Beam test of FARICH prototype with DPC (dSiPM)

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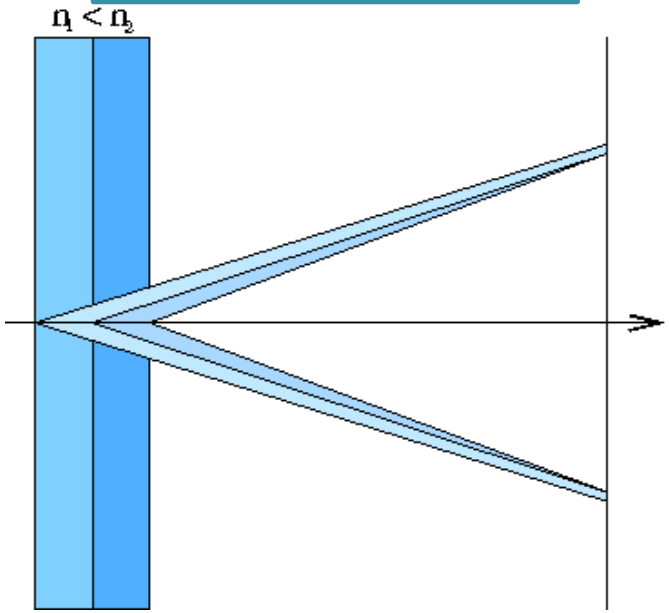
C. Degenhardt, R. Dorscheid , T. Frach, O. Muelhens, R. Schulze, B. Zwaans,
Philips Digital Photon Counting, Aachen, Germany

FARICH concept

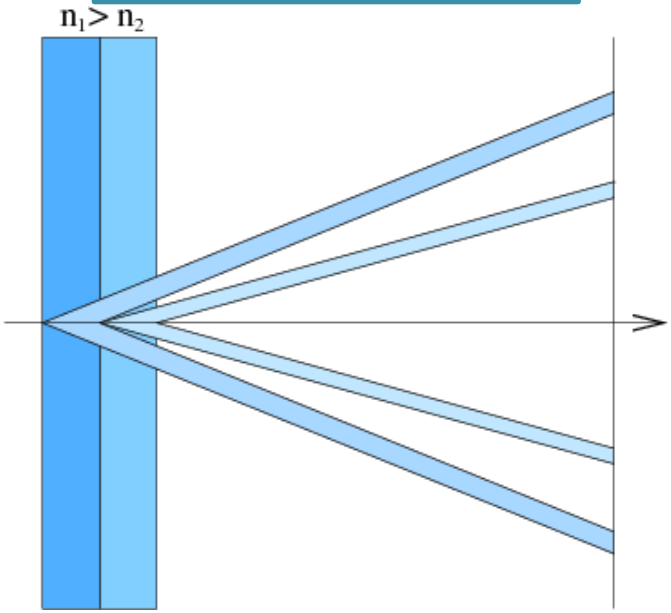
Focusing Aerogel RICH – FARICH

Improves proximity focusing design by reducing radiator thickness contribution into the Cherenkov angle resolution

Single ring option



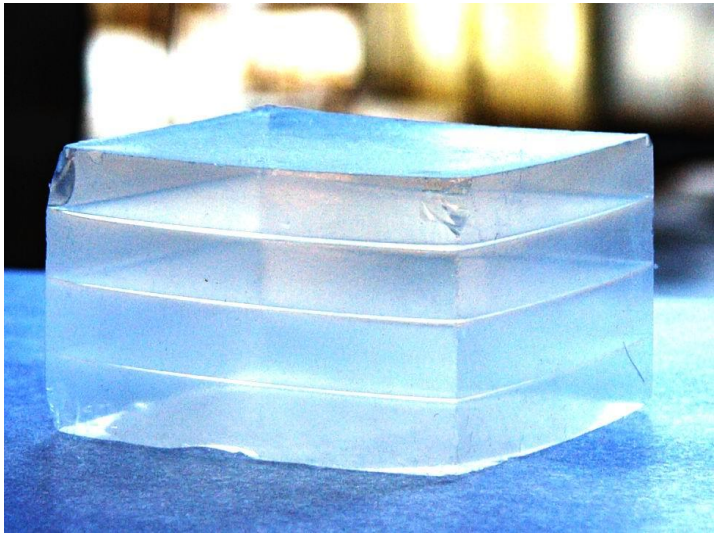
Multi-ring option

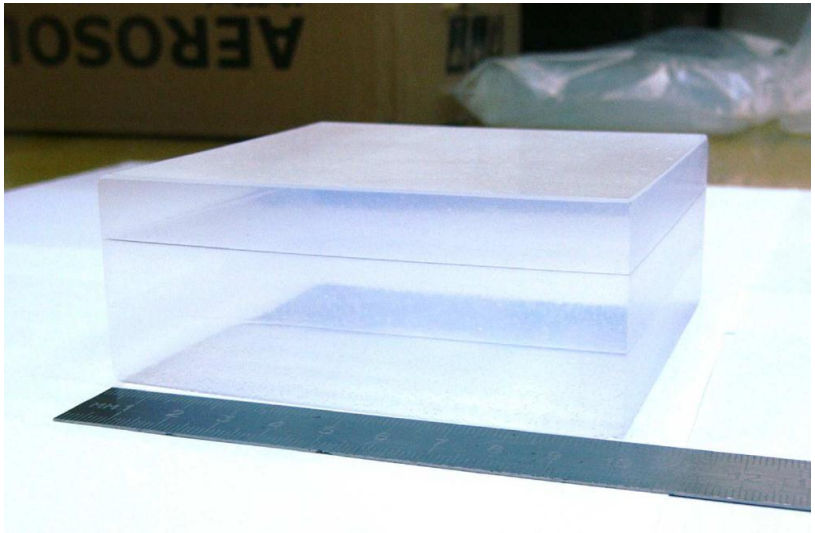


T.Iijima et al., NIM A548 (2005) 383
A.Yu.Barnyakov et al., NIM A553 (2005) 70

Multi-layer 'focusing' aerogels

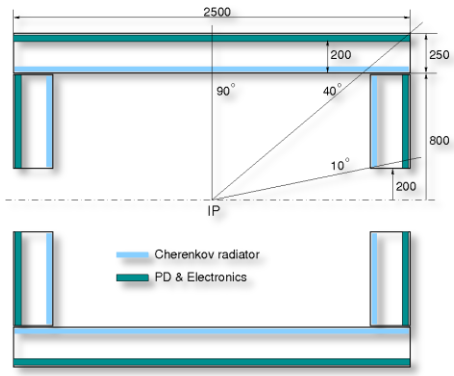
- Produced by Boreskov Institute of Catalysis (Novosibirsk) in cooperation with Budker Institute since 2004





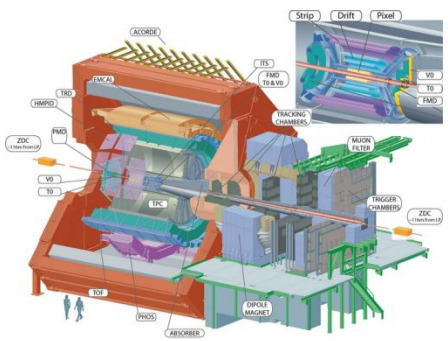
First 4-layer sample produced in 2004
A.Yu.Barnyakov et al., NIM A553 (2005) 70

FARICH projects and proposals



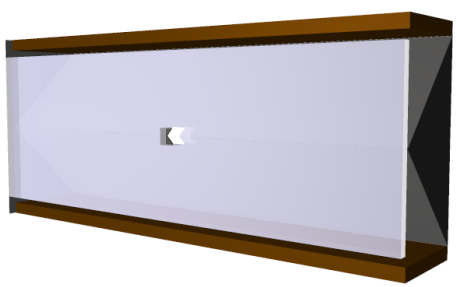
FARICH for Super Charm-Tau Factory (Novosibirsk)

Particle ID: μ/π up to 1.7 GeV/c
21m^2 detector area (SiPMs)
~1M channels



FARICH for ALICE HMPID upgrade

Particle ID: π/K up to 10 GeV/c, K/p up to 15 GeV/c
3m^2 detector area (SiPMs)



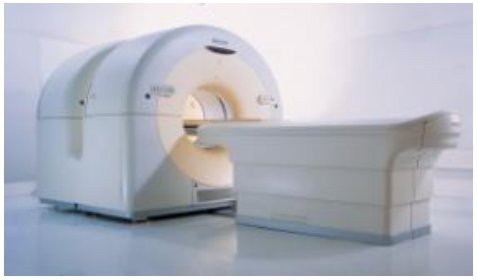
Forward Spectrometer RICH for PANDA

Particle ID: π/K/p up to 10 GeV/c
3m^2 detector area (MaPMTs or SiPMs)

Philips Digital Photon Counting (PDPC)

Philips Digital Photon Counting is designing and manufacturing **scalable** detectors based on **digital Silicon Photomultiplier (dSiPM) technology** – a new type of advanced solid state light detector, now called **Digital Photon Counter (DPC).**

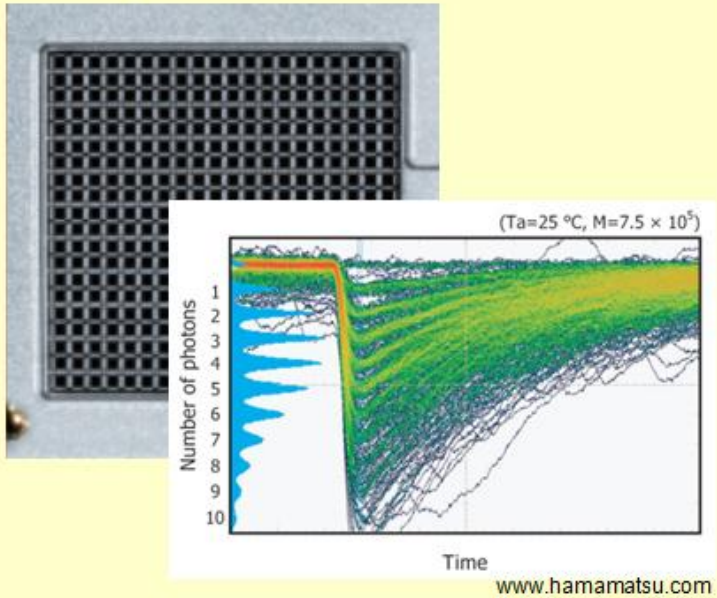
Potential Applications



- **Medical Imaging**
- **Life Sciences**
- **High Energy Physics**
- **Material Testing/Detection**
- **Process Control**

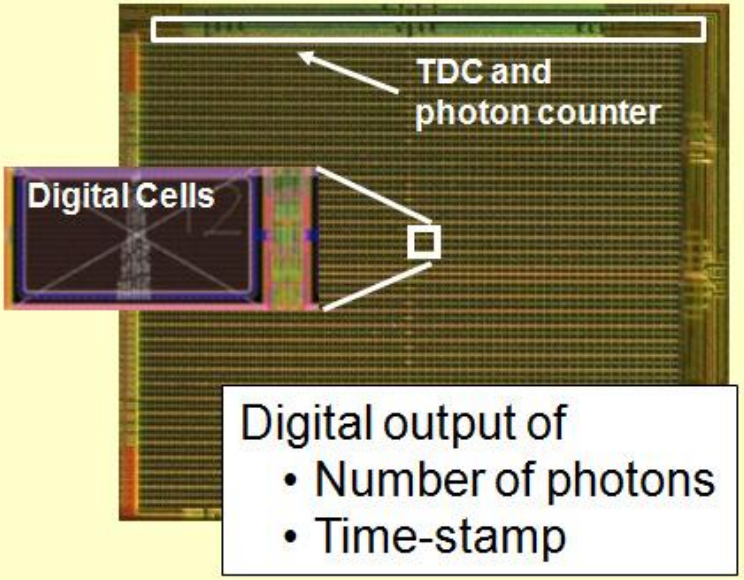
DPC: Front-end Digitization by Integration of SPAD & CMOS Electronics

analog SiPM



Summing all cell outputs leads to an analog output signal and limited performance

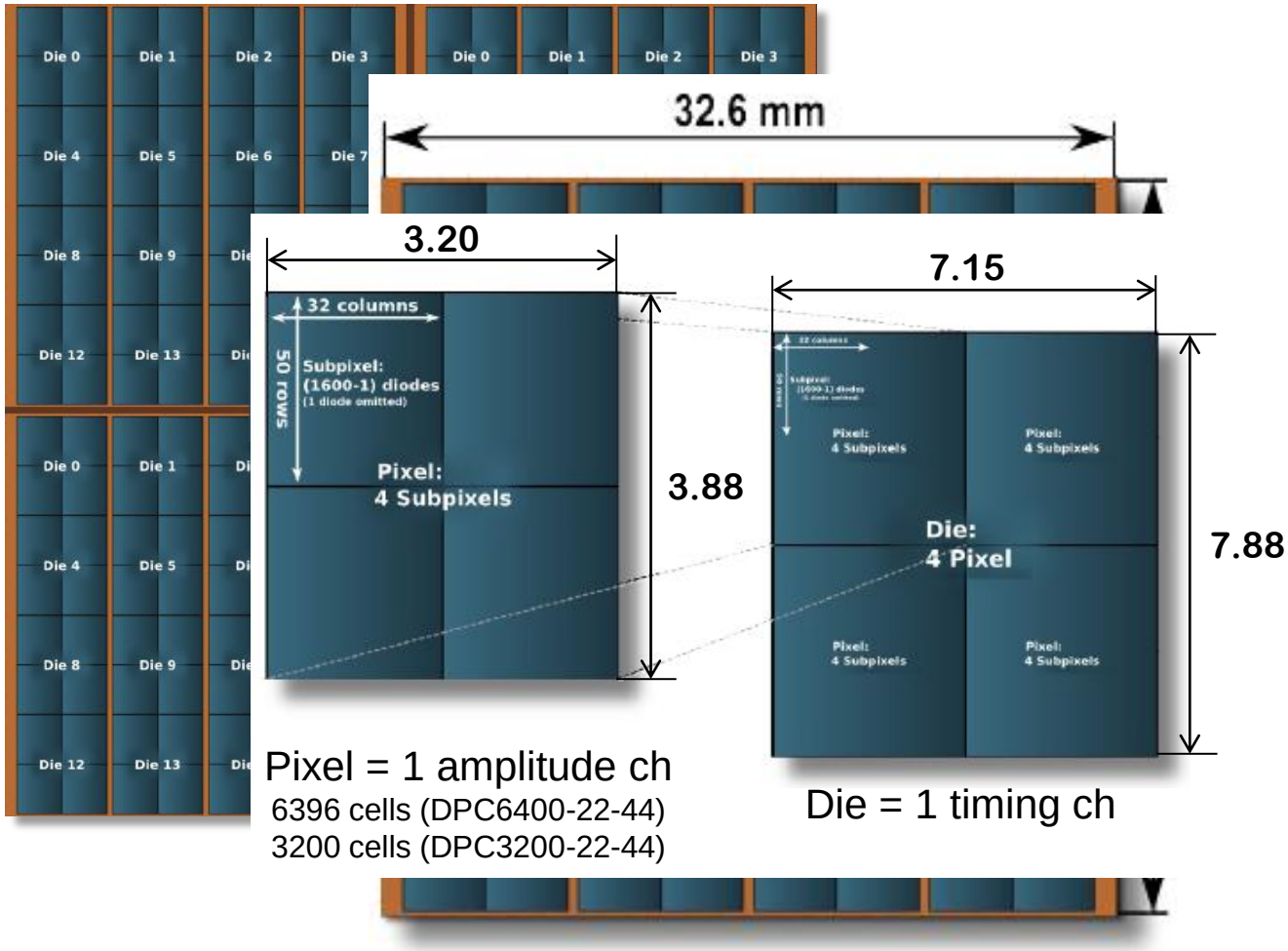
Digital Photon Counter (DPC)



Integrated readout electronics is the key element to superior detector performance

T. Frach, G. Prescher, C. Degenhardt, B. Zwaans, IEEE NSS/MIC (2010) pp.1722-1727
C. Degenhardt, T. Frach, B. Zwaans, R. de Gruyter, IEEE NSS/MIC (2010) pp.1954-1956

DPC hierarchy for FARICH prototype



Pixels in module packing density ~70%

First test of DPC in High Energy Physics: FARICH Detector @ CERN, June 2012

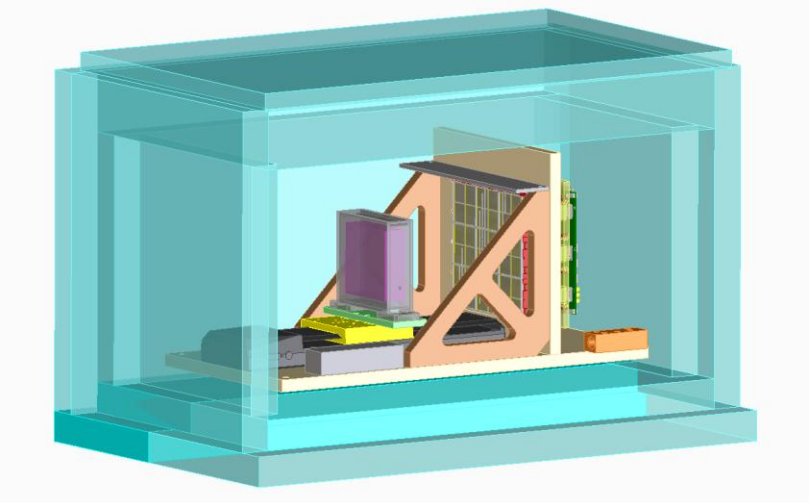
Main objective:

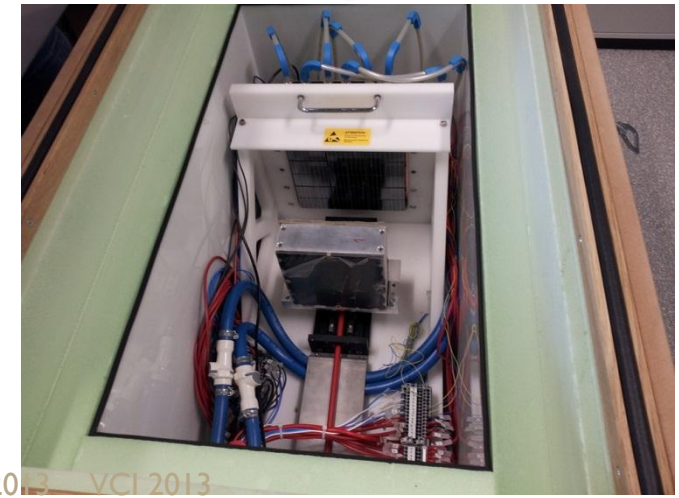
Proof of concept: full Cherenkov ring detection with DPC array

Timeline:

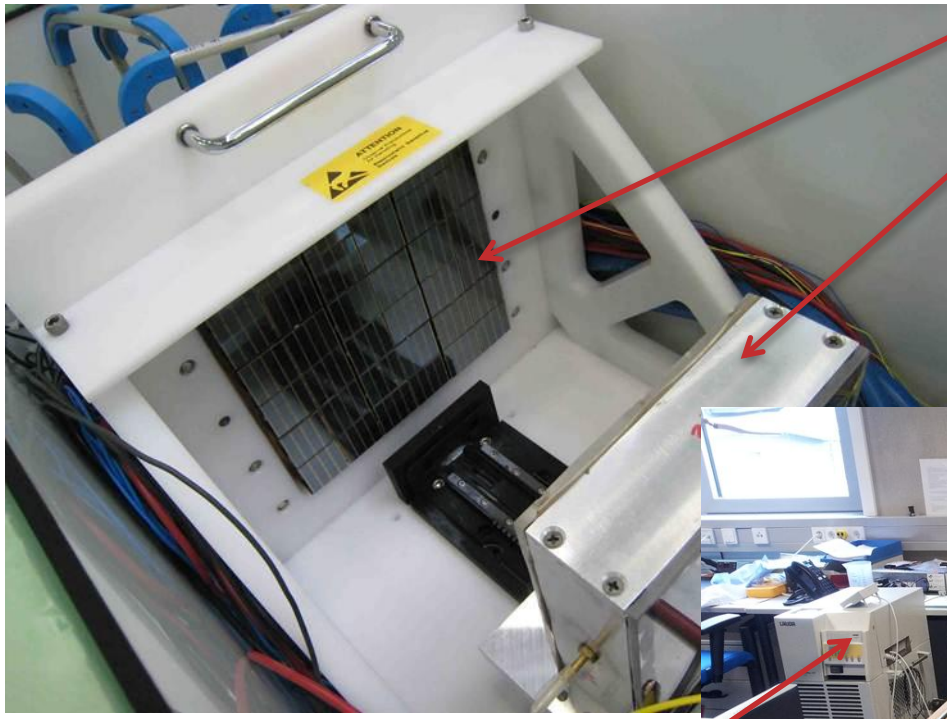
- Started to envisage: **28/02/12**
- Requirements for the FARICH prototype test setup fixed: **30/04/12**
- Prototype operational @ Aachen Labs: **03/06/12**
- Installed @ CERN: **12/06/12**
- Subsequent beam runs for 12 days until **25/06/12** with smooth setup operation

Fast prototyping!





FARICH prototype with DPC:
engineered and made by PDPC



DPC detector 20x20 cm2

Aerogel sample container on movable table

Operation at -40°C to suppress dark counts: DCR ~ 100 kcps/die. Blow dry N_2 to avoid condensation.

Process thermostat
LAUDA Integral XT

Thermal insulation:
10 cm styrofoam

FARICH prototype with DPC…

4-layer aerogel

- n_{max} = 1.046
- Thickness 37.5 mm
- Calculated focal distance 200 mm
- Hermetic container with plexiglass window to avoid moisture condensation on aerogel

Square matrix 20x20 cm^2

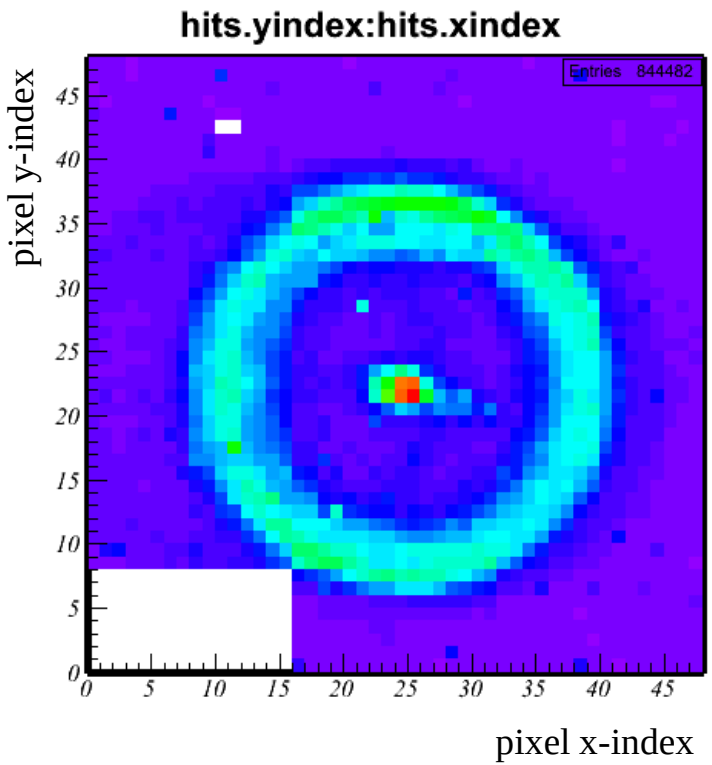
- Sensors: DPC3200-22-44
- 3x3 modules = 6x6 tiles = 24x24 dies = 48x48 pixels in total
- 576 time channels
- 2304 amplitude (position) channels
- 4 levels of FPGA readout: tiles, modules, bus boards, test board

FARICH prototype at CERN PS T10 beam channel

Inventor of DPC
Thomas Frach

Observation of Cherenkov ring

Pixel hit map



Test conditions

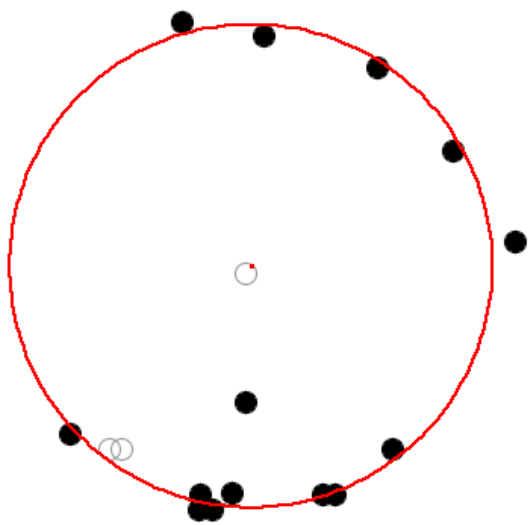
- Positive polarity

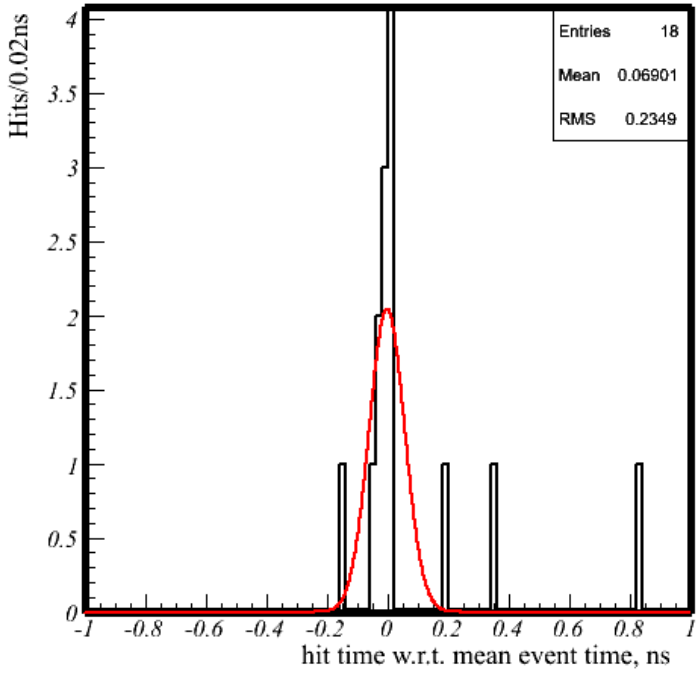
  $e^+, \mu^+, \pi^+, K^+, p$
- Momentum: 1 - 6 GeV/c
- Trigger: a pair of sc. counters 1.5x1.5 cm^2 in coincidence separated by ~3 m
- No external tracking, particle ID, precise timing of trigger
- Hardware hit selection in a programmable time window to fit in data bandwidth

Event-by-event ring fit

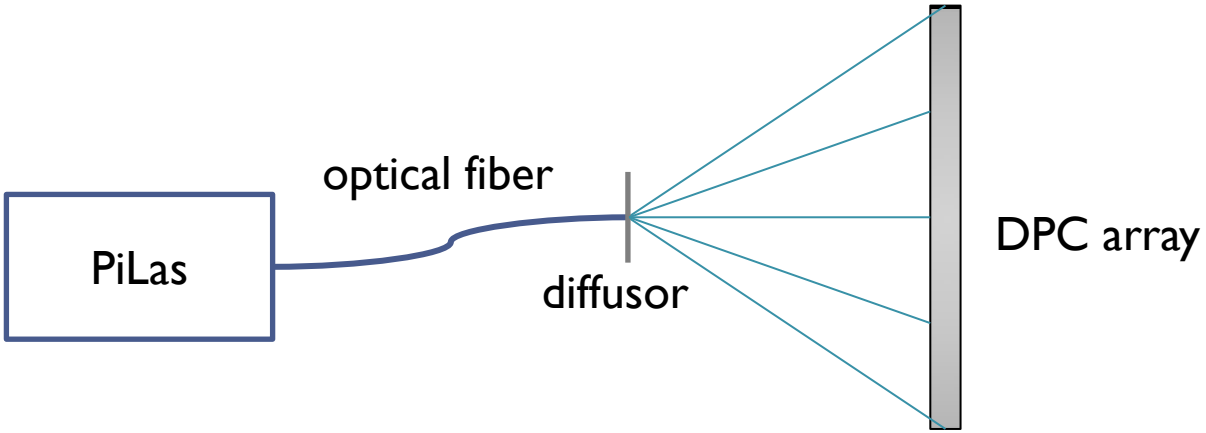
Hit selection and ring fit:

- Reject central hits
- Select hits in 4 ns time window
- More than 3 selected hits per event
- 4 parameters fitted: X_{center}, Y_{center}, R, t_0

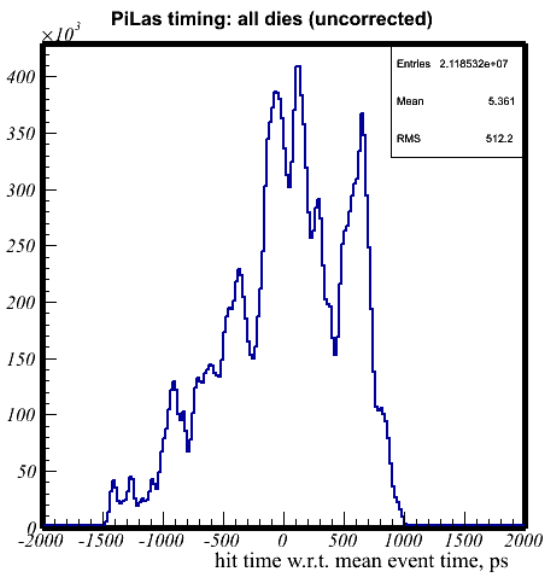




Die-to-die clock skew correction

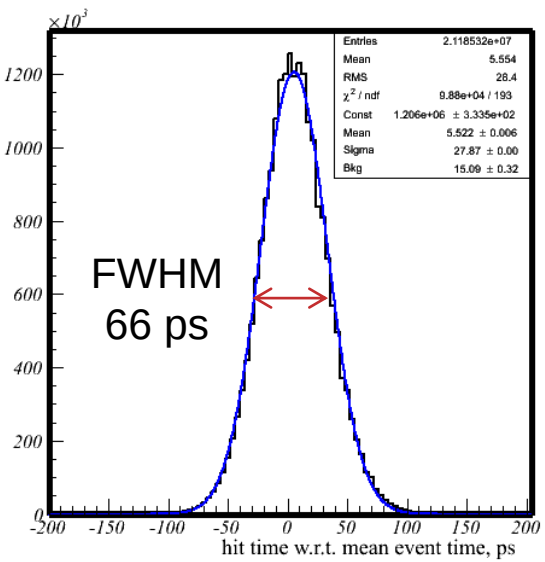


All dies hit times w.r.t. mean event time



~80 photons/die

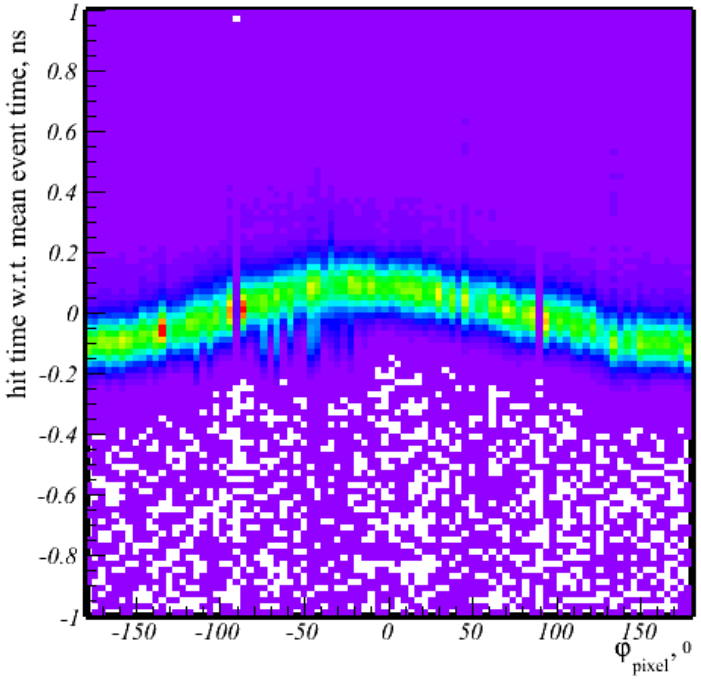
Clock skew correction between dies



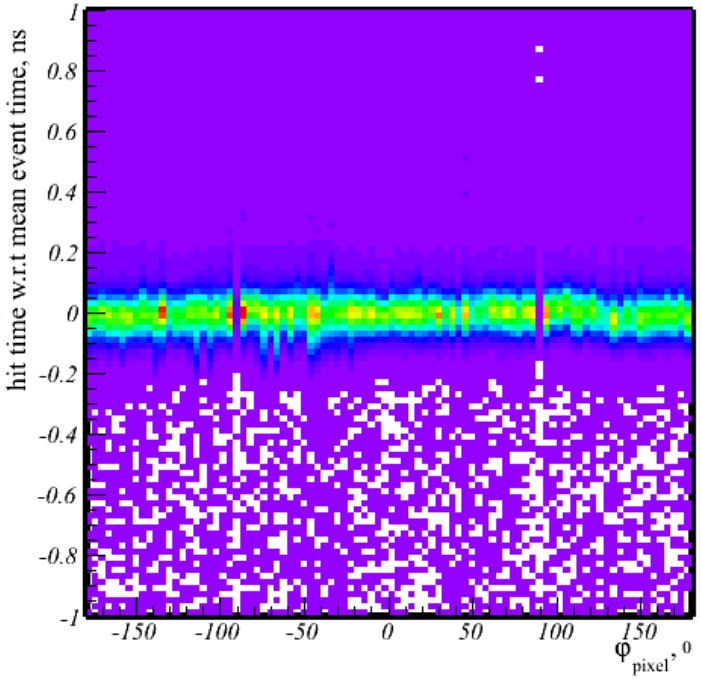
Timing correction by ring data

Hit timing vs φ-position

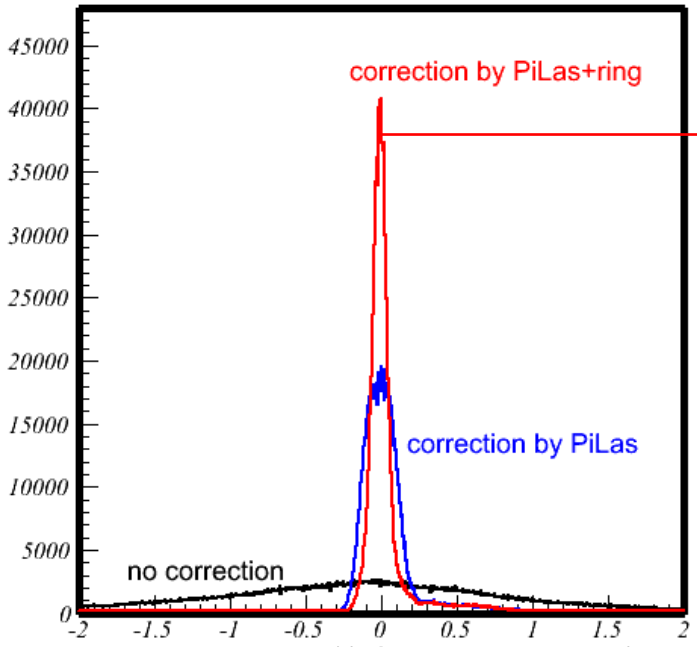
Before



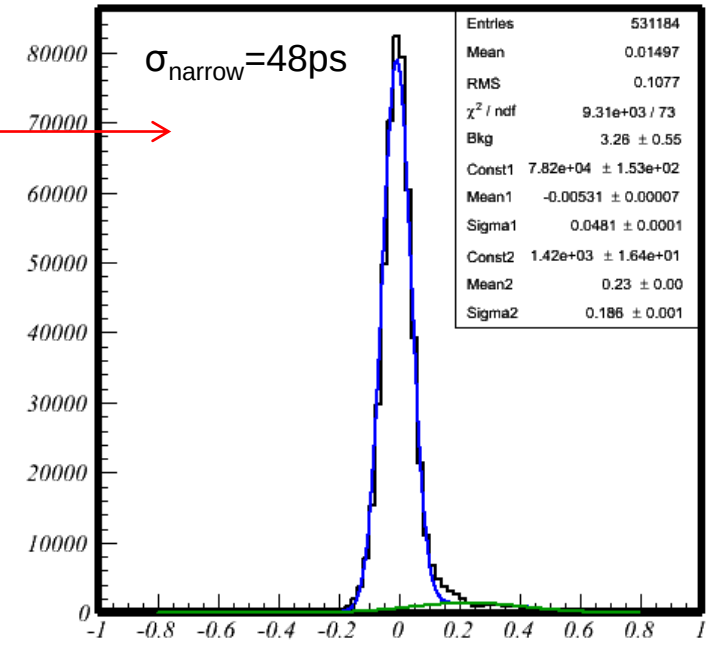
After



Timing resolution for Cherenkov photons



Hit time w.r.t. fitted event time, ns



Hit time w.r.t. fitted event time, ns

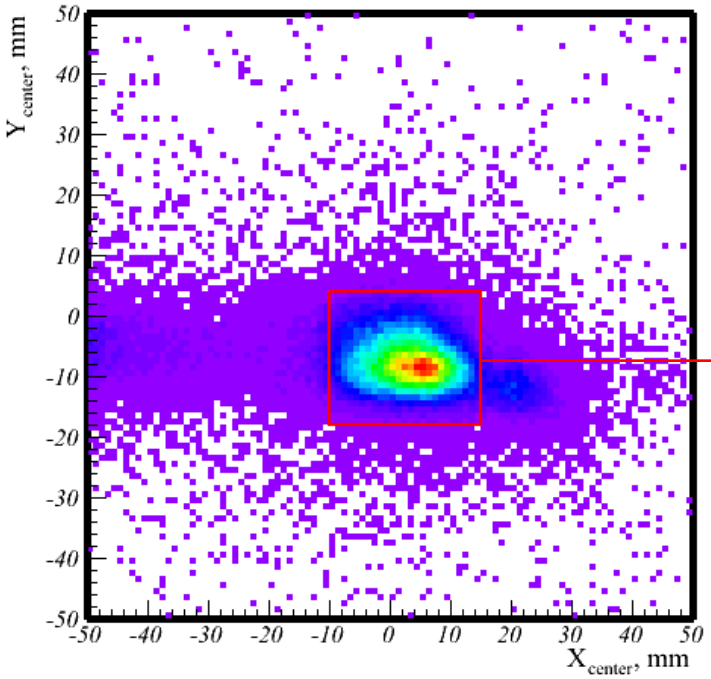
Fit two gaussians plus constant. 90% of area is contained in the narrow gaussian.

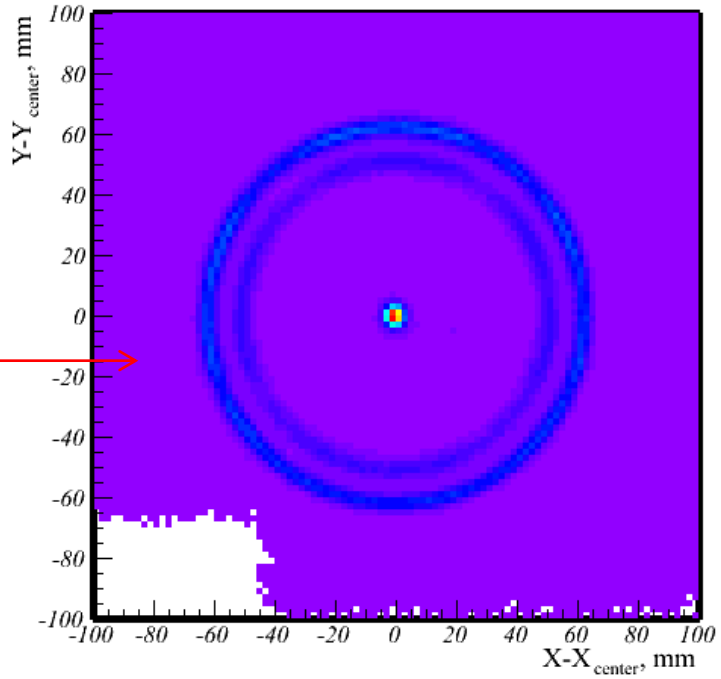
Ring center adjusted distributions

P=6 GeV/c, L=200mm

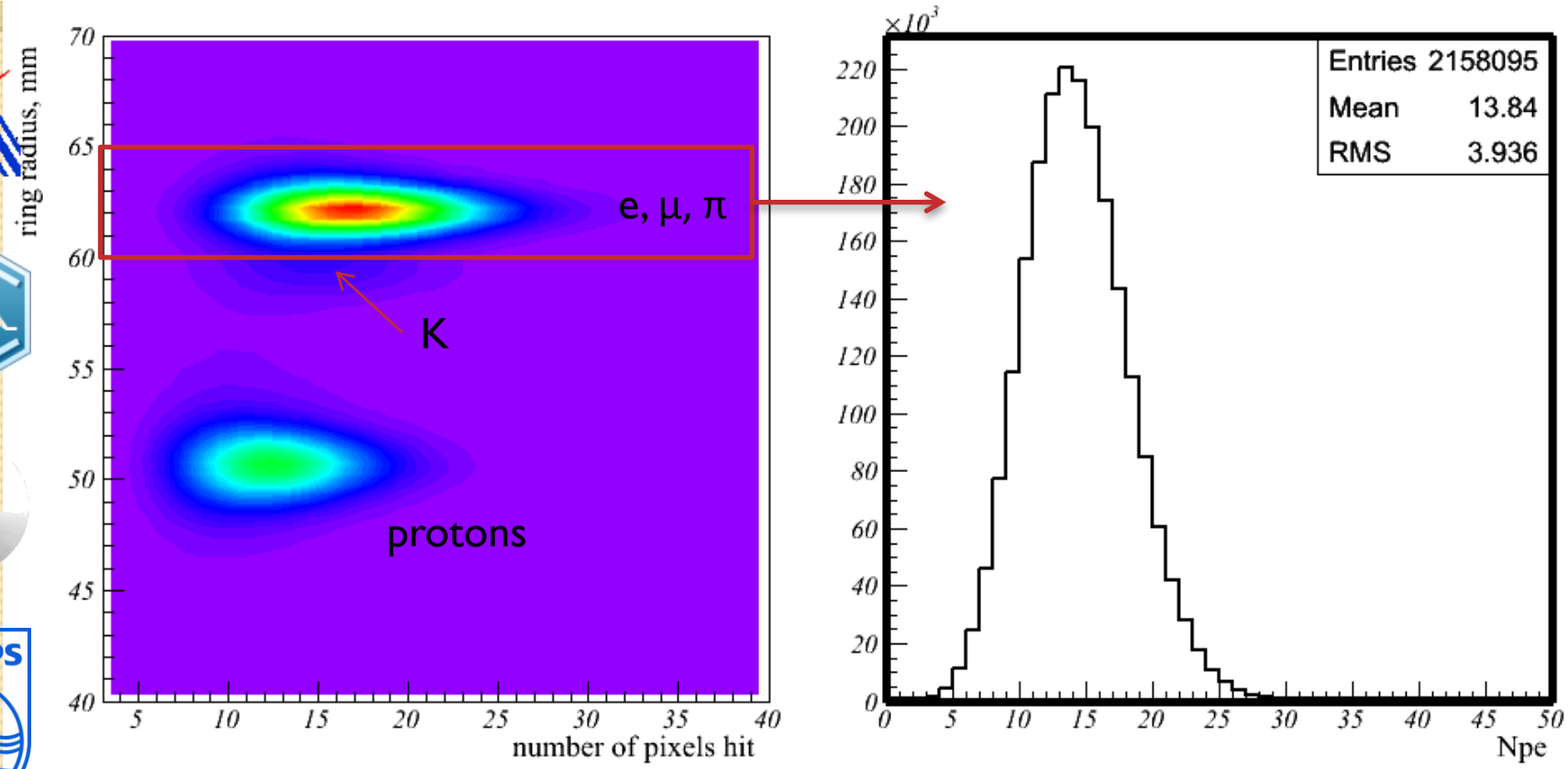
Ring center position in detector plane

Hit positions





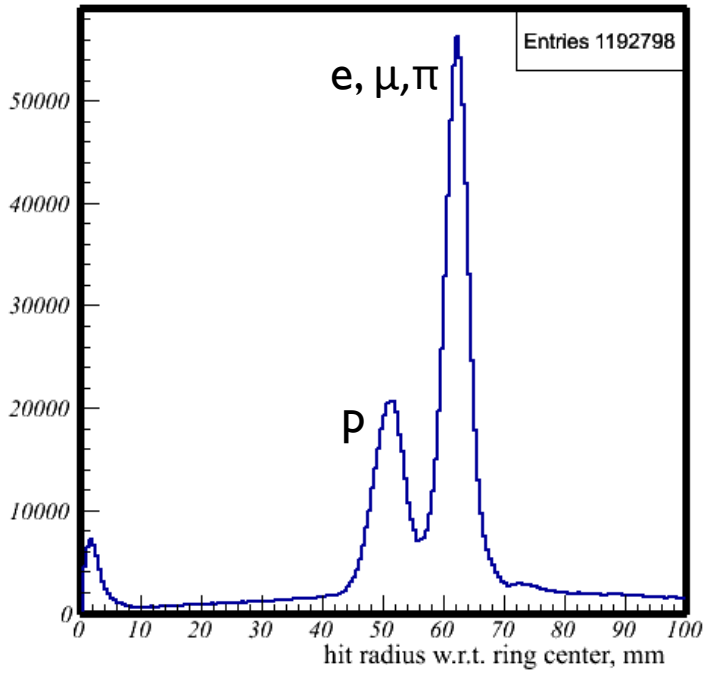
Number of photoelectrons



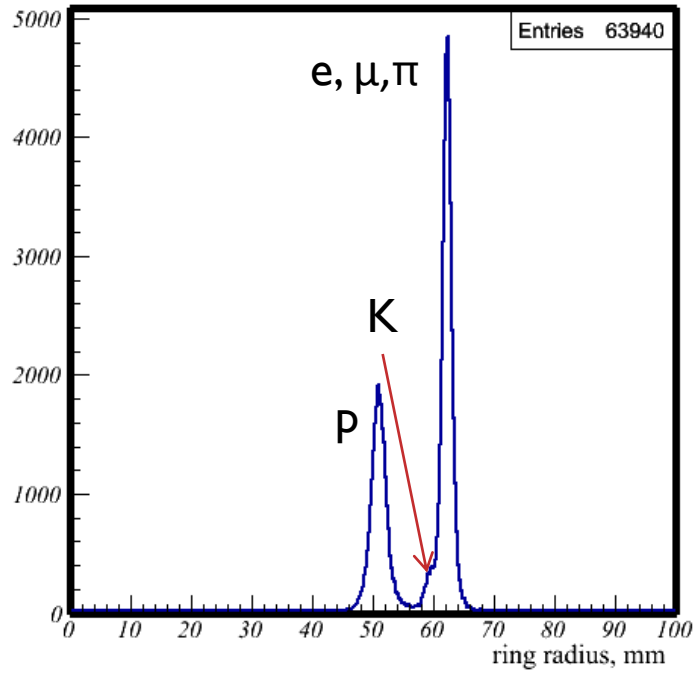
Radial distributions

P=6 GeV/c, L=200mm

Hit distribution on radius



Event distribution on radius



Ring radius distribution fit

Fit function

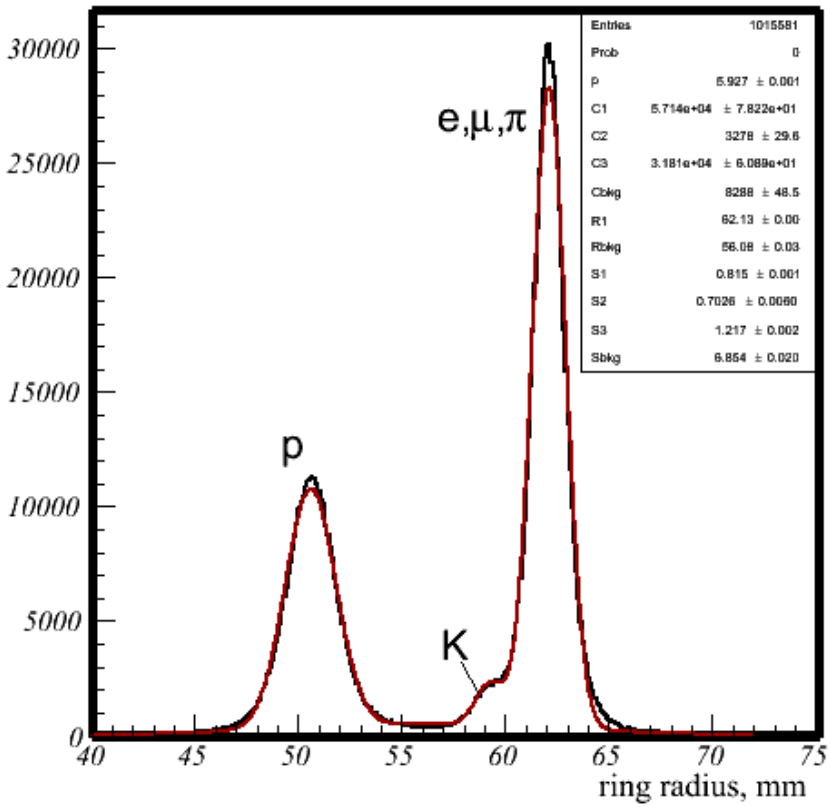
sum of three gaussians for each particle type with distinct radius plus gaussian background (to account for non-monochromatic particles in the beam)

Free parameters:

- Particle momentum
- Ring radius of rightmost gaussian (other radii derived from Cherenkov law)
- Constants and sigmas of all gaussians

Fixed parameter:

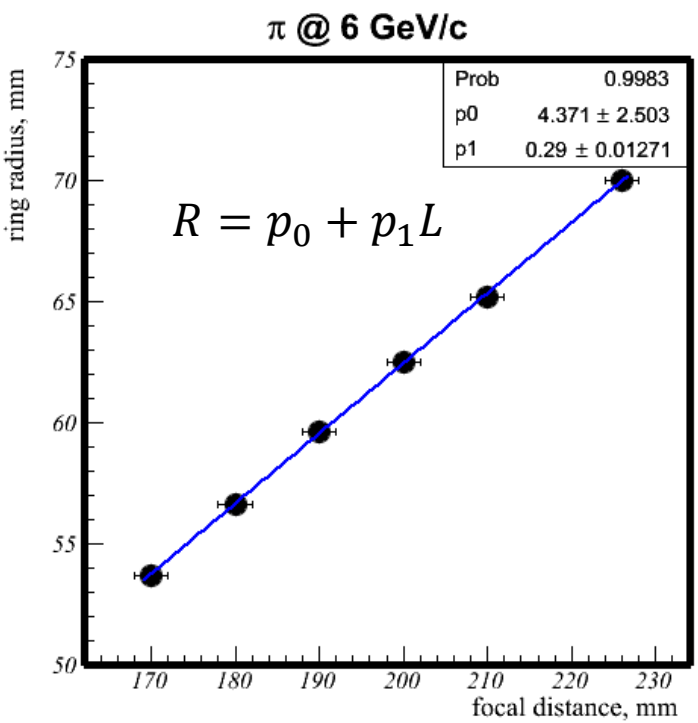
- Effective refractive index n_{eff}=1.038



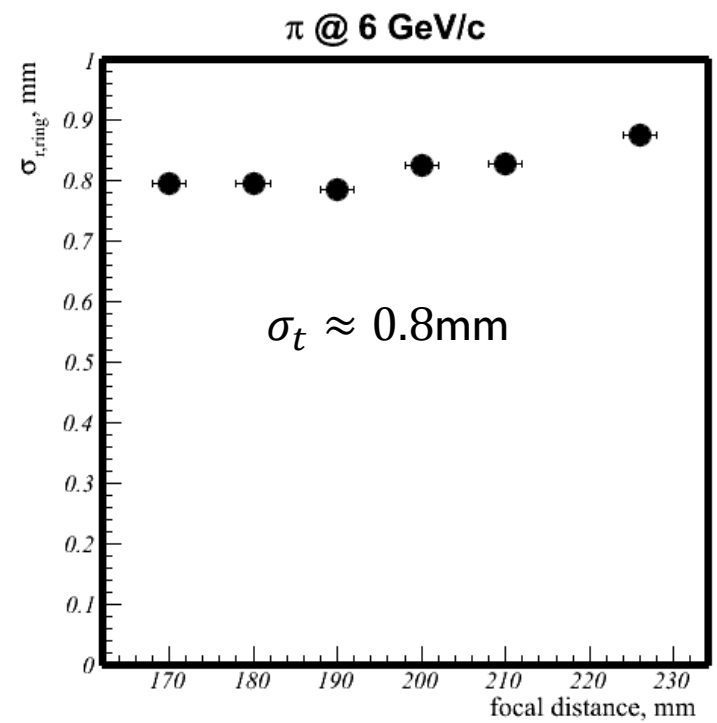
Aerogel-detector distance dependence

"pions" at P=6 GeV/c

Ring radius

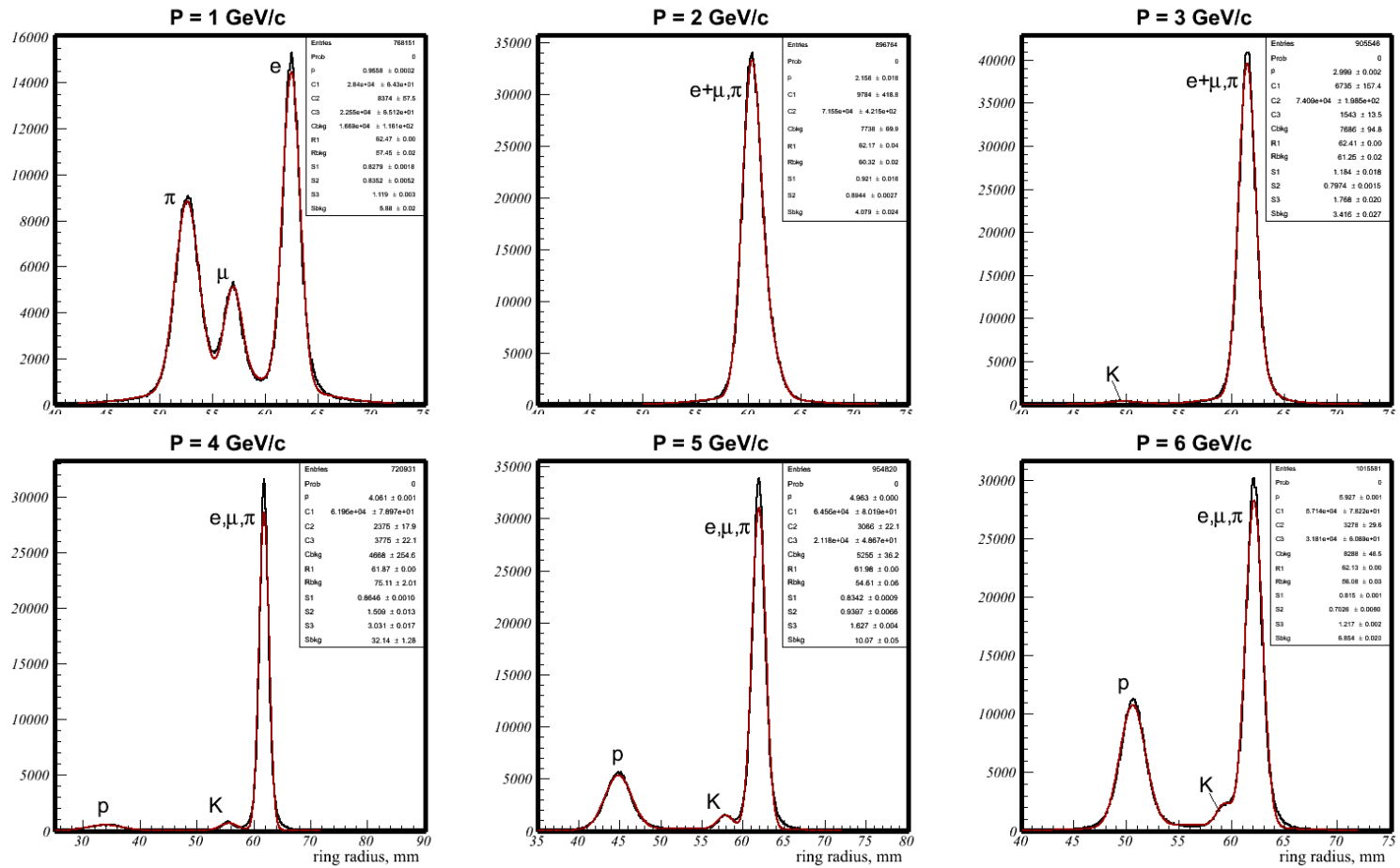


Ring radius sigma



Momentum dependence

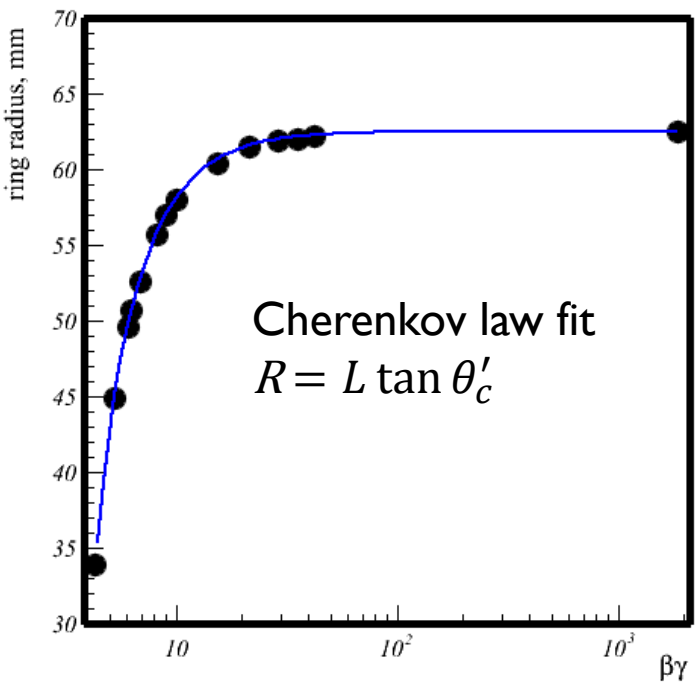
6 points on momentum



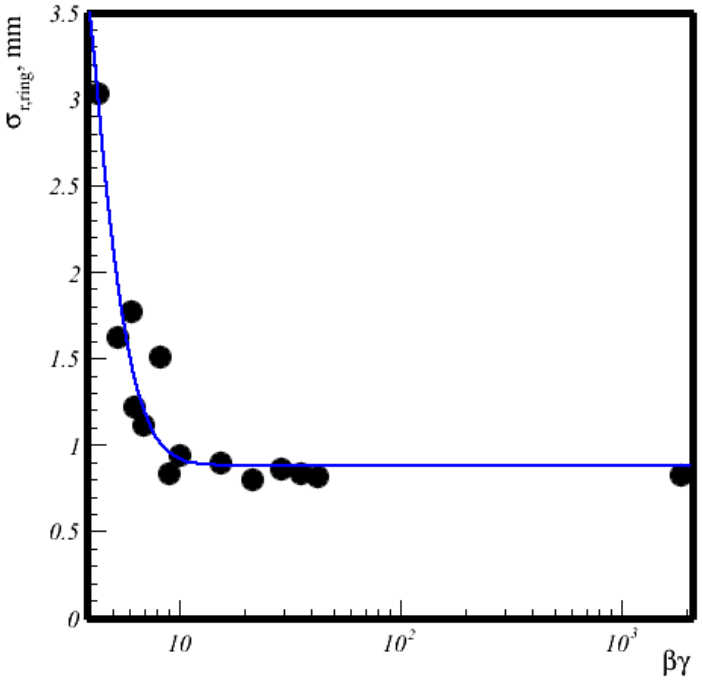
Not more than 3 particle peaks are fit in each point

Momentum dependence…

Ring radius vs βγ=p/M

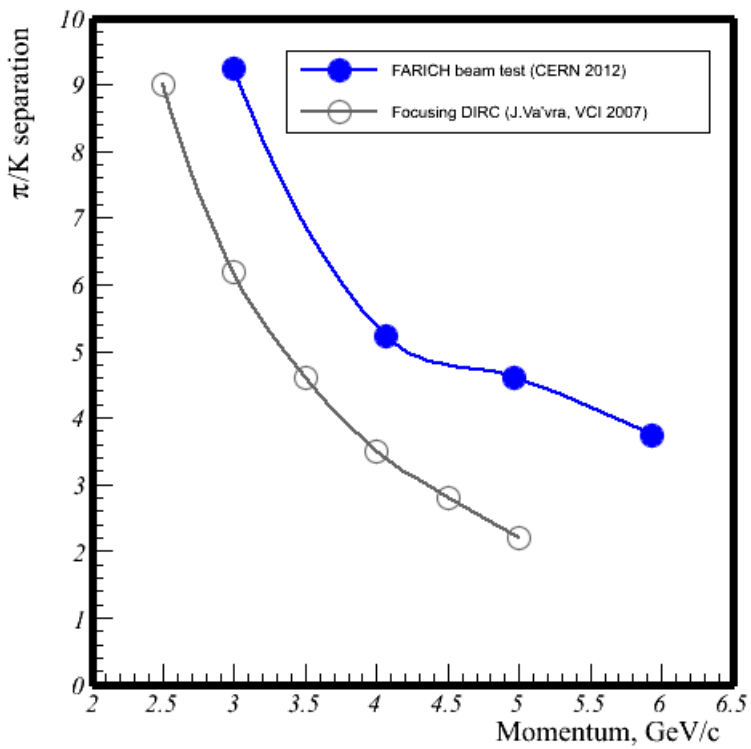


Ring radius sigma vs βγ



Particle separation

$$S=2\frac{R_\pi - R_K}{(\sigma_\pi + \sigma_K)}$$



π /K: 3.8σ @ 6GeV/*c*
μ/π: 4.5σ @ 1 GeV/*c*

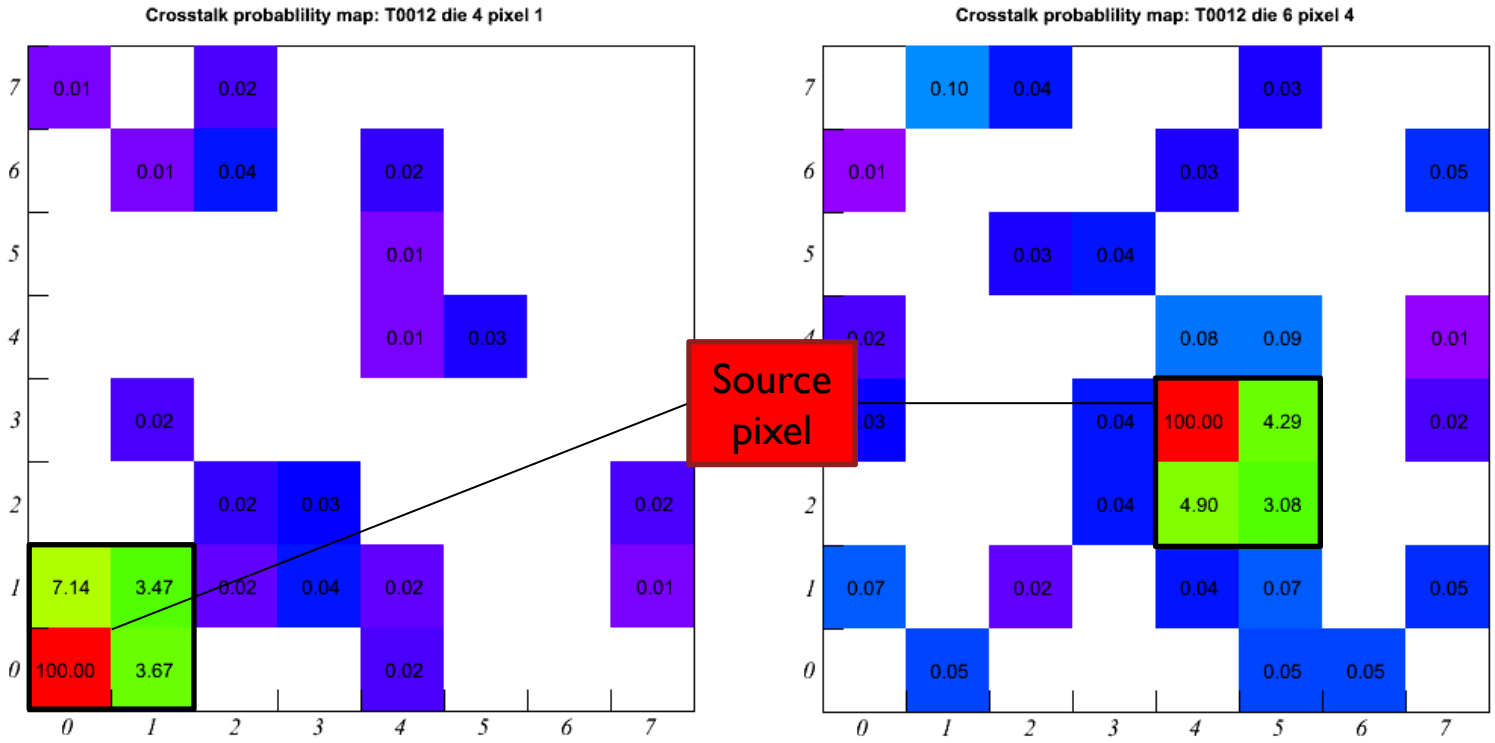
Rather idealized simulation for P=6 GeV/c gives
N_{pe} (π) = 24
π/K separation = 9 σ

Experimental results are far from simulated values, but there are reasons:

- Seems to be lower PDE than measured by PDPC previously (needs to be checked)
- Resolution deterioration due to pixel crosstalk
- No tracking (simulation relies on it)
- Probably: focusing aerogel tested gives wider ring than expected

Crosstalk between pixels

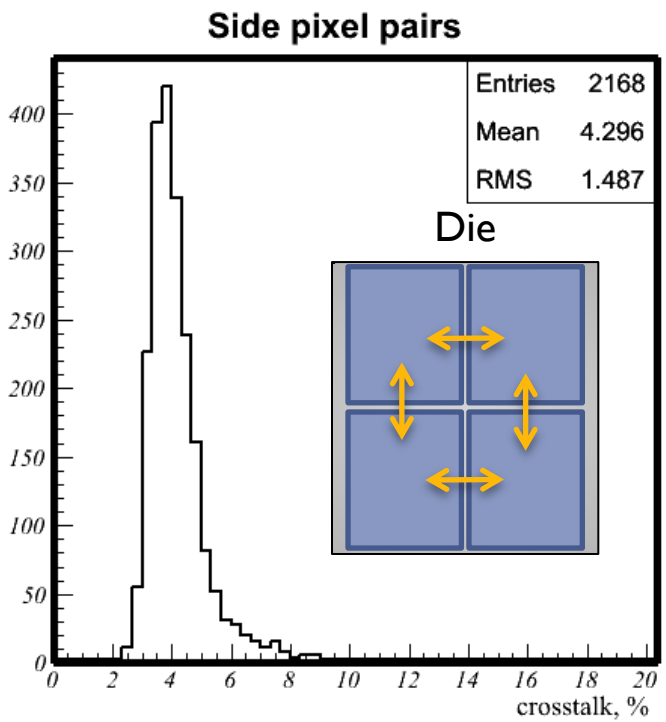
Crosstalk probability (%) on a tile pixel map
Special run with random trigger

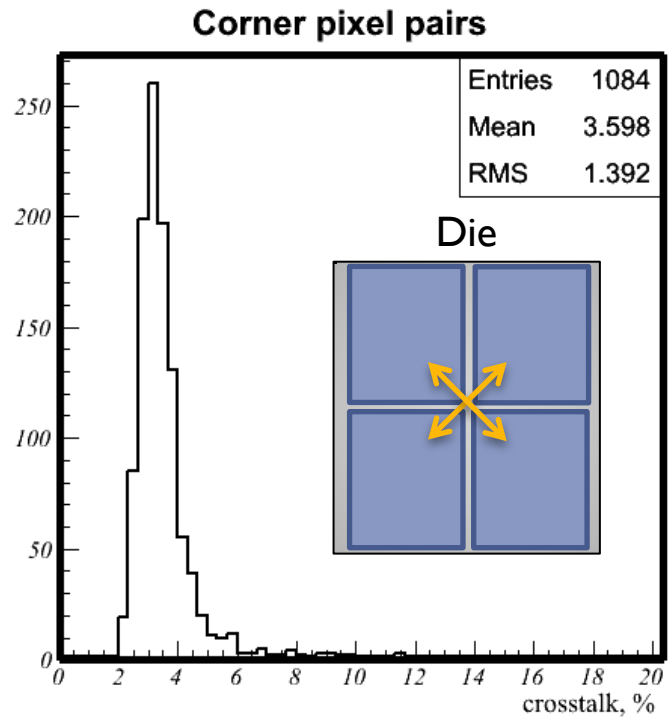


Crosstalk is significant only between pixels of one die

Crosstalk between pixels…

Crosstalk distribution of pixel pairs



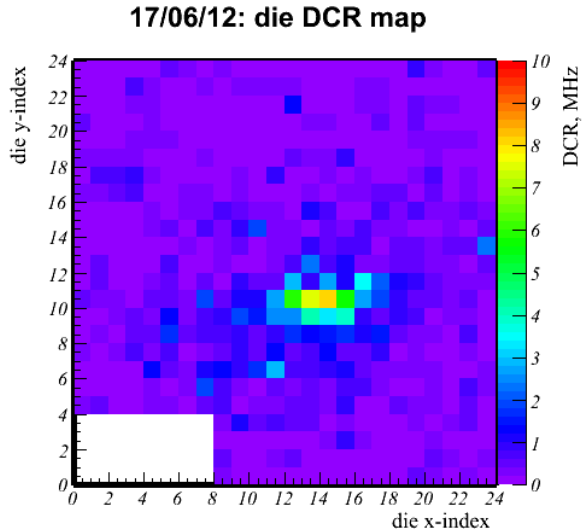


~4% crosstalk probability between pixels of one die → ring radius resolution deterioration

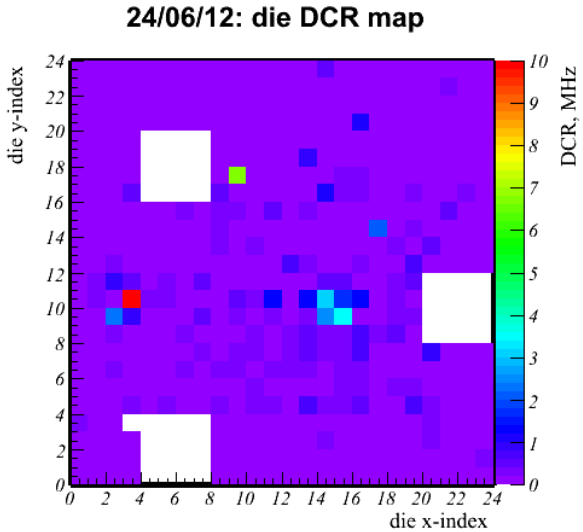
DPC detector stability

Note: radiation dose was not monitored during the experiment

Radiation damage: Dark count rate changing



5th day of beam



10th day of beam
with 2 days break
at +30°C

Partial recovery is observed after annealing for 2 days at 30°C

Breakage: only 4 of 36 tiles failed after 2 weeks and several thermal cycles. DPC modules and tiles was not designed to work routinely at low temperature with frequent thermal cycles. It was just a first test.

Conclusion

- Beam test of FARICH prototype with Philips DPC was prepared and successfully realized in a short time scale.
- Cherenkov rings are detected from focusing aerogel with ~14 photoelectrons for relativistic particles.
- Timing resolution of σ_t=48 ps is achieved for single Cherenkov photons.
- π/K separation obtained for P=6 GeV/c is 3.8σ,
  μ/π separation is 4.5σ for P=1 GeV/c.
- Signs of radiation damage are observed that partially recovered by annealing at room temperature.
- Very positive experience of 2 weeks operation of the large and complex setup.
- Tests were continued at electron test beam in BINP in January 2013. Results are coming up.

Thank you for attention!

Data acquisition chain

Die trigger
- 1st photon trigger
- no validation
- TDC timestamp

Die readout
- Number of photons
- Recharge
- Die is ready to detect next photons after 720ns

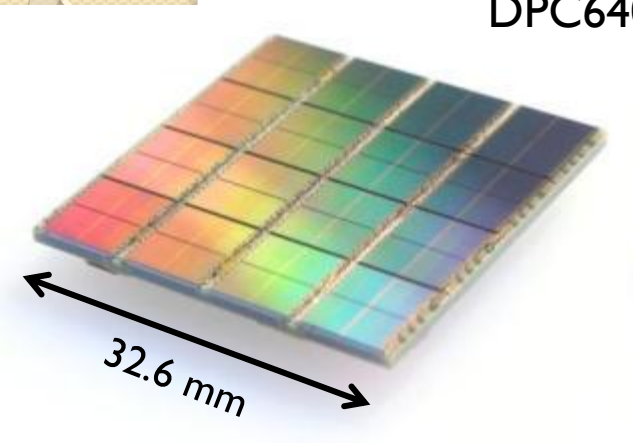
Hit selection
- Hits are selected in a programmable time window generated from ext. sync signal by tile FPGA

FPGA chain readout
- No additional data reduction
- Bottleneck is data transfer to PC by USB 1.1 link @ 12 Mbit/s

Most significant data loss happen at the die level:
- Dead time 720 ns
- DCR = 100 kcps @ -40°C
- Photon detection efficiency loss of ~ 7%

DPC is an Integrated "Intelligent" Sensor

DPC3200-22-44
DPC6400-22-44

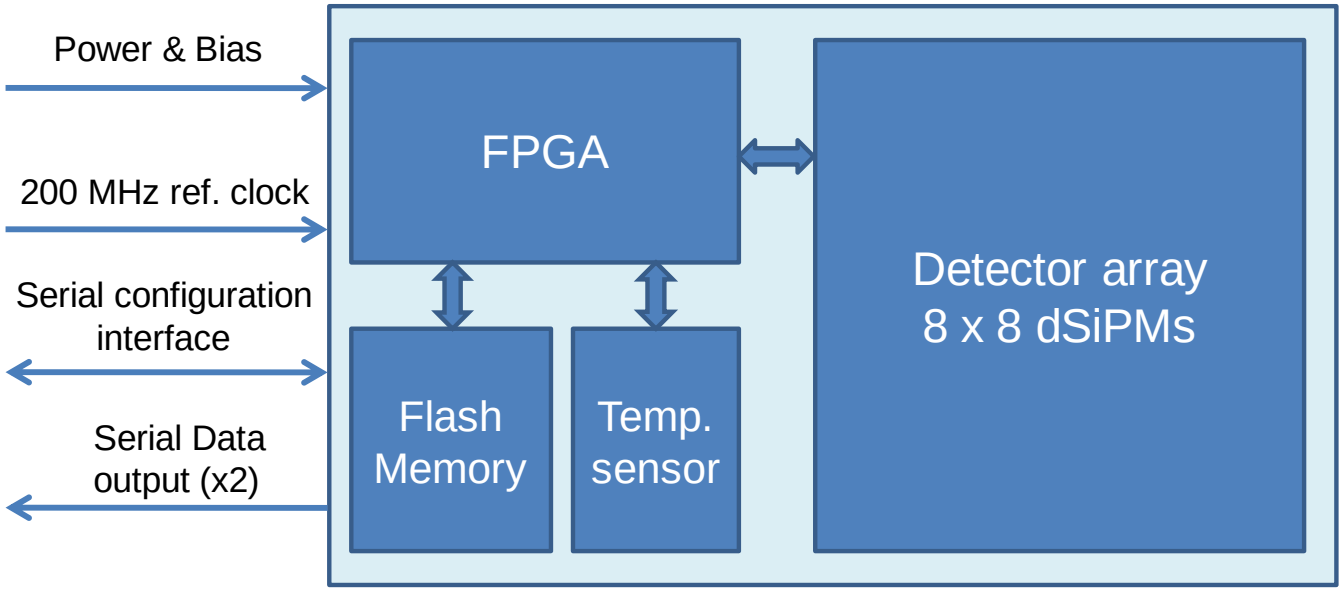


FPGA

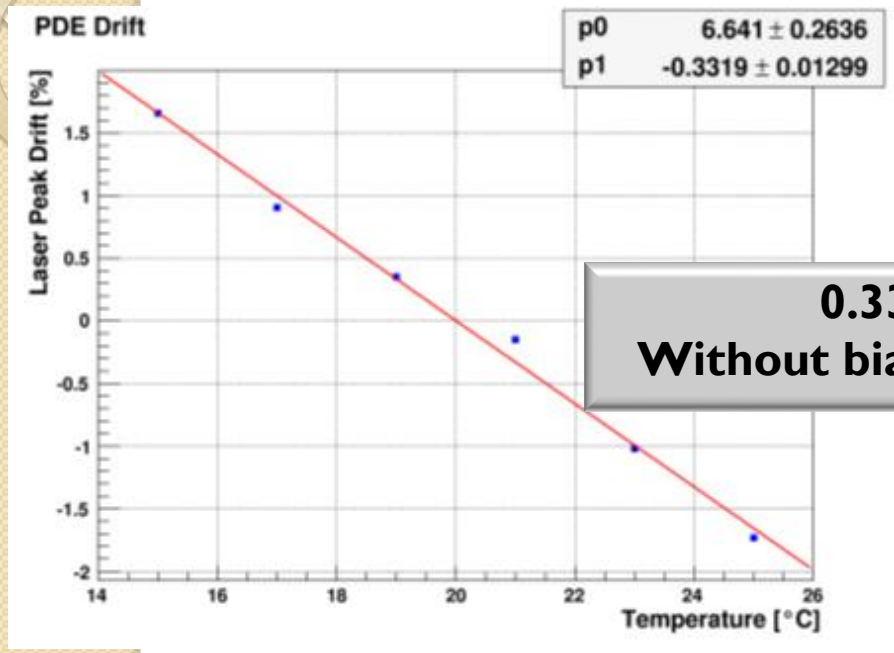
- Clock distribution
- Data collection/concentration
- TDC linearization
- Saturation correction
- Skew correction

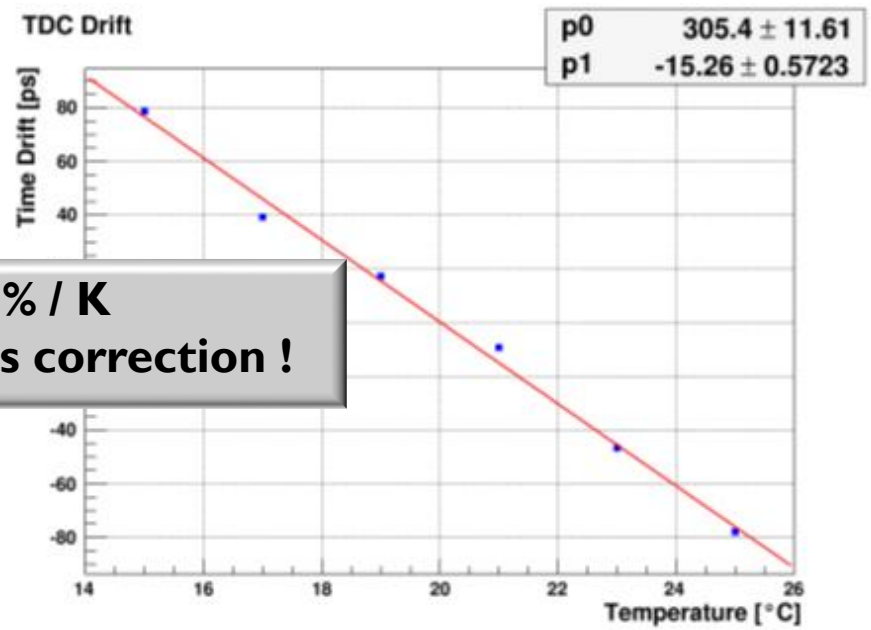
Flash

- FPGA firmware
- Configuration
- Inhibit memory maps



DPC: Front End Digitization Significantly Reduces Temperature Sensitivity





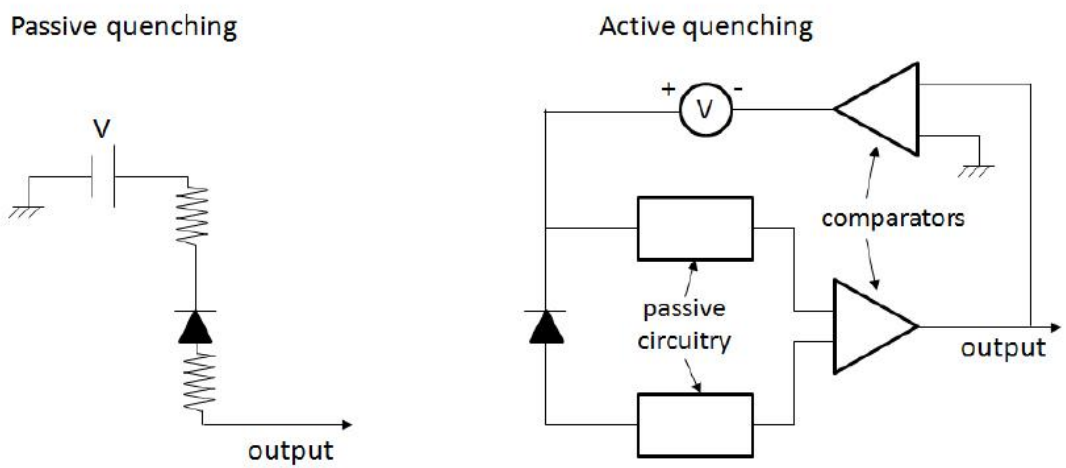
0.33% / K
Without bias correction !

- **24 ps** full-width at half-maximum timing resolution of ps-laser
- Photopeak changes **0.33%** per degree C due to changing PDE **(values of analog SiPM's are ranging from 2-8%)**
- Time changes **15.3 ps** per degree C (TDC + trigger network drift)

DPC: CMOS Integration Enables Active Quenching

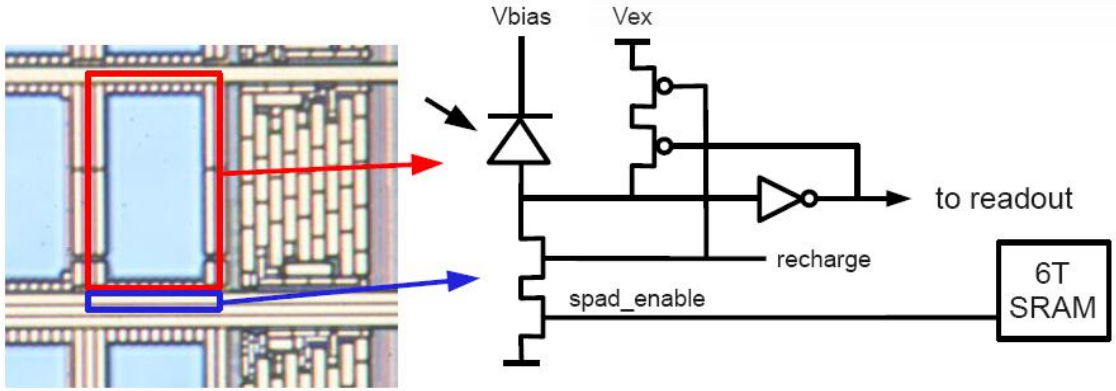
Figure 11. Generic schematics of a passive (left) and an active (right) quenching circuit employed at the micro-cell level (the micro-cell is represented by the diode symbol).

Graphics from Spanoudaki & Levin, Stanford, in: Sensors (10), 2010

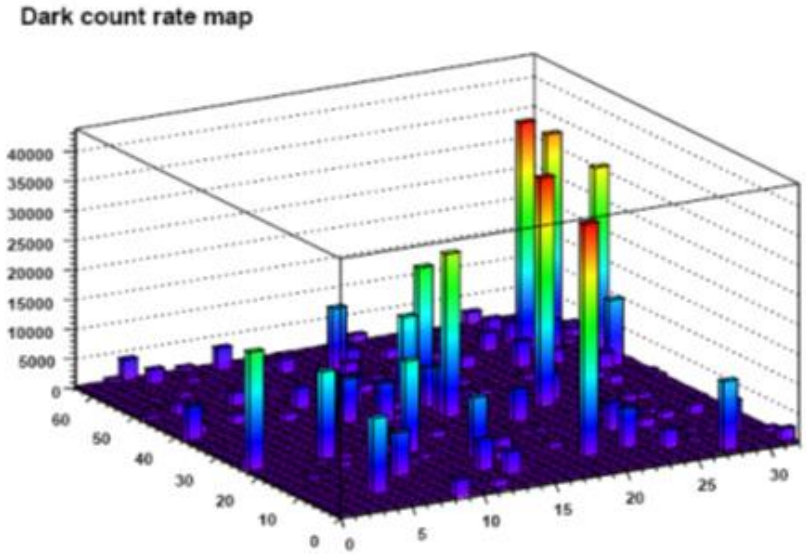


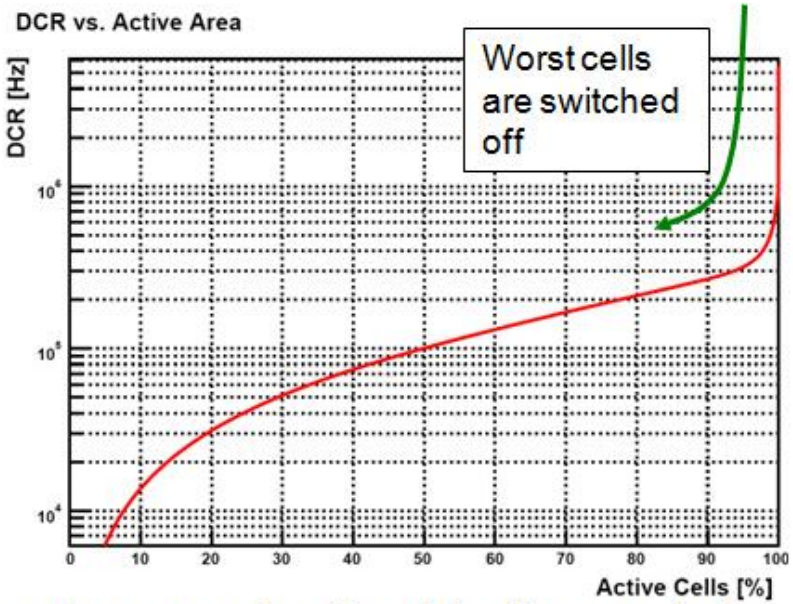
Digital SiPMs show reduced afterpulsing (0.3%) and crosstalk.

Cell layout of Digital SiPM cells: **Digital electronics take up only 3-6% of active area.**



DPC: CMOS Integration Allows Active Control of Dark Count Rate (DCR)

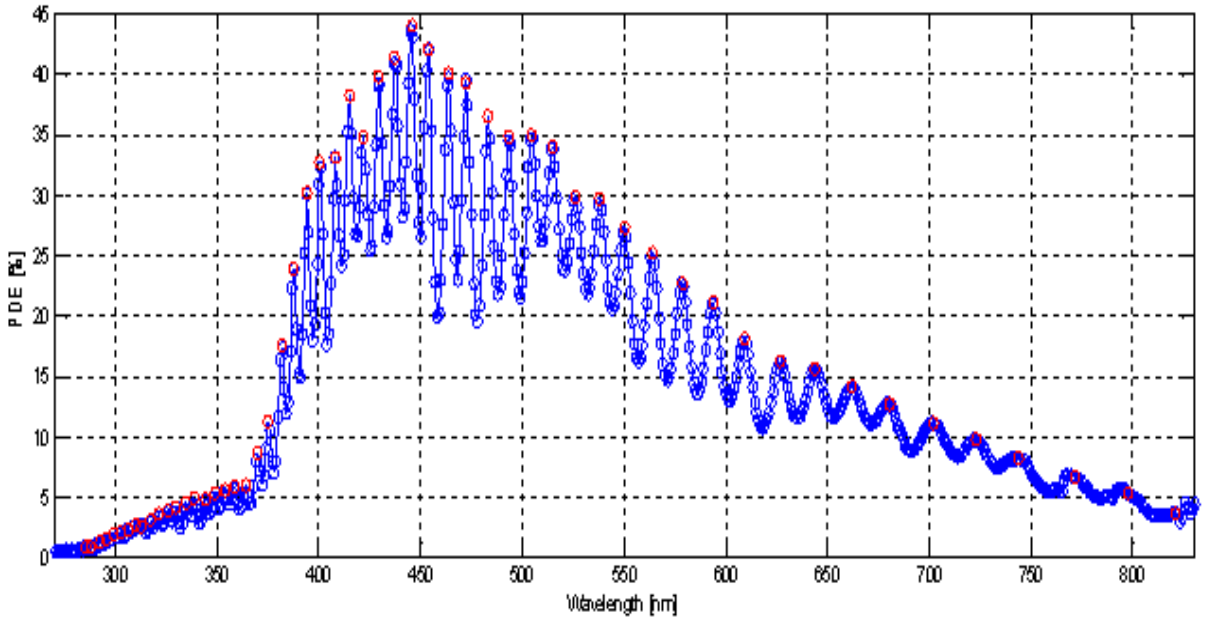




- **Silicon based light sensors have background noise (dark counts), varying with temperature.**
- **In digital SiPMs every cell can be addressed individually.**
- **Cells with high dark counts can be switched off.**
- **A few cells switched off (1-5%) reduces dark count levels by orders of magnitude.**

DPC PDE vs wavelength

DPC3200-22-44



Ring fit LH function

- PDF = gaussian on radius x gaussian on time + background

$$f(X_i, Y_i, t_i; X_0, Y_0, t_0, R) = \frac{N_{\mathrm{pe}} S_{\mathrm{px}}}{2\pi R} G\left(\sqrt{(X_i - X_0)^2 + (Y_i - Y_0)^2}; R, \sigma_R\right) \times G(t_i; t_0, \sigma_t) + B,$$

where

  - X_i, Y_i, t_i – pixel hit position and time
  - X_0, Y_0 – ring center position,
    t_0 – mean event time,
    R – ring radius,
  - N_{pe} – mean number of photoelectrons in a ring,
    S_{px} – pixel area,
    σ_R, σ_t – sigmas on radius and time,
    B – noise hit probability per pixel and time unit.
- The following function is minimized to fit the ring

$$-\log \mathrm{LH} = -\sum_{i=1}^{N_h} \log f(X_i, Y_i, t_i; X_0, Y_0, t_0, R)$$

Crosstalk treatment

Let's assume there are two channels (1 and 2) with independent probabilities to fire P_i^0 and dependent probabilities to fire determined by P_x (crosstalk probability), then:

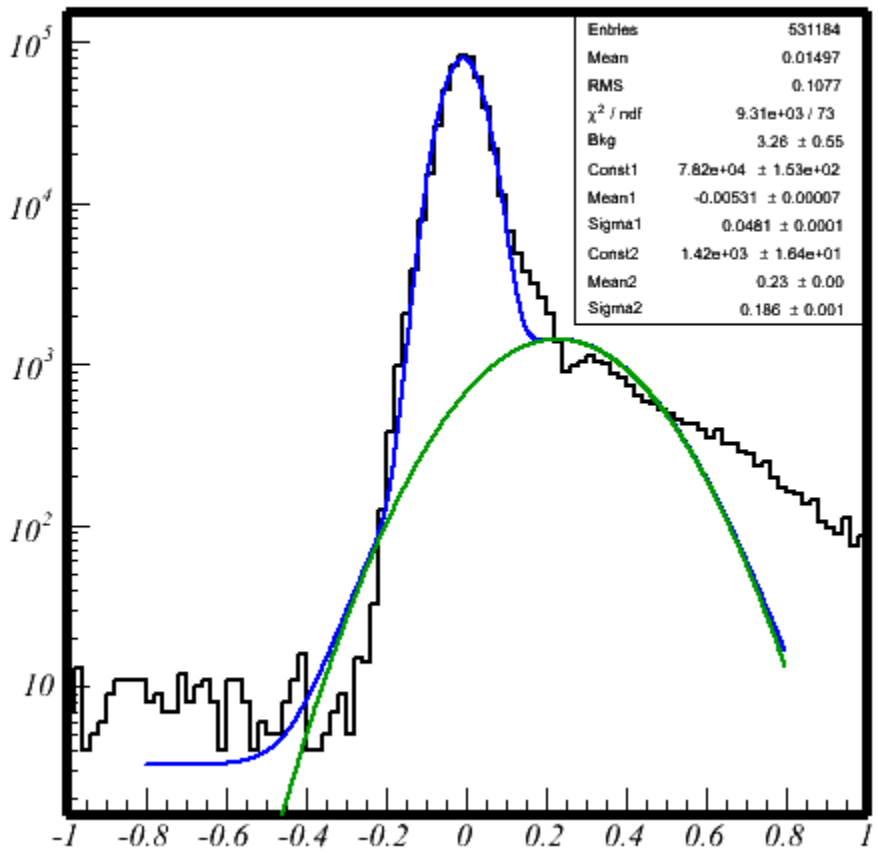
$P_{12} = P_1^0 P_2^0 + (1 - P_1^0) P_2^0 P_x + (1 - P_2^0) P_1^0 P_x$ – probability that both pixels fire
$P_{\bar{1}2} = (1 - P_1^0) P_2^0 (1 - P_x)$ – probability that 1st pixel does not fire and 2nd fires
$P_{1\bar{2}} = (1 - P_2^0) P_1^0 (1 - P_x)$ – probability that 1st pixel fires and 2nd does not fire
$P_{\overline{12}} = (1 - P_1^0)(1 - P_2^0)$ – probability that both pixels do not fire

As $P_{12} + P_{\bar{1}2} + P_{1\bar{2}} + P_{\overline{12}} = 1$, there are 3 independent equations and all unknowns (P_1^0, P_2^0, P_x) can be determined from observables $(P_{12}, P_{\bar{1}2}, P_{1\bar{2}})$.

The only pre-assumption that crosstalk probabilities are symmetric, i.e.:

$$P_{1\to 2} = P_{2\to 1} \equiv P_x$$

Timing resolution (log y-scale)



Hit time w.r.t. fitted event time, ns