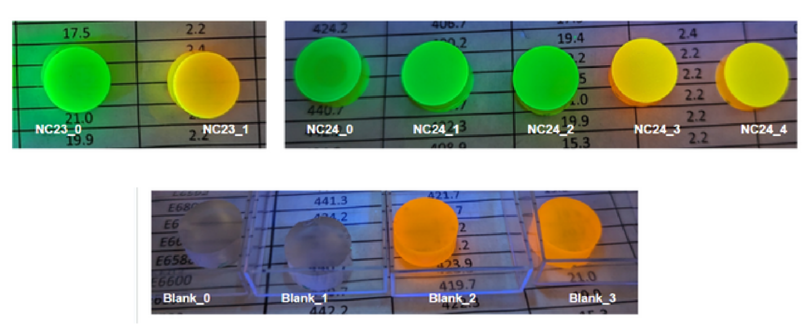
	α	β	γ*	δ	optical features (visual inspection)
Blank_0	0	0	-	0	transparent, colourless
Blank_1	1.5%	0	-	0	transparent, colourless
Blank_2	0	0	-	> 0	transparent, orange
Blank_3	1.5%	0	-	> 0	transparent, orange
NC23_0	1.5%	1.5%	Yb	0	a bit opaque, green
NC23_1	1.5%	1.5%	Yb	>0	a bit opaque, orange
NC24_0	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	very opaque, orange
NC24_4	1.5%	1.5%	F	>0	very opaque, orange

† $C_{20}H_{12}$







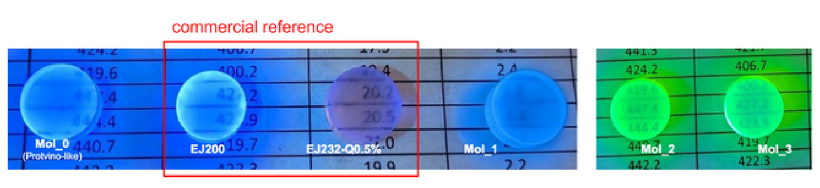


7. Molecular samples

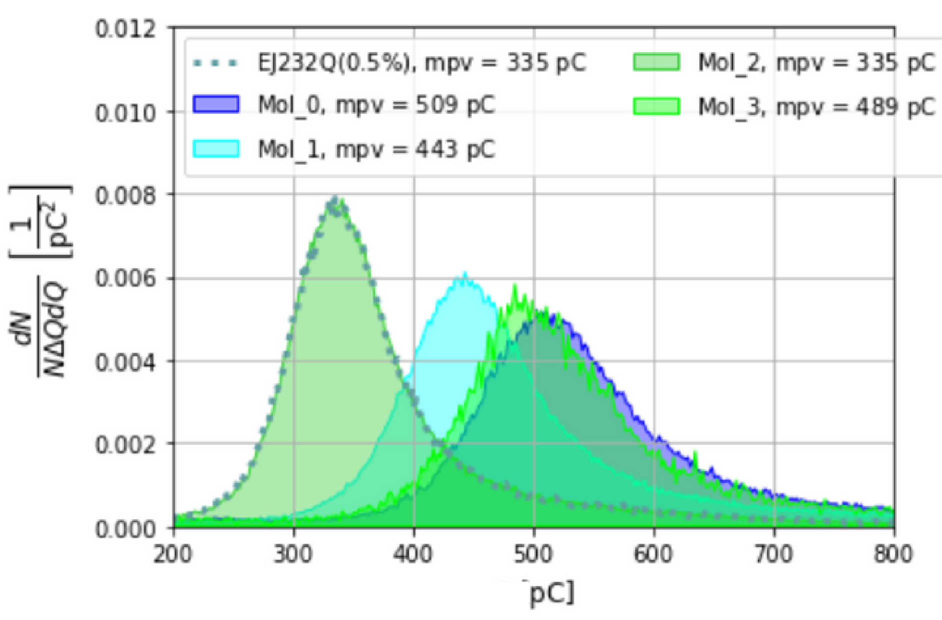
An alternative approach in the **optimization** of the **scintillators**: move away from quantum dots to explore **molecular samples**

PVT/DVB$_{90/10\%}$ + PTP$_{\alpha}$ + benzothiophene$_{\beta}$ + coumarin-6$_{\gamma}$

	α	β	γ	optical features (visual inspection)
Mol_0 Protvino-*like* with PVT instead of PS	1.5%	0 but POPOP$_{0.04\%}$	0	transparent colourless, blue under UV
Mol_1	1.5%	0.04%	0	transparent colourless, blue under UV
Mol_2	1.5%	0	0.04%	transparent, green
Mol_3	1.5%	0.04%	0.04%	transparent, green



Mol_3 (matrix + enzothiophene + coumarin-6) performs about like Mol_0 (Protvino-like), i.e. ~150% **EJ232Q** and ~50% **EJ200**



8. Conclusions & Outlooks

Improve the setup for laboratory characterization with cosmic rays and with particle beams:

- New **sample holders** for **better** optical **coupling**
- **Low noise** dedicated **electronics**
- **New DAQ system** for digitizers
- Addition of Medipix-2 **pixel detector** to BTF setup for **multiplicity counting**

Goal:
- Identification of the **best candidate** for a **small prototype** to be **tested** with **MIPs** and **electrons** @ CERN T9 in September 2024
- Better understanding of how NC scintillators work.

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