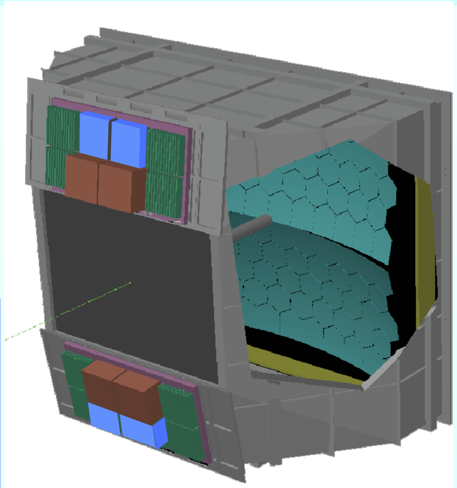
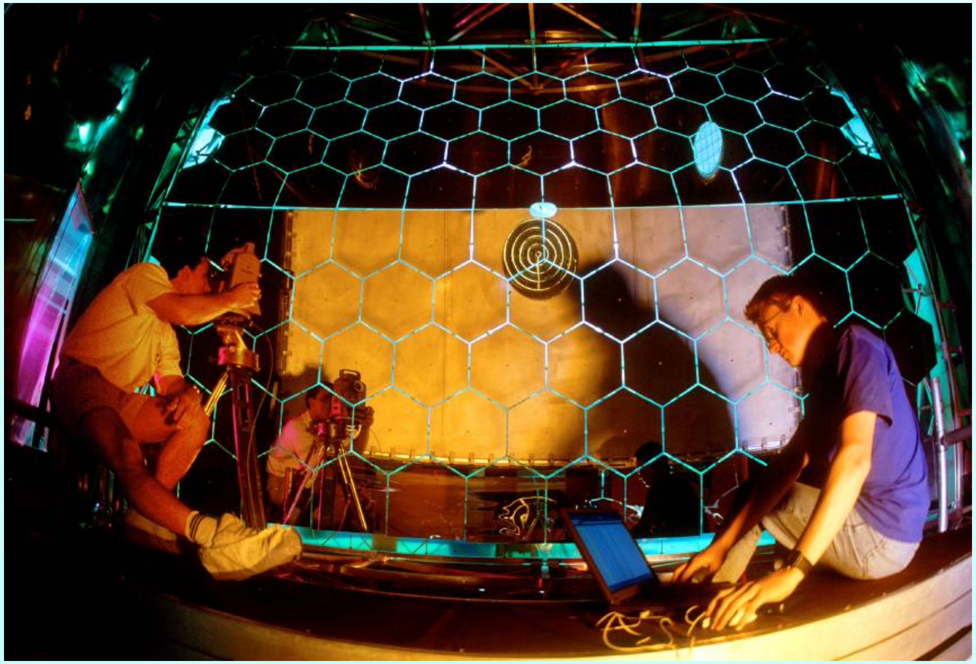
PID in COMPASS

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

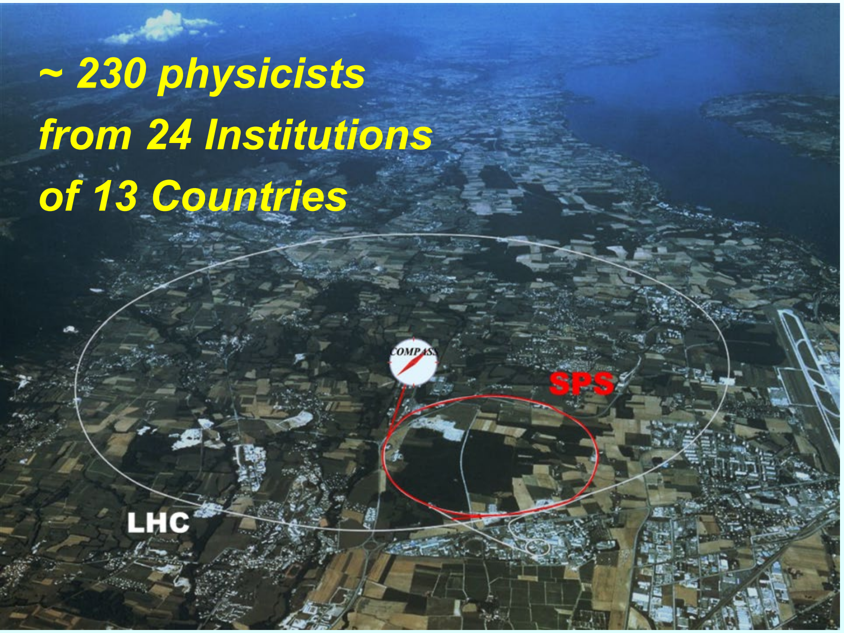
The MAPMT based detectors

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	Pion polarizability
Flavor decomposition	Diffractive and Central production
Transversity	Light meson spectroscopy
Transverse Momentum-dependent PDF	Baryon spectroscopy

COMPASS - II (2012 – 2018) …

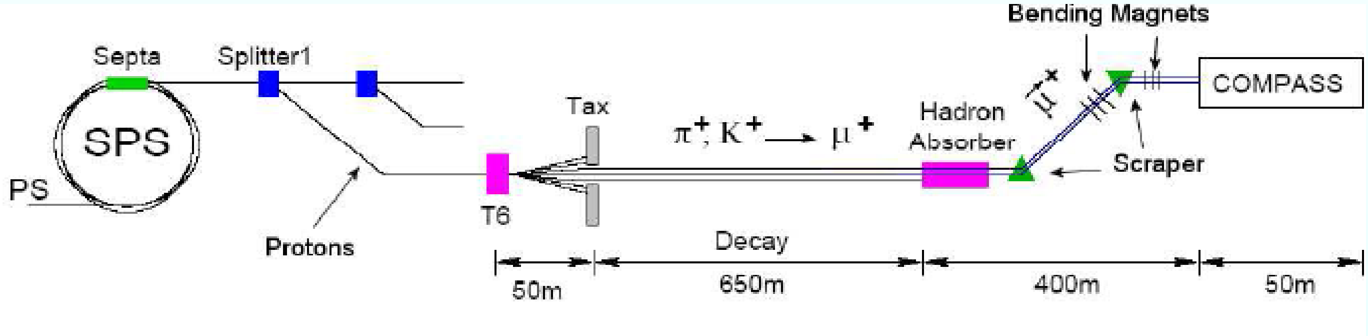
DVCS and HEMP	Pion and Kaon polarizabilities
Unpolarized SIDIS and TMDs	Drell-Yan studies

COMPASS data taking

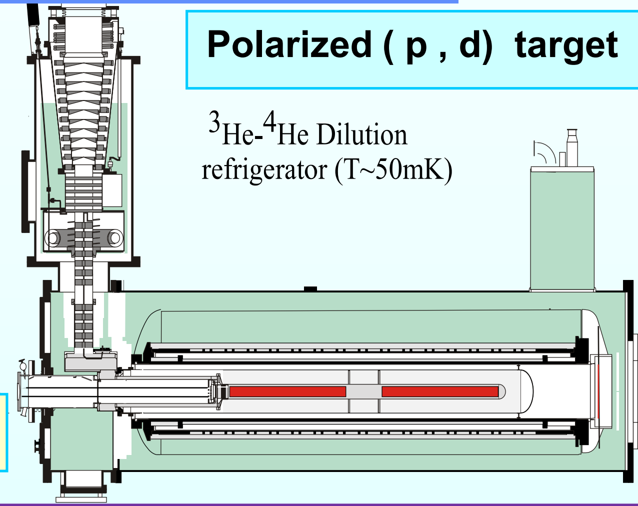
2002	nucleon structure with	160 GeV μ	L&T	polarised deuteron target
2003	nucleon structure with	160 GeV μ	L&T	polarised deuteron target
2004	nucleon structure with	160 GeV μ	L&T	polarised deuteron target
2005	*CERN accelerators shut down*			
2006	nucleon structure with	160 GeV μ	L	polarised deuteron 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



Polarized (p , d) target

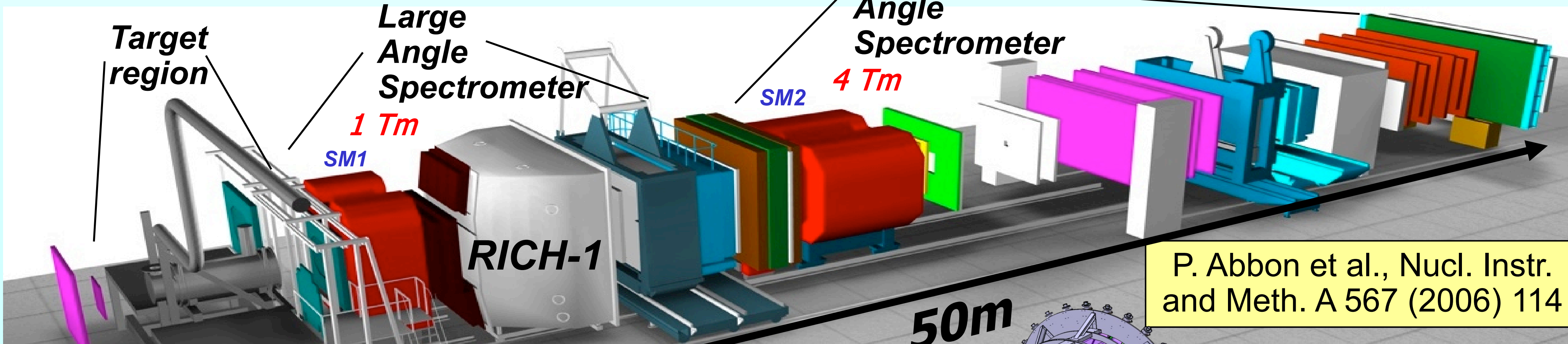


160 or 190 GeV/c μ^+ (or μ^-), $4 \cdot 10^8$ μ/spill, P_μ ~ 80%
190 GeV/c p, π^+, π^- , K^+ ,K^- beams

Various targets used

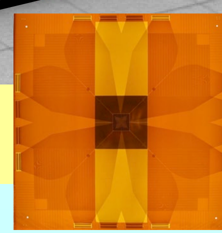
first GEMs and Micromegas used in a HEP Experiment

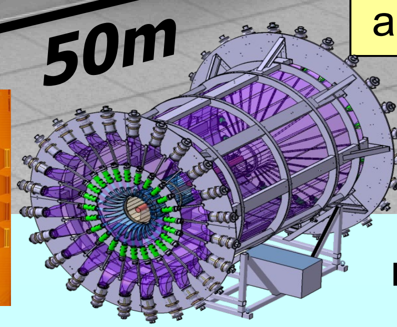
DAQ: 40 kB, 50 kHz, O(PB)



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

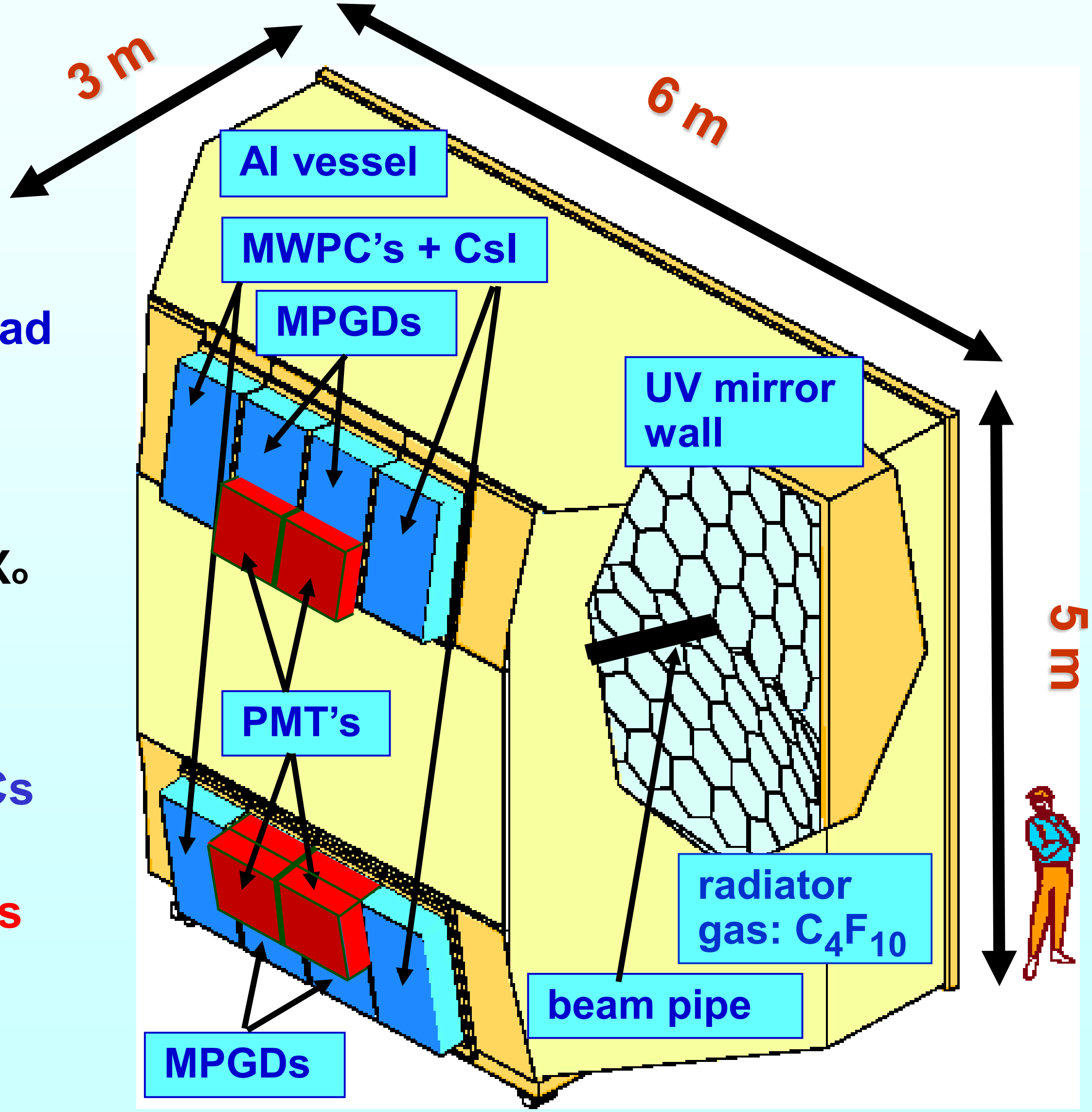
detector designed in 1996

in operation since 2002 with MWPCs

upgraded in 2006 with MAPMTs,

in 2016 with THGEMs + Micromegas

total investment: ~ 5 M €



COMPASS

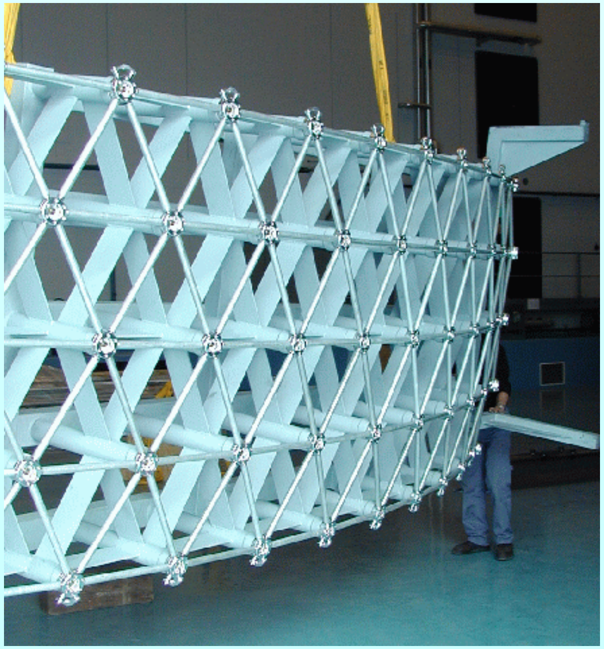
the vessel and the mirror support wall

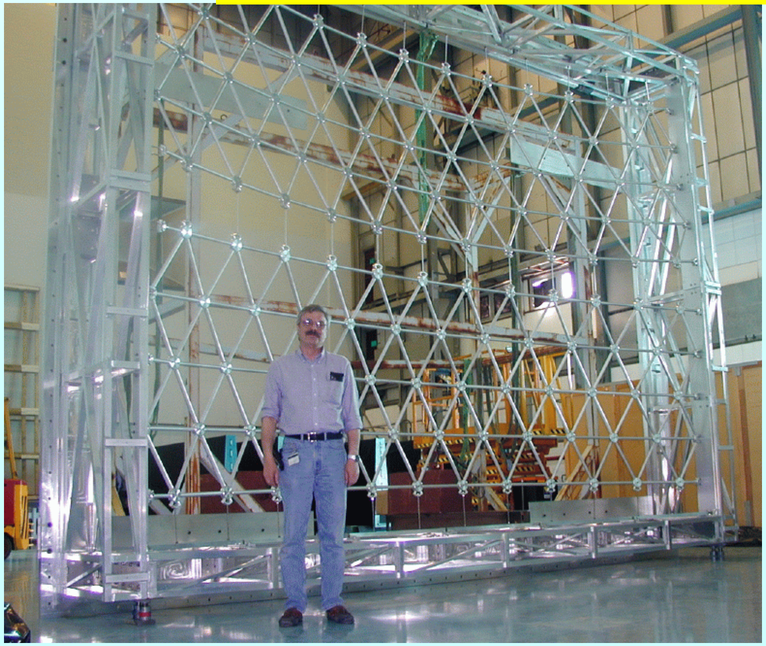
INFN Istituto Nazionale di Fisica Nucleare

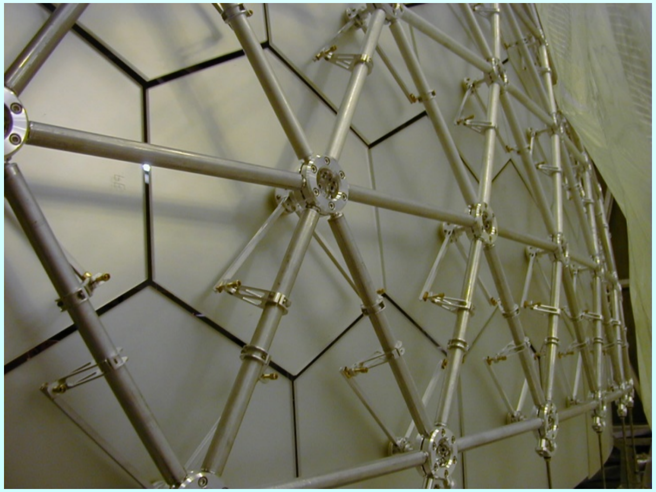
Large and accurate mechanics

light front and rear windows

100 m of O-rings, 80 m^3 C_4F_{10}



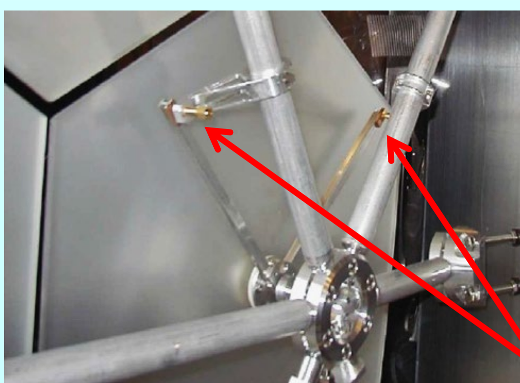


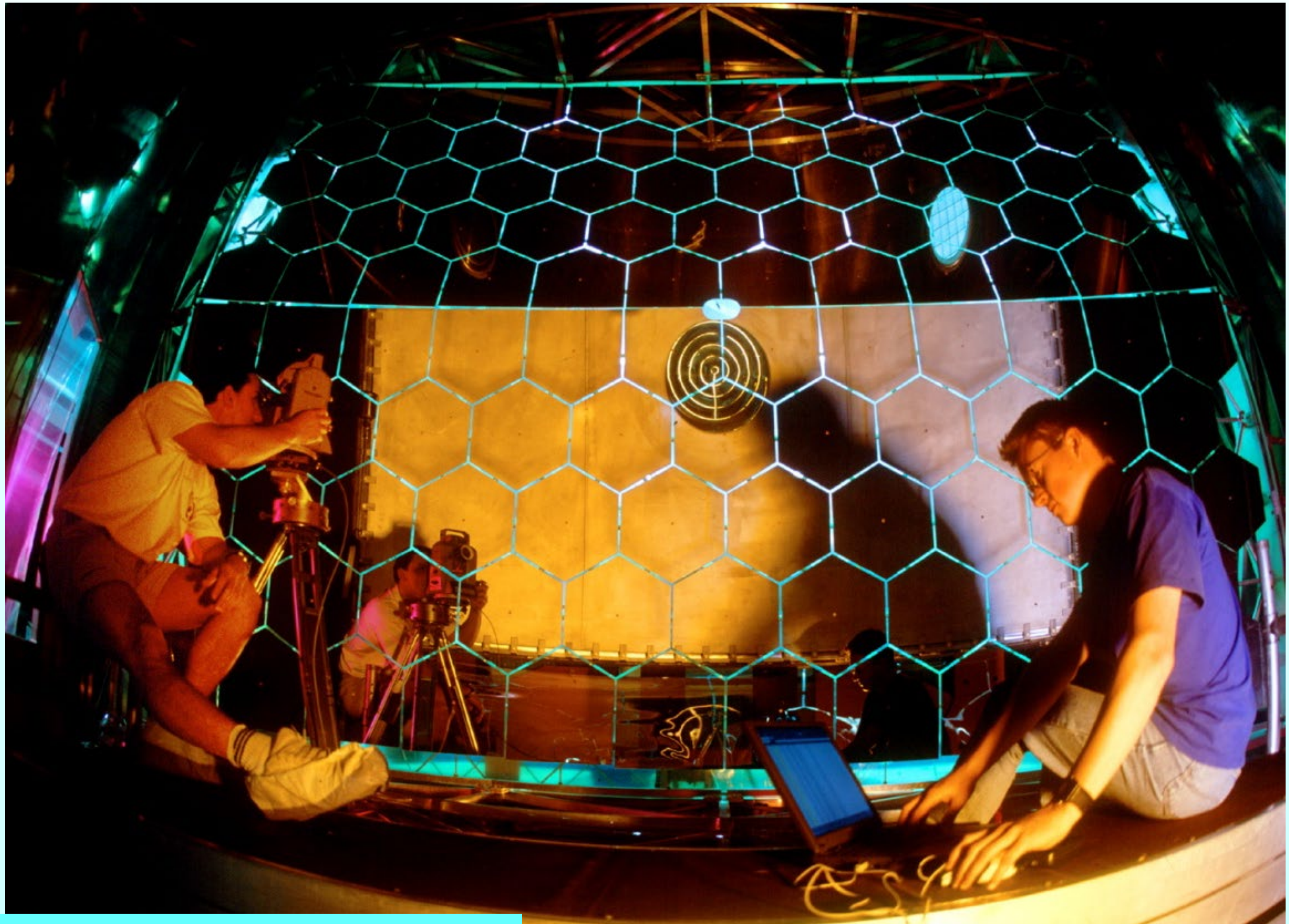


COMPASS

mirrors and alignment

INFN Istituto Nazionale di Fisica Nucleare



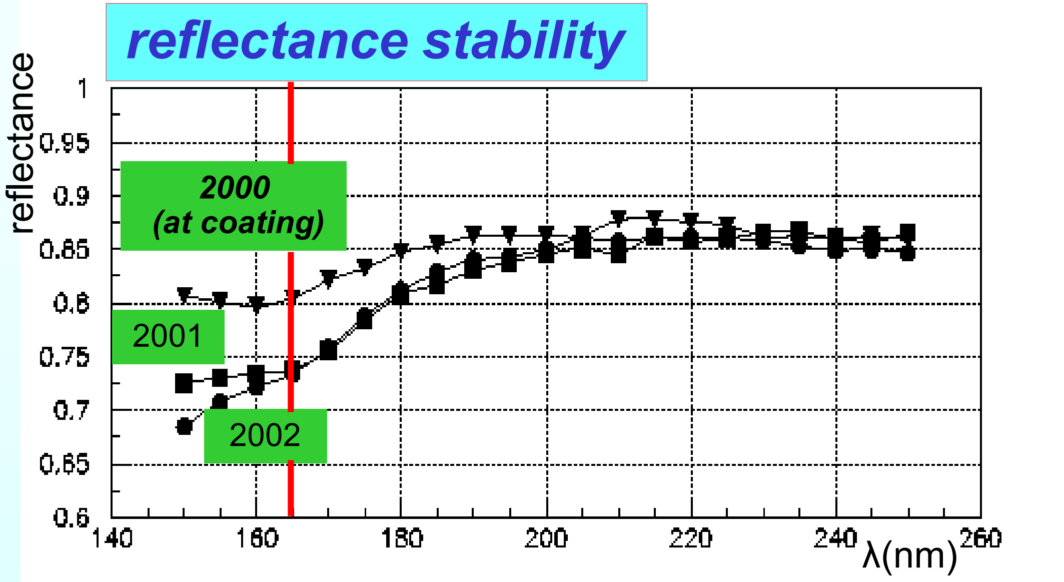


$21\ m^2$, 116 mirrors
radius: 6.6 m

angular regulation screws

measurement of mirror alignment
via laser autocollimation

problems with mirrors



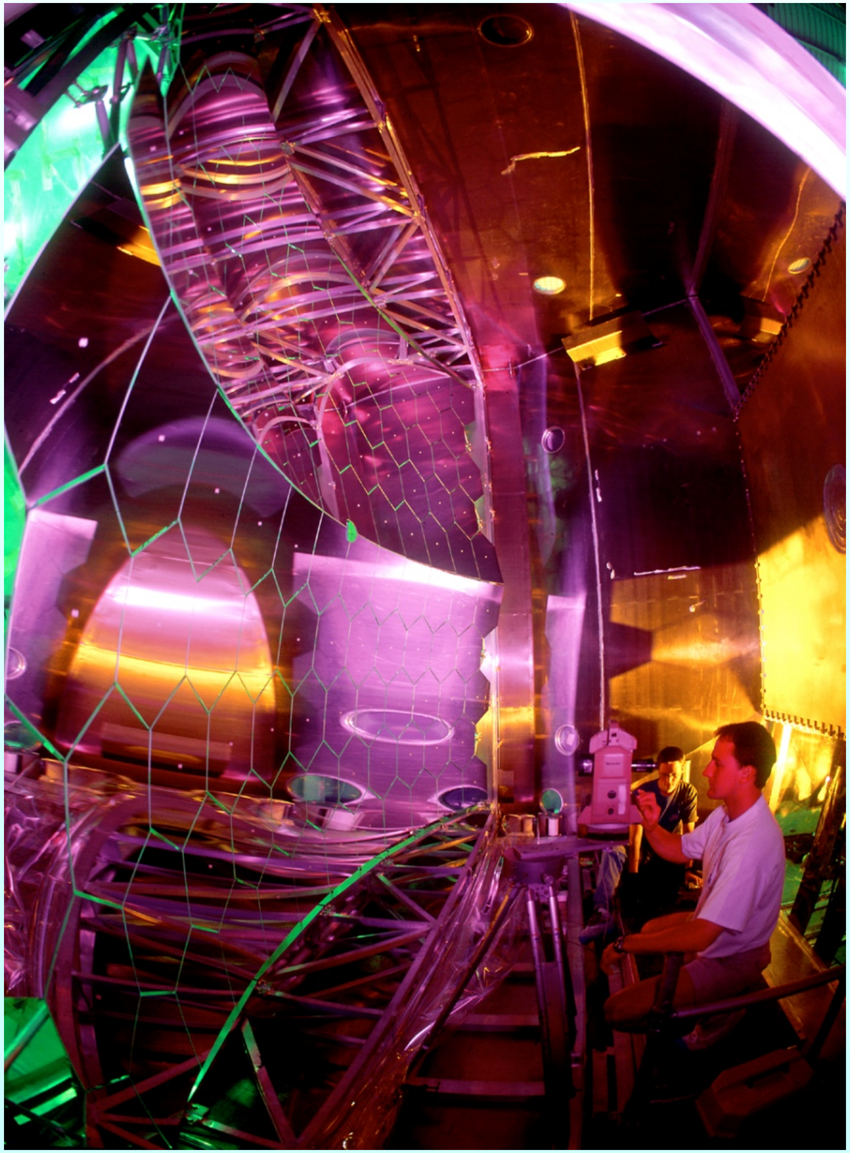
initial alignment accuracy: ~100 μrad

surveying accuracy: ~ 60 μrad

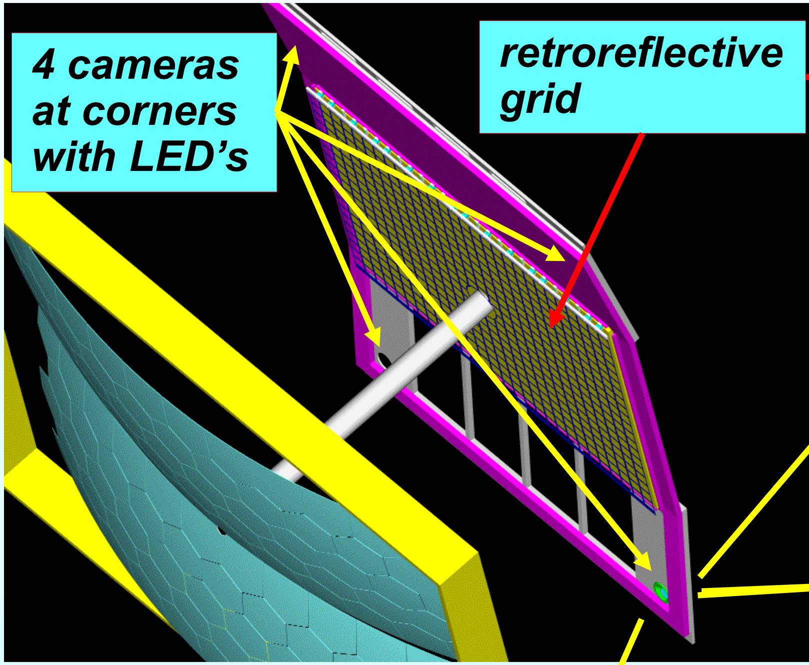
alignment instability: 1 mrad (first year)

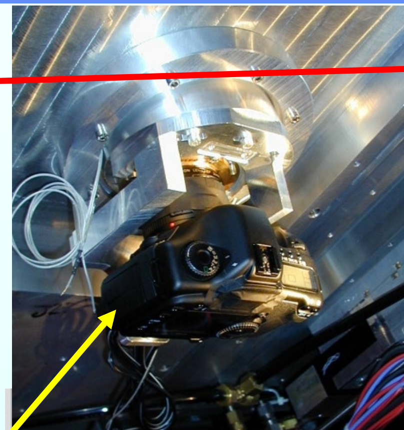
alignment instability: ~ 100 μrad after 2002

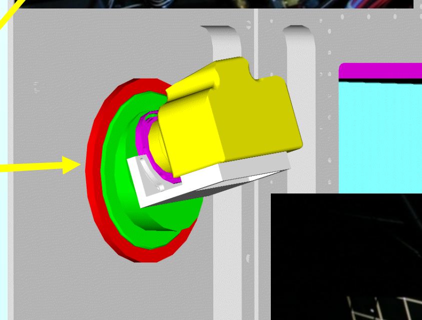
alignment check → surveyors inside → opening the vessel: contamination, dust, risky operations, work load, expenses.

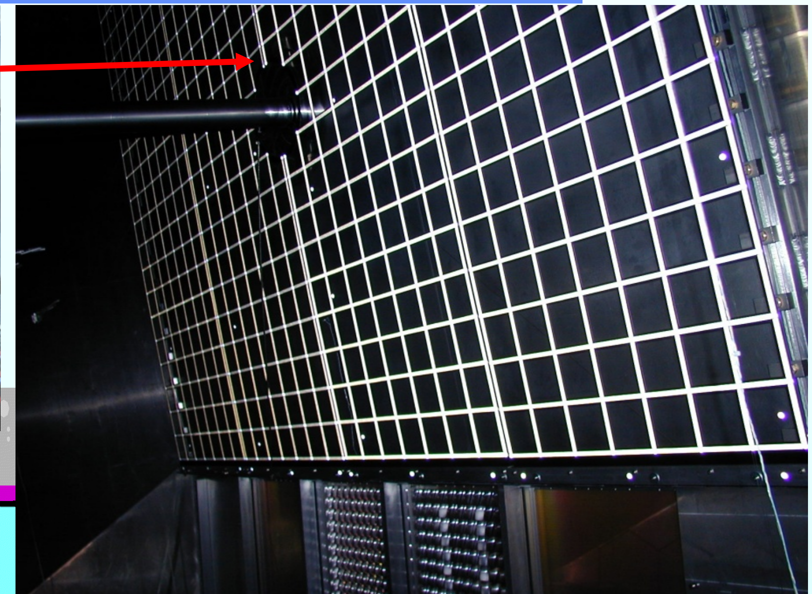


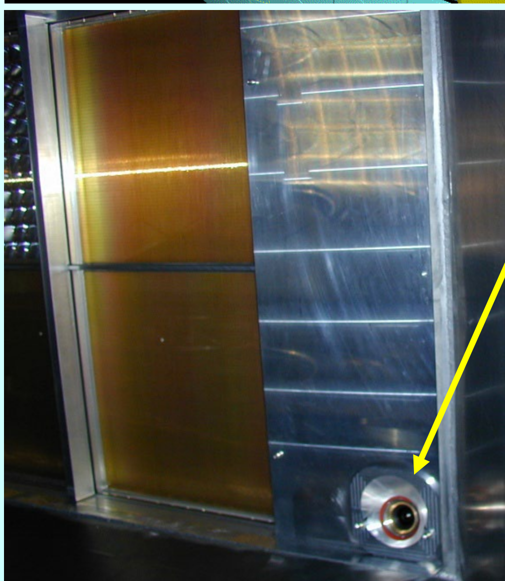
CLAM: mirror alignment monitoring







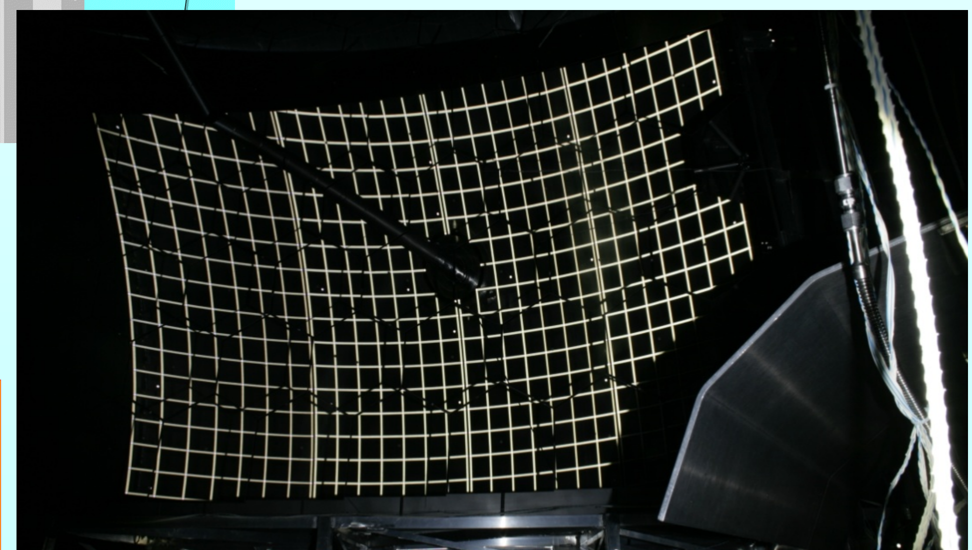




CLAM system in operation since 2007

accuracy: 30 μrad

photogrammetric calibration of cameras → measurement of absolute mirror tilt

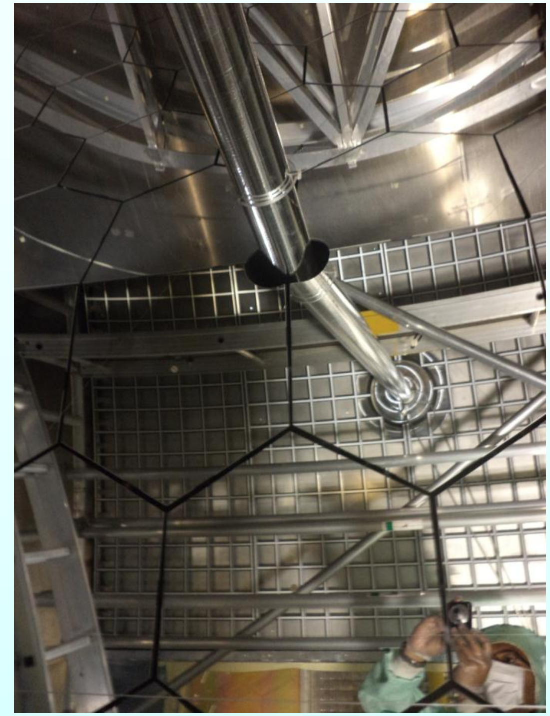


"CLAM" picture for mirror monitoring

2012: a new light beam pipe

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

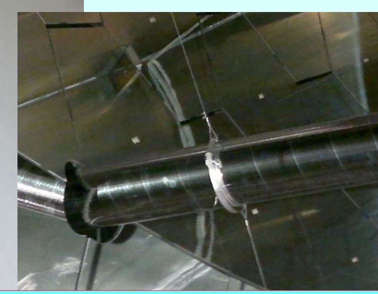
New pipe: 0.044 X_0 for orthogonal crossing

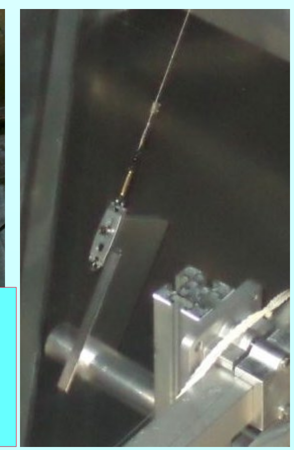


Material: 4 x 25 μm thick Mylar + 200 nm Al coating (by Sheldahl) ***winding by Lamina (6 μm glue)***

1 microflange for suspension + gas connection + window holding

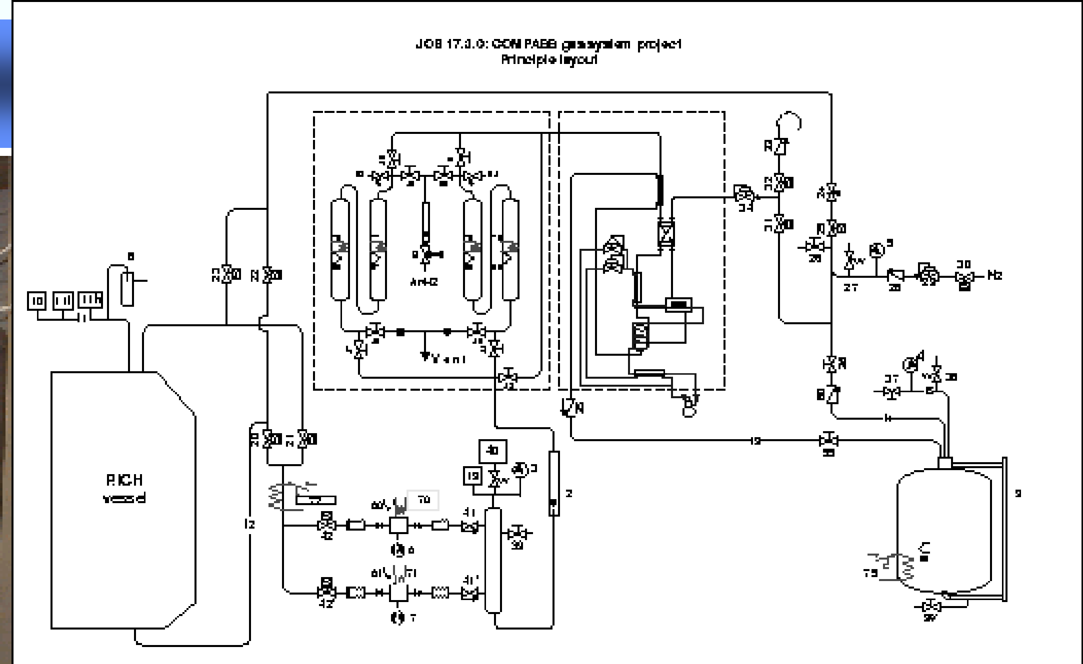
weight = 15 g



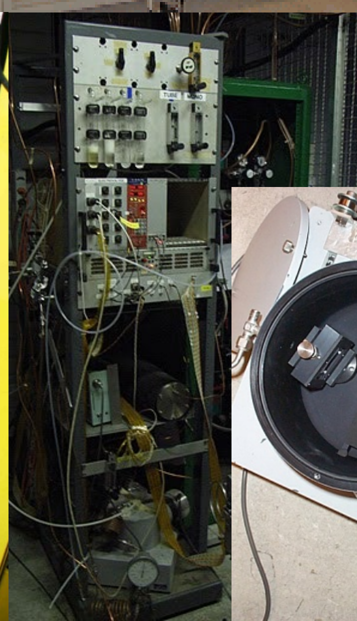


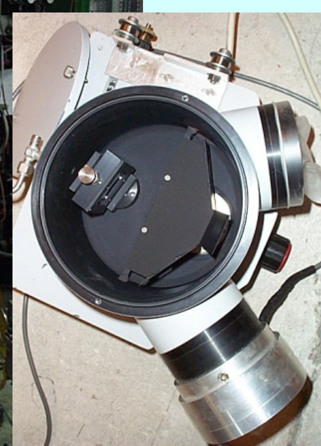
Suspension and tensioning system:
1 x 7 wires ss rope 30 μm diam.
1 microflange and 1

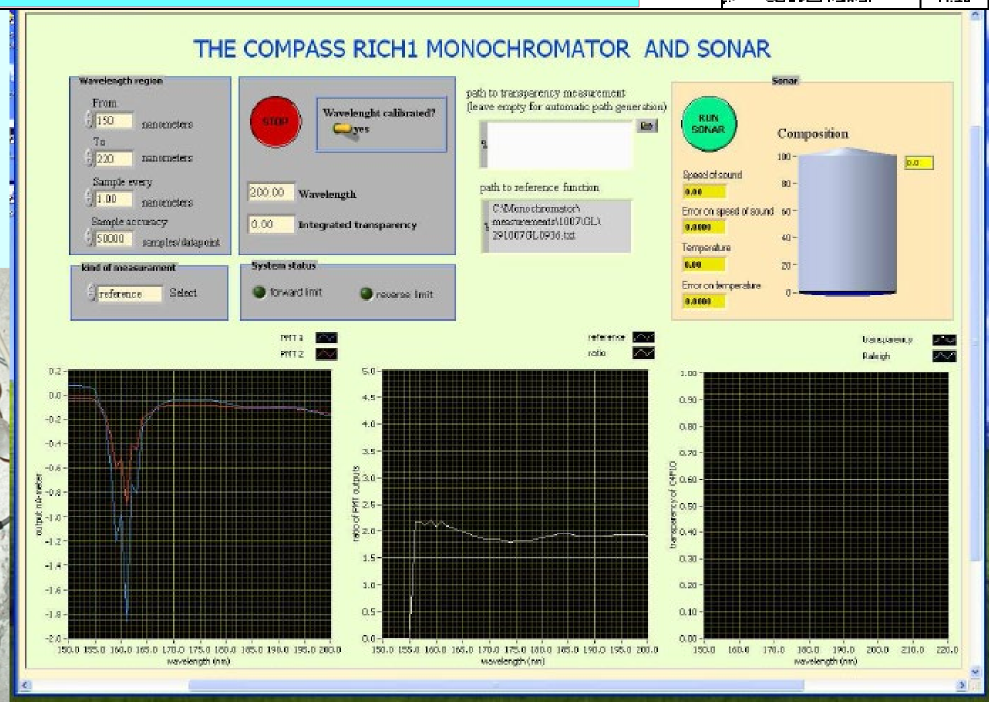
The radiator gas system



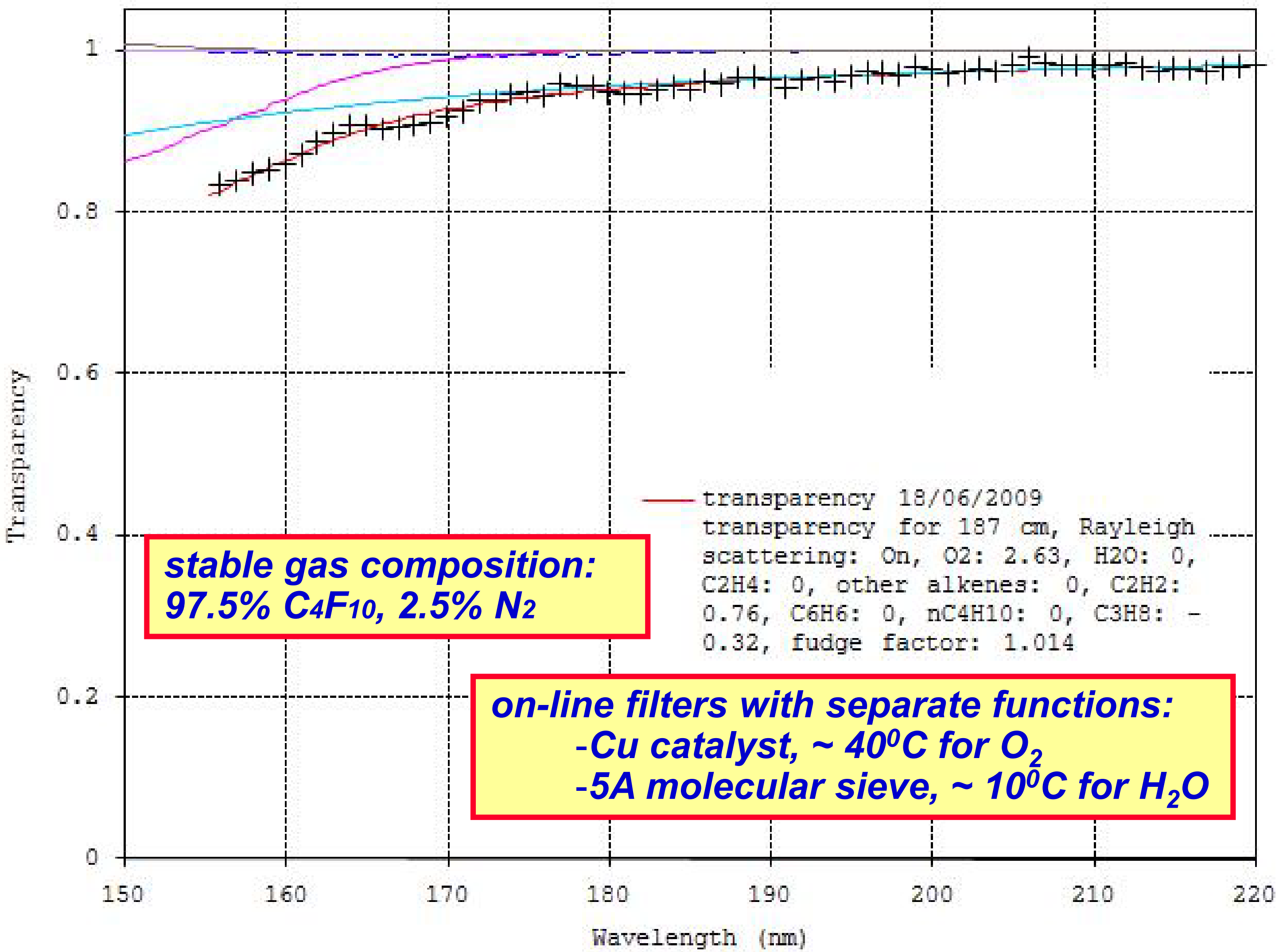
has excellent performance







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, ~ 40^0C for O_2**
- **5A molecular sieve, ~ 10^0C 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

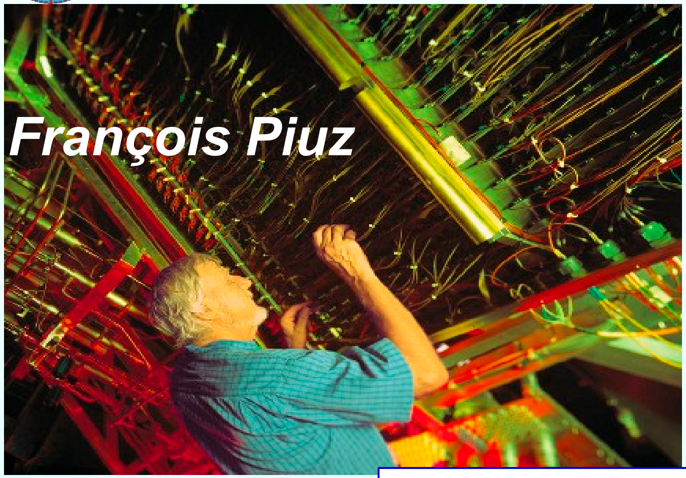
It integrates contaminants: some can be accepted (N_2, Ar), others need continuous filtering out (O_2, H_2O) ; the filters have limited capacitance (significant contaminations fill them quickly); regeneration takes several days

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

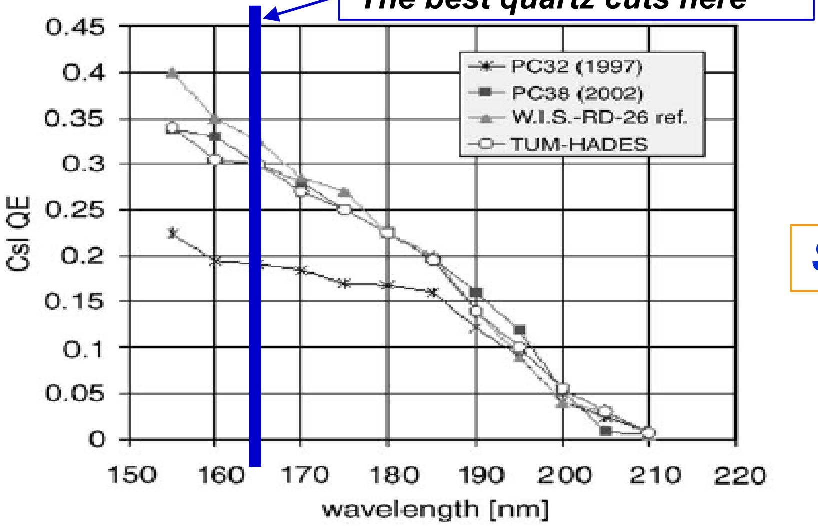
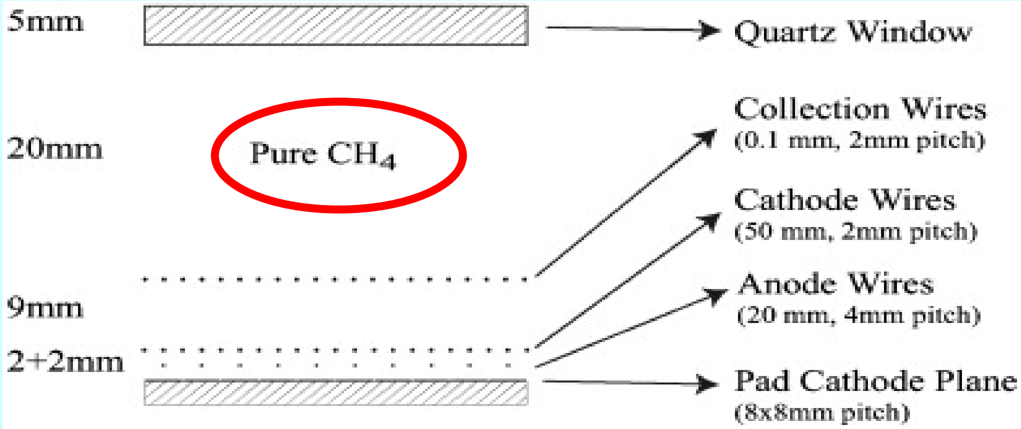


Fig. 1. The QE of CsI PCs produced at CERN for ALICE and at TUM for HADES, compared to that measured at the W.I.S. on small samples (reference for RD-26). PC32 is one of the four PCs equipping the ALICE-RICH prototype used in STAR at BNL.

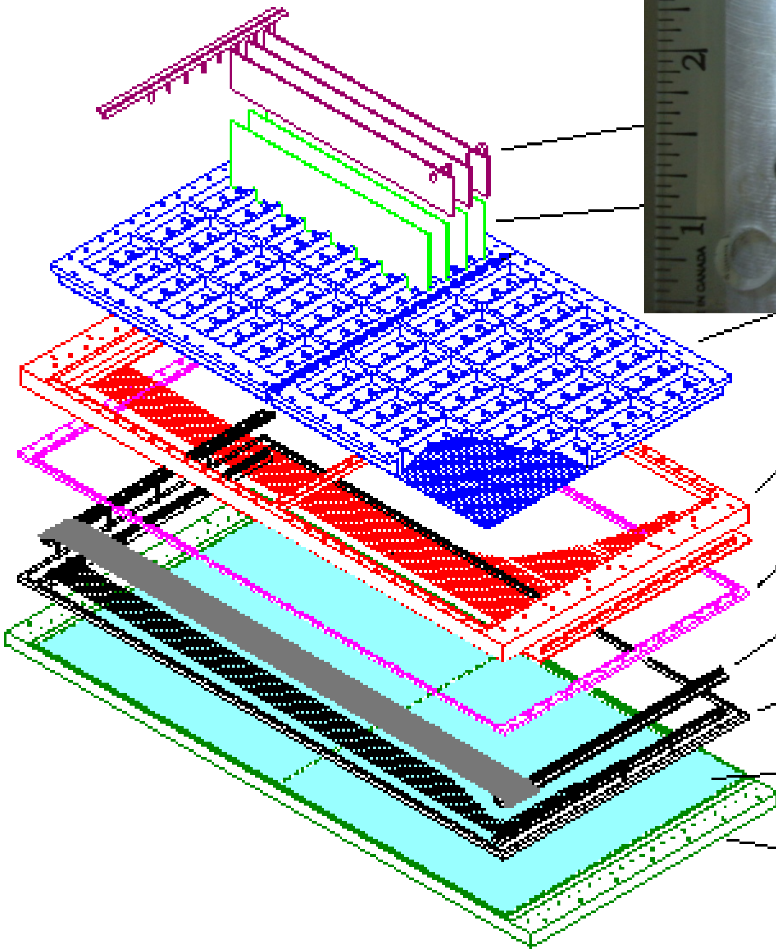
A. Di Mauro, NIM A 525 (2004) 173.

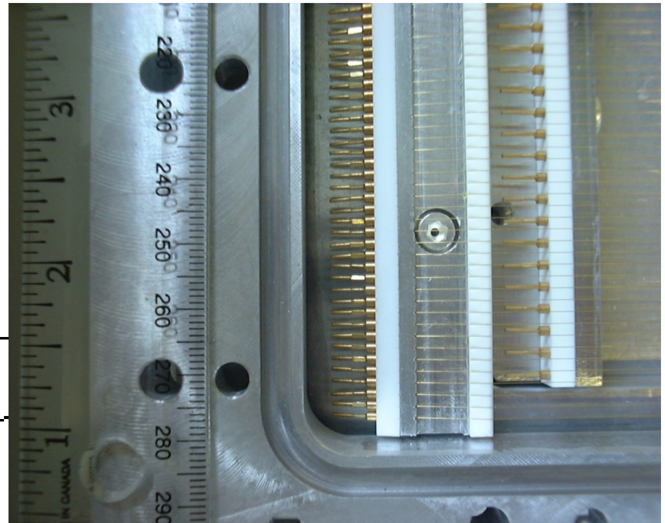
Schematic structure of the COMPASS Photon Detector:



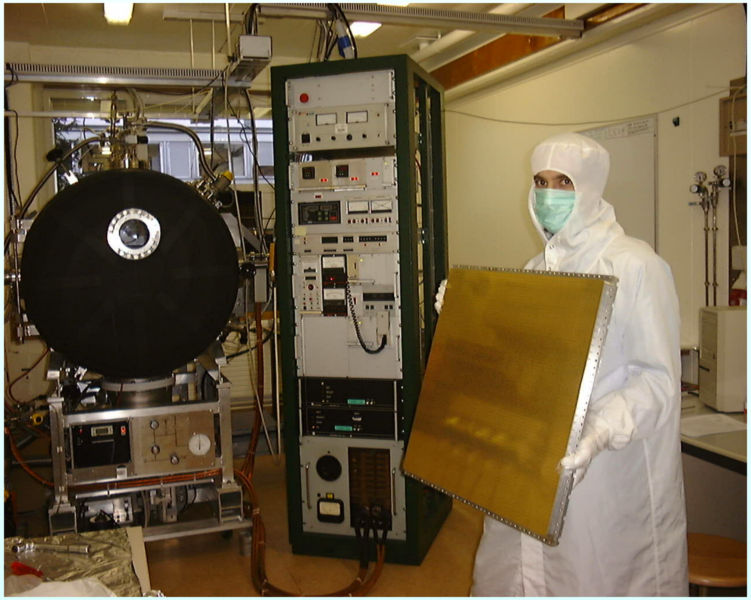
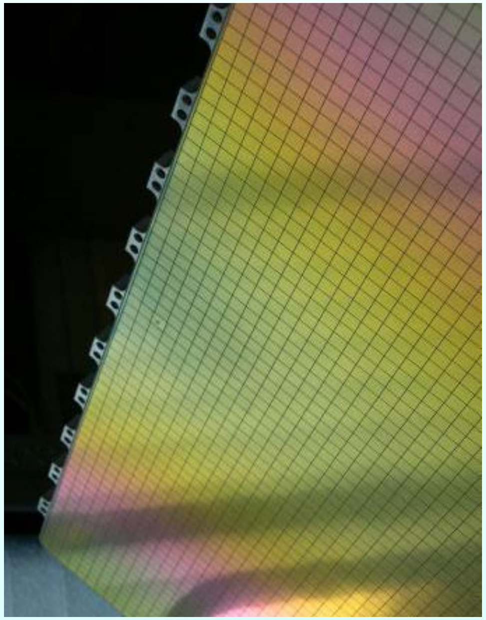
COMPASS: 8 MWPC's with CsI

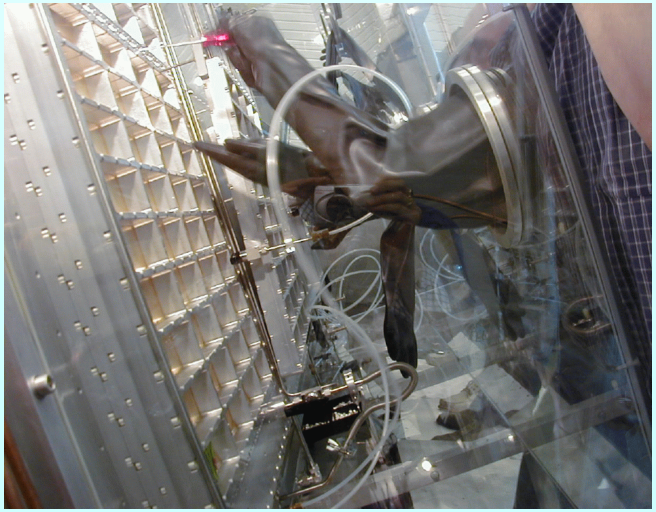
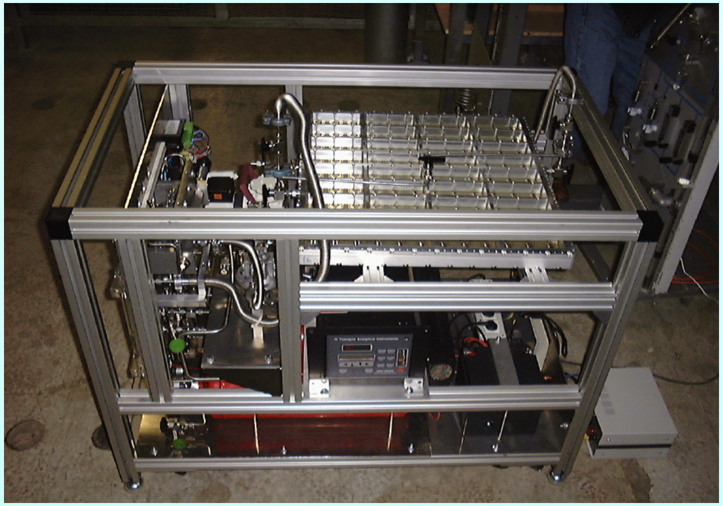
built in 1999 – 2000, after prototypes tests





The CsI photocathodes

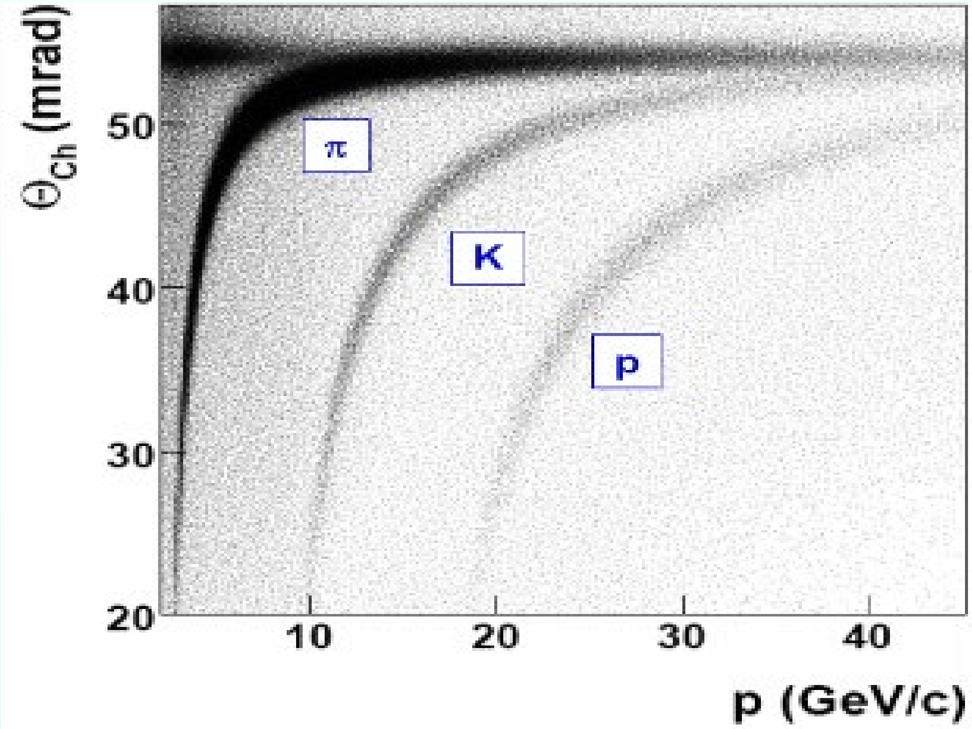



Good performance in low gain configuration

- *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

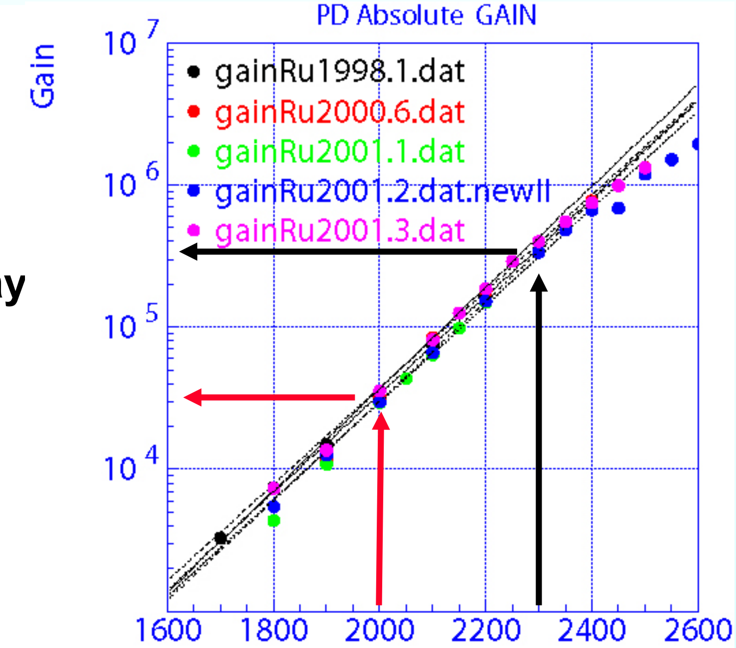
(in spill→ ph. flux: 0 - 50 kHz/cm^2 , mip flux: ~1 kHz/cm^2)

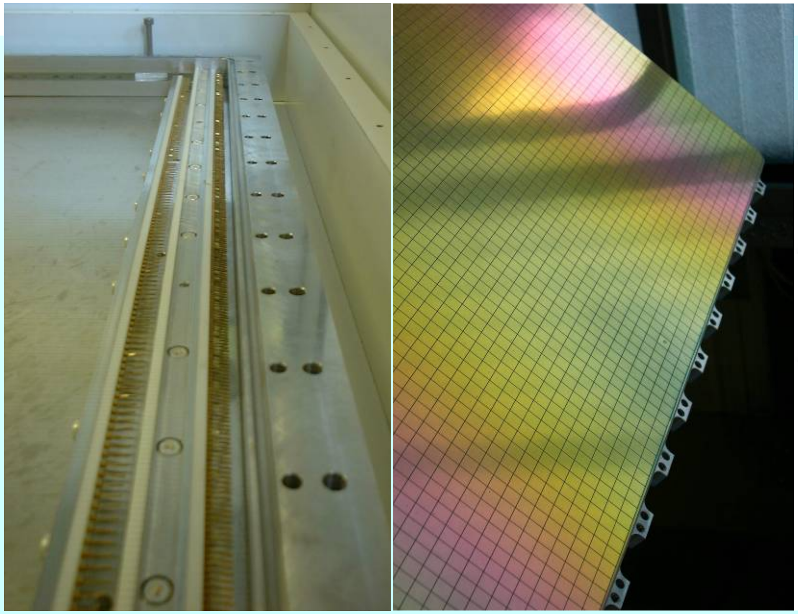
Whenever a severe discharge happens, recovery takes ~1 day

2) **Photocathode aging:**

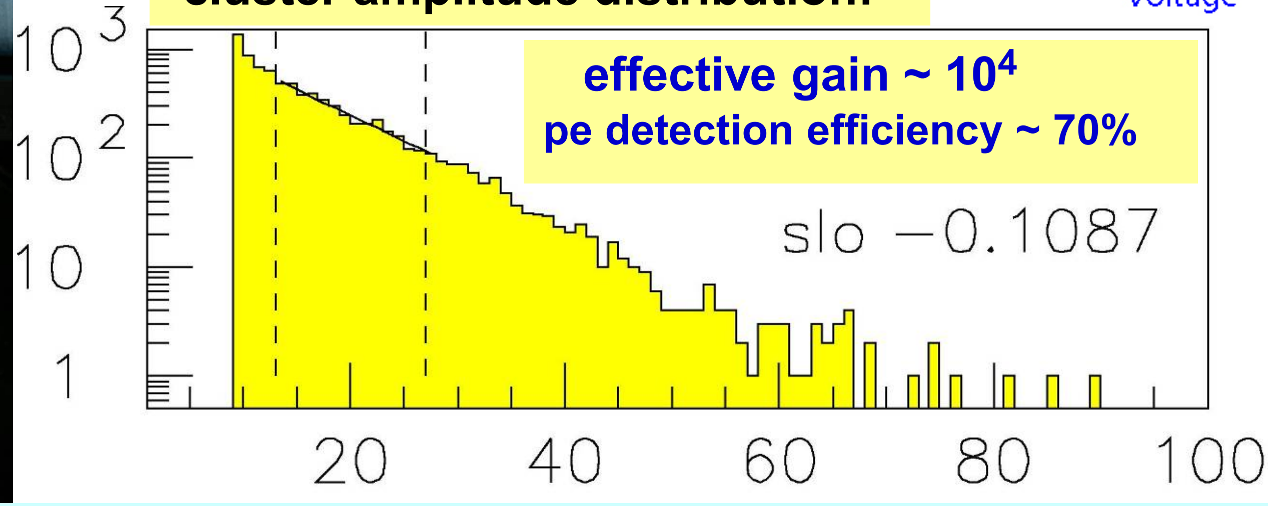
- our information from accidental contamination

- very detailed study by Alice team





cluster amplitude distribution:

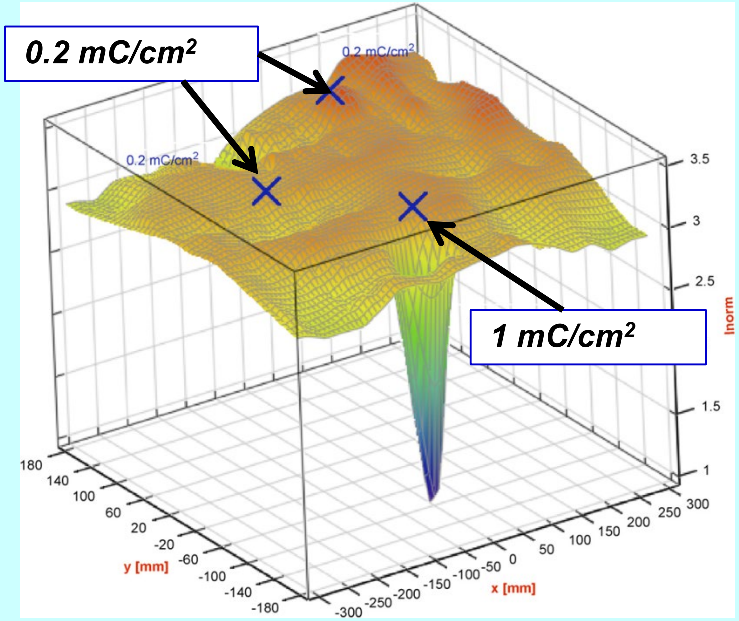


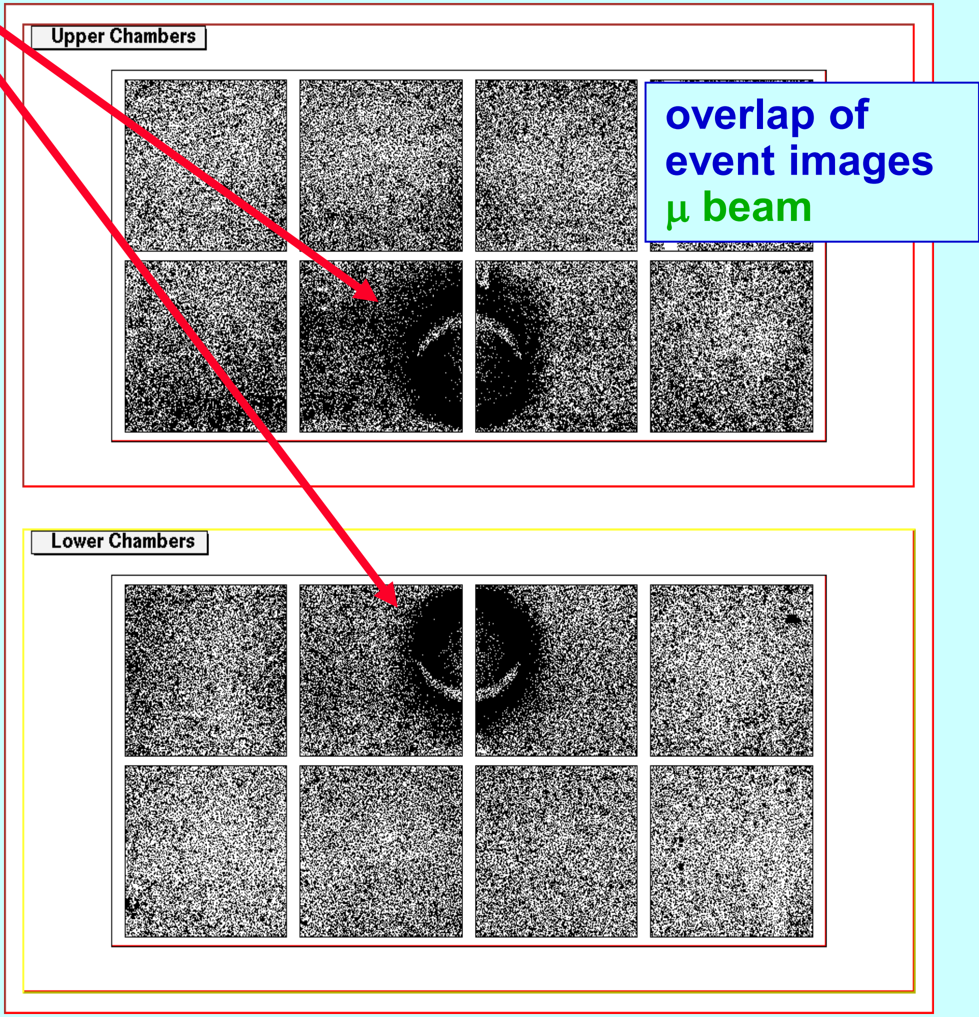
the central region before 2006

THE EXPERIMENTAL ENVIRONMENT

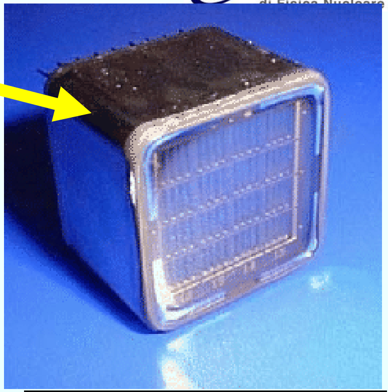
huge uncorrelated background related to the memory of the MWPCs + read-out

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



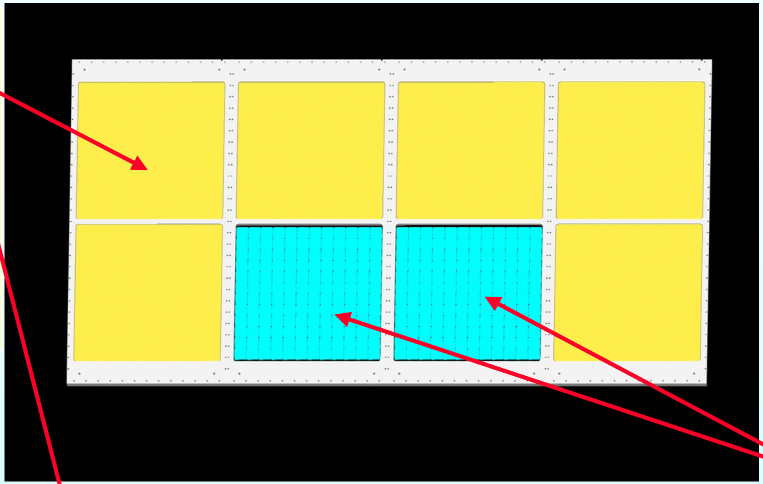


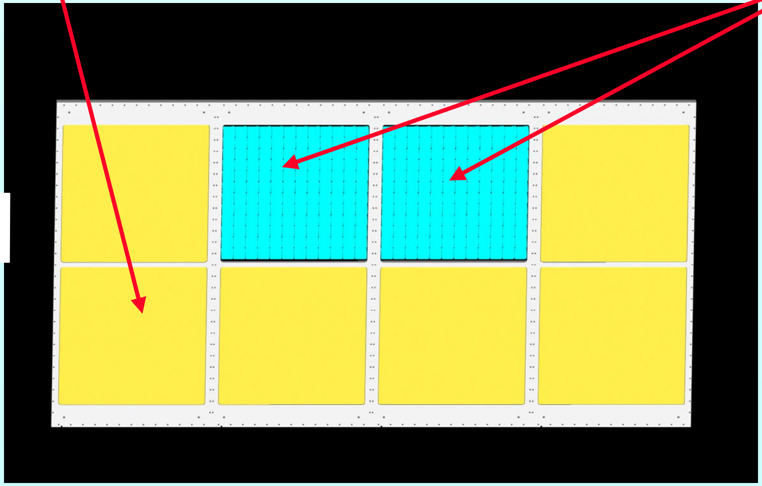
upgrade of RICH-1 with MAPMT's in the central region (2006)

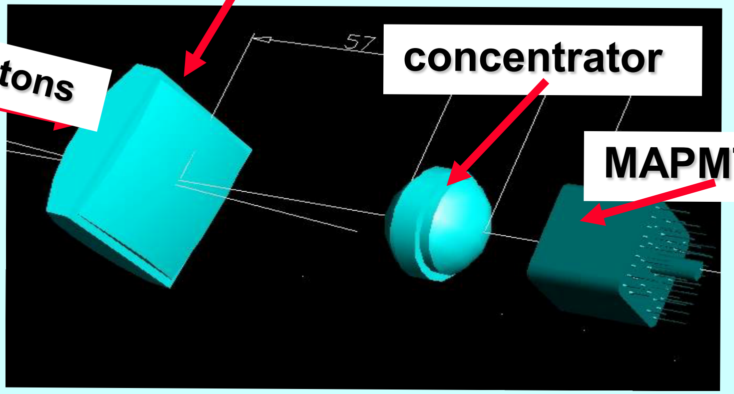


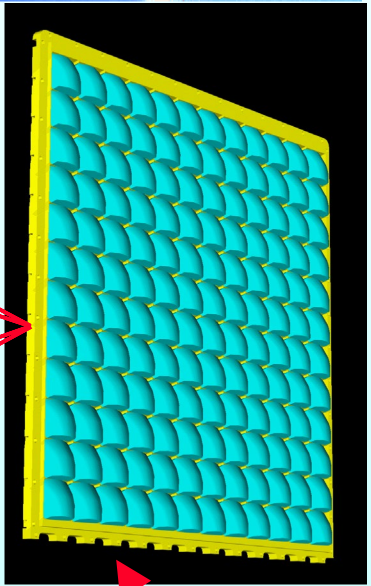
12 outer CsI cathodes: change electronics (use APV25-S1)

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







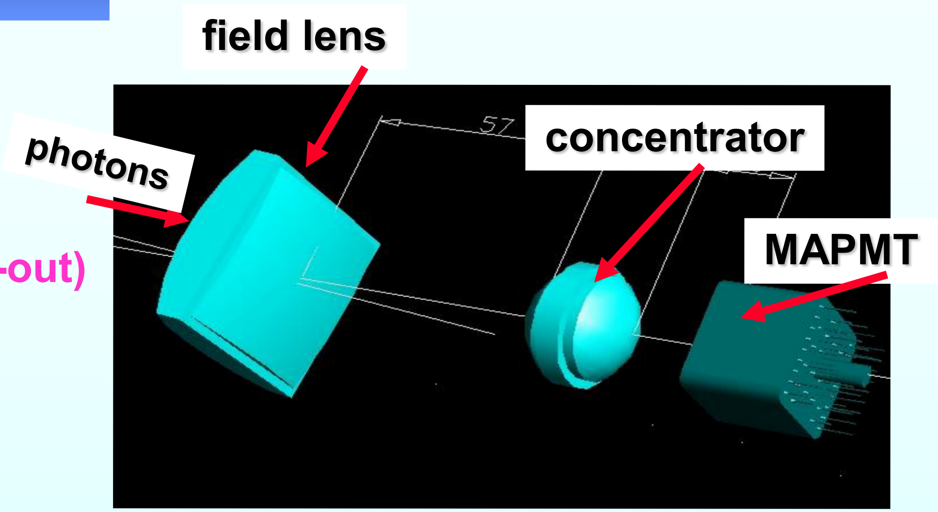


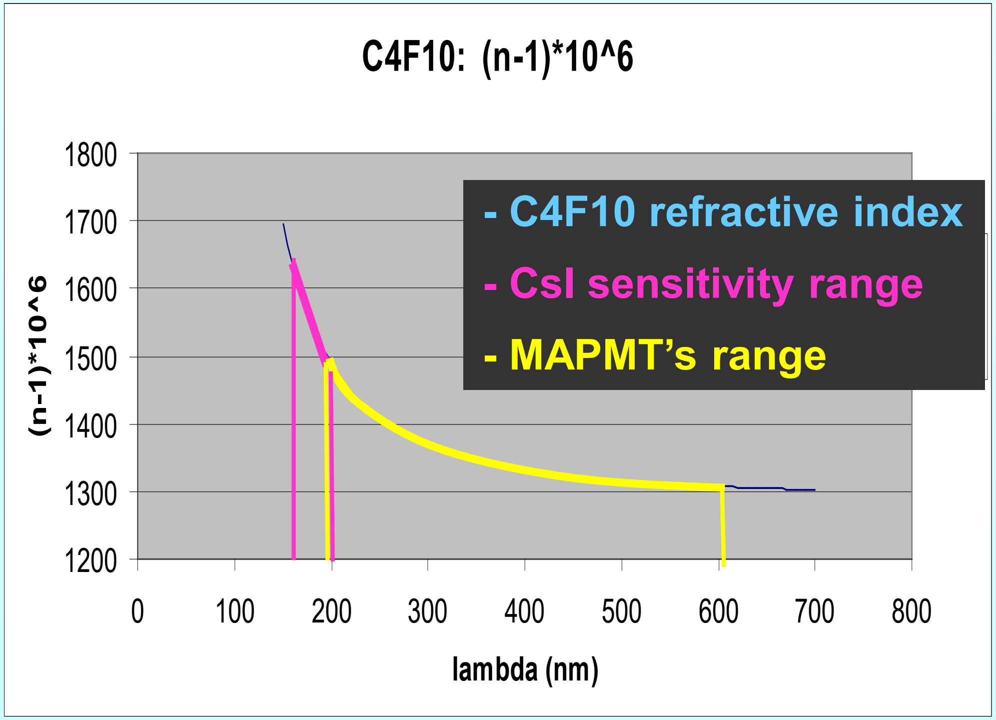
Same mechanics as CsI photo-cathode frame

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





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

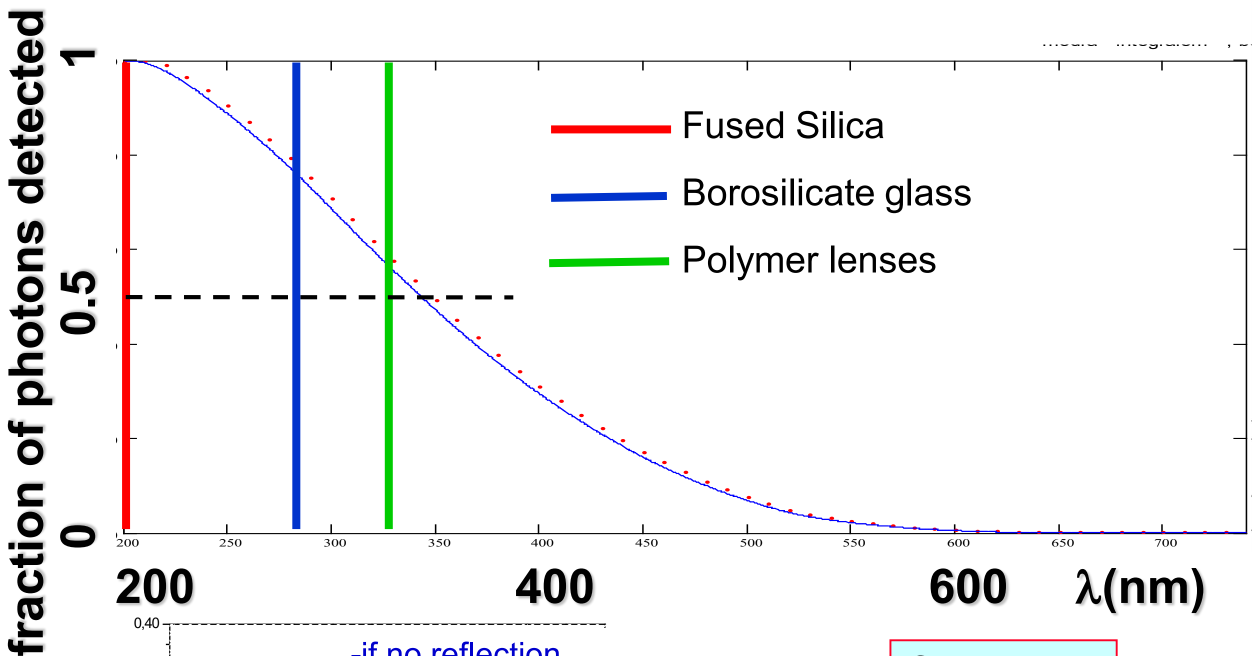
couple to a read-out system able to guarantee efficiency, high rate operation and to preserve time resolution

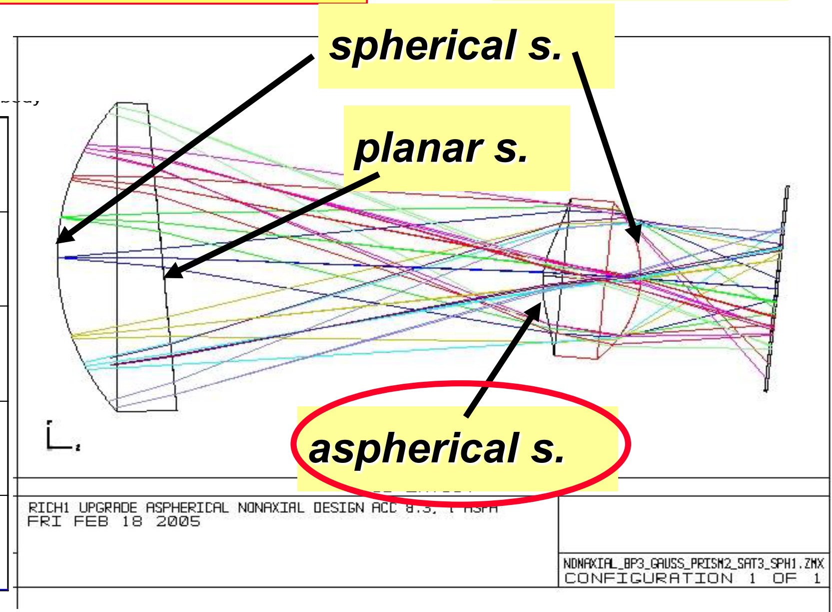
THE LENSES

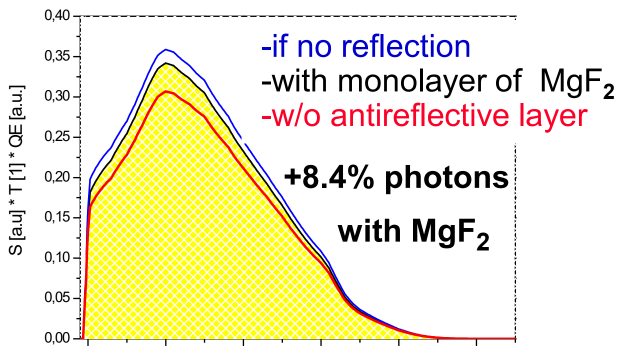
$$\int_{\lambda}^{800} QE(\lambda)\cdot S(\lambda)\cdot d\lambda \Big/ \int_{200}^{800} QE(\lambda)\cdot S(\lambda)d\lambda$$

material: fused silica, Corning 7980,

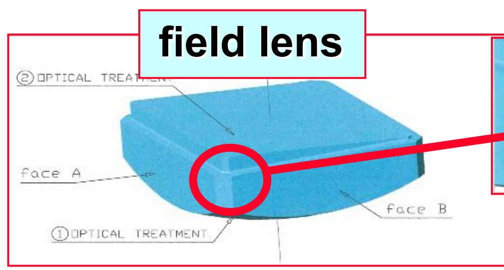
ZEMAX optimization:

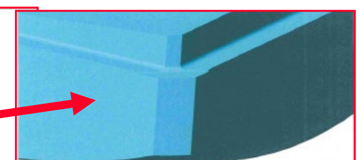




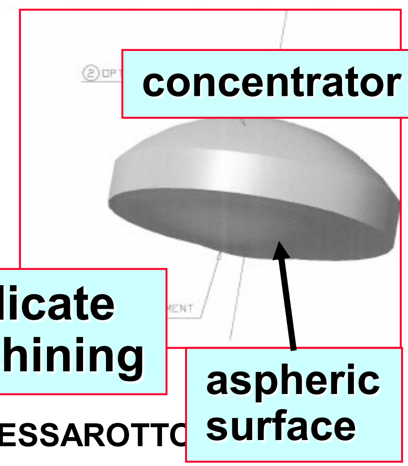


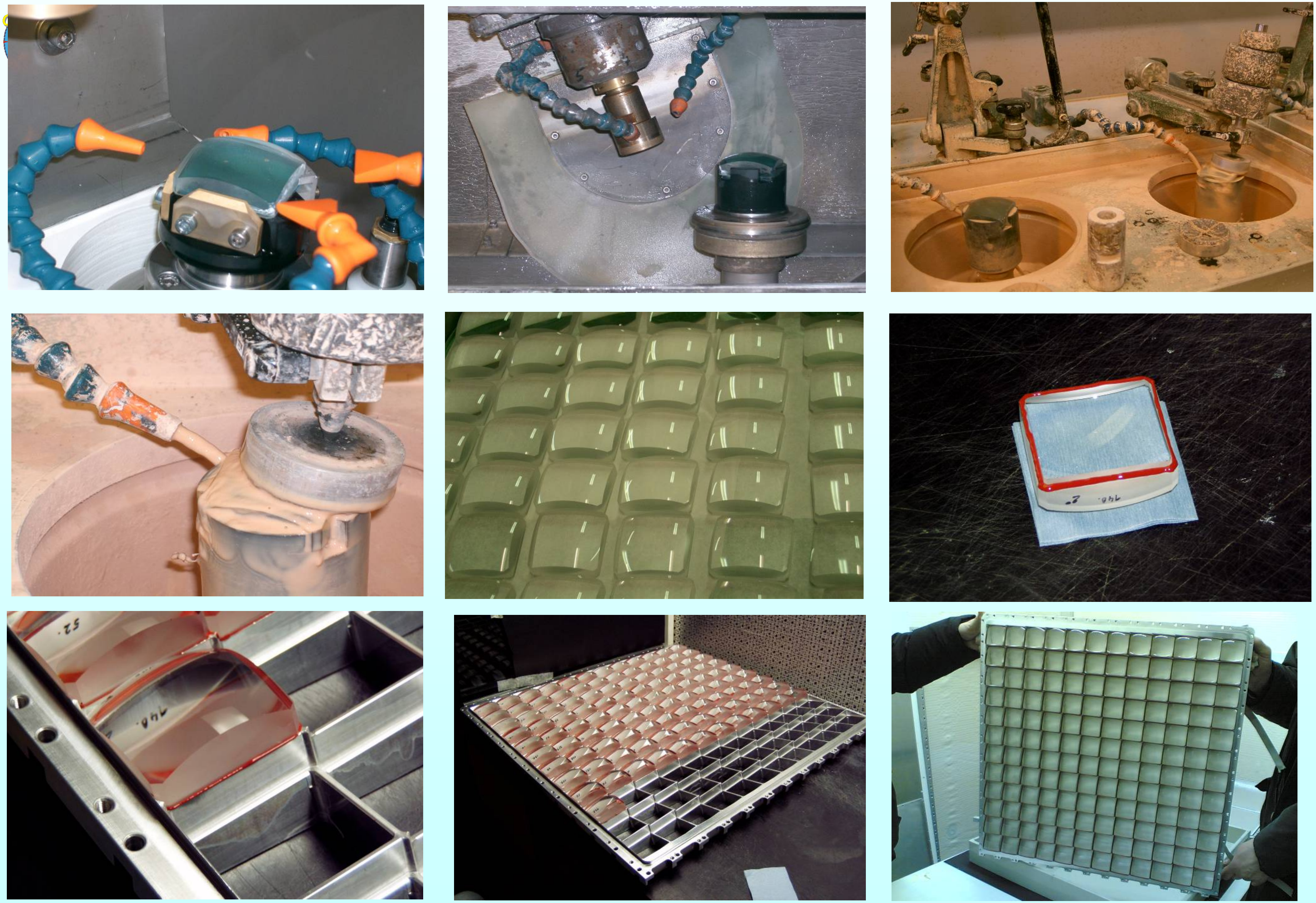
Convolution of Cherenkov light and effective QE





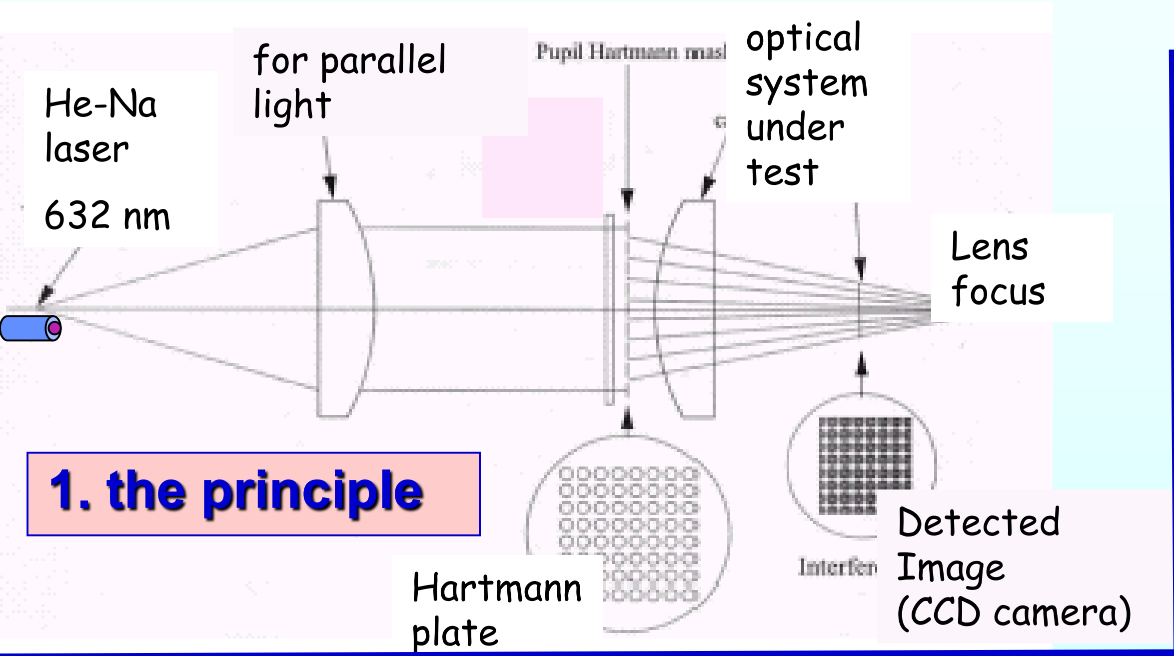
complex and delicate mechanical machining



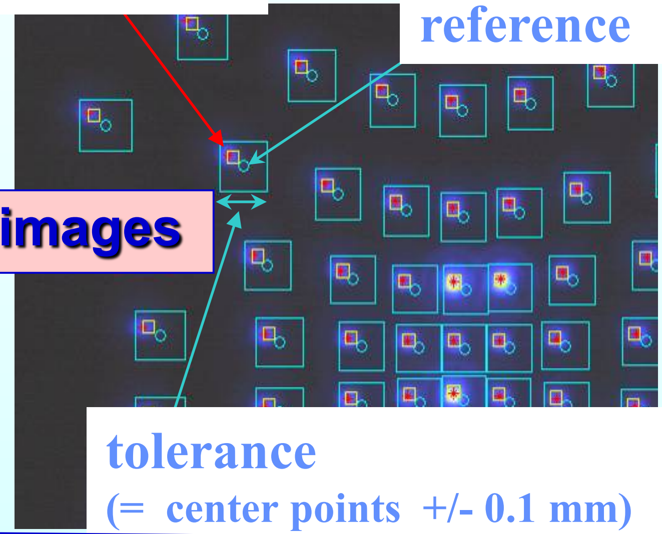


OPTICS QUALITY CONTROL WITH THE HARTMANN METHOD

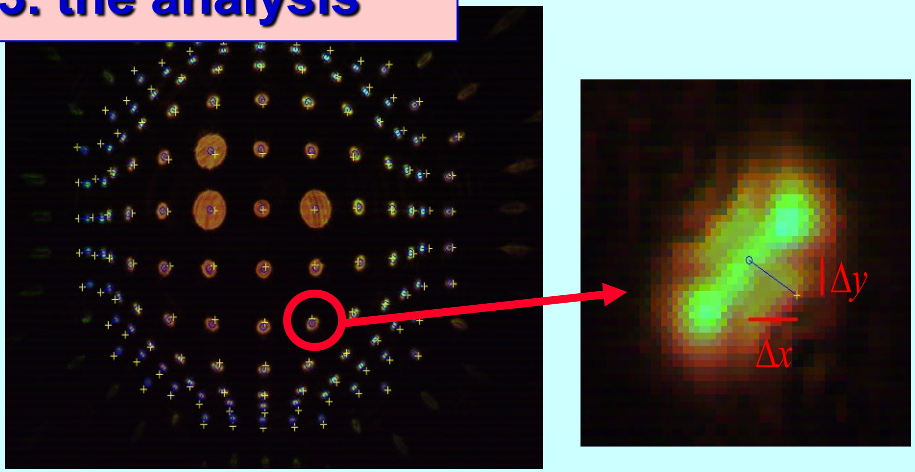
1. the principle



2. the images



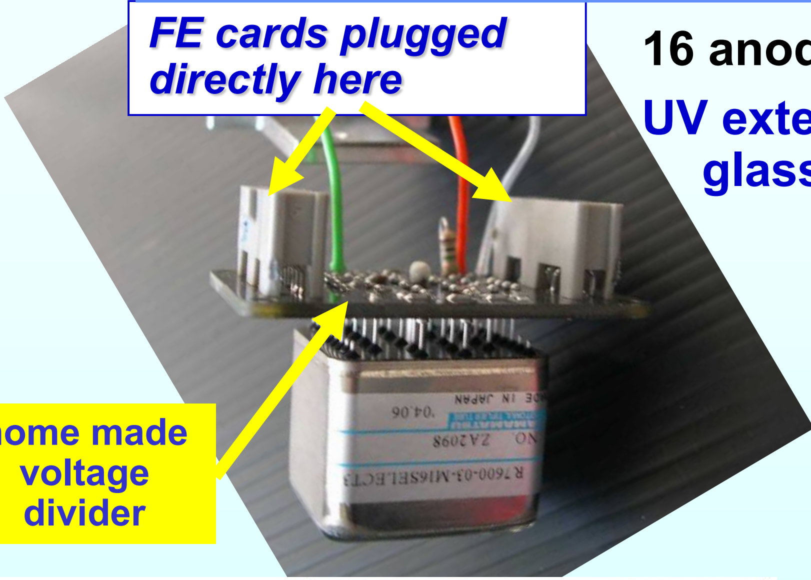
3. the analysis



576 TELESCOPES:

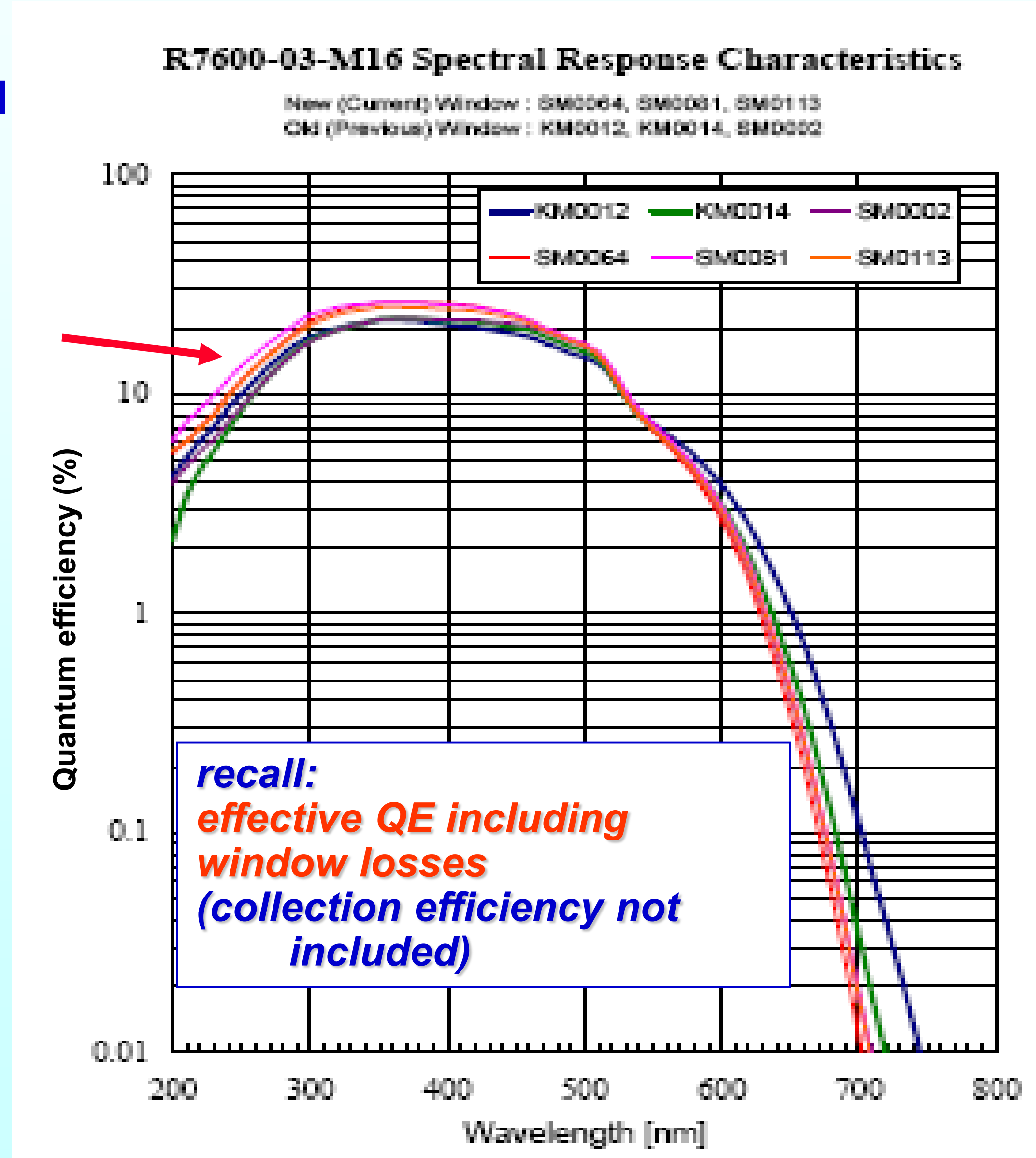
A) ~70% within 50 μm tolerance
B) ~20% within 100 μm tolerance
C) ~10% within 150 μm tolerances

MAPMT: HAMAMATSU R7600-03-M16



16 anodes

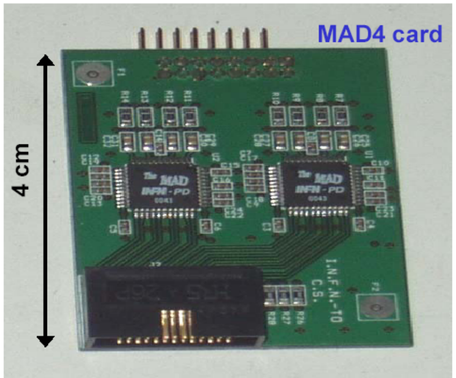
UV extended glass

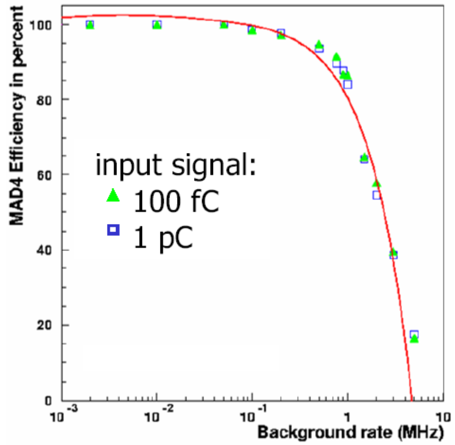


Analogue read-out electronics: MAD4 preamplifier

- 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

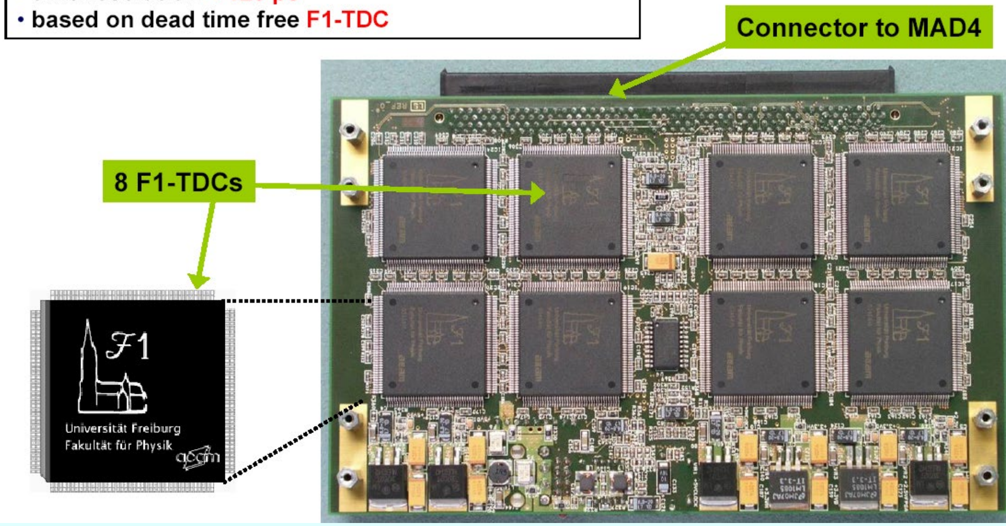


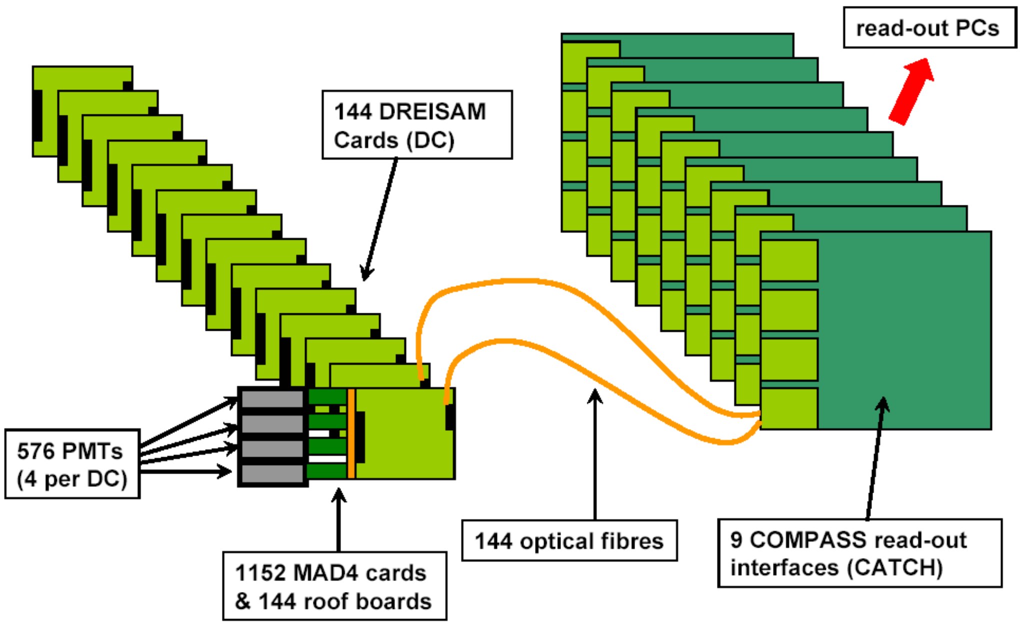


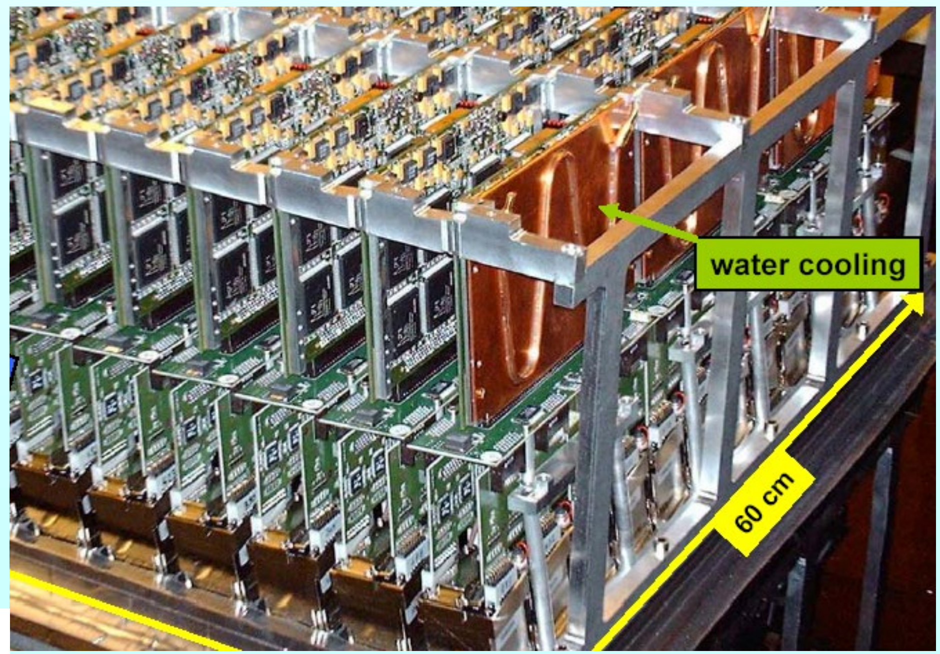
Digital read-out electronics: DREISAM card

- 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



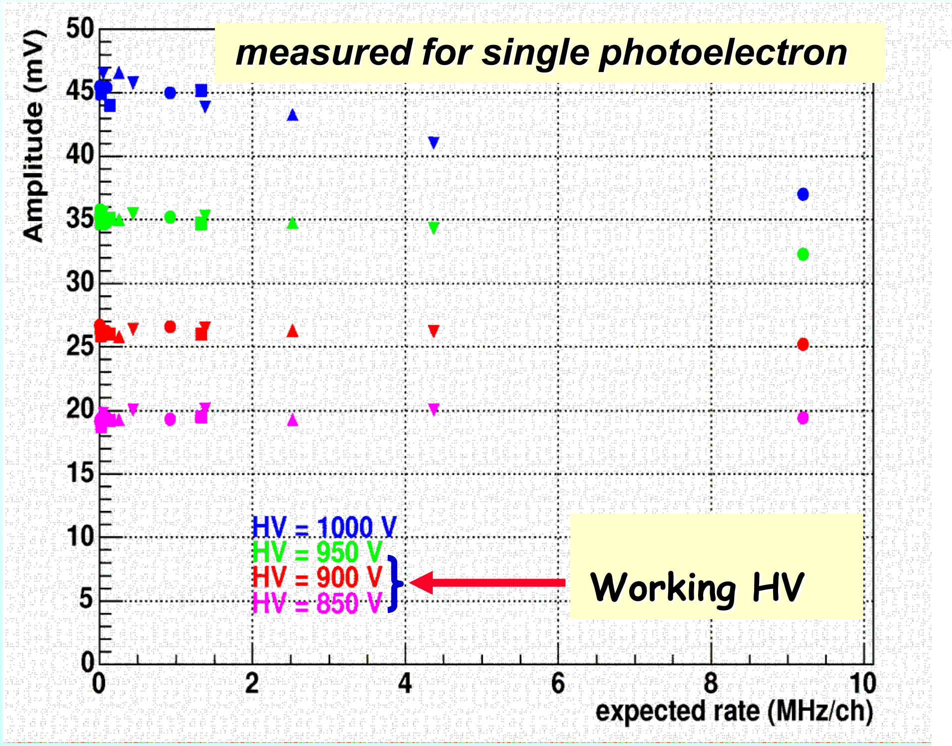




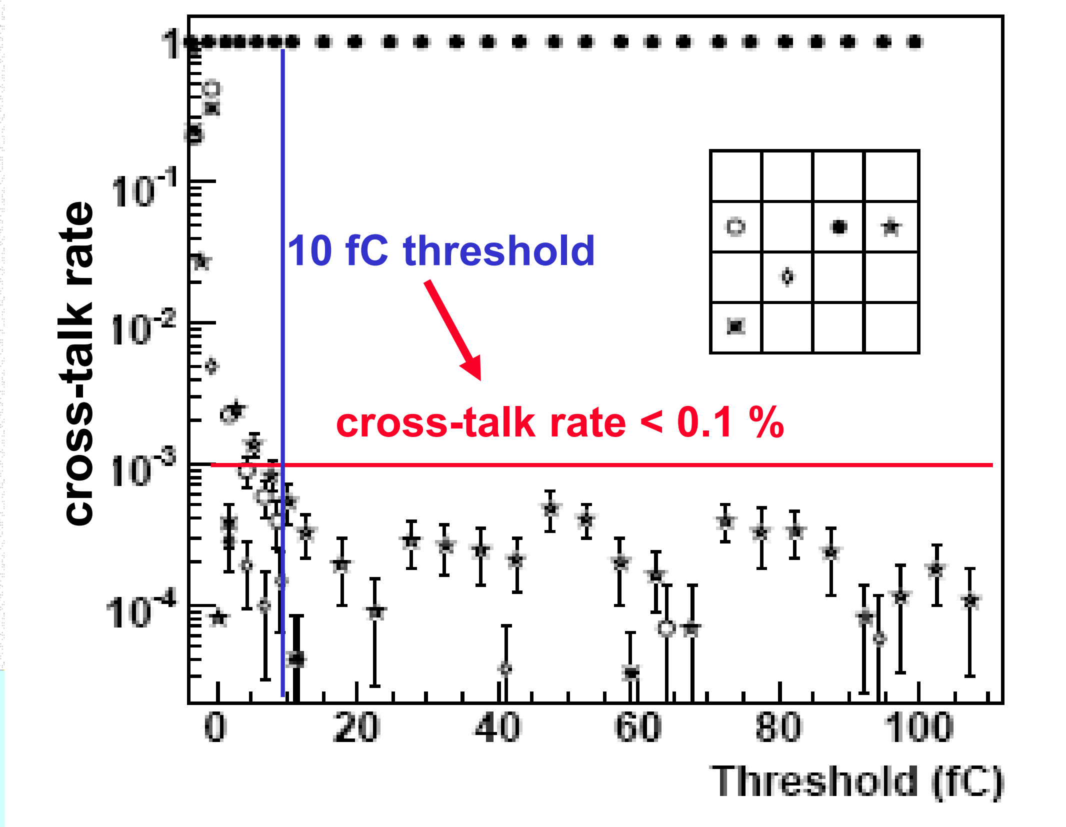
MAPMT GAIN AT HIGH RATE AND CROSS-TALK RATE

mean signal amplitude versus rate/pixel

pulsed light source synchronous to trigger + random background from lamp

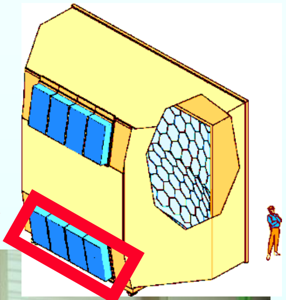


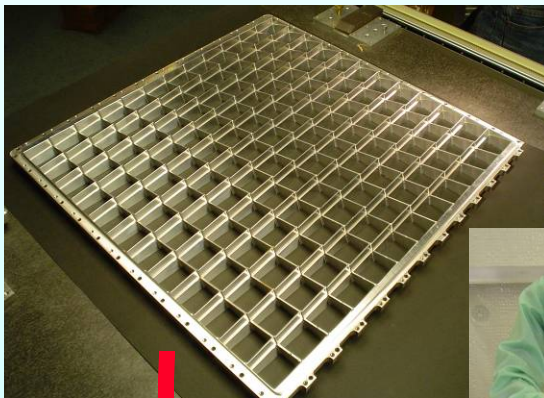
operate with single photoelectron rates up to 5MHz/pixel

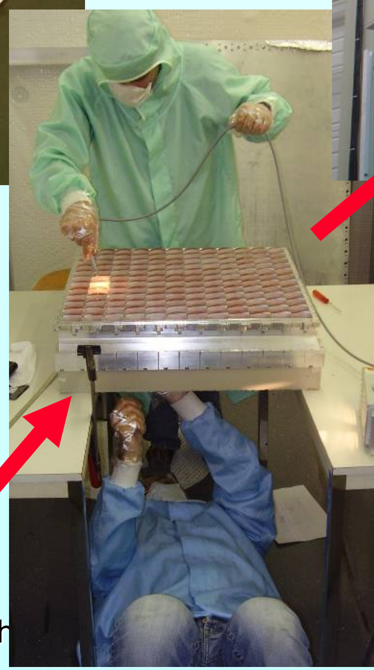


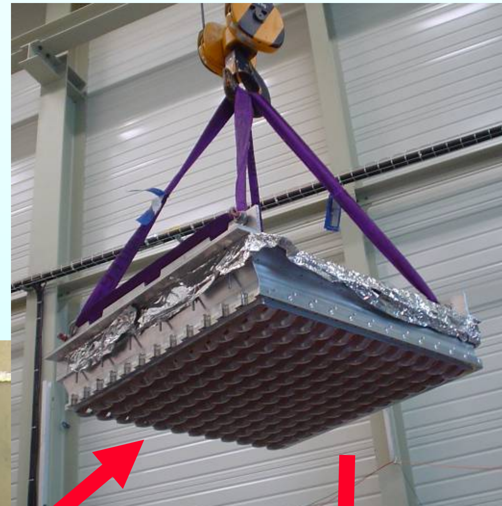
SCHEDULE OF ASSEMBLING

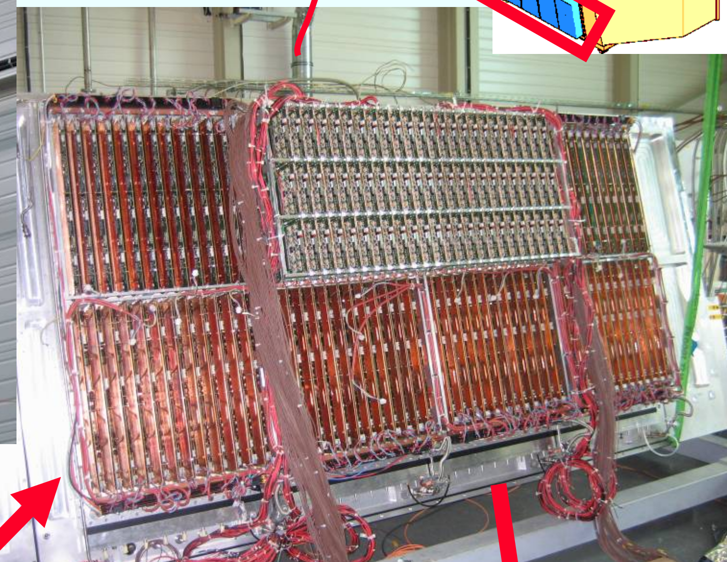
- Preliminary studies up to October 2004
- Project design November 2004 – March 2005
- Material procurement and constructions April 2005 - March 2006
- Assembly April-May 2006
- Ready for beam June 2006

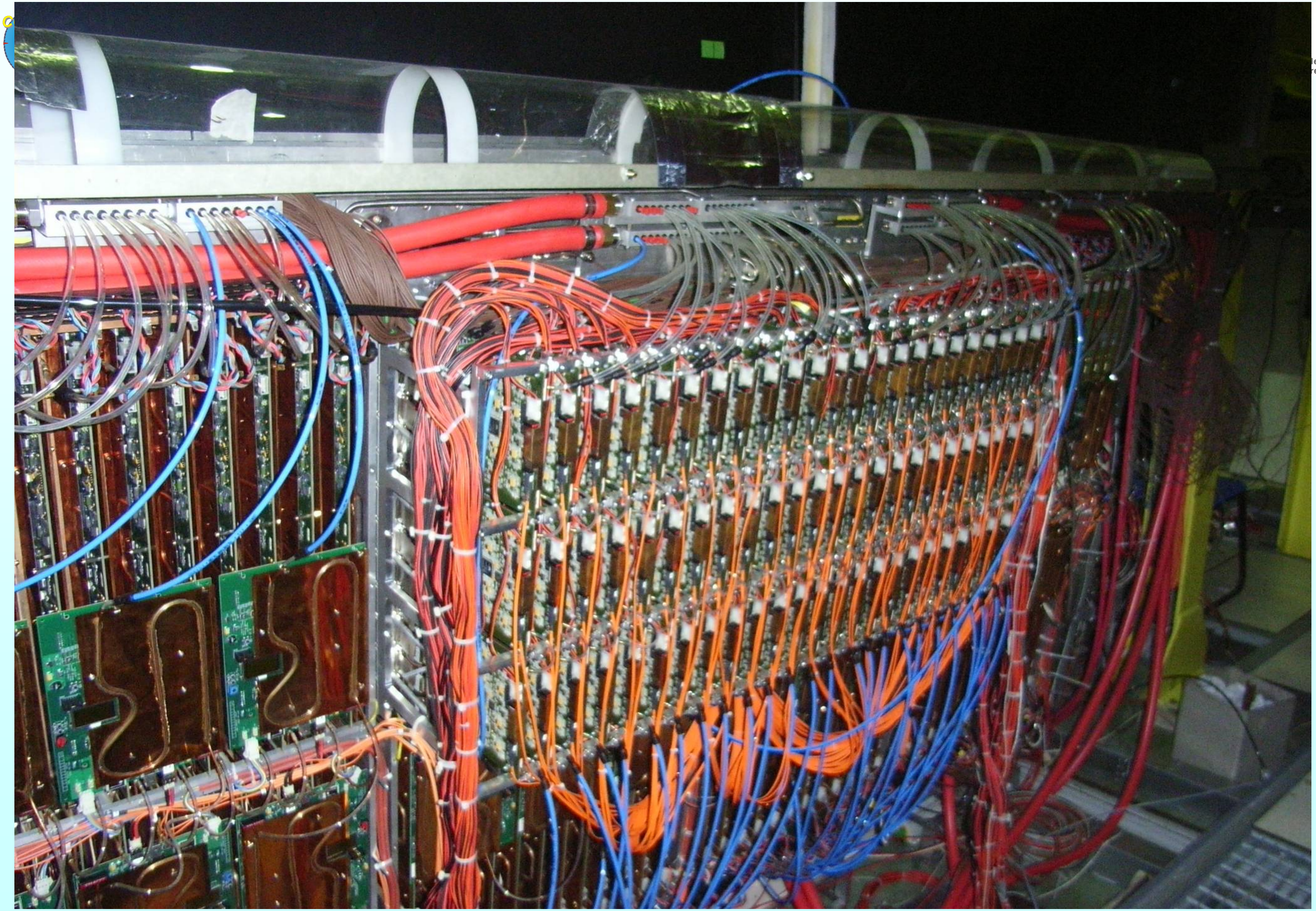




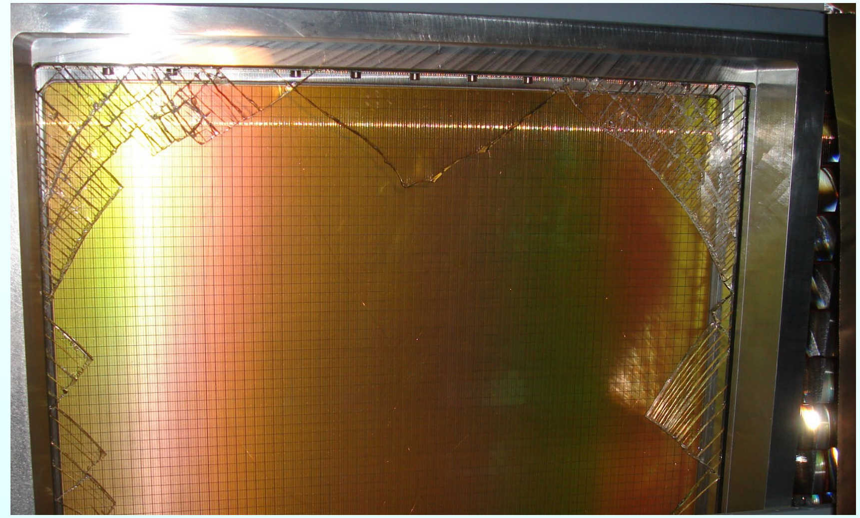


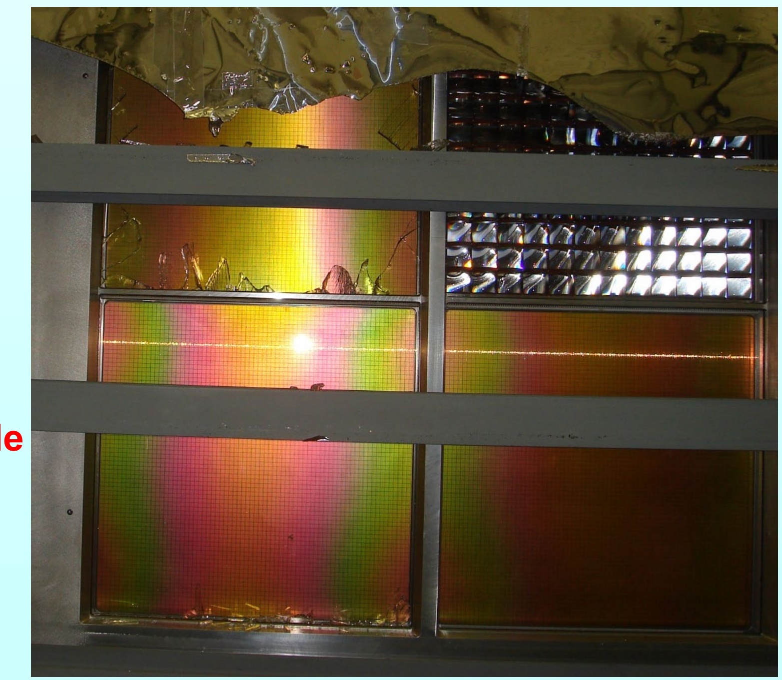






Not everything went smoothly





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

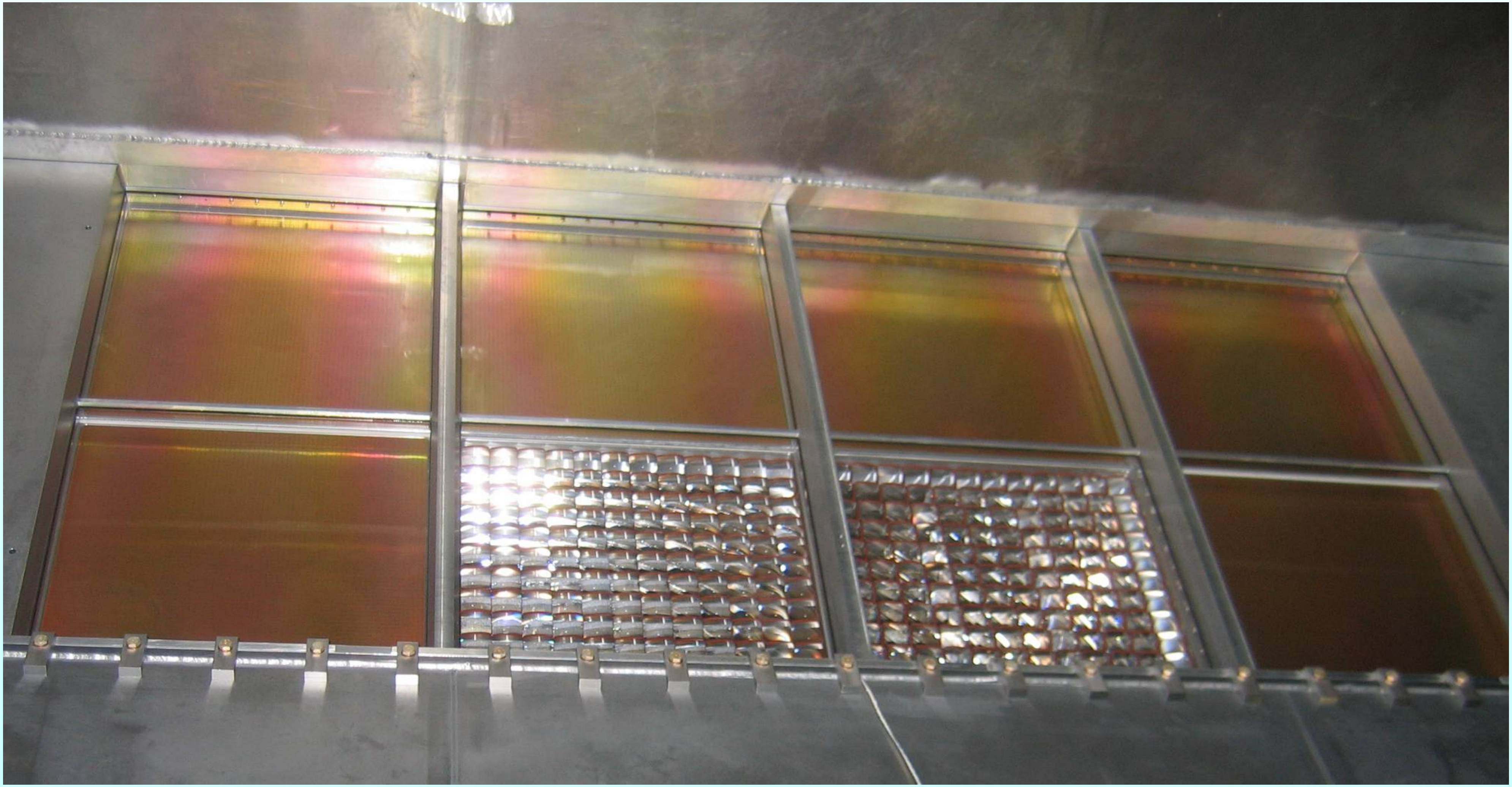
Spares of all pieces, including the large quartz windows were available

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

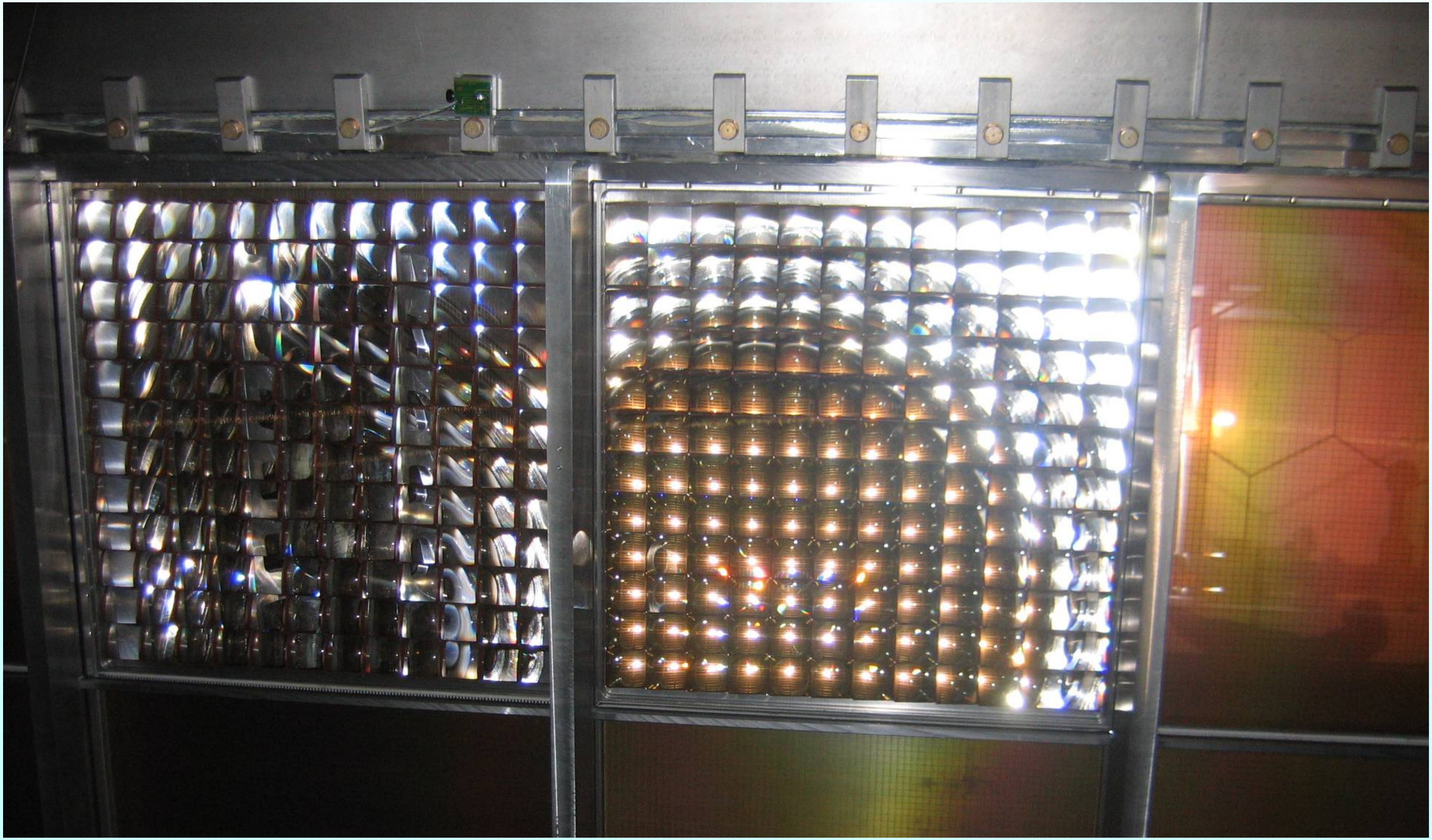
One month later, in time for the start of the run,

the repaired detector was installed

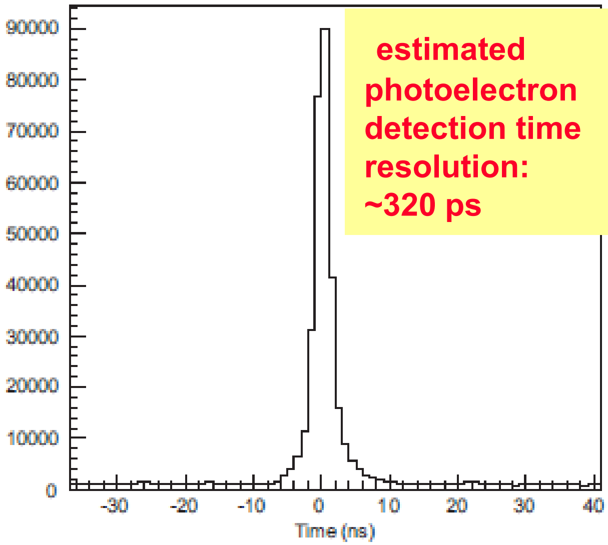
The Upper Detector from inside



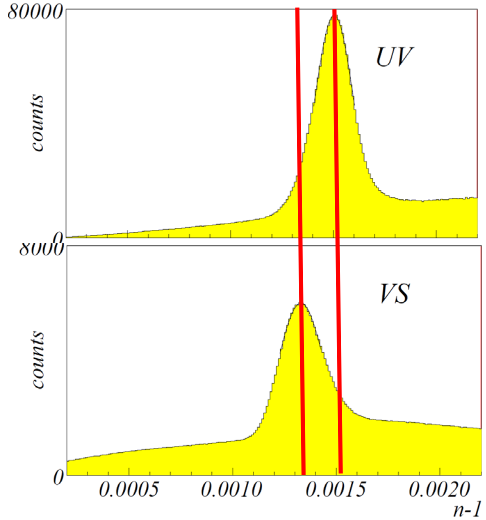
The central part of the lower detector

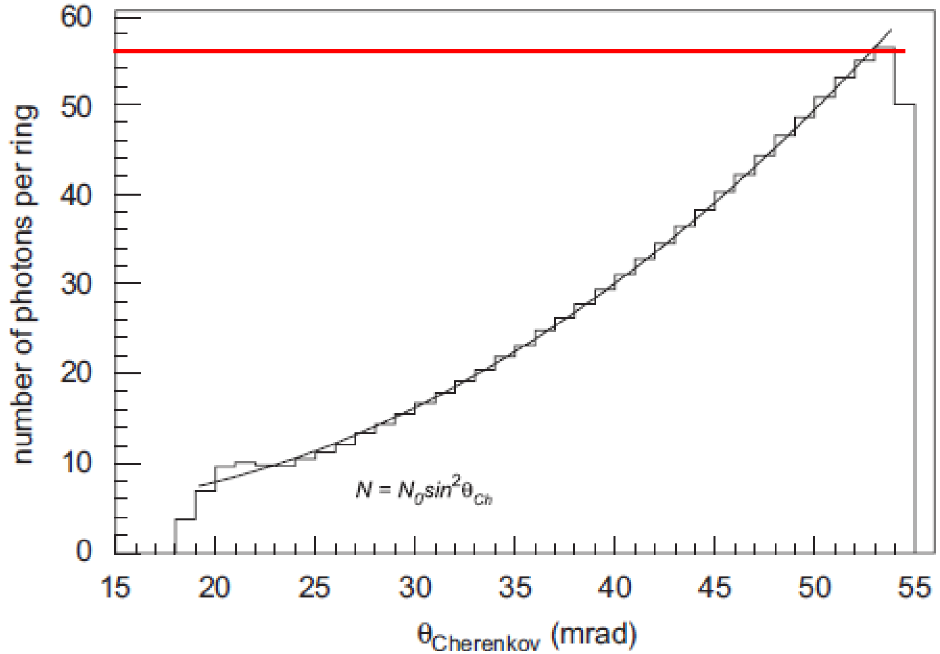


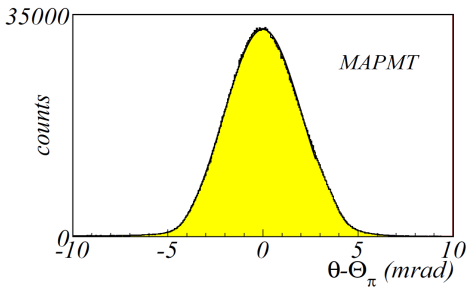
number of photons and resolutions

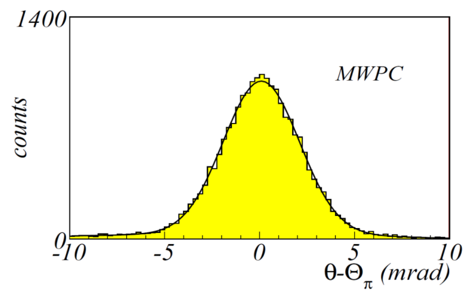


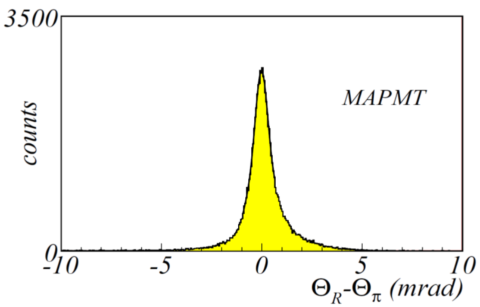
estimated photoelectron detection time resolution: ~320 ps

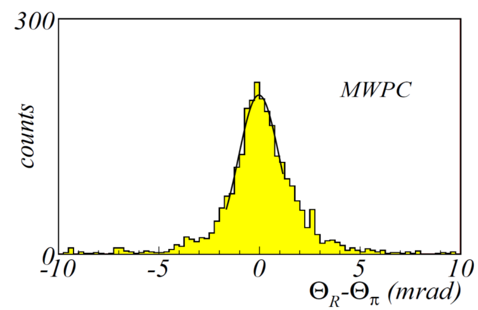


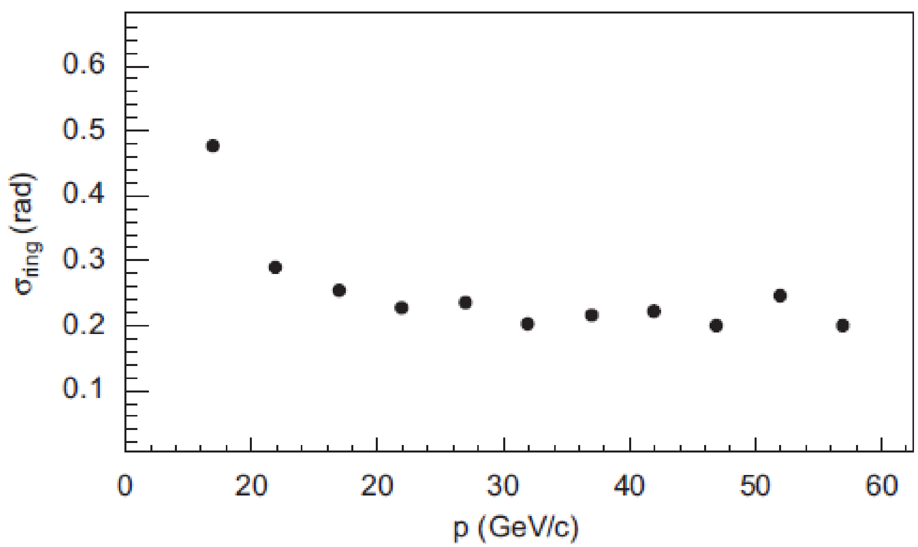




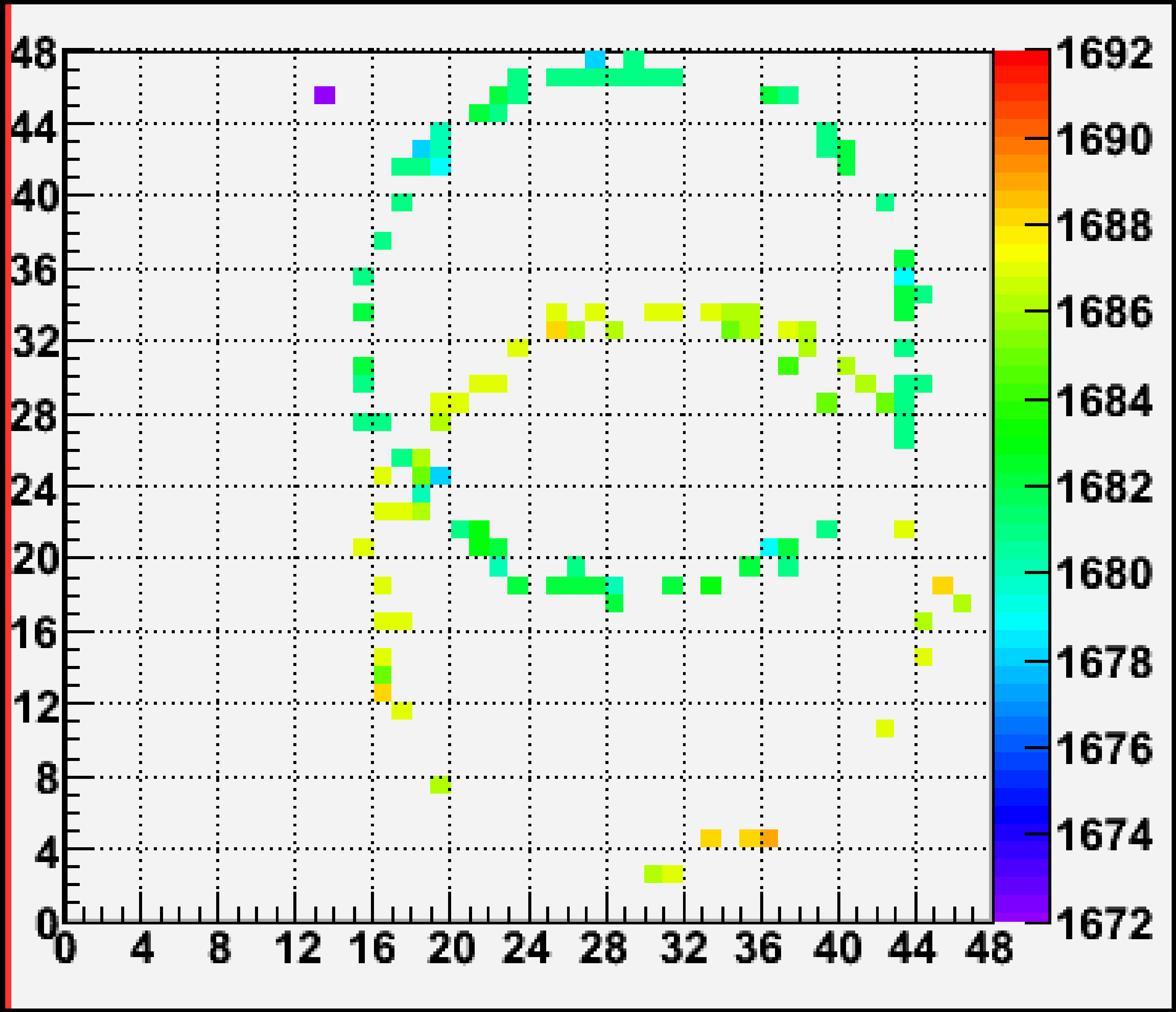








time resolution is useful for correctly assigning hits to rings



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.

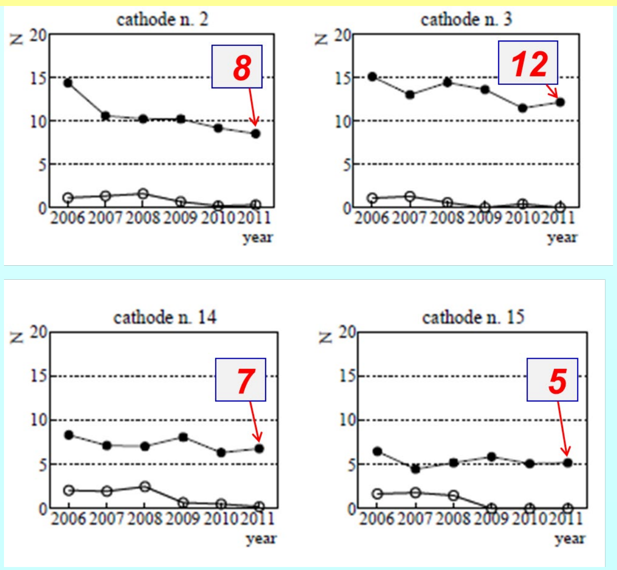
MPGD-based Photon Detectors are the best option

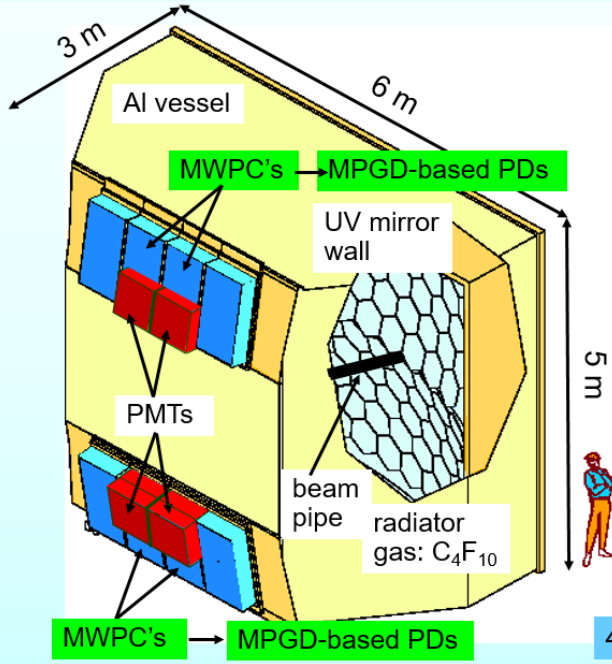
A dedicated R&D project to develop THGEM-based PDs achieved positive results

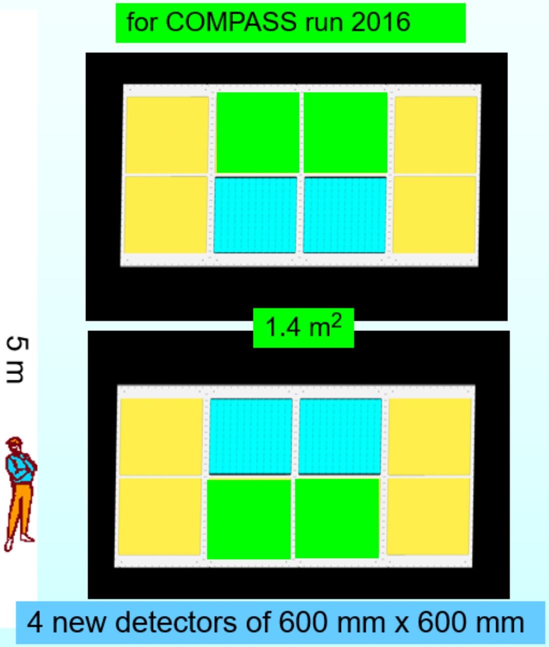
We decided to replace four COMPASS RICH-1 MWPC's with the new detectors

number of detected photons per ring at β = 1

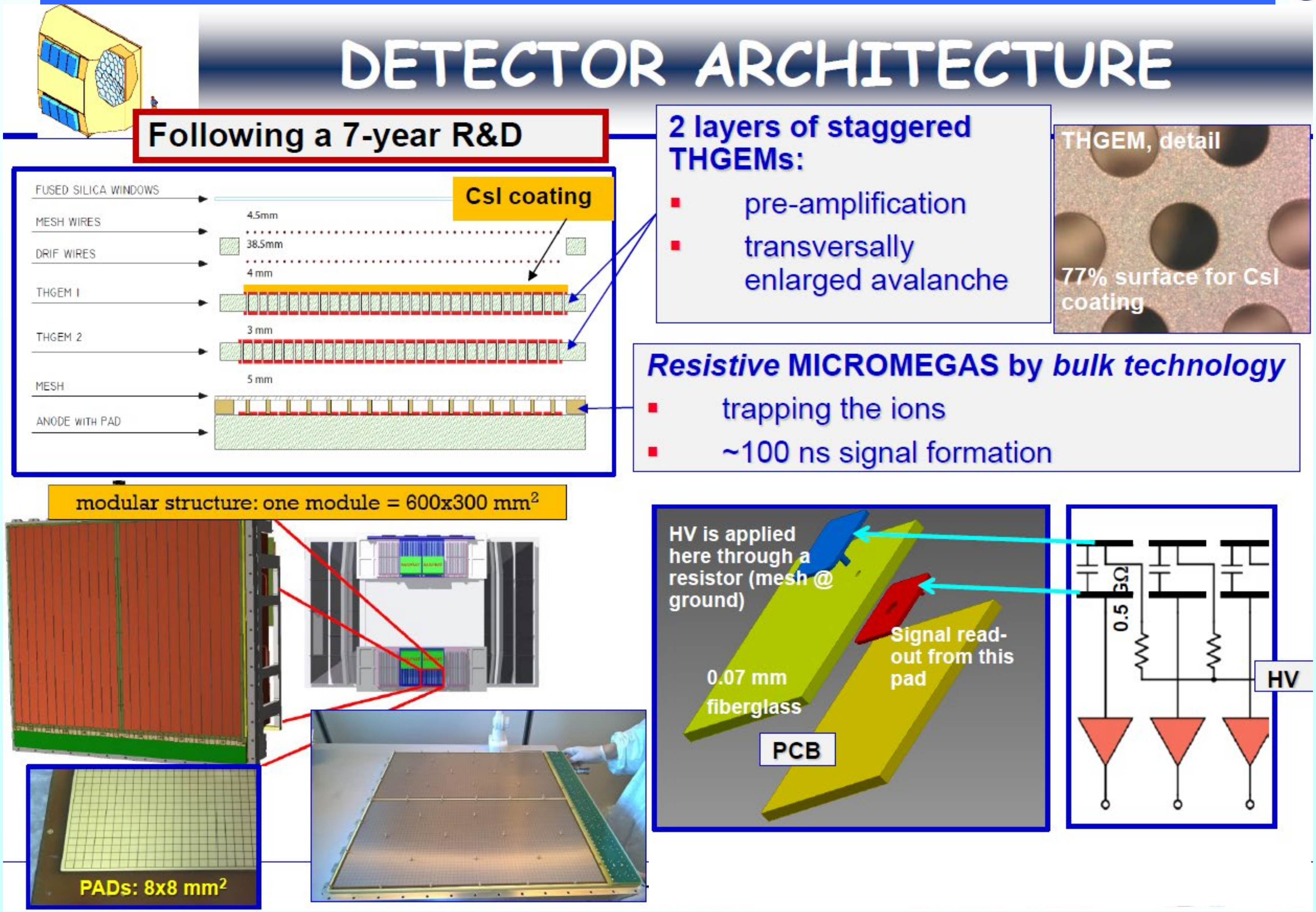
for the four central MWPCs with CsI



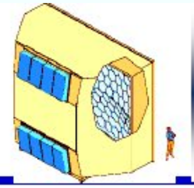




Hybrid MPGD-based PDs

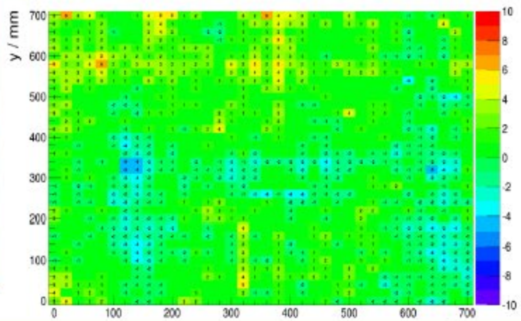


Hybrid MPGD-based PDs

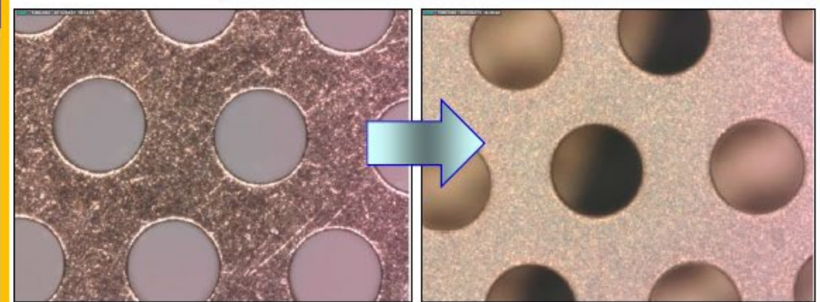


COMPONENT QA in a nutshell

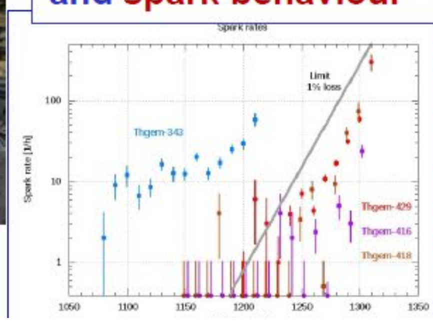
Measurement of the raw material thickness before the THGEM Production, accepted:
± 15 μm ↔ gain uniformity σ < 7%

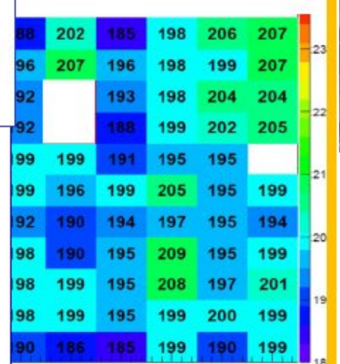


THGEM polishing with an "ad hoc" protocol setup by us:
>90% break-down limit obtained

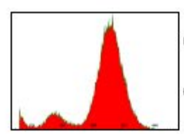


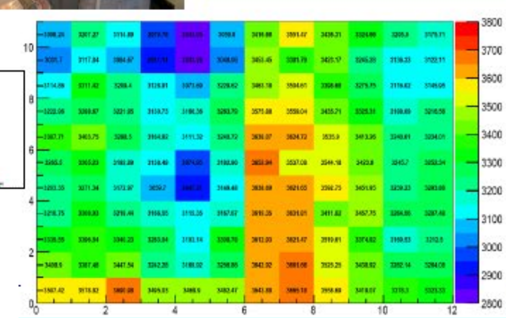
X-ray THGEM test to access gain uniformity (<7%) and spark behaviour



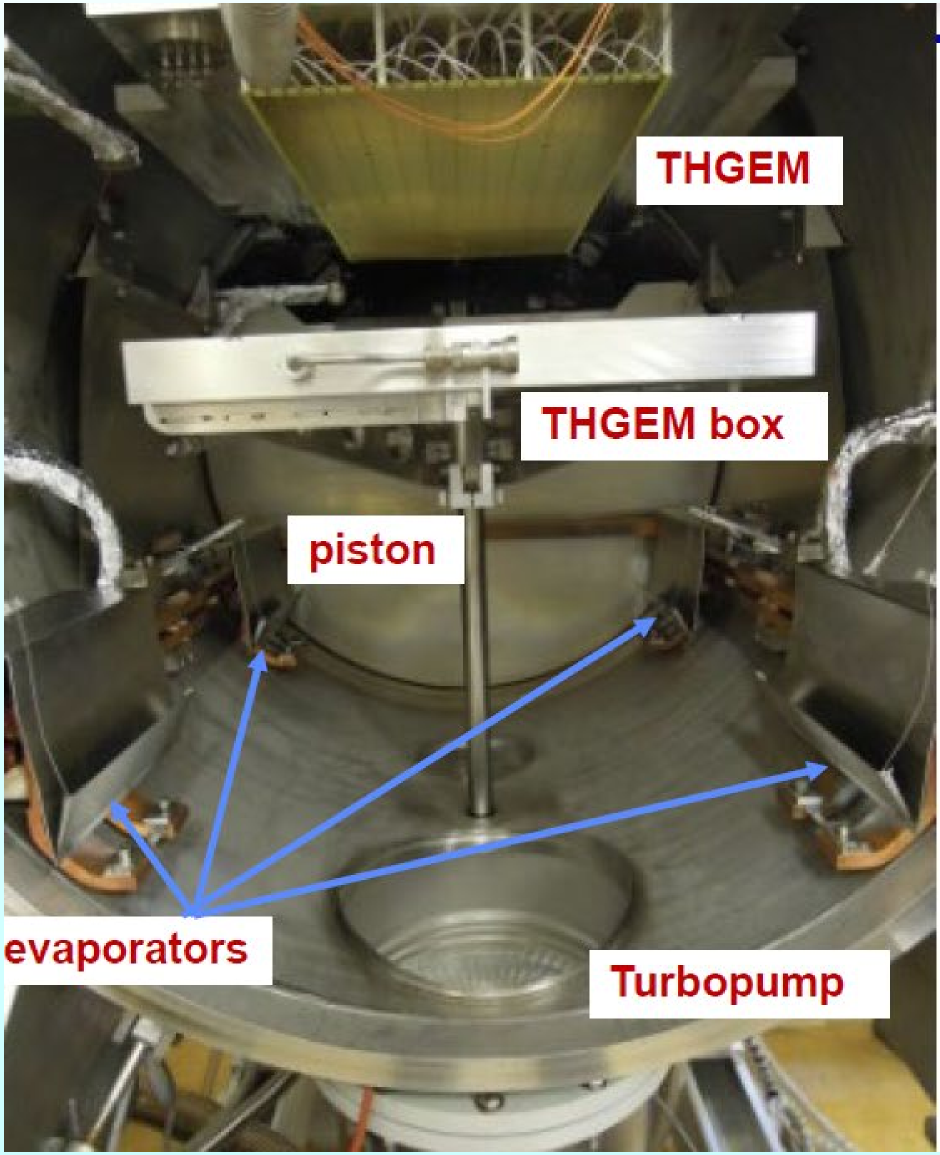


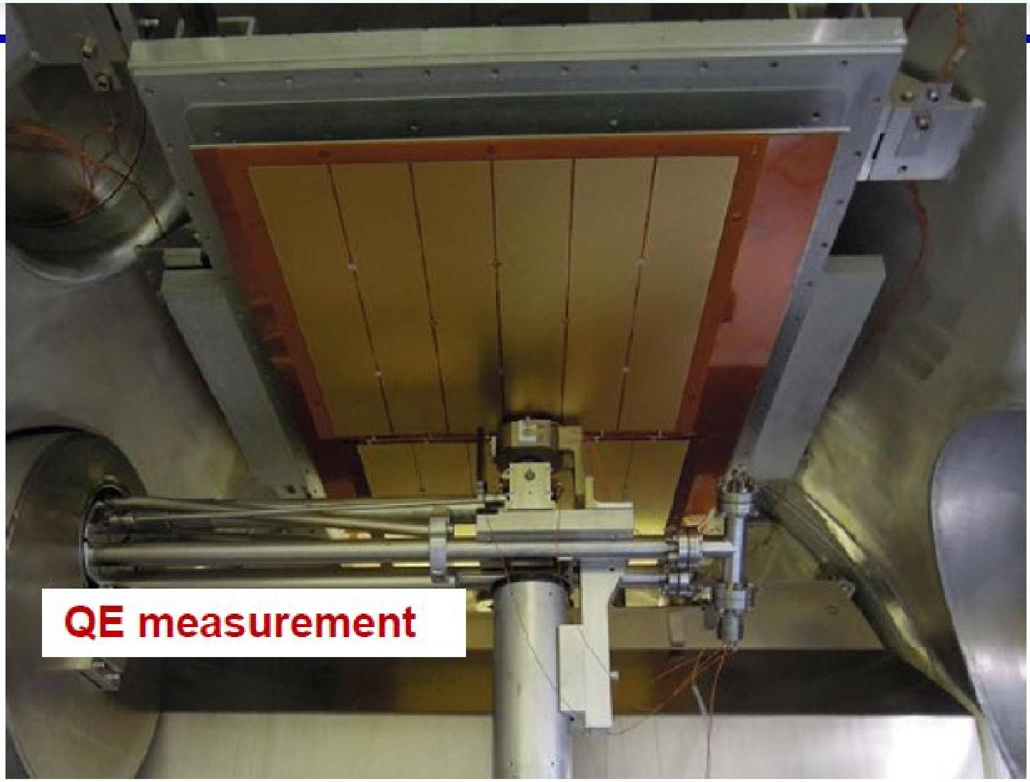
X-ray MM test to access integrity and gain uniformity (<5%)





CsI coating on THGEMs

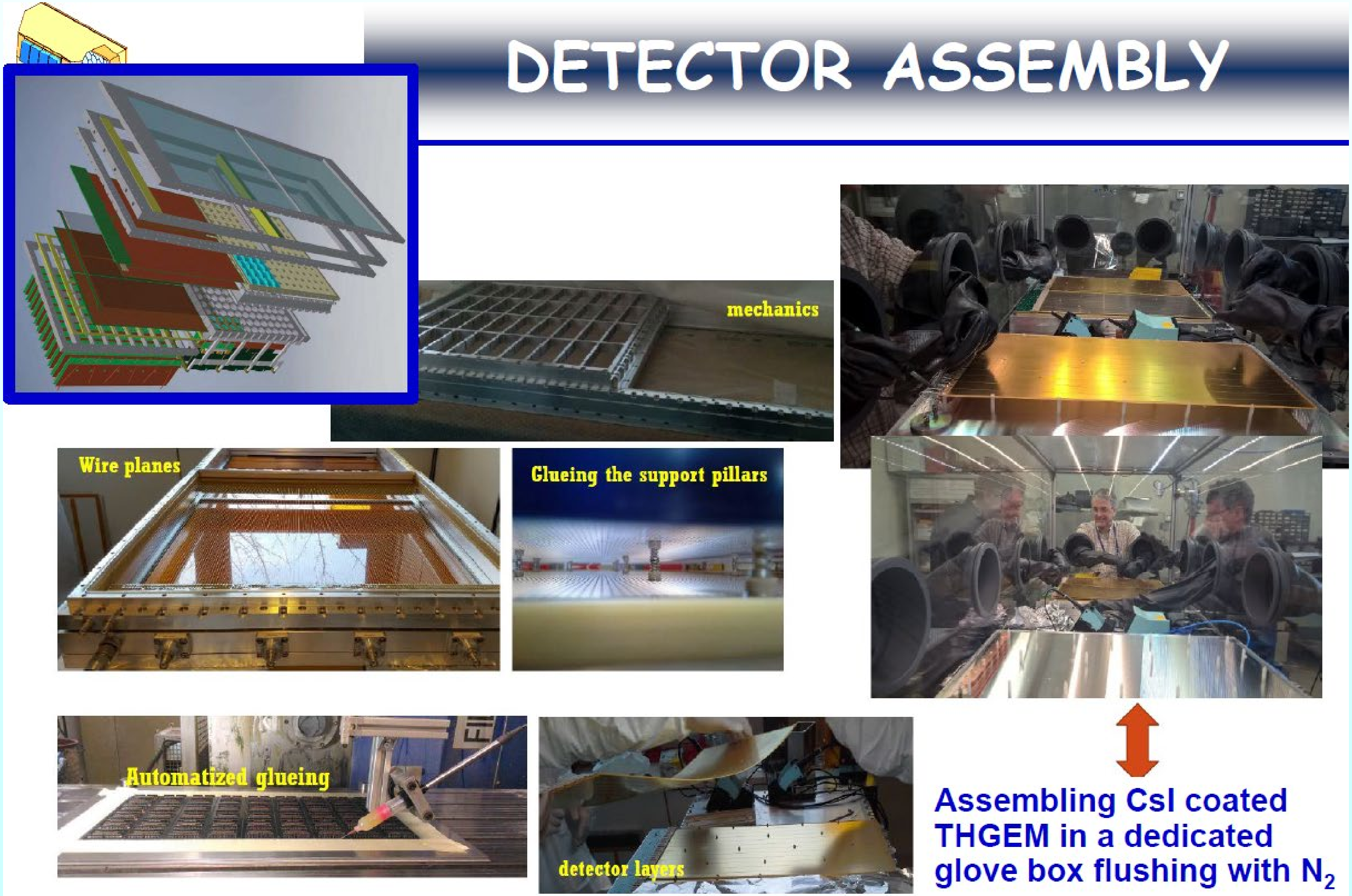




QE uniformity

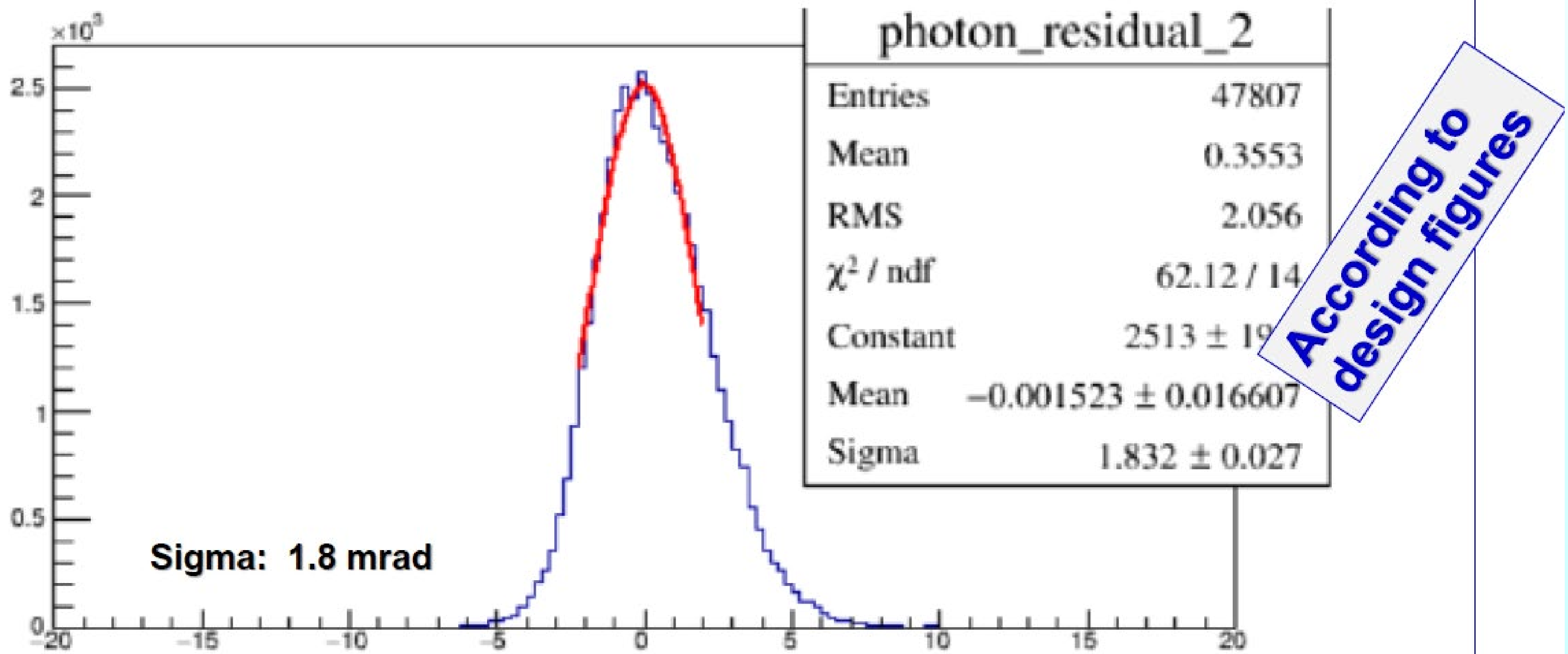
- 3 % r.m.s. within a photocathode
- 10 % r.m.s. among photocathodes
- mean value: 93% of reference

Hybrid MPGD-based PDs

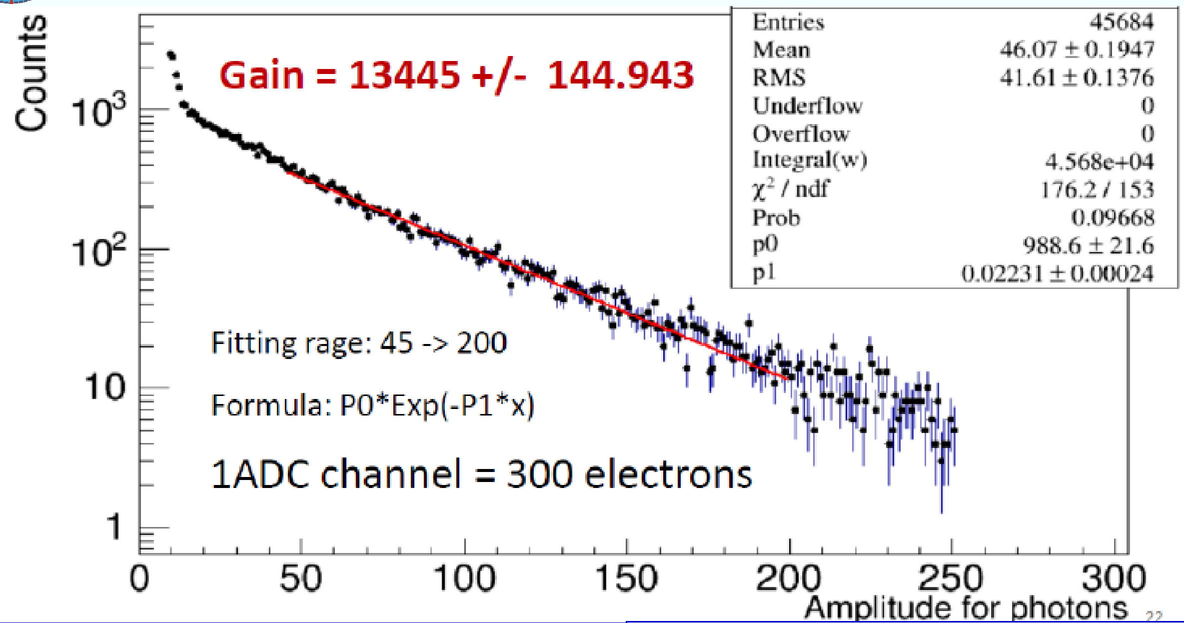


Intrinsic space resolution

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



Gain from a pure photon sample

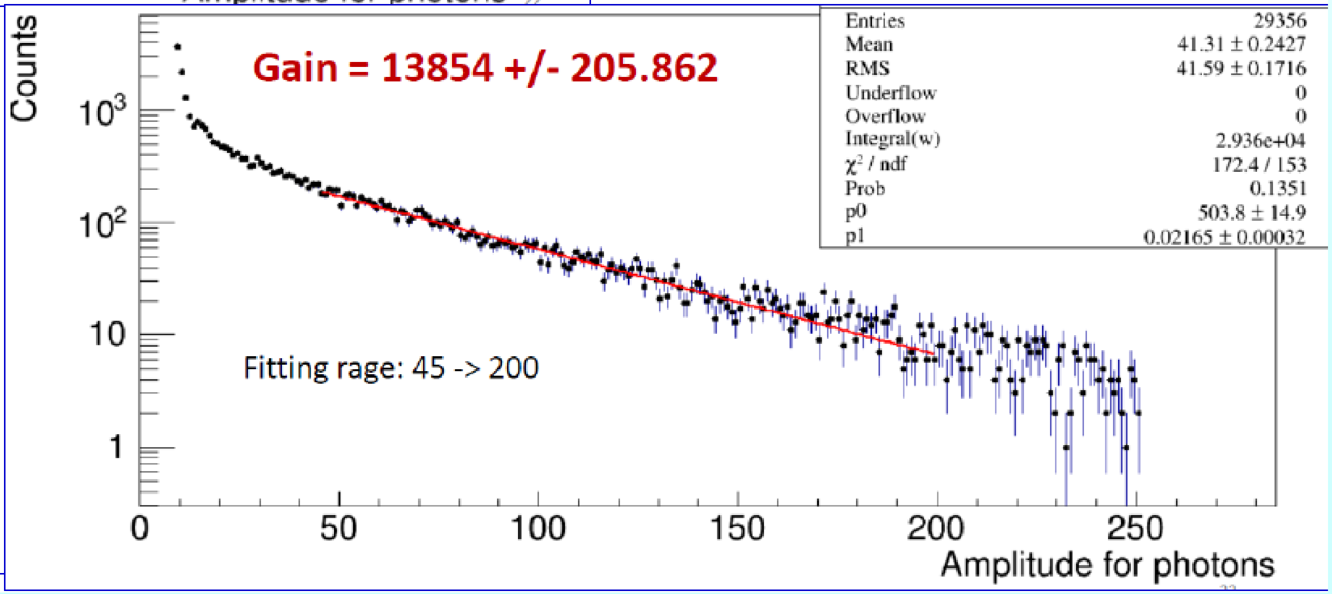


From electronic noise → Threshold

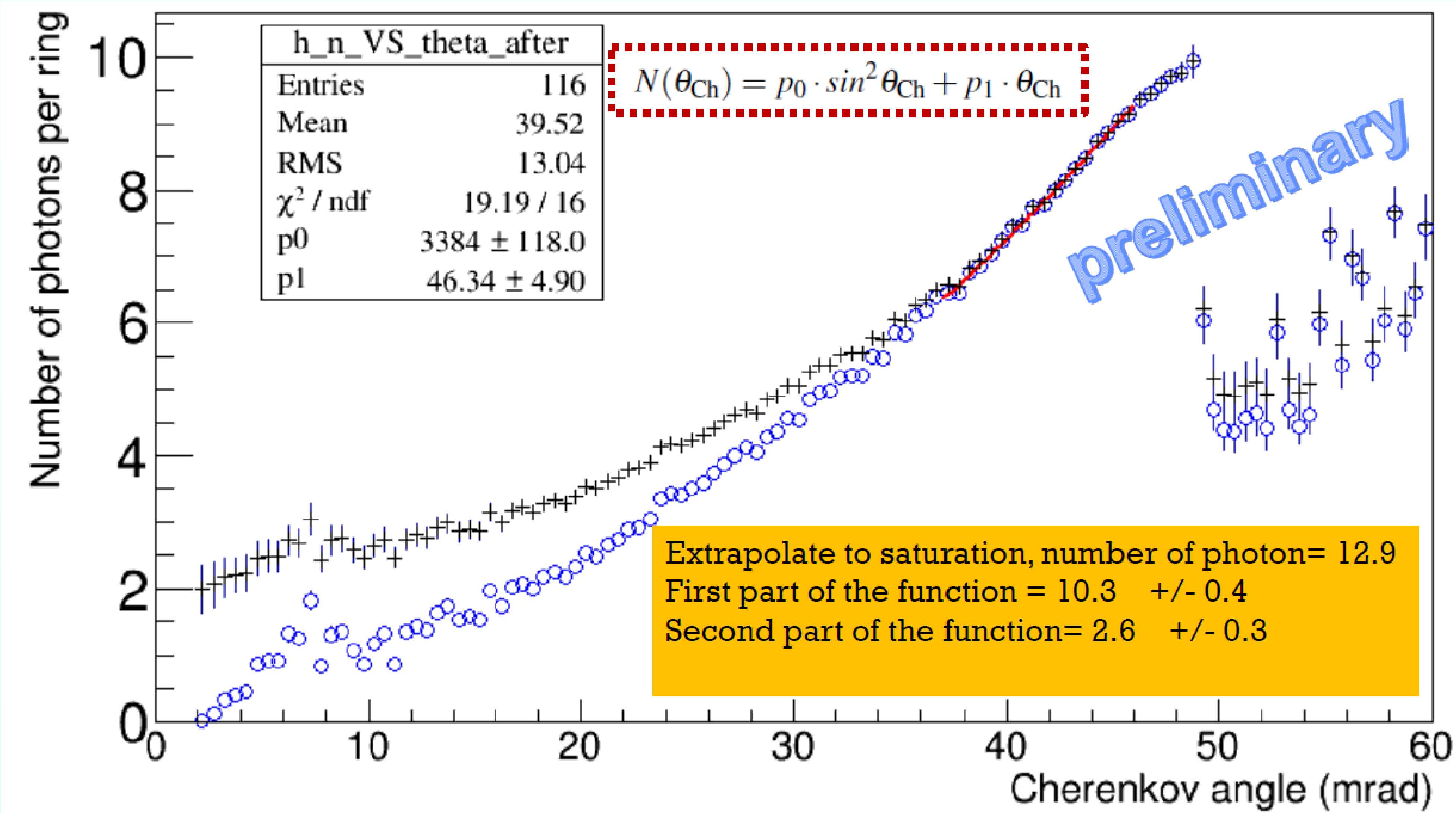
From threshold & gain → **photoelectron detection (effective) efficiency > 80%**

For comparison, in MWPCs: ~50-60%

from the extrapolated exponential an estimate of the **noise level under the signal: ~10%**



Detected photons per ring



PID from the likelihood function

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

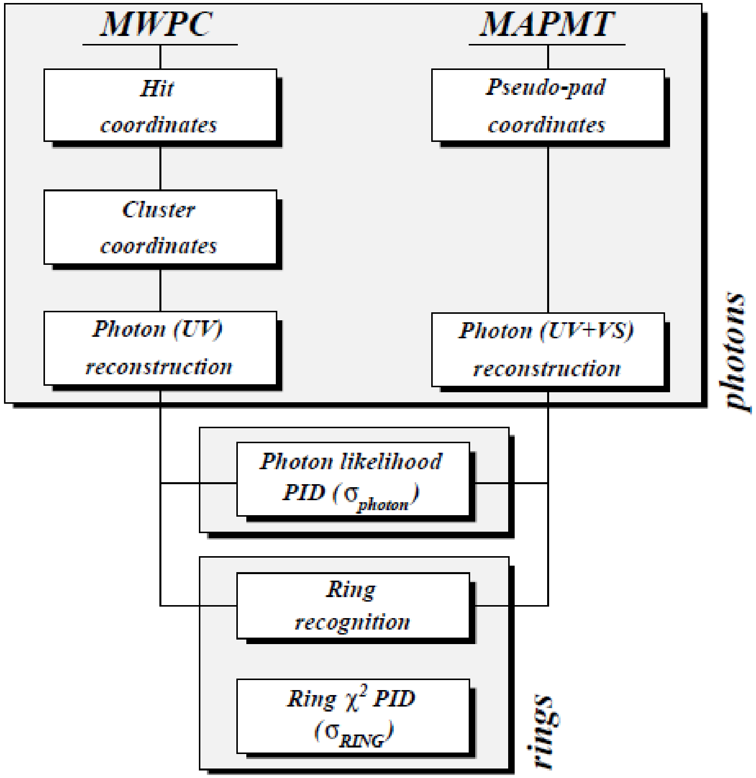
no reference to a reconstructed ring

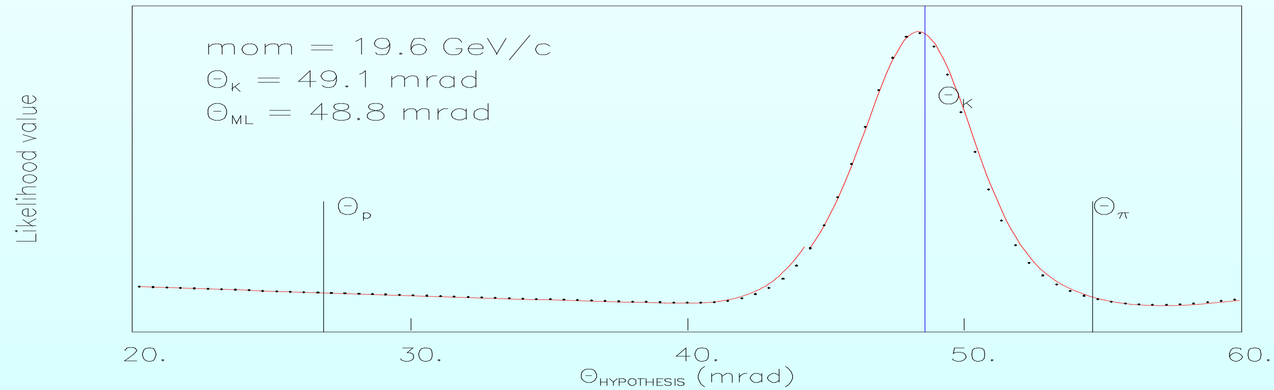
$$L_M = \prod_{j=1}^{N} \frac{s_M(\theta_j, \varphi_j) + b(\theta_j, \varphi_j)}{S_M + B}$$

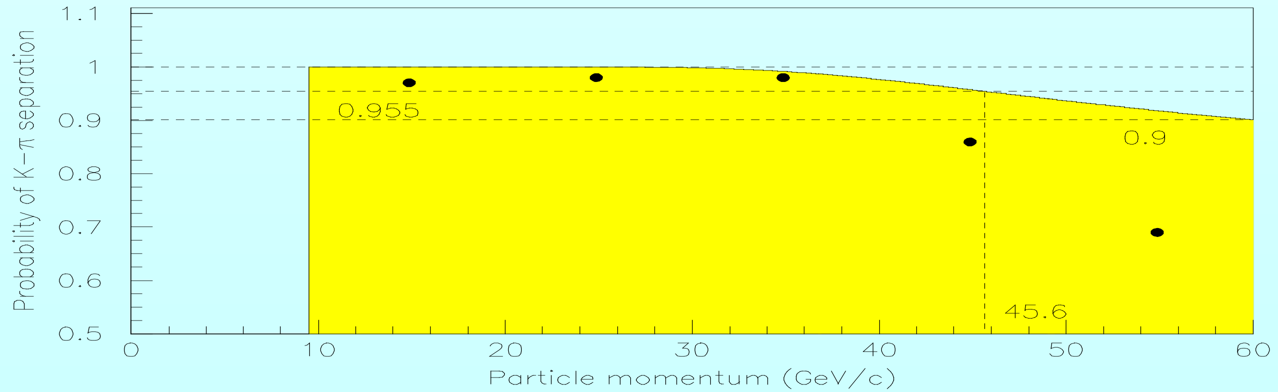
Computed for

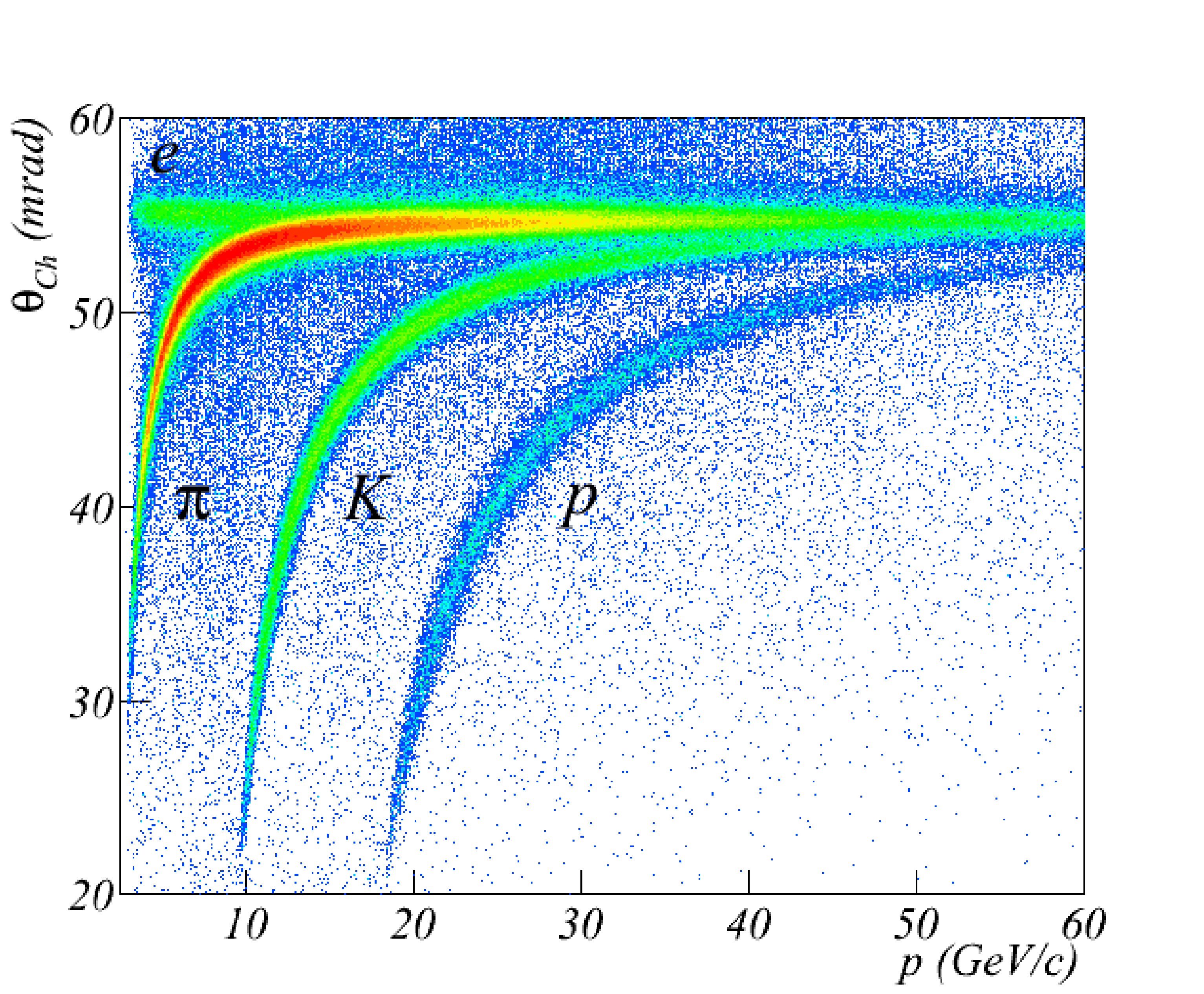
5 mass hypothesis $M = e, \mu, \pi, K, p,$

+ background hypothesis (no signal)



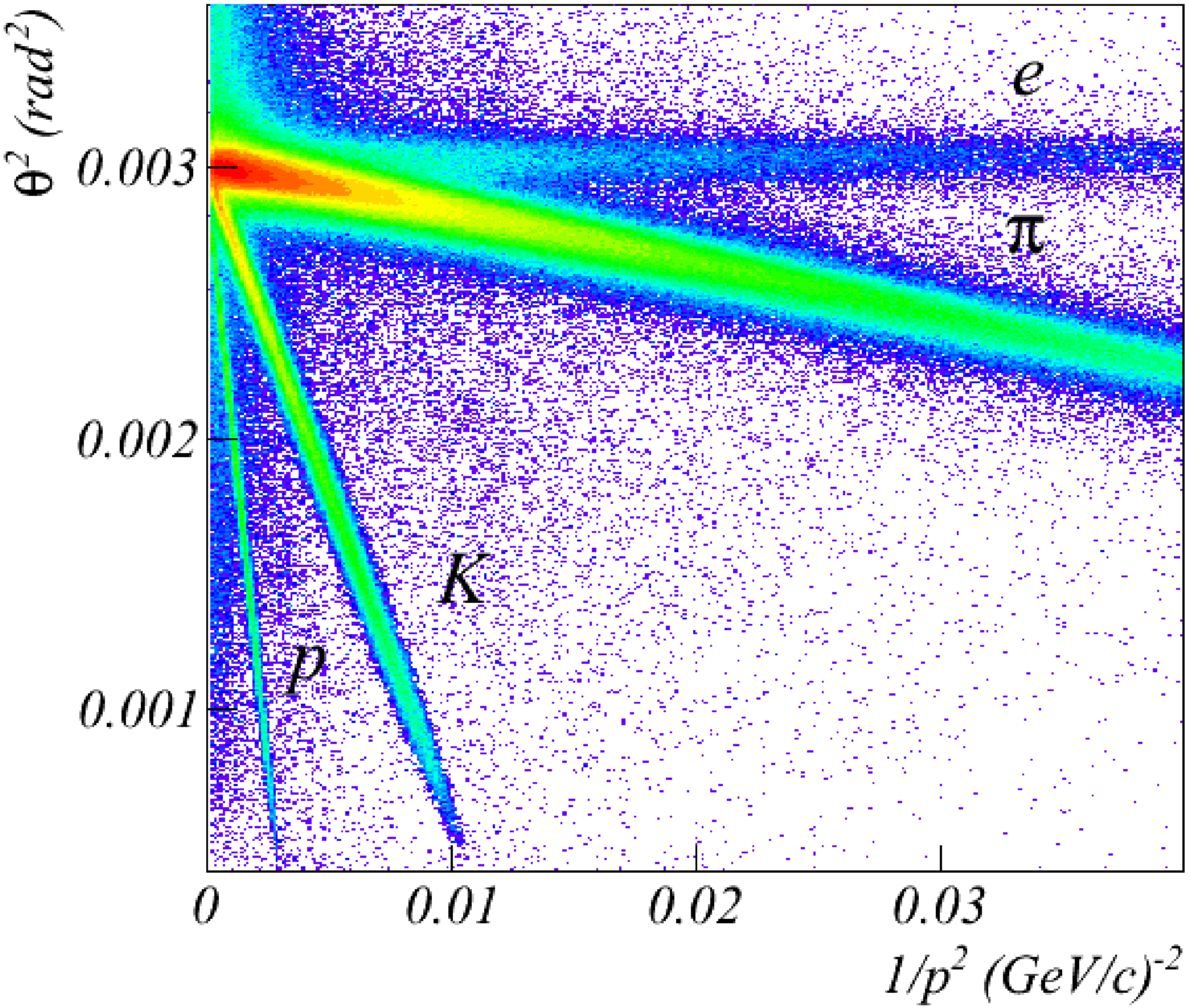






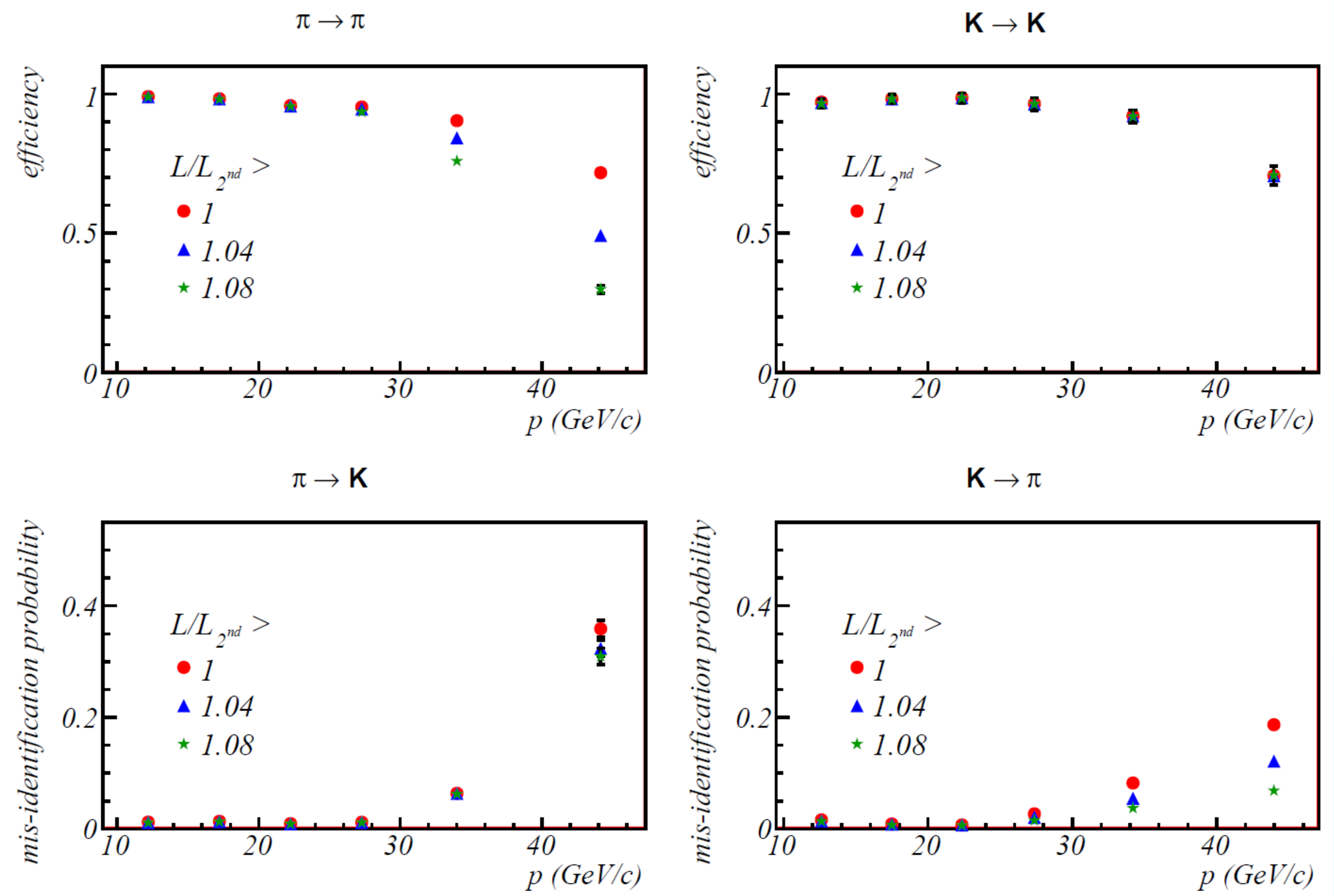
M (GeV/c²)

20

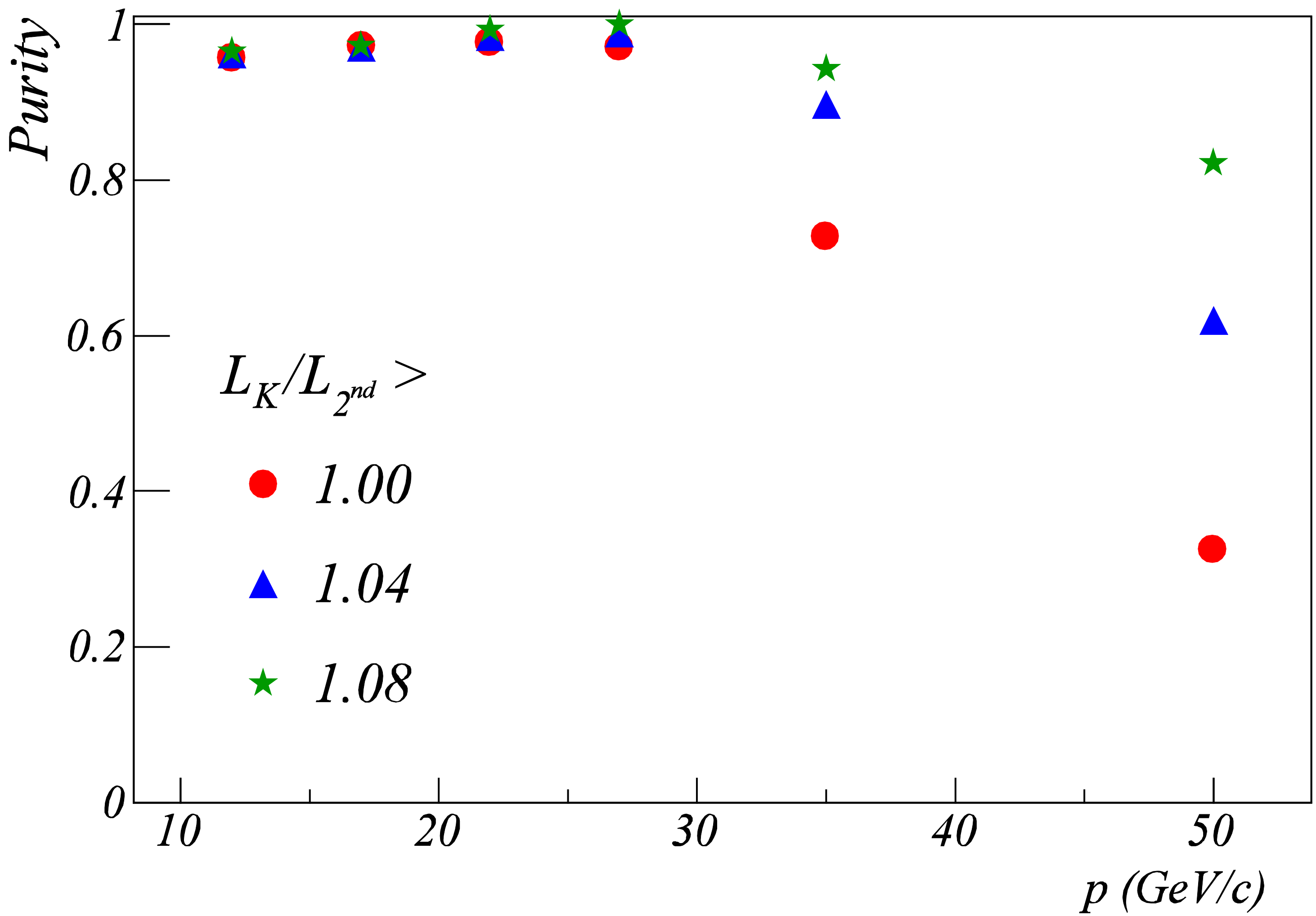


M
(GeV/c^2)

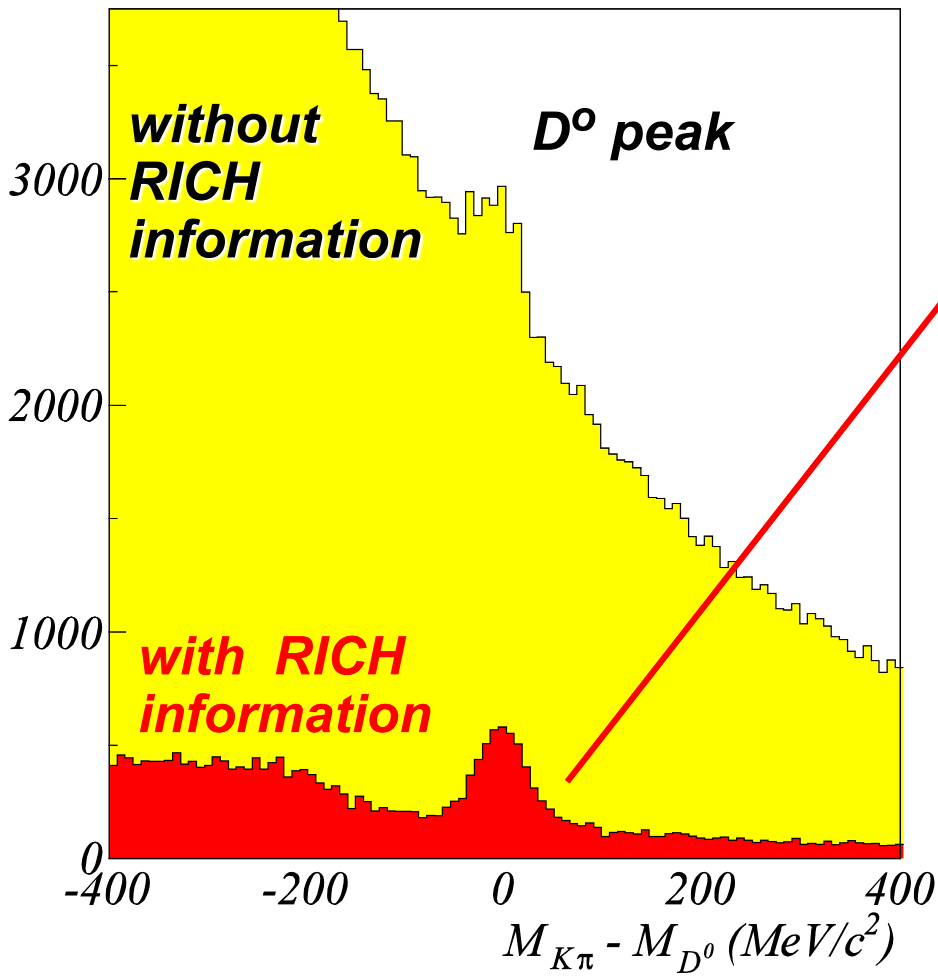
Identification and misidentification probability

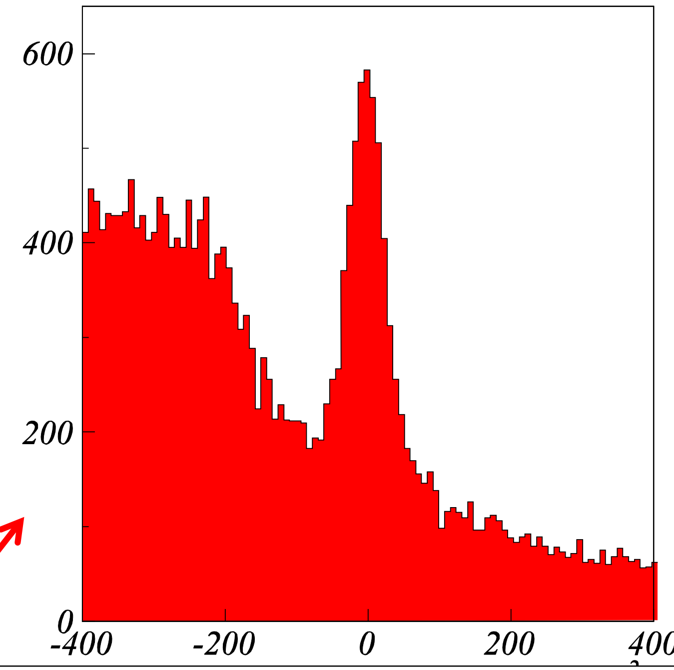


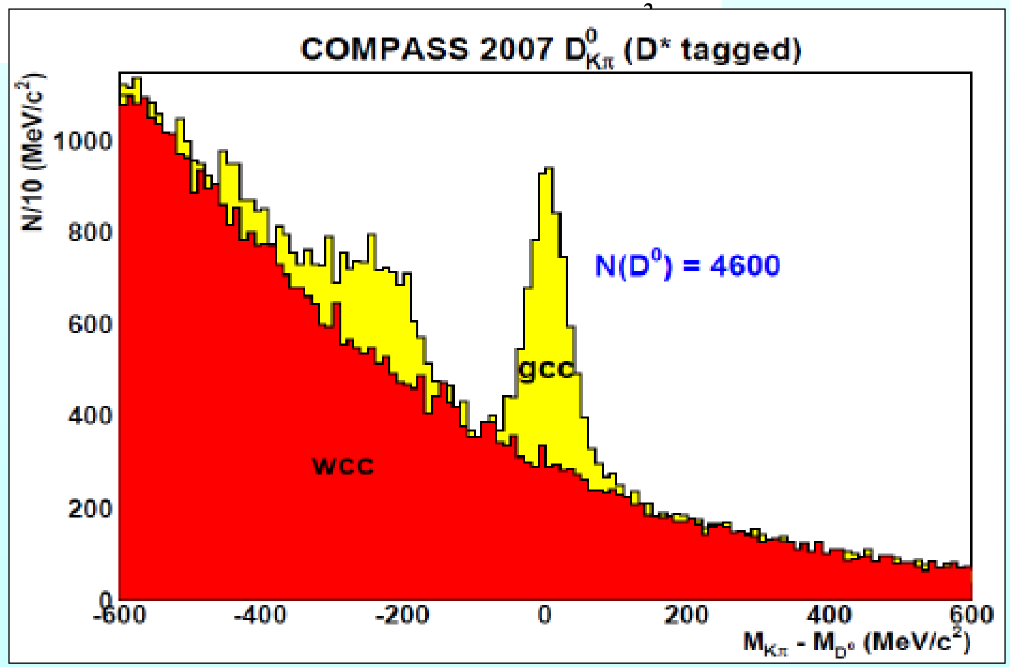
Purity of K samples



RICH PID information in the D° analysis







RICH PID information in Λ analysis