The $K^+\to\pi^+\nu\nu$ decay at the NA62 experiment

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On behalf of the *NA62 collaboration*:
Bern ITP, Birmingham, CERN, Dubna, Ferrara, Fairfax, Florence, Frascati,
IHEP, INR, Louvain, Mainz, Merced, Naples, Perugia, Pisa, Rome I,
Rome II, San Luis Potosi, SLAC, Sofia, Triumf, Turin

Outline

Physics Motivations

Experimental strategy

NA62 apparatus

Update of the R_K measurement

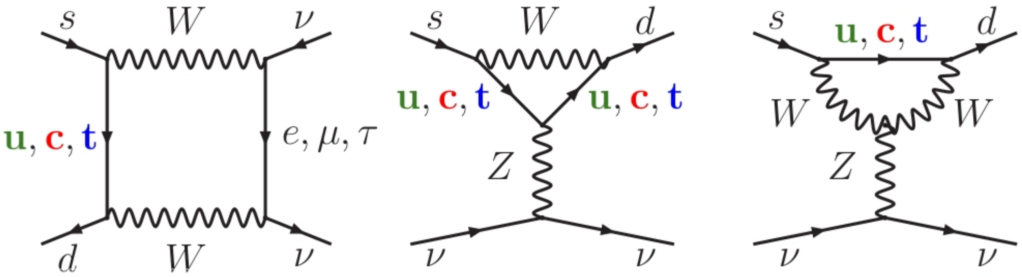
Conclusions

Physics Motivation (I):

$K^+ \to \pi^+ \nu\nu$ and $K_L \to \pi^0 \nu\nu$

the two "golden plates" decays in the SM

Flavour Changing Neutral Currents (FCNC) are forbidden at tree level in the SM (CKM Matrix unitarity)
Only one loop contributions possible:
Boxes and Penguins



Physics Motivation (II)

The very small BR (~ 10^{-10}) predicted with high precision in the SM:

1) Short distance contributions (Wilson coefficients i.e. perturbative QCD) are dominant (hard GIM mechanism): $A_q \sim (m_q)^2/(m_W)^2\, V_{qs}V_{qd}$

top quark is dominant, smaller contribution from charm negligible from up

2) The hadronic matrix element (LD) uncertainness benefits from the Isospin symmetry and well measured semileptonic $K^+ \to \pi^0 e^+ \nu_e$ decays:

$$\left|\frac{\langle \pi^+ \nu\bar{\nu} | H_w | K^+ \rangle}{\langle \pi^0 e^+ \nu_e | H_w | K^+ \rangle}\right|^2 = \left|\frac{\langle \pi^+ | H_w | K^+ \rangle}{\langle \pi^0 | H_w | K^+ \rangle}\right|^2 = 2r_+$$

$$BR(K^+ \to \pi^+ \bar{\nu}\nu) = 6 r_{K^+} BR(K^+ \to \pi^0 e^+ \nu) \frac{|G_l|^2}{G_F^2 |V_{us}|^2}$$

$$G_l = \frac{\alpha\, G_F}{2\pi \sin^2 \Theta_W} \left[V_{ts}^* V_{td} X(x_t) + V_{cs}^* V_{cd} X_{NL}^l \right]$$

Effective coupling constant

Theoretical estimations

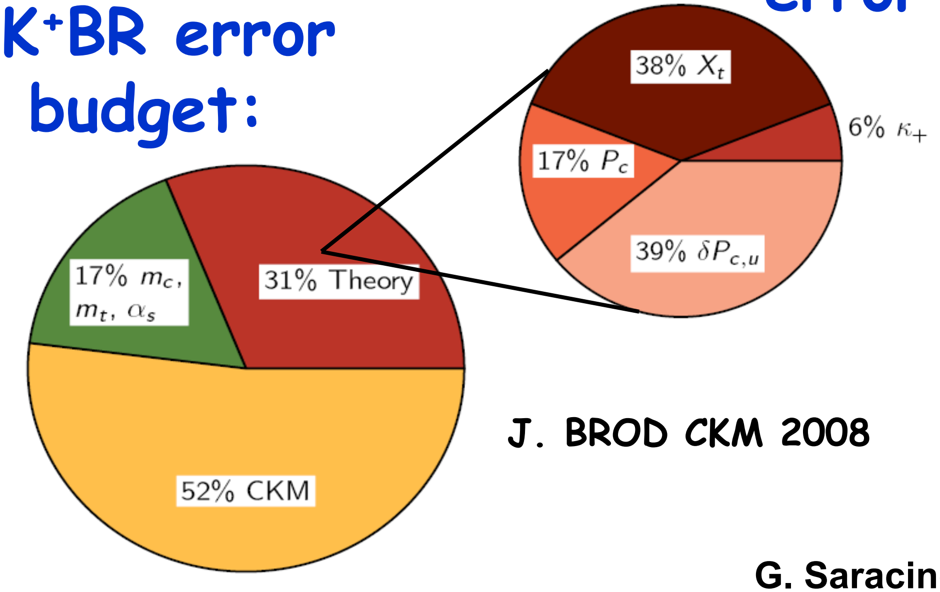
$BR(K^+ \rightarrow \pi^+ \nu\nu) = (8.5 \pm 0.7) \times 10^{-11}$ **8% error**

$BR(K_L \rightarrow \pi^0 \nu\nu) = (2.8 \pm 0.4) \times 10^{-11}$ 14% error

$m_c(m_c) = 1286 \pm 13$ MeV

K+ theory error budget:

K+BR error budget:



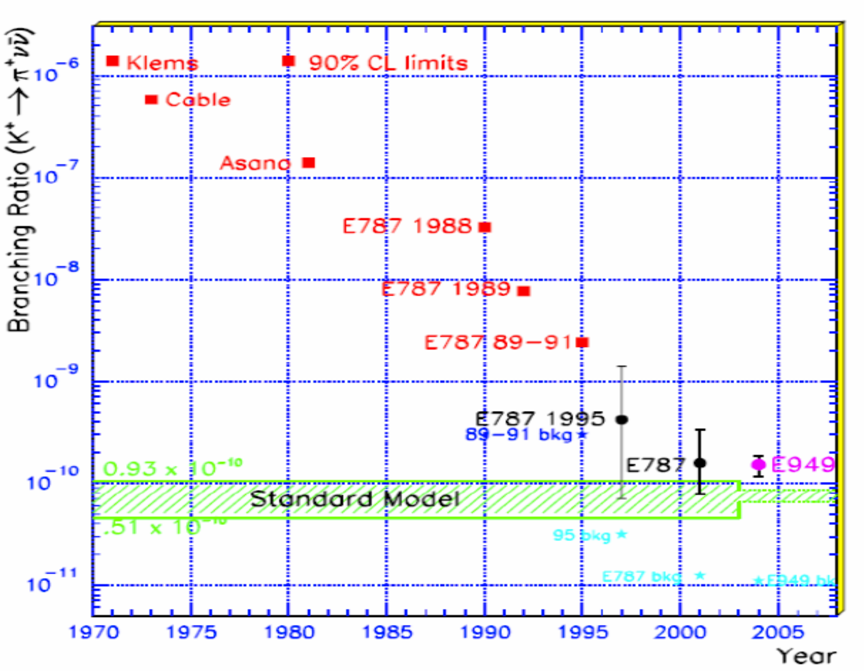
J. BROD CKM 2008

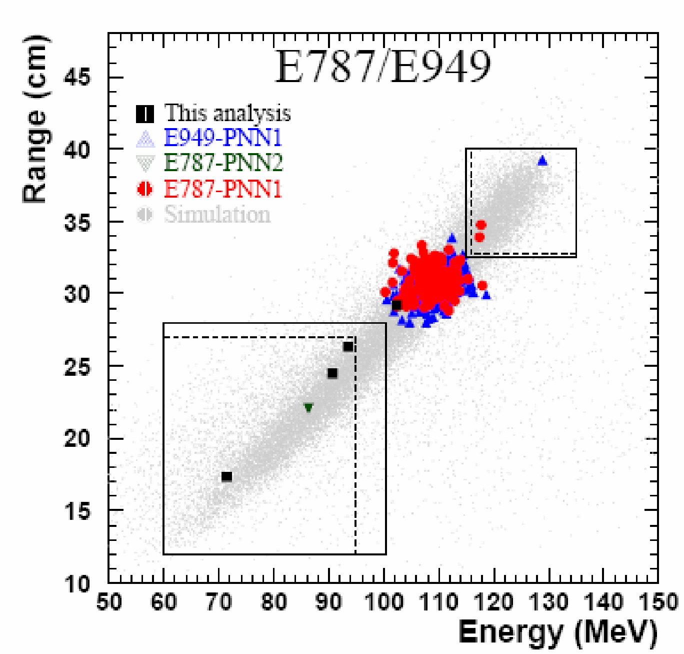
dominated by CKM elements
theory error can still be reduced

And experimental status

$BR(K^+ \to \pi^+ \nu\nu)_{exp} = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$

based on 7 candidates at BNL E787+E949





Probability that all 7 events are due to background: 10^{-3}

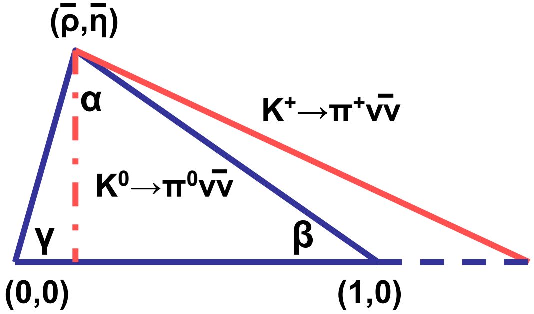
first experimental observation of $K^+ \to \pi^+ \nu\nu$

they have shown that all physics background can be under control at 10^{-11} level !

Relevance of a precise measurement

1) Extract the V_{td} matrix element with a ~10 % error

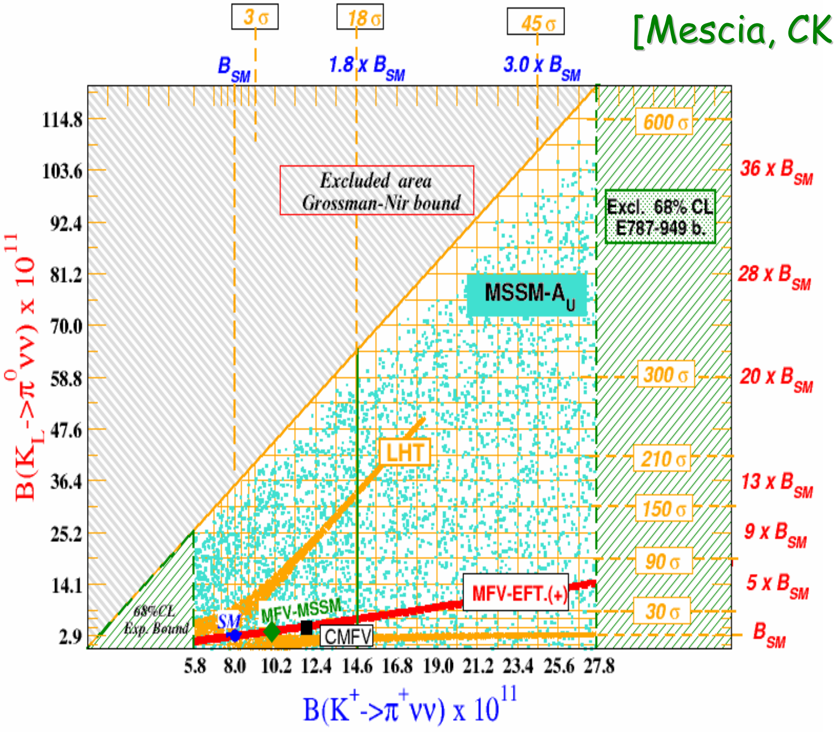
2) Accurate determination of unitarity triangle independent of that executed within the B system



If LHC discovers new particles the BR measurement will provide a very helpful tool to discriminate among different models

A precise test of SM -> sensitive to new physics

New physics effects could be seen without significant signals in $B_{d,s}$ decays and, in specific scenarios, even without new particles within the LHC reach



[Mescia, CKM06]

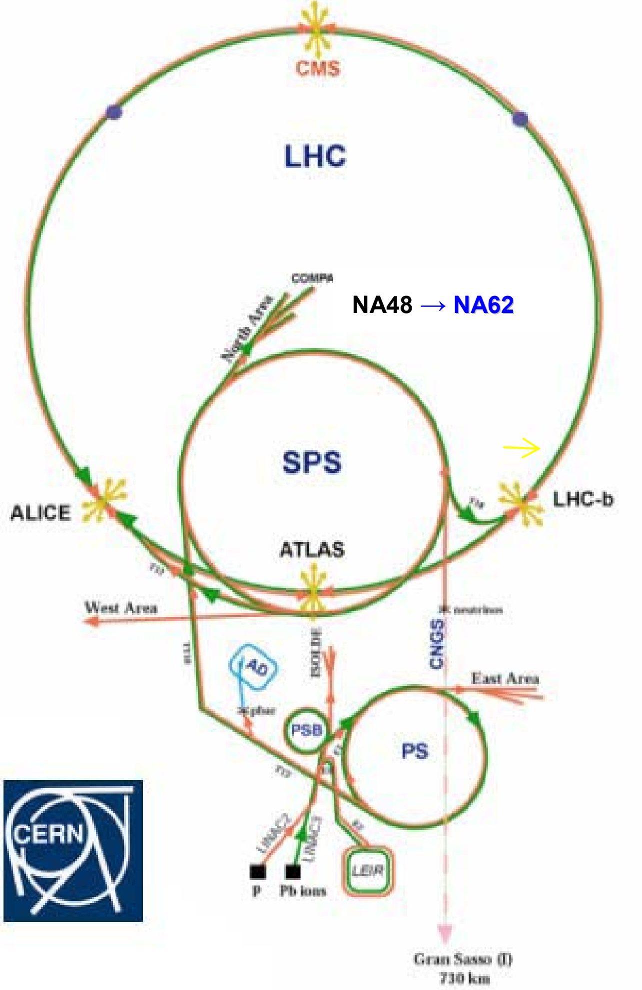
NA62 experiment

Our goal:
- collect **~100 $K^+ \rightarrow \pi^+ \nu\nu$** decays
- **~10%** background

with a BR **8.5×10^{-11}** and a **10%** acceptance we need:

~10^{13} K^+ decays

available in 2 years of data taking using the same SPS p line of the NA48/2 experiment (not limited by proton flux)



In 2007-2008 the NA62 coll. performed two runs using part of the previous NA48 exp. to measure the R_K ratio → see last part of this talk

Measurement principles

$K^+ \rightarrow \pi^+ \nu\nu$ aka $K^+ \rightarrow \pi^+$ + nothing ...

The main problem is to reject all the possible background decays at 10^{12} level (living some signal still alive...)

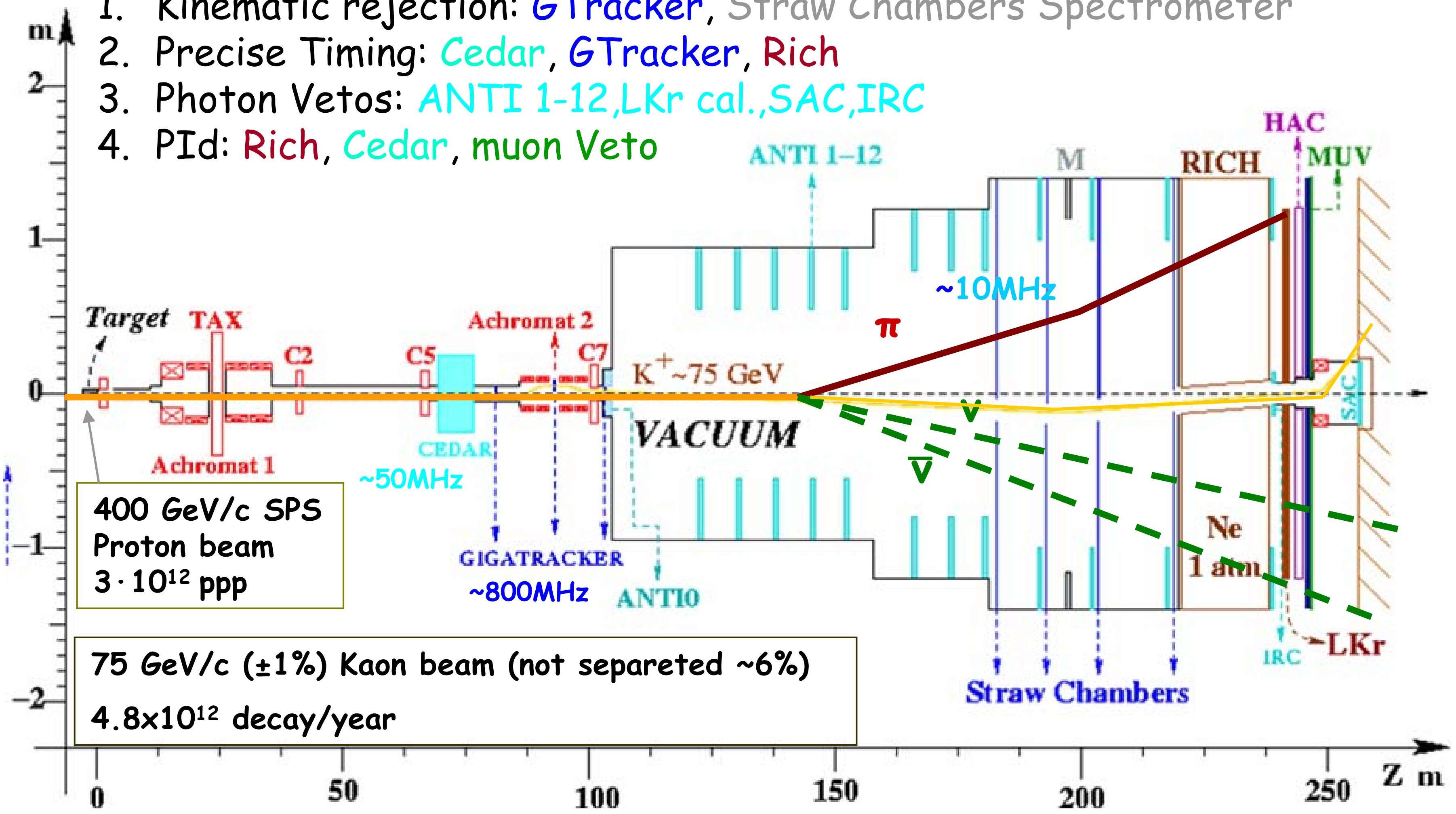
Strategy:

- in flight decay technique, high momentum kaons
  → no beam background w.r.to stopping kaon experiments
  → improvement in the π^0 induced background
- kinematical reconstruction → two and tree body bk supp
- precise timing → to match the π^+ with the right K^+
- almost hermetic photon vetos → π^0 rejection
- particle id. → K/π (primary beam) and π^+/μ^+ (final decay)

Only combining together this techniques with high efficiency we can achieve the rejection factor needed

Detector layout

1. Kinematic rejection: GTracker, Straw Chambers Spectrometer
2. Precise Timing: Cedar, GTracker, Rich
3. Photon Vetos: ANTI 1-12,LKr cal.,SAC,IRC
4. PId: Rich, Cedar, muon Veto

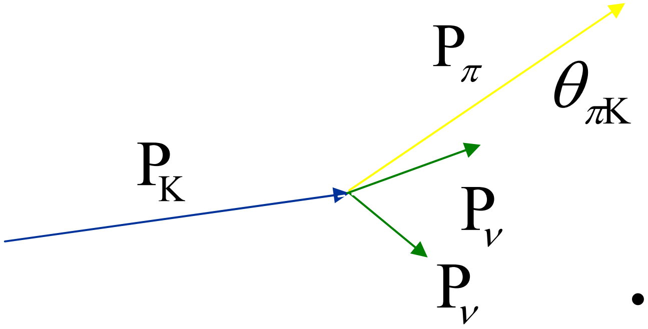


400 GeV/c SPS
Proton beam
$3 \cdot 10^{12}$ ppp

75 GeV/c (±1%) Kaon beam (not separeted ~6%)

4.8x10^{12} decay/year

Kinematic reconstruction



$$m^2_{miss} \cong m^2_K\left(1-\frac{|P_\pi|}{|P_K|}\right)+m^2_\pi\left(1-\frac{|P_K|}{|P_\pi|}\right)-|P_K||P_\pi|\theta^2_{\pi K}$$

Requirements:

- low mult. scattering

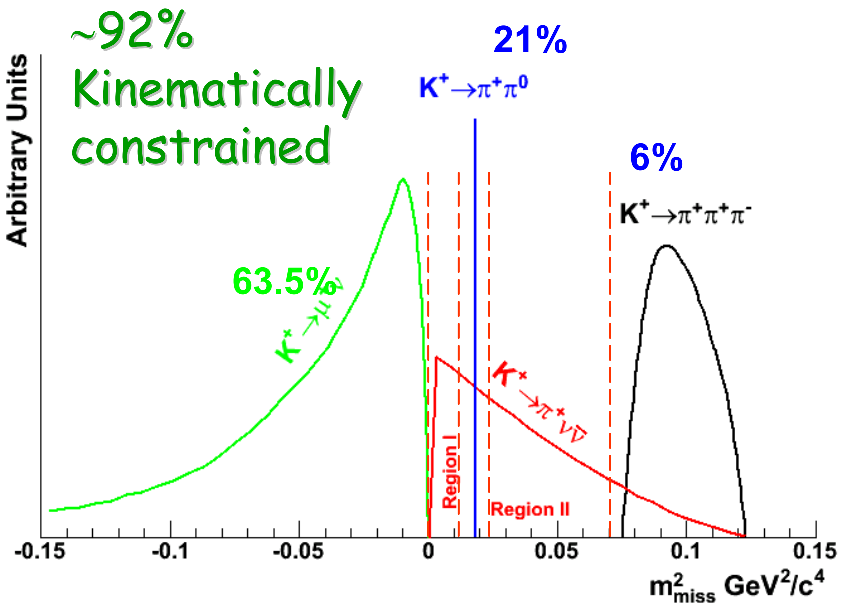
→ low mass tracker operating in vacuum

- good space resolution (~100 μm)

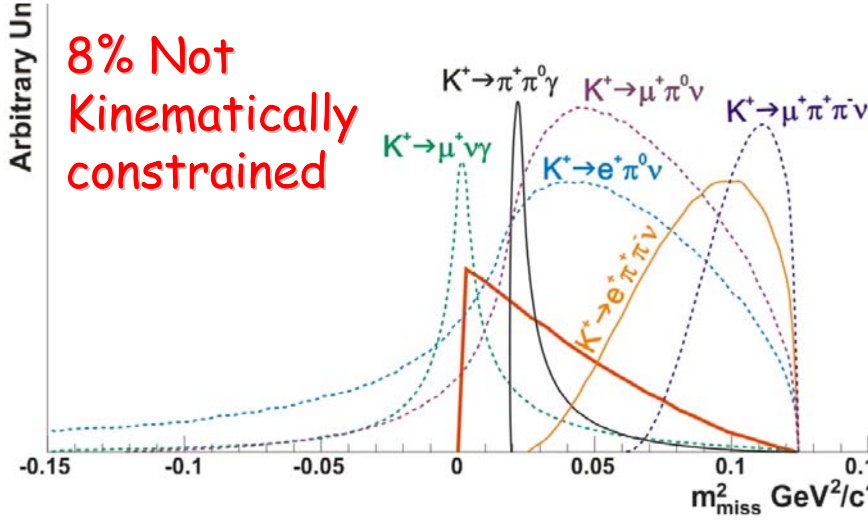
Detectors:

- GigaTracker
- Straw Chamber Spectrometer

two bk free regions



~92% Kinematically constrained



8% Not Kinematically constrained

Gigatracker (I)

Three tracking stations to provide a precise measurement of K^+ beam (momentum, direction and time)

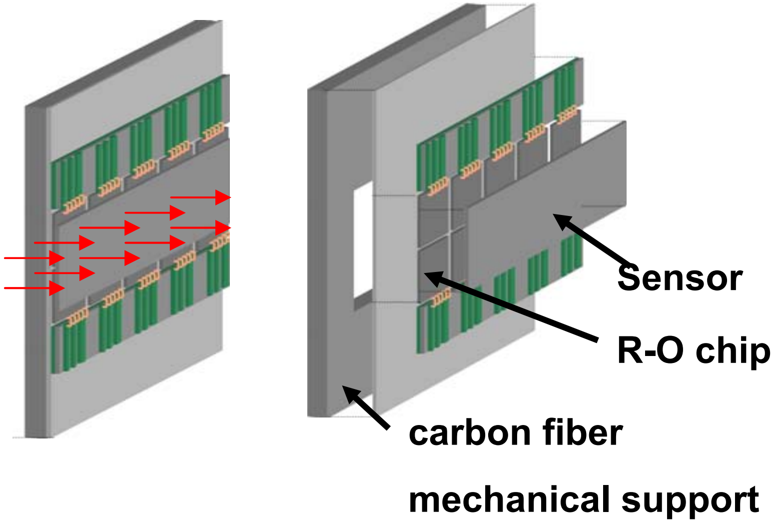
main features

- low mass (multiple scattering),
- operating in vacuum (power dissipation...)
- severe environment: 1.5MHz/mm^2, 800 MHz total rate

Solution: silicon pixel stations

- 60x27 mm^2 area (beam profile)
- 300x300 μm^2 pixel size
- 200 μm thick sensor (15000 e^- for a MIP)
- 10 R-O chips 100 μm thick cmos
- 130 MHz rate/chip (max)
- 140 nm technology
- 0.5 % X_0 /station material budget
- 200 ps /station time resolution
- ~14 μrad track resolution
- ~0.15 GeV/c momentum resolution
- Total dose in 1 year: ~10^5 Gy

exploded view



Gigatracker (II)

High rates means:

- Colling problems:

  GENERATED POWER: 32,4 W

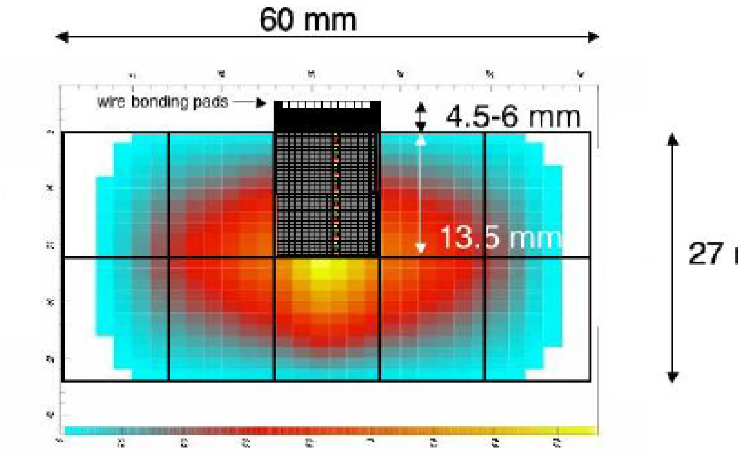
  HEAT FLUX: 2 W/cm^2

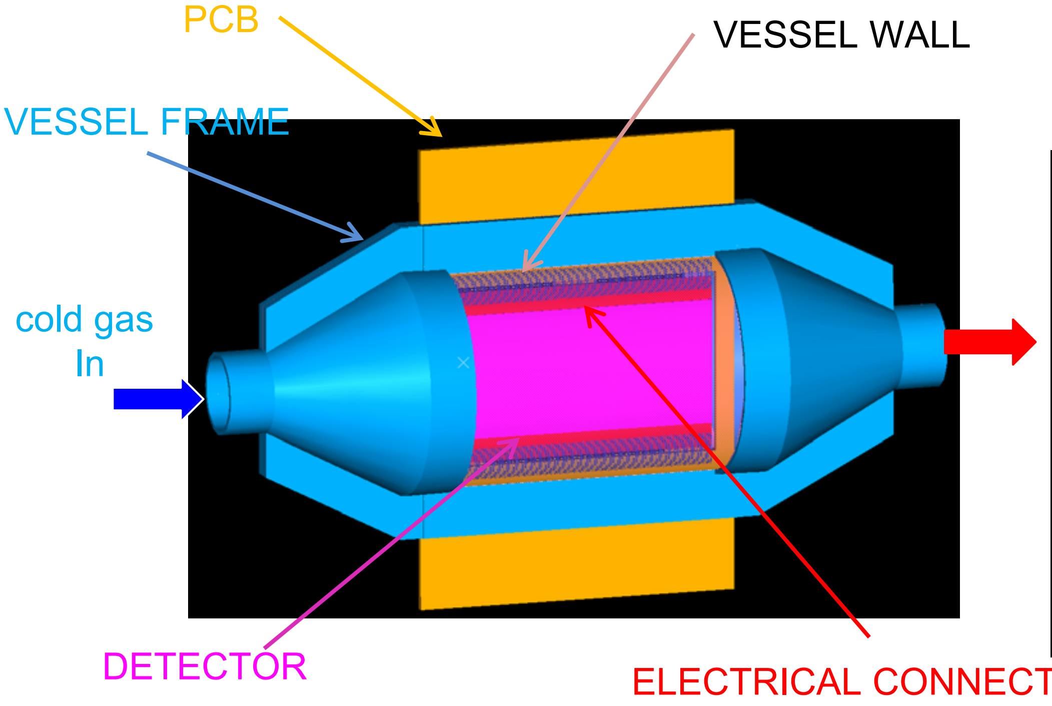
  → cooling gas flux

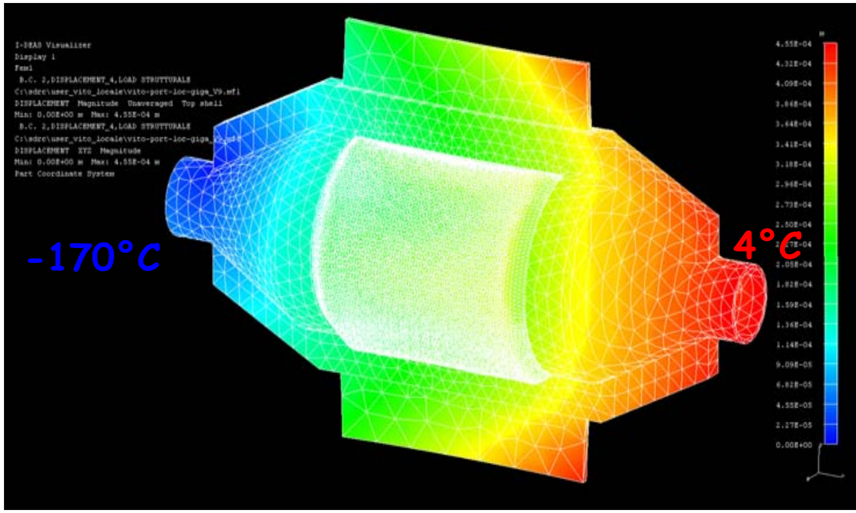
- Radiation hardness: 2×10^{14} 1MeV neutron cm^{-2}/yr

(equivalent to 10 years exposure of silicon strip tracker at LHC)

→ change 1 station/year







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Part Coordinate System
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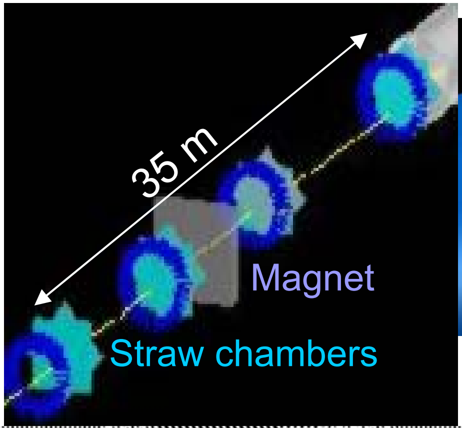
Straw chamber spectrometer (I)

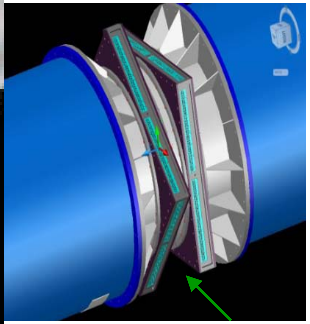
to measure momentum and direction of K^+ decay

Requirements:
- low mass (multiple scattering),
- operating in vacuum
- good spatial and momentum resolution
- small inactive area around primary beam

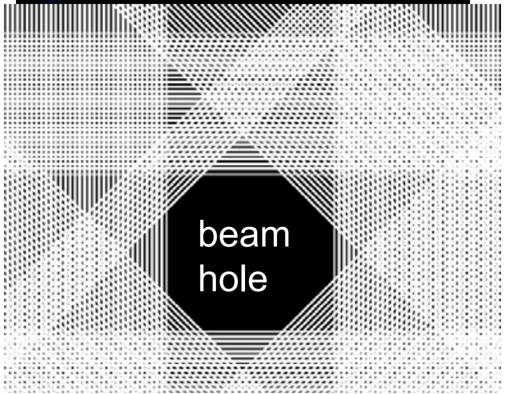
Solution:

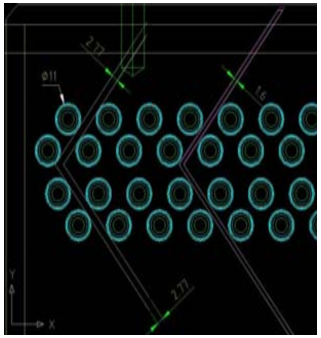
four straw chambers and one magnet 256 MeV/c P_t
- 4 view/chamber XYUV
- 4 staggered layer/view (L/R ambiguity)
- 500 straws/view, 8000 grand total
- 9.6 mm radius mylar tube
- 2.1 m long
- X/X_0 ~0.1% per view

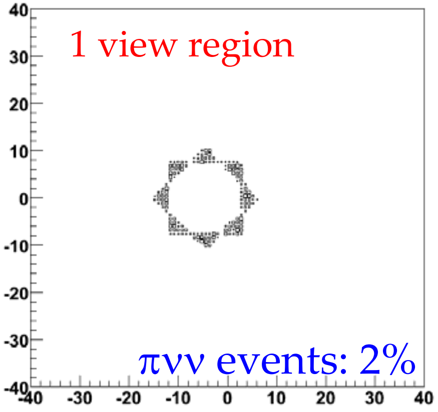


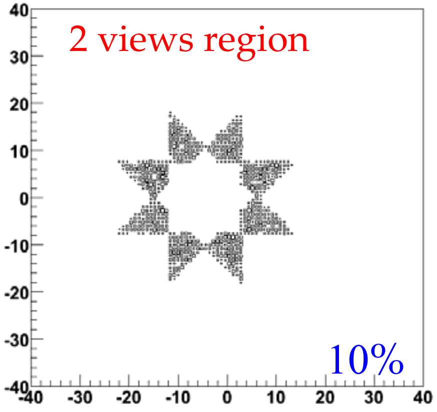


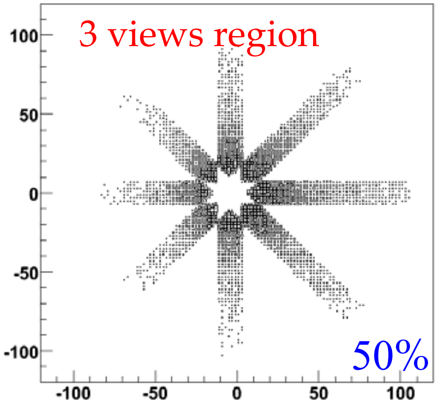
Two "cartesian" frames tilted of 45°

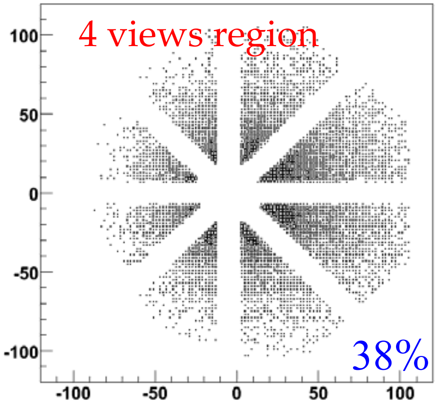






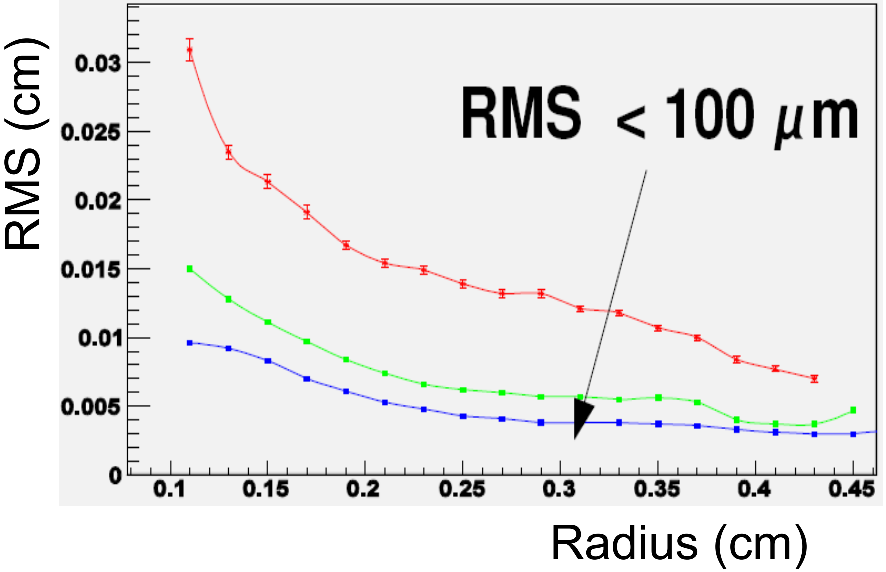


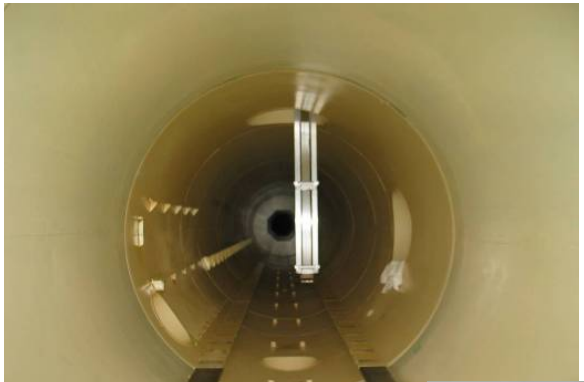




Straw chamber spectrometer (II)

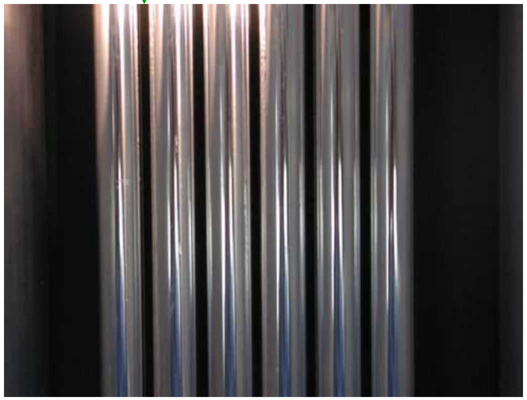
Prototype test beam in vacuum
muon tracks reconstruction

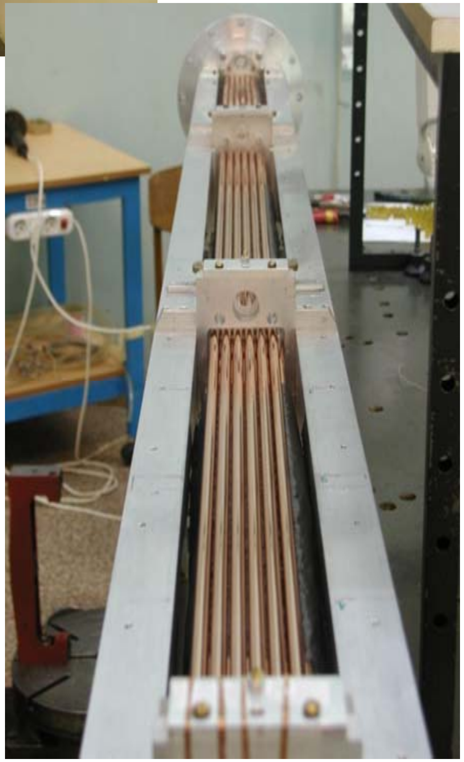




Gas Mixture:
CO_2:Iso$C_4H_{10}CF_4$ 80:10:10
HV: 2500 V

Small gap for diameter expansion under vacuum





ultrasonic welded mylar
- no glue no out gassing
- better load and resistance

Impact of the kinematic reconstruction

The rejection factors estimated by a Geant4 Simulation

Table of resolutions

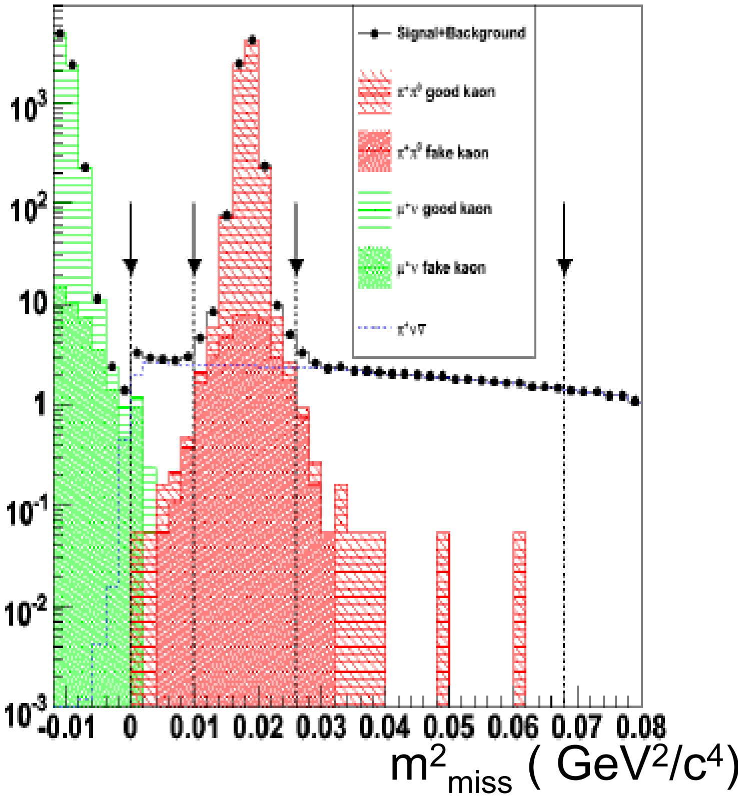
particle	**P**	**direction**
K^+	**0.2%**	**17 μrad**
π^+/μ^+	**0.3%**	**15-45 μrad**

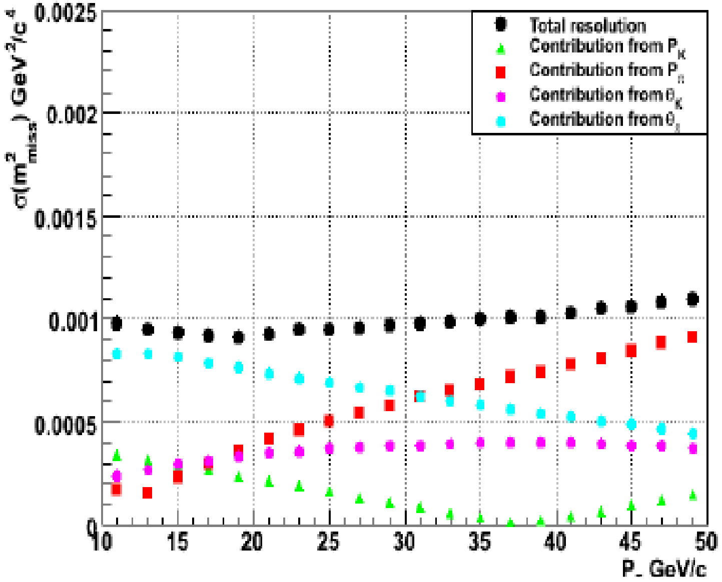
Table of rejection factors for two body decays

decay	**R.F.**
$K^+ \to \pi^+\pi^0$	**10^4**
$K^+ \to \mu^+\nu$	**10^5**

Main sources of inefficiencies:

- non Gaussian tails in the multiple scattering
- K^+/π^+ mismatch in the primary beam





Particle Identification and photon VETO

Rejection factor needed: 10^{12}

Table of rejection factors for two body decays

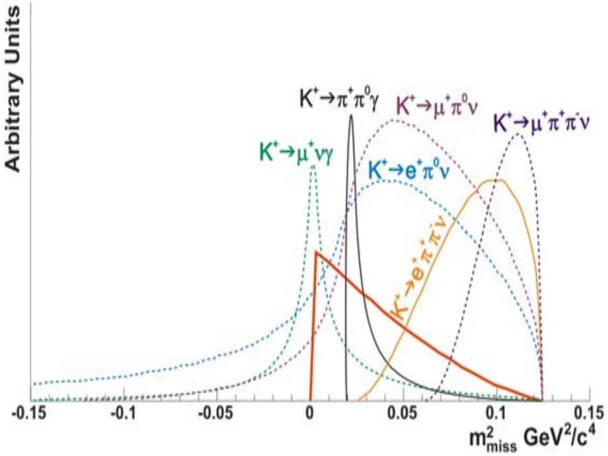
decay	R.F.
$K^+ \to \pi^+\pi^0$	10^4
$K^+ \to \mu^+\nu$	10^5

high efficiency detectors:

Photon veto: for $K^+ \to \pi^+\pi^0$ supp.

RICH and MUON VETO
for muon suppression

Not constrained decays (8%)



other possible source of background:
- **beam related**
- **beam interaction with the last GT station or with the residual gas**

The Ring Image Cherencov detector (I)

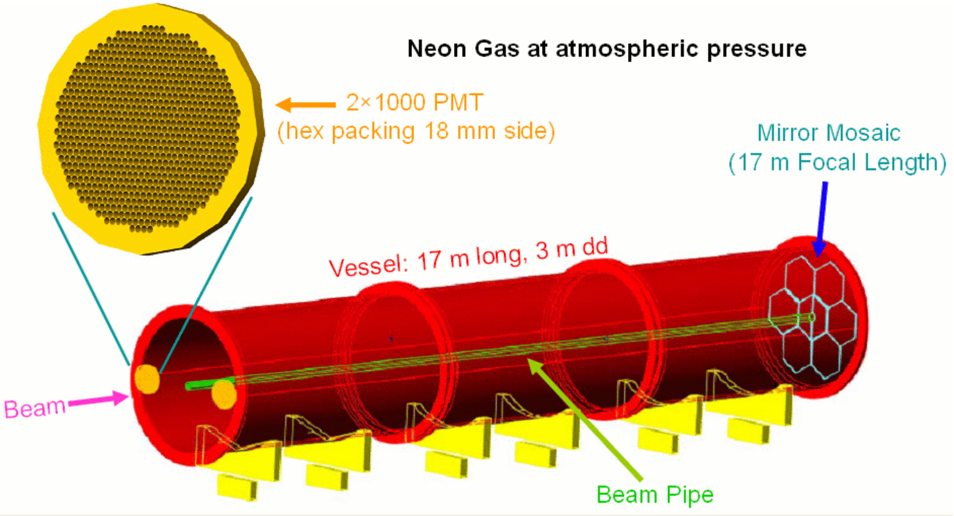
Requirements:

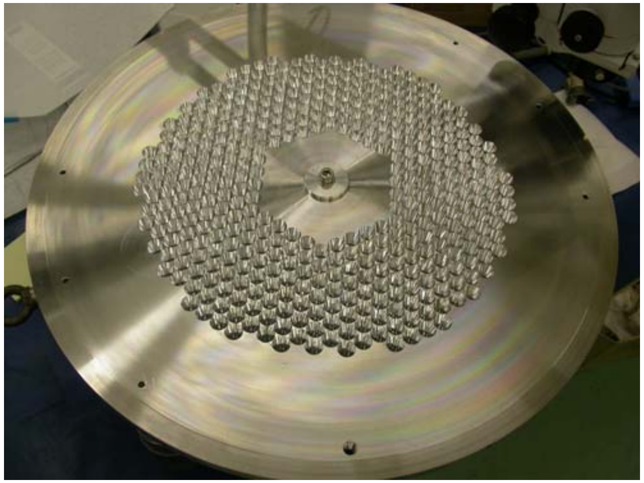
- π/μ separation at 5×10^{-3} in the range $15<p<35$ GeV/c
- track time with 100 ps res
- main trigger for charged particle

RICH

18 m long tube filled with Neon (1atm)

- 3 m diameter
- Mirrors with f=17 m
- 2000 single anode PMTs, 1 cm in diameter
- 18mm “pixel” with Winston cones





The Ring Image Cherencov detector (II)

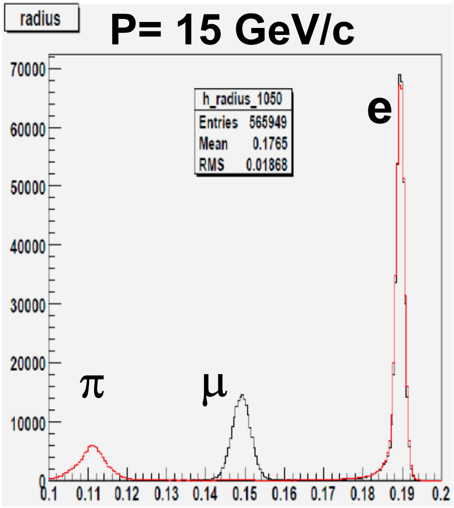
first prototype test beam results:

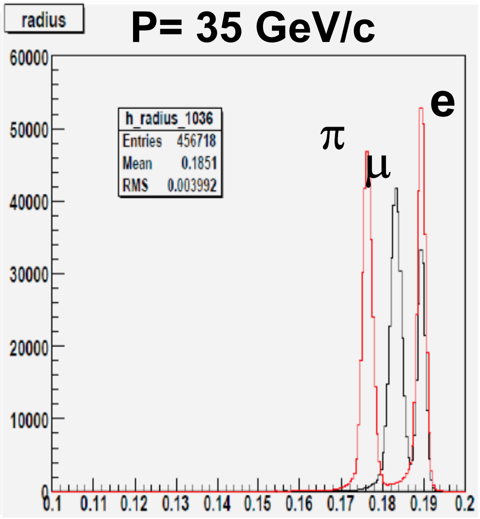
- N_{hits}/event ~ 17
- Δt_{event} ~ 70 ns
- $\Delta\Theta$ ~ 50 μrad (biased by PM geometry)

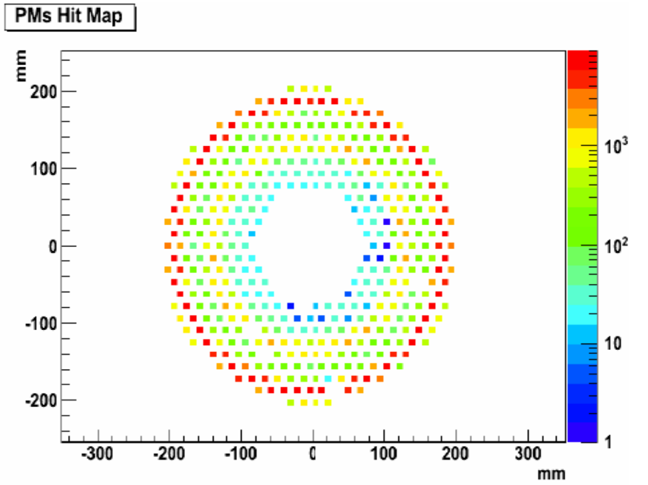
NIM A 593, 2008

A full length prototype (0.5 m diameter) was tested in may

π,μ and ***e*** separation results (preliminary)







The Photon Veto System

To obtain the required rejection factor on **$K^+ \rightarrow \pi^+ \pi^0$** a photon detectors system with **10^8 rejection factor on $\pi^0 \rightarrow \gamma\gamma$ is required**

Three different angular regions to be covered

- LAV: Large Angle Veto: (10:50 mrad)
- LKr: Liquid Kripton calorimeter (1:10 mrad)
- IRC and SAC <1mrad

requiring P(π^+) < 35 GeV we get P(π^0)> 40GeV and high energy photons: photons > 1 GeV hit the LKr → high detection efficiency

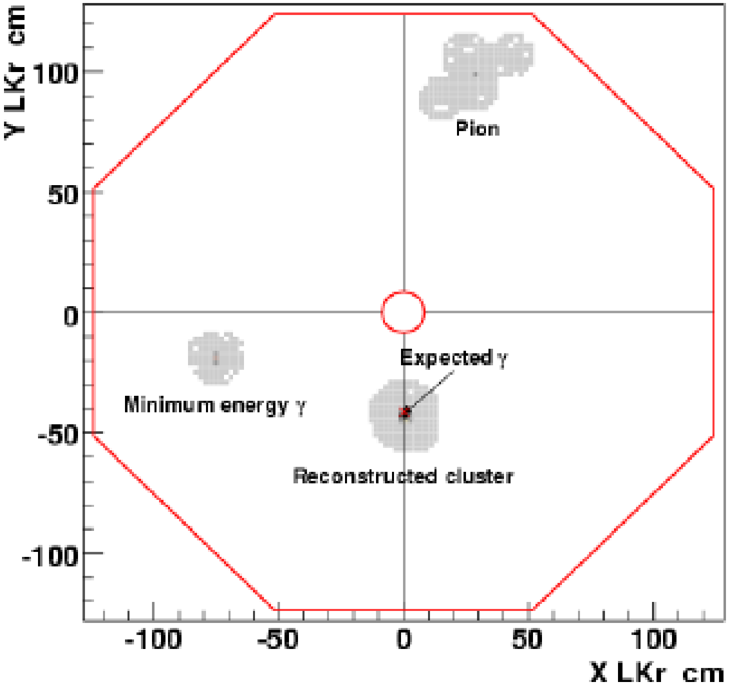
The Liquid Kripton Calorimeter

The NA48 calorimeter with new front-end readout, cryogenic system and electronic for fast triggering

photon efficiency measured with data: two runs:

- 2006 electron runs: **$E_\gamma > 2$ GeV** (bremstralung)
- 2004 NA48 run with **$K^+ \to \pi^+\pi^0$**: $E_\gamma > 10$ GeV)

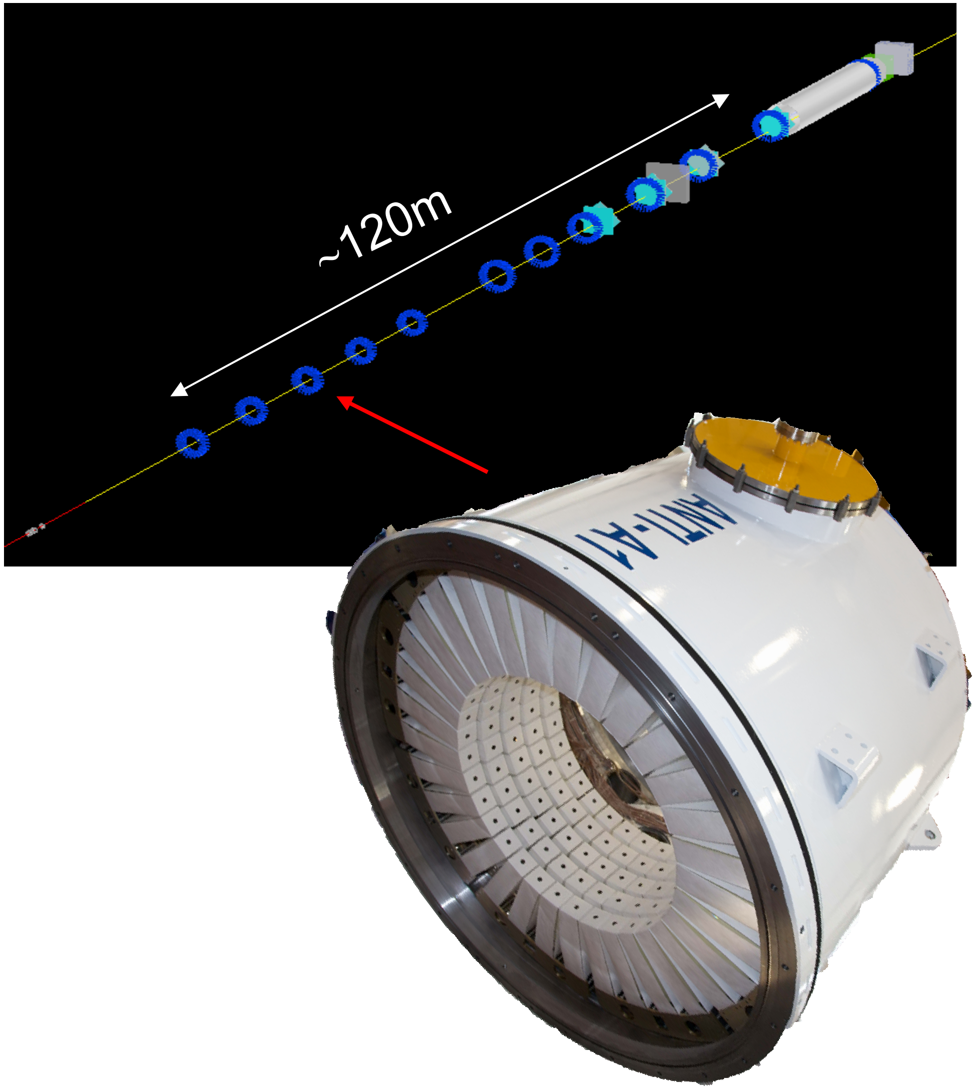
E (GeV)	Inefficiency
2.5 – 5.5	$< 10^{-3}$
5.5 – 7.5	$< 10^{-4}$
7.5 – 10	$< 5 \times 10^{-5}$
> 10	$< 8 \times 10^{-6}$

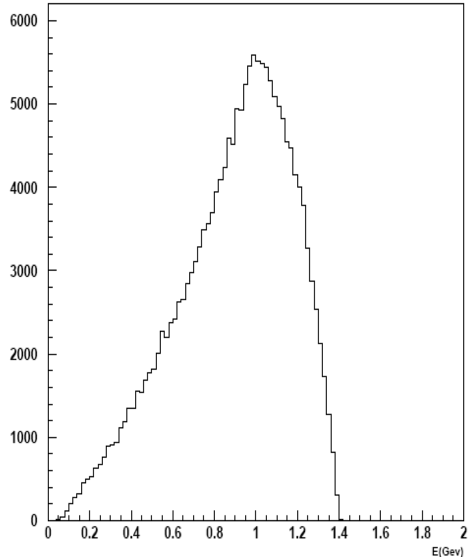


Large Angle Veto (I)

12 rings to cover the large angle photons:
requirements:

- Inner-outer radii: 60-96 to 90-140 cm
- Almost hermetic
- Large area: ~30 m^2
- Good efficiency down to “low” energy (200 MeV) photons
- Operating in vacuum

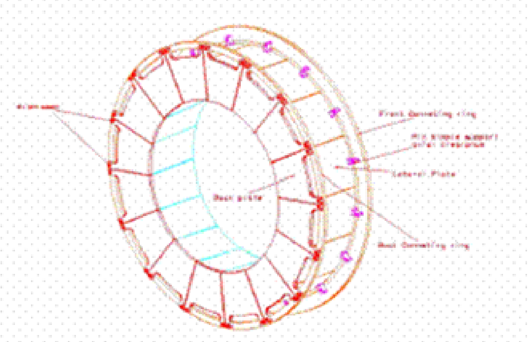


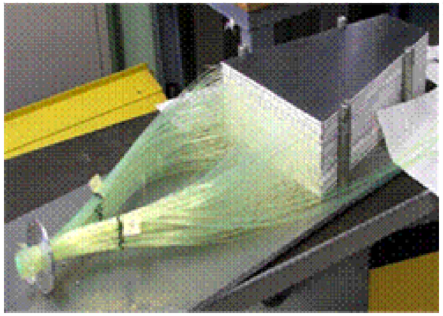


Large Angle Veto (II)

R&D three different technologies studied:

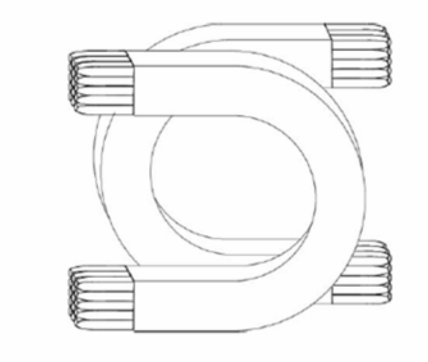
Tile calorimeter:
lead-plastic
scintillator foils
with WLS fibres

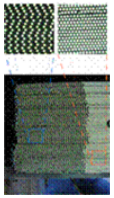




one sector prototype
borrowed by CKM
prop. exp. at FNAL

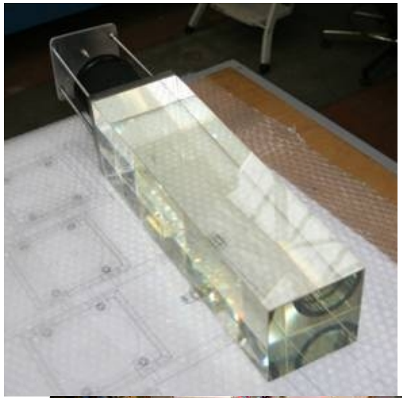
Scintillating fibres
embedded in lead
foils (EMC KLOE)





one U prototype
build at LNF

Lead-glass blocks
from the LEP OPAL
EMC



some blocks from
OPAL store at CERN

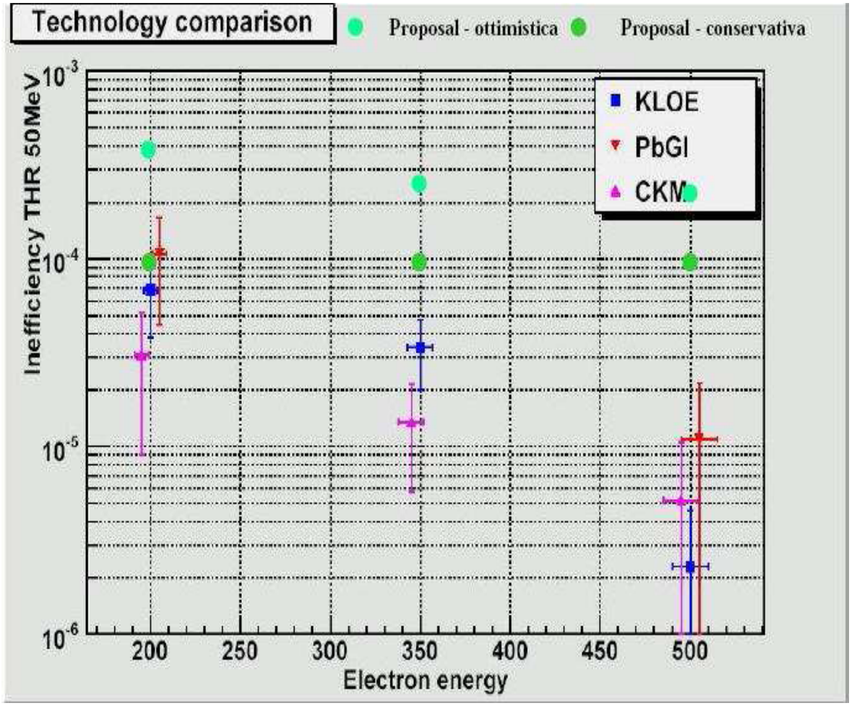
Large Angle Veto (III)

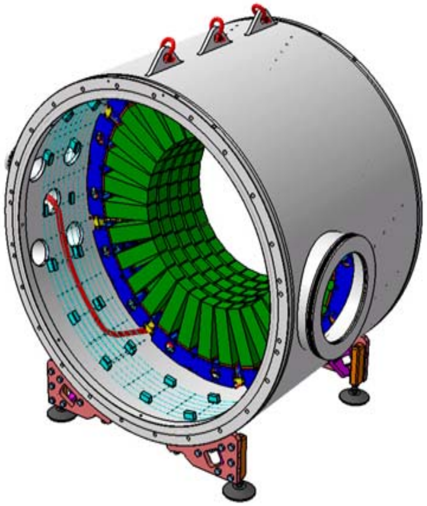
The three prototype tested at the BTF a LNF in Frascati:
50 Hz single e^+/e^- 200-500 MeV

all detectors fulfilled the requested efficiencies

OPAL LG choice for economic reasons

mechanic to hold the blocks was designed

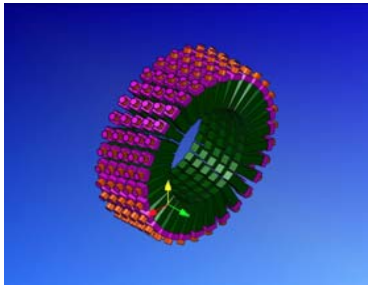


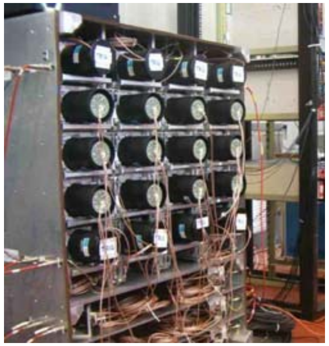


Large Angle Veto (IV)

3606 blocks available (thanks to Tokyo-OPAL coll.)
2946 needed for the 12 stations
each station has 5 layer with a relative phase

All the blocks have to be polished, tested, re-cabled, reinforced and wrapped again Gain and PeY are measured by LED and Cosmic





A first station assembled at LNF (160 bloks) and arrived to CERN for the installation in the vacuum tube (22/709)

Large Angle Veto (pictures)

~10 tons

Trigger and DAQ

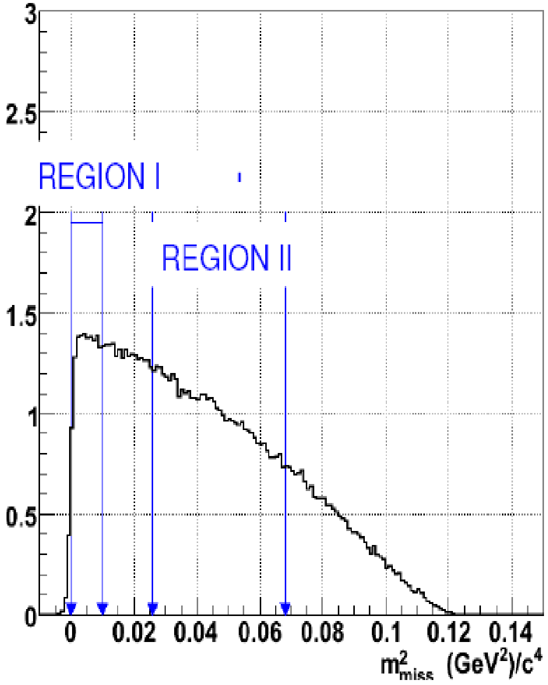
- Quasi-triggerless paradigma: L0 hardware and L1 software
- High trigger efficency (>95%)
- Acquisition losses $< 10^{-8}$
- Fully monitored system: inefficiency, dead time and Xoff recording
- Low random veto probability: very high online time and double pulse resolution
- Integrated Trigger and DAQ fully digital system
- Readout without zero suppression for candidates
- Scalability in terms of bandwidth
- As uniform as possible for most detectors
- Exploit as much as possible existing and commercial solutions developed for existing or new experiments

detector	Rate (MHz)
CEDAR	50
GTK	800
LAV (total)	9.5
STRAW (each)	8
RICH	8.6
LKR	10.5
MUV	9.2
SAC	1.5

- L0 input rate: ~10MHz
- Conditions on LKr, MUV and RICH multiplicity can reduce the rate ~ 1 MHz

NA62 Sensitivity: acceptance and background

Realistic simulation has shown a ~14.4% final acceptance



3.5 % in region I 10.9 % in region II
50% loss are due to 15 <P(π^+) < 35 GeV/c cut
(photon and muon efficiency and RICH functionality)

the 10% acceptance goal seems not impossible

Decay Mode	
Signal	**55** *evt/year*
$K^+ \to \pi^+\pi^0$	**4.3% (7.5%)**
$K^+ \to \mu^+\nu$	**2.2%**
$K^+ \to e^+\pi^+\pi^-\nu$	**≤3%**
Other 3 – track decays	**≤1.5%**
$K^+ \to \pi^+\pi^0\gamma$	**~2%**
$K^+ \to \mu^+\nu\gamma$	**~0.7%**
$K^+ \to e^+(\mu^+)\ \pi^0\nu$, others	negligible
Expected background	**≤13.5% (≤17%)**

Background seem around
the request

NA62: R_K short update (I)

R_K: a sensitive probe of New Physics

One way to look for LFV (forbitten in SM) is in ratio R_K, where the non perturbative form factors f_K cancels out allowing a very precise (SM) theoretical estimation (*)

$$R_K = \frac{\Gamma\left(K^\pm \to e^\pm \nu_e\right)}{\Gamma\left(K^\pm \to \mu^\pm \nu_\mu\right)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \left(1 + \delta R_{QED}\right) = \left(2.477 \pm 0.001\right) \cdot 10^{-5}$$

δR_{QED} = -3.8%

$\delta R_K / R_K \sim 0.04\%$

Radiative corrections

as pointed out by a recent work (**) it's possible to find in MSSM value of tanβ and M_H such that the R_K value can shift at the percent level the SM prediction.

$$R_K^{LFV} \approx R_K^{SM}\left[1 + \left(\frac{m_K^4}{m_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right)\left|\Delta_{31}\right|^2 \tan^6 \beta\right]$$

$$R_K^{LFV} = R_K^{SM}\,(1 + 0.013)$$

$\tan\beta = 40$ $M_H = 500$ GeV/c^2 $\Delta_{31} = 5\times10^{-4}$

(*) V. Cirigliano and I Rosell, JHEP 0710:005 (2007) (**) Masiero, P. Paradisi, R. Petronzio hep-ph/0511289 PRD74 (2006))

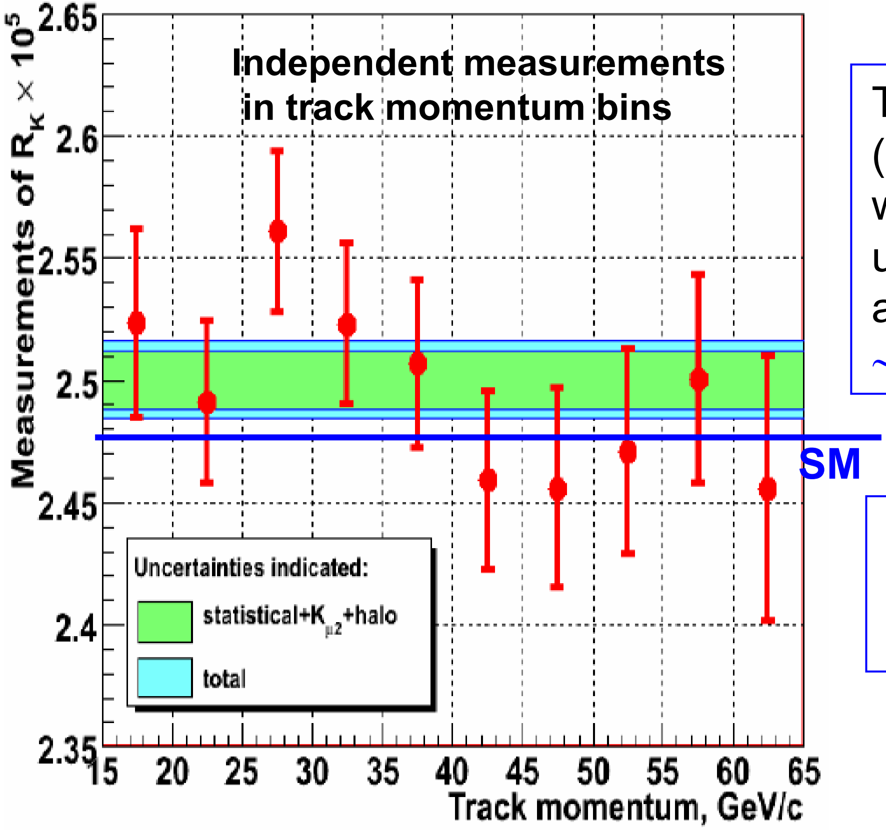
NA62: R_K short update (II)

preliminary result (40% sample)

$$R_K = (2.500 \pm 0.012_{stat} \pm 0.011_{syst}) \times 10^{-5} =$$

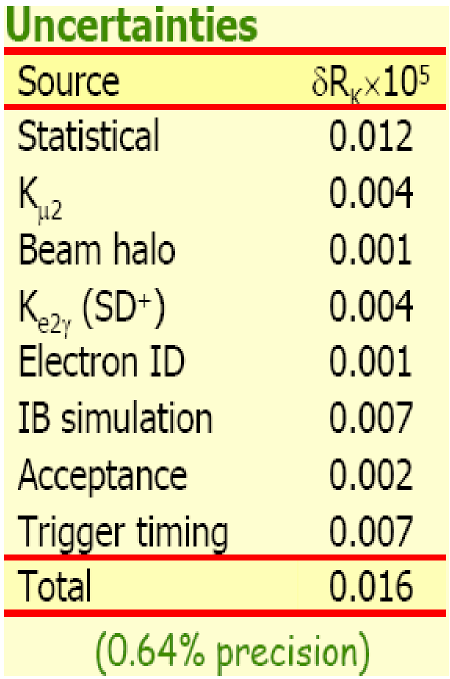
$$(2.500 \pm 0.016) \times 10^{-5}$$

jun 2009



The whole sample ($\sim 10^5$ K_{e2}) will allow a stat. uncertain ~0.3% and total uncertainness ~0.4-0.5%

The NA62 K_{e2} sample is ~10 times the world sample



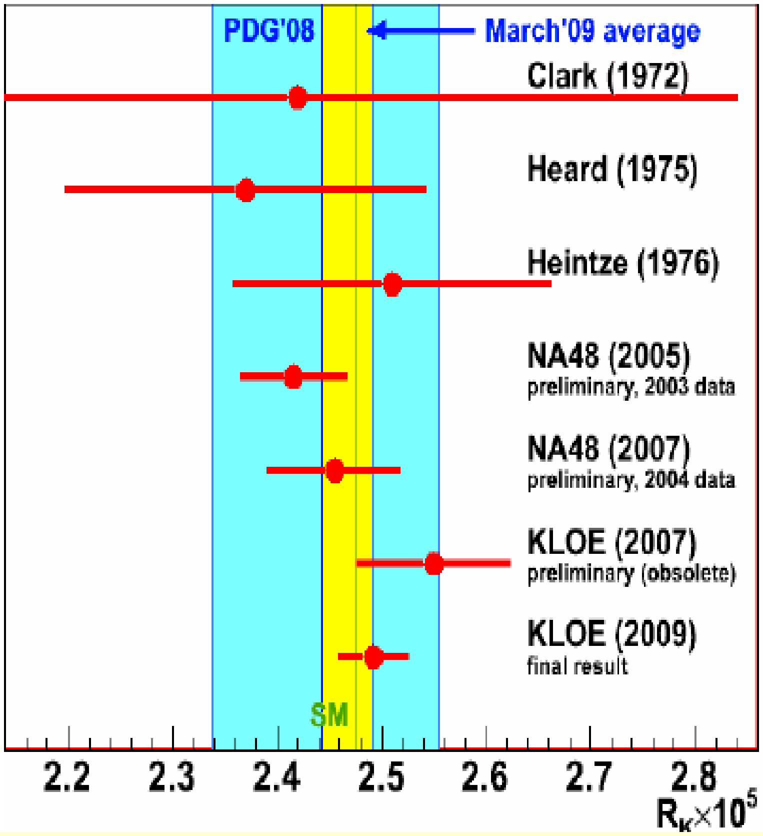
Uncertainties

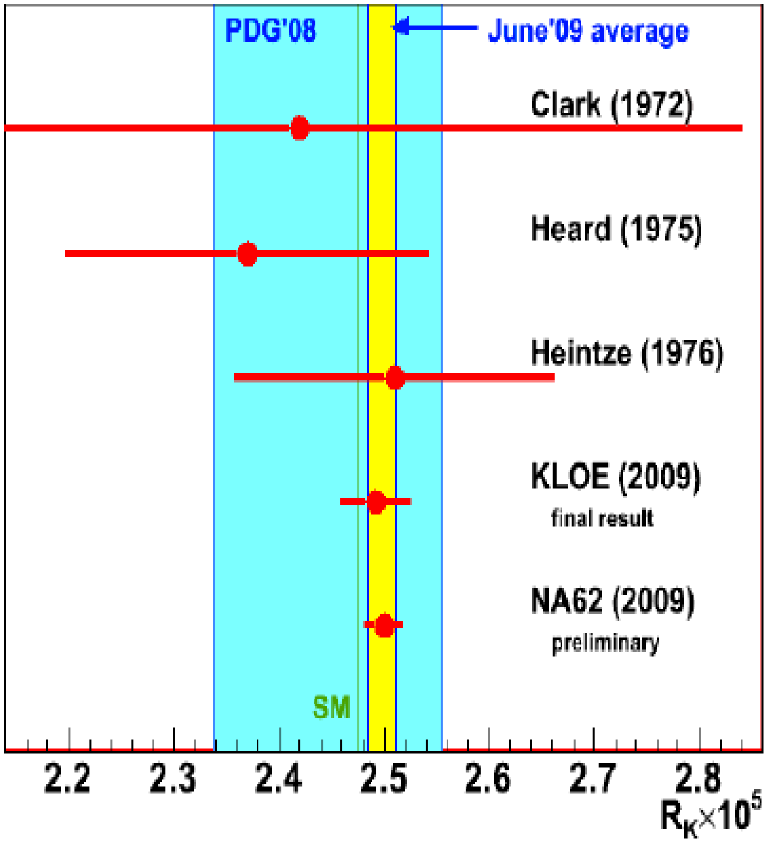
Source	$\delta R_K \times 10^5$
Statistical	0.012
$K_{\mu2}$	0.004
Beam halo	0.001
$K_{e2\gamma}$ (SD^+)	0.004
Electron ID	0.001
IB simulation	0.007
Acceptance	0.002
Trigger timing	0.007
Total	0.016

(0.64% precision)

NA62: R_K short update (III)

R_K: world data comparison





World average	$\delta R_K \times 10^5$	Precision
March 2009	2.467±0.024	0.97%
June 2009	2.498±0.014	0.56%

Theory $_{SM}$ **2.477± 0.001**

Conclusions

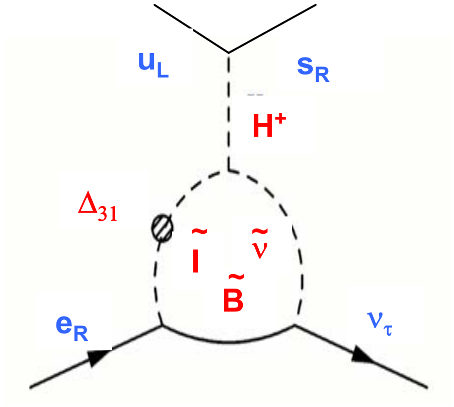
- a precise measurement of BR($K^+ \to \pi^+ \nu\nu$) is significant still in the LHC era
- R&D almost completed: tech. proposal in autumn
- Results from test beam and M.C. are encouraging
- first LAV ring is at the CERN and ready to be installed in the line.
- a precise measurement of R_K provided in the meantime

data taking start: 2011-2012

Spares

Ke2: Susy

- In the MSSM large tanβ scenario, the presence of LFV terms (charged Higgs coupling) introduces extra contribution to the SM amplitude



$$lH^\pm\nu_\tau \to \frac{g_2}{\sqrt{2}}\frac{m_\tau}{M_W}\Delta_R^{3l}\tan^2\beta$$

$$R_K^{LFV} = \frac{\Gamma_{SM}(K\to e\nu_e) + \Gamma_{LFV}(K\to e\nu_\tau)}{\Gamma_{SM}(K\to\mu\nu_\mu)}$$

$$R_K^{LFV} = R_K^{SM}\left[1+\left(\frac{m_K}{m_H}\right)^4\left(\frac{m_\tau}{m_e}\right)^2|\Delta_{13}|^2\tan^6\beta\right]$$

- Sizeable effects are predicted for reasonable SUSY parameters

$\Delta_{13} = 5\times10^{-4}$, tanβ = 40, M_H = 500 GeV → $R_K^{LVF} \cong R_K^{SM}(1+0.013)$

NA62-I: Analysis strategy

Signal events

Particle ID eff.

Trigger efficiency

$$R_K = \frac{1}{D}\,\frac{N(K_{e2})-N_B(K_{e2})}{N(K_{\mu2})-N_B(K_{\mu2})}\,\frac{f_\mu \cdot A(K_{\mu2})\cdot\varepsilon(K_{\mu2})}{f_e \cdot A(K_{e2})\cdot\varepsilon(K_{e2})}\,\frac{1}{f_{LKR}}$$

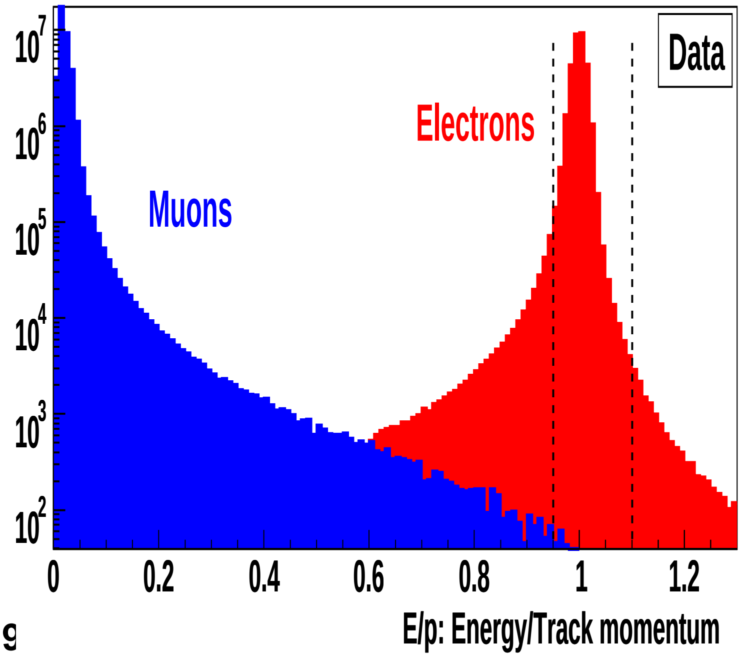
$K\mu2$ downscaling

Background events

Geometrical acceptance

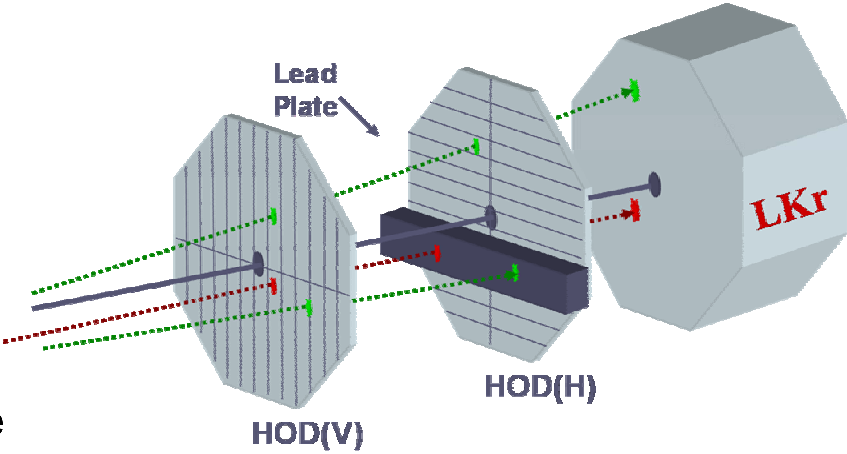
Global LKr readout eff.

- MC simulation used to a limited extent
- Analysis in bins of reconstructed lepton momentum
- Missing mass reconstruction (kaon momentum measured with $K \rightarrow 3\pi$)
- Particle identification with E/p (LKr and spectrometer)
- Decay vertex defined with closest distance aproach of lepton with kaon axis
- Lepton momentum in 15-65 GeV

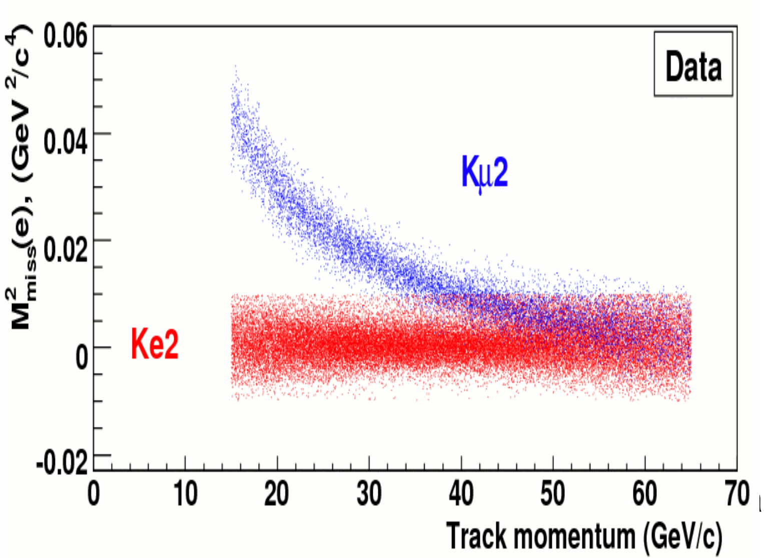


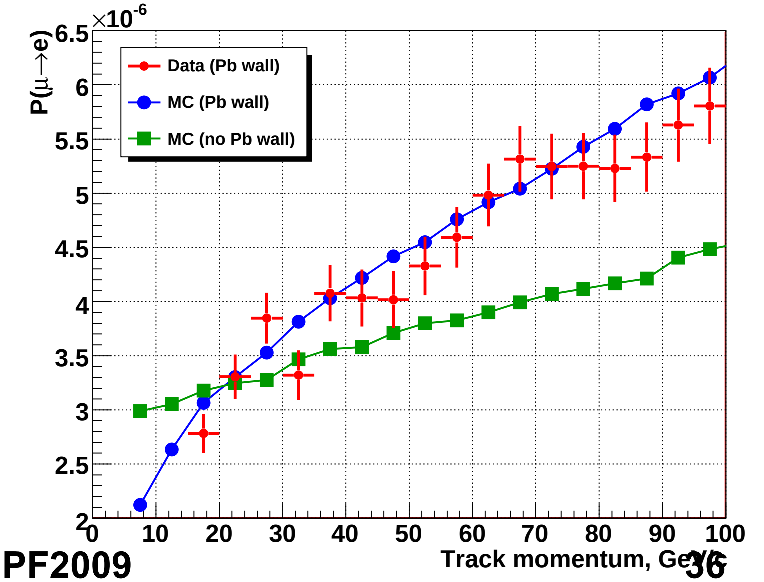
NA62-I: Background

- The main background in the ke2 sample comes from the muonic catastrophic bremsstrahlung
- It's important at high momentum where the missing masses are indistinguishable
- To measure directly P(μ→e) a "lead wall" (~ 8.9X_0) has been installed on ~18% LKr surface for ~50% of the run time



- The reliability of these technique has been studied in special "muon runs". The result agrees perfectly with Geant4 simulation (P(μ→e) ~ (3-5)·10^{-6} depending on momentum)
- B/S (7.4±0.2)%





NA62-I: Other backgrounds

- Beam Halo B/S=(1.3±0.1)%
  - Directly measured on the data with special runs
- Muon decay B/S=(1.3±0.1)%
  - Measured with MC including also the contribution of μ decay in spectrometer
- Ke2γ B/S=(1.6±0.3)%
  - Limited by the error on the measured BR (20%). Strong improvement expected by our new measurement in this channel
- Ke3 B/S=0.1%
- K2π B/S=(0.6 ±0.1)%
- fe uncertainty <0.1%
  - Measured with Ke3 from KL special runs and confirmed with charged Ke3 (at lower energy)
- In the $K_{\mu 2}$ sample the only relevant background is due to the beam halo (0.2%)