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Efficiency of a Cherenkov based PET module with an array of SiPMs

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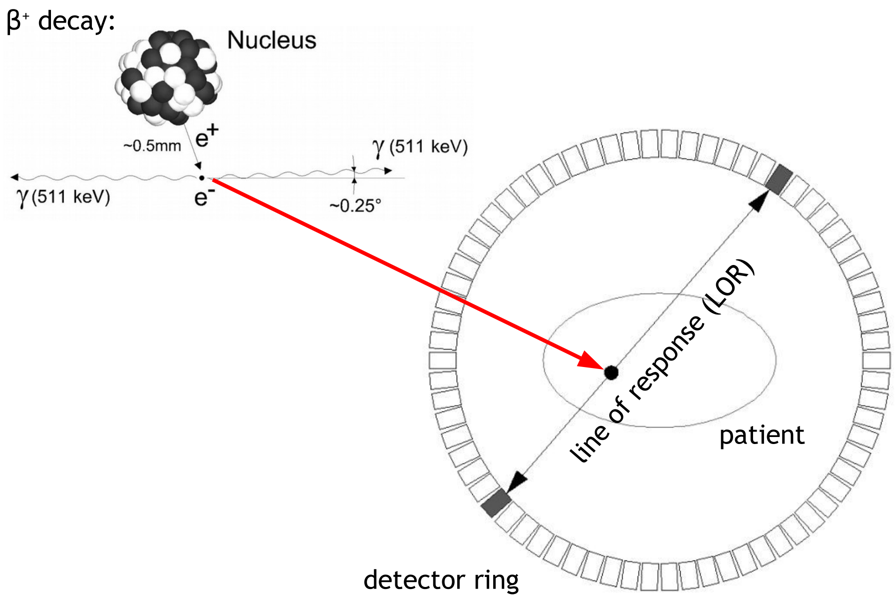
Outline

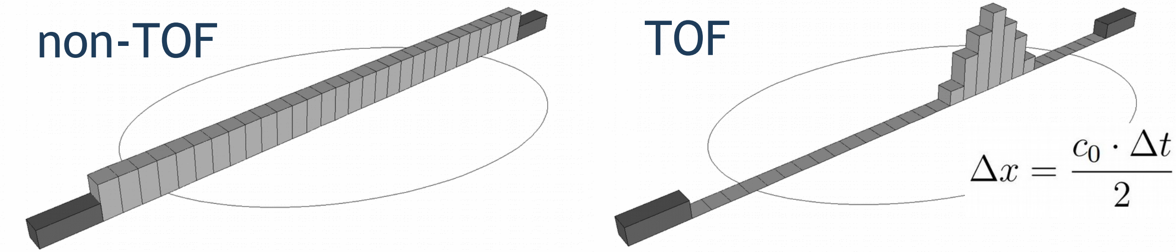
- Time-of-flight (TOF) positron emission tomography (PET)
- Use of Cherenkov radiation for TOF PET
- Previous experiments
  - microchannel plate photomultipliers (MCP PMT) as photodetectors
  - silicon photomultipliers (SiPM) as photodetectors
- 16 channel Cherenkov PET module
  - measurements of detection efficiency
- Summary

Positron emission tomography

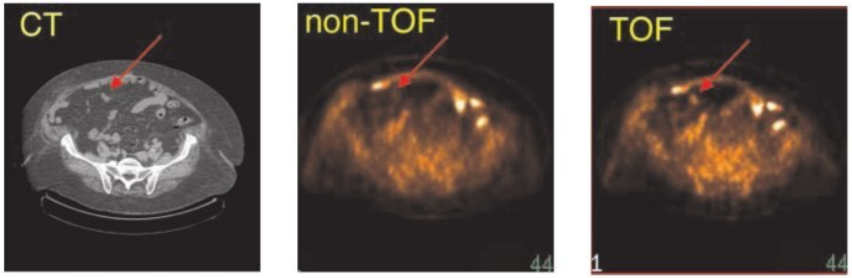
- Positron emission tomography (PET)
  - medical physics modality, enabling in-vivo imaging of biological processes via coincident detection of 511 keV annihilation γ rays

- Time-of-flight (TOF)
  - measurement of arrival times of the two γ can be used to limit the reconstructed position of annihilation
  - improves the quality (contrast-to-noise ratio) of reconstructed images





$$\Delta x = \frac{c_0 \cdot \Delta t}{2}$$



Philips Gemini TF PET/CT, TOF resolution of 600 ps
[PET Center of Excellence Newsletter, Vol.3 Issue 3 (2006)]

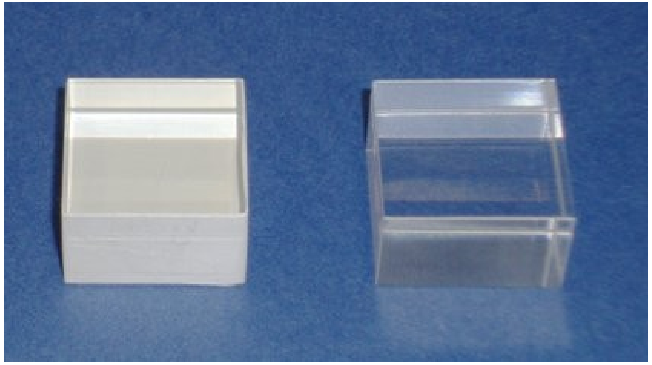
- γ detectors in traditional PET: scintillator crystal + photodetector

	BGO	LSO	$LaBr_3(Ce)$	PbF_2
Density (g/cm^3)	7.1	7.4	5.1	7.77
μ_{511keV} (cm^{-1})	0.96	0.87	0.43	1.06
Photofraction for 511 keV (*)	0.41	0.32		0.46
Decay time (ns)	300	40	17	-
Light yield (/511 keV)	3,000	15,000	30,000	10 (‡)

(*) [XCOM: Photon Cross Sections Database]

(‡) in 250-800 nm wavelength interval

- Lead fluoride (PbF_2) crystal
  - exclusively Cherenkov light produced (prompt)
  - excellent properties for stopping 511 keV annihilation γ
  - excellent light transmission (down to 250 nm)
  - low cost
  - low light yield - single photon detection

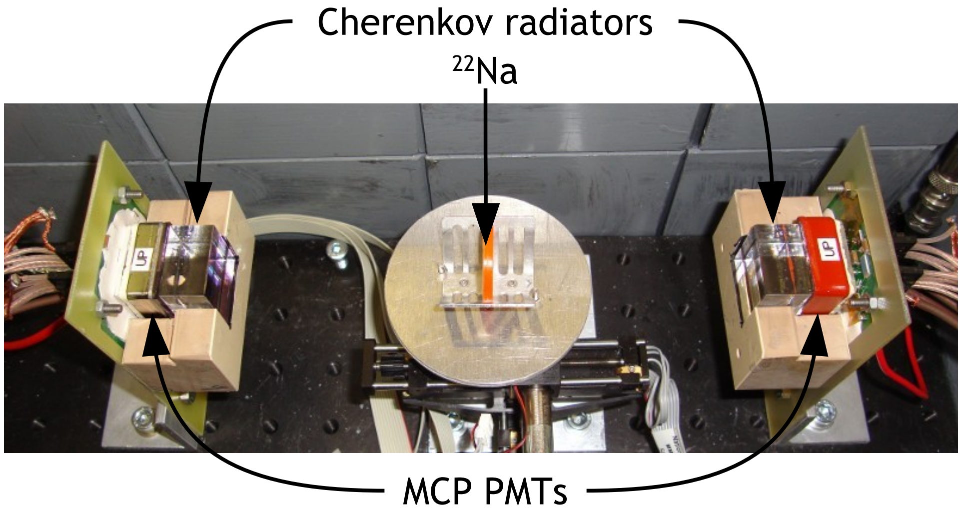


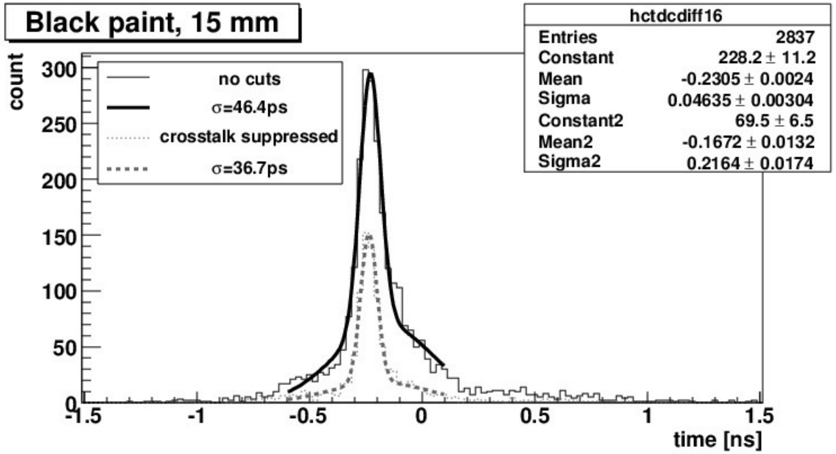
Previous results (MCP PMT)

- Two detectors in back-to-back configuration
- Cherenkov radiators
  - 25x25x5 or 25x25x15 mm^3 PbF_2
- Photodetectors
  - microchannel plate photomultiplier tubes (MCP PMTs)
  - single photon timing ~ 50 ps FWHM
  - active surface 22.5x22.5 mm^2
- TOF (coincidence) resolution:
  - **71 ps FWHM** (5 mm thick, black painted PbF_2)
  - **95 ps FWHM** (15 mm thick, black painted PbF_2)

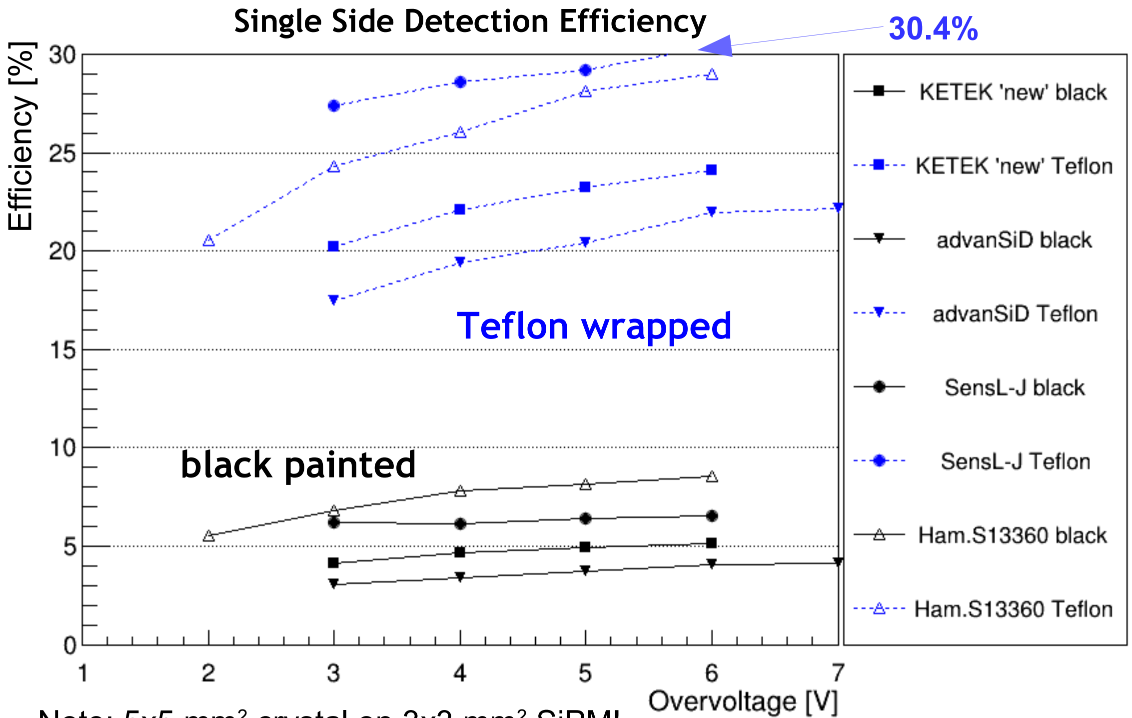
NIM A 654 (2011) 532

- Low efficiency ~ 6% (single side)
  - traditional scintillation detectors ~ 30%

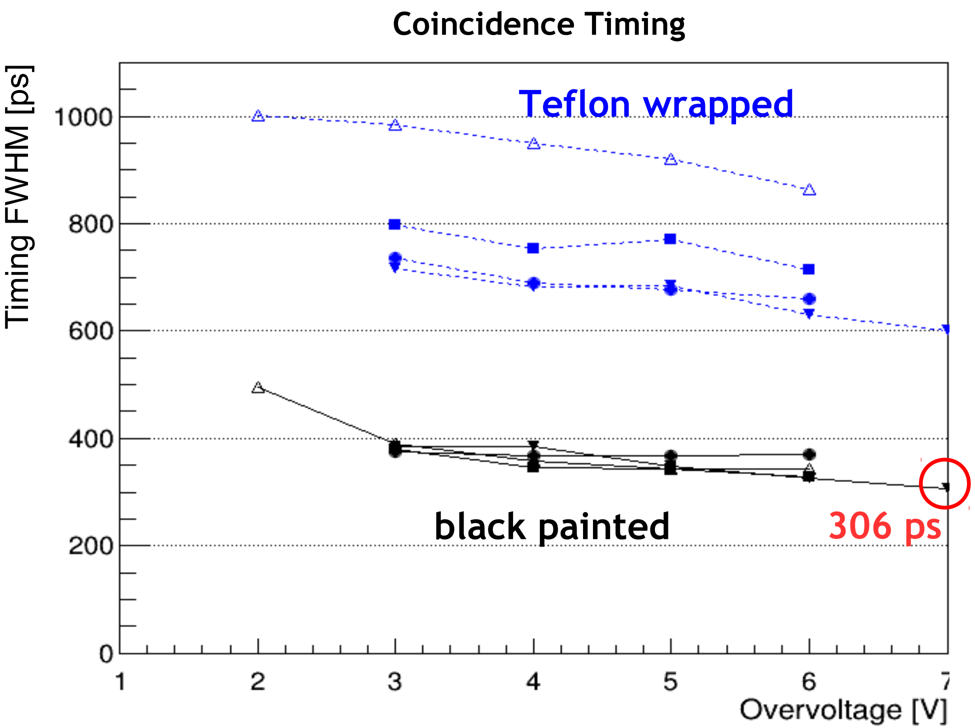




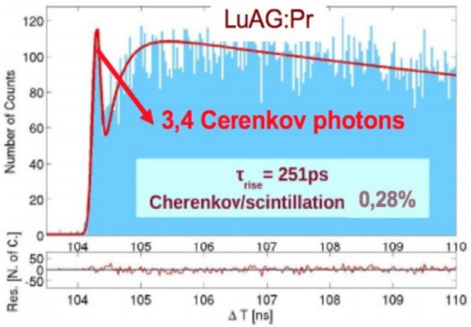
- Two detectors in back-to-back configuration
- Cherenkov radiators: 5x5x15 mm^3 PbF_2
- Photodetectors: 3x3 mm^2 silicon photomultipliers
  - cooled to -25°C (SiPM dark counts)
- TOF (coincidence time) resolution:
  - 306 ps FWHM (AdvanSiD, black paint)
- Efficiency:
  - 30% single side (SensL-J, Teflon wrapped)



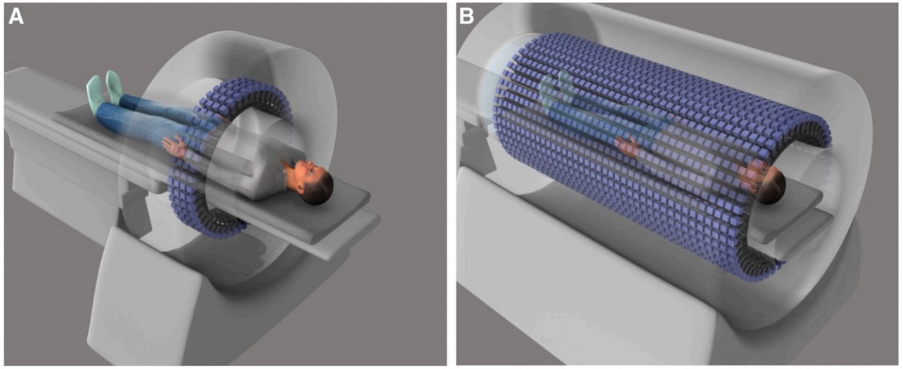
Note: 5x5 mm^2 crystal on 3x3 mm^2 SiPM!



- Excellent TOF PET timing achievable using exclusively Cherenkov light:
  - 95 ps FWHM coincidence timing with 15 mm thick PbF_2 (~ γ stopping power of 20 mm of LSO)
  - Cherenkov considered for the goal of 10 ps TOF PET [P. Lecoq]
- Very few (single) photons
  - efficiency an issue
- Silicon photomultipliers
  - Cherenkov PET efficiency competitive to scintillators (~30% single side)
  - timing an issue (especially with configuration optimized for efficiency)
- Cost of PbF_2 ~ 20% of LSO (cost of scintillator ~ 50% of PET scanner)
  - lower cost PET scanners
  - total-body PET scanners [S. Cherry]
- Our next step
  - **PET module, optimized of efficiency and price**



[Lecoq et al., IEEE TRPMS, Vol. 1, No. 6 (2017)]

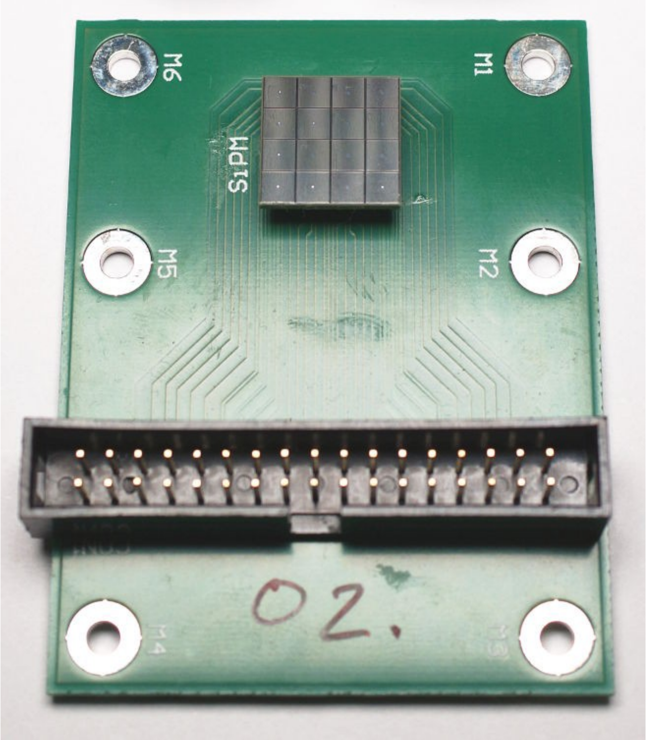


[Cherry et al., The Journal Of Nuclear Medicine, Vol. 59, No. 1 (2018)]

16 channel PET module

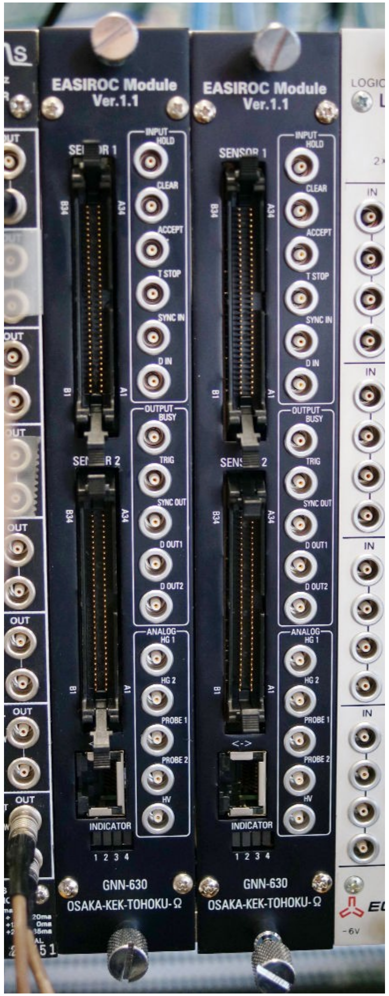
- Cherenkov radiators
  - 4x4 array of 3x3x15 mm^3 PbF_2

    [Shanghai SICCAS High Technology Corporation]
  - white reflector (black paint where noted)
- Photodetectors
  - 4x4 array of 3x3 mm^2 SiPM
  - Hamamatsu MPPC S13361-3075AS-04
    - 75 µm pixels (1600 / 3x3 mm^2)
    - peak sensitivity ~ 50% PDE @ 450 nm
    - breakdown voltage ~ 53 V
    - dark count ~ 0.5 Mcps (/ 3x3 mm^2), crosstalk prob. ~ 7% (overvoltage V_{ov} = 3 V)
- Custom connector board
- 3D printed crystal supports
- SiPM bias provided by readout module - EASIROC



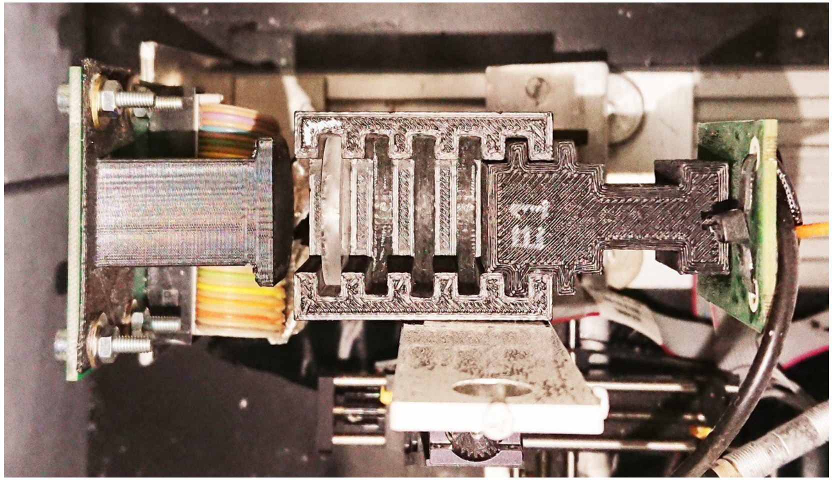
Readout - EASIROC

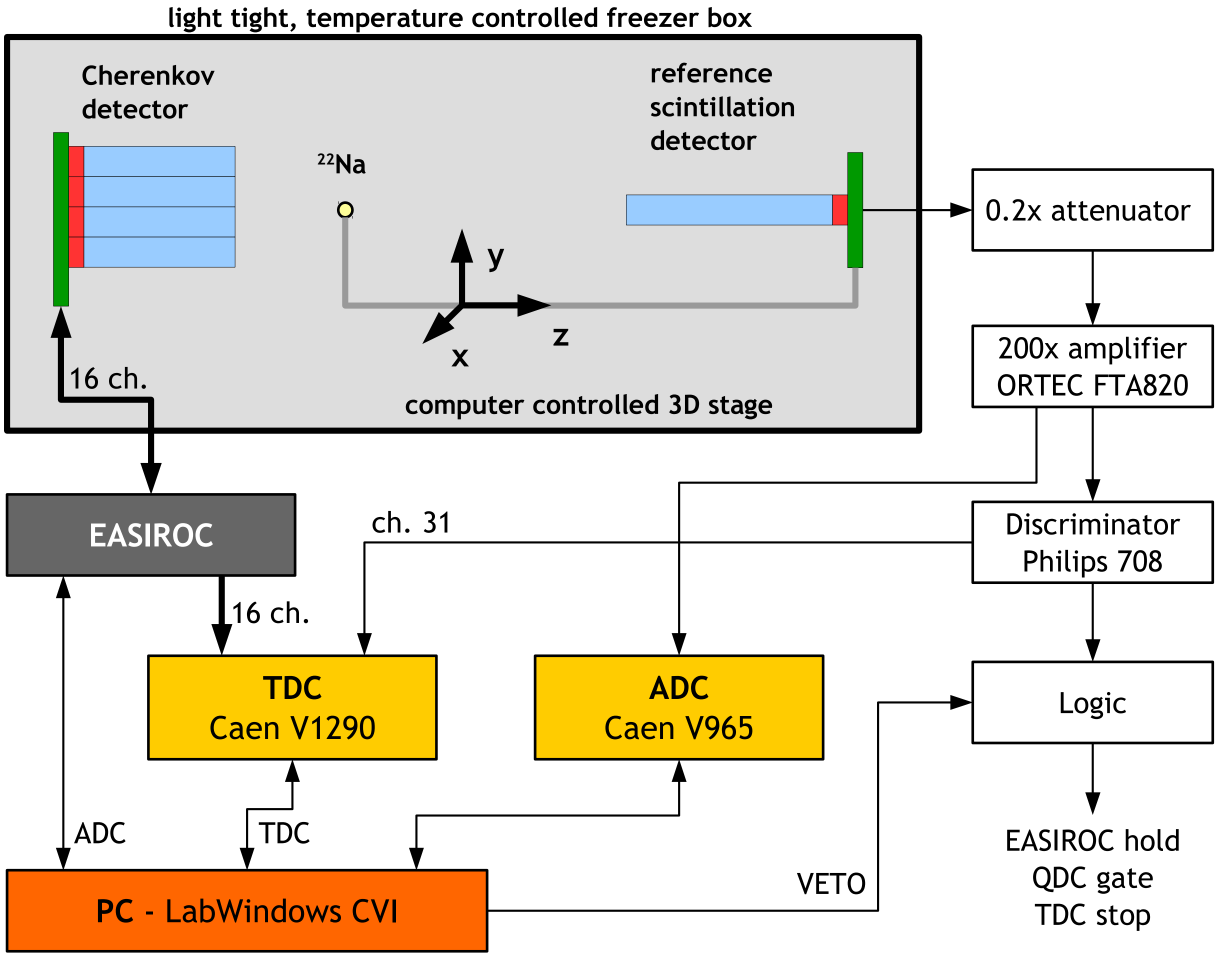
- EASIROC chip [OMEGA group]
  - Extended Analogue Silicon pm Integrated Read Out Chip
  - 32 channel ASIC dedicated to read-out of SiPM detectors
    - Internal input 8-bit DAC for individual SiPM gain adjustment
    - Individually addressable calibration injection capacitance
    - Energy measurement : 14-bit dynamic range
    - Trigger output
- EASIROC module [Osaka, KEK]
  - 2 x 16 channels per module
  - **SiPM bias supply**, adjustable by 4.5V for each channel
  - **ADC**,12bit, dual range
  - LVDS **trigger** outputs (for external TDC)
  - possibility to perform TDC in FPGA (~ 1ns resolution)
  - Ethernet connection to PC



Experimental setup

- Cherenkov detector:
  - 4x4 array of 3x3x15 mm^3 PbF_2
  - 4x4 array of 3x3 mm^2 SiPM
- Reference detector
  - 3x3x30 mm^3 LYSO scintillator
  - 3x3 mm^2 SiPM
- Annihilation γ source
  - ^{22}Na point source (D = 0.3 mm)
  - activity = 0.6 MBq
- Temperature: -25°C (SiPM dark counts)





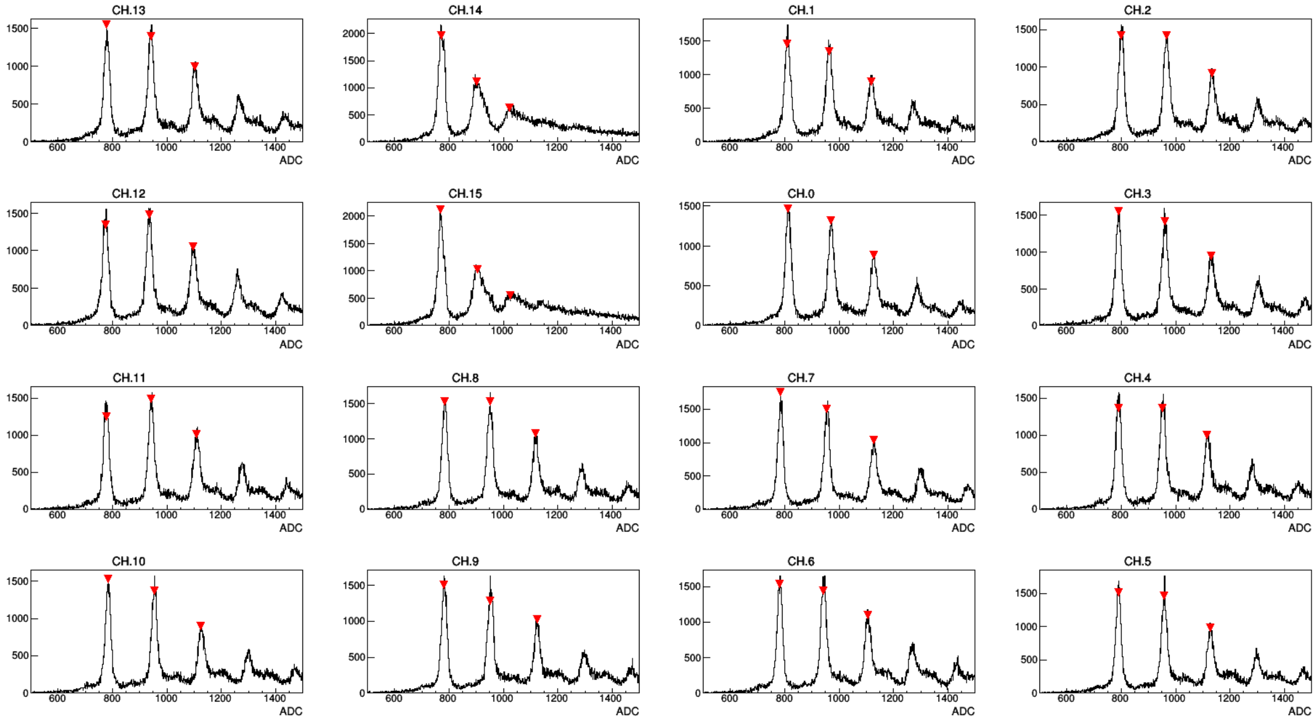
* ch.0 next to ground - more noisy; ch.15 TDC not connected

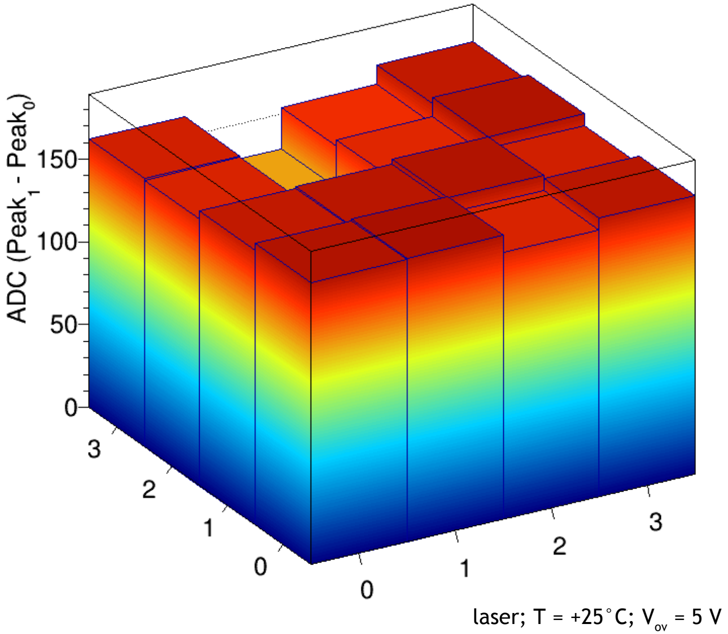
Laser calibration

- Laser illumination instead of reference scintillation detector
  - ~1 mm laser spot scanned over each SiPM array channel center (w/o PbF_2 crystals)
  - gain ~ (ADC 1 p.e. peak) - (ADC noise peak)
  - adjusted for each channel

Channel

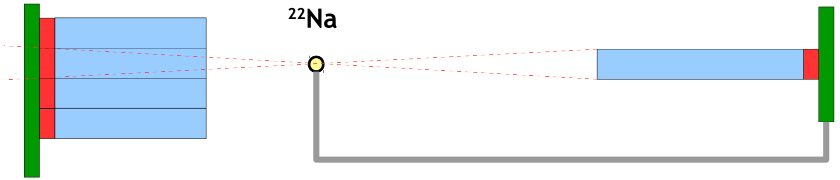
13	14	1	2
12	15	0	3
11	8	7	4
10	9	6	5





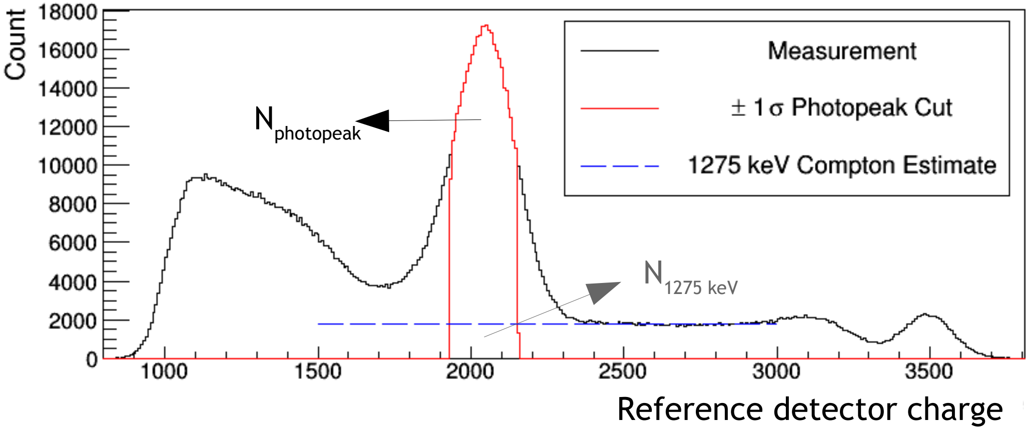
Detection efficiency estimation

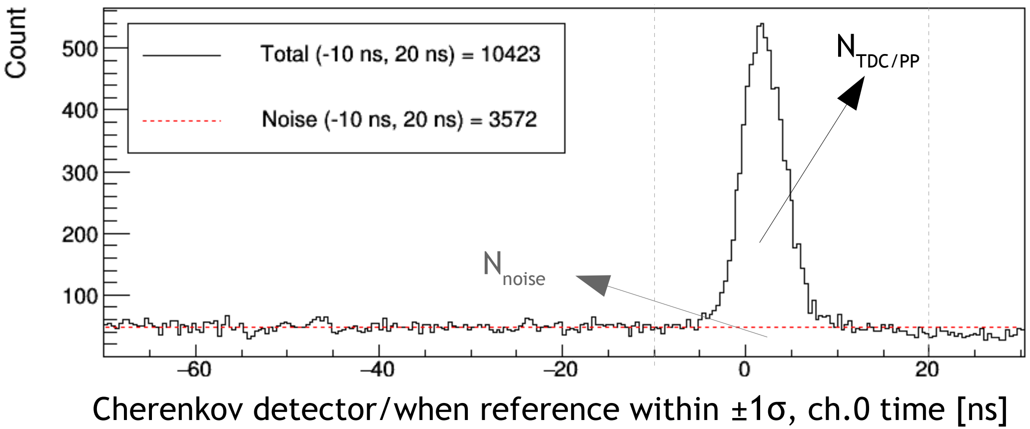
- Geometrical collimation of coincidences - reference detector further away from the source



- When the reference scintillation detector is hit with one 511 keV γ, the other annihilation γ hits the Cherenkov detector
  - reference detector hit: event cut within ±1σ of 511 keV photopeak
    - corrected for estimated 1275 keV γ (^{22}Na) Compton contribution
  - Cherenkov detector hit: TDC within 30 ns
    - corrected for noise, estimated from constant fit in off-time window

$$Efficiency = \frac{N_{TDC/PP} - N_{noise}}{N_{photopeak} - N_{1275\,keV}}$$





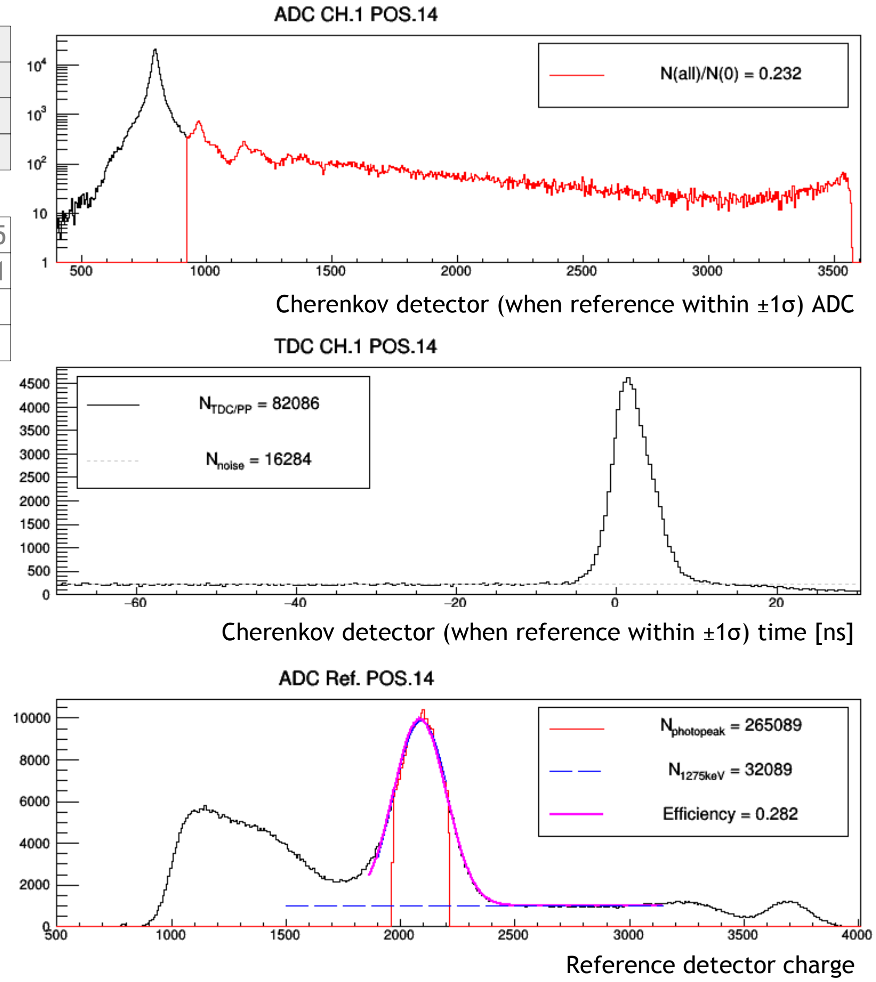
Results: source position on channel / off channel

Channel

13	14	1	2
12	15	0	3
11	8	7	4
10	9	6	5

Position

12	13	14	15
8	9	10	11
4	5	6	7
0	1	2	3



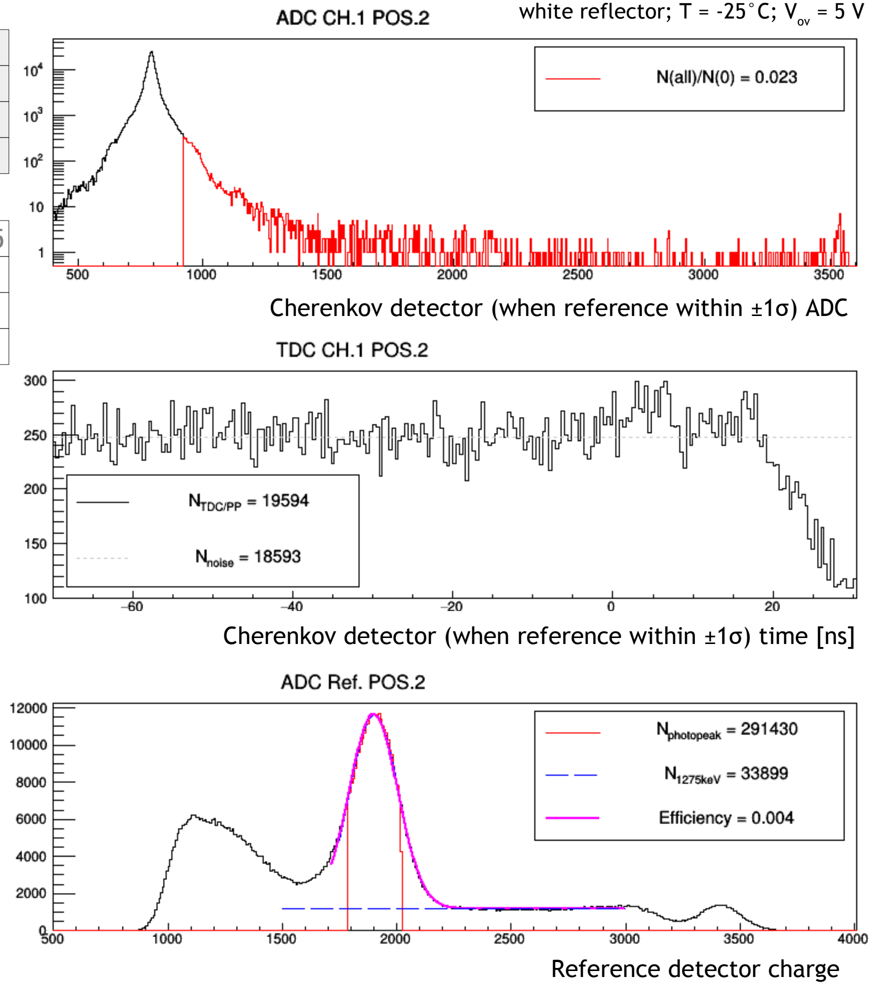
Channel

13	14	1	2
12	15	0	3
11	8	7	4
10	9	6	5

Position

12	13	14	15
8	9	10	11
4	5	6	7
0	1	2	3

white reflector; T = -25°C; V_{ov} = 5 V



Results: efficiency map

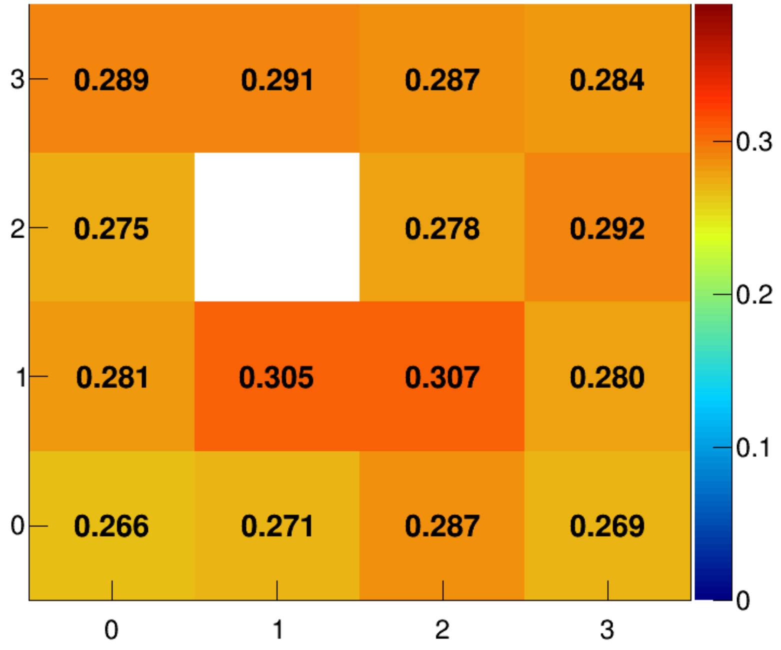
- Efficiency of each channel when collimated with the source
  - average = 28.4% (previous single ch. result ~ 25% - 30%)

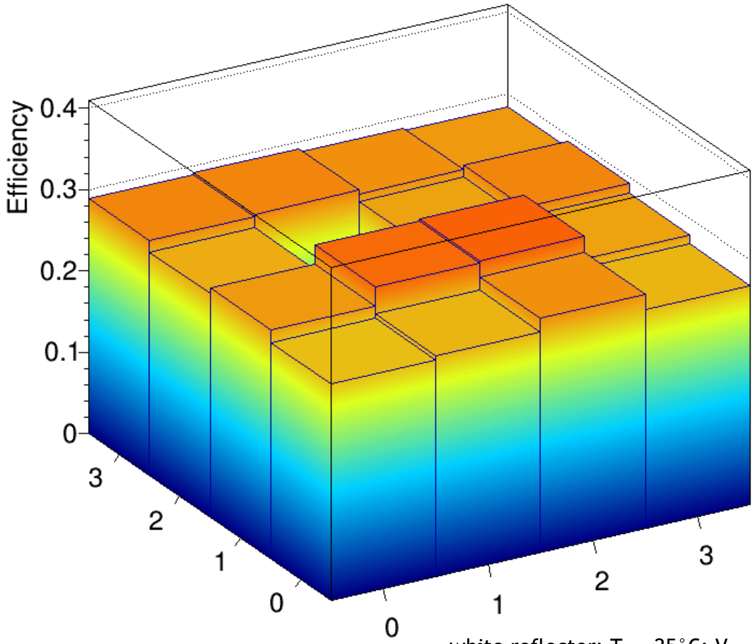
Channel

13	14	1	2
12	15	0	3
11	8	7	4
10	9	6	5

Position

12	13	14	15
8	9	10	11
4	5	6	7
0	1	2	3





white reflector; T = -25°C; V_{ov} = 5 V

* ch.0 next to ground - more noisy; ch.15 TDC not connected

Results: cross talk

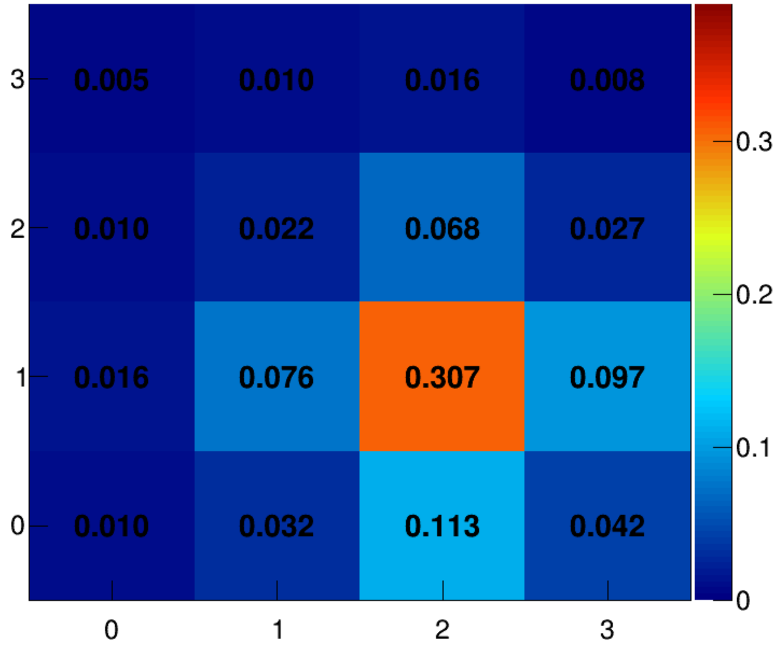
- Efficiency of channel 7, for all 16 source positions
  - nearest neighbors average 26% crosstalk
  - diagonal neighbors average 7% crosstalk
- Sources of crosstalk:
  - miss-collimation
  - optical leakage between channels
  - Compton scattering

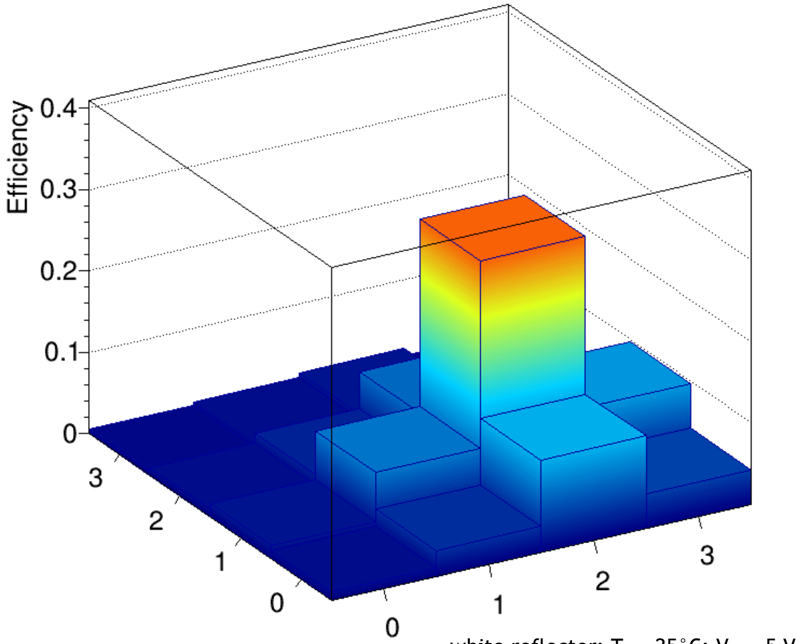
Channel

13	14	1	2
12	15	0	3
11	8	7	4
10	9	6	5

Position

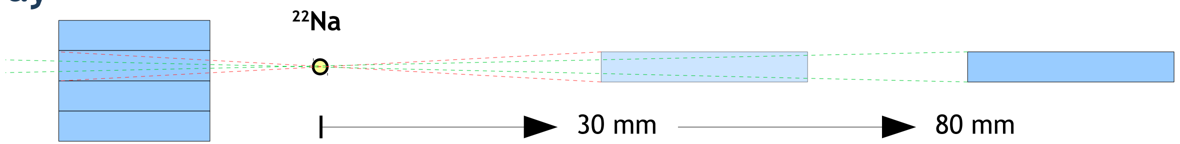
12	13	14	15
8	9	10	11
4	5	6	7
0	1	2	3





white reflector; T = -25°C; V_{ov} = 5 V

- When reference detector **moved further away**
  - nearest neighbors average 22% crosstalk
  - diagonal neighbors average 5% crosstalk

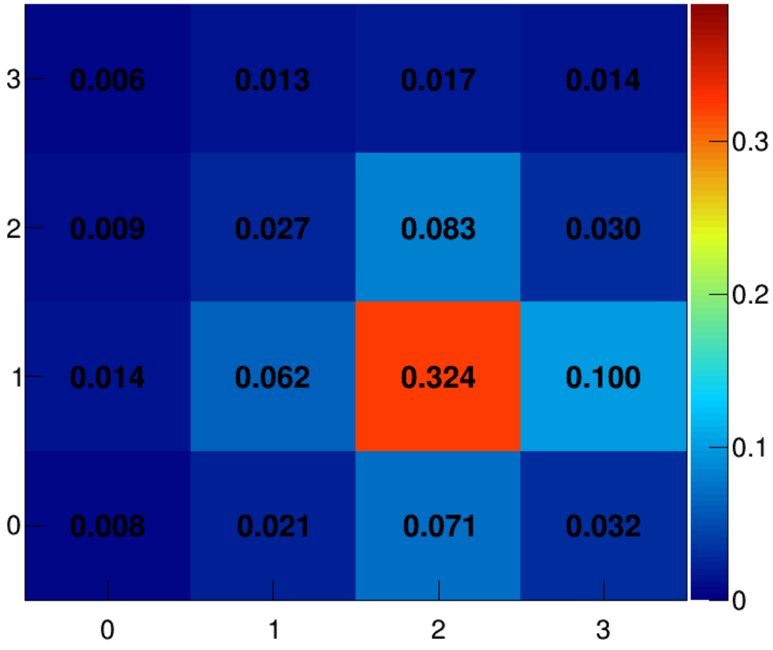


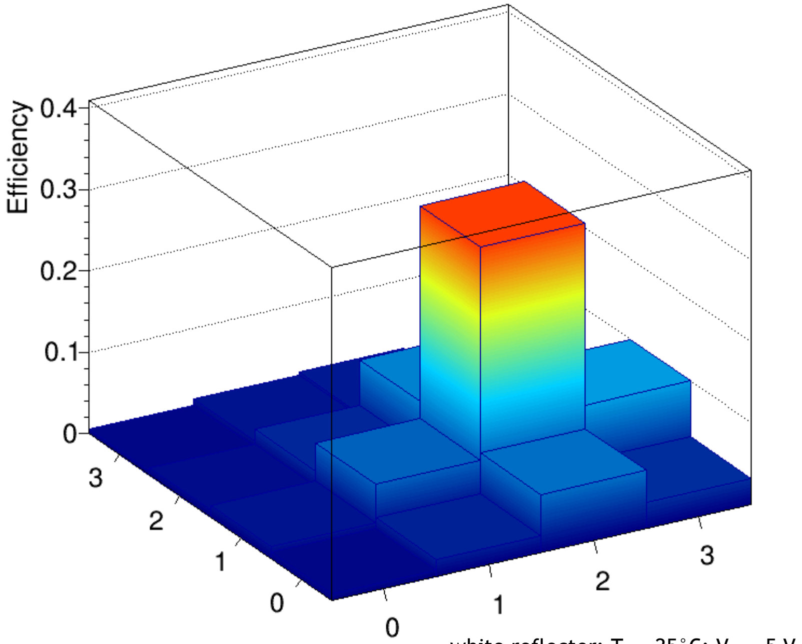
Channel

13	14	1	2
12	15	0	3
11	8	7	4
10	9	6	5

Position

12	13	14	15
8	9	10	11
4	5	6	7
0	1	2	3





white reflector; T = -25°C; V_{ov} = 5 V

Results: cross talk - optical leakage between channels

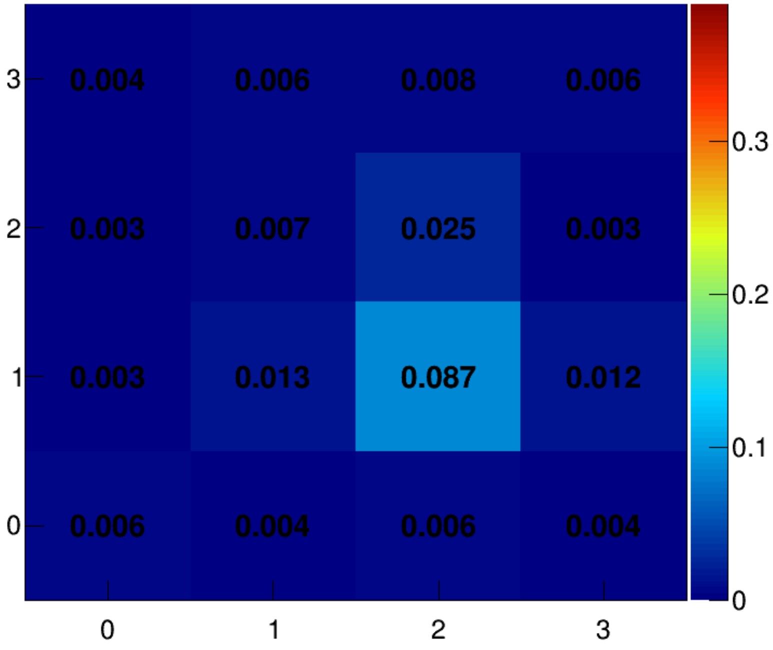
- Crystal array **black painted** instead of white reflector
  - nearest neighbors average 11% crosstalk
  - diagonal neighbors average 0% crosstalk

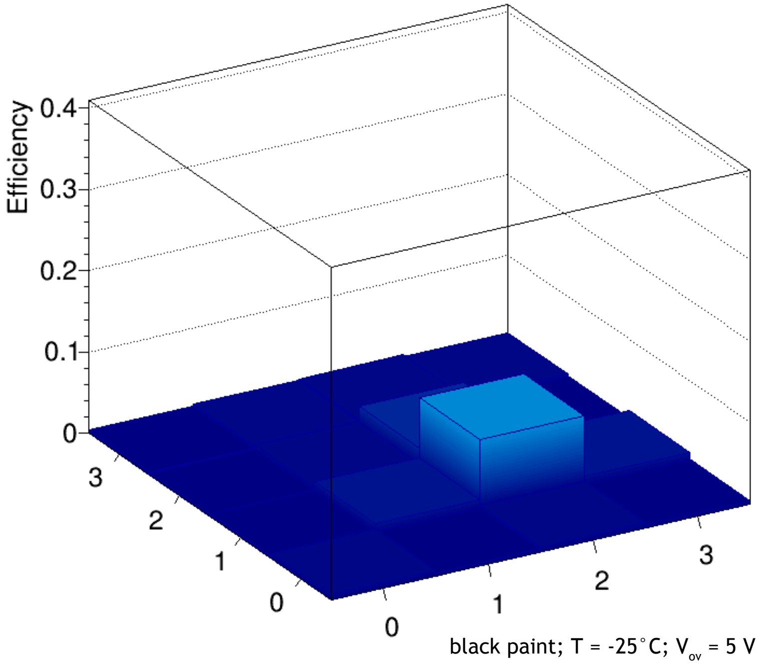
Channel

13	14	1	2
12	15	0	3
11	8	7	4
10	9	6	5

Position

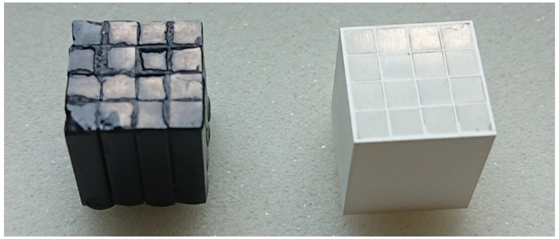
12	13	14	15
8	9	10	11
4	5	6	7
0	1	2	3





Results: efficiency map for black painted array

- Efficiency of each channel when collimated with the source
  - average = 6.9% (previous single ch. result ~ 5% - 8%)
  - much less homogeneous results
    - lower quality of crystal array assembly



Channel

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Position

12	13	14	15
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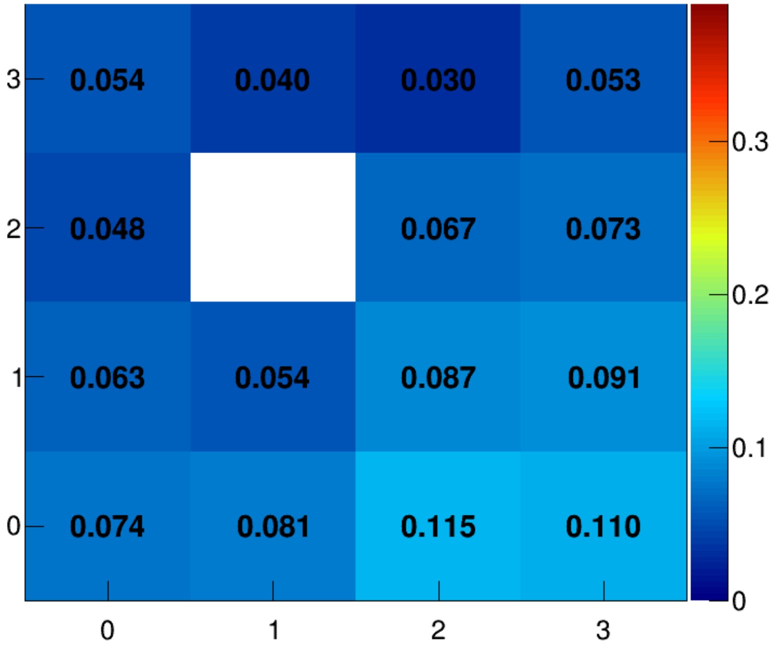
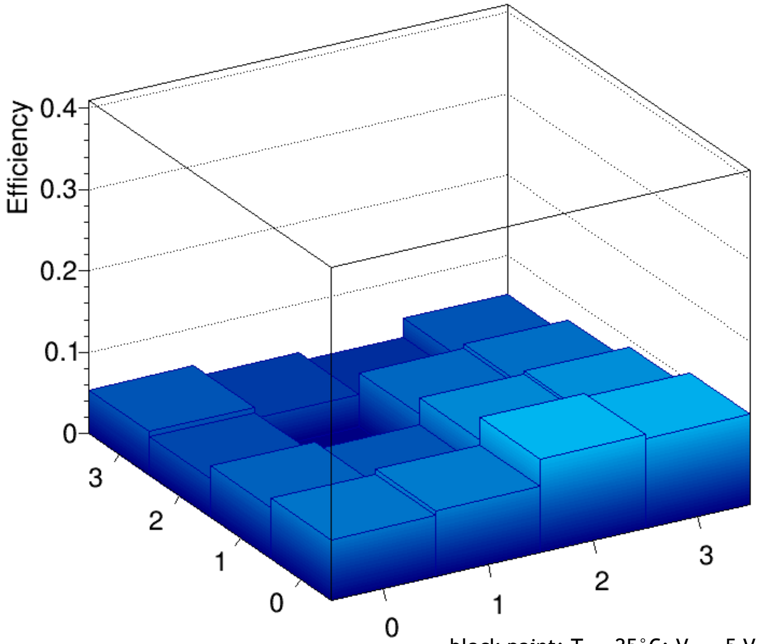
4	5	6	7
0	1	2	3

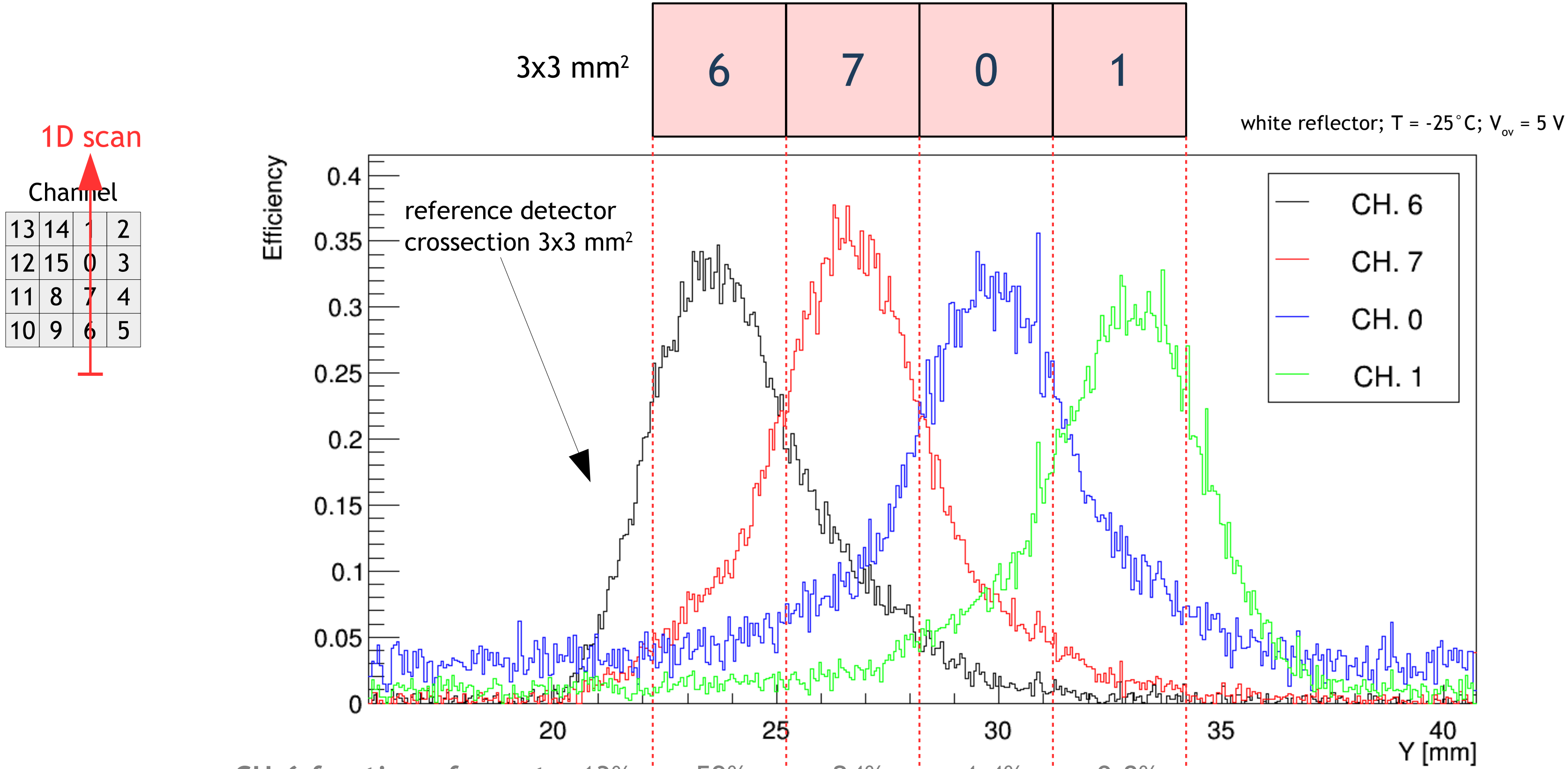




black paint; T = -25°C; V_{ov} = 5 V

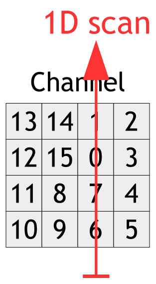
Results: cross talk

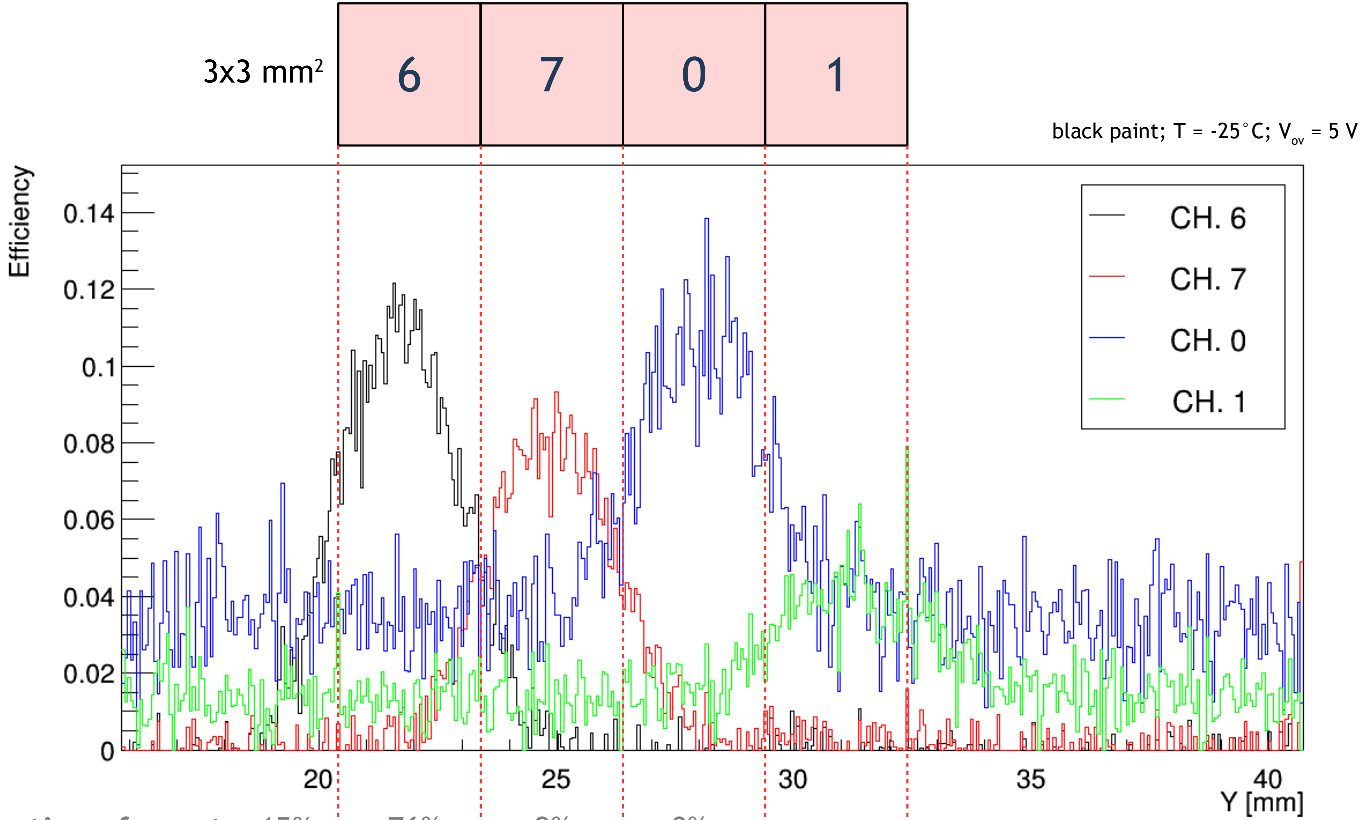
- Source scanned over one column of SiPM array



CH.6 fraction of events:	13%	59%	24%	4.4%	0.8%
CH.7 fraction of events:	2%	19%	56%	18%	4%

- Source scanned over one column of SiPM array - black painted array



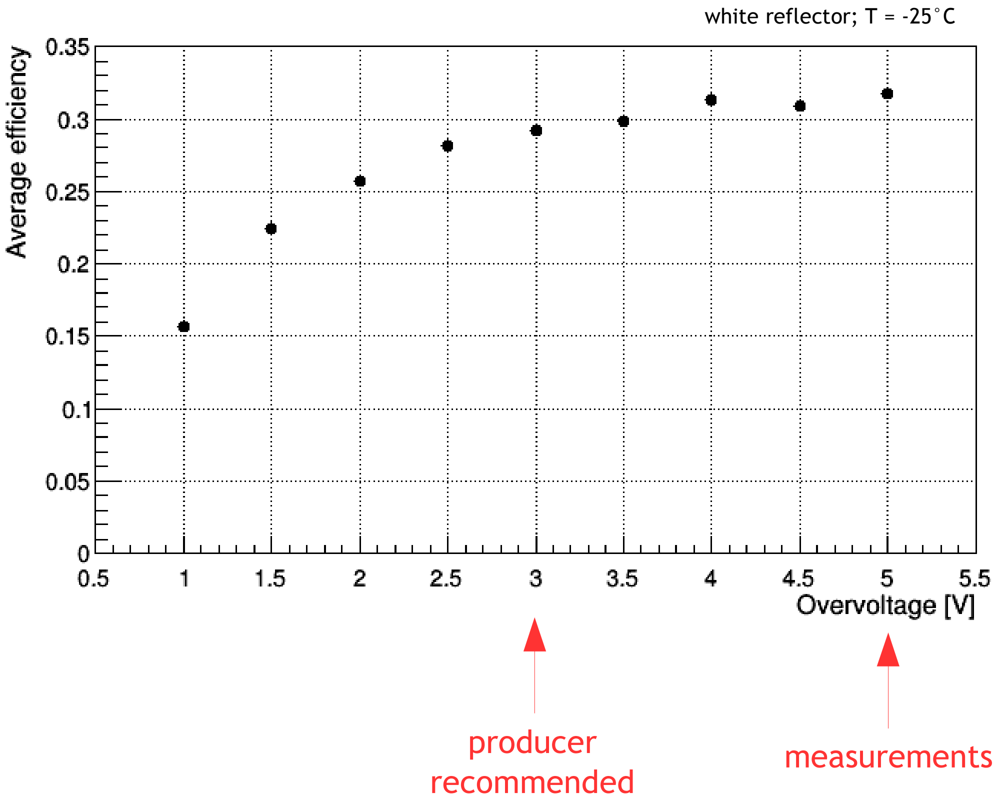


CH.6 fraction of events:	15%	76%	9%	0%	
CH.7 fraction of events:	2%	12%	71%	13%	3%

→ most crosstalk due to optical leakage

Results: efficiency vs. SiPM overvoltage

- Average efficiency over all (15 connected) channels



Summary

- Use of Cherenkov light in PET
  - TOF resolution <100 ps FWHM (limited efficiency)
  - efficiency 30% single side (limited TOF resolution)
- Low cost of PbF_2
  - reduce cost PET of scanners (limited TOF, but still competitive performance)
  - total-body PET scanners
- 16 channel PET module
  - 4x4 array of 3x3 mm^2
    - PbF_2 Cherenkov radiator + SiPM photodetector
  - eficiency 28% single side
  - good uniformity
  - optical crosstalk between channels should be reduced
- Next steps
  - 2-4 modules in coincidence
  - study effects of Compton events