

High Intensity and Rare Decay Detectors

Augusto Ceccucci / CERN
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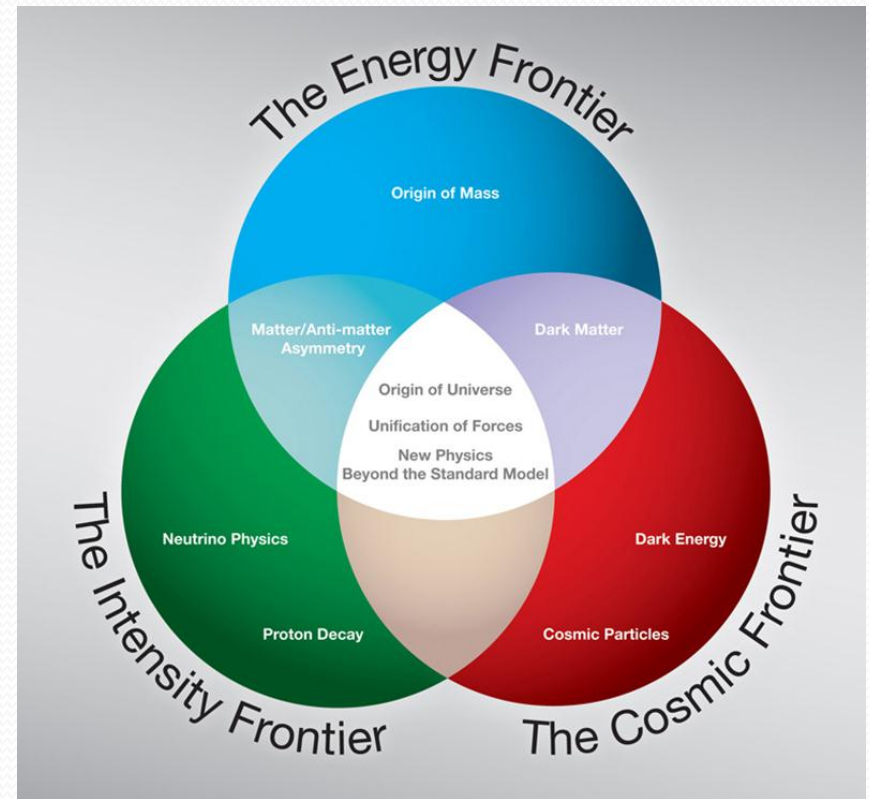
The School of Excellence in Detector and Instrumentation Technologies was created to ensure that researchers entering the field today get the hands-on experience they need to successfully further their careers.

<http://detectors.fnal.gov/EDIT2012>



Forward

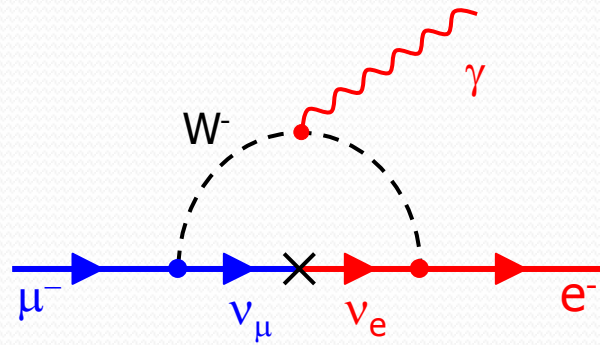
- Intense proton sources enable us to study processes which are either forbidden or extremely suppressed but well predicted in the Standard Model (SM)
- A measured deviation from the SM prediction would point to something new: rare processes in muon and kaon decays are particularly sensitive probes
- After an overview of the experiments under construction or planned at the intensity frontier....
-I will use the NA62 experiment at the CERN SPS, devoted to the study of kaon rare decays, to give you some examples of state-of-the-art detectors



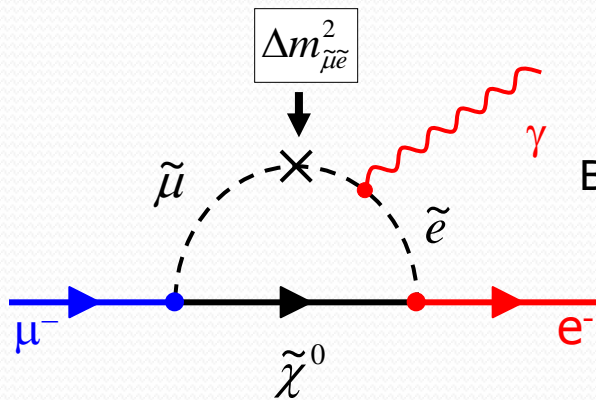
“High Intensity” proton Labs

Lab	Machine	Experiment	Physics
PSI	600 MeV Cyclotron	MEG	$\mu \rightarrow e \gamma$
FNAL	8 GeV Booster	g-2 Mu2e	μ - e conv. K^+ at rest μ , K
	120 GeV Main Injector Project X	ORKA	
J-PARC	30 GeV Main Ring	KOTO g-2 COMET	K^0_L μ - e conv.
CERN	400 GeV SPS	NA62	K^+ in flight

LFV in SUSY

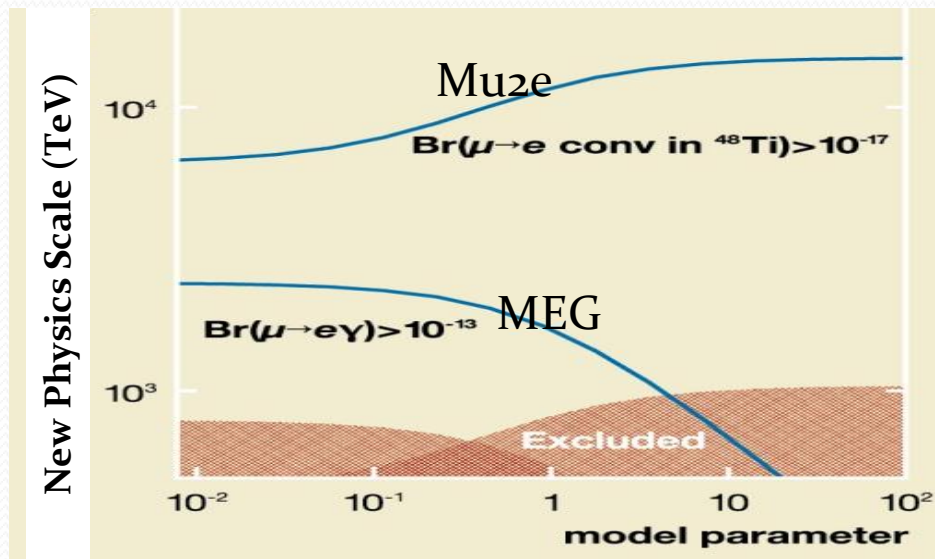


$$\text{BR}(\mu^- \rightarrow e^- \gamma) \Big|_{\text{SM}} \propto \frac{m_\nu^4}{m_W^4} \approx 10^{-60}$$

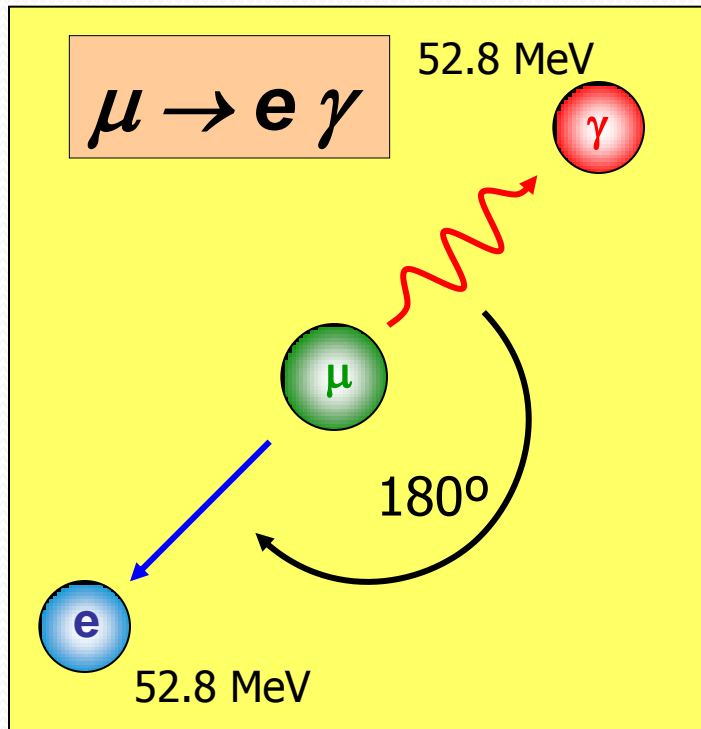


$$\text{BR}(\mu^- \rightarrow e^- \gamma) \Big|_{\text{SUSY}} \approx 10^{-5} \frac{\Delta m_{\tilde{e}\tilde{\mu}}^2}{\tilde{m}_\ell^2} \left(\frac{100 \text{ GeV}}{m_{\text{SUSY}}} \right)^4 \tan^2 \beta \approx 10^{-12}$$

- While Lepton Flavor Violation (LFV) is forbidden in SM, it is possible in SUSY



MEG: Search for $\mu \rightarrow e \gamma$

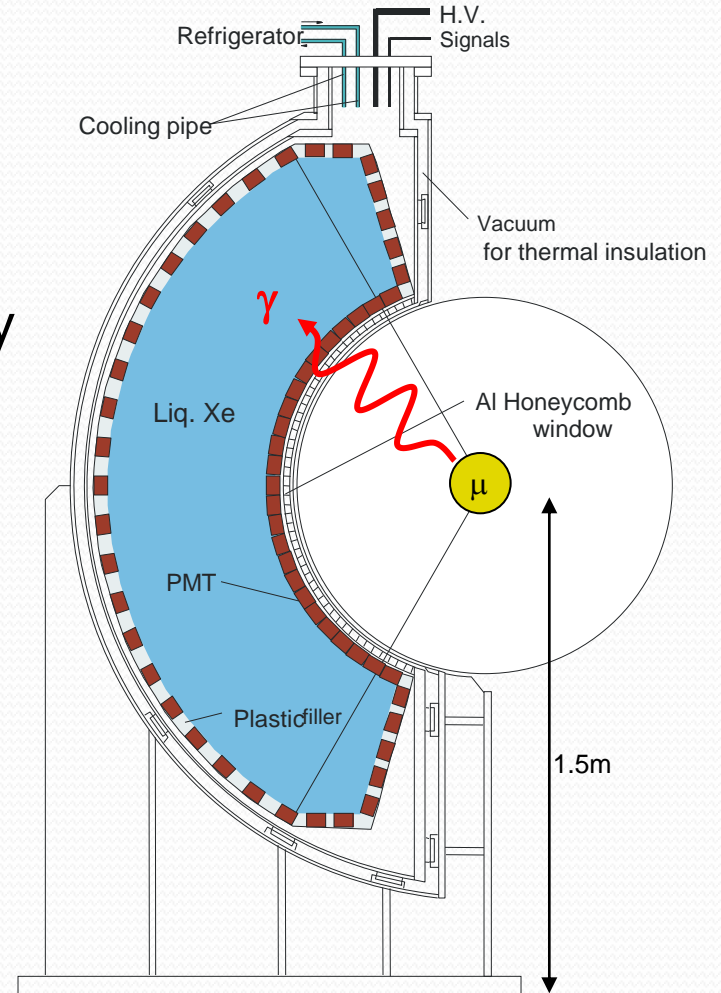


$\mu \rightarrow e \gamma$ signal very clean

- $E_g = E_e = 52.8 \text{ MeV}$
- $\theta_{\gamma e} = 180^\circ$
- e and γ in time

MEG Liquid Xenon Calorimeter

- Calorimeter: Measure γ Energy, Position and Time through scintillation light only
- Liquid Xenon has high Z and homogeneity
- ~ 900 l (3t) Xenon with 848 PMTs (quartz window, immersed)



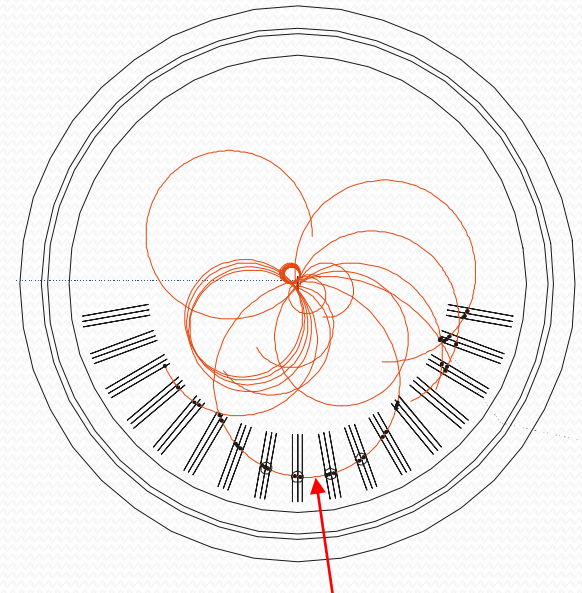
Positron Spectrometer

Ultra-thin ($\sim 3\text{g/cm}^2$) superconducting solenoid with 1.2

Homogeneous Field

high p_t track

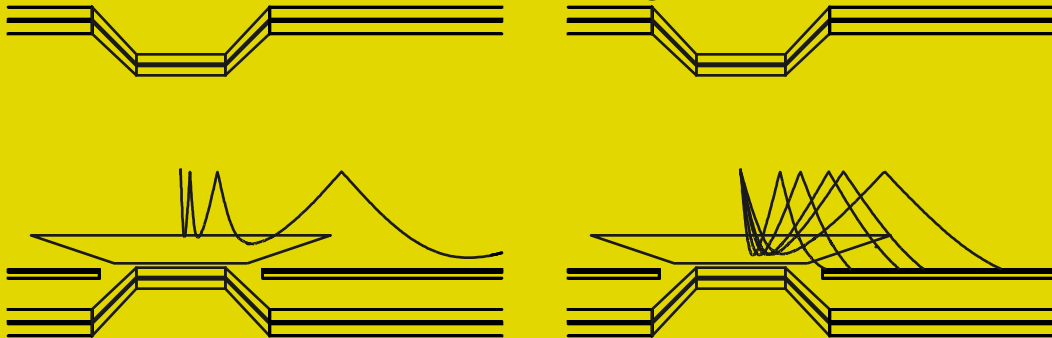
constant $|p|$ tracks



e^+ from $\mu^+ \rightarrow e^+ \gamma$

Gradient Field

(**C**onstant-**B**ending-**R**adius)

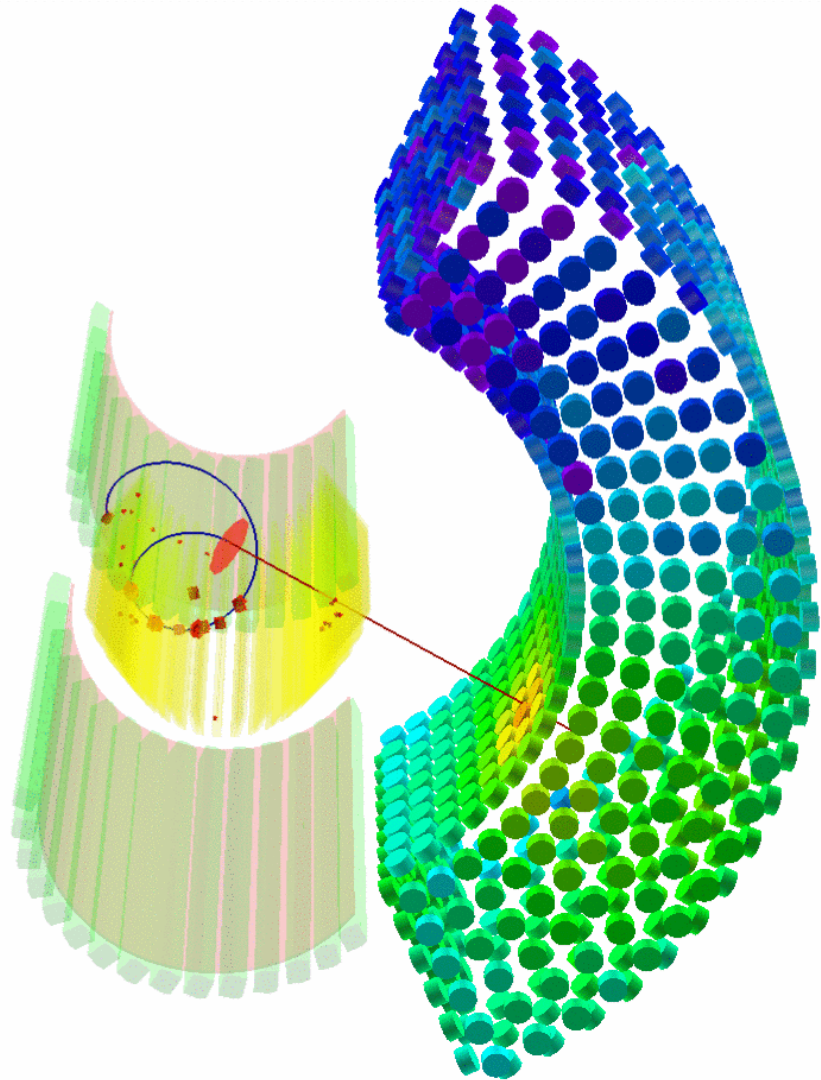


MEG Display

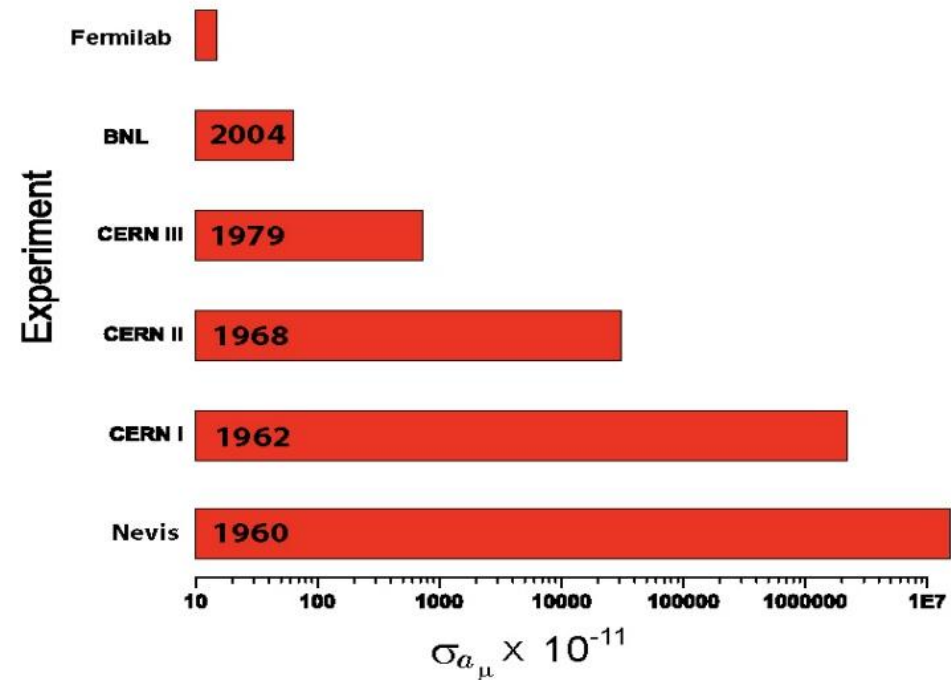
MEG recently published
the best limit (90% CL):

$$\text{BR}(\mu \rightarrow e \gamma) < 2.4 \times 10^{-12}$$

Phys.Rev.Lett. 107 (2011) 171801
e-Print: [arXiv:1107.5547](https://arxiv.org/abs/1107.5547) [hep-ex]

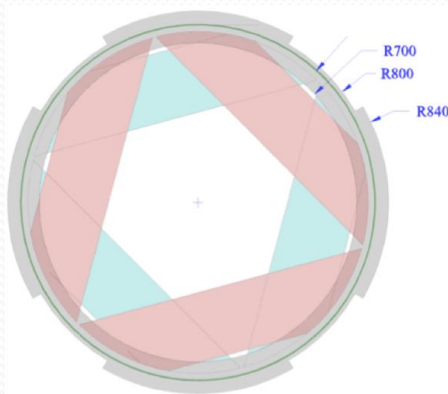
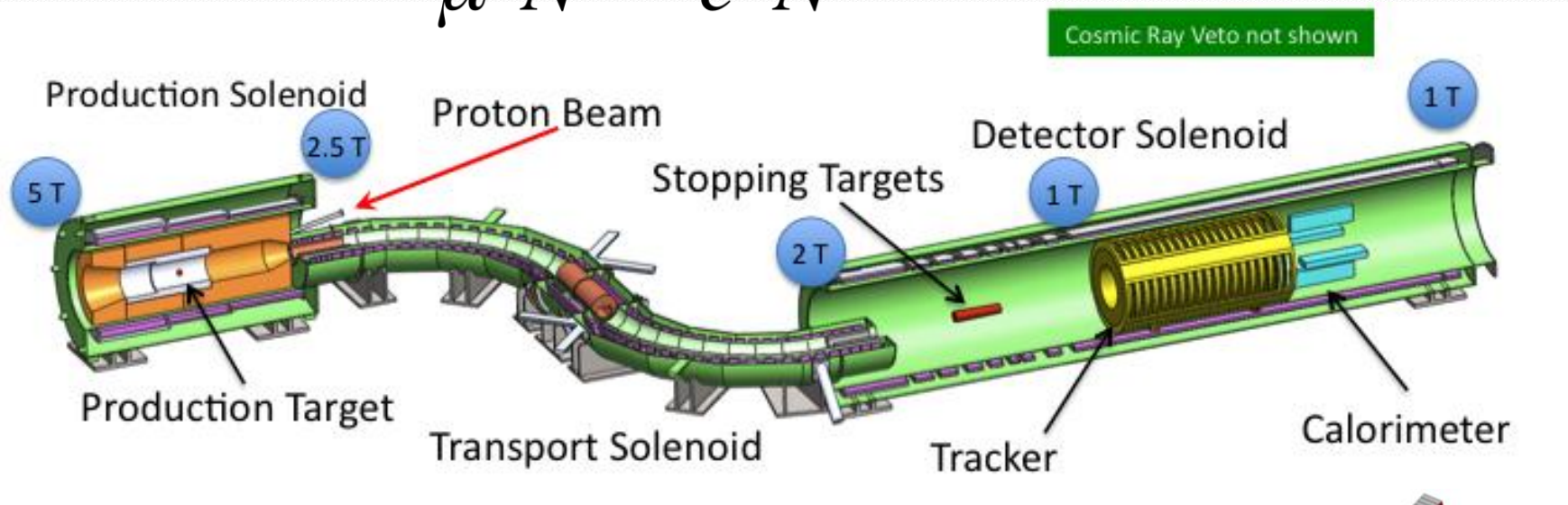


FNAL-E989: $g-2$ to 0.14×10^{-11}

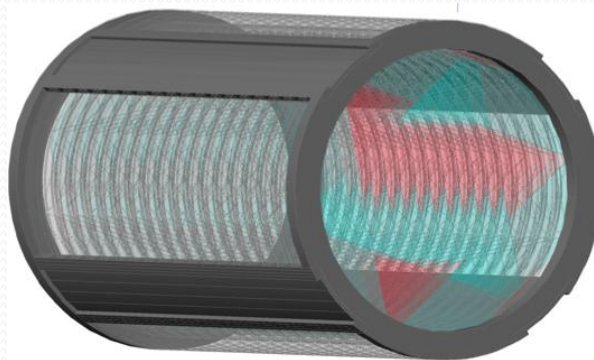


FNAL Mu2e: $\mu - e$ conversion

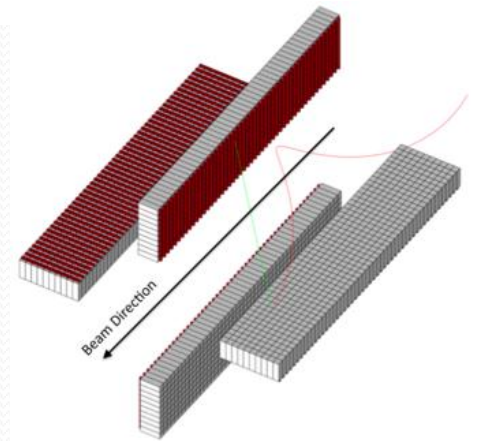
$$\mu^- N \rightarrow e^- N$$



One Tracking Plane



Straw Tracker



LYSO Calorimeter

Rare K Decays

Decay	Branching Ratio ($\times 10^{10}$)	
	Theory (SM)	Experiment
$K^+ \rightarrow \pi^+ \nu \bar{\nu} (\gamma)$	$0.85 \pm 0.07^{[1]}$	$1.73^{+1.15}_{-1.05}{}^{[2]}$
$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$	$0.27 \pm 0.04^{[3]}$	$< 260 \text{ (90\% CL)}^{[4]}$

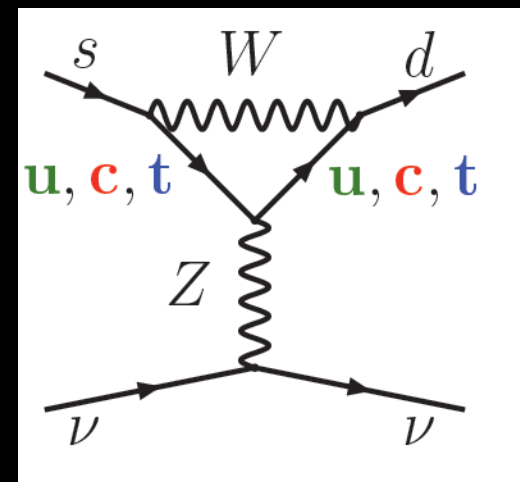
[1] J.Brod, M.Gorbahn, PRD78, arXiv:0805.4119

[2] AGS-E787/E949 PRL101, arXiv:0808.2459

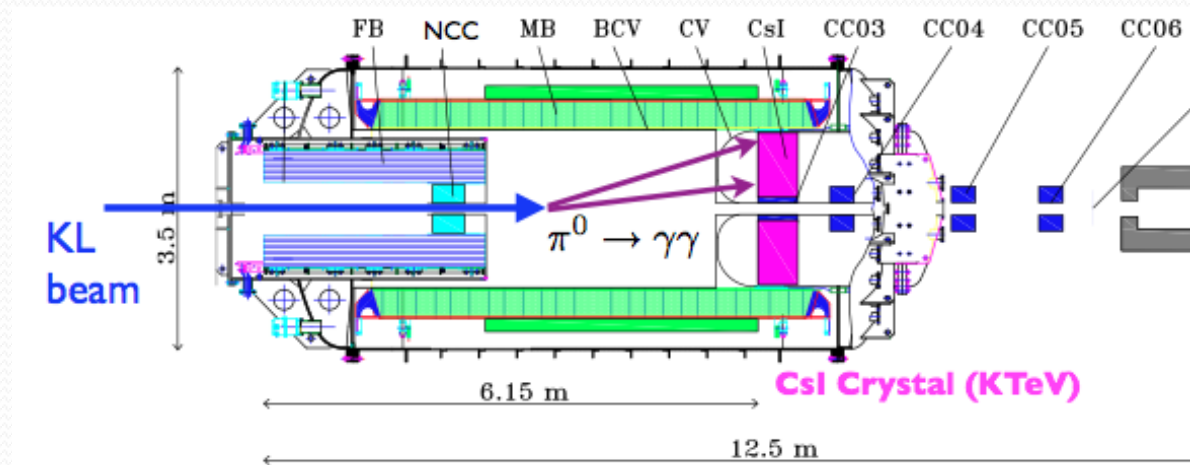
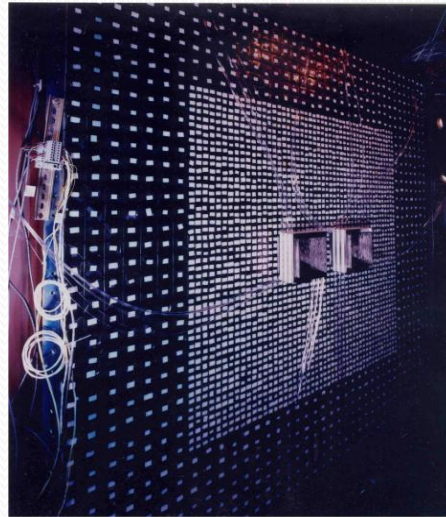
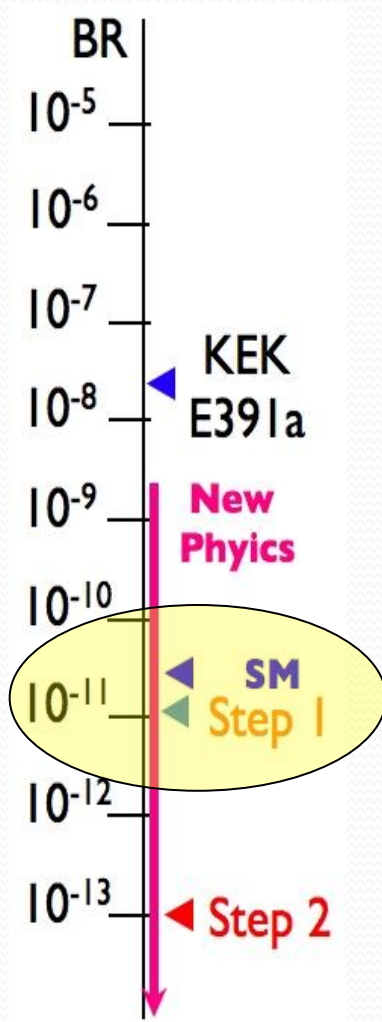
[3] M. Gorbahn, arXiv:0909.2221

[4] KEK-E391a, arXiv:0911.4789v1

- Must bridge the existing gap between theory and experiment
- A measurement of $\text{BR}(K^+ \rightarrow \pi^+ \nu \nu)$ to 10 % determines V_{td} without input from Lattice QCD!
- The strong suppression of the SM component ($< 10^{-10}$) offers good sensitivity to NP



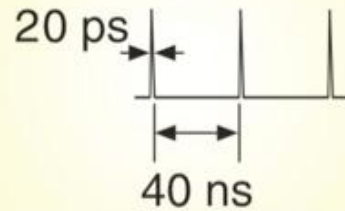
KOTO at JPARC



Example : $K^0 \rightarrow \pi^0 \nu \bar{\nu}$ @ Project X

Pico-bunches

3 GeV Protons

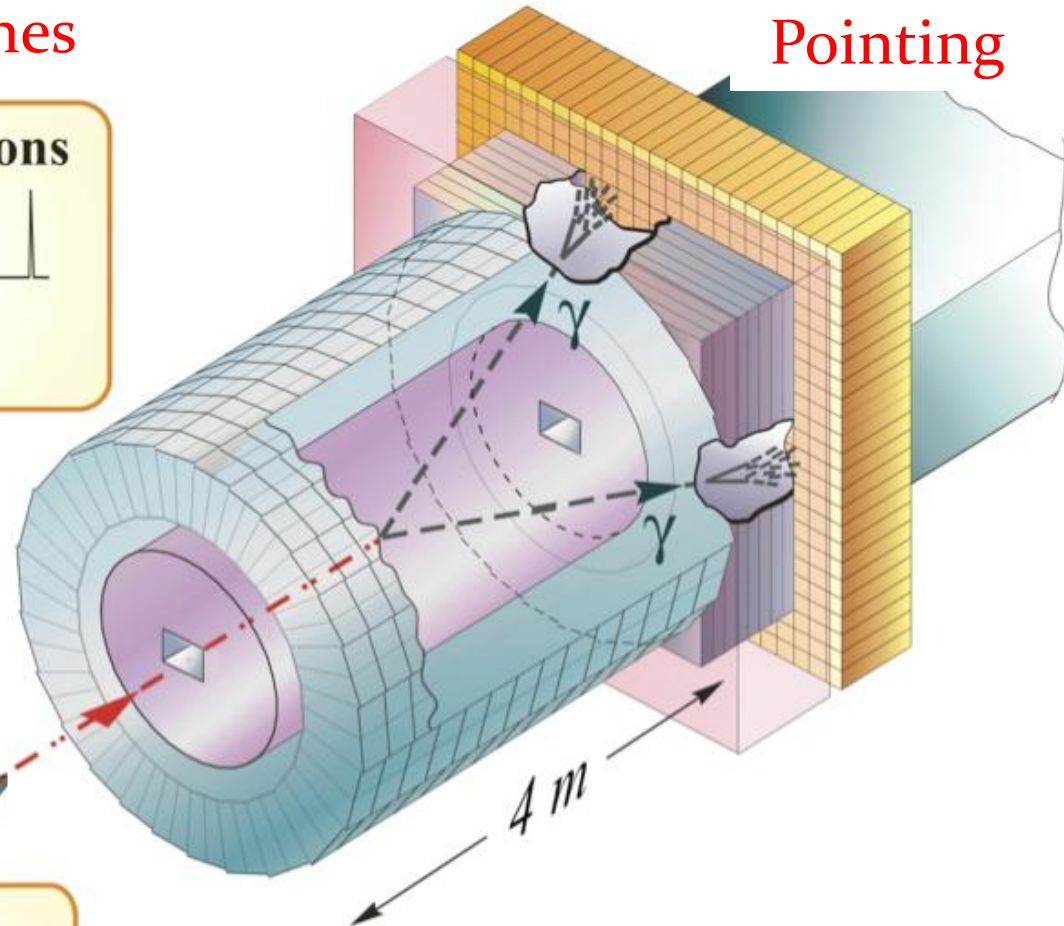
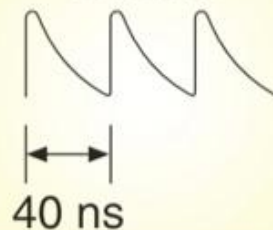


Pointing

Pencil beam

K_L^0

Kaons



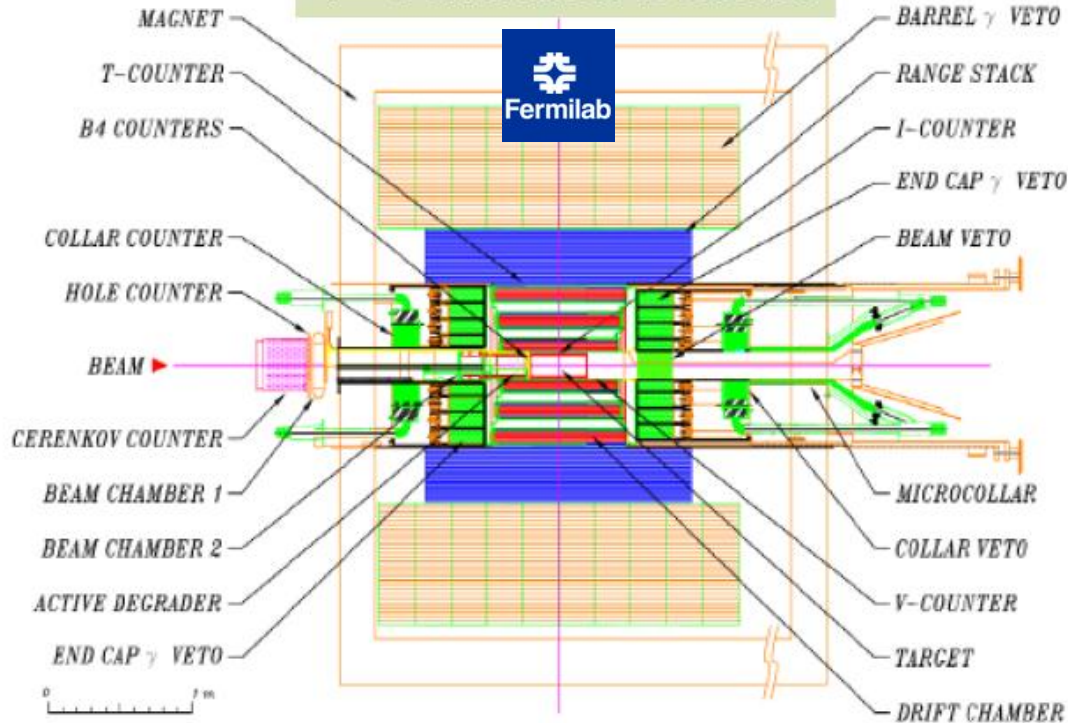
$$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$$

ORKA

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$

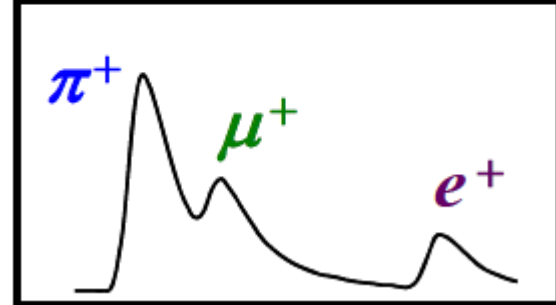
1st 2nd 3rd generation at BNL
= 7 event data sample

4th Generation Detector

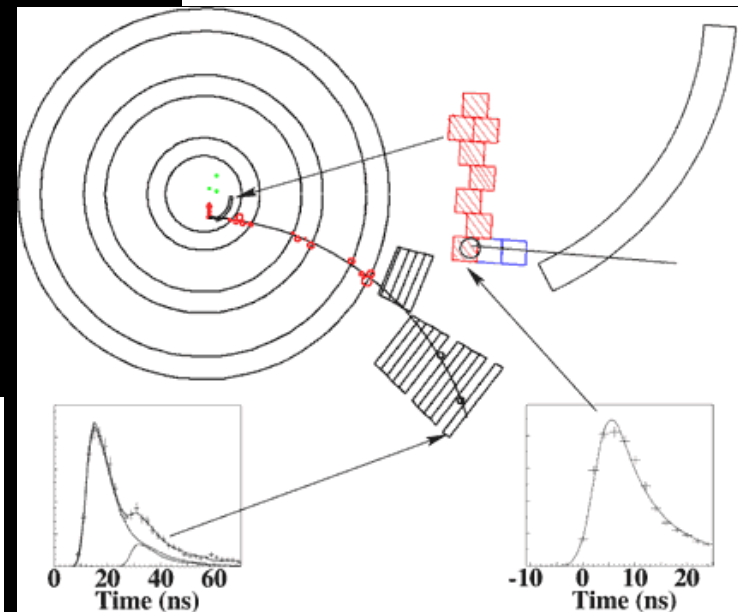


4th generation experiment with beam
from Main Injector and continuing
with Project X

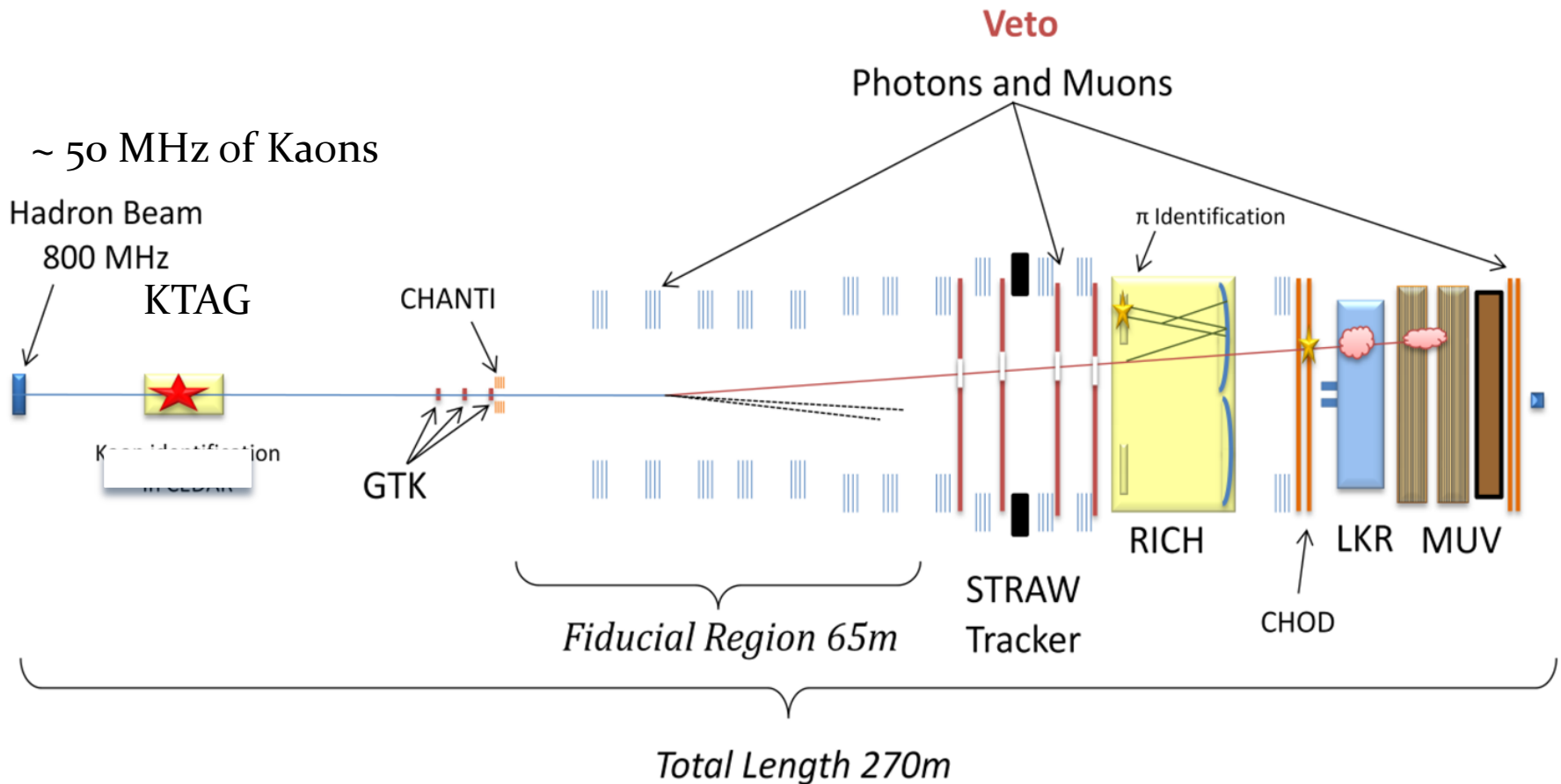
$\pi^+ \rightarrow \mu^+ \rightarrow e^+$ Decay Sequence



BNL E787 event display



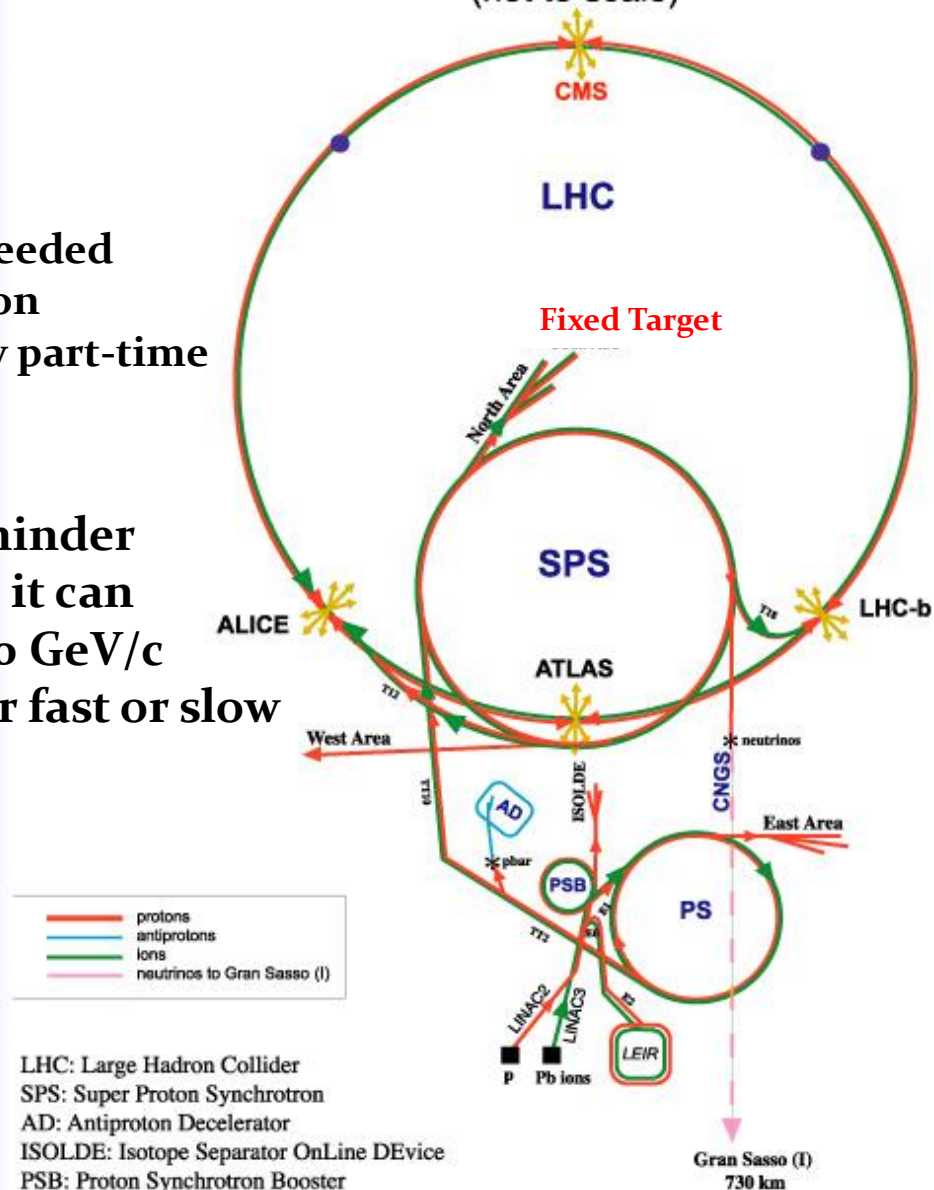
NA62: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ in-flight @ the CERN-SPS



CERN Accelerators (not to scale)

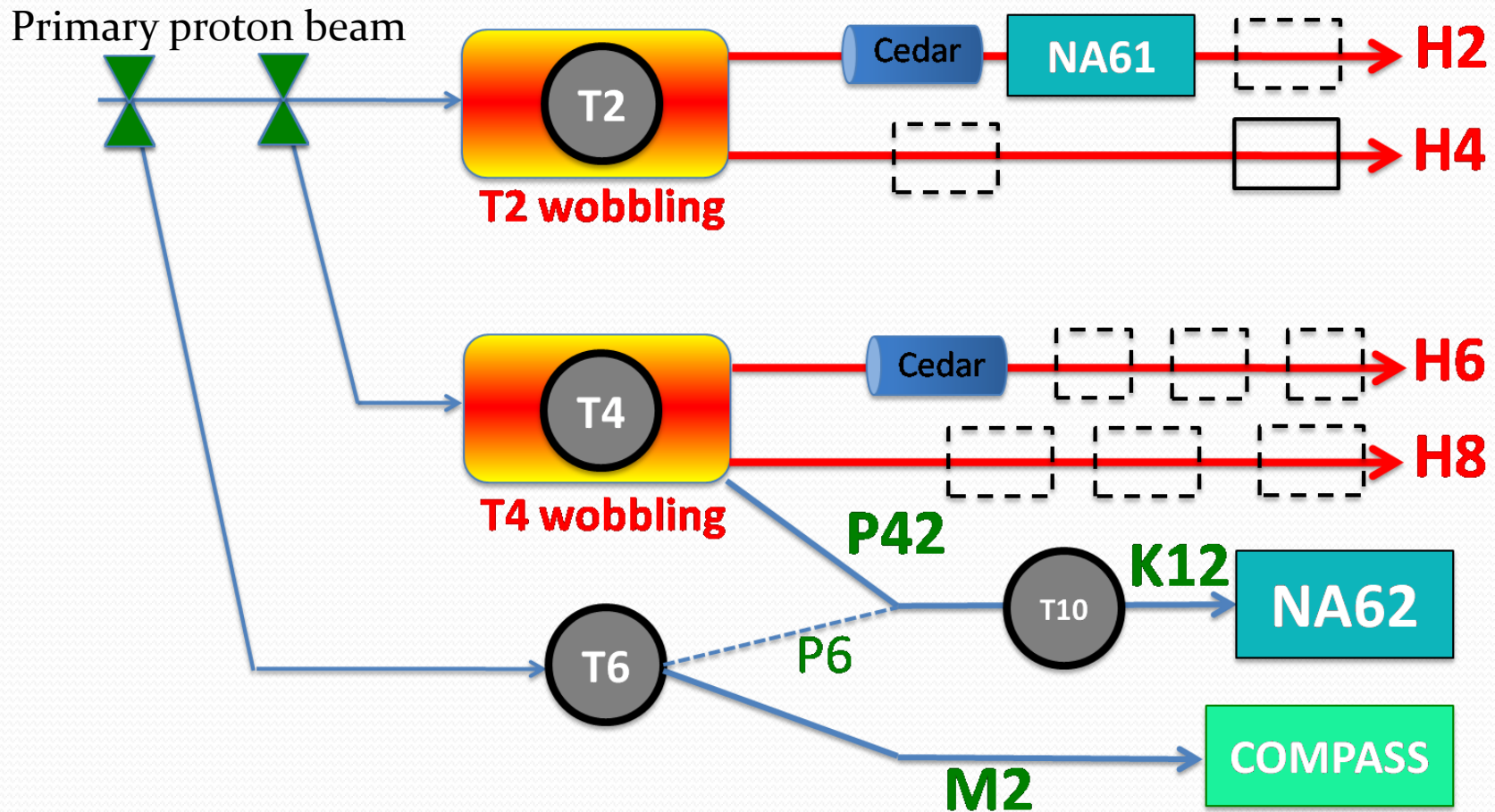
The SPS is needed
as LHC proton
injector only part-time

For the reminder
of the time it can
provide 400 GeV/c
protons for fast or slow
extraction



LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINEar ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

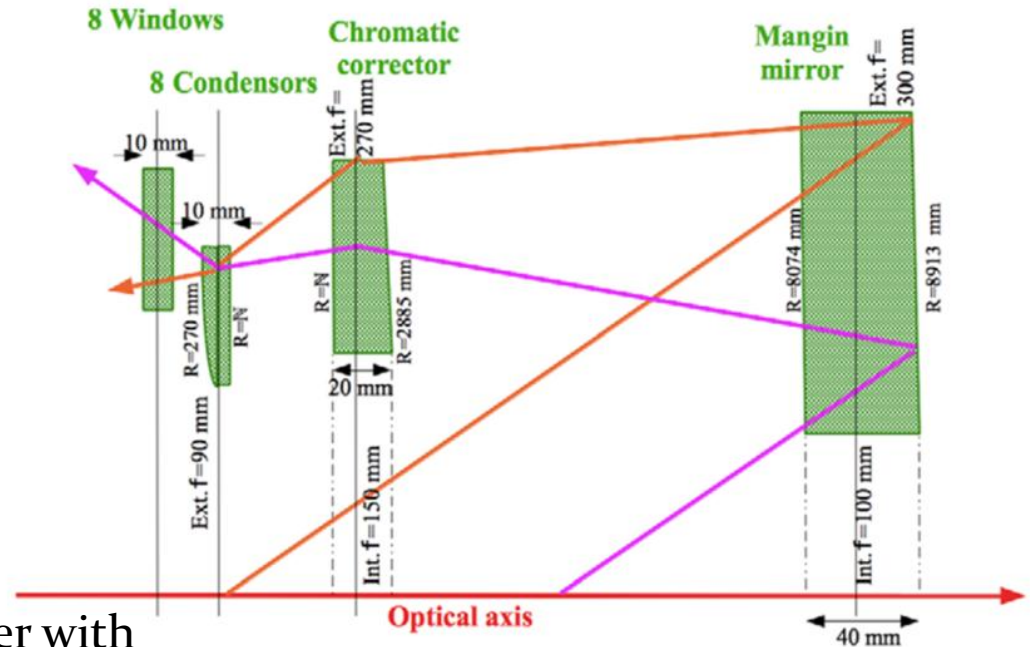
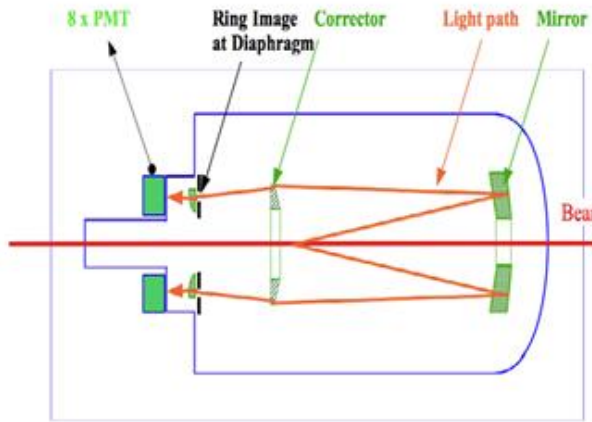
CERN-SPS North Area beams



NA62 Main Detectors

- KTAG
 - It positively identifies the kaons before they enter the decay region. It must tag approx. **50 MHz of Kaons** and be as thin as possible
- Gigatracker (GTK)
 - Silicon Pixel tracker to measure direction and momentum on event-by-event basis. The beam rate is almost **one GHz** (hence the detector name...). It must be very thin to avoid too many inelastic interactions...Excellent time resolution is required to time stamp each track (**< 200 ps / hit**)
- Photon Vetoes
 - A large system of detectors surrounding the decay tank to suppress the π^0 background by **8 orders of magnitude!**
- Straw Tracker
 - Reconstructs the decay charged particles. To reduce the multiple scattering, this large acceptance spectrometer is housed in the vacuum tank. The overall thickness of the 16 tracking views does not exceed **a few % X_0**
- RICH
 - Pion / Muon identification up to 35 GeV/c is achieved by means of a Ring Imaging Cherenkov Counter (RICH). It also provides the time reference to correlate the pion to the correct incoming kaon track (**100 ps or better**)
- Muon Vetoes
 - To suppress the muons at the trigger and analysis level. They consist of hadron calorimeters made of iron and plastic scintillator and a fast veto plane

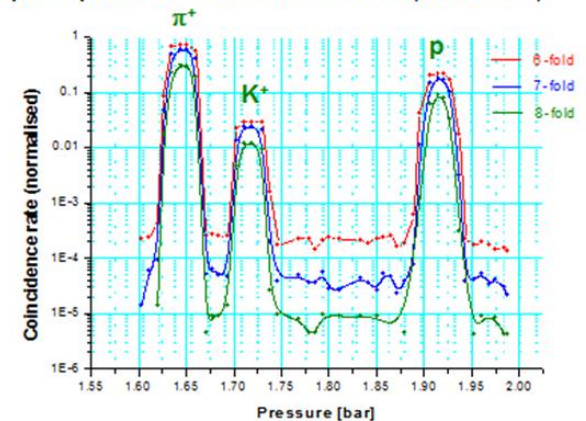
CEDAR



The Differential Cherenkov Counter with Achromatic Ring focus (CEDAR) was developed at CERN in the 80's to operate up to a few MHz tagging rates

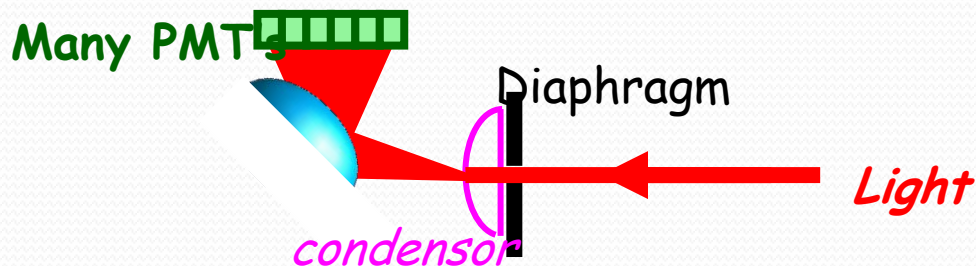
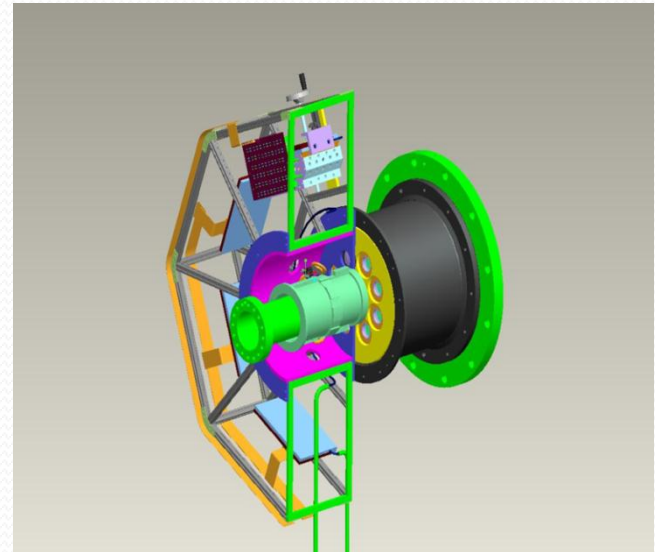
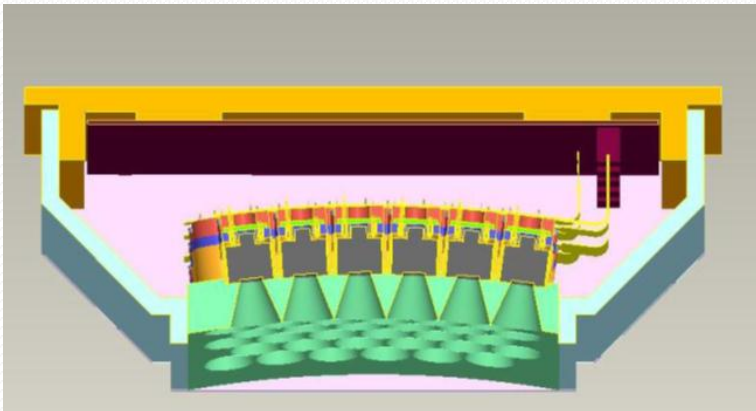
Mangin mirror (negative meniscus with reflecting surface on the rear surface) and chromatic corrector

Example of a pressure scan at 75 GeV/c in H2 beam (October 2007):



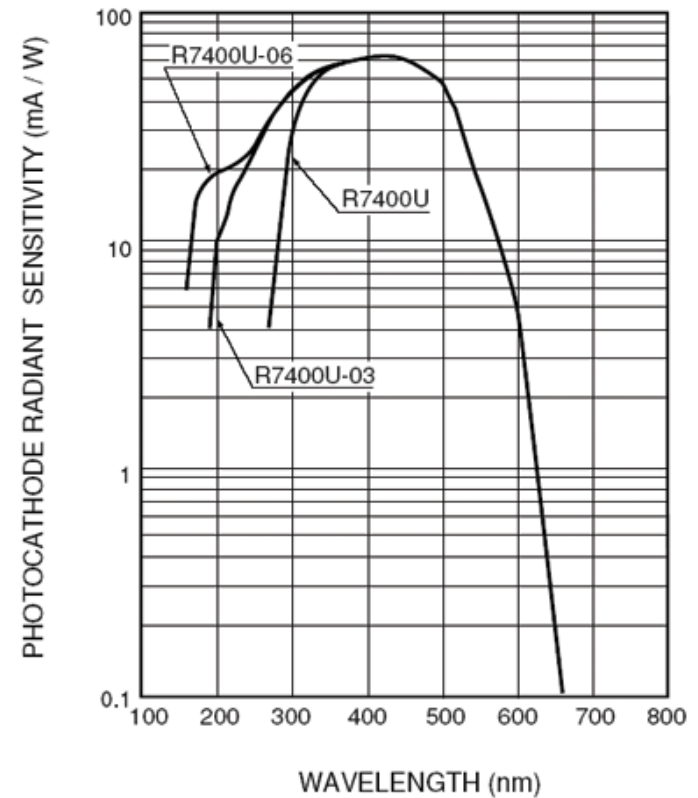
KTAG=CEDAR + new optics

With 50 MHz kaon rate one must spread the photon rate on many photo-detectors (PMTs)



The Photomultipliers

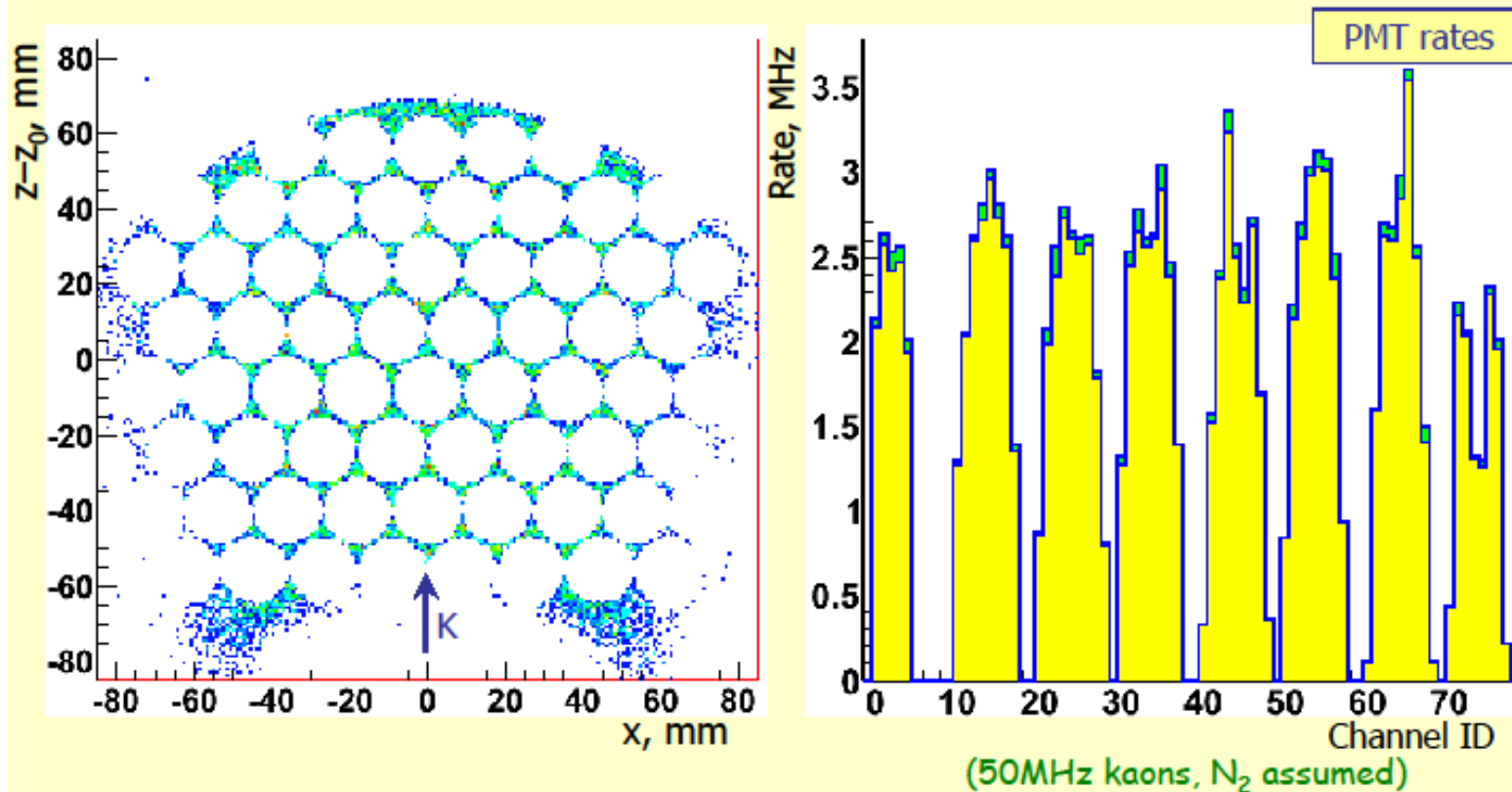
- Hamamatsu R7400U-03
- UV-glass, bialkali, 8 dyn
- 16 mm wide (8 mm active)
- Gain $1.5 \cdot 10^6$ @900 V
- 280 ps time jitter (FWHM)
- 185-650 nm response (420 nm peak)
- Q.E. around 20% on peak
- PM output (1 p.e.): 240 fC, peak at 200 μ A or -10 mV (50 Ω)
- Rise time: 0.78 ns, fall time~1.6 ns





(2) 2014 layout: 64 PMTs

Spherical mirrors: $R=64.6\text{mm}$; optical cap lenses: $F=300\text{mm}$.



Cones per row: $5+8+9+8+9+8+9+8 = 64$

Example: 64 PMT / spot, N_2

Evgueni Goudovski

Why Hydrogen in the KTAG

KTAG type	Gas filling P (bars)	Length (m)	Windows (Al)	Total X/X ₀	X',Y' RMS (mrad)	Inel Scatt Probability
Cedar-W	Hydrogen 3	5.642	0.1+0.2 mm	$6.4 \cdot 10^{-3}$ [20.8]	0.016 [0.029]	$1.2 \cdot 10^{-3}$ [2.8]
Cedar-N	Helium 10	6.042	2 x 0.3 mm	$18.3 \cdot 10^{-3}$ [32.7]	0.027 [0.036]	$6.5 \cdot 10^{-3}$ [8.1]
Cedar-W	Nitrogen 1.7	5.642	2 x 0.1 mm	$33.0 \cdot 10^{-3}$ [47.4]	0.036 [0.044]	$6.4 \cdot 10^{-3}$ [8.0]
3 GTK	Si	3x0.45 mm	—	$14.4 \cdot 10^{-3}$	0.024	$1.6 \cdot 10^{-3}$

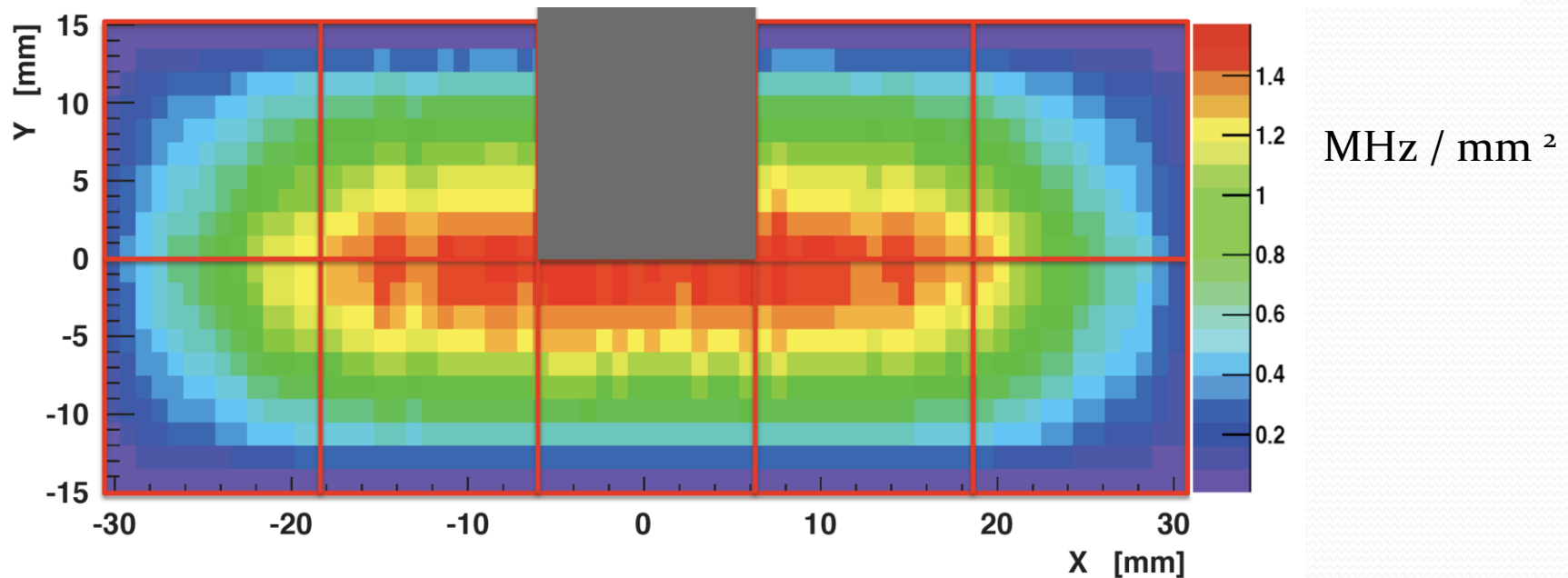
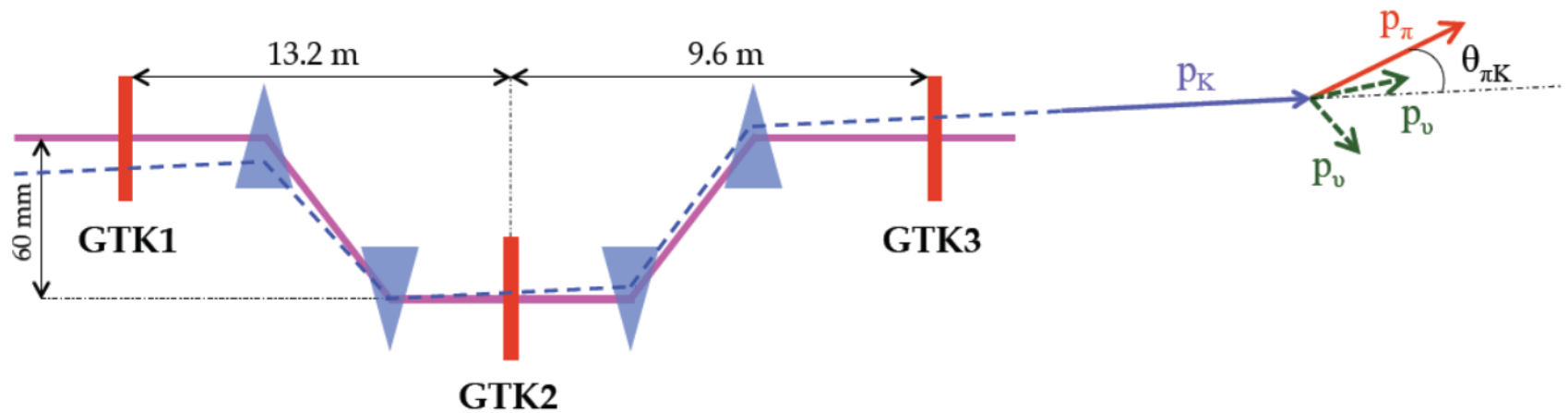
Lau Gatignon

Figures in [] include 3 GTK stations

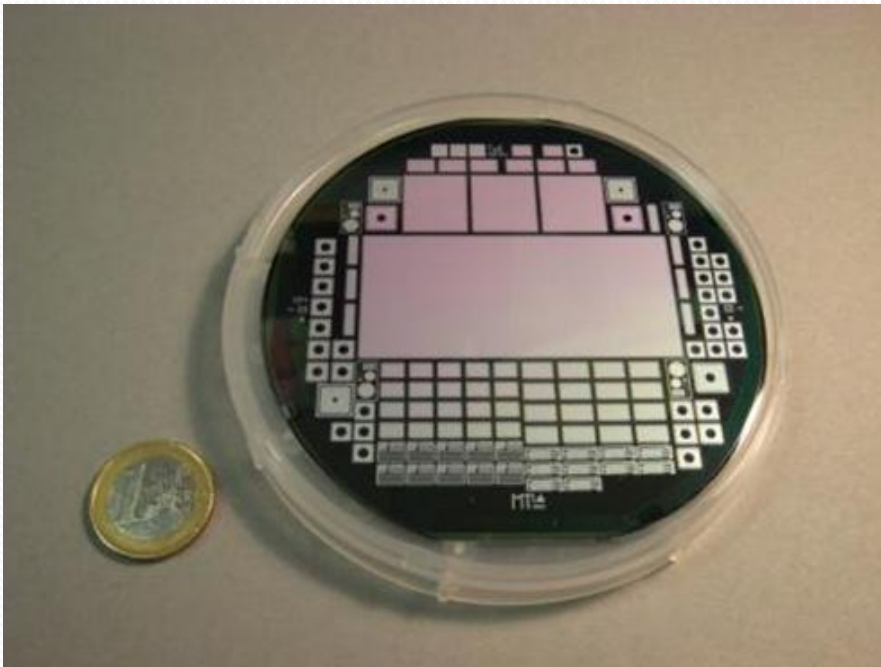
Gigatracker (GTK)

- Requirements:
 - Total rate: ~ 1 GHz /station (hence the name!)
 - Time resolution: 200 ps / station
 - Position resolution: pixel size $300\text{ }\mu\text{m} \times 300\text{ }\mu\text{m}$
 - Thickness : $0.5\text{ }\%$ X_0 / station
 - Expected fluence: 2×10^{14} 1 MeV n_{eq} / year / cm^2
- Technology:
 - hybrid Si pixel
 - Flip-chip bonding
 - ASIC R/O chip 130 nm IBM CMOS with ToT front-end, DLL TDC
- Choice of sensor:
 - Planar Si $200\text{ }\mu\text{m}$ thick
 - Reverse Bias Voltage as high as possible (but at least 300 Volts)

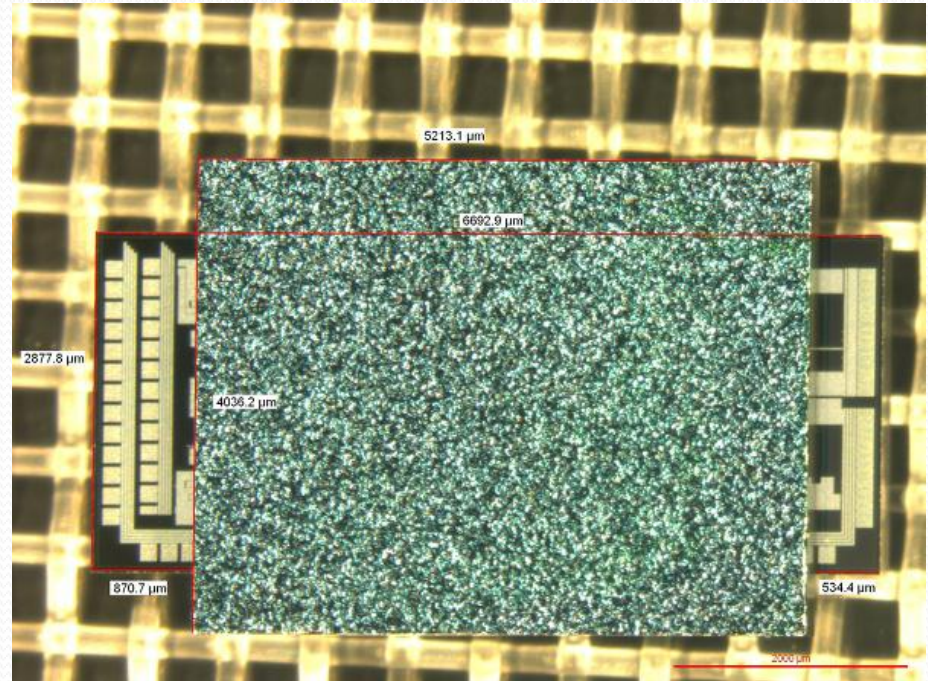
GTK: Layout & Rate



GTK: Sensor and Assembly

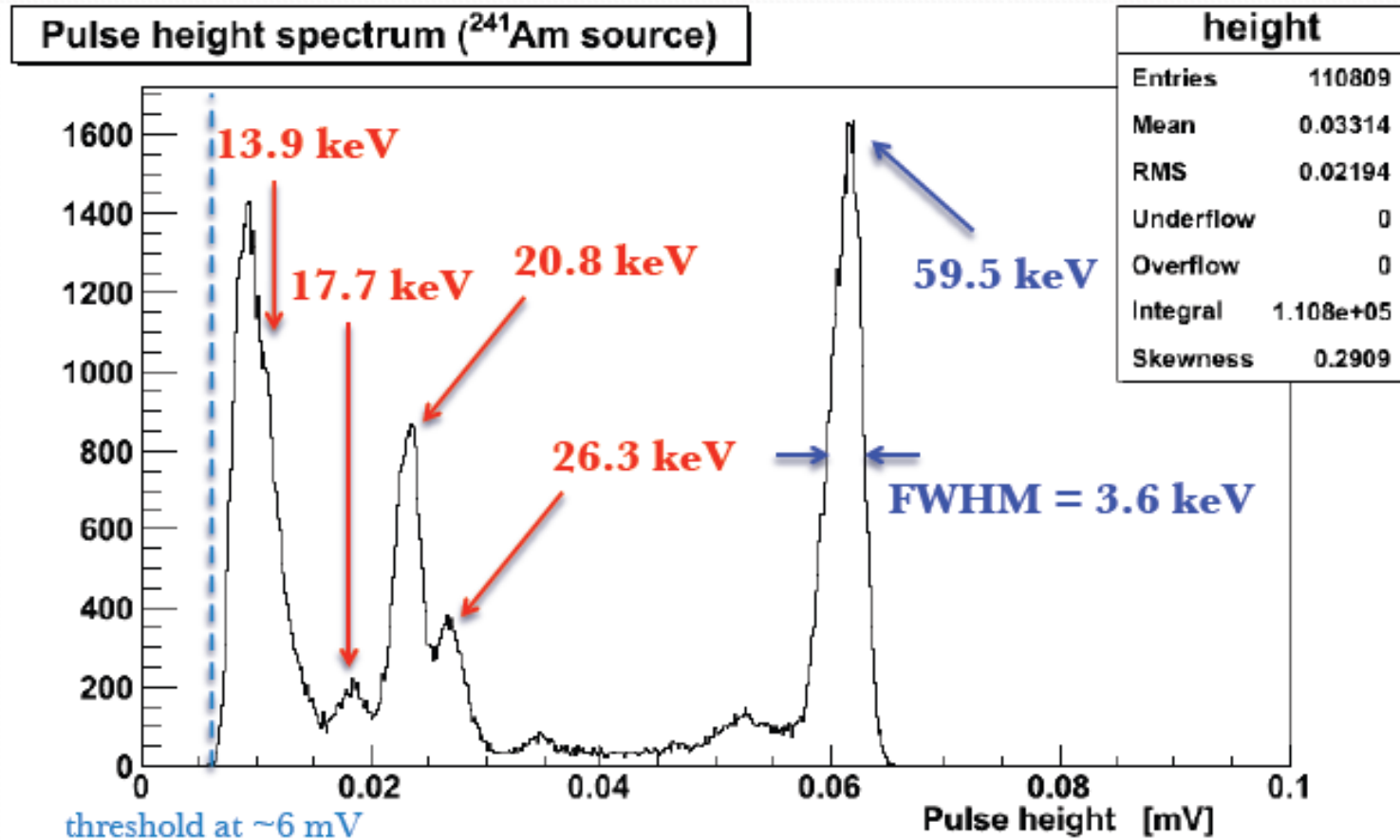


p on n sensor from FBK (Trento, Italy)



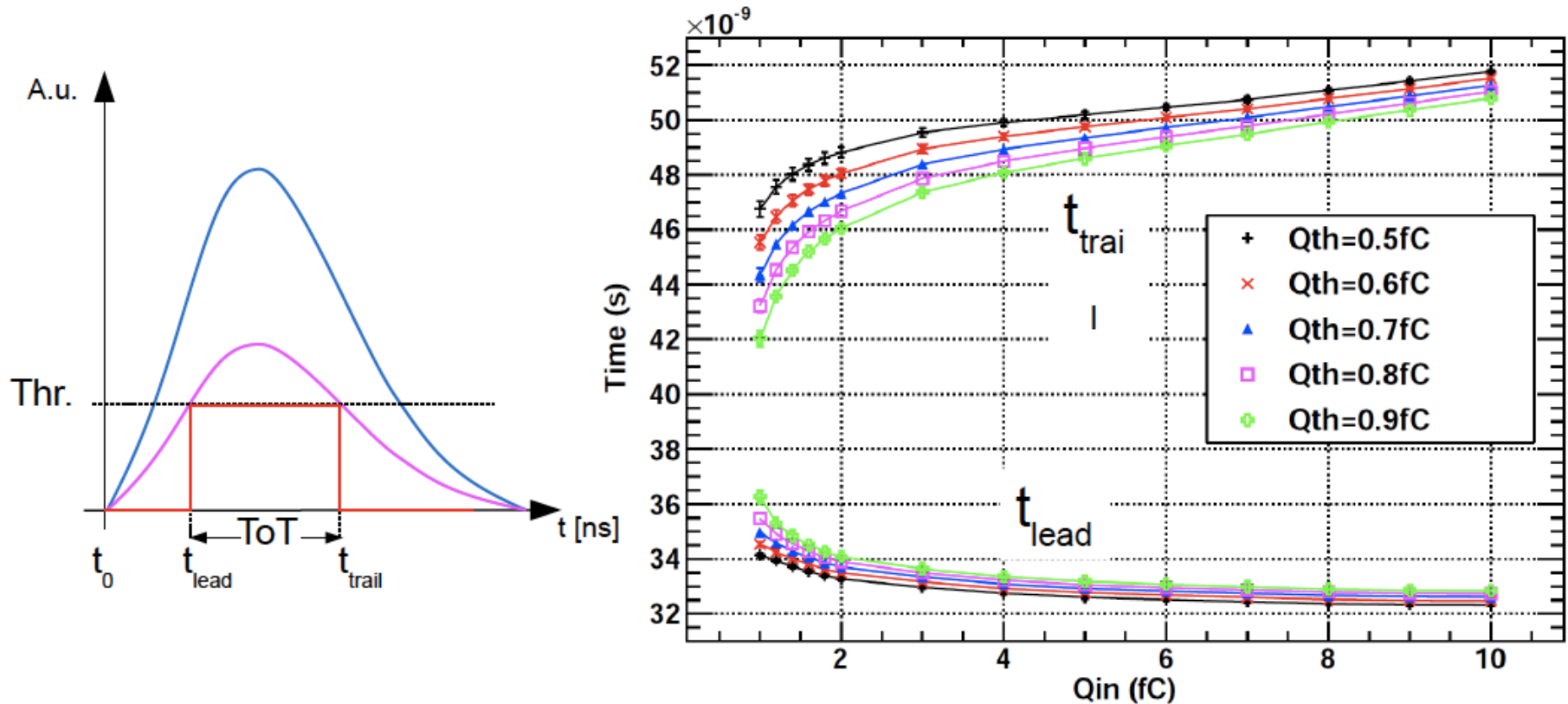
Flip-chip bonding by IZM (Berlin, Germany)

^{241}Am Spectrum



GTK Prototype pulse height distribution (analogue output) Massimiliano Fiorini

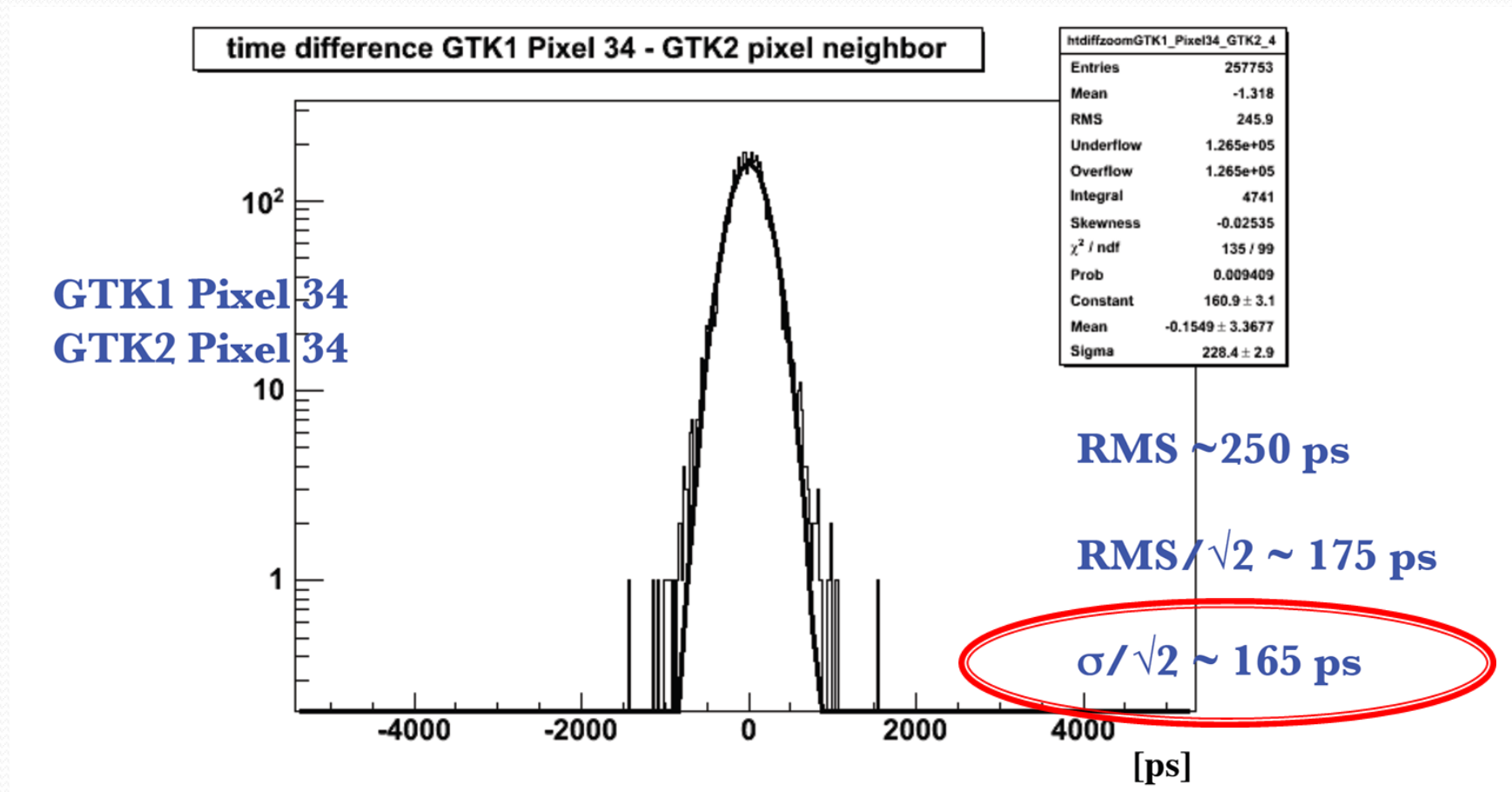
GTK: ToT Method



The Time over Threshold (ToT) front-end provides a correction for the slewing correction

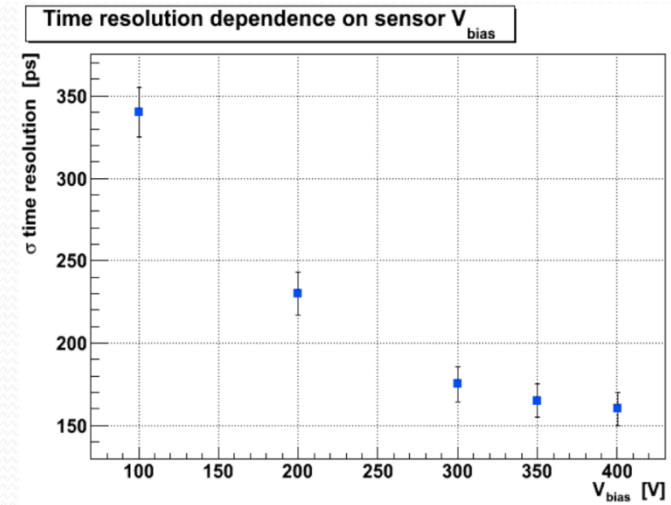
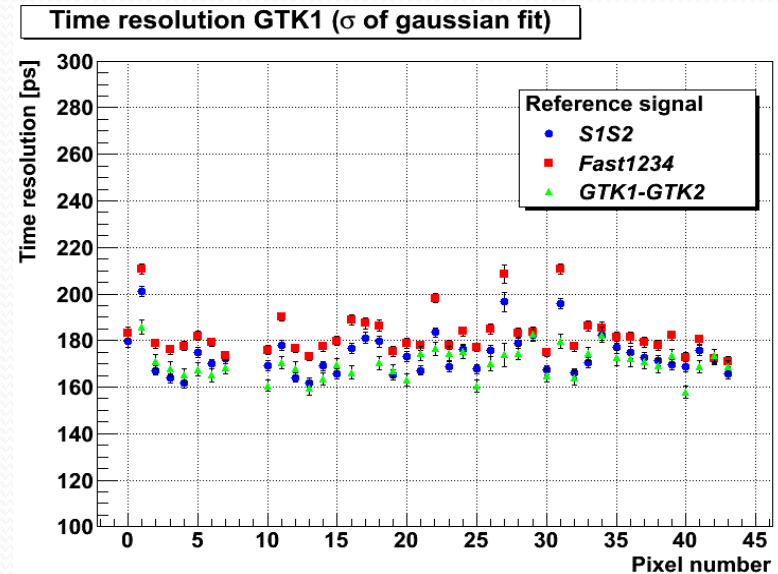
The noise is about 180 electrons / channel \rightarrow jitter 75 ps @ 3 fC

GTK: Prototype Time resolution



GTK: Test Beam Analysis

- CERN PS T9 (10 GeV/c π^+ and p)
- Time resolution better than 200 ps per hit for sensor bias voltages higher than 300 V across the whole pixel matrix (45 pixels)
- Time-walk correction and alignment procedures have been validated with real data
- Clear dependence of time resolution on sensor bias voltage
- The operation at 300 V over-depletion is mandatory

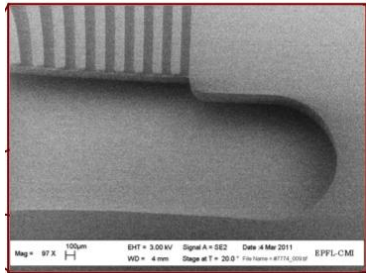


GTK: Micro-Channel Cooling

Final cross section of the cooling plate

Operating temperature -25 C

Channels = 200 x 70 μm
Wall thickness = 200 μm
Cover thickness = 30 μm

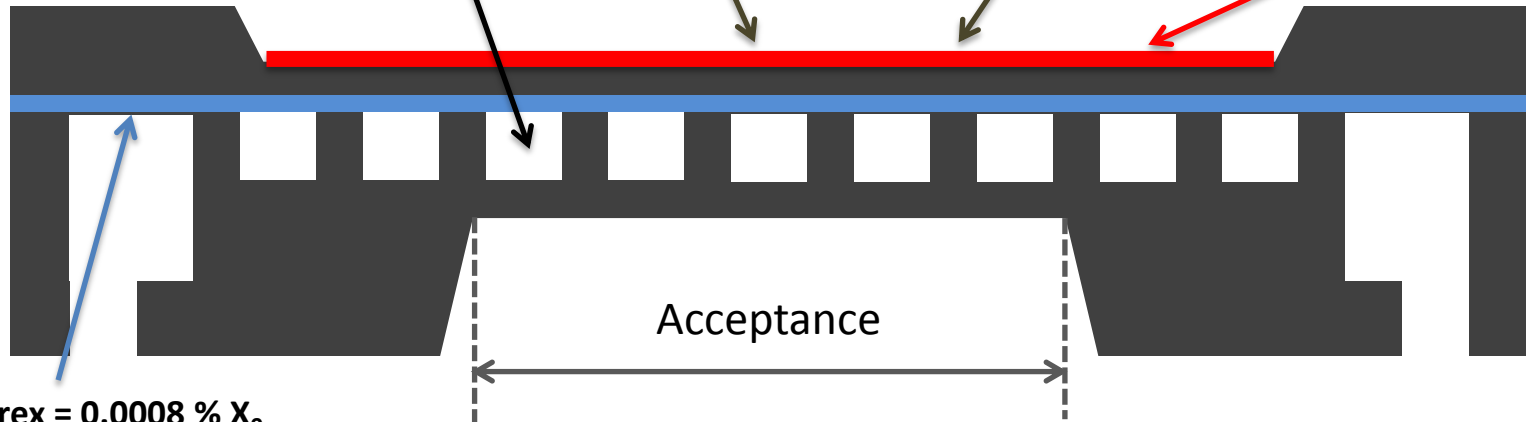


30 + 30 μm Silicon = 0.0064 % X_0
(above and below channels)

30 + 30 + 70 μm Silicon = 0.0139 % X_0
(between channels)

70 μm C6F14 = 0.0037 % X_0

30 μm epoxy = 0.0008 % X_0



10 μm Pyrex = 0.0008 % X_0
(removed in final production)

Paolo Petagna

Total material budget in the acceptance area = 0.013 % X_0
(min 0.011% - Max 0.015%)

NA62 Vetoes

- Photon vetoes to reject $K^+ \rightarrow \pi^+ \pi^0$

$$P(K^+) = 75 \text{ GeV}/c$$

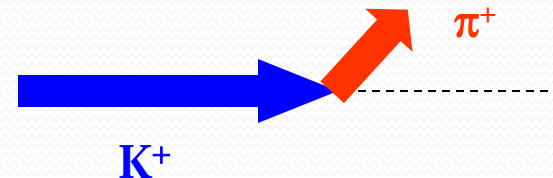
$$\text{Requiring } P(\pi^+) < 35 \text{ GeV}/c$$

$P(\pi^0) > 40 \text{ GeV}/c$  It can hardly be missed in the calorimeters

8 orders of magnitude π^0 suppression required

Signature:

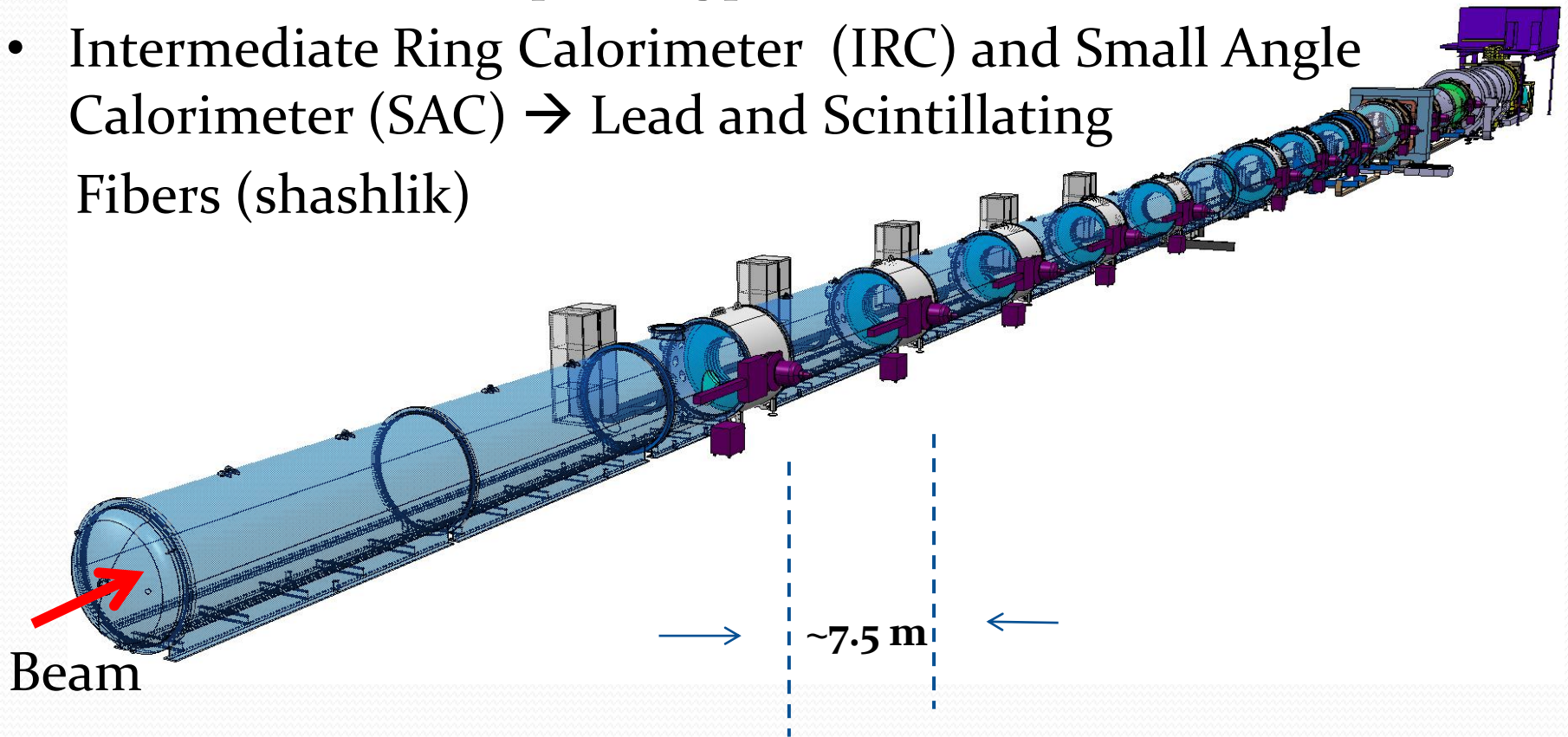
- Incoming **high momentum** K^+
- Outgoing **low momentum** π^+



- Muon Veto to reject $K^+ \rightarrow \mu^+ \nu$

NA62 Photon Vetoes

- Large Angle Vetoes (LAV) → Lead Glass Cherenkov Counters (former LEP-OPAL barrel)
- Forward Veto → Liquid Krypton (Ionization Chamber)
- Intermediate Ring Calorimeter (IRC) and Small Angle Calorimeter (SAC) → Lead and Scintillating Fibers (shashlik)

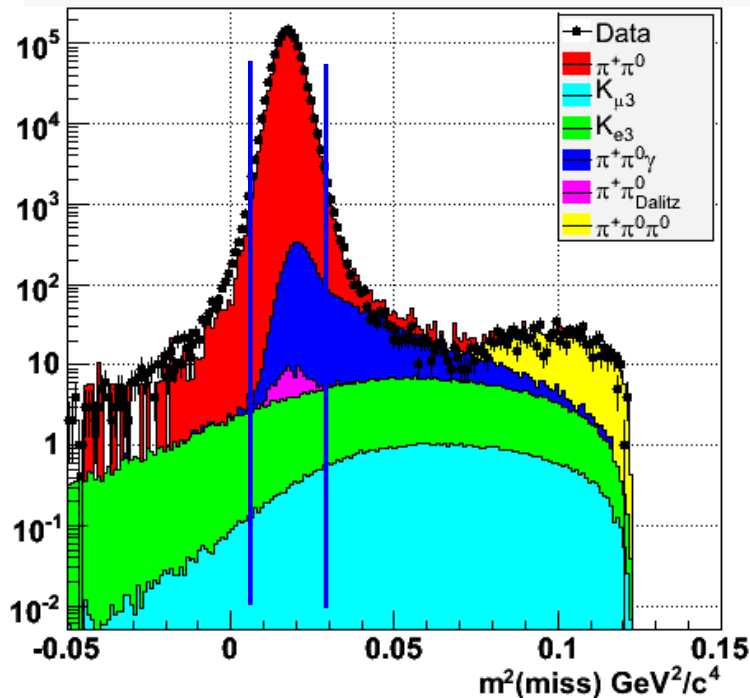


Liquid Krypton Calorimeter (NA48) as Forward Photon veto for NA62

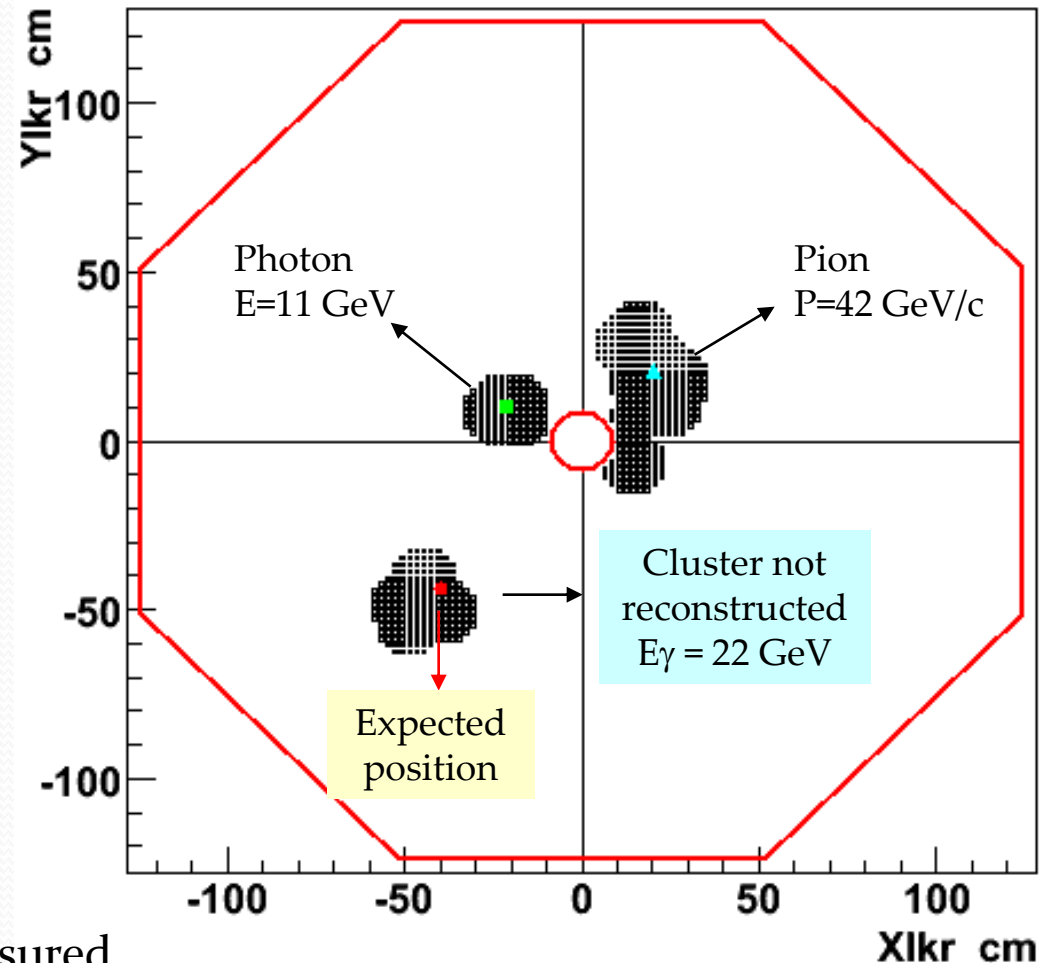
LKr ineff. per γ ($E_\gamma > 10$ GeV):

$$\eta \sim 7 \times 10^{-6} \quad (\text{preliminary})$$

$K^+ \rightarrow \pi^+ \pi^0$ selected kinematically

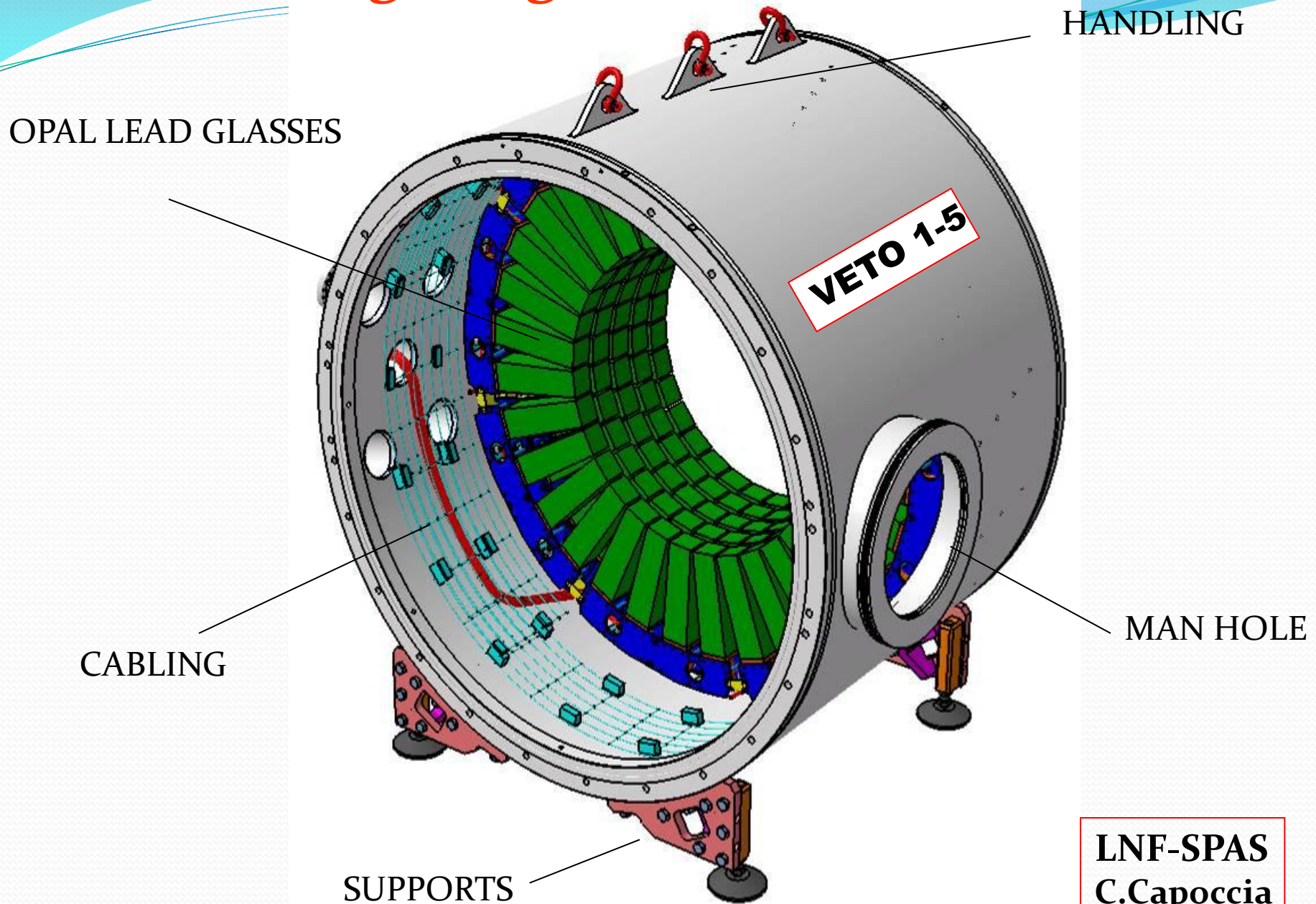


π^+ track and lower energy γ are used to predict the position of the other γ



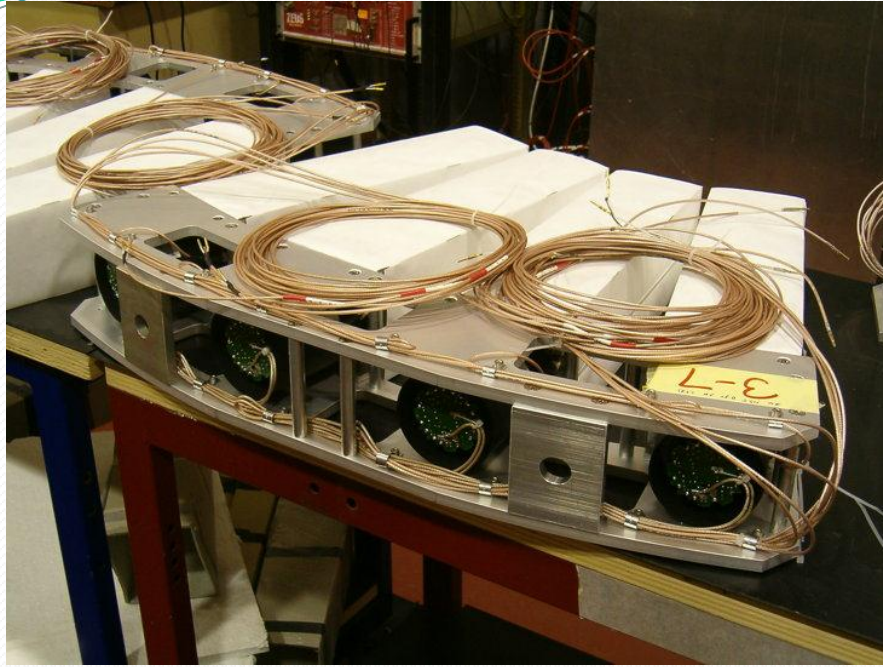
LKr γ Detection Efficiency was Measured from NA48 data

Large Angle Vetoes (LAV)



LNF-SPAS
C.Capoccia

NA62 LAV

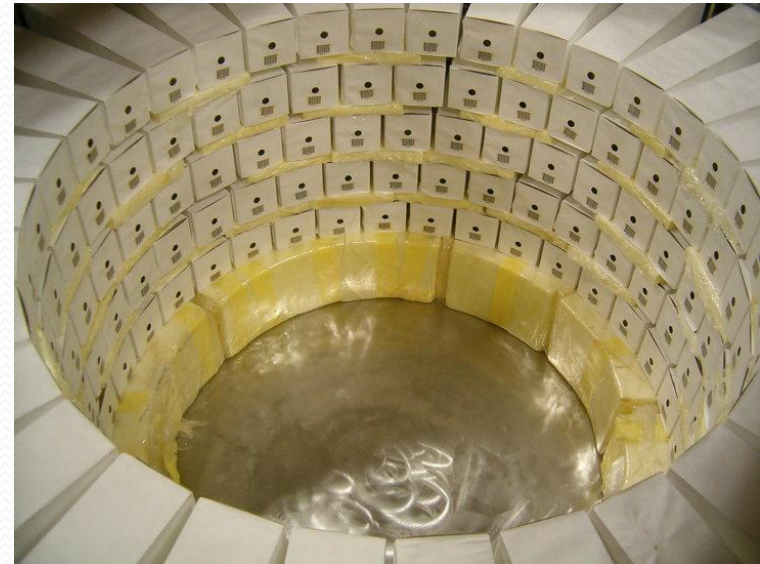


NA62 LAV

30 Nov 10:41



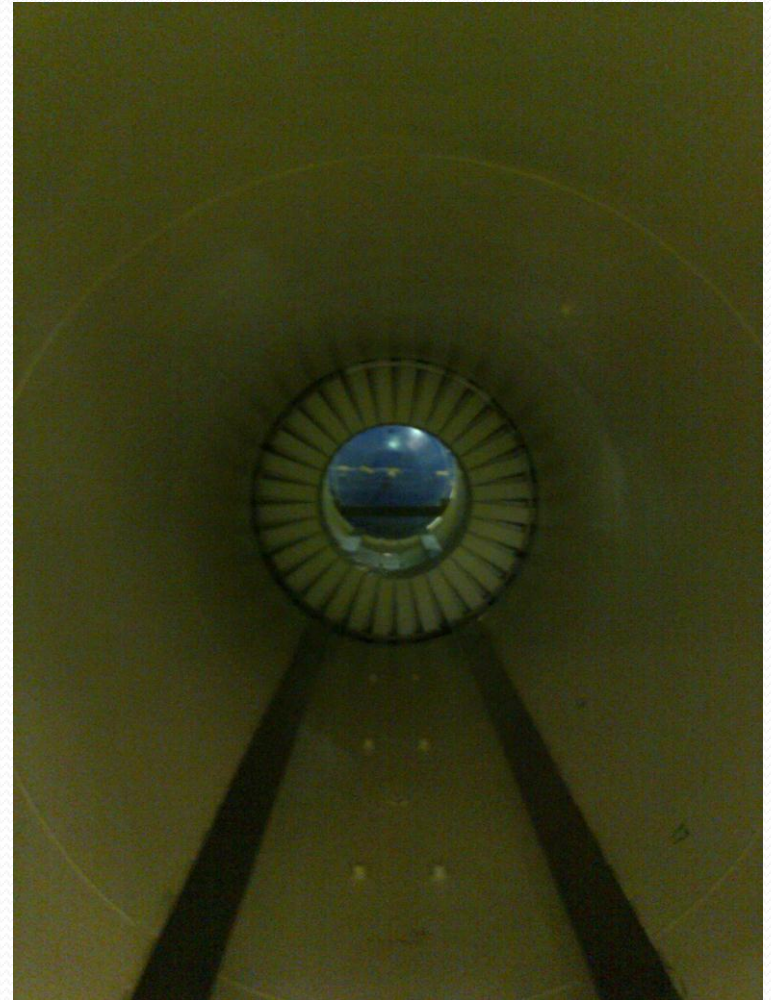
Handling Lead Glass Crystals requires great care, including temperature control during transport



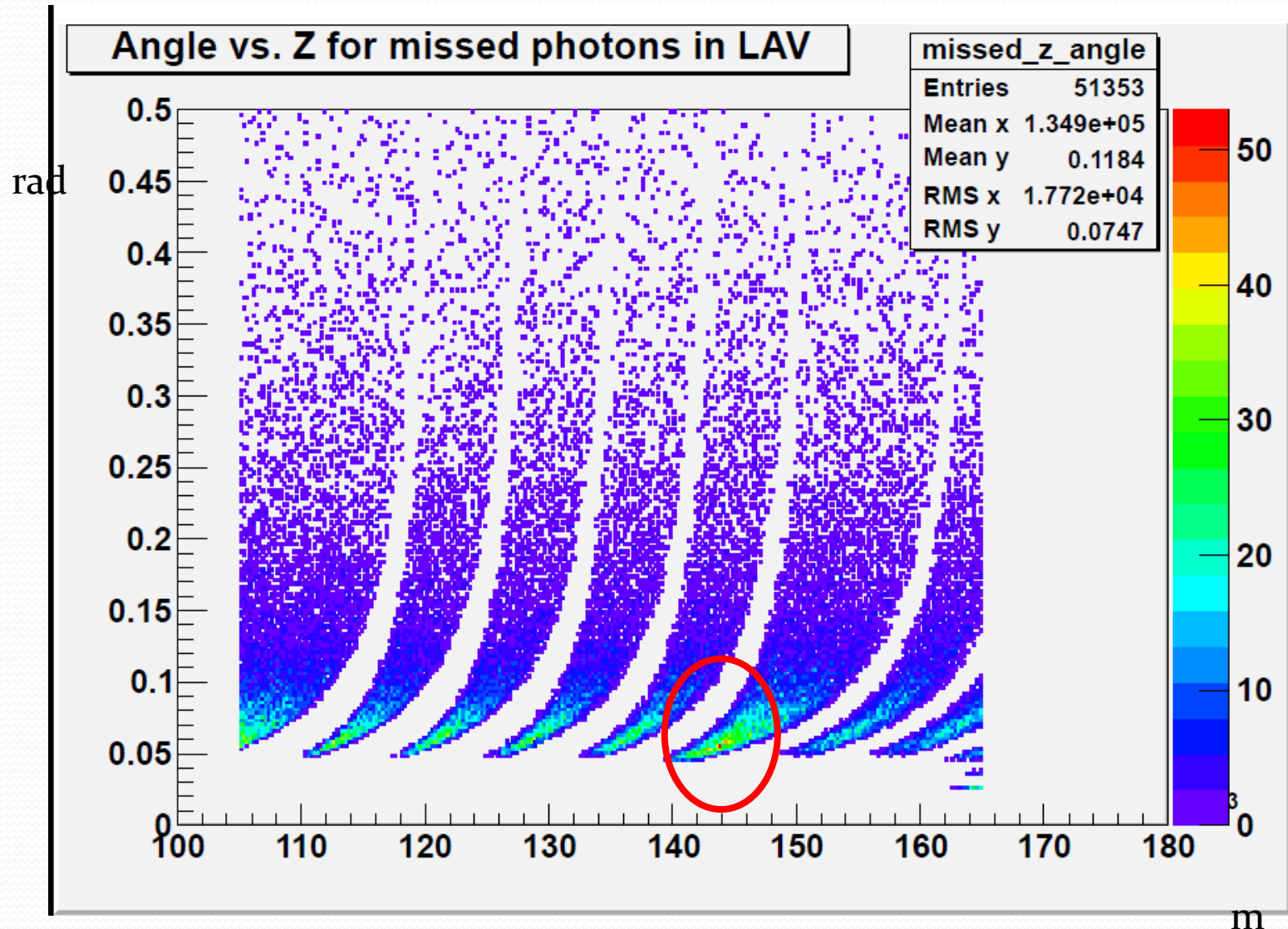
30 Nov 11:23

NA62 LAV Installation

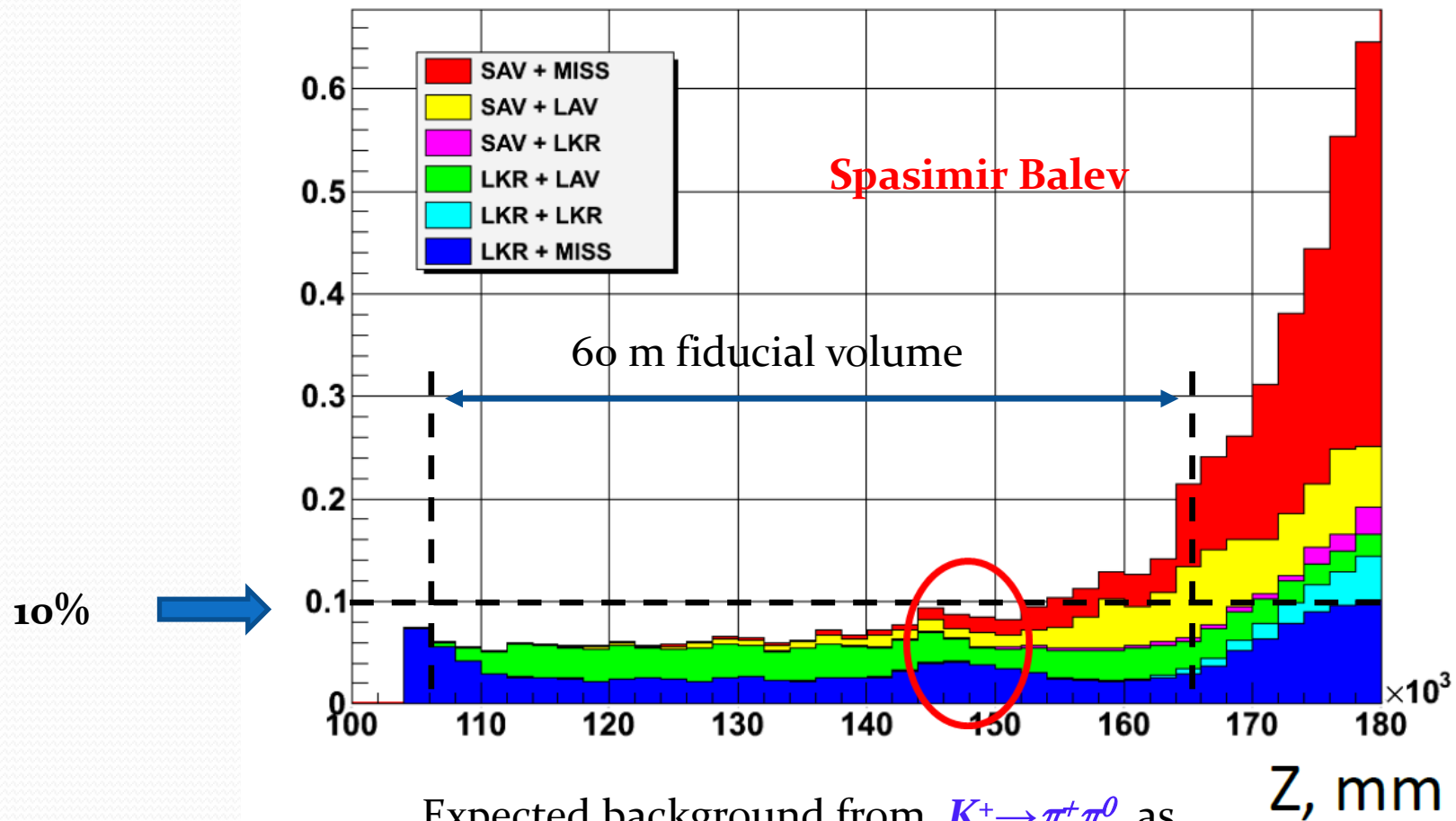
Lead Glass blocks, PMTs and cabling are all placed inside the vacuum tank



Photon Veto Acceptance



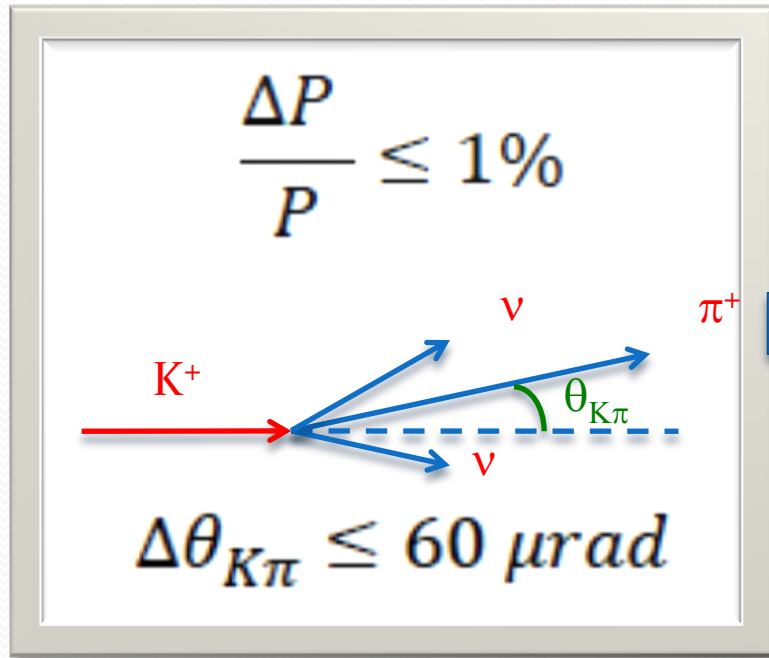
NA62 photon vetoes: expected π^0 rejection $\sim 5 \times 10^{-8}$



Expected background from $K^+ \rightarrow \pi^+ \pi^0$ as fraction of the $K^+ \rightarrow \pi^+ \nu \nu$ (SM) signal as a function of the kaon decay vertex

Straw Tracker in NA62

- There are two main performance requirements for secondary particles:



From this follow the main requirements on the straw detector:

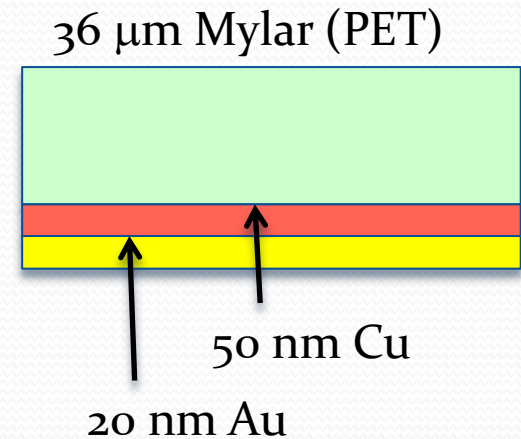
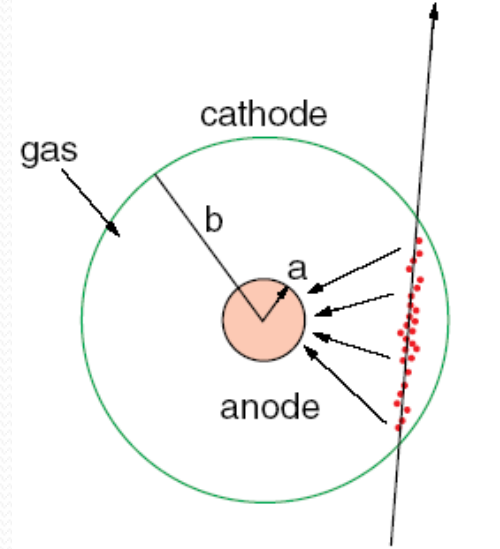
- ◆ Spatial resolution $\leq 130 \mu m$ per coordinate and $\leq 80 \mu m$ per space / point
- ◆ $\leq 0.5\%$ of a radiation length (X_0) for each chamber
- ◆ Installation inside the vacuum tank ($P < 10^{-5}$ mbar) with minimum gas load for the vacuum system ($\sim 10^{-1}$ mbar* l/s)
- ◆ For straws near the beam, operation in a high rate environment (up to 500kHz/Straw)
- ◆ Possible multiplicity veto for triggering

The NA62 Straw Tracker

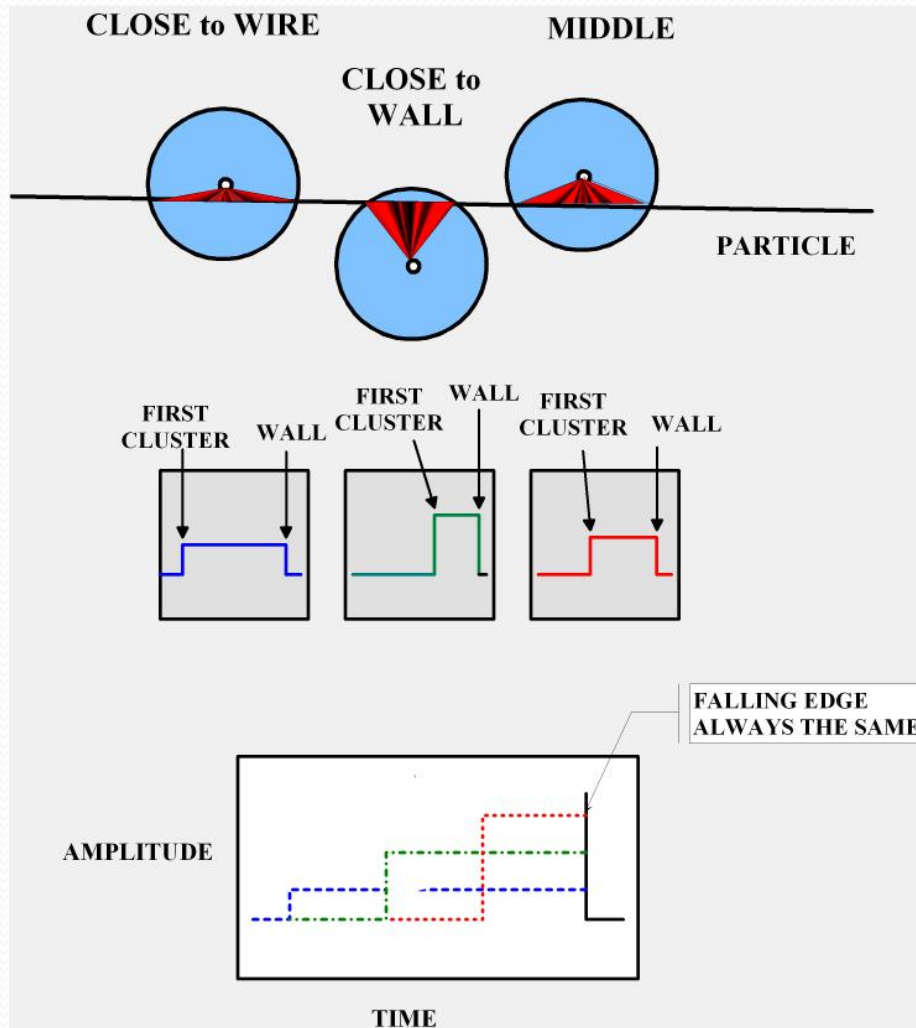
- Principle
- Straw Tube
 - Basic material
 - Ultrasound Welding,
 - Qualification (gas permeation, tensile strength, creep, long time behavior, pressure test)
 - Validation of components under radiation
- Module design
 - Frame as part of vacuum vessel
 - Spacers, geometry control
 - Signal, Max rate, Front End, performance....

The straw

- ◆ Tube 2.1 meter with a diameter of 9.8 mm
- ◆ The base material is PET with thickness 36 μm
PET = Poly Ethylene Terephthalate
(Hostaphan (Mitsubishi) RNK 2600)
- ◆ The foil were coated on the inside with 50 nm of Cu and 20 nm of Au by sputtering at Fraunhofer FEP (Dresden, Germany)
- ◆ The anode wire is 30 μm in diameter and made from gold-plated tungsten
- ◆ Gas mixture (non-flammable): a fast and a slow option were studied: Ar (70%) + CO₂ (30%) and CO₂ (90%) + CF₄ (5%) + Isobutan (5%)



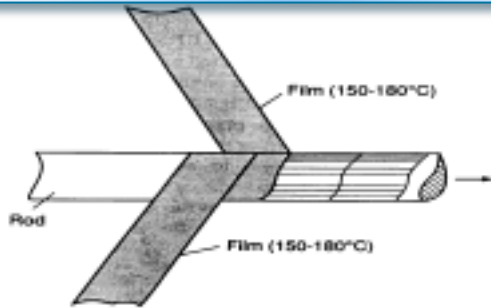
Straw Principle



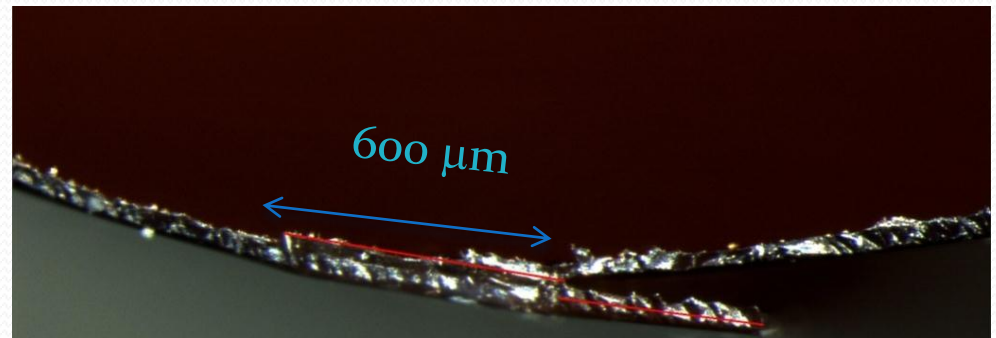
- Falling edge has the same time for all straws on track.
- Rising edge gives the arrival time of the first cluster
- The closer is the track to the wall, the bigger is the signal (clusters closer)
- Don't want to see clusters => shaping must be chosen in relation to gas properties
- Tracks from drift time measurement.

Ultrasonic welding of straws

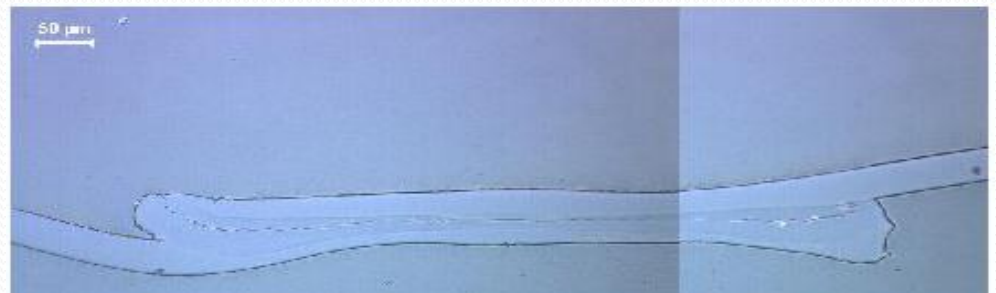
“Classical” straw winding



Microscope pictures of a straw cross-section for quality control of the weld

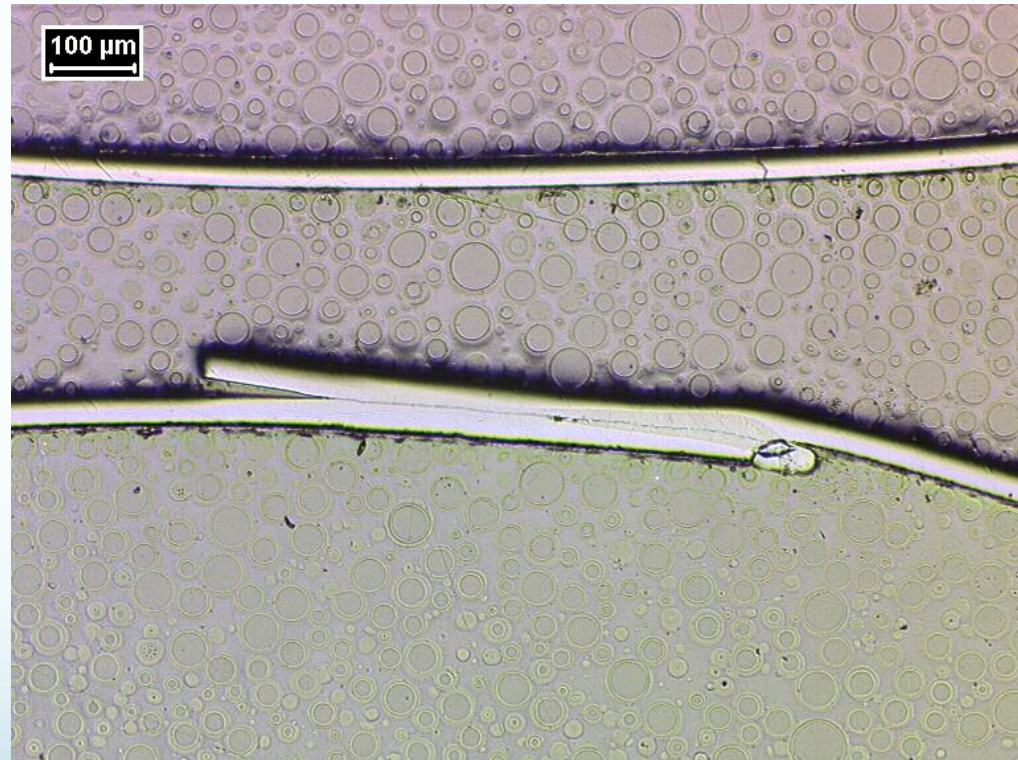
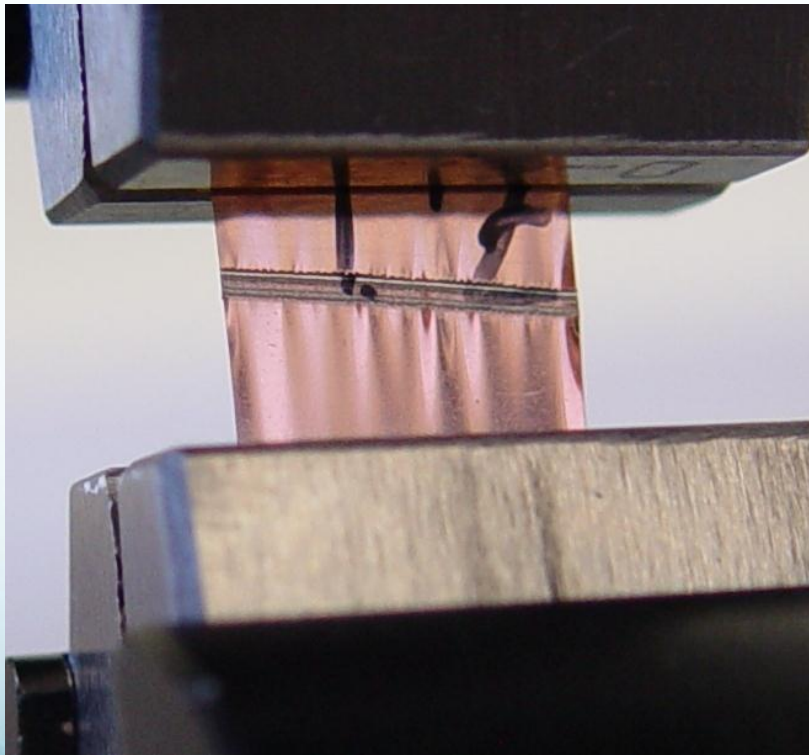


NA62 Ultrasonic welding
(Metalized PET)

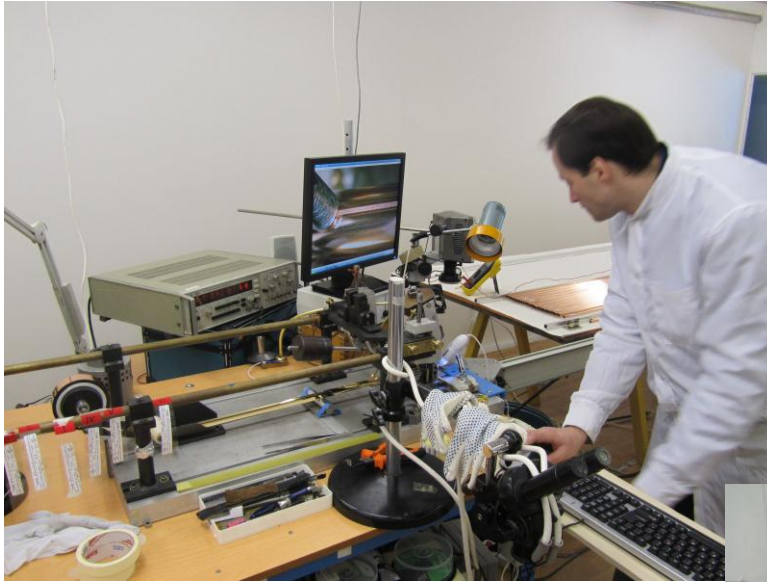


Delicate tuning of production parameters for welding

Ultra-sound weld validation



Straw production

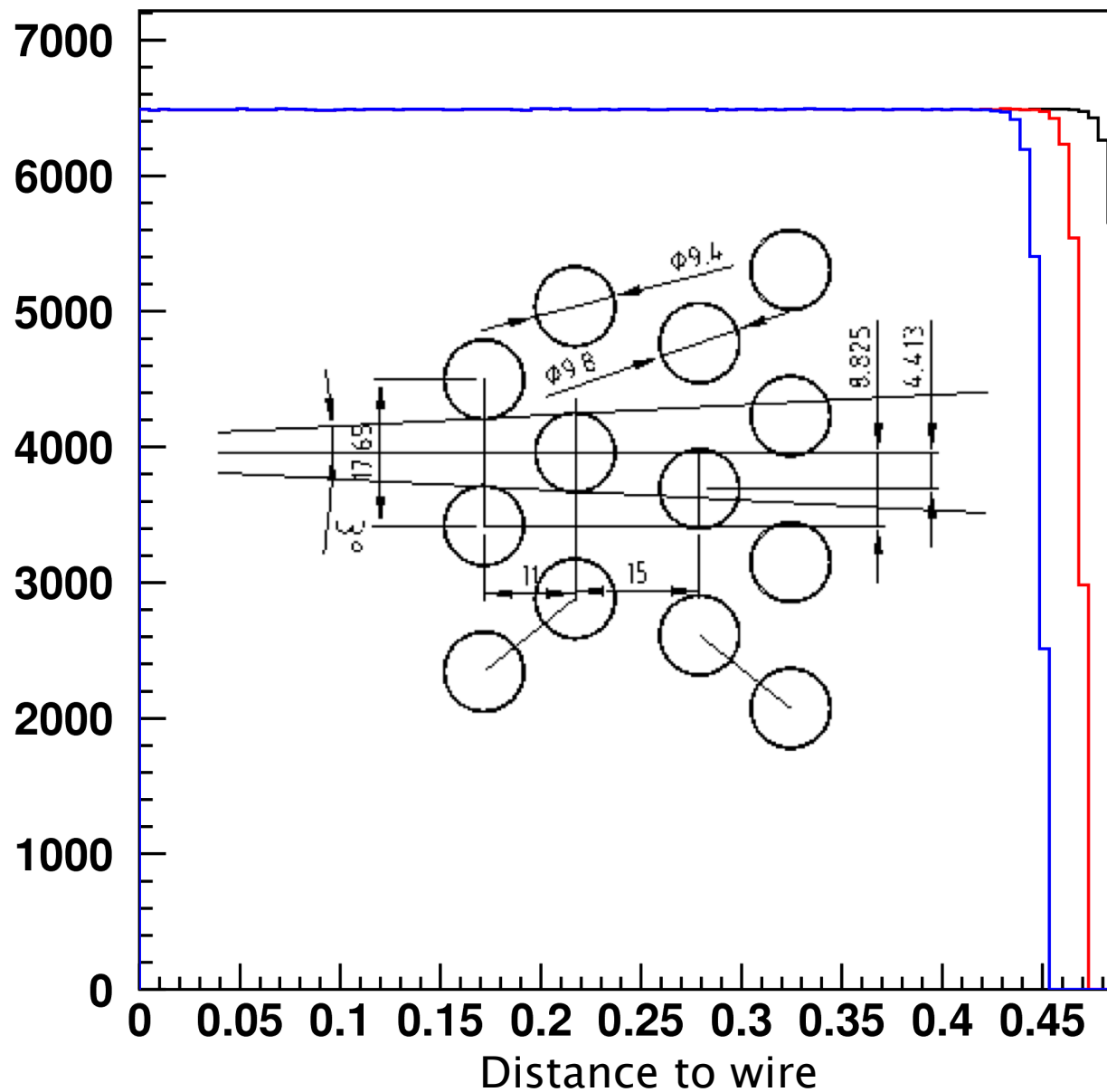


Straws are handled and transported under pressure



Number of efficient hits
 $\times 10^3$

Efficiency variation:
0,200,400 μm of lost
radius

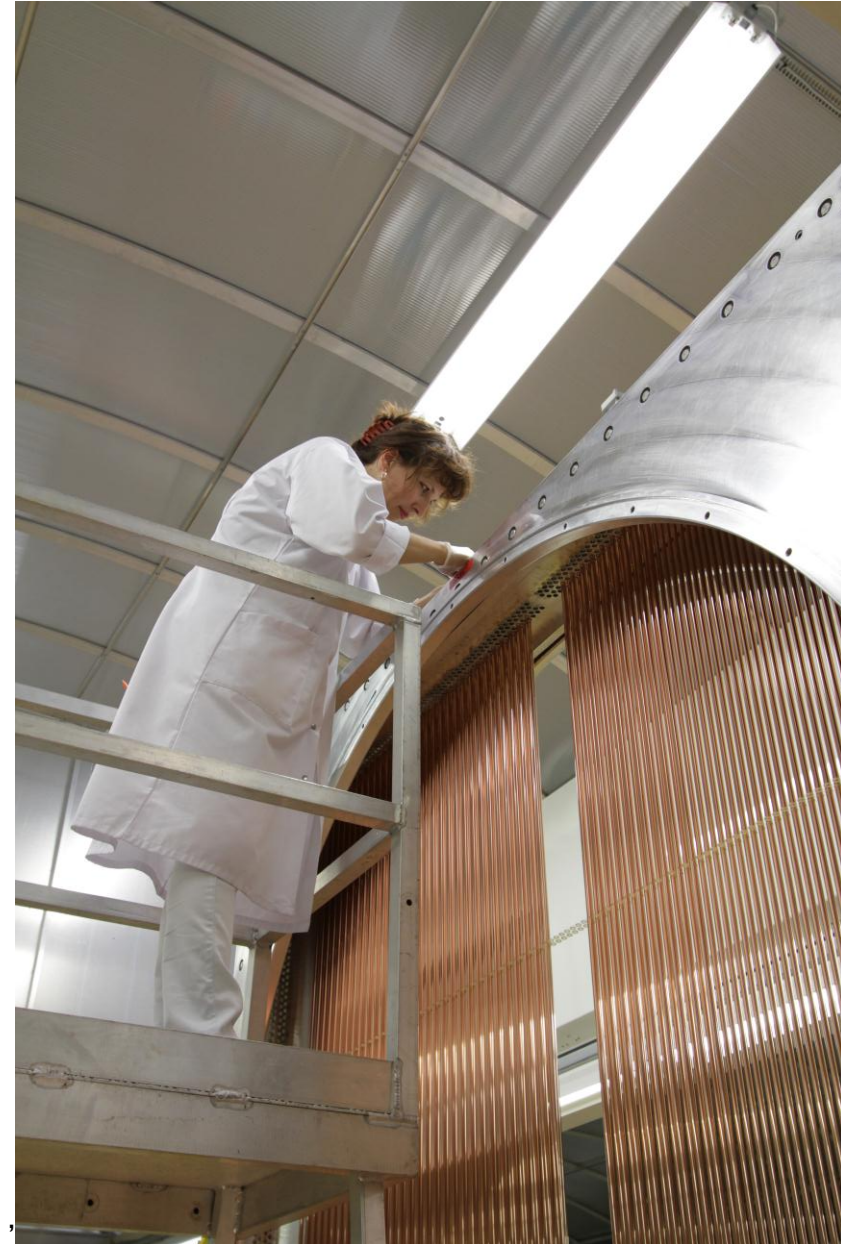


(Simulation)

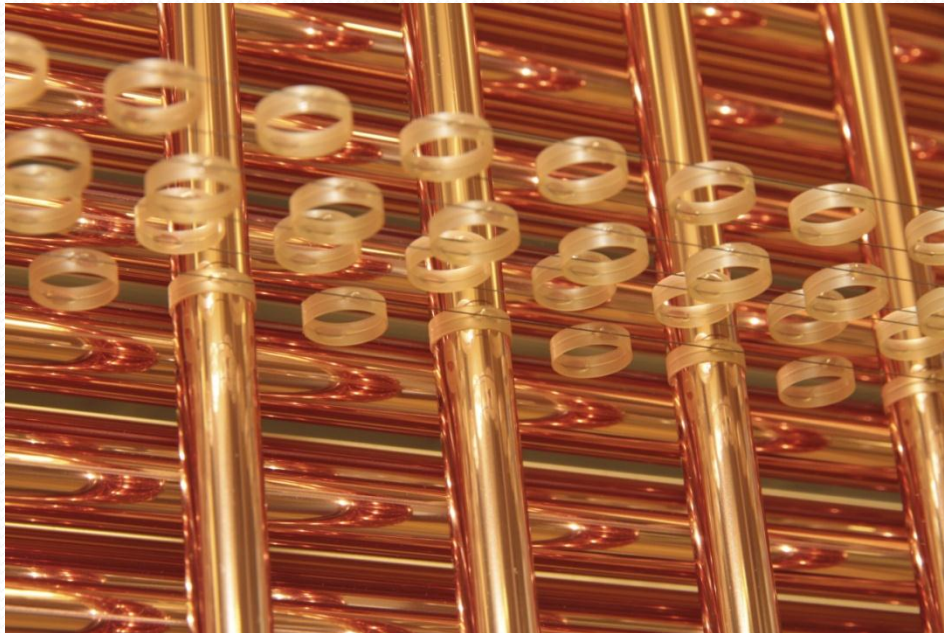
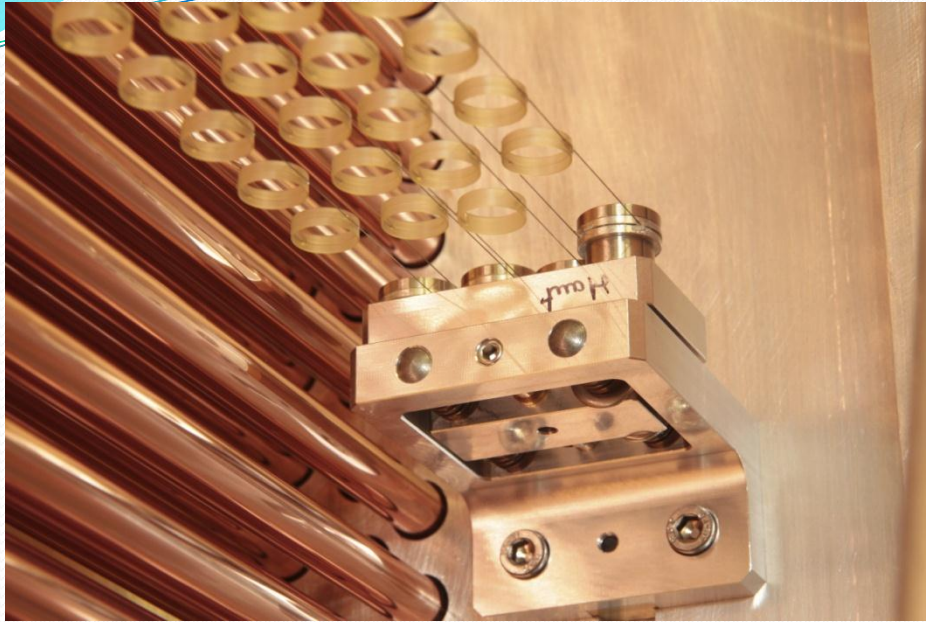
Aluminum Frame



Module assembly – straw insertion

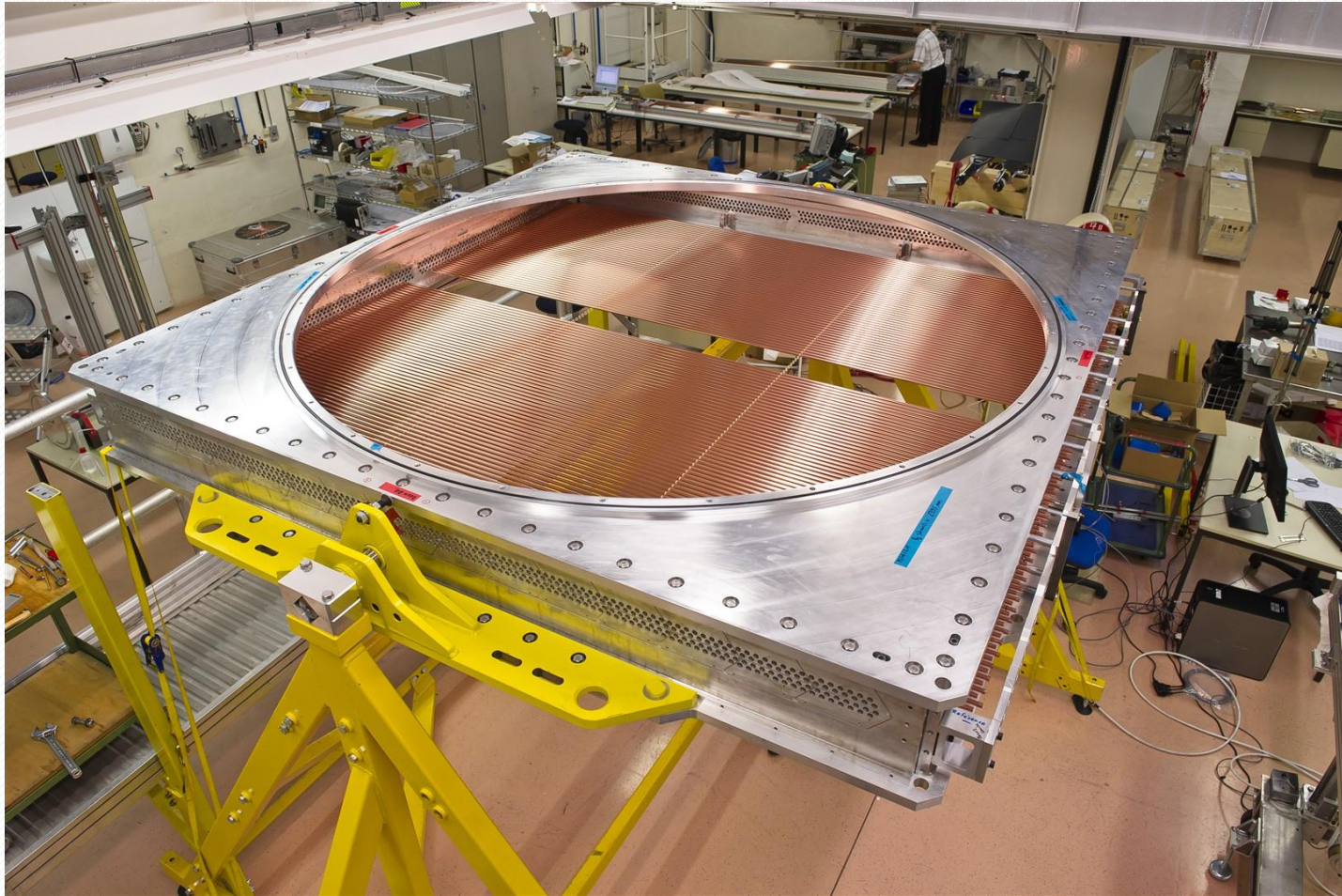


Spacers



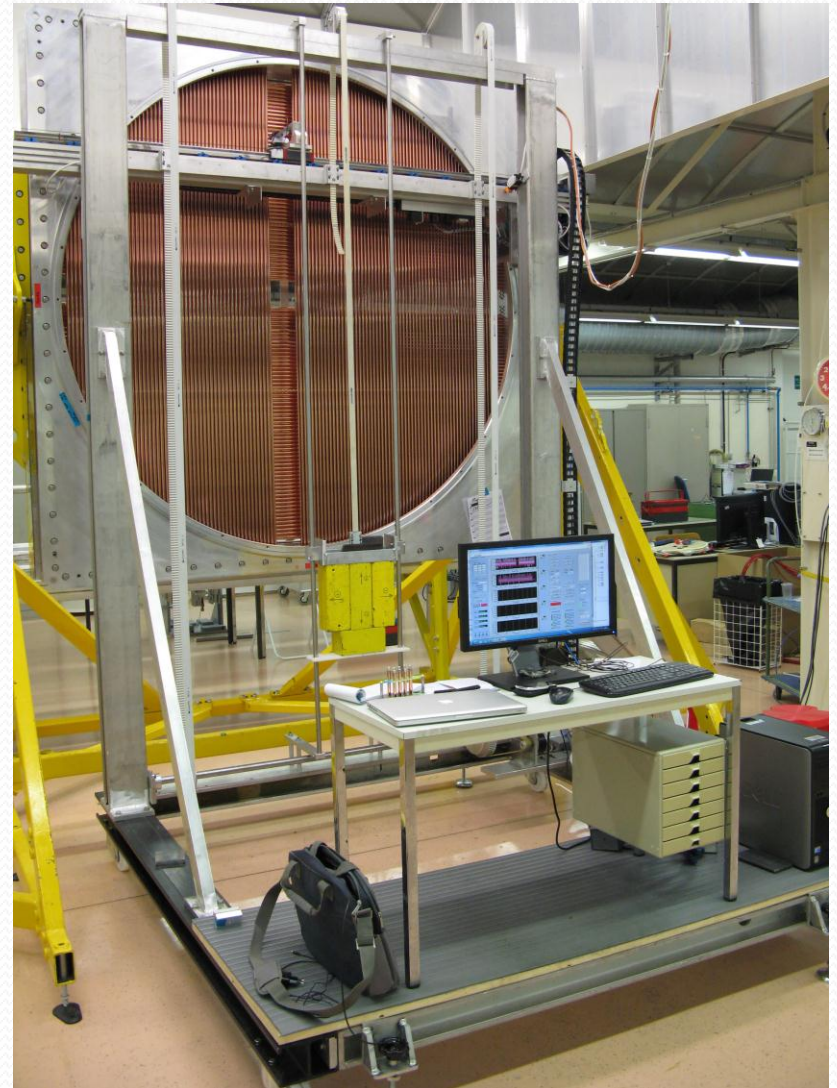
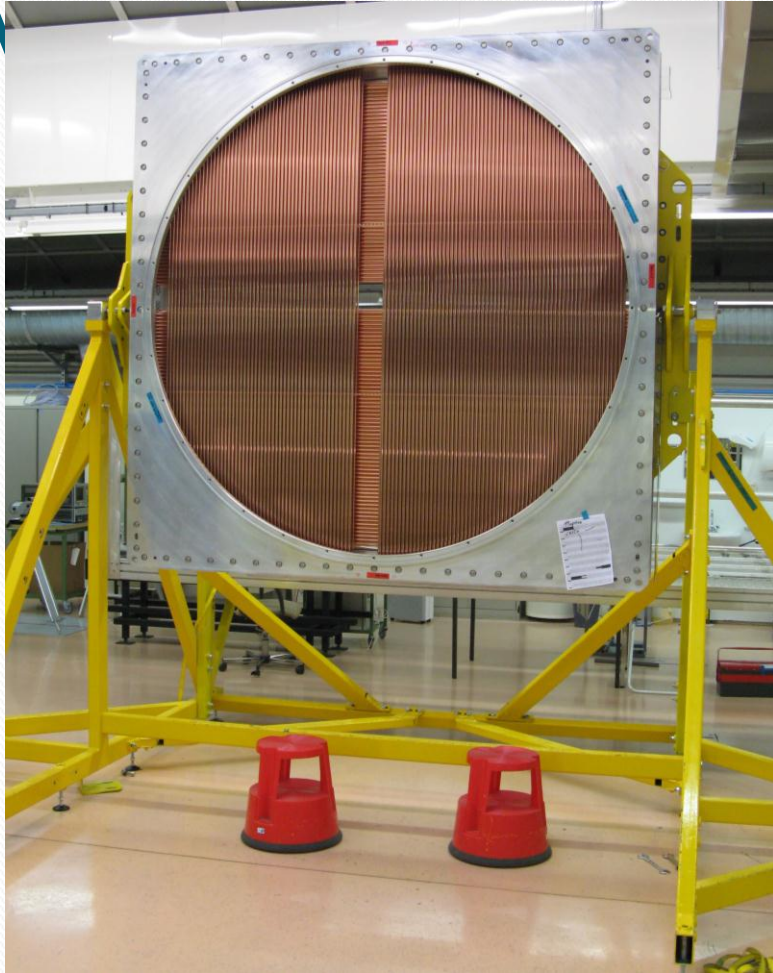
Courtesy of Hans Danielsson
PH-DT

Straw Module

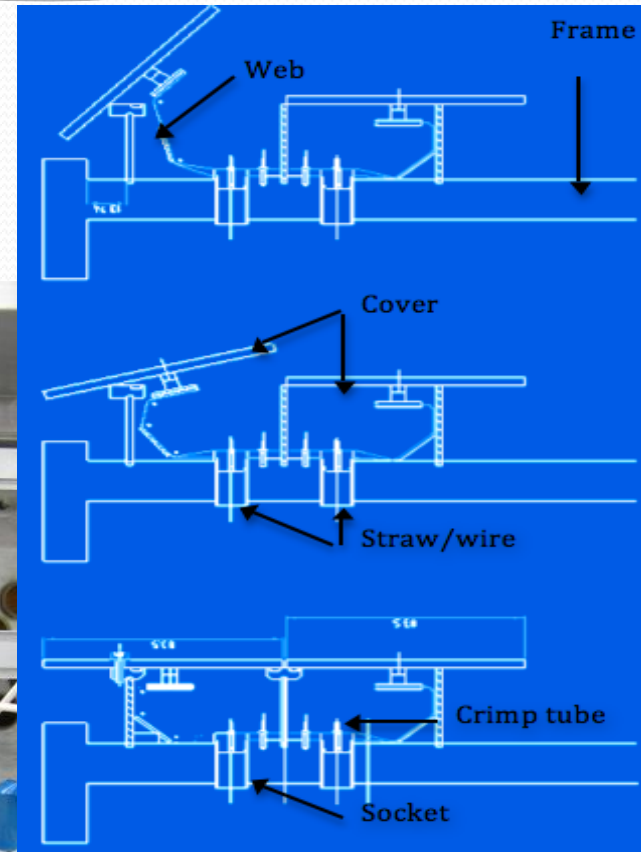
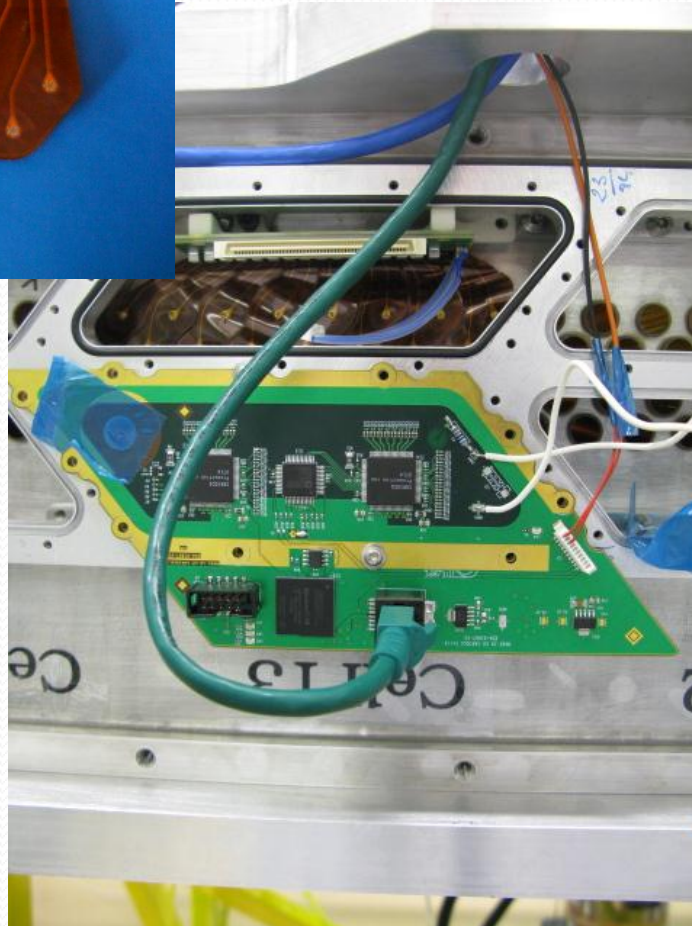
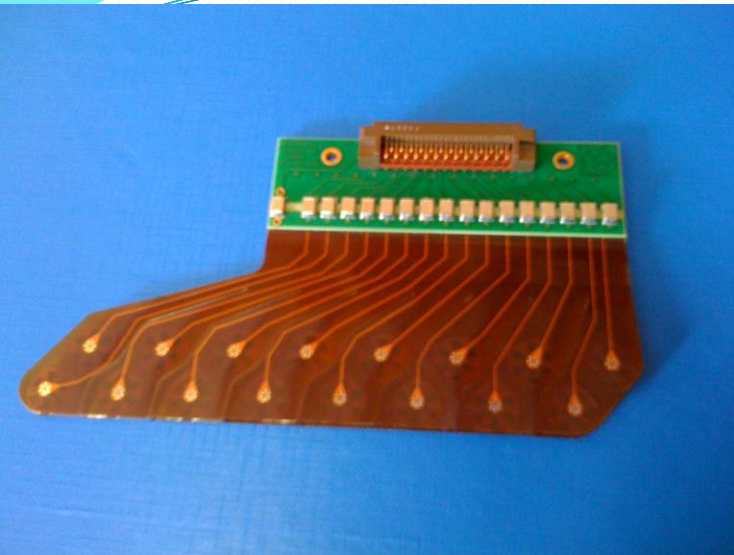


Straw Module

996 straws

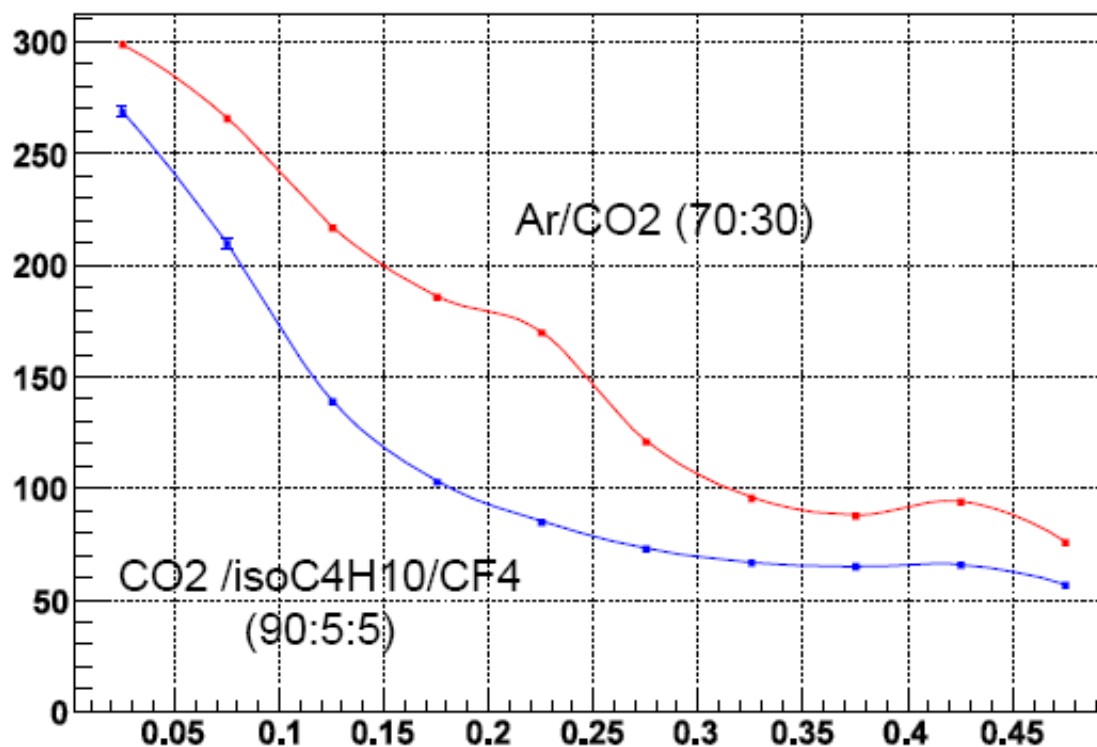


Straw Connection to FE



Dependence of residuals from R (muon runs)

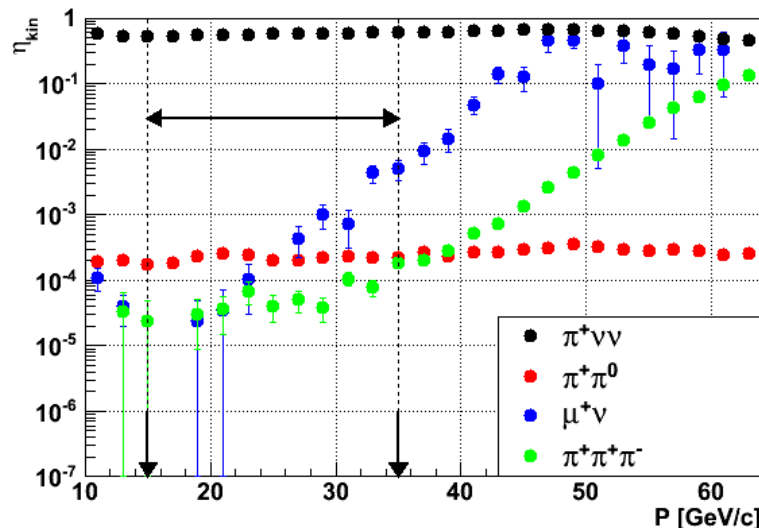
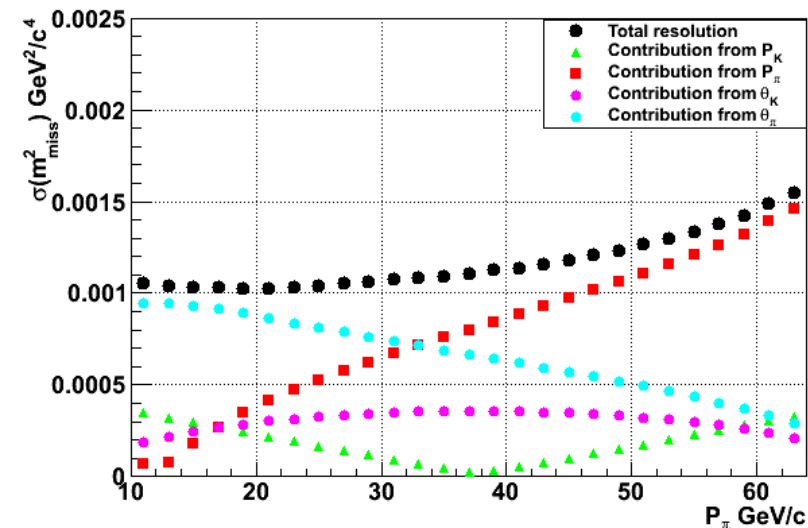
Dependence of residuals from drift distance:
red – run 21318, blue – run 21228



HOD trigger resolution:
~ 1.3 ns

NA62 Spectrometer Reconstruction

Giuseppe Ruggiero



Missing Mass Resolution

Kinematic Rejection

- × The simulation includes:
- × Multiple and Single large angle Coulomb scattering
- × δ -rays
- × Elastic and inelastic nuclear interactions
- × Errors in the straw spectrometer pattern recognition

NA62 RICH



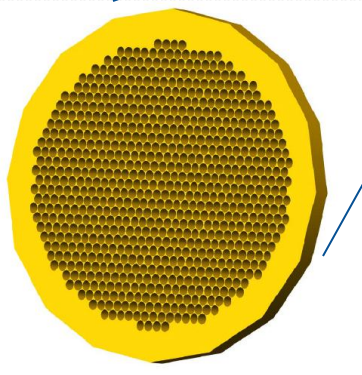
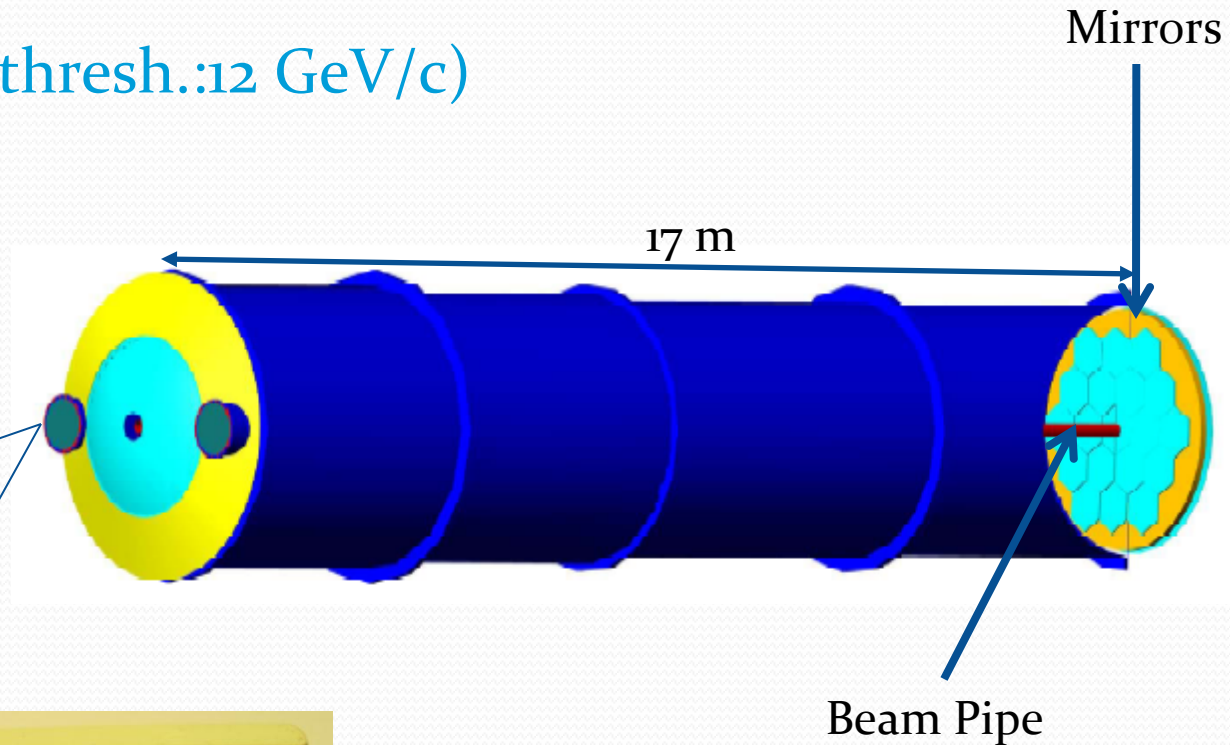
- $K_{\mu 2}$:largest BR: 63.4%
- Need $\sim 10^{-12}$ rejection factor
- Kinematics (GTK +STRAW) : 10^{-5}
- Muon Veto: 10^{-5}
- Particle ID (RICH): 10^{-2}
- Essential to match the pion track seen by the straw with track (kaon) seen by the beam spectrometer (rate: 800 MHz)
- To avoid a wrong match which spoils the kinematic suppression, the RICH must measure the pion time to 100 ps or better to connect to the kaon measured in the GTK

The NA62 RICH



3σ π - μ separation (15-35 GeV/c)

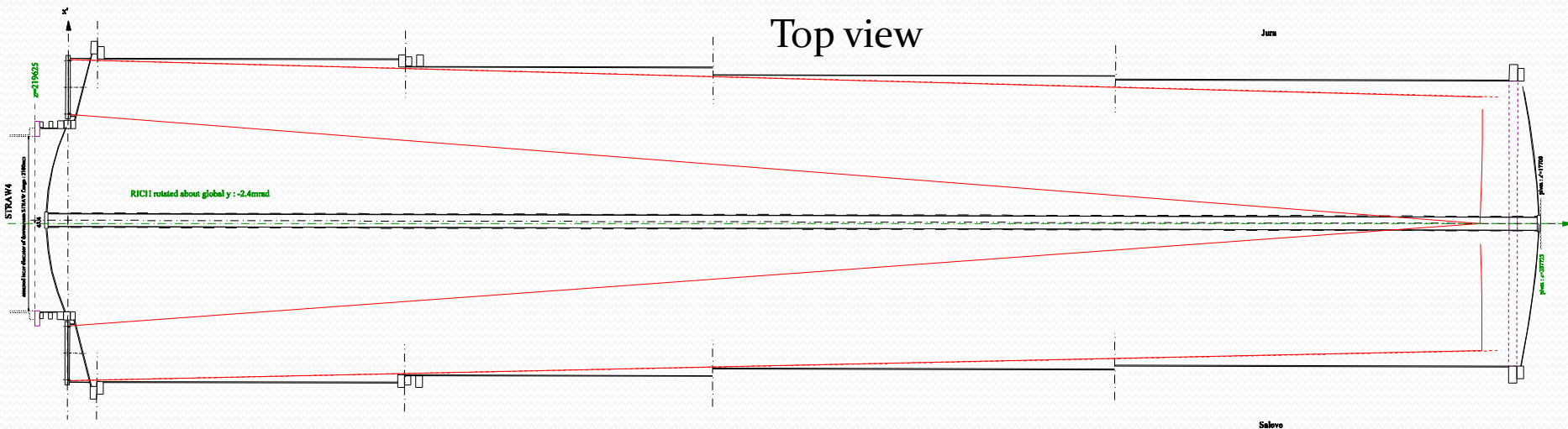
- Neon at 1 atm (π thresh.: 12 GeV/c)
- 2000 PMT
- 18 mm pixel
- 100 ps



PMT: Hamamatsu R7400 Uo3

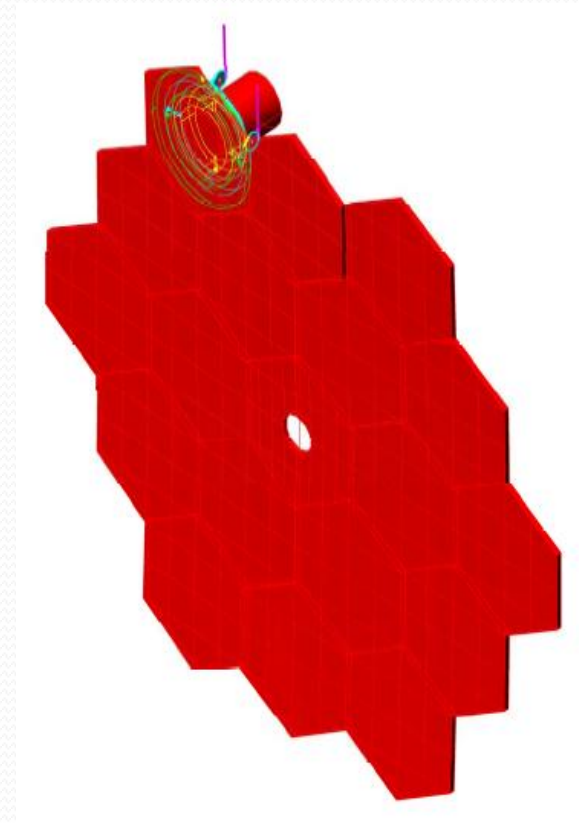
The RICH Vessel

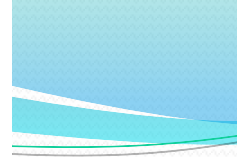
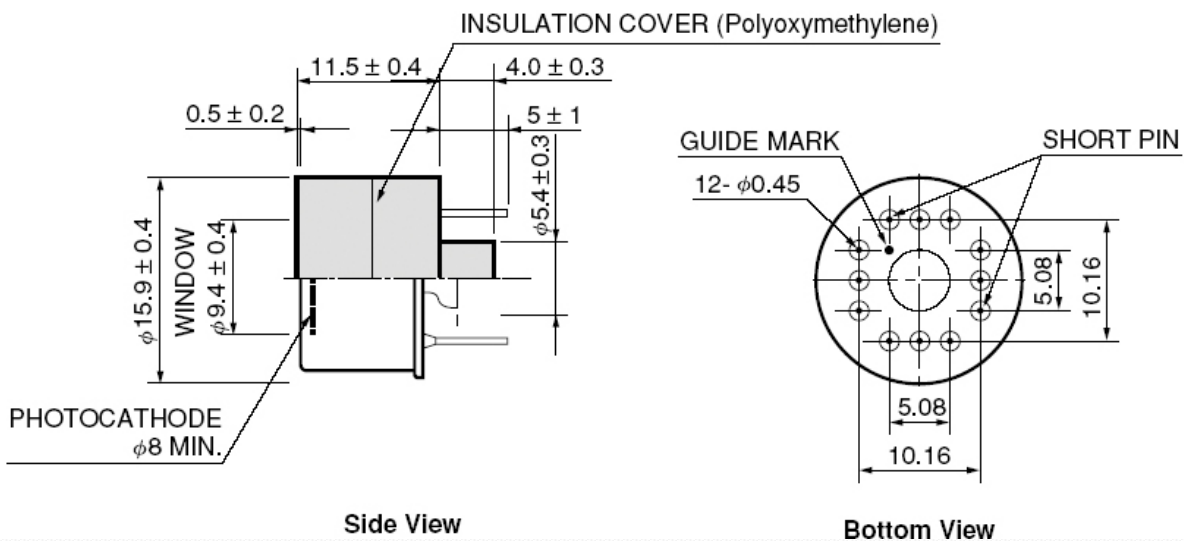
- 17 m long vessel in construction steel, vacuum proof
- max overpressure: 150 mbar
- ~4 m wide (beginning)
- beam pipe (\varnothing 16 cm) going through
- thin aluminium entrance and exit windows



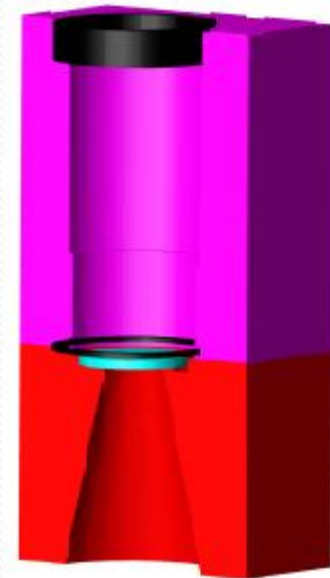
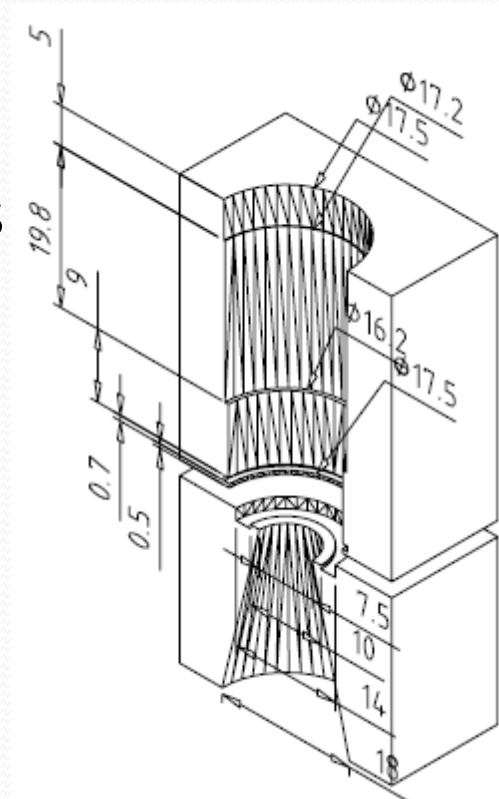
The Mirror system

- 20 mirror pieces
- 18 hexagonal
- 2 semi-hex + pipe hole
- 700 mm wide, 25 mm thick glass
- 17 m focal length, $D_0 < 1$ mm



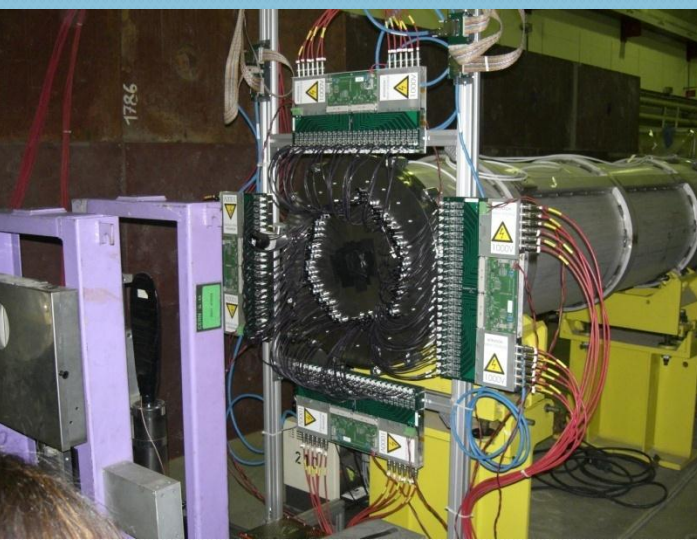


- 1000 PM packed per spot
- Cooling is an issue
- Light collection: Winston cones with aluminized mylar foil
- Quartz window to separate Neon from air
- O-rings for light tightness and thermal contact



RICH prototype

- 17 m long, 0.6 m wide cylindrical vessel
- 17 m focal, 0.5 m wide mirror
- 96(2007) or 414(2009) PM
- Vessel evacuated, then Neon filled
- Prototype placed along the old NA₄₈ beam line at CERN



RICH-100 Prototype 2007 Test Beam

96 PMT

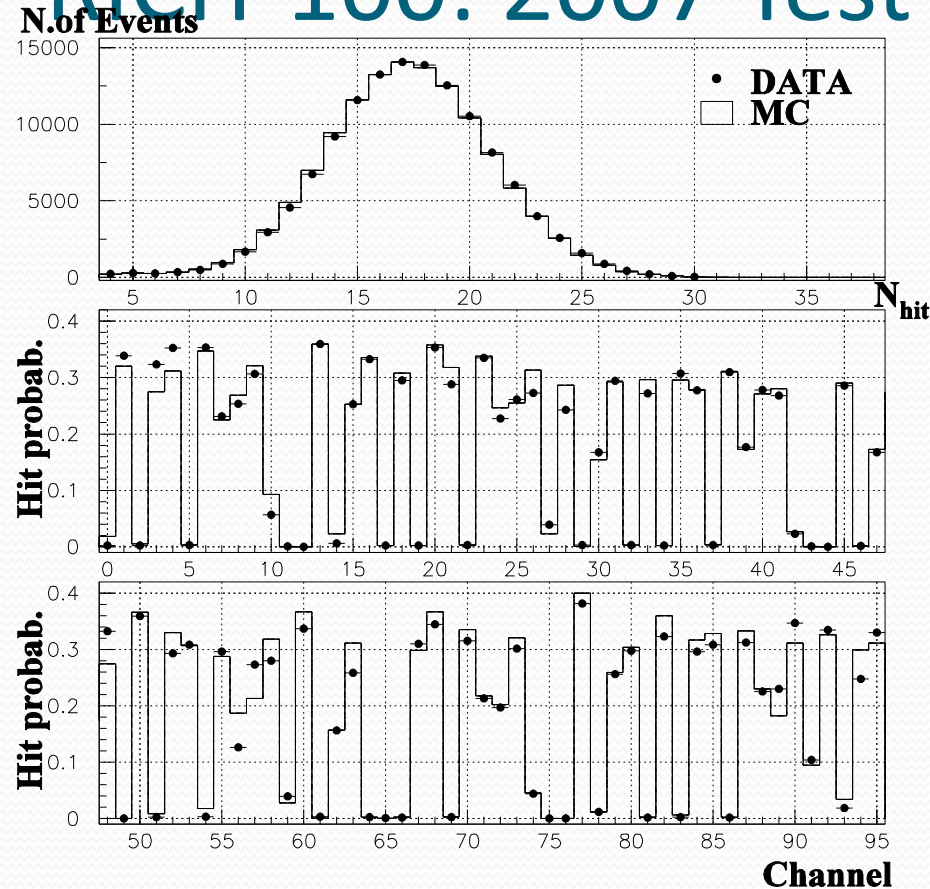


π^- $p=200$ GeV/c (SPS)
CERN Cavern ECN₃

Mirror $f=17$ m

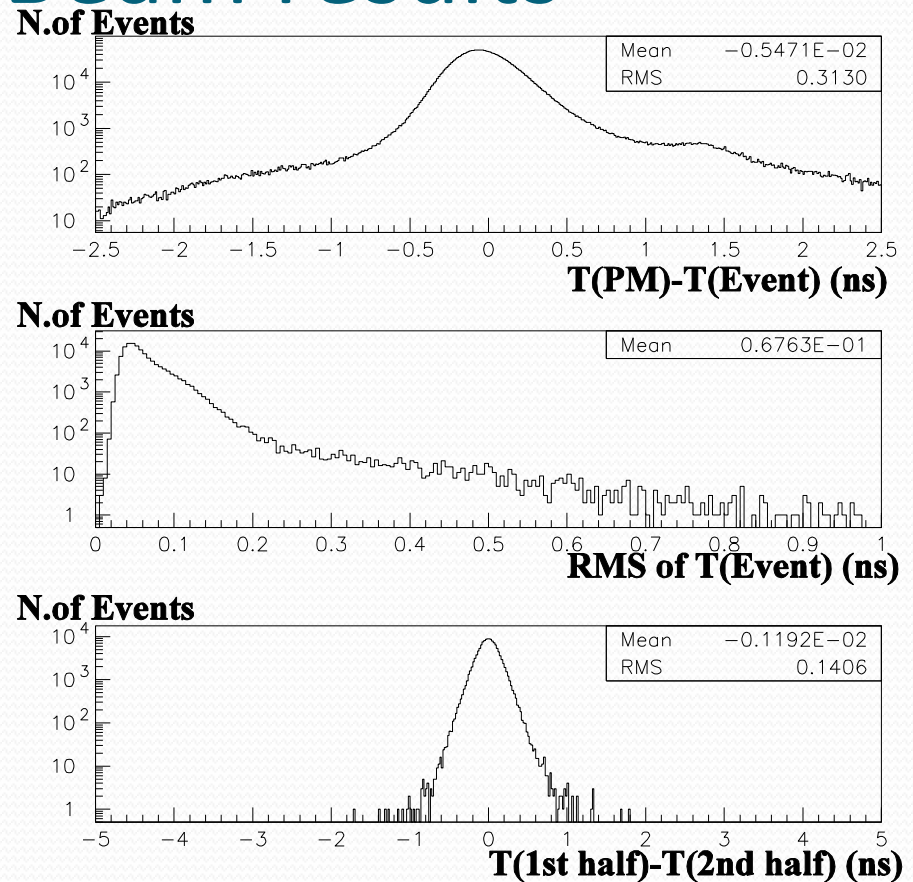


RICH-100: 2007 Test Beam results



$$N_{\text{Hits}} \approx 17$$

G. Anzivino et al., NIM A593 (2008), 314-318

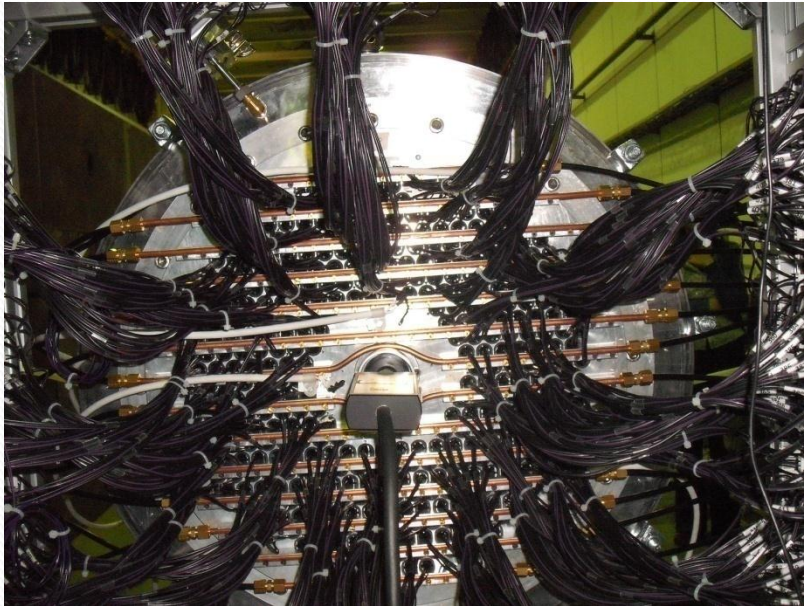


$$\Delta t_{\text{Event}} \approx 70 \text{ ps}$$

RICH-400:

2009 test beam

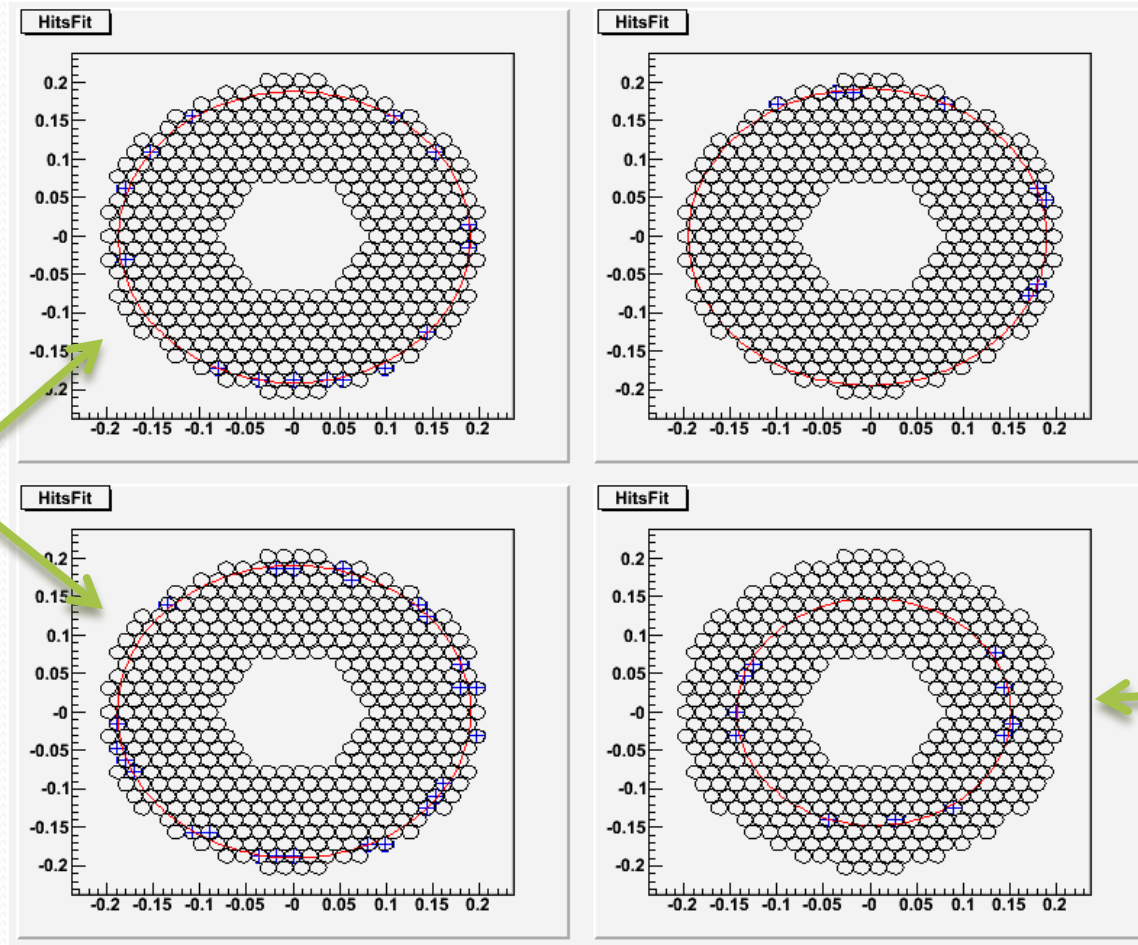
- 414 PMT + FE and DAQ , cooling
- Pions at tunable energy



RICH-400: fitted rings

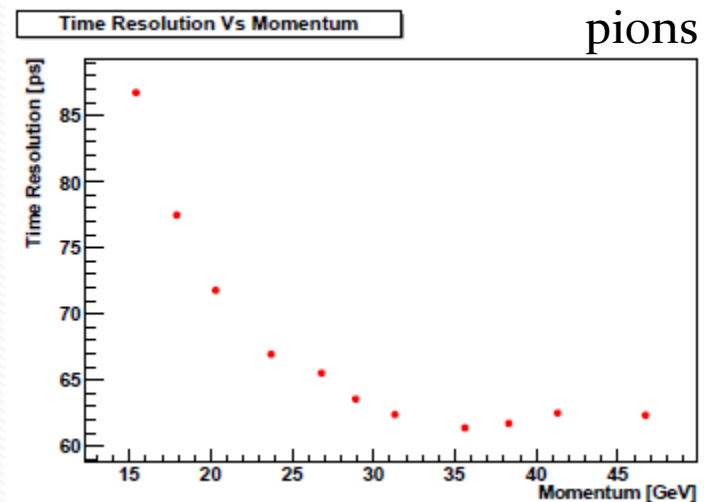
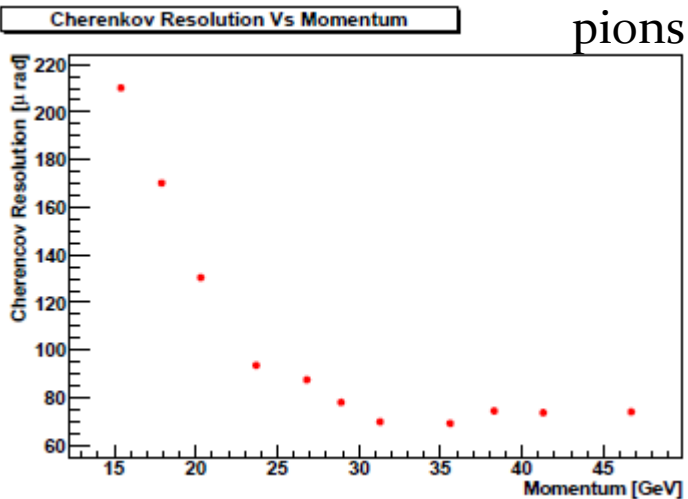
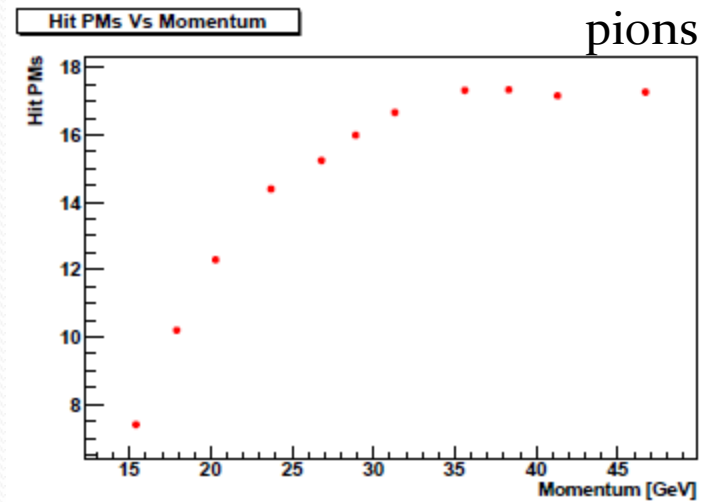
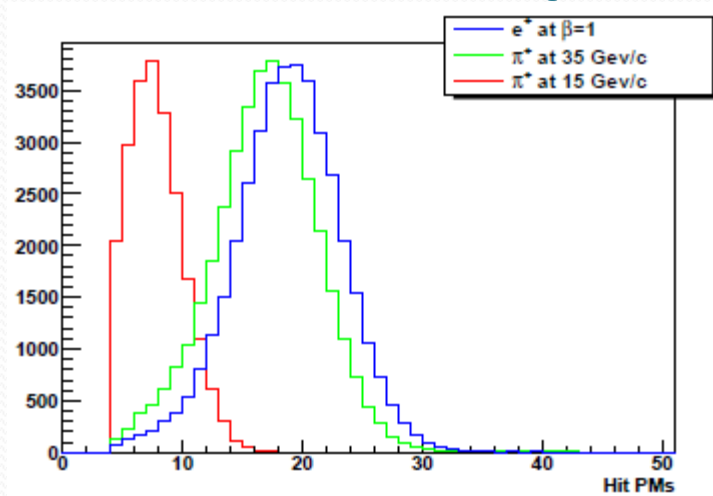
20 GeV/c

positrons

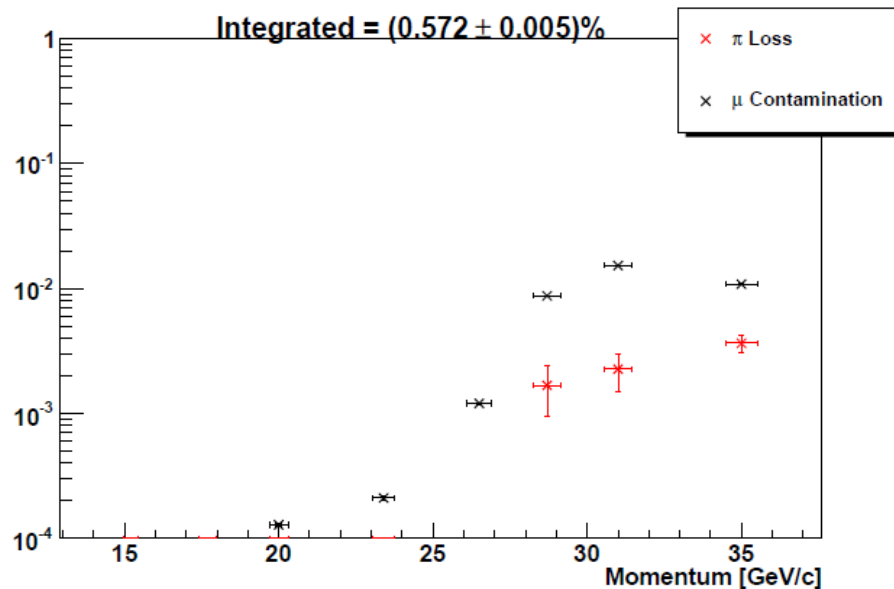


pion

RICH400: performance

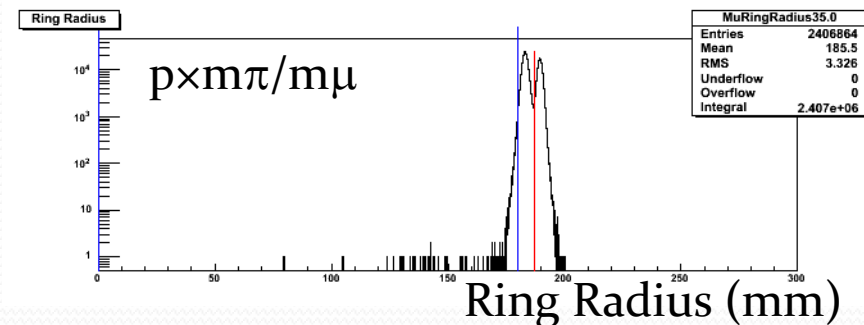
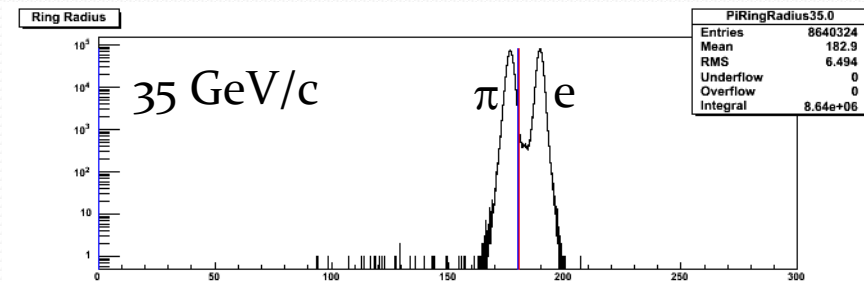
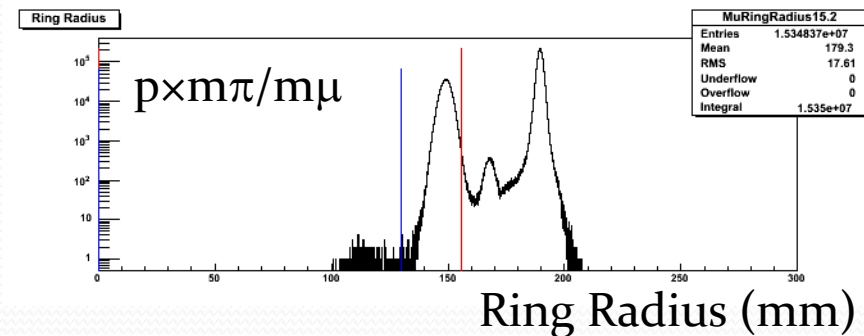
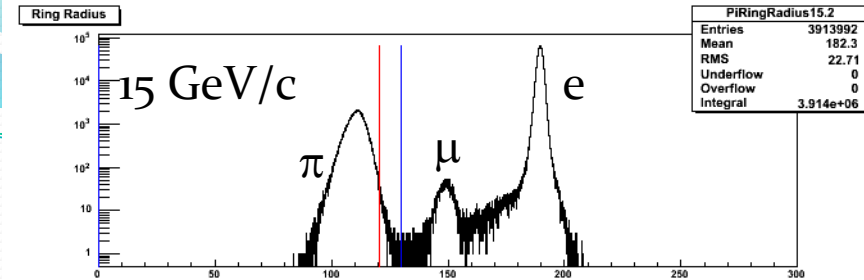


RICH-400: results



Muon suppression (15-35 GeV/c):
0.7%

B. Angelucci et al., NIM A621 (2010) 205-211



High Intensity and Rare Decay Detectors --- Summary

- In this lecture I have reviewed a few examples of modern detectors employed at the intensity frontier
- I made no attempt to be exhaustive. The frontiers of particle physics have a large mixing angle: for instance rare decays of D and B mesons and τ leptons are studied at hadron and $e^+ e^-$ colliders
- We have seen that a broad, world-wide, experimental program exists to push the science of rare processes at existing and planned proton facilities
- The bottom line is that high intensity and rare decay experiments tend to be tailored to perform a specific measurement, **a lot of ingenuity and care to detail is required!**