Recent Progress in PMTs for Cherenkov Counters

Samo Korpar

University of Maribor and Jožef Stefan Institute

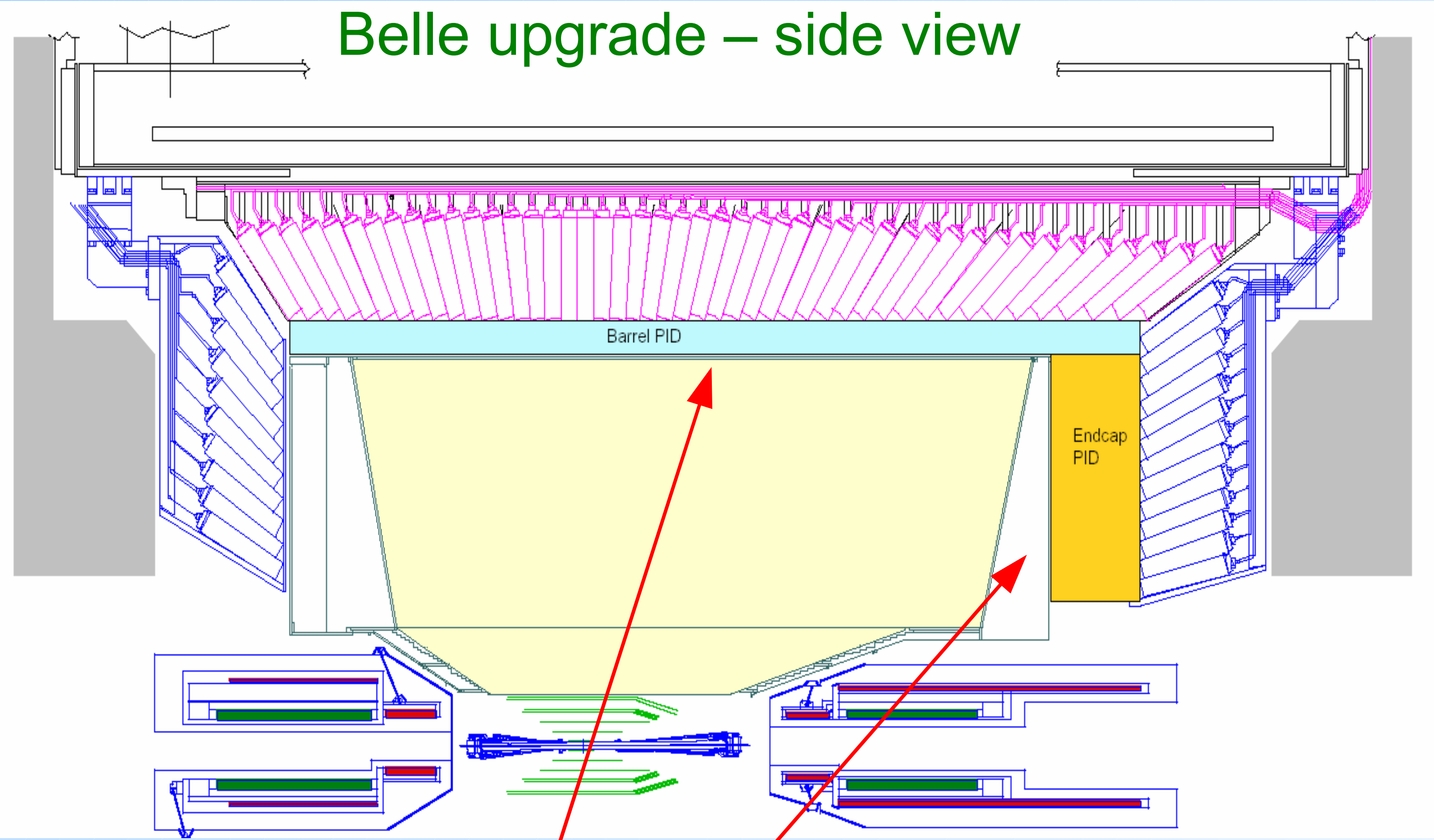
September 23 – 28, 2007

LIGHT07, Ringberg Castle, Tegernsee

Outline of the talk:

- Photon detectors for RICH counters operating in high magnetic fields:
  - Belle: TOP, aerogel RICH(+TOF)
  - BaBar: focusing DIRC
- Crosstalk study of BURLE MCP-PMTs
- Summary and plan

Belle: Proposed PID upgrade



Two new particle ID devices, both RICHes:

- Barrel: Time-Of-Propagation (TOP) or focusing DIRC, TOF
- End-cap: proximity focusing aerogel RICH

TOP principle

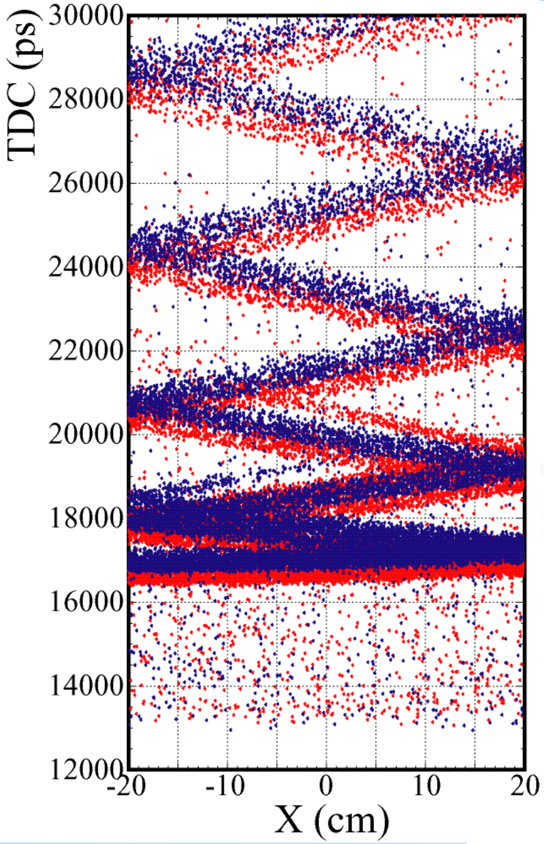
Time-of-Propagation counter:

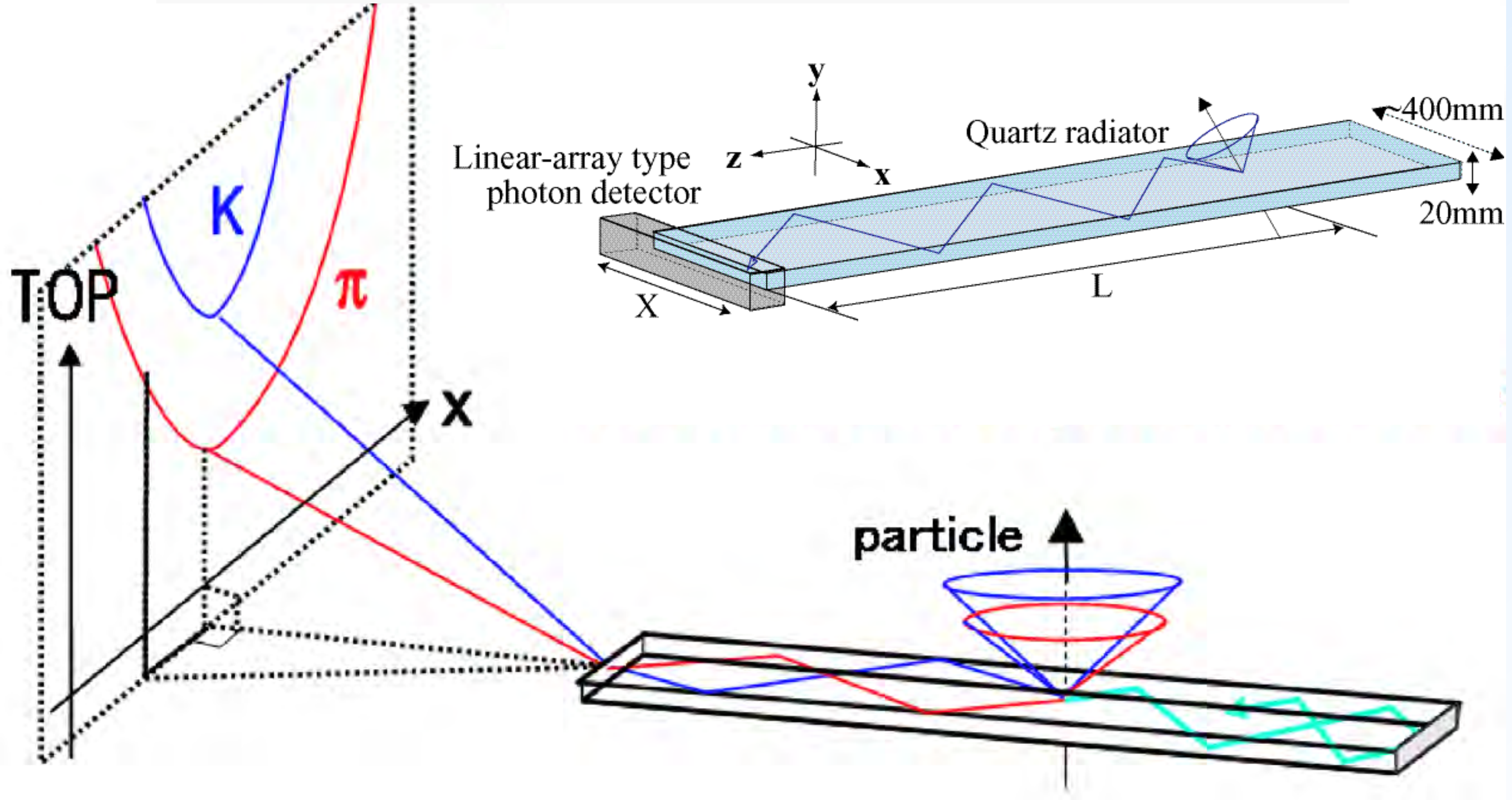
Measurement of

- One (or two coordinates) with a few mm precision
- Time-of-arrival (+TOF)

Excellent time resolution < ~40ps required for single photons at 1.5T

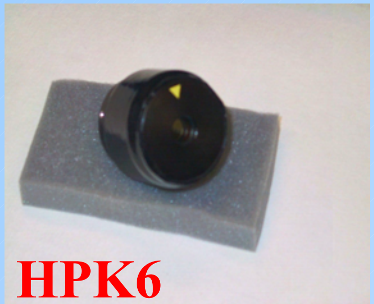
Simulation
2GeV/c, θ=90 deg.

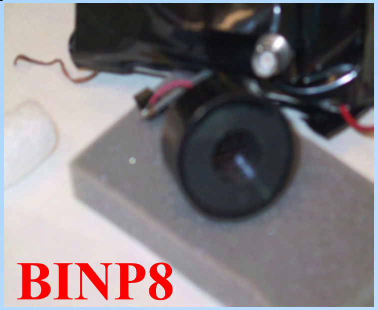


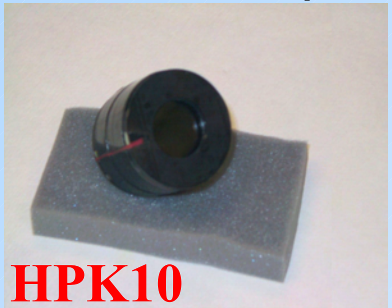


MCP-PMT for single photon

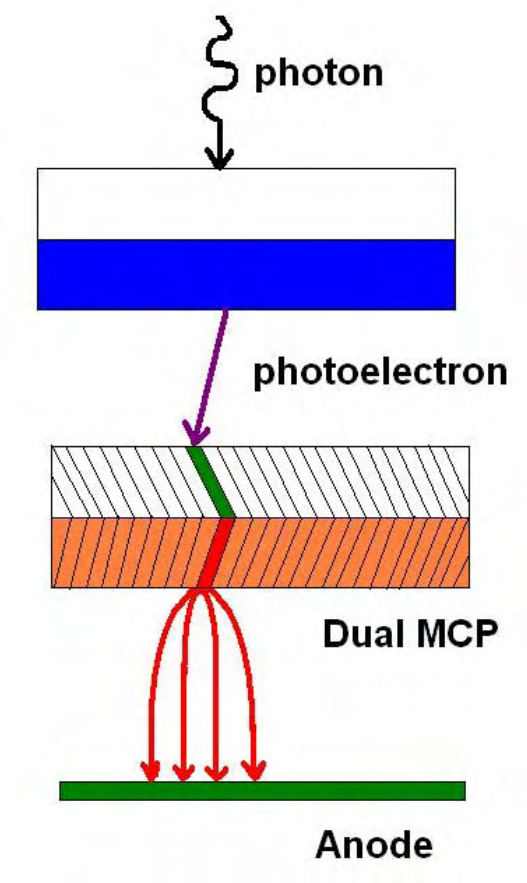
- Timing properties under B=0~1.5T parallel to PMT







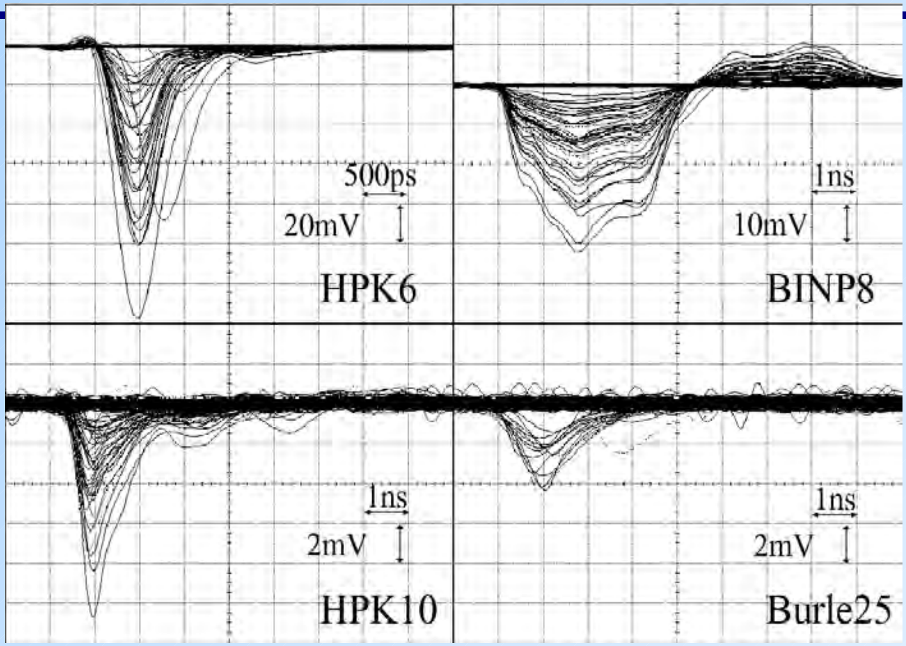
MCP-PMT	HPK6 R3809U-50-11X	BINP8 N4428	HPK10 R3809U-50-25X	Burle25 85011-501
PMT size(mm)	45	30.5	52	71x71
Effective size(mm)	11	18	25	50x50
MCP hole diameter(μ m)	**6**	**8**	**10**	**25**
Length-diameter ratio	40	40	43	40
Bias angle (deg.)	13	5	12	10
Max. H.V. (V)	3600	3200	3600	2500
photo-cathode	multi-alkali	multi-alkali	multi-alkali	bi-alkali
Q.E.(%) (λ =408nm)	26	18	26	24

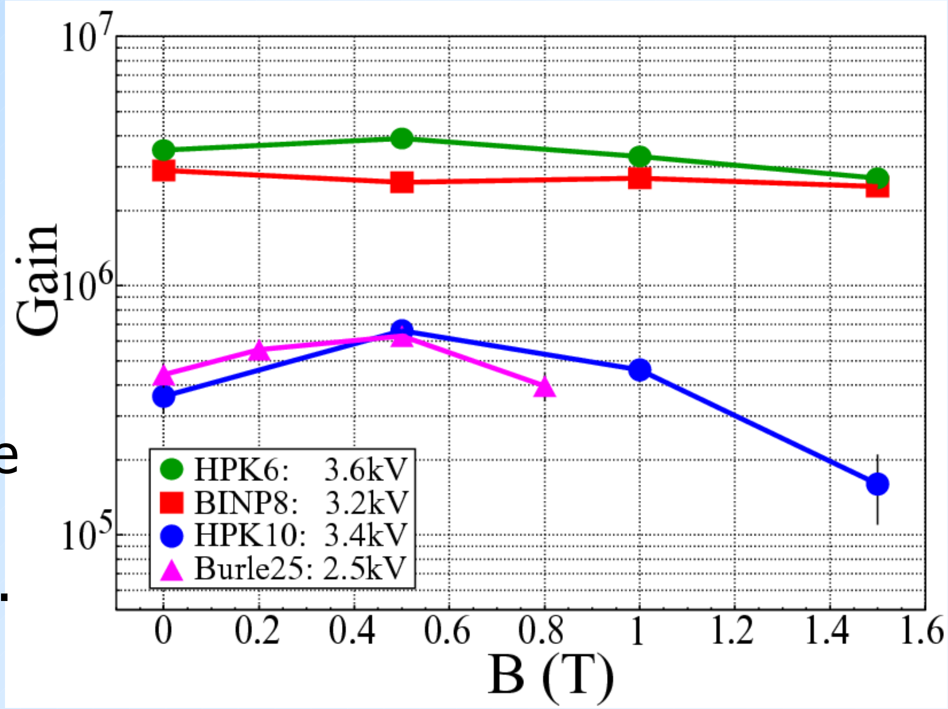


K. Inami @PD07

Pulse response

- Pulse shape (B=0T)
  - Fast raise time (~500ps)
  - Broad shape for BINP8
    - Due to mismatch with H.V. supply and readout cable
    - No influence for time resolution
- Gain v.s. B-field
  - Small hole diameter shows high stability against B-field.
  - Explained by relation btw hole size and Larmor radius of electron motion under B-field.



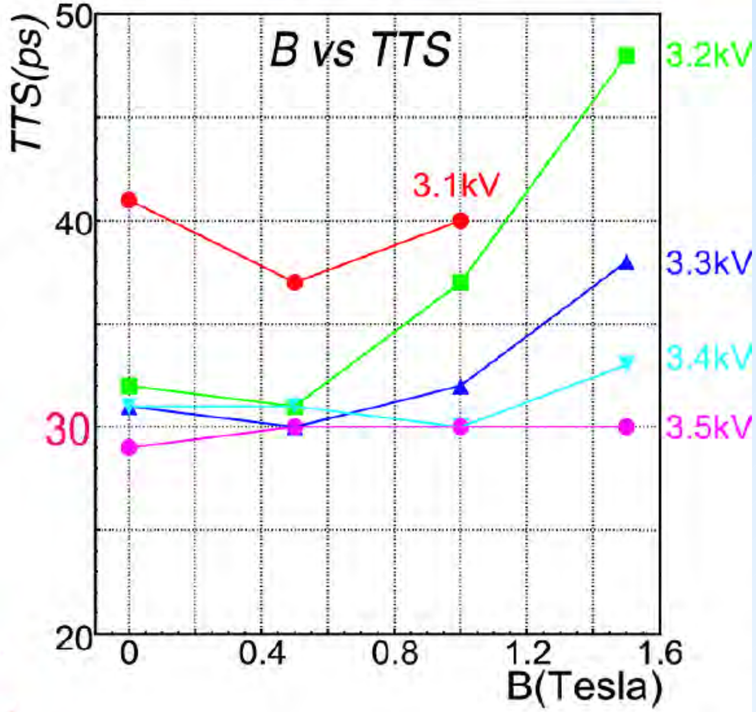


K. Inami @PD07

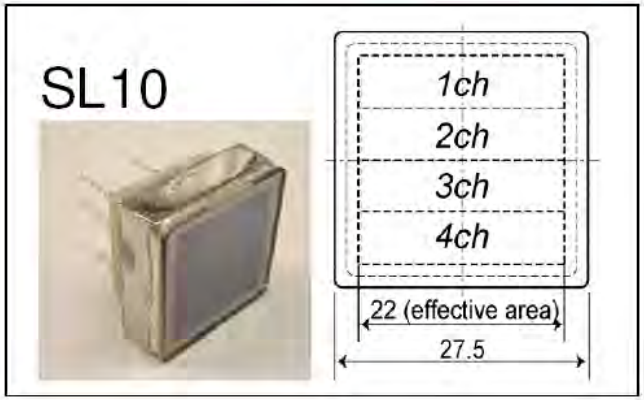
Fast photon detection: Hamamatsu MCP-PMT SL10

- 4ch linear array MCP-PMT

Photo cathode	mutli-alkali
MCP ch ϕ	10 μm
# of MCP	2 stage
# pixel/size	1×4 / 5mm×22mm
Geometrical C.E.	50%
Eff. area(2cmT)	77%
Gain (HV)	2×10^6 ($-$3.5 kV)
σ_{TTS}(HV, B)	~30ps ($-$3.5 kV, 1.5T)

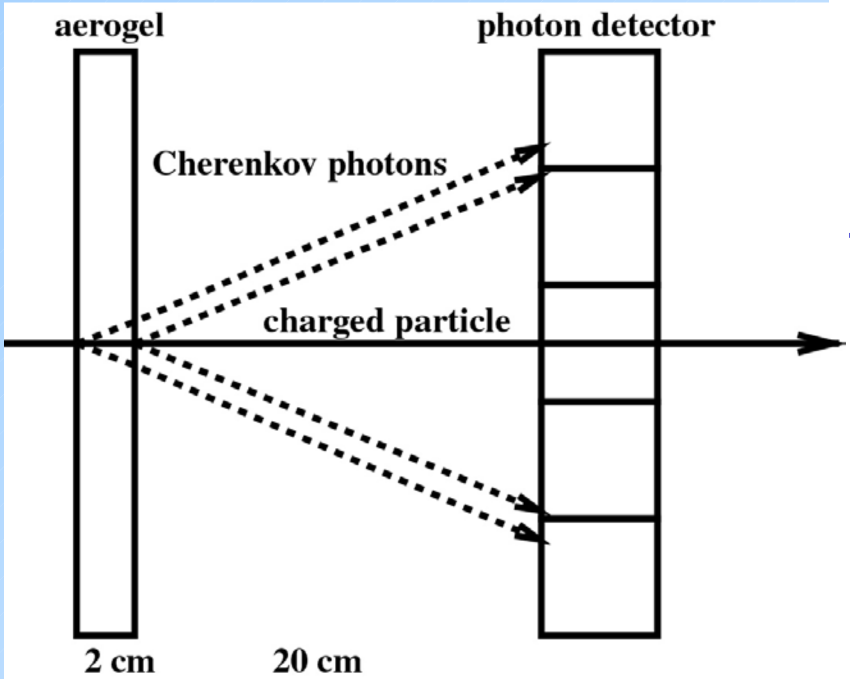


- Gain $> 10^6$, $\sigma_{TTS} \sim$ 30ps in B =1.5 T : Confirmed



Status of TOP Counter, 2005.04.20 Super B-Factory Workshop – p.14/22

Endcap: Proximity focusing RICH



K/π separation at 4 GeV/c:

$\theta_c(\pi) \sim 308$ mrad (n = 1.05)

$\theta_c(\pi) - \theta_c(K) \sim 23$ mrad

For single photons: $\delta\theta_c$(meas.)$=\sigma_0 \sim 14$ mrad,

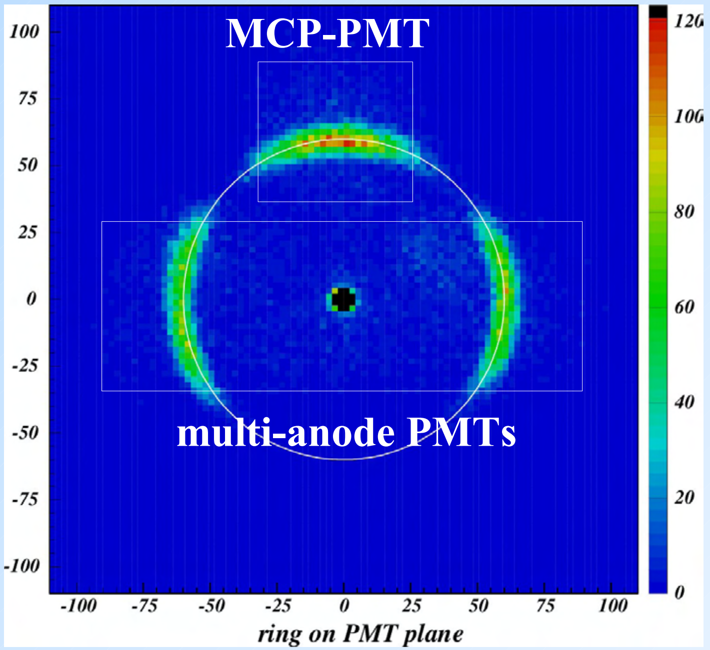
typical value for a 20mm thick radiator and 6mm PMT pad size

Per track: $$\sigma_{track} = \frac{\sigma_0}{\sqrt{N_{pe}}}$$

Separation: $[\theta_c(\pi) - \theta_c(K)]/\sigma_{track}$

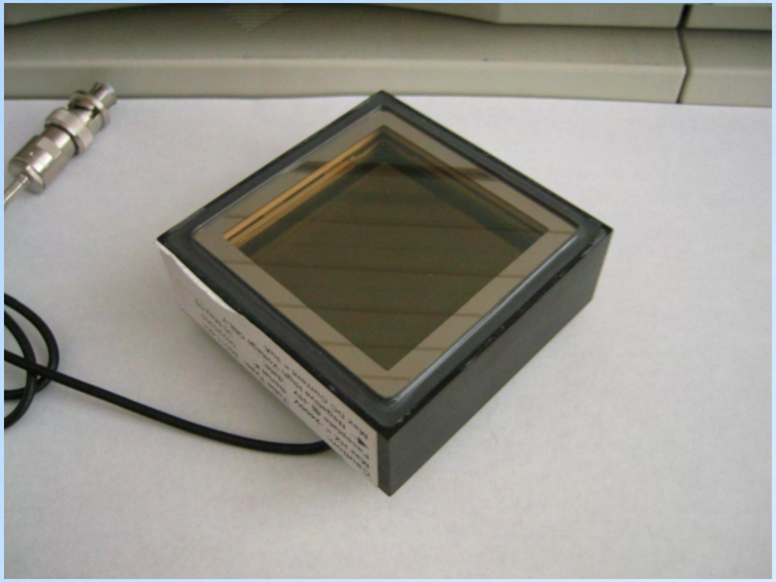
→ 5σ separation with $N_{pe} \sim 10$

PHOTON DETECTION WITH MCP-PMT



BURLE 85011-501 MCP-PMT:

- multi-anode PMT with two MCP steps
- 25 μm pores
- bialkali photocathode
- gain ~ 0.6 x 10^6
- collection efficiency ~ 60%
- box dimensions ~ 71mm square
- 64(8x8) anode pads
- pitch ~ 6.45mm, gap ~ 0.5mm
- active area fraction ~ 52%



- Tested in combination with multi-anode PMTs

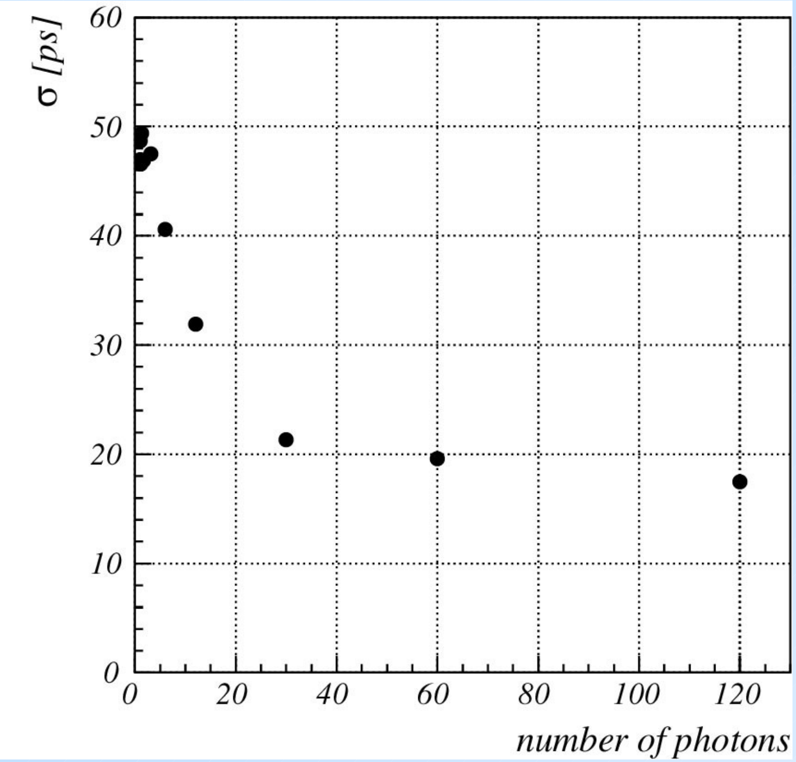
- σ_ϑ ~13 mrad (single cluster)
- number of clusters per track N ~ 4.5
- σ_ϑ ~ 6 mrad (per track)
- → ~ **4 σ π/K separation at 4 GeV/c**

- 10 μm pores required for 1.5T
- collection efficiency and active area fraction should be improved
- aging study should be done

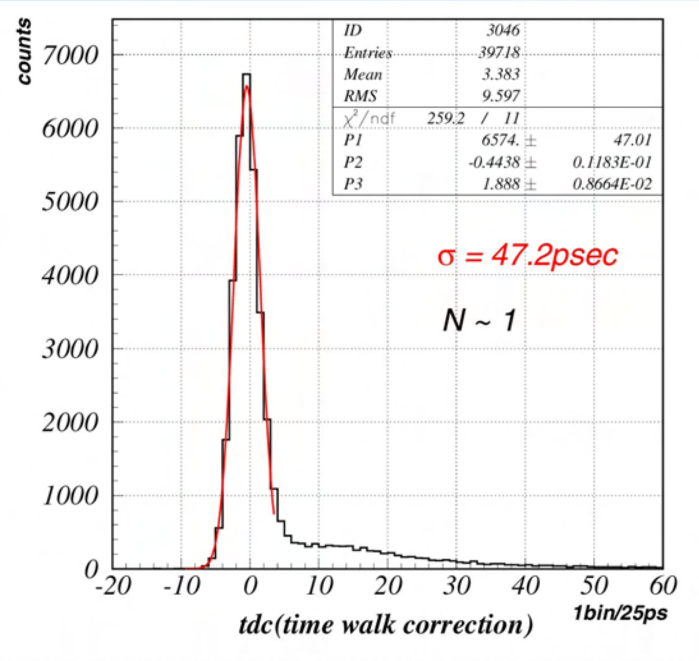
MCP-PMT TIMING PROPERTIES

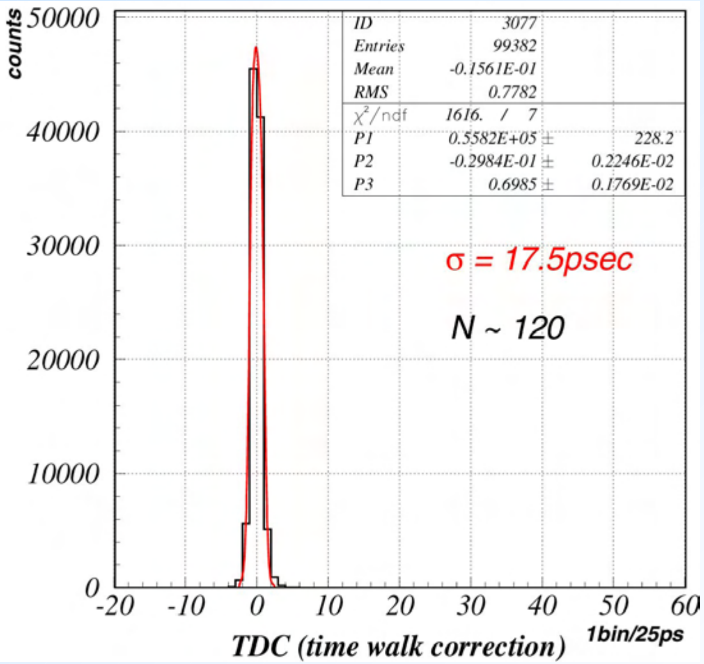
Bench tests with pico-second laser:

- amplifier ORTEC FTA820A
- discriminator PHILIPS 308
- CAMAC TDC Kaizu works KC3781A, 25ps LSB
- CAMAC charge sensitive ADC



Time resolution as a function of the number of detected photons.



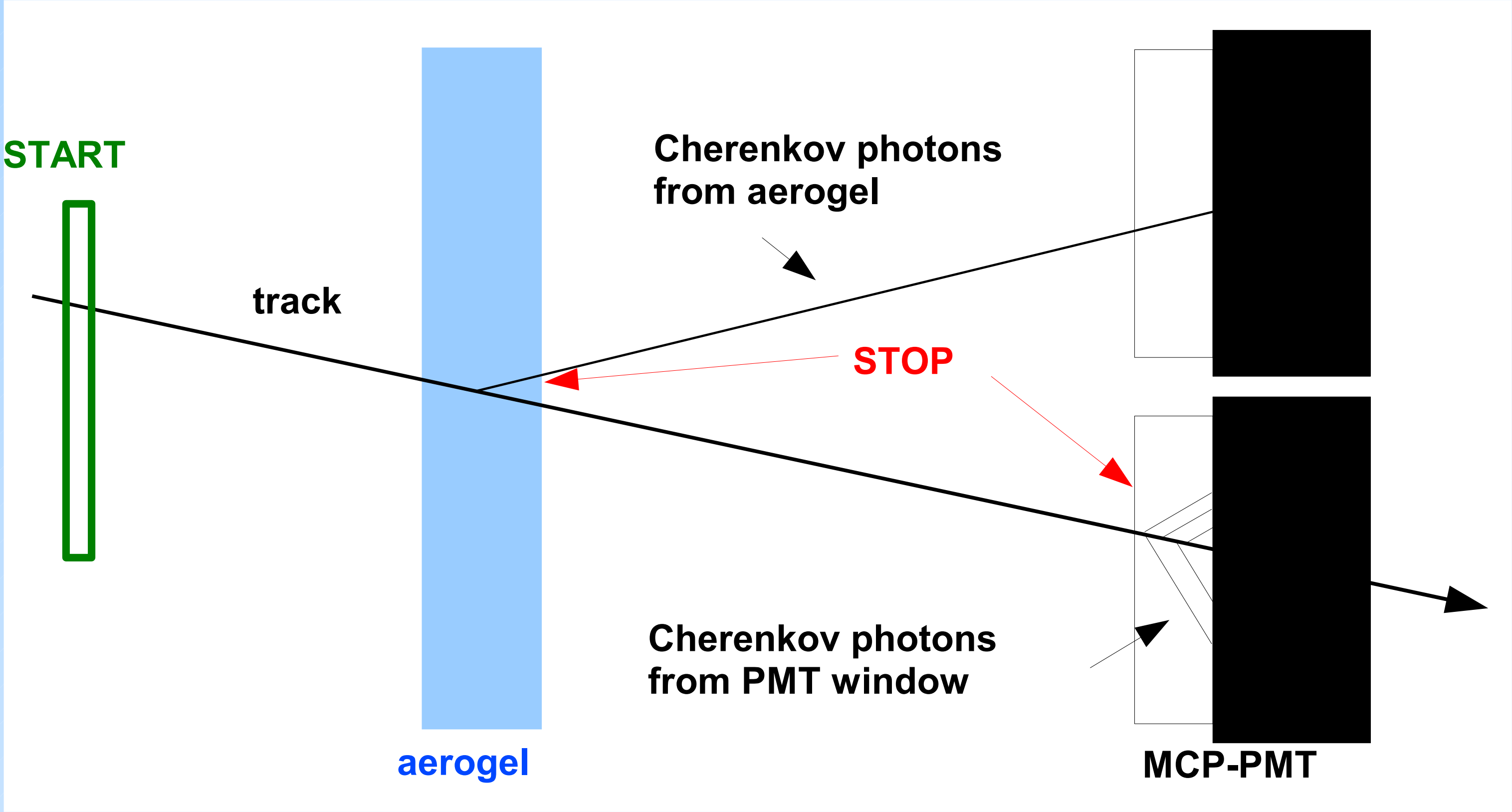


TOF CAPABILITY

With the use of a fast photon detector a proximity focusing RICH counter can be used also as a time-of-flight counter.

Cherenkov photons from two sources can be used:

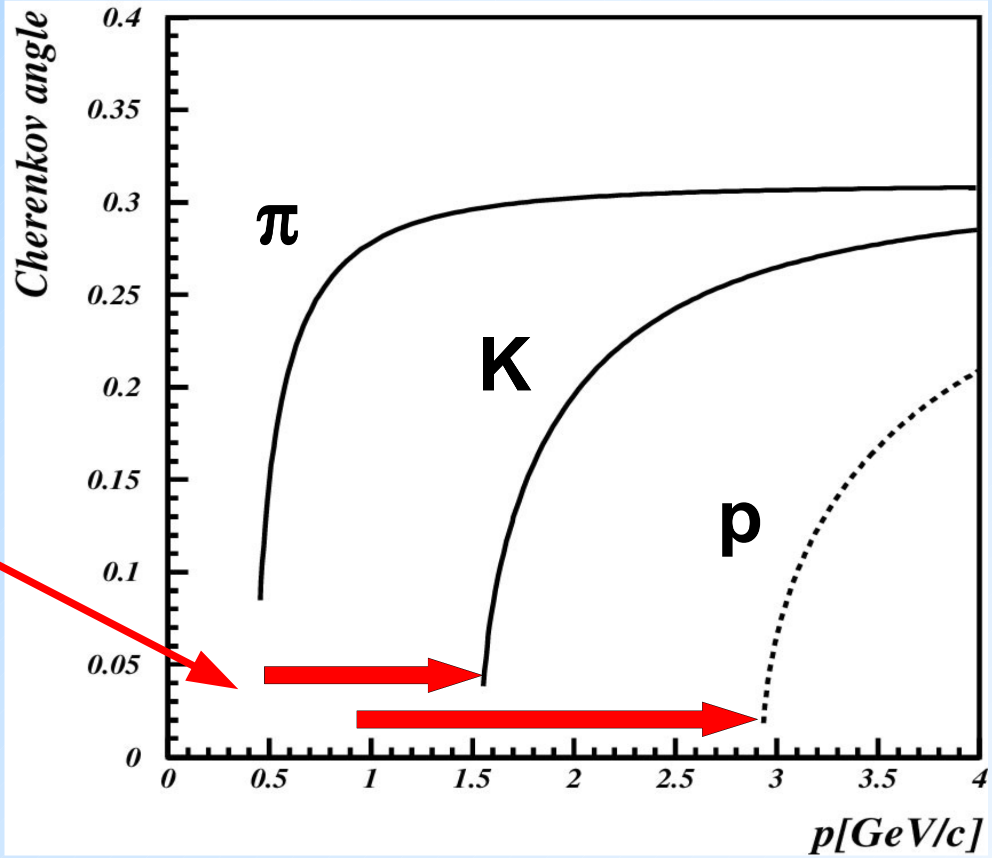
- photons emitted in the aerogel radiator
- photons emitted in the PMT window



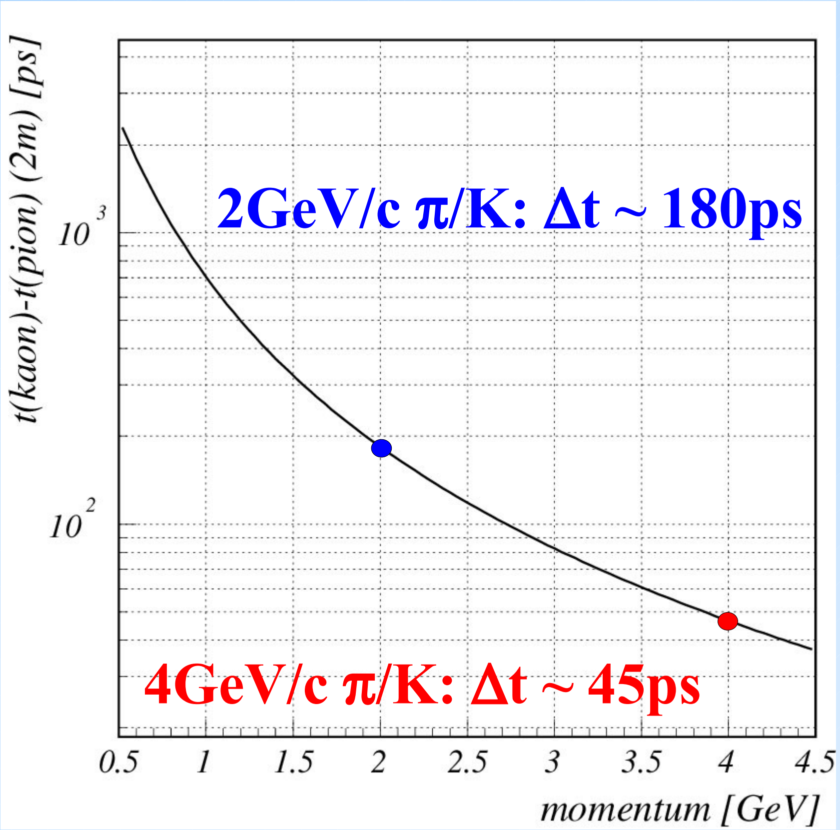
TOF CAPABILITY

Using Cherenkov photons emitted in the PMT window (n~1.46) PID can be extended into the lower momentum region:

Kaons and protons can be positively identified below the Cherenkov threshold in aerogel (n~1.05).



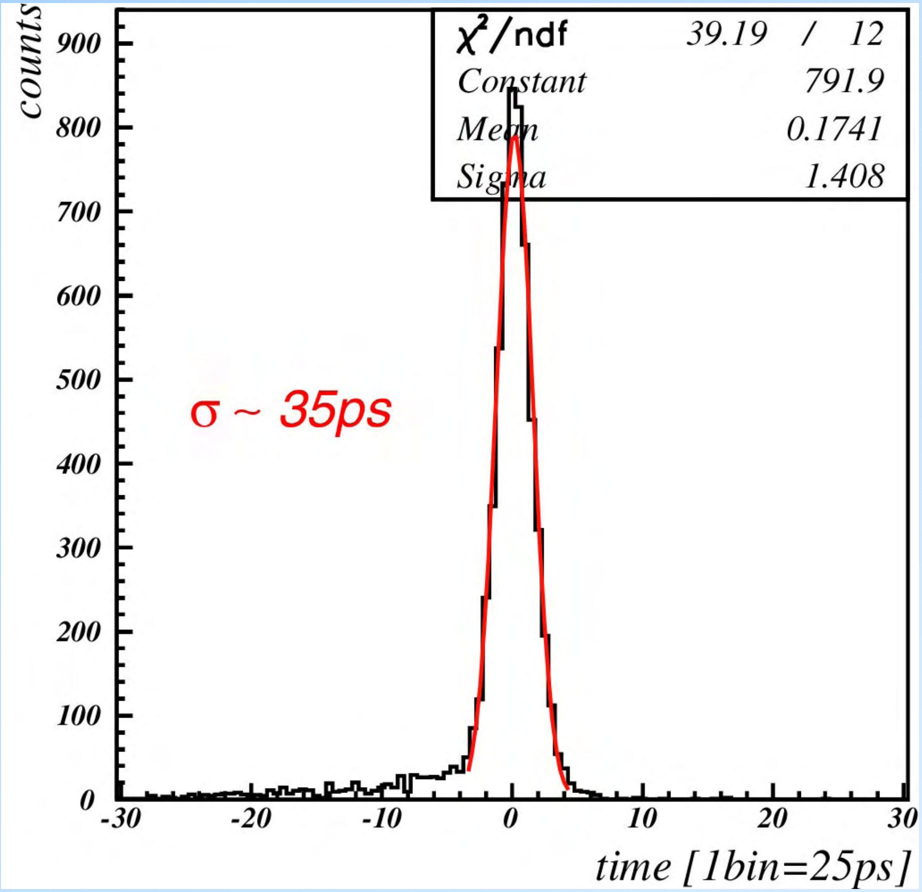
Cherenkov angle in aerogel (n=1.05) for pion, kaon and proton.

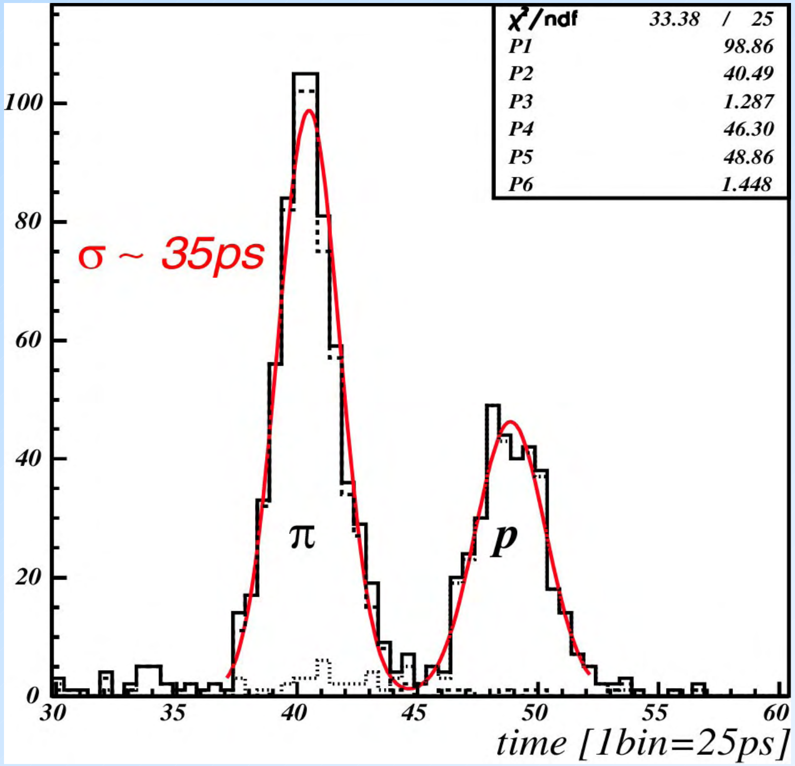


Time-of-flight difference for pions and kaons from IP to forward PID (2m).

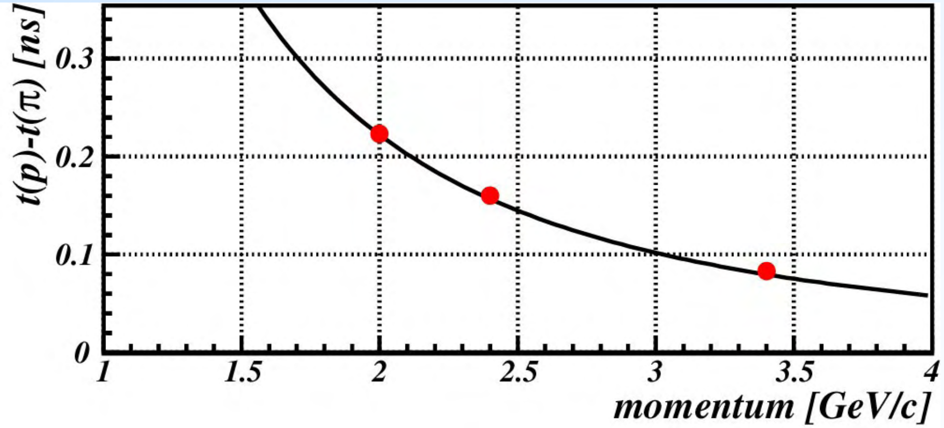
TOF: WINDOW PHOTONS

- expected number of detected Cherenkov photons emitted in the PMT window(2mm) is ~ 12 and expected resolution ~ 32 ps
- obtained resolution for window photons is ~ 35ps

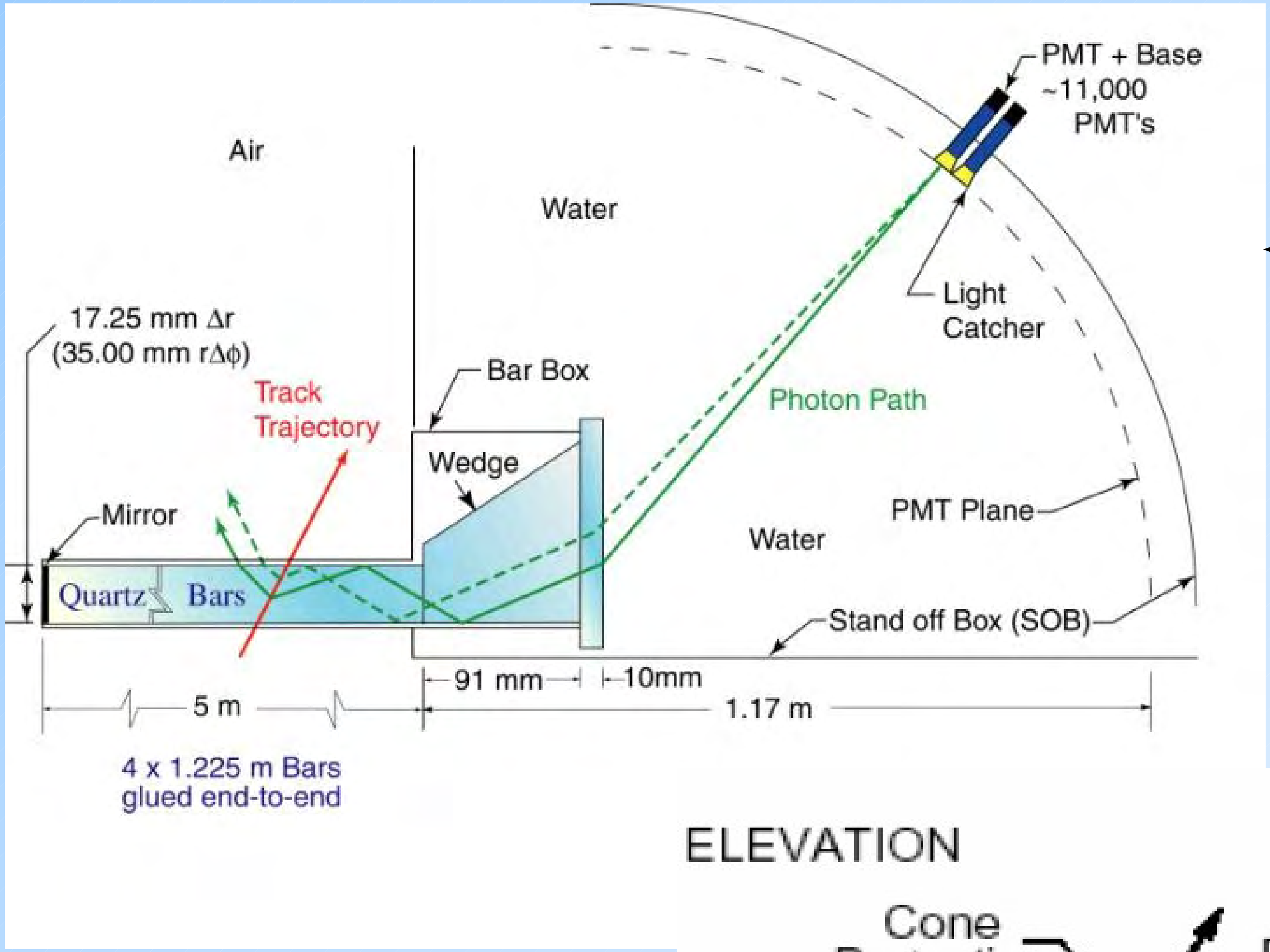




- TOF test with pions and protons at 2 GeV/c
- distance between start counter and MCP-PMT is 65cm

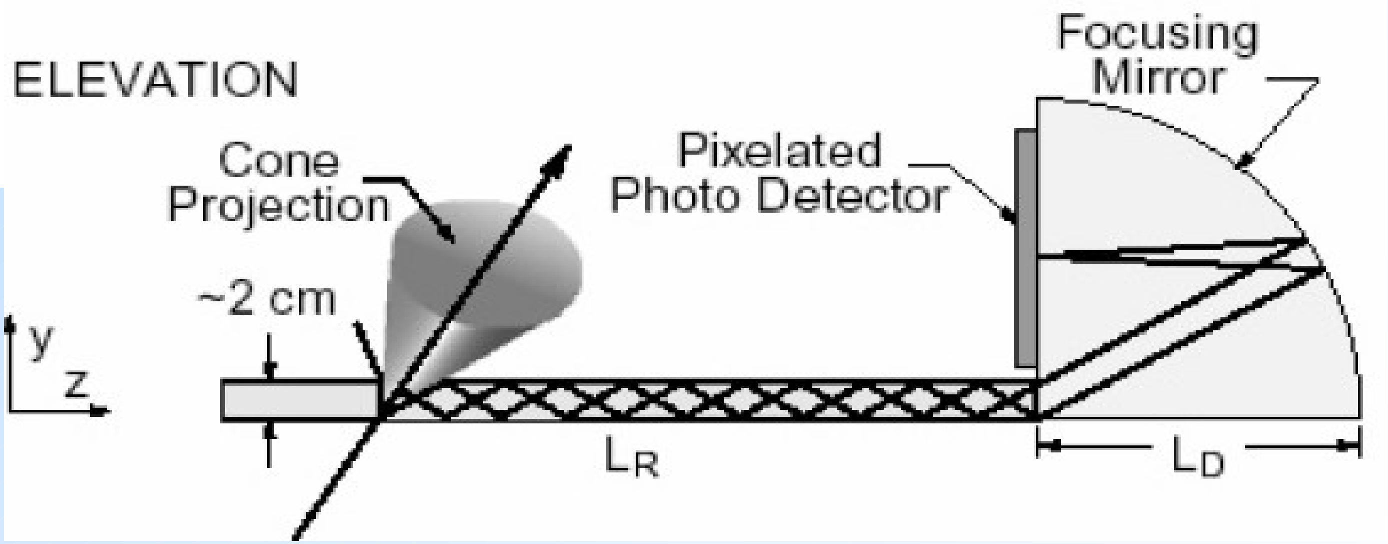


BaBar: Focusing DIRC



← Standard DIRC

Remove the stand-off box
→ Focusing DIRC



Focusing DIRC

Super-B factory: 100x higher luminosity => DIRC needs to be smaller and faster

Focusing and smaller pixels can reduce the expansion volume by a factor of 7-10 !

Timing resolution improvement: σ ~1.7ns (BaBar DIRC) → $\sigma \leq$150-200ps (~10x better) which allows a measurement of the photon color to correct the chromatic error of θ_c.

Photon detector requirements:

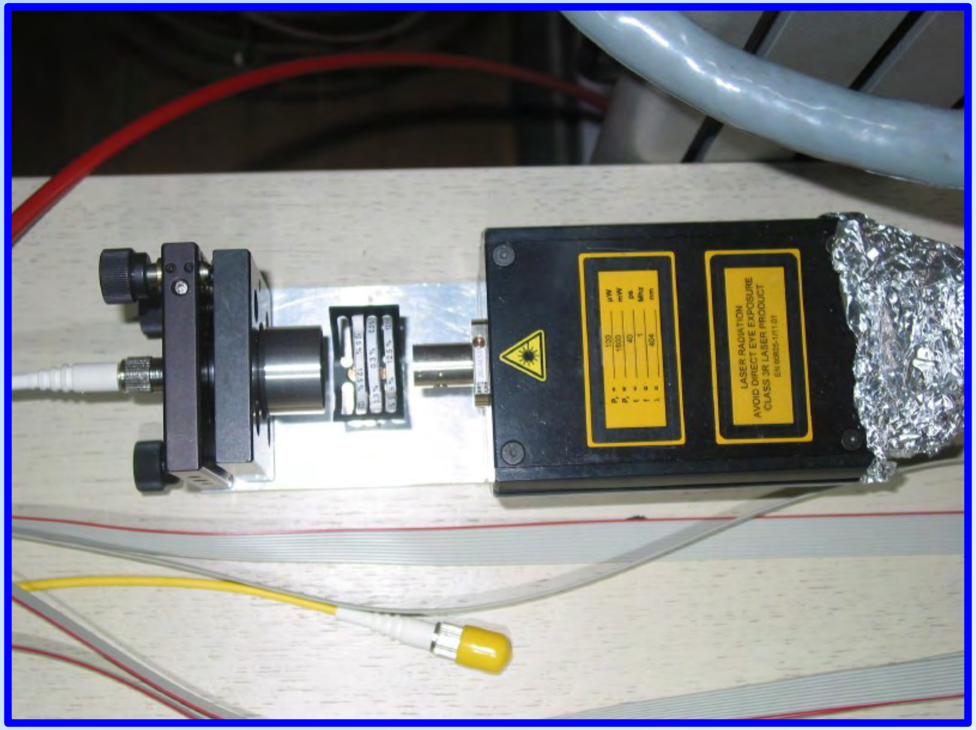
- Pad size <5mm
- Time resolution ~50-100ps

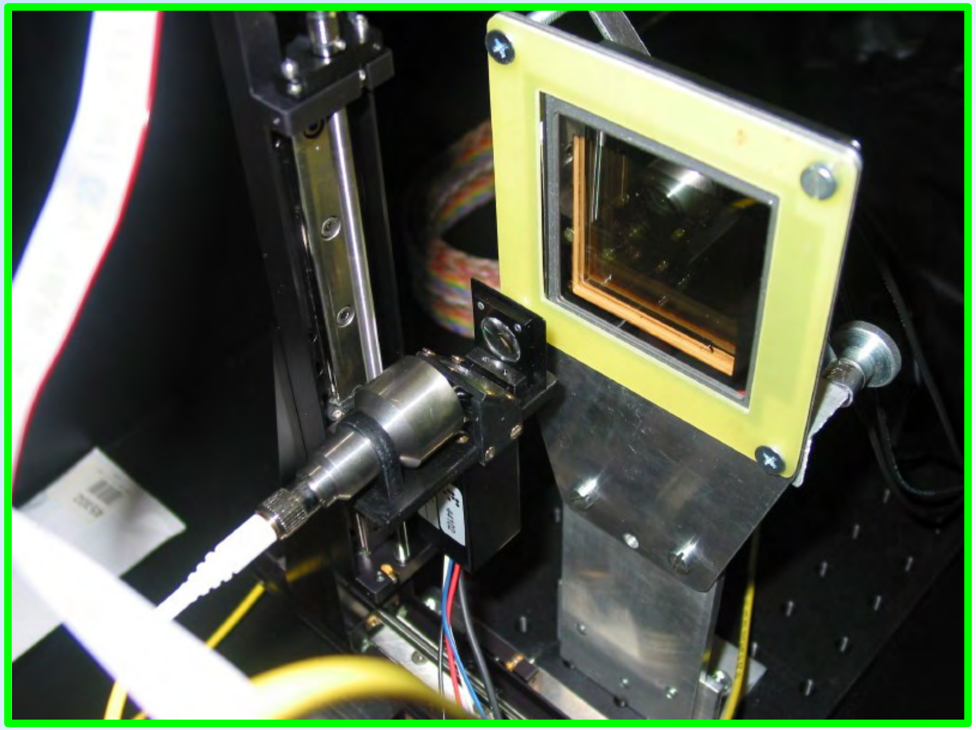
Scanning setup: optical system

Outside dark box:
- PiLas diode laser system EIG1000D (ALS)
- 404nm laser head (ALS)
- filters (0.3%, 12.5%, 25%)
- optical fiber coupler (focusing)

- optical fiber (single mode,~4μm core)

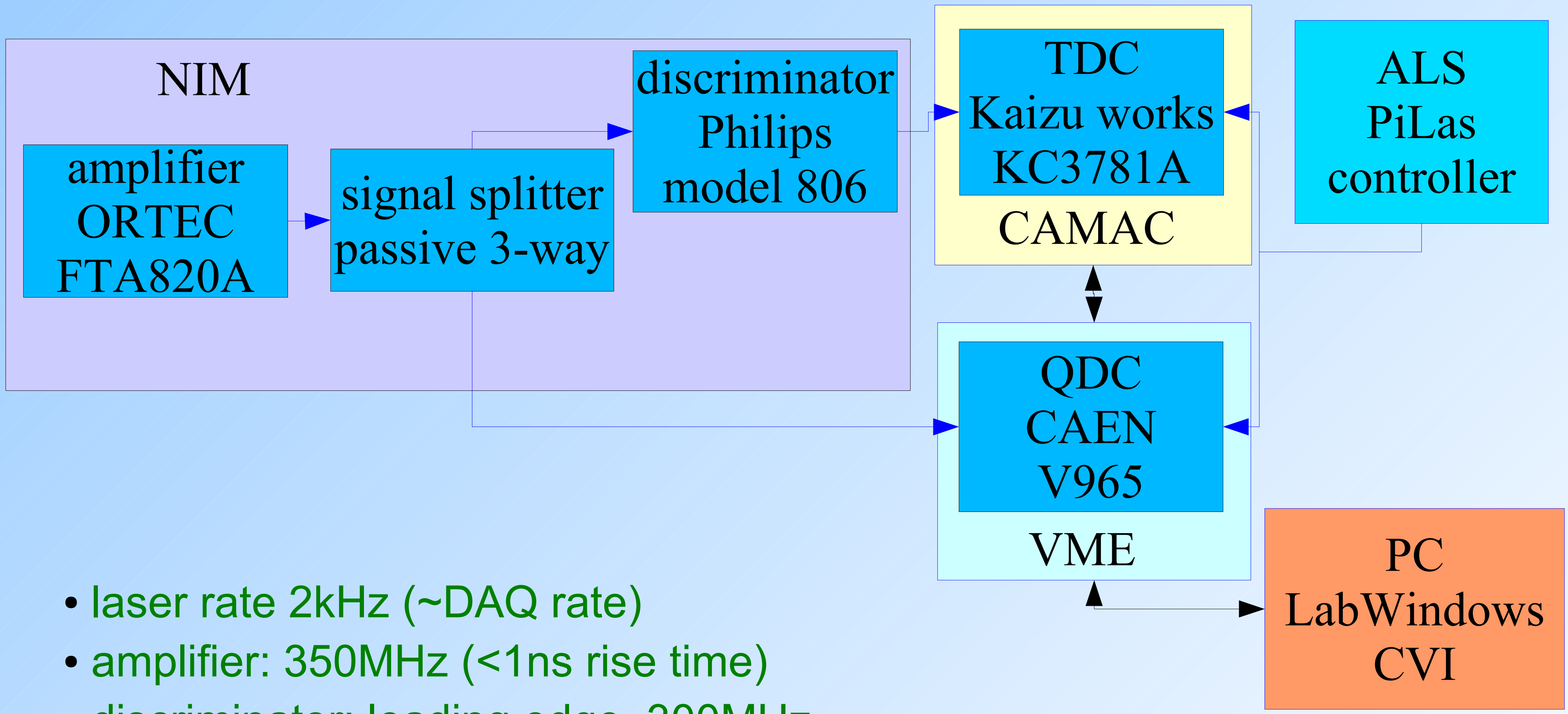
Inside dark box mounted on 3D stage:
- optical fiber coupler (expanding)
- semitransparent plate
- reference PMT (Hamamatsu H5783P)
- focusing lens (spot size σ ~ 10μm)





Samo Korpar
University of Maribor and Jožef Stefan Institute

Scanning setup: readout

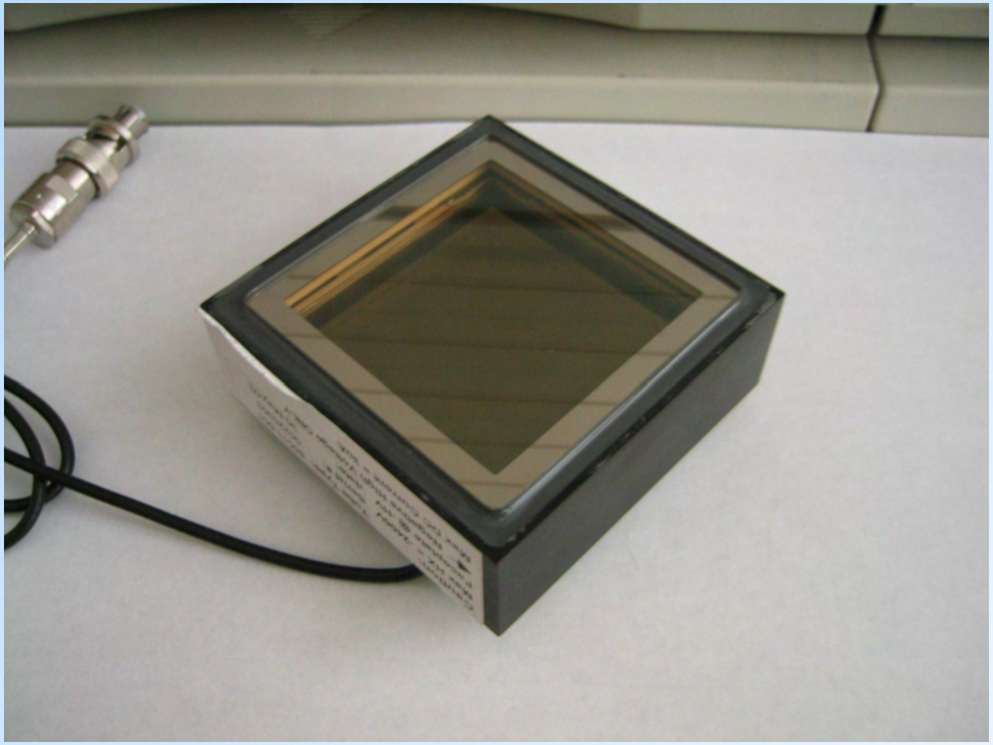


- laser rate 2kHz (~DAQ rate)
- amplifier: 350MHz (<1ns rise time)
- discriminator: leading edge, 300MHz
- TDC: 25ps LSB(σ~11ps)
- QDC: dual range 800pC, 200pC
- HV 2400V

Samo Korpar
University of Maribor and Jožef Stefan Institute

Basic parameters of BURLE MCP-PMTs

- multi-anode PMT with two MCP steps
- bialkali photocathode
- gain ~ 0.6 x 10^6
- collection efficiency ~ 60%
- box dimensions ~ 71mm square
- active area fraction ~ 52%
- 2mm quartz window



BURLE 85011 MCP-PMT
- 64(8x8) anode pads
- pitch ~ 6.5mm, gap ~ 0.5mm
- 25 μm pores

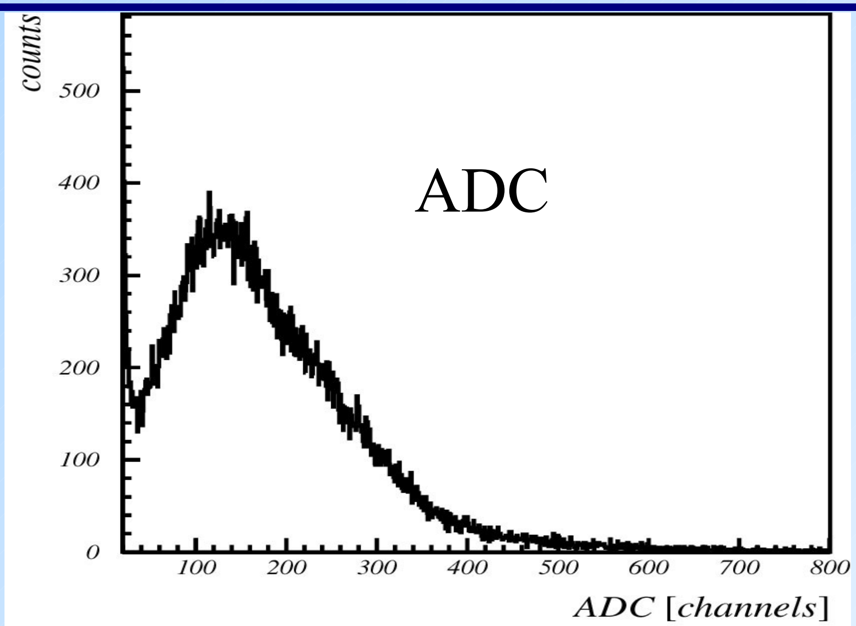
BURLE 85001 MCP-PMT
- 4(2x2) anode pads
- pitch ~ 25mm, gap ~ 1mm
- 10 μm pores

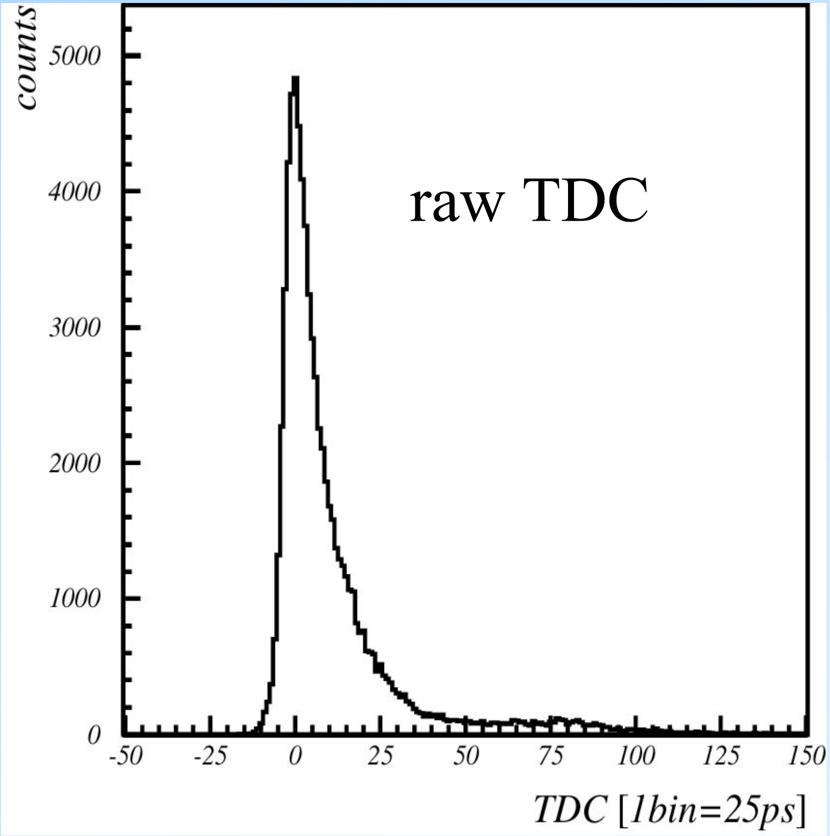
Time walk correction

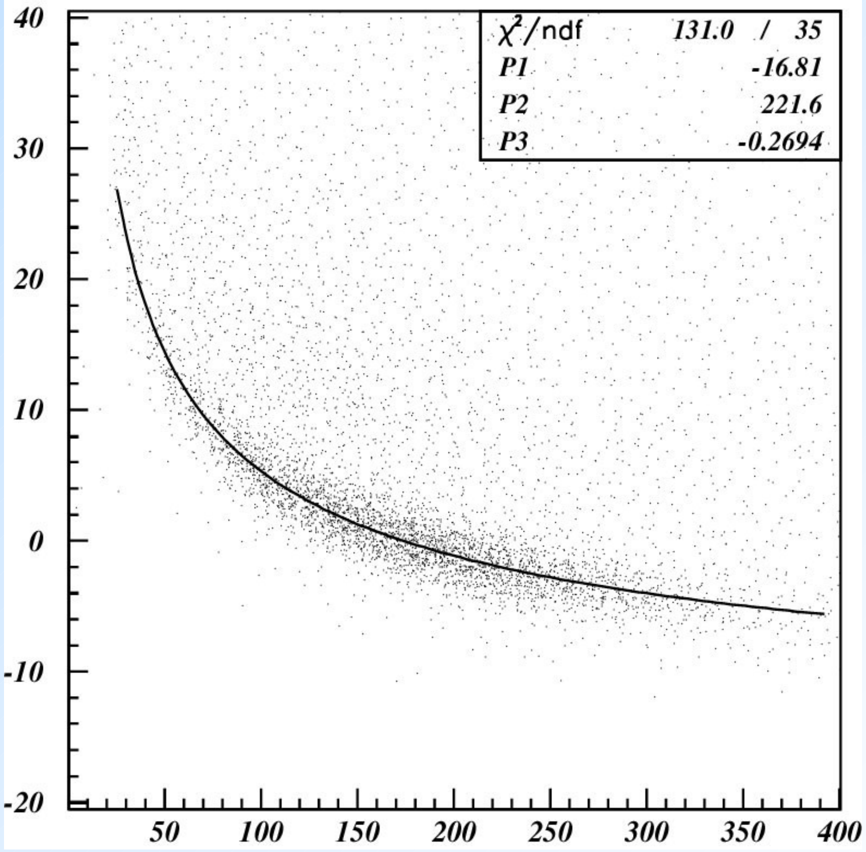
- TDC vs. ADC correlation is fitted with

$$TDC = P1 + \frac{P2}{\sqrt{ADC - P3}}$$

and used for TDC correction



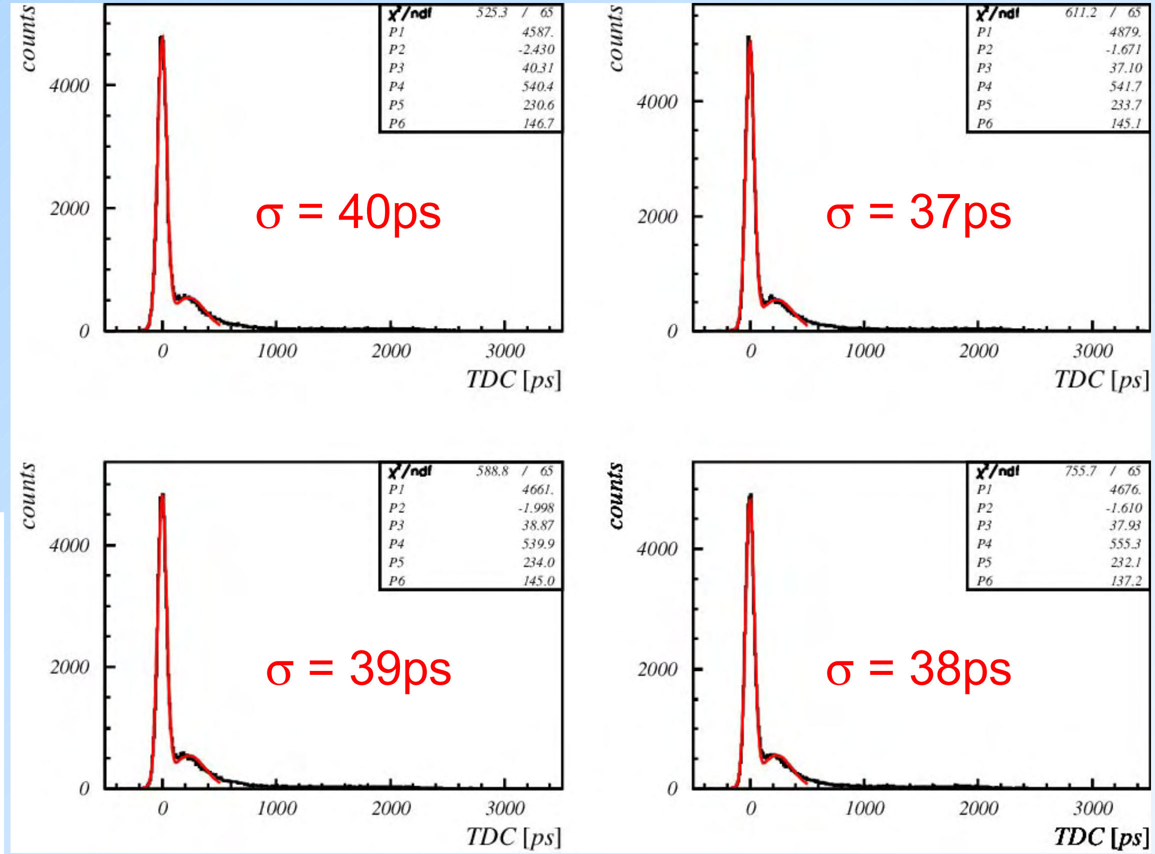


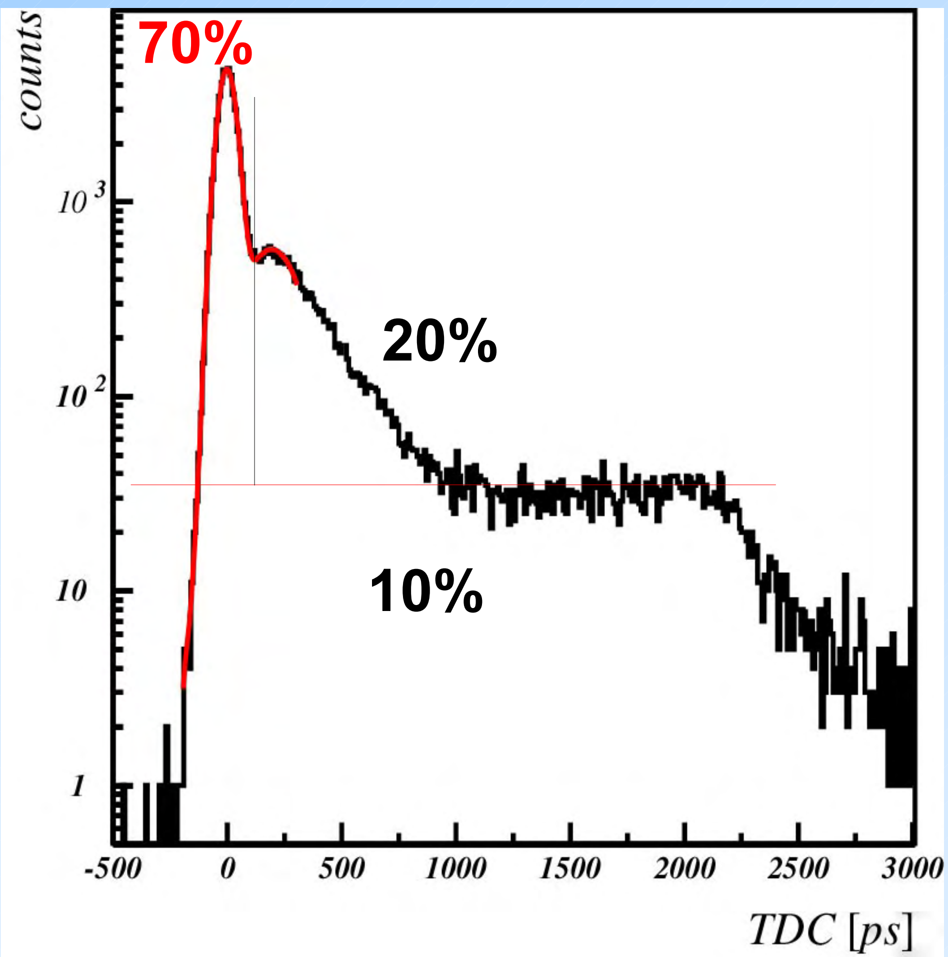


Samo Korpar
University of Maribor and Jožef Stefan Institute

Corrected TDC

- corrected TDC distributions for all pads





- prompt signal ~ 70%
- short delay ~ 20%
- ~ 10% uniform distribution

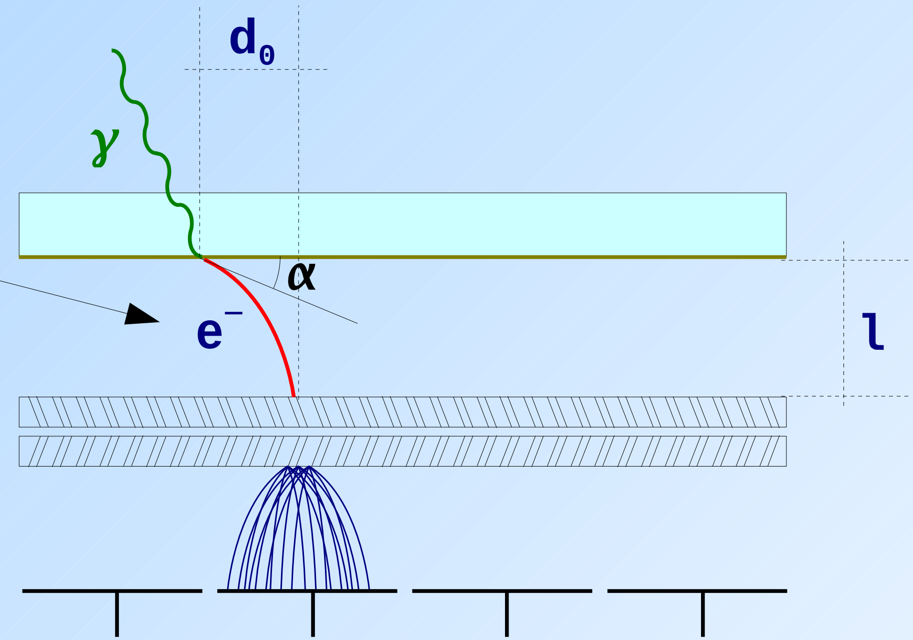
Photon detection

Parameters used:

- $U = 200$ V
- $l = 6$ mm
- $E_0 = 1$ eV
- $m_e = 511$ keV/c^2
- $e_0 = 1.6\ 10^{-19}$ As

Photo-electron:

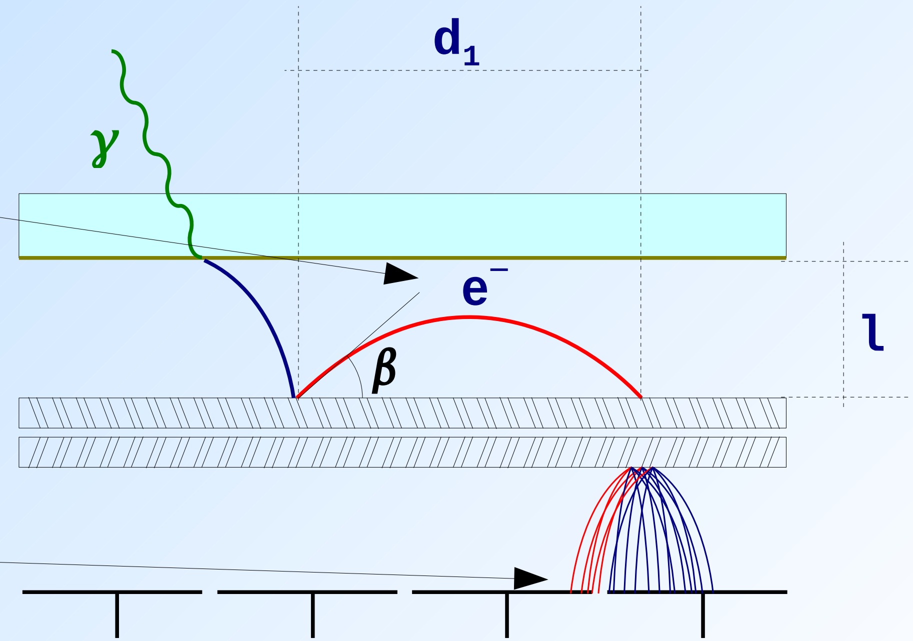
- $d_{0,max} \sim 0.8$ mm
- $t_0 \sim 1.4$ ns
- $\Delta t_0 \sim 100$ ps



Backscattering:

- $d_{1,max} \sim 12$ mm
- $t_{1,max} \sim 2.8$ ns

Charge sharing

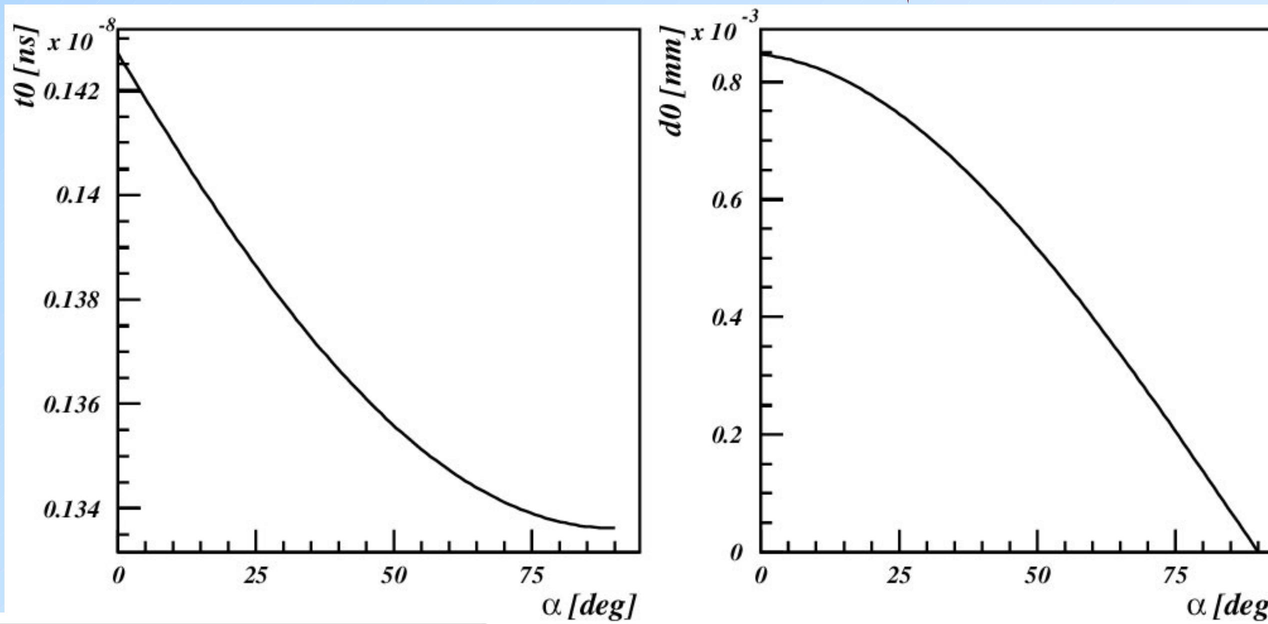


Samo Korpar
University of Maribor and Jožef Stefan Institute

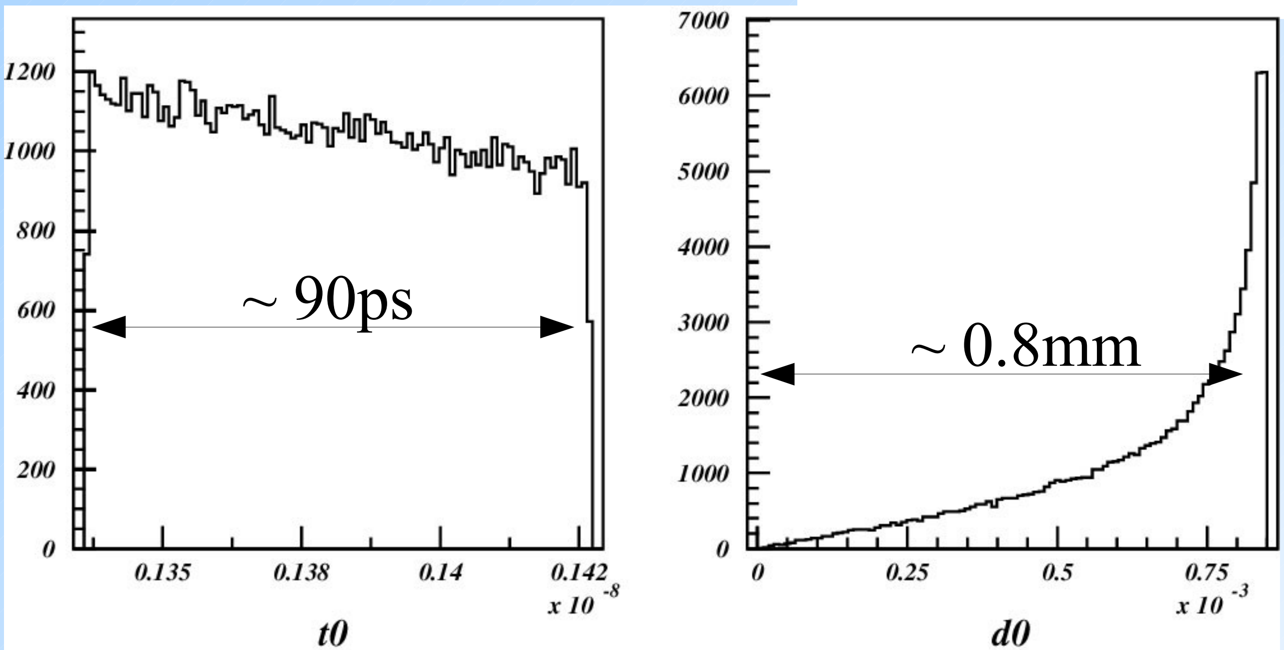
Photo-electron

$$t_0 \approx l\sqrt{\frac{2m_e}{U e_0}}$$

$$d_0 \approx 2l\sqrt{\frac{E_0}{U e_0}}\cos(2\alpha)$$



Generated distributions assuming that photo-electron is emitted uniformly over the solid angle



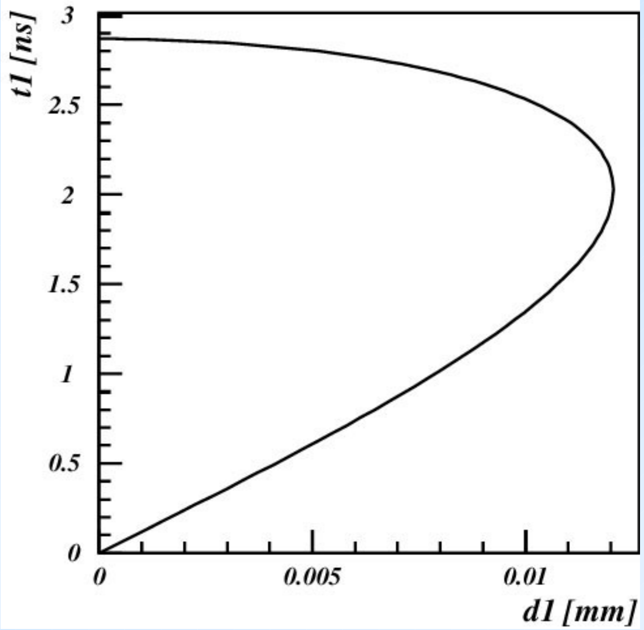
Maximum variation of photo-electron travel time.

$$\Delta t_0 \approx t_0\sqrt{\frac{E_0}{U e_0}} = \frac{l}{U e_0}\sqrt{2 m_e E_0}$$

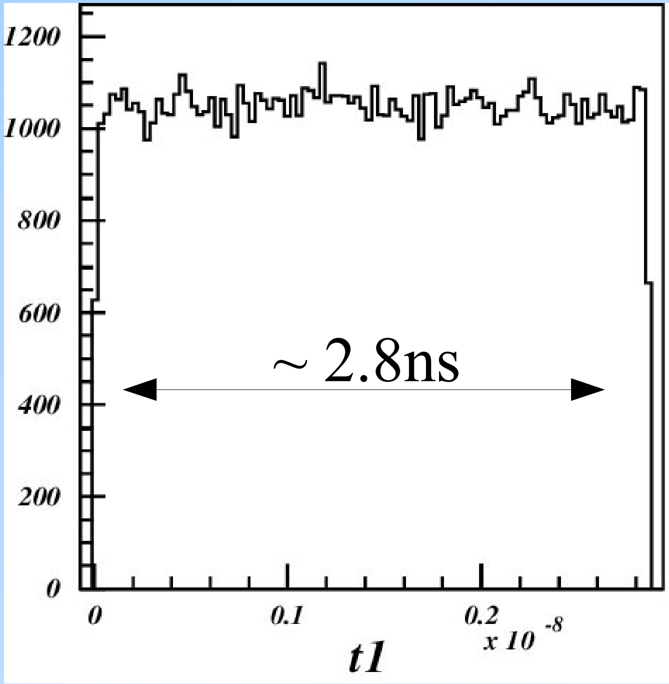
Samo Korpar
University of Maribor and Jožef Stefan Institute

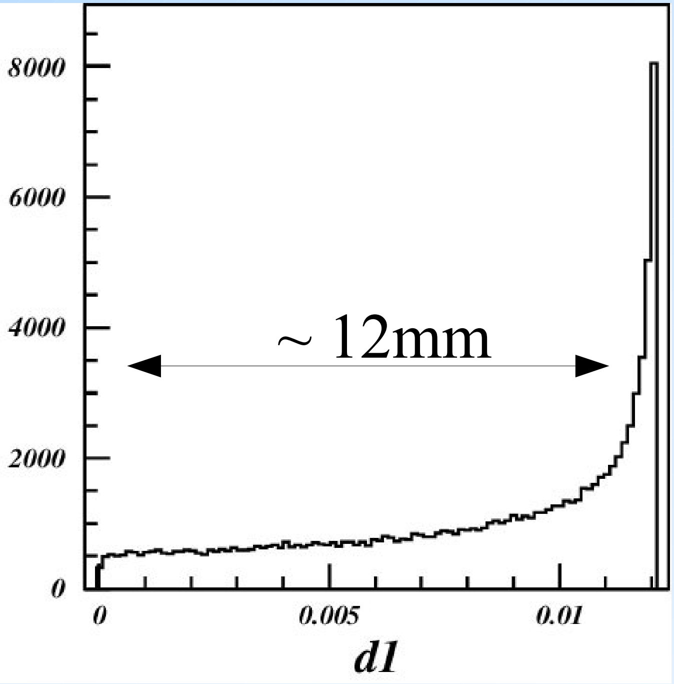
Elastic backscattering

Generated distributions assuming that backscattering is uniform over the solid angle



Travel time vs. travel distance



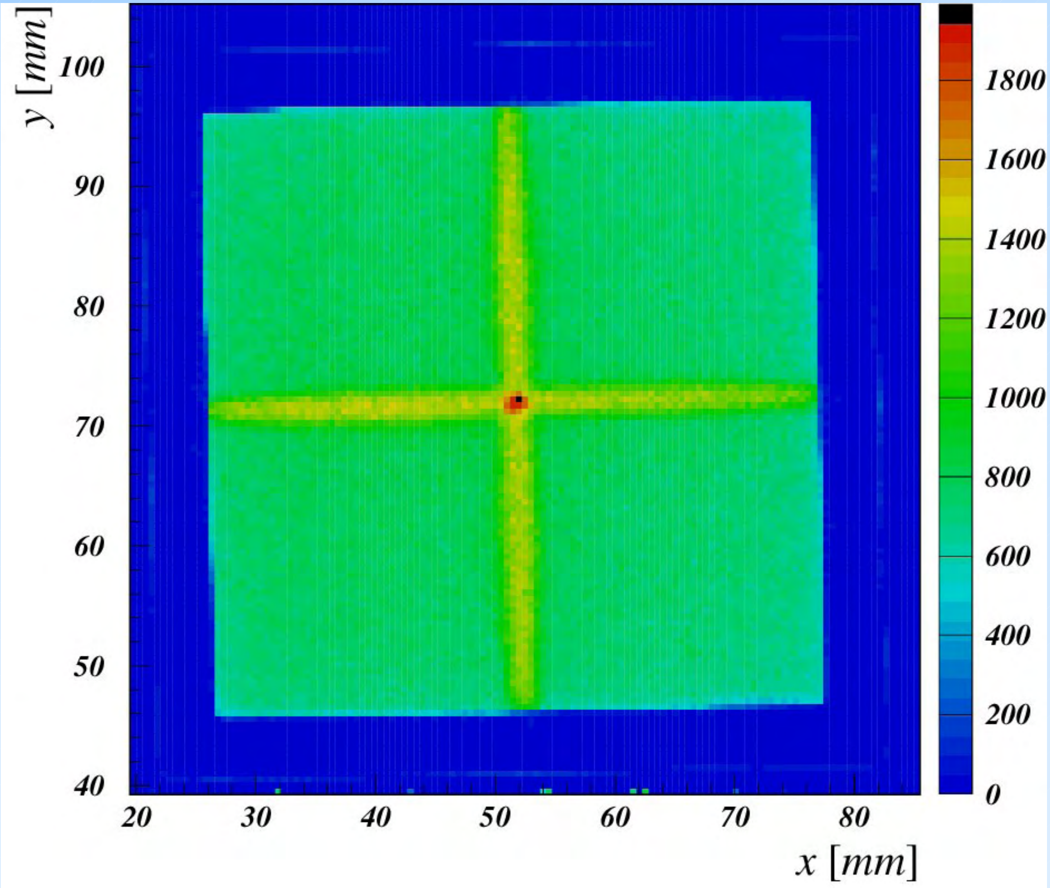


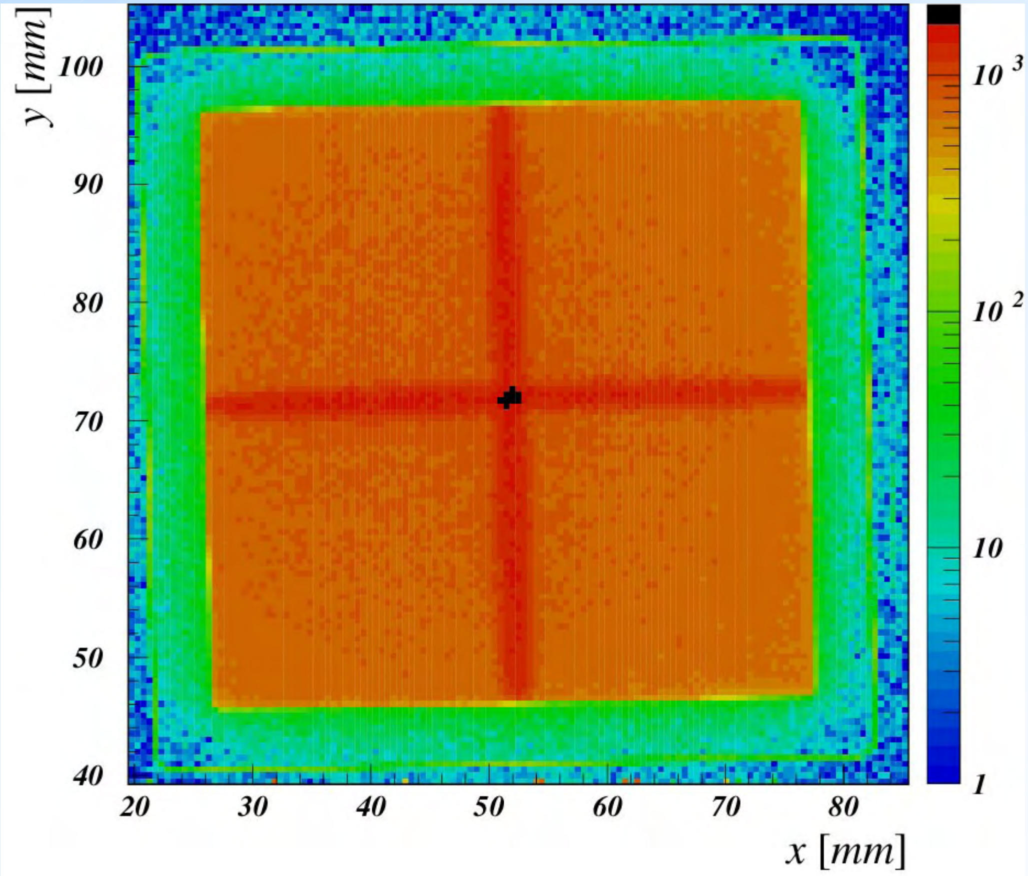
$$t_1 = 2 t_0 \sin(\beta)$$

$$d_1 = 2 l \sin(2\beta)$$

Photon detection uniformity

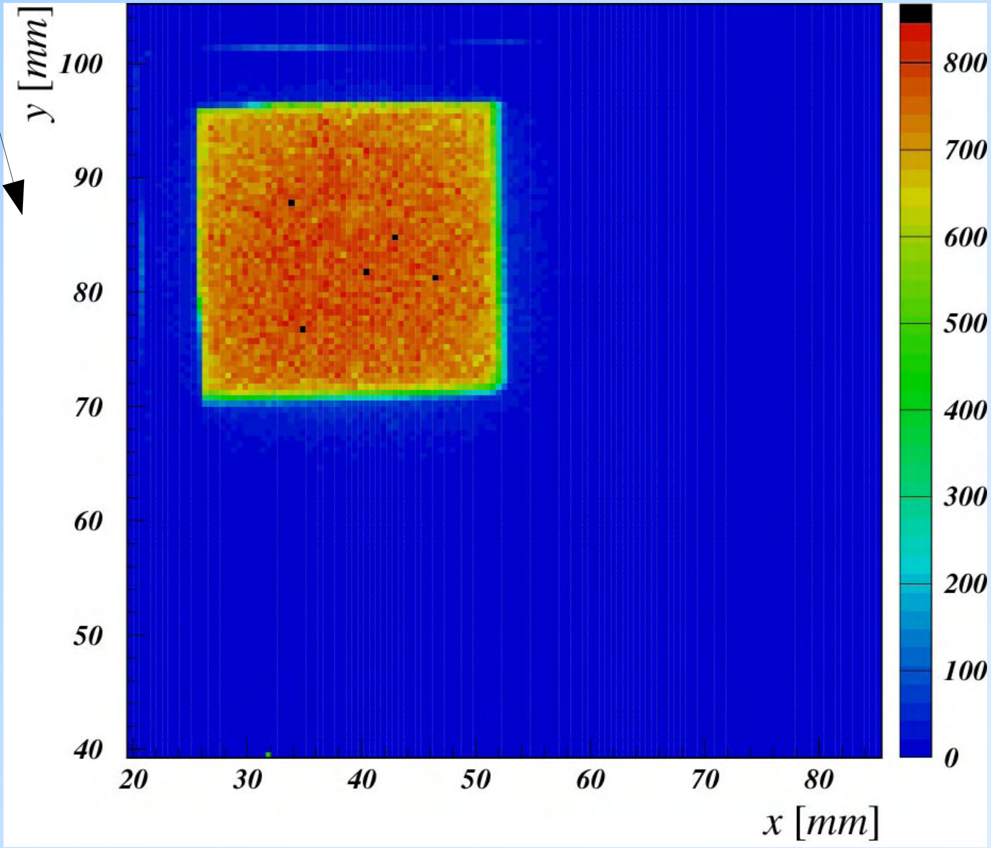
- Number of detected events at different positions of light spot – sum of all 4 channels
- double counting at pad boundaries due to charge sharing

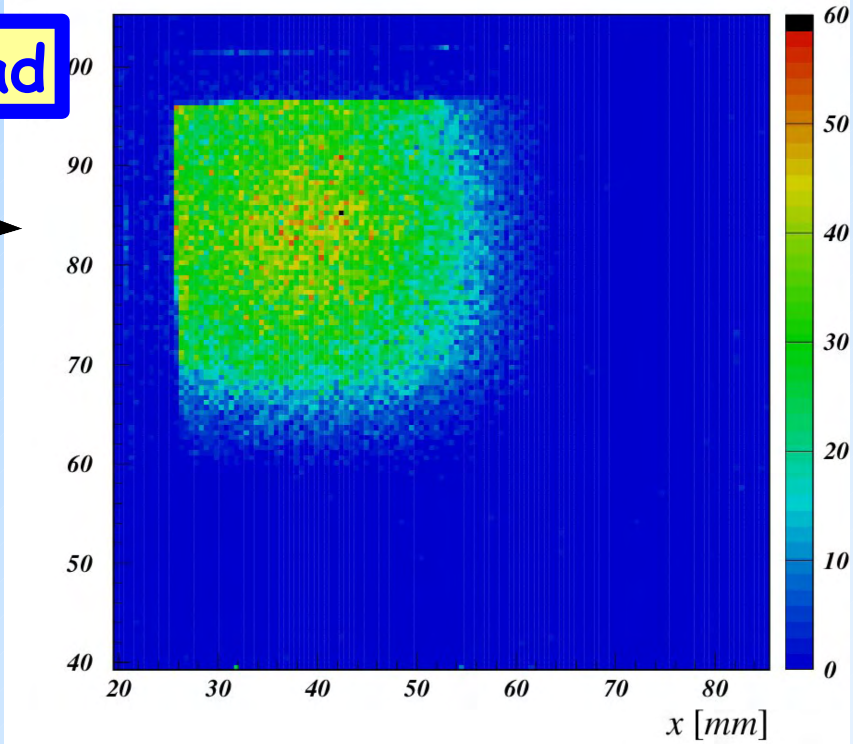


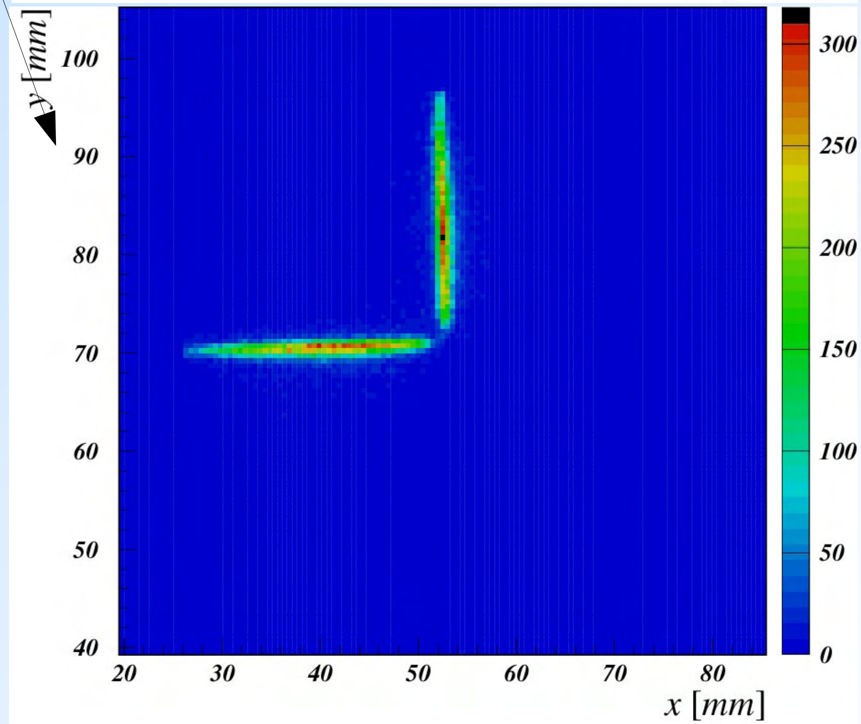


Photon detection uniformity – single pad

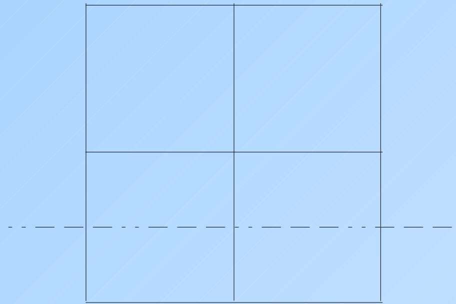
- number of delayed events with maximum signal detected by the pad
- number of events with maximum signal detected by other pads
- number of all detected events with maximum signal detected by the pad



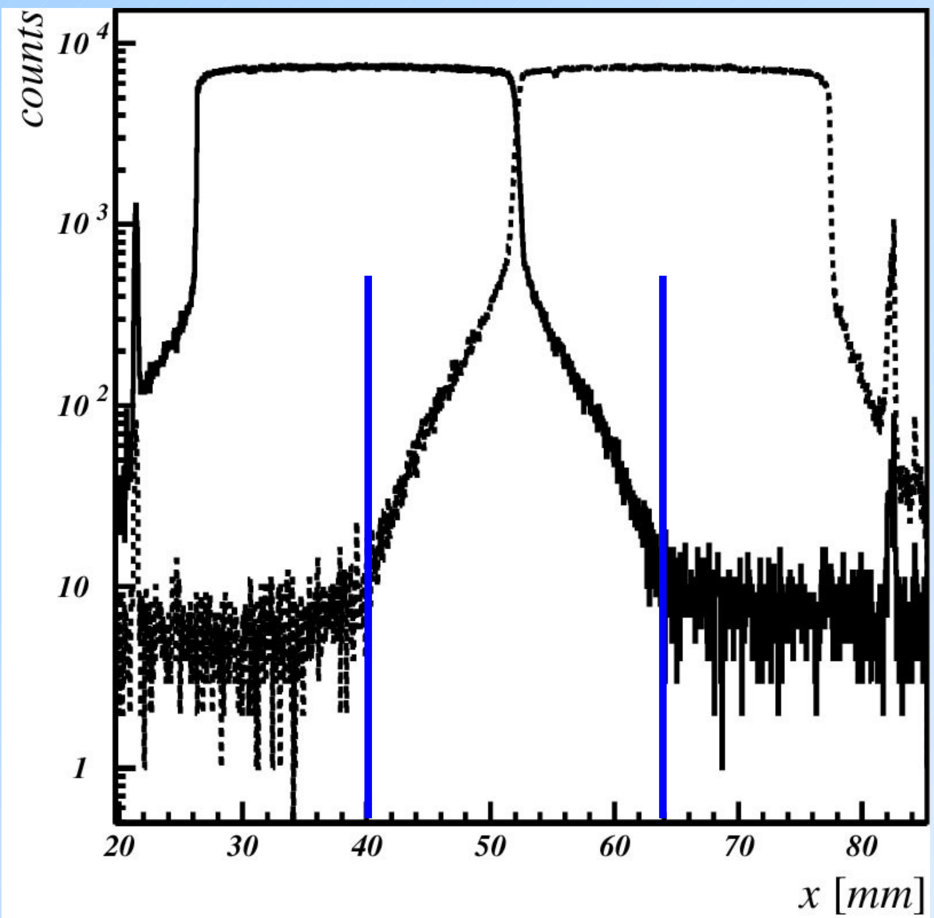




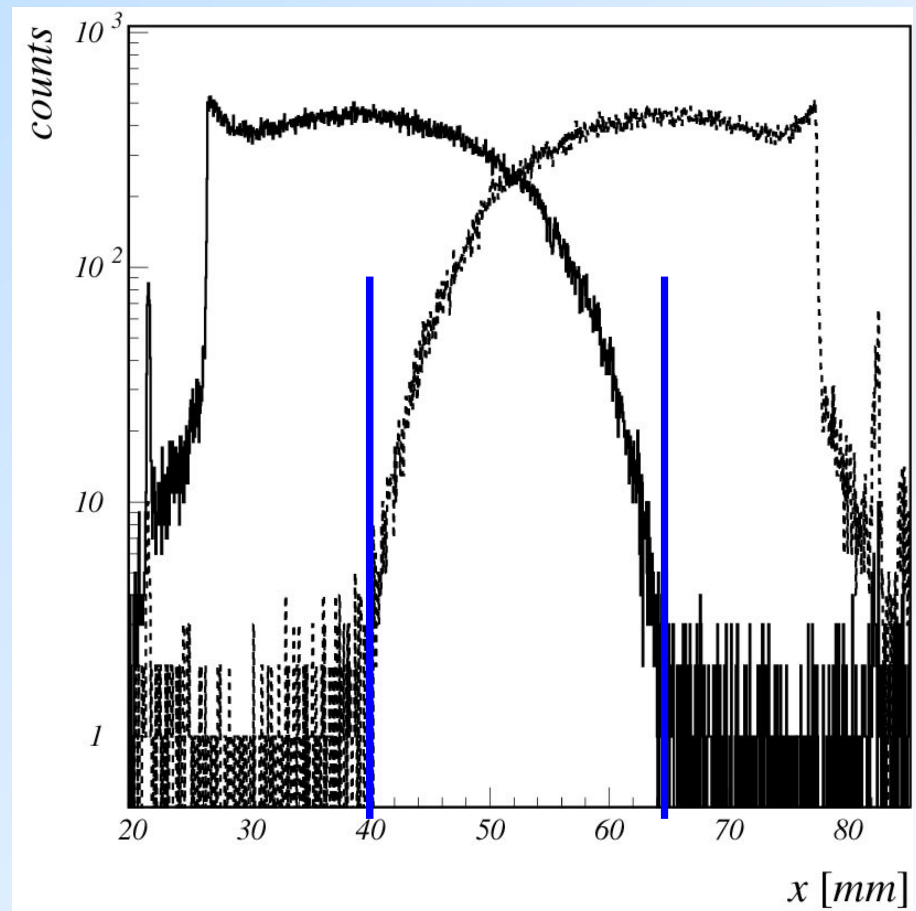
Detailed 1D scan



all events with maximum signal on channels 1 and 2

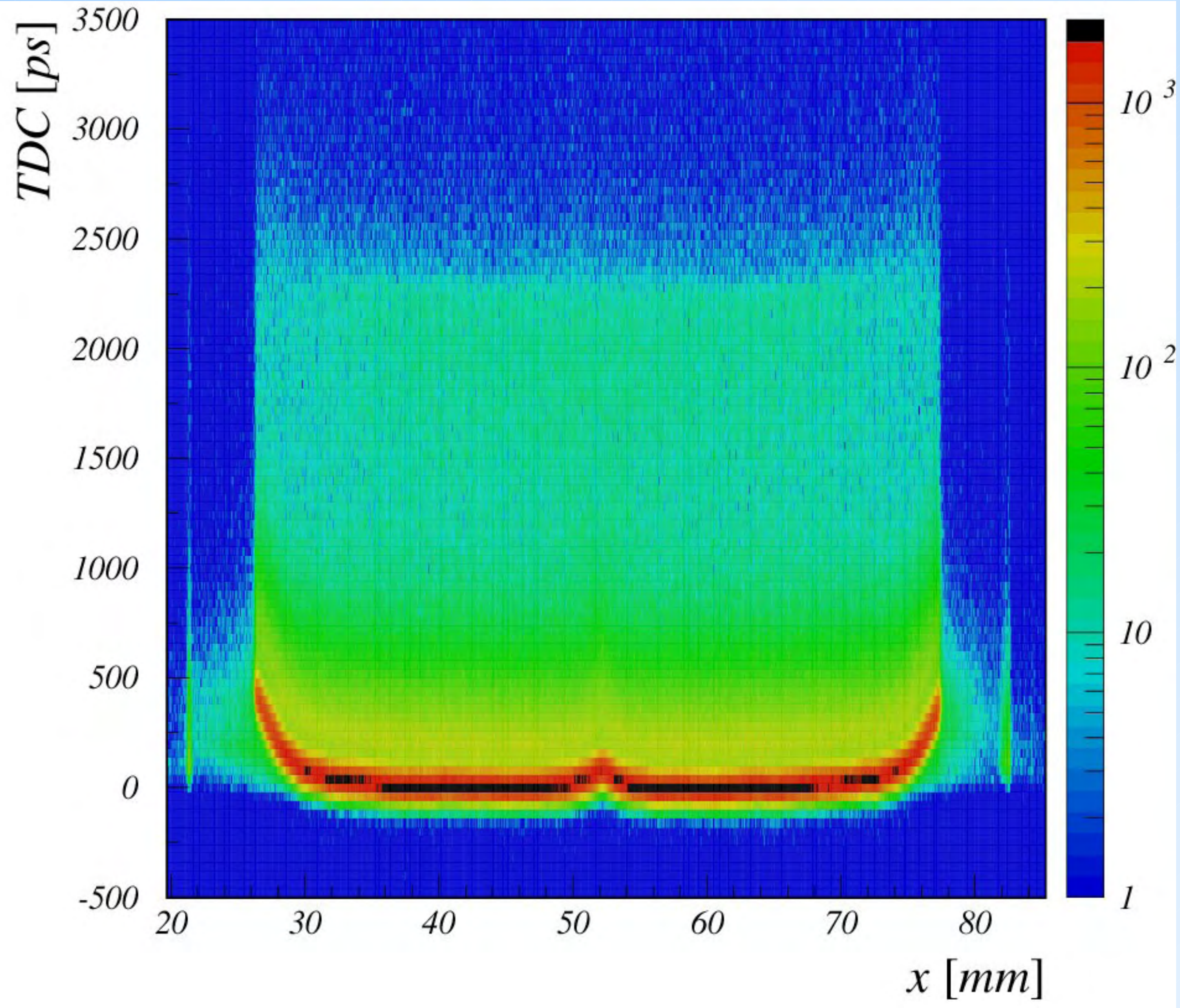


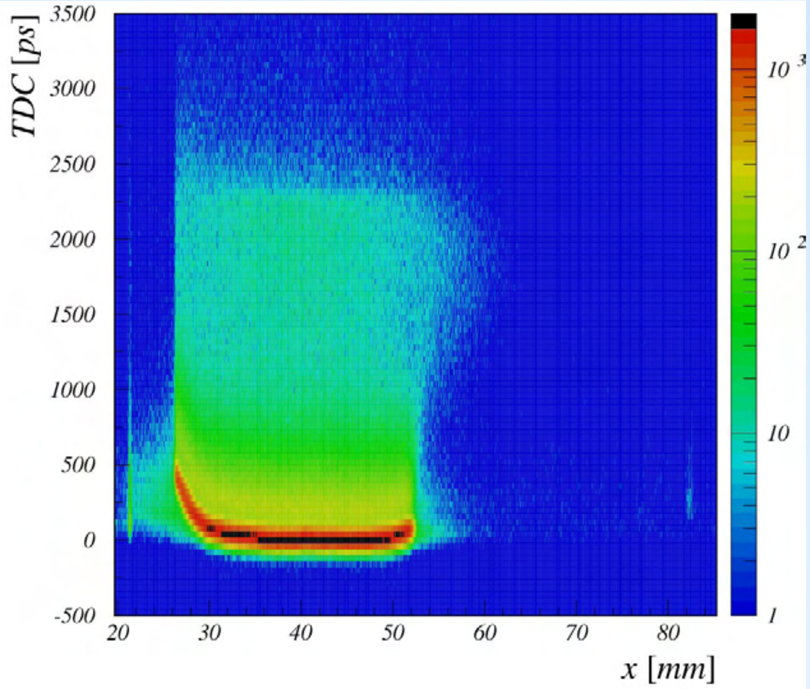
delayed (>1.1ns) events with maximum signal on channels 1 and 2

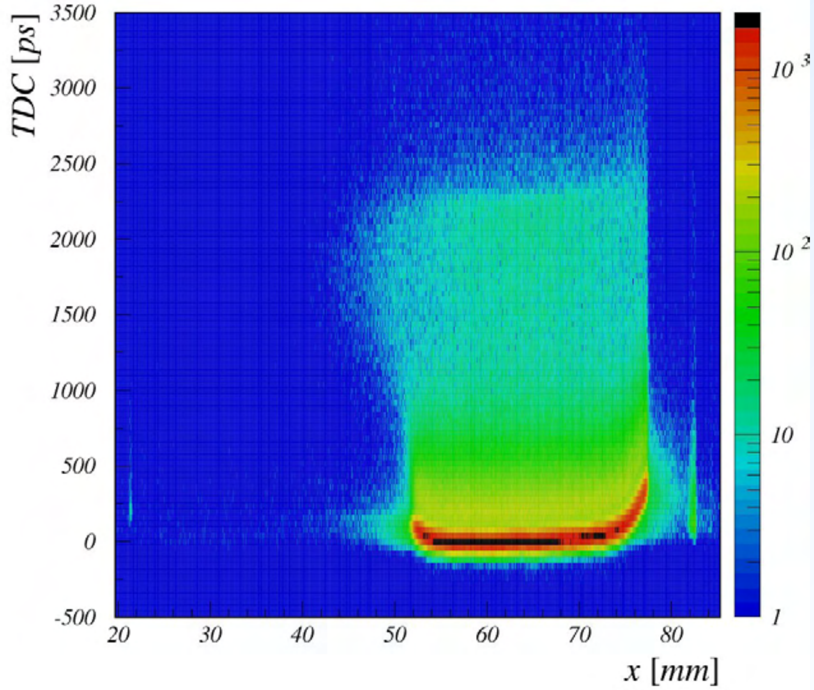


Timing uniformity

- TDC vs. x for channels 1 and 2
- large deviation at active area edge
- small deviation at pad boundaries

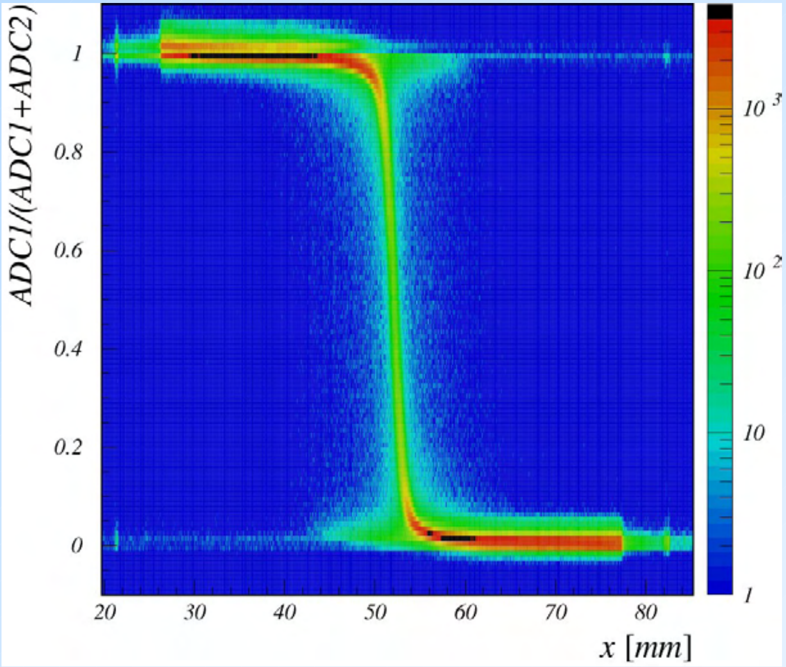


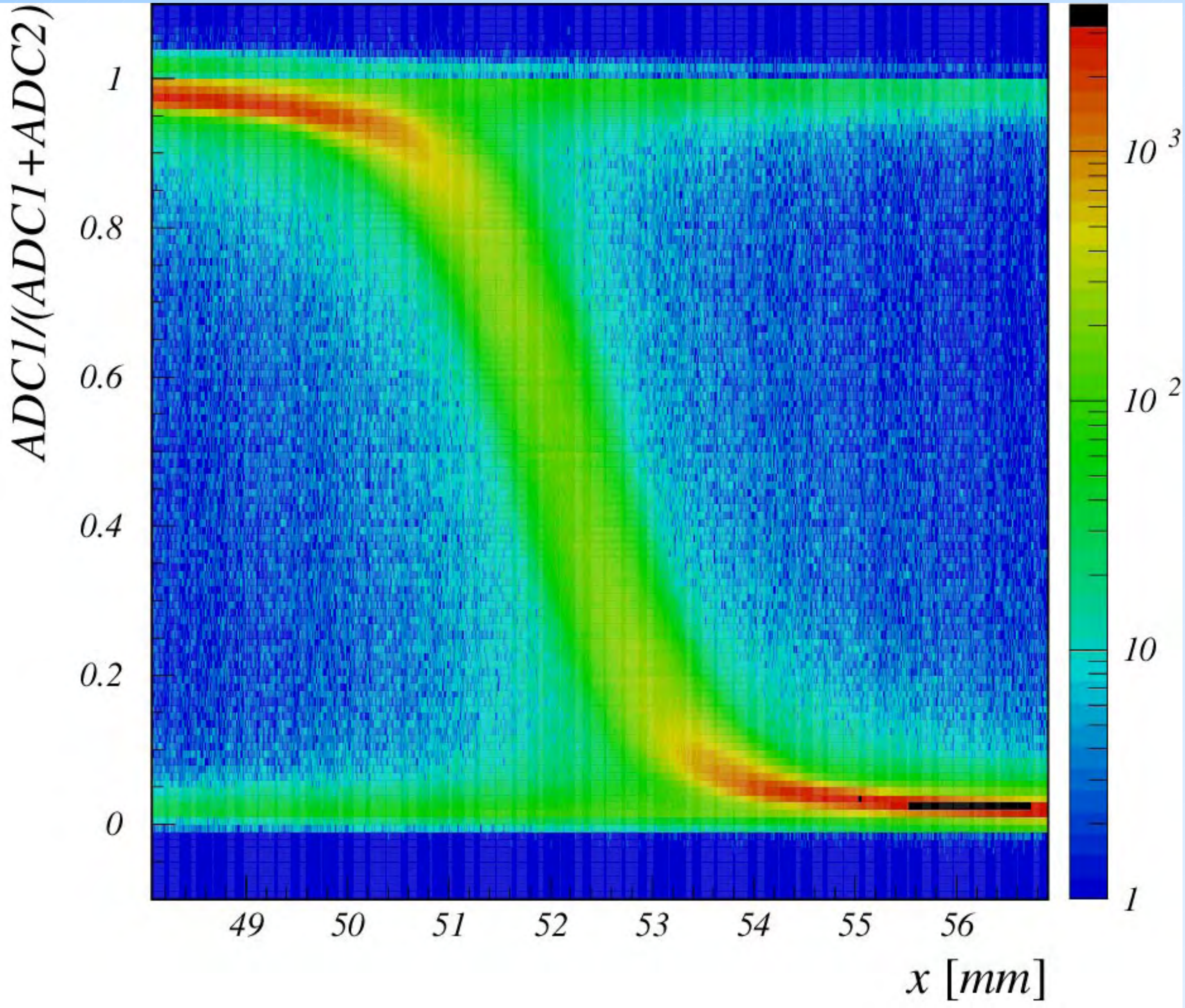




Charge sharing

- fraction of the signal detected on channel 1 vs. x position of light spot

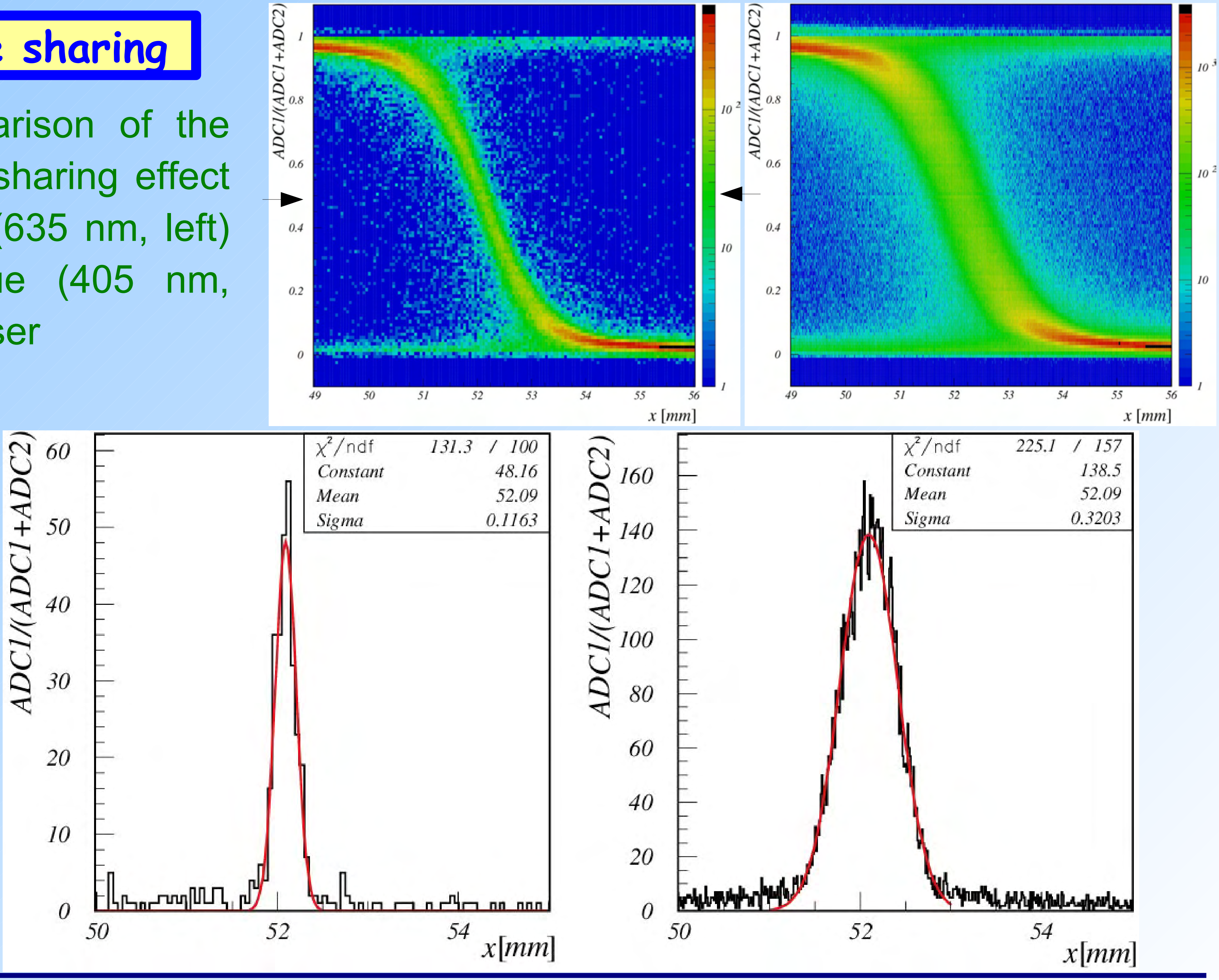




- sizable charge sharing in ~2mm wide boundary area
- can be used to improve position resolution

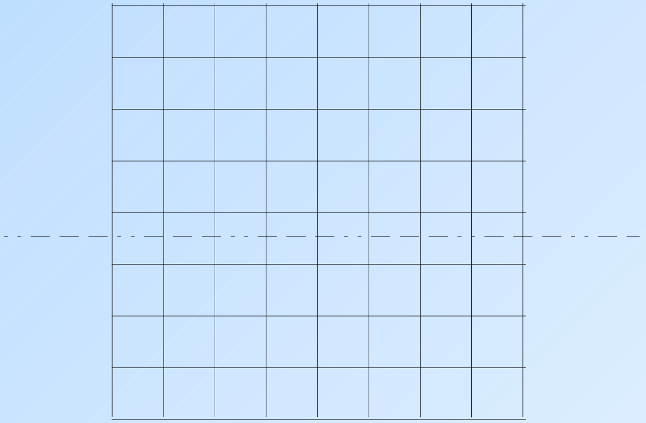
Charge sharing

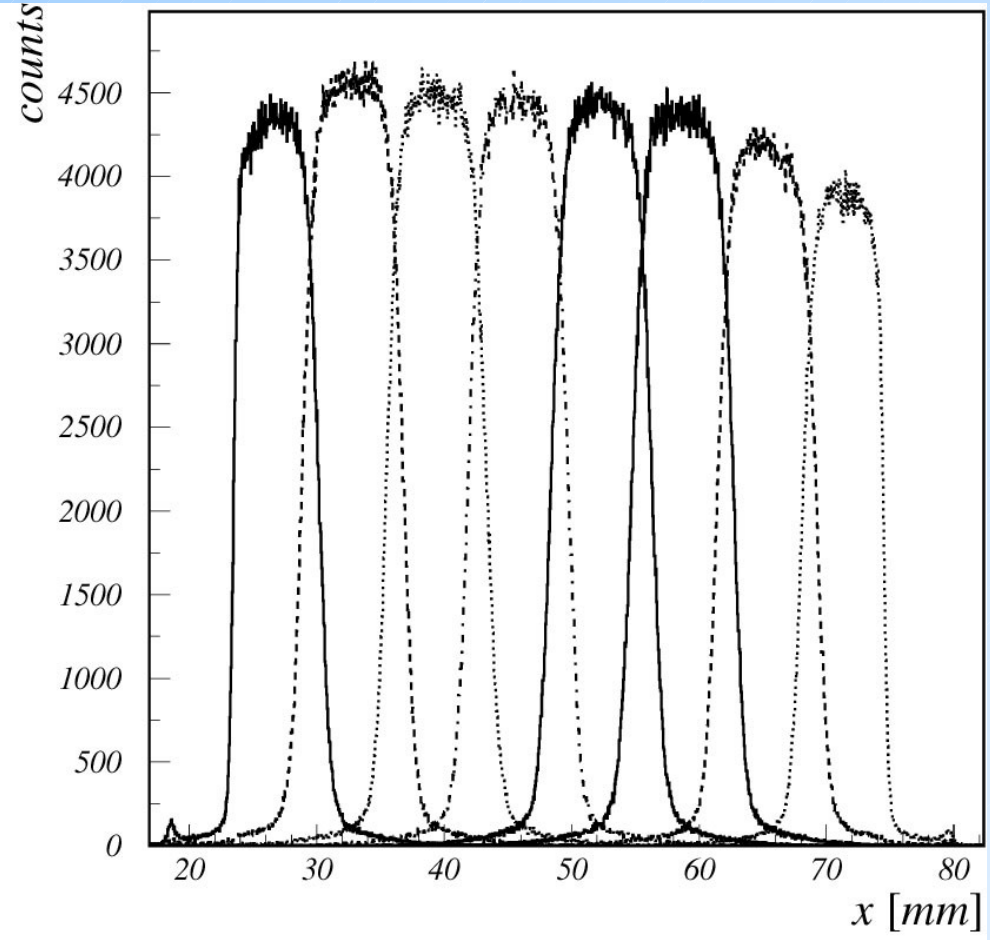
- comparison of the charge sharing effect for red (635 nm, left) and blue (405 nm, right) laser

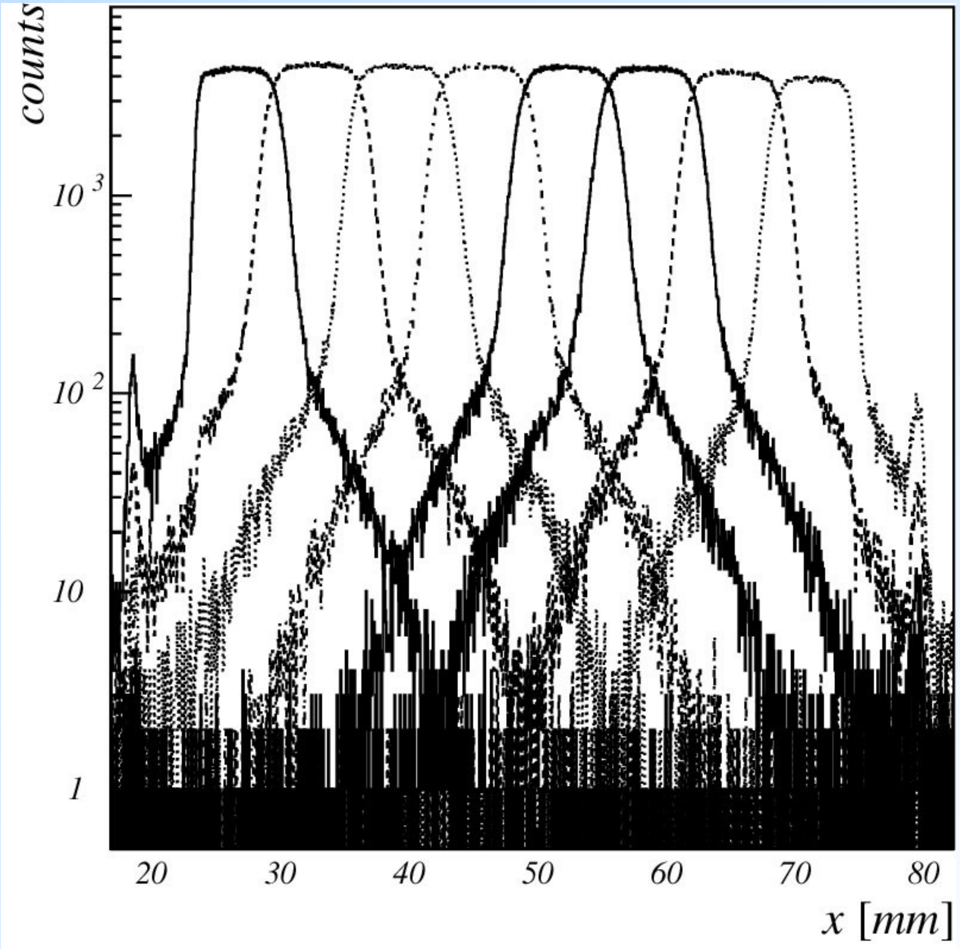


8x8: detection vs. x

- Number of detected signals vs. x
- Small variation over central part

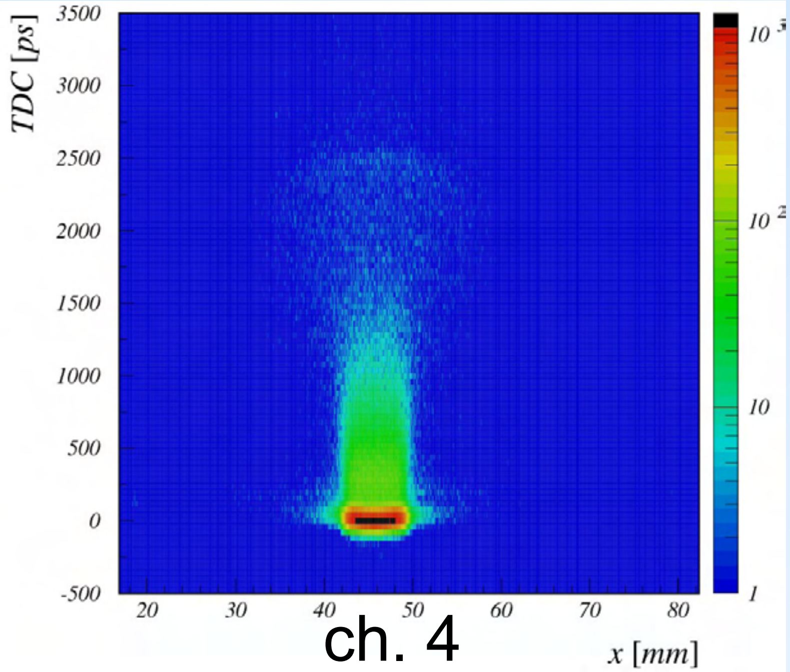


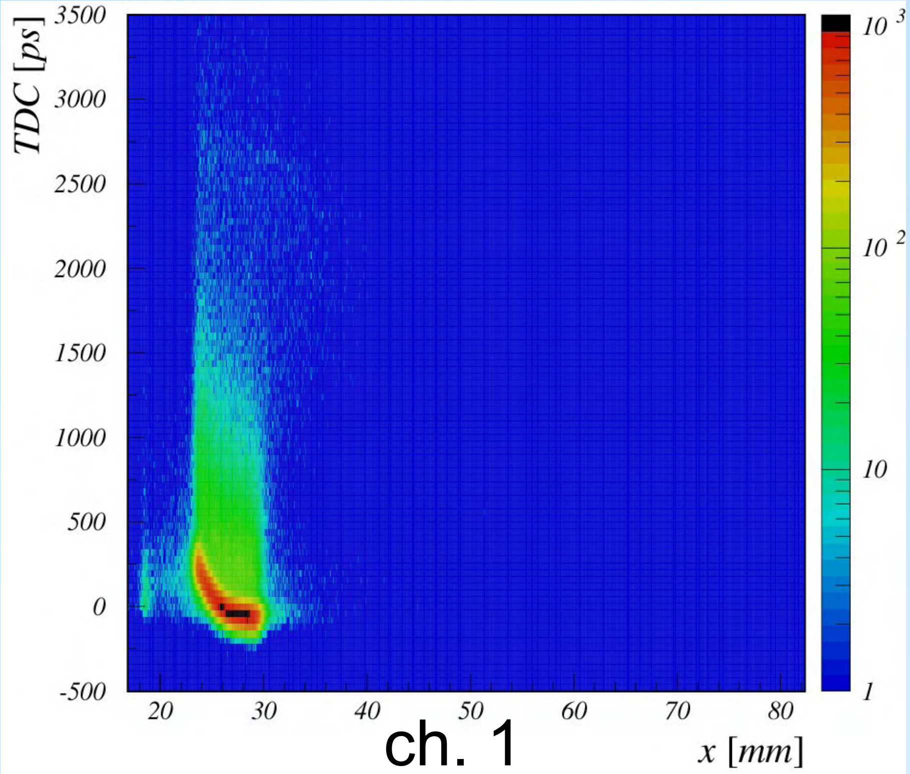


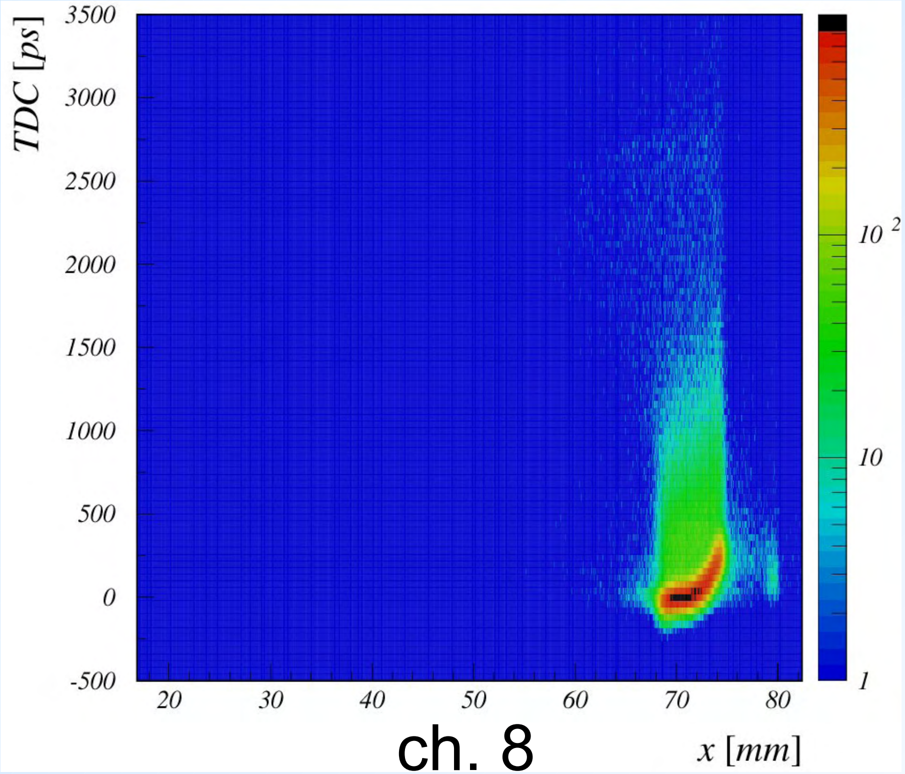


8x8: Timing uniformity for single pads

- TDC vs. x correlation of single pads
- uniform for central pads
- large variation for pads at the edge

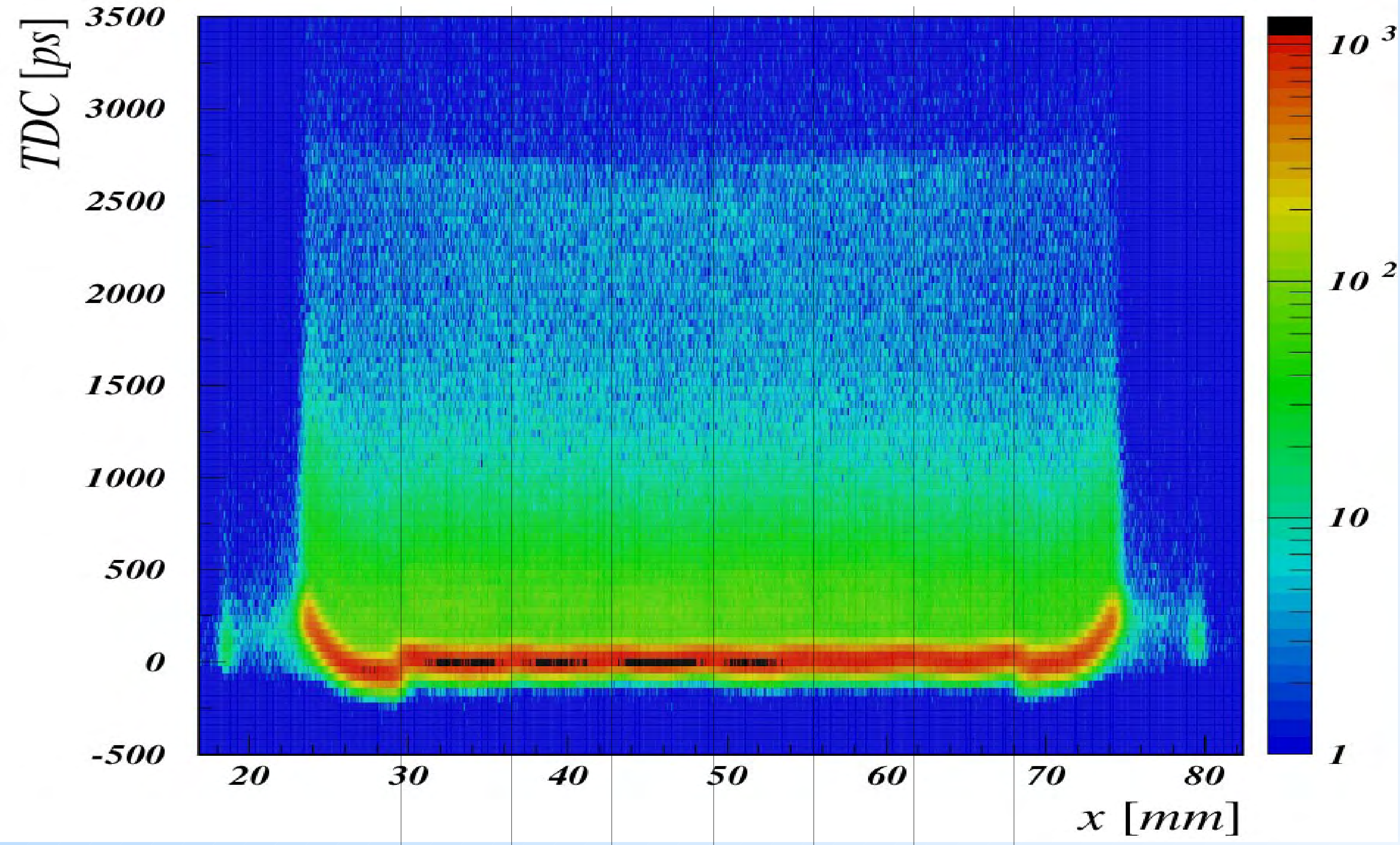






8x8: Timing uniformity

- TDC vs. x distribution for all channels

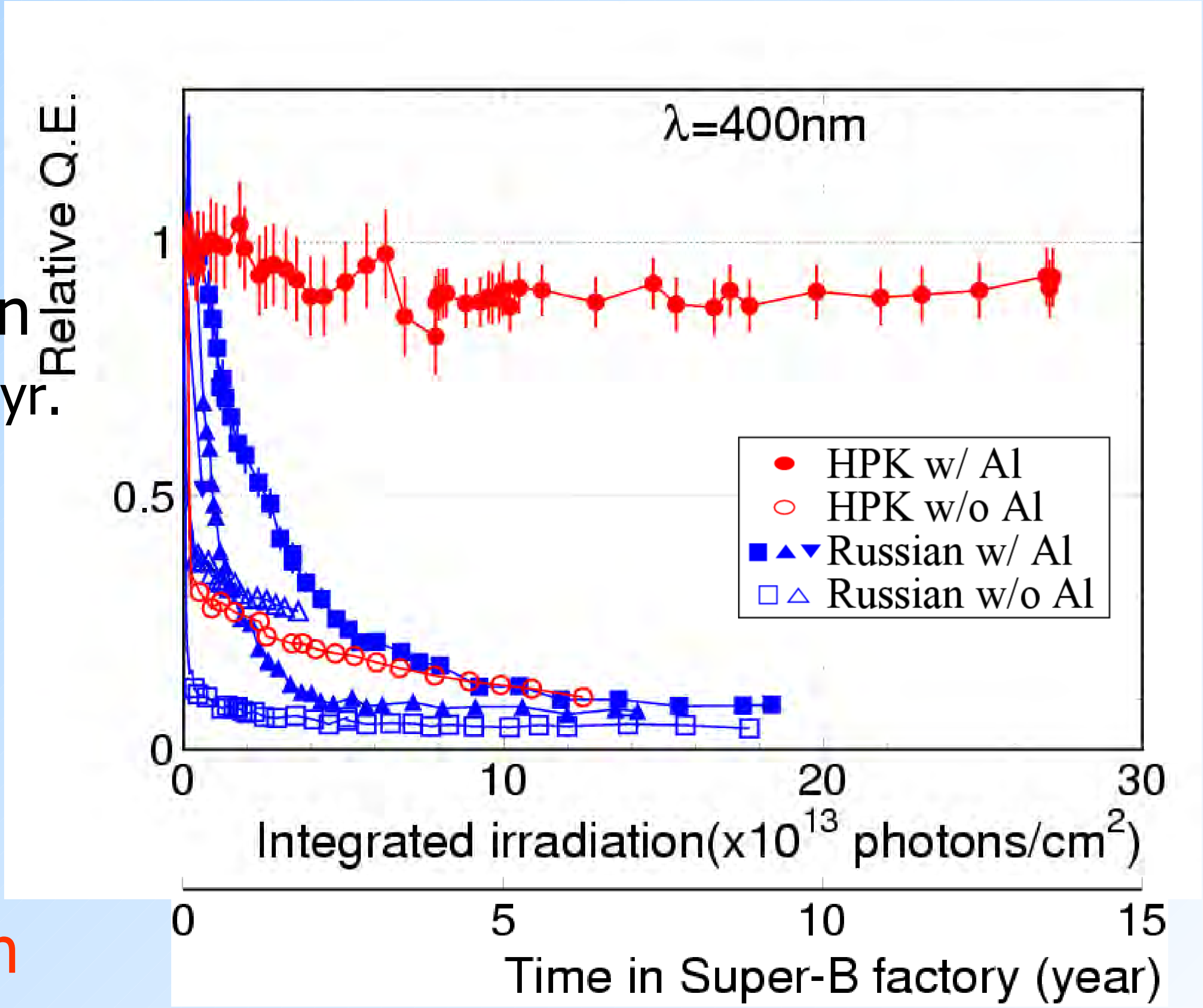


σ = 50.4 46.5 43.8 40.5 45.3 44.4 46.5 53.4 ps

Samo Korpar
University of Maribor and Jožef Stefan Institute

Lifetime - Q.E. -

- Relative Q.E. by single photon laser
- Without Al protection
  - Drop <50% within 1yr.
- With Al protection
  - Long life
  - Not enough for Russian PMTs
- Enough lifetime for HPK's MCP-PMT with Al protection layer



K. Inami @PD07

Summary and Plan

- RICH detectors for super B factories require fast single photon detectors that work in high magnetic field and have a spatial resolution of a few mm.
- The best candidates at the moment are MCP-PMTs. They are proven to work in high magnetic field with excellent time resolution better than 50 ps for single photon signals.
- The main remaining issues are aging and price.

Plan for the bench tests:

- Test with multi photon pulses.
- Test with simultaneous hits on different channels.
- Measure optical cross-talk (photon scatering)
- Test in magnetic field ...

Samo Korpar
University of Maribor and Jožef Stefan Institute

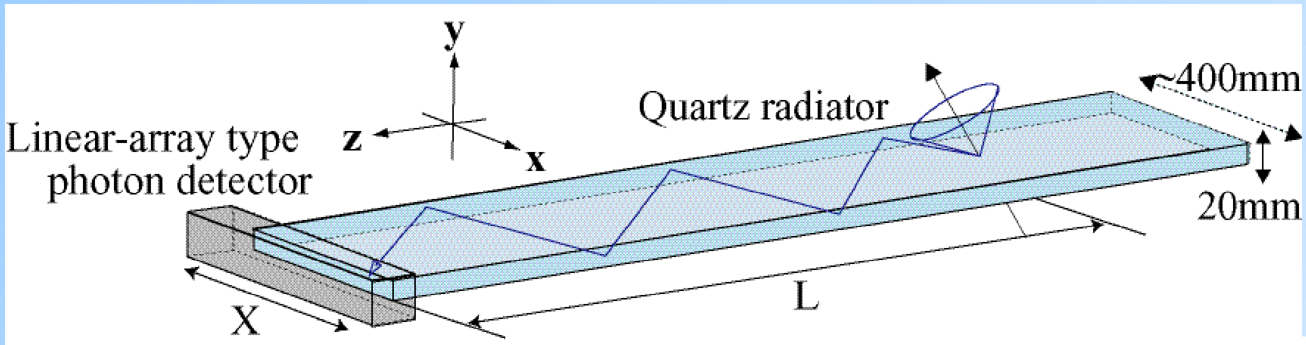
BACKUP SLIDES

Samo Korpar
University of Maribor and Jožef Stefan Institute

Possible cross-talk sources:

- electron backscattering (max signal, delayed)
- charge sharing (not-max/max, prompt signal)
- electronics (position independent)
- induced charge (position dependant) ?
- photon scattering/reflections ?

TOP principle

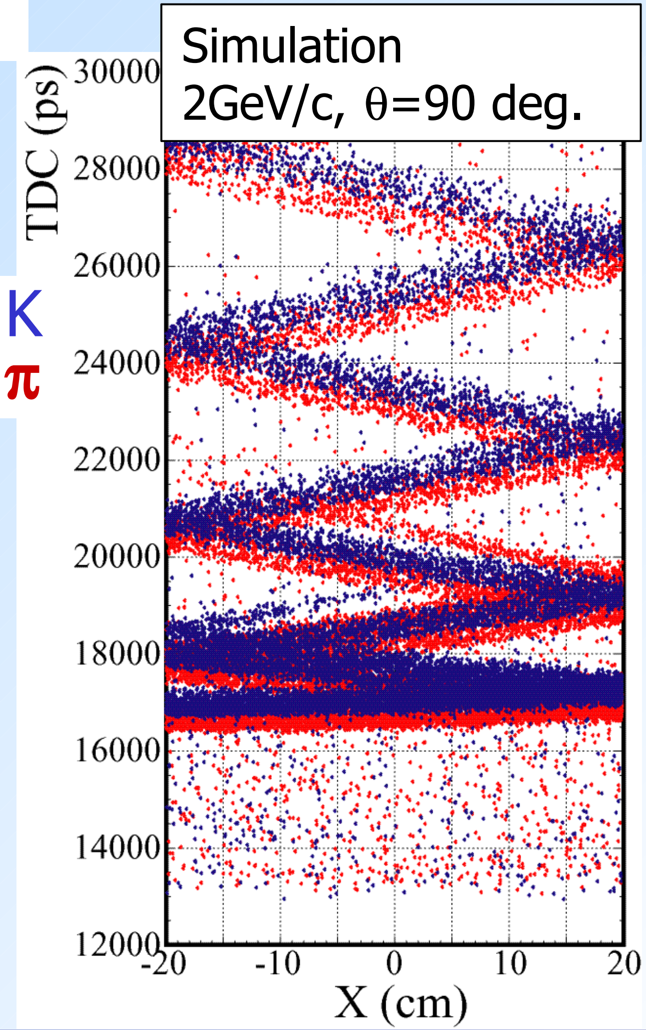


Time-of-Propagation counter:

Measurement of

- One (or two coordinates) with a few mm precision
- Time-of-arrival

Excellent time resolution < ~40ps required for single photons at 1.5T

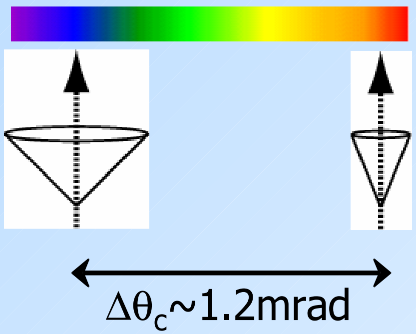


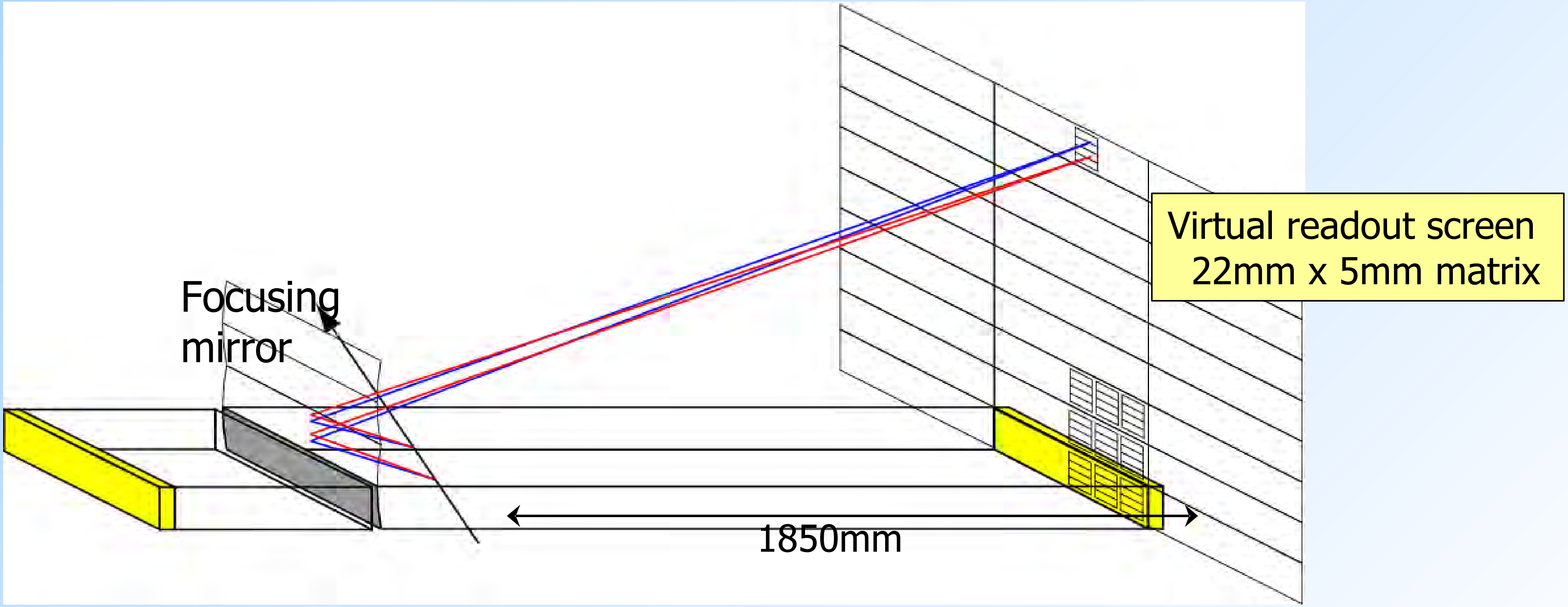
Samo Korpar
University of Maribor and Jožef Stefan Institute

Focusing TOP

Using λ dependence of Cherenkov angle for chromatic error correction:

- Angle information → y position
- Use t, x and y for ring image reconstruction
- good color separation due to the long path

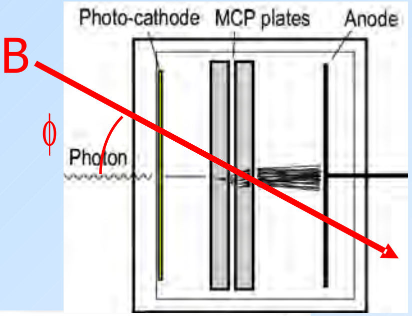


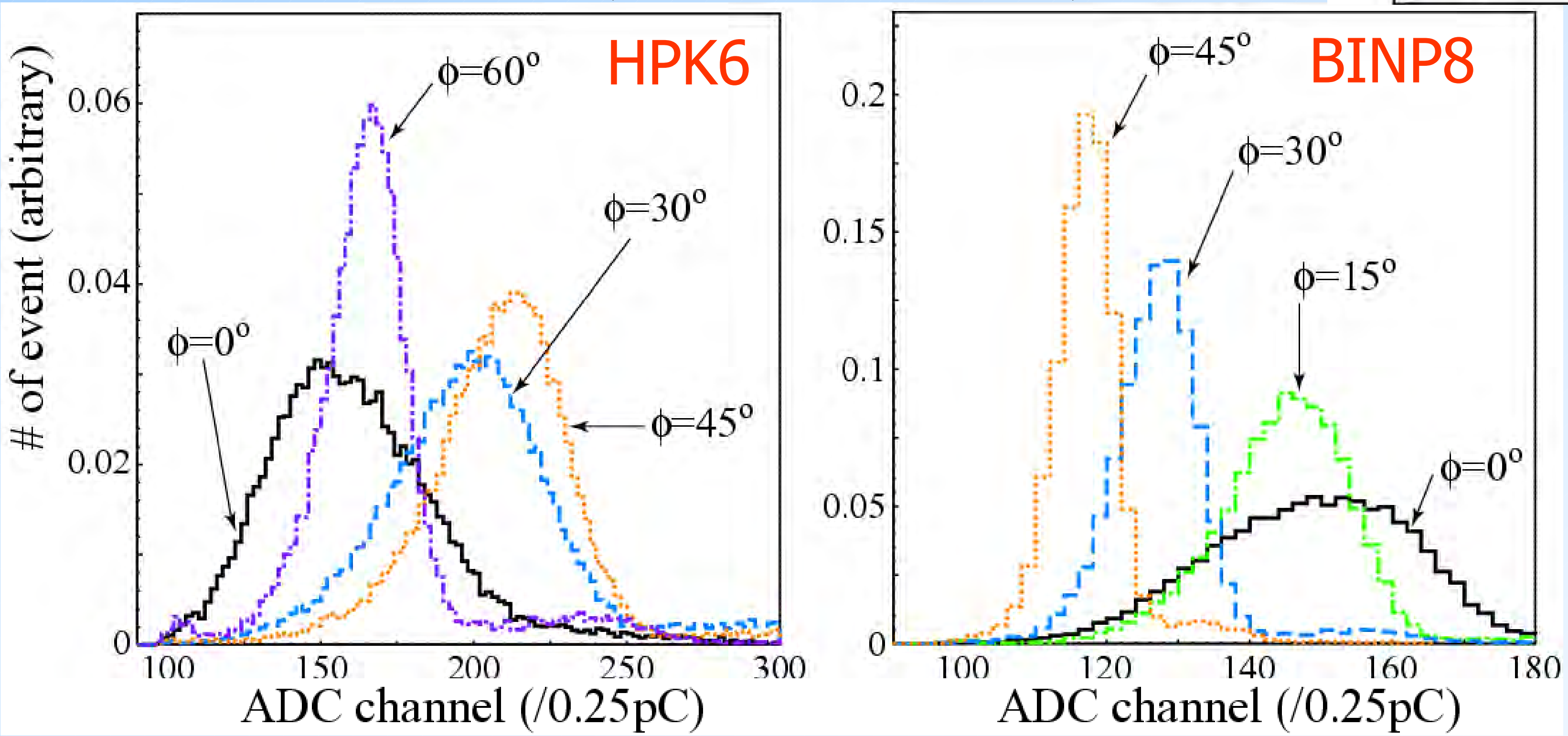


Samo Korpar
University of Maribor and Jožef Stefan Institute

MCP-PMT in B-field

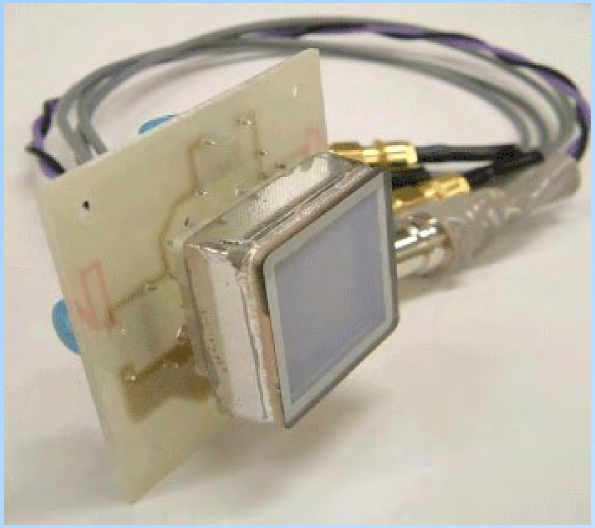
- ADC spectra with different angles under B=1.5T
  - Gain depends on the angle.
  - Behaviors are slightly different.
    - Because of the different bias angle of MCP hole
      - HPK6: 13deg, 6µ m, BINP8: 5deg, 8µ m

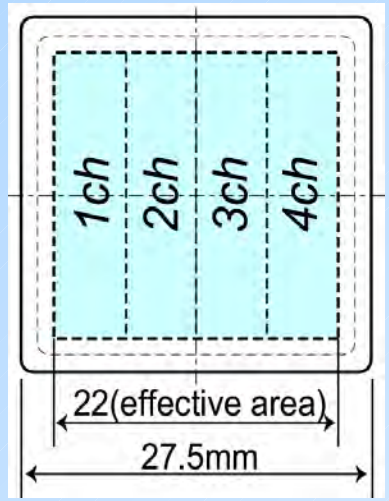




K. Inami @PD07

Multi-anode MCP-PMT (1)





Size	27.5 x 27.5 x 14.8 mm
Effective area	22 x 22 mm(**64%**)
Photo cathode	Multi-alkali
Q.E.	~20%(λ =350nm)
MCP Channel diameter	10 μm
Number of MCP stage	2
Al protection layer	No
Aperture	~60%
Anode	4 channel linear array
Anode size (1ch)	5.3 x 22 mm
Anode gaps	0.3 mm

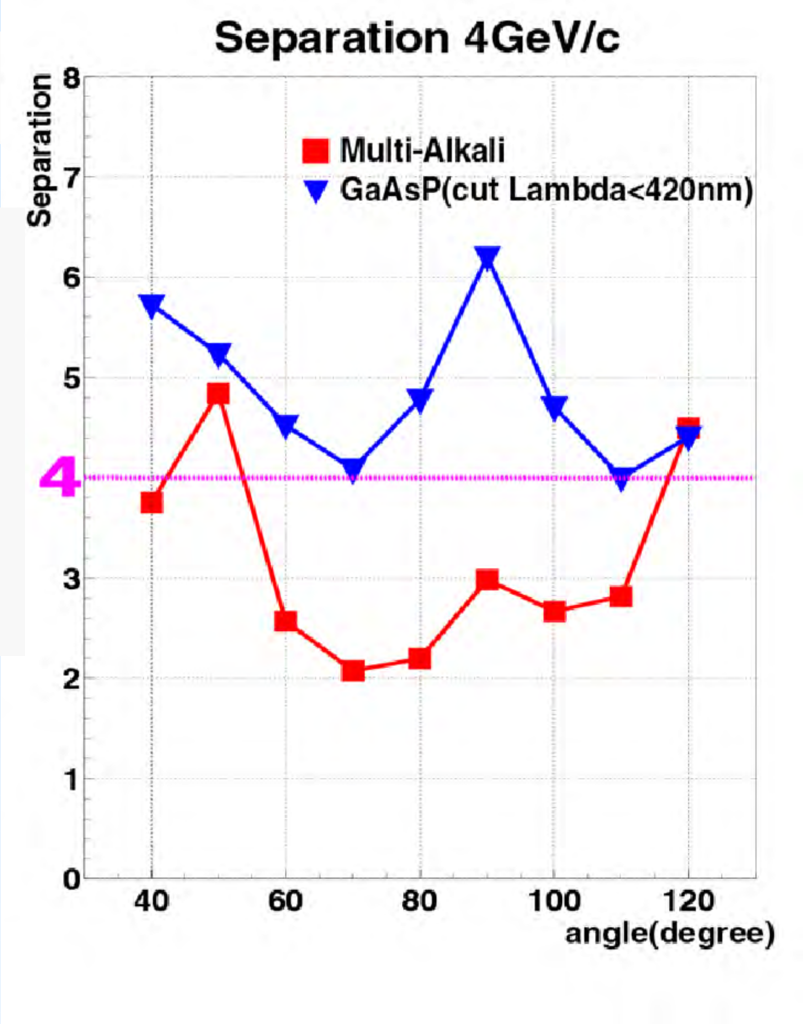
SL10

R&D with Hamamatsu
for TOP counter

- Large effective area — 64% by square shape
- Position information — 4ch linear anode (5mm pitch)

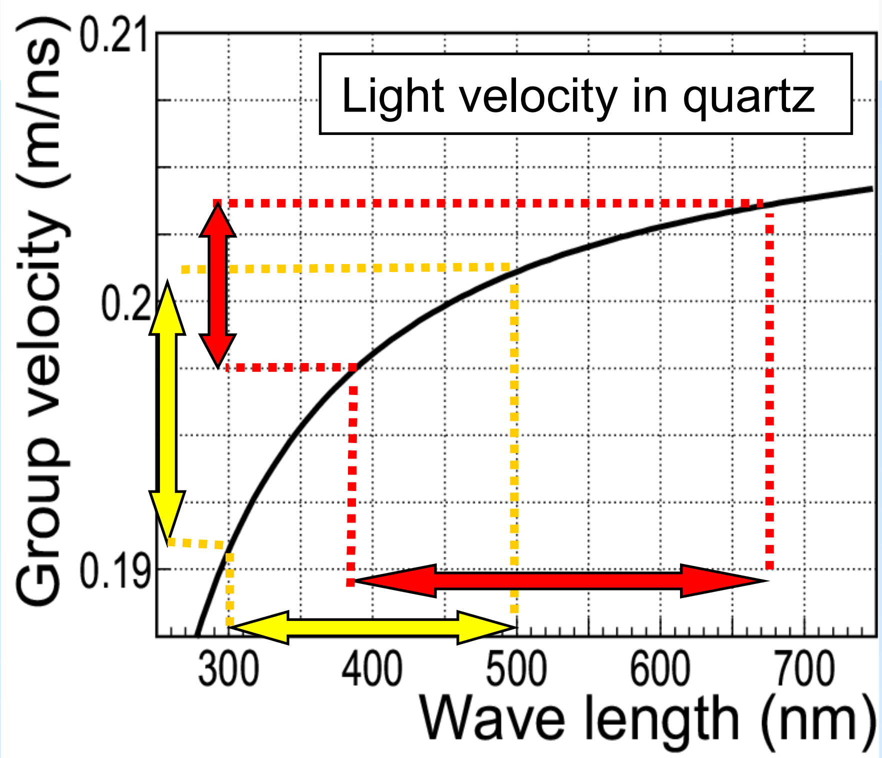
K. Inami @PD07

TOP counter MC



Expected performance with:

bi-alkali photocathode: <4σ π/K separation at 4GeV/c (← chromatic dispersion)



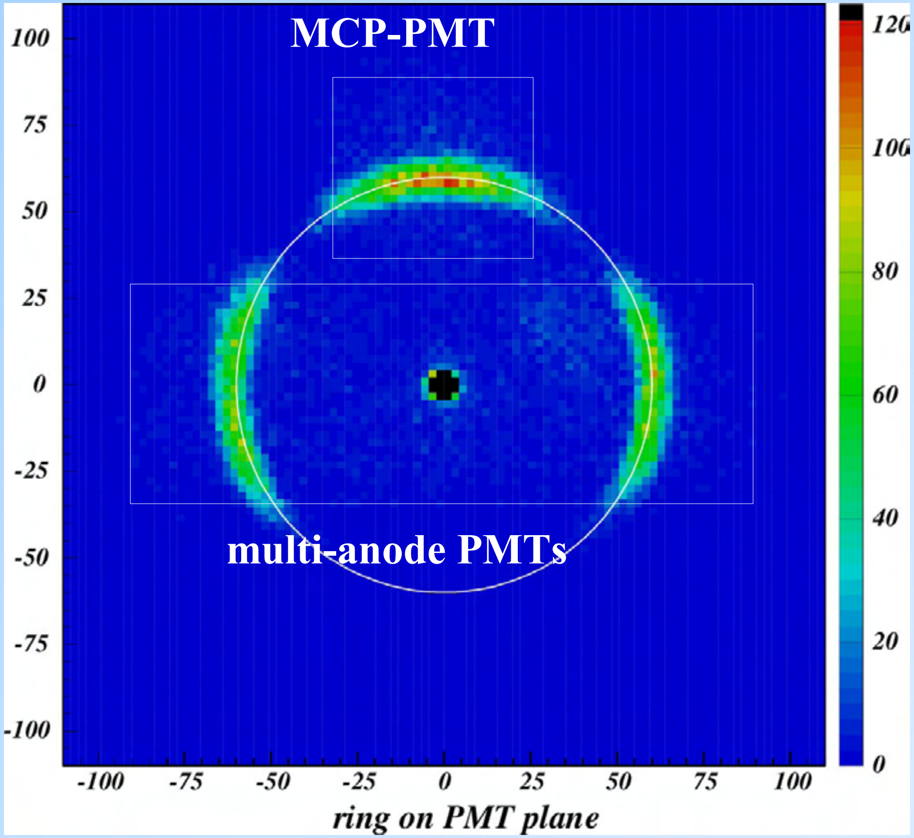
with GaAsP photocathode: >4σ π/K separation at 4GeV/c

Samo Korpar
University of Maribor and Jožef Stefan Institute

Motivation: possible applications (Belle aerogel RICH group)

RICH detector

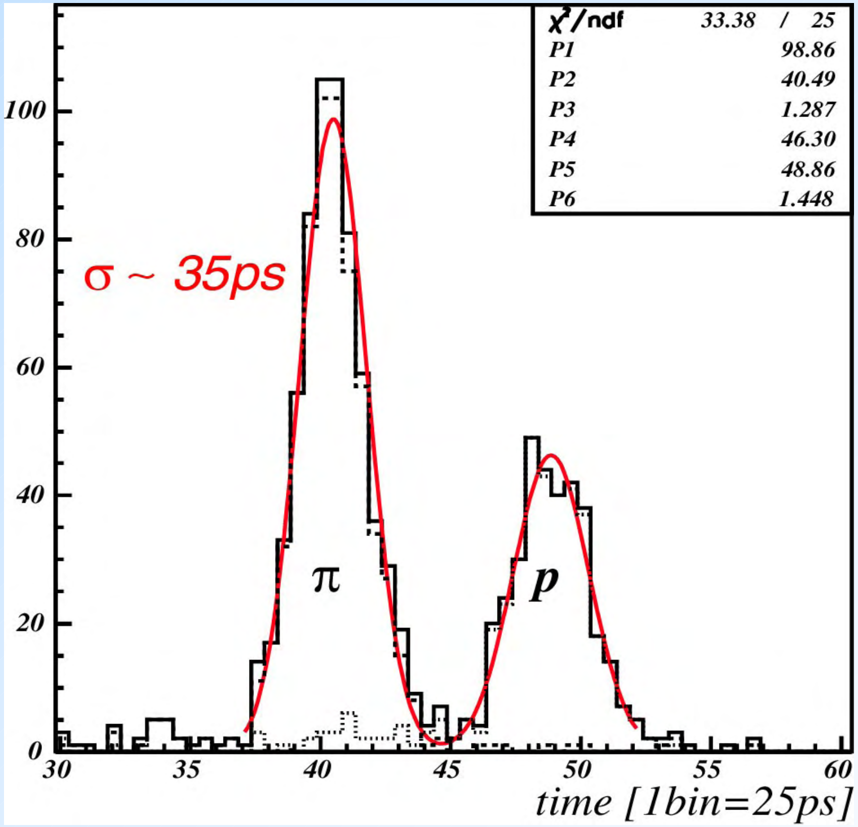
- $\sigma_\vartheta \sim$ 6 mrad (per track)



NIM A567 (2006) 124

TOF counter

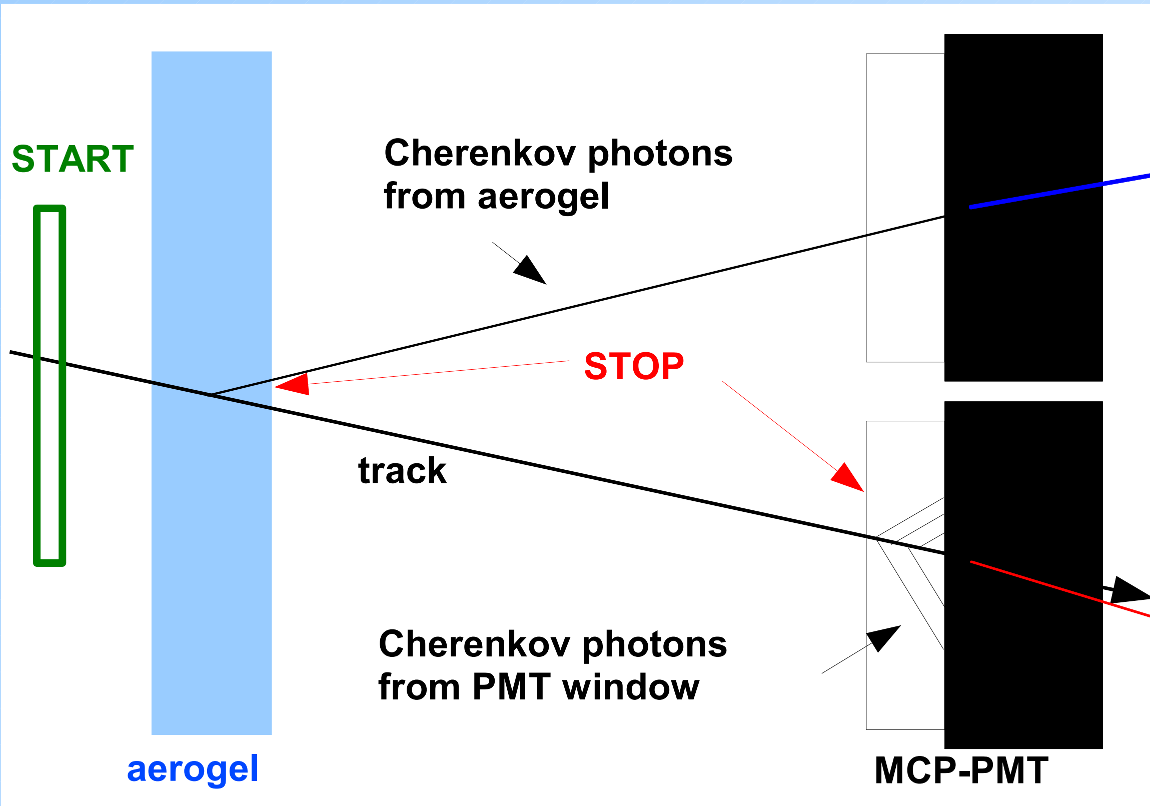
- test with pions and protons at 2 GeV/c (65 cm)

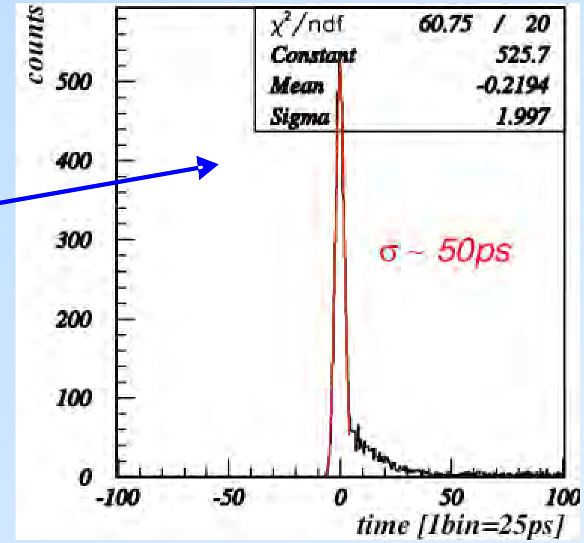


NIM A572 (2007) 432

Additional feature: RICH+TOF

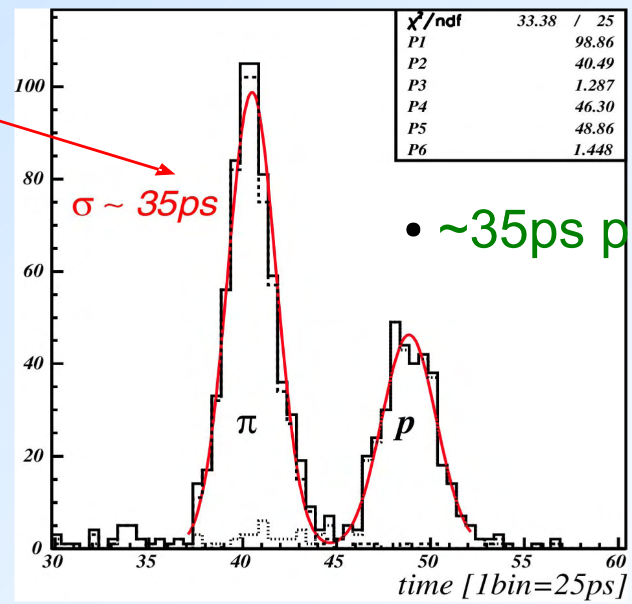
Make use of fast photon detectors: measure time-of-flight with Cherenkov photons from PMT window and aerogel





Beam test:

- 50ps per single photon (~20ps per track)



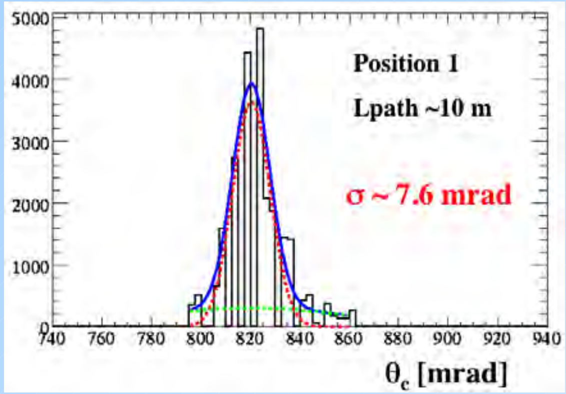
- ~35ps per track

- Cherenkov photons from the window can be used to positively identifiy particles below the threshold in aerogel

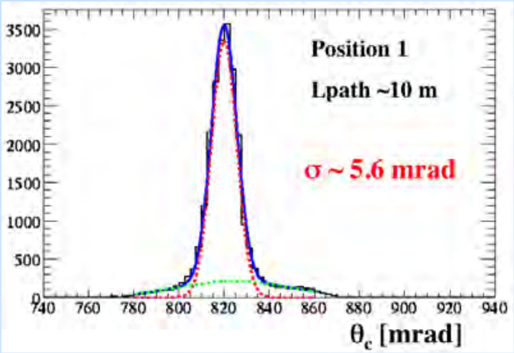
Focusing DIRC- the chromatic correction

θ_C resolution and chromatic correction for 3mm pixels:

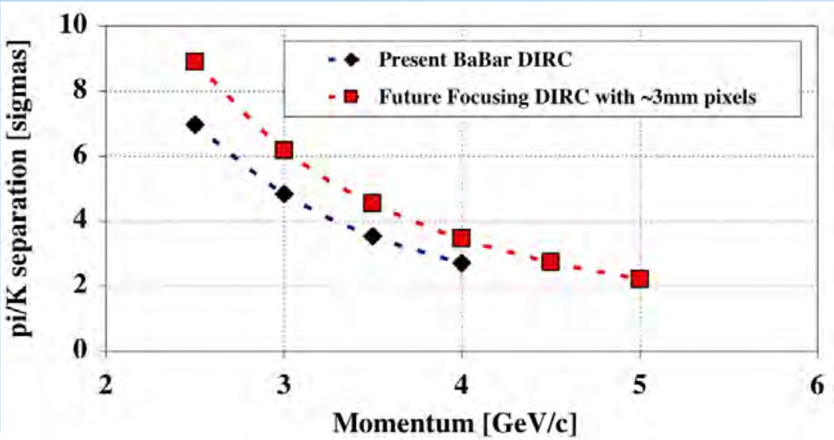
Correction off:

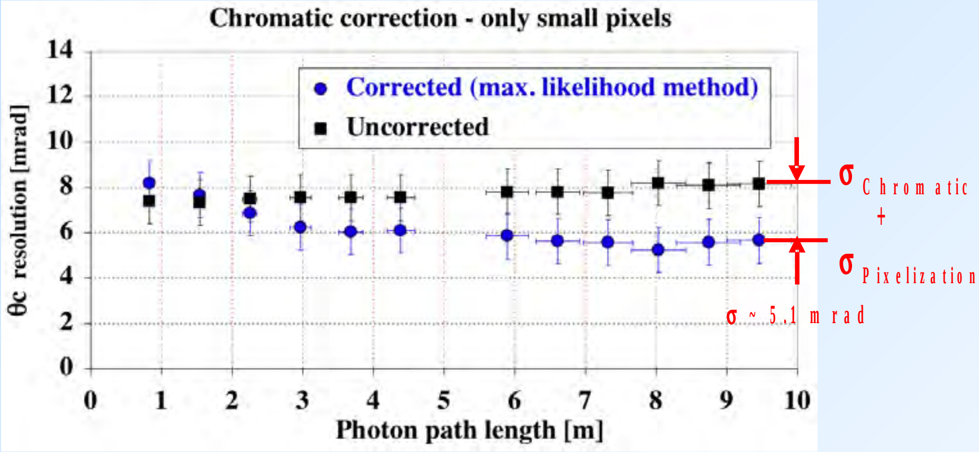


Correction on:



Expected performance:

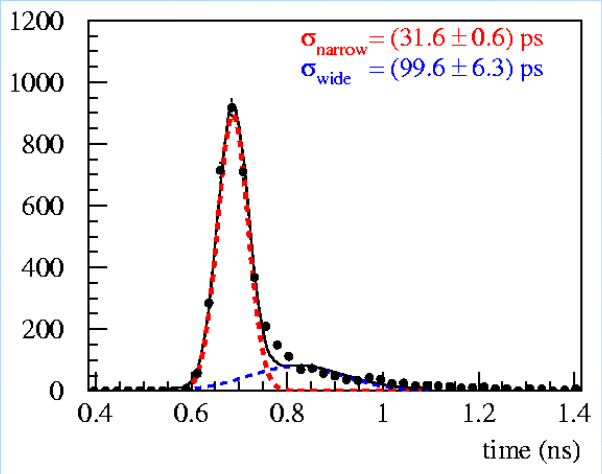




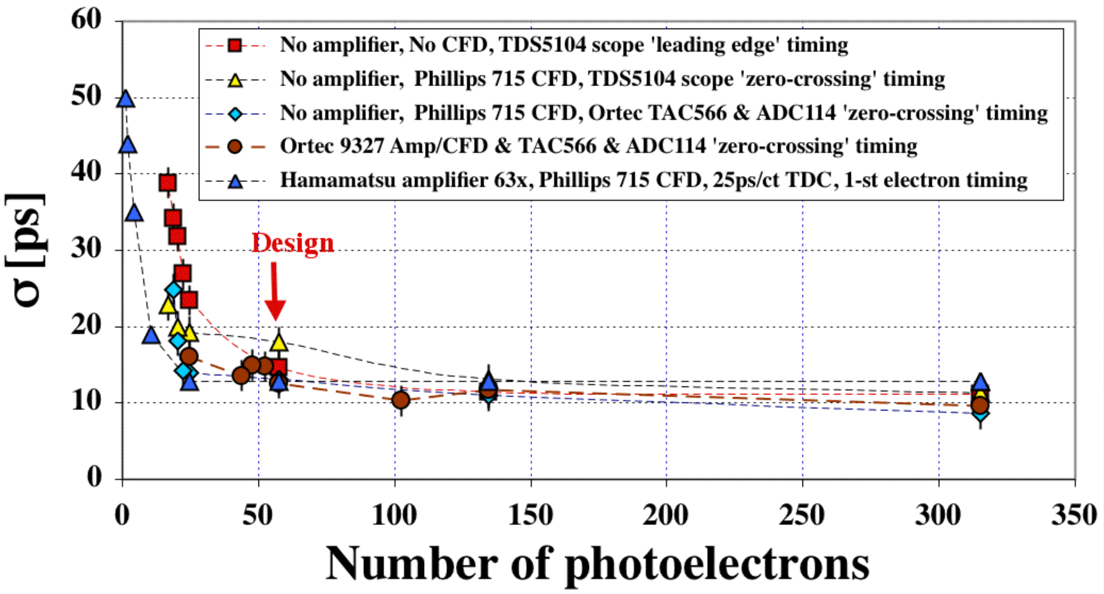
- Expected performance: $N_o = 31\ cm^{-1} \rightarrow N_{pe} \sim 28$ for 1.7 cm fused silica bar thickness
- 3mm pixel size is preferred choice.

TOF counter with Burle/Photonis MCP-PMT

σ_{TTS} - single photo-electrons:



Timing resolution σ = f(Npe):



- **TOF counter: Burle/Photonis MCP-PMT with a 1cm thick quartz radiator**
- **Our present best results with the laser diode:**
  - **σ ~ 12 ps for Npe ~ 50-60**, which is expected from 1cm of the radiator.
  - **σ_{TTS} ~ 32 ps for Npe ~ 1**.
  - **Upper limit on the MCP-PMT contribution: $\sigma_{MCP\text{-}PMT}$ < 6.5 ps**.
  - **TAC/ADC contribution to timing: σ_{TAC_ADC} < 3.2 ps**.
  - **Total electronics contribution: $\sigma_{Total\_electronics}$ ~ 7.2 ps**.

→ Talk by J. Va'vra

Samo Korpar
University of Maribor and Jožef Stefan Institute

Photon detection

Parameters used:

- $U = 200$ V
- $l = 6$ mm
- $E_0 = 1$ eV
- $m_e = 511$ keV/c^2
- $e_0 = 1.6\ 10^{-19}$ As

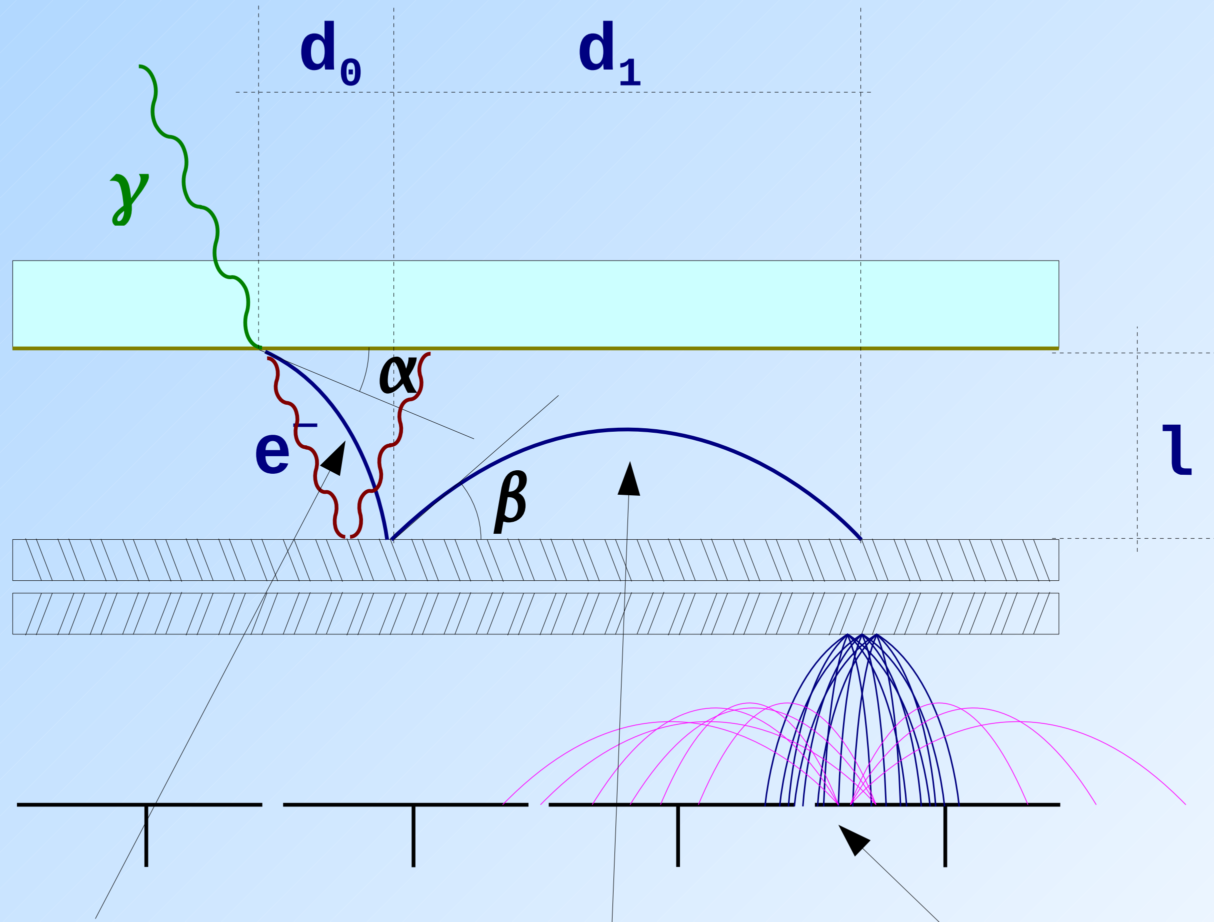


Photo-electron:

- $d_{0,max} \sim 0.8$ mm
- $t_0 \sim 1.4$ ns
- $\Delta t_0 \sim 100$ ps

Backscattering:

- $d_{1,max} \sim 12$ mm
- $t_{1,max} \sim 2.8$ ns

Charge sharing

MCPPMT: photo-electron

$$v'_{0x} = v'_0 \cos(\alpha) \qquad v'_0 = \sqrt{\frac{2E_0}{m_e}}$$
$$v'_{0y} = v'_0 \sin(\alpha)$$

$$a = \frac{Ue_0}{lm_e}$$

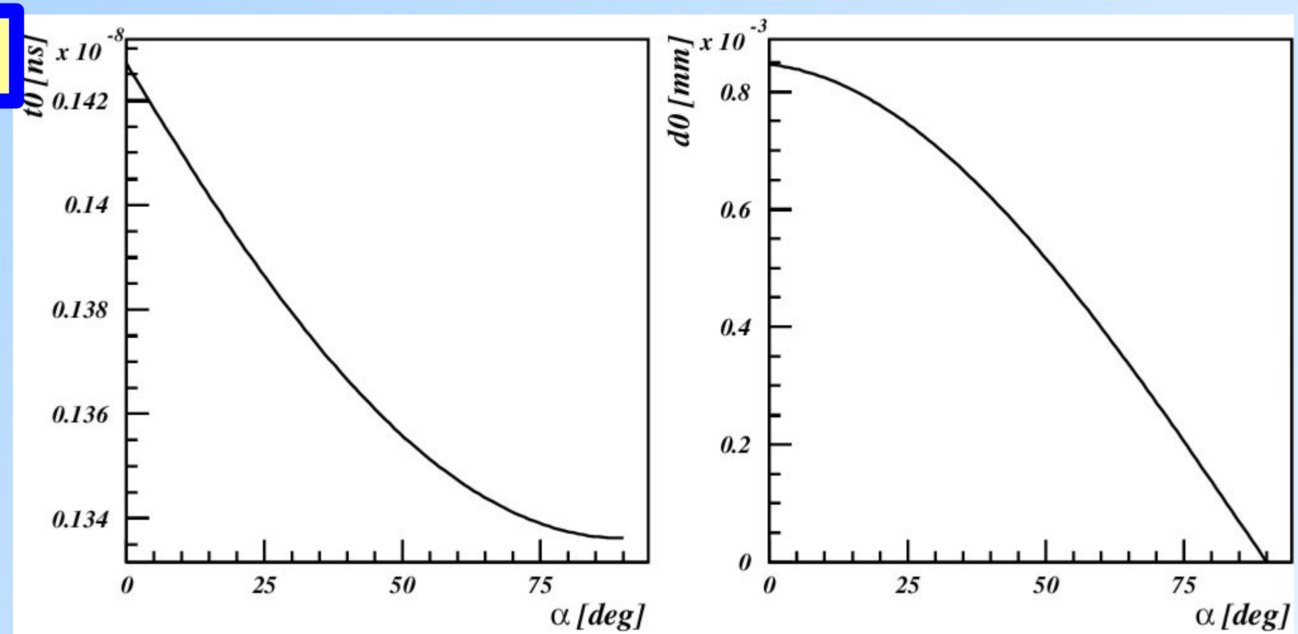
$$v_0 = \sqrt{\frac{2(E_0 + Ue_0)}{m_e}}$$

$$v_{0x} = \sqrt{\frac{2E_0\cos^2(\alpha)}{m_e}}$$

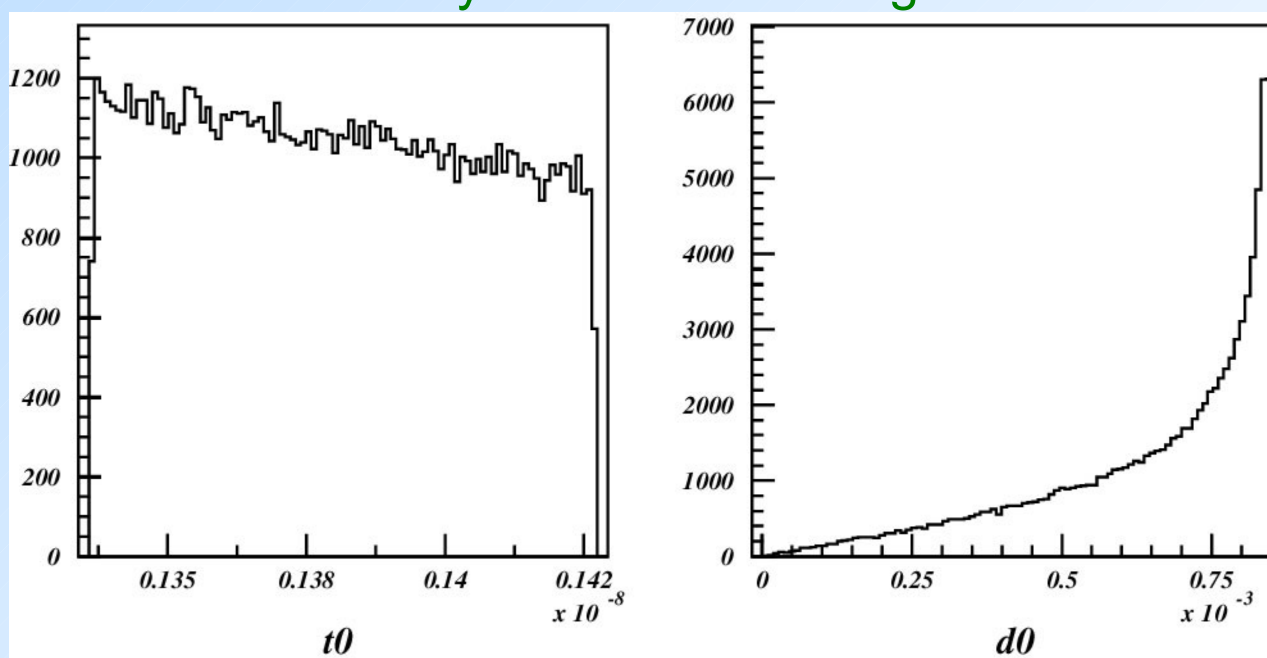
$$v_{0y} = \sqrt{\frac{2(E_0\sin^2(\alpha) + Ue_0)}{m_e}}$$

$$d_0 \approx 2l\sqrt{\frac{E_0}{Ue_0}}\cos(2\alpha)$$

$$t_0 \approx \sqrt{\frac{2m_e l^2}{Ue_0}}$$



Generated distributions assuming that photo-electron is emitted uniformly over the solid angle



8x8: TDC vs. x

- TDC vs. x for pad in the middle