The NA62 Experiment

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on behalf of NA62 Collaboration:

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

Les Rencontres de Physique de la Vallée d'Aoste,
La Thuile, 1-7 March 2009

Rare Kaon Decays: $K \to l\nu$ and $K \to \pi\nu\bar{\nu}$

New Physics effects in Flavour Physics

Two main roads

MFV

Weakly coupled and SM Higgs secor [~ MSSM small tanβ]

- Most of the (present) flavour constraints naturally satisfied after imposing EWPO
- Only notable exception provided by $B \to X_s \gamma$

Strongly coupled or weakly coupled and large tanβ

- Helicity suppressed observ particularly interesting: $B \to ll$, $K \to l\nu$
- Charged-currents as interesing as FCNCs → precision tests of CC both in K and B

non -MFV

- Long list of useful observables (B and K physics: leptonic, radiative & non-leptonic channels), manily FCNCs
- The absence of significant deviations from the SM in any of these, makes generic non-MFV scenarios highly contrived / fine-tuned
- In several realistic cases (GUT scenarios, new couplings only for the 3rd family, etc...) the most significant constraints are derived from Kaon physics (λ^5 suppression in the SM, because of $1 \leftrightarrow 3 \leftrightarrow 2$).

$R_K = \Gamma(K \to e\nu / K \to \mu\nu)$

- In the ratio $R_K = \Gamma(K \to e\nu / K \to \mu\nu)$ hadronic uncertainties cancel (no f_K)
- The **SM prediction** is known with excellent accuracy ($\delta R_K / R_K$ = **0.04%**)

[V. Cirigliano and I. Phys. Lett. 99 (2007) 231801]

$$R_K^{SM} = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \left(1 + \delta R_{QED}\right) = \left(2.477 \pm 0.001\right) \times 10^{-5}$$

accounts for helicity suppression (V-A coupling) and enhances the sensitivity to non SM-effects

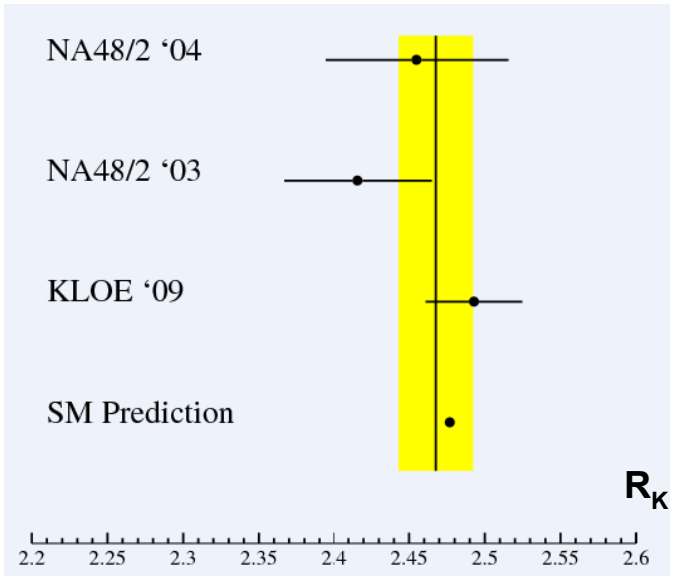
correction due to the IB part of the radiative $K \to e\nu\gamma$ process included in R_K (few %)

- **PDG average** based on 3 experiments from 70's

$$R_K = \left(2.45 \pm 0.11\right) \times 10^{-5} \left(\delta R_K / R_K = \mathbf{4.5\%}\right)$$

- Significant improvements due to **NA48/2 ('07) and KLOE ('09) preliminary results** :

$$R_K = \left(2.468 \pm 0.025\right) \times 10^{-5} \left(\delta R_K / R_K = \mathbf{1\%}\right)$$

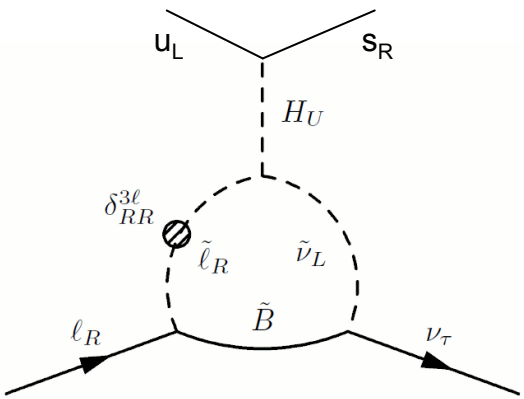


R_K beyond the SM

Variations of the order of 1% with respect to R_K^{SM} may be present from breaking of μ-e universality in SUSY

$$R_K^{LFV} = \frac{\sum_i K \to e\nu_i}{\sum_i K \to \mu\nu_i} \cong \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)}, \quad i = e, \mu, \tau$$

effective pseudoscalar LFV amplitude



effective coupling :

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

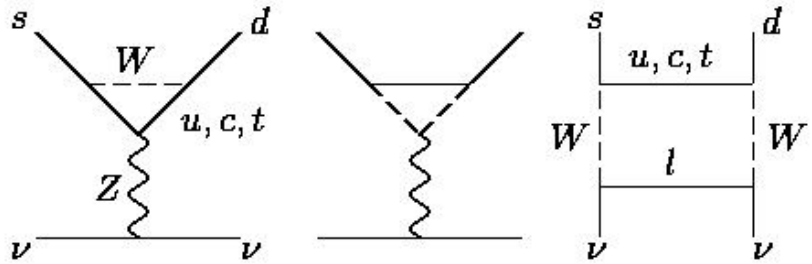
$$R_K^{LFV} = R_K^{SM}\left[1 + \left(\frac{m_K}{m_H}\right)^4 \left(\frac{m_\tau}{m_e}\right)^2 |\Delta_{13}|^2 \tan^6\beta\right]$$

[A. Masiero, P.Paradisi, R. Petronzio Phys. Rev. D74 (2006) 0011701]

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

$K \to \pi \nu \bar{\nu}$

Strong sensitivity to flavor structure of physics beyond the SM



- **Smallness** of the CKM suppression factor ($V_{ts}^{*}V_{td} \sim \lambda^5$)
- **High theoretical cleanness**:
  - Dominated by short-distance dynamics
  - Hadronic matrix elements extracted by $K^+ \to \pi^0 e^+ \nu$
  - In case of $K^+ \to \pi^+ \nu\nu$ small effects of long distance contributions due to charm

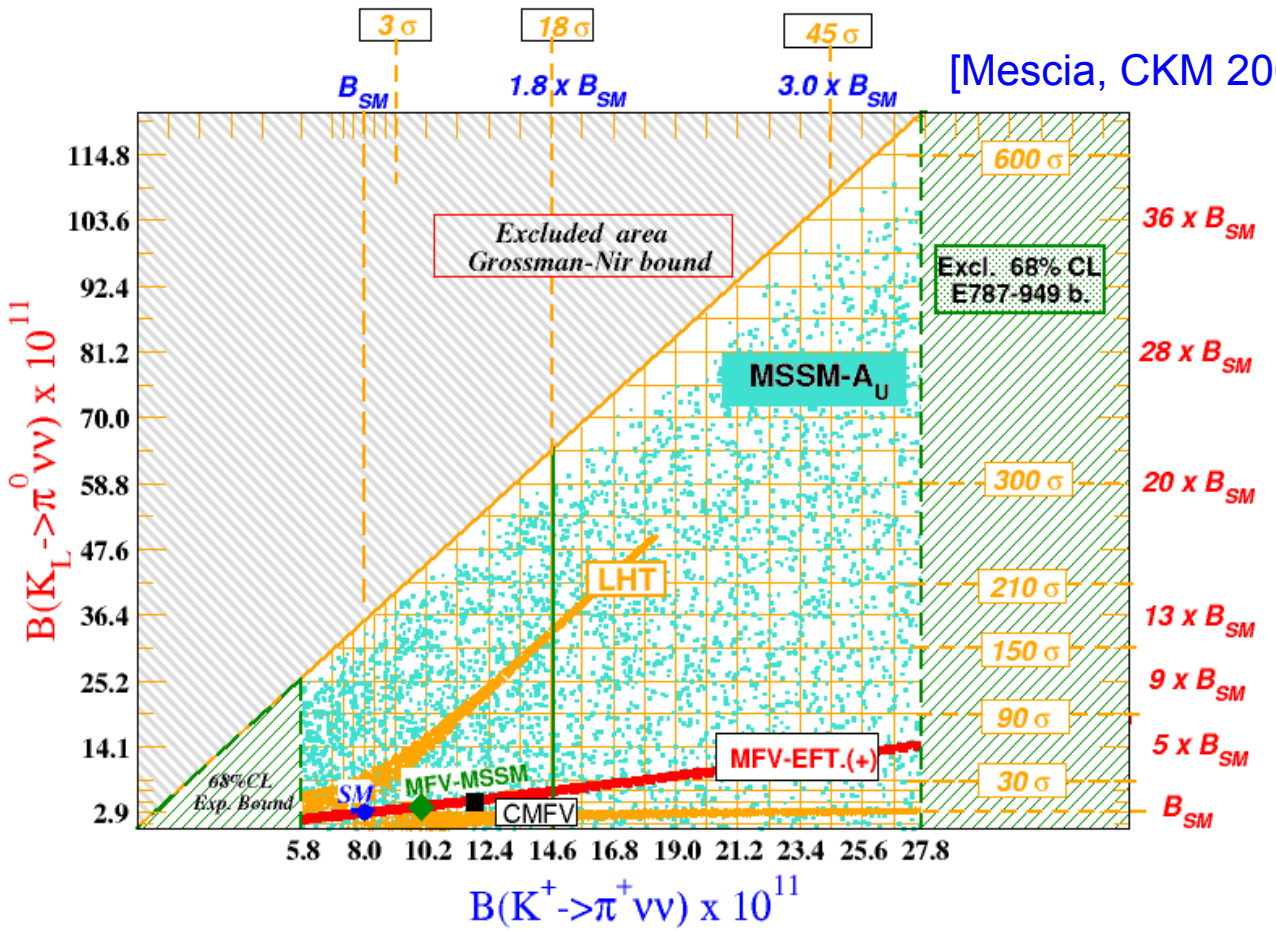
$$BR_{TH}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) \approx \left(0.85 \pm 0.07\right) \times 10^{-10}, \quad BR_{TH}\left(K_L \to \pi^0 \nu\bar{\nu}\right) \approx \left(2.76 \pm 0.40\right) \times 10^{-11}$$

for m_c=(1286 ± 13) MeV [as reported by J. Brod, CKM08]

Experimental status: $[\mathrm{E787/E949\,'08}]: BR\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = 1.73^{+1.15}_{-1.05} \times 10^{-10}$

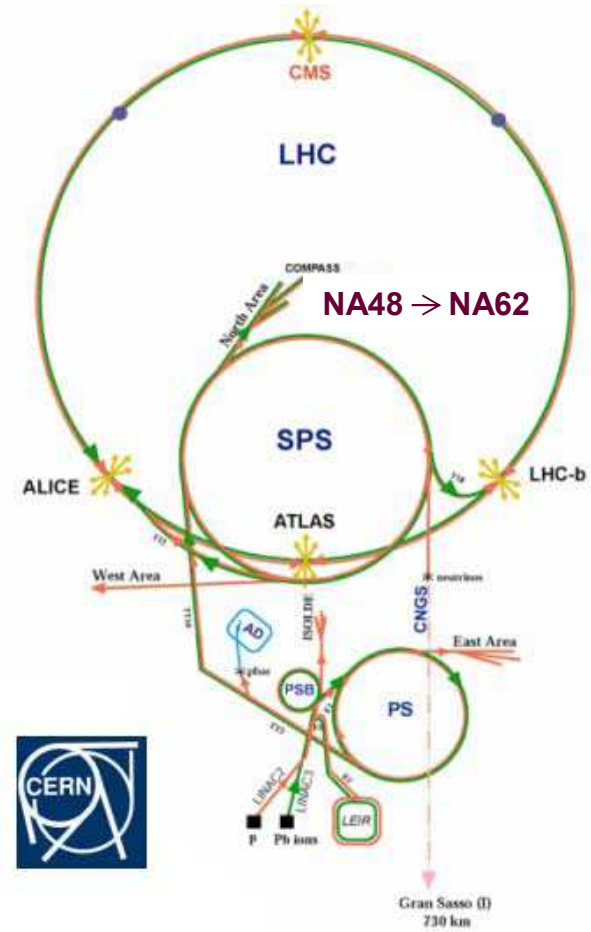
$K \to \pi \nu \bar{\nu}$ beyond the SM

[Mescia, CKM 2006]



NA62 Experiment

A fixed target experiment at the CERN SPS



The SPS delivers protons of 400 GeV/c momentum with fast or slow extraction

The SPS is here to stay as injector of the LHC (as it was for LEP)

Experience, Infrastructure and **(some) detectors from NA48 to NA62**

NA62: R_K Measurement

The aim is a measurement of R_K with an accuracy better than 0.4%

[CERN-SPSC-2006-033]

Running conditions optimized for the K_{e2} measurement by exploiting the experience of the earlier NA48/2 K_{e2} studies on 2003 and 2004 data

- **2007 and 2008 data taking**:

  $160 \cdot 10^3$ K_{e2} candidates collected with ~ 10% background

- **K^+/K^- beams**:

  p_K = 75 GeV/c, $\delta p_K/p_K$=2%
  ~90% K^+ only, ~10% K^- only

Analysis Strategy

- K_{e2} and $K_{\mu 2}$ collected simultaneously
- MC simulations used to a limited extent
- Analysis performed in bins of the reconstructed momentum

background events

acceptance

LKr trigger efficiency

$$R_K = \frac{1}{D} \cdot \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu 2}) - N_B(K_{\mu 2})} \cdot \frac{f_\mu \times A(K_{\mu 2}) \times \varepsilon(K_{\mu 2})}{f_e \times A(K_{e2}) \times \varepsilon(K_{e2})} \cdot \frac{1}{f_{LKR}}$$

signal events

measured PID efficiency

LKr readout

R_K: Detector

Magnetic spectrometer:

$\sigma_p/p = (0.47 \oplus 0.02\ p)\%$ (p in GeV/c)

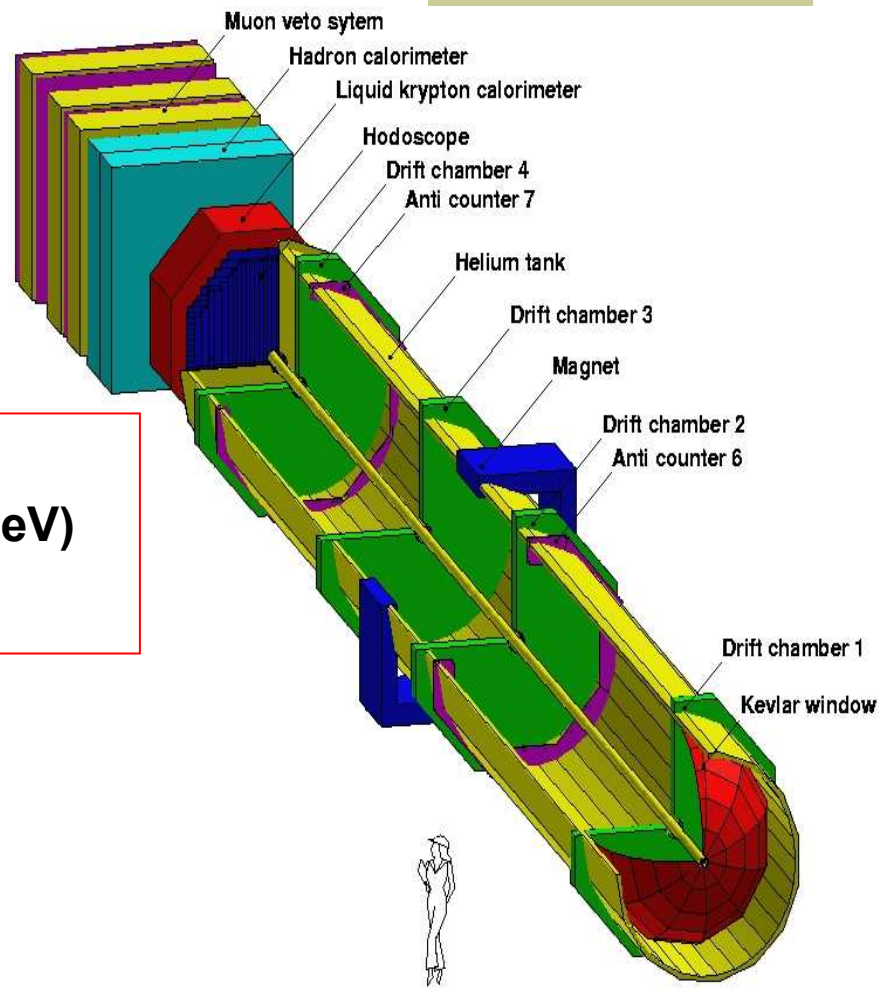
LKr electromagnetic calorimeter:

$\sigma_E/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$ (E in GeV)

$\sigma_x = \sigma_y \sim 1.5$mm for E=10 GeV

Hodoscope:

$\sigma_t \sim 200$ps



$K^{\pm}$

R_K: Event Selection

Geometry

- One reconstructed charged track
- $15 < p < 65$ [GeV/c]
- Good reconstructed vertex
- Geometrical acceptance cut
- Upper limit on LKr energy deposition not associated to the track

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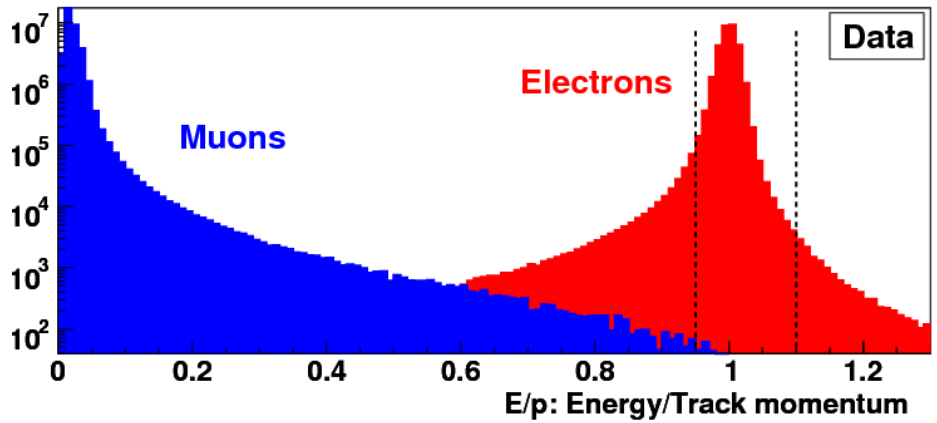
Particle ID (E_{LKR}/p_{spectr})

- **e** ($0.95 < E/p < 1.10$)
- μ ($E/p < 0.2$)



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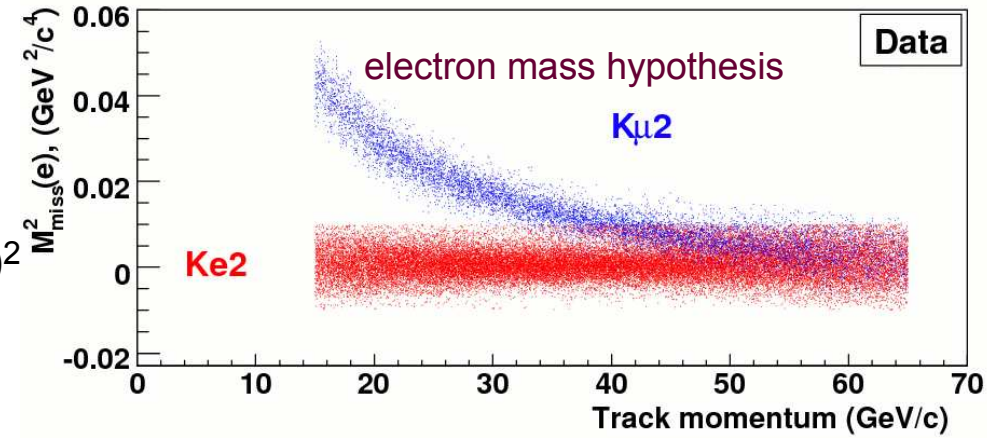
Kinematics

- Missing mass: $M_{miss}^2(l)=(p_K-p_l)^2$
- $|M_{miss}^2(l)| < 0.01$ [GeV/c^2]^2



kinematically undistinguishable at high momenta

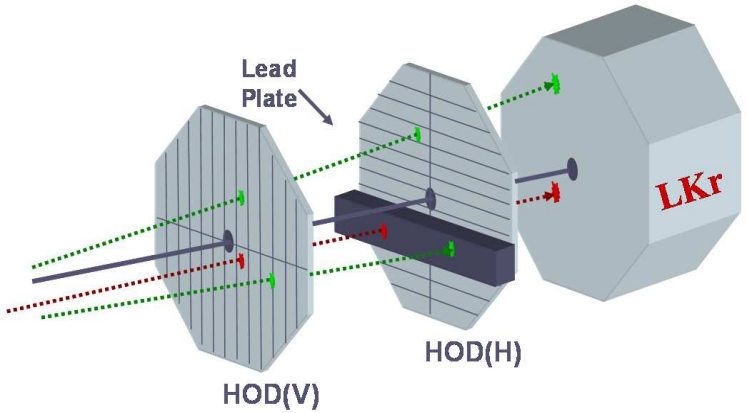
R_K: Background

Dominant background source in the K_{e2} sample is due to $K_{\mu 2}$

- **Bkg in K_{e2} sample**

  $K_{\mu 2}$:
  - catastrophic energy loss in LKr
    $P(\mu \to e) \sim 3\times10^{-6} \to P(\mu \to e)/R_K \sim 10\%$
  - $\mu \to e$ decay before first DCH

- Need direct measurement of $P(\mu \to e)$
- To avoid electron contamination from muon decay ($\sim10^{-4}$) a lead wall covering 18% of the acceptance was installed between the HOD planes



(45 mm Pb +20 mm Fe ≈ **8.9 X_0**)

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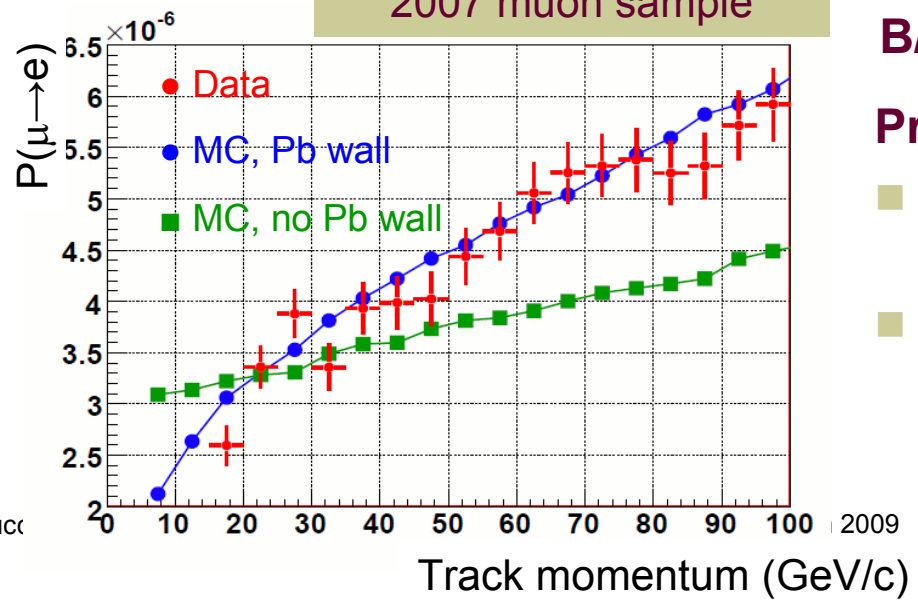
2007 muon sample



B/S = (8.07±0.21)%

Prospect:

- 2008 muon sample is twice as large as the 2007 one
- muons from $K_{\mu 2}$ decays in $K_{e2}/K_{\mu 2}$ separation region

R_K: Background

- **Bkg in K_{e2} sample**

  $K_{\mu 2}$:

  - catastrophic energy loss in LKr

    $P(\mu \to e) \sim 3\times10^{-6} \to P(\mu \to e)/R_K \sim 10\%$
  - $\mu \to e$ decay before first DCH

  $K^+ \to e^+ \nu \gamma$ (SD) $\longrightarrow$ B/S estimated by MC simulation

  B/S = (1.29±0.32)%

Rate known with very poor precision

Theory: BR=(1.12-1.34)$\times10^{-5}$

Experiment: BR=(1.52±0.23)$\times10^{-5}$

Prospect:

Improve B/S estimated uncertainty by direct measurement with NA62 2007 data

R_K: Background

- **Bkg in K_{e2} sample**

  $K_{\mu 2}$:
  - catastrophic energy loss in LKr

    $P(\mu \to e) \sim 3\times10^{-6} \to P(\mu \to e)/R_K \sim 10\%$
  - $\mu \to e$ decay before first DCH

  $K^+ \to e^+ \nu \gamma$ (SD)

  Beam halo → Directly measured with K^- only sample

  B/S = (1.23±0.07)%

- **Bkg in $K_{\mu 2}$ sample**

  Beam halo

Prospect:

2008 K^- sample will improve precision

R_K: Background

- **Bkg in K_{e2} sample**

  $K_{\mu 2}$:
  - catastrophic energy loss in LKr

    $P(\mu \to e) \sim 3\times10^{-6} \to P(\mu \to e)/R_K \sim 10\%$
  - $\mu \to e$ decay before first DCH

  $K^+ \to e^+ \nu \gamma$ (SD)

  Beam halo

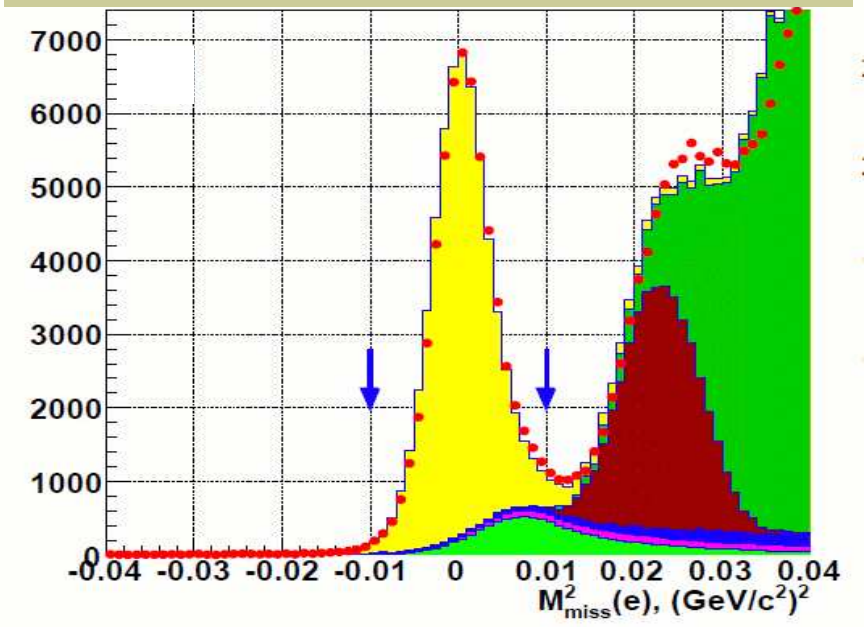
  $K^+ \to \pi^0 e^+ \nu$, $K^+ \to \pi^+ \pi^0$
- **Bkg in $K_{\mu 2}$ sample**

  Beam halo

  $K^+ \to \pi^+ \pi^0$

R_K: Background Summary

Missing invariant mass, K_{e2} candidates



K_{e2} background sources in the signal region:

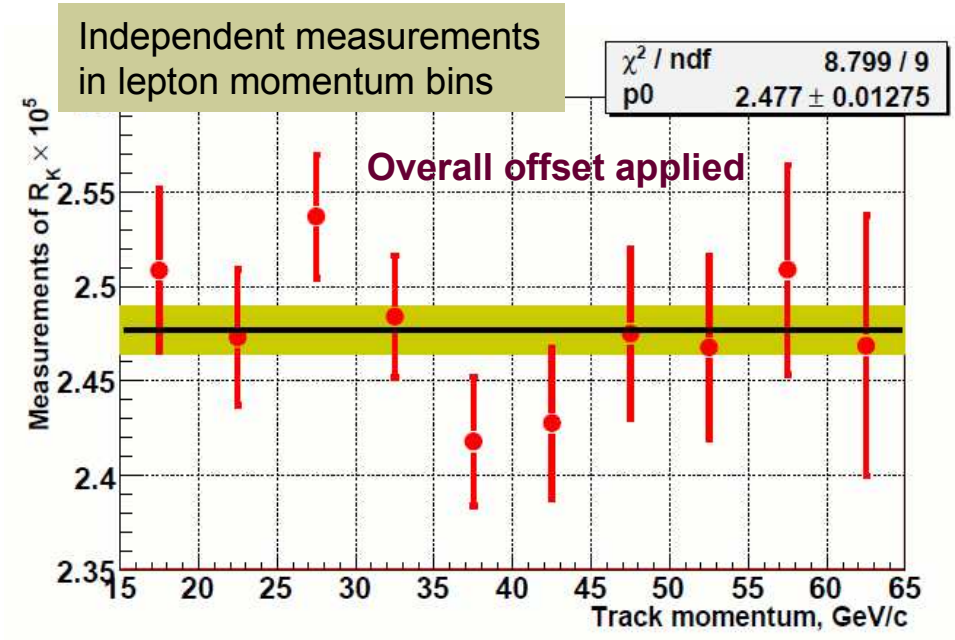
	$K_{\mu 2}$	(8.07±0.21)%
	$K_{e2\gamma}$ (SD)	(1.29±0.32)%
	Beam halo	(1.23±0.07)%
	$K_{2\pi}$	0.11%
	K_{e3}	0.03%

Analyzed data sample: ~ $60 \cdot 10^3$ K_{e2} candidates
Sum of 3 main contribution B/S = 10.59%

R_K: Other Effects

- **Electron ID efficiency f_e**
  directly measured with a kinematic selection of electrons from $K^{\pm}\rightarrow\pi^0 e^{\pm}\nu$ and $K_L\rightarrow\pi^{\pm}e\nu$ (0.988-0.992)
- **Muon ID efficiency f_μ**
  measured with a pure muon sample from a special muon run (0.996-0.998)
- **Acceptance correction $A(K_{\mu 2})/A(K_{e2})$**
  momentum dependent
  K_{e2} radiative (IB) corrections strongly affect the acceptance (1.2-1.4)
- **Trigger efficiency correction $\varepsilon(E_{LKr})$**
  measured using control trigger samples < 0.1%

R_K: Analysis Summary and Prospects



Main uncertainties
(40% of the data sample)

Statistical	0.43%
$K_{\mu 2}$	0.25%
$K_{e2\gamma}$ (SD)	0.32%
Beam halo	0.10%
Total	**~0.60%**

By analyzing **the whole data sample** (~ $160 \cdot 10^3$ K_{e2}) **statistical uncertainty below 0.3%**
Systematic uncertainties from **$K_{\mu 2}$ and beam halo background** subtraction will be improved by using the **special data sets** collected in 2008
Uncertainty due to **$K_{e2\gamma}$ (SD)** will be decreased by a **direct measurement** of this decay

Total uncertainty of 0.4% within reach

NA62: $K \rightarrow \pi \nu \bar{\nu}$ Measurement

Measure the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay with a 10% accuracy

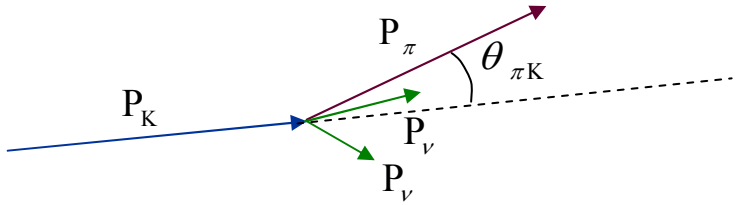
- Observe ~ 100 signal events in 2 years
- 10% signal acceptance
- 10:1 signal to background

} Need 10^{13} Kaon decays

The experimental technique exploits:

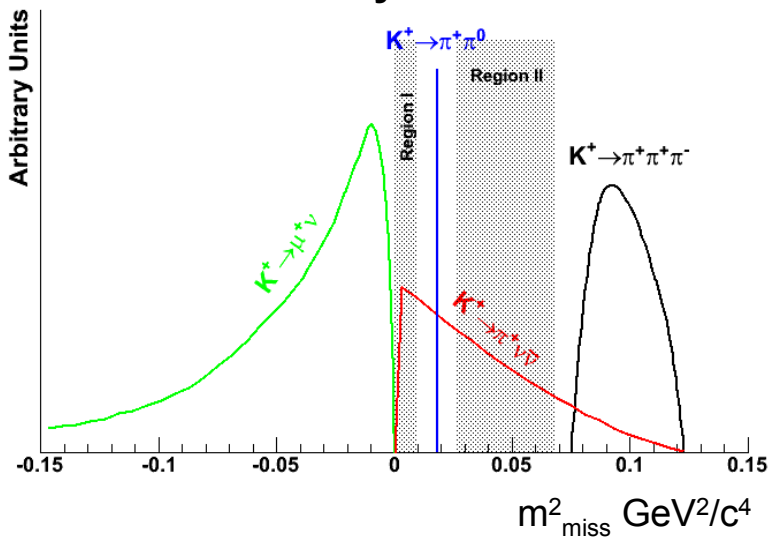
- **Precise Timing** to associate the outgoing π^+ to the correct incoming K^+
- **Kinematical Rejection** of two- and three-body backgrounds
- **Vetoes** (γ and μ)
- **Particle Identification** (K/π, π/μ)

Kinematics and Backgrounds



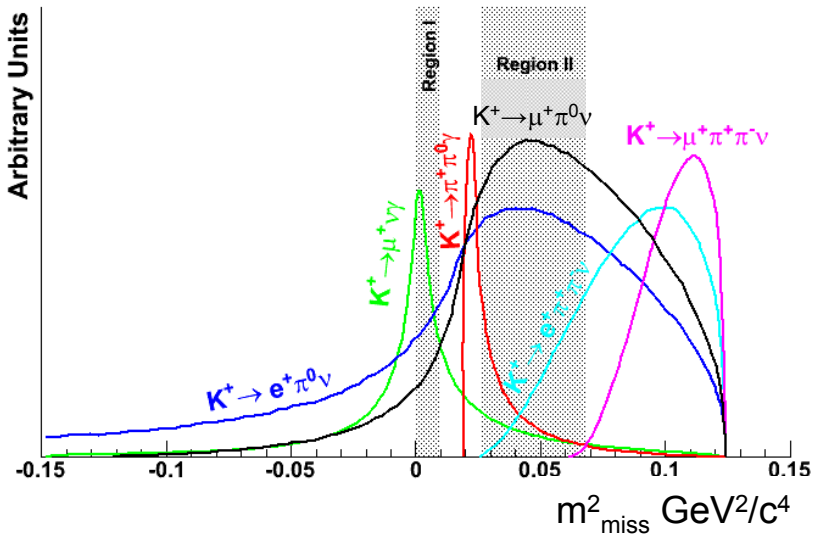
$$m^2_{miss} \cong m^2_K\left(1-\frac{|P_\pi|}{|P_K|}\right)+m^2_\pi\left(1-\frac{|P_K|}{|P_\pi|}\right)-|P_K||P_\pi|\theta^2_{\pi K}$$

Kinematically constrained



92% of total background

Not kinematically constrained



8% of total background

Background Rejection

$K^+ \rightarrow \mu^+ \nu$ ($K_{\mu 2}$)

BR: 63.4% $\Rightarrow$ ~ 10^{-12} rej factor

- kinematics: 10^{-5}
- muon veto: 10^{-5}

  MUV+HAC
- PID: ~ 5×10^{-3}

  RICH

$K^+ \rightarrow \pi^+ \pi^0$ ($K_{2\pi}$)

BR: 20.9% $\Rightarrow$ ~ 10^{-12} rej factor

- kinematics: 5×10^{-3}
- photon veto: 10^{-5}
  - Large angle veto

    12 ANTIs (10<acceptance<50 mrad)
  - Medium angle veto

    NA48 LKr (1<acceptance<10 mrad)
  - Small angle veto

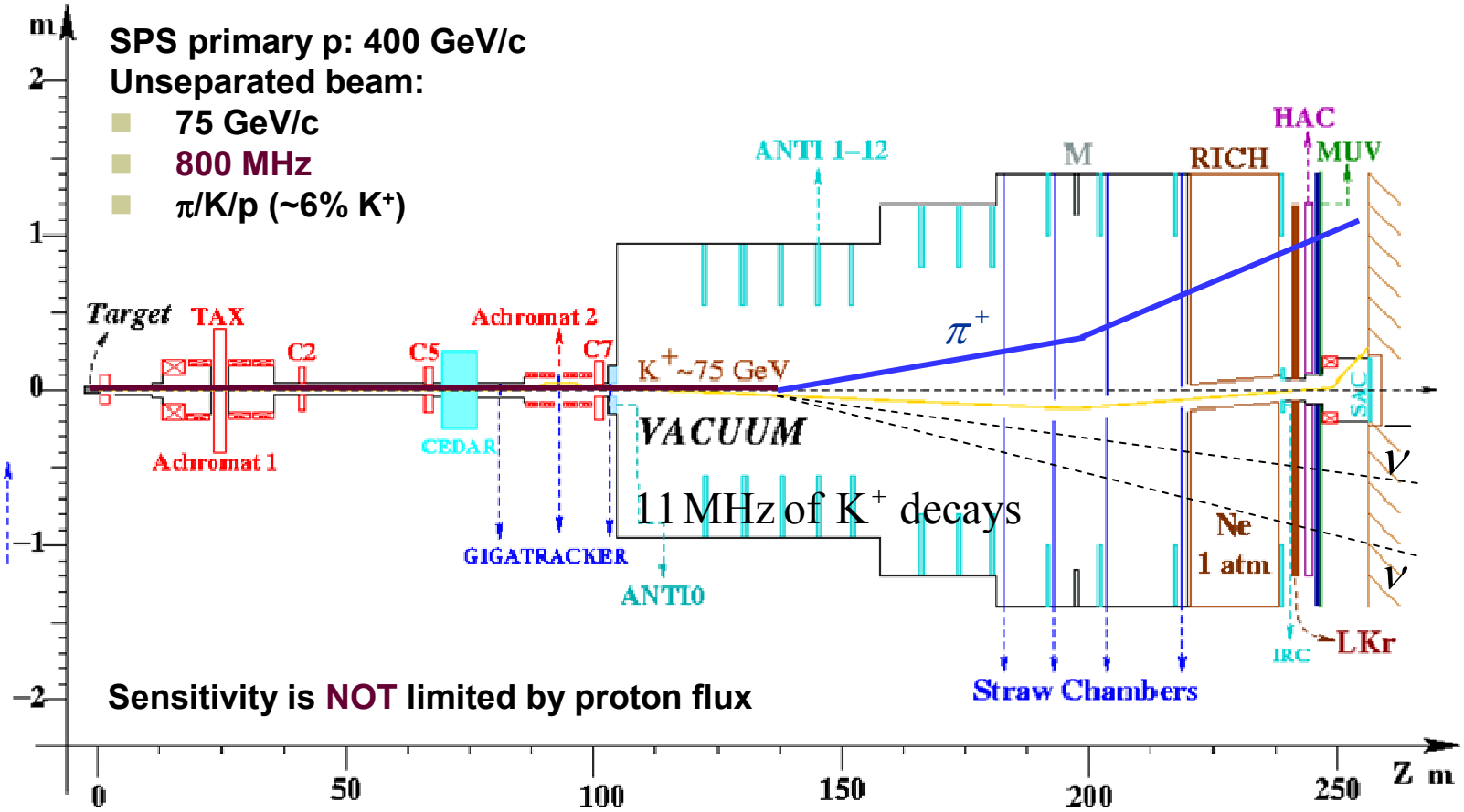
    IRC+SAC (acceptace < 1mrad)

with 10% acceptance,

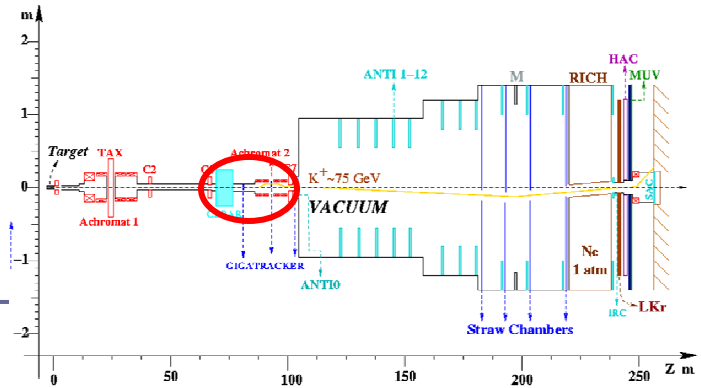
S/B >10 if $\sigma(m^2_{miss}) \sim 10^{-3}$ GeV^2/c^4:

- $\sigma(p_K) < 0.5\%$ and $\sigma(\theta_K) < 25\mu$rad $\rightarrow$ **GIGATRACKER**
- minimize MS $\rightarrow$ **STRAW CHAMBERS** in vacuum

Detector Layout



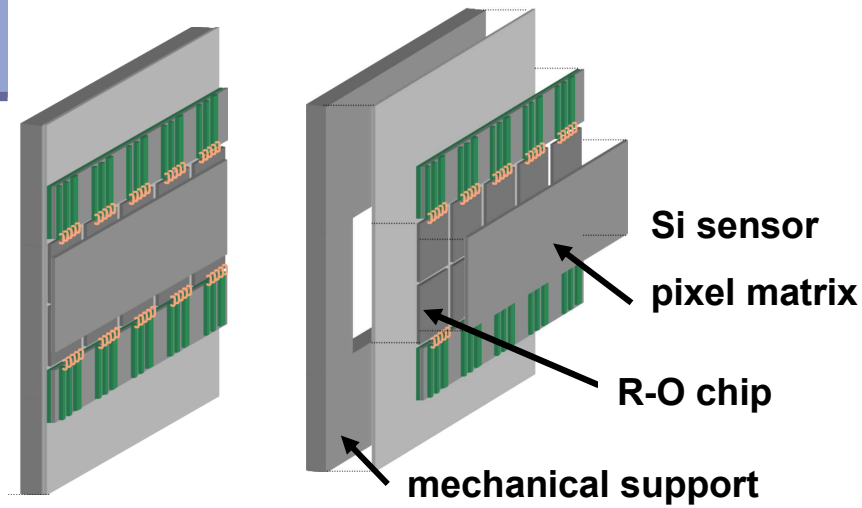
Gigatracker



Three silicon pixel stations (60(X)×27(Y) mm^2) placed along the beam line

Requirements

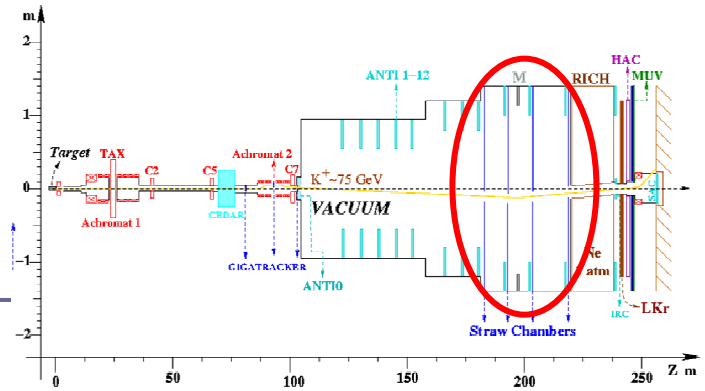
- Good space resolution not to spoil the squared missing mass resolution → **300×300 μm pixels**
- ~ 0.5 X_0/station not to spoil the beam → **200 μm Si sensor+100 μm chip**
- Excellent time resolution for K^+/π^+ association: **$\sigma(t)$ ~ 200ps**/station → **Complex readout chip bump-bonded on the sensor (0.13 μm CMOS tech)**



Important R&D studies under-way:

- **Sensor: FBK-IRST (Italy)**
- **Bump-bonding: VTT (Finland)**
- **Cooling**
- **Front-End**

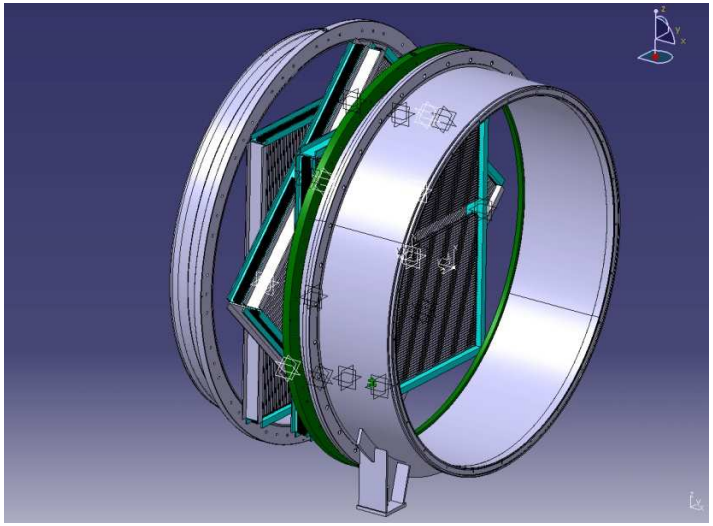
Straw Chambers



- 4 chambers (u,v,x,y views/chamber)
- Each view made of four planes of straws (~500 straws)

Requirements

- Low X/X_0 to minimize MS → **Operate in vacuum, X/X_0~0.1% per view**
- Good space resolution → **130 μm per hit**
- Veto for charged particle → **7.5 cm radius beam hole displaced in the bending plane according to the 75 GeV/c beam path**



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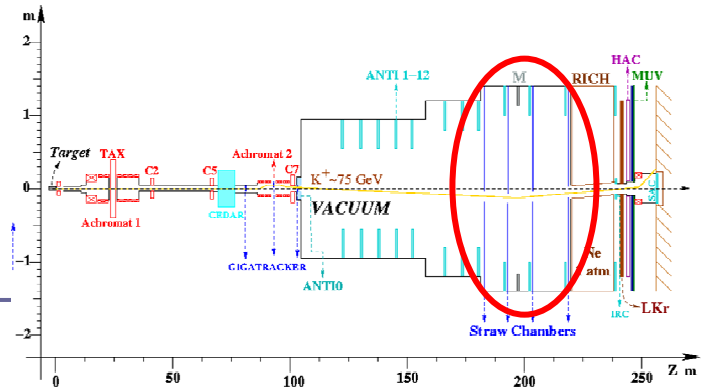

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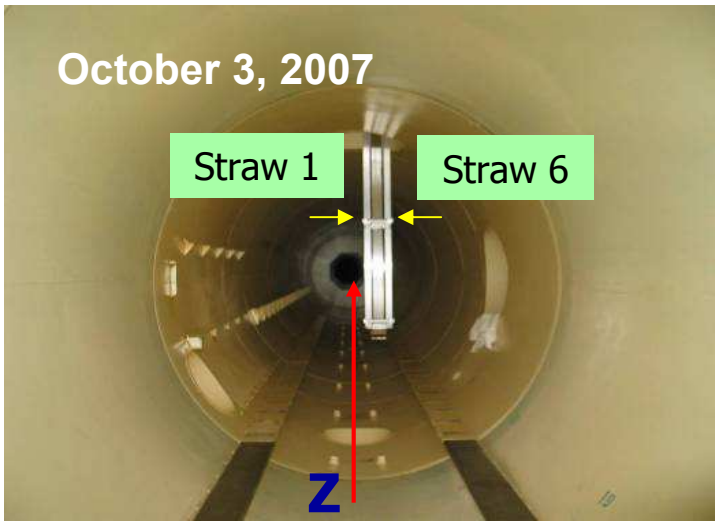
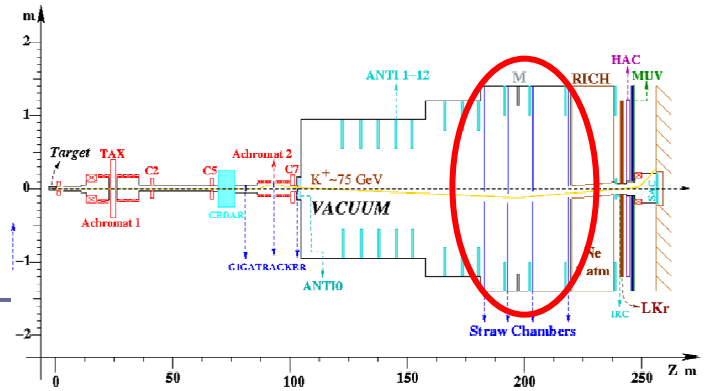


A full length (2.1m) 48-straw prototype was tested inside the vacuum tube (end of 2007 run of NA62)

Residual

- μ: RMS=104μm, σ=45μm
- π: RMS=100μm, σ=43μm
- K: RMS=122μm, σ=45μm

Straw Chambers



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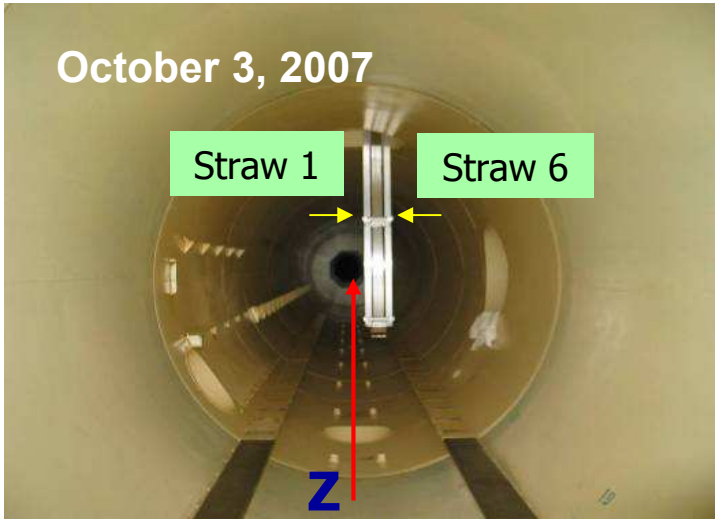
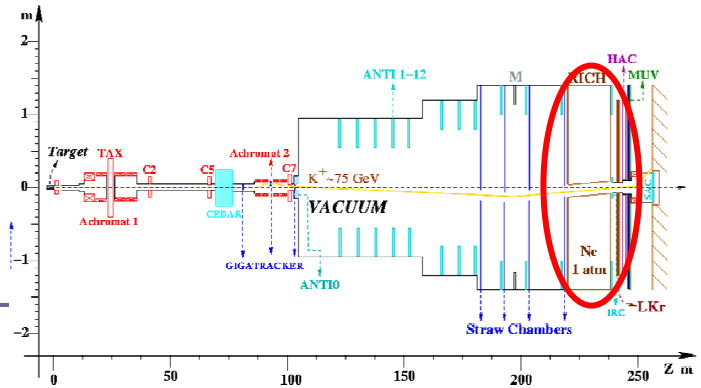
- Good space resolution → **130 μm per hit**
- Veto for charged particle → **7.5 cm radius beam hole displaced in the bending plane according to the 75 GeV/c beam path**



Same straw prototype as in 2007 equipped with two types of FE was ready to take data in October 2008. Unfortunately the beam was stopped on October 6

RICH



Requirements

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

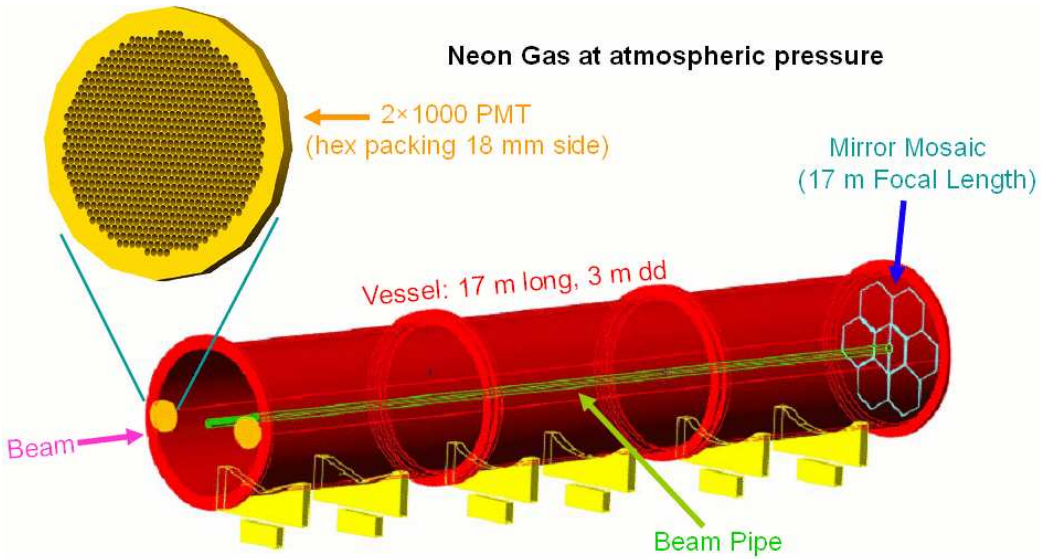
18 m tube filled with Ne at 1atm

2 tilted mirrors (f=17m)

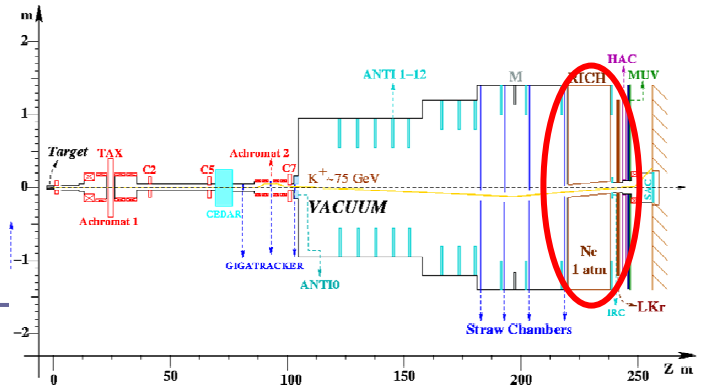
Beam pipe going through

2000 PMT in two spots

Single anode PMTs matrix on the focal plane with compact hex pack (18mm pixel size)



RICH



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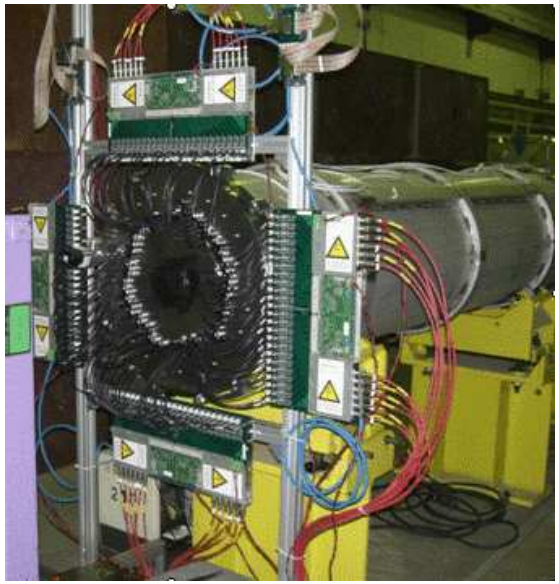
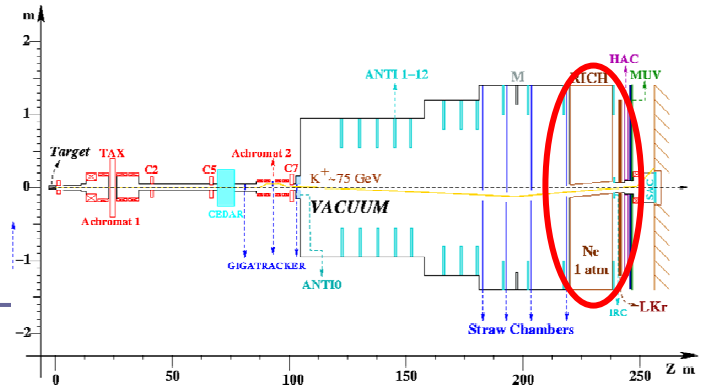


Full scale (longitudinal) RICH built and tested with negative beam from SPS@200GeV/c

RICH



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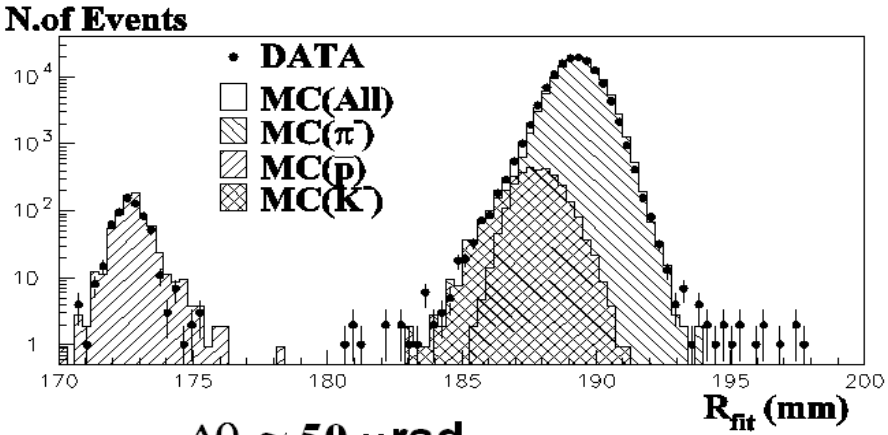


$\Delta\theta_c \approx 50\ \mu rad$

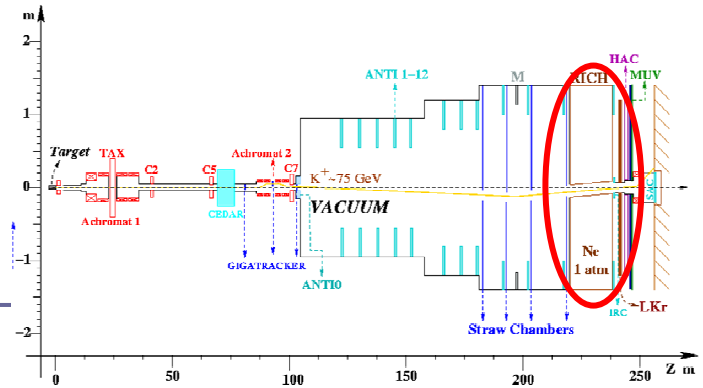
(biased by PM geometry)

Full scale (longitudinal) RICH built and tested with negative beam from SPS@200GeV/c

$N_{Hits} \approx 17$

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

RICH



Requirements

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18 m tube filled with Ne at 1atm

2 tilted mirrors (f=17m)

Beam pipe going through

2000 PMT in two spots

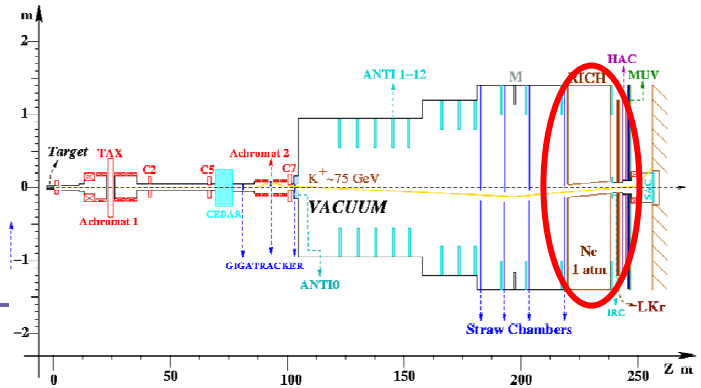
Single anode PMTs matrix on the focal plane with compact hex pack (18mm pixel size)

New Prototype

- PM endcap changed
- 414 PMTs (20% of final detector)
- Validate π-μ separation in 15<p<35 GeV/c
- Improve PM cooling

Test scheduled: Oct 19 – Nov 12, 2008
Postponed to 2009 (LHC incident)

RICH



Requirements

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- Measure track time with 100 ps res
- Provide the main trigger for charged particle

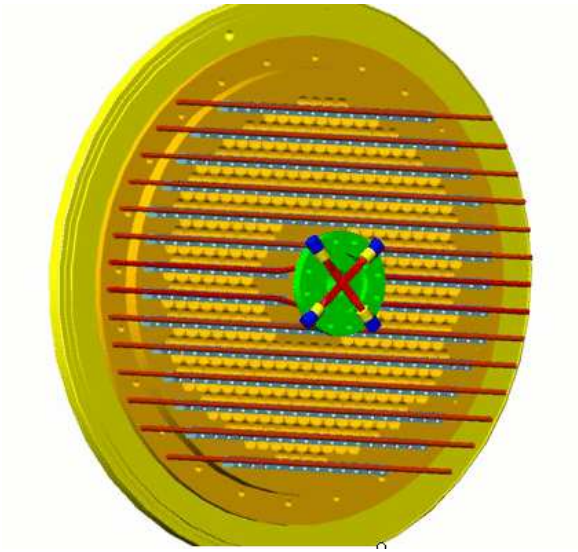
18 m tube filled with Ne at 1atm

2 tilted mirrors (f=17m)

Beam pipe going through

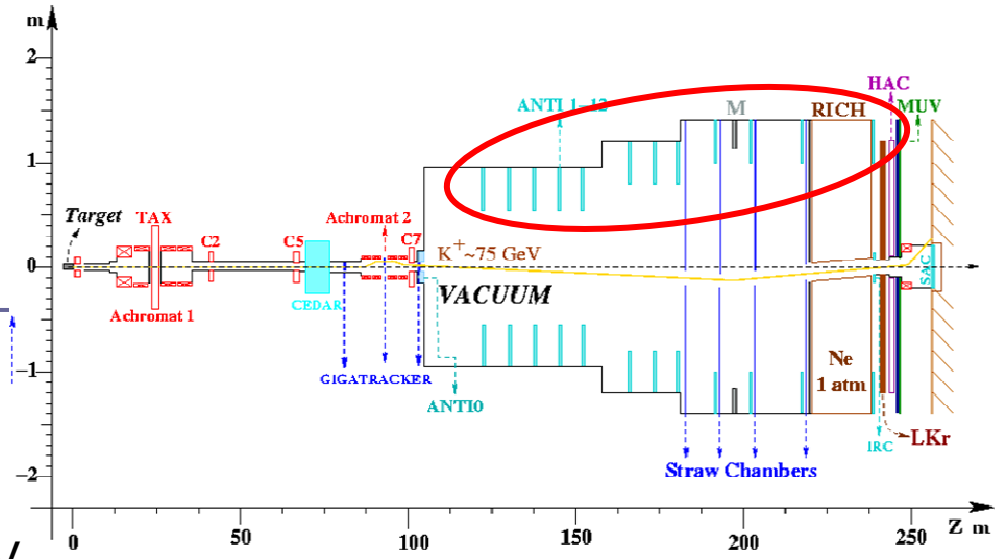
2000 PMT in two spots

Single anode PMTs matrix on the focal plane with compact hex pack (18mm pixel size)



Test scheduled: Oct 19 – Nov 12, 2008
Postponed to 2009 (LHC incident)

Photon Vetoes

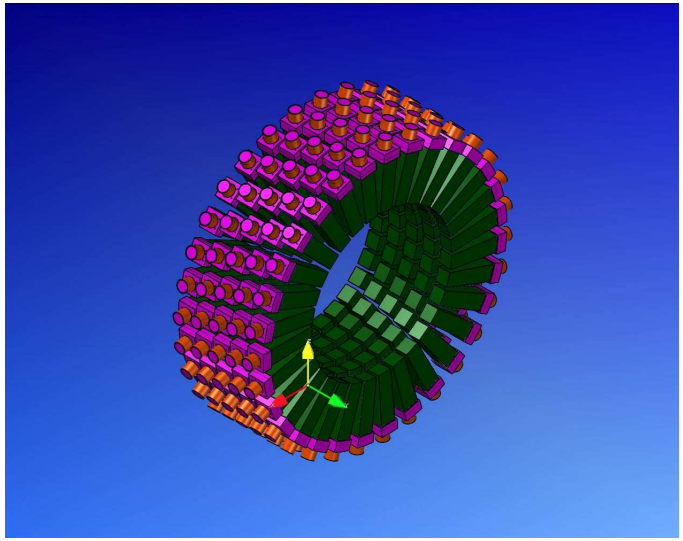


Requirements

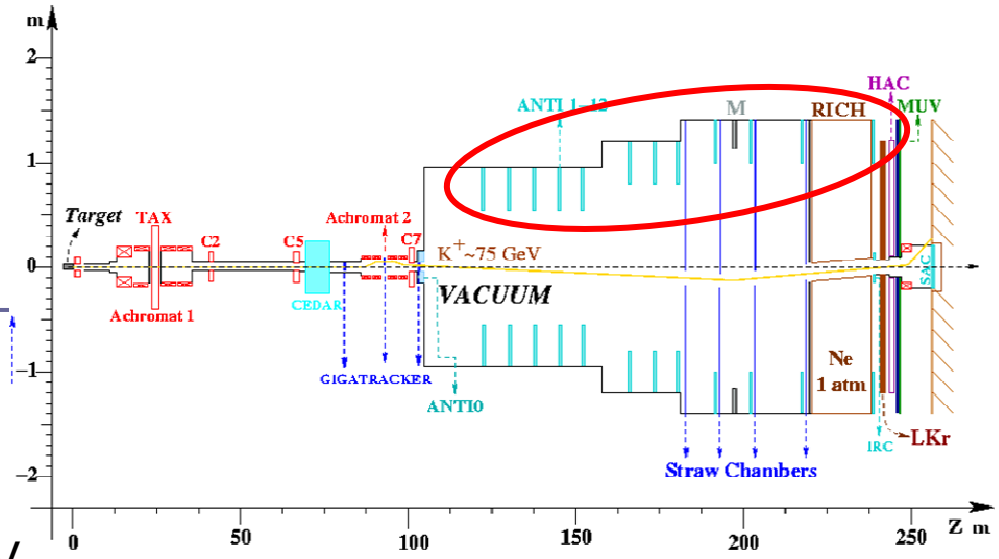
10<acceptance<50 mrad

- 10^{-4} inefficiency for $0.05<E_\gamma<1$GeV
- 10^{-5} inefficiency for $E_\gamma>1$GeV

12 LAV stations formed by 4 to 5 overlapping rings of OPAL lead-glasses



Photon Vetoes



Requirements

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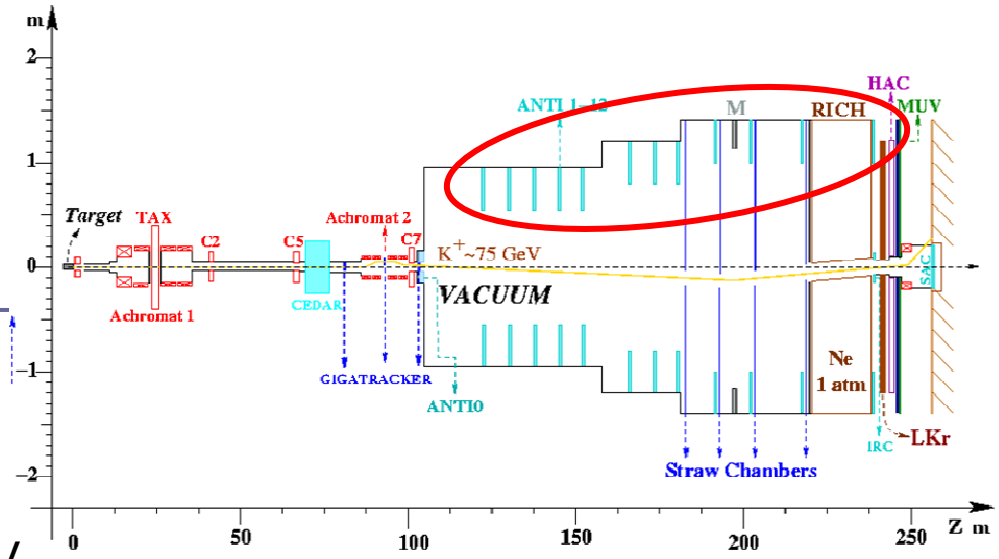
- 10^{-4} inefficiency for $0.05<E_\gamma<1$GeV
- 10^{-5} inefficiency for $E_\gamma>1$GeV

12 LAV stations formed by 4 to 5 overlapping rings of OPAL lead-glasses

A 25 blocks prototype tested at BTF in Frascati with 471 MeV electron beam

Photon Vetoes



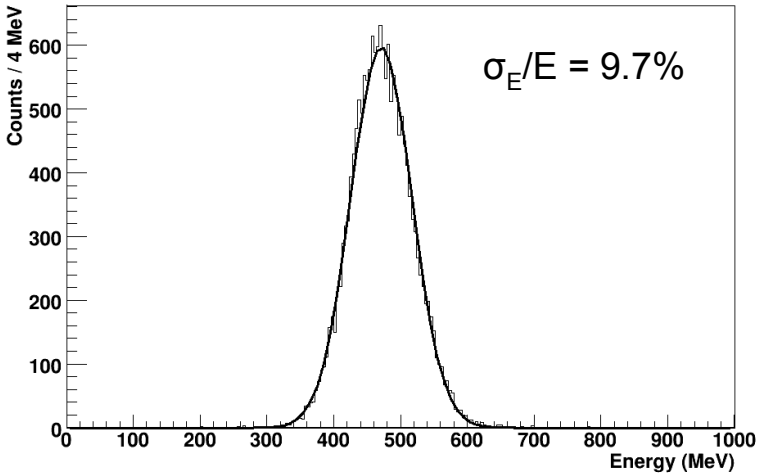
Requirements

10<acceptance<50 mrad

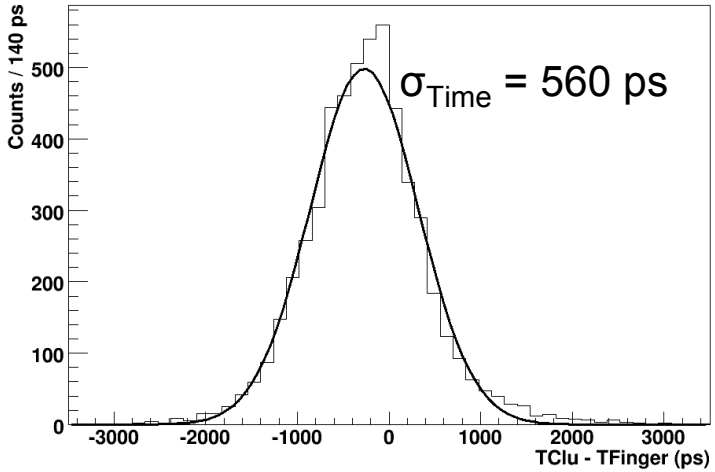
- 10^{-4} inefficiency for $0.05<E_\gamma<1$GeV
- 10^{-5} inefficiency for $E_\gamma>1$GeV

12 LAV stations formed by 4 to 5 overlapping rings of OPAL lead-glasses

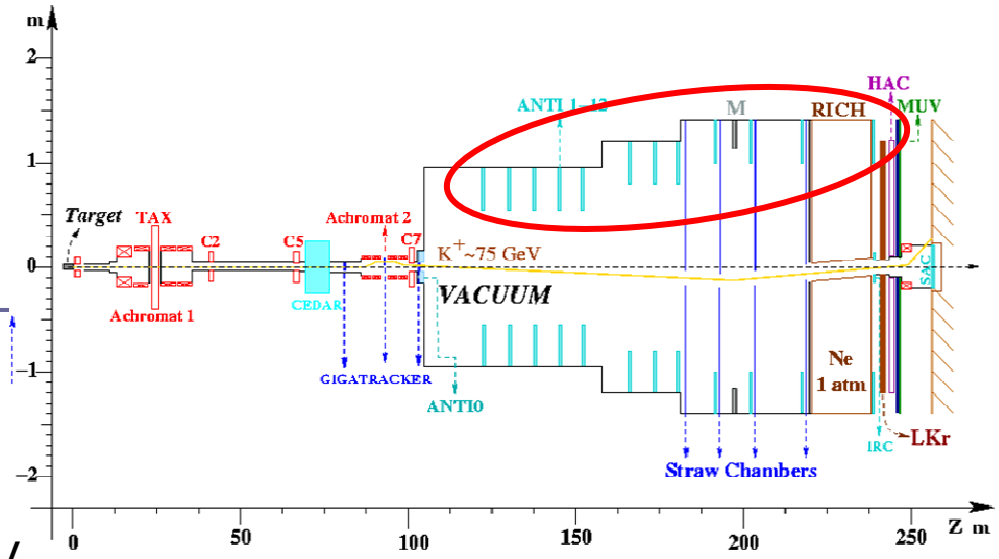
Energy Resolution



Cluster time Resolution



Photon Vetoes

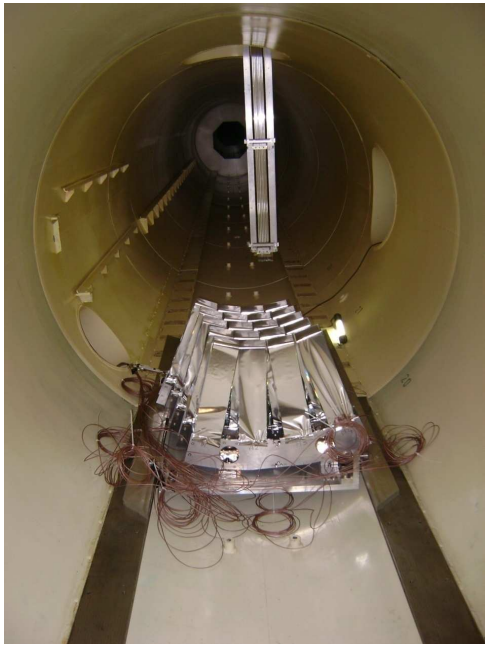


Requirements

10<acceptance<50 mrad

- 10^{-4} inefficiency for $0.05<E_\gamma<1$GeV
- 10^{-5} inefficiency for $E_\gamma>1$GeV

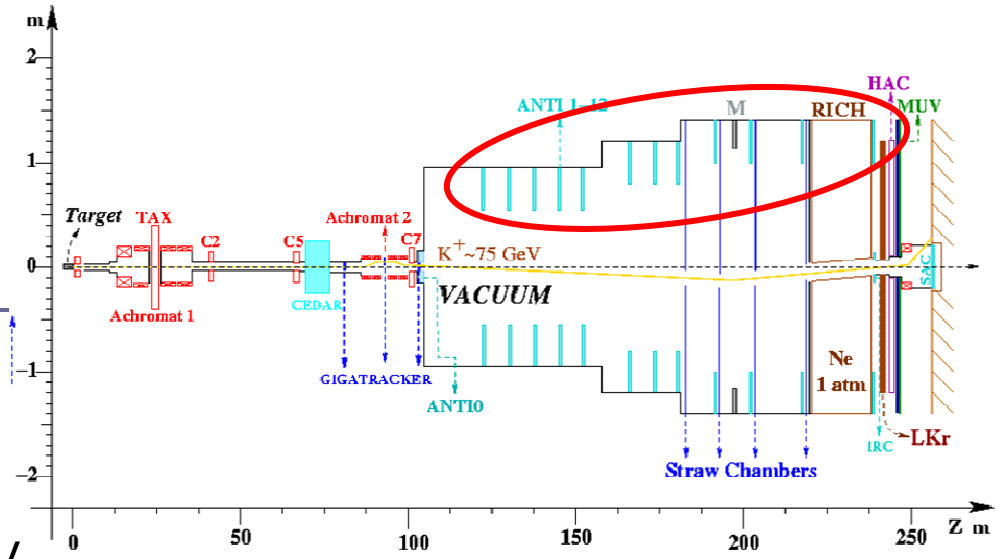
12 LAV stations formed by 4 to 5 overlapping rings of OPAL lead-glasses



A 20 blocks LAV prototype tested at CERN

μ and K from the 2nd to the 6th of October '08

Photon Vetoes

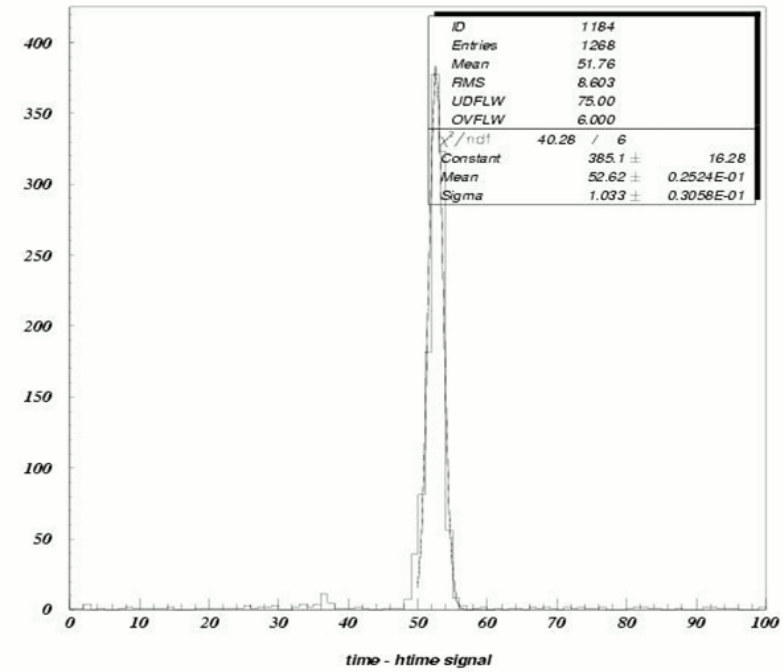


Requirements

10<acceptance<50 mrad

- 10^{-4} inefficiency for $0.05<E_\gamma<1$GeV
- 10^{-5} inefficiency for $E_\gamma>1$GeV

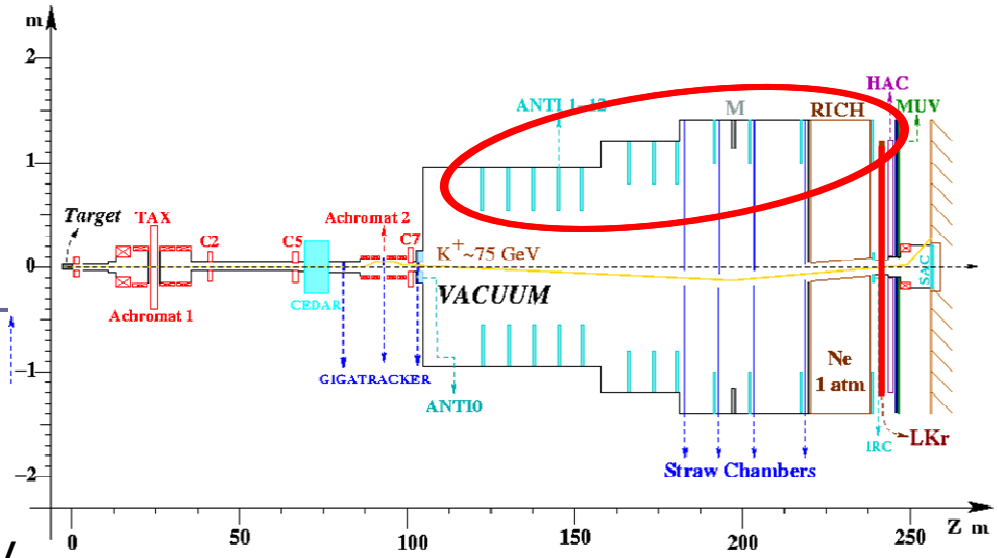
12 LAV stations formed by 4 to 5 overlapping rings of OPAL lead-glasses



Preliminary time resolution with kaons

σ_t = 1.02 ns

Photon Vetoes



Requirements

10<acceptance<50 mrad

- 10^{-4} inefficiency for $0.05<E_\gamma<1$GeV
- 10^{-5} inefficiency for $E_\gamma>1$GeV

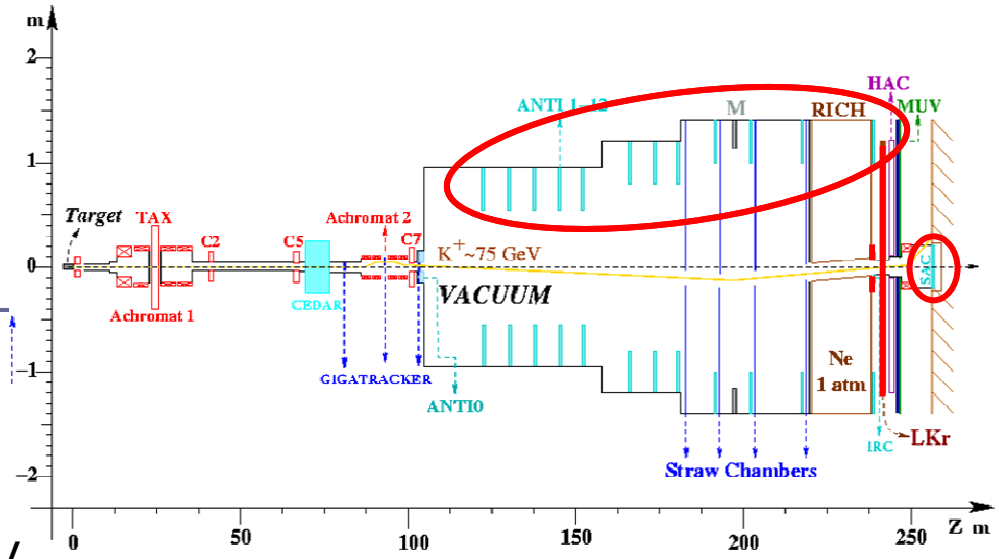
1<acceptance<10 mrad

- 10^{-4} inefficiency for $1<E_\gamma<5$GeV
- 10^{-5} inefficiency for $E_\gamma>5$GeV

NA48 calorimeter

$10m^3$ of liquid Kr, ~13000 cells, 2×2 cm2, $27X_0$

Photon Vetoes



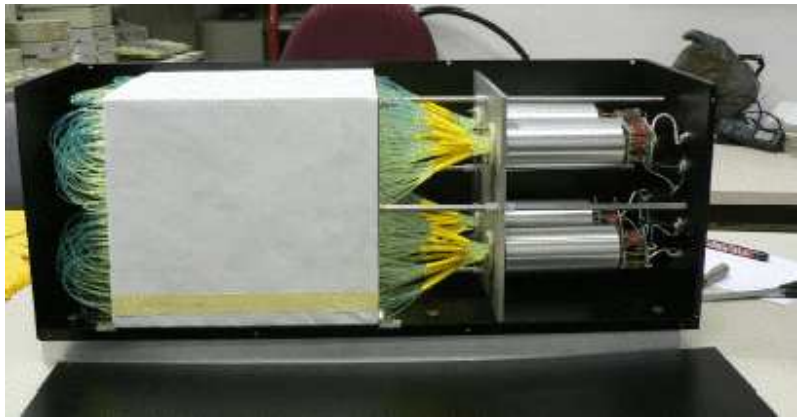
Requirements

10<acceptance<50 mrad

- 10^{-4} inefficiency for $0.05<E_\gamma<1$GeV
- 10^{-5} inefficiency for $E_\gamma>1$GeV

1<acceptance<10 mrad

- 10^{-4} inefficiency for $1<E_\gamma<5$GeV
- 10^{-5} inefficiency for $E_\gamma>5$GeV



acceptance<1 mrad

- 10^{-4} inefficiency (high energy photons)

Lead and scintillator planes+fibers
Prototype tested in October 2006
with 25 GeV SPS electron beam
using the NA48 setup

Conclusions

NA62: R_K measurement

- The analysis of a partial data sample (~40%) is well advanced and aims at a preliminary R_K result with ~0.7% accuracy
- The analysis demonstrates that the overall uncertainty of 0.4%, as declared in the proposal, is within reach

NA62: $K \rightarrow \pi \nu \nu$ measurement

- The experiment has been approved by the CERN SPSC and Research Board
- The Collaboration is in the phase of completing the R&D and preparing the construction
- Construction is foreseen during the 2009-2011 period data taking should start in 2011-2012

A stringent test of SM is within reach

Spares

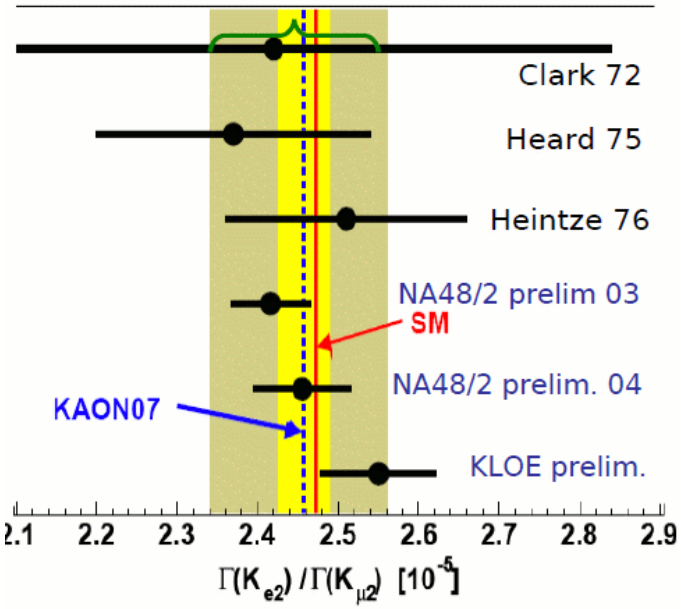
NA48/2 and KLOE Preliminary Results

- 2003 data
  - $(4670 \pm 77_{stat}{}^{+29}_{-8\ syst})$ events $R_K = (2.416 \pm 0.043 \pm 0.024) \cdot 10^{-5}$
  - Trigger efficiency is the biggest systematic effect
- 2004 data
  - $(3407 \pm 63_{stat} \pm 54_{syst})$ events $R_K = (2.455 \pm 0.045 \pm 0.041) \cdot 10^{-5}$
  - The biggest systematic is the $K_{\mu 2}$ background subtraction
- KLOE
  - ~8000 events [arXiv:0707.4623]
  - Based on 1.7 fb^{-1}

$$R_K = (2.55 \pm 0.05 \pm 0.05) \cdot 10^{-5}$$

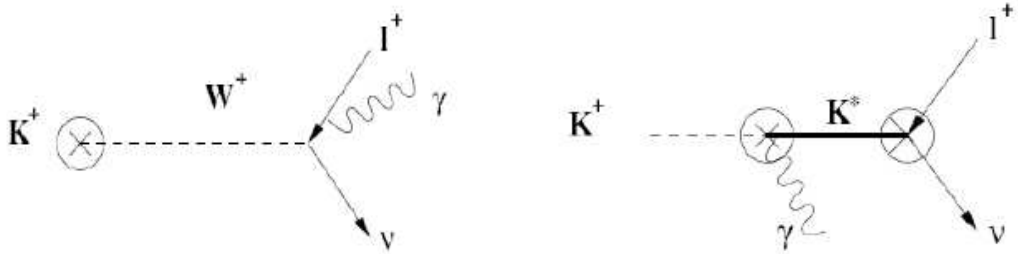
- Combining results
  - Great improvement w. r. to PDG

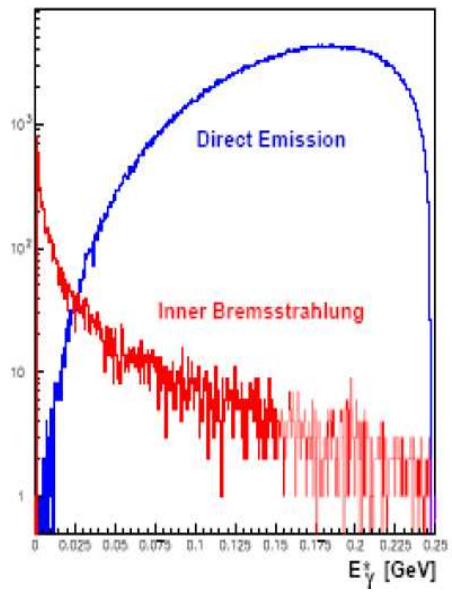
$$R_K = (2.457 \pm 0.032) \cdot 10^{-5}$$



Radiative Corrections

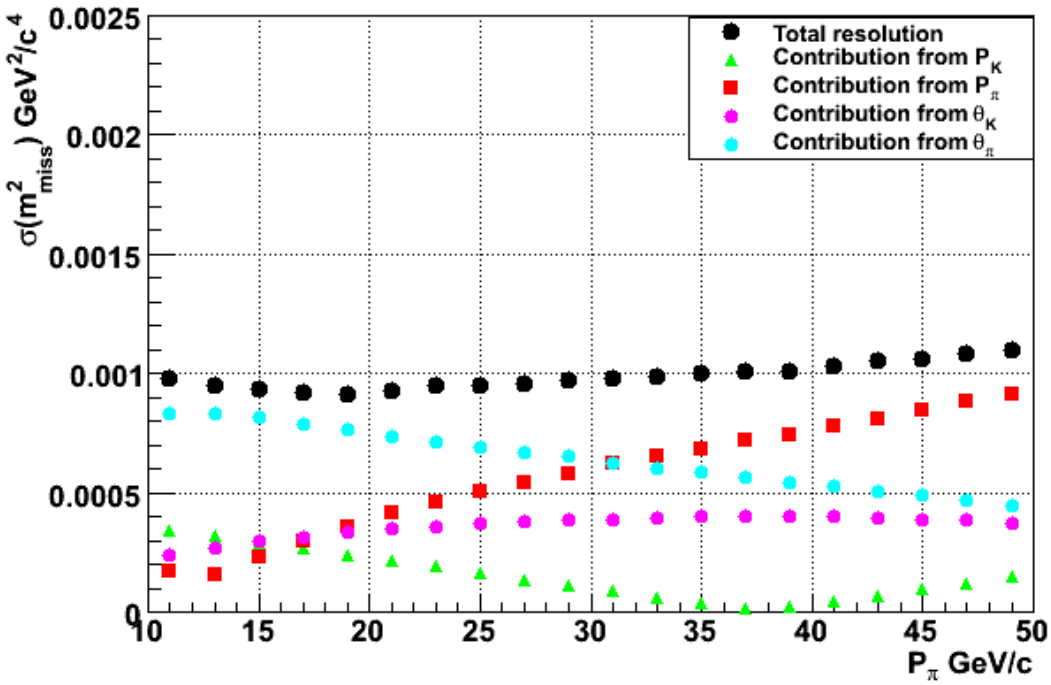
- Radiative decays receive 2 types of contribution: inner bremsstrahlung (IB) and structure-dependent (SD)





- SD gives the dominant contribution to K_{e2} decay rate
- All experiments measure inclusive $\Gamma(K_{e2(\gamma)})/\Gamma(K_{\mu 2(\gamma)})$ and subtract the dominant contribution
- There are more than one model for SD process, which lead to quite different E_γ spectra
- Effects on acceptance

Missing Mass Resolution



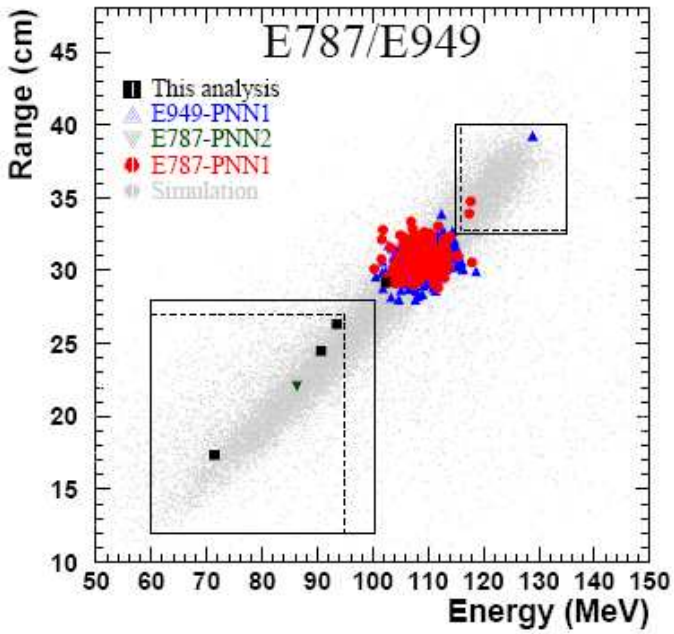
Outlook

- $K^0_L \rightarrow \pi^0 \nu\nu$
  - State of the art: KEK E391a
  - Prospects (short term) : J-PARC E14;
  - Prospects (long term) : KLOD@U70, Project X (à la KOPIO), CERN
- $K^+ \rightarrow \pi^+ \nu\nu$
  - State of the art: BNL E787/E949
  - An In flight experiment at Fermilab (CKM) was cancelled
  - Prospects: in-flight CERN NA62

Experimental Status: New measurement of the $K^+ \to \pi^+ \nu\nu$ branching ratio (BNL E949)

Three events for the decay $K^+ \to \pi^+ \nu\bar{\nu}$ have been observed in the pion momentum region below the $K^+ \to \pi^+ \pi^0$ peak, $140 < P_\pi < 199$ MeV/c, with an estimated background of $0.93 \pm 0.17(\text{stat.})^{+0.32}_{-0.24}(\text{syst.})$ events. Combining this observation with previously reported results yields a branching ratio of $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ consistent with the standard model prediction.

2



Process	Background events
$K_{\pi 2}$ TG	$0.619 \pm 0.150^{+0.067}_{-0.100}$
$K_{\pi 2}$ RS	$0.030 \pm 0.005 \pm 0.004$
$K_{\pi 2\gamma}$	$0.076 \pm 0.007 \pm 0.006$
K_{e4}	$0.176 \pm 0.072^{+0.233}_{-0.124}$
CEX	$0.013 \pm 0.013^{+0.010}_{-0.003}$
Muon	0.011 ± 0.011
Beam	0.001 ± 0.001
Total	$0.927 \pm 0.168^{+0.320}_{-0.237}$

TABLE I: Summary of the estimated number of events in the signal region from each background component. Each component is described in the text.