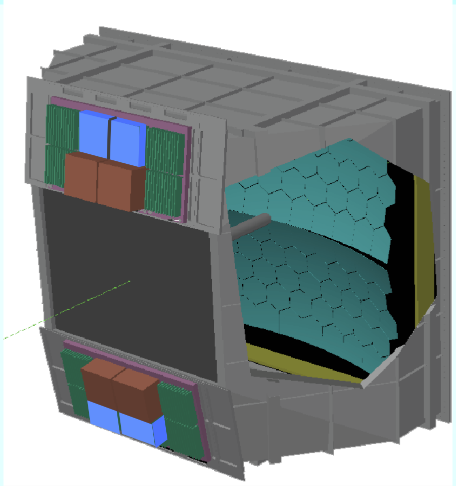
PID in COMPASS

Fulvio Tessarotto
(I.N.F.N. – Trieste)
For the COMPASS RICH Group



The COMPASS Experiment at CERN SPS

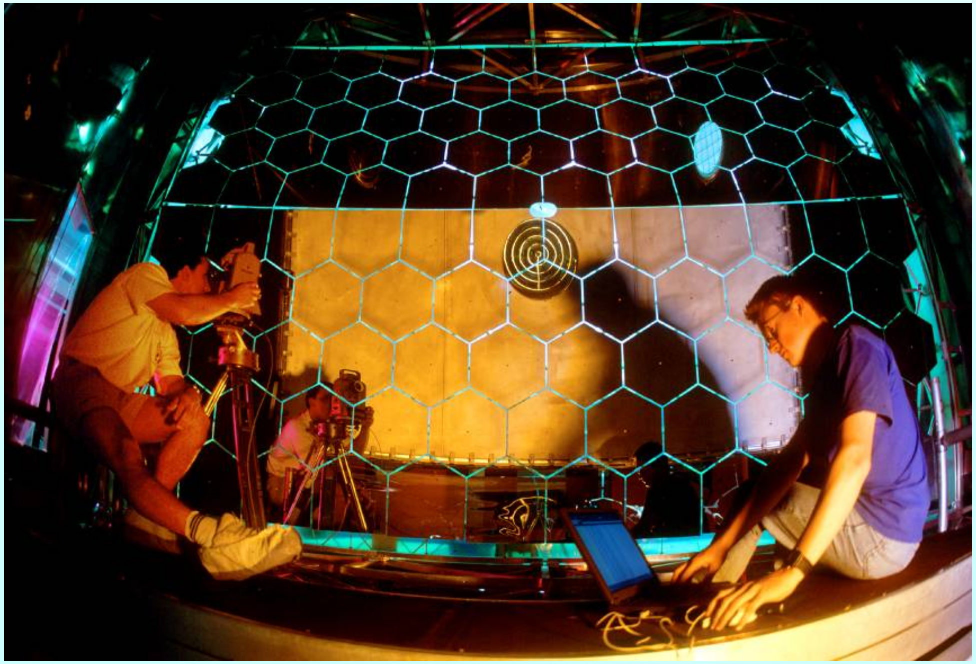
RICH-1 Vessel, radiator gas and mirrors

MWPC's with CsI photocathodes

The MAPMT based detectors

The upgrade with MPGD-based PDs

PID Performance of COMPASS RICH-1

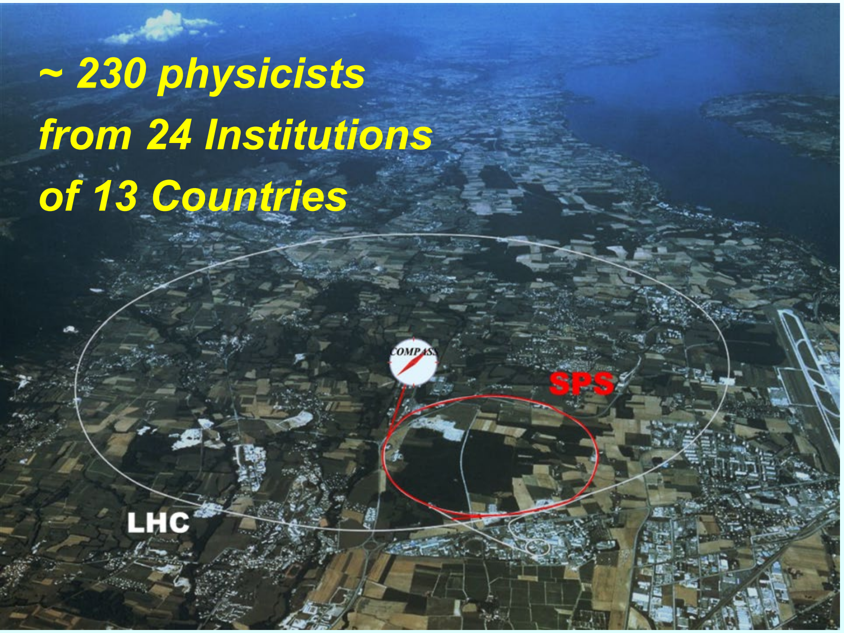


The COMPASS Collaboration

~ 230 physicists

from 24 Institutions

of 13 Countries



Дубна (LPP and LNP), Москва (INR, LPI, State University), Протвино

Warsawa (NCBJ), Warsawa (TU) Warsawa (U)

Praha (CU/CTU)
Liberec (TU)
Brno (ISI-ASCR)

Calcutta (Matriviani)

Taipei (AS)

CERN

Yamagata

Lisboa/Aveiro

Tel Aviv

Bochum, Bonn (ISKP & PI), Erlangen, Freiburg, Mainz, München TU

USA (UIUC)

Saclay

Torino (University, INFN), Trieste (University, INFN)

Experiments with muon beam:

Experiments with hadron beams:

COMPASS - I (2002 – 2011)

Spin structure, Gluon polarization
Flavor decomposition
Transversity
Transverse Momentum-dependent PDF

Pion polarizability
Diffractive and Central production
Light meson spectroscopy
Baryon spectroscopy

COMPASS - II (2012 – 2018) …

DVCS and HEMP
Unpolarized SIDIS and TMDs

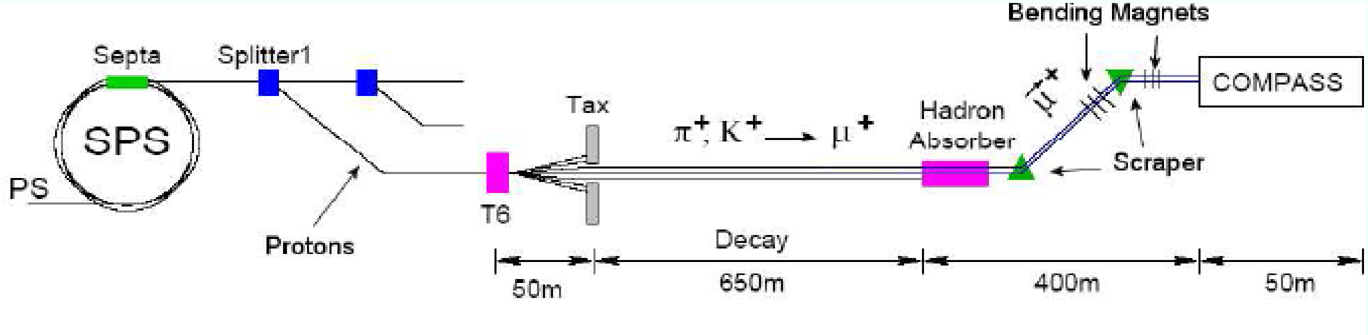
Pion and Kaon polarizabilities
Drell-Yan studies

COMPASS data taking

2002	**nucleon structure with**	**160 GeV μ**	**L&T**	**polarised deuteron target**
2003	**nucleon structure with**	**160 GeV μ**	**L&T**	**polarised deuteron target**
2004	**nucleon structure with**	**160 GeV μ**	**L&T**	**polarised deuteron target**
2005	*CERN accelerators shut down*			
2006	**nucleon structure with**	**160 GeV μ**	**L**	**polarised deuteron target**
2007	**nucleon structure with**	**160 GeV μ**	**L&T**	**polarised proton target**
2008	***hadron spectroscopy***			
2009	***hadron spectroscopy***			
2010	**nucleon structure with**	**160 GeV μ**	**T**	**polarised proton target**
2011	**nucleon structure with**	**190 GeV μ**	**L**	**polarised proton target**
2012	**Primakoff & DVCS / SIDIS test**			
2013	*CERN accelerators shut down*			
2014	Test beam Drell-Yan process with π beam and T polarised proton target			
2015	**Drell-Yan process with π beam and T polarised proton target**			
2016	**DVCS / SIDIS with μ beam and unpolarised proton target**			
2017	**DVCS / SIDIS with μ beam and unpolarised proton target**			
2018	**Drell-Yan process with π beam and T polarised proton target**			

➡ ***2021* *nucleon structure with 160 GeV μ T polarized deuteron target***

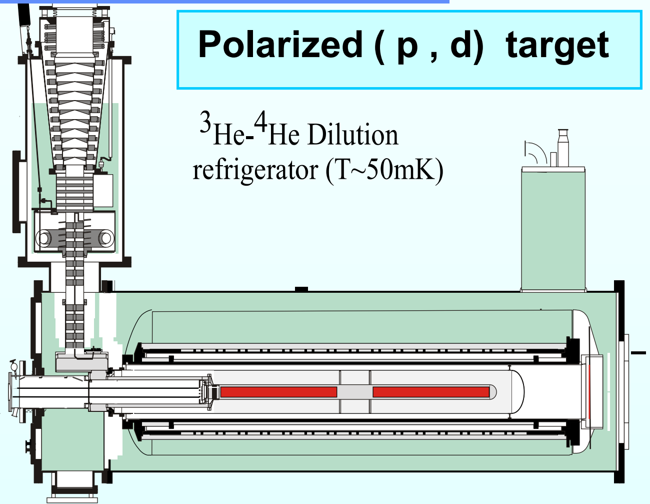
BEAM, TARGET AND SPECTROMETER



160 or 190 GeV/c μ^+ (or μ^-), $4 \cdot 10^8$ µ/spill, P_μ ~ 80%
190 GeV/c p, π^+, π^-, K^+, K^- beams

Various targets used

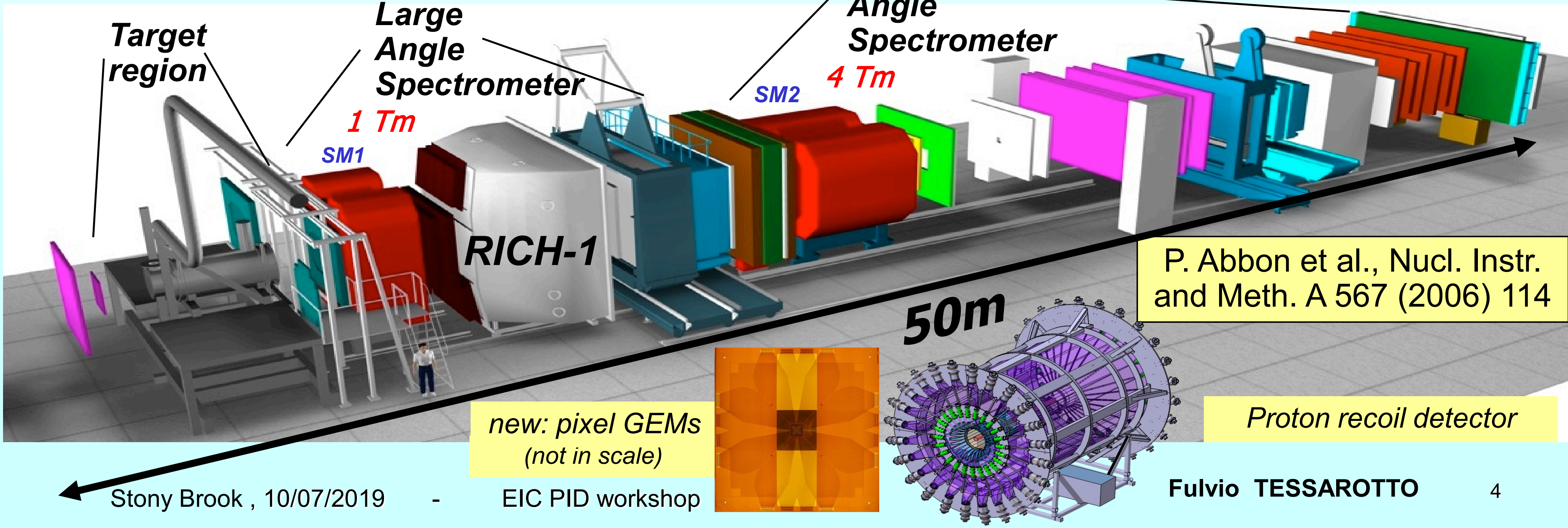
Polarized (p , d) target



^{3}He-^{4}He Dilution refrigerator (T~50mK)

first GEMs and Micromegas used in a HEP Experiment

DAQ: 40 kB, 50 kHz, O(PB)



P. Abbon et al., Nucl. Instr. and Meth. A 567 (2006) 114

new: pixel GEMs
(not in scale)

Proton recoil detector

COMPASS RICH-1

is a large gaseous RICH

providing:

hadron PID from 3 to 60 GeV/c

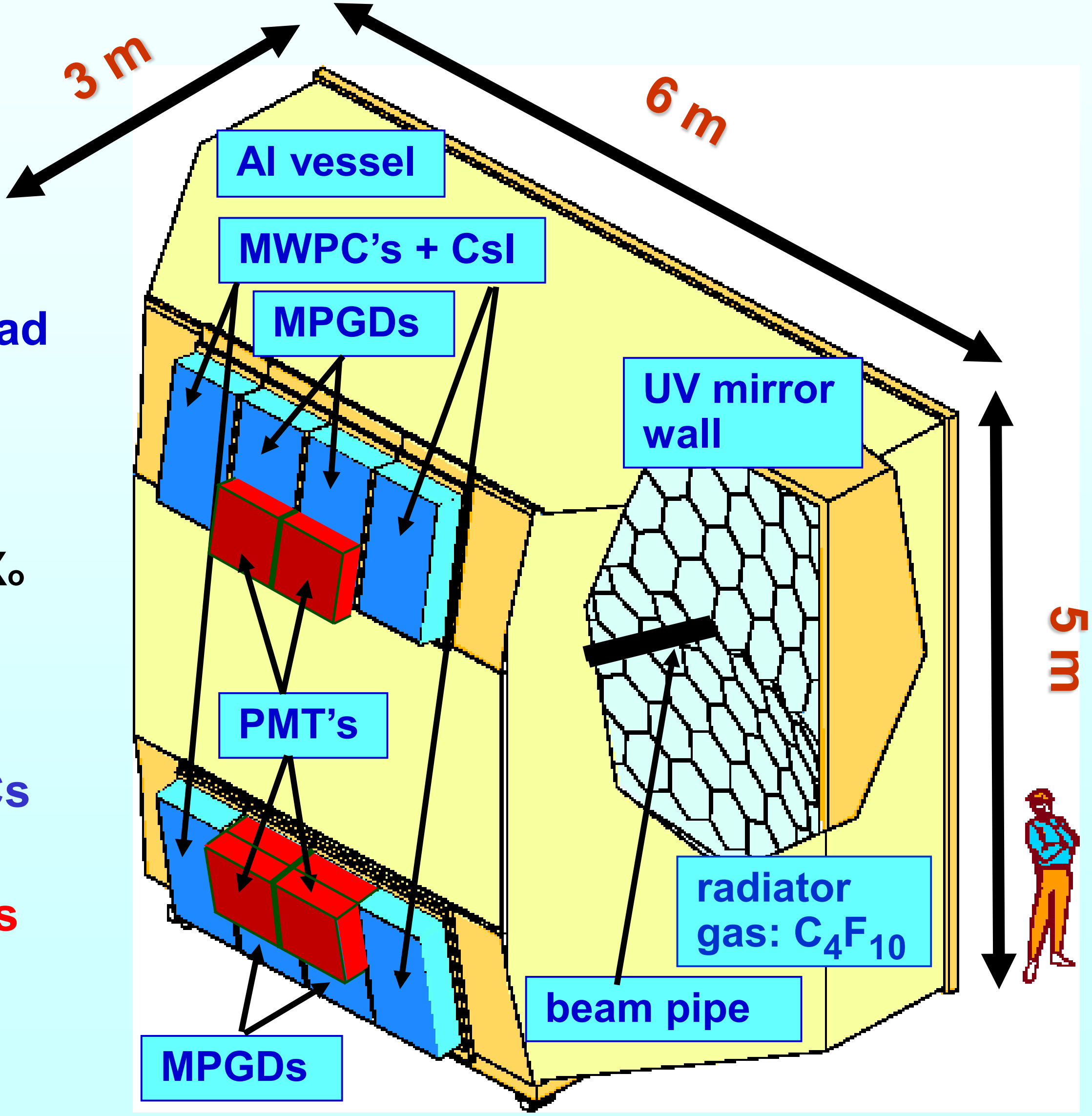
acceptance: H: 500 mrad V: 400 mrad

trigger rates: up to ~50 KHz
beam rates up to ~10^8 Hz

material in the beam region: 1.2% X_o
material in the acceptance: 22% X_o

detector designed in 1996
in operation since 2002 with MWPCs
upgraded in 2006 with MAPMTs,
in 2016 with THGEMs + Micromegas

total investment: ~ 5 M €

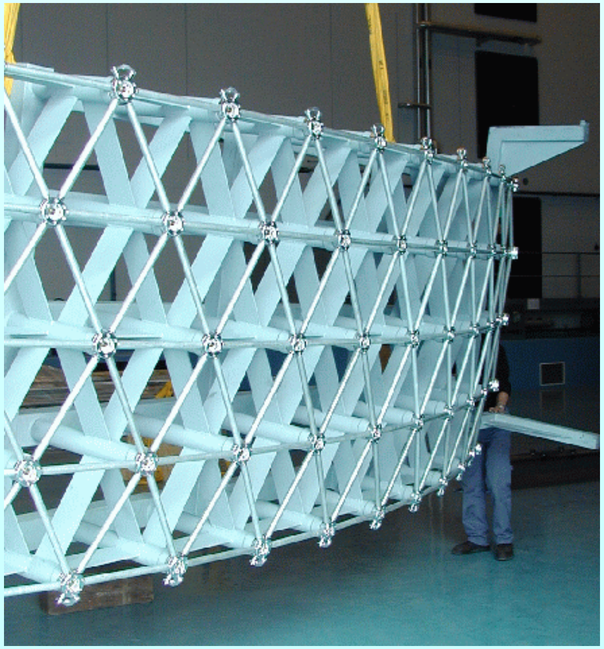


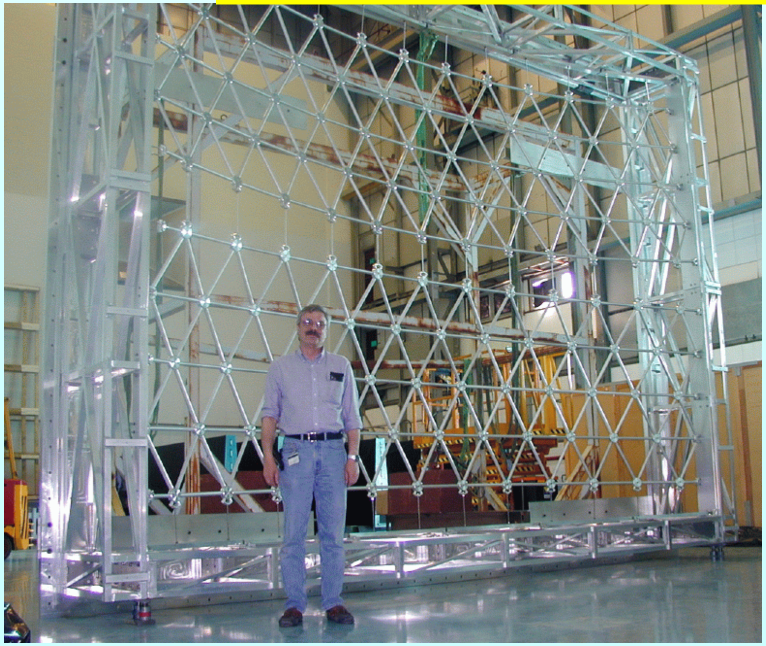
the vessel and the mirror support wall

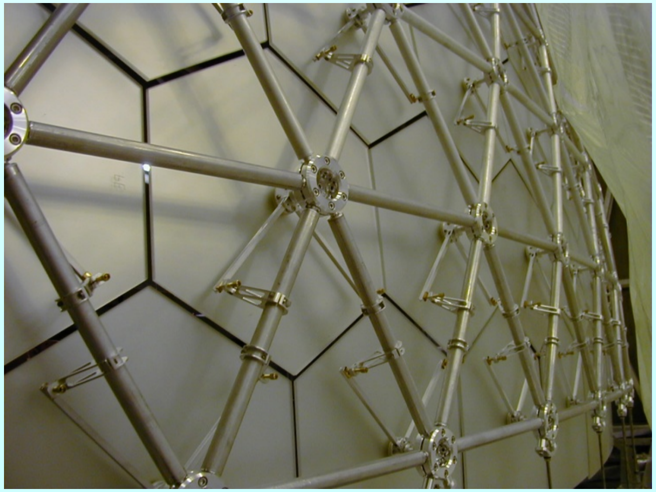
Large and accurate mechanics

light front and rear windows

100 m of O-rings, 80 m^3 C$_4$F$_{10}$

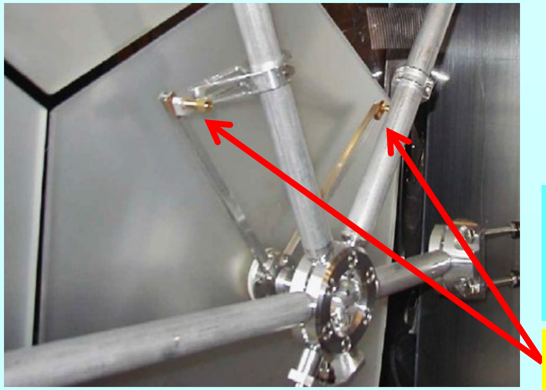


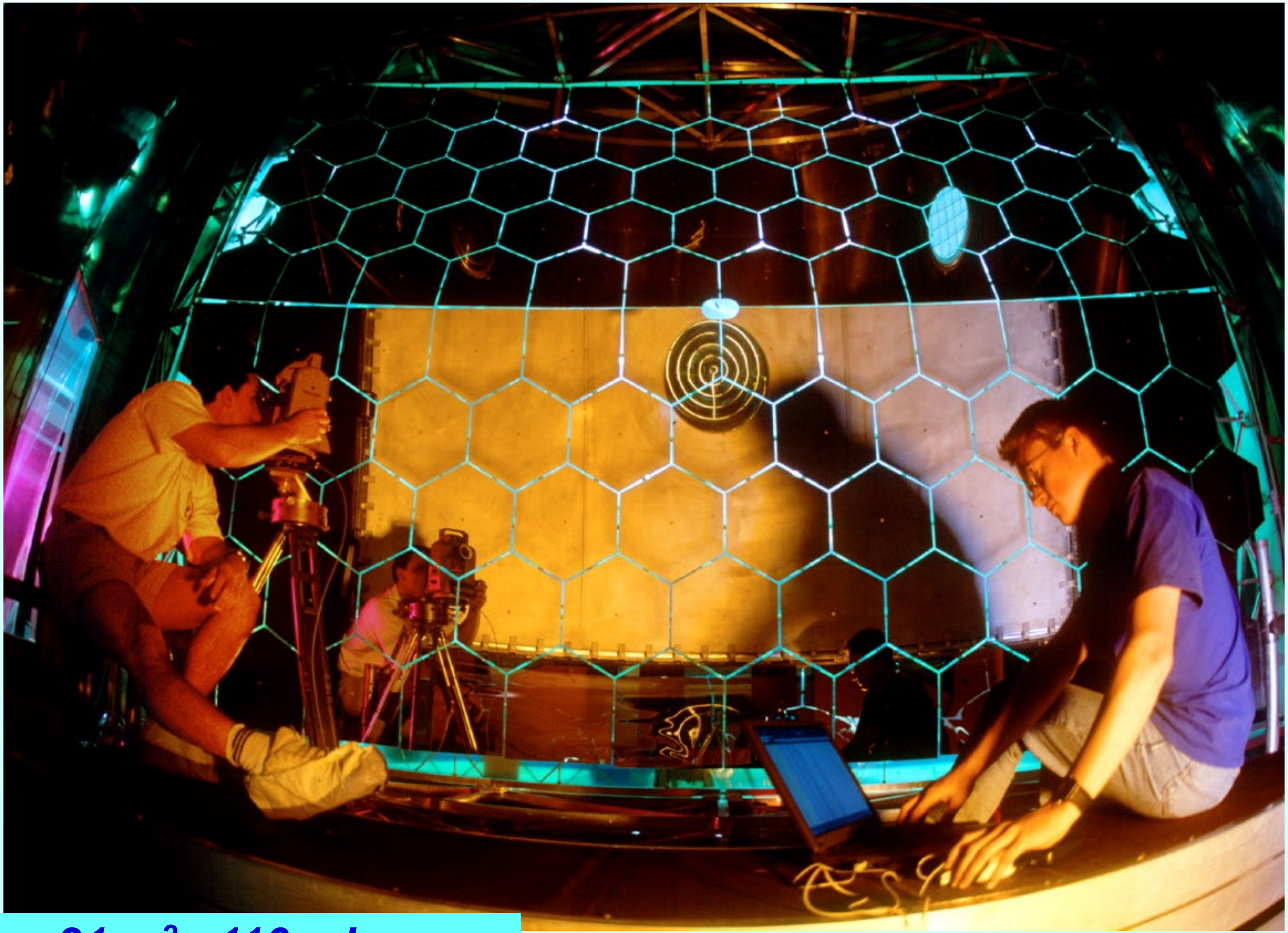




Fulvio TESSAROTTO

mirrors and alignment





21 m^2, 116 mirrors
radius: 6.6 m

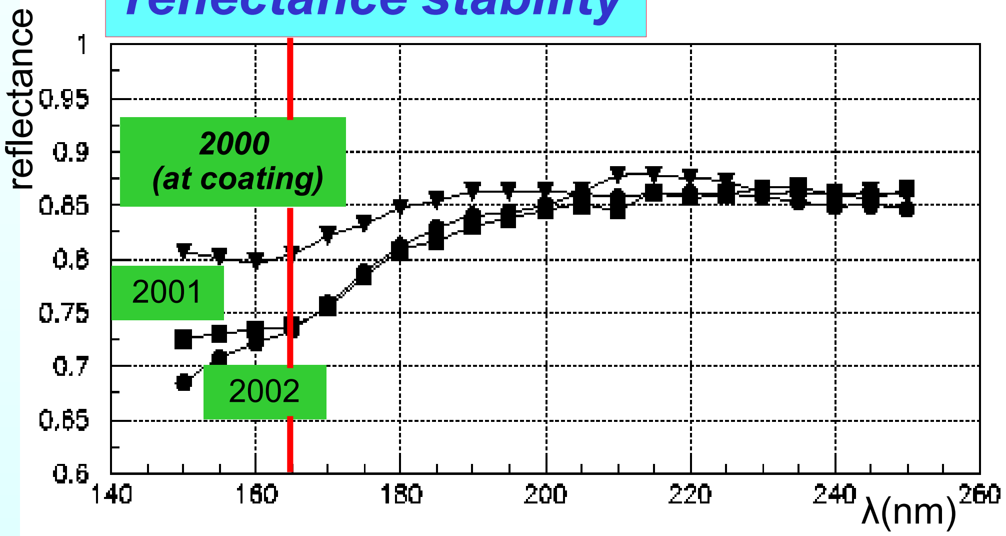
angular regulation screws

measurement of mirror alignment

via laser autocollimation

problems with mirrors

reflectance stability



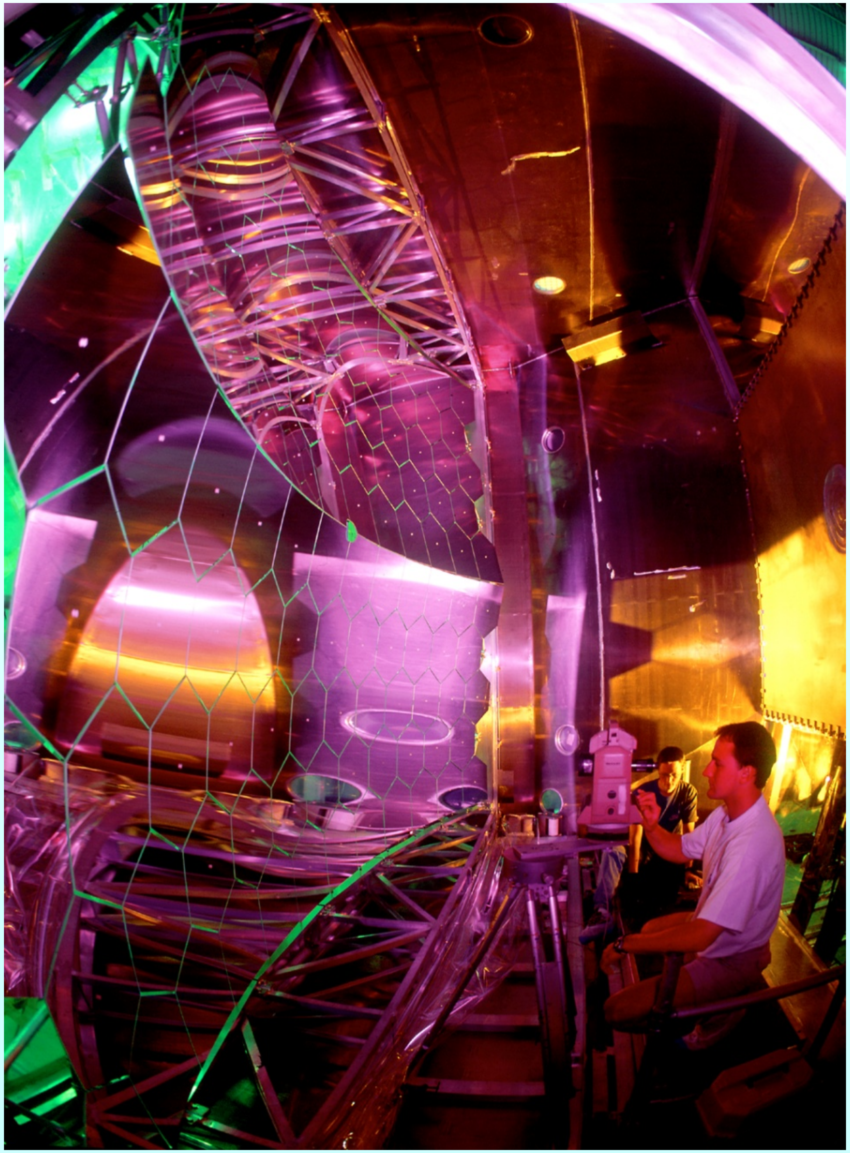
initial alignment accuracy: ~100 µrad

surveying accuracy: ~ 60 µrad

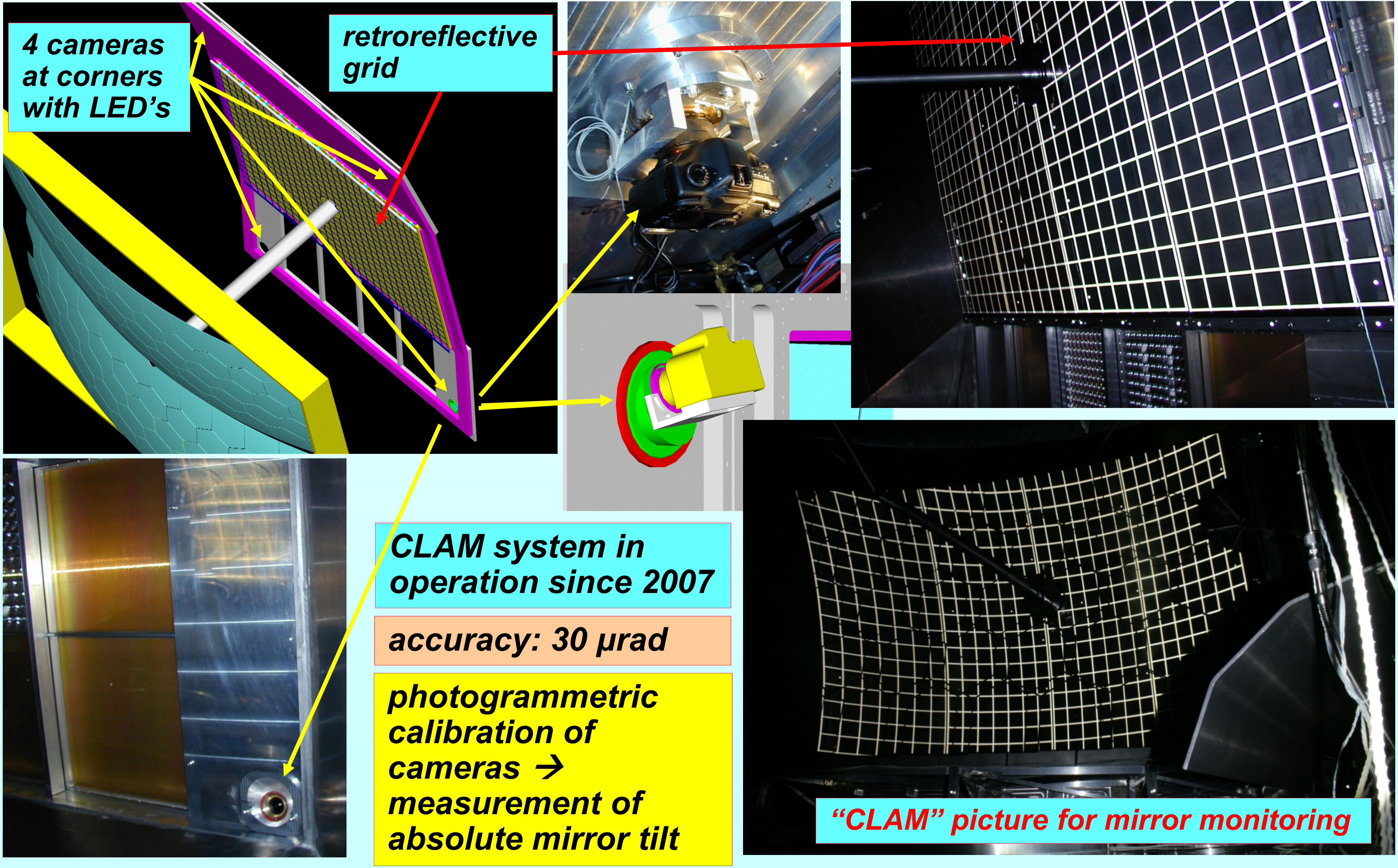
alignment instability: 1 mrad (first year)

alignment instability: ~ 100 µrad after 2002

alignment check → surveyors inside → opening the vessel: contamination, dust, risky operations, work load, expenses.



CLAM: mirror alignment monitoring



4 cameras at corners with LED's

retroreflective grid

CLAM system in operation since 2007

accuracy: 30 µrad

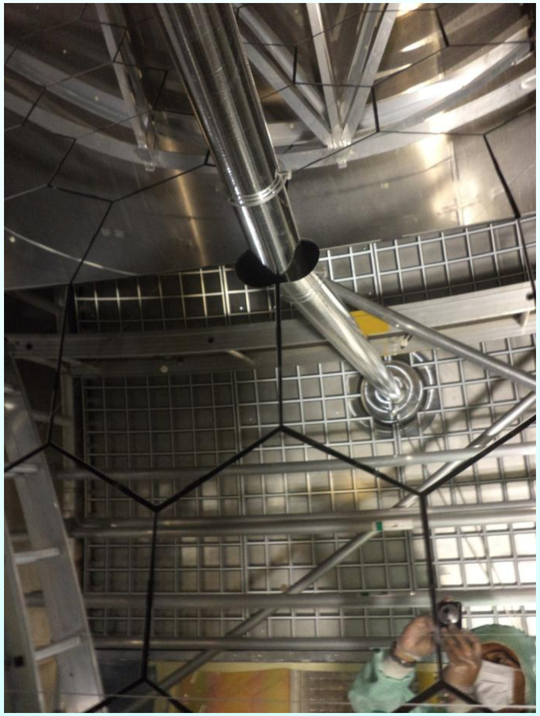
photogrammetric calibration of cameras → measurement of absolute mirror tilt

"CLAM" picture for mirror monitoring

2012: a new light beam pipe

Old: 150 µm thick stainless steel pipe: 0.85 % X_0 for orthogonal crossing

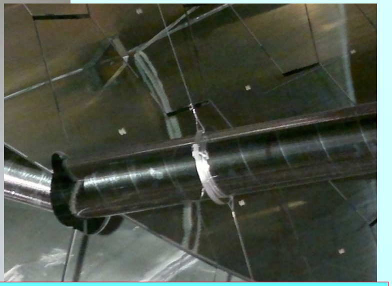
New pipe: 0.044 X_0 for orthogonal crossing

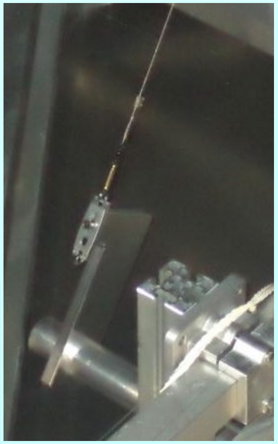


Material: 4 x 25 µm thick Mylar + 200 nm Al coating (by Sheldahl) ***winding by Lamina (6 µm glue)***

1 microflange for suspension + gas connection + window holding

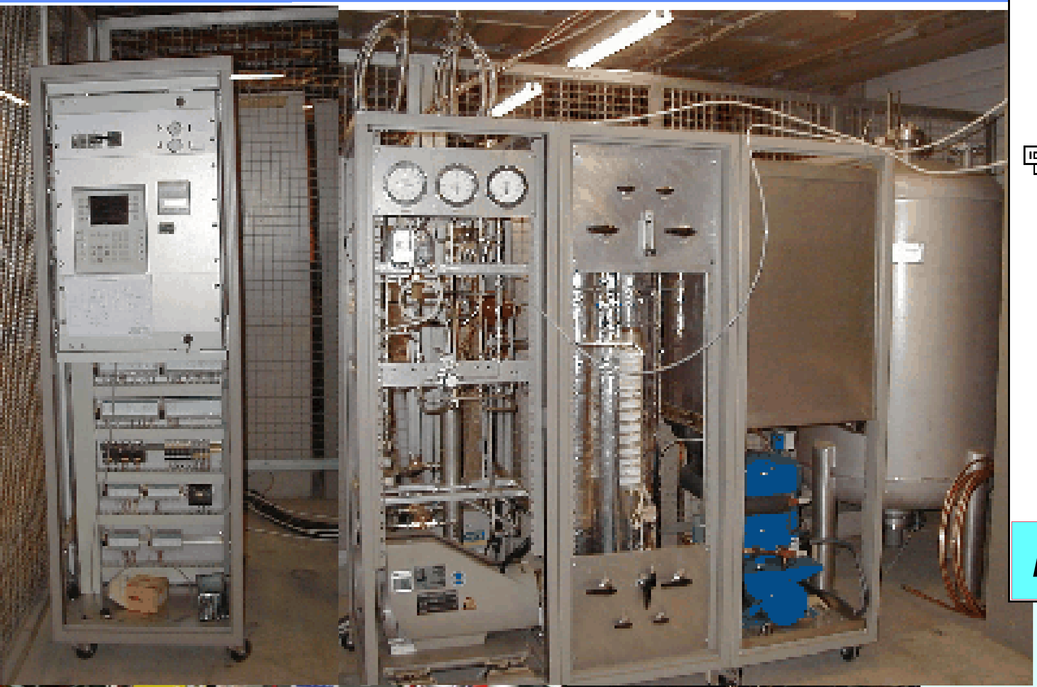
weight = 15 g

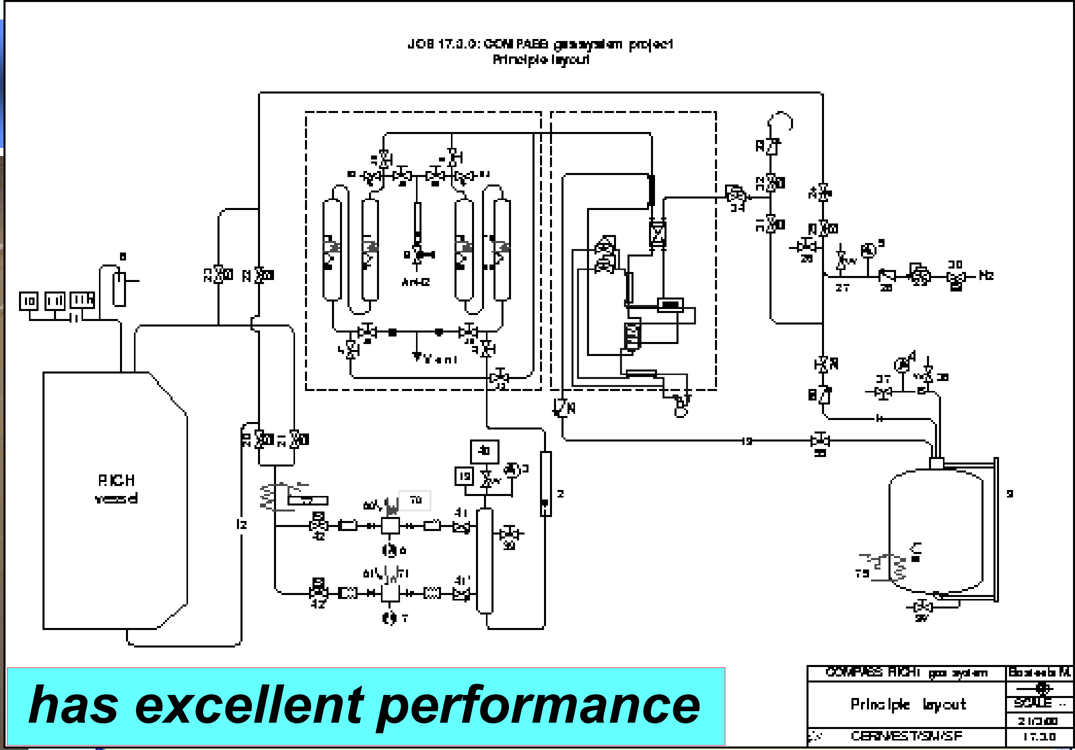




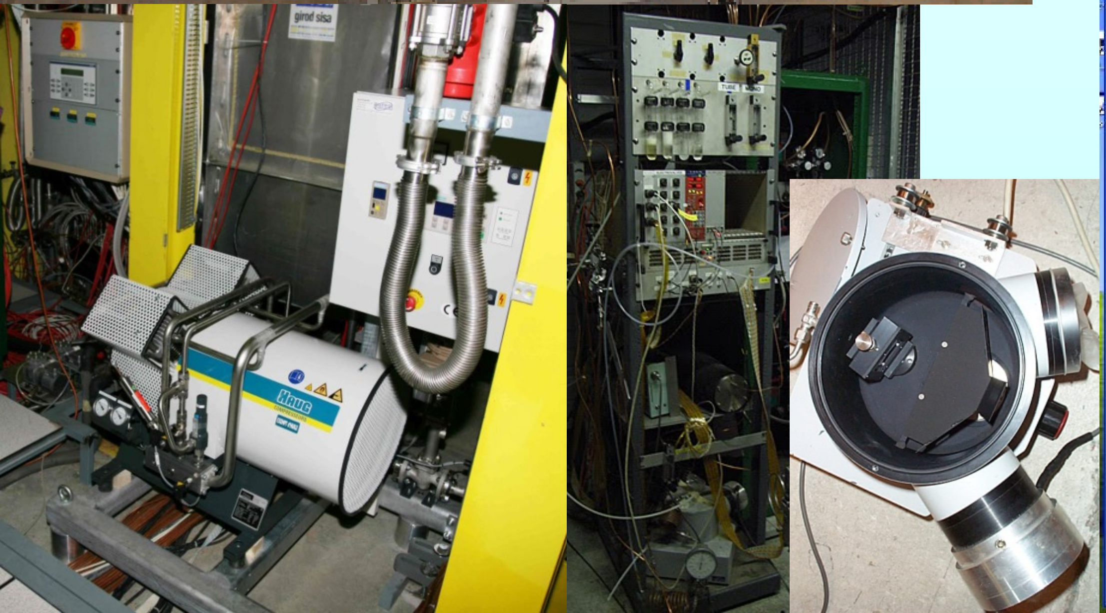
Suspension and tensioning system:
1 x 7 wires ss rope 30 µm diam.
1 microflange and 1

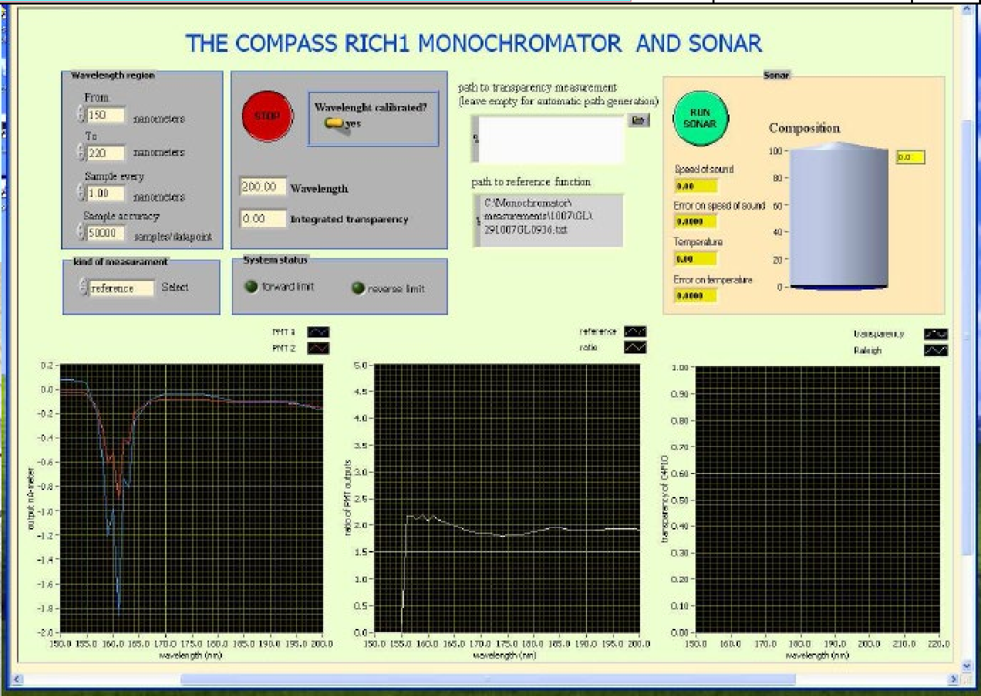
The radiator gas system





has excellent performance





THE COMPASS RICH1 MONOCHROMATOR AND SONAR

Wavelength region

From 150 nanometers

To 220 nanometers

Sample every 1.00 nanometers

Sample accuracy 50000 samples/datapoint

Wavelenght calibrated? yes

200.00 Wavelength

0.00 Integrated transparency

path to transparency measurement
(leave empty for automatic path generation)

path to reference function
C:\Monochromator\measurements\1007GL\291007GL0936.txt

kind of measurement

reference Select

System status

● forward limit ● reverse limit

Sonar

Composition 0.0

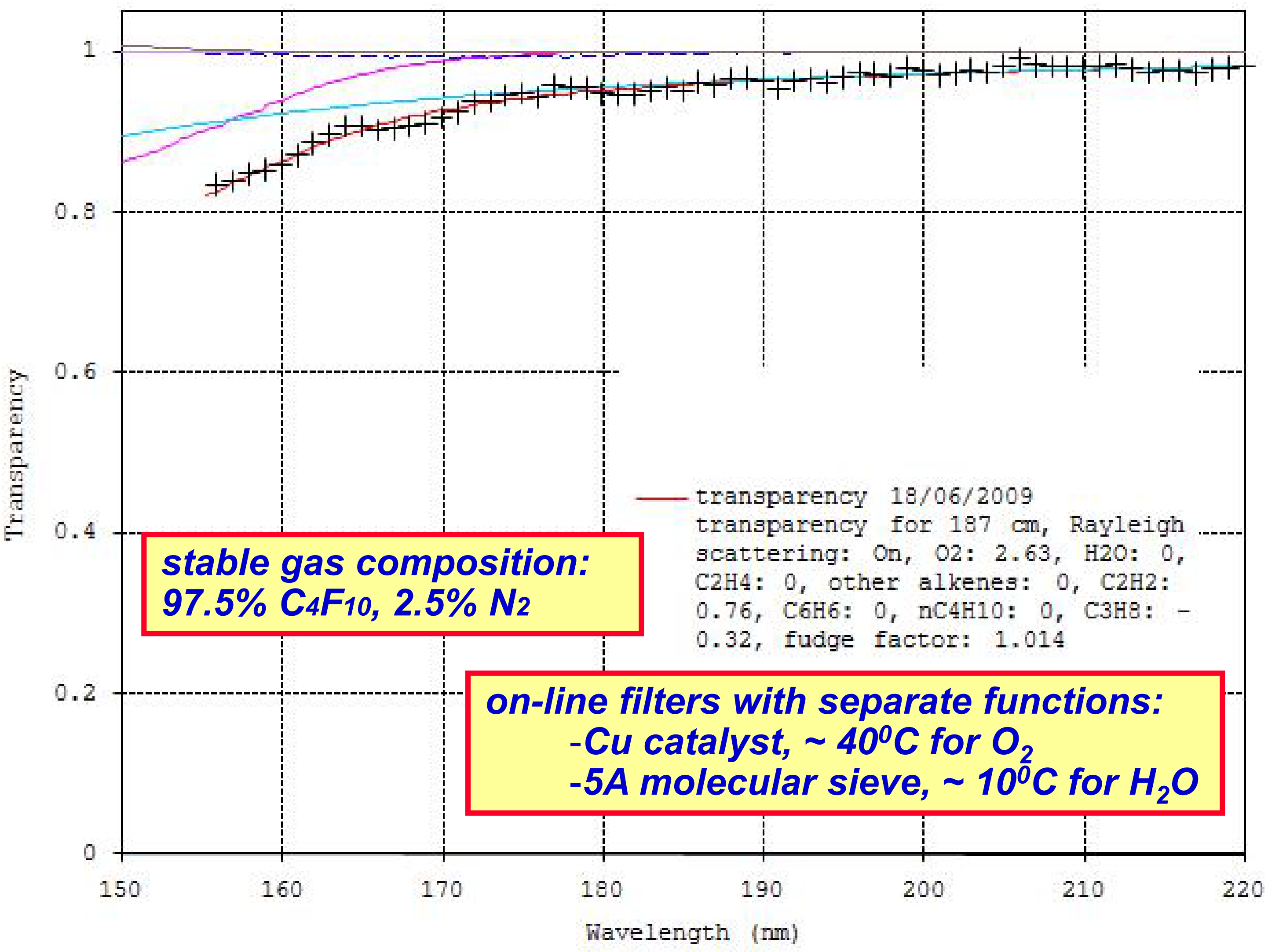
Speed of sound 0.00

Error on speed of sound 0.0000

Temperature 0.00

Error on temperature 0.0000

Typical RICH-1 C_4F_{10} transparency



stable gas composition:
97.5% C_4F_{10}, 2.5% N_2

on-line filters with separate functions:
- ***-Cu catalyst, ~ 40^{0}C for O_2***
- ***-5A molecular sieve, ~ 10^{0}C for H_2O***

Problems with the radiator gas

Buying C_4F_{10} is non trivial (out of market for years)

It comes dirty (very dirty sometimes): pre-cleaning is a must (dedicated system, unavoidable losses, expert manpower)

Inserting it into the vessel (and recovering it) is delicate, losses ~ 2%, incomplete (97.5% maximum)

Critical circulation system with feedback to keep $\Delta p < 0.1$ mbar challenged by weather

C_4F_{10} leaks out (50 l/day): refill is needed

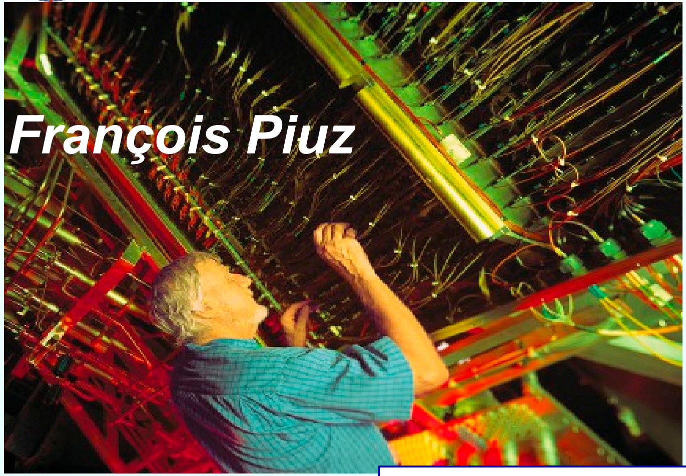
It integrates contaminants: some can be accepted (N_2, Ar), others need continuous filtering out (O_2, H_2O) ; the filters have limited capacitance (significant contaminations fill them quickly); regeneration takes several days

Monitoring the transparency is a must (dedicated system, expert manpower, significant gas consumption for each measurement)

Thermal gradients problem: → fast circulation (20 m^3/h) implemented in 2009

Accidents can become disasters; emergency intervention to be granted in short time: EXPERT ON CALL 24 h/day, 7 days/week for 7 months/year: heavy load on experts

RD26: MWPC + CsI



1992, F. Piuz et al. Development of large area advanced fast-RICH detector for particle identification at LHC operated with heavy ions

TO ACHIEVE HIGH CsI QE:

Substrate preparation:

Cu clad PCB coated by Ni (7 µm) and Au(0.5 µm), surface cleaning in ultrasonic bath, outgassing at 60 °C for 1 day

Slow deposition of 300 nm CsI film:

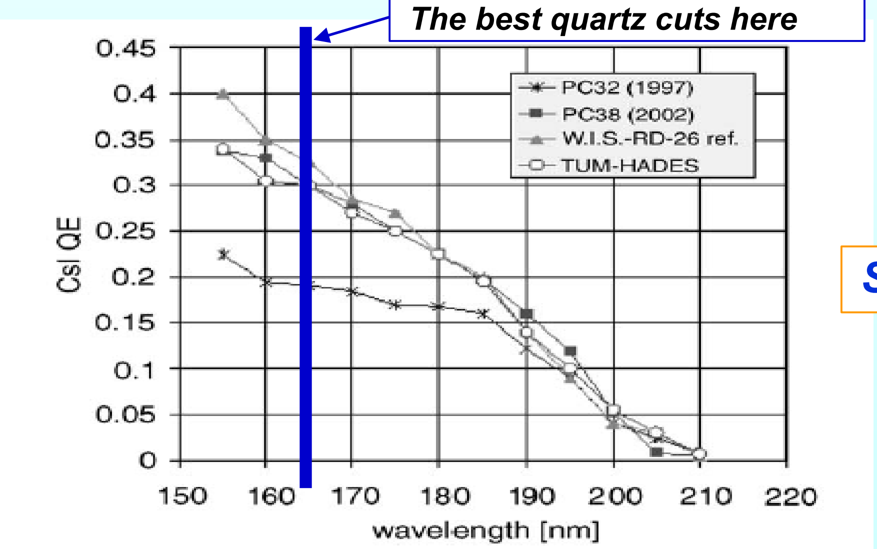
1 nm/s (by thermal evaporation or e$^-$-gun) at a vacuum of ~ 10^{-7} mbar, monitoring of residual gas composition

Thermal treatment:

after deposition at 60 °C for 8 h

Careful Handling:

measurement of PC response, encapsulation under dry Ar, mounting by glove-box.

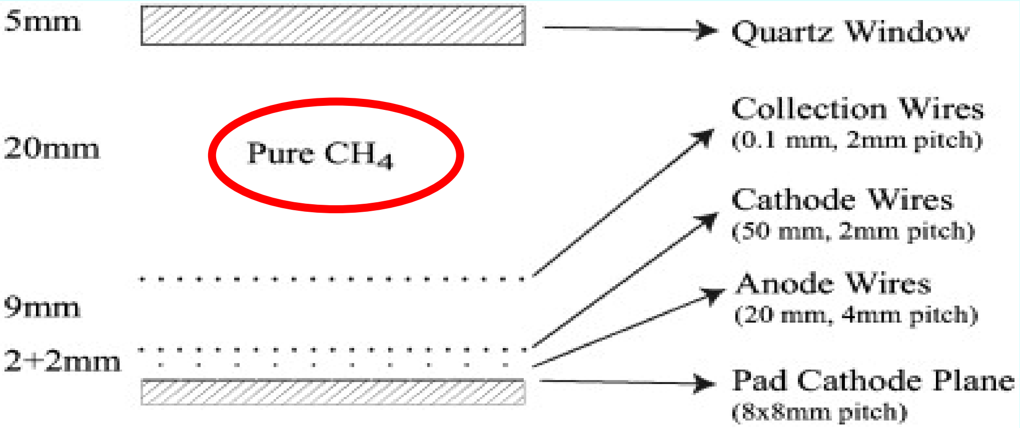


The best quartz cuts here

Fig. 1. The QE of CsI PCs produced at CERN for ALICE and at TUM for HADES, compared to that measured at the W.I.S. on small samples (reference for RD-26). PC32 is one of the four PCs equipping the ALICE-RICH prototype used in STAR at BNL.

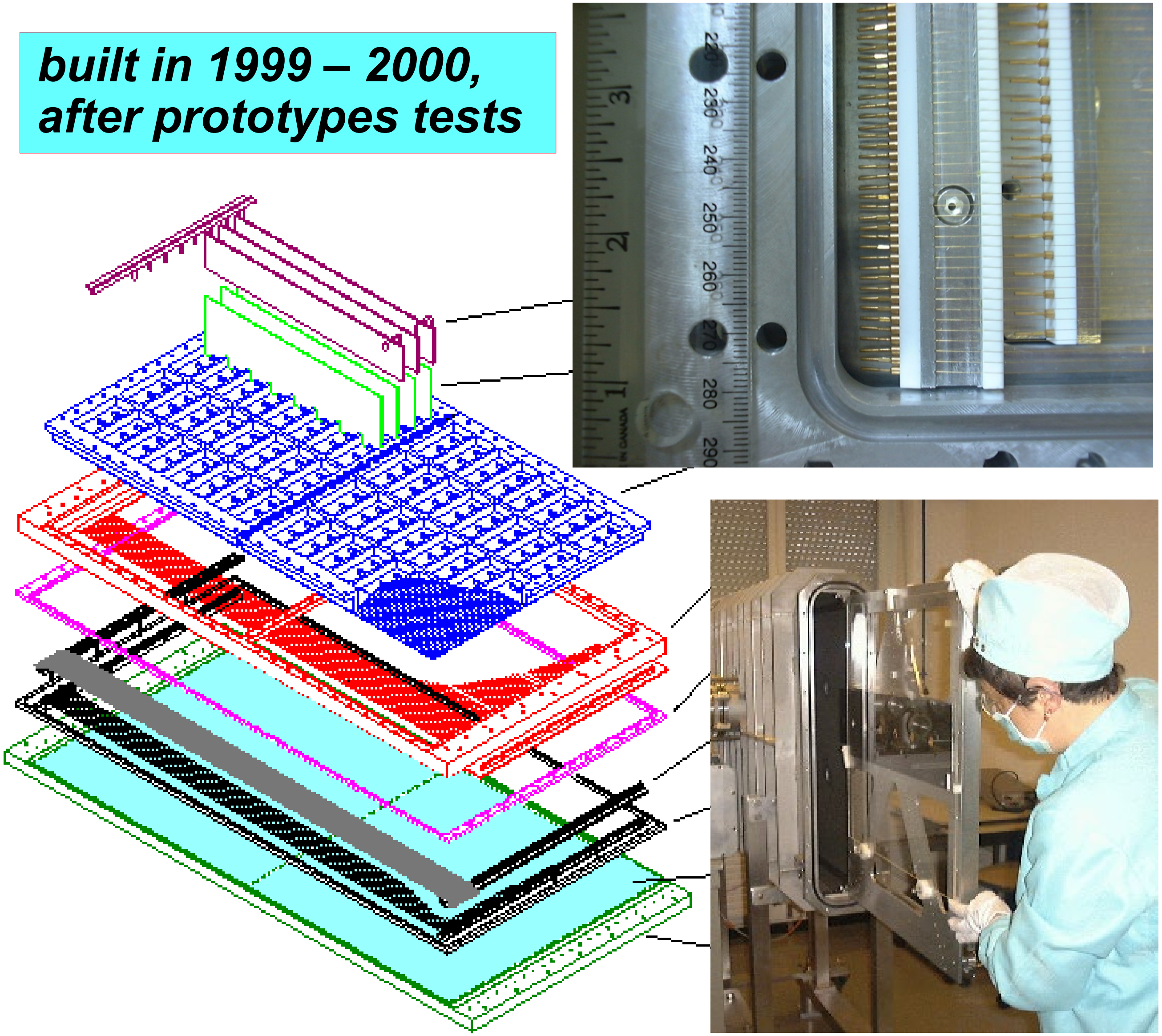
A. Di Mauro, NIM A 525 (2004) 173.

Schematic structure of the COMPASS Photon Detector:

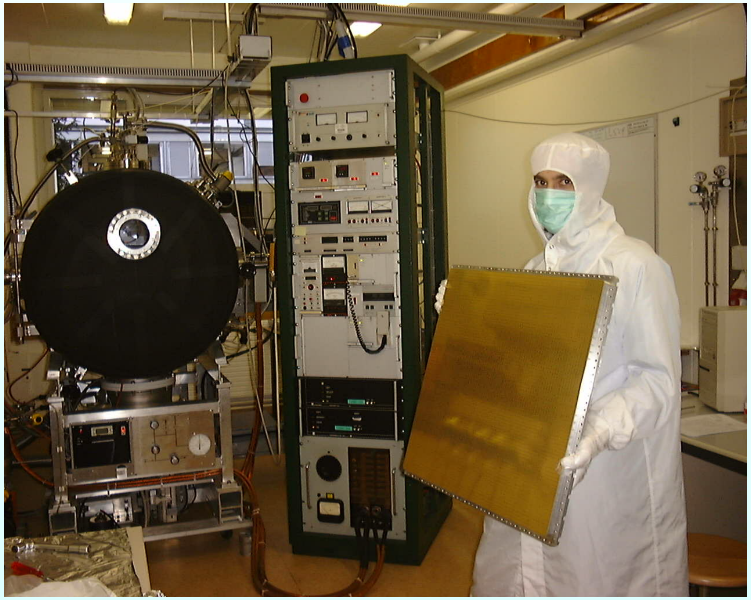


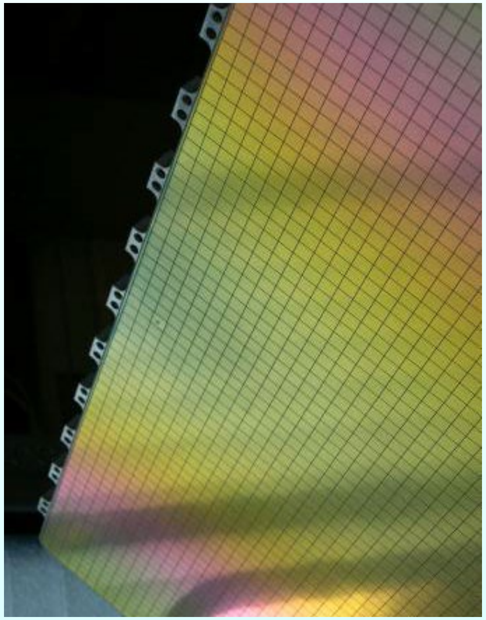
COMPASS: 8 MWPC's with CsI

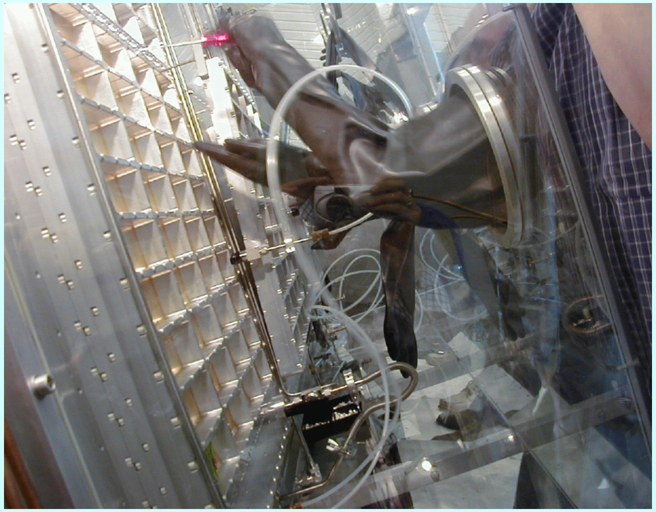
built in 1999 – 2000, after prototypes tests

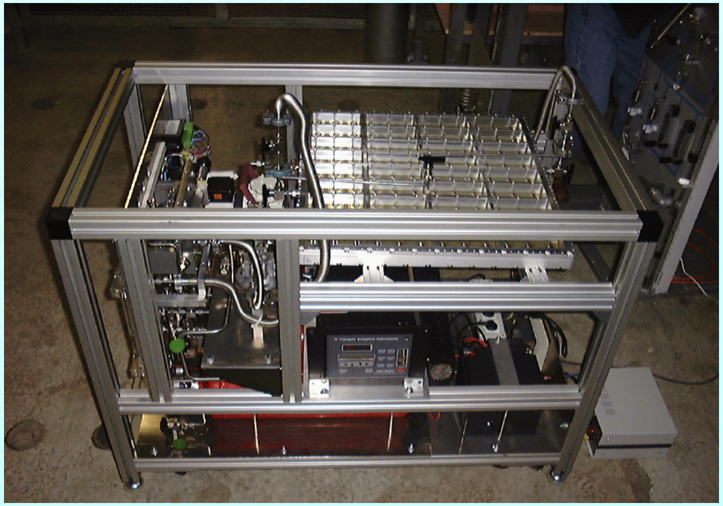


The CsI photocathodes





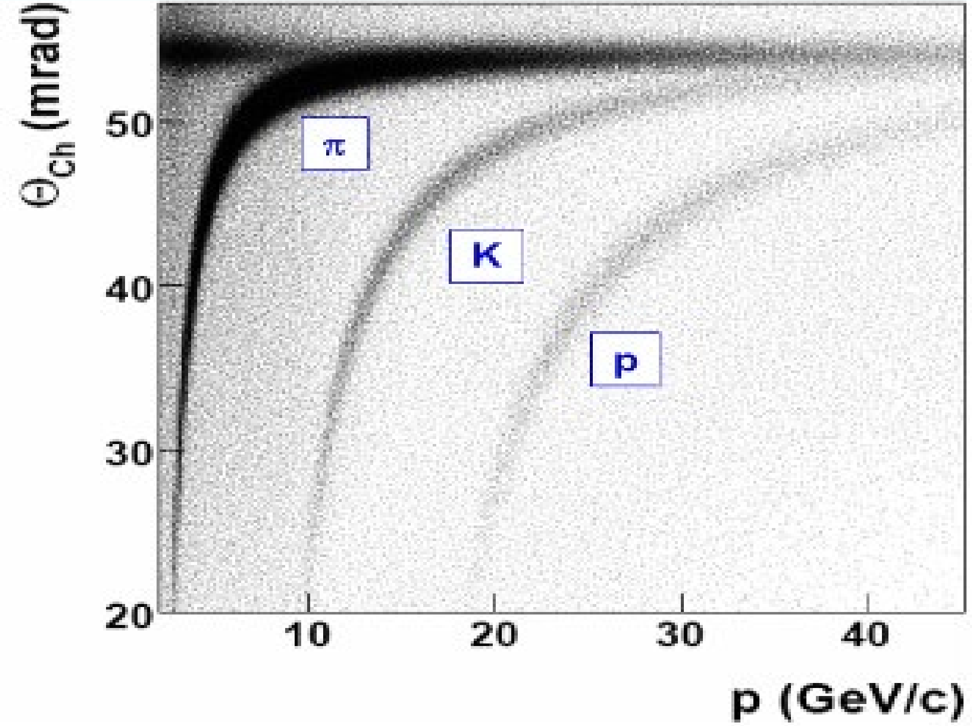




Good performance in low gain configuration

- *photons / ring ($\beta \approx 1$):* ***~10***
- $\sigma_{\theta\text{-}ph}$: ***~1.4 mrad***
- σ_{ring} : ***~0.6 mrad***
- *2σ π - K separation @* ***40 GeV/c***
- *PID efficiency* ***> 90%*** *for θ_{Ch} > 30 mrad*

except for the forward region



After a long fight for increasing electrical stability at high m.i.p. rates and systematic studies at the CERN GIF we came to the same conclusion as Ypsilantis and Seguinot:

J. Seguinot et al., NIM A 371 (1996), 64:

CsI-MWPC with 0.5 mm gap to minimize ion collection time, fast front-end electronics (20 ns int. time):

stable operation is not possible at 10^5 gain because of photon feedback, space charge and sparks

limits of MWPC's with CsI in COMPASS

1) **MWPCs with CsI photocathodes in COMPASS:**

beam off: stable operation up to > 2300 V

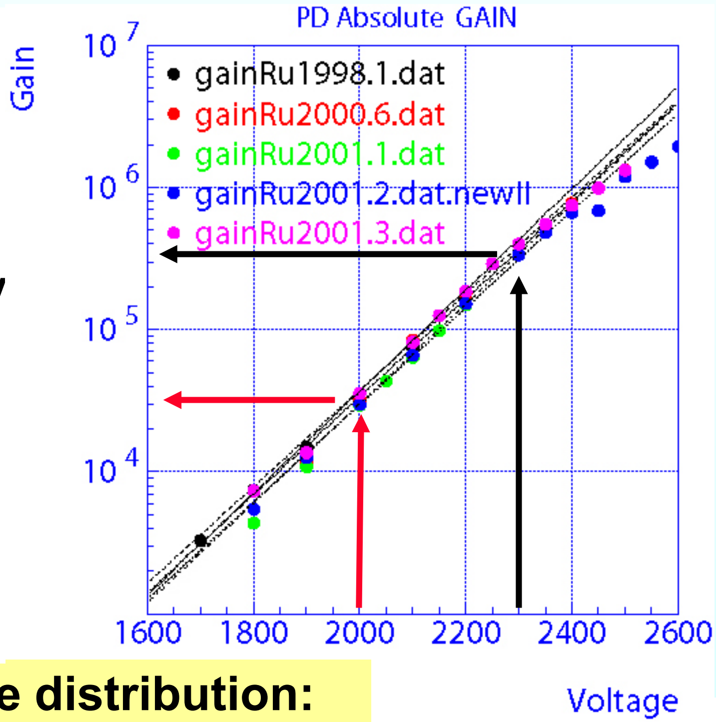
beam on: stable operation only up to ~2000 V

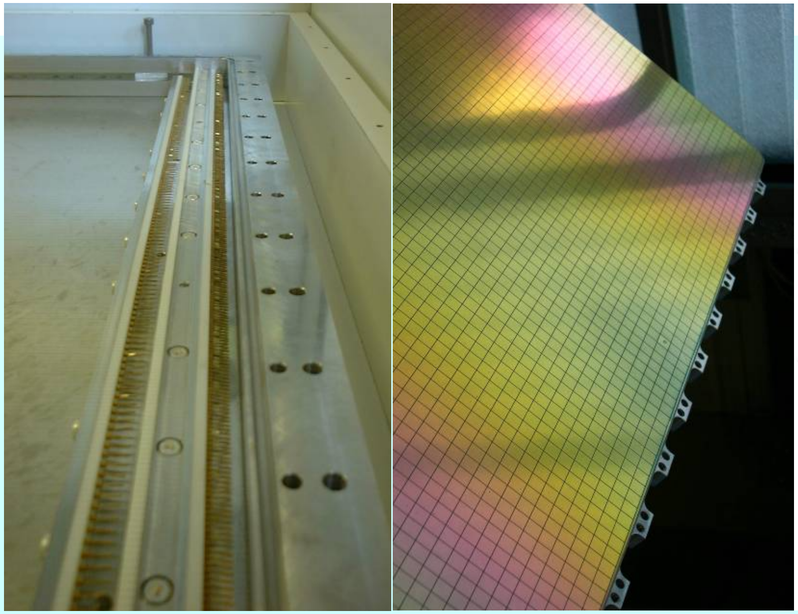
(in spill→ ph. flux: 0 - 50 kHz/cm^2 , mip flux: ~1 kHz/cm^2)

Whenever a severe discharge happens, recovery takes ~1 day

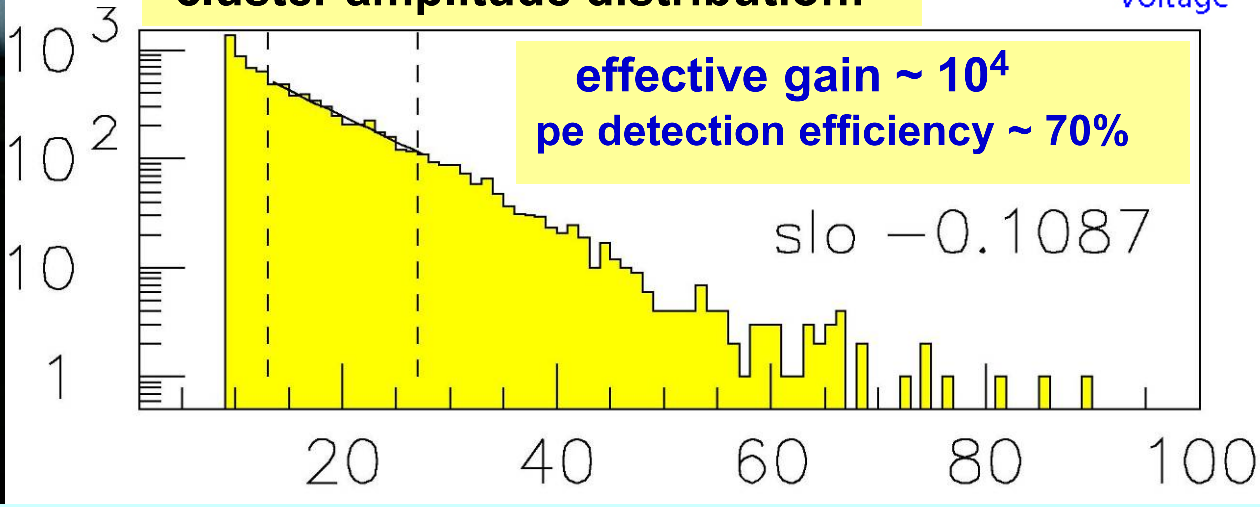
2) **Photocathode aging:**

- **our information from accidental contamination**
- **very detailed study by Alice team**





cluster amplitude distribution:



effective gain ~ 10^4

pe detection efficiency ~ 70%

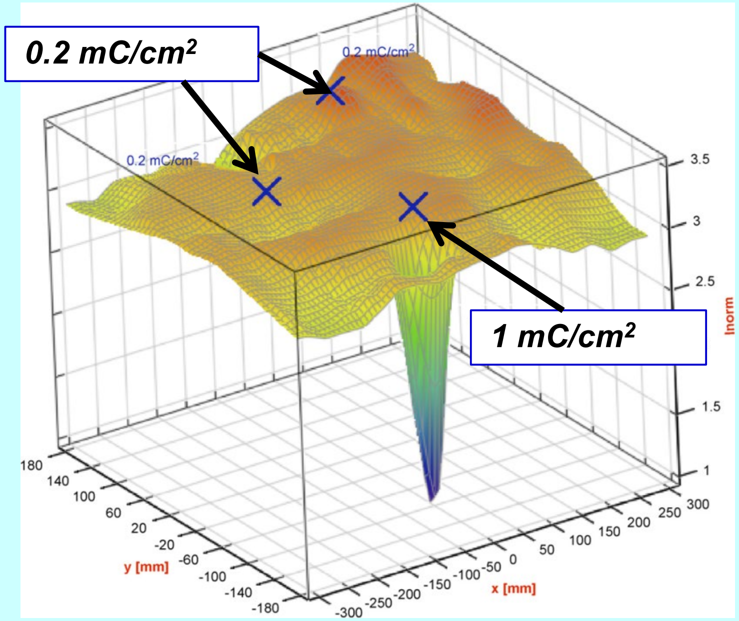
the central region before 2006

THE EXPERIMENTAL ENVIRONMENT

huge uncorrelated background related to the memory of the MWPCs + read-out

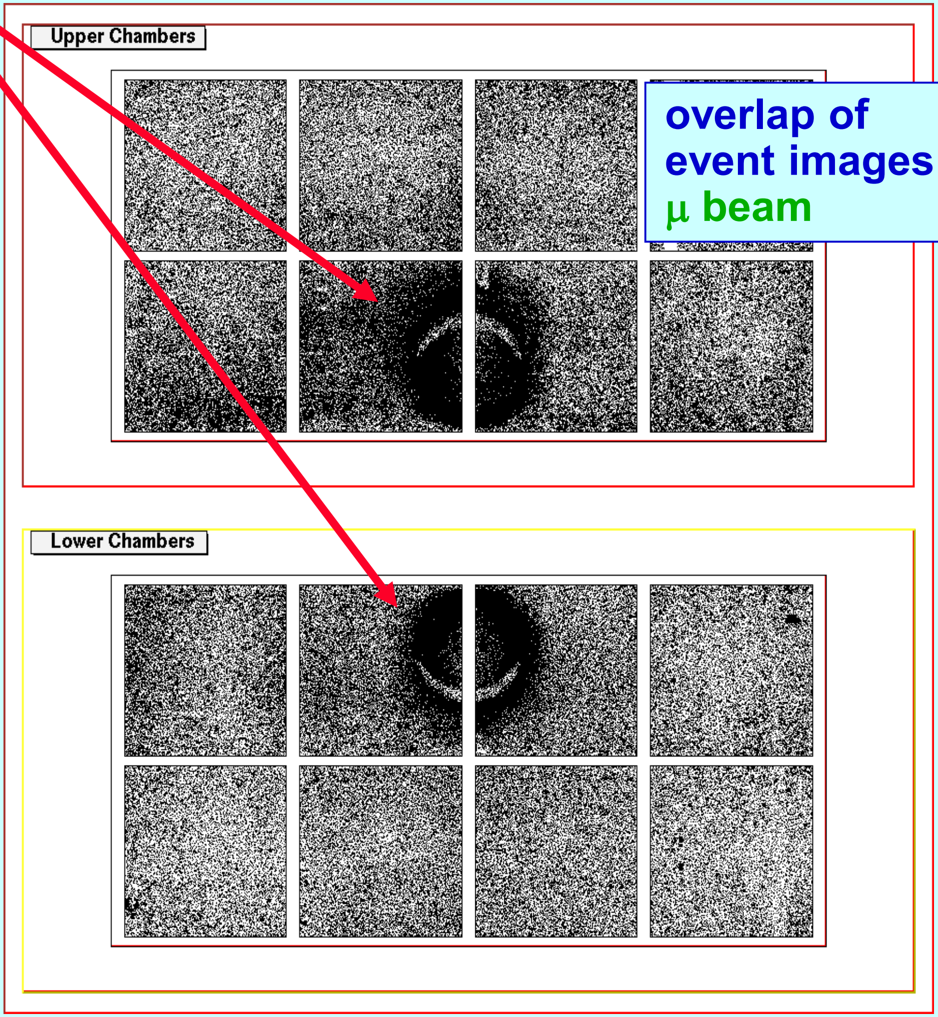
Accelerated ageing test

H. Hoedlmoser et al., NIM A 574 (2007) 28.



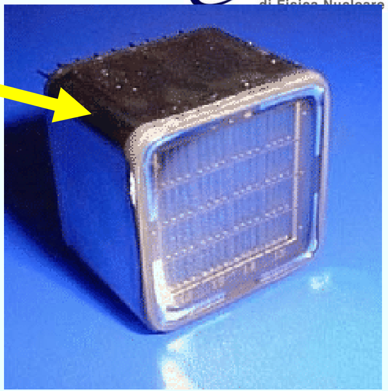
0.2 mC/cm^2

1 mC/cm^2



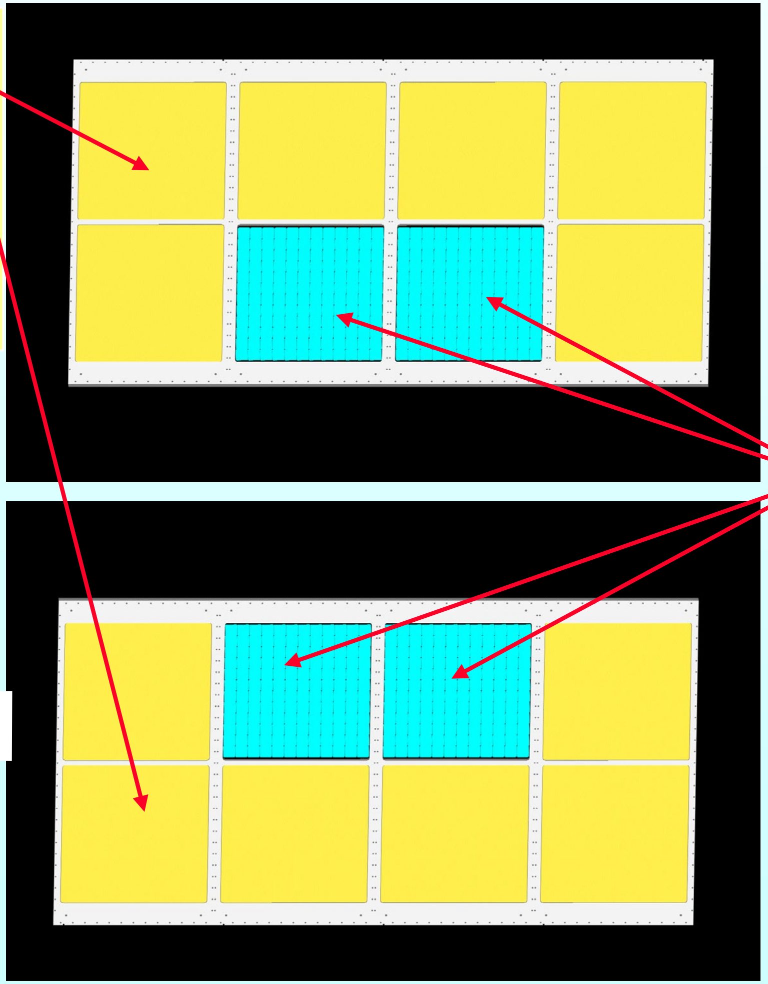
overlap of event images
μ beam

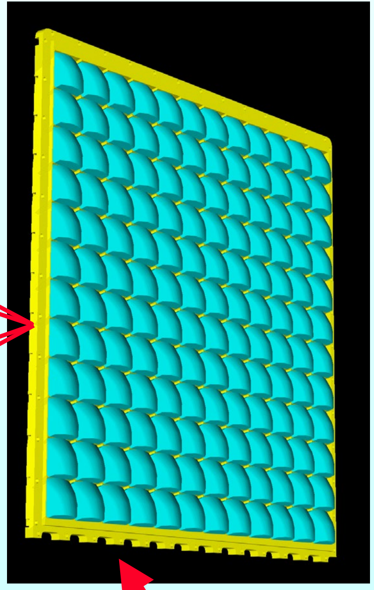
upgrade of RICH-1 with MAPMT's in the central region (2006)



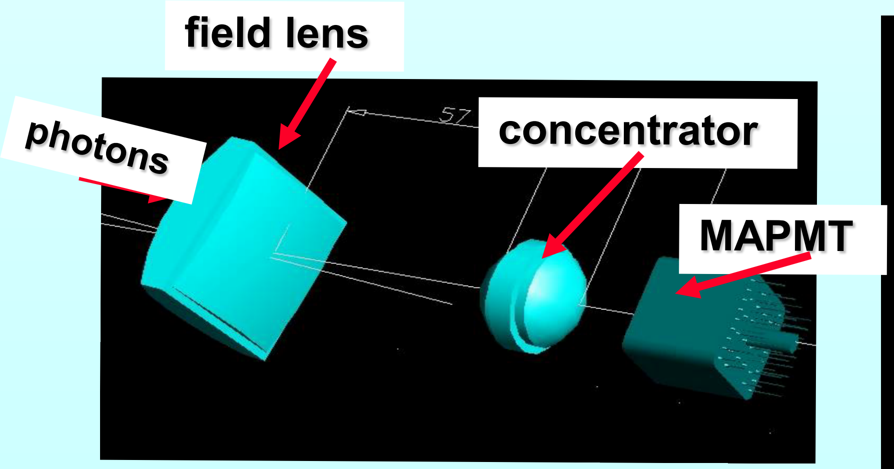
12 outer CsI cathodes: change electronics (use APV25-S1)

4 central CsI cathodes: remove and insert frames with MAPMTs and lense telescopes





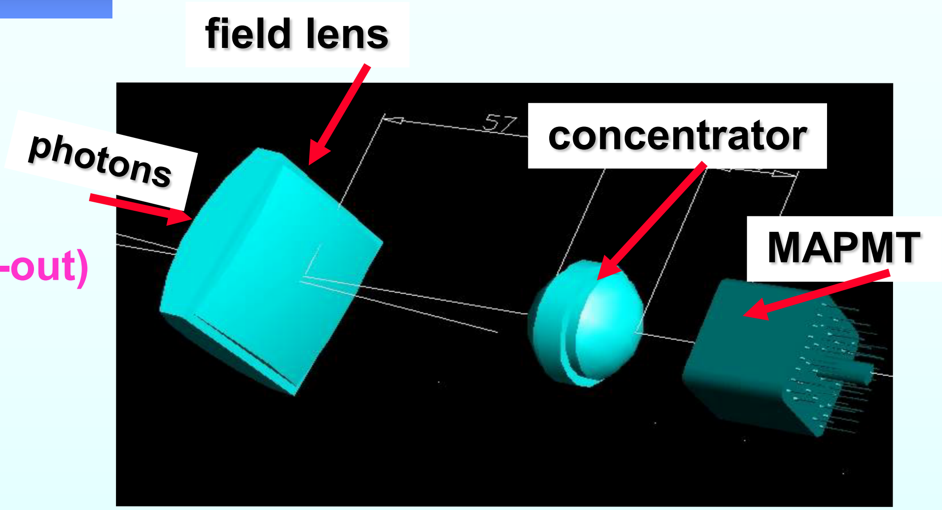
Same mechanics as CsI photo-cathode frame

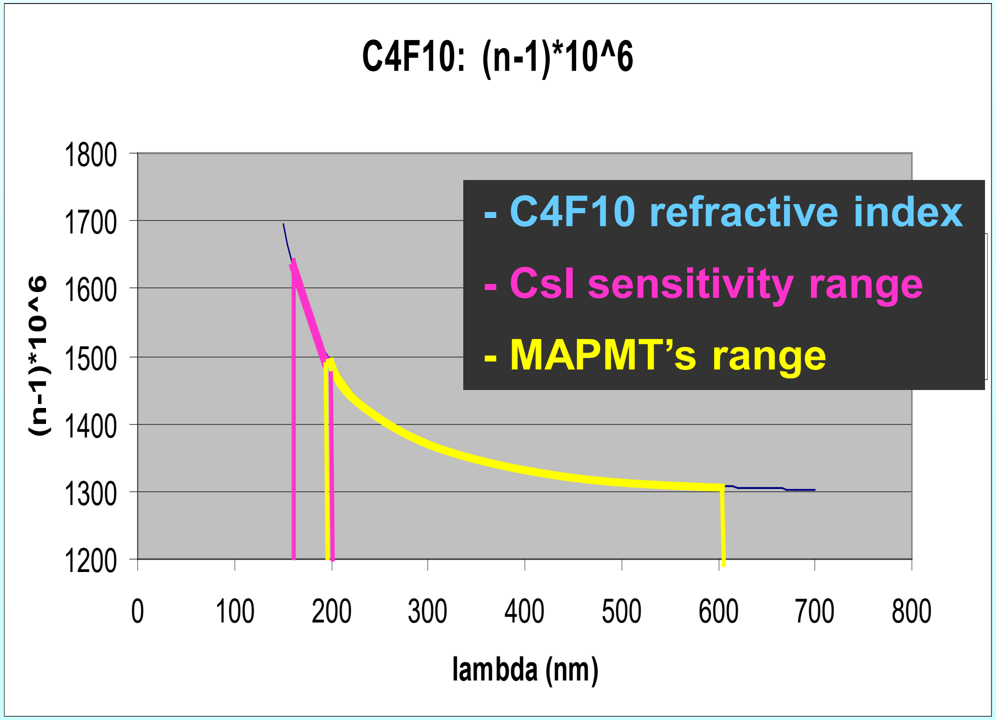


The difference

MAPMT's have:

- wide wavelength range
- time resolution < 1 nsec
- short detection system memory (MAPMT + read-out)
- adequate for high rate operation
- robustness
- high efficiency for single photon detection




C4F10: (n-1)*10^6

challenges:

large ratio of the collection and photocathode areas with minimal image distortion

→ ratio = 7.3 ←→ critical LENS SYSTEM design

UV range ←→ fused silica LENSES

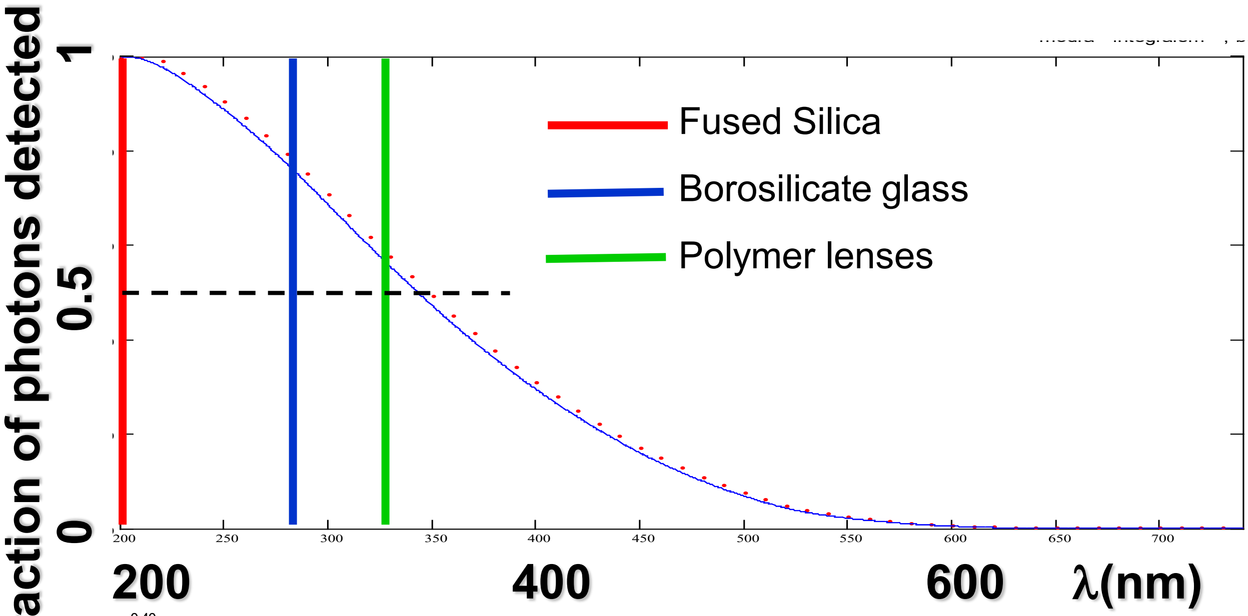
couple to a read-out system able to guarantee efficiency, high rate operation and to preserve time resolution

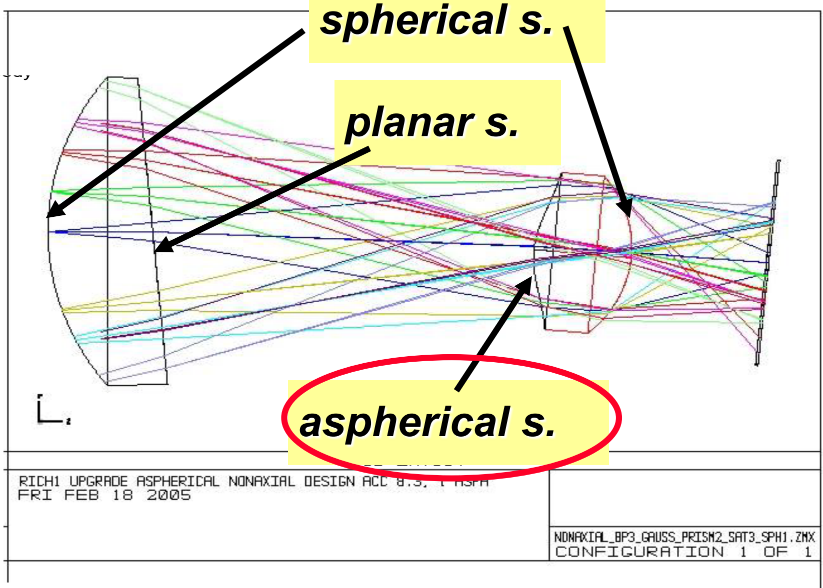
THE LENSES

$$\int_{\lambda}^{800} QE(\lambda)\cdot S(\lambda)\cdot d\lambda \Big/ \int_{200}^{800} QE(\lambda)\cdot S(\lambda)d\lambda$$

material:
fusedd silica, Corning 7980,

ZEMAX optimization:

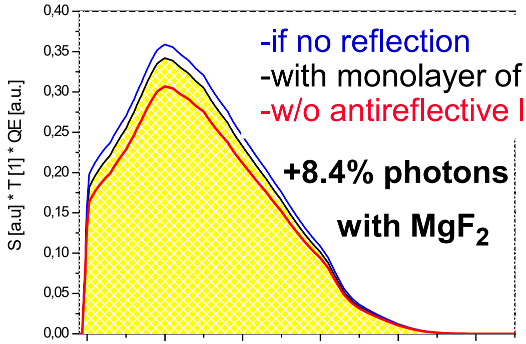




spherical s.

planar s.

aspherical s.

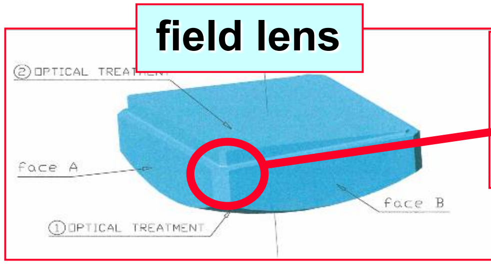


-if no reflection
-with monolayer of MgF_2
-w/o antireflective layer

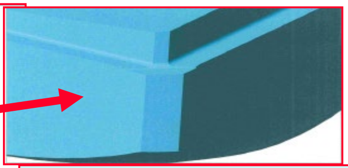
+8.4% photons

with MgF_2

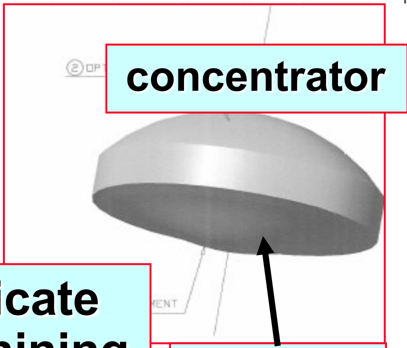
Convolution of Cherenkov light and effective QE



field lens

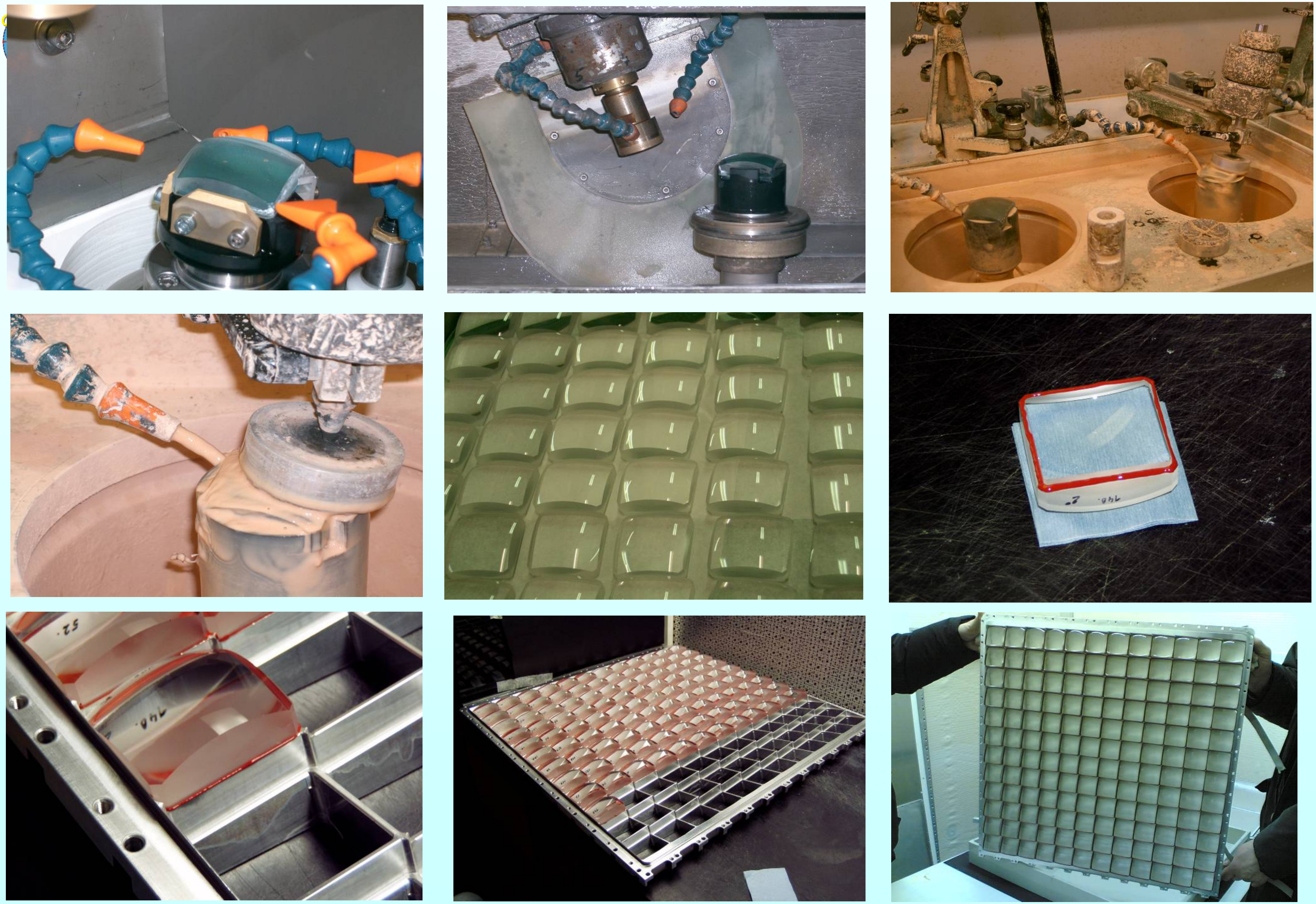


complex and delicate mechanical machining

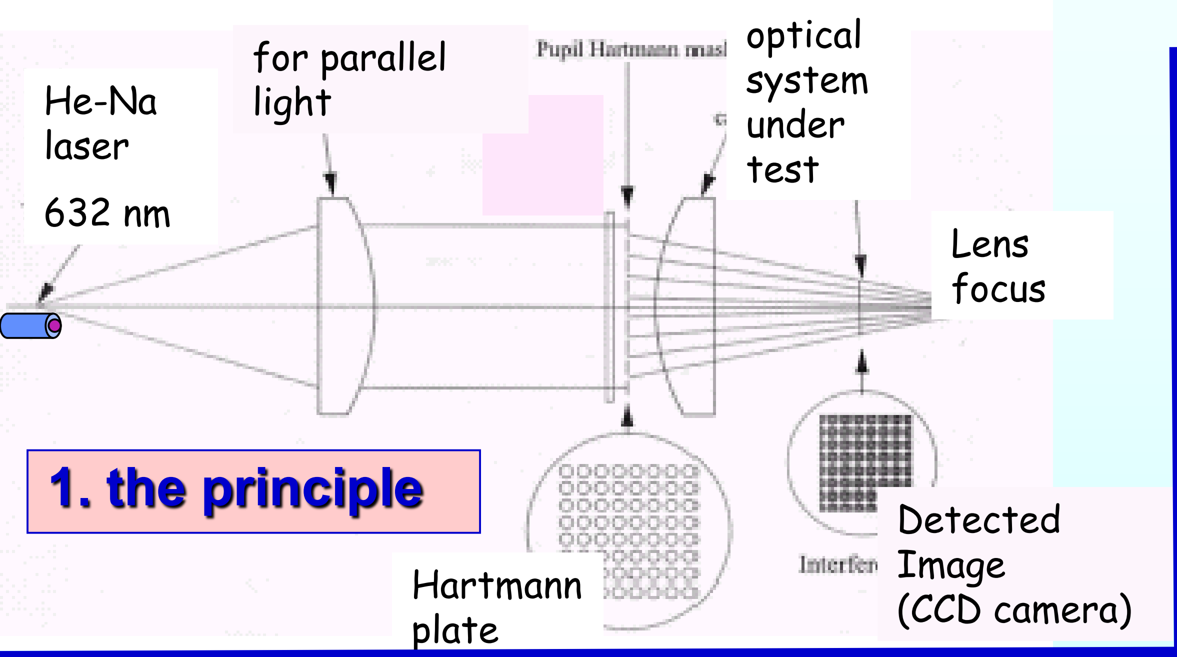


concentrator

aspheric surface



OPTICS QUALITY CONTROL WITH THE HARTMANN METHOD



1. the principle

He-Na laser

632 nm

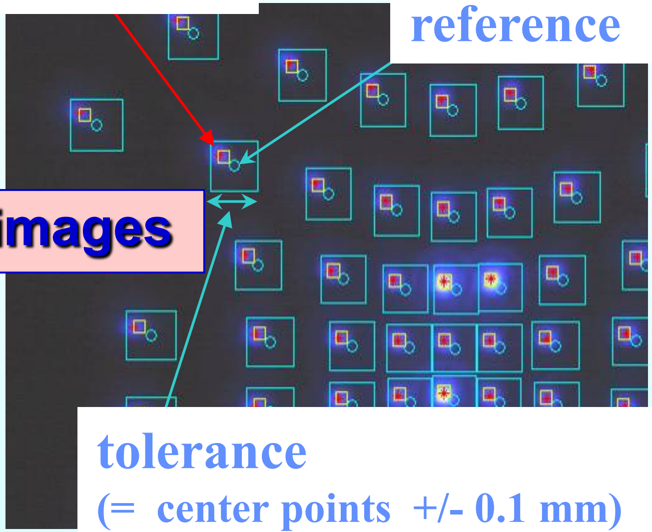
for parallel light

optical system under test

Lens focus

Hartmann plate

Detected Image (CCD camera)



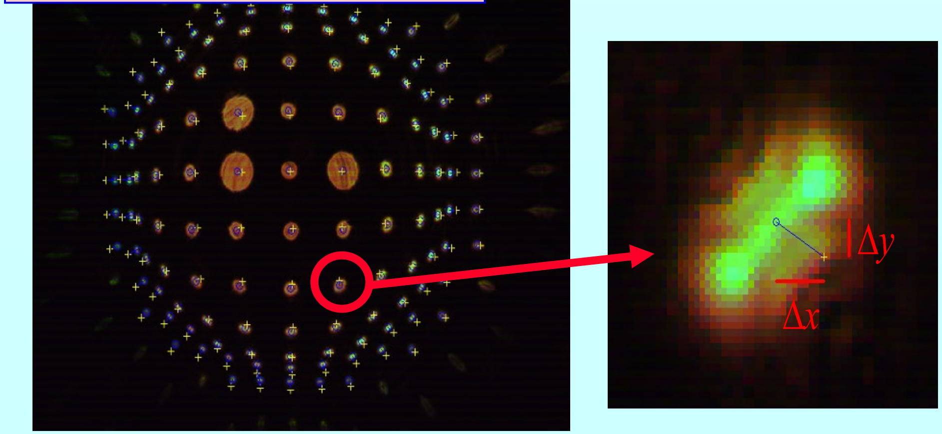
2. the images

image centroide

Theoretical reference

tolerance

(= center points +/- 0.1 mm)

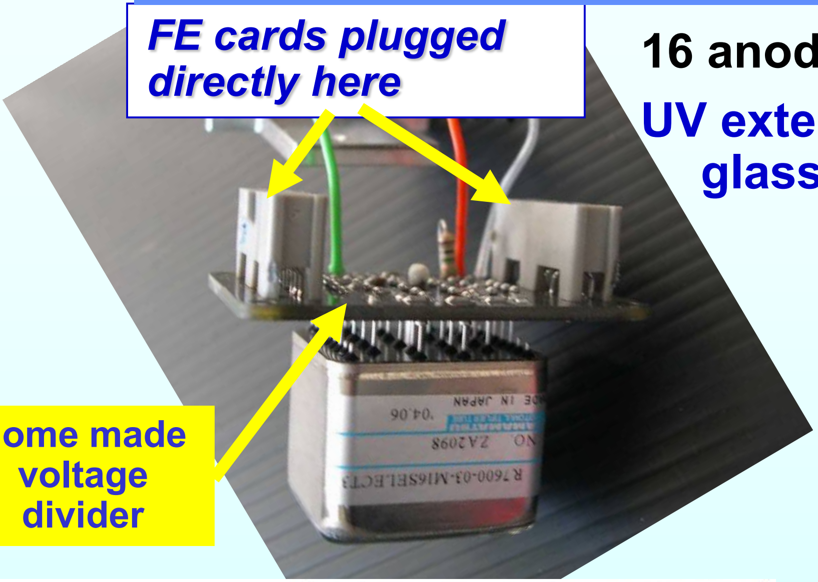


3. the analysis

576 TELESCOPES:

A) ~70% within 50 μm tolerance
B) ~20% within 100 μm tolerance
C) ~10% within 150 μm tolerances

MAPMT: HAMAMATSU R7600-03-M16



FE cards plugged directly here

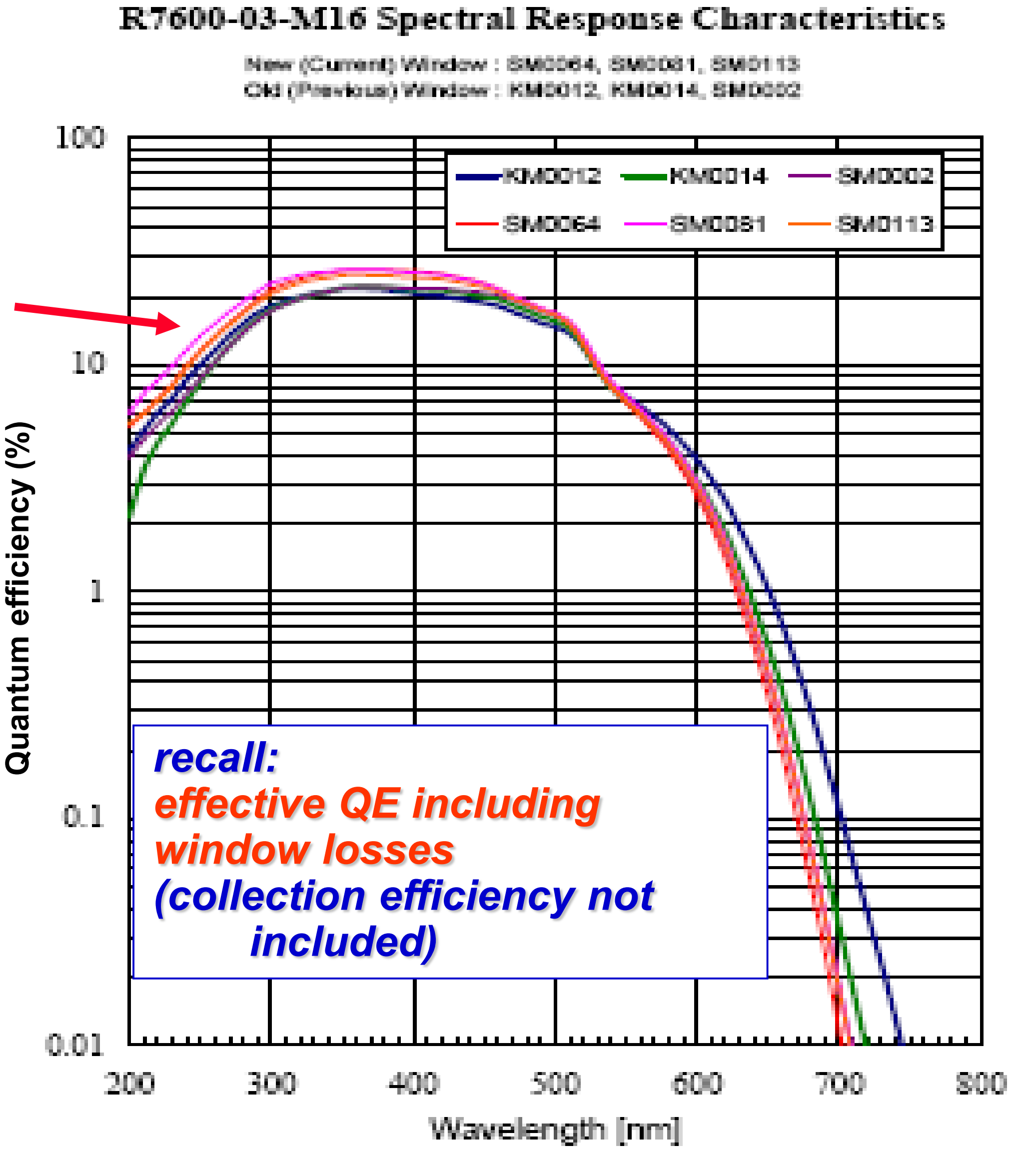
home made voltage divider

16 anodes

UV extended glass

PMT in soft iron box

protects against B ≤ 200 G and guarantees good alignment

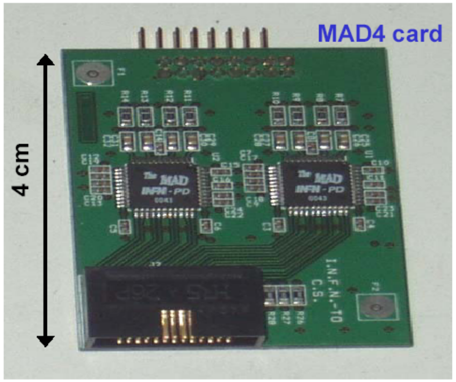


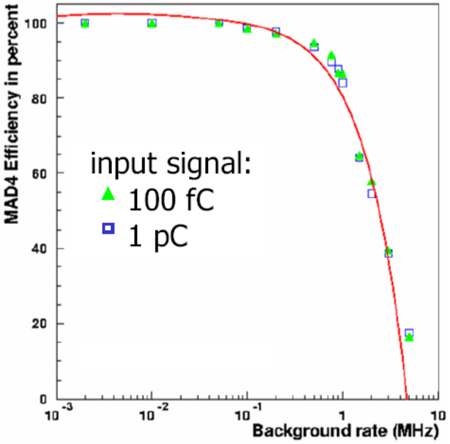
recall:
effective QE including window losses
(collection efficiency not included)

Analogue read-out electronics: MAD4 preamplifier

- up to ≈ 1 MHz / channel
- low noise ≈ 5-7 fC
- single photon PMT signal ≈ 1 pC (at 900 V)
- clear separation signal / noise

further development by INFN TORINO: CMAD in 2007
up to 5 MHz / channel

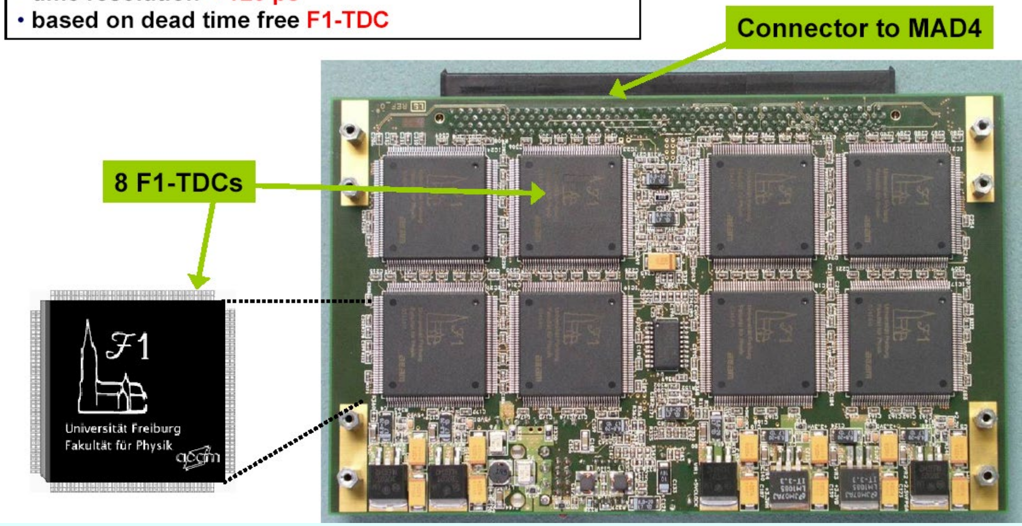




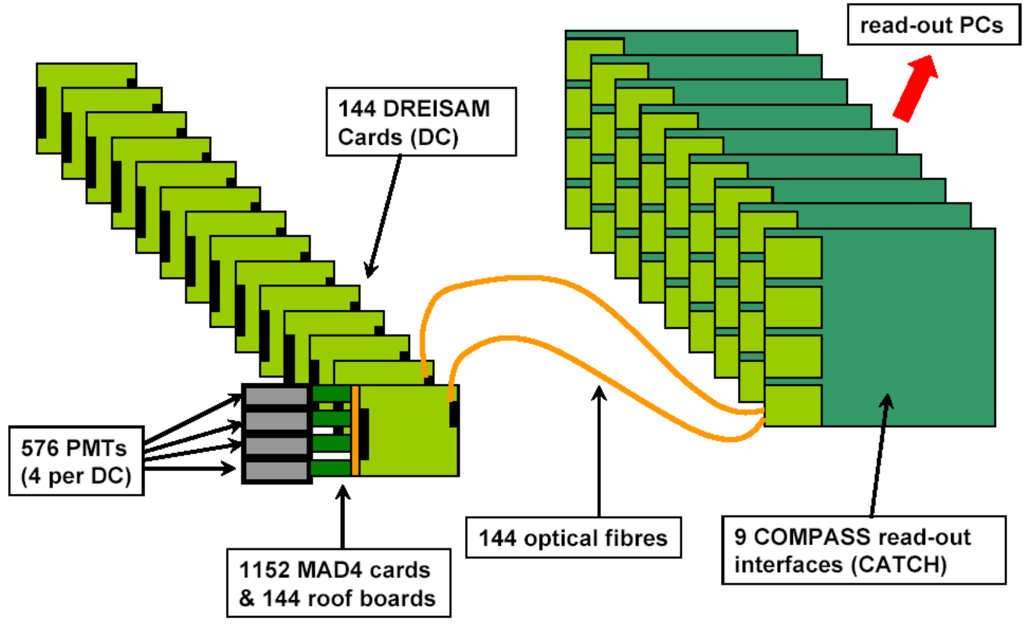
Digital read-out electronics: DREISAM card

- 64 channels per card, compact solution
- optical data transfer (40 MByte/s)
- high rates per channel 10 MHz @ 100 kHz trigger rate
- time resolution < 120 ps
- based on dead time free F1-TDC

complete digitalisation on the detector


Connector to MAD4

8 F1-TDCs


read-out PCs

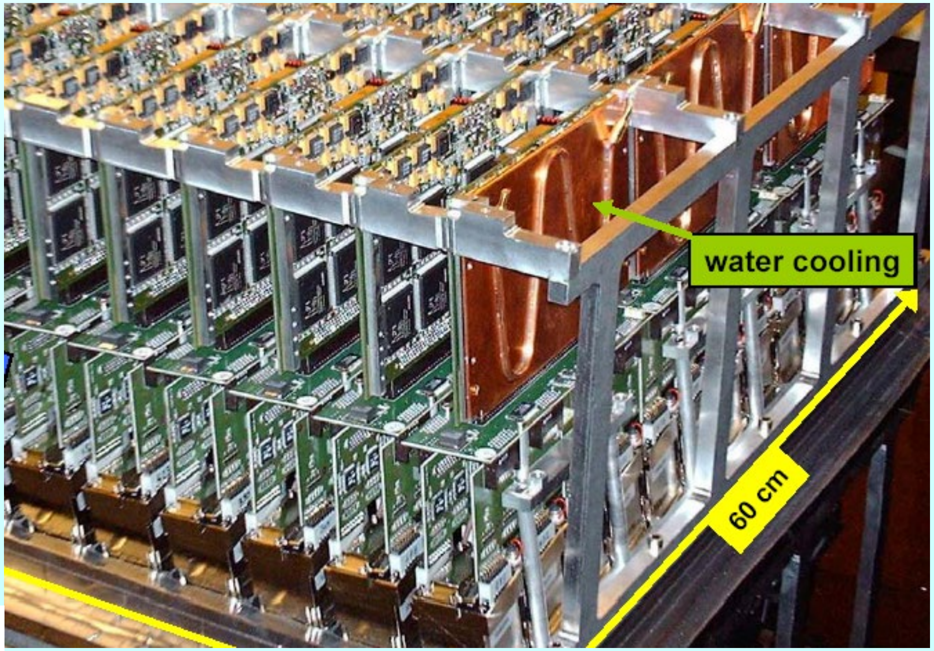
144 DREISAM Cards (DC)

576 PMTs
(4 per DC)

1152 MAD4 cards
& 144 roof boards

144 optical fibres

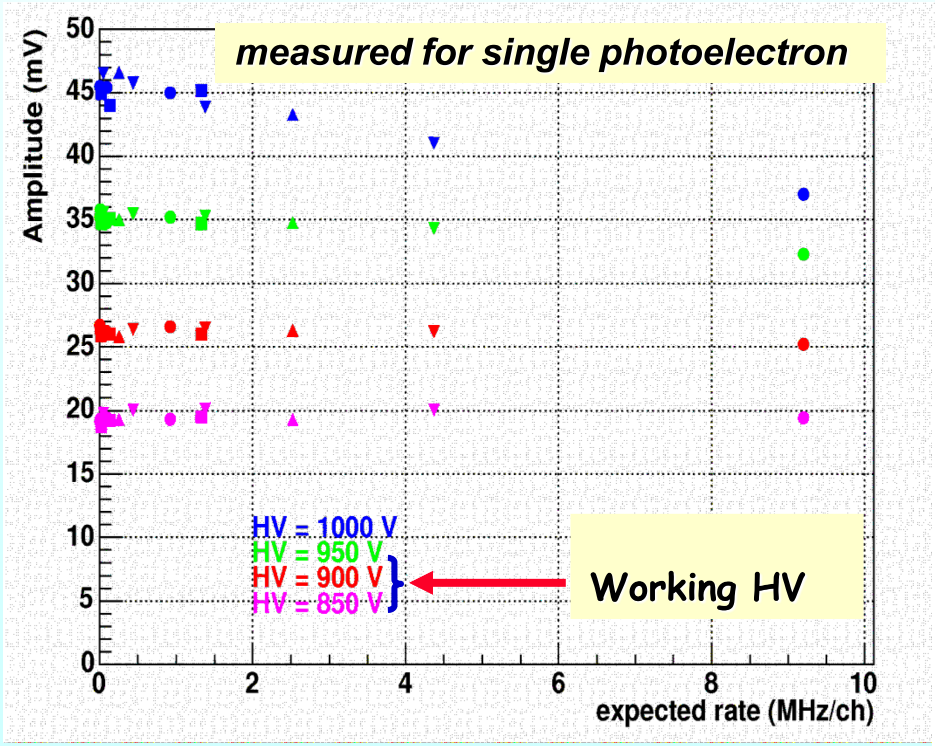
9 COMPASS read-out
interfaces (CATCH)



MAPMT GAIN AT HIGH RATE AND CROSS-TALK RATE

mean signal amplitude versus rate/pixel

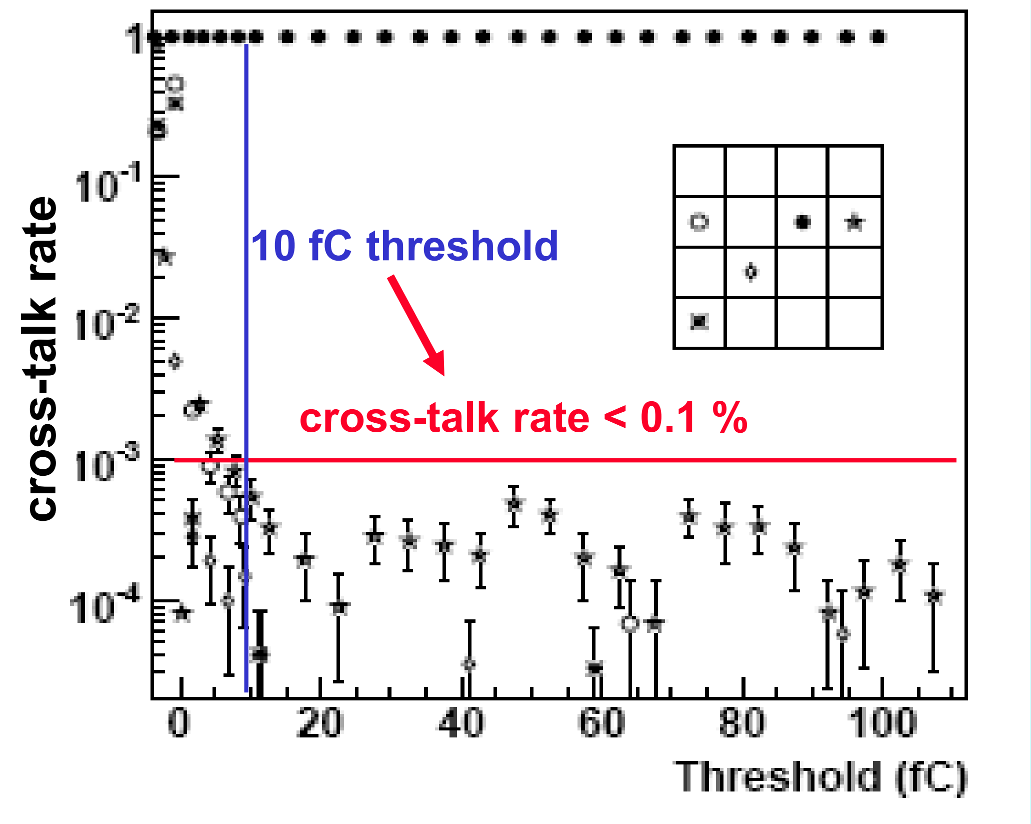
pulsed light source synchronous to trigger + random background from lamp



measured for single photoelectron

Working HV

operate with single photoelectron rates up to 5MHz/pixel



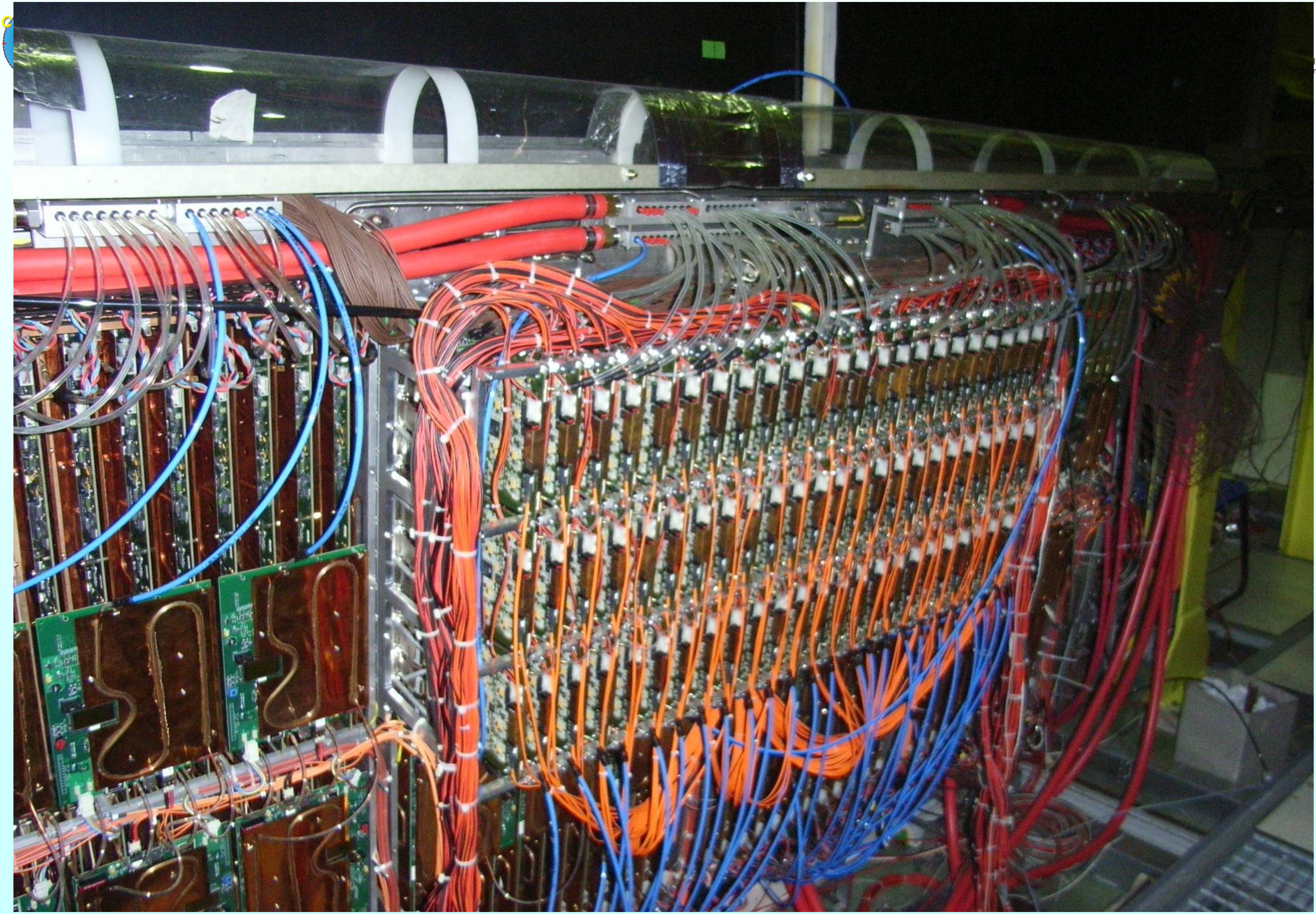
10 fC threshold

cross-talk rate < 0.1 %

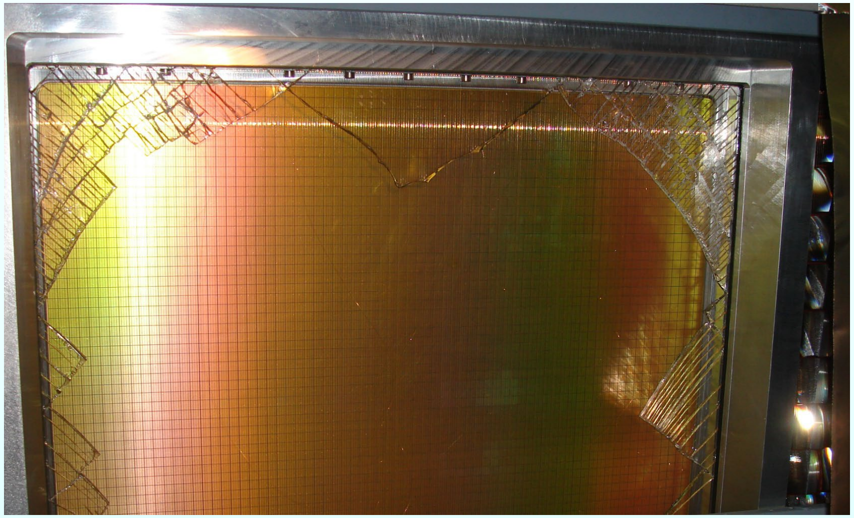
SCHEDULE OF ASSEMBLING

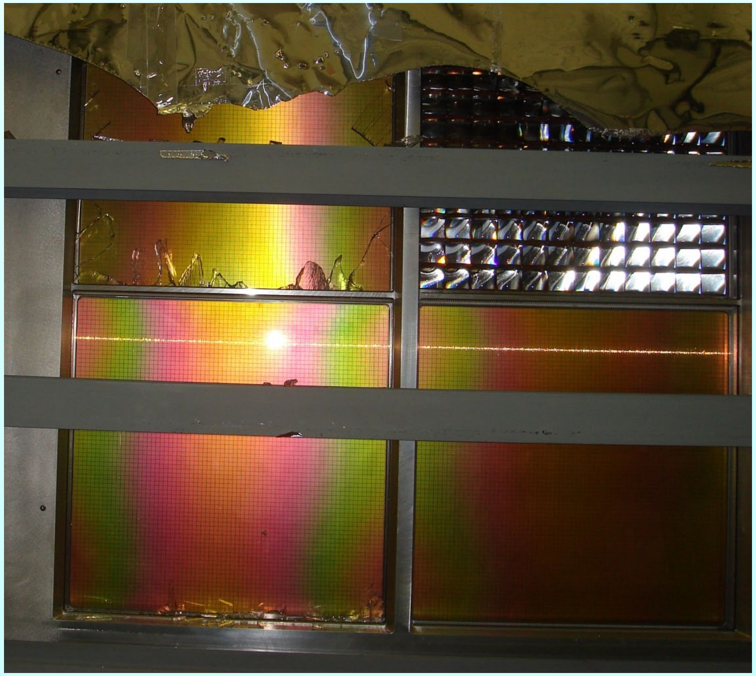
- Preliminary studies up to October 2004
- Project design November 2004 – March 2005
- Material procurement and constructions April 2005 - March 2006
- Assembly April-May 2006
- Ready for beam June 2006

th



Not everything went smoothly





It was May 18, 2006. A beautiful sunny day in Geneva.

At 11:45 the detector was ready for craning.

Suddenly a bang was heard.

The repair started on the same day

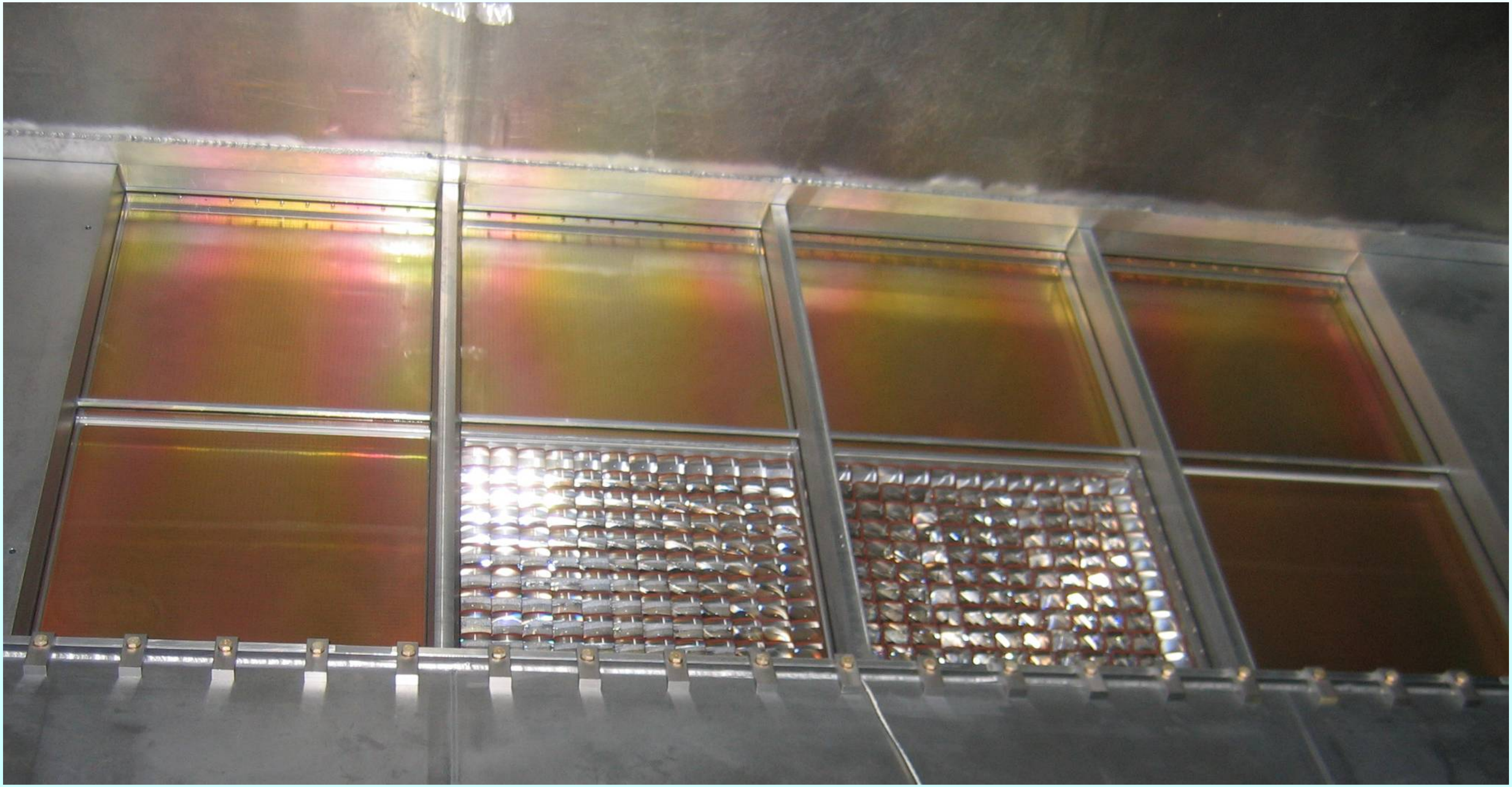
Spares of all pieces, including the large quartz windows were available

The accident was carefully studied and understood in detail (20 mbar overpressure)

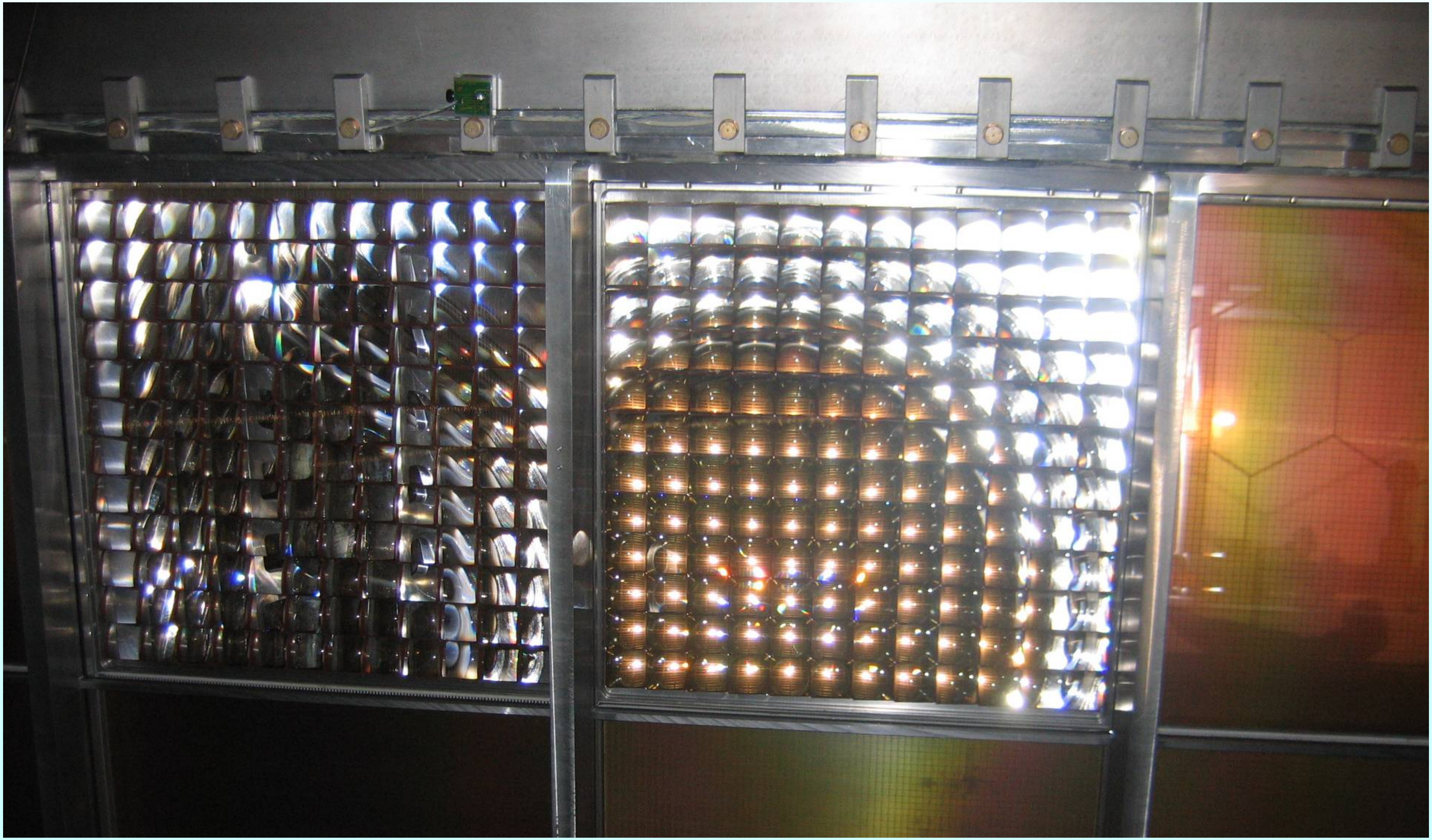
One month later, in time for the start of the run,

the repaired detector was installed

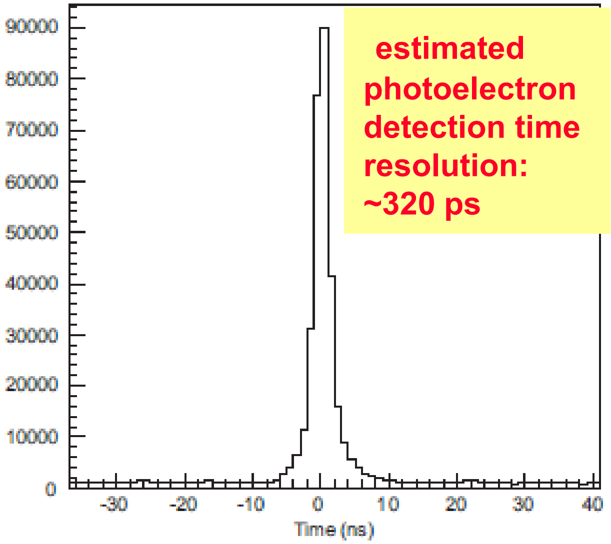
The Upper Detector from inside



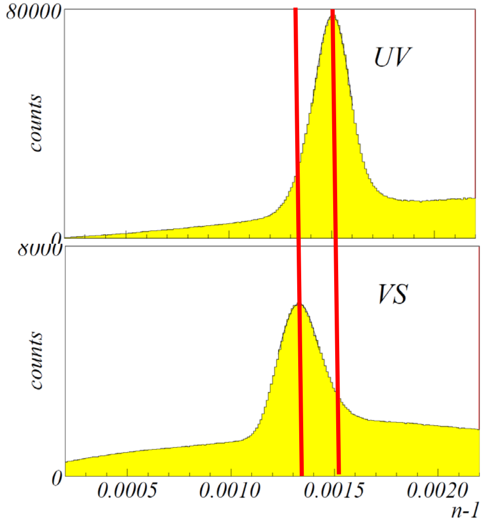
The central part of the lower detector

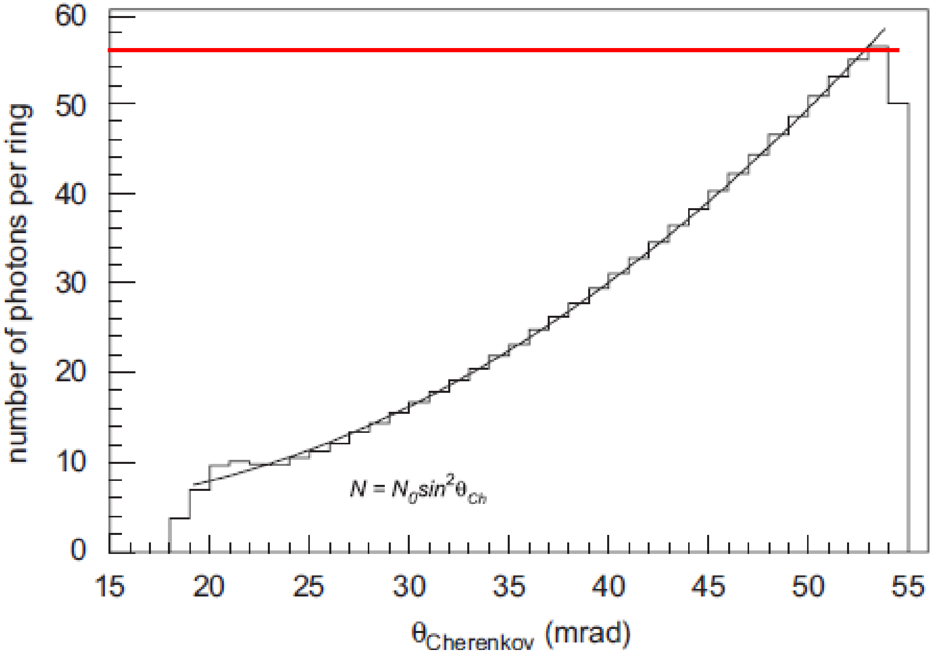


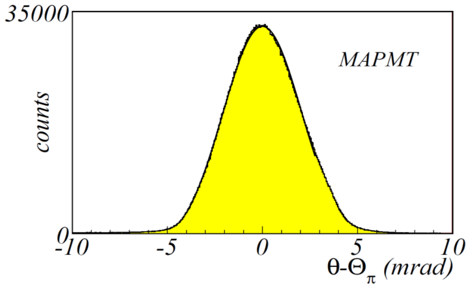
number of photons and resolutions

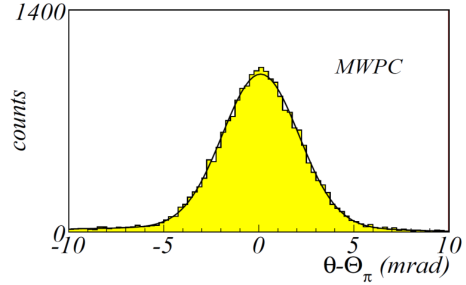


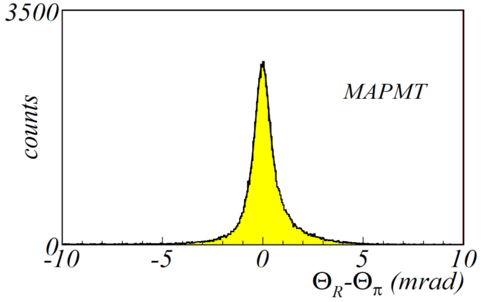
estimated photoelectron detection time resolution: ~320 ps

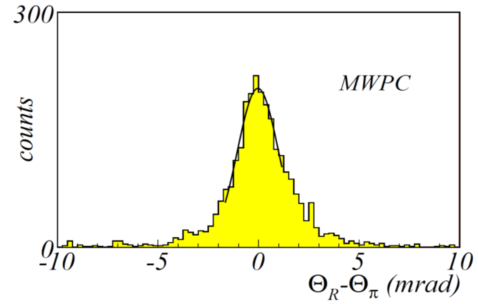


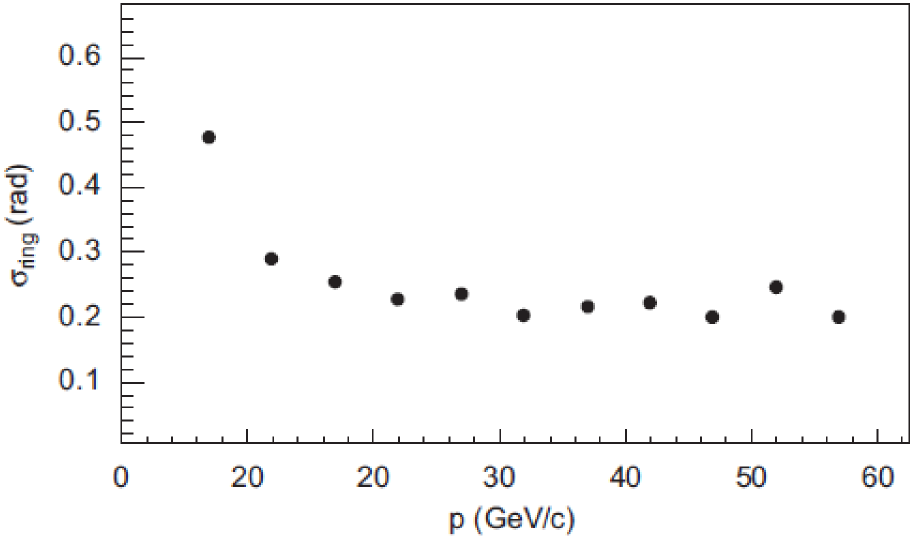




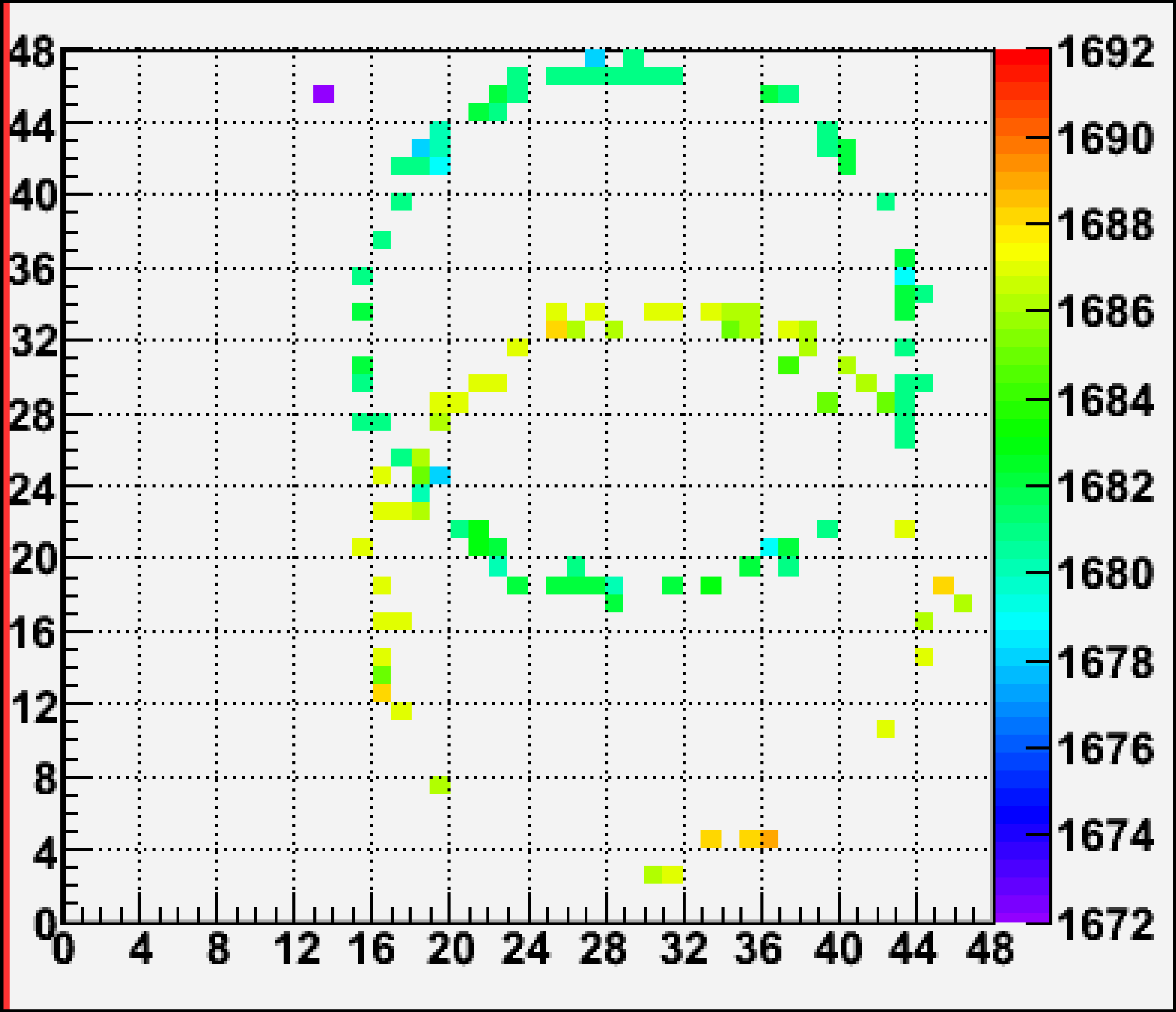








time resolution is useful for correctly assigning hits to rings



RICH-1 upgrade with MPGDs

Exclusive channels have low cross-section

Precision measurements require high efficiency and very stable response

MWPC + CsI operate at low gain ➔ the response depends on threshold and background stability

Precise comparison of data with different background levels is needed

Reduction of systematics ➔ larger gain and faster signals

PMTs not adequate because of the wide angular acceptance ➔ only small demagnification factor of optical system allowed (large distortions) → 5 m^2 of dense PMTs not affordable.

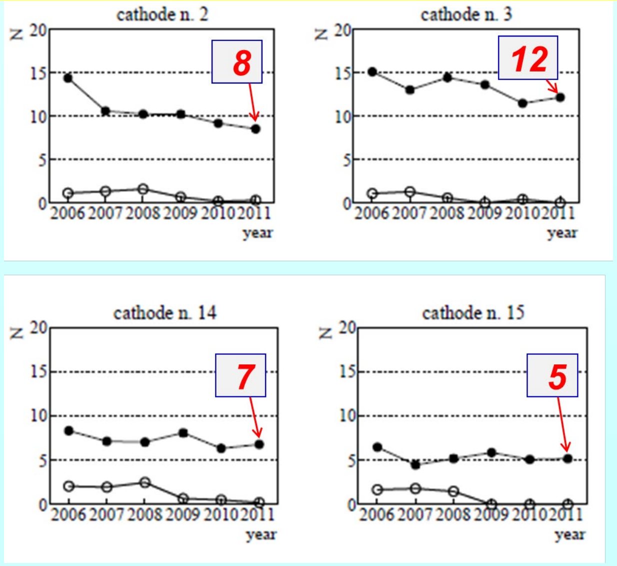
MPGD-based Photon Detectors are the best option

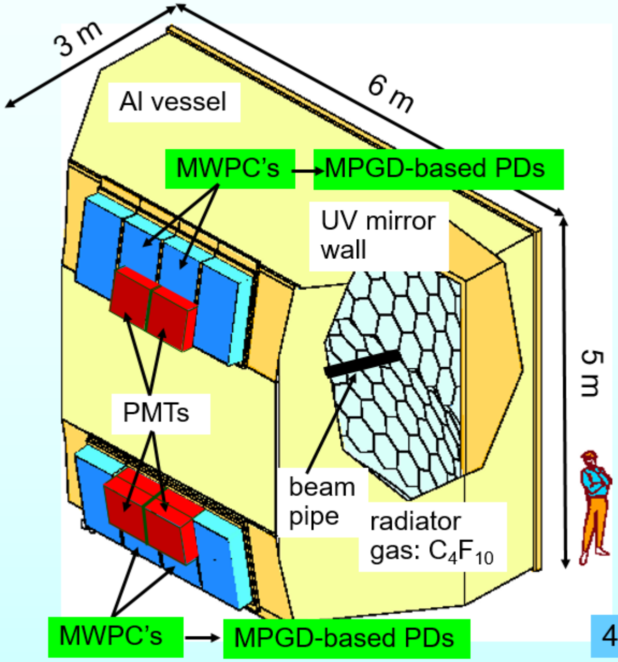
A dedicated R&D project to develop THGEM-based PDs achieved positive results

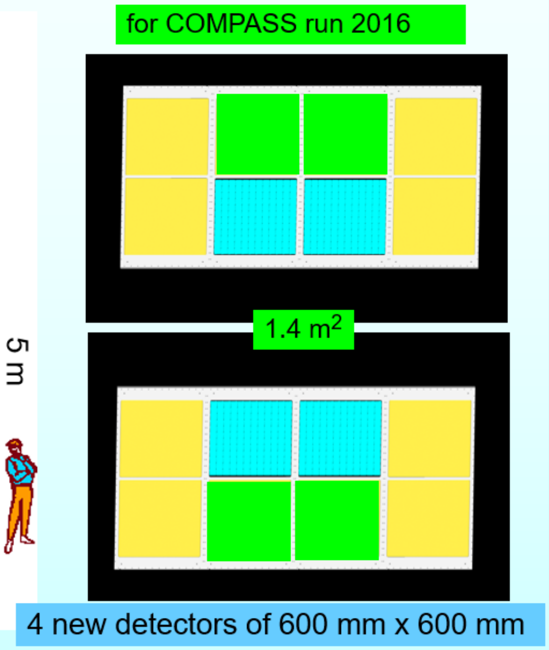
We decided to replace four COMPASS RICH-1 MWPC's with the new detectors

number of detected photons per ring at β = 1

for the four central MWPCs with CsI

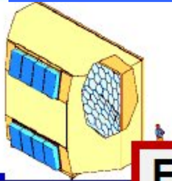






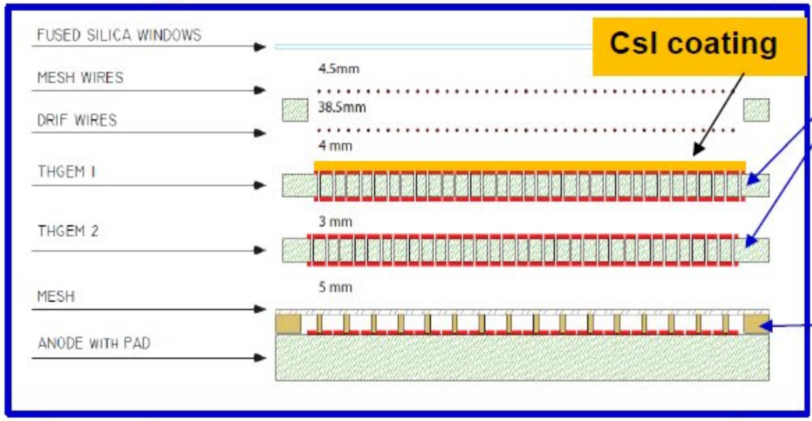
4 new detectors of 600 mm x 600 mm

Hybrid MPGD-based PDs



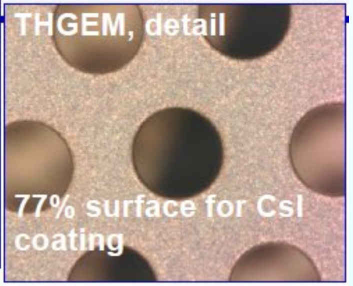
DETECTOR ARCHITECTURE

Following a 7-year R&D



2 layers of staggered THGEMs:

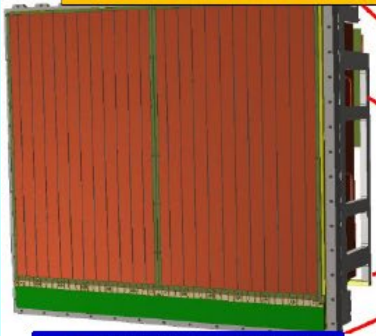
- pre-amplification
- transversally enlarged avalanche

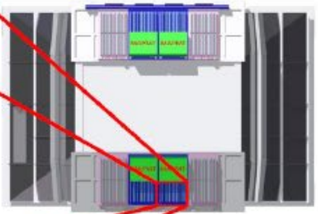


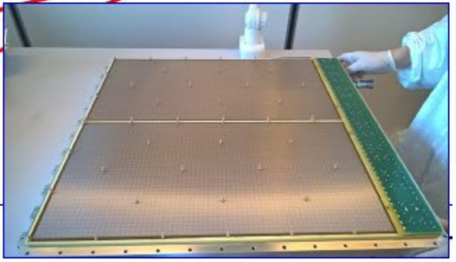
Resistive* MICROMEGAS by *bulk technology

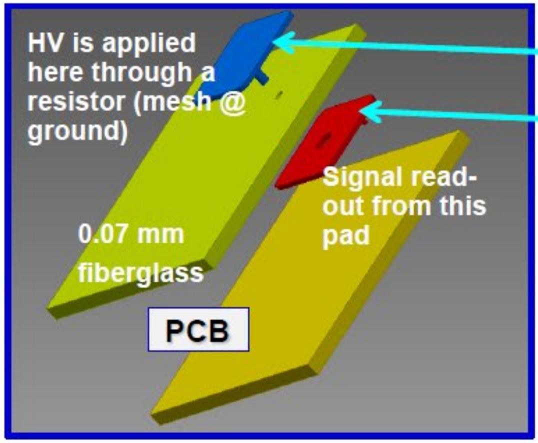
- trapping the ions
- ~100 ns signal formation

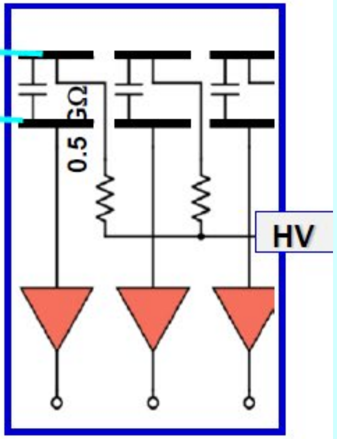
modular structure: one module = 600x300 mm^2





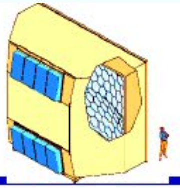




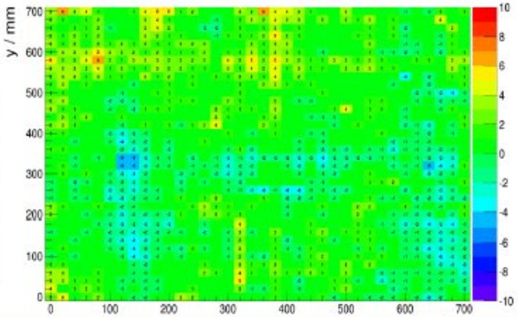


Hybrid MPGD-based PDs

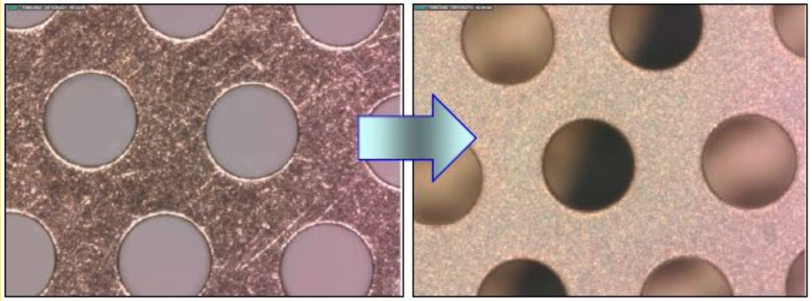
COMPONENT QA in a nutshell

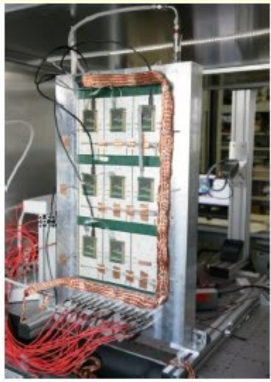


Measurement of the raw material thickness before the THGEM Production, accepted:
± 15 μm ↔ gain uniformity σ < 7%

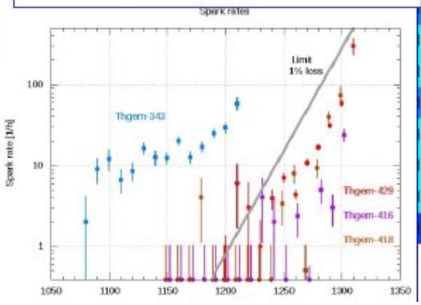


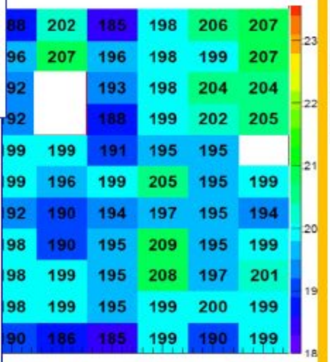
THGEM polishing with an "ad hoc" protocol setup by us:
>90% break-down limit obtained





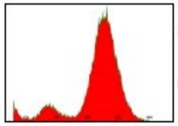
X-ray THGEM test to access gain uniformity (<7%) and spark behaviour

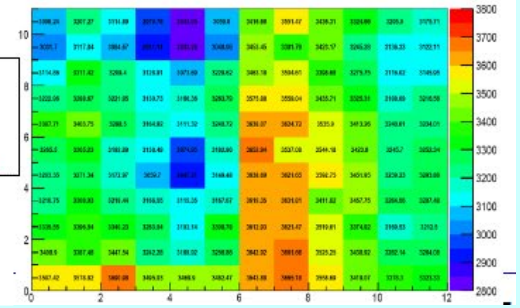




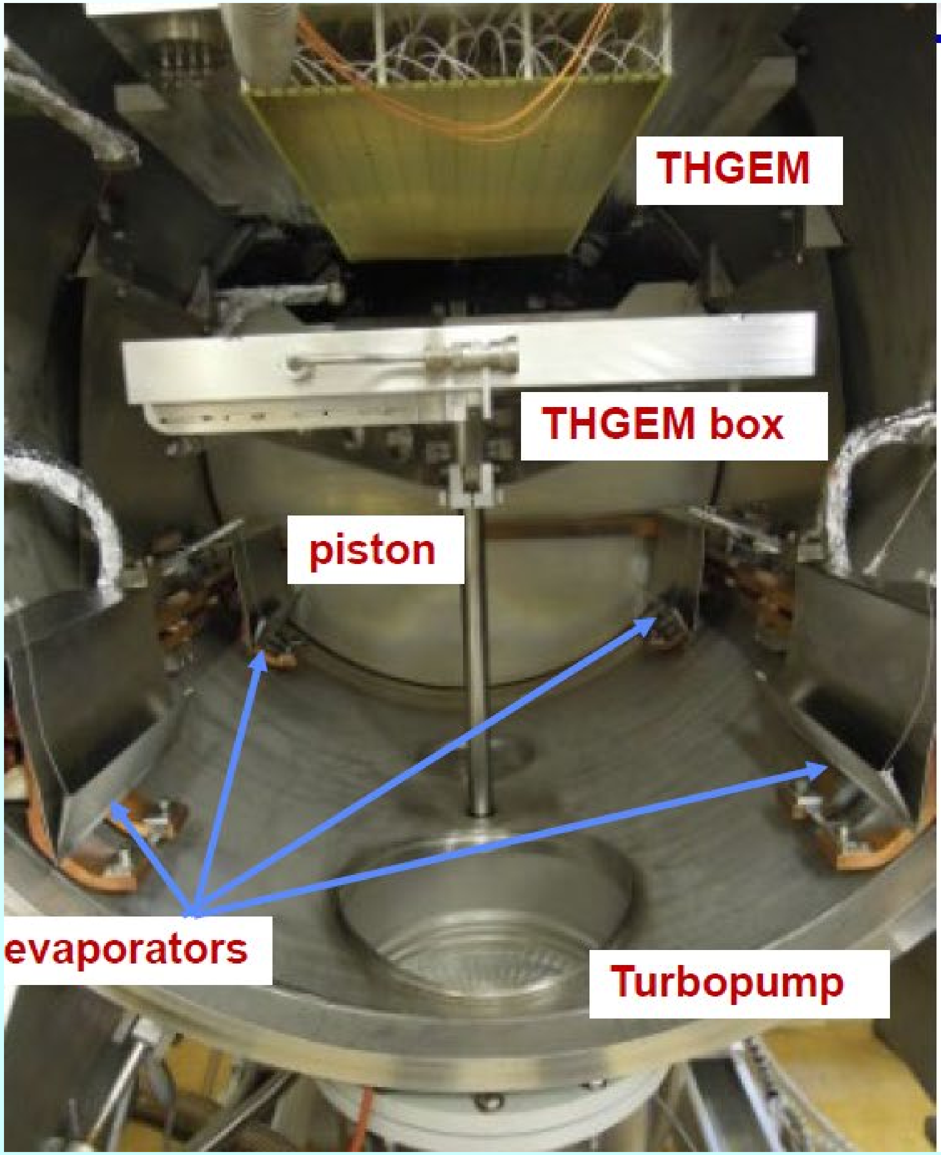
88	202	185	198	206	207
96	207	196	198	199	207
92		193	198	204	204
92		188	199	202	205
99	199	191	195	195	
99	196	199	205	195	199
92	190	194	197	195	194
98	190	195	209	195	199
98	199	195	208	197	201
98	199	195	199	200	199
90	186	185	199	190	199

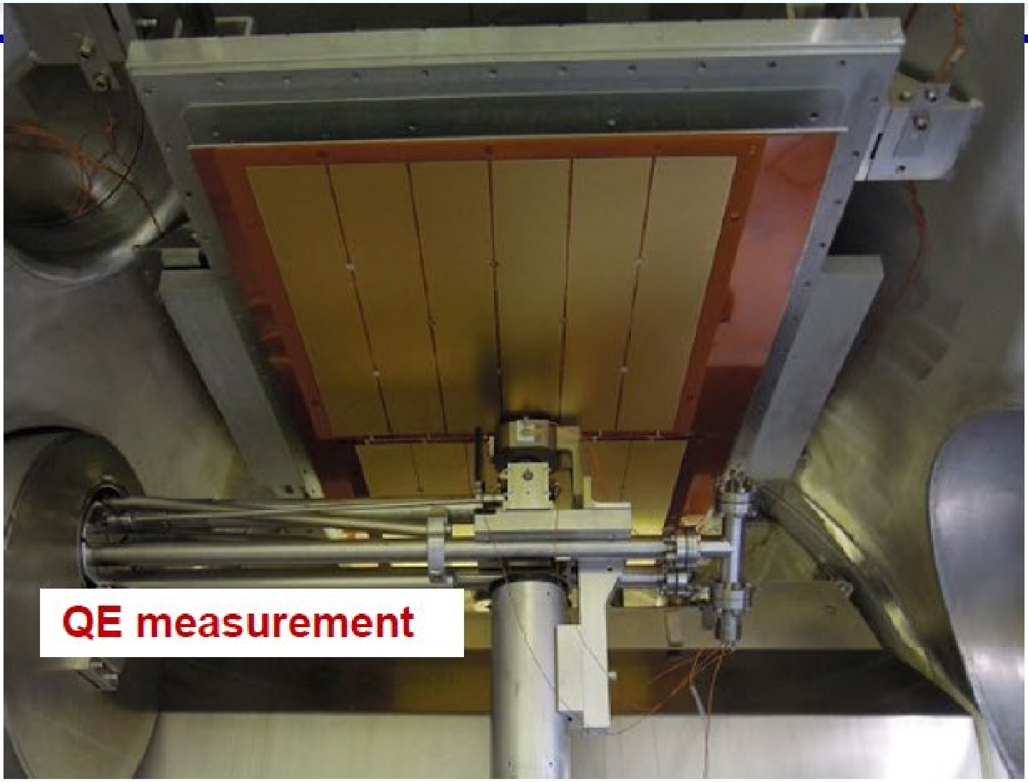
X-ray MM test to access integrity and gain uniformity (<5%)





CsI coating on THGEMs

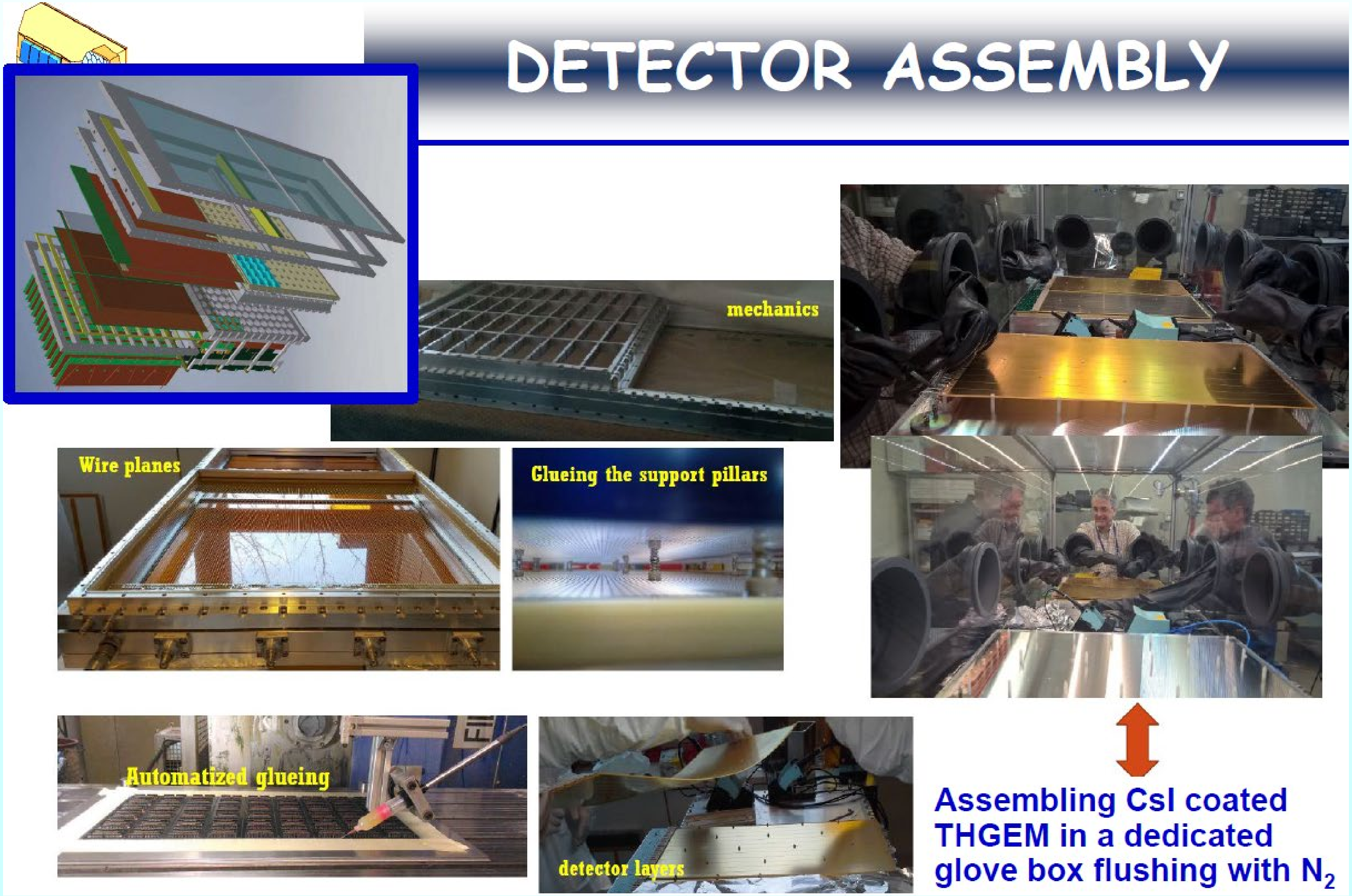




QE uniformity

- 3 % r.m.s. within a photocathode
- 10 % r.m.s. among photocathodes
- mean value: 93% of reference

Hybrid MPGD-based PDs



DETECTOR ASSEMBLY

mechanics

Wire planes

Glueing the support pillars

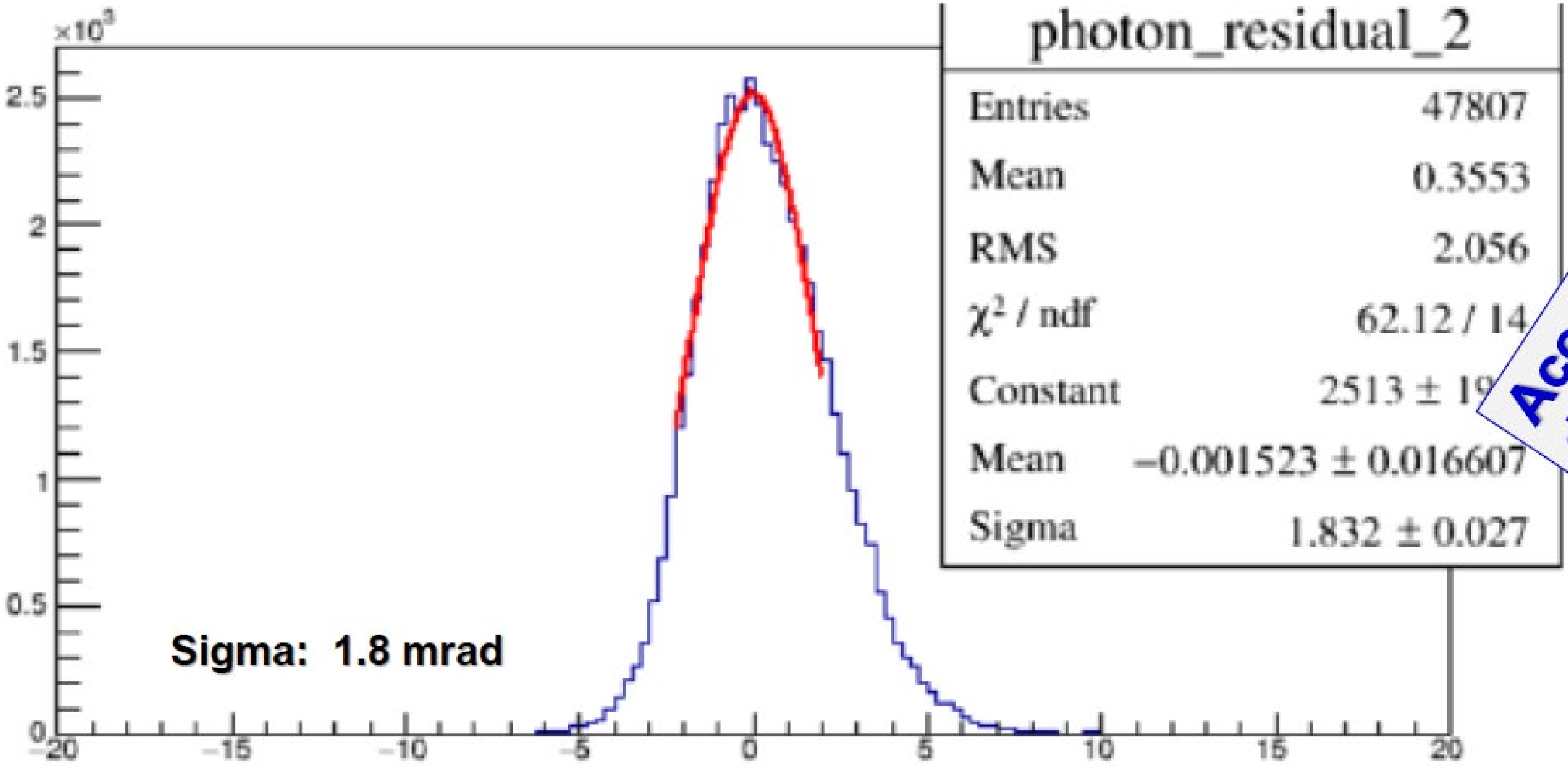
Automatized glueing

detector layers

Assembling CsI coated THGEM in a dedicated glove box flushing with N_2

Intrinsic space resolution

Residual distribution for individual photons (preliminary):
$\theta_{\text{calculated}} - \theta_{\text{photon}}$



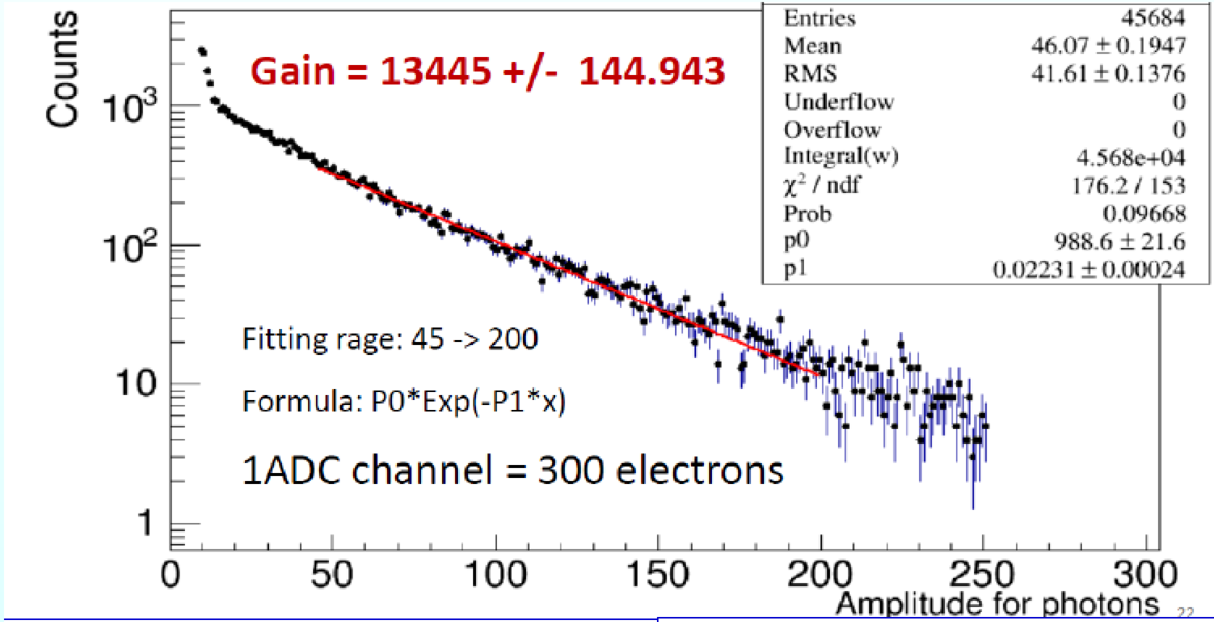
photon_residual_2

Entries	47807
Mean	0.3553
RMS	2.056
χ^2 / ndf	62.12 / 14
Constant	2513 ± 19
Mean	−0.001523 ± 0.016607
Sigma	1.832 ± 0.027

Sigma: 1.8 mrad

According to design figures

Gain from a pure photon sample



Gain = 13445 +/- 144.943

Fitting rage: 45 -> 200

Formula: P0*Exp(-P1*x)

1ADC channel = 300 electrons

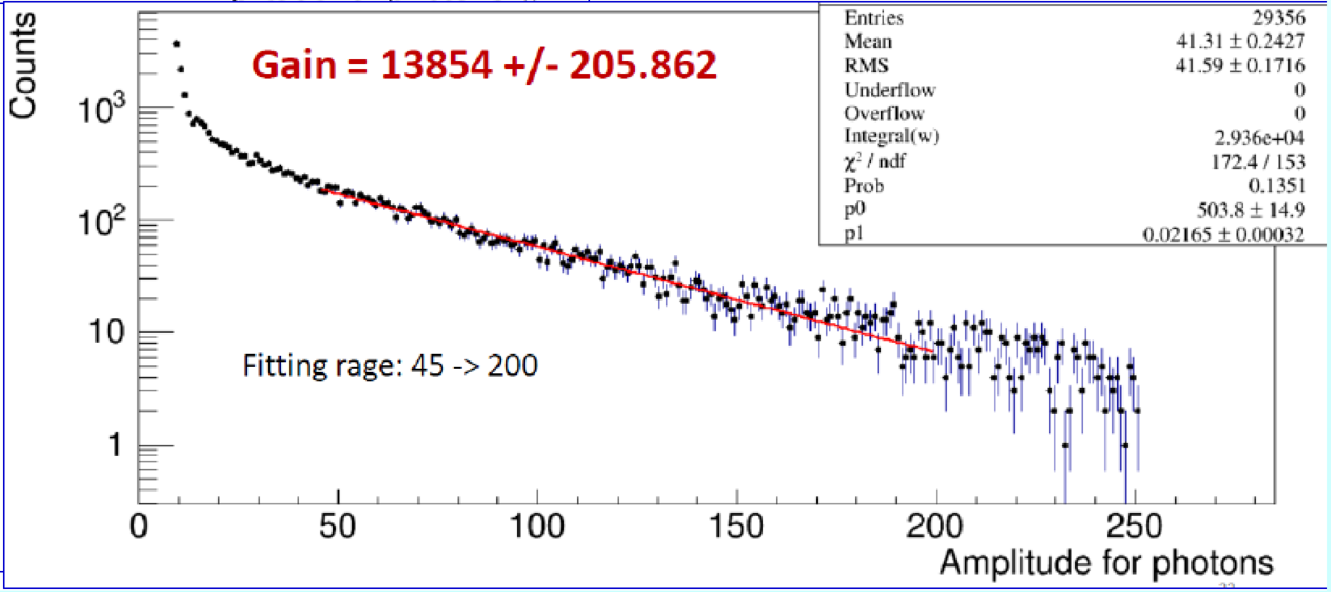
From electronic noise → Threshold

From threshold & gain → **photoelectron detection (effective) efficiency > 80%**

For comparison,
in MWPCs: ~50-60%

from the extrapolated exponential an estimate of the **noise level under the signal:**

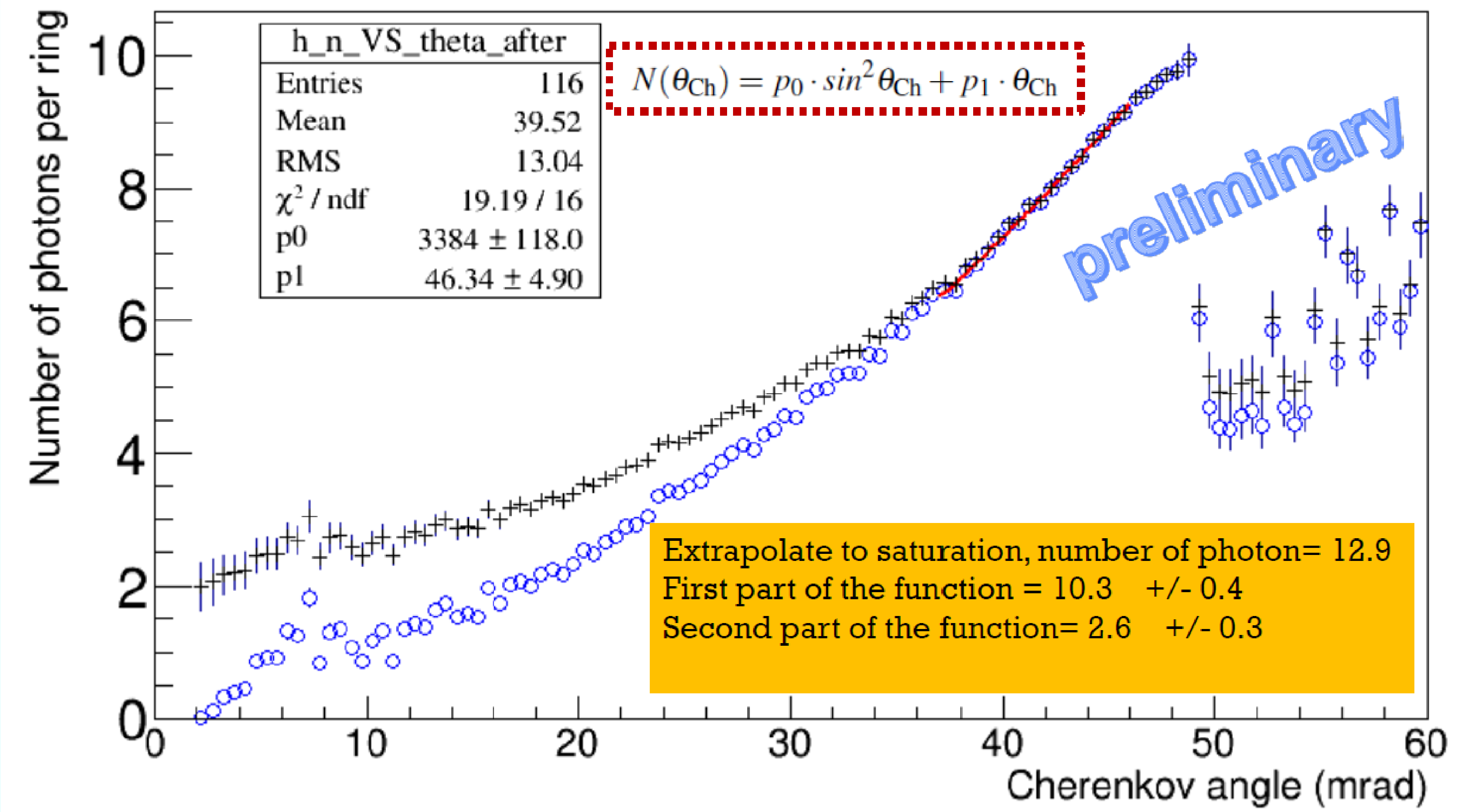
~10%



Gain = 13854 +/- 205.862

Fitting rage: 45 -> 200

Detected photons per ring



$$N(\theta_{Ch}) = p_0 \cdot sin^2\theta_{Ch} + p_1 \cdot \theta_{Ch}$$

Extrapolate to saturation, number of photon= 12.9
First part of the function = 10.3 +/- 0.4
Second part of the function= 2.6 +/- 0.3

PID from the likelihood function

PID relies on a Likelihood function, built from all the photons associated to the particle

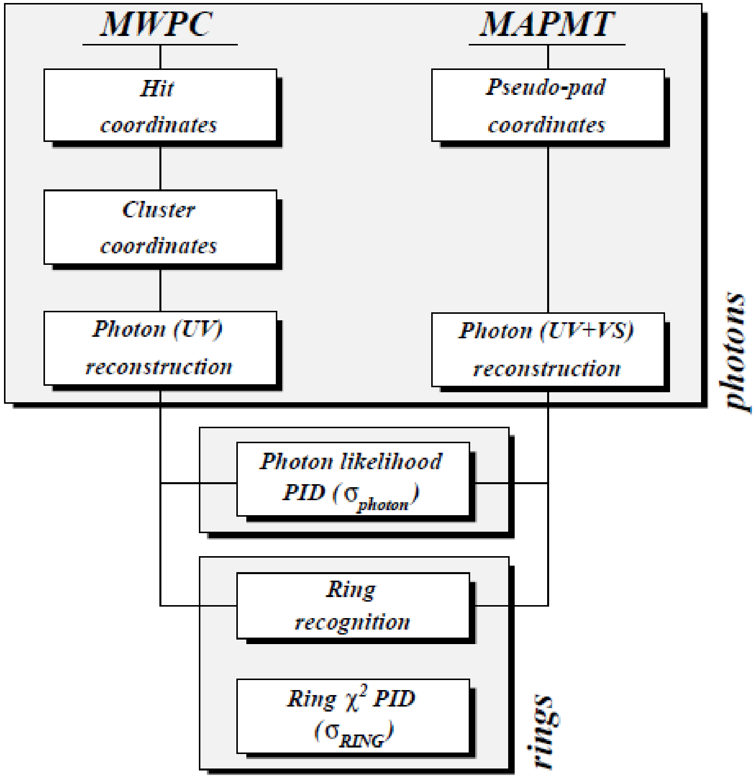
no reference to a reconstructed ring

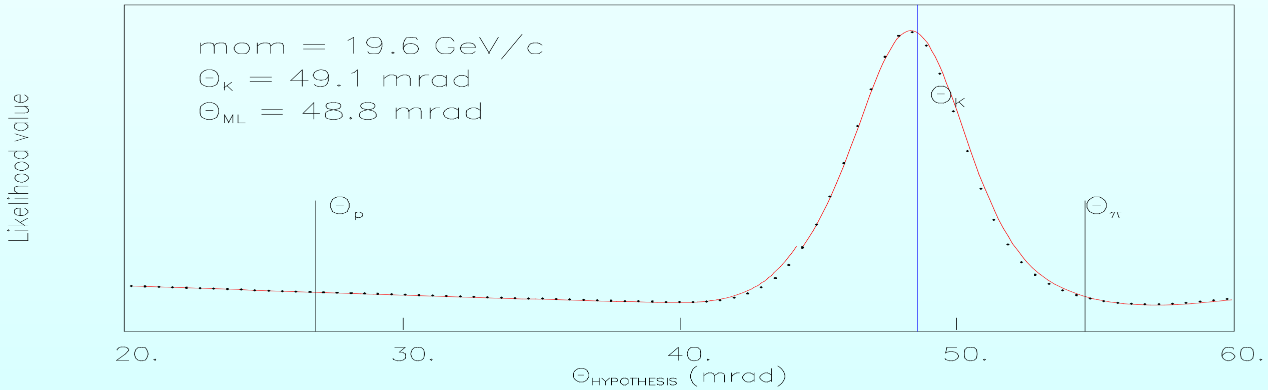
$$L_M = \prod_{j=1}^{N} \frac{s_M(\theta_j, \varphi_j) + b(\theta_j, \varphi_j)}{S_M + B}$$

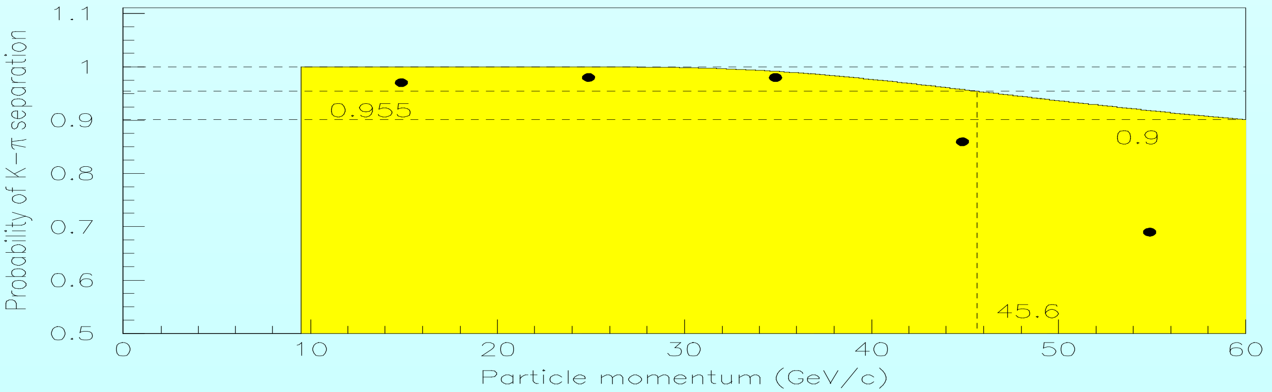
Computed for

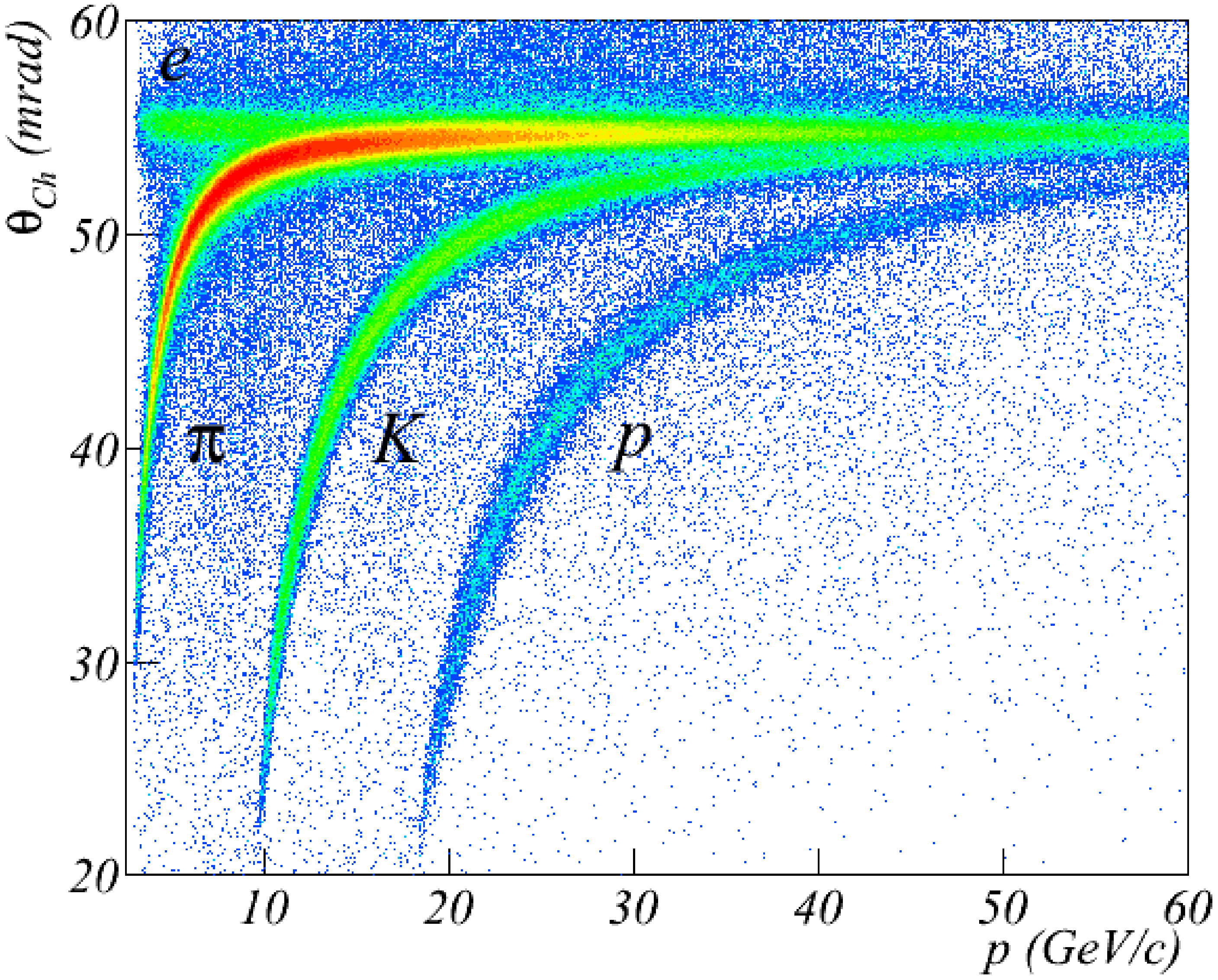
5 mass hypothesis $M = e, \mu, \pi, K, p,$

+ background hypothesis (no signal)



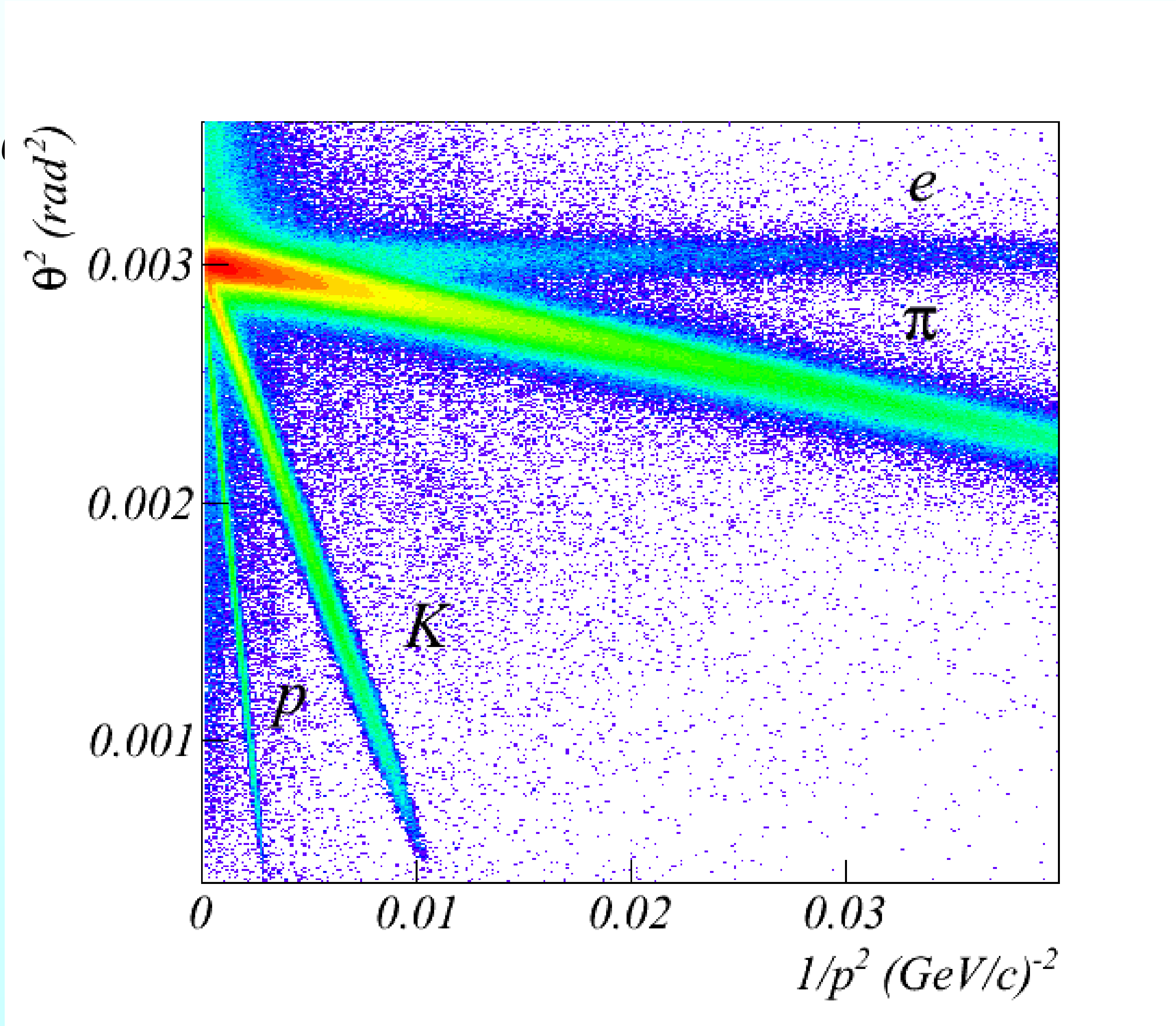






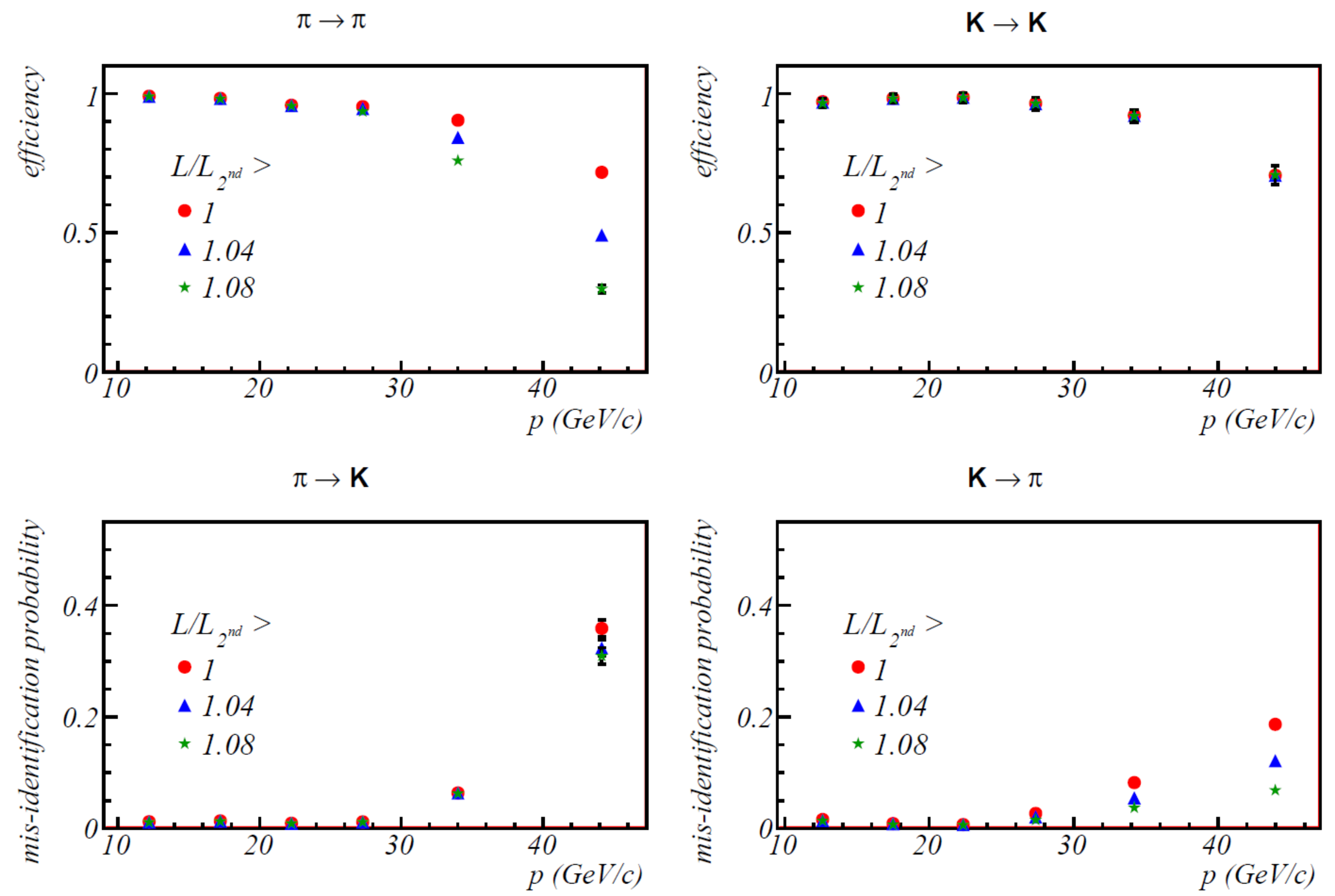
M
(GeV/c²)

20

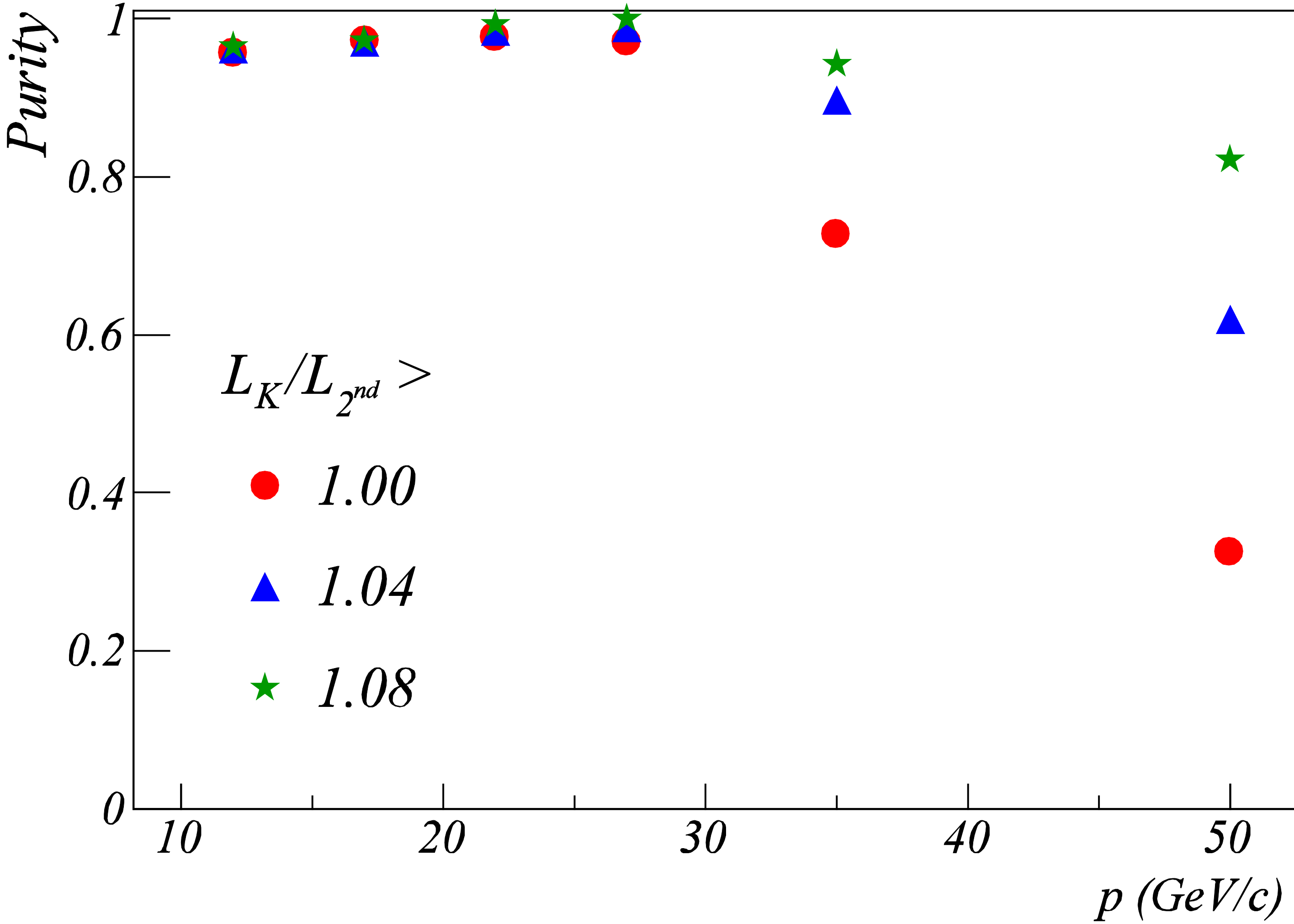


M (GeV/c²)

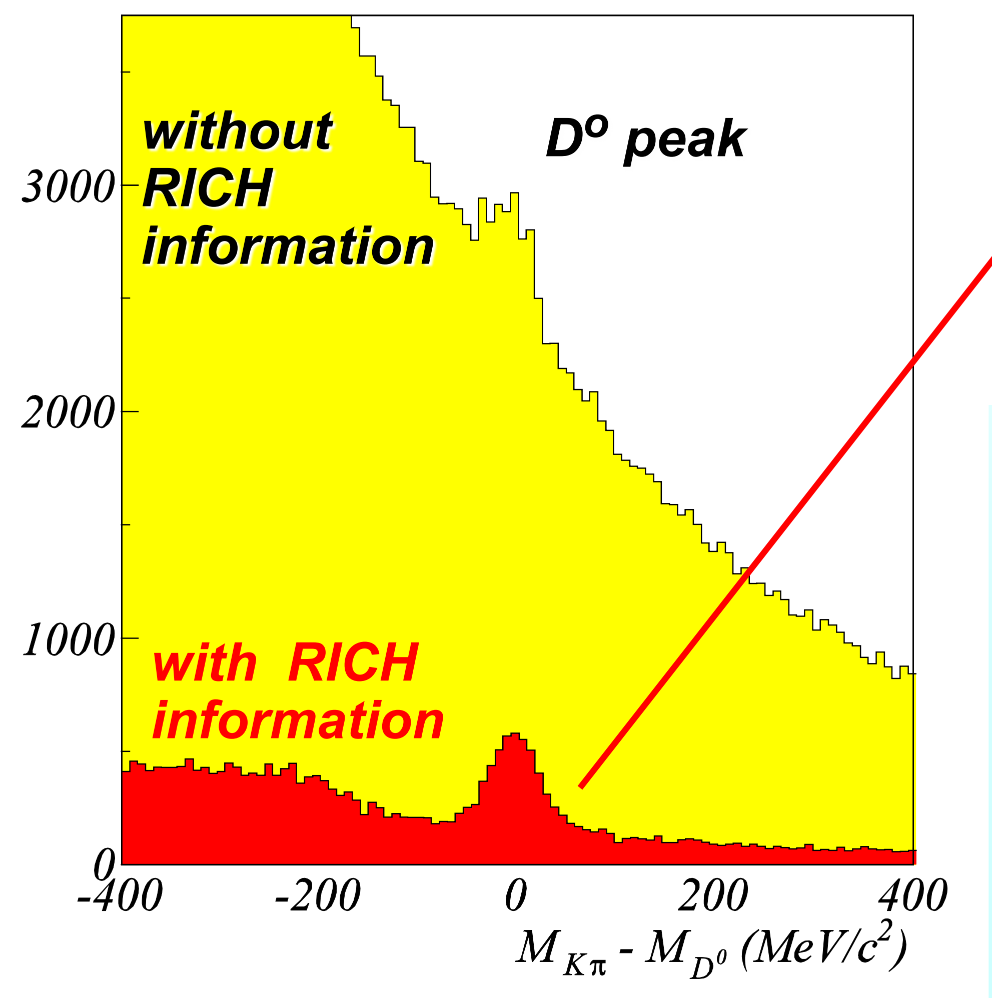
Identification and misidentification probability

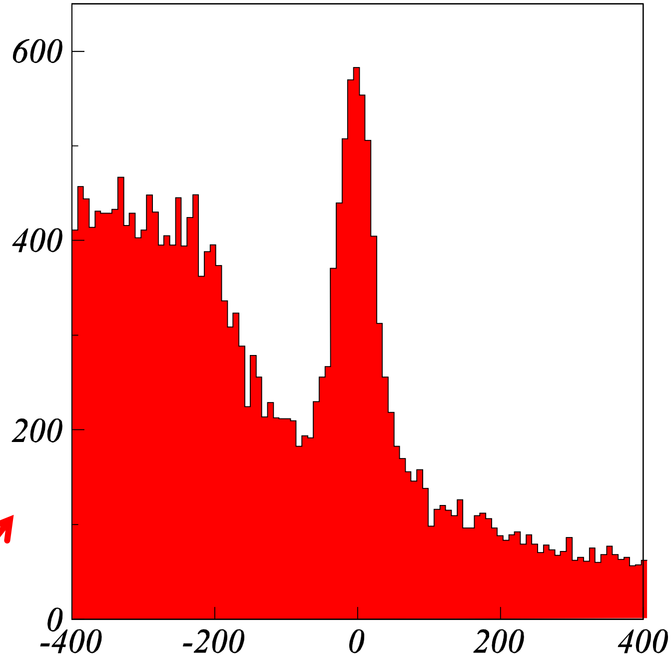


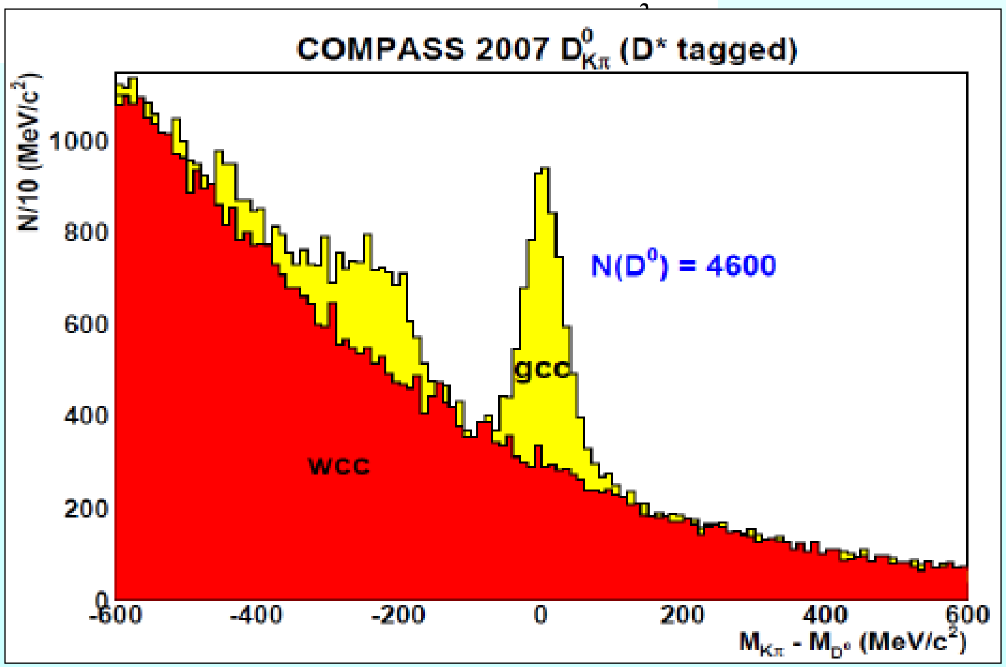
Purity of K samples



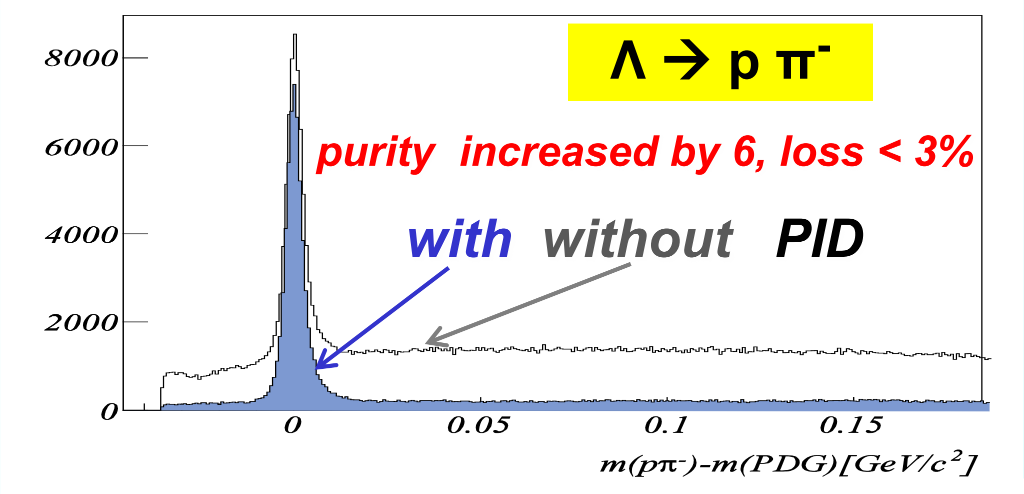
RICH PID information in the D° analysis







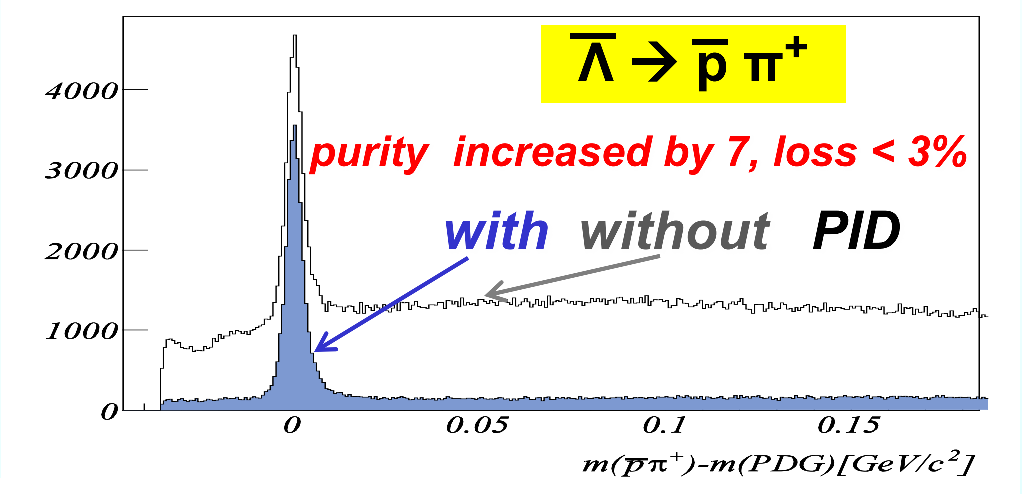
RICH PID information in Λ analysis



$\Lambda \rightarrow p\,\pi^-$

purity increased by 6, loss < 3%

with without PID

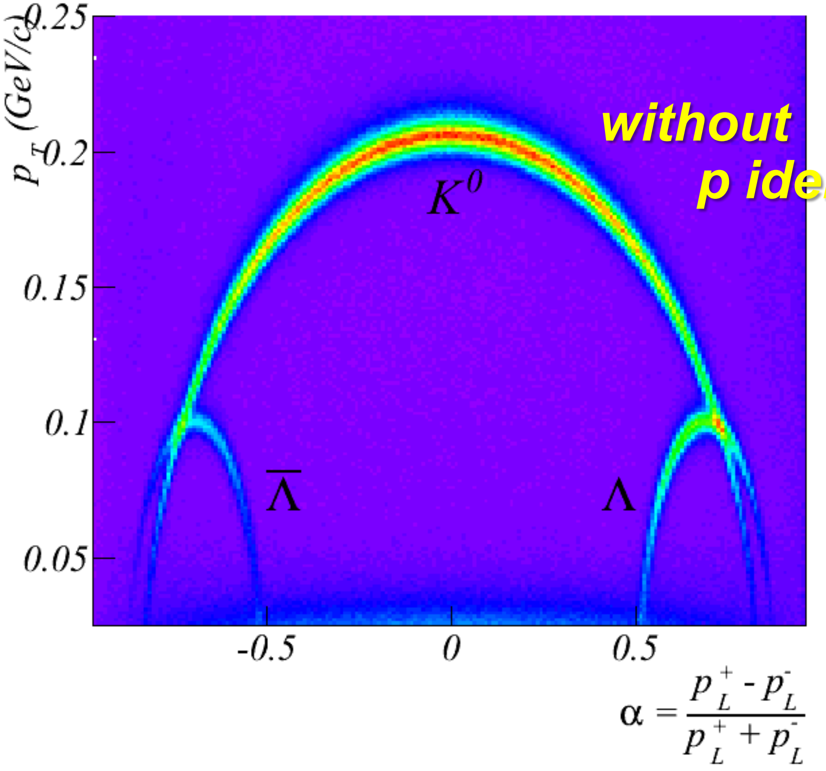


$\overline{\Lambda} \rightarrow \overline{p}\,\pi^+$

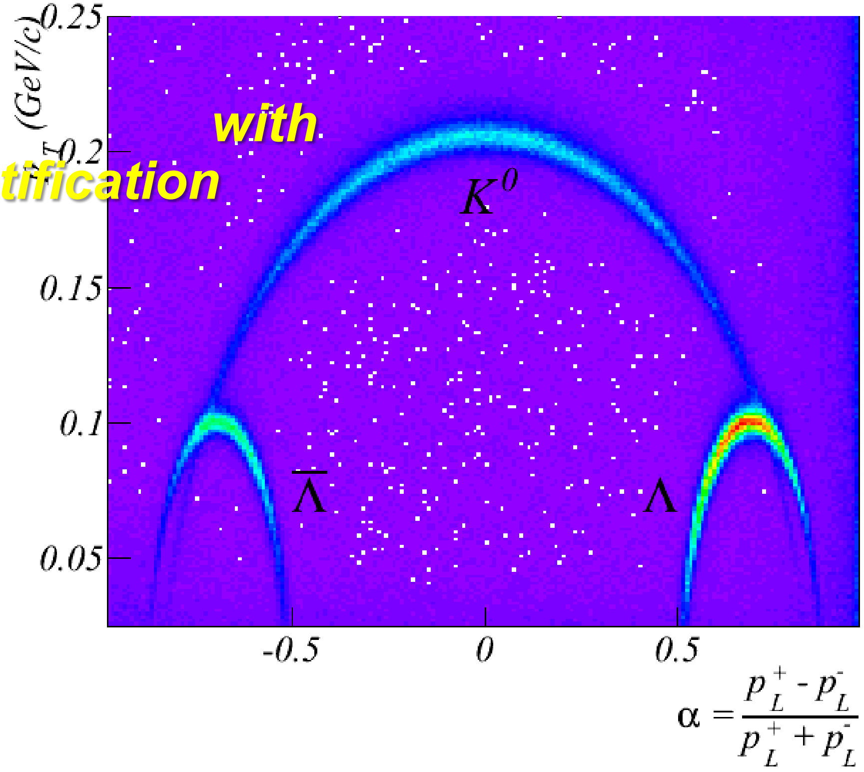
purity increased by 7, loss < 3%

with without PID

without p identification with



$\alpha = \frac{p_L^+ - p_L^-}{p_L^+ + p_L^-}$



$\alpha = \frac{p_L^+ - p_L^-}{p_L^+ + p_L^-}$