High-D Consortium Meeting

2022-02-21

Bundesministerium
für Bildung
und Forschung

AP 2.1 – 2.3:

WOM-LS

Introduction to a WOM-based Liquid Scintillator detector

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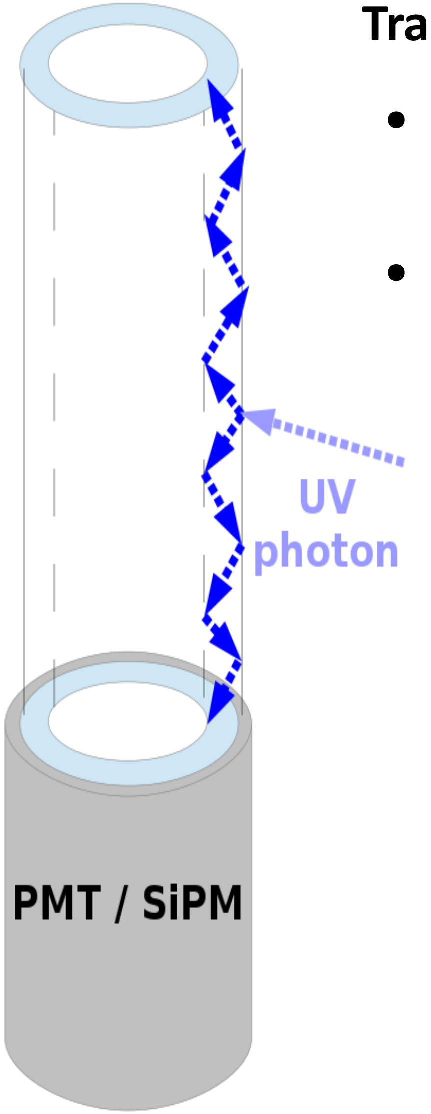
Detector Technologies

WOM: Wavelength-Shifting Optical Module



Transparent tube:

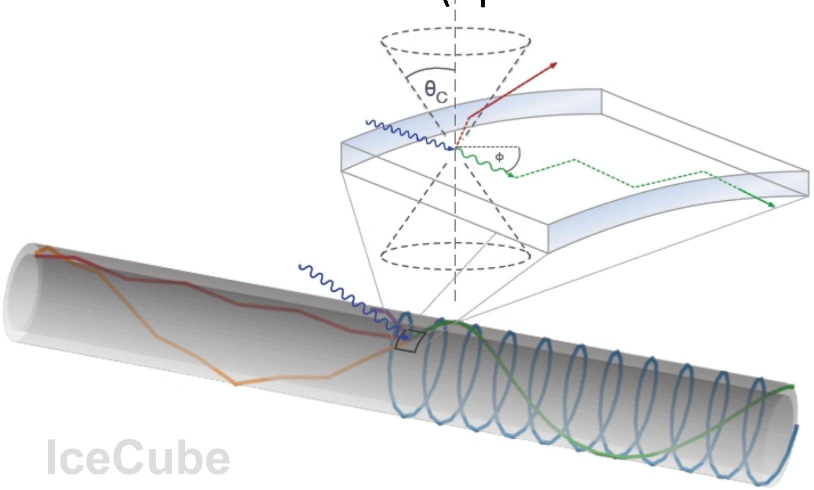
- **Large effective area** (w.r.t. actual photo sensor)
- Low material budget

WLS coating:

- **UV / blue absorption** (up to 100% efficiency)

► **Isotropic visible light emission**

► Internal **total reflection** (up to 75% collection efficiency)



► Instrumentation of **large detector volumes**

► Ideal for **Cherenkov & scintillation** detectors

The Wavelength-Shifting Optical Module (Sensors 2022, 22, 1385)

WOMs in IceCube

IceCube:

- 86 strings
- 5160 optical sensors
- 1 km^3
- ▸ E 100 GeV – 100 TeV
- ▸ Cosmic ν...

IceCube-Gen2:

- 120 strings
- ▸ 10 km^3
- ▸ E 10 TeV – 10 EeV
- ▸ Cosmic ν...

IceCube Upgrade:

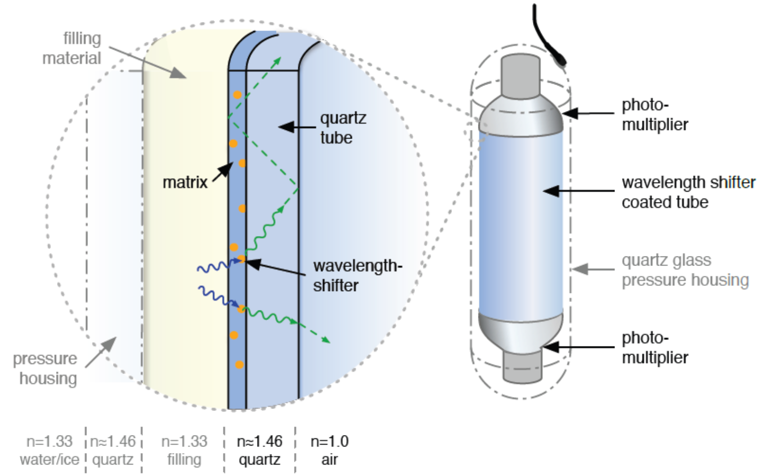
- +7 strings (incl. **DeepCore**)
- +750 optical sensors
- ▸ E > 1 GeV
- ▸ Atmospheric ν oscillation...

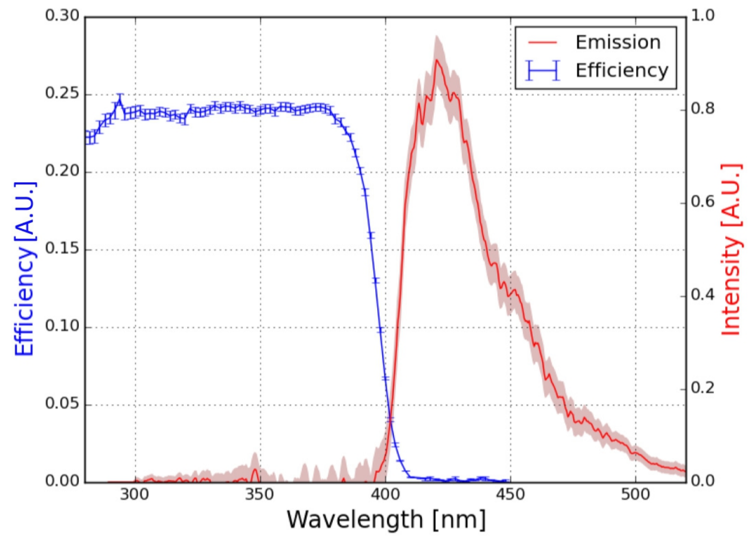
Future upgrades:

- ▸ **WOM** strings

The IceCube WOM

- **Quartz glass tube:**
  60mm ⌀, 700mm length, 2.5mm wall
- **WLS paint coating (inside):**
  Bis-MSB + p-Terphenyl
  - UV / blue absorption
  - Visible light emission [420 nm]
- **PMT readout (both sides):**
  Hamamatsu R14689 3.5“ [450 nm]
  - Single-photon sensitivity
  - Signal-to-noise (x8.9 increase)
- **Pressure housing**: Quartz glass



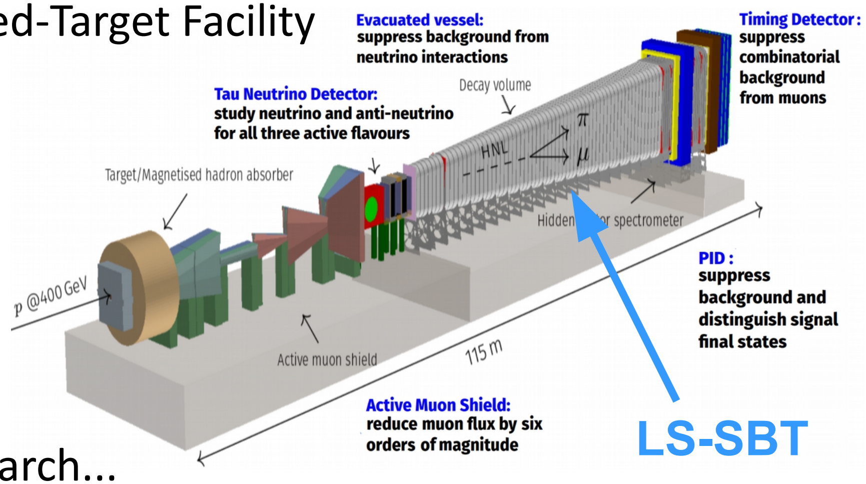


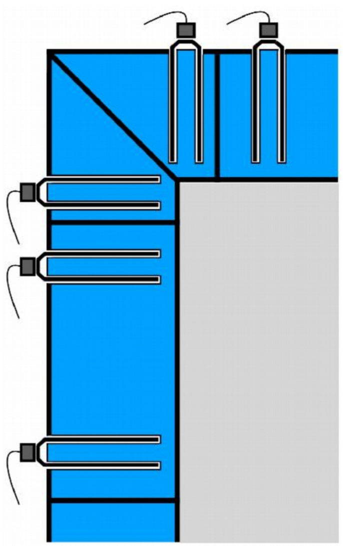
The Wavelength-Shifting Optical Module (Sensors 2022, 22, 1385)

WOMs in SHiP: LS-SBT

Search for Hidden Particles (SHiP): General-Purpose Fixed-Target Facility

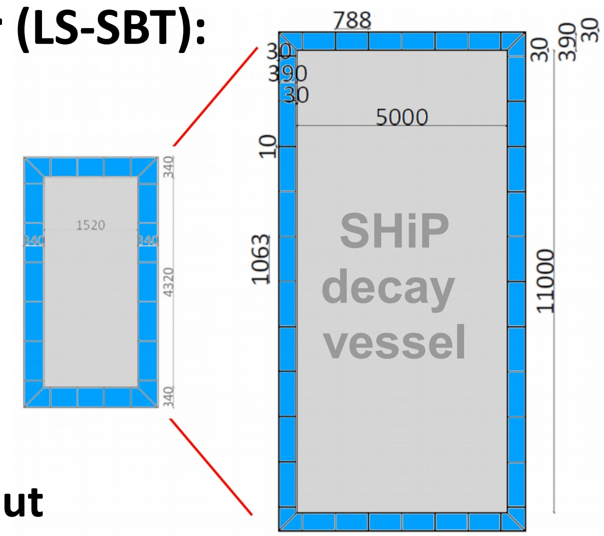
- Part of the **CERN Physics Beyond Colliders** program
- **SPS NorthArea:** 400 GeV protons
  - Search for weakly interacting particles ($m \leq 10$ GeV/c^2): HNL, dark γ, light scalars, SUSY, axion-like particles...
  - ν_τ physics, lepton flavour-violation, direct Dark Matter search...



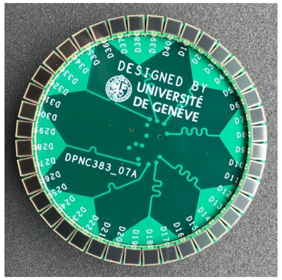


Liquid Scintillator Surrounding Background Tagger (LS-SBT):

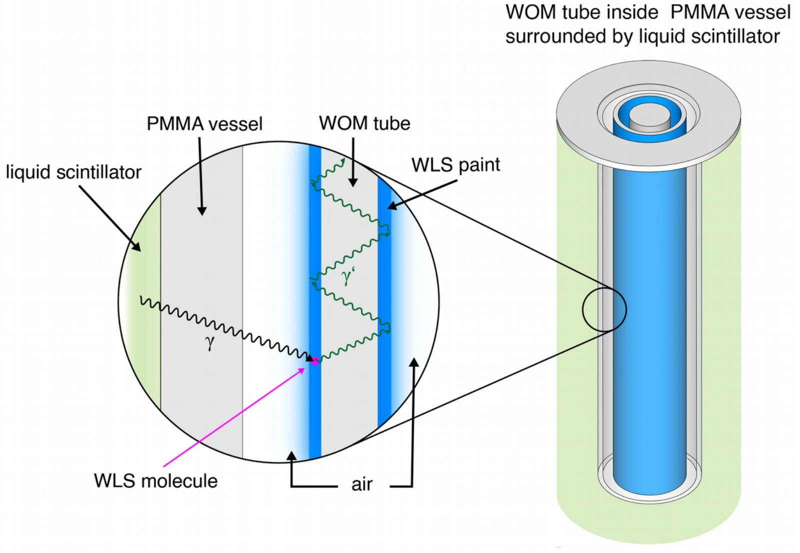
- Tagging of μ- and ν-induced BG:
  - **High efficiency:** 99.9% for m.i.p.
  - **Good time resolution:** $\mathcal{O}$(1 ns)
- Segments $\mathcal{O}$(2000): Filled with **LS** (LAB + PPO)
- Instrumentation with **WOMs** $\mathcal{O}$(4000) & **SiPM readout**

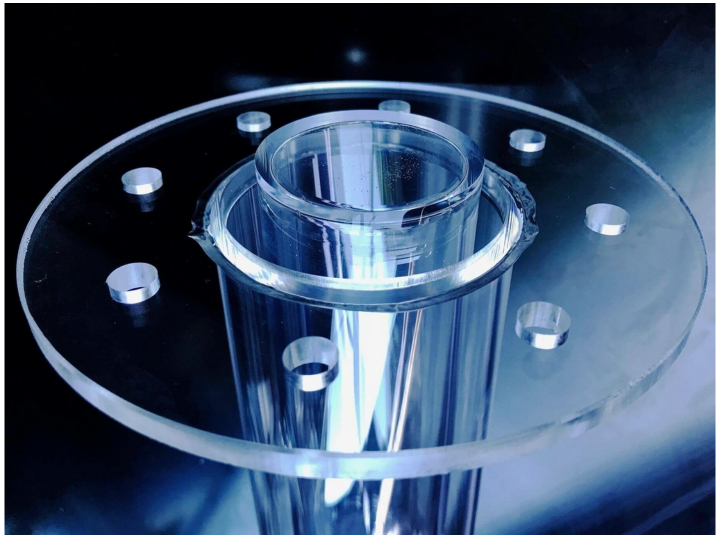


The SHiP WOM



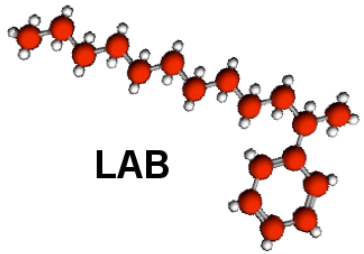
- **PMMA tube:**
  60mm ⌀, 200mm length, 3mm wall
- **WLS paint coating (both sides):**
  Bis-MSB (+ p-Terphenyl)
  - UV / blue absorption
  - Visible light emission [420 nm]
- **SiPM readout (one side):**
  Hamamatsu S14160-3050PE [450 nm]
  - 40 3x3 mm^2
  - Directional information (?)
- **Insulation from LS:** PMMA vessel

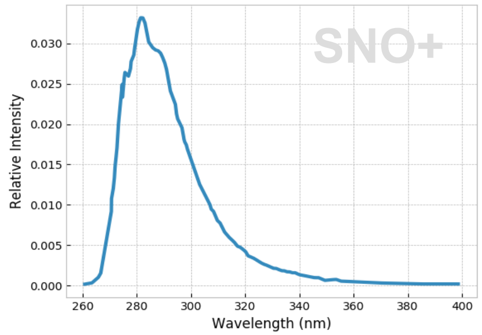




Liquid Scintillator (LS)

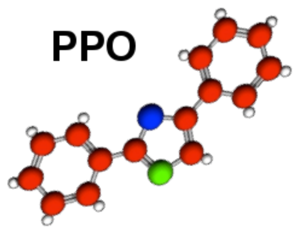
Solvent: Linear alkylbenzene **(LAB)**

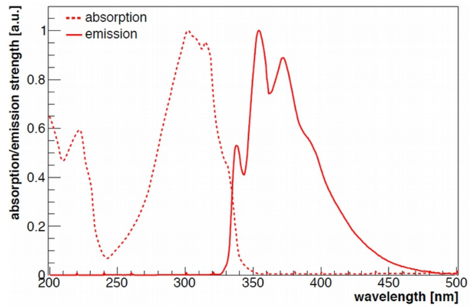




λ_{scat} ~ 20m @400nm

Fluor: 2,5-diphenyl-oxazole **(PPO)**

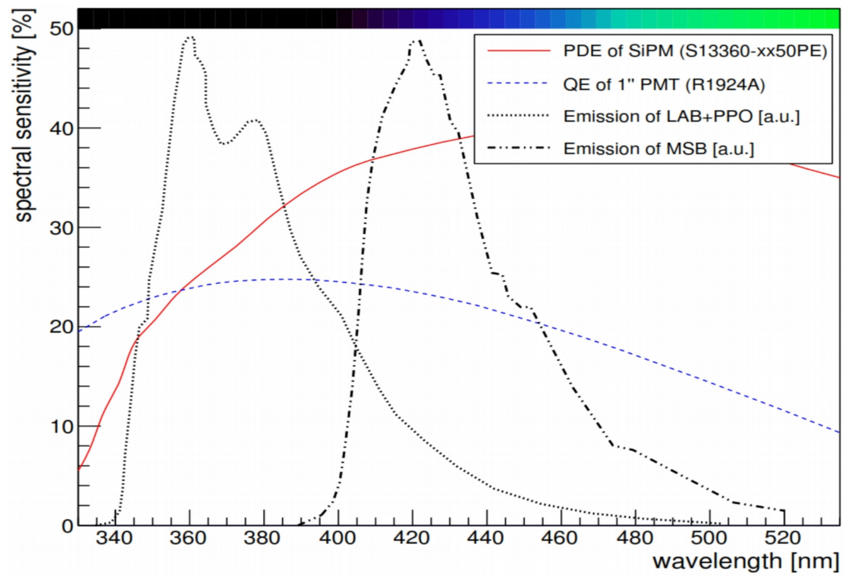




τ_{PPO} ~ 1.6ns, $\tau_{LAB+PPO}$ ~ 5ns

Scintillator emission spectrum:

- **LS:** LAB + 2.0 g/l PPO [350 – 380 nm]
- **WLS paint:** Bis-MSB [420 nm]



Photodetector quantum efficiency (QE):

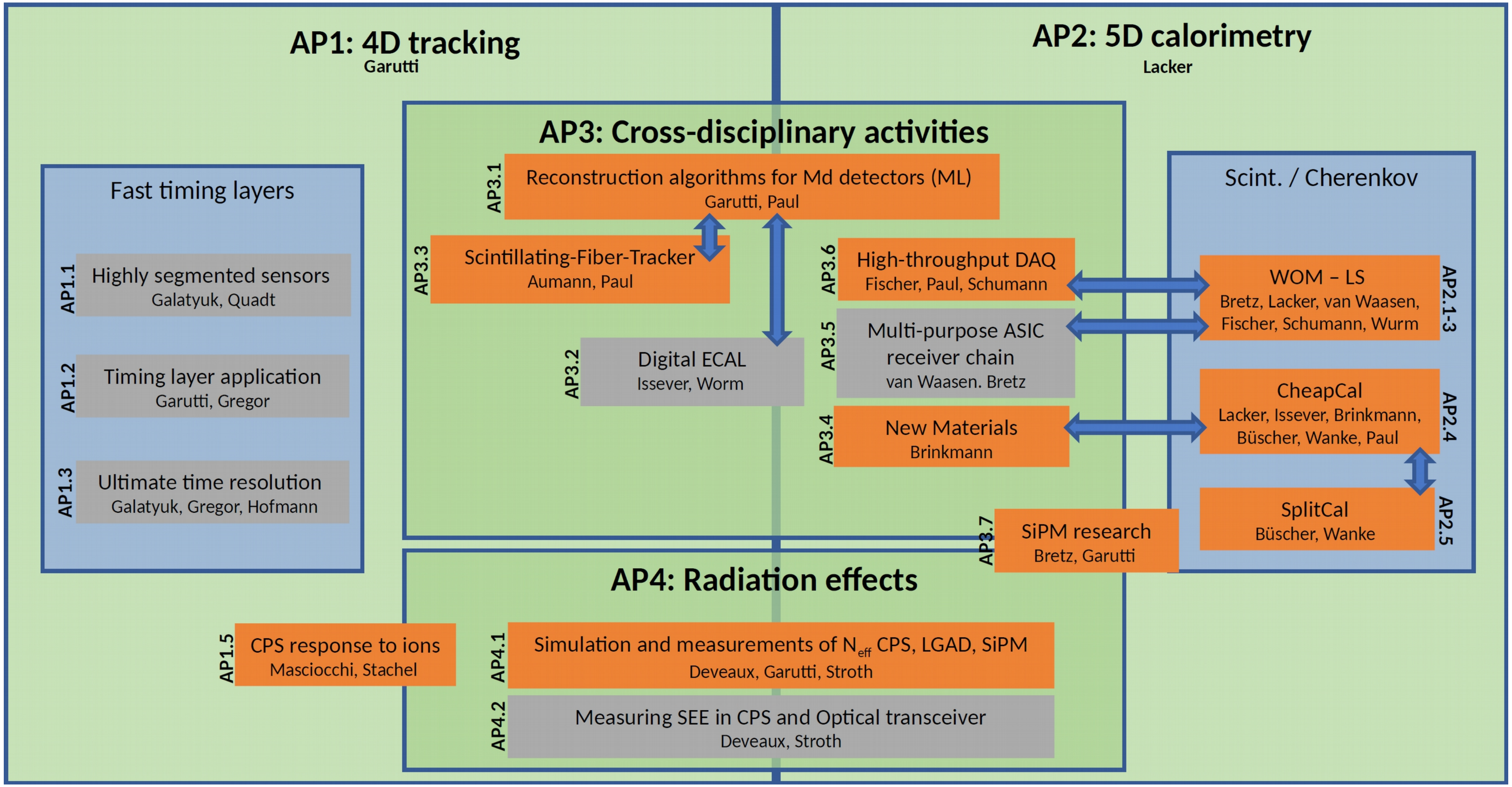
- **PMT:** e.g. R1924A [350 – 420 nm]
- **SiPM:** e.g. S13360-xx50PE [400 – 520 nm]

High-D

High-D Overview

Receive BMBF funds
Receive other funds

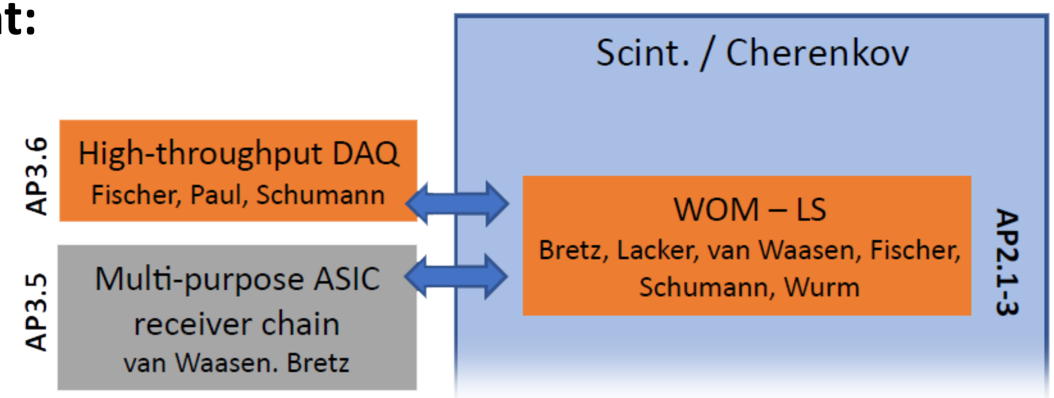
High-granular Multi-dimensional detectors



R&D for a new generation of high-precision detectors with unprecedented spatial, time, and energy resolution

WOM-LS: Objectives & Goals

Particle identification & energy measurement:



- Spatial resolution
- Time resolution
- Light yield
- Cherenkov / scintillation light separation
  - Extreme granularity
  - Innovative geometries

- **Higher level of segmentation:** Novel concepts for detector segmentation, new technologies in readout electronics & data acquisition
- **New reconstruction algorithms:** Taking into account the whole detector system

Application: SHiP LS-SBT @CERN-BDF, future neutrino experiments...

WOM-LS: Work Packages

AP 2.1

Multi-dimensional particle reconstruction using a WOM-based liquid scintillator detector

AP 2.2

Improving the spatial (+time?) resolution of a WOM-based liquid scintillator detector

AP 2.3

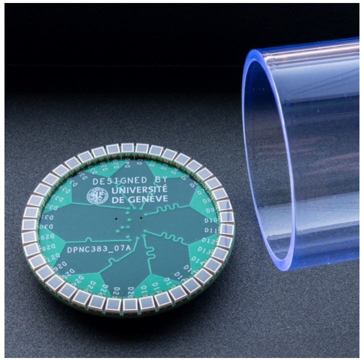
Separation of Cherenkov and scintillation light via wavelength selection

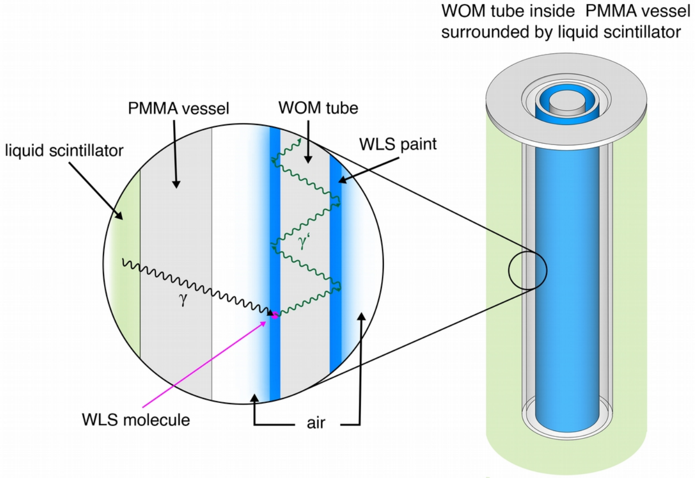
AP 2.1: WOM-LS

Multi-dimensional particle reconstruction using a WOM-based liquid scintillator detector

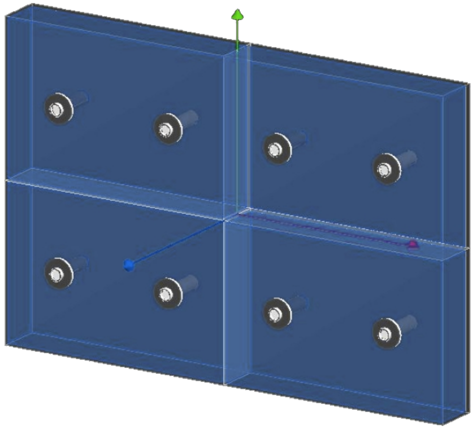
WOM-LS detector with SiPM readout:

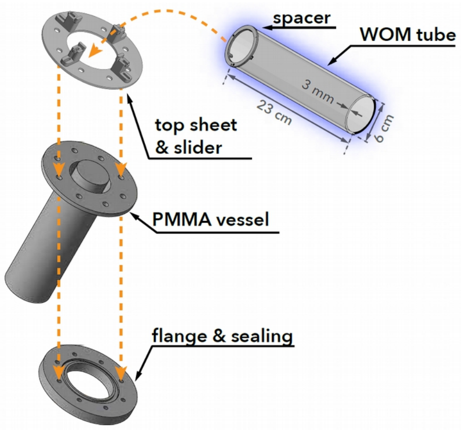
- Liquid Scintillator
- WOM & WLS
- SiPM readout
- DAQ & frontend electronics





- Proof-of-principle: (2019 JINST 14 P03021) -



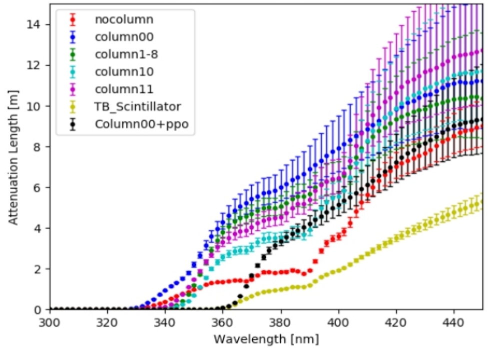


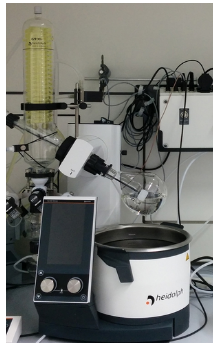
4-cell WOM-LS prototype detector:

- PMMA vessel & WOM / PCB integration
- Support structure & LS filling system
- CERN test beam exposure
- ▸ **Multi-dimensional particle reconstruction**

AP 2.1: WOM-LS

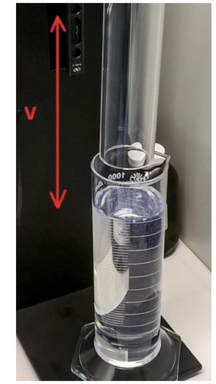
LS optimisation:

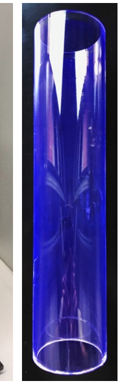




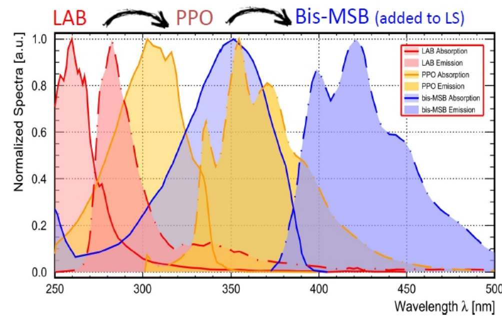
- **Increase transparency:**
  - ▸ Al_2O_3 purification / vacuum distillation
  - ▸ Dilute solvent (Heptane) ?
- **Increase light yield:**
  - ▸ Increase PPO concentration
  - ▸ Different fluor (p-Terphenyl, POPOP...) ?
- **Shift emission spectrum:**
  - ▸ Add 2ry WLS (Bis-MSB, POPOP...) ?

WLS paint R&D:

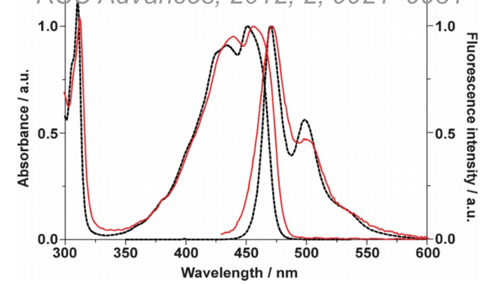




- **Dip-coating procedure:**
  - ▸ Temperature, speed
  - ▸ Inside / outside of WOM
- **Adjust fluor:** BPEA ?
  - ▸ 'Cyan WOMs': 470 - 500 nm emission
  - ▸ Use green-sensitive SiPMs



RSC Advances, 2012, 2, 9921–9931



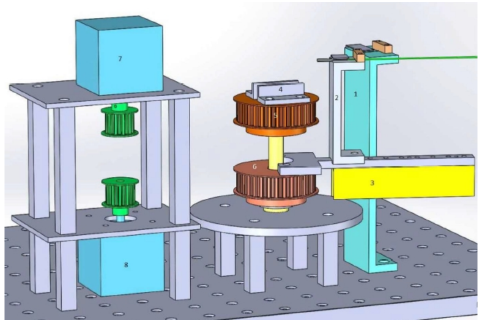
Jakob Schmidt:
Improving the light absorption probability in WOMs

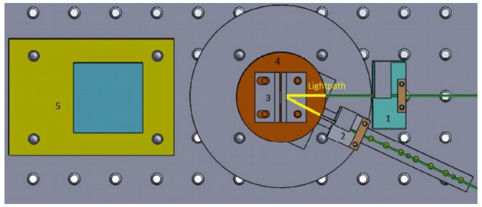
AP 2.1: WOM-LS

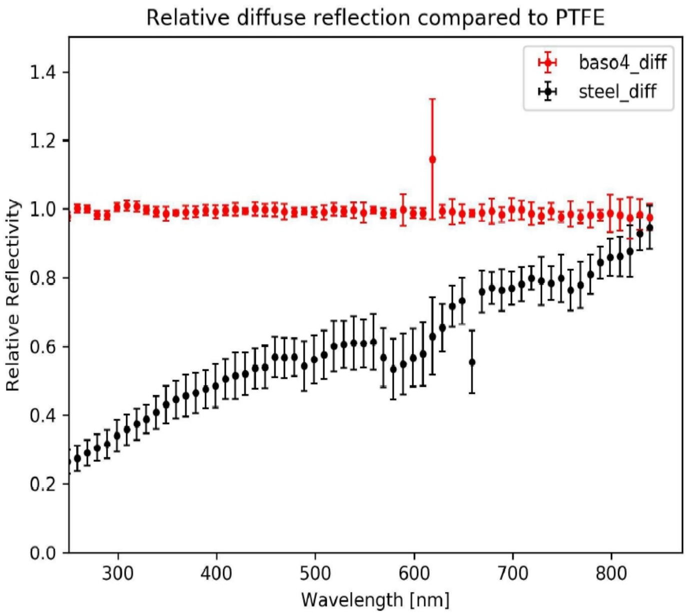
LS cell inner surface: (un)polished steel vs. reflective coating

- **Highly reflective walls:**
  - **Light yield increase up to x5** (MC photo transport simulations)

- **Reflective Coating:**
  - **Specular vs. diffuse** reflection
  - Relative **reflectivity**
  - **Material compatibility** & **long-term stability** (paint, LS)
  - Application procedure



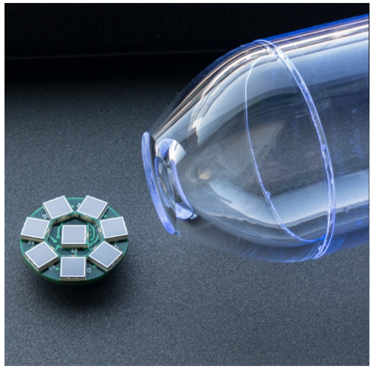


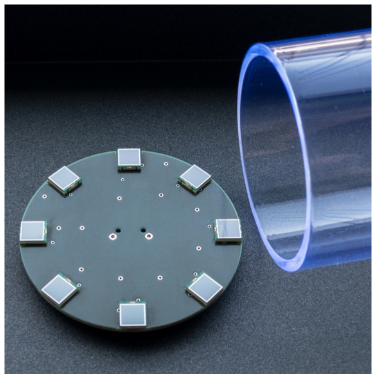


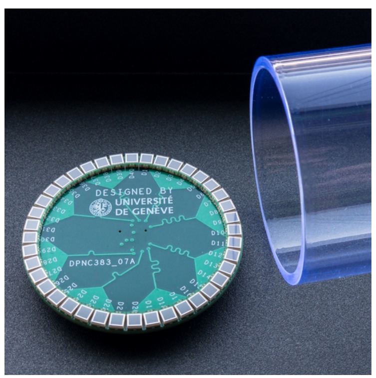
- **Most promising candidate:** $BaSO_4$

Patrick Deucher:* *Reflectivity Coating of a WOM-LS prototype detector

AP 2.1: WOM-LS

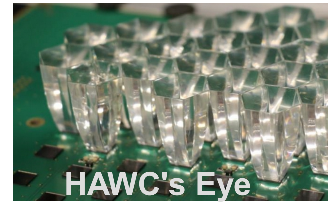


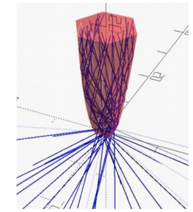




Possible light guides:

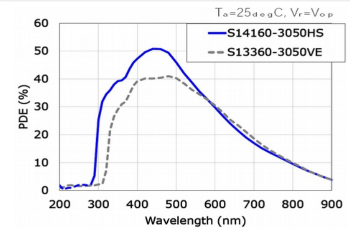
- Injection molding / 3D printing

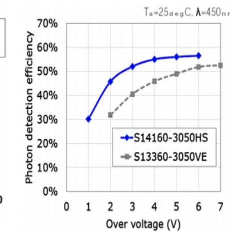




New SiPMs:

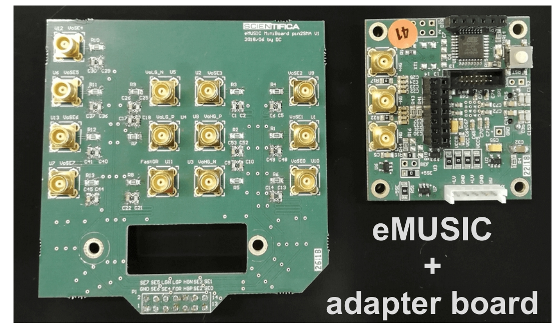
- **Hamamatsu S14160-3050:**
  Higher PDE, lower OV

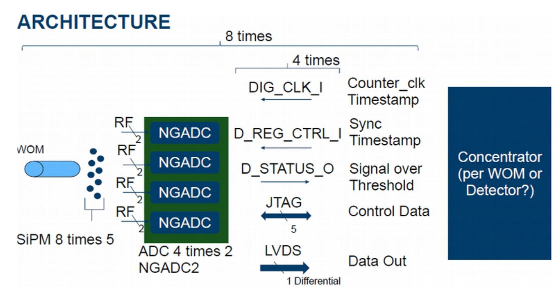




Readout & DAQ:

- **Improved PCB:** 40 SiPM (grouped to 8 channels)
- **eMUSIC (ampl.) + WaveCatcher (digit.):**
  Small detector prototype cells
- **CITIROC / TRIROC-based DAQ:**
  Upcoming 4-cell prototype
- ▸ **Custom ASIC front end electronics (AP 3.5):**
  Integrated ADC, feature extr., signal transm., HV

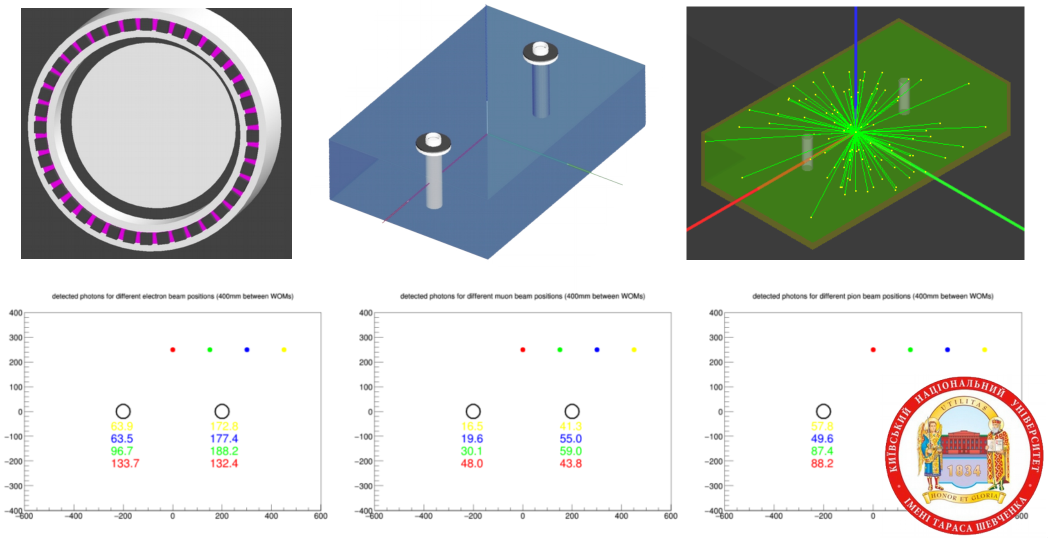


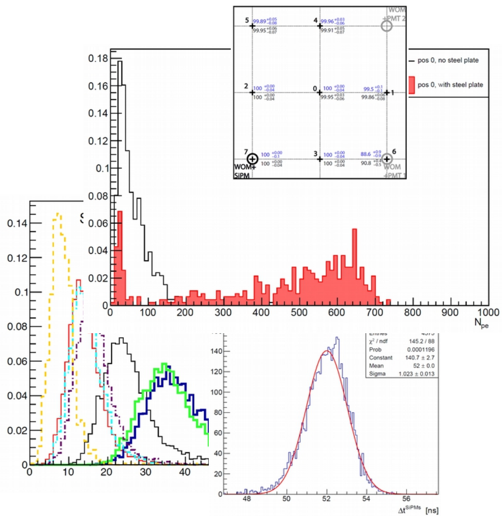


AP 2.1: WOM-LS

MC simulation (GEANT4):

- **Photon transport & detector response:**
    - ▸ LS composition & layer thickness
    - ▸ Cell dimensions & wall reflectivity
    - ▸ WOM length & position
- **DAQ & signal processing**





Multi-dimensional event reconstruction:

- Validate simulation with test beam and laboratory measurements

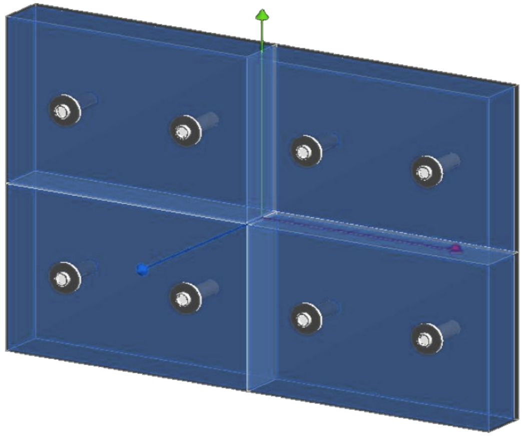
▸ Extend reconstruction scheme to **multi-cell WOM-LS detectors**, providing: **Particle ID, energy, timing, point of impact, primary (photon) direction**

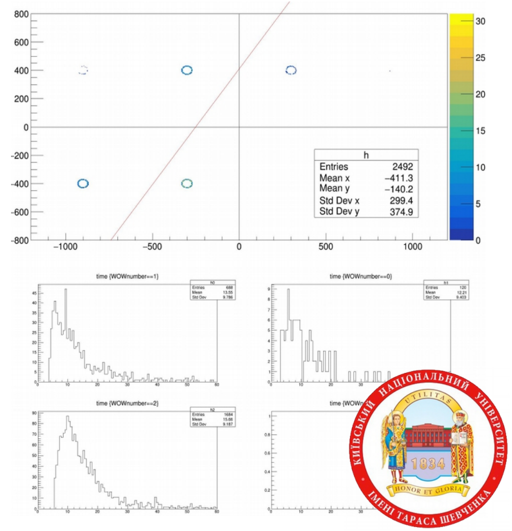
▸ Based on: **Spatial & time** information of **all WOMs** (same / adj. cells), **absolute light yield** and **light yield distribution** between **WOMs** or within the **SiPM array**

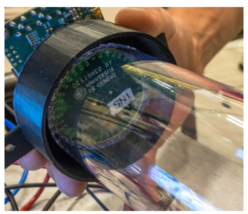
AP 2.1: WOM-LS

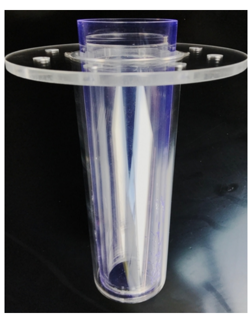
4-cell WOM-LS prototype detector: CERN test beam (2023 / 2024)

- **Multi-dimensional event reconstruction:**
  - Light yield & energy deposition
  - Spatial information & incident angle
  - Time resolution $\mathcal{O}$(1 ns)
  - **Particle identification:** e/γ, μ, π



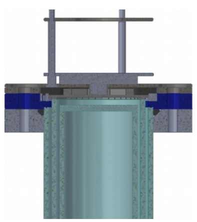


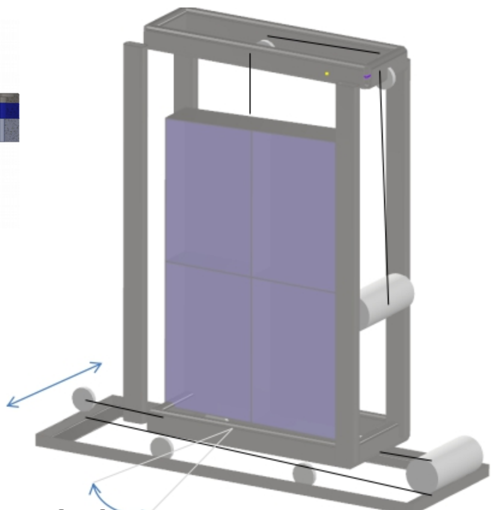




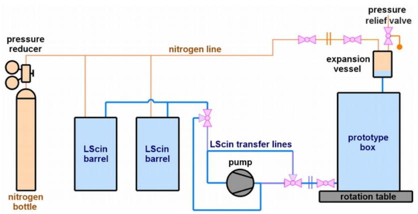
Mechanical integration:

- PMMA vessel design & WOM / PCB integration
- Support structure: Enabling movement incl. rotation
- LS handling & filling system



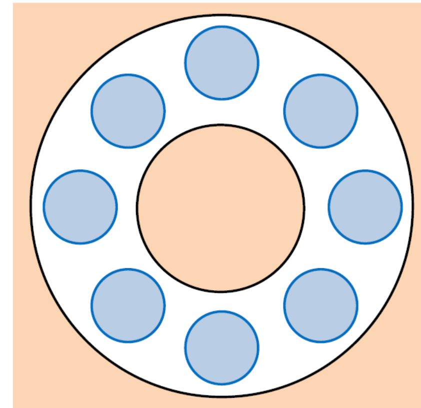


Fairhurst Lyons: First multi-cell WOM-LS prototype



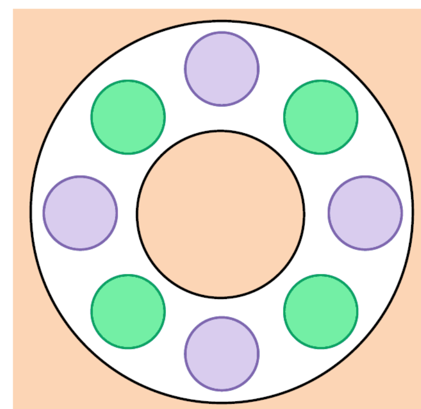
AP 2.2 + AP 2.3

AP2.2: ***Improving the spatial (+time?) resolution of a WOM-based liquid scintillator detector***



- **Increase detector granularity: 8 WOM rods** in circular array
  - **Individual readout:** 6x6 mm^2 SiPM
  - ▸ **Improved directional information:** Resolving left-right ambiguities
  - ▸ Improved time resolution (?)
- ▸ Installation in **small 1-cell LS prototypes**, measurement **of cosmic μ**

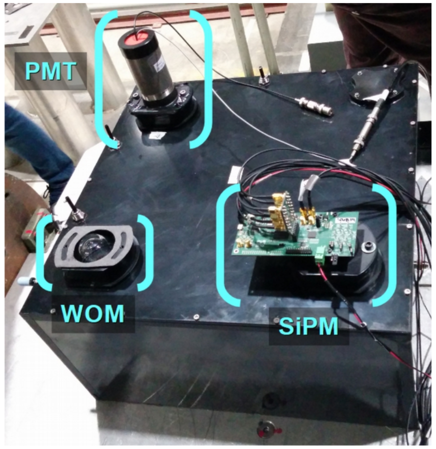
AP2.3: ***Separation of Cherenkov and scintillation light via wavelength selection***



- Employing the WOM rod array of 2.2:
  - **Alternating rod coating with different WLS** (e.g. BPEA)
  - ▸ Sensitivity to **Cherenkov** light **OR scintillation** light
  - ▸ **Adjustment of LS fluors necessary:** Blue → green
- ▸ Installation in **small 1-cell LS prototypes**, measurement **of cosmic μ**

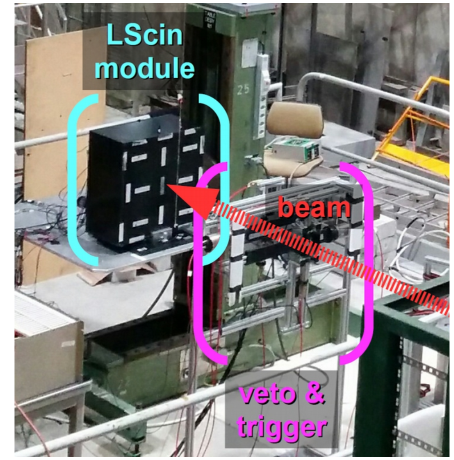
Detector Prototypes & Outlook

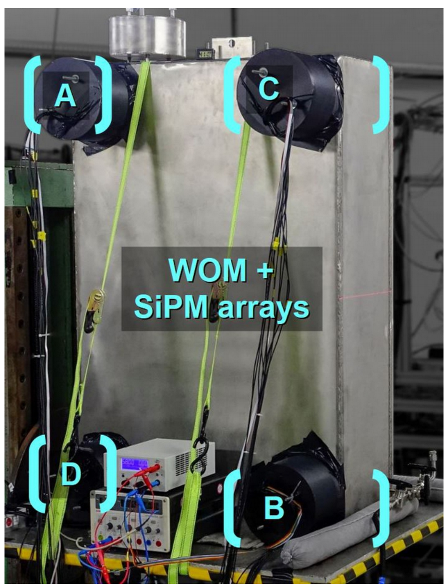
Previous Detector Prototypes & Measurements



Small detector cell (60l, plastic, Tyvek lining):

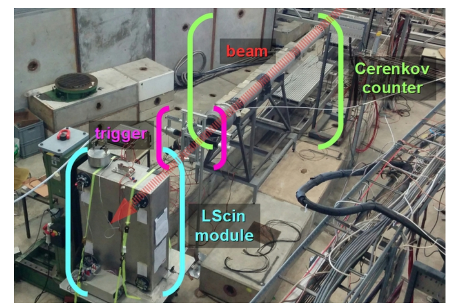
- LAB + PPO (1.5 g/l)
- 3 WOMs with light guide (PMT / SiPM readout)
- **2017 CERN SPS:**
  e^- (20 GeV) / μ^+ (150 GeV) / π^+ (150 GeV)

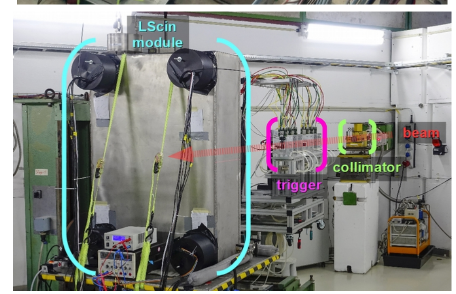




Full-size detector cell (300l, stainless steel):

- LAB + PPO (2.0 g/l)
- 4 WOMs (SiPM readout)
- **2018 CERN PS:**
  e^+ (6 GeV) / μ^+ (3 GeV) / π^+ (1 – 6 GeV)
- **2019 DESY:** e^- (1.4 / 2.6 / 5.2 GeV)

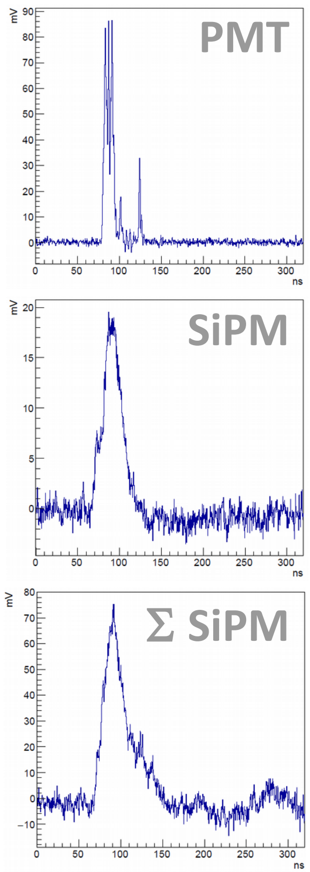




Previous Detector Prototypes & Measurements

Proof-of-principle measurements with a liquid-scintillator detector using wavelength-shifting optical modules at the CERN SPS **(2019 JINST 14 P03021)**

Typical waveforms:



Number of detected PE:

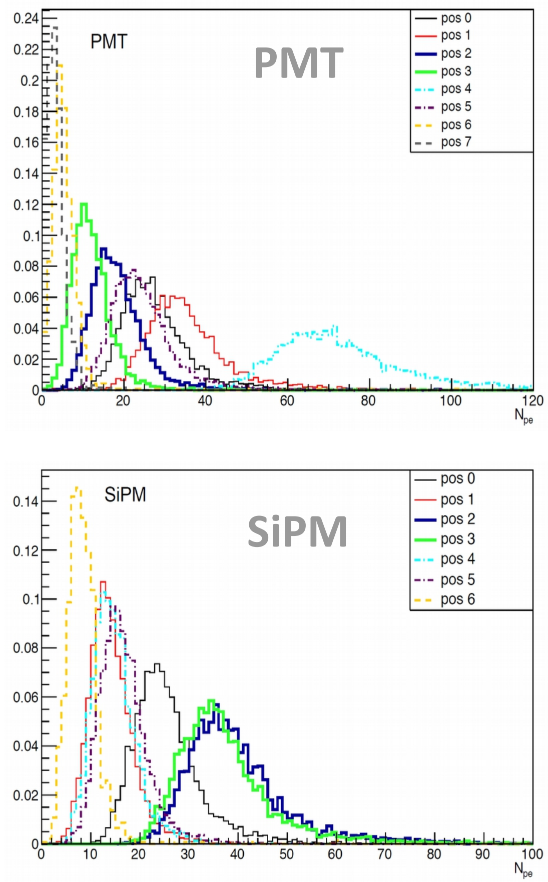
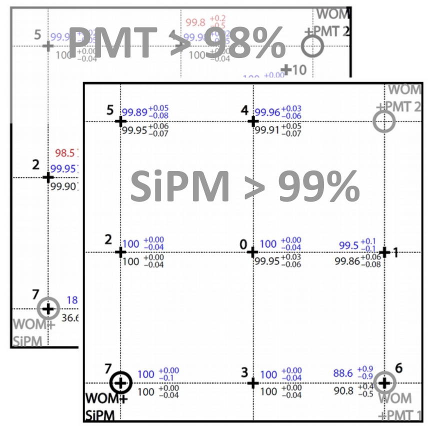
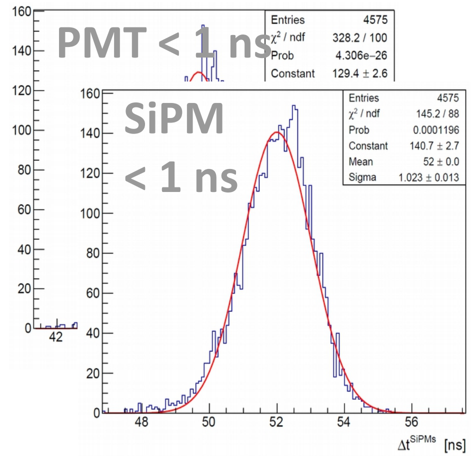


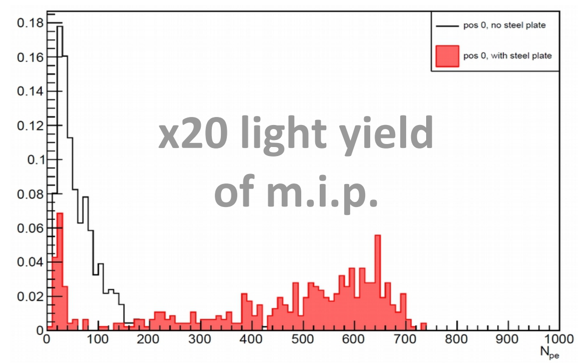
Photo detection efficiency:



Time resolution:



Response to em showers:



Outlook: Very Active R&D

Research topics:

- **Material compatibility & optimisation:** Base materials, LS, WLS, cell coating
- **Detector geometry:** Cell dimensions, WOM shape, sensor distribution, light guides
- **Readout & DAQ:** SiPM, PCB, signal shape & digitisation, FE & concentrator electronics
- **Prototype detectors:** Performance & reconstruction, calibration, interfaces, support structures
- **MC simulation:** Light transport, detector response, readout

Upcoming detector prototypes & milestones:

- **Small 1-cell prototypes (AP 2.2, AP 2.3):** Cosmics & DESY test beam (2021 / 2022)
  - Different cell inner surface / coating → *Patrick Deucher*
  - New WOM geometries & WLS coatings → *Jakob Schmidt*
- **Full-size 4-cell prototype (AP 2.1):** CERN test beam (2023 / 2024)
  - **First multi-cell WOM-LS detector** enabling **high-level particle reconstruction** → *Fairhurst Lyons*

High-D Consortium Meeting

2022-02-21

Bundesministerium
für Bildung
und Forschung

Auf gute Zusammenarbeit!

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