The Silicon Photomultipliers in Particle Physics: Possibilities and Limitations

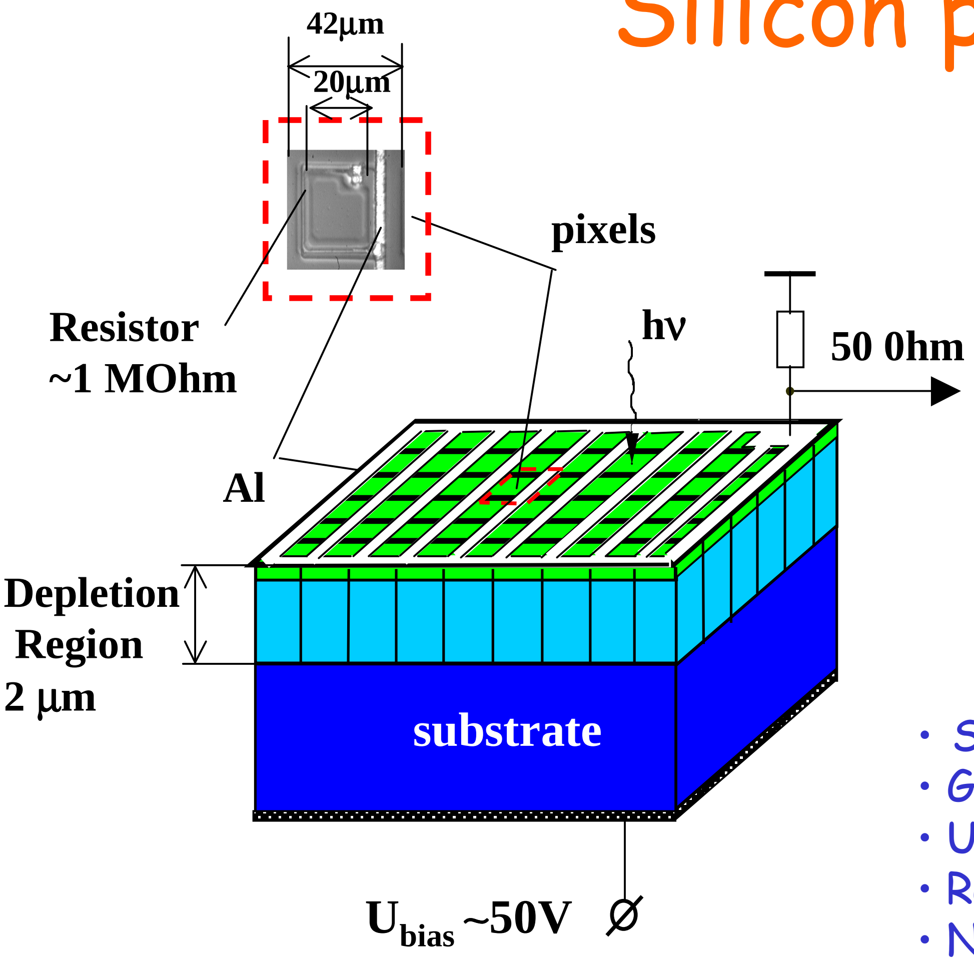
Boris Dolgoshein
(MEPhI, Moscow)

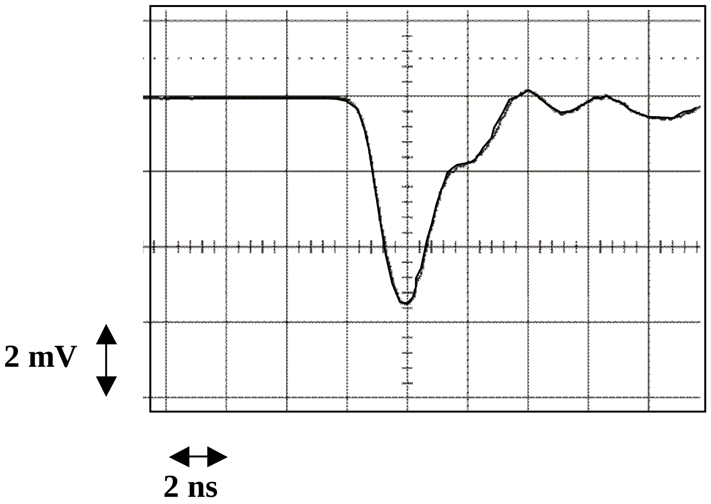
Email: boris@mail.cern.ch

Content:

- ☐ SiPM's:
  main characteristics
- ☐ SiPM's:
  - possible applications in particle physics
  - drawbacks and limitations
- ☐ SiPM's:
  perspectives of the development

Silicon photomultiplier (SiPM)





SiPM main features:

- Sensitive size 1x1mm^2 on chip 1.5x1.5 mm^2
- Gain $2 \cdot 10^6$
- U_{bias}~50V
- Recovery time < 100 ns/pixel
- Number of pixels: ~ 1000/mm^2
- Nuclear counter effect: negligible (due to Geiger mode
- Insensitive to magnetic field
- Dynamic range ~10^3/mm^2

for details: NIMA 504(2003)48

Single pixel device:

S ingle

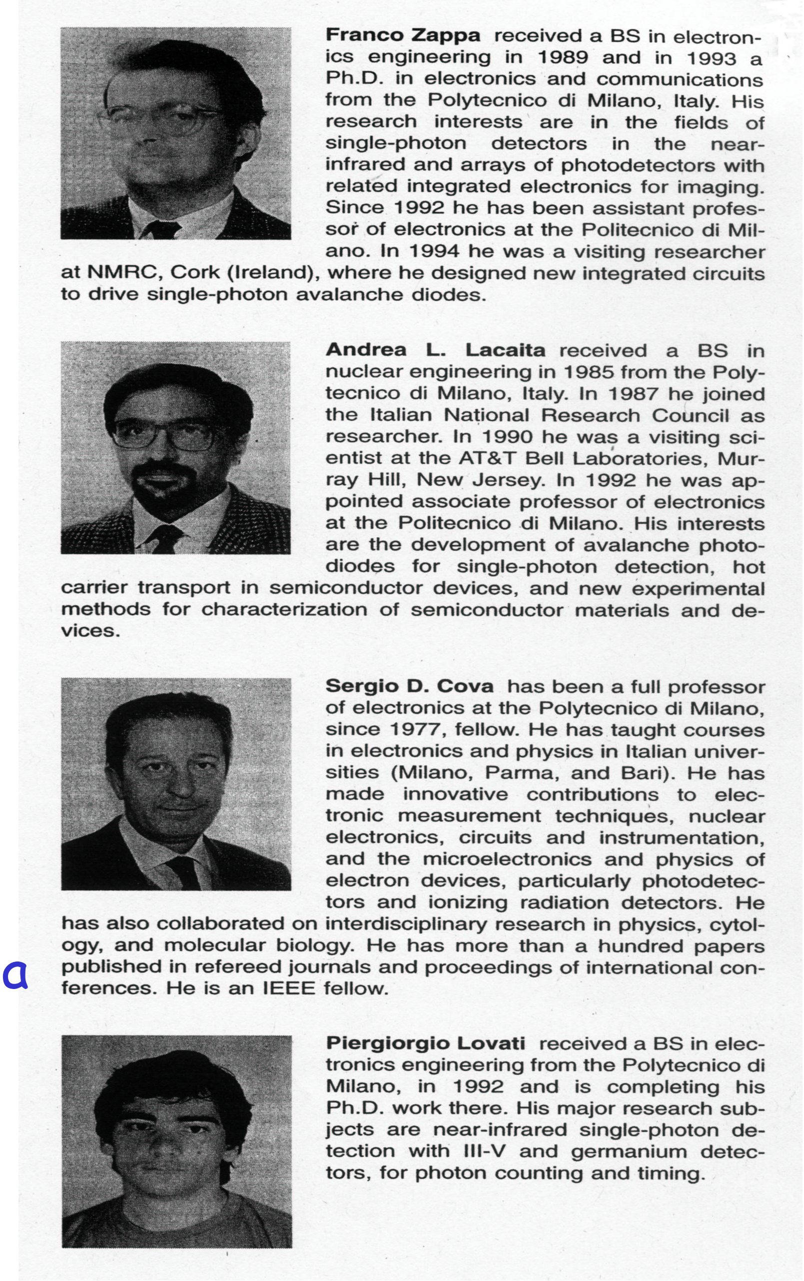
P hoton

A valanche

D etector

F.Zappa.A.Lacaita,S,Cova,P.Lovati,
Opt.Engineering J.,35(1996)938

S.Cova,M.Ghioni,A.Lacaita.C.Samori,F.Zappa
Applied Optics,35(1996)1956



Franco Zappa received a BS in electronics engineering in 1989 and in 1993 a Ph.D. in electronics and communications from the Polytecnico di Milano, Italy. His research interests are in the fields of single-photon detectors in the near-infrared and arrays of photodetectors with related integrated electronics for imaging. Since 1992 he has been assistant professor of electronics at the Politecnico di Milano. In 1994 he was a visiting researcher at NMRC, Cork (Ireland), where he designed new integrated circuits to drive single-photon avalanche diodes.

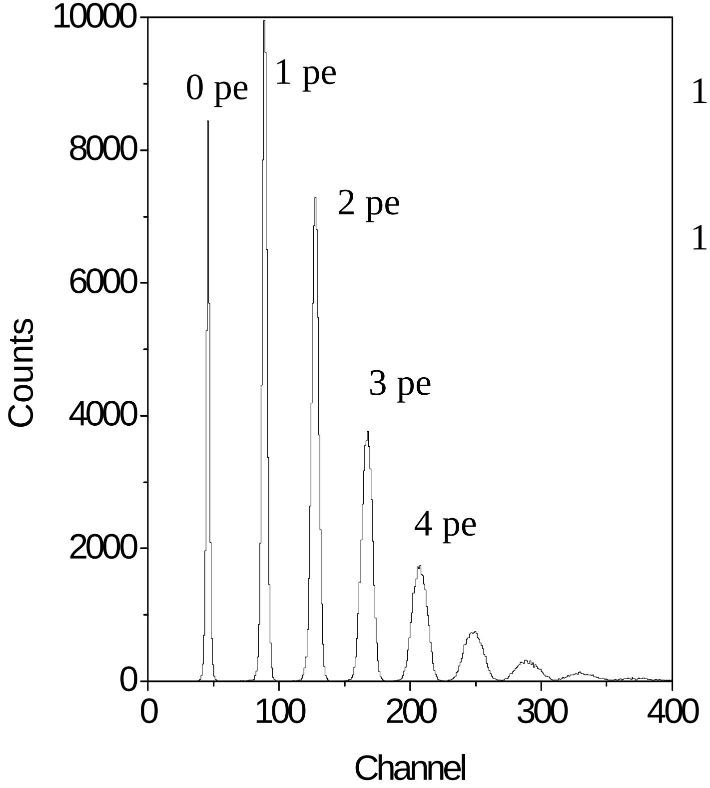
Andrea L. Lacaita received a BS in nuclear engineering in 1985 from the Polytecnico di Milano, Italy. In 1987 he joined the Italian National Research Council as researcher. In 1990 he was a visiting scientist at the AT&T Bell Laboratories, Murray Hill, New Jersey. In 1992 he was appointed associate professor of electronics at the Politecnico di Milano. His interests are the development of avalanche photodiodes for single-photon detection, hot carrier transport in semiconductor devices, and new experimental methods for characterization of semiconductor materials and devices.

Sergio D. Cova has been a full professor of electronics at the Polytecnico di Milano, since 1977, fellow. He has taught courses in electronics and physics in Italian universities (Milano, Parma, and Bari). He has made innovative contributions to electronic measurement techniques, nuclear electronics, circuits and instrumentation, and the microelectronics and physics of electron devices, particularly photodetectors and ionizing radiation detectors. He has also collaborated on interdisciplinary research in physics, cytology, and molecular biology. He has more than a hundred papers published in refereed journals and proceedings of international conferences. He is an IEEE fellow.

Piergiorgio Lovati received a BS in electronics engineering from the Polytecnico di Milano, in 1992 and is completing his Ph.D. work there. His major research subjects are near-infrared single-photon detection with III-V and germanium detectors, for photon counting and timing.

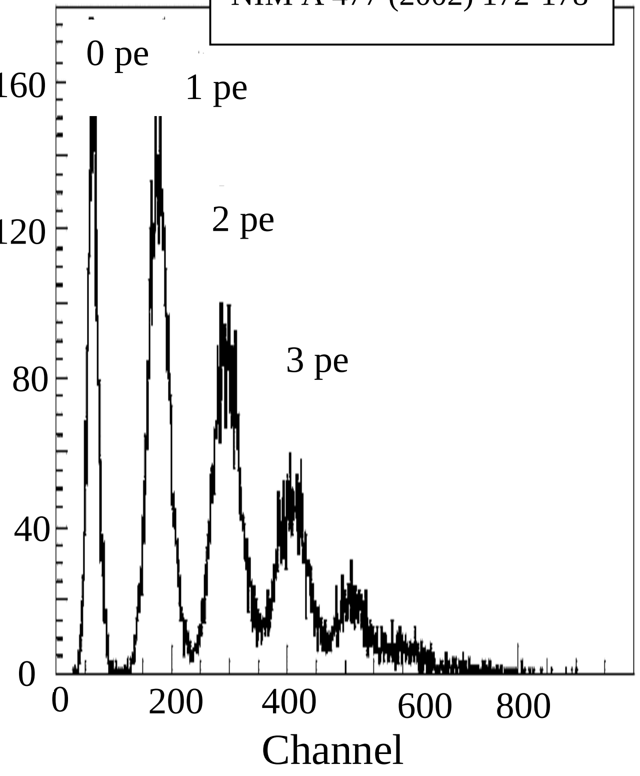
Single photoelectron (single pixel) spectra

SiPM



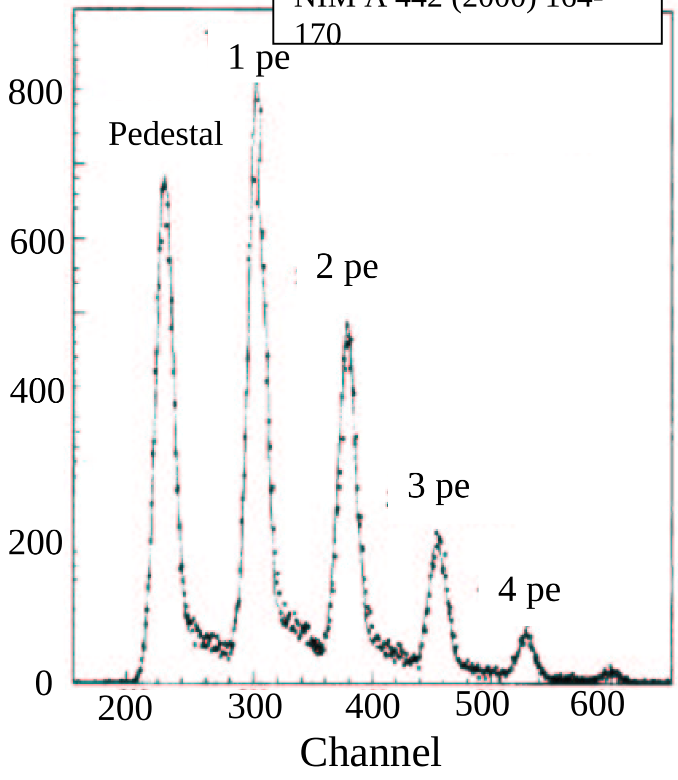
VLPC

NIM A 477 (2002) 172-178



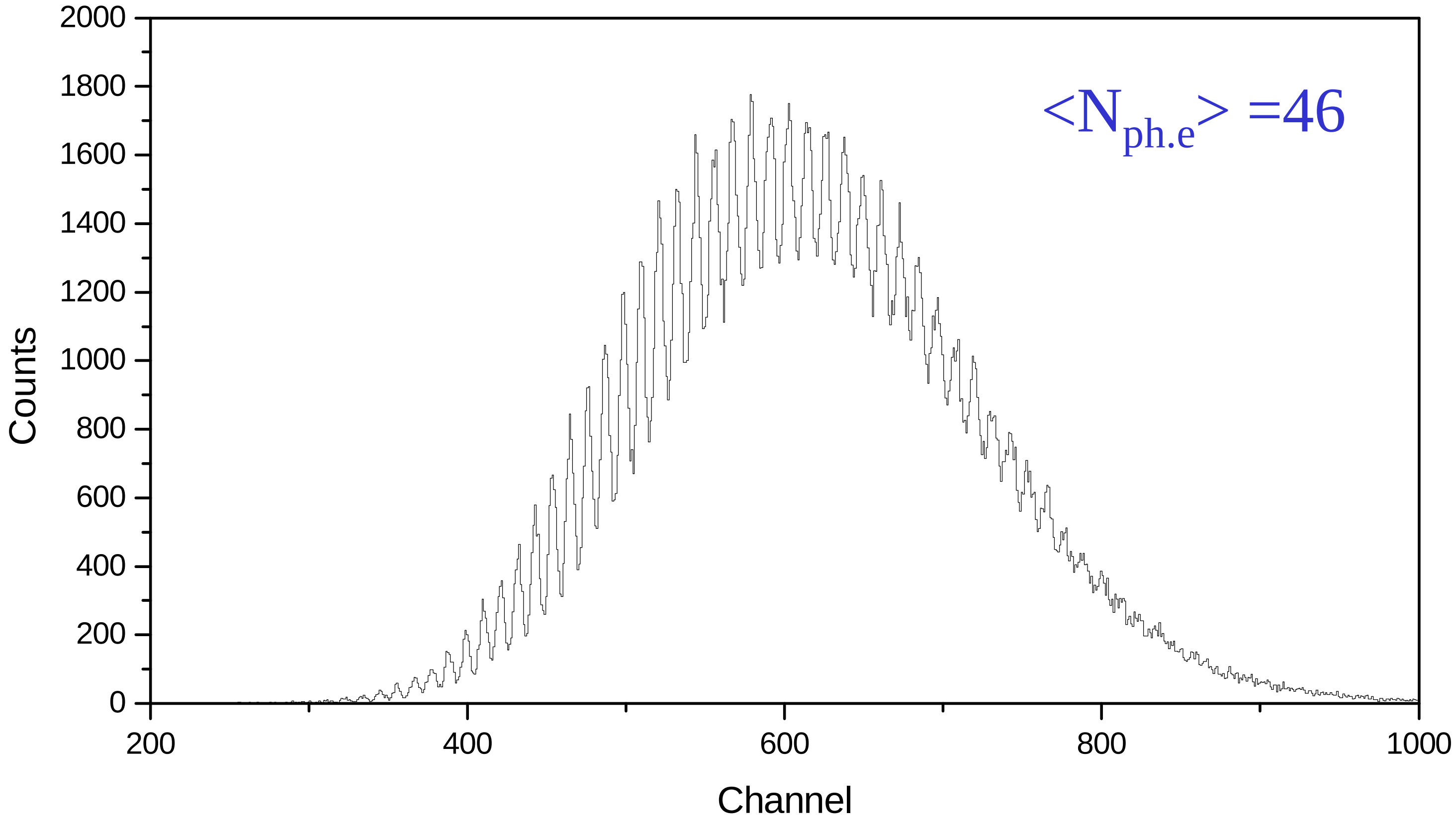
HPD

NIM A 442 (2000) 164-170

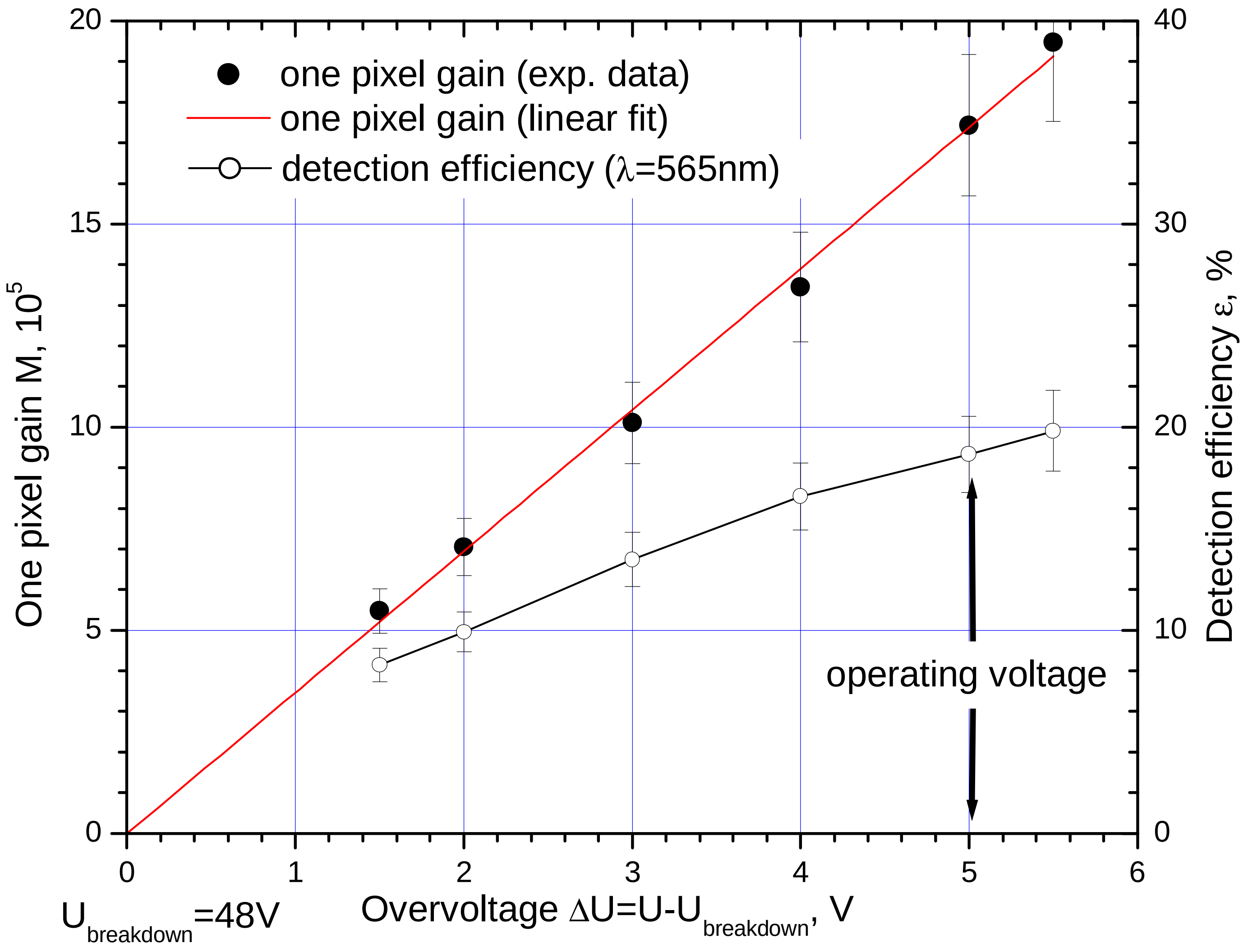


SiPM:
- excellent single photoelectron resolution
- low ENF expected

More about pixel signal resolution: tens of photoelectrons



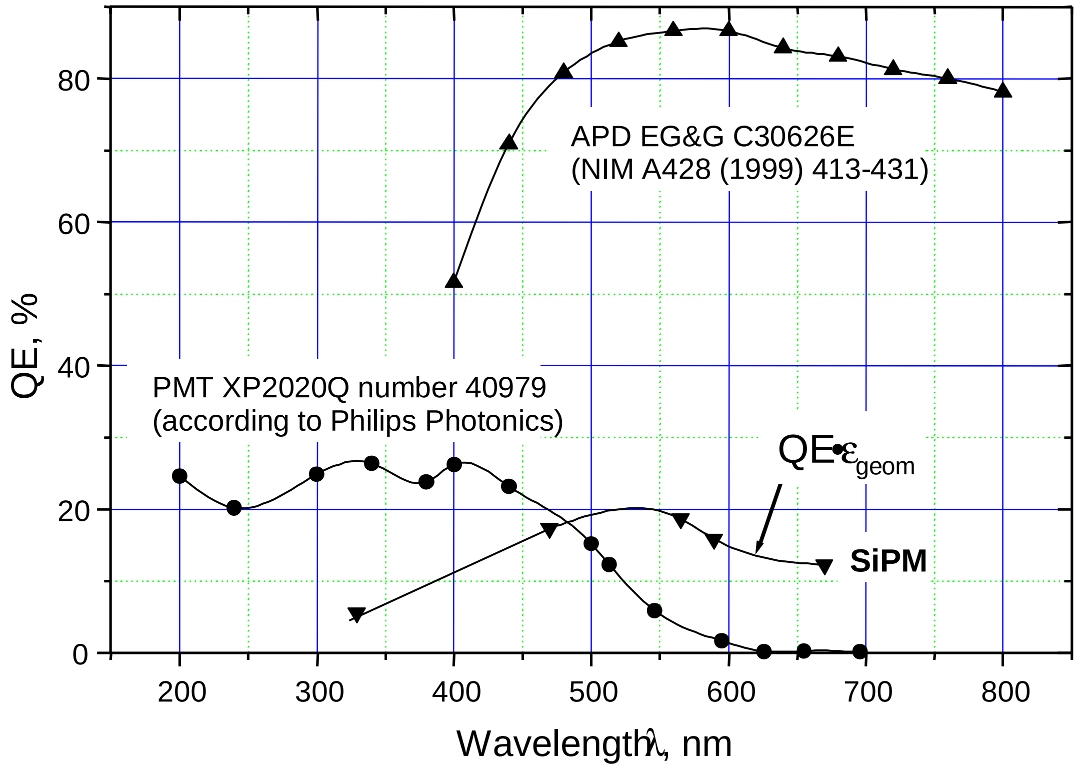
- SiPM consists of a large number of pixel photoelectron counters with binary readout for each pixel, working as analogue device
- signal uniformity from pixel to pixel is quite good



Photon detection efficiency $\varepsilon = QE \cdot \varepsilon_{geom}$

Photon detection efficiency

Spectral dependence of quantum efficiency for different photodetectors
(room temperature)



SiPM: $\varepsilon = QE \cdot \varepsilon_{geom}$, $\varepsilon_{geom} \sim 0.3$ (possible improvement up to ~ 0.7)

SiPM gain: temperature and voltage dependence

Photodetector	ΔT for $\Delta M/M=1\%$	$\Delta V/V_0$ for $\Delta M/M=1\%$
APD EG&G C30626E*	0.15^{o}	$0.4V/400V = 10^{-3}$
APD Hamamatsu S5345 (high capacitance)*	0.3^{o}	$0.04V/300V = 1.5\cdot10^{-4}$
SiPM $M=2\cdot10^{6}$	2.0^{o}	$0.05V/50V = 10^{-3}$

*) for APDs M=100 /Karar et al NIM A428(1999) 413/

Timing by SiPM

- SiPM is quite fast: discharge time is typically about 500 ps

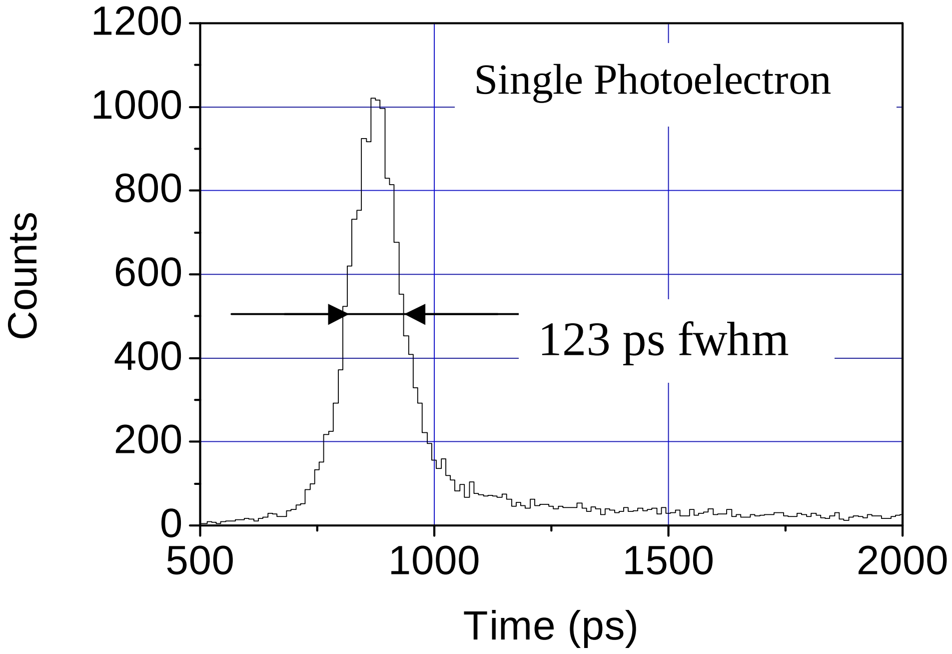
  - Rise time is ~1 ns

  Single pixel recovery time<100ns ($R_{pixel} \times C_{pixel}$ ~30 ns)

- Timing by SiPM has been studied using very fast laser(FWHM=40 ps)

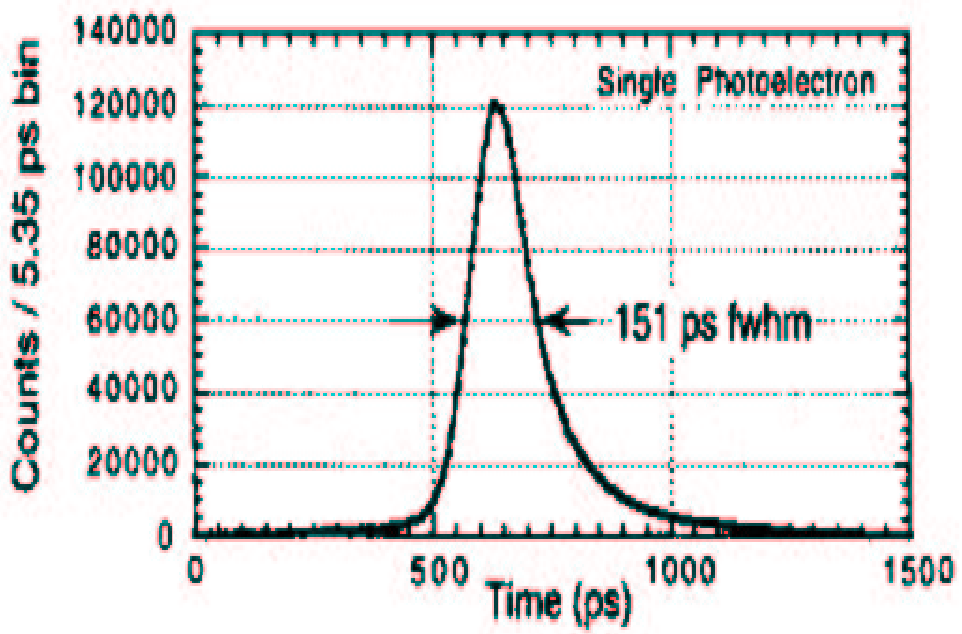
Timing by SiPM

SiPM



The best

PMT R-5320



FWHM: Laser (40 ps) + electronics (40 ps) => SiPM (100 ps)

- 50 ps sigma for single ph.e. by leading edge discriminator
- SiPM timing performance competes with MCP PM

SiPM: arguments in favour

- ✓ Low noise,high gain
- ✓Good single electron resolution
- ✓Very good timing
- ✓Small recovery time
- ✓Low charge particle/photon sensitivity
- ✓Insensitivity to B
- ✓Low bias voltage
- ✓Low power consumption
- ✓Compactness
- ✓Room temperature operation
- ✓Good temperature and voltage stability
- ✓Simplest electronics
- ✓Relatively low cost(low resistivity Si,simple technology)

SiPM: drawbacks and limitation

MANY-

to be considered separately for concrete application

SiPM: Possible Applications in Particle Physics

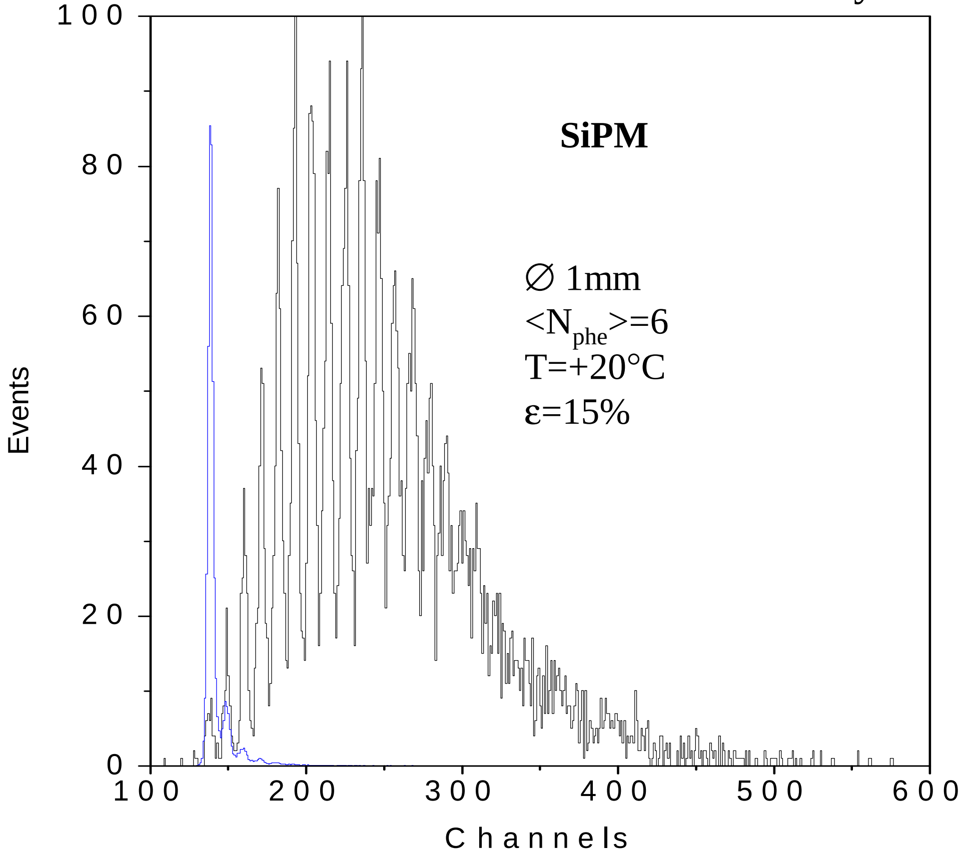
The main field

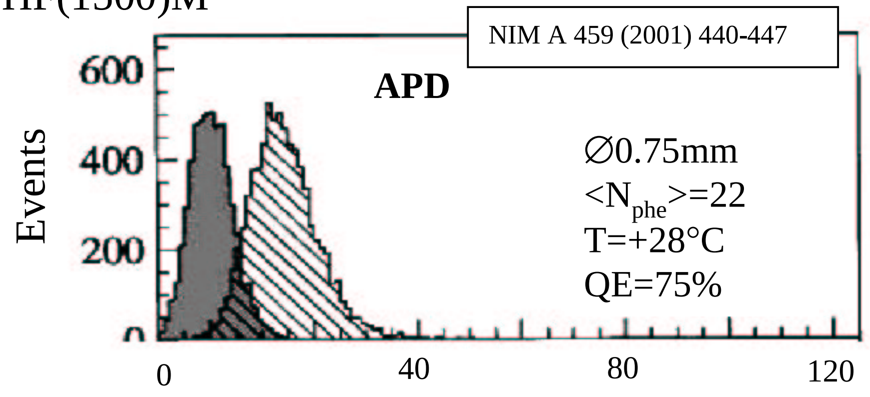
Low Light Level (LLL) detection:

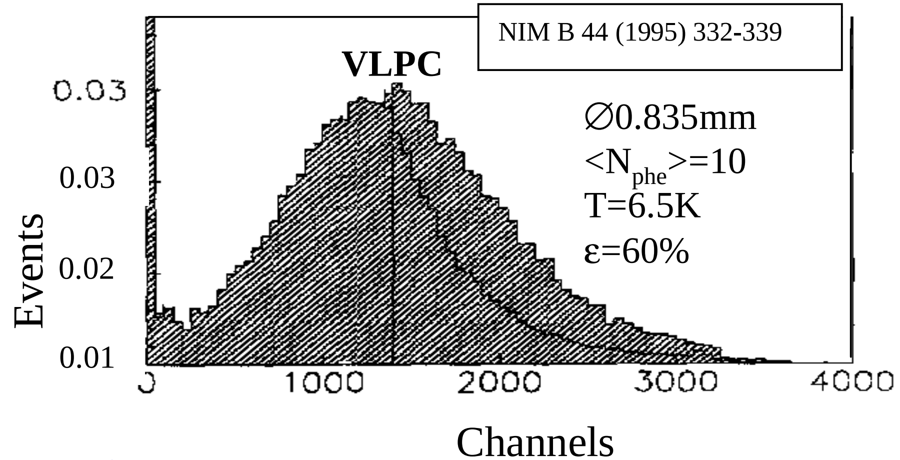
- LLL scintillation Readout
- Single Photon Counting
- Fast(<100 ps) timing for single photon

SiPM application for sci fiber MIP detection

Kuraray SCSF-3HF(1500)M



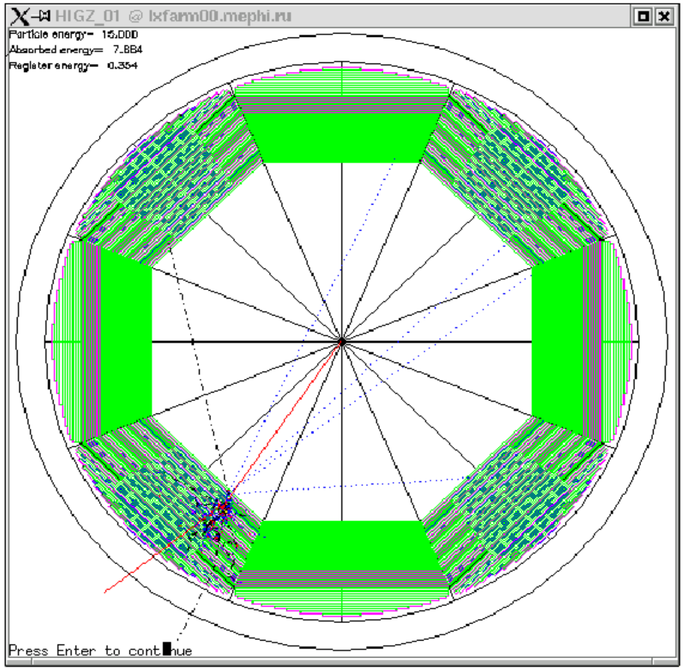

NIM A 459 (2001) 440-447


NIM B 44 (1995) 332-339

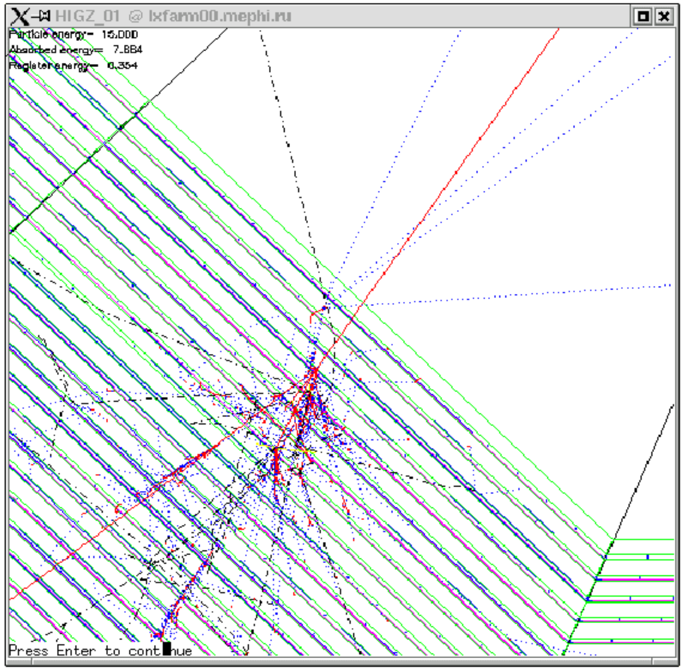
- SiPM is better than APD for room temperature
- SiPM at room temperature is good enough even compared to VLPC at 6.5°K.

Limitation: Higher photon detection efficiency (30-40%) is desirable

Hadron Tile Calorimeter
for TESLA Experiment, MC



```
Particle energy=  15.000
Absorbed energy=  7.884
Register energy=  0.354
Press Enter to continue
```

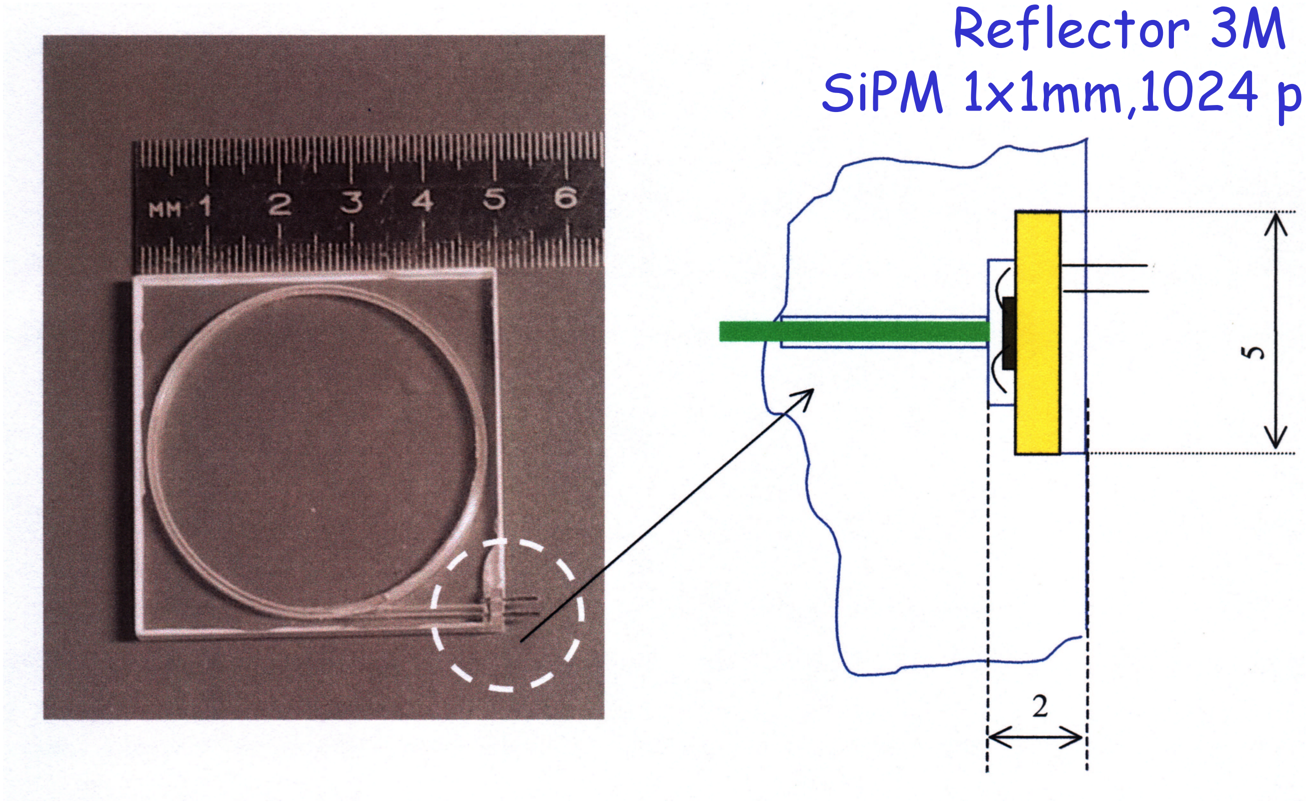


```
Particle energy=  15.000
Absorbed energy=  7.884
Register energy=  0.354
Press Enter to continue
```

Sci tile+WLS fiber readout – Application for Hadron Tile Calorimeter

TESLA HCAL-sci tiles 50x50x5mm interlayered by 2 cm Fe

Plastic sci “Vladimir”
WLS fiber Kuraray Y-11; 1mm
Reflector 3M
SiPM 1x1mm,1024 pixels



Electron 4 GeV

Test beam DESY

MiniHCAL TESLA

9 layers of 3x3 sci tiles

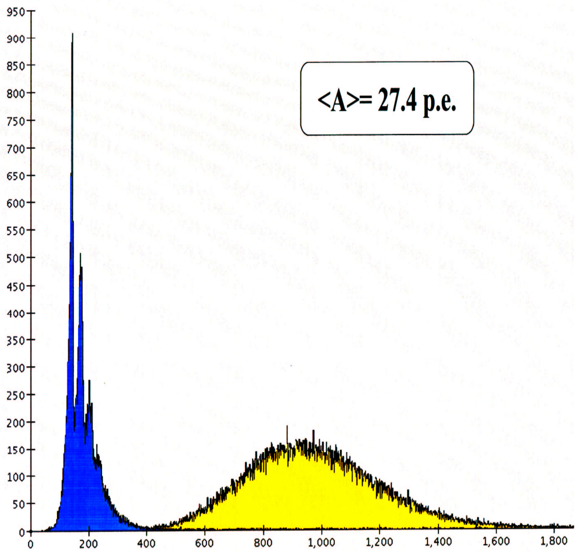
+ WLS+SiPM's

with 2cm Fe in between

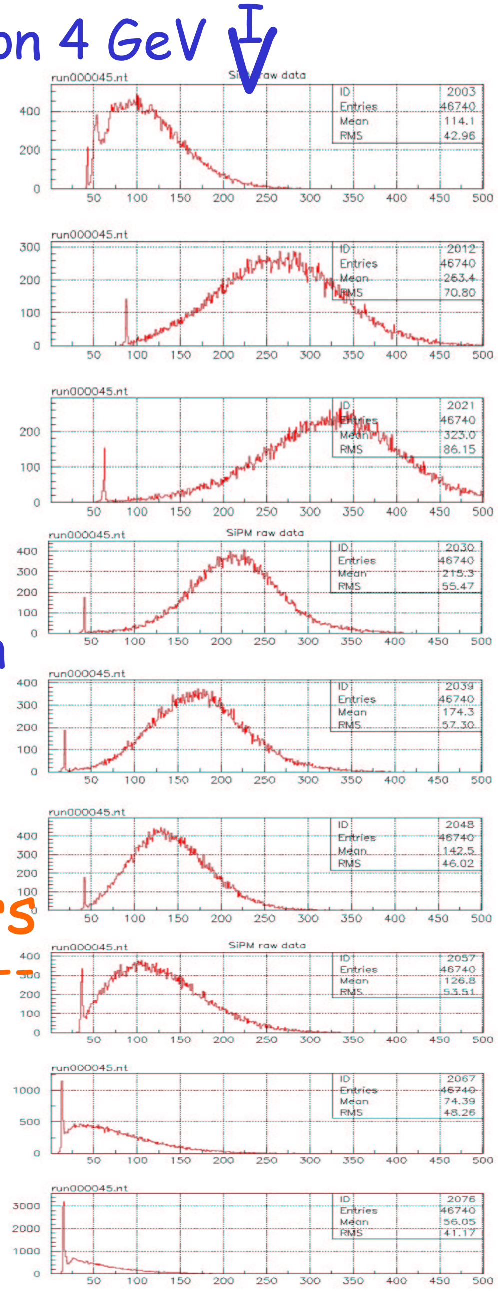
Readout by SiPM's

Without any amplifiers

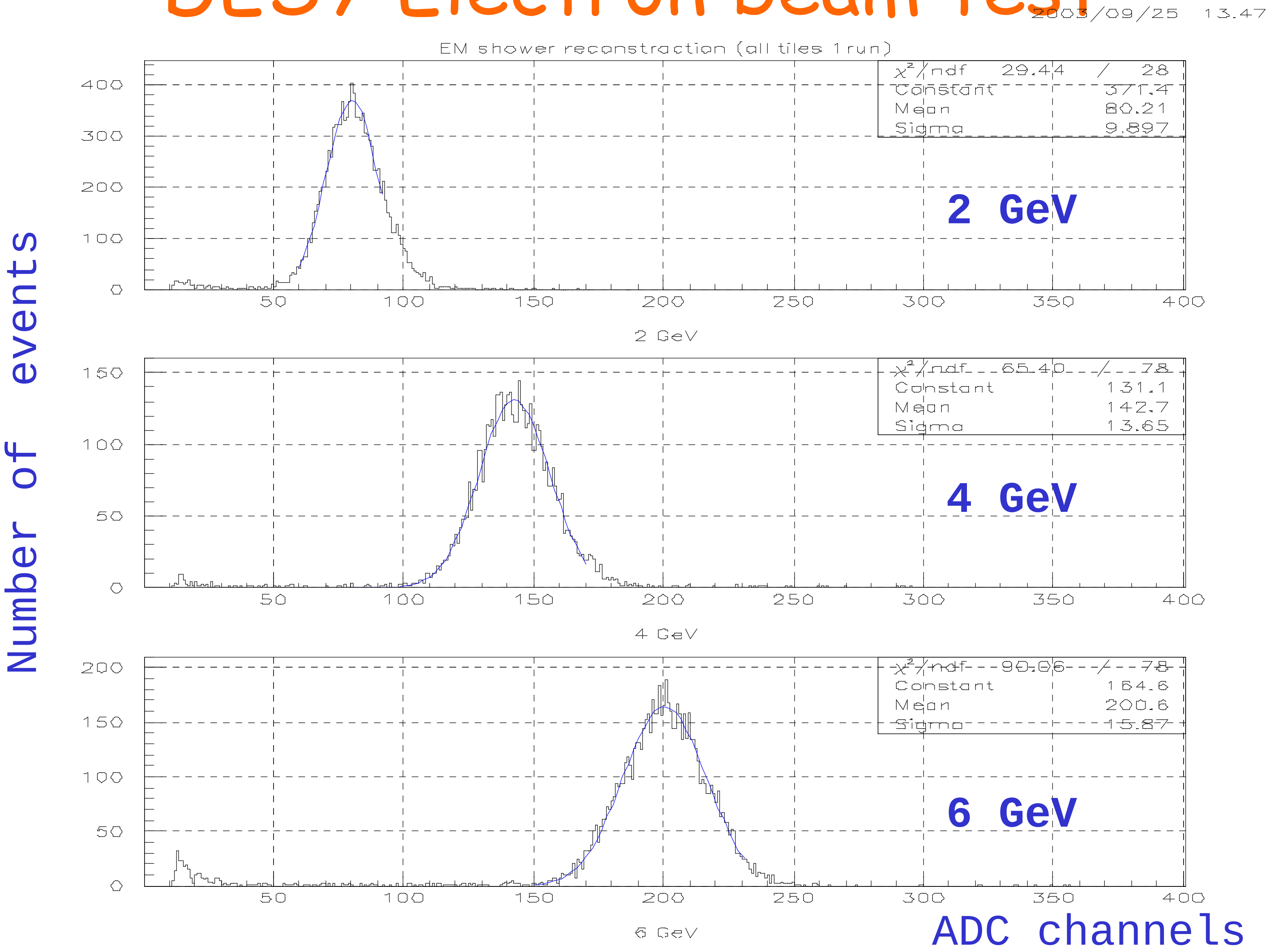
Picture from PC screen: LED and electron spectra



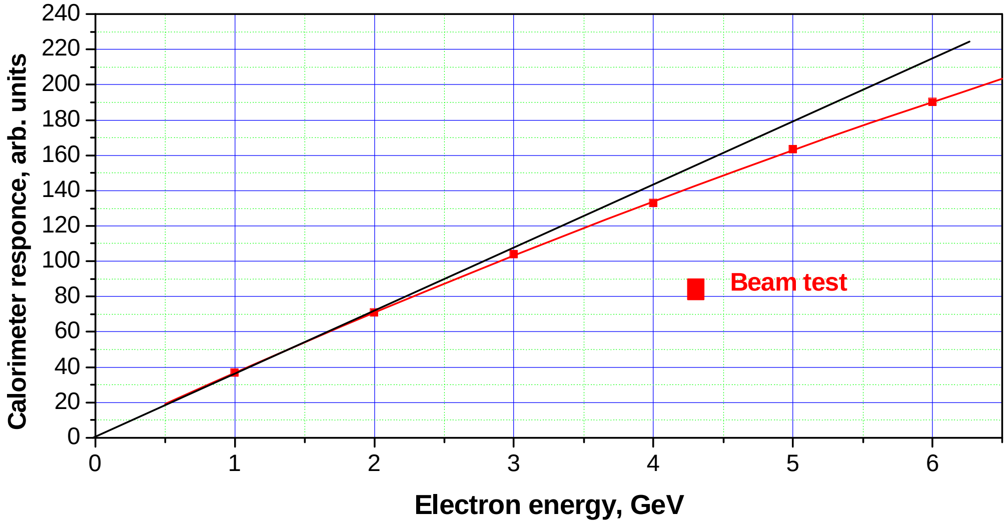
MIP in Sci tile 50x50x5 mm^3

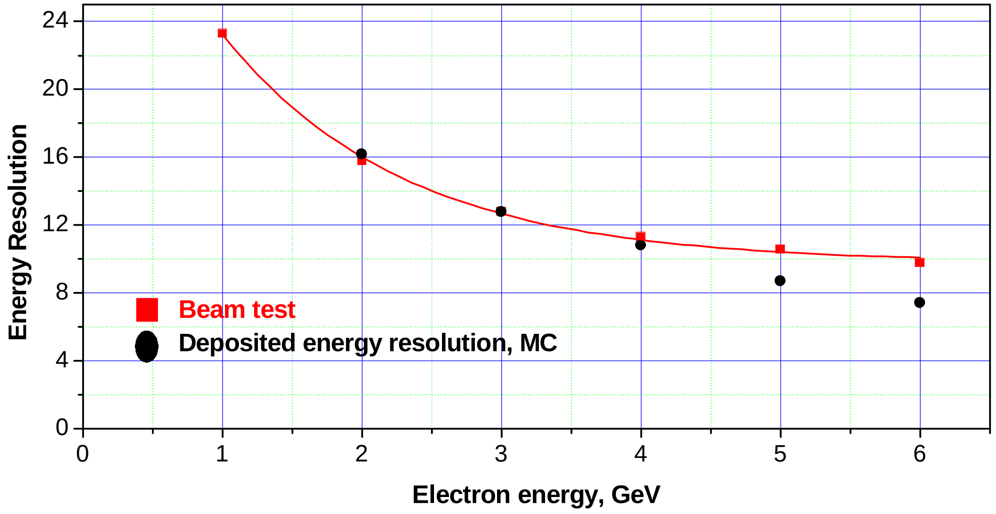


TESLA MINICAL with SiPM readout
DESY Electron beam test



TESLA MINICAL with SiPM readout
DESY Electron beam test





SiPM:

Limitations for Tile calorimetry based on Sci+WLS fiber+SiPM readout

1. Limited dynamic range

Number of photoelectrons/tile ‹ number of SiPM pixels(=1024)

- GEANT3 based simulations show:
no impact on HCAL energy resolution up to hadron jet energy of 25 GeV

SiPM signal

- The output SiPM signal is proportional to the number of pixels fired N

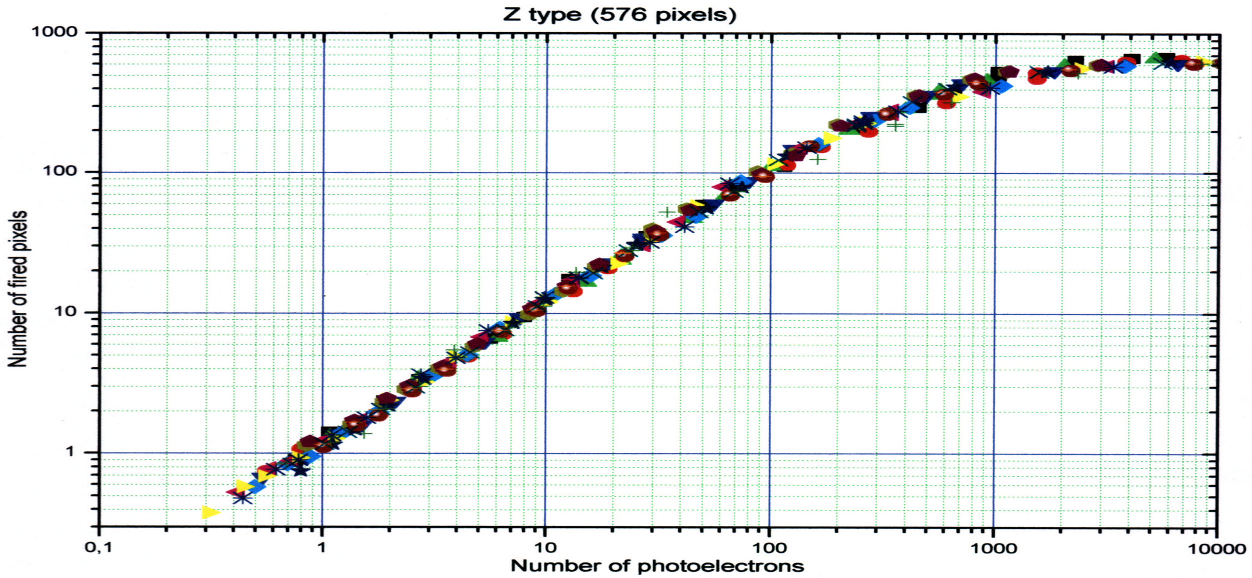
$$S \approx N_{pixel\_fired} = m \cdot (1 - e^{-\frac{N_{ph} \cdot \varepsilon}{m}})$$

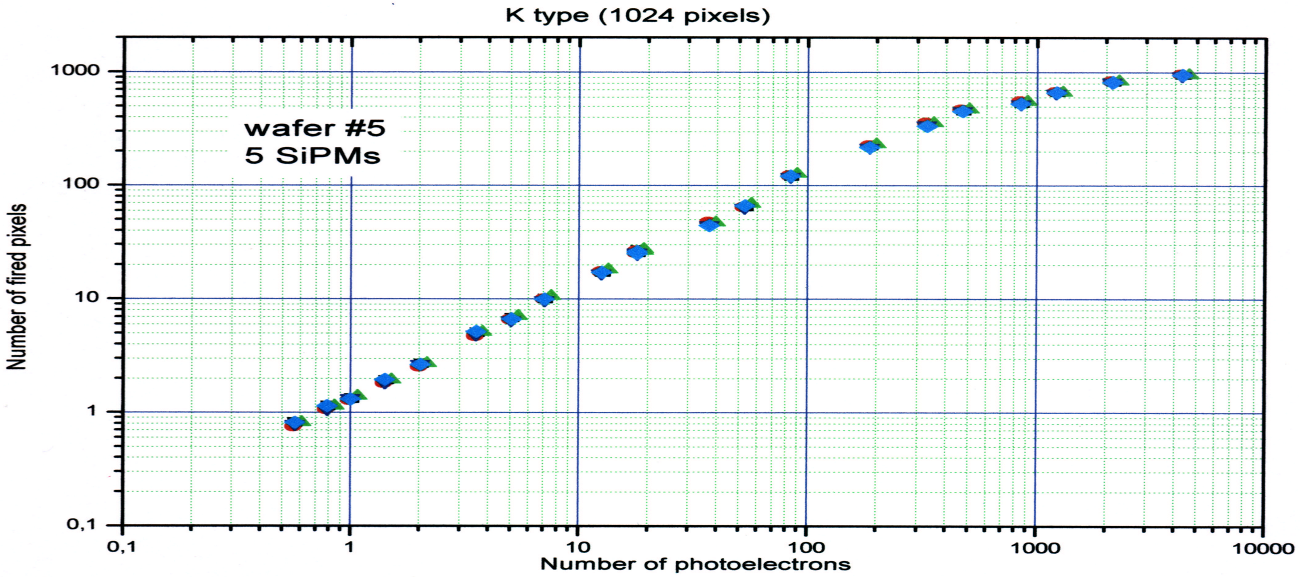
where m- total number of pixels

N_{ph}- number of photons

ε - photon detection efficiency

⇨ saturation of the signal


Z type (576 pixels)
Number of fired pixels
1000
100
10
1
0,1
1
10
100
1000
10000
Number of photoelectrons


K type (1024 pixels)
wafer #5
5 SiPMs
Number of fired pixels
1000
100
10
1
0,1
0,1
1
10
100
1000
10000
Number of photoelectrons

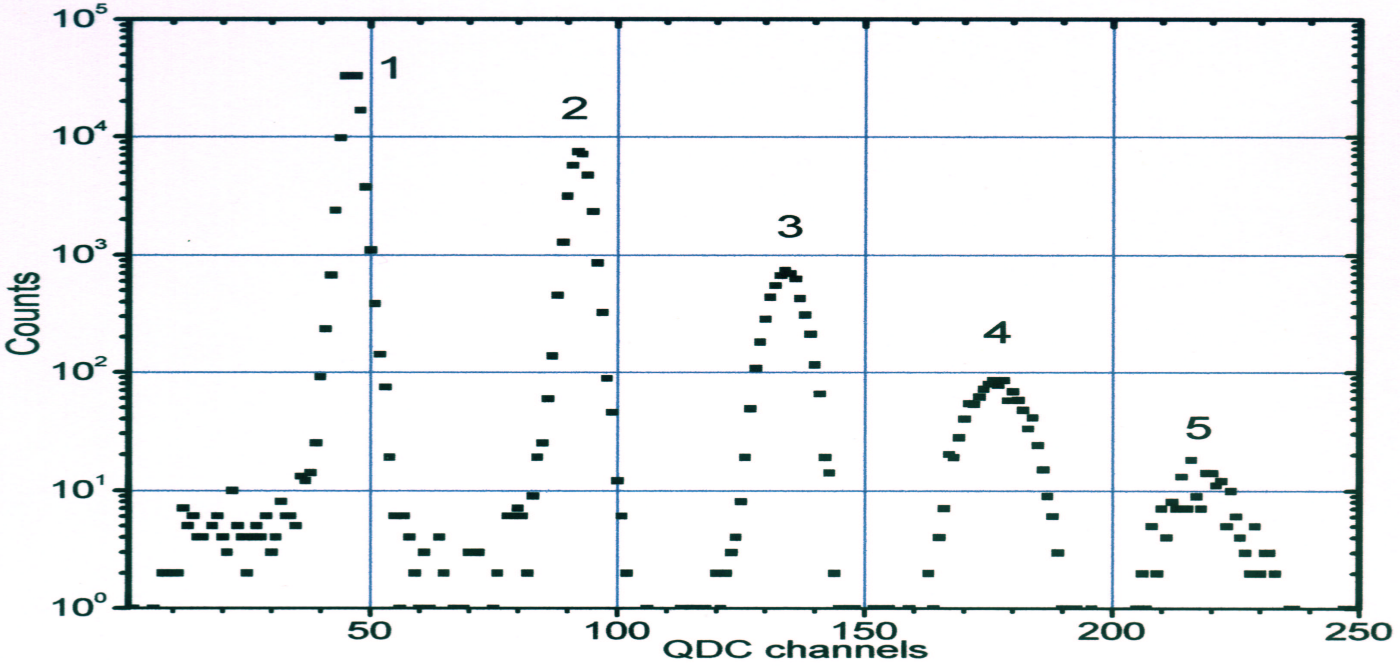
SiPM:

Limitations for Tile calorimetry based on Sci+WLS fiber+SiPM readout

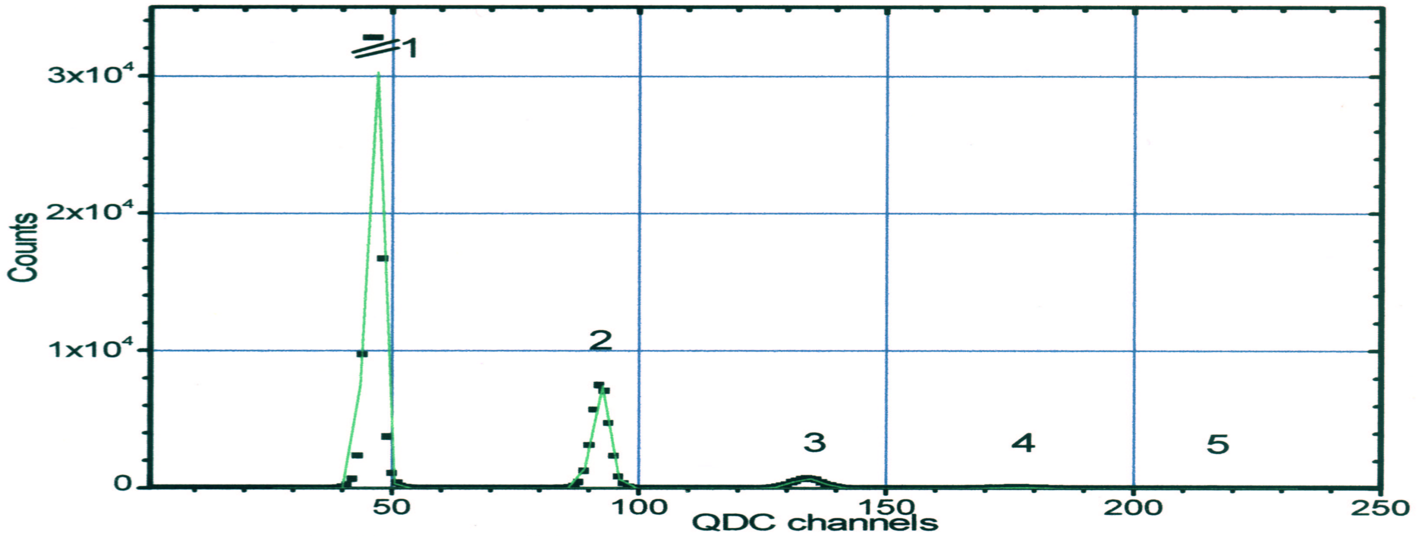
2. Optical cross-talk between the pixels:

\# of the photons emitted by one electron in avalanche is ~ 1/10000(fortunately!),nevertheless…

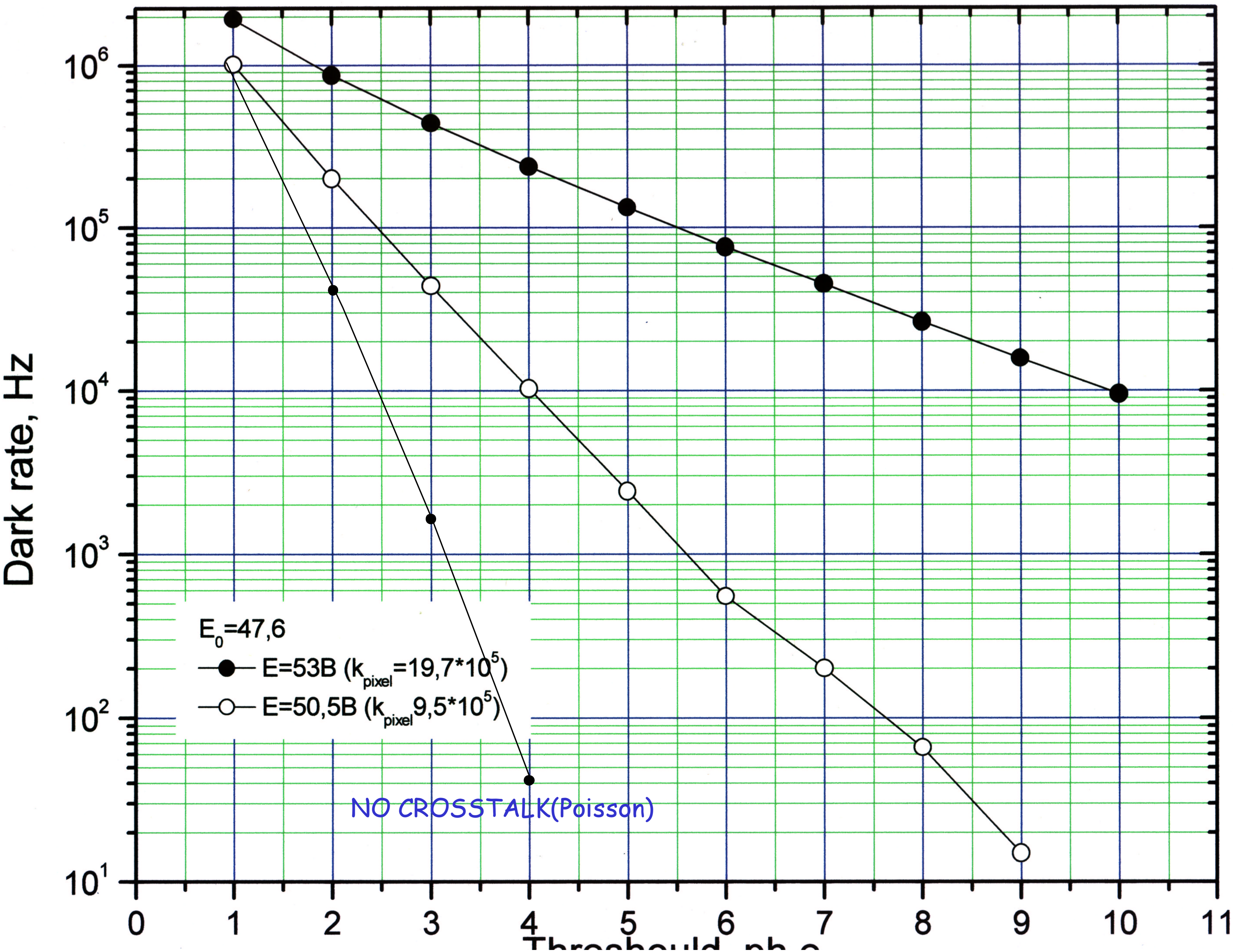
- Increase the dark rate for high thresholds
  - Limit the SiPM gain at level of 100000

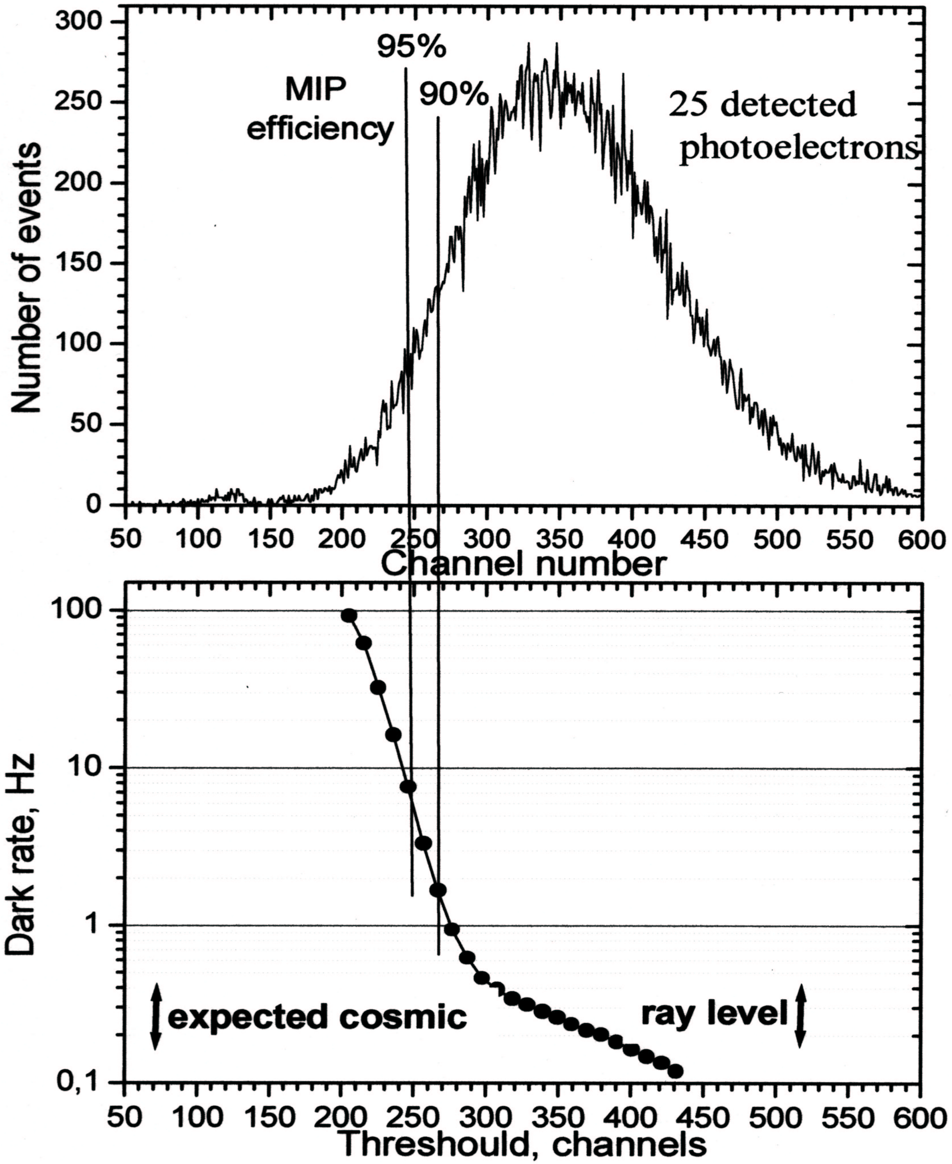


SiPM pulse hight spectra for noise pulses, n<<1

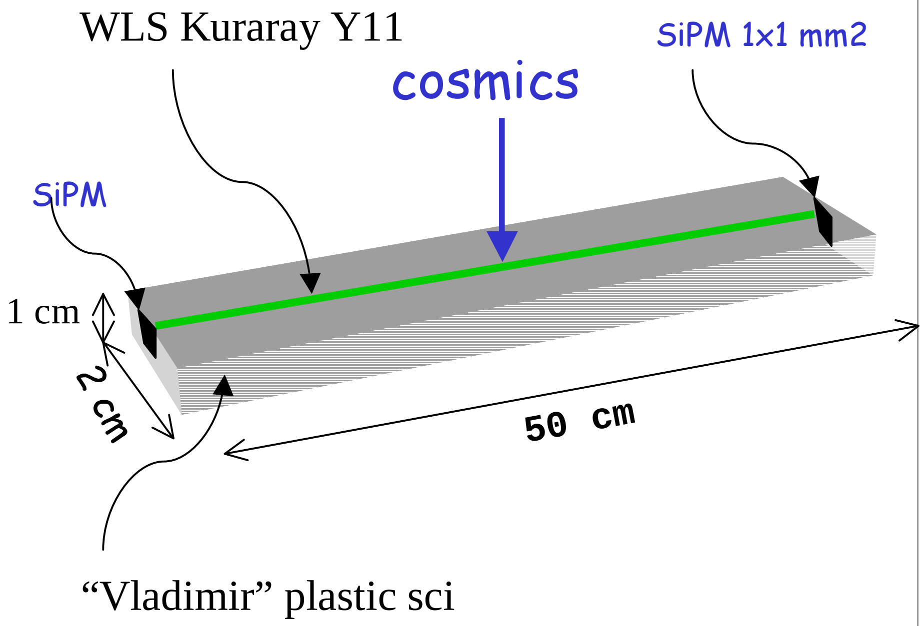


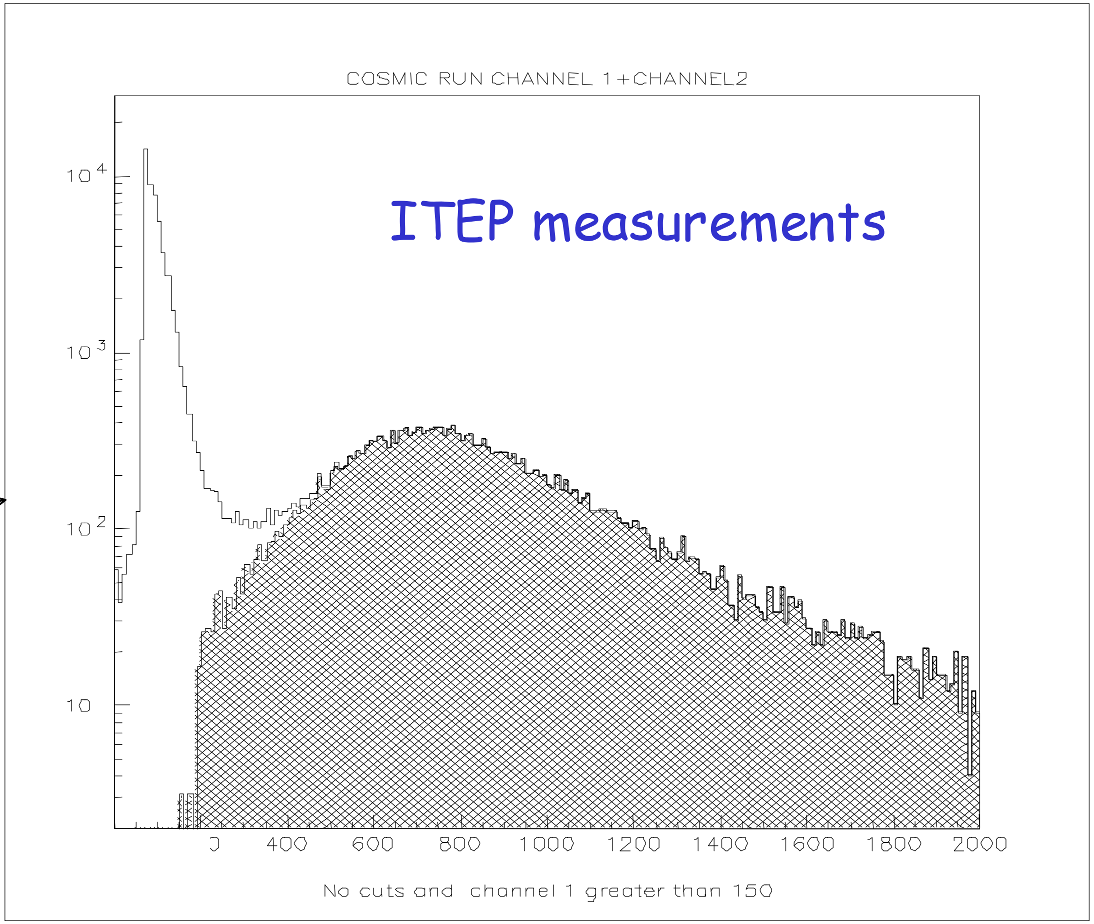
SiPM pulse hight spectra for noise pulses, n<<1


Dark rate, Hz
10^6
10^5
10^4
10^3
10^2
10^1
0
1
2
3
4
5
6
7
8
9
10
11
Threshould, ph.e
E_0=47,6
E=53B (k_{pixel}=19,7*10^5)
E=50,5B (k_{pixel}9,5*10^5)
NO CROSSTALK(Poisson)


Number of events
300
250
200
150
100
50
0
95%
MIP
efficiency
90%
25 detected
photoelectrons
50
100
150
200
250
300
350
400
450
500
550
600
Channel number
Dark rate, Hz
100
10
1
0,1
expected cosmic
ray level
50
100
150
200
250
300
350
400
450
500
550
600
Threshould, channels

SiPM: Application for muon tracking (TESLA experiment)

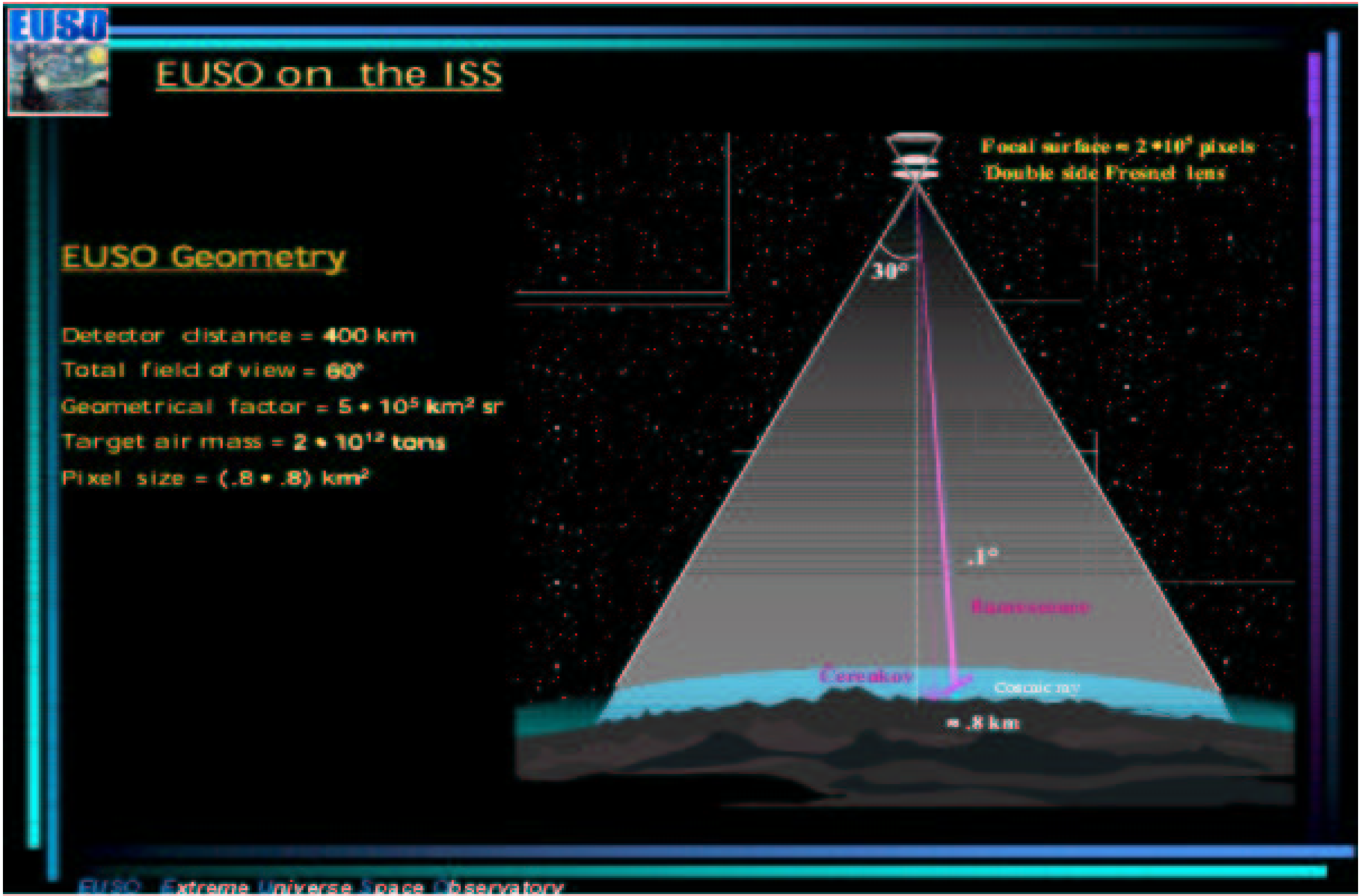




SiPM for a single photon counting: Possible application for EUSO experiment

EUSO-

E xtreme U niverse S pace O observatory



EUSO on the ISS

EUSO Geometry

Detector distance = 400 km

Total field of view = 60°

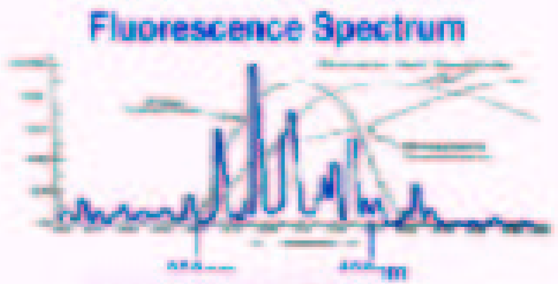
Geometrical factor = $5 \cdot 10^5$ km^2 sr

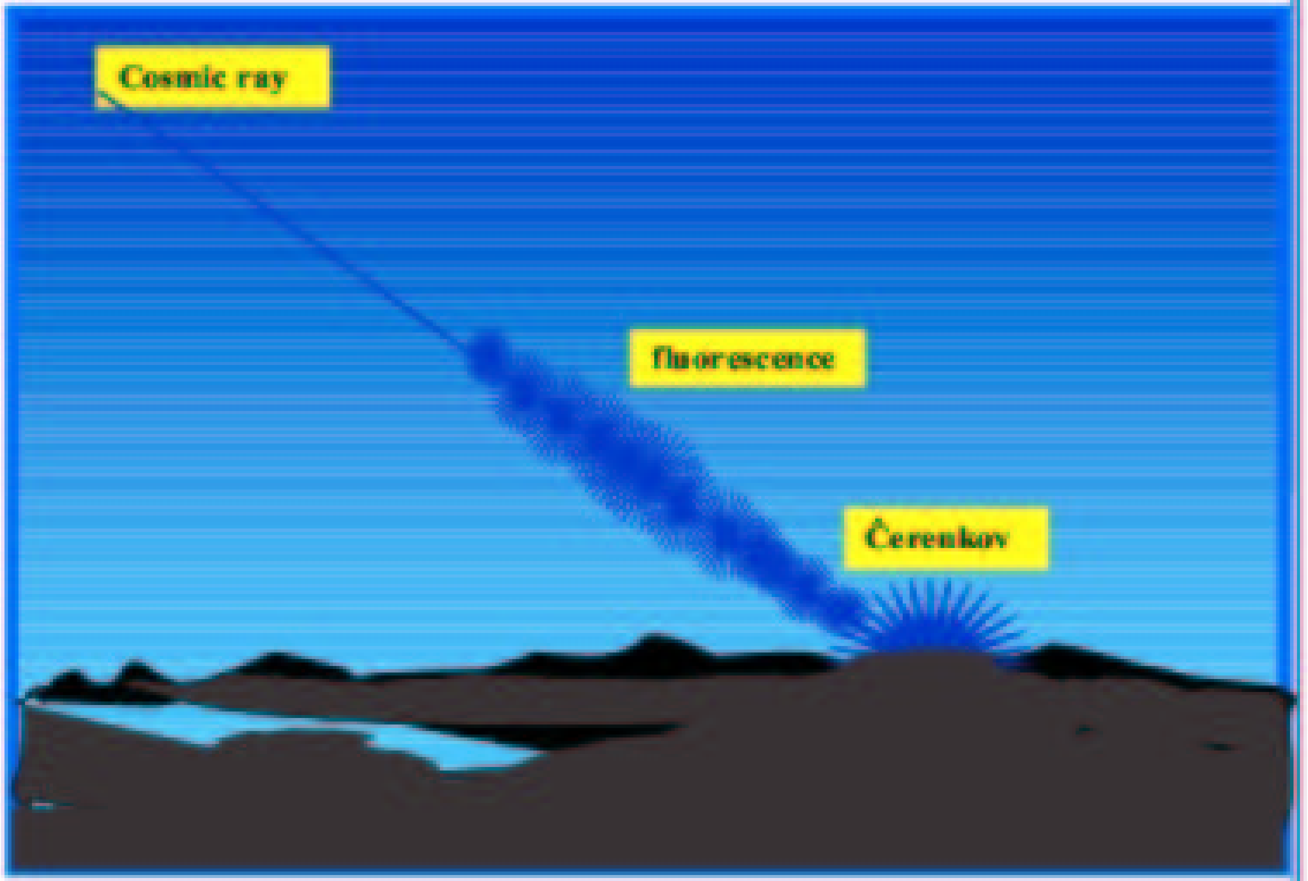
Target air mass = $2 \cdot 10^{12}$ tons

Pixel size = $(.8 \cdot .8)$ km^2

EUSO Extreme Universe Space Observatory

EUSO Approach





EUSO needs:

- 300000 Photodetectors,working in a single photon counting mode("TPC Calorimeter")
- Sensitivity in 300-400 nm range,PD eff 30-40%
- Fast(<10 ns), compact,low weight,
  low power consuming
- Size 4x4(5x5) mm

Baseline option is MAPMT's
(weght?power consumption?packing eff?QE?)

- SiPM's ?

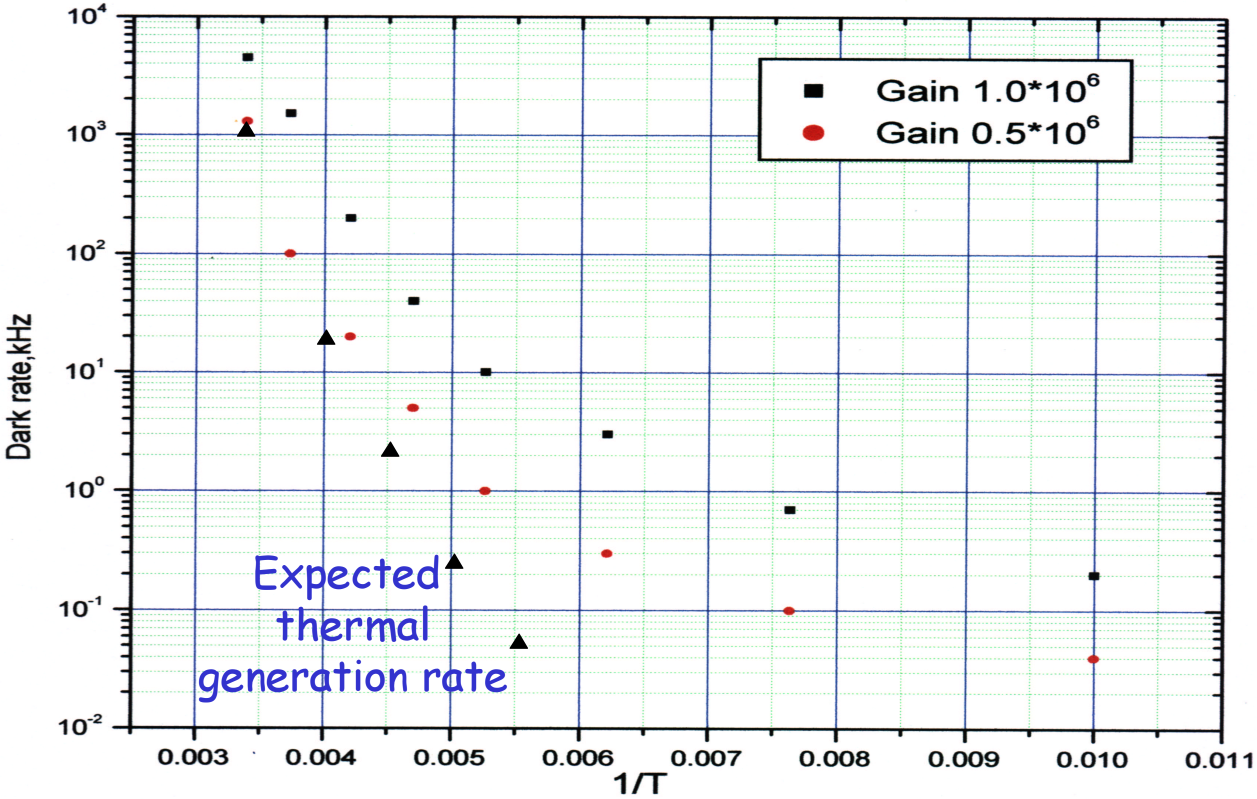
SiPM's for EUSO: limitations for today

1. Photon detection efficiency for 300-400 nm is too low(a few %)

2. Size 1x1 mm is only carefully studied

3. Single ph.e. dark rate should be less than dark sky rate(~1 MHz/5x5 mm)

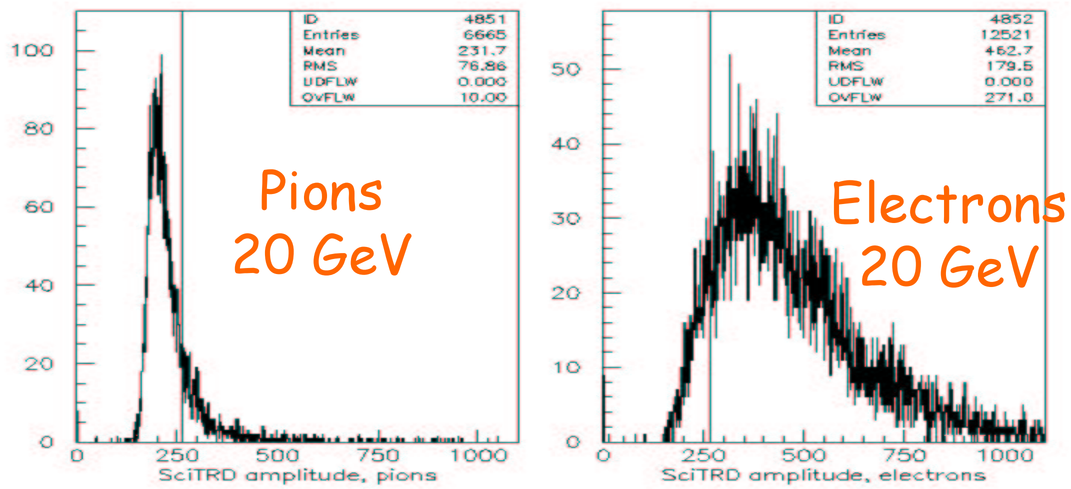
SiPM 1x1 mm^2



SiPM dark rate vs temperature for different SiPM gains

- ❑ Two components of dark rate: thermal and high electric field assisted
- ❑ Minimized expected rate for 4x4 mm SiPM is ~20MHz for room temperature
  - ➢ Working temperature ~ -30 C is needed to lower dark rate down ~300 KHz

SiPM: TRD based on thin scintillator



V.Sosnovtsev talk
SciTRD: Radiator 40 cm
+ 30 mkm CsI(Na)+PMT

Agavantages compared to Xe based TRD:

- No gas-> inportant for space experiments
- No dE/dX relativistic rise for hadrons→ better rejection power expected for 30 <E/mc< 300

Multiset radiator-detector TRD is possible only with small amount of the photodetector material → SiPM(< 0.5%X_0)

Limitation: need to have SiPM size ~5x5 mm^2

SiPM for fast single photon timing: Possible applications for a new generation of Cherenkov Imaging Detectors for High Luminosity B-factories(10^{36} $cm^{-2}s^{-1}$):

Detector of Internal Reflected Cherenkov light

DIRC

Time Of Propagation detector

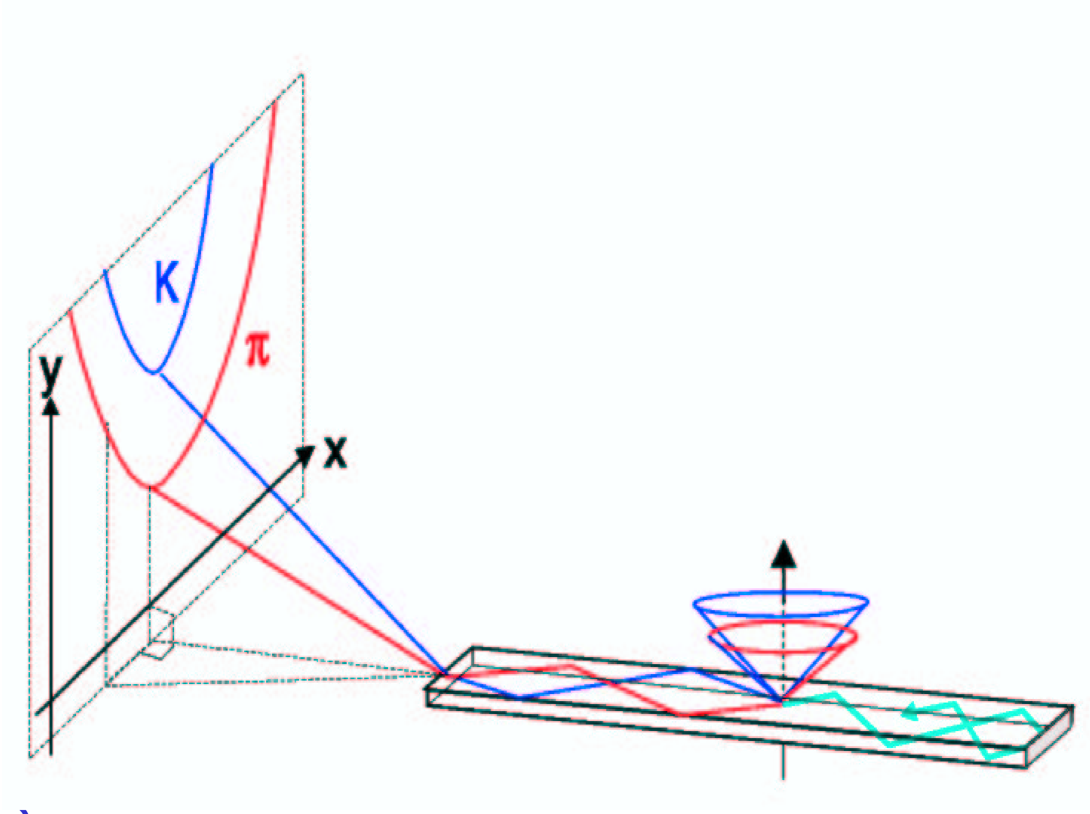
TOP

DIRC for BaBar upgrade:

Cherenkov angle is extracted from (x,y) space image

Single photon timing info:

- ☐ To reject the BG hits
- ☐ To reduce the chromatic aberrations



Requirements:

Timing~100 ps

Candidates:

MA Hamamatsu PMT H8500(138 ps)
Burle 8501 MPC PMT(54 ps)

-> low gain,non uniform response

SiPM?

SiPM for TOP counter(BELLE upgrade):

- Cherenkov angle is extracted from (x,t)space-time image of the light cone

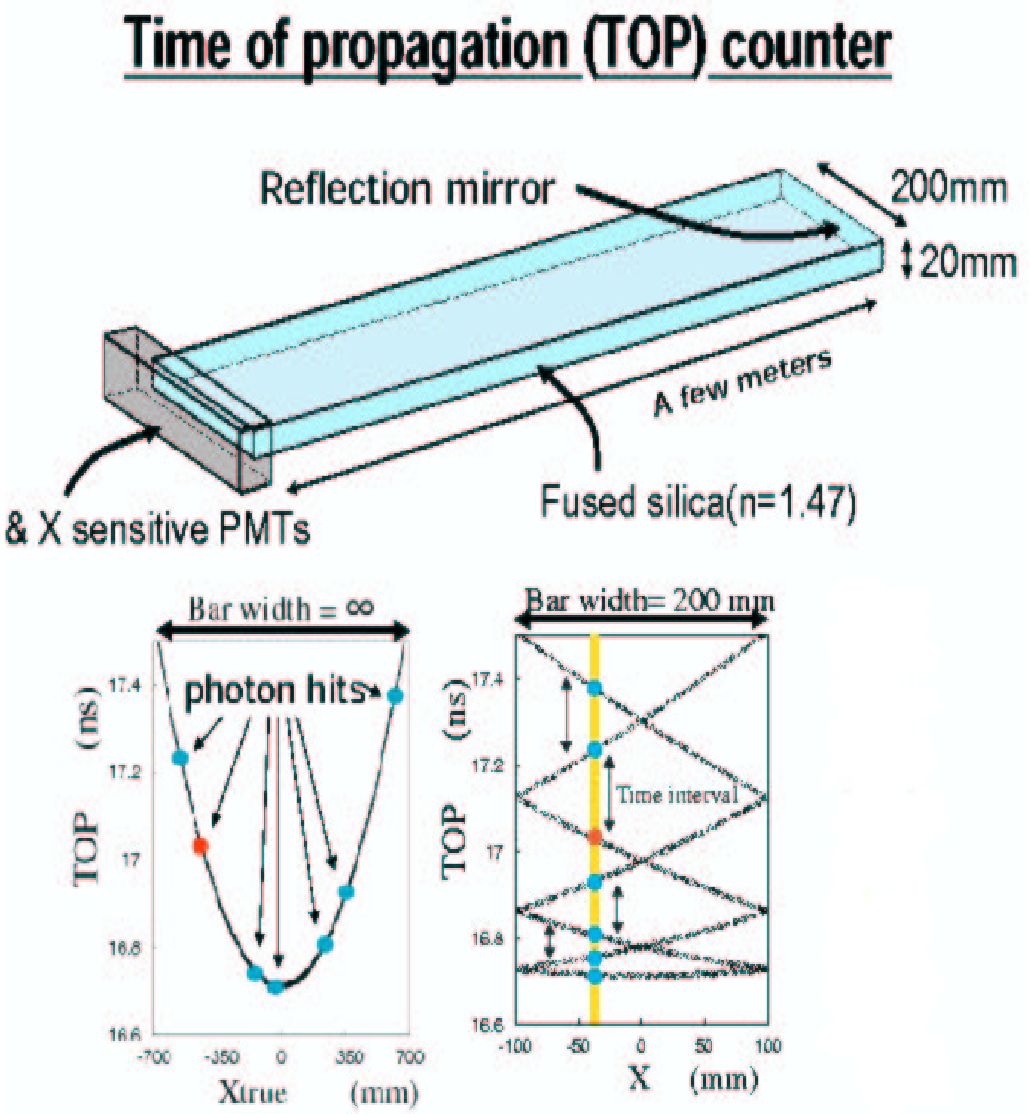
Needs:

Timing of ~50 ps

Candidate:

MCP R3809U-50,
timing 50 ps at 1.5T

SiPM?



SiPM for DIRC and TOP counters, limitations:

1. Size -> 4x4 mm^2

2. Dark rate -> < 300 KHz(temperature -> -30 C)

3. Photon detection efficiency->30% in 400-700 nm range

SiPM: Summary
of drawbacks/limitations for today

- Small size (only 1x1 mm is carefully studied)
- The photon detection efficiency is not high enough(<20%)
- High dark rate
- Optical cross-talk$_{2}$between pixels (20% for gain 10^{6})
- Limited dynamic range(1000/mm^{2})

SiPM's: perspectives of the developments

MEPhI/PULSAR(SiPM's producer) are planning to come as near as possible to SiPM parameters needed for most important applications (2004?)

Parameter	Method	Goal
Size	Better purity Si substrate, Better gettering	4x4(5x5)mm^2
Photon detection efficiency	Increase the geometrical packing efficiency, new pixel topology	30-40% for 300-700 nm
Dark rate	New pixel topology with more uniform electric field, Better purity Si substrate Better gettering	200-300 KHz/5x5mm at –30 C
Optical cross-talk	Optical isolation between pixels or reduction of single pixel gain	< 2%