Neutron PID and 3D-Printing with Plastic Scintillators

PRISMA+ DETECTOR LAB

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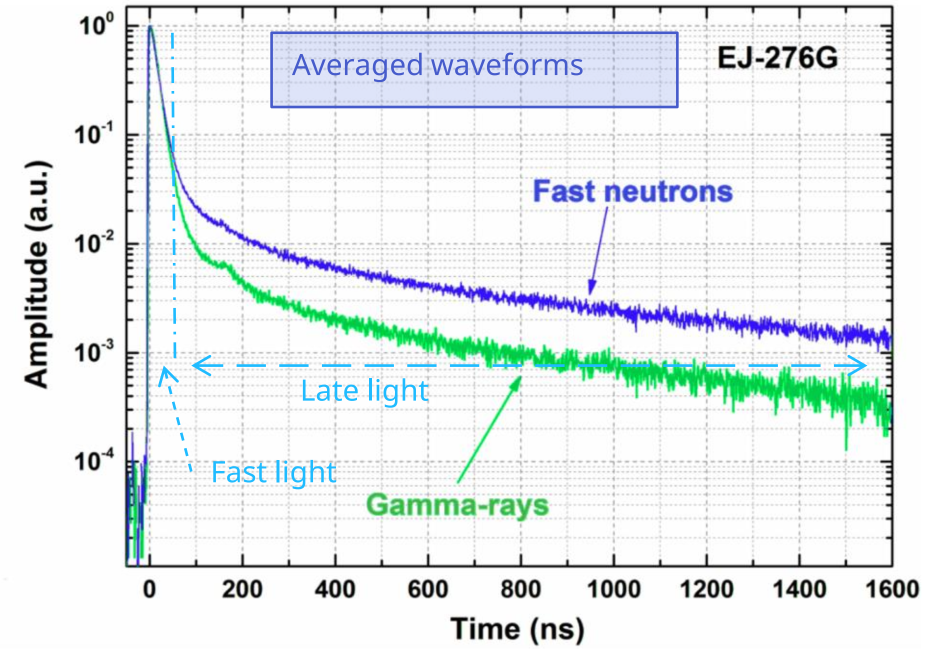
Neutron - Gamma Particle Identification with Plastic Scintillators

INTRODUCTION TO PULSE SHAPE DISCRIMINATION (PSD)

- Certain scintillators have different intrinsic responses to neutron and gamma excitation
- Most prominent in delayed response (late light signals)
- Usual process chain:
  - Neutron scattering
  - Proton recoil
  - Distinguishable signal

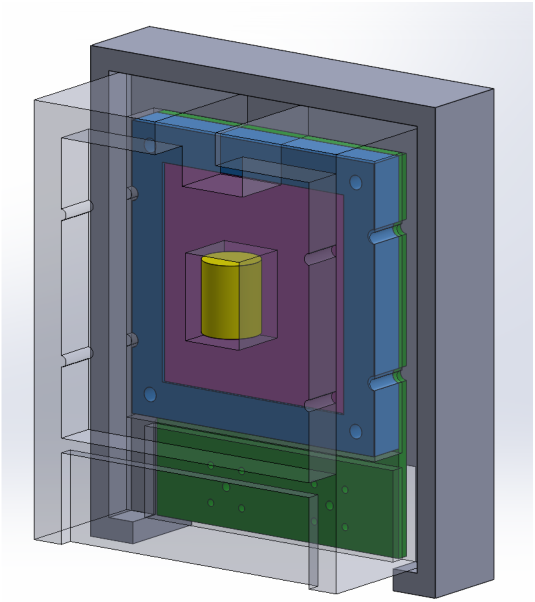


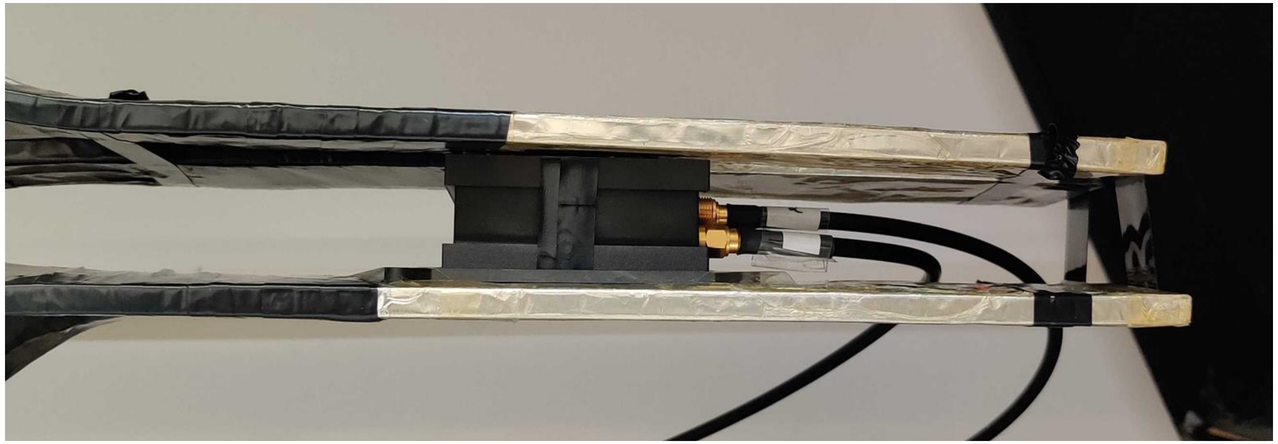
M. Grodzicka-Kobylka et al.

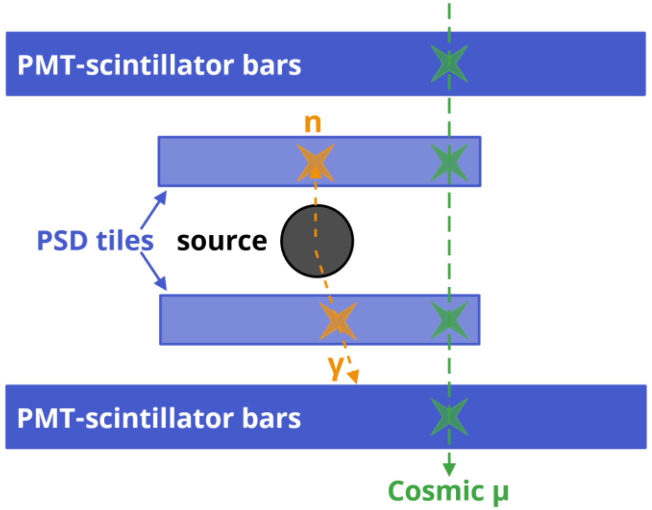
particle	Medium decay constant		Long decay constant			
Gamma	13±1 ns	84%	110±10 ns	7%	800±80 ns	9%
Neutron	14±1 ns	62%	95±10 ns	13%	800±80 ns	25%

THE SETUP

- AmBe source emits gammas and neutrons in coincidence
- Source surrounded by 2 PSD scintillator tiles (EJ-276G) read out by SiPMs
- Possibility to tag coincidence signal as n + γ
- Cosmic muon veto above and below

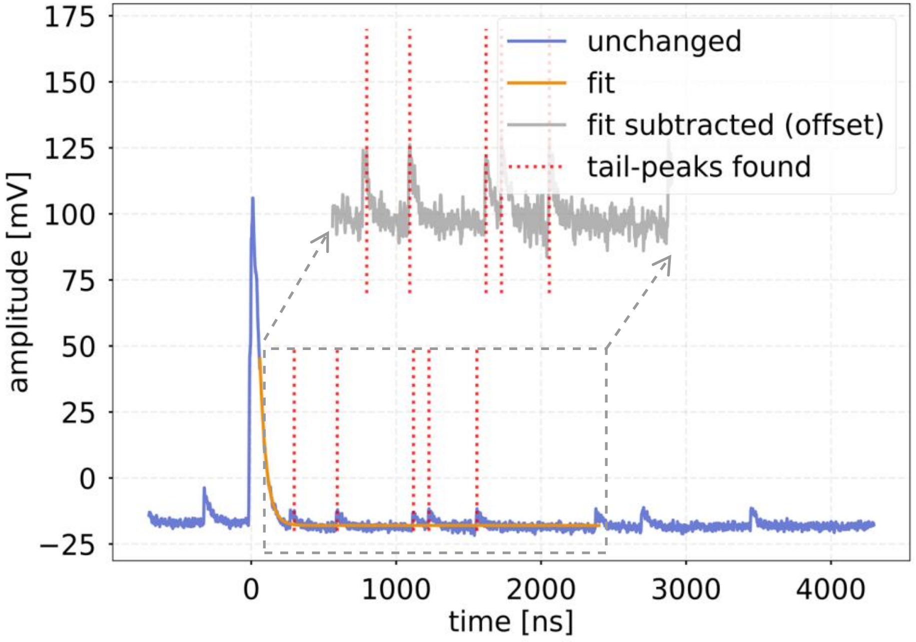






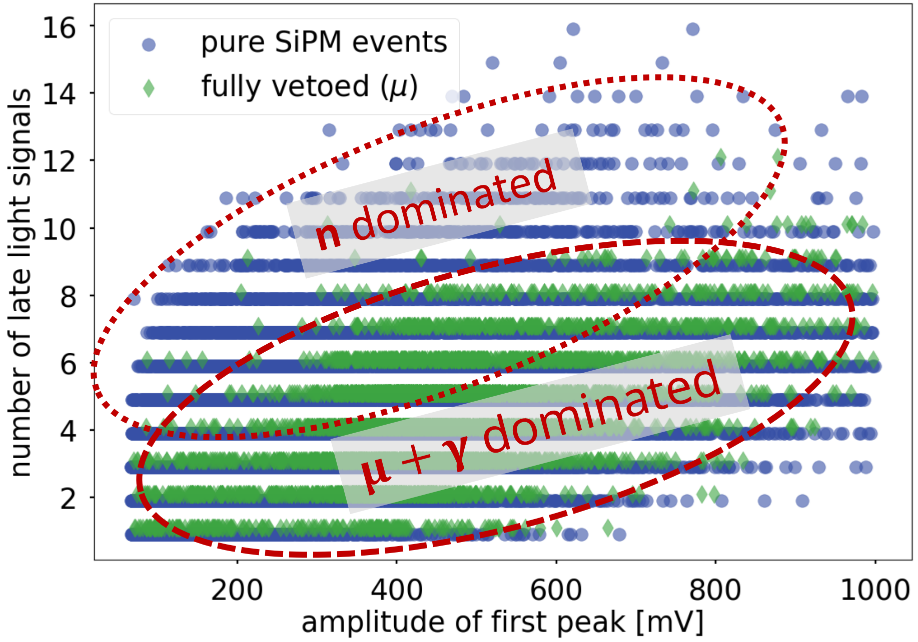
DATA TAKING

- Taking data with oscilloscope (full waveform)
- Information about time and amplitude of all peaks per event
- Compare fast component/initial peak with slow component light output



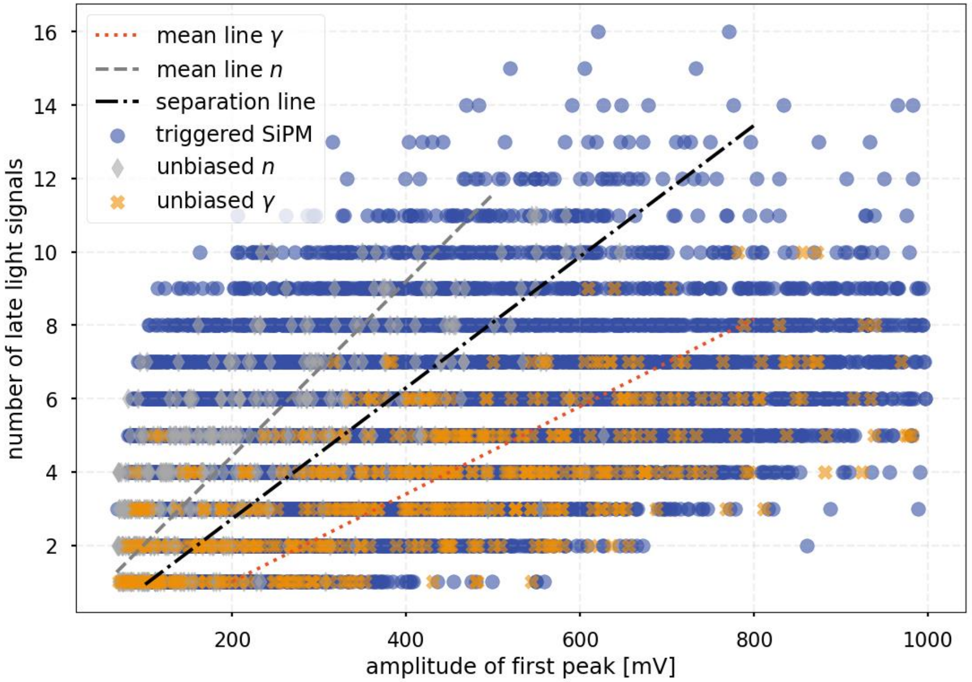
do this for all SiPM data

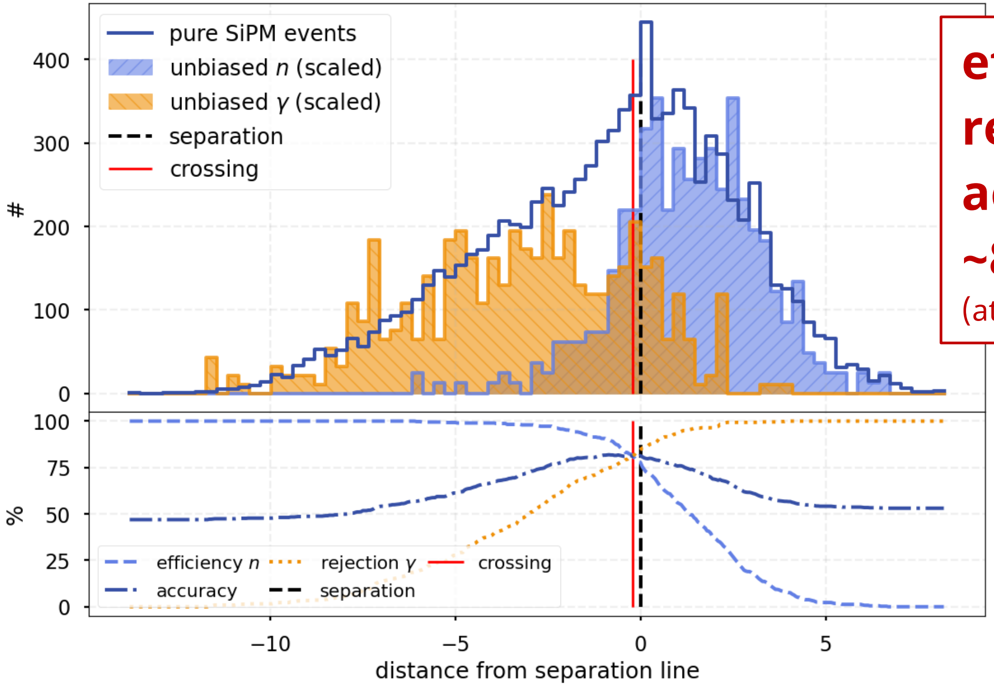
- μ's tagged by veto
- SiPM data exclusively pairs of two entries (one **n** + one γ)



EVALUATING SEPARATION POWER

- Calculate mean lines of unbiased distributions and take mean of those for separation of neutrons and gammas
- Calculate distance for every event from the separation line



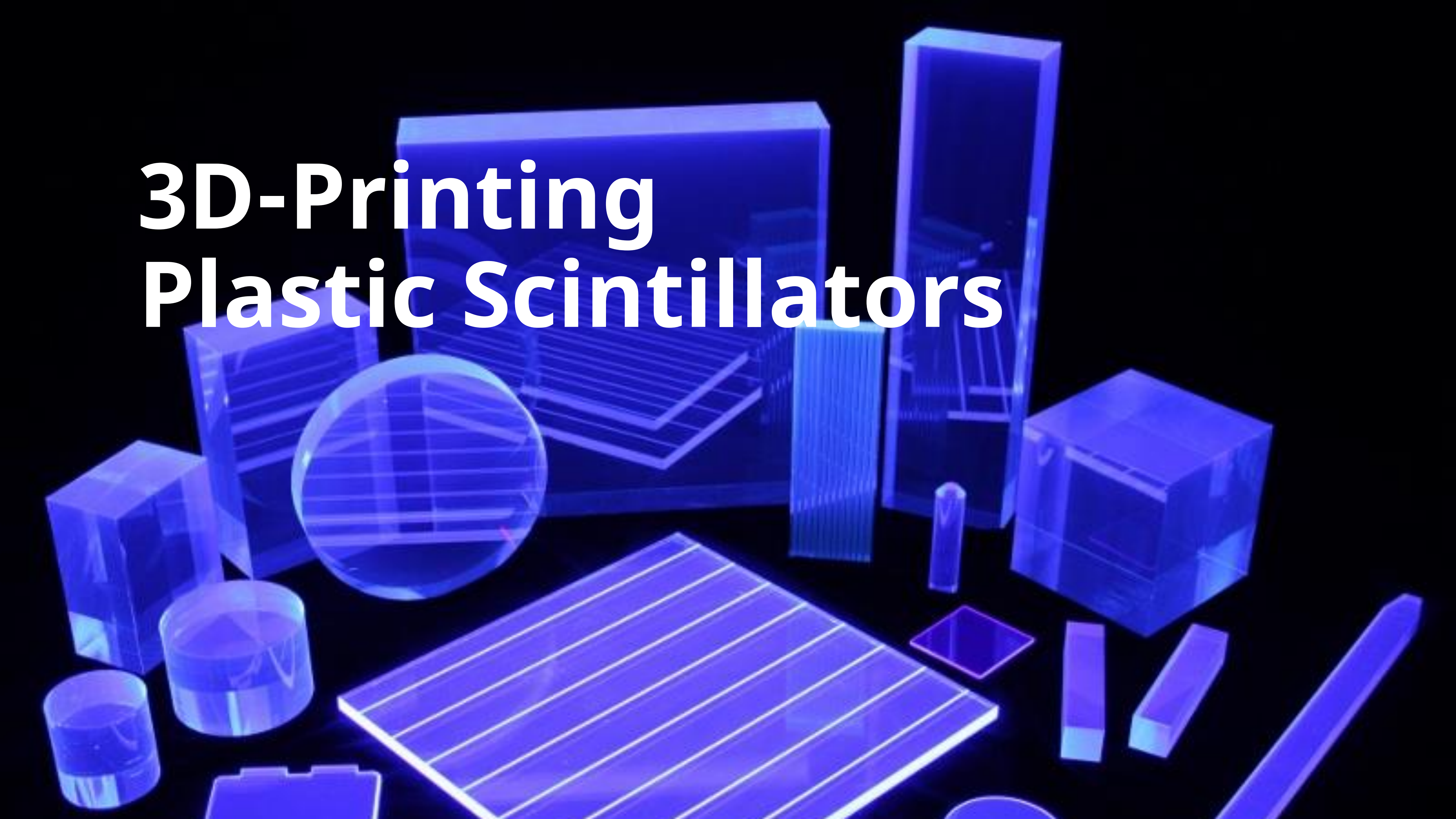


efficiency, rejection, accuracy ~80%
(at crossing)

OUTLOOK

- Data taking with new oscilloscope
  - much better S/N
  - easier peak finding
- Further increase SiPM size from 4 to 9 mm² to improve separation power

- Change from peak counting to signal integration to get closer to real live application



3D-Printing Plastic Scintillators

Introduction and Motivation

- **Plastic scintillators** are widely used in physics detectors
  (trigger/veto systems, CALs, neutron/gamma detectors, TOF, etc...)
  - Mainly 3 components: polymer base, fluor and wavelength shifter (all application specific, matched to sensor)

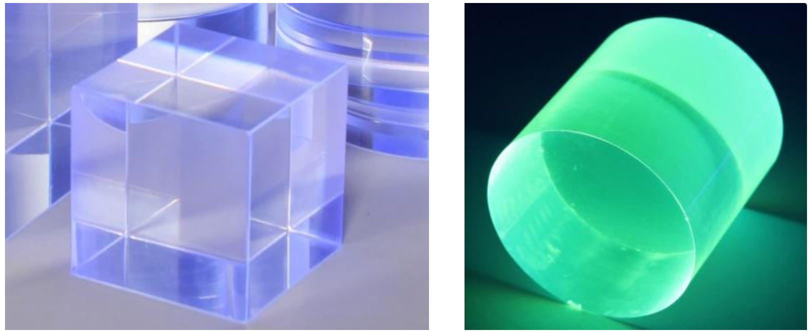
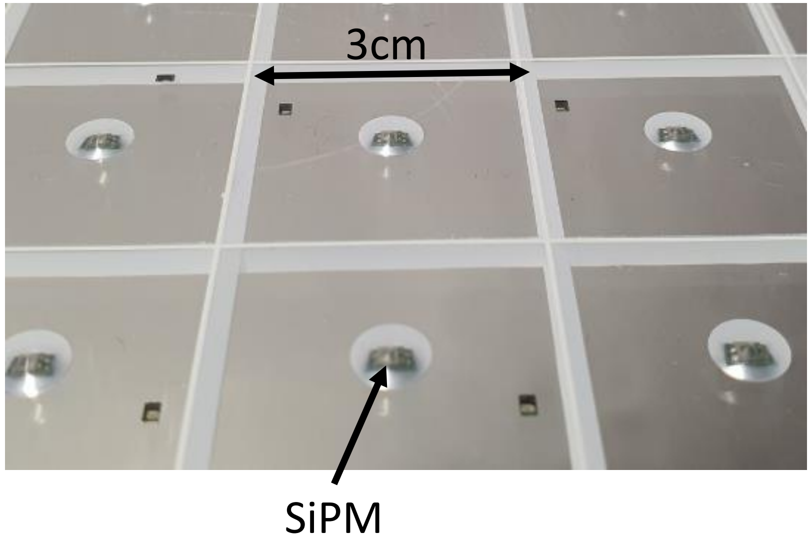


Image source: NUVIATech Instruments [2]

- 3D-printing offers production of free shaped parts eventually integrating different materials in one process
  - Entirely new method to shape scintillators
  - Challenges: transparency and surface quality



- Future R&D prospects:
  - High-granularity calorimeters (structured scintillators)
  - Increasingly complex shapes (e.g. dimples for tiles)

Technology

- **ARBURG Plastic Freeforming** (APF [3]):
  - original granulates (no softener or starter)
  - in-line drying (N2 option, pre-drying if needed)
  - droplet discharging (hundreds/s, 200µm nozzle, build volume of freeformer 300-3X: 234 x 134 x 230 mm³)

- Other approaches to 3D-print scintillators:
  - Fused Deposition Modeling (FDM [5], filament)
  - Digital Light Processing (DLP [6], resin)

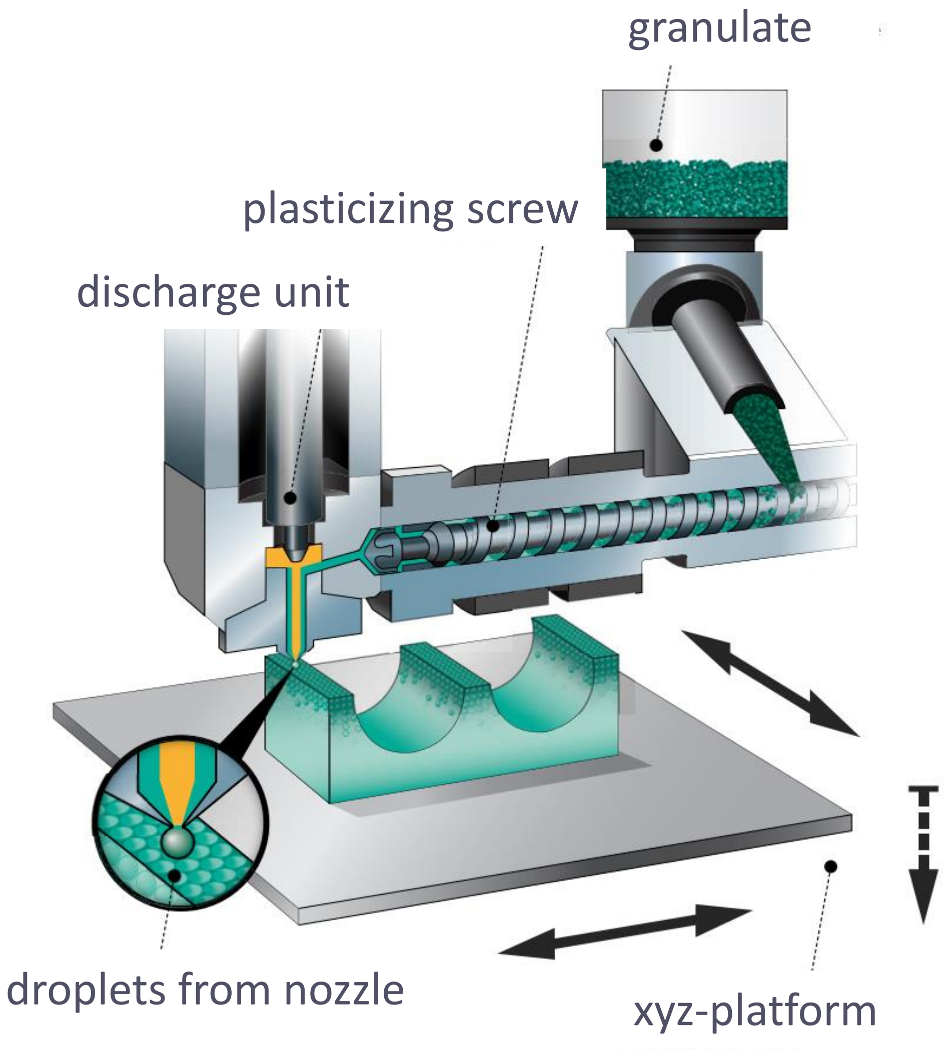


Image source: ARBURG Media Centre [4], labels adapted

TRANSPARENCY STUDIES WITH DIFFERENT BASE MATERIALS

- **UV/Vis spectrometer** analysis

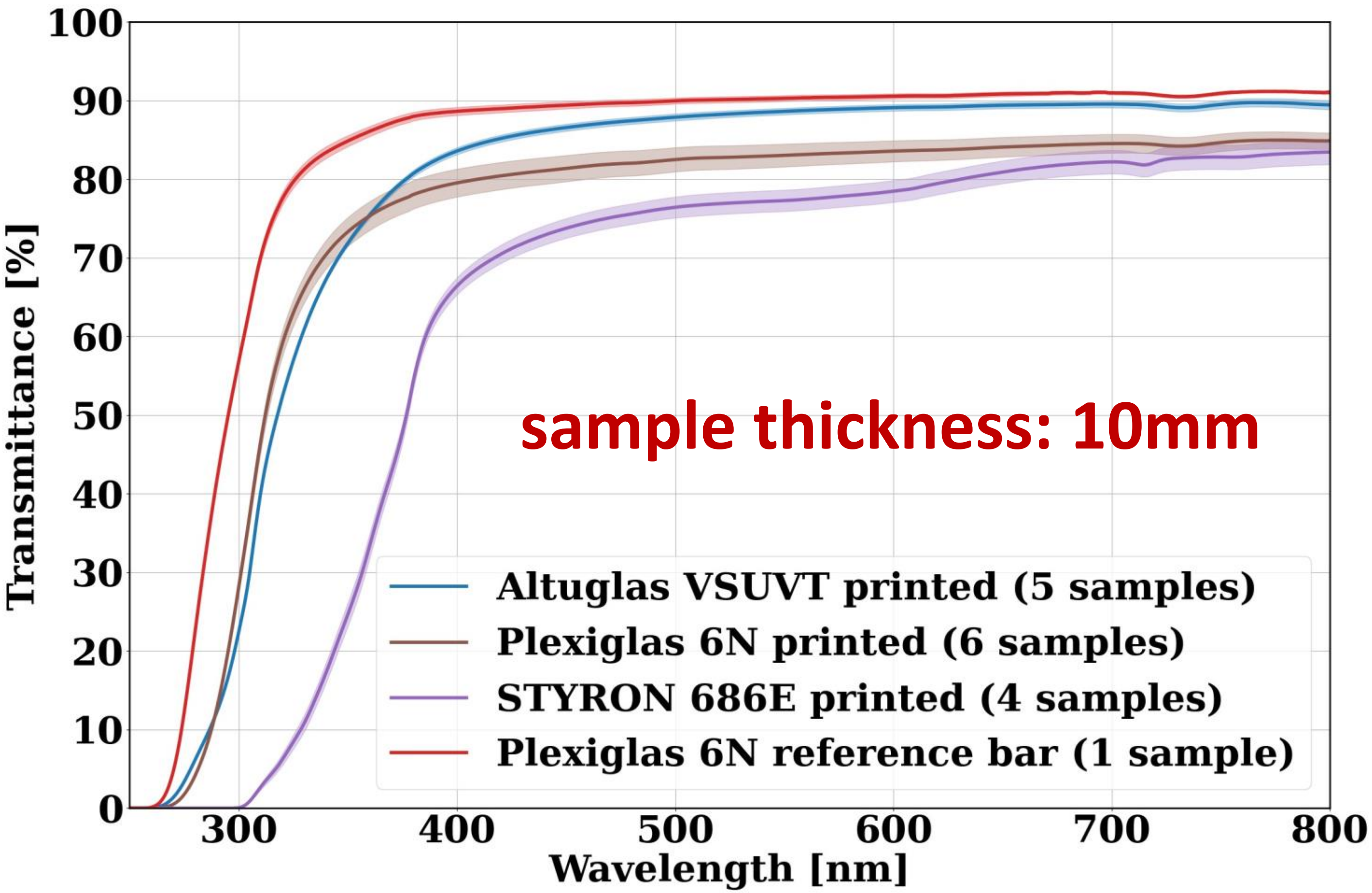
  → 10mm of material passed

  (usually, transparency given for 3mm thickness)

  → $A(\lambda) = -\log_{10} T(\lambda)$

  (absorbance *A*, transmittance *T*, wavelength *λ*)

- Fresnel losses of 8% (PMMA) and 10% (PS)
- Best PMMA samples almost reach reference
- PS prints less transparent than PMMA (especially below 400nm)
- Desired PS not available atm



Average $T(\lambda)$ curves, 95% confidence intervals, $T(\lambda)$ not corrected for Fresnel losses

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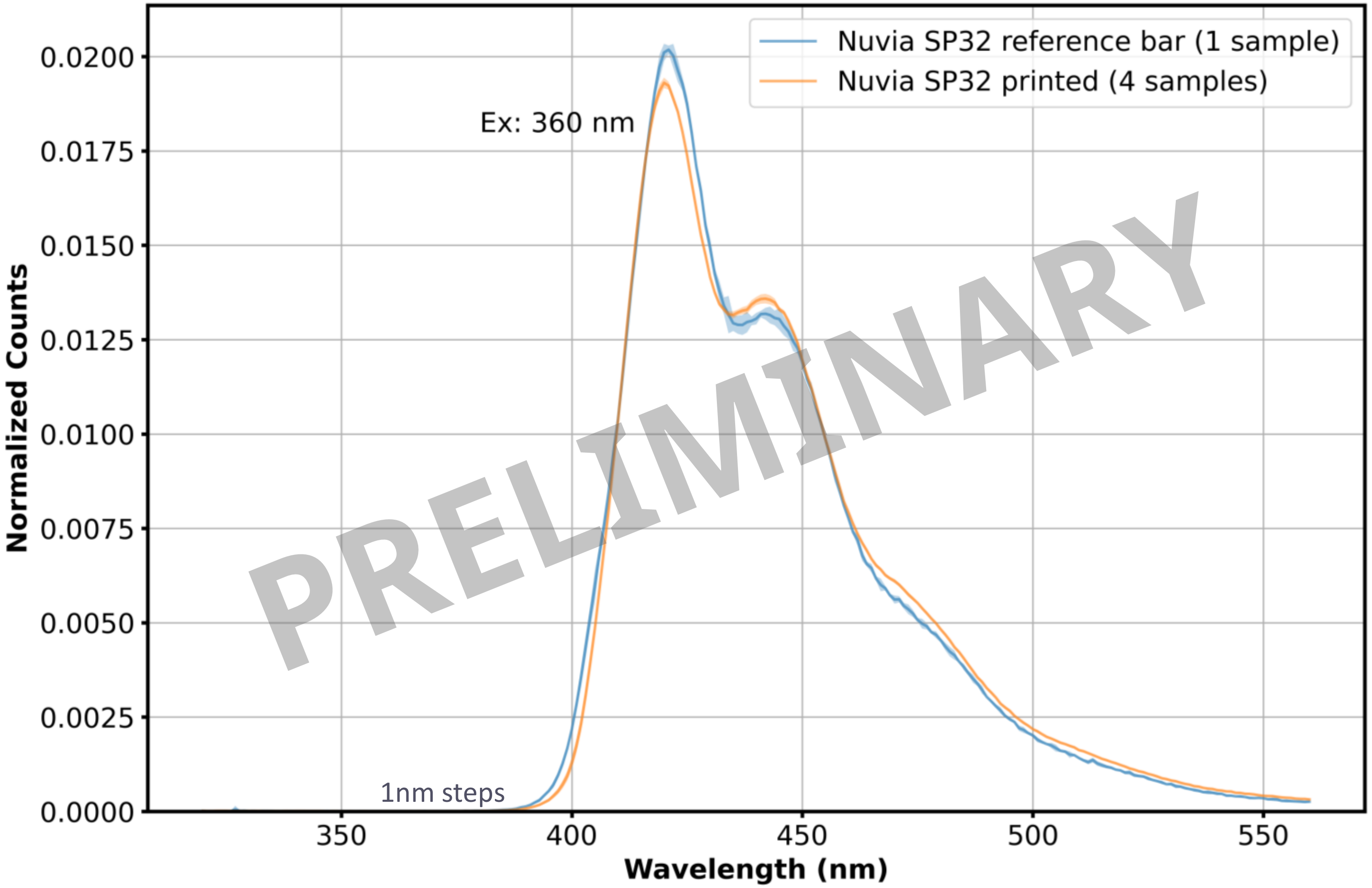
Q. Weitzel et al., “3D-printing of transparent granulate materials for light guides and scintillation detectors” Nucl. Instrum. Meth. A 1046, 167682, (2023)

EMISSION SPECTRA FOR NUVIA SP32

(3D-printed and reference)



- **Composition:**
  - polystyrene
  - p-terphenyl
  - POPOP
- Each sample measured in four positions (including rotation)
- Characteristic POPOP peaks
- No p-therphenyl signature visible
  (very efficient transfer)
- Very similar spectra
  (slight λ-right-shift for printed samples)
- no apparent damage on scintillating components from printing

Q. Weitzel et al., "3D-printing of polystyrene-based scintillator granulates for particle detectors"
European Physical Society Conference on High Energy Physics, 21 – 25 August 2023

DECAY TIME MEASUREMENTS WITH NUVIA SP32

- Time-Correlated Single Photon Counting (TCSPC) using FS5 spectrometer
  - ➢ light source: pulsed LED (255±10nm wavelength, 900ps pulse width, 5MHz rate)

PRiSMA+ DETECTOR LAB Q. Weitzel et al., “3D-printing of polystyrene-based scintillator granulates for particle detectors”
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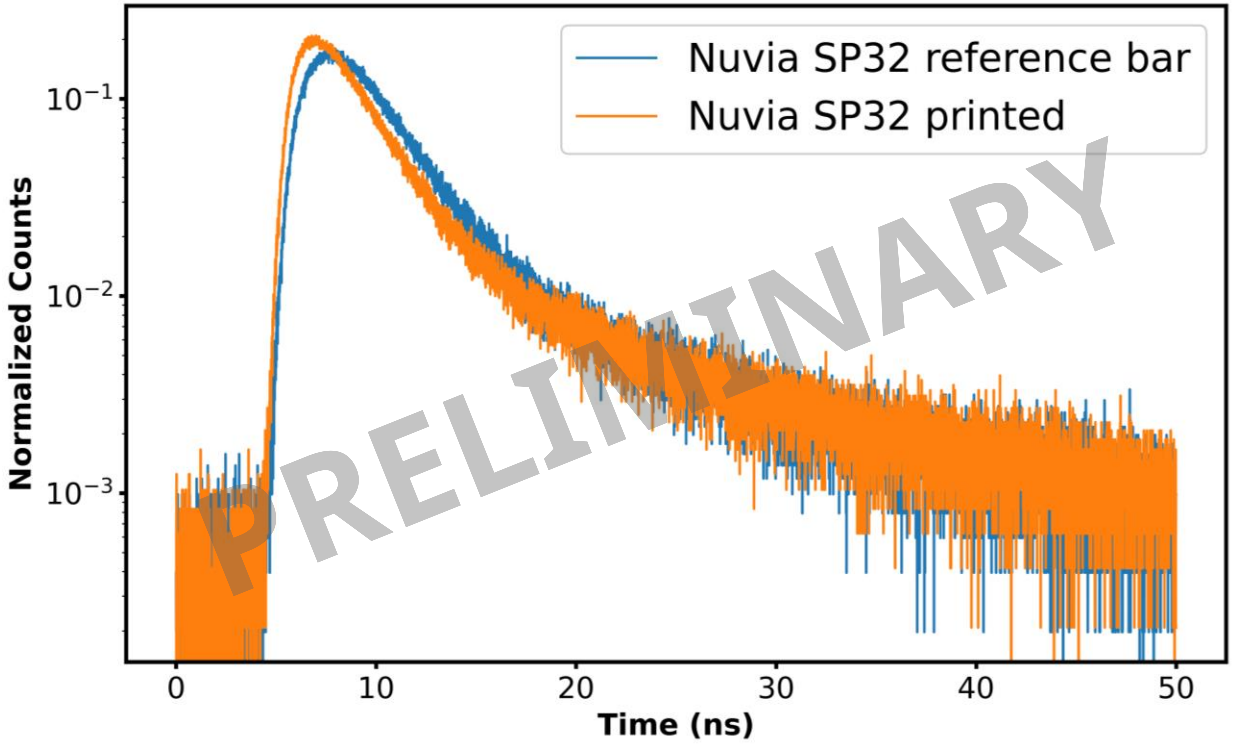
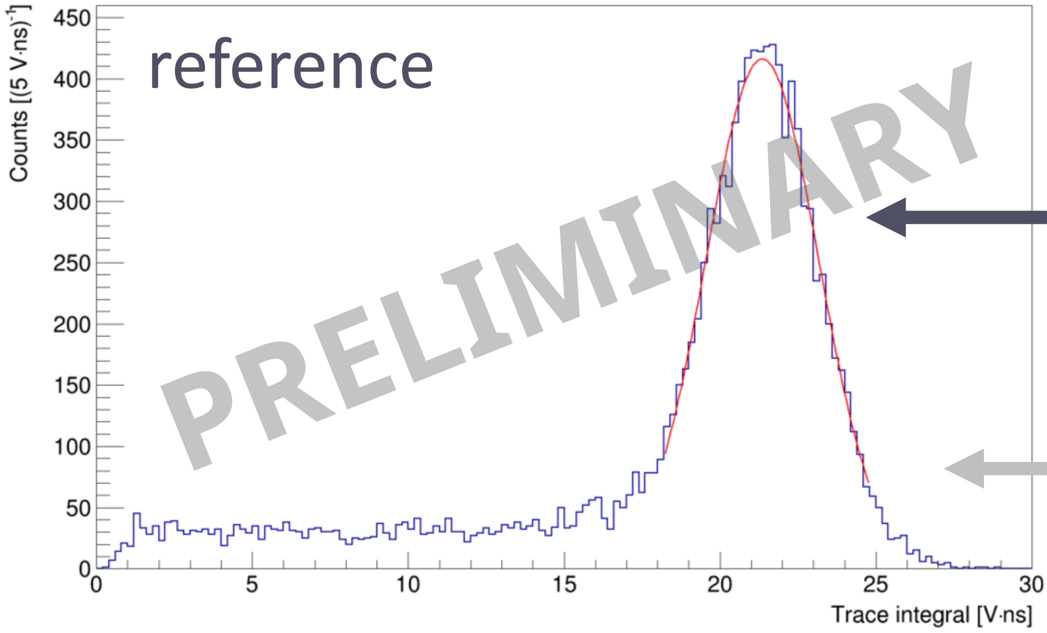
- Two time components visible
  (ca. 3ns and ca. 16ns decay time)
- Very similar distribution
  (fast decay slightly enhanced for printed sample)
- no apparent damage on scintillating components from printing

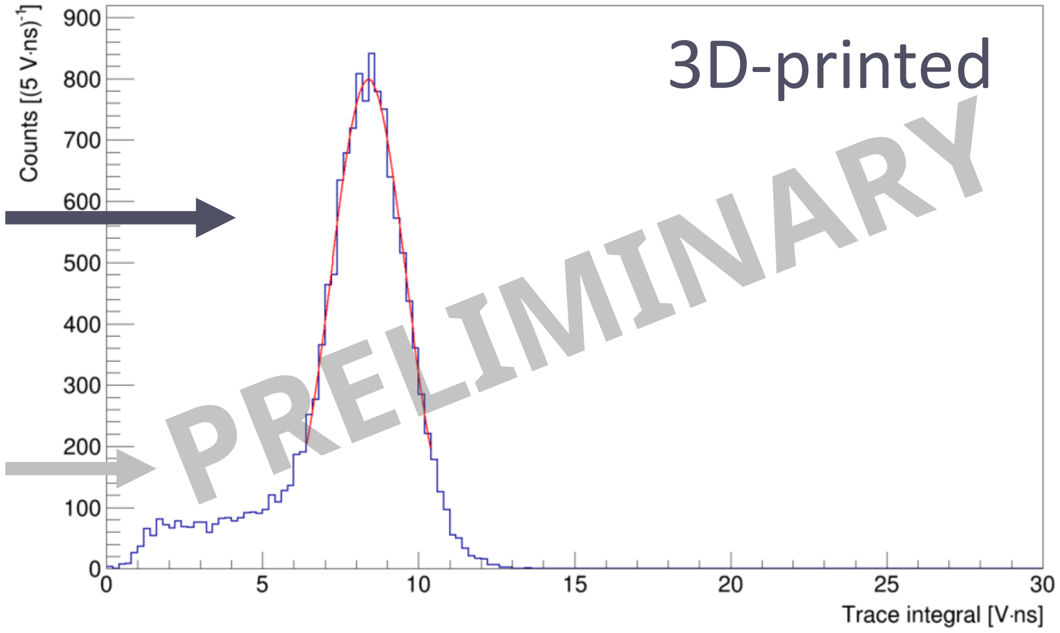


LY MEASUREMENT WITH NUVIA SP32



position of
478 keV peak

integrated PMT
signals for
selected events



Datasheet [2]: ~9700 photons/MeV

(56% relative to anthracene, cross-checked with EJ301)

39.6%* relative to reference

(~3900 p.e./MeV, losses mainly suspected
from quenching and transparency)

*Uncertainties: ± 0.09% PMT peak position, ± 1.3% re-positioning and selection
$LaBr_3$(Ce) backscatter peak effect of correction on emission spectrum folded with PMT quantum efficiency: +0.3%

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Q. Weitzel et al., “3D-printing of polystyrene-based scintillator granulates for particle detectors”
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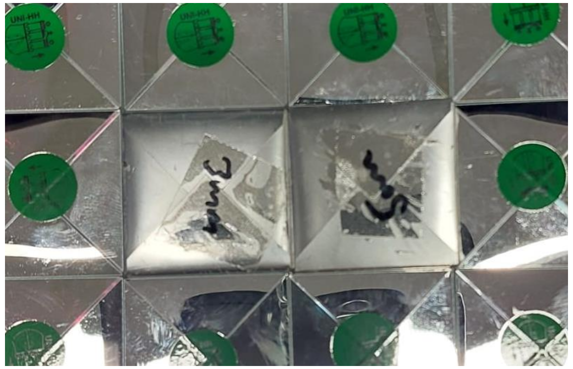
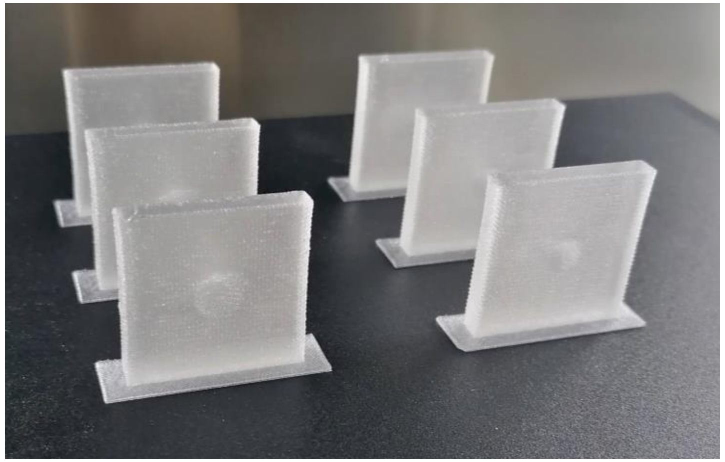
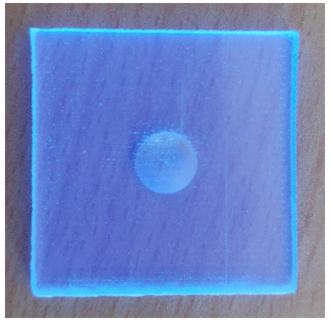
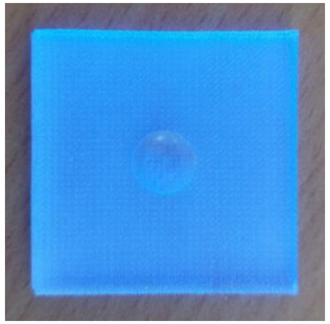
3D-PRINTING AHCAL-LIKE TILES



- First tests with AHCAL-like 3D-printed tiles
- Limited post processing
- Wrapped in ESR foil
- Added to one of the single tile layers in the cosmic-ray test stand in Mainz
- Processed with standard analysis chain

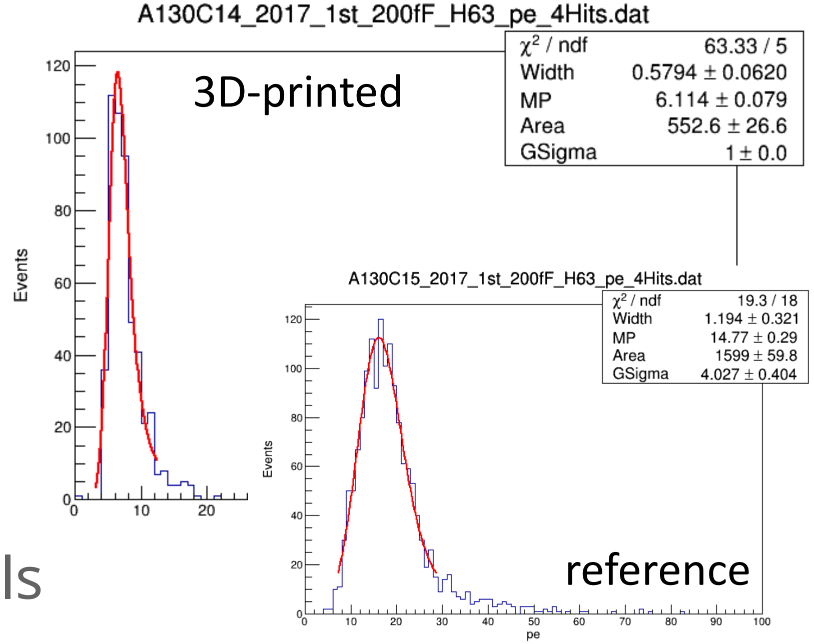




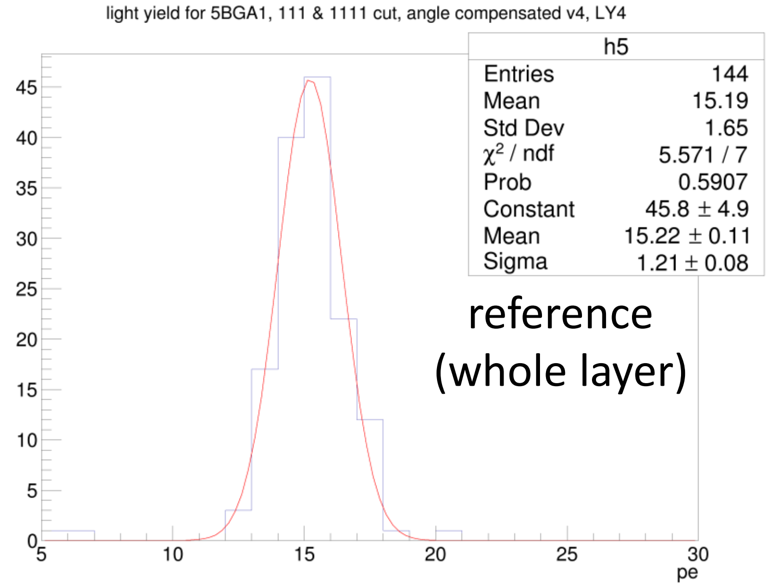


FIRST RESULTS

- Maximum LY reached so far: **6.2 pe/MIP**
  (with top and bottom face milled and polished)
- About **40% - 47%** of reference tiles (13 - 15 pe/MIP)
- Consistent with characterization measurement of materials

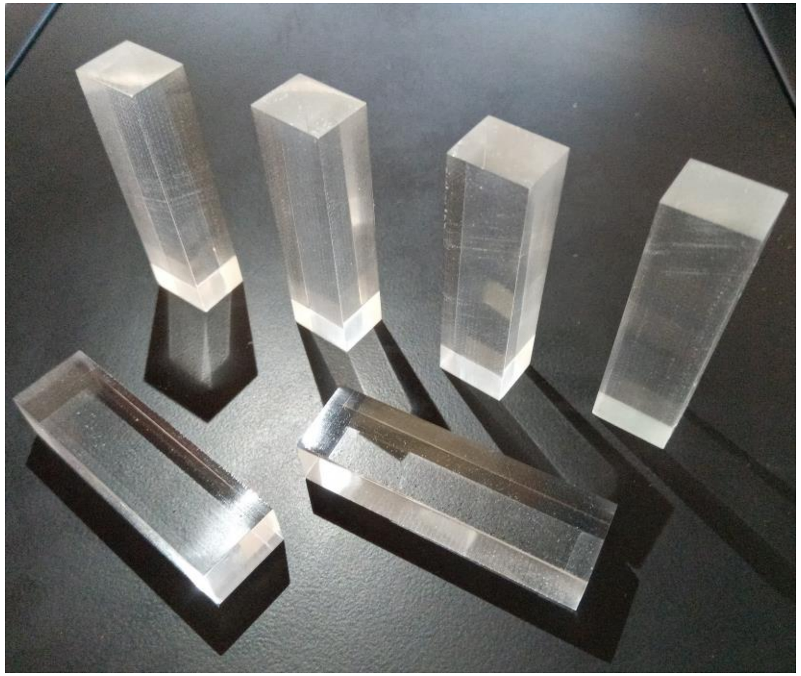


- **Caveats:**
  - Scintillators not 100% the same
  - Small number of tests performed so far
- **Still plenty of room for improvements:**
  - Print setup not tuned for this application yet
  - Only limited postproduction strategies tested



FUTURE PLANS FOR 3D-PRINTING

- Optimize printing parameters for better transparency
- Test other PS granulates
- Further studies on efficient postproduction
- Introduce optically isolating material (TiO2 doped) to print Megatile-like segmented scintillators (second nozzle)



Printed Plexiglas® 6N bars for spectrometers [7]

- Proceedings for EPS-HEP in preparation

SUMMARY AND OUTLOOK

- Ability to **separate γ and n efficiently** with peak counting
  - Improve further by using **larger SiPM**
  - Move to **charge integration for real live applicability**

- **3D-printing** of scintillators works well
  - Granulate printing can use **cheap original materials**
  - Further optimize **surface quality and transparency**
  - **Application specific** prints of segmented scintillators upcoming

BACKUP

REFERENCES

[1] Q. Weitzel et al., *Development of Structured Scintillator Tiles for High-Granularity Calorimeters*, Conf. Rec. of 2020 IEEE NSS MIC, pp. 1-7, (2020)

[2] NuviaTech Instruments, *NuDET Plastic Scintillation Detectors*, specification sheet, www.nuviatech-instruments.com, (2023)

[3] A. Kloke et al., *Droplets to the Beat of Milliseconds*, Kunststoffe international 11/2018, (2018)

[4] ARBURG GmbH + Co KG, *freeformer*, https://www.arburg.com/en/gb/company/media-centre/brochures, (2023)

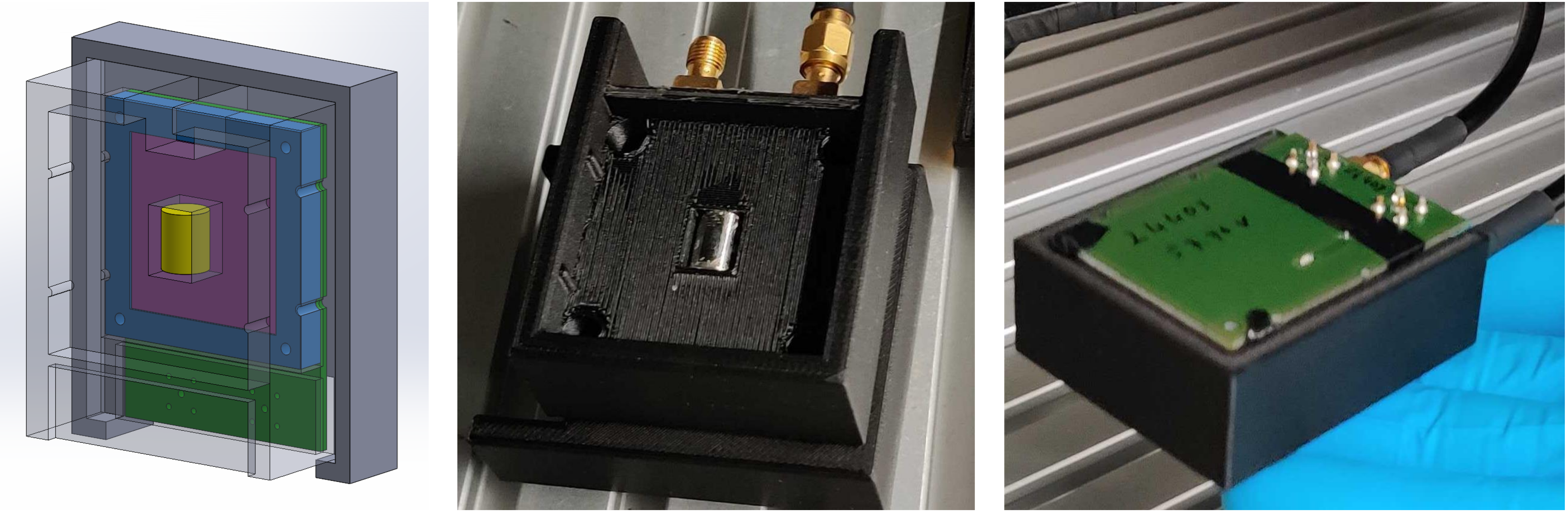
[5] T. Sibilieva et al., *3D printing of inorganic scintillator-based particle detectors*, JINST 18 P03007, (2023)

[6] D.G. Kim et al., *Enhanced characteristics of 3D-Printed plastic scintillators based on bisphenol fluorene diacrylates*, Rad. Phys. Chem. 198, 110255, (2022)

[7] Q. Weitzel et al., *3D-printing of transparent granulate materials for light guides and scintillation detectors*, Nucl. Instrum. Meth. A 1046, 167682, (2023)

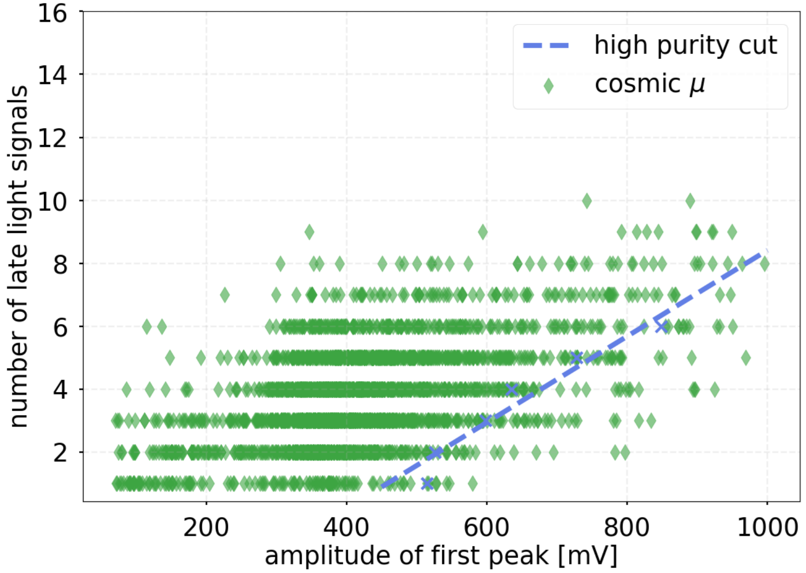
[8] Edinburgh Instruments Ltd., *FS5 Spectrofluorometer*, https://www.edinst.com/products/fs5-spectrofluorometer, (2023)

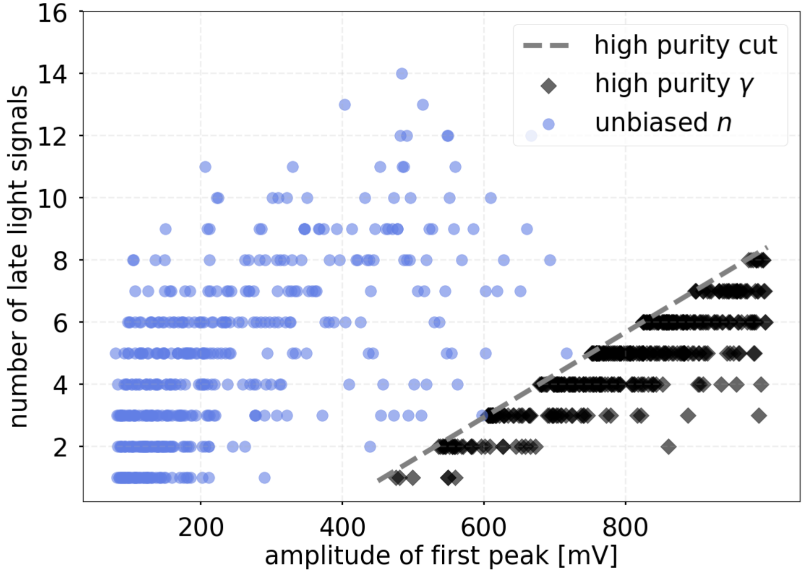
SETUP



HIGH PURITY γ/ COSMIC M CUT

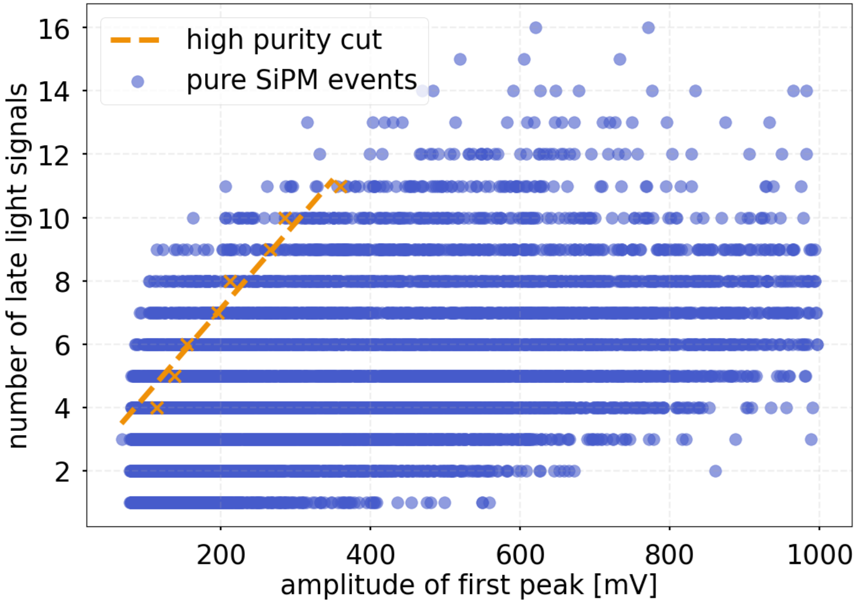
- Select cosmic muon events for neutron separation
- Step 1) determine high purity gamma cut
- Step 2) select events below cut as high purity gamma sample and corresponding events from other tile as unbiased neutron sample

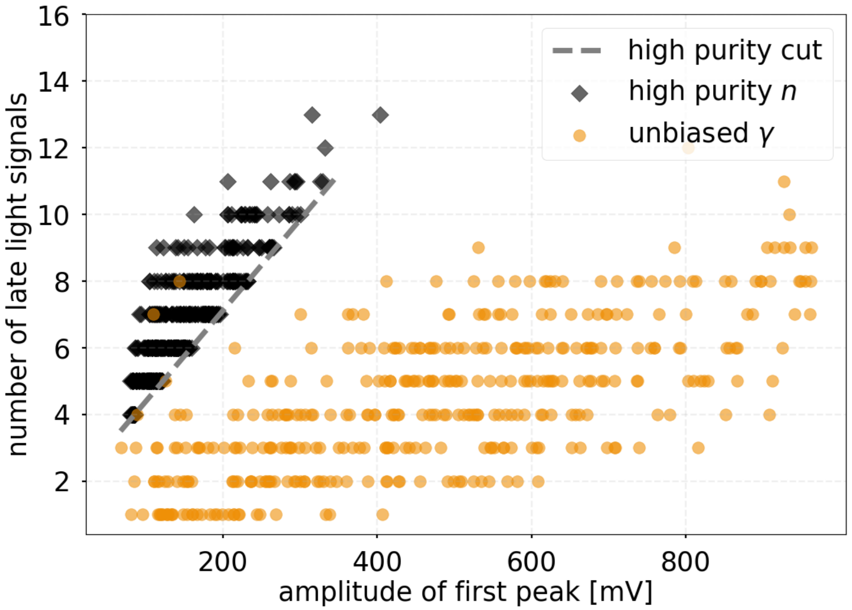




HIGH PURITY NEUTRON CUT

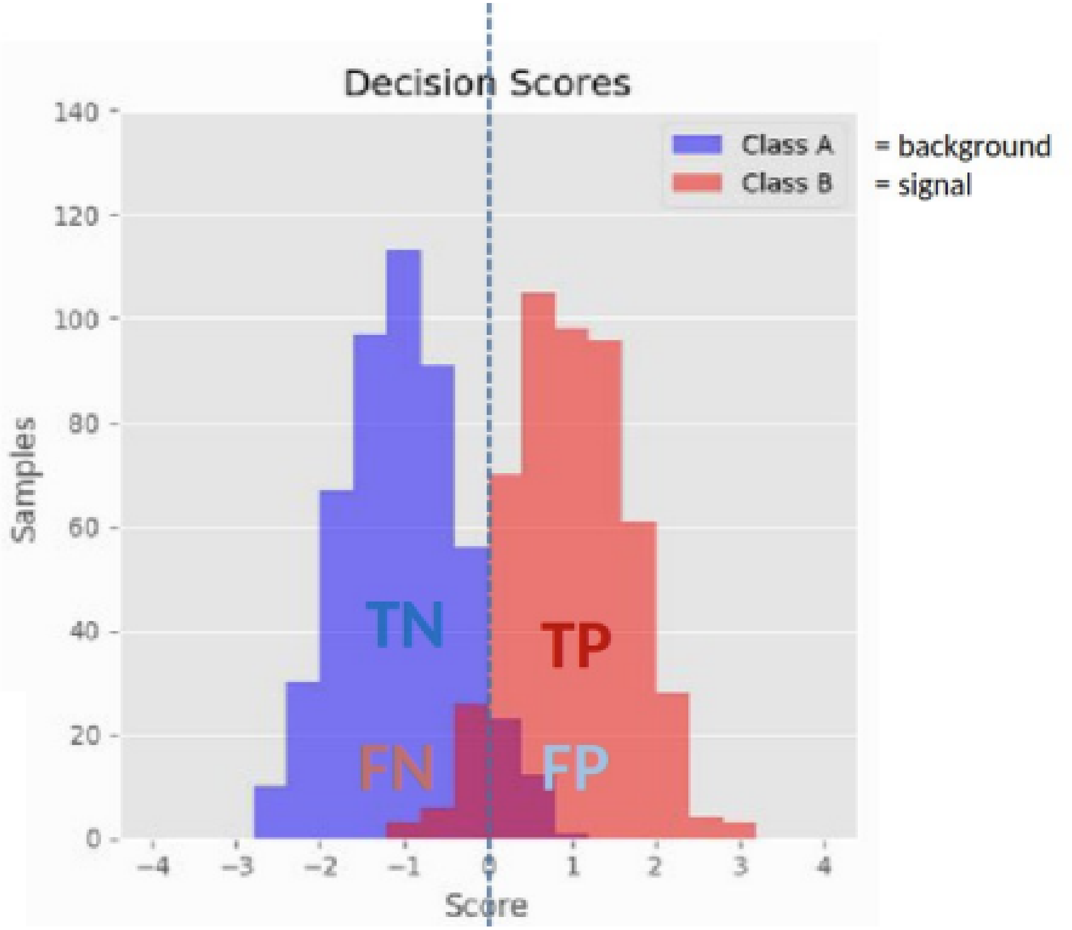
- Step 1) determine high purity neutron cut
- Step 2) select events above cut as high purity neutron sample and corresponding events from other tile as unbiased gamma sample





Efficiency, Purity, Accuracy

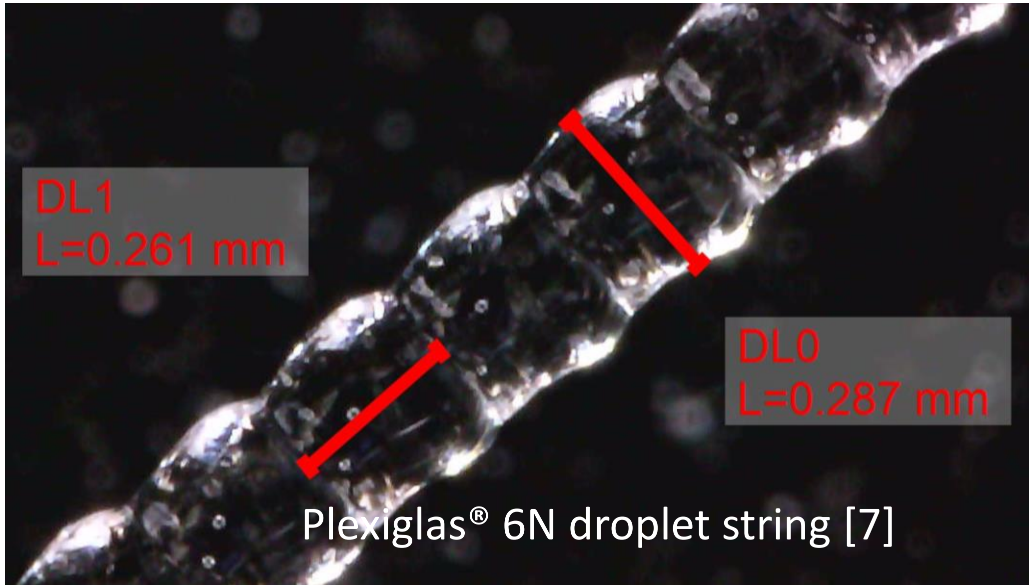
- Efficiency
  - TP / (TP + FN)
- Purity
  - TP / (TP + FP)
- Accuracy
  - (TP + TN) / (TP + FP + TN + FN)



Key quantities:
- True positives (**TP**)
- False positives (**FP**)
- False negatives (**FN**)
- True negatives (**TN**)

MATERIAL QUALIFICATION AND SAMPLE PRODUCTION

Q. Weitzel et al., “3D-printing of polystyrene-based scintillator granulates for particle detectors”
European Physical Society Conference on High Energy Physics, 21 – 25 August 2023



Plexiglas® 6N droplet string [7]

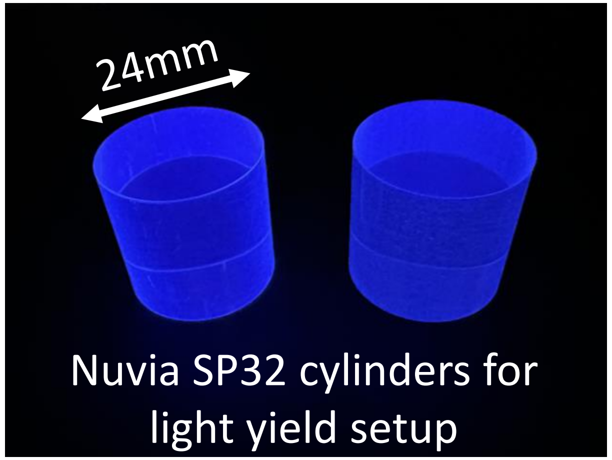
- Adjust machine settings for each material
  (microscope images of droplet strings [7], avoid air inclusions)
- Print samples, **post-processing** (milling, polishing)

Base Granulate	Type	T_{melt} (°C)	T_{lum} (%)
Plexiglas® 6N*	PMMA	220-260	92
Altuglas® 6N	PMMA	~200	92
STYRON™ 686E	polystyrene	190-240	~90

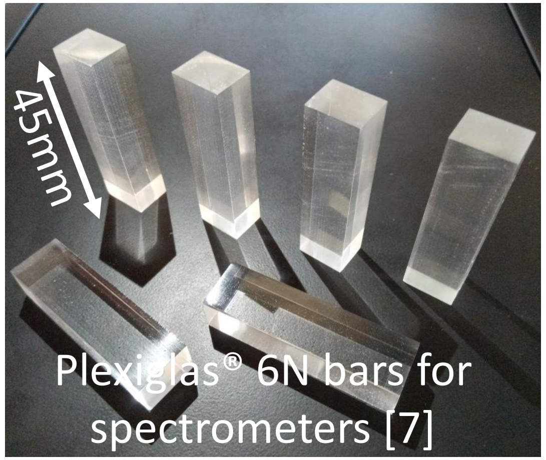
Scintillator Granulate (bought)	Additive 1	Additive 2	Ref.
SP32 (blue emitting, PS-based)*	p-terphenyl	POPOP	[2]

Scintillator Granulate (self-made)	Additive 1	Additive 2
PS (STYRON™) + PPO + Bis-MSB	1% PPO	0.04% Bis-MSB

*For these, reference samples were obtained from the manufacturers (made by press-molding or cast polymerization)



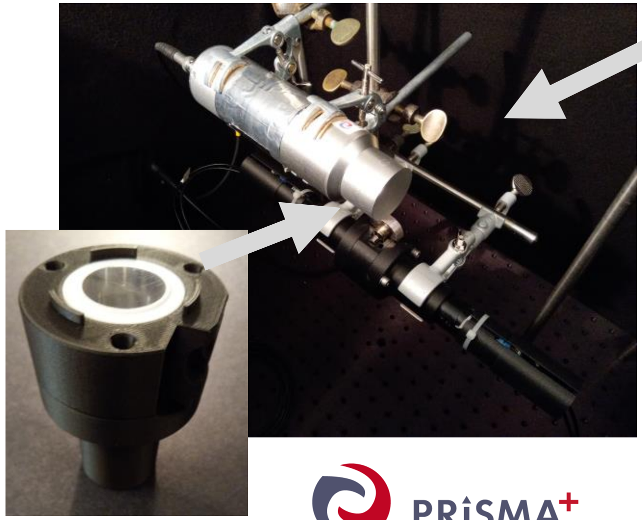
Nuvia SP32 cylinders for light yield setup

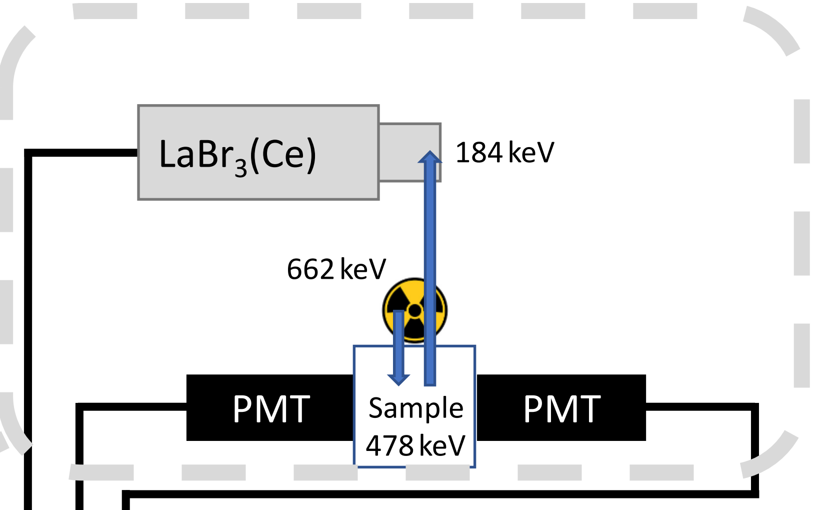


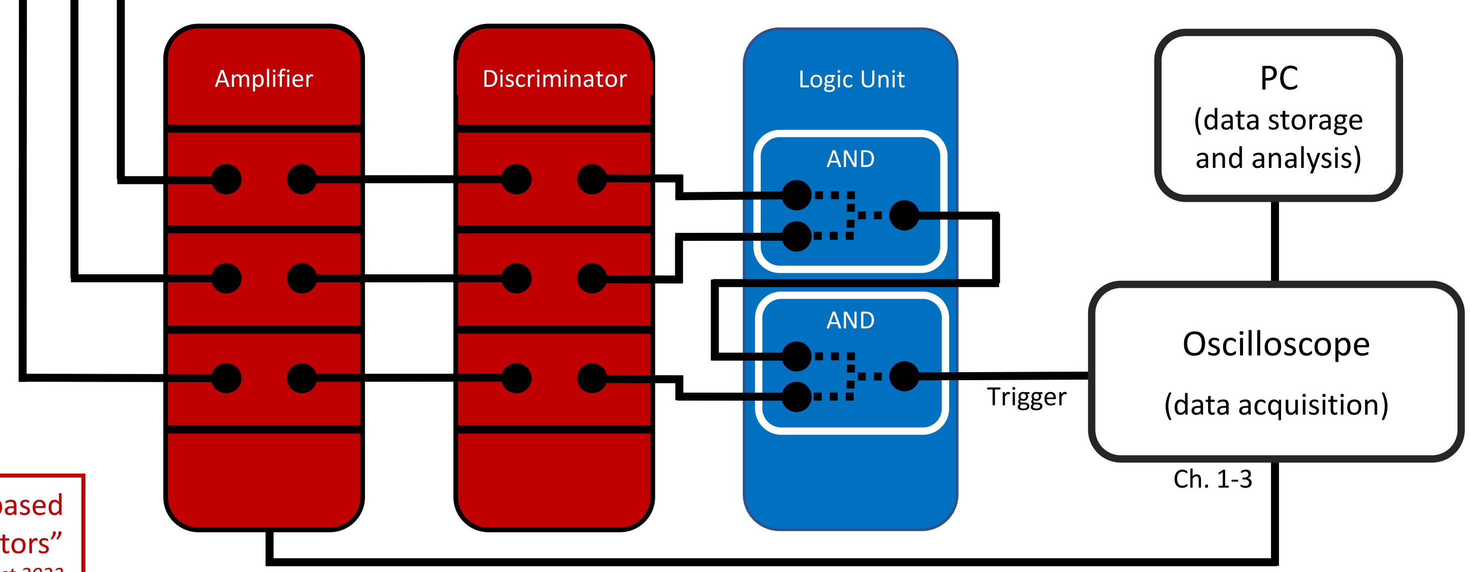
Plexiglas® 6N bars for spectrometers [7]

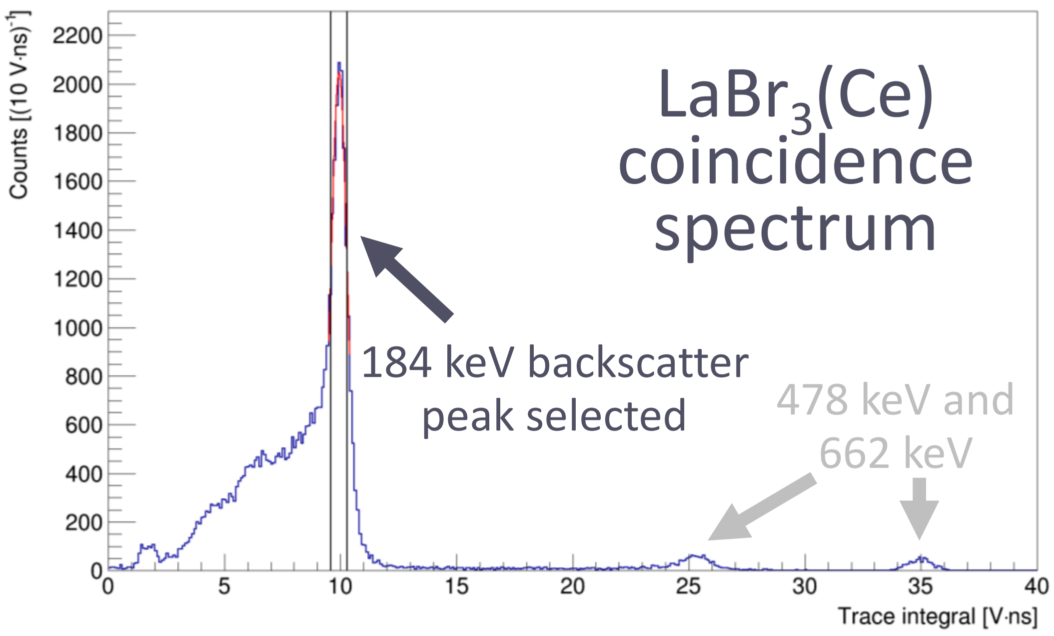
LIGHT YIELD SETUP

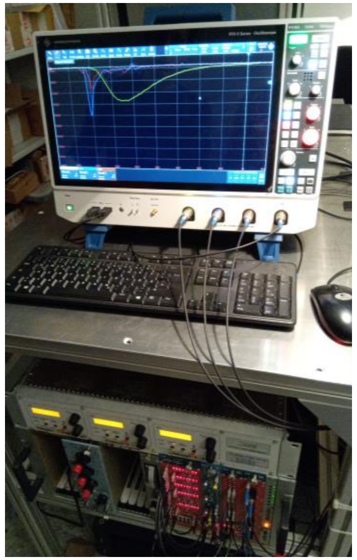
- ^{137}Cs source
- **Compton** events
- Triple coincidence
- 180° scattering











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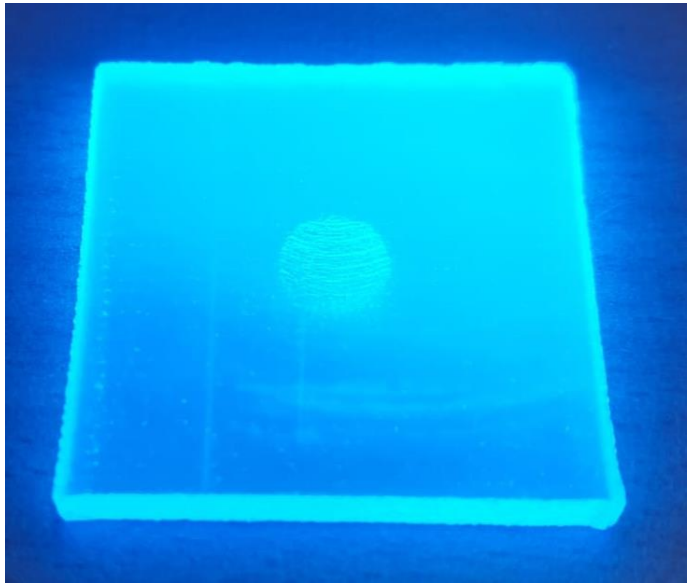
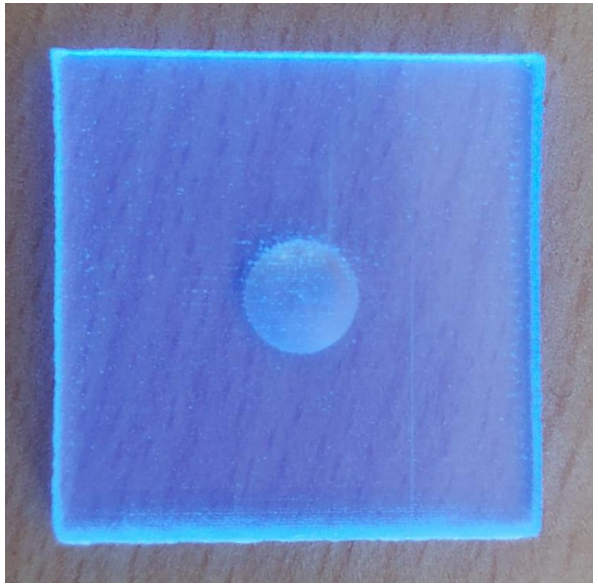
BASELINE TEST TILES



- First:
  - Postprocessing: milling dimple
  - Surfaces still in print finish
  - LY: **6.1 p.e./MIP**



- Second:
  - Postprocessing: top and bottom faces milled + polished
  - Dimple still in print finish
  - LY: **6.2 p.e./MIP**

SCINTILLATOR COMPARISON

- CALICE:
  - PS + 2% PPO + 0.1% POPOP
  - LY measured: 15 p.e./MIP (injection molded)
  - LY: 45% / 75% w.r.t. Anthracene (https://agenda.linearcollider.org/event/7630/contributions/39724/attachments/32040/48438/calice_collaboration_meeting_tokyo2017.pdf)
  - LY: 33% w.r.t. Anthracene (https://knepublishing.com/index.php/KnE-Energy/article/view/1768)

- NE110-like tile:
  - PVT based
  - LY measured: 24.5 p.e./MIP (machined from large plate)
  - LY: 60% w.r.t. Anthracene (https://eljentechnology.com/products/plastic-scintillators)

- NUVIA SP 32:
  - PS + p-terphenyl + PPO
  - LY measured: 6.2 p.e./MIP (3D printed)
  - LY: 56% w.r.t. Anthracene (https://www.nuviatech-instruments.com/wp-content/uploads/sites/3/2022/03/NVG-375011-NUVIATECH-CatalogueInstrument-Juillet2019-BD.pdf)

- Corrected performance of 3D-printed tile to reference AHCAL tile between **24 – 55 %**