Ottimizzazione e misura della efficienza (PDE) della X-Arapuca per HD & VD.

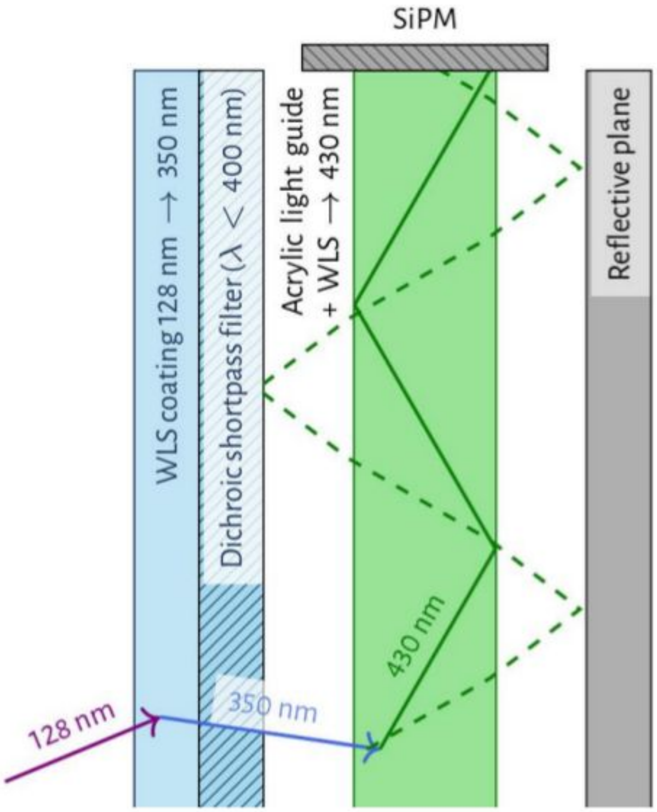
C. Brizzolari, C.M. Cattadori, L.Meazza & DUNE MiB group
F. Bruni, F. Meinardi (ScMat UniMIB)
N. Canci, F. Di Capua & DUNE Napoli group

Valencia DUNE
CIEMAT DUNE

DUNE-IT Meeting 2024
30 Ottobre 2024 - Ferrara

Photon detection system building block: X-ARAPUCA (XA)

VUV Light detector equipped with:
- a glass entrance window, pTP(F), Dichroic(B)
- a wavelength shifting light guide (WLS-LG) coupled to SiPMs.
- a reflective back plane (or a second entrance window)



PDS LY requirement to boost the trigger (p-decay) and energy resolution (SN ν) capabilities of the DUNE PDS::

- LY_{min} > 0.5 PE/MeV
- LY_{ave} > 20 PE/MeV
- **PDE of XA: 2%-3%**
- S/N > 4
- DCR/ch < 1 kHz

This talk: summary and conclusions of the XA optimization process (4-yrs long) aiming to maximize its PDE.

HD-XA PDE performances

- HD-XA PDE assessed in Milano-Bicocca and CIEMAT
- cross-talk corrected

https://doi.org/10.1140/epjc/s10052-024-13393-2

		FBK + EJ	FBK + G2P	HPK + EJ	HPK + G2P
CIEMAT	ε_{MAD}	1.34 ± 0.24	-	1.59 ± 0.29	2.13 ± 0.38
CIEMAT	ε_{MiB}	1.61 ± 0.12	-	1.86 ± 0.15	2.50 ± 0.21
MiB	ε_{MiB}	1.80 ± 0.15	2.22 ± 0.19	-	2.40 ± 0.20

+30% with G2P

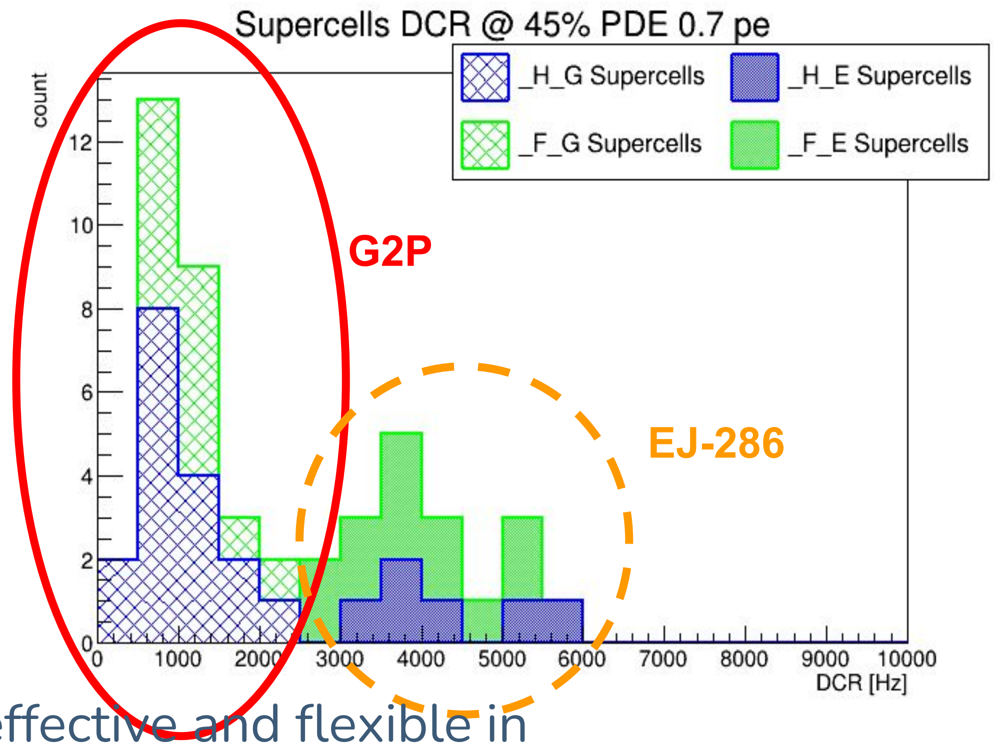
ε_{MAD}: alpha wfm amplitude measured by XA vs calibrated VUV4-SiPMs
ε_{MiB}: from known LY, alpha spectra amplitude and LAr purity correction
Same SIPMs (exchanged between CIEMAT & MiB) but different WLS bars

PDE 50% for HPK and 45% for FBK (compatible gain + these PDE correspond to the operating voltages of the two SiPMs in ProtoDUNE/DUNE)

HD-XA S/N and DCR performances

- All 160 HD-XA installed in ProtoDUNE-HD at CERN were tested at CIEMAT & MiB
- S/N and DCR measurements
- G2P WLS bar outperformed the Eljien product (EJ286) both w.r.t. the PDE and the DCR (PVT is a scintillator, PMMA is not)
- Our self-developed and produced PMMA based WLS_LG allowes to match the 1 kHz requirement for the PDS.

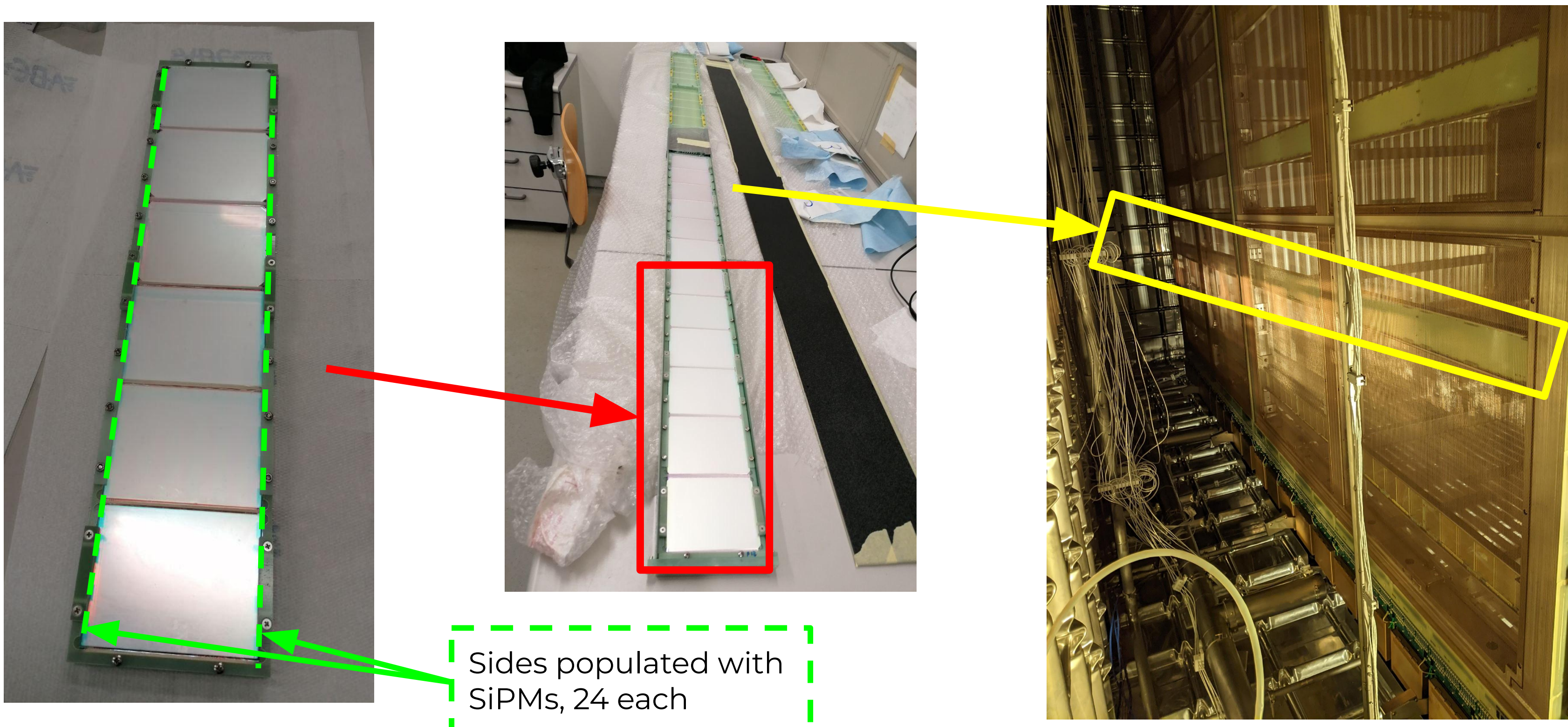
Subset of HD-XA for ProtoDUNE tested @ MiB in shallow lab, DCR measurement



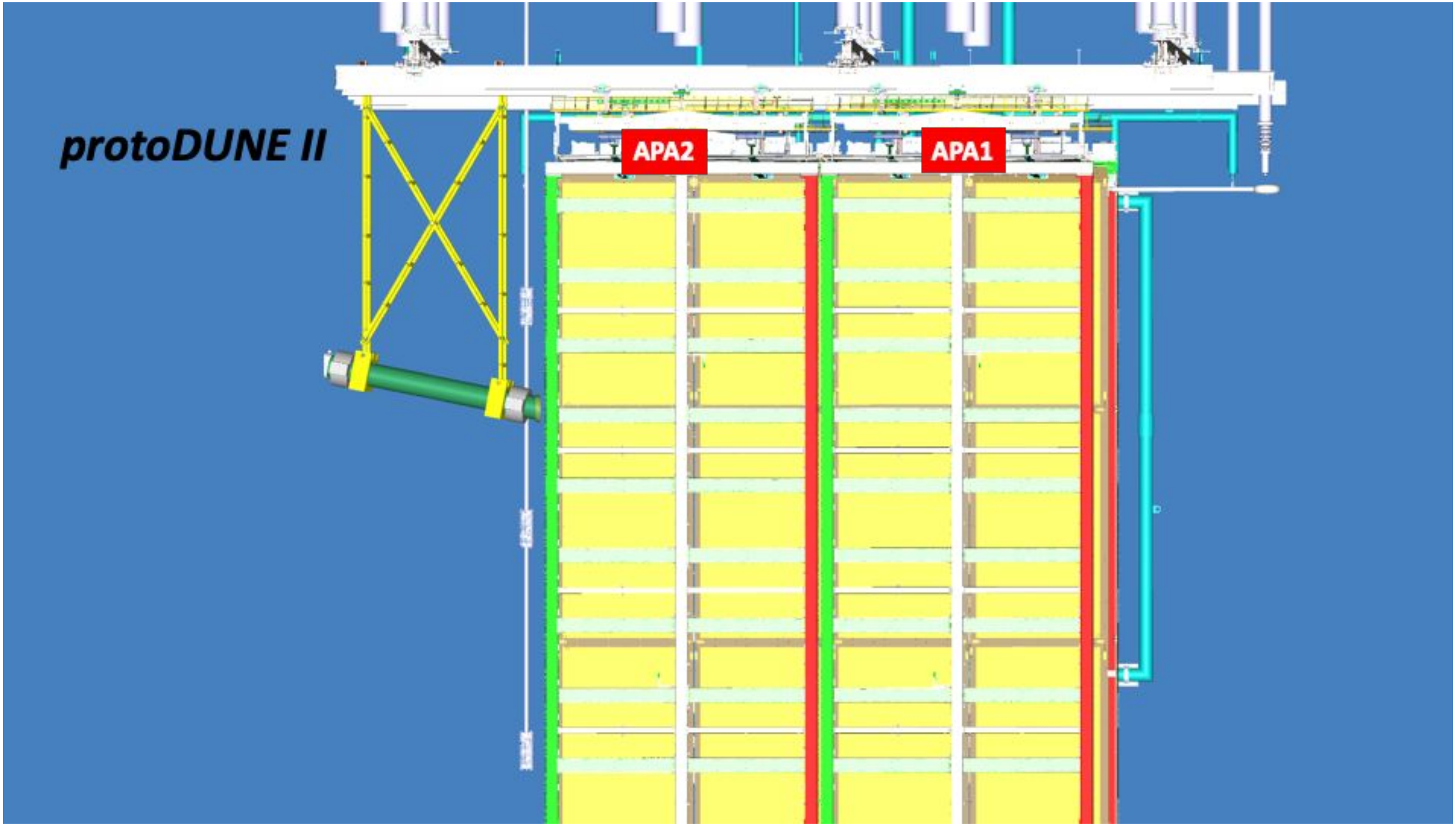
- The Industrial Partner is Cost-effective and flexible in adjusting size,shapes, dye concentration etc.

The Horizontal Drift X-Arapuca (HD-XA)

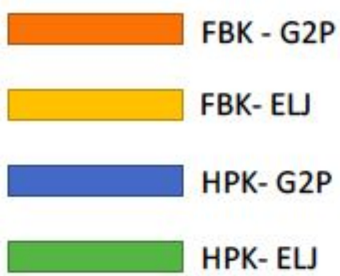
- X-ARAPUCA design: **48 SiPMs** passively ganged in one readout channel, active window 46.2 x 10 cm^2)
- **Si/WLS-LG surface = 3.9%**
- SiPMs are integral with the frame (not with the WLS-LG) hence a gap opens at LAr T



ProtoDUNE-HD at CERN



ProtoDUNE-HD: PDS configurations on APA



The four configurations are equally represented in pDUNE-HD NP04 and balanced in number and position w.r.t. the beam, for a fair comparison

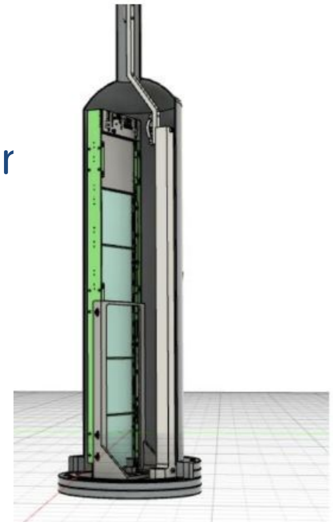
What is the distribution of the four classes of XA-PDE?

All configurations w/ OPTO-Campinas (Brazil) dichroic filters, substrate B270, size 7.7 x 10 cm^2.

Ganging of 48 SiPM with S/N>4 for both types.

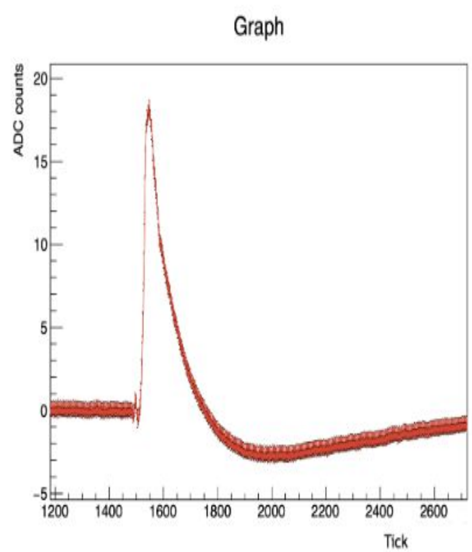
The MiB facility for absolute PDE assessment

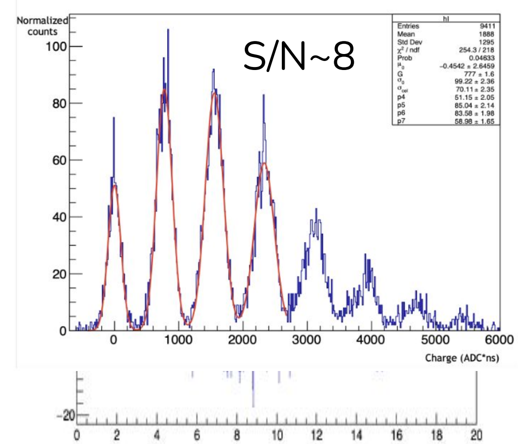
- XA assemblato con le componenti da testare
- Camera in acciaio inox ideata per i test a vuoto e in LA (d = 150 mm, h = 550 mm, 9.7 l volume)
- “Bagno Maria” LAr 70 l
- ^{241}Am scorre lungo l’asse longitudinale del XA
- Primo stadio di amplificazione a freddo



PRESA DATI in LAr

- Determinazione di Gain e S/N (LED)
- Alpha: misura PDE media del dispositivo
- Muoni: correzione LAr purity

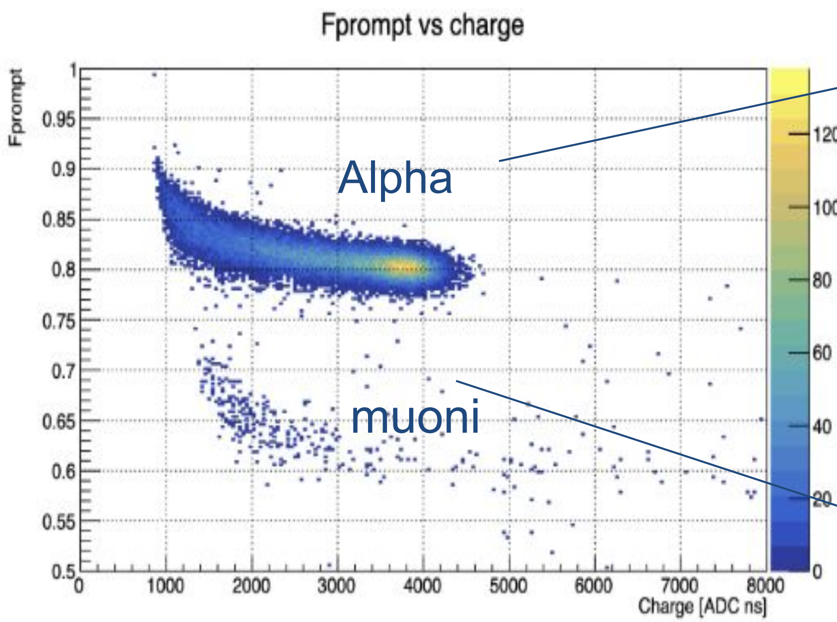




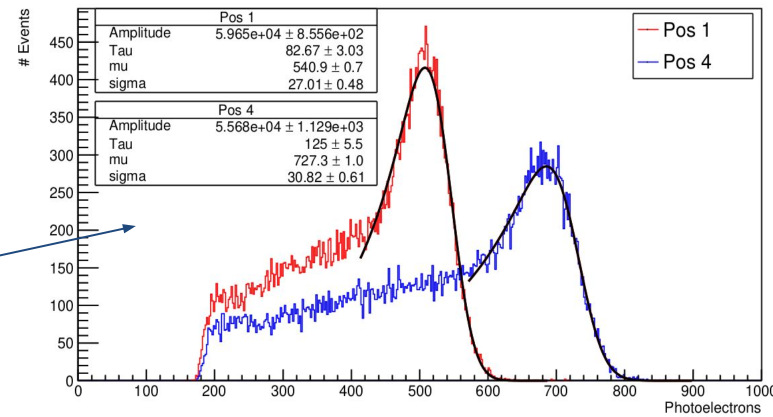
Muon and alphas data sets

$$\epsilon = \frac{4\pi \cdot \alpha\ \mathrm{peak(ADC)}}{\mathrm{s.ph.e.(ADC)} \cdot f_{int} \cdot \mathrm{LY_{LAr}} \cdot \mathrm{En}_{\alpha} \cdot \mathrm{q}_{\alpha} \cdot \Omega}$$

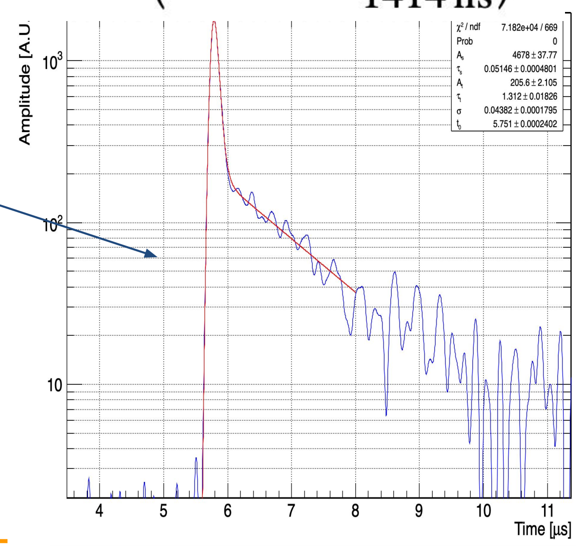
The XA PDE is measured by the alpha spectra amplitude corrected by the actual LAr purity



F_{prompt} = prompt charge/ total charge

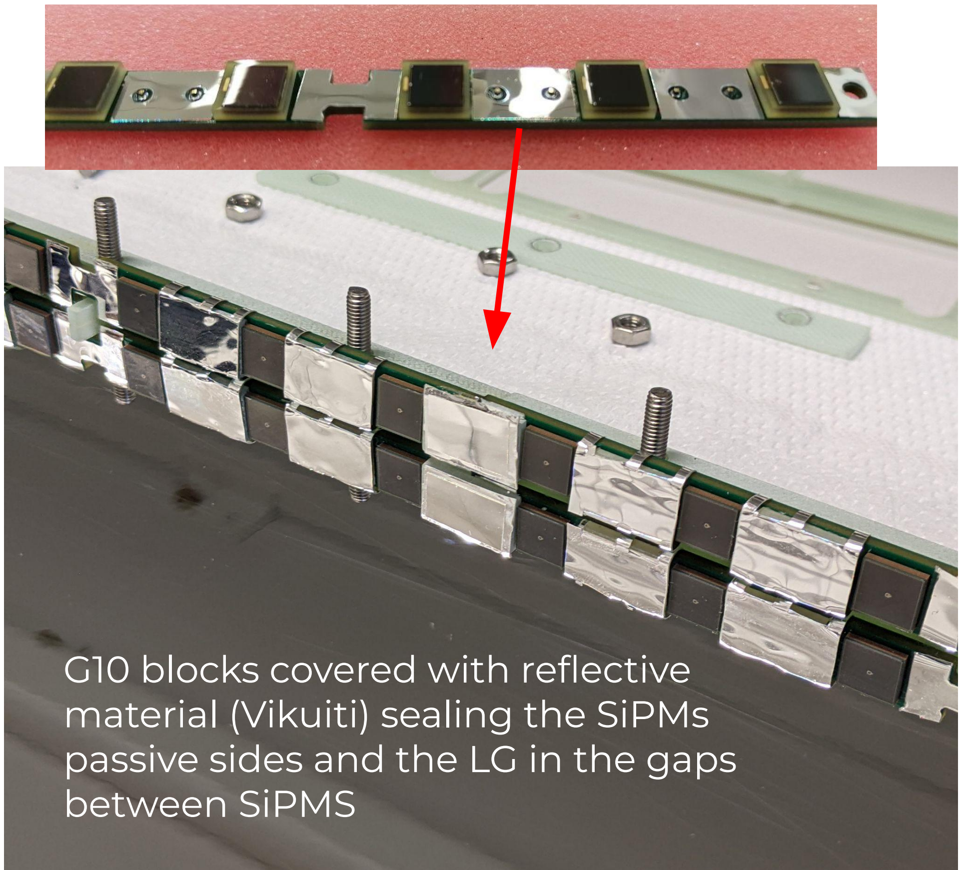


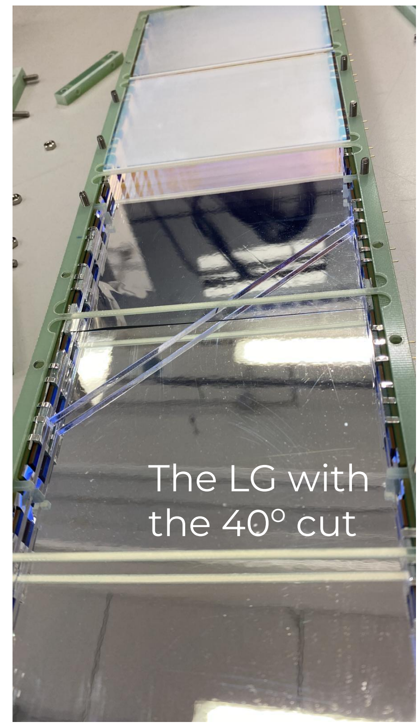
$$P_{\mathrm{LAr}} = \left(A_S + A_T \times \frac{\tau_T}{1414\,\mathrm{ns}}\right)^{-1}$$

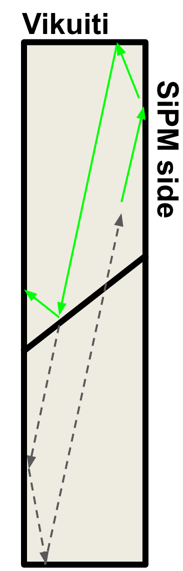


HD-XA PDE enhancement

Simulation-driven optimization in Milano-Bicocca in 2023-2024 with increased WLS light sealing and different light guide geometry (40° cut in the middle).



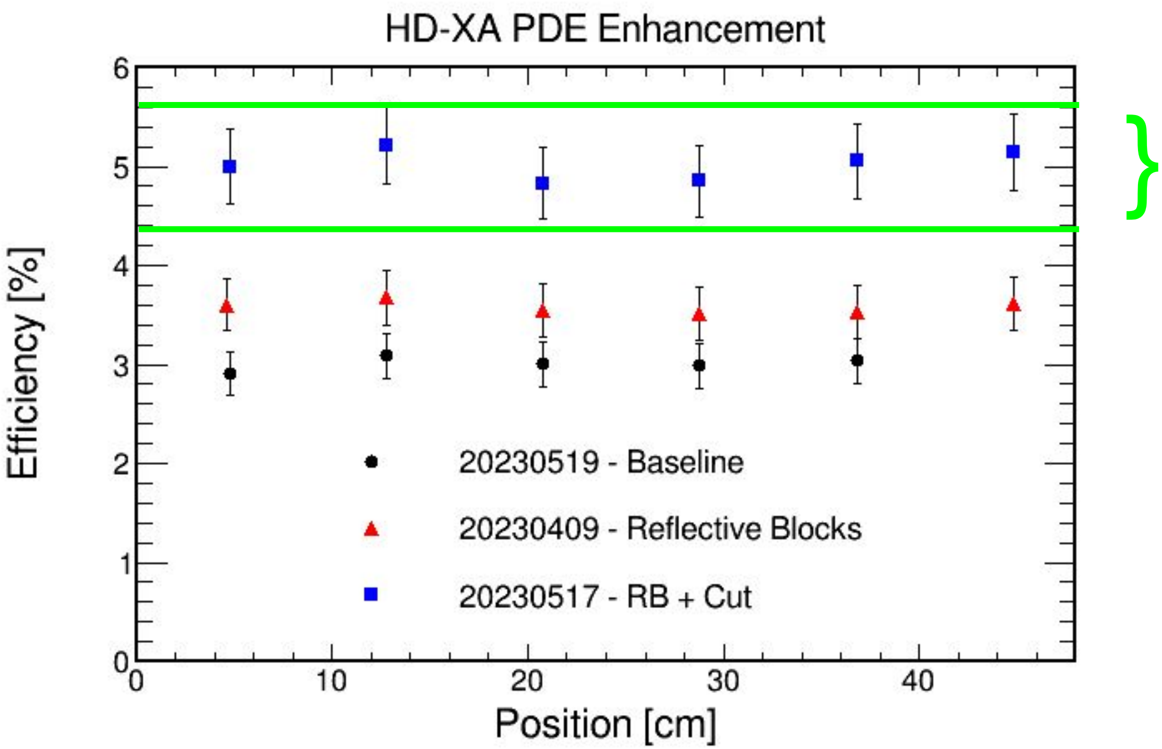




Reflective material placed directly on the short sides and on the diagonal cut of the LG

HD-XA PDE enhancement

HD-XA PDE improvement with reflective blocks: ~+20% wrt baseline (highly depends on the tolerances)
HD-XA PDE improvement with reflective blocks and 40° cut: +45-67% wrt baseline



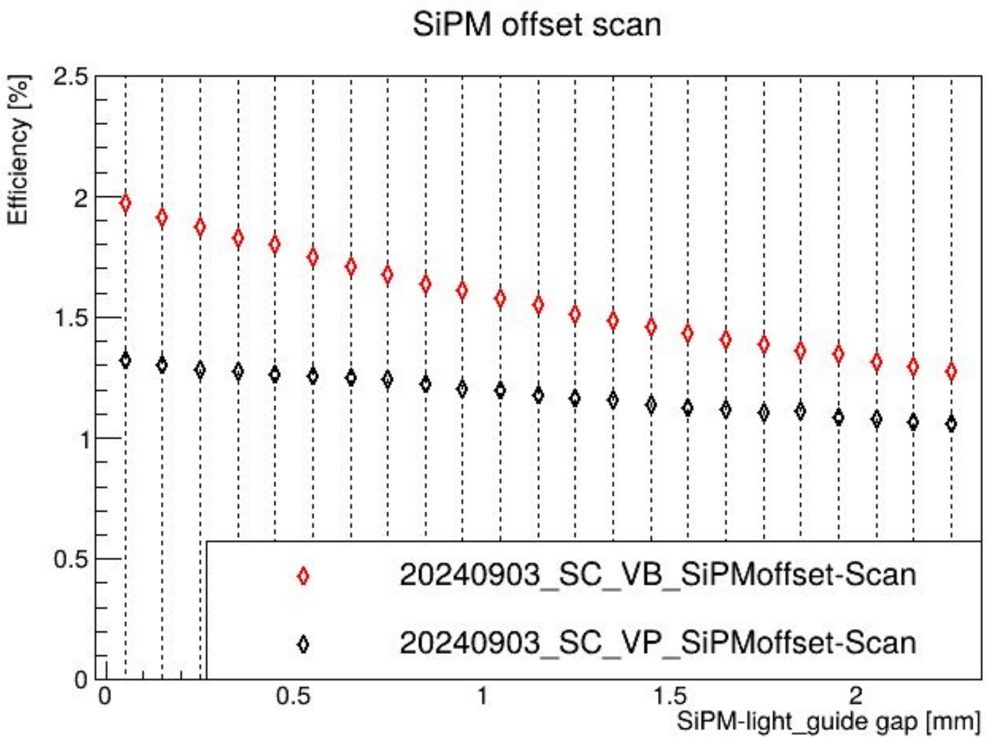
Improvement range given by variability of the assembly and mechanical tolerances.

Efficiency values not cross-talk corrected

Option is currently being evaluated for the PDS of FD1: it brings in some extra-complexity of the assembly

HD-XA PDE enhancement: Simulations

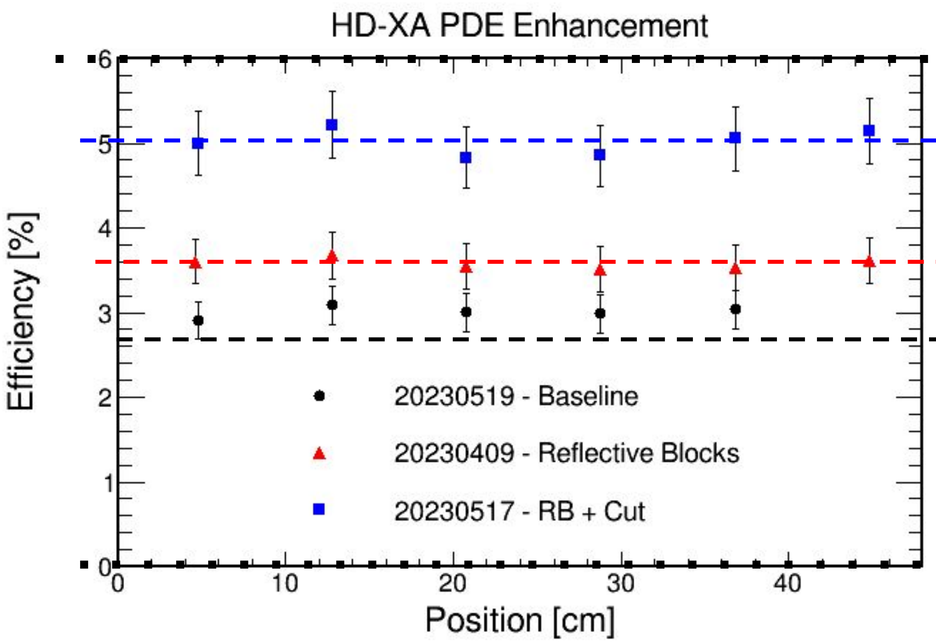
L'accoppiamento ottico tra SiPM e guida di luce dipende principalmente da:
1. il gap tra i sensori e la guida di luce e
2. l'intrappolamento dei fotoni nella guida di luce lungo la superficie perimetrale non coperta dai SiPM

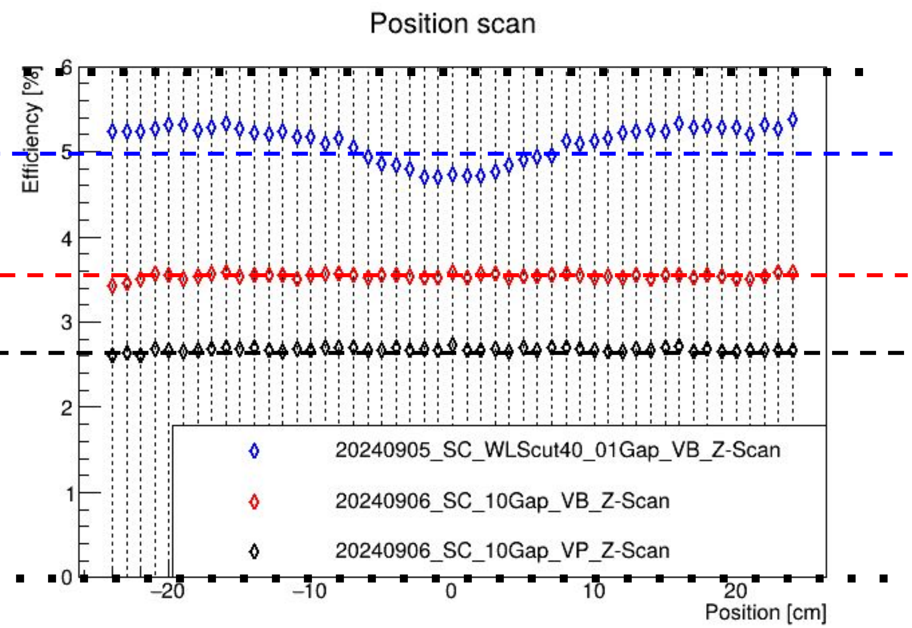


- In rosso la configurazione che permette un miglior intrappolamento dei fotoni nella guida di luce
- in entrambi i casi, al diminuire della distanza tra sipm e guida di luce si osserva un aumento di efficienza
- quando il riflettore e' complanare alla superficie dei SiPM l'incremento è maggiore

HD-XA PDE enhancement: Simulations

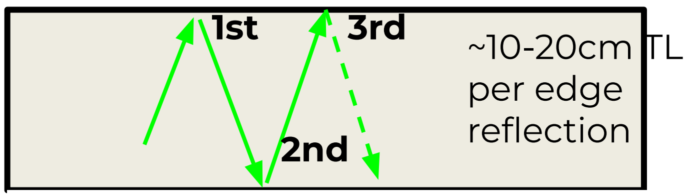
- I risultati della simulazioni sono riscalati in modo tale che la simulazione della configurazione con lastra in due parti corrisponda alla misura.
- La misura con lastra singola di baseline è leggermente superiore al risultato della simulazione in quanto in essa non sono presenti dicroici.
- Le misure suggeriscono che per la WLS-LG in due parti la presenza dei dicroici non influisce sulla PDE, mentre per la configurazione di baseline PDE +10-15%



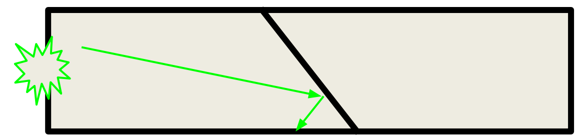


HD-XA PDE enhancement: Optical Path

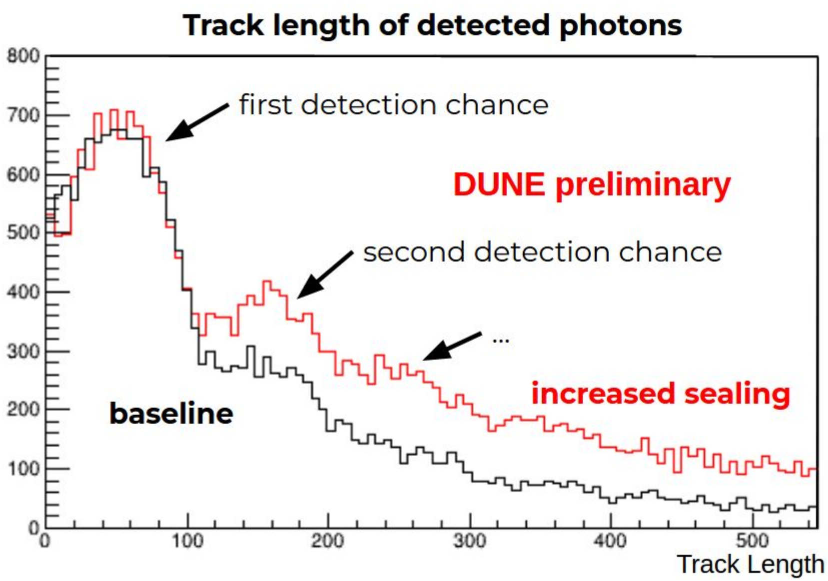
Simulation. Plot of the optical path of detected photons, “track length” between photon generation (lg WLS process 350->440nm) and detection in a SiPM peaks correspond to photons reaching an edge instrumented with SiPM and being detected.

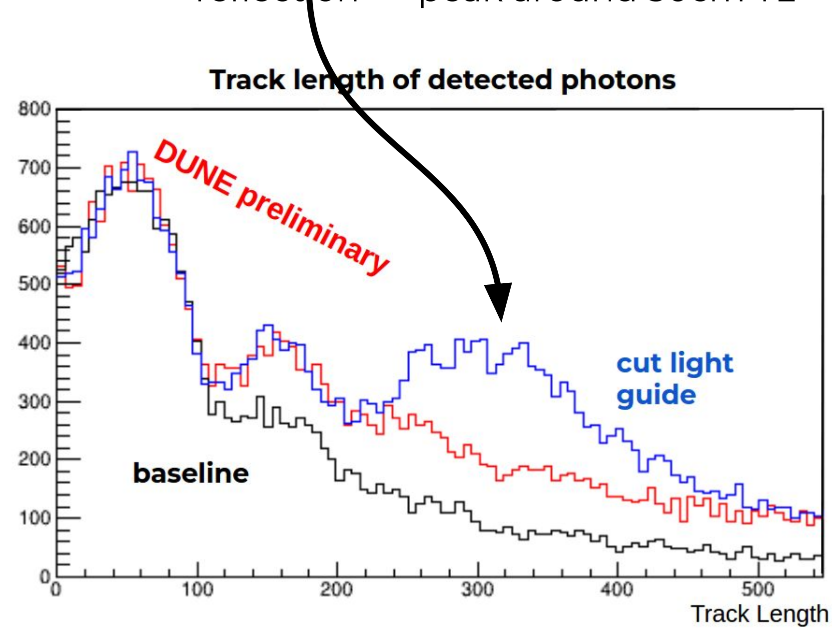


source at the edge of the SC in this test



~25cm from the short side + ~5cm from the reflection => peak around 30cm TL



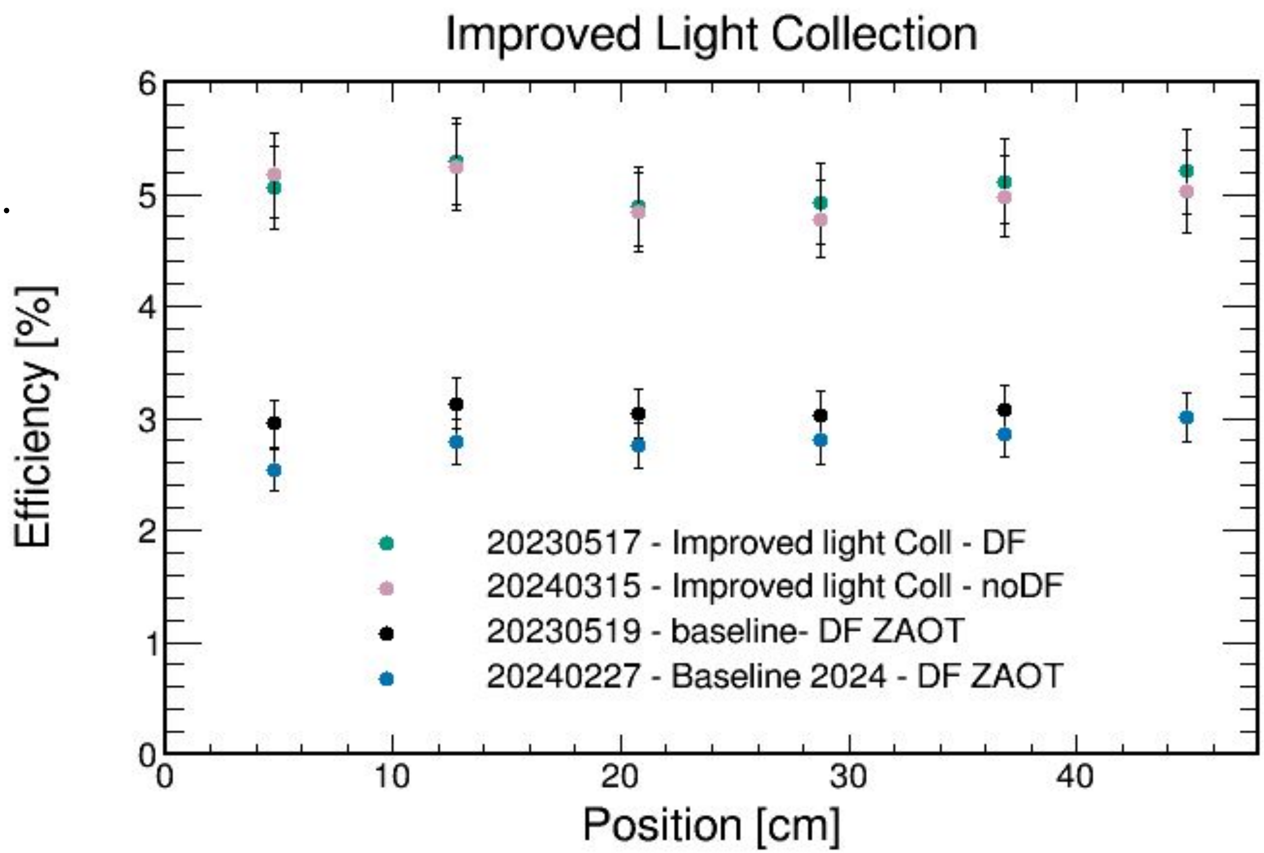


FD1-XA - Improved light collection w/w.o. DF

Lightguide (LG) from the pDUNE-HD batch.

Improved Light Collection

- LG with 40° cut
- LG & SiPMs sides optically sealed by Vikuiti lined blocks



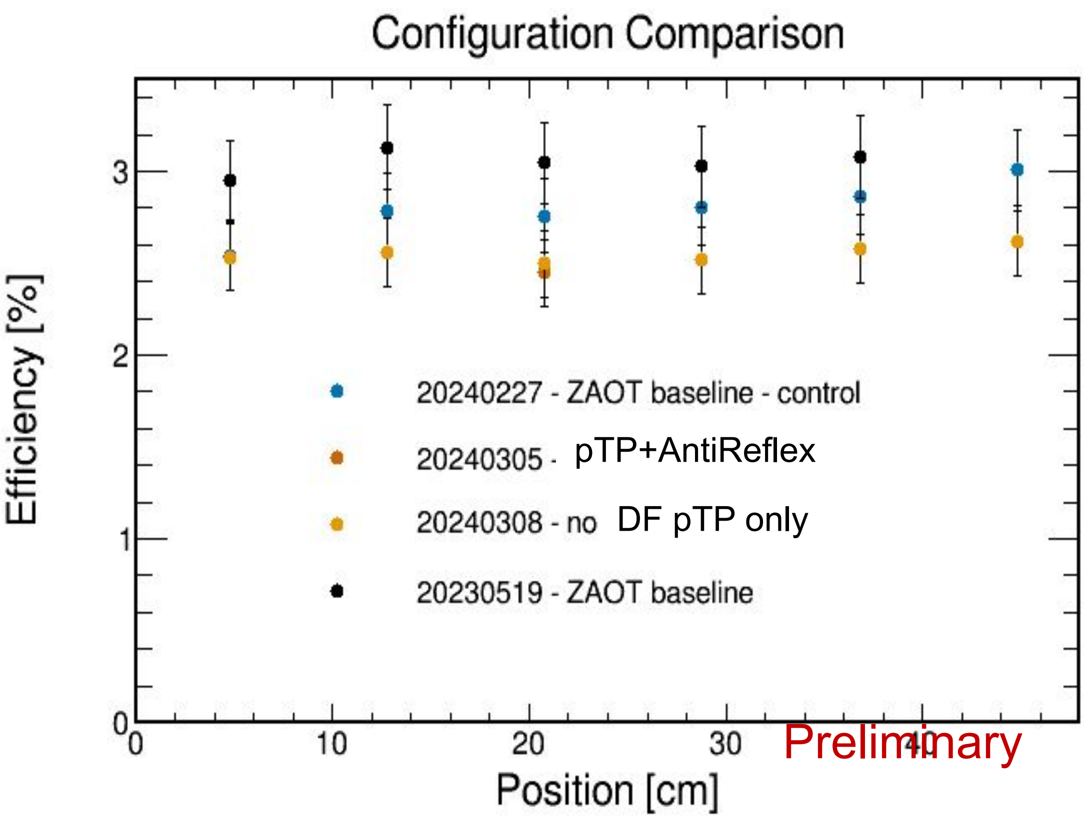
DF: minor improvement of the PDE most for improved Light Collection and a <10% for the BL configurations (with ZAOT DF instead of OPTO)

FD1-XA - Impact of Dichroic Filters on BL design

Three sets sof ZAOT entrance windows

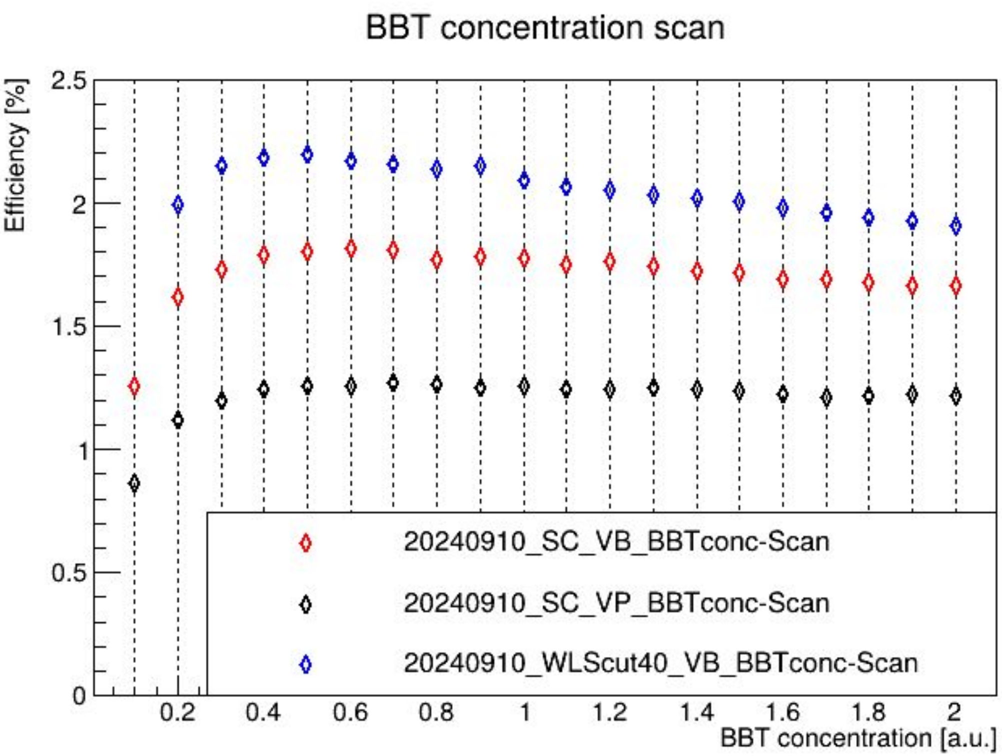
1. pTP+ DF (adopted for FD2 M0 & M1)
2. pTP +no DF (but anti reflective (AR) coating)
3. pTP only (no AR or DF coating)

DFs provide a ~10% increase in PDE with respect to the blank substrate for the Bl design w. ZAOT DF



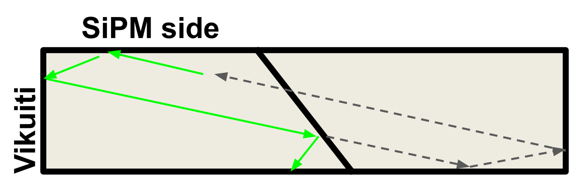
The WLS-LG chromophore concentration

- La concentrazione di cromoforo all'interno della guida di luce non è un fattore critico per FD1-XA.
- Le dimensioni contenute del modulo O(10cm) rendono l'auto-assorbimento della luce *downshiftata* un fattore minore.
- La lunghezza media di assorbimento è infatti nell'ordine dei 30cm per la concentrazione nominale di 80mg/800ml di MMA

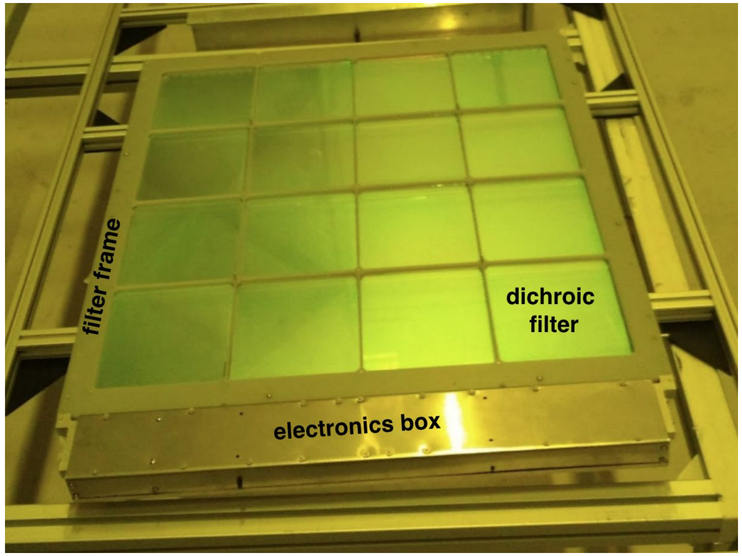


Simulazione delle tre configurazioni presentate nelle slide precedenti:

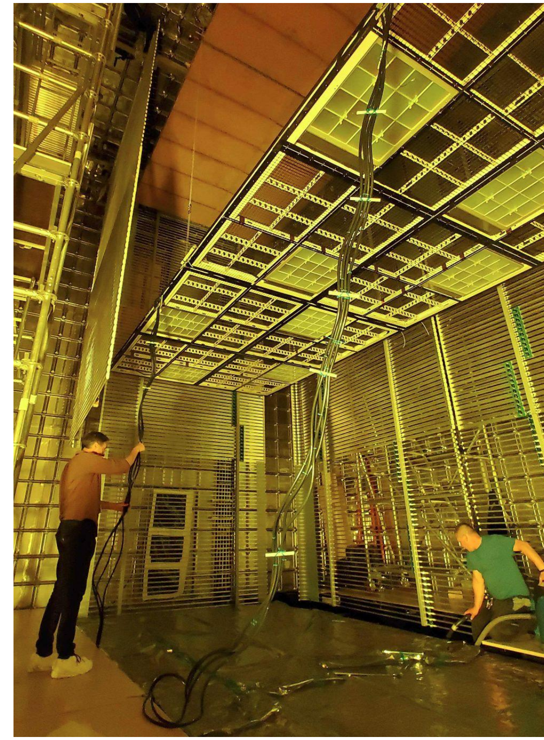
1. all'aumentare della concentrazione di cromoforo si raggiunge un plateau in efficienza
2. eccezione quando la guida di luce e' divisa in due parti → si recuperano ph. che rimarrebbero intrappolati nella guida (lati corti) → cammino libero medio maggiore



The Vertical Drift X-Arapuca (VD-XA)



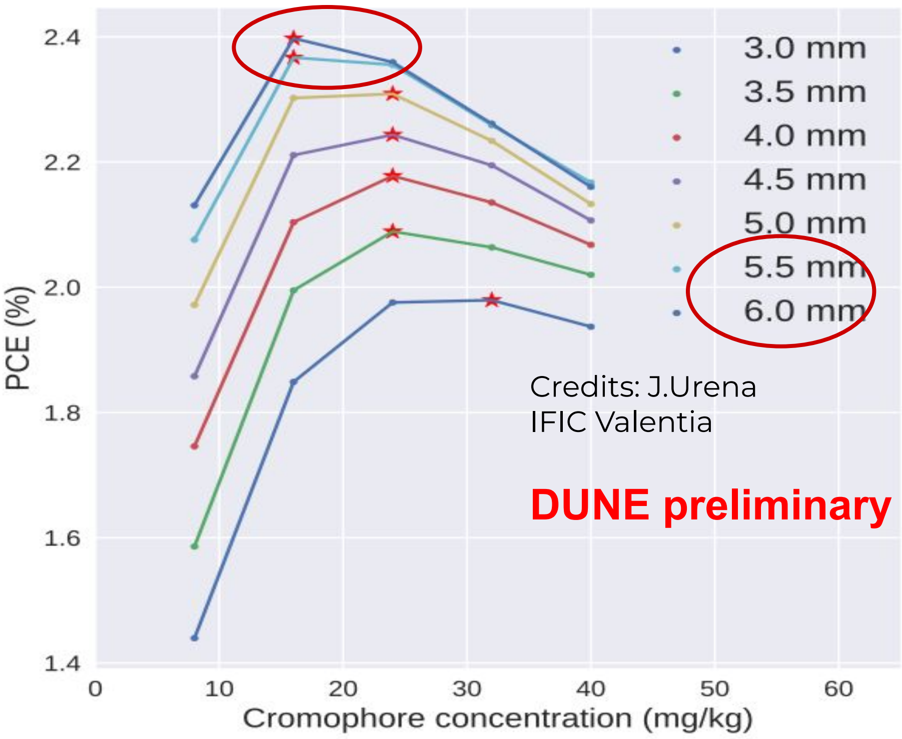
All 4 sides populated with SiPMs, 40 each, grouped in 2 channels



- Module size ~ 620 x 620 mm
- WLS-LG plate: 607 x 607 x 5.7 mm^3 → **SiPM coverage: 1.6%**
- **SiPMs mounted on flex circuits** (proposed by INFN-MiB in 2019)
- a **<u>spring loaded system</u> ensures contact of SiPMs w. WLS in LAr** environment (PMMA shrinking ~4.0 mm at LAr T)
- **DF size 144 x 144 mm^2** to maximize active area (minimize inactive frame ribs surface). Studied different DF designs

VD-XA PDE enhancement and assessment of components contribution

- Due to multiple reflections the optical path inside large size WLS may reach a couple of meters → dye concentration tailored to VD-XA size and optical path → optimization driven by simulations
- The max. PDE is found for WLS-plate: 5.5-6.0 mm thick 16-24 mg/kg chromophore concentration



VD-XA PDE measurements

PDE measurement performed at **CIEMAT (Madrid)** and **University of Naples**.

Membrane (no PoF) XA equipped with:

- G2P WLS plate with 80 (24) mg/kg chromophore concentration (as in HD-XA), and 3.8 (5.7) mm thick
- FBK TT-SiPMs

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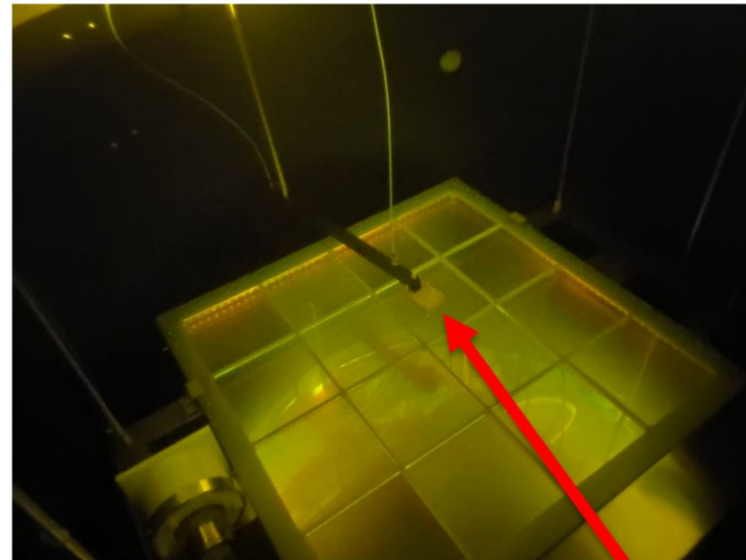
3 calibration boxes each with 2 reference VUV SiPMs triggering on scintillation from an ^{241}Am α source (3 α sources in total). Megacell tested in vertical.



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Preliminary lower limit
ε=2.15 ± 0.20%
at 45% SIPM PDE uncorrected for WLS bending effect.

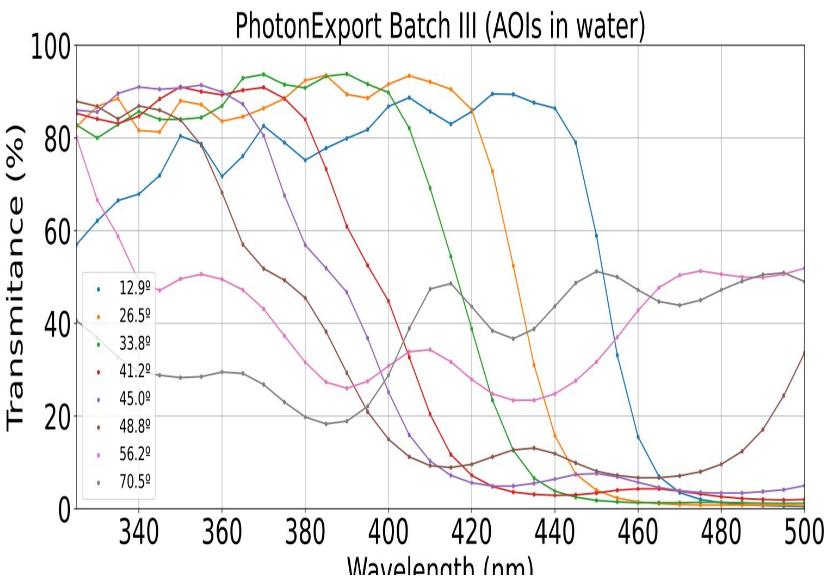
α source (^{241}Am) mounted on a rotating arm to scan different positions. Megacell tested in horizontal.

The DF T curves measured in H2O

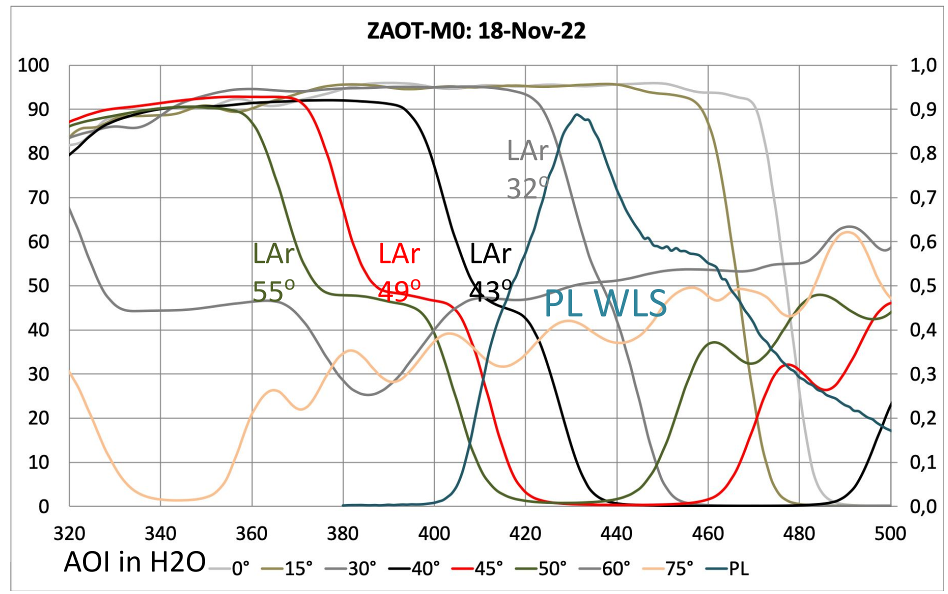
AOI H2O-to-LAr trasnformed by Snell law

Cutoff (n) => $\lambda = \lambda_0 \sqrt{1 - \frac{n_1^2}{n_2^2} \sin^2 \theta}$

PE- DF: T Curves: 14.5 x 14.5 cm^2 for Module-0



ZAOT-DF: T Curves: 14.5 x 14.5 cm^2 for Module-0



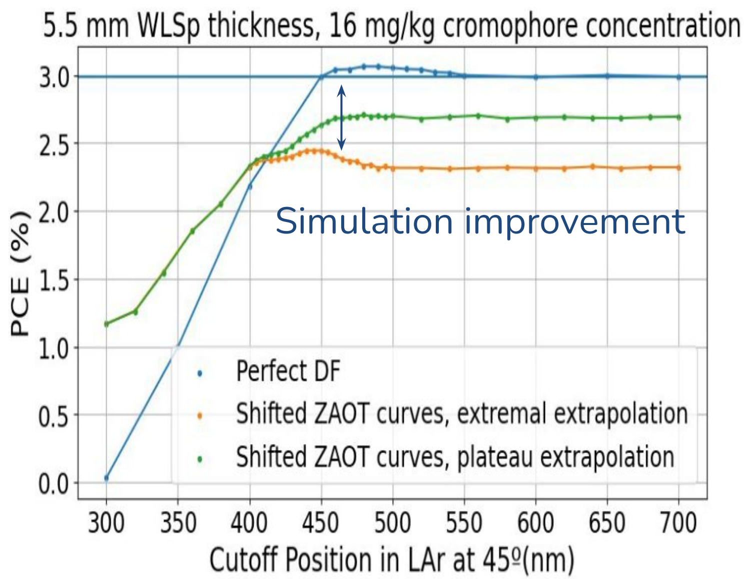
Two vendor scheme:

- PhotonExport (Spain). Problems with pTP adhesion at cold in M0 &CB
- **ZAOT (Italy) Produced most (few hundreds) of the DF/blank glass substrates for: CB,M0, M1 and Naple and CIEMAT PDE measurement facilities**

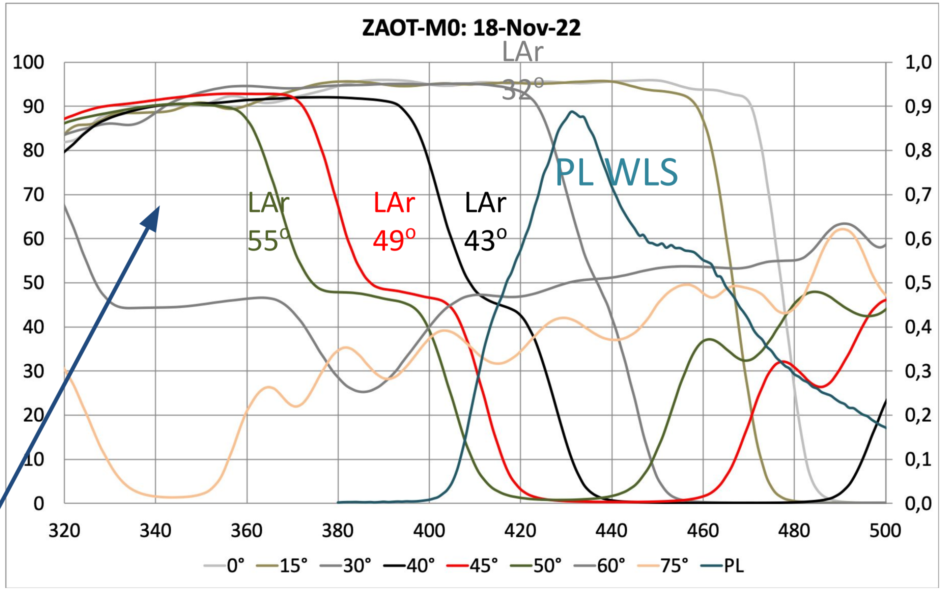
The DF T curves measured in H2O

AOI H2O-to-LAr transformed by Snell law

PE- DF: T Curves: 14.5 x 14.5 cm^2 for Module-0



ZAOT-DF: T Curves: 14.5 x 14.5 cm^2 for Module-0



AOI in H2O

- Simulations showed a significant improvement without DF.
- This because of the DF reduced Trasmittance < 380 nm photons (emitted by pTP at large angles >55º)
- → produced BF33 glasses pTP coated (Campinas w.o DF)
- One XA MegaCell was tested @ CIEMAT w.o. DF

Vertical Drift FD-XA: Configurations Tested at CIEMAT

- All mount FBK-TT SiPM.
- With and without dichroic filter:

→ Test **non-ideal DF transmittance worsening PDE for VD-XA**.

- Optimize WLS-Bar **thickness** and **chromophore concentration** to maximize attenuation length at constant abs. of pTP Photons

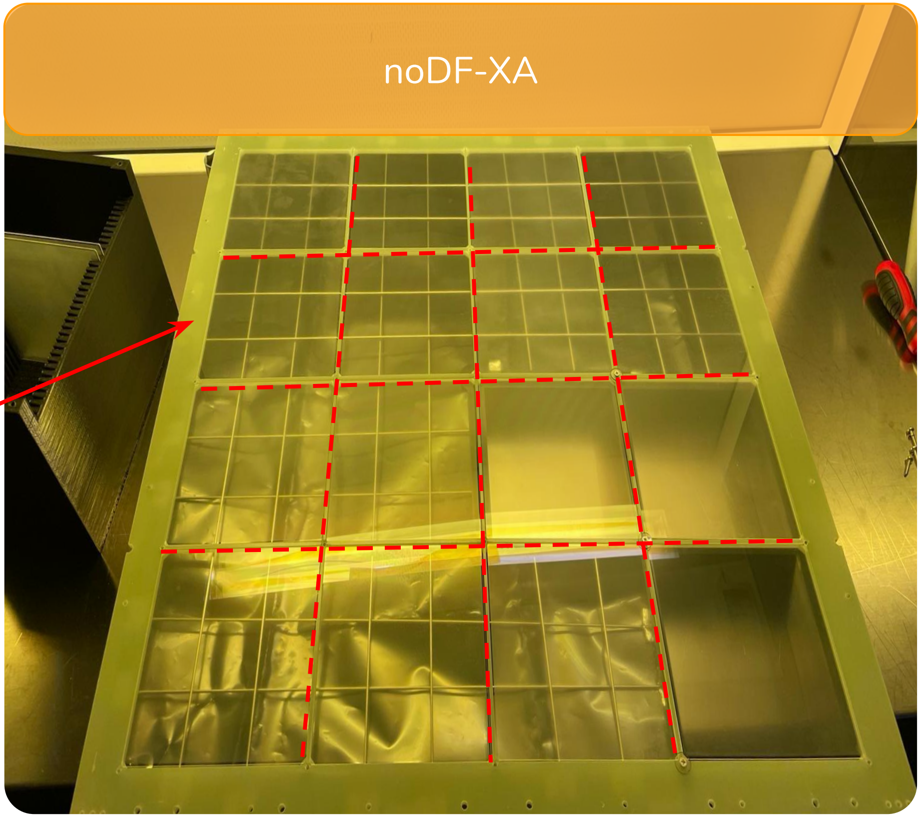
XA	WLS	Dichroic	pTP	Sided
1. Dichroic Single-Sided	a	ZAOT	ZAOT	Single
2. Dichroic Double-Sided	a	ZAOT	ZAOT	Double
3. Non-Dichroic Single-Sided	a	x	P.E.	Single
4. Non-Dichroic Double-Sided	a	x	ZAOT	Double
5. Non-Dichroic Single-Sided	b	x	P.E.	Single

→ Tested bars:

a. **3.8 mm & 80 mg/kg**
b. **5.7 mm & 24 mg/kg**

Vertical Drift FD-XA: Components

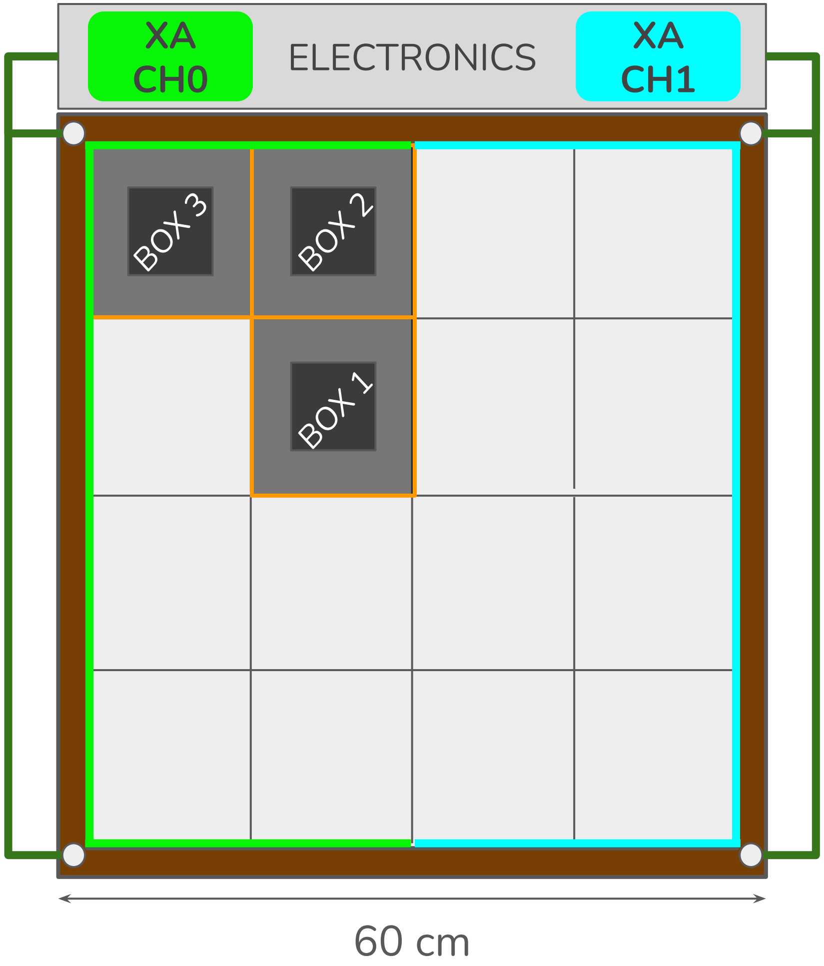
- **Design for VD**: XA tiles (~ 60 x 60 cm²) double-/single-sided for cathode/membrane.
- Mounted **160** sensors (8x (flex circuits x 20 SiPMs passively ganged in groups of 5)) read-out by two FE cold channels.



VD-XA: Calibration Layout

Absolute **PDE measurement**:

- XA read-out split into **2 channels** (combined during data analysis).
- **Calibration boxes** positioned in the **3 uniquely distinct** XA positions.
- Each box mounts **1 alpha source** & **2 ref. SiPM** with known PDE.
- **Average XA PDE** computed from weighted average of 3 calib. boxes.

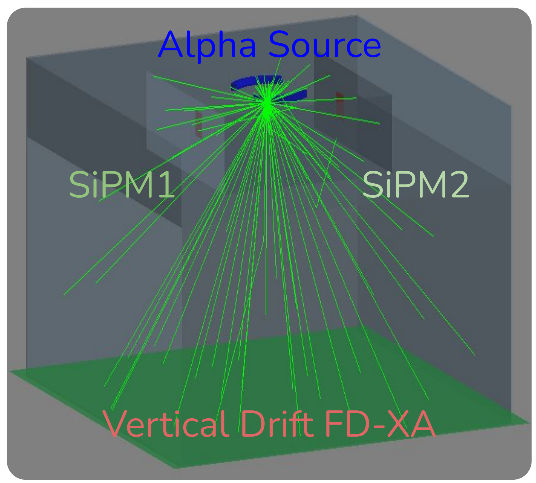


Calibration System: Simulation

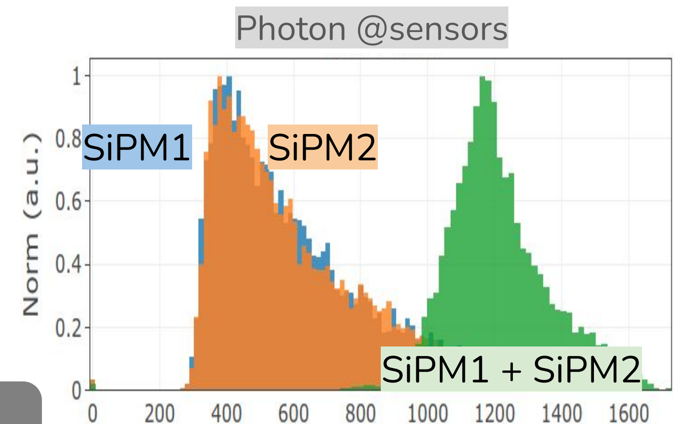
- Relative solid angle by **standalone GEANT4 simulation.**
- Accounts for the **differences in sizes/positioning** of ref. sensors.

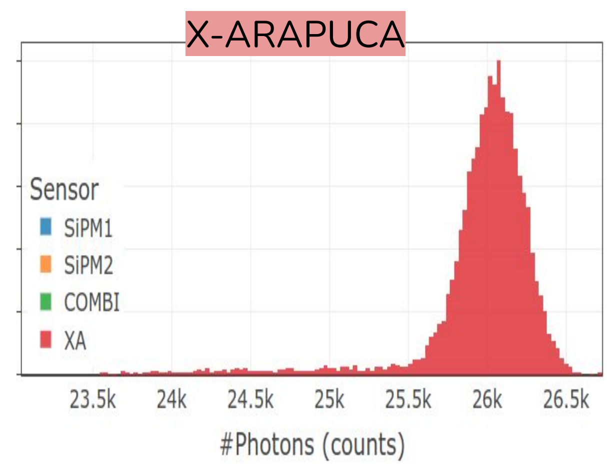
$$f_{\text{geom}} = \frac{\Omega(\text{Ref.})}{\Omega(\text{XA})} = 0.047 \pm 0.001$$

Sensor	MEAN Ph.
XA-VD (21170 mm²)	25920
SiPM (12 mm²)	1206



14.55 x 14.55 cm²





PDE: Results

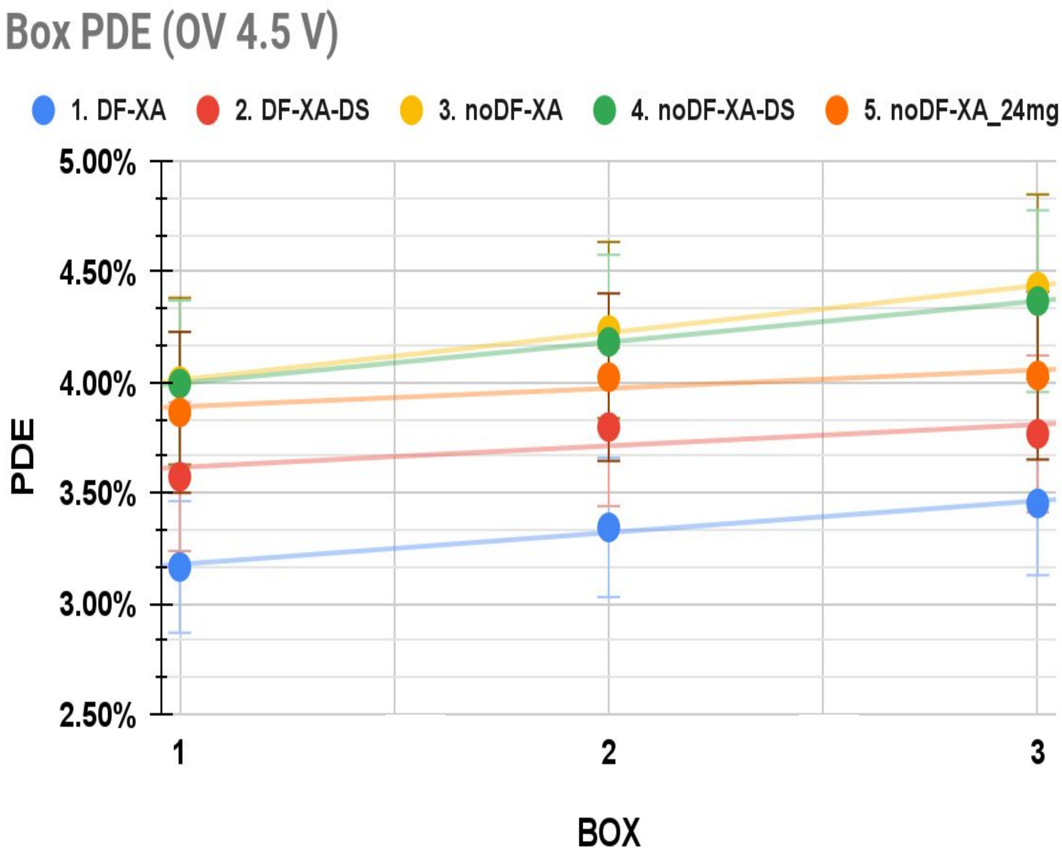
- **PDE** values are computed from **weighted average** of 3 calibration boxes:
    - OV 3.5, 4.5 & 7 V corresponding to 40, 45 & 50% SiPM eff.

	Dichroic Filter		Non-Dichroic Filter		
	Single-Sided	**Double-Sided**	**Single-Sided**	**Double-Sided**	**Single-Sided**
OV	1. DF-XA	2. DF-XA-DS	3. noDF-XA	4. noDF-XA-DS	5. noDF-XA_24mg
4.5	**(3.3 ± 0.4) %**	**(3.7 ± 0.4) %**	**(4.2 ± 0.4) %**	**(4.1 ± 0.4) %**	**(4.0 ± 0.4) %**

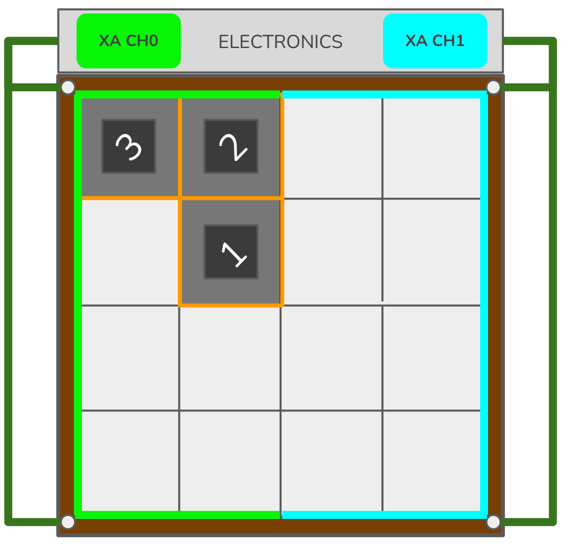
- Conclusions:
    - **Compatible performance** of **single vs. double-sided XA** configs.
    - **Improvements** (27 - 11 %) when **removing dichroic filters** due to non-ideal entrance transmittance and shifting cut-off for different angles.
    - Compatible performance of both tested **WLS-bar** configurations.

PDE: Results

- PDE **homogeneity** across different positions always **within ~3%**. The **flattest distribution** corresponds to **XA 5.** mounting WLS-bar **w.** 24 mg / kg chromophore concentration.



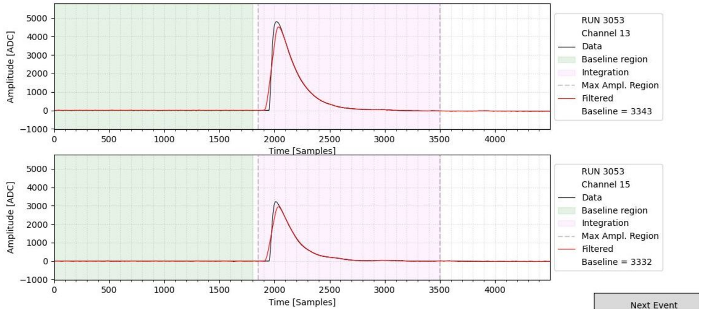
Calibration Box Arrangement



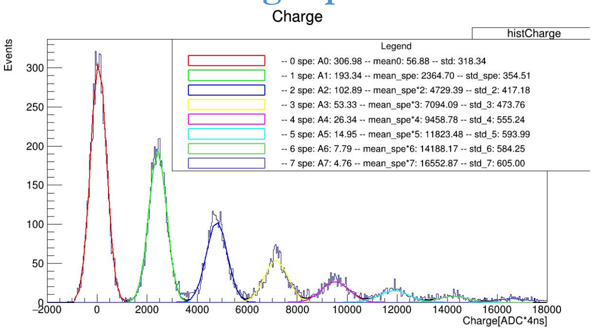
Fd2-XA Test in Napoli in LAr signal analysis

SiPM charge: single photon calibration

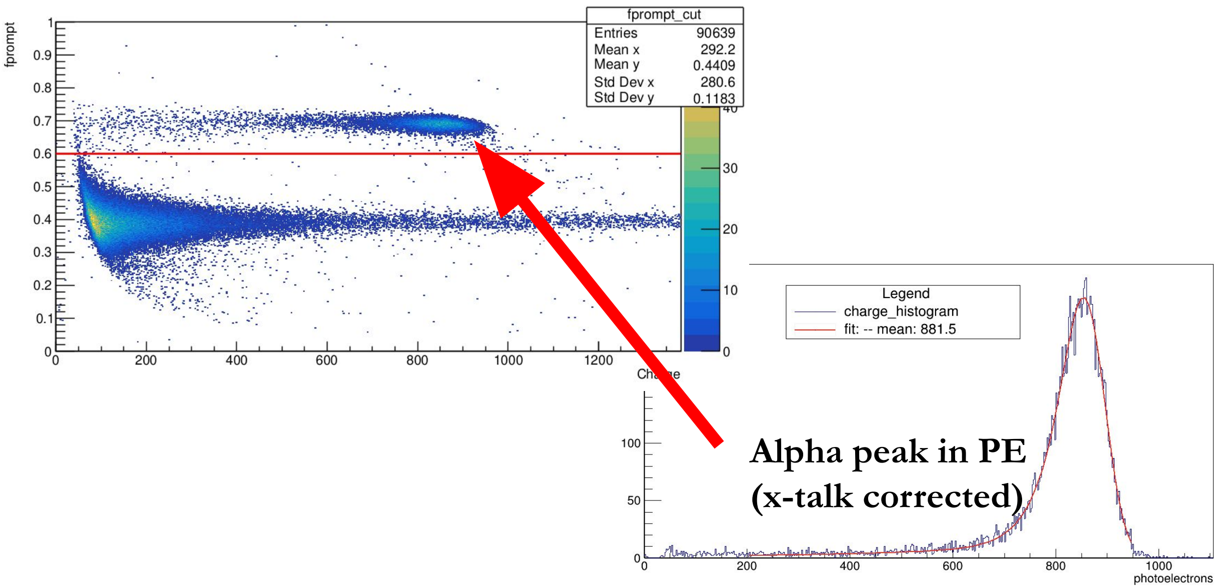
Waveform integration



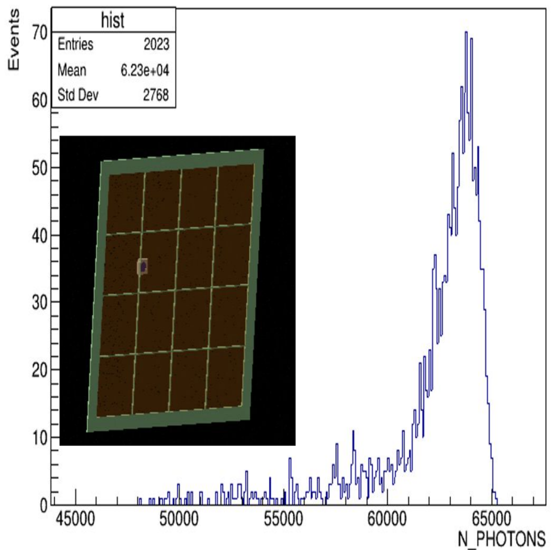
Charge spectra



Alpha source charge signal



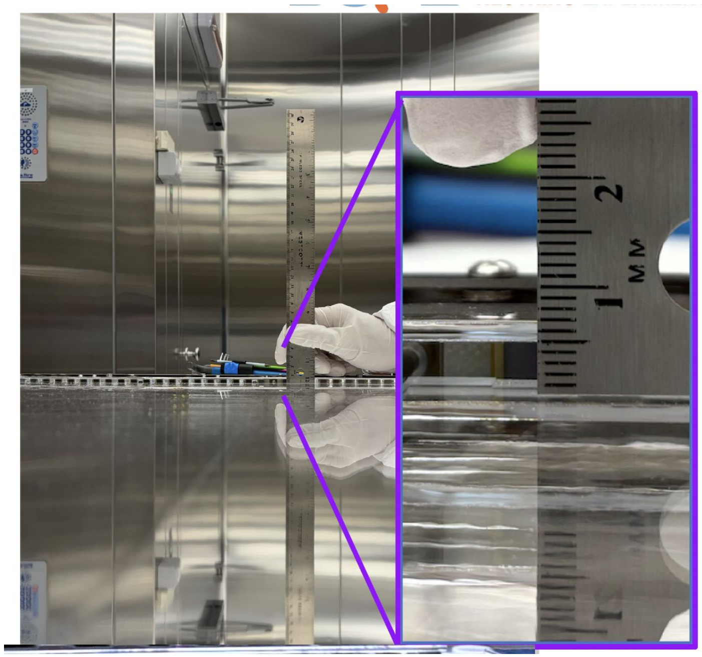
Geant4 simulation of expected number of photons



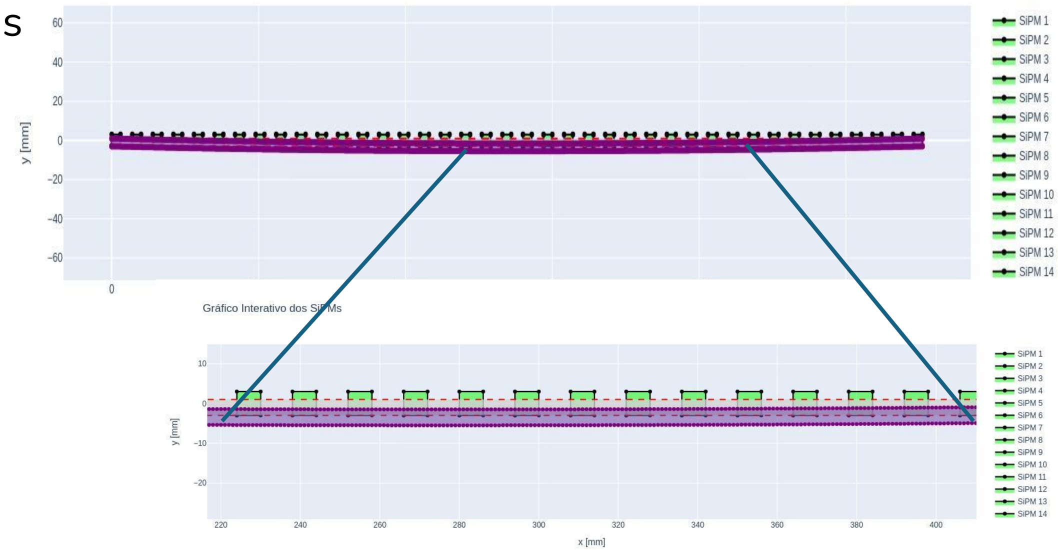
Slide from. F. Di Capua

Photon Collection Efficiency Estimation

Bending of the WLS-LG (suboptimal assembly, no stands!!!):
→No good match among SiPM flex boards and lightguide



Modelling the observed effect



OV (V)	PDE(%) - Pos 2
4.5	3.3±0.4
6	4.0±0.5
7	4.2±0.6

Results in agreement with the measurement perfomed in a parallel test at CIEMAT after geometrical correction factor

Slide from. F. Di Capua

X-ARAPUCA: Evolution

- XA optimization responds to a **collaboration-wide effort**.
- See LIDINE 2022 [C. Palomares et al.] & 2023 [C. Cattadori et al.].

Baseline **HD-XA** PDE **<= 2%** (initially).

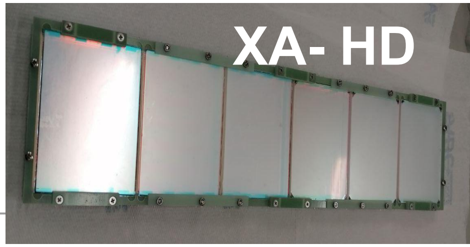
- **Change of WLS** → PDE ~2.5%.
  - G2P PMMA now BL for FD-HD & -VD.
- SiPM-WLS **contact/reflection** → PDE ~3.5%.
- **WLS cut** to recover photons → **PDE ~5%**

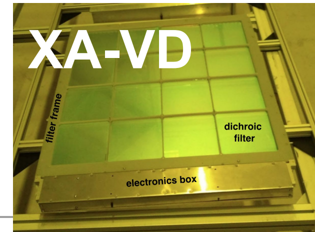
VD-XA PDE optimization presented today:

- **SiPM-WLS contact** (experience from HD).
- Understanding of the **filter application**.
- Simulation driven **WLS properties**.
- Abs & PhotoLuminescence WLS measurements drive simulations

Configuration	2022 HD-XA (G2P)	2023 HD-XA (Improvements)	2024 VD-XA (noDF)
Surface / SiPM	500 cm² / 48	500 cm² / 48	3600 cm² / 160
PDE	2.5 %	5 %	4.2 %
PDE · Surface / #SiPM	26	52	95

XA vs WLS-coated Lightguides Figure of Merit





	Size	n. SiPM	Si/LG area[%]	PDE* [%]	**FOM [PDE/(Si/LG)]**
XA - FD1 https://doi.org/10.1140/epjc/s10052-024-13393-2	480 x 93	48 ganged	3.9	2.5 - 5 (0.2)	**0.64 -1.2**
XA - FD2 (No DF) LIDINE 2024 S. Manthey	607 x 607	160 gang 2x80	1.6	4.2 (0.4)	**2.62**
pDUNE-I (double shift LG) *B. Abi et al. 2020 JINST 15 P12004*	2007 x 83	12	0.3	0.2	**0.66**
pDUNE-I (single shift LG) (pure PMMA TPB coated)	2007 x 83	12		0.08	**0.27**

(*50% SiPM PDE)

Summary & Conclusion

- Results of 4 yrs activity: **Components optimization, sims, & measurement**
  - **HD-XA PDE: 2.5% -** (@50% PDE of SiPM) (HPK; G2P BL configuration)
  - **HD-XA PDE: 4%-5%** - (@50% PDE of SiPM) (HPK; G2P Optimized Config.)
  - **VD-XA PDE: 4.2 ± 0.4 % @OV 4.5 V**. With compatible results between single- and double-sided measurements.
- Confirmed **improvement in PDE (27 - 11 %) without dichroic filters**.
  - VD-XA Decision on removal of DF from FD2-XA almost taken.
  - HD-Xa will go with DF (mostly for political reasons)
  - Bring to home message: the most photons are trapped in the WLS-LG the less need for DF (this is why the VD-XA WLS-LG thickness increased up to 5.7 mm)
- One (Two) papers in preparation for the VD-XA Optimization and PDE measurements
- Clear progress in **DUNE's XA design** HD-XA → VD-XA:

  → Figure of merit **PDE / $(Si/LG)_{Surface}$ (HD 0.64 - 1.2 vs VD 2.62).**

Preproduction of Glass substrates and WLS-LG

- Primo batch di Preproduzione di ZAOT glass substrati per pTP coating consegnato

545 units (corrispondenti a 34 Single Side XA) of x BF33 substrates for FD2 delivered preproduction Ready to be shipped at the coating facilities (Campinas, Napoli, Pavia)

- Preproduzione di 36 WLS-LG per VD entro 2024. Procedura di ordine in corso