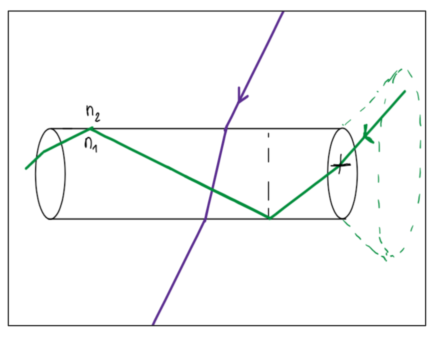
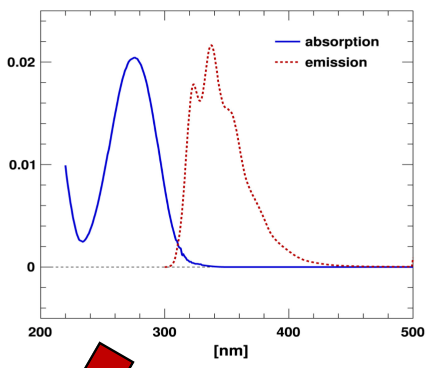
Optimized Wavelength-shifting Fibers (OWLs) for a high Photon Capture-rate

Bastian Keßler

What Are Wavelength-shifting (WLS) Fibers

Optical fibers **transport light** via total internal reflection (TIR) from one end surface to the other.
Light entering from the side of the fiber is **not captured**.

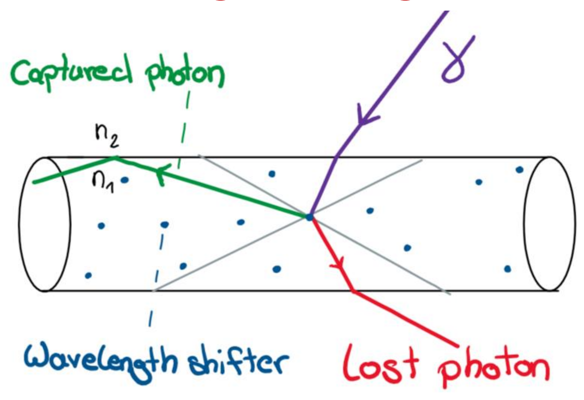




Wavelength shifters **absorb light** in a specific wavelength region and **reemit** it at a higher wavelength.
The emission is **isotropic**.

Wavelength-shifting fibers

WLS fibers are a **combination** of optical fibers and wavelength shifters.
In these fibers, light can be **absorbed and re-emitted** by the doped shifter

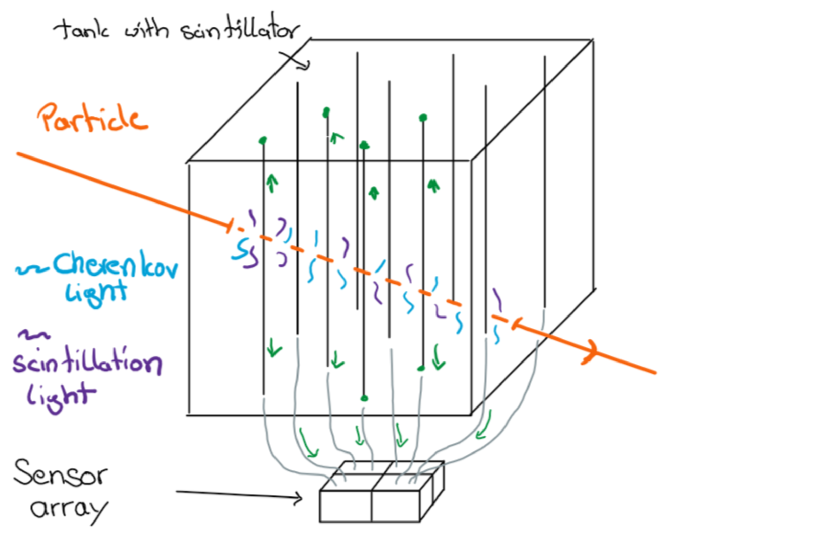


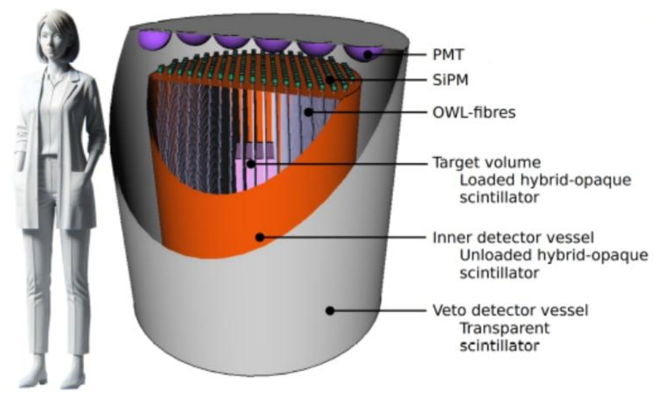
The portion of isotropic emitted light that **fulfills** the **TIR condition** is **captured** and guided toward the end face.
This makes wavelength-shifting fibers effective **passive light collectors**

What are WLS-Fibers used for

As passive light collectors WLS-fibers can be used to **gather Cherenkov and scintillation** light from large detector volumes. The captured light is then **guided to a photosensor** array, where it is detected.

This approach is especially **important for opaque scintillators** with a low scattering length, where the **light remain localized** around its point of creation. In such cases, **WLS fibers** are the only practical means of **light collection**.





https://nudoubt.uni-mainz.de

Such a detector design is employed in the **NuDoubt**$^{++}$ experiment, **searching for double** β^{++} **decays of Kr-78** in a Linear alkylbenzene (LAB) based opaque scintillator. In this context, only **400-800 Photons per Event** are expected, limiting the achievable energy resolution.
Since the **capture efficiency** of **commercially** available **WLS-fibers are around 5% [1]**, any **improvement** in their performances generally would directly enhance the experiment's sensitivity.

[1] = Plastic Scintillating Fibers , kuraray

Optimizing Capture-rate

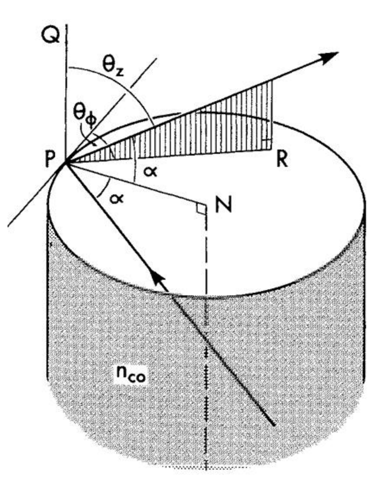
A photon is captured if its incident angle α satisfies the condition for TIR, which primarily depends on the difference in refractive index between the fiber core n_c and the surrounding medium n_m.

$$0 \leq \alpha \leq \alpha_c$$

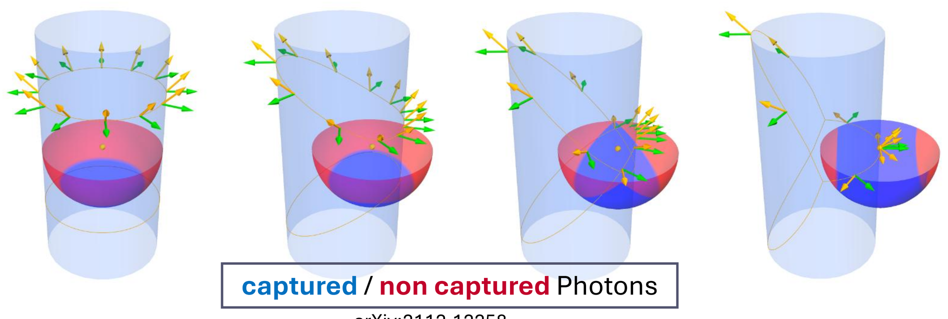
$$\cos \theta_c = n_m / n_c = \sin \alpha_c$$

$$\cos \alpha = \sin \theta_z \sin \theta_\Phi$$

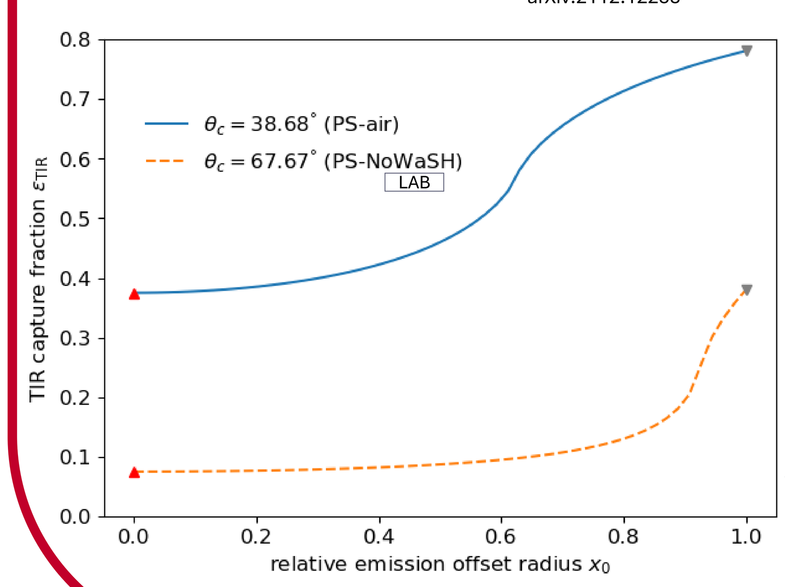
For photons emitted from the center of the fiber, only the axial angle θ_z contributes to the incident angle α, which limits the capture efficiency.
For emissions closer to the fiber surface, the azimuthal angle θ_Φ also contributes to α, increasing the likelihood that the TIR condition is met.
Photons emitted close to the surface have a higher change of being captured.



Allan W. Snyder, John D. Love
Optical Waveguide Theory



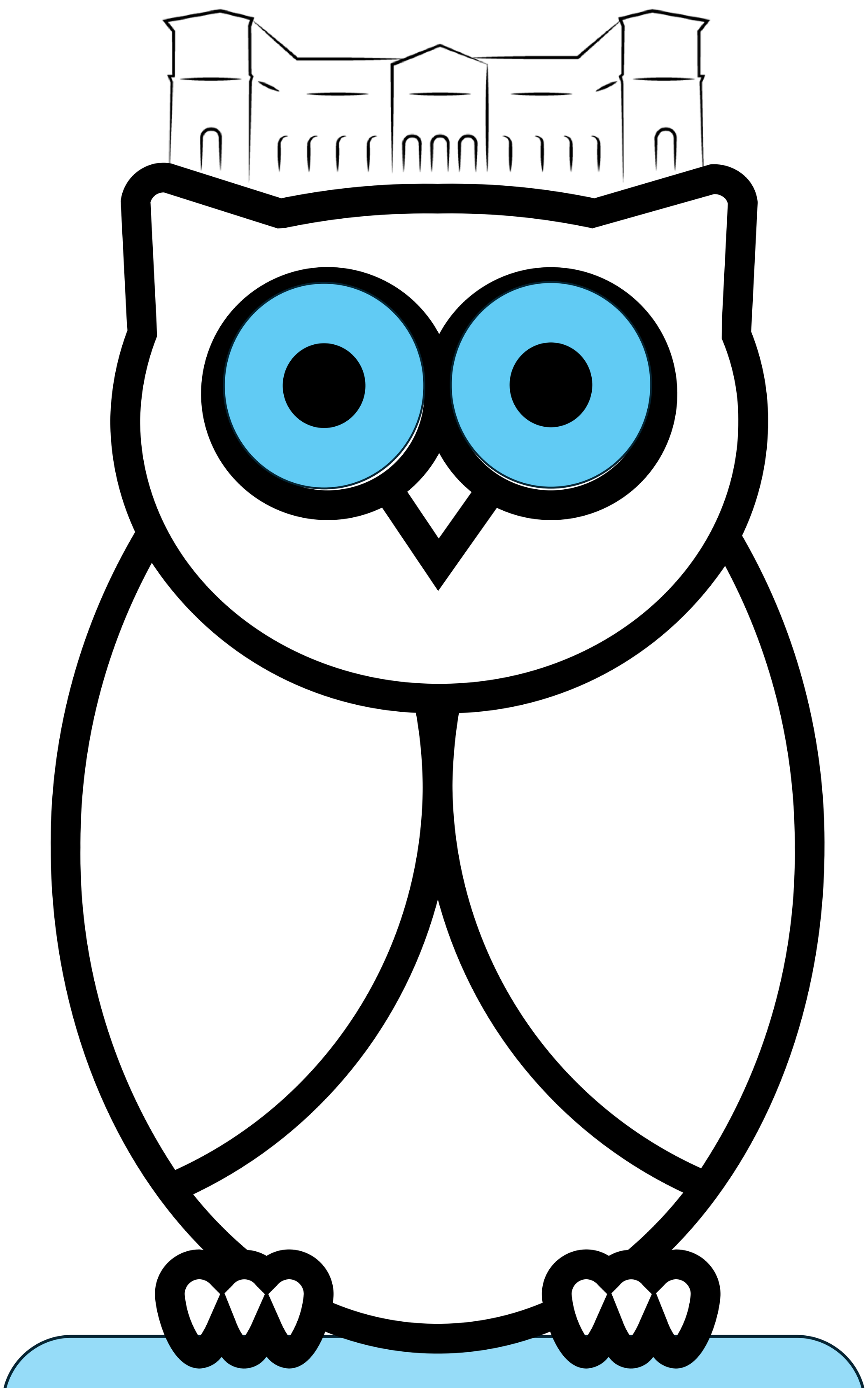
captured / **non captured** Photons
arXiv:2112.12258



arXiv:2407.05999

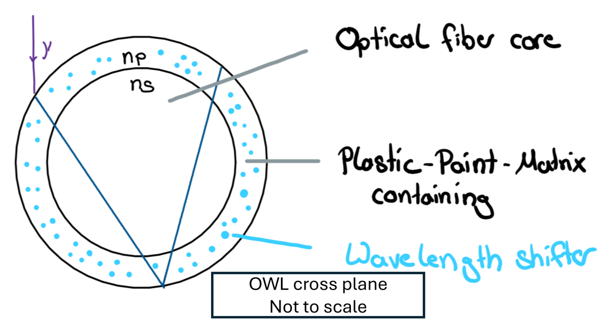
In commercial fibers the WLS is homogenous distributed in the fiber. Forcing the point of emission towards the surface maximize the TIR capture efficiency. This Gain is especial interesting for small differences in refractive indexes like a WLS fiber in a Scintillator

Optimized Wavelength-shifting fiber
OWL



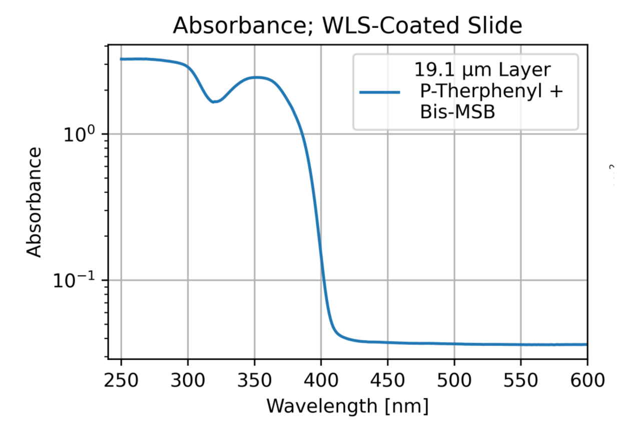
Construction of OWLs

To bring the photon emission closer to the fiber surface, a **highly absorbance WLS layer** must be placed at the outermost layer of the fiber.



WLS Paint (P-T + Bis-MSB) under UV light

This is accomplished by **coating an optical fiber** with a highly doped **WLS paint**. The paint consists of a plastic matrix containing the desired wavelength-shifter, dissolved in a solvent that evaporates after the paint is applied to the core.

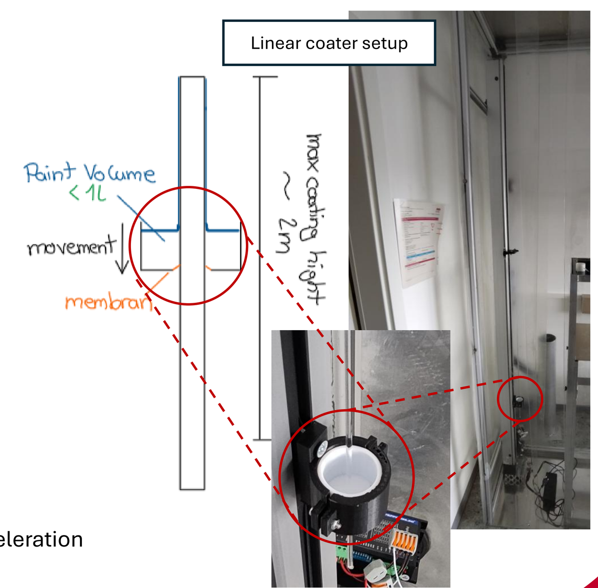


Dip-coating

Here, a paint vessel is moved along the fiber axis, applying a constant layer. The thickness can be controlled with the coating speed U_0 and the viscosity η, following the Landau–Levich equation, allowing paint thicknesses h in the 10 to 100 µm range.

$$h = 0{,}94 \cdot \frac{(\eta U_0)^{2/3}}{\gamma^{1/6} (\rho g)^{2/3}}.$$

γ = Surface tension , ρ = Density , g = Earth Acceleration

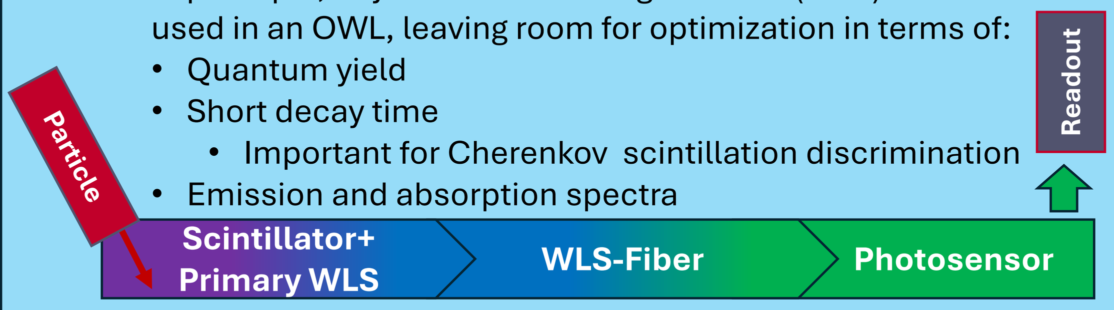


OWL-Prototypes under UV light

Wavelength-shifter

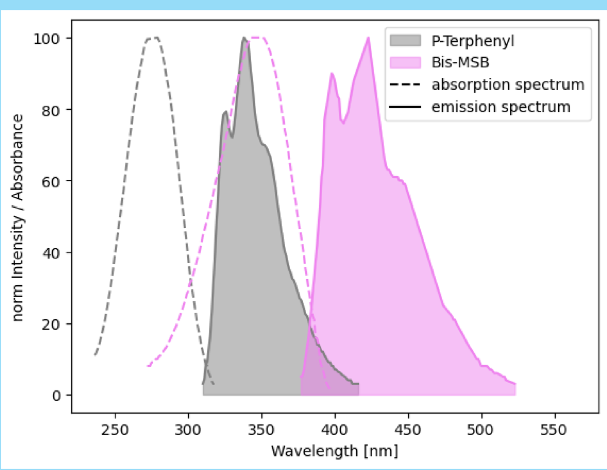
In principle, any soluble wavelength shifter (WLS) can be used in an OWL, leaving room for optimization in terms of:

- Quantum yield
- Short decay time
  - Important for Cherenkov scintillation discrimination
- Emission and absorption spectra



The absorption and emission spectra must be matched with the Scintillator emission and the photosensors quantum efficiency spectrum, without absorbing too much of its own light due to self absorption

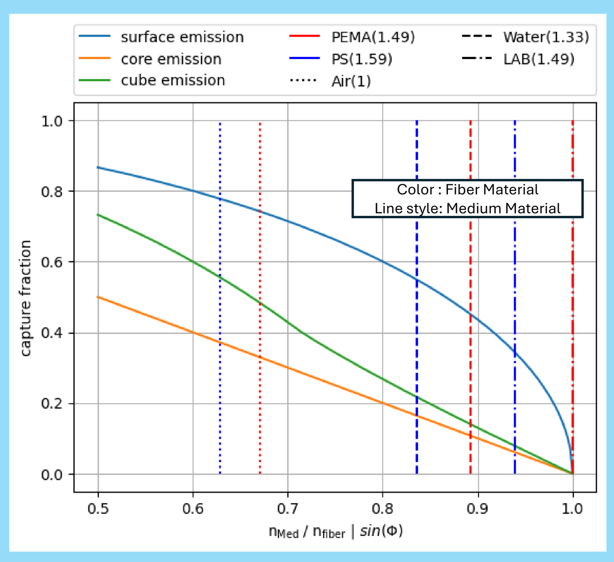
Example WLS	Shifting from → to
P-Terphenyl	UV → UV
Bis-MSB	UV → Blue
BPEA	Blue → Green



Core and Matrix Materials

Refractive Index

To achieve a high capture rate, the refractive index n of the fiber must be higher than that of the surrounding medium. For an LAB-based scintillator, the fiber's core and matrix refractive index n must be at least above 1,49.

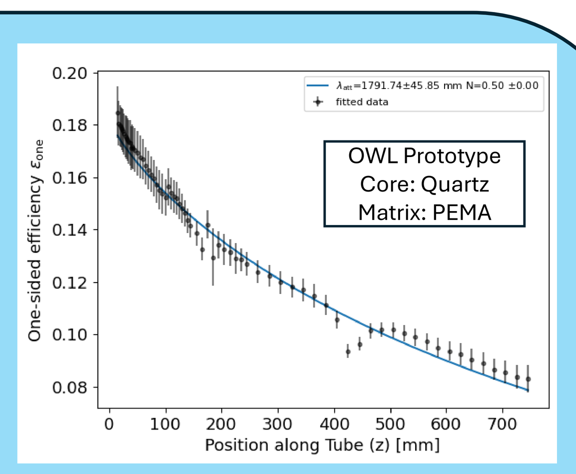


Also, the refractive indices of the core and the coating needs to match to prevent interface effects.

Material	n (588nm)	Attenuation length [m] (420nm)	LAB Resistance
PS	1.59	2-4	-
PVT	1.58	2-4	-
PMMA	1.49	4-10	+
PEMA	1.49	4-10	-
Pure Silica	1.45	>10	+

Attenuation

High attenuation length of the Material for the emitted light is also crucial for a high-performing fiber, to avoid losing photons on the way to the sensor.



Chemical Stabel

Since the fibers need to operate stably over a long period of time in a scintillator, they must not be attacked by it or must otherwise be protected.

Radiopurity

For the NuDoubt^{++} experiment, the decay chains of U-238 and Th-232 is one major background source. Fused silica can achieve radiopurity levels in the ppb region, organic materials can reach levels in the ppt

EPS HEP2025 Marseille 07-11 July 2025
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
Cluster of Excellence PRISMA+ Precision Physics, Fundamental Interactions and Structure of Matter
NuDoubt++