Results on searches for new physics with kaons

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on behalf of the NA62 Collaboration

Bern ITP, Birmingham, CERN, Dubna, Fairfax, Ferrara, Florence, Frascati, IHEP, INR, Louvain, Mainz, Merced, Naples, Perugia, Pisa, Rome I, Rome II, San Luis Potosi, SLAC, Sofia, Triumf, Turin

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Outline

- NA62 measurement of $R_K = \Gamma_{Ke2}/\Gamma_{K\mu 2}$
- Prospects for measurement of $BR(K^+ \rightarrow \pi^+ \nu\nu)$

Physics motivations

$$R_K = \frac{\Gamma(K \to e\nu(\gamma))}{\Gamma(K \to \mu\nu(\gamma))} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1 + \delta R_K)$$

- Excellent accuracy due to cancellation of hadronic uncertainties in the ratio
- Helicity suppression of electronic mode, enhancement of sensitivity to non-SM effects

$R_K(SM) = (2.477 \pm 0.001) \cdot 10^{-5}$ 0.04% precision!!

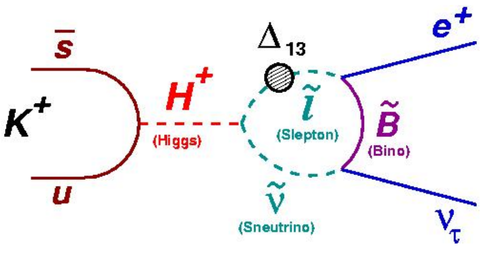
(V. Cirigliano, I. Rosell JHEP 0710:005 (2007))

- δR_K due to IB part of the radiative $K \to e\nu\gamma$ process
- $K \to e\nu\gamma$(IB) included by default in R_K

R_K beyond the Standard Model

- The value of R_K could be different in case of SUSY LFV
  - Masiero, Paradisi, Petronzio, Phys. Rev. D74 (2006) 011701
    - "Charged Higgs mediated SUSY LFV contributions can be strongly enhanced in kaon decays into an electron or a muon and a tau neutrino"

$$R_K^{LFV} \approx R_K^{SM} \left[1 + \left(\frac{m_K^4}{M_{H\pm}^4} \right) \left(\frac{m_\tau^2}{M_e^2} \right) |\Delta_{13}|^2 \tan^6 \beta \right]$$

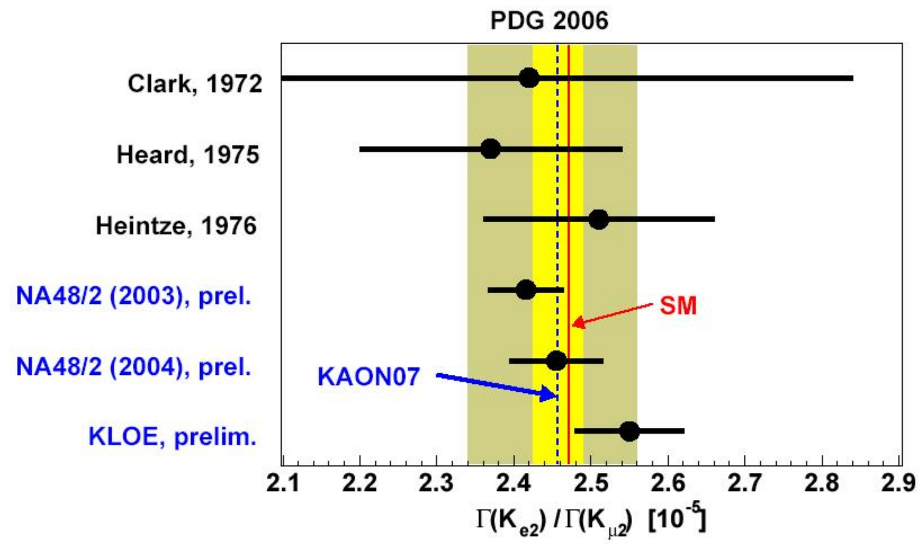


- Δ_{13}= $6 \cdot 10^{-3}$, M_H=500 GeV, $\tan\beta$=40 $\rightarrow$ $R_K^{LFV} \sim R_K^{SM} \cdot (1+0.013)$

  - Analogous SUSY effects in pion decays are suppressed by a factor $(m_\pi/M_K)^4 \sim 6 \cdot 10^{-3}$

The experimental situation

- Three esperiments from the 70's
  - $R_K = (2.45 \pm 0.11) \cdot 10^{-5}$
  - $\delta R_K / R_K = 4.5\%$
- Recent significant improvement by the preliminary results of NA48/2 and KLOE
  - $R_K = (2.457 \pm 0.032) \cdot 10^{-5}$
  - $\delta R_K / R_K = 1.3\%$
- Final result from KLOE (Mar 2009)
  - ~10000 K_{e2} candidates
  - $R_K = (2.493 \pm 0.025 \pm 0.019) \cdot 10^{-5}$
  - $\delta R_K / R_K = 1.3\%$



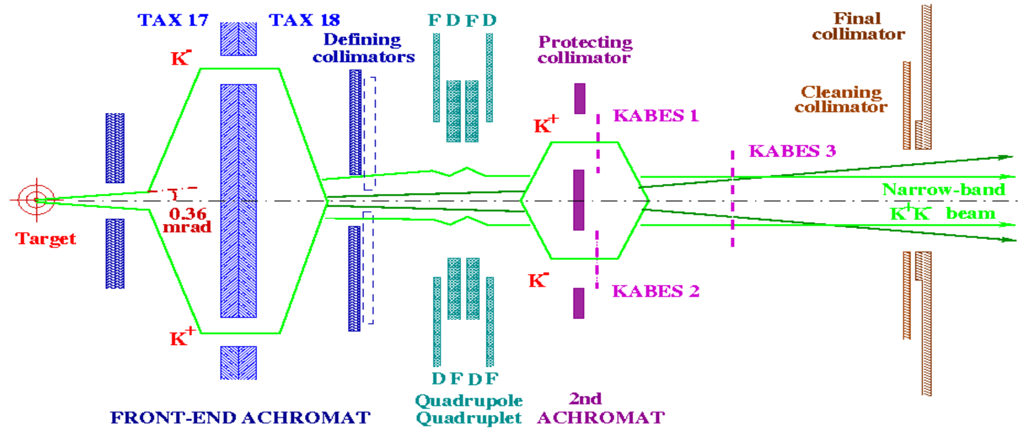
- NA62 goals from the proposal
  - ~150000 K_{e2} events
  - 0.4% accuracy

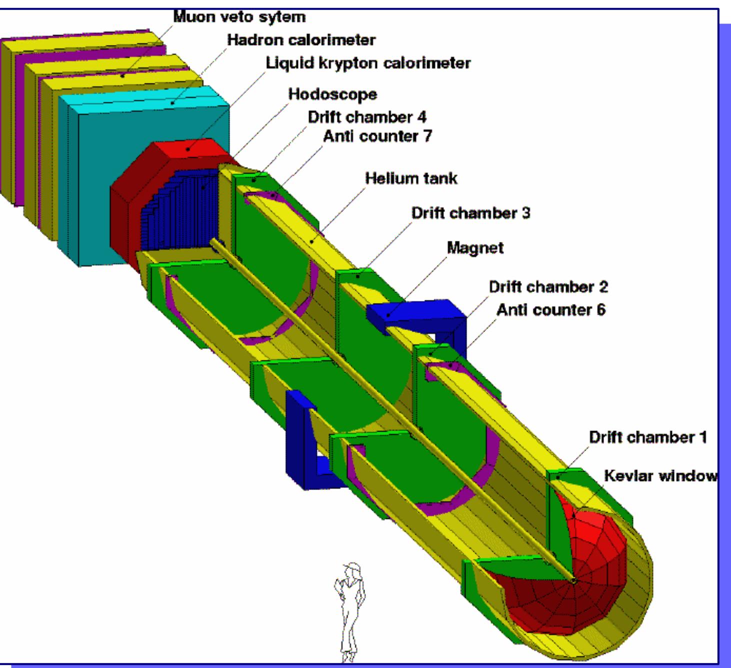
The NA62 Beam and Detector

The NA48/2 beam has been optimized for R_K measurement

Simultaneous K^+ and K^- beams with $P_K = (75 \pm 2\ \mathrm{GeV}/c)$

Maximum spectrometer P_T kick to improve missing mass resolution





Use the NA48 detector

LKr Calorimeter:

$\sigma(E)/E \cong 3.2\%/\sqrt{E} \oplus 90\ \mathrm{MeV}/E \oplus 0.42\%$

Energy resolution ~1%, spatial resolution 1 mm

Spectrometer:

$\sigma(P)/P \cong 0.48\% \oplus 0.009\ P[\mathrm{GeV}/c]\%$

Scintillator hodoscope: fast trigger and good time resolution

2007 and 2008 runs

- 2007 sample, 4 months
  - Minimum bias trigger
  - ~400 K SPS spills, 90 TB of raw data
  - All data reprocessed and ready for the complete analysis
  - Beam halo background much higher for K^- (~20%) than for K^+ (~1%)
    - Due to the configuration of muon sweepers
    - 90% of the data sample is K^+ only
    - K^+ only and K^- only data allow precise cross-measurement of beam halo background
- 2008 sample, 2 weeks
  - Special runs for systematics study
- The following results are based on 40% of the statistics with pure K^+ beam

NA62 R_K measurement

- Analysis strategy
  - K_{e2} and $K_{\mu2}$ decays collected simultaneously
    - Indipendence from the kaon flux
    - Many systematic effects cancel in the ratio
  - Limited use of MC simulations
    - Geometric acceptance correction
    - Simulation of catastrophic bremsstrahlung by muons
  - Perform analysis in momentum bins
    - Background composition varies with momentum

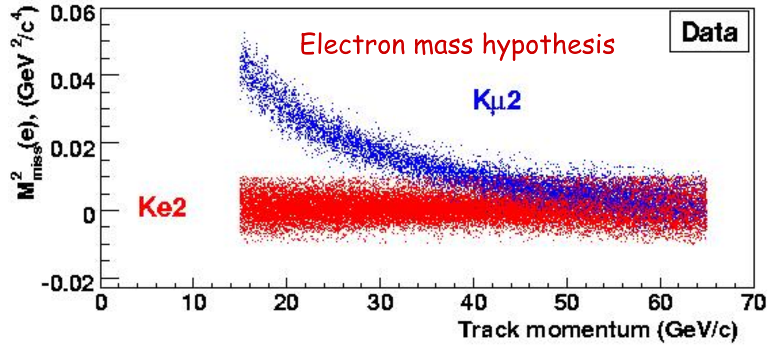
Signal events — PID efficiencies

$$R_K = \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu2}) - N_B(K_{\mu2})} \bullet \frac{A(K_{\mu2}) \times f_\mu \times \varepsilon(K_{\mu2})}{A(K_{e2}) \times f_e \times \varepsilon(K_{e2})} \bullet \frac{1}{f_{LKr}}$$

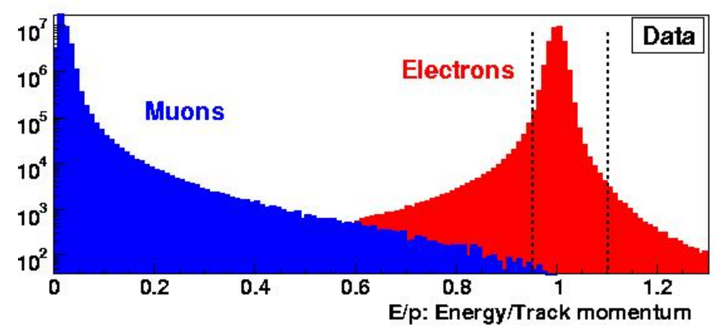
Bckg events — Acceptances — Trigger efficiencies — LKR readout efficiency

K_{e2} and $K_{\mu 2}$ selection

- Common selection
  - One reconstructed track, $15 < P < 65$ GeV/c
  - Common geometrical cuts
  - Decay vertex defined as closest distance of approach track-nominal K axis



- Kinematical separation
  - Use missing mass squared $M^2_{miss}=(P_K-P_\ell)^2$
  - P_K is measured from the data with $K \to 3\pi$
    - No $K_{\mu 2}$ background in K_{e2} sample below 25 GeV/c

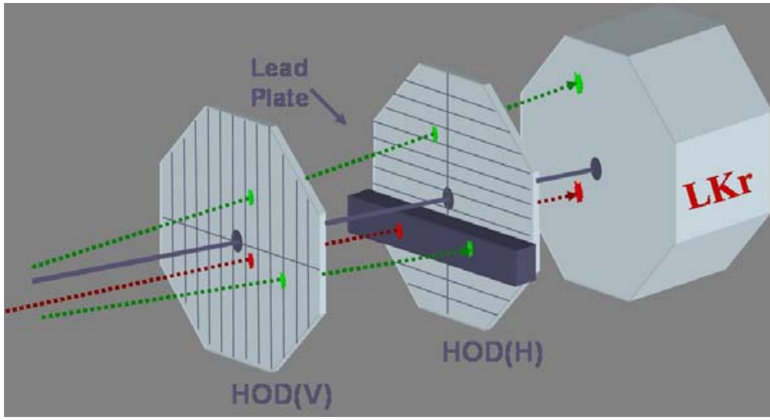


- Particle ID
  - $E_{LKr}/P_{spect} < 0.2$ for muons, between 0.95 and 1.10 for electrons

The major background to K_{e2} - 1

- Catastrophic bremsstrahlung of muons in the LKr
  - Gives $E/p > 0.95 \rightarrow$ tag the event as K_{e2}
  - Probability $\sim 3 \cdot 10^{-6}$
    - $K_{\mu 2}/K_{e2} \sim 40000 \rightarrow$ background O(10%)
  - Need a direct measurement to validate the muon bremsstrahlung cross section in this region

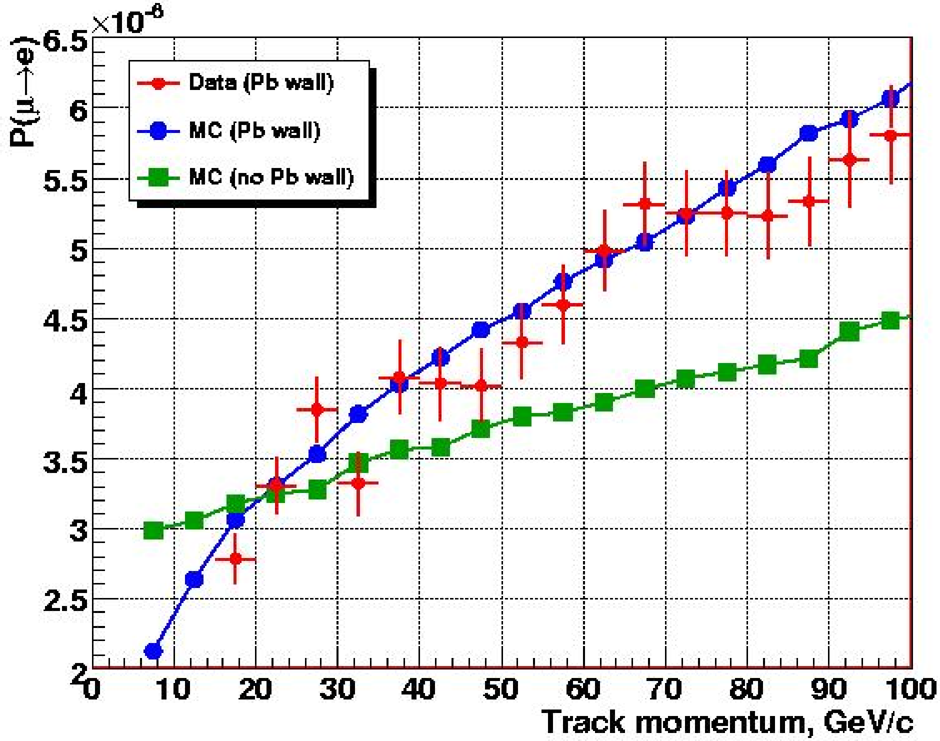
- Measure it putting 9 X_0 of lead in front of the calorimeter
  - For about 50% of the run time, 18% acceptance reduction
  - Tracks traversing the lead are pure muons
  - Compare with simulation and then extrapolate to the configuration without lead



The major background to K_{e2} - 2

- $P(\mu \to e)$: measurement vs simulation
  - Very good agreement
  - Modified wrt P without wall by
    - Muon ionization losses at low P
    - Muon bremsstrahlung in the lead at high P
  - $P(\mu \to e) = (7.4 \pm 0.2)\%$

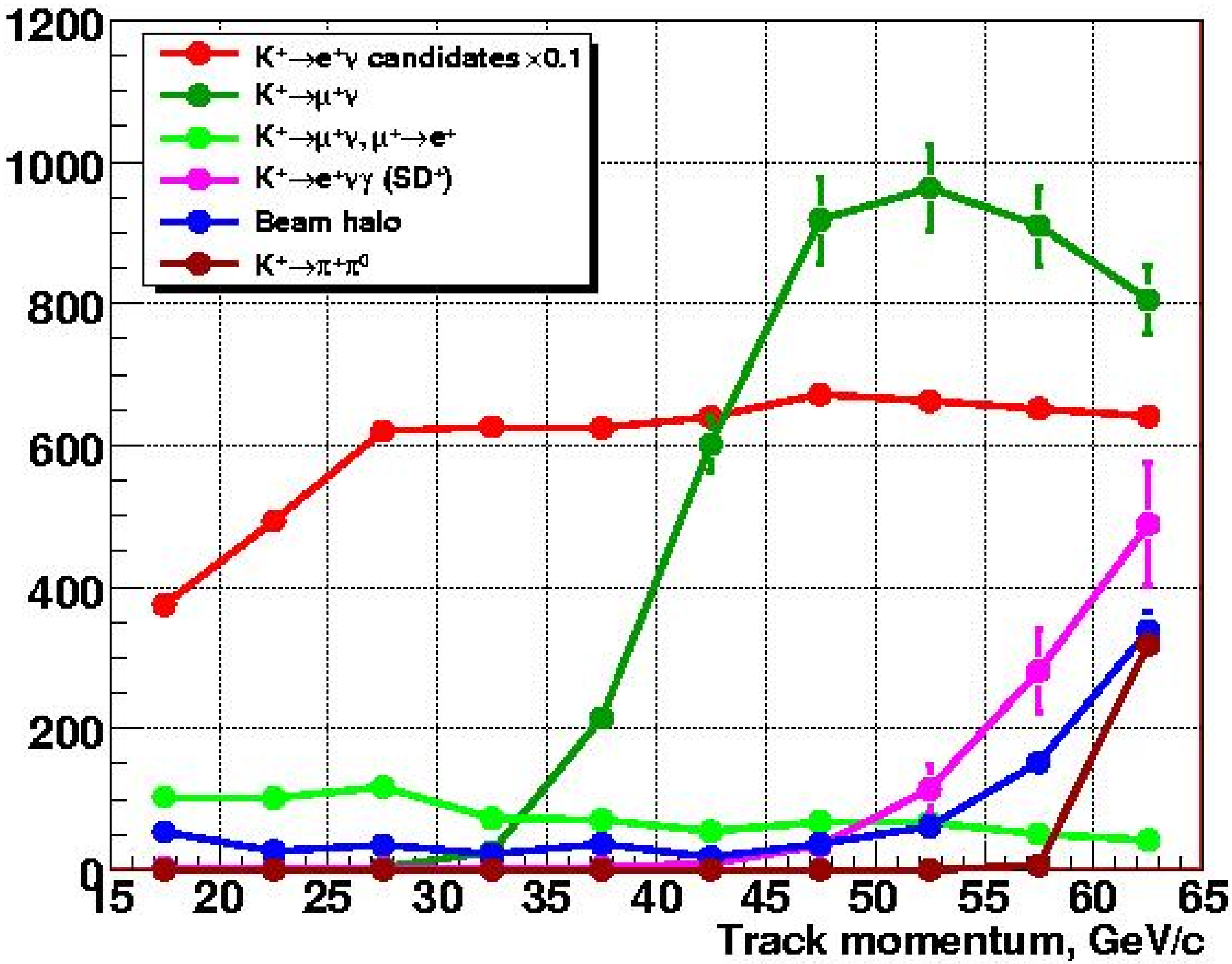
- Improvements are possible
  - Uncertainty due the size of the data sample used for the comparison
  - 2x sample collected during the run in 2008
  - Use muons from $K_{\mu 2}$ decays in the momentum region below 25 GeV/c



Other backgrounds to K_{e2}

- Beam halo — 1.3 ± 0.1 %
  - Beam halo muons decaying to electrons
  - Measured using K^- only sample
  - Special data collected in 2008 will improve the statistical error
- $K_{\mu 2}$ with $\mu \rightarrow e$ decay — 1.3 ± 0.1 %
  - Included in the MC simulation
- $K_{e2\gamma}$ (SD+) — 1.6 ± 0.3 %
  - Default background, R_K includes only IB
  - Rate similar to K_{e2}, the theory is form factor model-dependent
  - Branching ratio known to ~20% $BR=(1.52\pm0.23)\cdot10^{-5}$
  - Improvement with a direct measurement from an ongoing analysis of 2007 NA62 data

Summary of the backgrounds



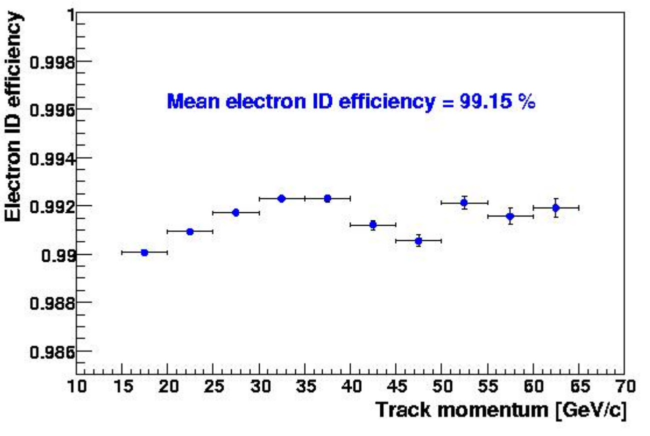
Background increasing with momentum

Systematic effect: 0.4%

Improvements foreseen for each component

More systematics

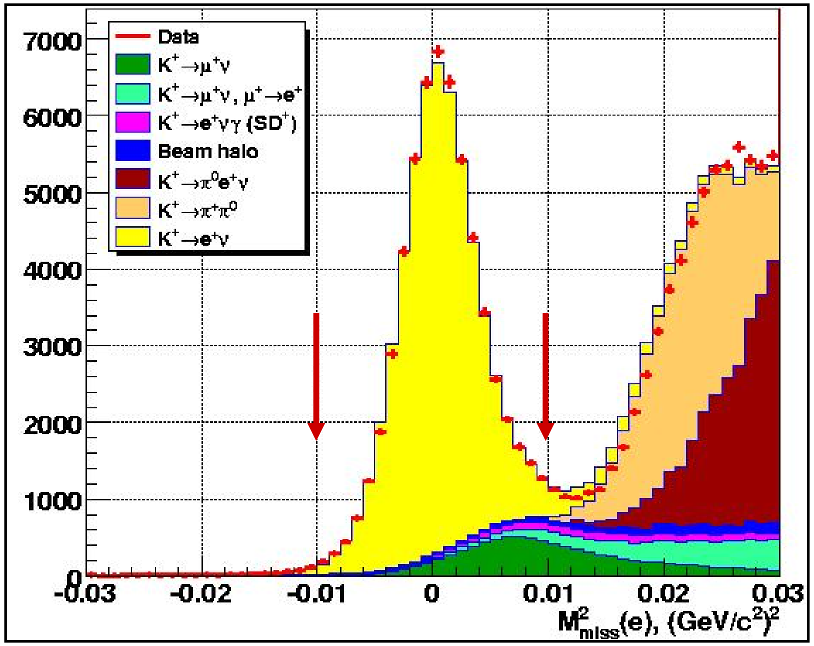
- Electron ID efficiency f_e
  - Measured with pure electron samples from $K^{\pm} \rightarrow \pi^0 e^{\pm}\nu$ collected during the main data taking (P<50 GeV/c) and with $K_L \rightarrow \pi^{\pm} e^{\pm}\nu$, collected with a special K_L run
  - Good agreement between the two, f_e= 99.15%, error better than 0.1%

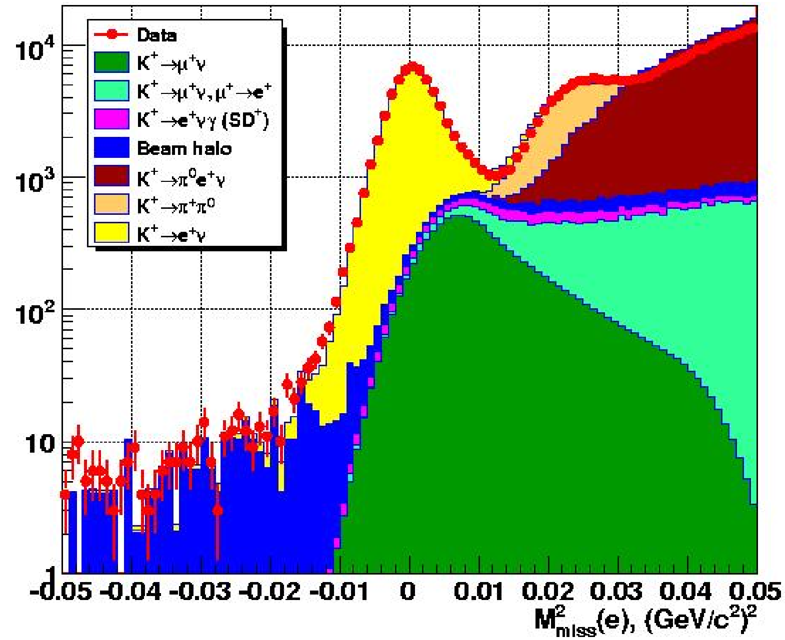


- Muon ID efficiency f_μ
  - From a special muon run
  - f_μ=(0.996-0.998)

- Acceptance correction
  - Momentum dependent
  - Strongly affected by K_{e2}(IB) radiative correction (1.2-1.4)
- Trigger efficiency correction
  - Measured using control trigger samples, better than 0.1%

K_{e2} candidates





K_{e2} background summary (%)

$K_{\mu 2}$	7.4 ± 0.2
$K_{\mu 2}$, $\mu \to e$	1.3 ± 0.1
$K_{e2\gamma}$(SD+)	1.6 ± 0.3
Beam halo	1.3 ± 0.1
K_{e3}	0.1
$K_{2\pi}$	0.6 ± 0.1

Only 40% of data used

Total estimated sample:

140k K^+ and 20k K^- candidates

Proposal: 150k candidates

Analysis summary

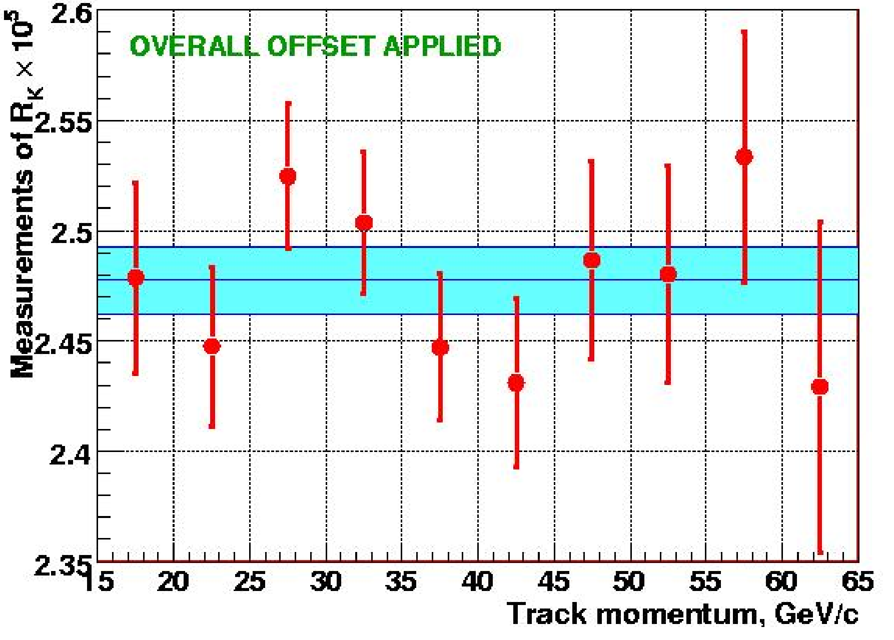
40% of the data sample used

10 momentum bins

Result stable vs momentum

Main uncertainties

Statistical	0.4%
$K_{\mu 2}$	0.2%
$K_{e2\gamma}$(SD+)	0.3%
Beam halo	0.1%
IB simulation	0.3%
Expected total	0.6-0.7%



Still room to improve systematic errors

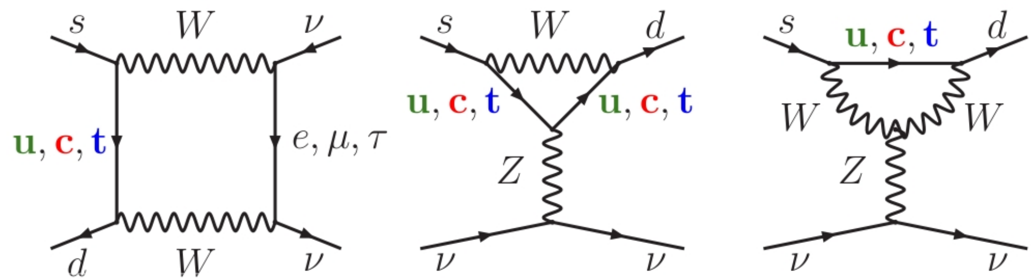
With the total sample of ~160k candidates

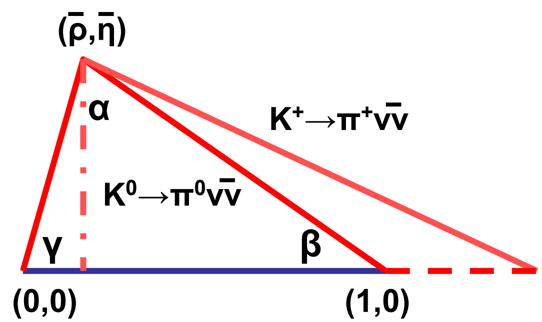
statistical error below 0.3%

total uncertainty of 0.4-0.5%

Prospects: $K^+ \to \pi^+ \nu\nu$

- FCNC process forbidden at tree level
- Only one loop contributions: Boxes and Penguins
- Top contribution is dominant: small coupling in CKM between t and d,s $\to \lambda^5$
- Clean theoretical environment: small contribution by hadronic matrix element and long distance terms

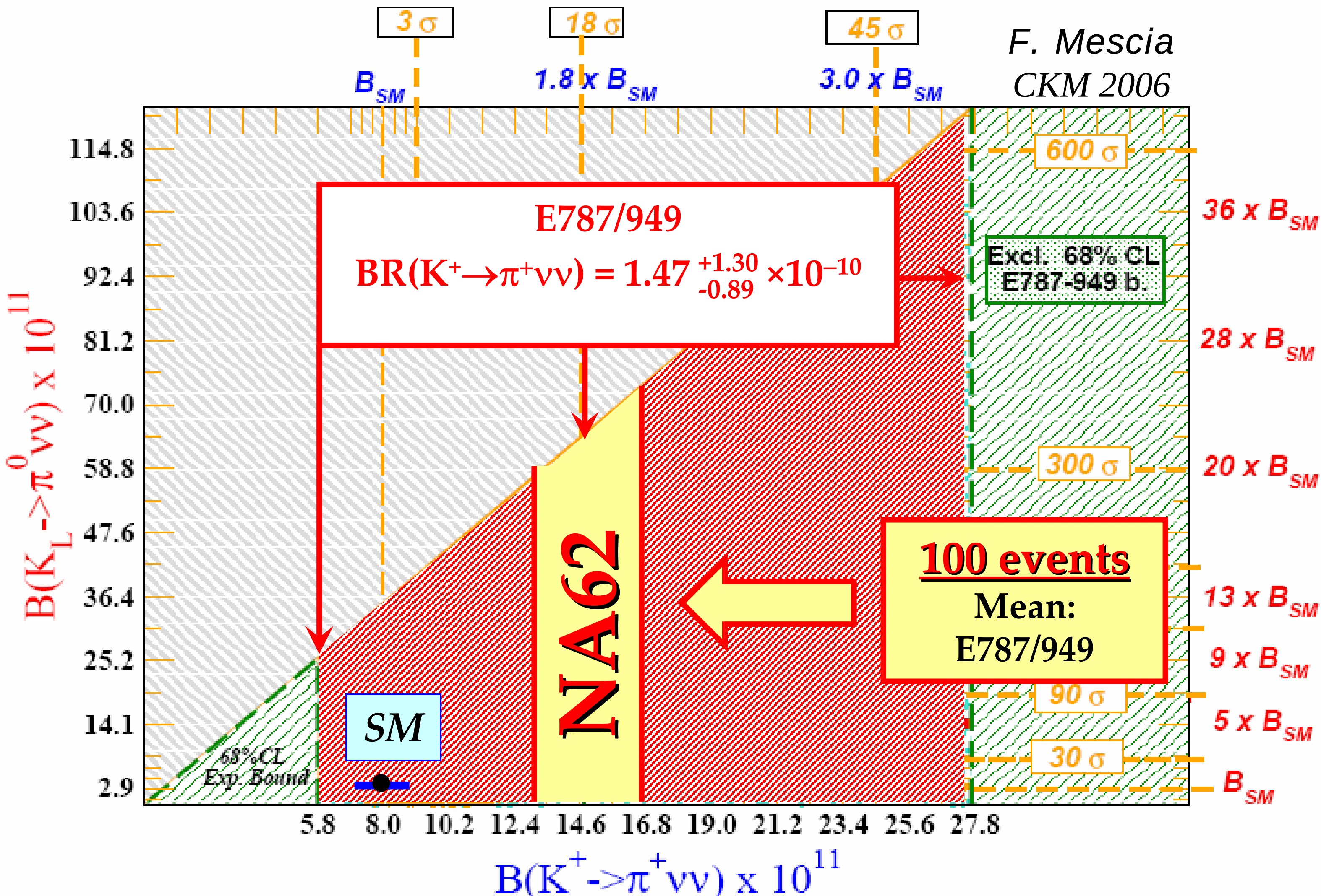




- Cleanest way to extract **Vtd** and to give independent determination of the unitarity triangle
- Complementarity with B physics
- Very sensitive to New Physics

- Theoretical expectations (as of CKM08)
  - BR $(K^+ \to \pi^+ \nu\nu) \sim (0.85 \pm 0.07) \cdot 10^{-10}$ for $m_c = (1286 \pm 13)$ MeV
  - BR $(K_L \to \pi^0 \nu\nu) \sim (2.76 \pm 0.40) \cdot 10^{-11}$
- Experimental status from E787/E949 (2008)
  - BR $(K^+ \to \pi^+ \nu\nu) \sim 1.73^{+1.15}_{-1.05} \cdot 10^{-10}$

$K^+ \to \pi^+ \nu \bar{\nu}$ beyond the SM



Possible values from many NP models

A way to distinguish between models

NA62 $K^+ \to \pi^+ \nu\nu$ measurement

- Measure the $K^+ \to \pi^+ \nu\nu$ decay with 10% accuracy
  - Collect ~100 signal events in 2 years
  - 10% signal acceptance
    - Need 10^{13} Kaon decays
  - 10:1 signal to background ratio

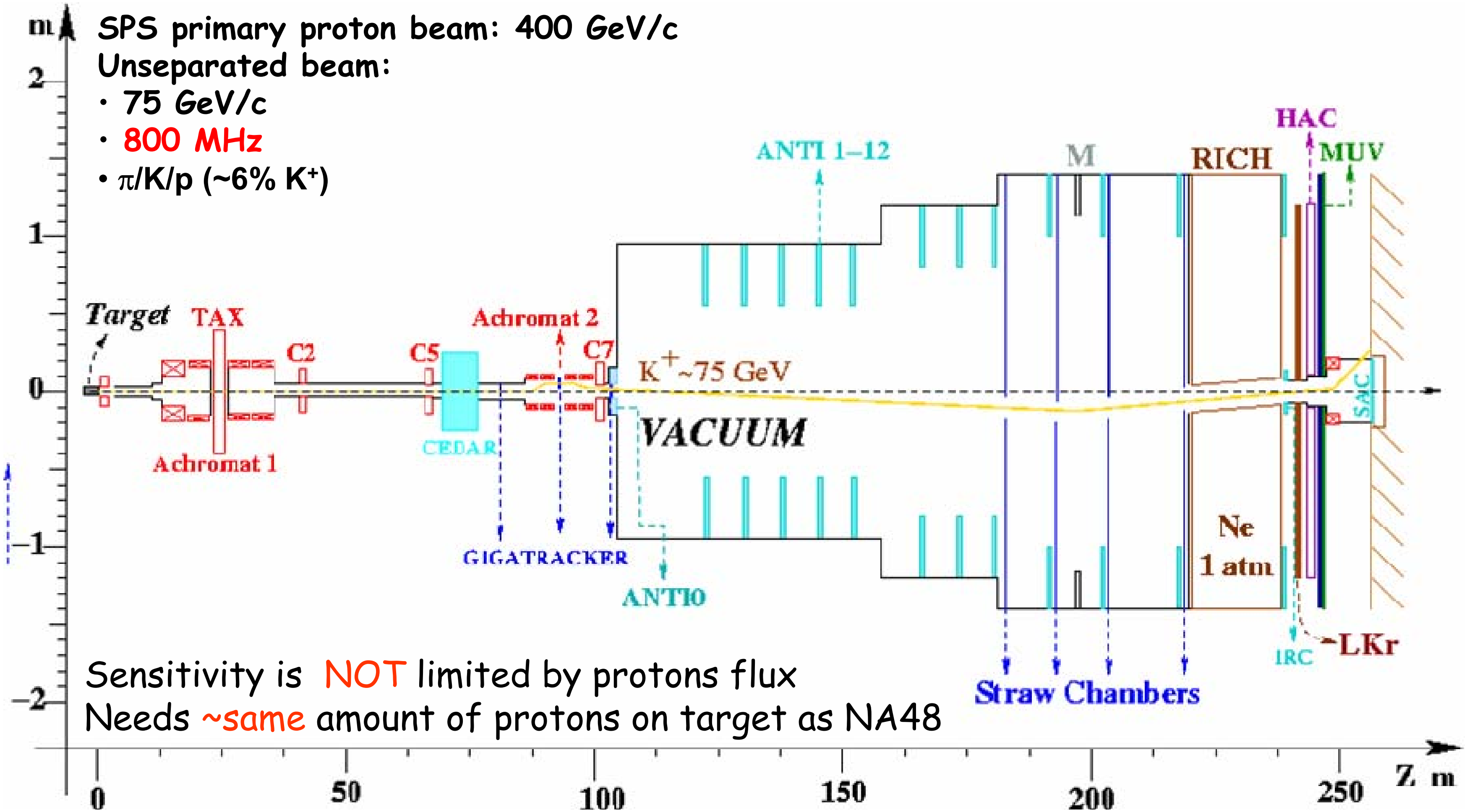
- The path to the measurement
  - Proposal and R/D started in 2004
  - Eventually approved by funding agencies
  - Build the detector in 2009-2010
  - Get data in 2011-2012

NA62 $K^+ \to \pi^+ \nu\nu$ detector

SPS primary proton beam: 400 GeV/c

Unseparated beam:

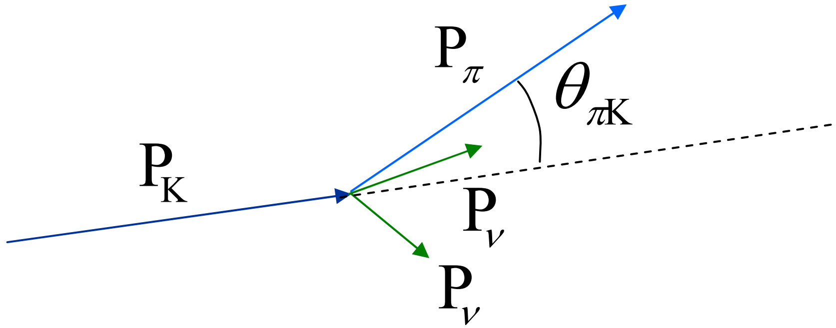
- 75 GeV/c
- 800 MHz
- π/K/p (~6% K^+)



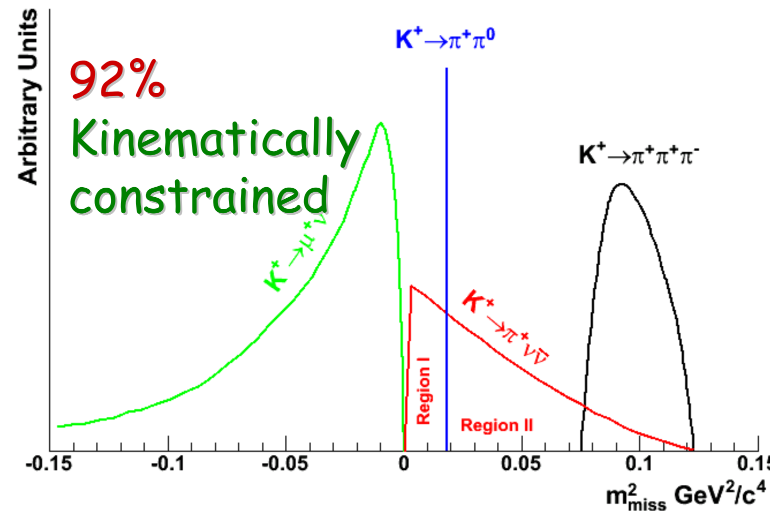
Sensitivity is NOT limited by protons flux

Needs ~same amount of protons on target as NA48

The experimental principle



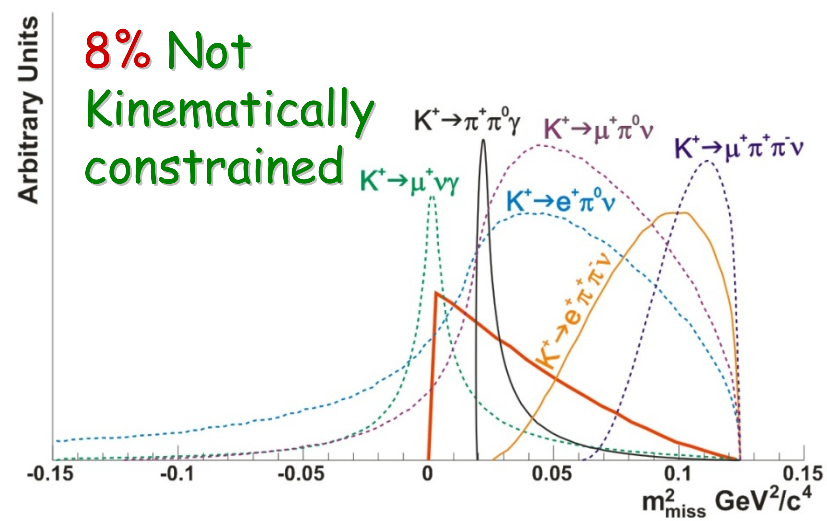
$$m_{miss}^2 \cong m_K^2\left(1-\frac{|P_\pi|}{|P_K|}\right)+m_\pi^2\left(1-\frac{|P_K|}{|P_\pi|}\right)-|P_K||P_\pi|\theta_{\pi K}^2$$



Single track signature → Kaon and pion momentum measurement

Kinematically and not constrained bkg → PID and Veto

Ultrarare signal → High intensity beam and good trigger system (1 Mhz L0 trigger rate)



Updated Sensitivity vs. Proposal

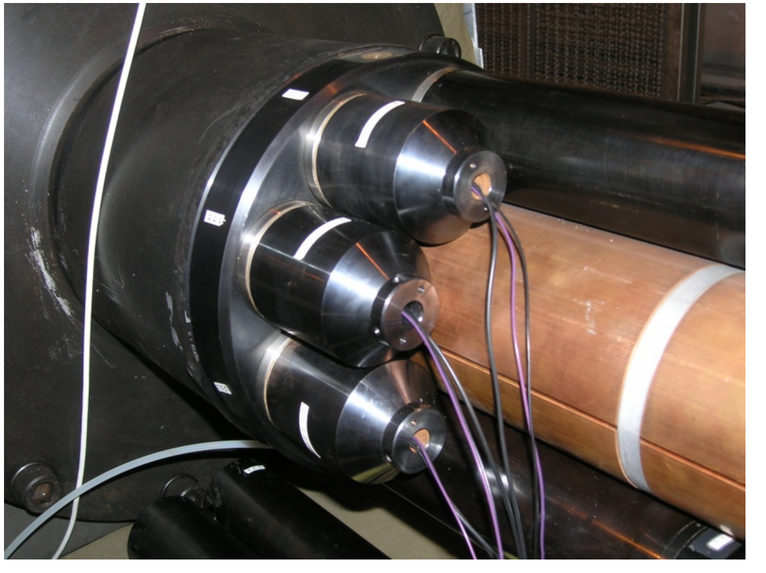
Decay Mode	New layout	Proposal
Signal: $K^+ \to \pi^+ \nu\nu$ *[flux = 4.8×10^12 decay/year]*	55 *evt/year*	65 *evt/year*
$K^+ \to \pi^+ \pi^0$ [$\eta_{\pi 0}$ = 2×10^-8 (3.5×10^-8)]	4.3% (7.5%)	4.2%
$K^+ \to \mu^+ \nu$	2.2%	1.9%
$K^+ \to e^+ \pi^+ \pi^- \nu$	≤3%	~3%
Other 3 – track decays	≤1.5%	~1.5%
$K^+ \to \pi^+ \pi^0 \gamma$	~2%	2%
$K^+ \to \mu^+ \nu \gamma$	~0.7%	0.7%
$K^+ \to e^+ (\mu^+) \pi^0 \nu$, others	negligible	negligible
Expected background	≤13.5% (≤17%)	~13%

NA62 $K^+ \to \pi^+ \nu\nu$ measurement

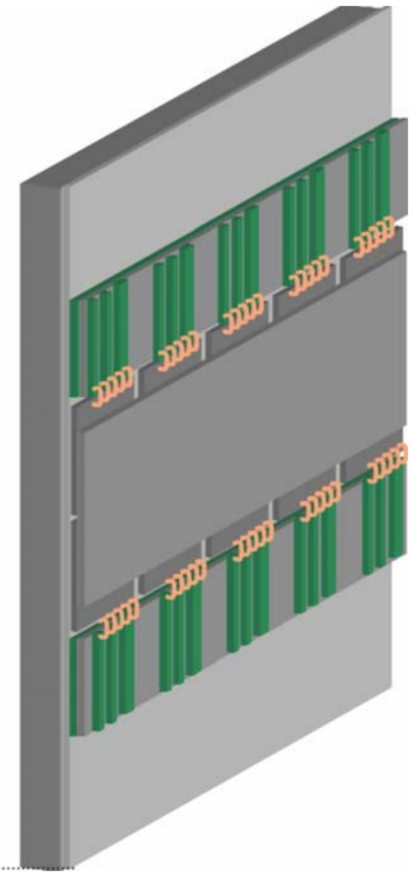
- Challenging detector and experimental technique
  - Precise timing to associate the pion to the parent kaon
    - High-rate tracker for the time of the parent particle
  - Kinematical rejection (cut on missing mass) of two- and three-body decays
    - High-rate tracker for K momentum measurement and a spectrometer based on straws in vacuum
  - Vetoes (for photons and muons)
    - Fast muon hodoscope plane
    - OPAL lead glass blocks arranged in rings for photon veto, together with the existing NA48 LKr calorimeter and small angle vetoes
  - Cerenkov particle identification (K/π in the beam, π/μ in the decay region)
    - Hydrogen-filled CEDAR in the beam line to separate K from π
    - Neon-filled RICH after the spectrometer to separate π from μ and to give a fast trigger signal
- For all these detectors, extensive R/D and prototype tests to validate the choices

CEDAR

- Standard CERN CEDAR W-type filled with N_2 tested at CERN in November 2006, using a 100 GeV hadron beam with 10^5 – 10^7 ppp, mainly to study time capability
- Test of fast photomultipliers using Cherenkov light
- It needs an improved readout to cope with the Ghz rate
- Mandatory replacement of old PMs with faster ones or with SiPM
- It needs modifications to be operated with hydrogen



Gigatracker Station



800 MHz beam

300 x 300 mm Si pixel

2x5 chips → 1800 pixels/chip

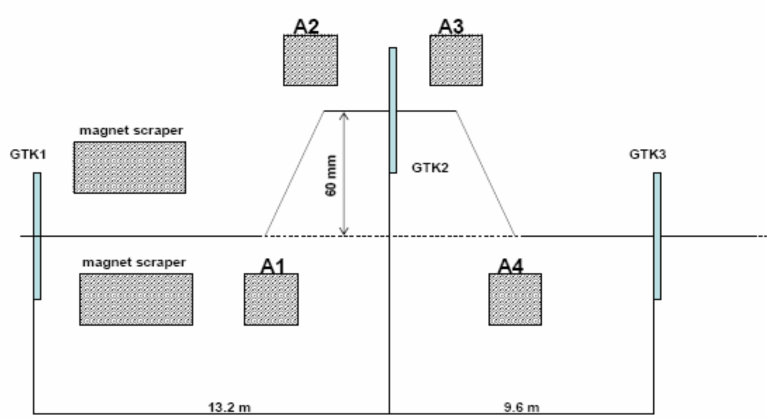
Station total thickness: 0.5% X_0

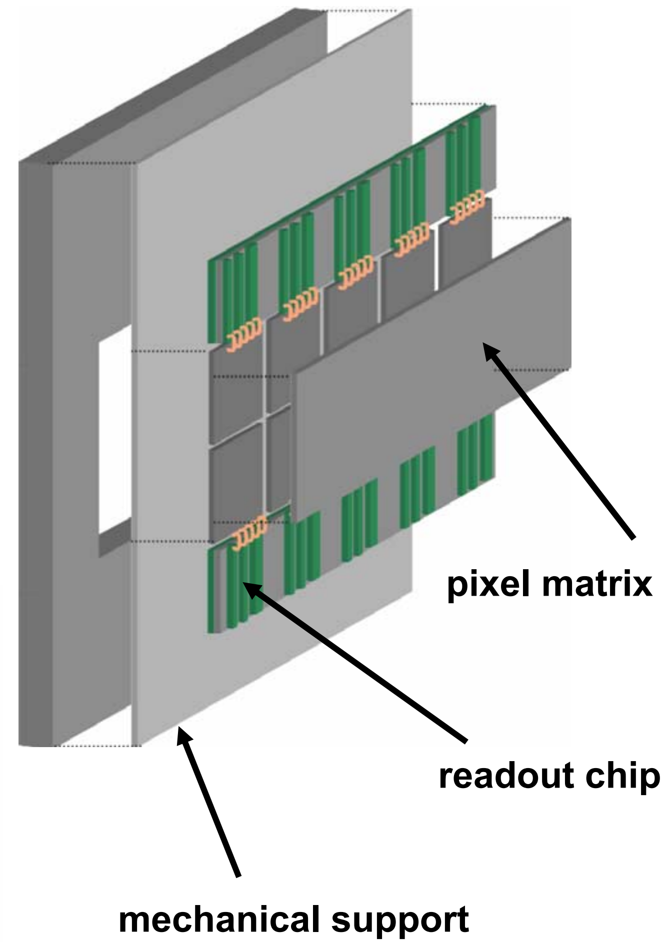
200 ps time resolution/station

Power budget: 2 W/cm^2 → 2 mW/pixel

Input dynamic range: 5000 ÷60000 e

Average data rate: 50 MHz/ cm^2

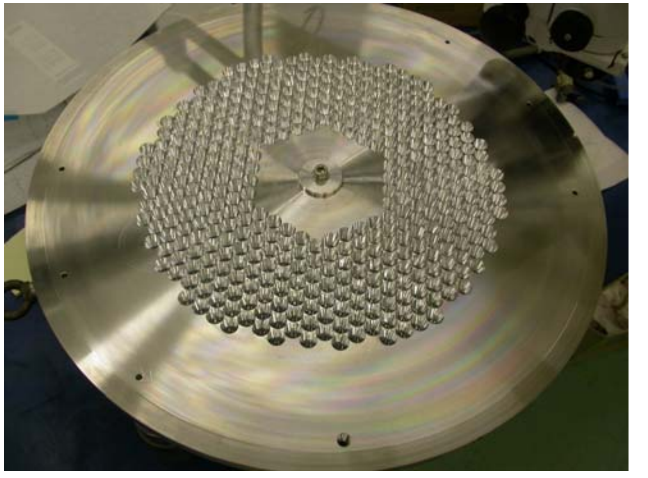


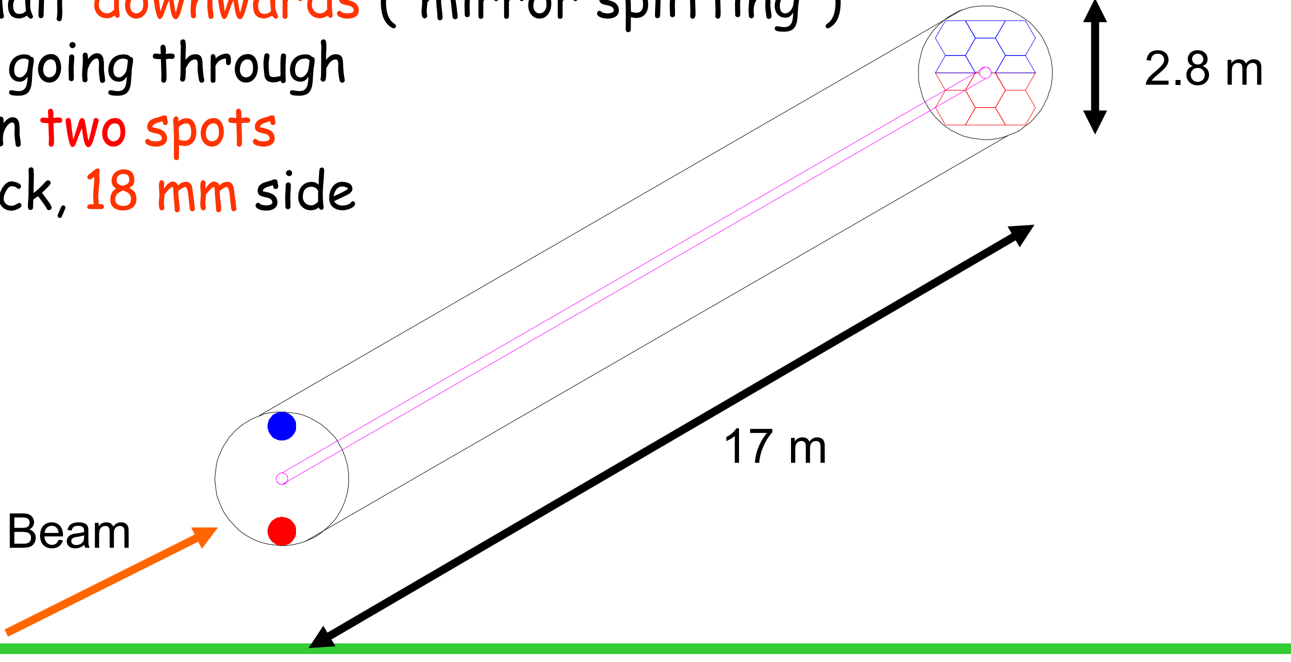


The RICH detector

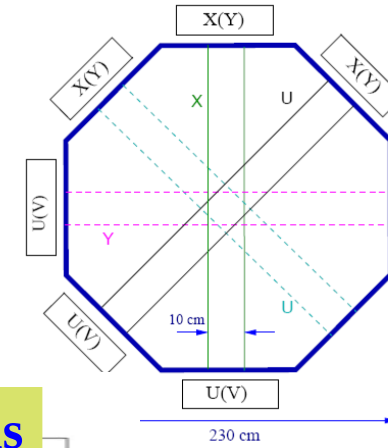
- Reject μ in π at 5×10^{-3} (15 <p< 35 GeV/c)
- Measure the track time at 100 ps level
- Main Charged trigger

- Neon gas as radiator (atm. pressure)
- Mirrors mosaic (f=17 m): half pointing upwards, half downwards ("mirror splitting")
- Beam pipe going through
- 2000 PM in two spots
- PM hex pack, 18 mm side

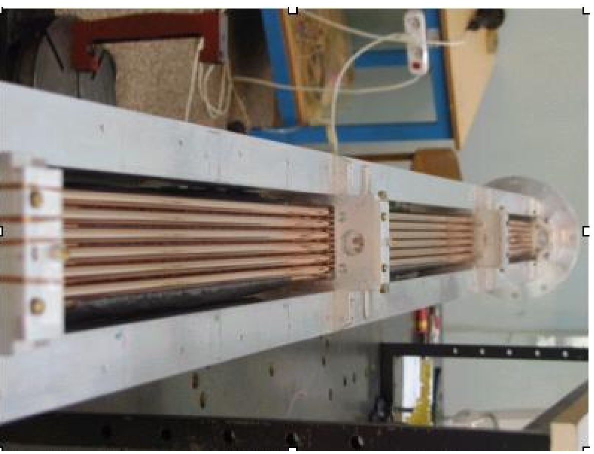


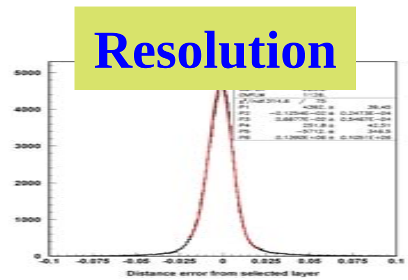


Straw tracker

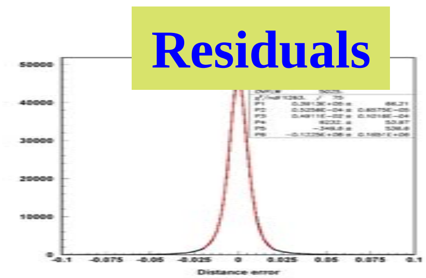


Straw Trackers operated in vacuum wrt NA48 layout:
- Remove the multiple scattering due to the Kevlar Window
- Remove the acceptance limitations due to the beam-pipe
- Remove the helium between the chambers



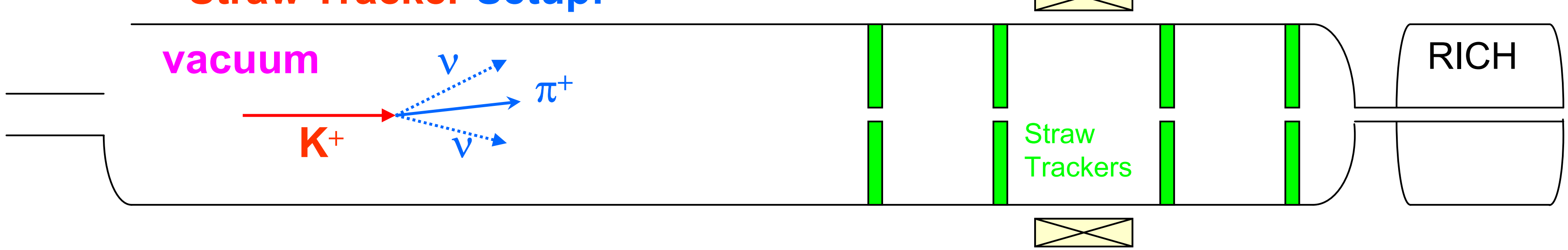


R.M.S.=130 μm
sigma=67 μm



R.M.S.=113 μm
sigma=49 μm

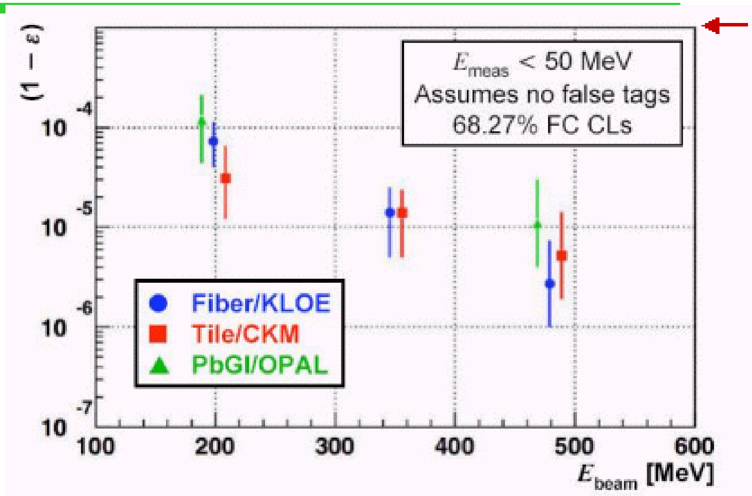
Straw Tracker Setup:



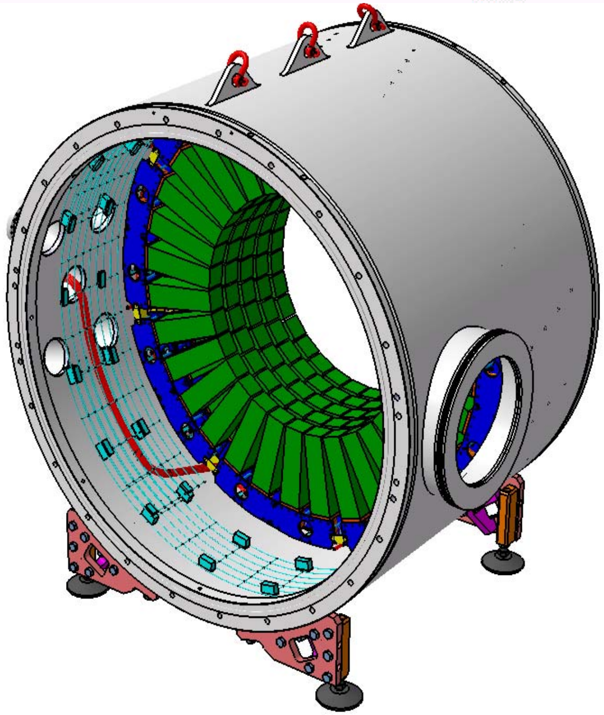
- The Straw Tracker is essential to study ultra-rare-decays in flight

Photon Vetoes

- Needed to reject $K^+ \rightarrow \pi^+ \pi^0$
  - Global inefficiency to π^0 ~10^{-8}
  - Hermetic coverage up to 50 mrad
  - R/D to test three technologies for large angle vetoes
    - Lead/scintillating fibers, lead/scintillator with WLS fibers, OPAL lead glasses
    - All three fulfill requirements, OPAL lead glass chosen
  - Completed by the LKr calorimeter and small angle detectors
    - $P(K^+) = 75$ GeV/c, requiring $P(\pi^+) < 35$ GeV/c $\rightarrow P(\pi^0) > 40$ GeV/c
      It can hardly be missed in the calorimeters



With inefficiency at this level, the LAV contribution to the average inefficiency is $0.2 \cdot 10^{-8}$



Conclusions

- The measurement of $R_K = \Gamma_{Ke2}/\Gamma_{K\mu 2}$ is well-suited for a test of lepton universality and for search for new physics
- NA62 in 2007 has increased the world K_{e2} sample by an order of magnitude
  - ~ 160K K_{e2} candidates
  - Data taking optimized for K_{e2}
- Analysis is in progress and additional specific data collected in 2008 will improve the systematic error
- With 40% of the data analyzed, the total error on R_K is 0.6%
- An overall uncertainty of 0.4% is within reach with all the data

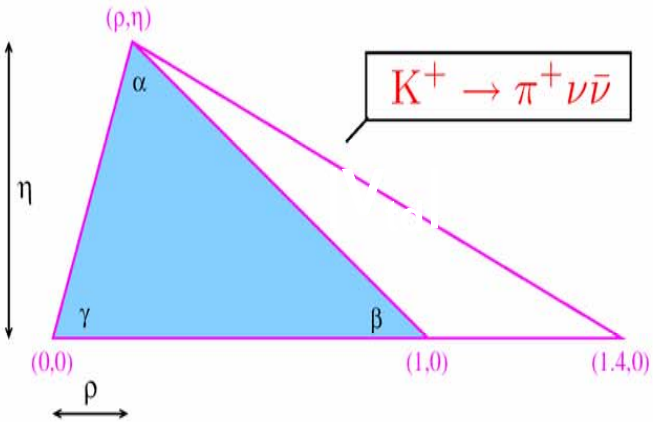
- NA62 is now preparing a new detector for the measurement of $BR(K^+ \to \pi^+ \nu\nu)$
- Aim to collect ~100 events in 2 years (2011-2012) for a measurement of the branching ratio at 10% level

Spares

Kaon Rare Decays and the SM

$K_L \to \pi^0 \nu \bar{\nu}$ **(holy grail)**

$K_L \to \pi^0 e^+ e^-$ $\begin{cases} K_S \to \pi^0 e^+ e^- \\ K_L \to \pi^0 \gamma\gamma \\ K_L \to ee\gamma\gamma \end{cases}$

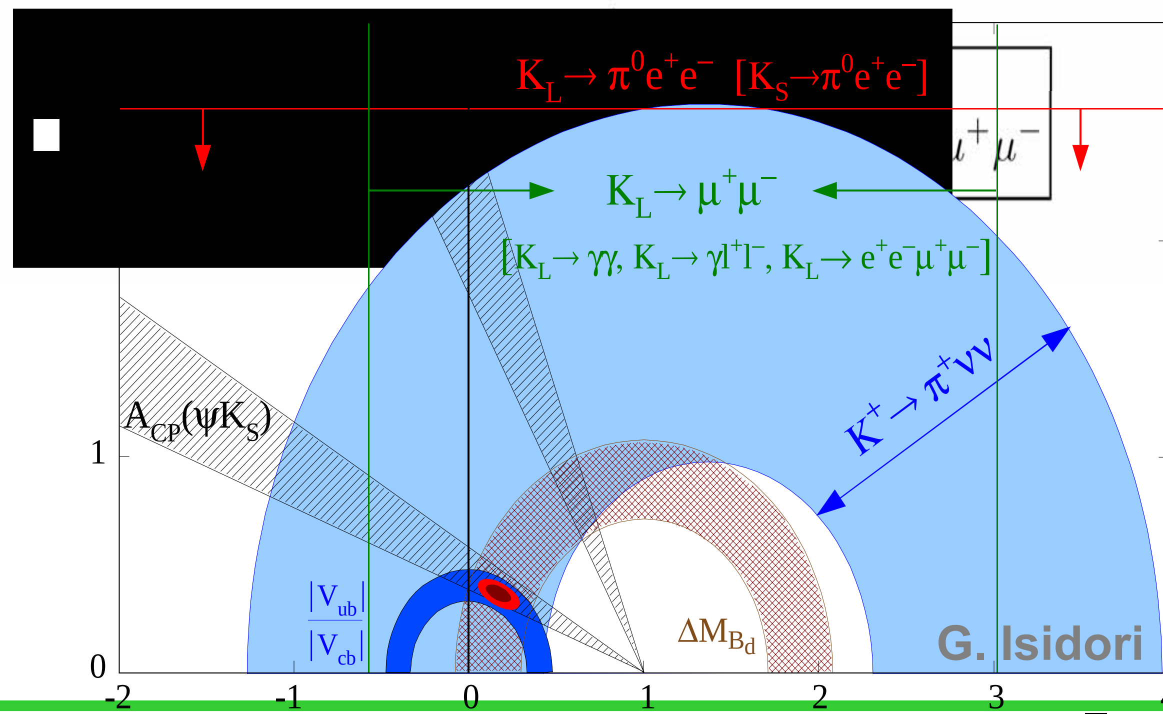


Kaons provide quantitative tests of SM independent from B mesons…

…and a large window of opportunity exists!

$Im\ \lambda_t = A^2 \lambda^5 \eta$

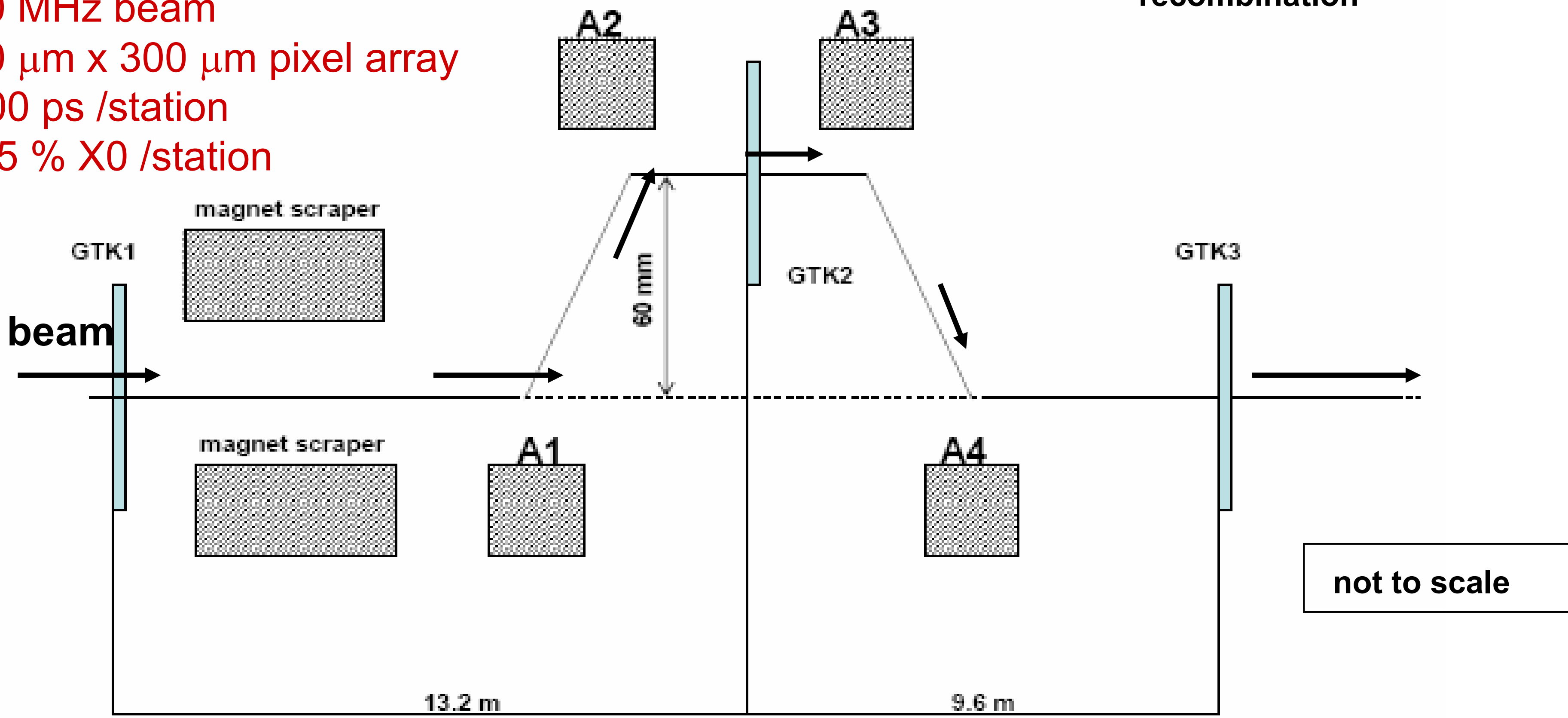
$Re\ \lambda_t = A^2 \lambda^5 \rho$



Gigatracker

A1÷A4: achromat dipole magnets to provide the momentum selection and recombination

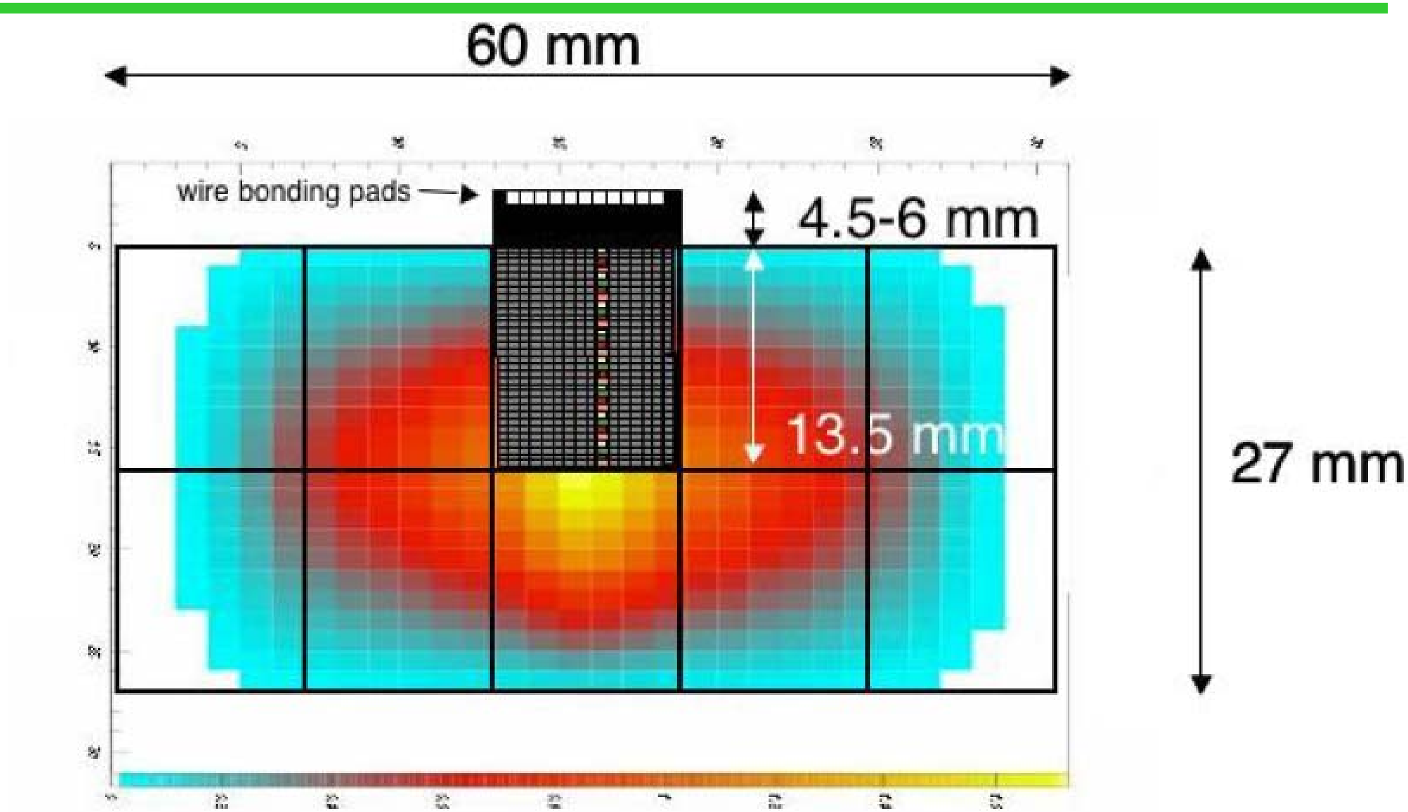
800 MHz beam
300 μm x 300 μm pixel array
~200 ps /station
<0.5 % X0 /station



Layout of the beam on the horizontal plane

Beam momentum is derived from the hit coordinate in GTK2 with respect to GTK1 and GTK3 coordinates: **75 GeV/c -> 60 mm**

Detector layout & beam profile

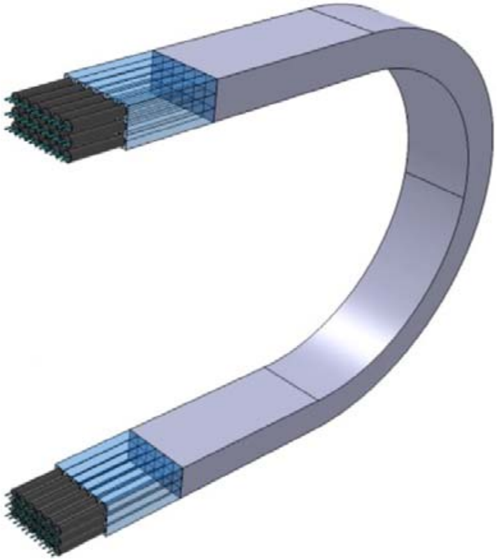


Dose/year ~10^5 Gy

10^{14} 1 MeV n_{eq} /cm^2 per year

→ Change the detector every ~60 days

The fiber prototype



KLOE-type lead/scintillating fiber calorimeter

1-mm diameter scintillating fibers

0.5-mm thick lead foils, grooved to house fibers

Full-scale prototype of smallest rings

1/3 of final radial thickness

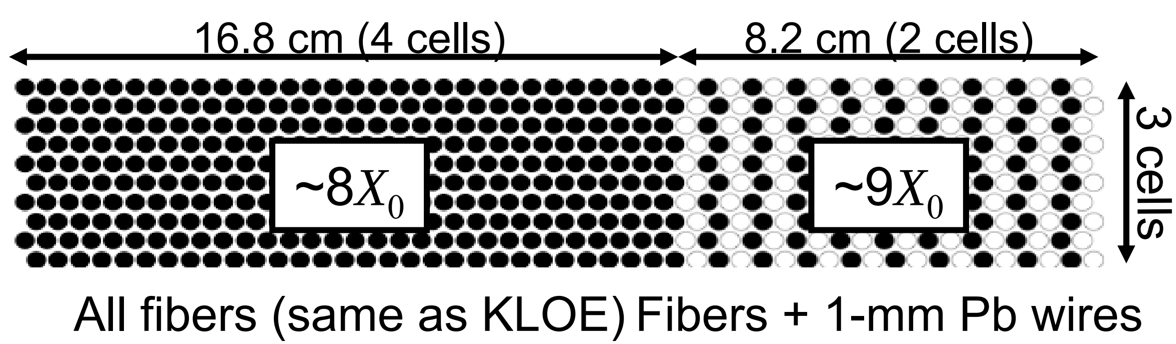
Inner/outer radius: 60 cm - 72.5 cm

Inner/outer length: 309.5 cm - 348.8 cm

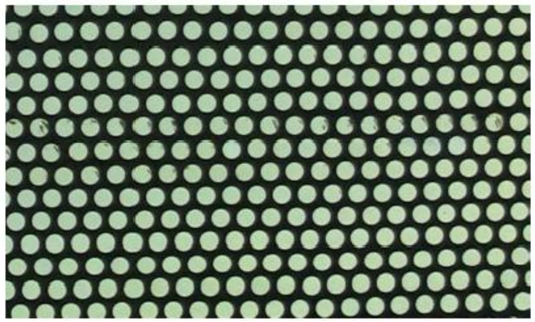
Readout granularity: 18+18 cells, 4.2 x 4.2 cm^2

Readout from two sides to have φ measurement

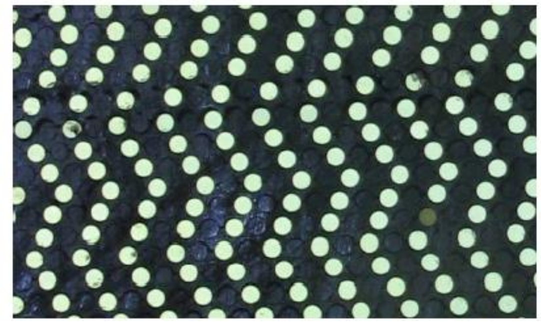
Hamamatsu R6427 photomultipliers

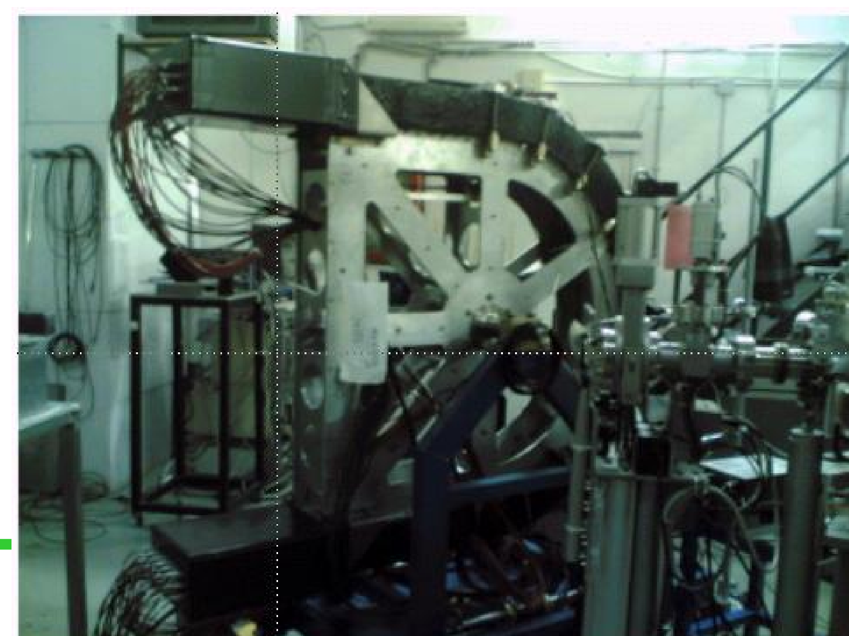


All-fiber region

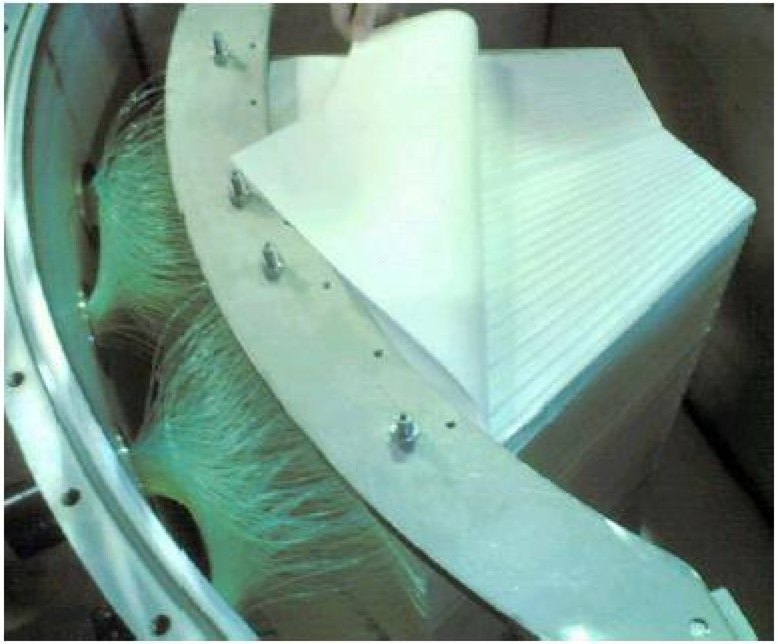


Fibers + lead wires



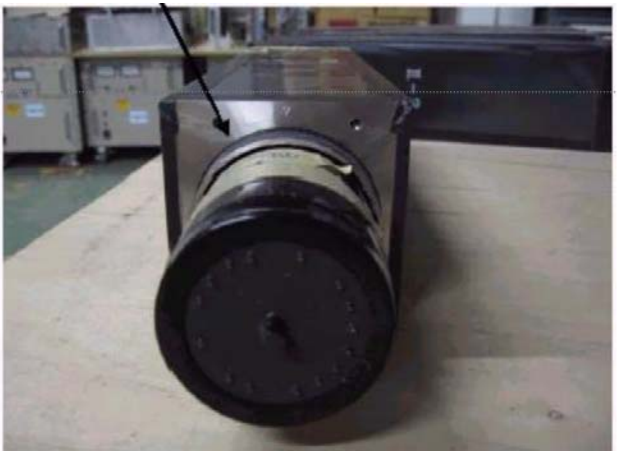


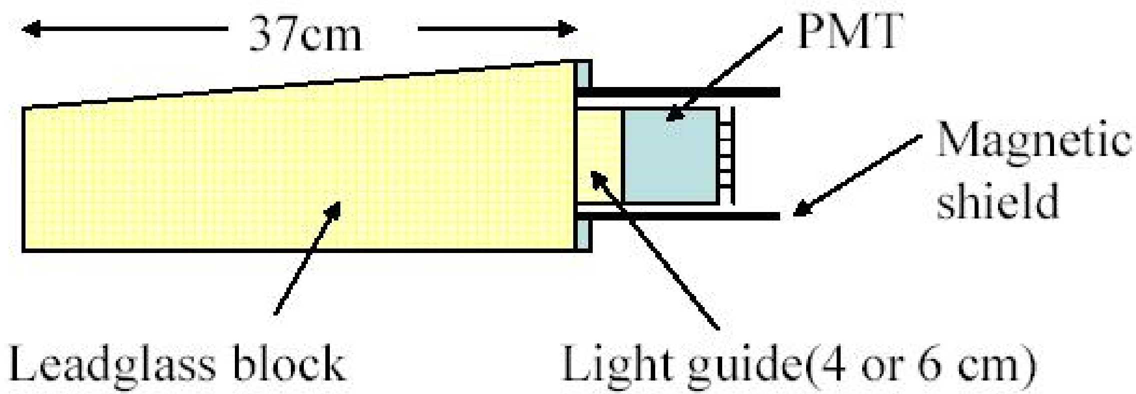
The CKM prototype



- Two 22.5^0 sectors, 80 layers, 1 mm lead/5 mm scintillator
- WLS readout, EMI 9954B photomultipliers
- On loan from Fermilab
- Tested by the CKM Collaboration at the Jefferson Lab
  - Measured inefficiency for electrons: $3 \cdot 10^{-6}$ at 1 GeV

The OPAL lead glasses





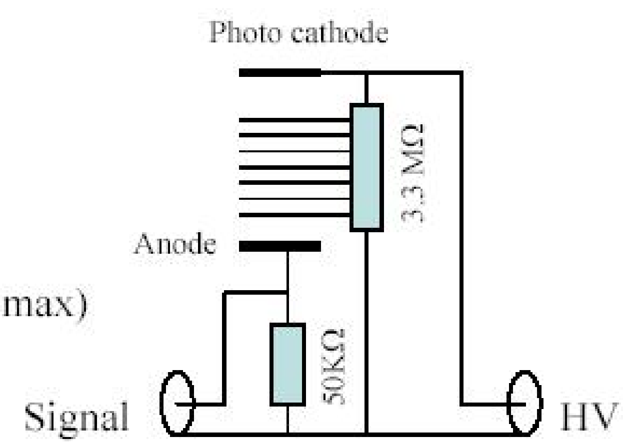
Leadglass + light guide : Schott SF57

- Density : 5.6 gr/cm^3
- Refractive index : 1.85
- Radiation length : 1.5 cm
- Moliere radius : 2.6 cm

PMT : Hamamatsu R2238

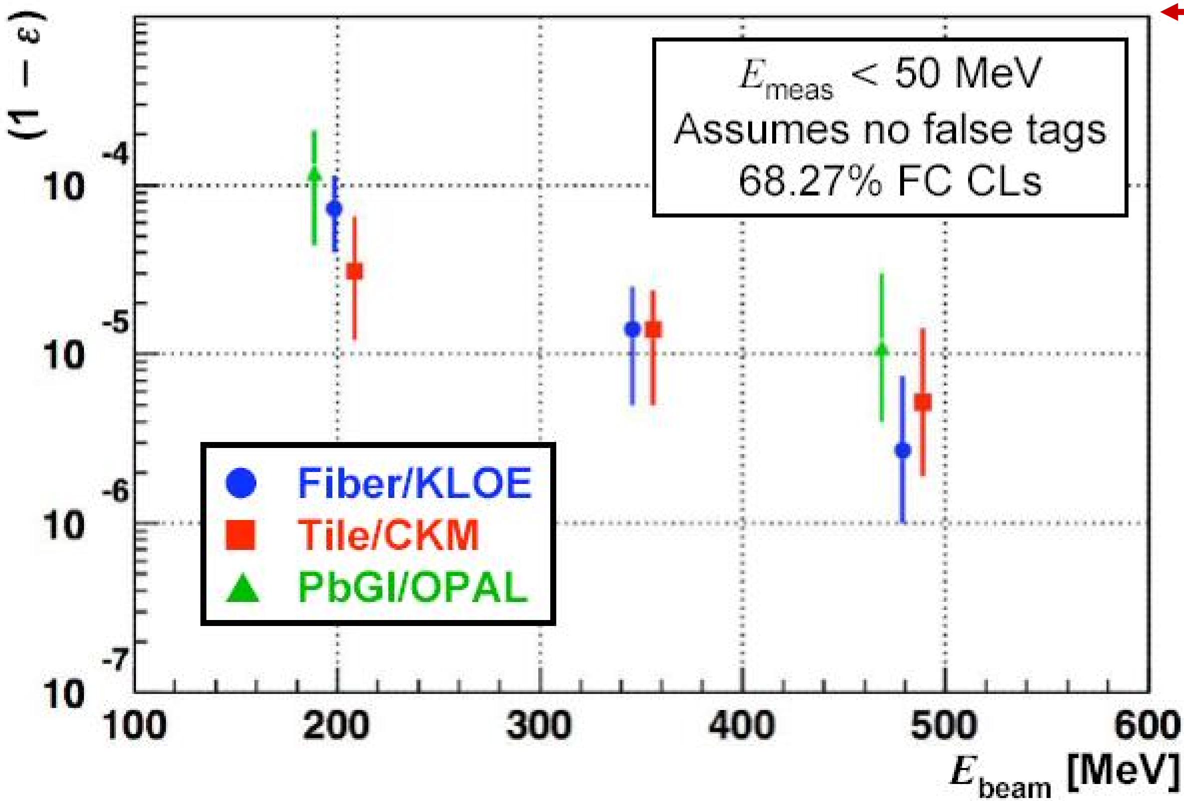
- 12 stage mesh dynode
- Gain 10^5 at typical HV=950V (1.5kV max)
- $G \sim V^n$, $n \sim 7.5$

Sensitivity : ~ 10pC/GeV for e/γ at $G=10^5$



Inefficiency results - Summary

Efficiencies for electron detection similar for all 3 technologies



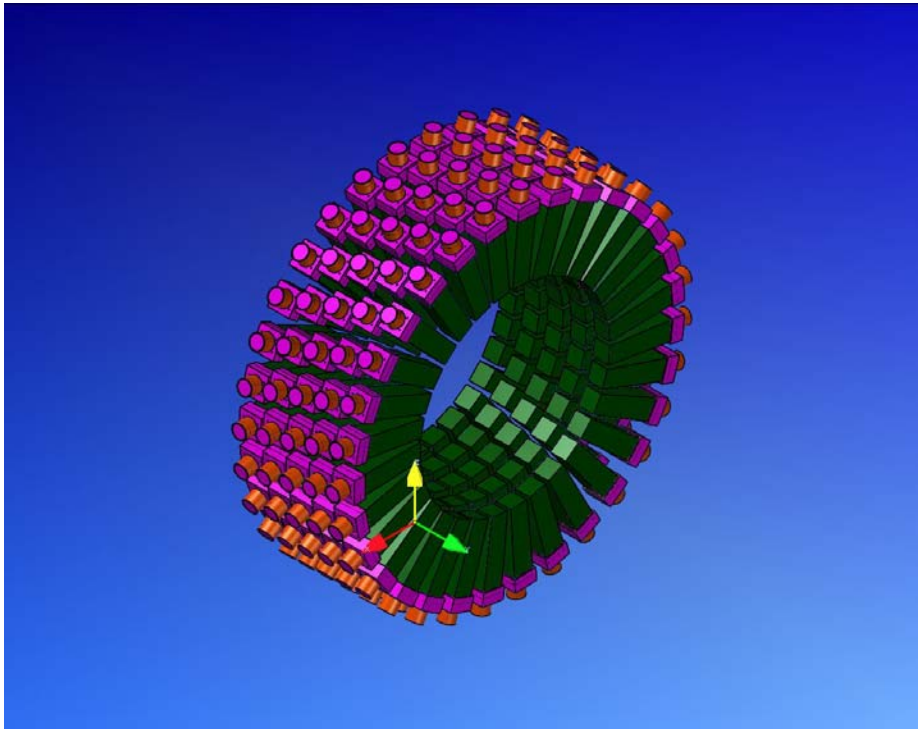
With inefficiency at this level, the LAV contribution to the average inefficiency is $0.2 \cdot 10^{-8}$

Tile (CKM) and lead glass (OPAL) results are preliminary

Baseline design

- Radially mounted blocks
- 5 layers, each layer shifted by an angle to avoid cracks
- For any impact position, at least 3 blocks hit

- Mounted on a section of the decay tube
  - One hole for each PM
  - Additional mechanical piece connected to the steel flange of the block to reinforce it and to house the vacuum seal
  - Cabling outside vacuum



F. Raffaelli, S. Bianucci

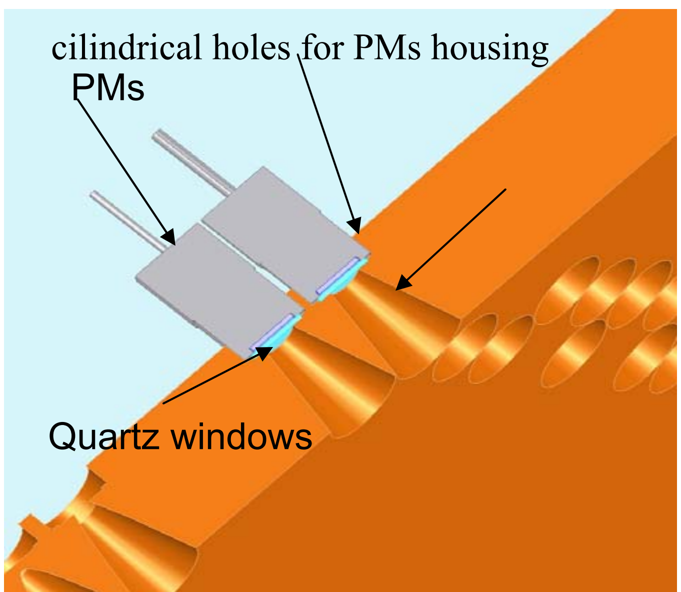
LKr inefficiency – a crucial issue

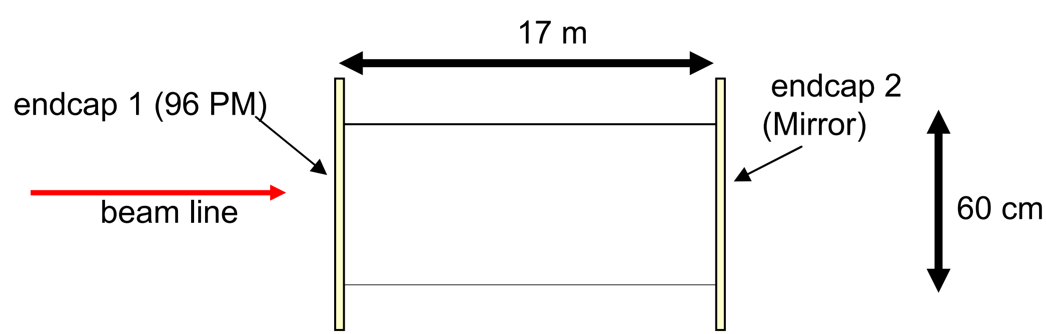
- Final results from 2004 run
  - Analysis of $K^+ \to \pi^+\pi^0$
  - The LKr inefficiency is less than $0.9 \cdot 10^{-5}$ (90% CL, $E\gamma > 10$ GeV)
- Preliminary results from 2006 run
  - Bremsstrahlung photons from an electron beam
  - The analysis is not straigthforward
    - Below 4 GeV the background from bremsstrahlung in the air after the momentum selection is too high
    - Needs accurate simulation of the beam line, of radiation effects in the decay volume and of the cluster merging effects
  - Preliminary results

$E\gamma$ (GeV)	Inefficiency
2.5 – 5.5	$< 10^{-3}$
5.5 – 7.5	$< 10^{-4}$
7.5 – 10	$< 5 \cdot 10^{-5}$
> 10	$< 8 \cdot 10^{-6}$

Full length RICH prototype built and tested in 2007

- Vessel: recovered from the nearby beamline in ECN3 and adapted (three new sections built)
- Mirror: 50 cm large, f = 17 m mirror (by MARCON)
- Vessel cleaning: vacuum, N_2, vacuum
- Radiator:Neon at 980 mbar, 24 ^0C
- Test: Oct 29 – Nov 10, 2007 in the NA62 beam line

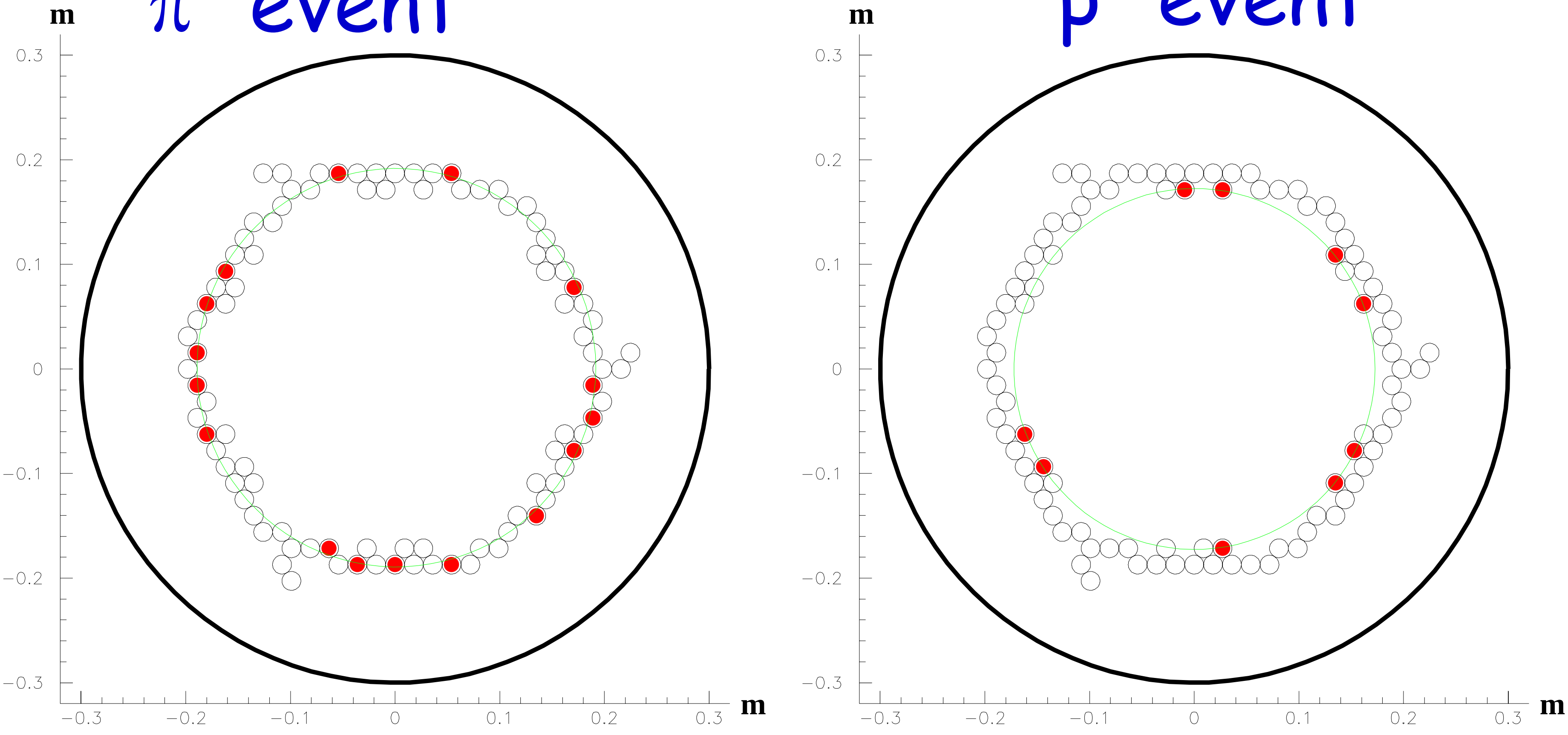




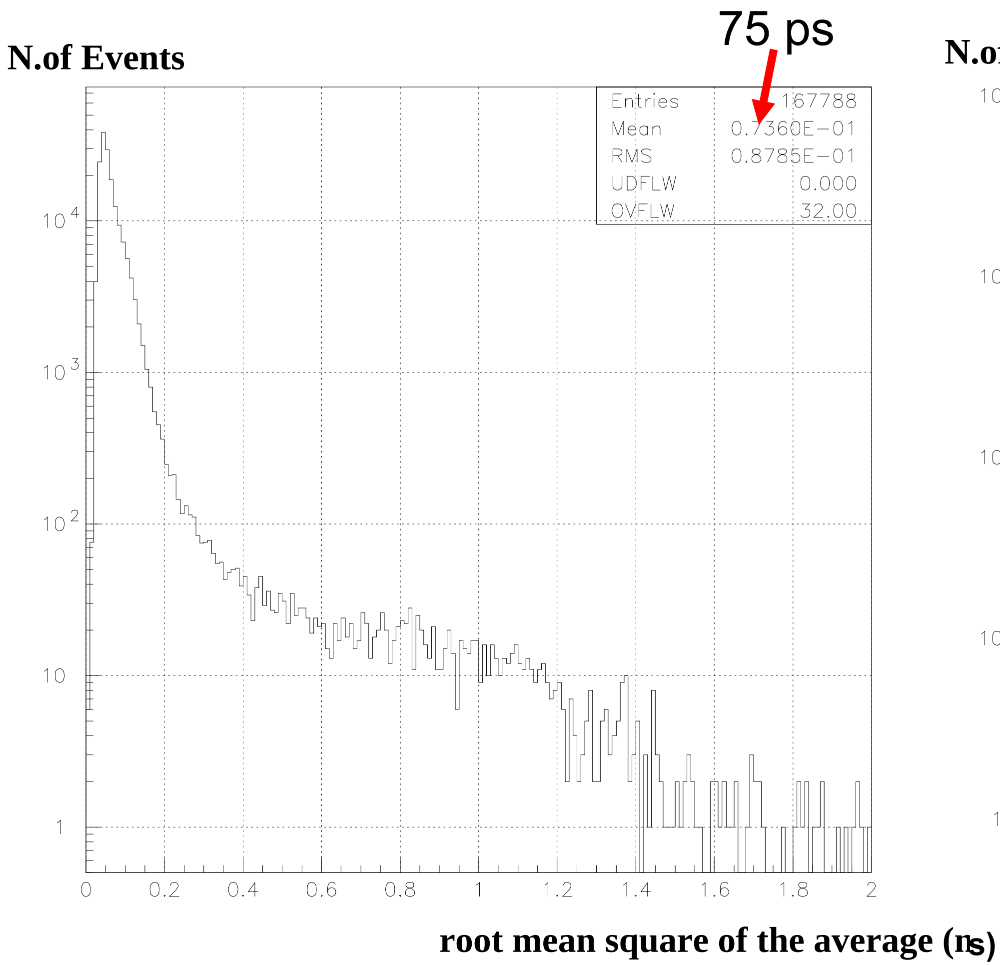
Particle indentification

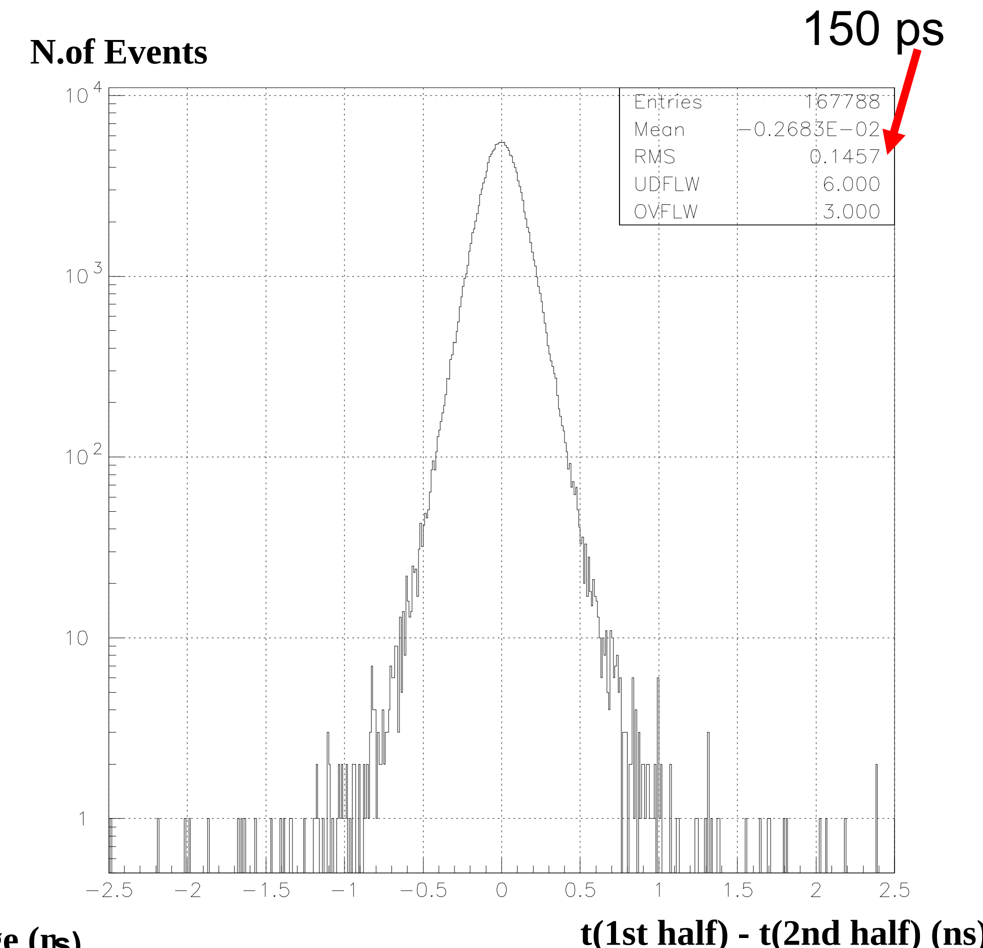
- 400 GeV/c p on T4 → 200 GeV/c negative beam ($\Delta p/p \approx 1.8\%$, 30 μrad)
- At production: 94.3% π, 4.9% K, 0.7%p
- After 910 m: 96.2% π, 3.0% K, 0.8% p

"π" event "$\bar{p}$" event

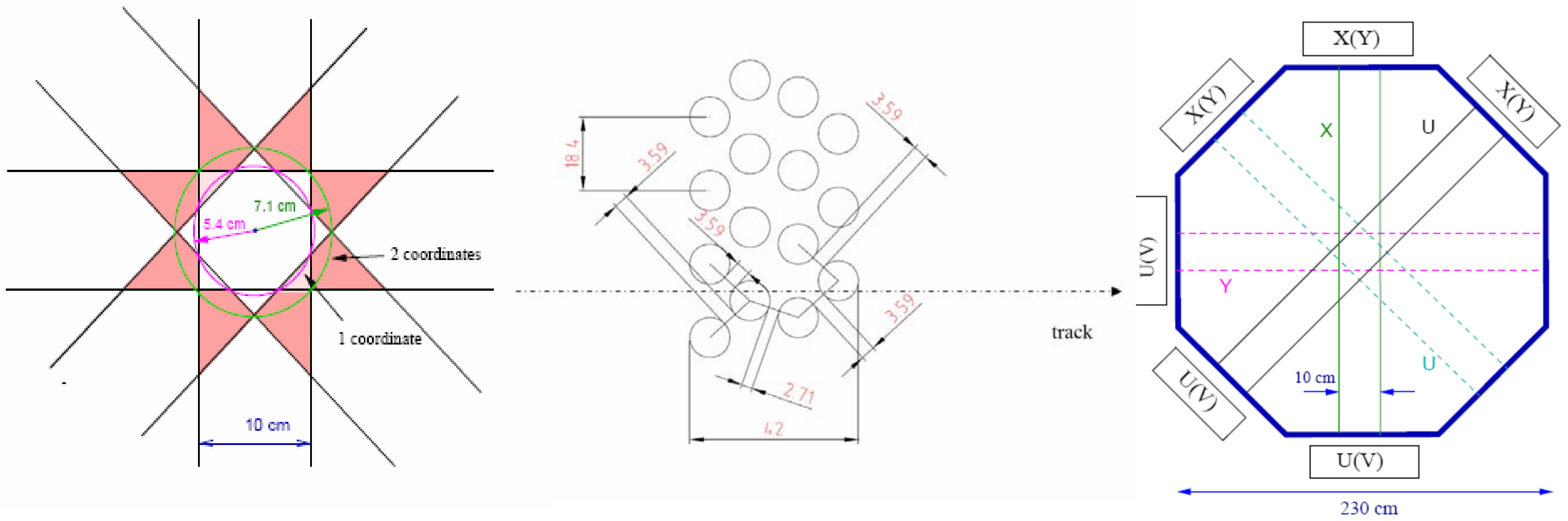


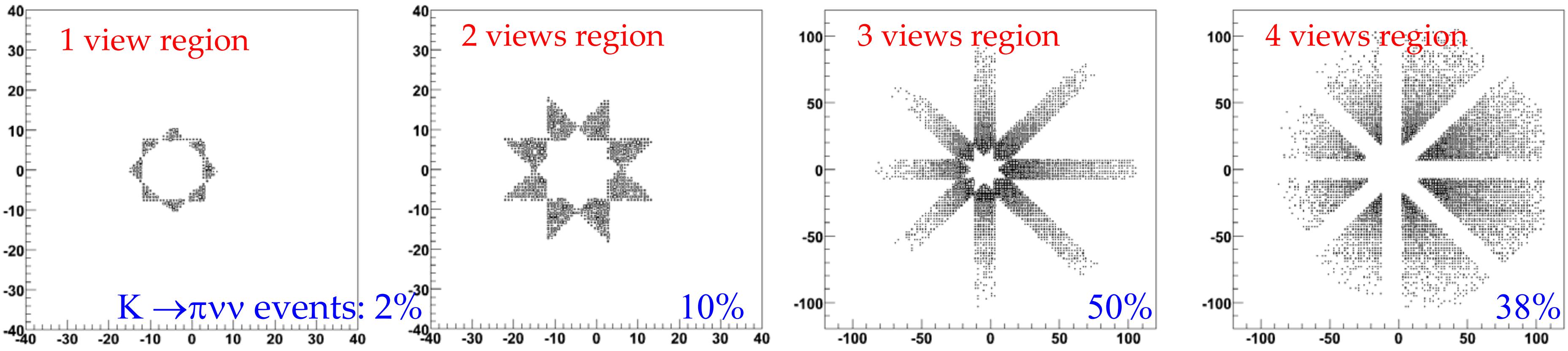
Time resolution per event: 75 ps



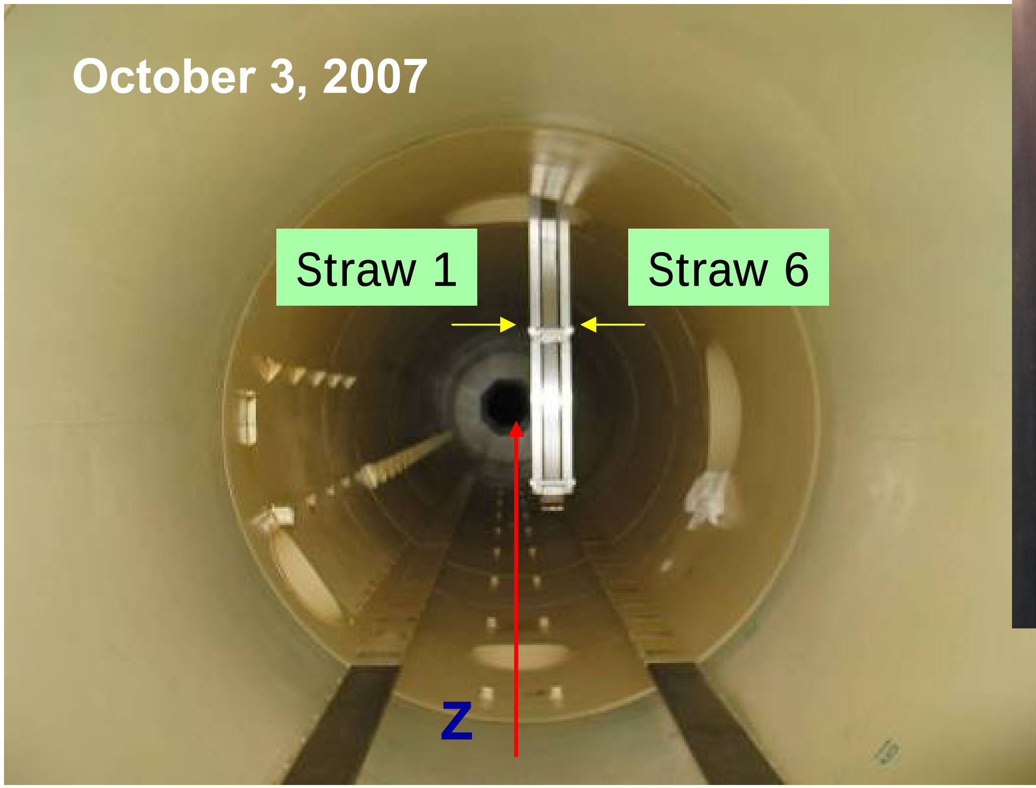


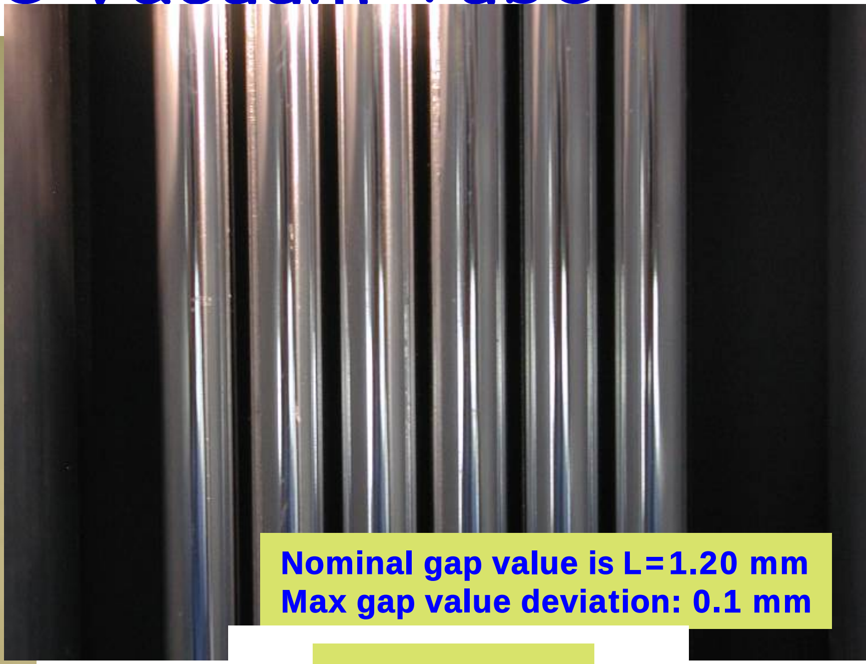
Straw Chamber layout





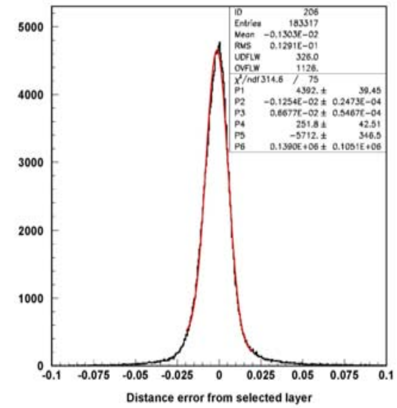
Straw Prototype inside the Vacuum Tube





Nominal gap value is L=1.20 mm
Max gap value deviation: 0.1 mm

Resolution



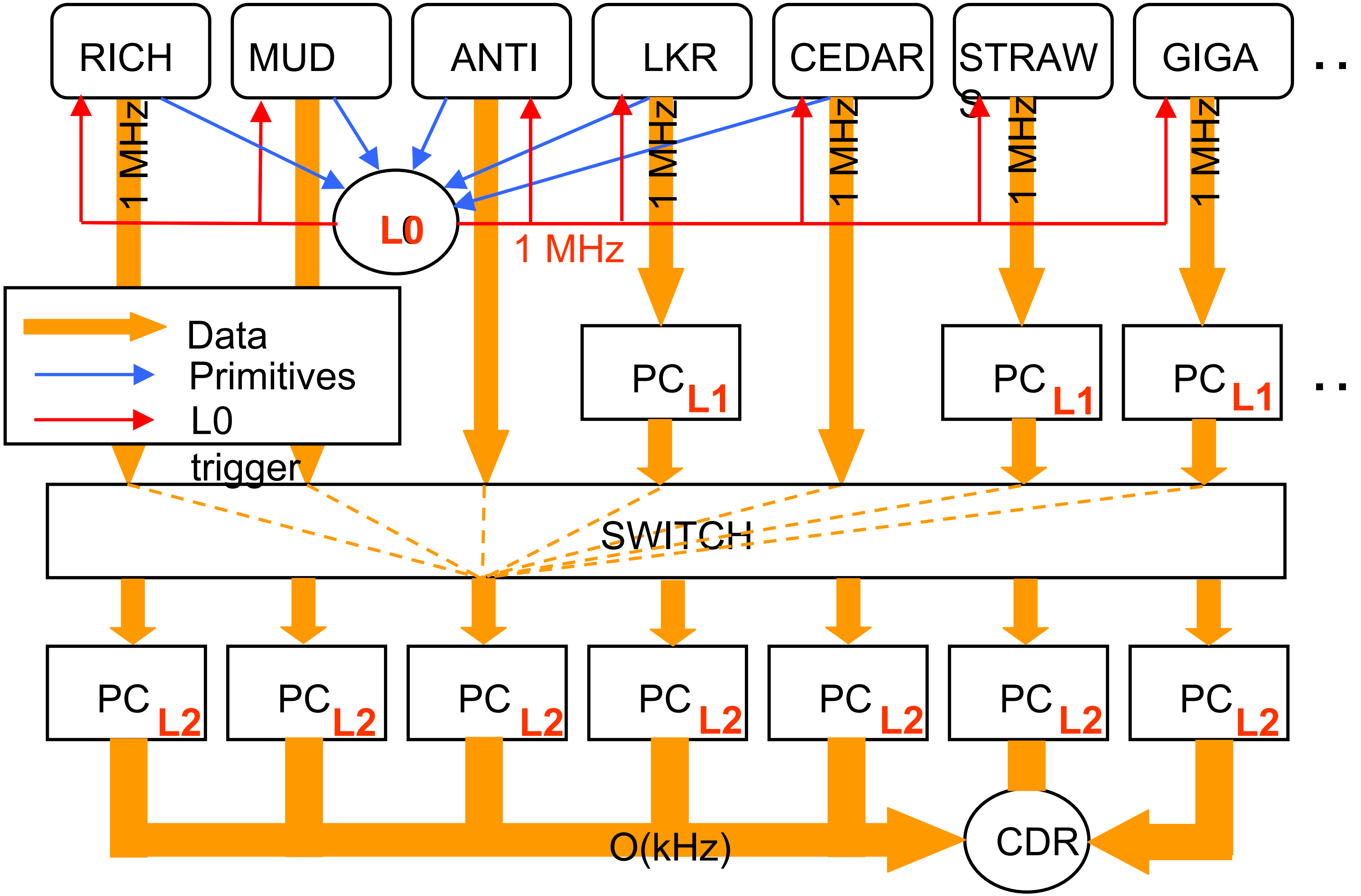
- Data were collected with hadron, muon and kaon decays
- The test in the actual vacuum tank enables one to address realistic issues

R.M.S.=130 μm
sigma=67 μm

Trigger/readout driving ideas

1. Integrated trigger/DAQ system (cost, reproducibility, control, flexibility)
2. Completely digital trigger (trigger data recorded into data stream)
3. As much software as possible
4. Commercial solutions (=PCs) as much as possible (cost, scalability, upgradability)
5. Simplicity
6. Use of existing solutions where available

Level 0 implementation



L0 (hardware) trigger

- Fast MC simulation: positive RICH + high-resolution online MU vetoing + high-resolution online “quadrant” LKr vetoing (+ ANTIs) can limit rate below 1 MHz. CEDAR as an option in L0.
- Each sub-detector involved in L0 produces digital high time resolution primitives (e.g. LKr quadrant energies…), calibrated and corrected, from the same FADC/TDC of main data, using FPGAs
- L0 time-stamped primitives are asynchronously collected and sent to a central L0 processor (hw or possibly PC), with fixed maximum latency
- The L0 central processor re-orders and performs digital time-coincidences producing the L0 trigger (1 MHz) with maximum latency 1 ms (to start read-out into PCs)