

# Photon counting with a FDIRC Cherenkov prototype readout by SiPM arrays

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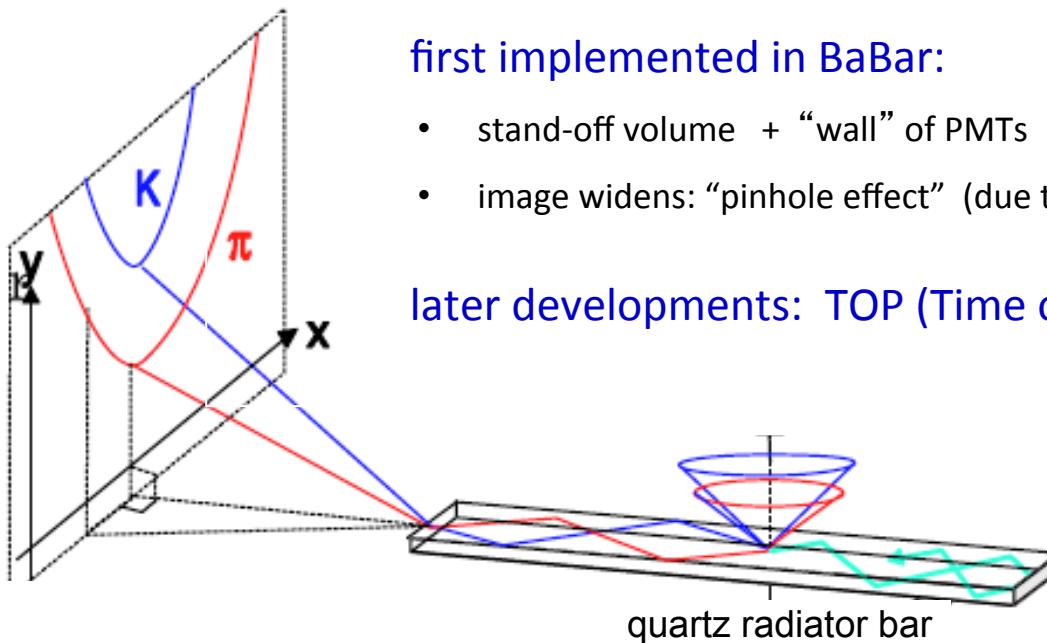


VCI 2016  
14° Vienna Conference on Instrumentation  
February 15-19, 2016



**A**

## DIRC: Detection of Internally Reflected Cherenkov light



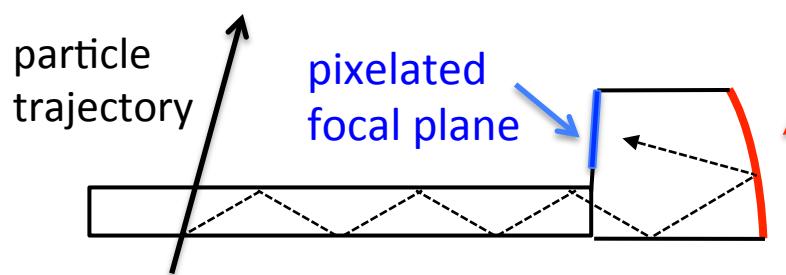
first implemented in BaBar:

- stand-off volume + “wall” of PMTs
- image widens: “pinhole effect” (due to finite width of quartz bar)

later developments: TOP (Time of Propagation), etc...

**B**

## A focalization scheme is introduced: FOCUSING DIRC (**FDIRC**)



Focusing block:  
spherical or cylindrical mirror

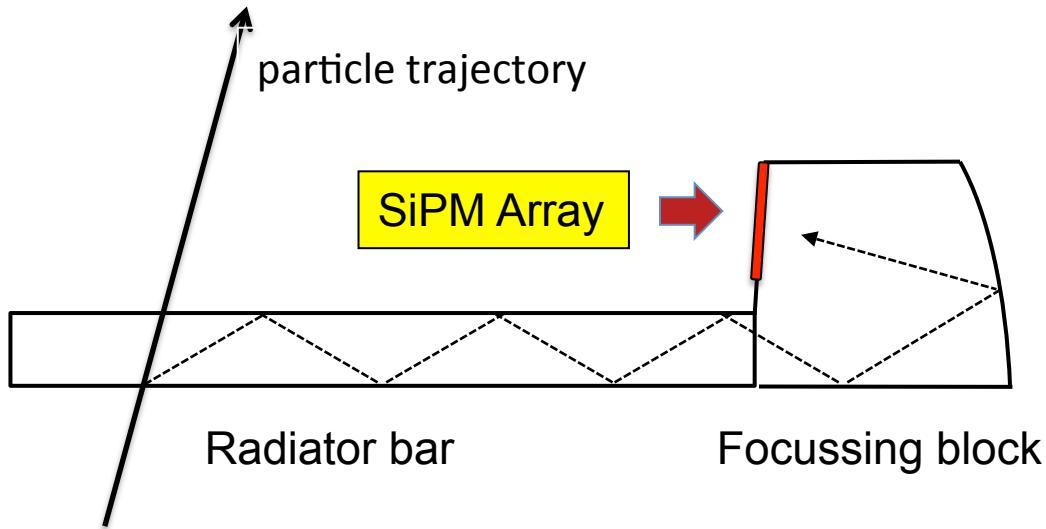
Focal plane instrumented either with:

- pixelated photosensors (e.g. MAPMT, HPD, MCP):
  - Limited number of pixels
  - Large pixel size
- or fiber bundles coupled to pixelated photosensors → Low light trapping efficiency

this talk

# Digital FDIRC

FDIRC with high resolution SiPM array



Focal plane instrumented with a  
**mosaic of SiPM arrays:**

- small pixels ( $\text{mm}^2$  or sub- $\text{mm}^2$ )
- large number of sensors ( $\sim 10^3$ )
- photon counting

## Possible applications

### **High Energy Physics:**

- PID @ a few GeV momenta (e.g.:  $\pi/\text{K}$  separation as in BABAR, BELLE, PANDA)

### **Astroparticle Physics:**

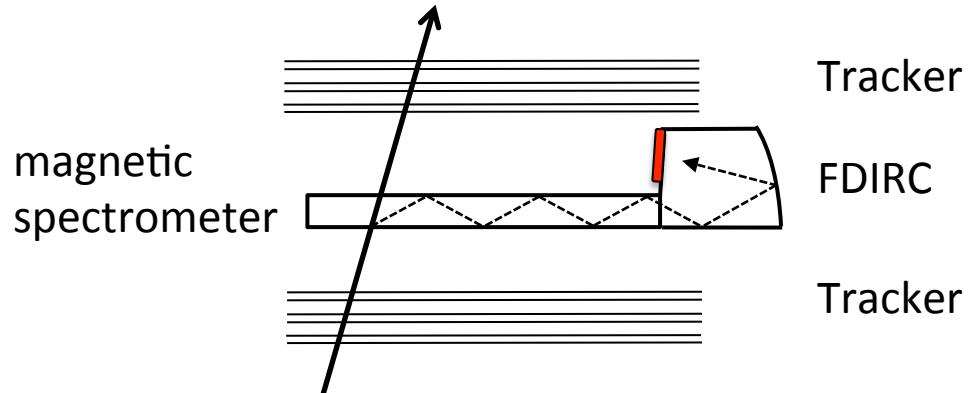
- Charge identification of cosmic ray nuclei
- **isotopic separation** in cosmic rays (for space/balloon borne experiments)

# Isotopic separation by momentum + velocity (FDIRC) measurements

For **not too large** total-particle momenta  $P$  ( $\sim$  tens of GeV/c) an accurate measurement of  $\beta$  can provide an adequate mass separation for fully stripped ions of atomic number  $Z$  and mass  $A$ : 
$$\left(\frac{\sigma_M}{M}\right)^2 = \left(\frac{\sigma_{P_T}}{P_T}\right)^2 + \left(\gamma^2 \frac{\sigma_\beta}{\beta}\right)^2$$

## CONCEPT

- FDIRC embedded in a magnetic spectrometer:
- non destructive measurement of  $\beta$
  - track measured **before** and **after** FDIRC
  - **large photostatistics**  $\sim Z^2$  for **charged ions**

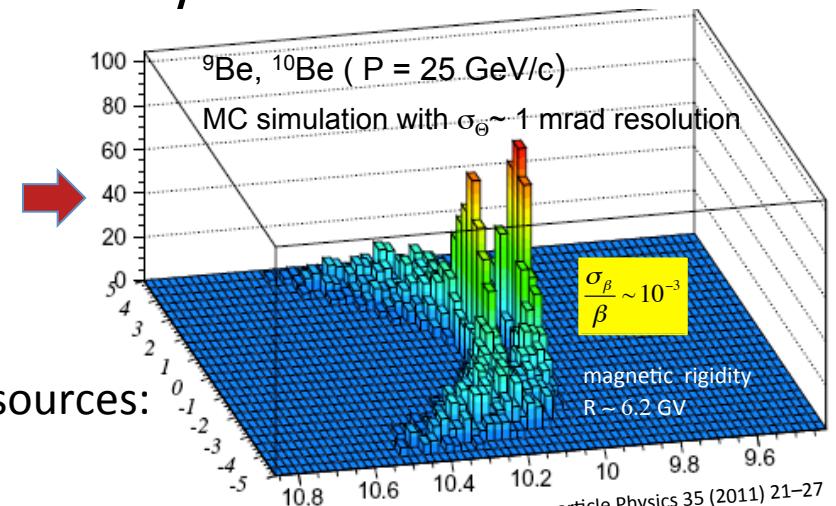


Example:  $\Delta\Theta_c$  difference in Cherenkov angles for  ${}^9\text{Be}$ ,  ${}^{10}\text{Be}$  ions with  $P = 25$  GeV/c is  $\Delta\Theta_c \sim 11$  mrad

A mass separation better than 0.2 a.m.u. can be achieved with an angular resolution of  $\sigma_\Theta = 1.5$  mrad and  $\sigma_p/p \sim 1\%$

Not easy to achieve:  $\sigma_\Theta$  is affected by several error sources:

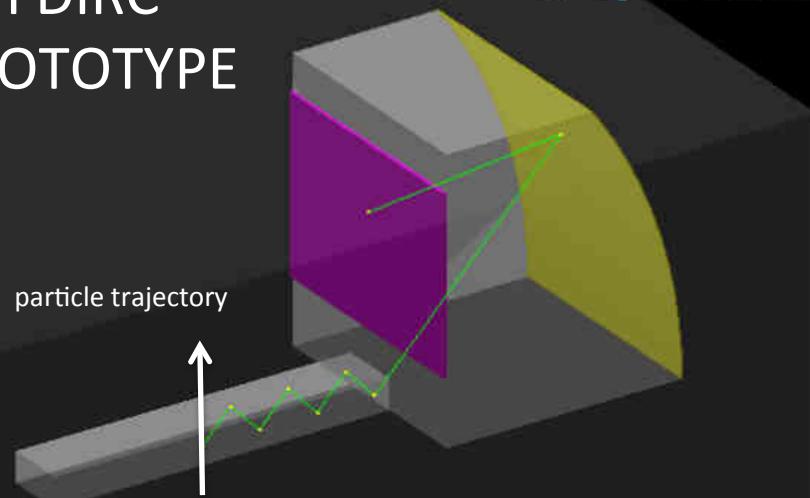
- FDIRC {
- geometry/optics
  - **chromatic dispersion** along the optical path
  - bar imperfections (surface and angles)
  - pixel size, etc...



tracking angular error

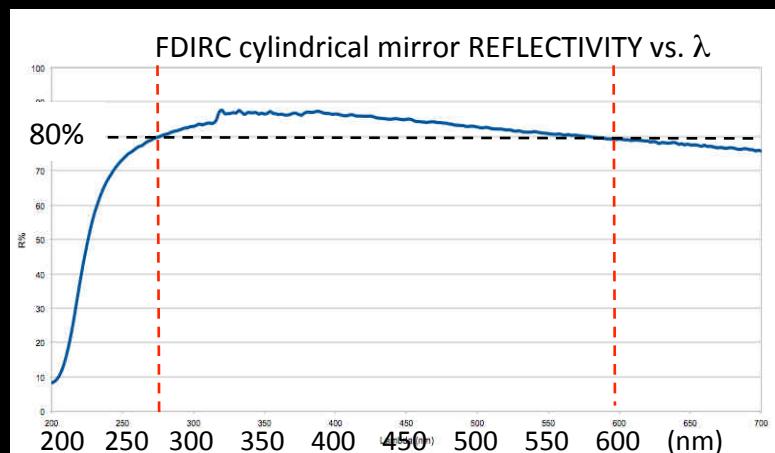
# FDIRC PROTOTYPE

Thu Sep 4 14:04:13 2014



radius = 26 cm

width = 14 cm; height ~ 16 cm

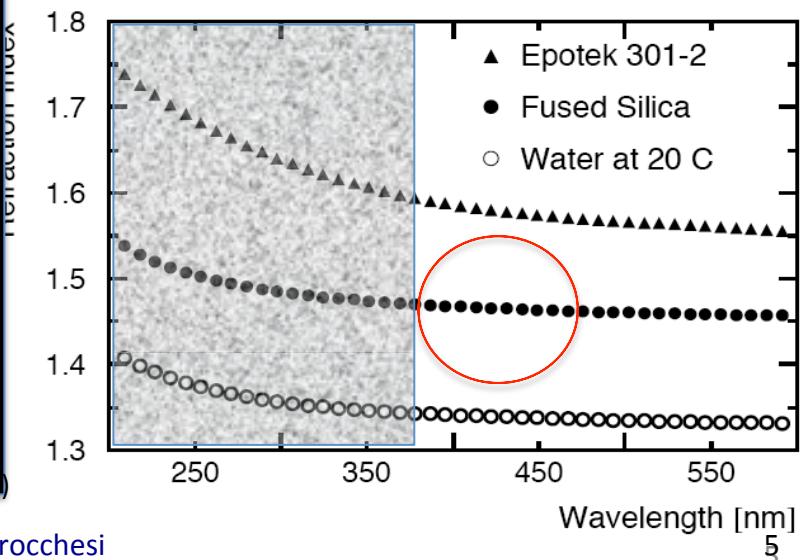


## Quartz radiator bar

- Fused Silica ( $\text{SiO}_2$ ) radiator bar
- 3 spare short bar segments from BaBar
- 17.25 mm (thickness) x 35 mm (width)
- 200 mm (long)

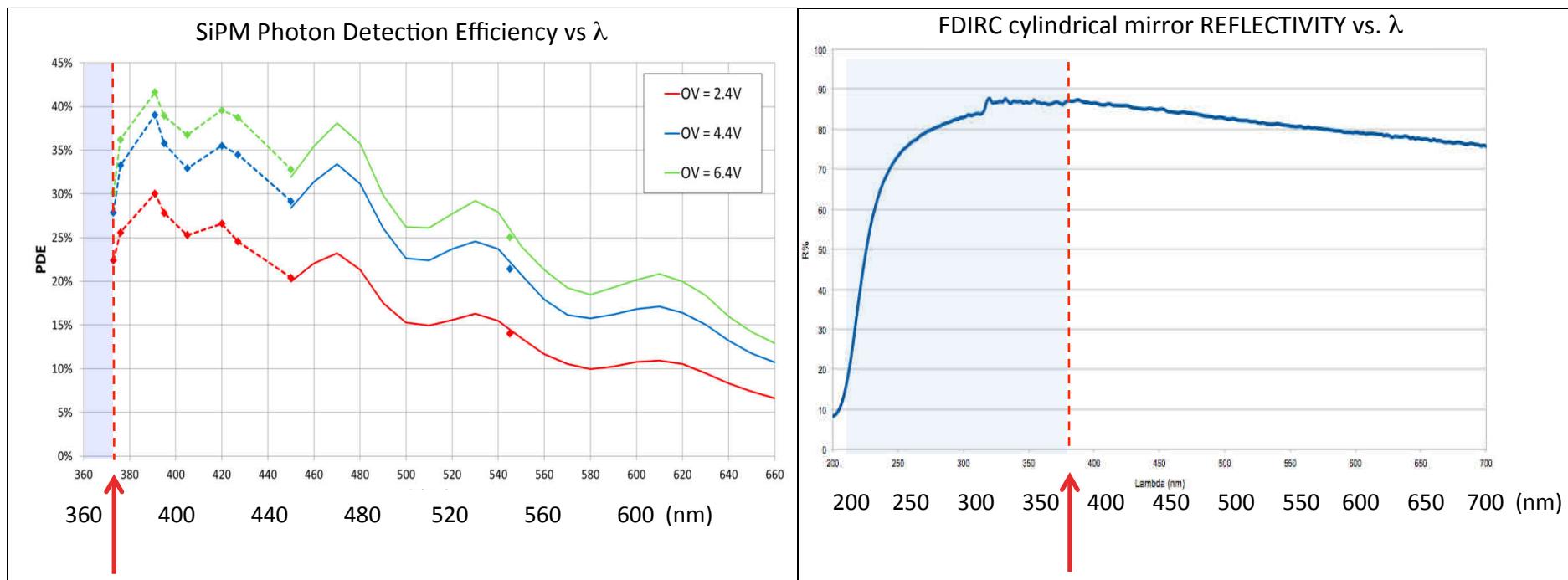
Dispersion relation in the radiator:

- **above  $\sim 370$  nm (PDE cutoff)**  
 $n(\lambda)$  is almost constant vs.  $\lambda$
- $n \sim 1.47$  at 435 nm

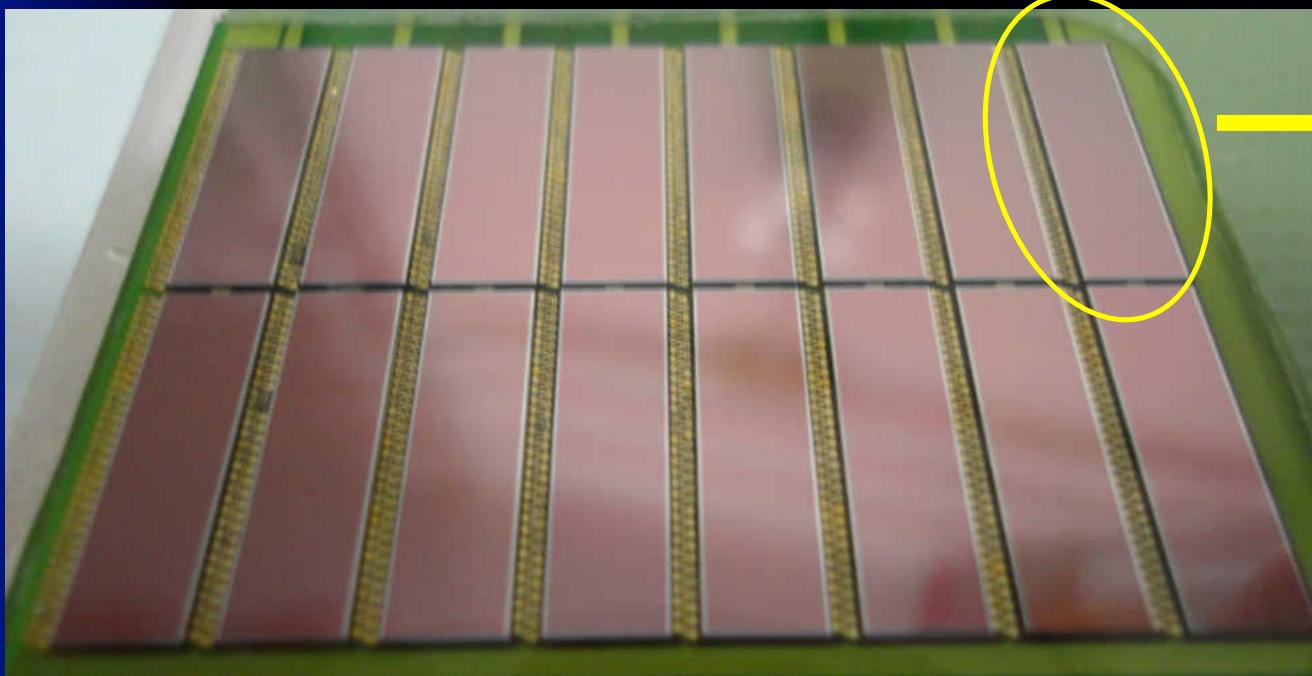


# Chromatic dispersion vs. bandwidth

- Cherenkov light yield  $\sim 1/\lambda^2 \rightarrow$  grows in the UV
- in  $\text{SiO}_2$  radiator, the rate of change of the index of refraction vs. wavelength  $d\eta(\lambda)/d\lambda$  is larger in the UV: angular resolution (**chromatic term**) gets worse
- tradeoff between light yield and bandwidth: in our case **mirror reflectivity** and **photon detection efficiency (PDE)** of SiPM limit the effective bandwidth to  $\sim 370 < \lambda < 600 \text{ nm}$



## FOCAL PLANE (4.3 cm x 2.7 cm)

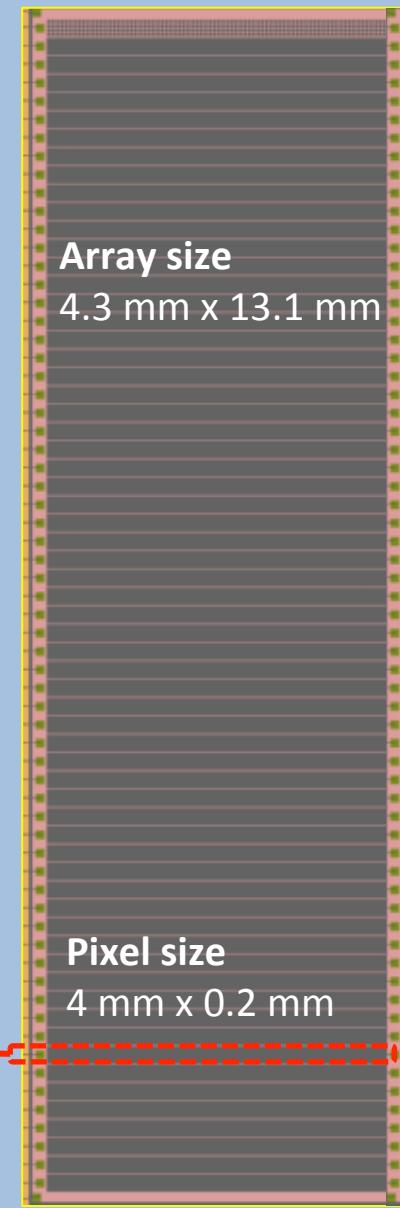


- Each **Array**: 64 pixels (SiPM sensors)  
inter-pixel gap 10  $\mu\text{m}$
- Each **Pixel** :  $4\text{ mm} \times 200 \mu\text{m} = 0.8 \text{ mm}^2$  SiPM  
 $4 \times 100$  micro cells

**16 SiPM Arrays  
(1024 SiPMs)**



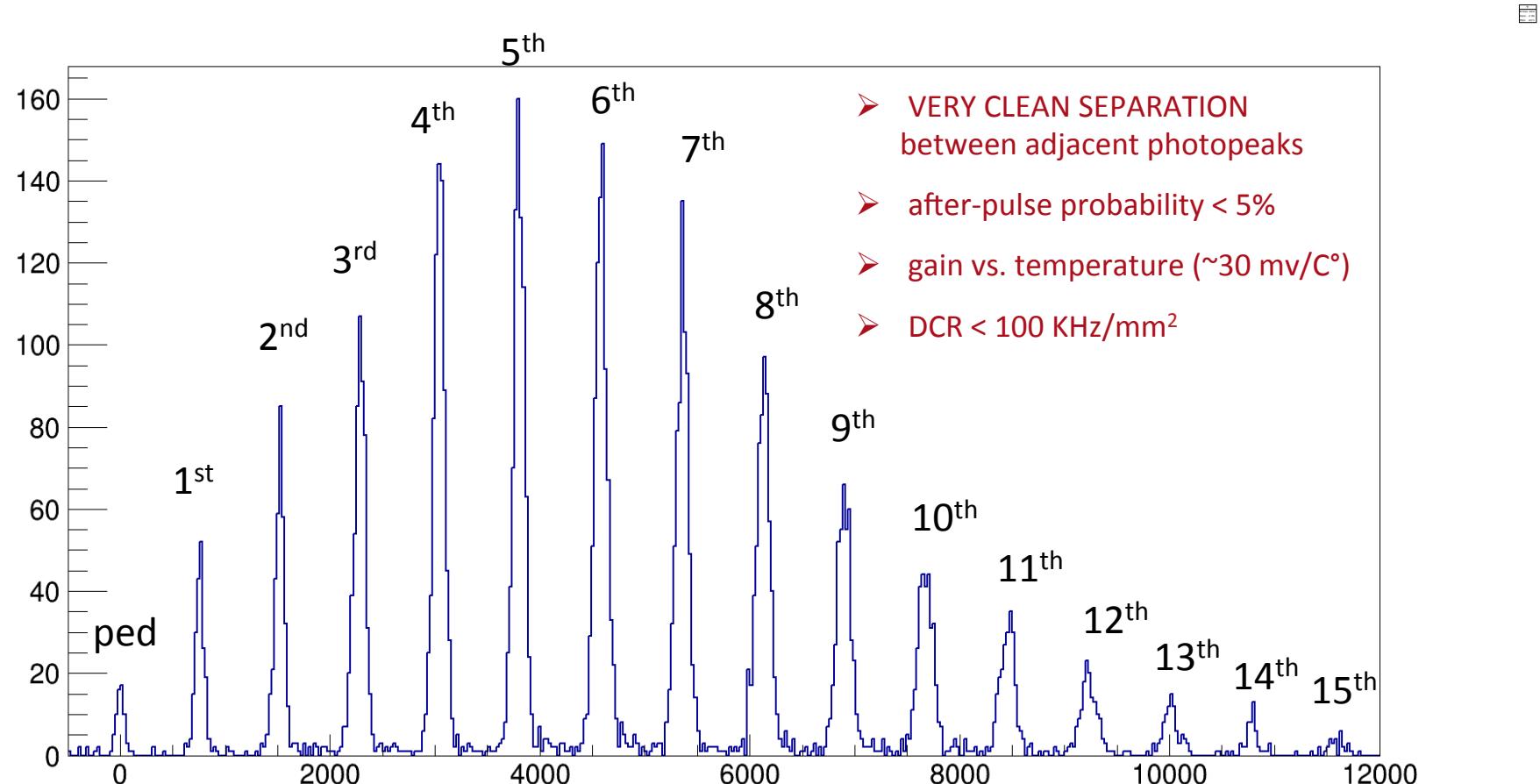
## Array of 64 SiPMs



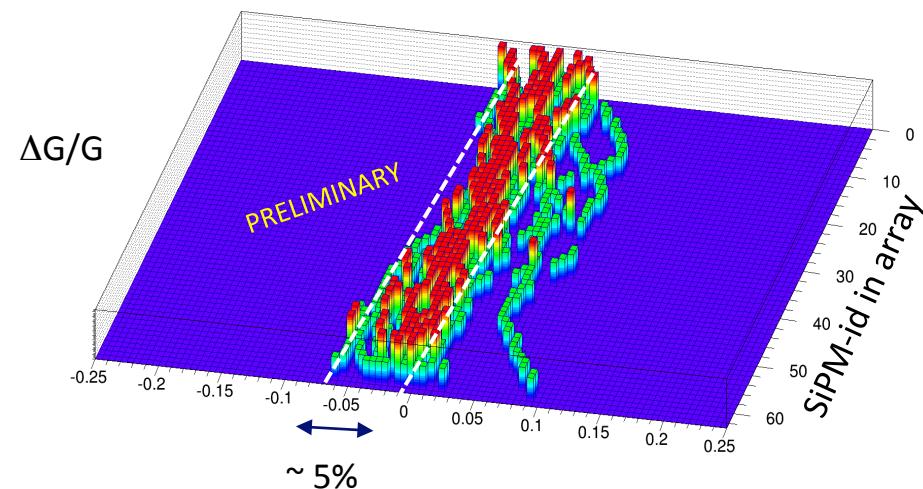
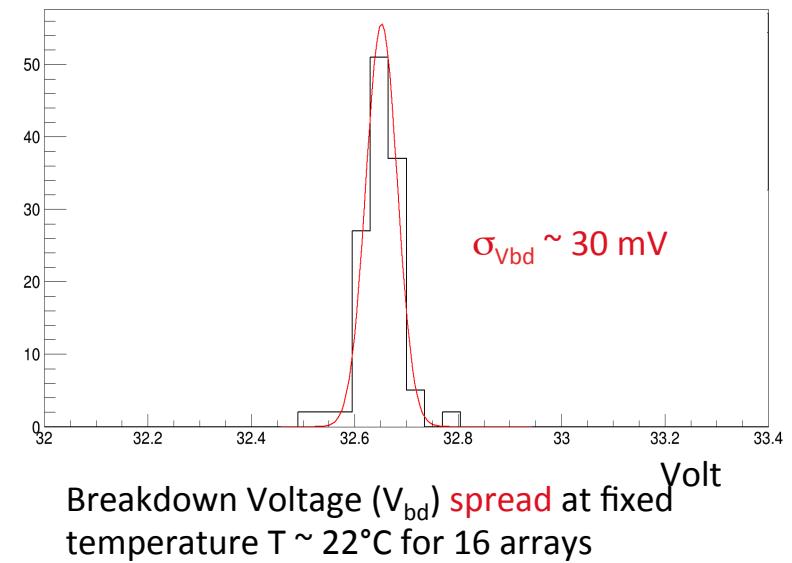
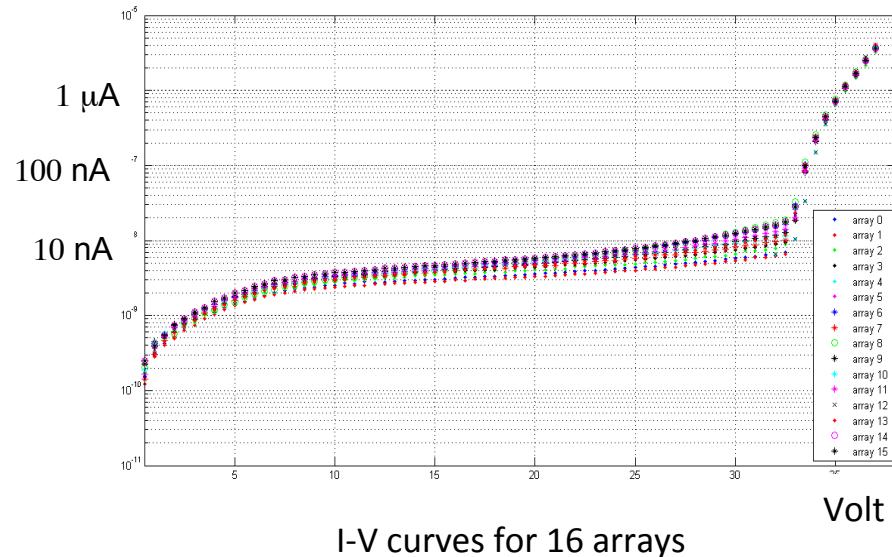
# A real Photon Counting Device at room temperature !

NUV-SiPM arrays developed at FBK-Trento

- designed for SPIDER2 R&D project under INFN funding
- delivered in December 2014

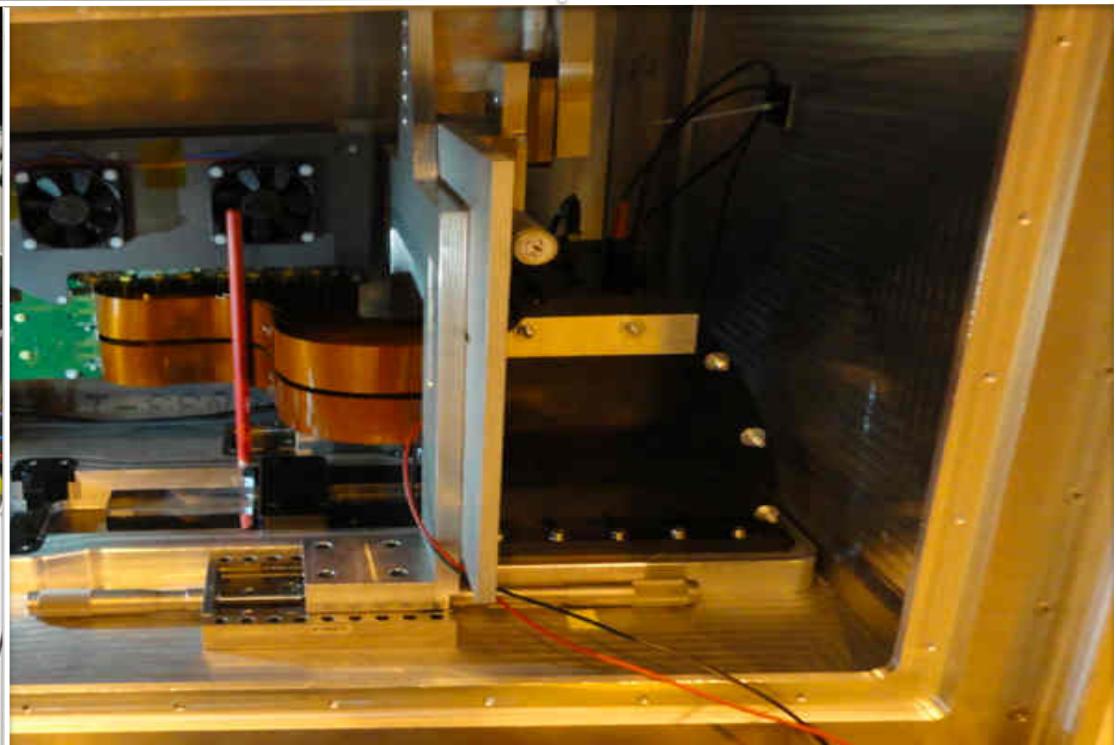
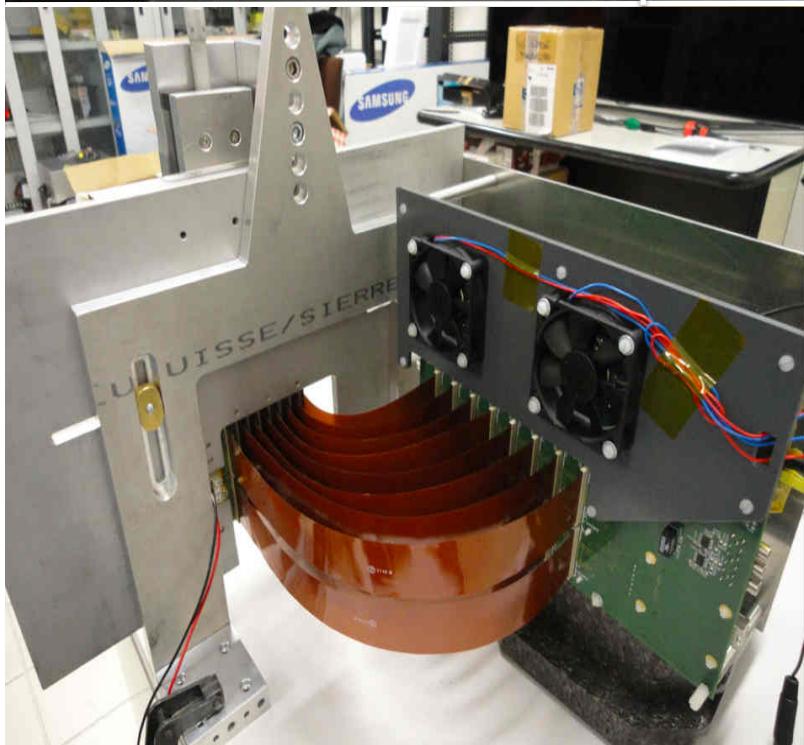
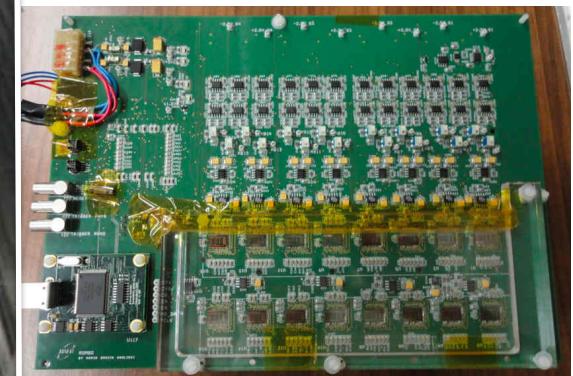
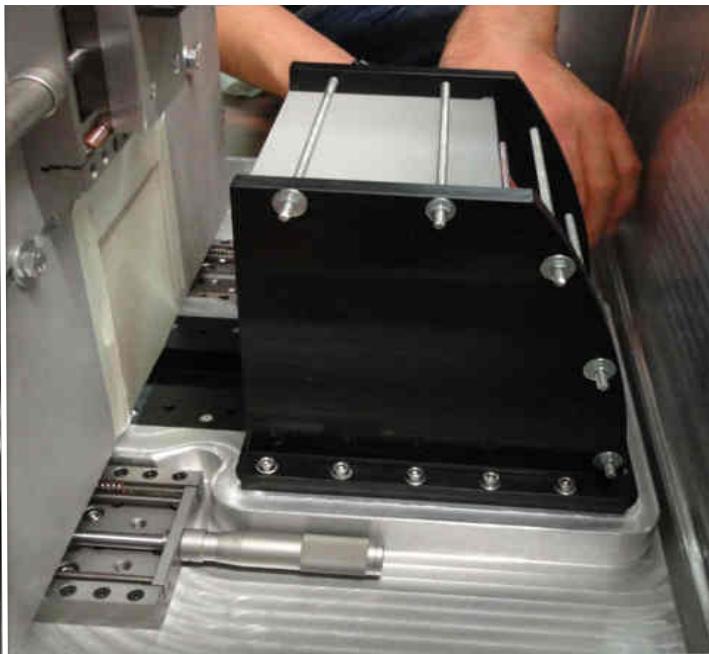


# Characterization of 16 SiPM arrays (1024 SiPM)

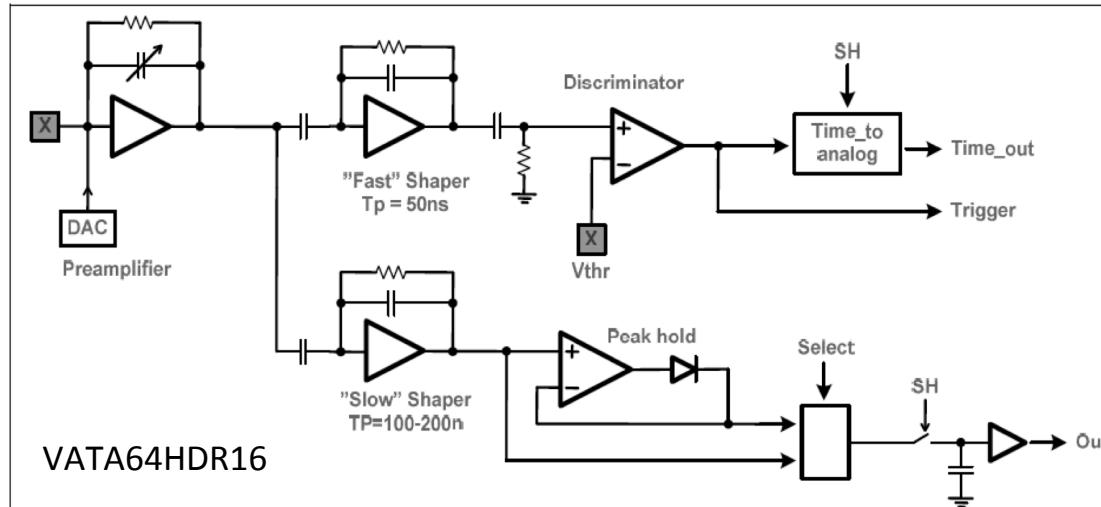


Gain spread  $\Delta G/G$  at fixed temperature for  $\sim 10^3$  channels  
(the gain spread of the FE electronics is FOLDED in)

## Prototype Construction in Siena/Pisa



# Front End electronics and readout of 1024 SiPMs



M.G. Bagliesi et al., Nucl.Phys.B (Proc.Suppl.) 215:344-348, 2011

## Custom ASIC VATA64HDR16:

- autotrigger mode / external trigger
- adjustable threshold / channel
- programmable slow shaper 50 – 300 ns
- Peak&Hold device → pulse height
- fast shaper + TAC → time measurement ( $\sim 160$  ps resolution)

## 2014: FDIRC readout board (1024 chns) developed in Siena/Pisa

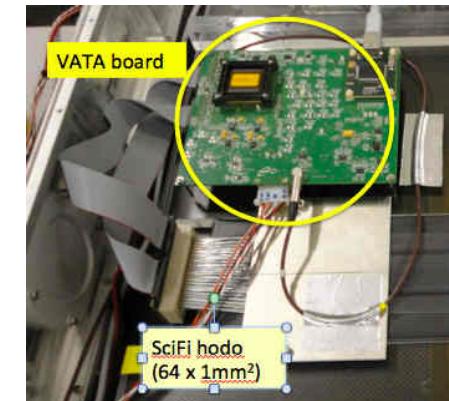
- 16 VATA chips
- 16 bit ADCs
- 1024 SiPM digitized signals
- 1024 time stamps
- autotrigger + 2 external triggers: random/physics
- USB-2 connection to PC

**2009/10: development of custom ASIC for SiPM readout (64 channels)**

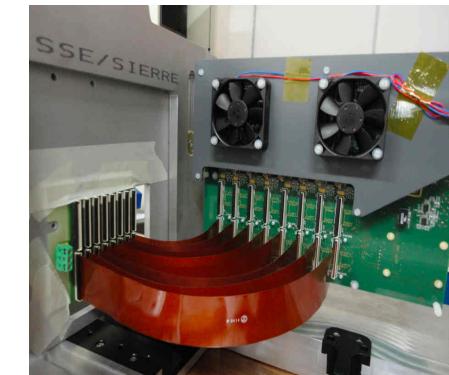
jointly funded by INFN (SPIDER project) and GM-IDEAS

- 64 pulse height measurements
- 64 time measurements
- **custom SiPM r/o board (64 chns)**

**2011** SciFi hodoscope with SiPMs

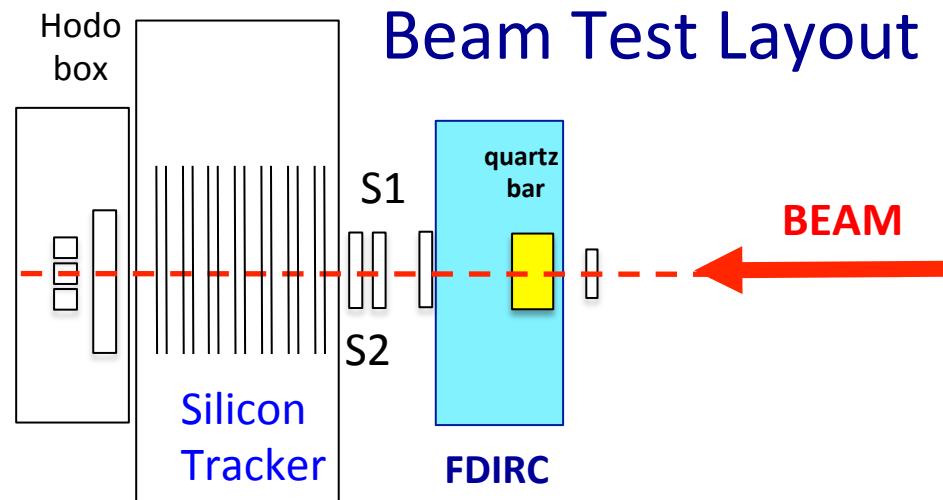
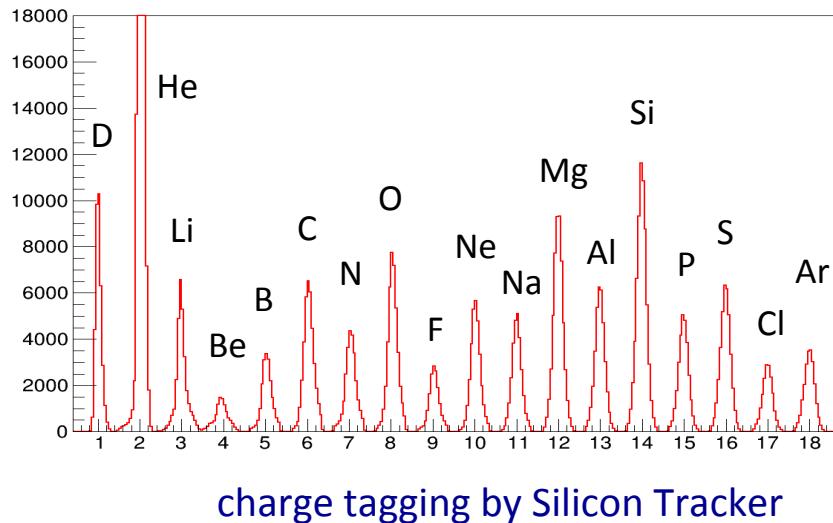


2013:  
Scintillation Fiber  
hodoscope  
(1 VATA)  
@CERN beam test



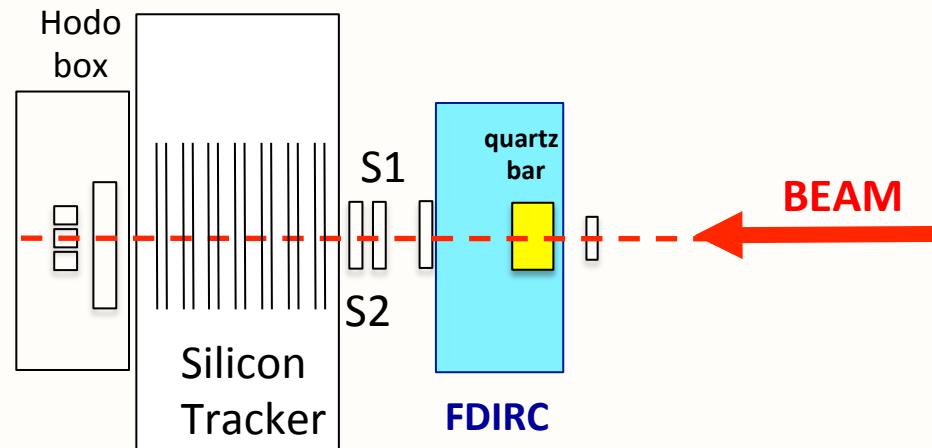
2014:  
FDIRC prototype  
(16 VATA)

- to test isotopic separation → need a LOW ENERGY ion beam ( $P < \text{few tens of GeV}/c$ )
- However, in March 2015 we had the opportunity of a parasitic beam test at CERN SPS (H8) primary Ar beam → internal target → ion fragments with  $A/Z=2$ :  $^2\text{H}$ ,  $^4\text{He}$ , ...,  $^{34}\text{Cl}$ ,  $^{36}\text{Ar}$
- available beam energies (13, 19, 30 GeV/n) too large: no chance for isotopic separation by  $\Delta\beta$  measurements. Nevertheless we decided to test the performance of the FDIRC prototype:

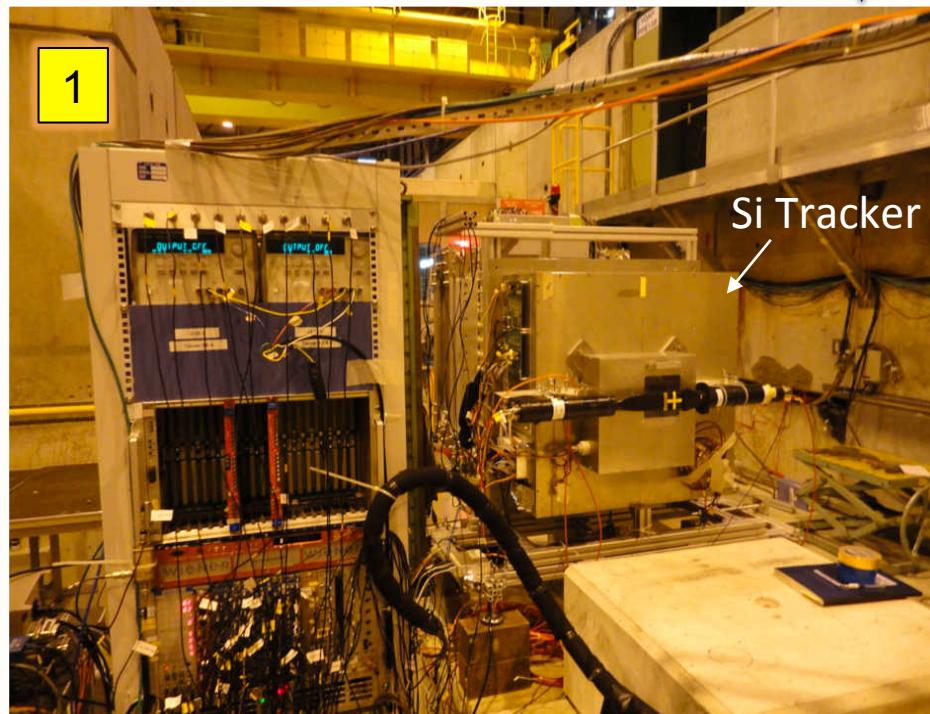


- Silicon Tracker identifies beam particles (+ interact. products in FDIRC)
- CHARGE-TAGGING: up to 14 independent  $dE/dx$  samples: 4 Si pixel layers + 10 Si strip layers

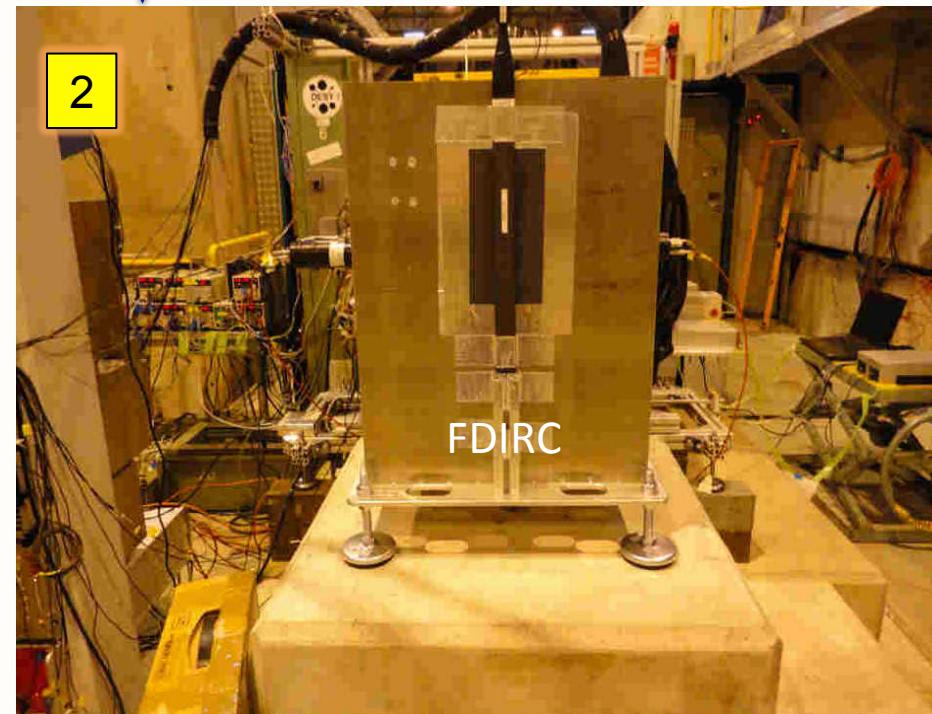
# CERN 2015 Ion Beam Test Layout



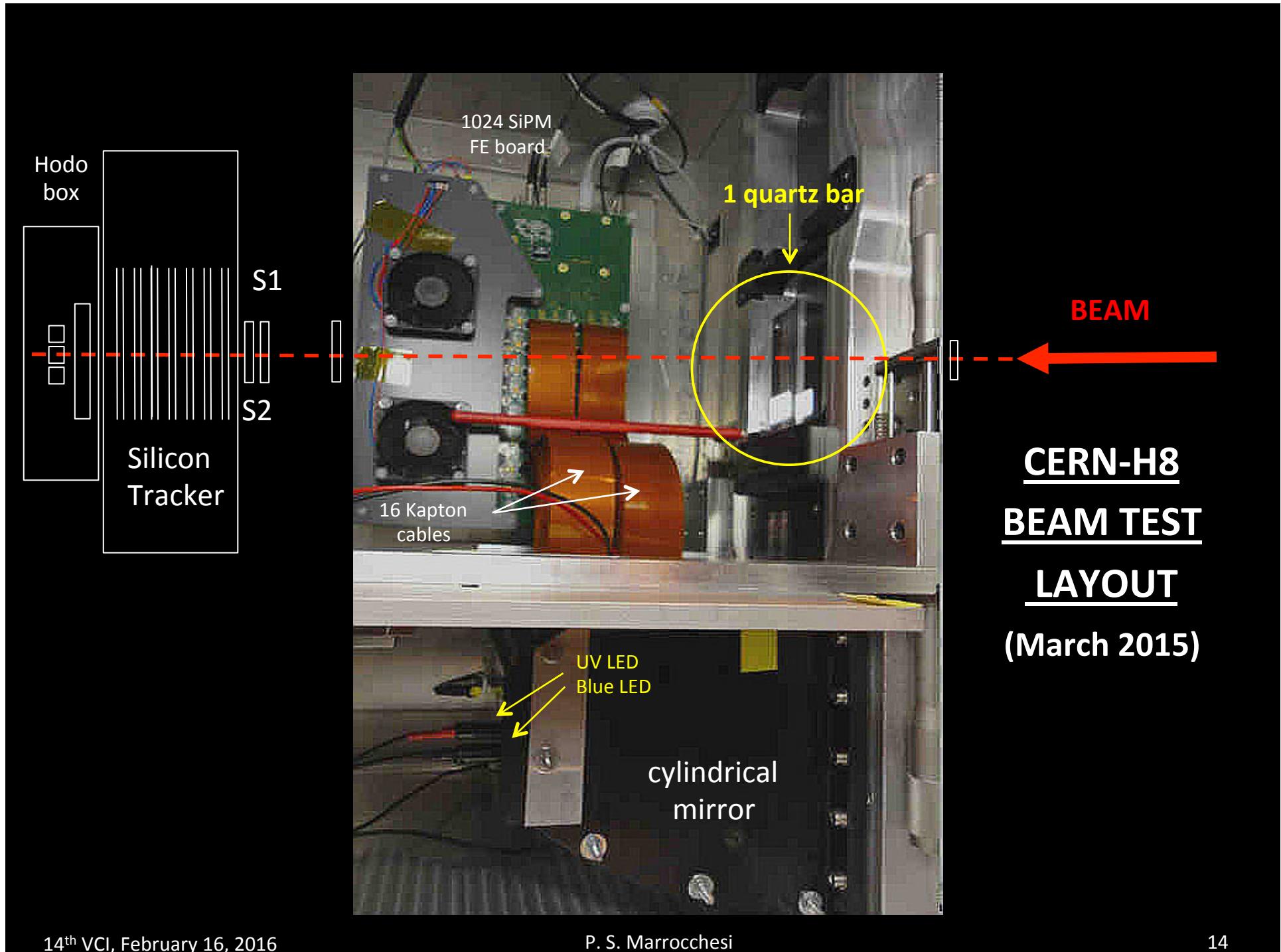
March 2015, SPS H8 beam line



beam line after TRACKER installation



beam line after FDIRC installation



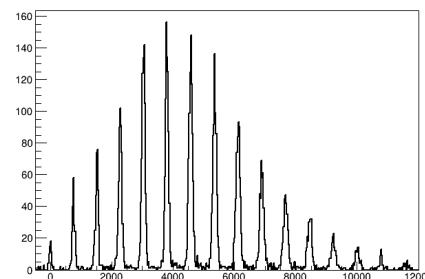
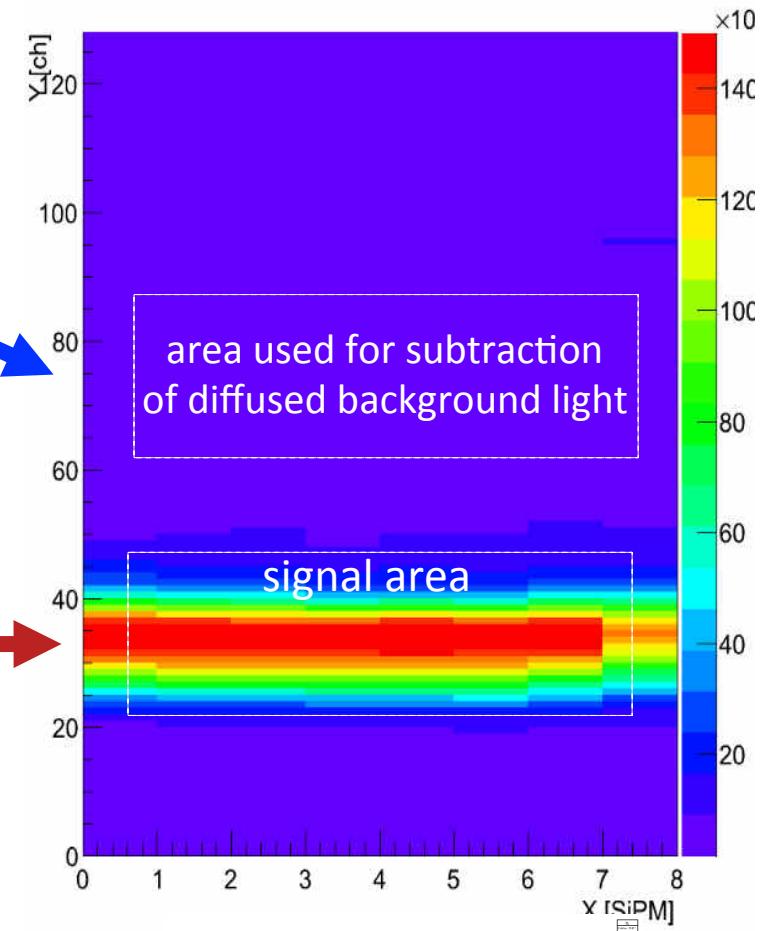
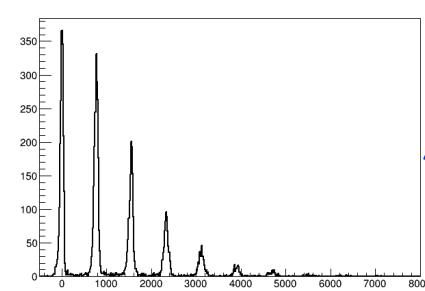
# FDIRC Signal and Background subtraction

## Diffused light background:

**reflected light:** mainly from the lateral walls of the mirror

- small ( $\sim 5\%$ )
- from Cherenkov light  
→ proportional to  $Z^2$
- measured with beam triggers

in a region with **same area** but **far away** signal region.



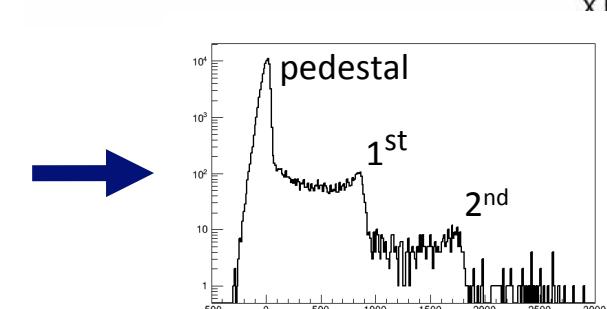
## Cherenkov signal:

- from signal illuminated band
- well below SiPM saturation

## Dark count background:

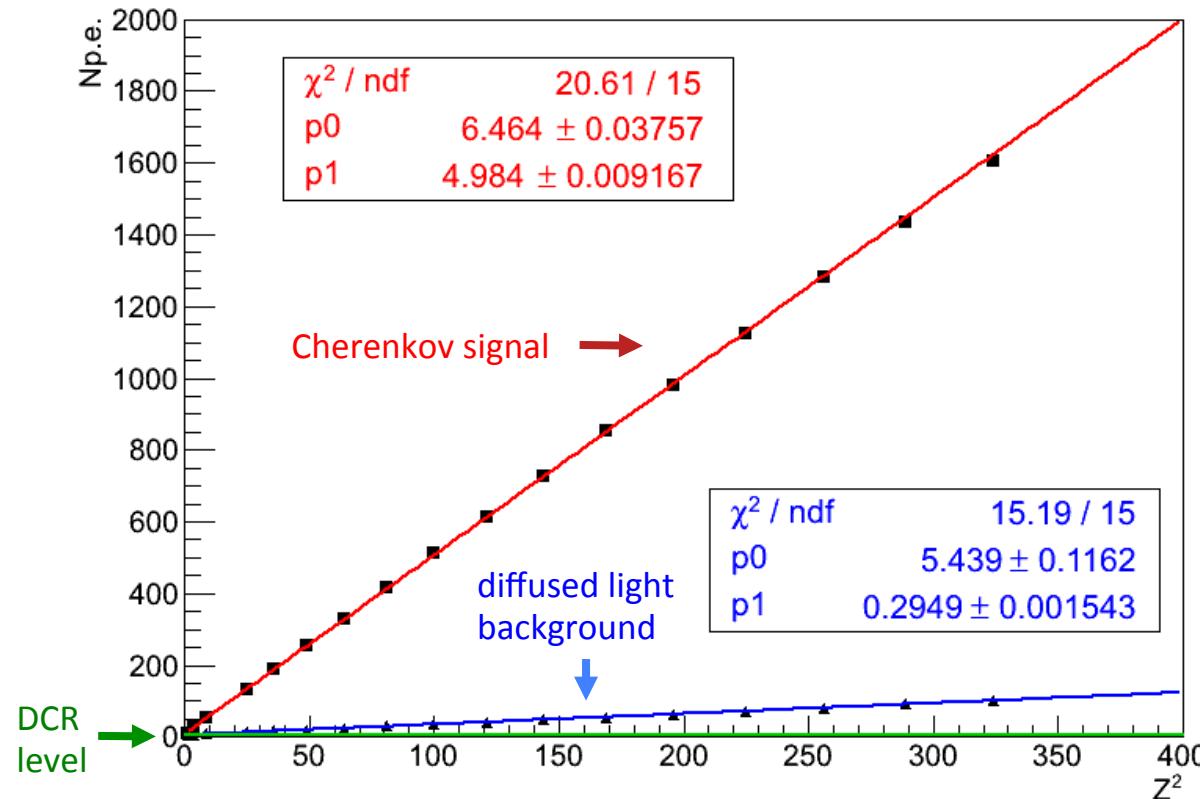
due to **SiPM dark count rate (DCR)**

- does not depend on atomic number  $Z$
- measured with **random triggers** (off spill: no beam triggers)
- **very small (%)** due to excellent performance of SiPM arrays

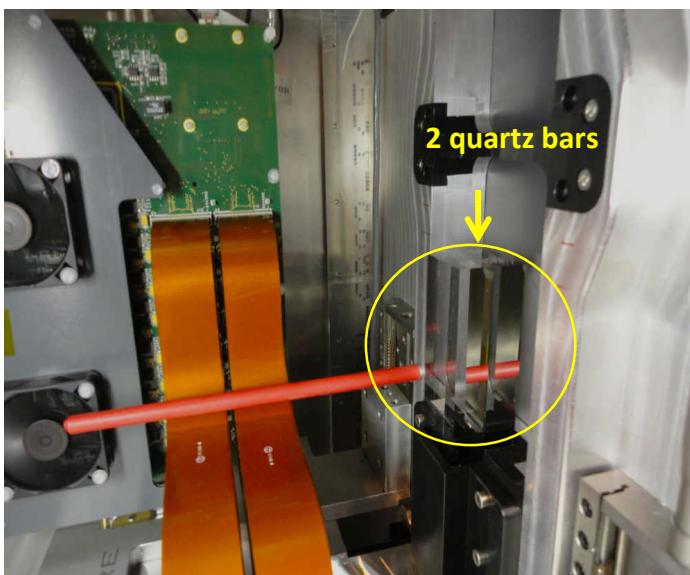
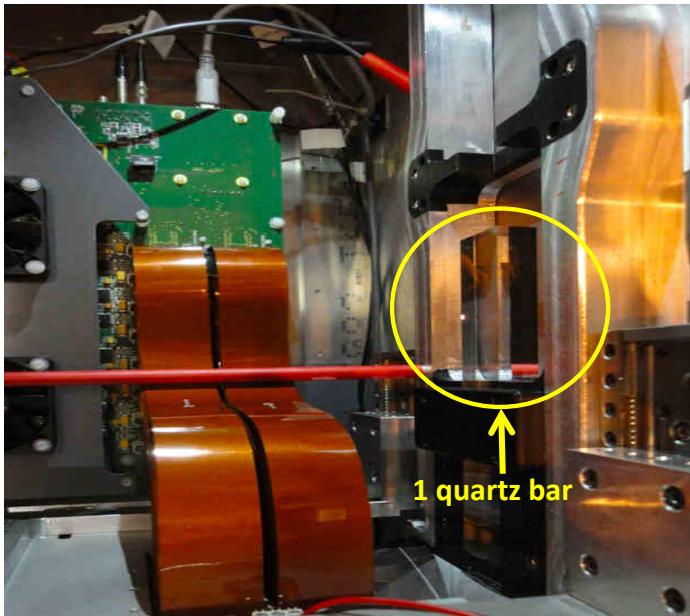


# $Z^2$ dependence of Cherenkov (integrated) signal

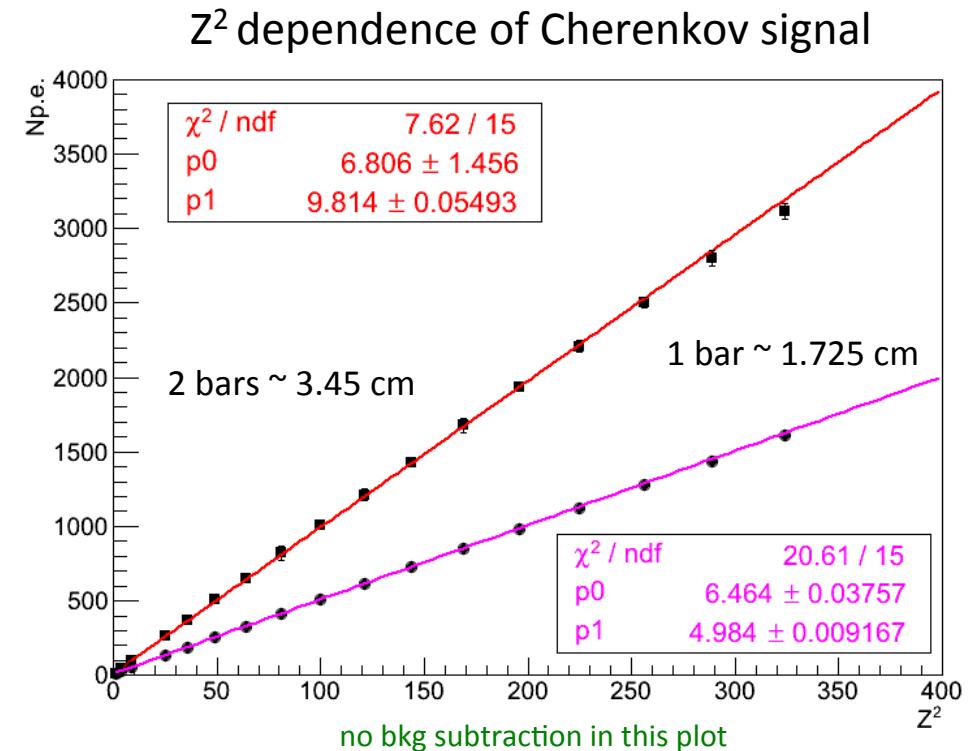
- INTEGRAL measurement: use **Cherenkov light yield  $\sim Z^2$**  to identify chemical elements by their CHARGE Z



Active area for the mosaic of 16 SiPM arrays is  $\sim 68\%$  of instrumented area (due to cracks among arrays). **For  $Z=1$  particles:**  $\sim 5$  p.e. in area covered by SiPM arrays ( $4.3 \times 2.7 \text{ cm}^2$ )  $\sim 1/3$  of the focal plane  $\rightarrow \sim 22$  p.e. expected on the whole focal plane.



## Integrated Cherenkov light from 2 radiators of different thickness

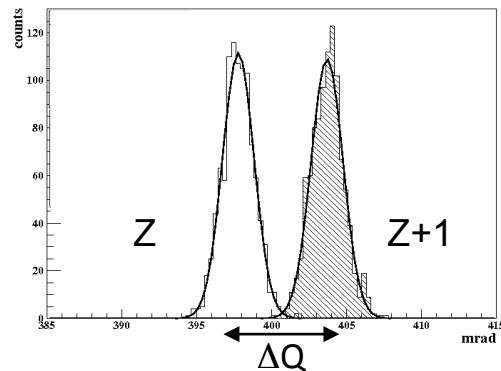


- scales linearly with radiator thickness
- NO SATURATION effects in the radiator as well as in the photosensors: each SiPM has 400 micro-cells and max photopeaks with 2 bars for Argon are < 50 → well below SiPM saturation

# Charge separation: Photon counting

- Integrated Cherenkov signal  $Q(Z) \sim N_{pe} Z^2$
- $\sigma_Q^2 \sim N_{pe} Z^2 + \sigma_{electronics}^2 + \dots$
- $\sigma_Q$  dominated by Poissonian photostatistics:  
scales  $\propto N_{pe}^{1/2} Z$  i.e. **linear in Z**

□ Charge separation  $\equiv \sigma_Q / \Delta Q$



For two adjacent ions with  $\Delta Z = 1$ :

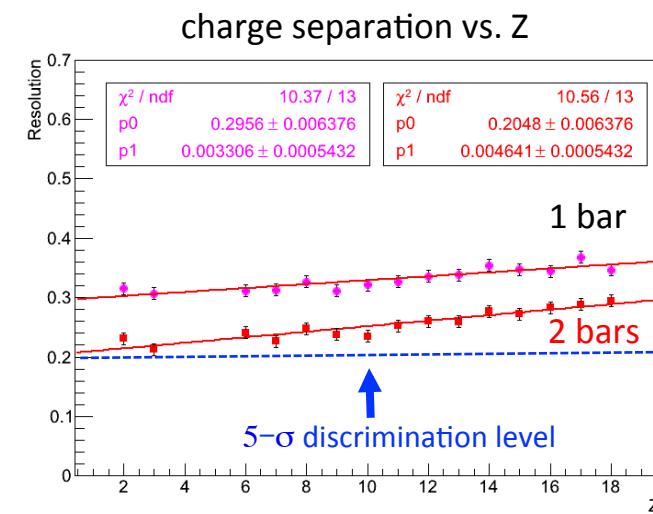
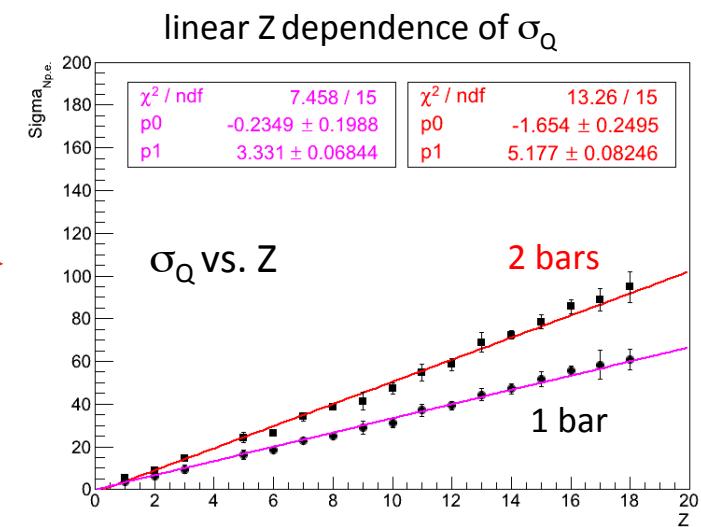
$$\Delta Q = Q(Z+1) - Q(Z) = (2Z+1) N_{pe}$$

$$\frac{\sigma_Q}{\Delta Q} \propto \frac{1}{2\sqrt{N_{pe}}}$$

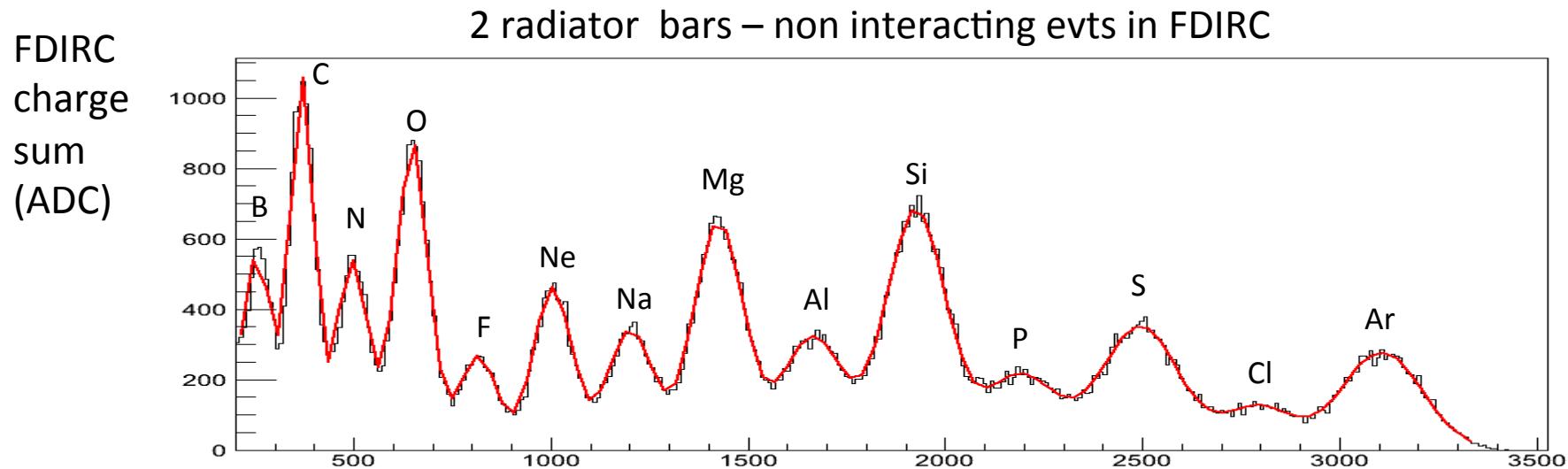
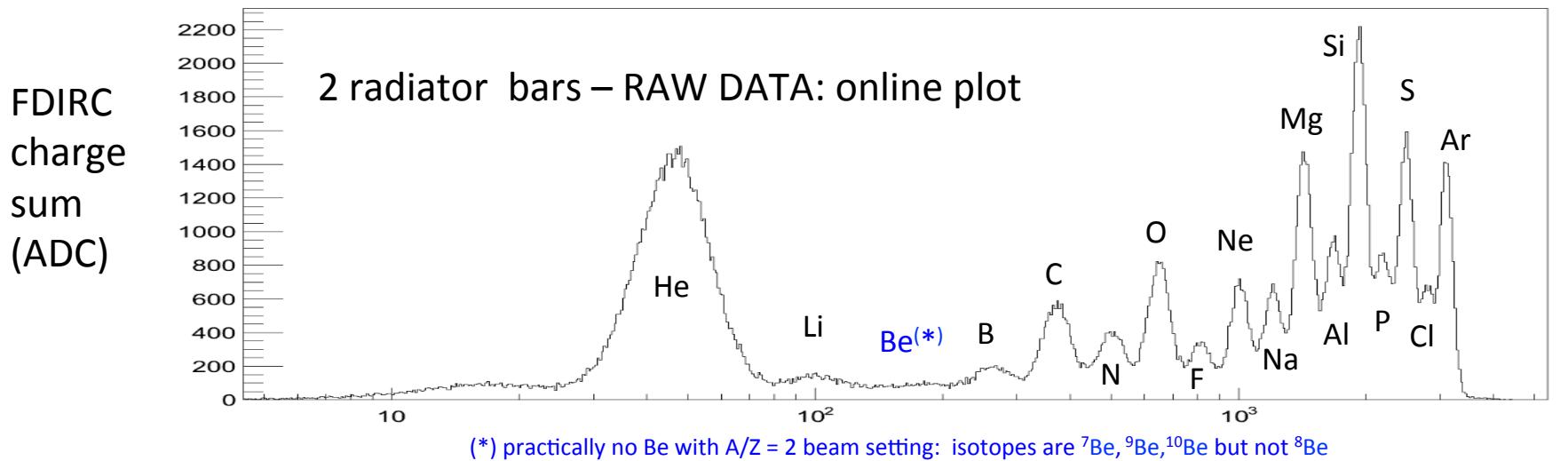
If purely Poissonian then charge separation should be independent of Z.

Residual linear Z dependence is observed in the data.

LEGENDA: Z = atomic number = charge of fully stripped ion  
 $N_{pe}$  = number of p.e. for Z=1 charge

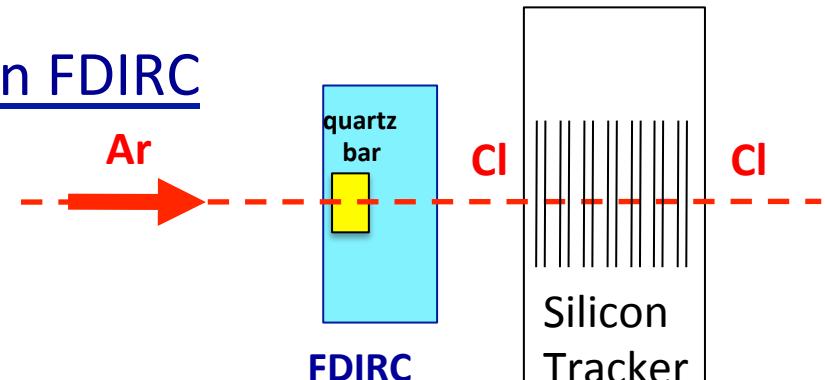
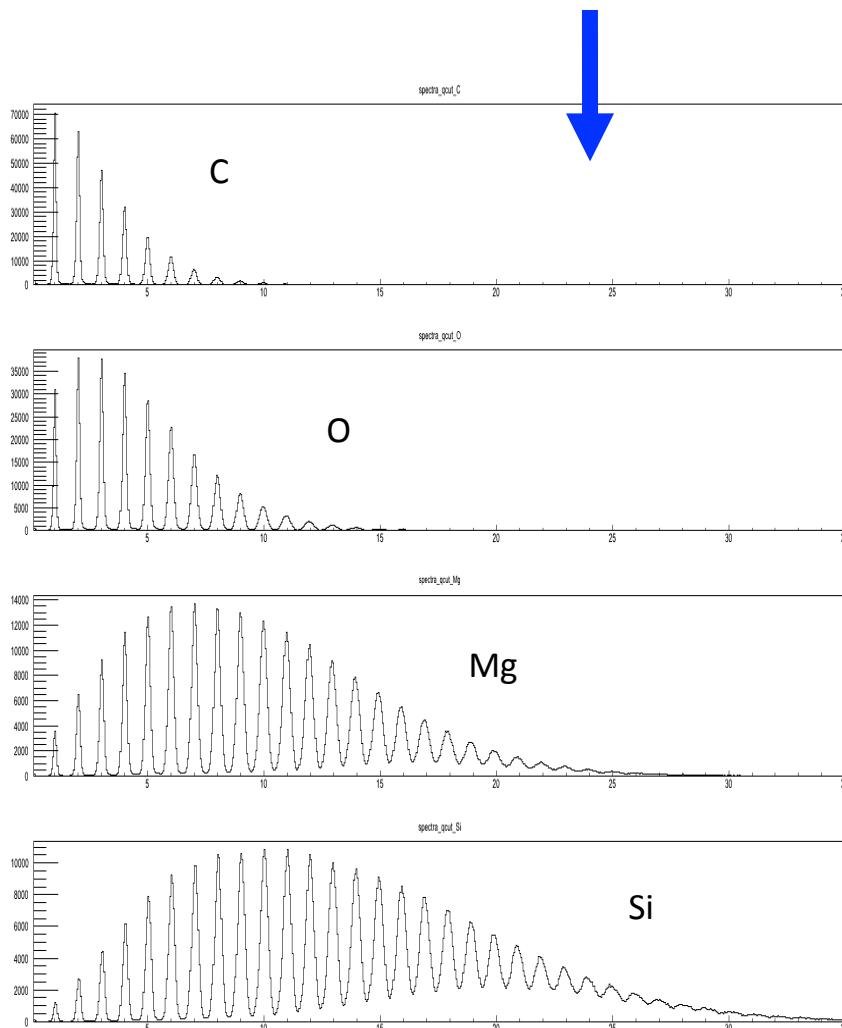


# Charge identification by FDIRC (integral measurement)

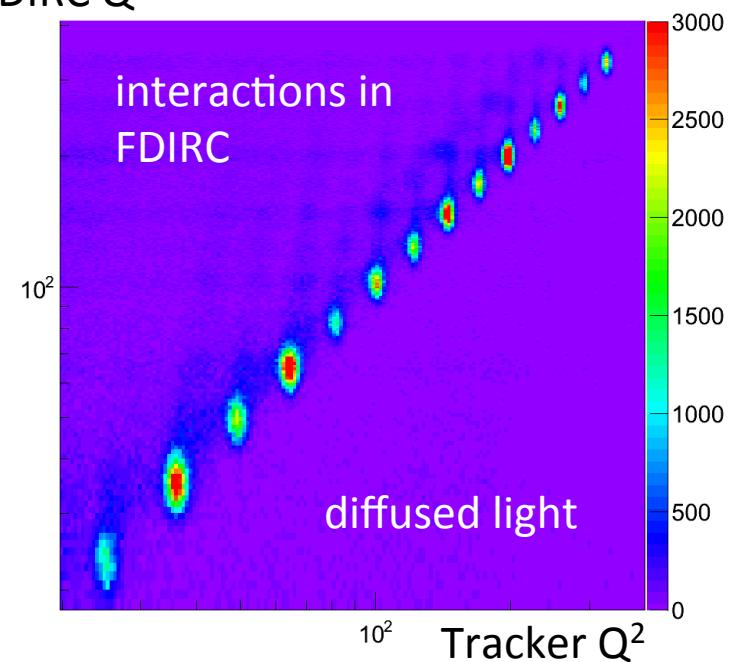


## Selection of non-interacting nuclei in FDIRC

Photopeak spectra for non-interacting ions:  
C, O, Mg, Si with 2 radiator bars



FDIRC  $Q^2$

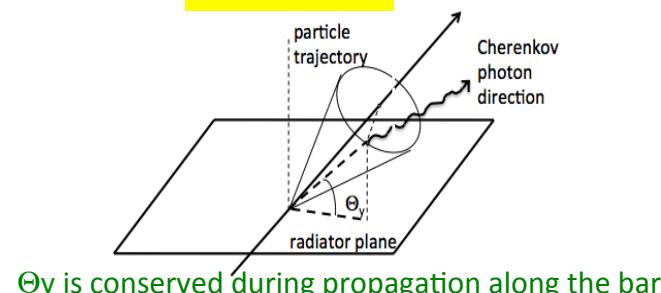
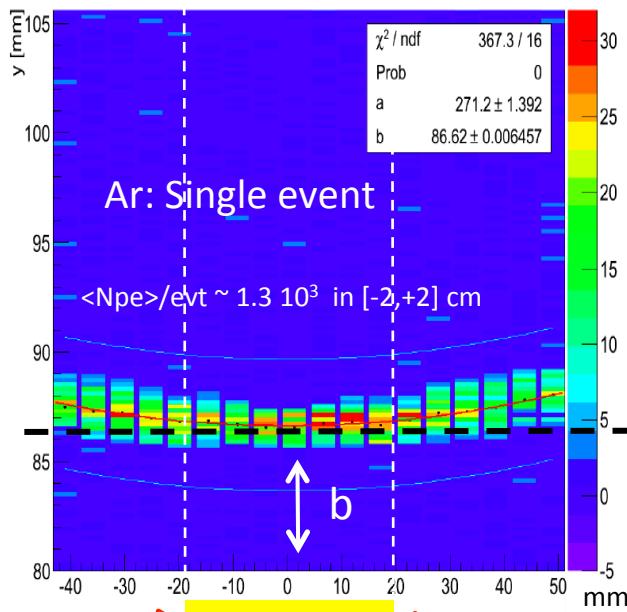


Use charge tagging from Tracker (downstream FDIRC): impose the same charge.

# Cherenkov pattern fit: MC simulation vs beam test data

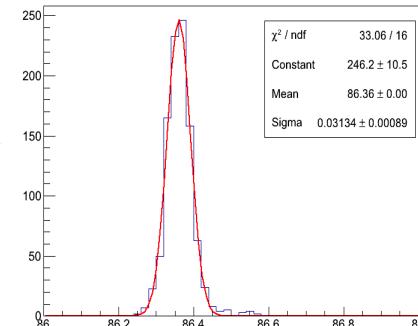
- DIFFERENTIAL measurement : fit Cherenkov pattern and measure FDIRC angular resolution.
- For tracks at normal incidence on the radiator the focal plane (FP) pattern is hyperbolic.

Geant4 simulation: 30 GeV/n Ar  
(beam center shifted on the left as at beam test)

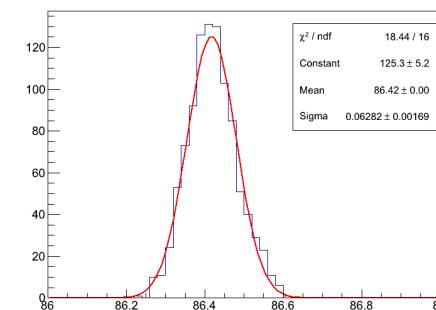


14<sup>th</sup> VCI, February 16, 2016

- Dead areas among SiPM arrays implemented in the simulation.  
In total 68% of instrumented FP area is active.
- **fit FP pattern event-by-event:**
  - Cherenkov angle  $\Theta_y$
  - apex of hyperbola (b parameter)



MC simulation:  
**fitted b parameter**  
 $\sigma_b \sim 31 \mu\text{m}$  for Ar

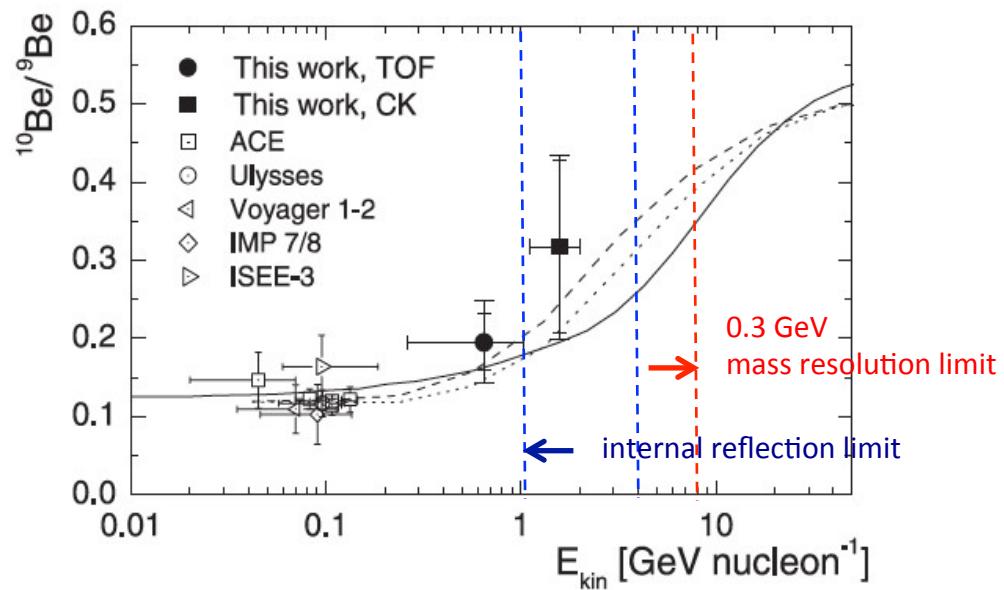


beam test data:  
**fitted b parameter**  
 $\sigma_b \sim 63 \mu\text{m}$  for Ar

Beam data fit to b-parameter is  $\sim 2$  times larger than MC.  
**However:** geometry + bar imperfections affecting light propagation along the bar are not simulated as well as diffused light background.

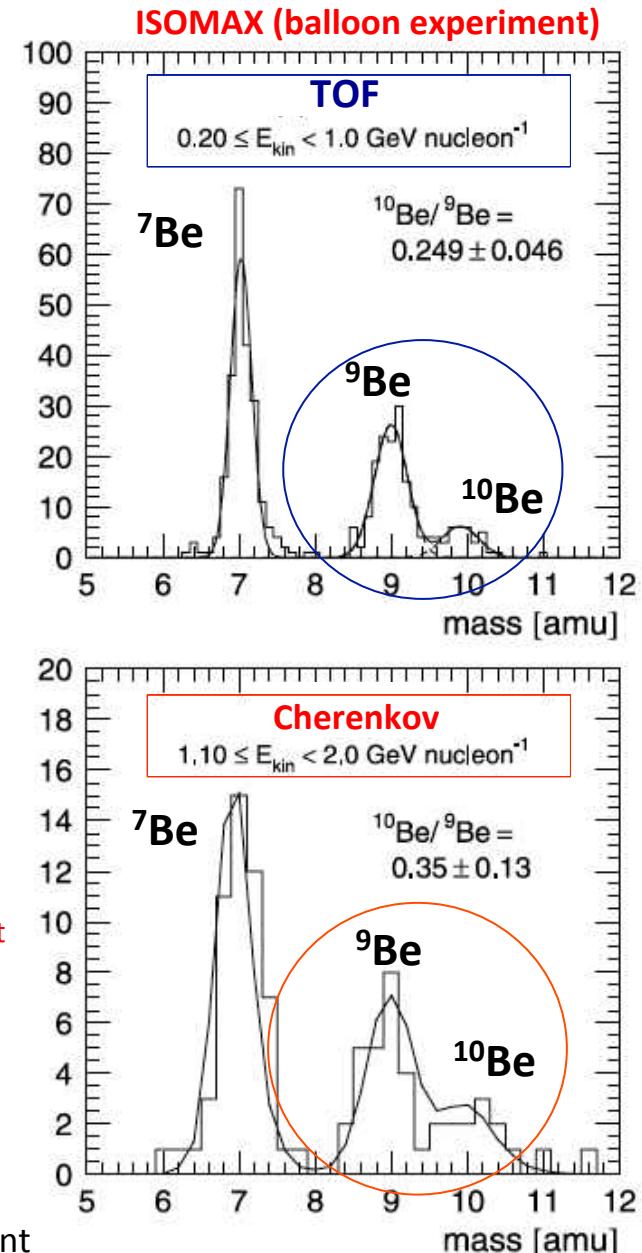
# Cosmic $^{10}\text{Be}/^{9}\text{Be}$ Isotopic Ratio

- $^{10}\text{Be}$  decays to stable  $^{9}\text{Be}$  isotope
- “radioactive clock” to measure propagation time in the galaxy: very important for astrophysics models
- few measured points vs kinetic energy per nucleon
- need better accuracy + extension above 2 GeV/n

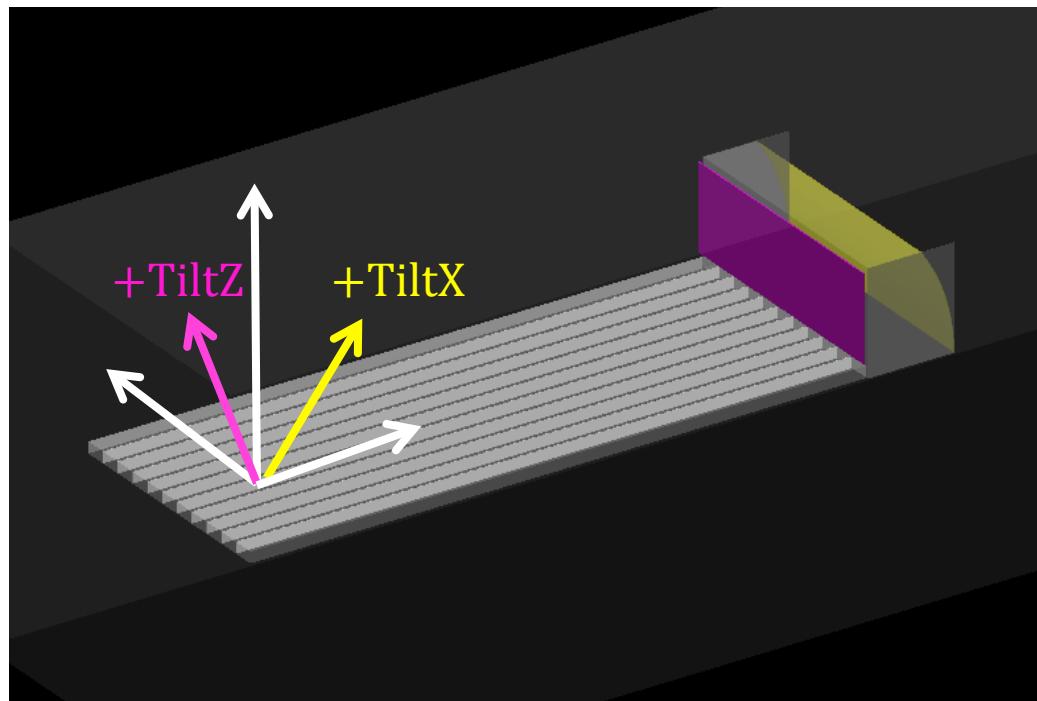


T. Hams et al., The Astrophysical Journal, 611:892–905, 2004

$^{10}\text{Be}/^{9}\text{Be}$  isotopic ratio measurement by ISOMAX (balloon experiment with magnetic spectrometer) in the energy interval  $0.2 < E_{\text{kin}} < 2.0$  GeV/n



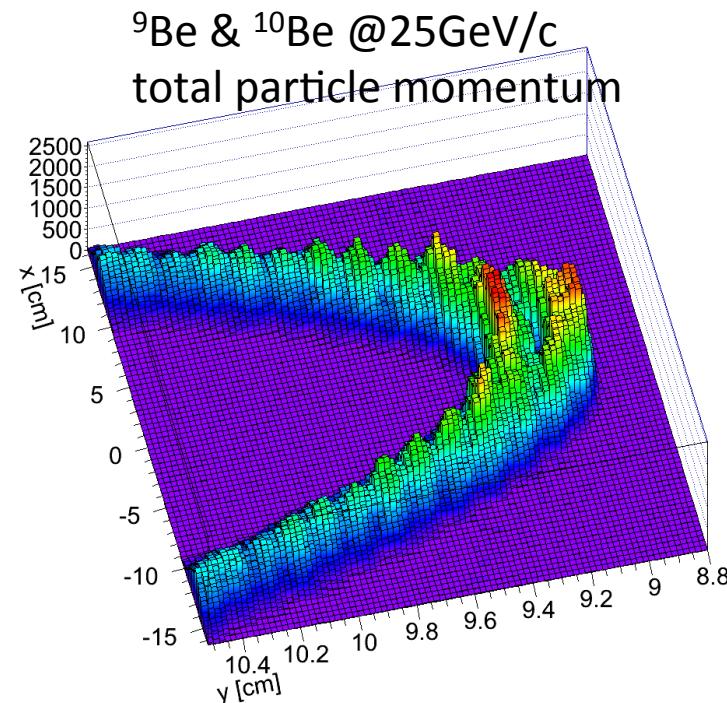
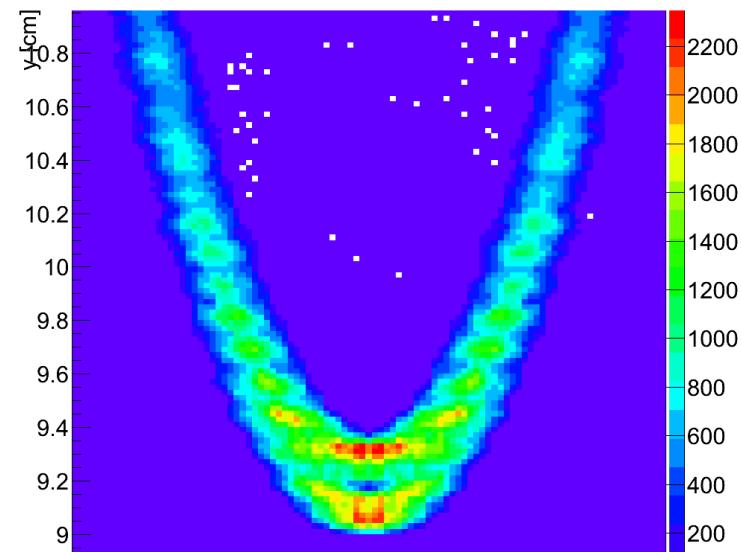
# Simulation of flight detector with cosmic-ray ISOTROPIC flux



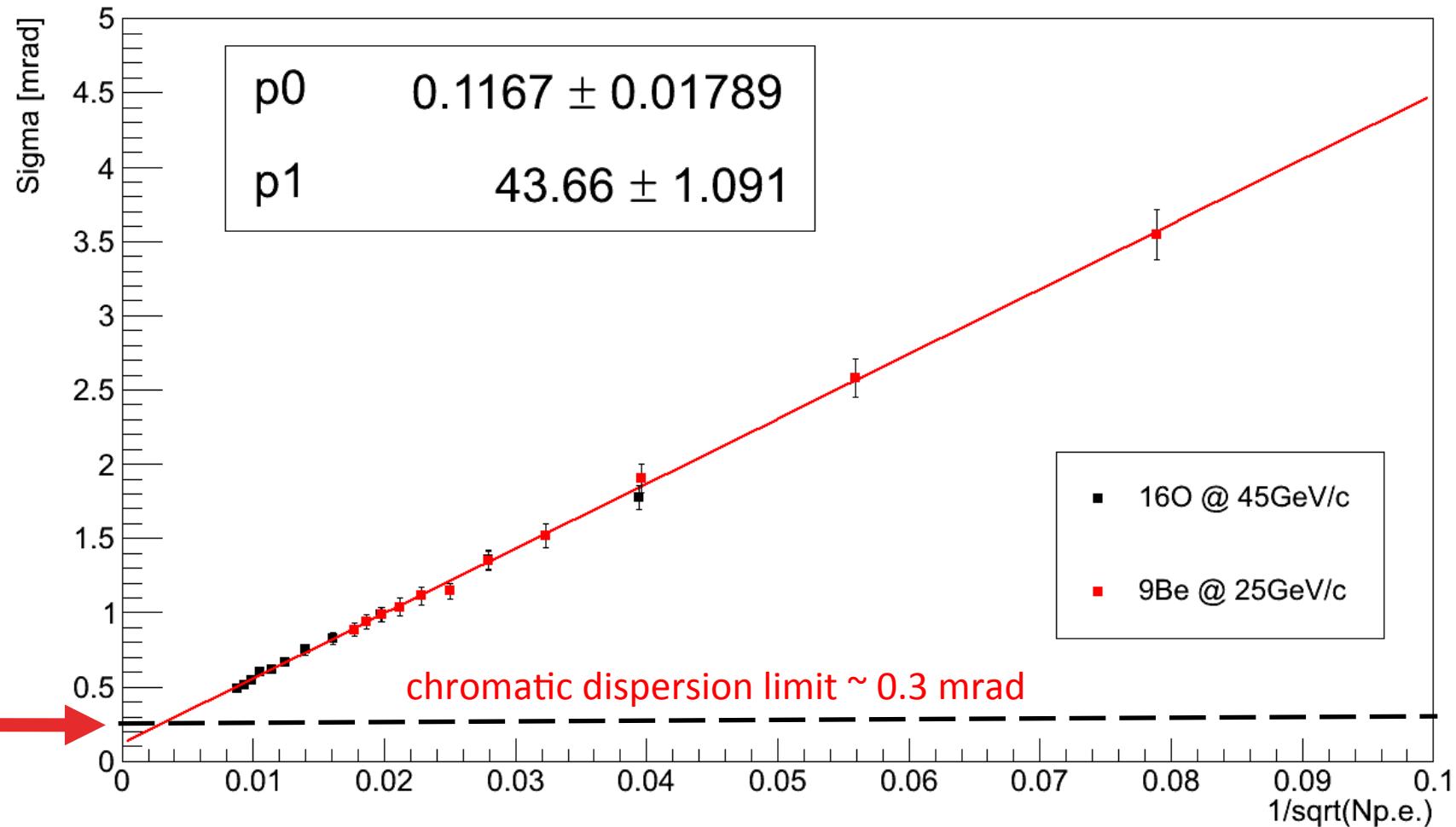
Radiator : 1 m long x 38.5 cm wide (11 bars)

Gap between radiators : 100  $\mu\text{m}$

Cylindrical Mirror :  $\geq 40$  cm long



# Angular resolution vs $1/\sqrt{N_{\text{p.e.}}}$



## Conclusions

- Good beam test performance of our **first prototype** of FDIRC with SiPM readout
- **Outstanding performance of the SiPM arrays**
- **Digital FDIRC** in “photon counting mode” governed by Poissonian statistics
- Ion beam test data very useful to study detector’s full **dynamic range**
- Proof-of-principle for isotope separation requires **lower** beam momentum

### Next:

- $^{10}\text{Be}/^9\text{Be}$  measurement is feasible but not easy.
- Effect of isotropic direction of incident track vs. mass resolution is under study.
- 1-2% momentum resolution from mag spectrometer required in [18, 50] GeV/c
- Quartz bars with the required precision are **very expensive** (see BaBar + Belle2)
- Focal plane coverage with  $\sim 1.1 \times 10^4$  SiPM channels (172 arrays)
- New SiPM arrays (identical to NUV but with HD technique) delivered by FBK

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# Extra slides

# Np.e./cm/MIP vs FC instrumented x-range

