“13th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon (MENU 2013)”

(Rome, September 30 - October 4)

Lepton Flavour Universality & Conservation tests in Kaon decays at CERN

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on behalf of the NA62 collaboration

Outline

- ✧ Kaon Physics and Experiments at **CERN**;
- ✧ Search for **Lepton Number Violation** (LNV):
  - ☑ NA48/2: $K^{\pm} \rightarrow \pi^{\mp}\mu^{\pm}\mu^{\pm}$
- ✧ **Lepton Flavour Universality** (LFU) test:
  - ☑ NA62: $R_K = K \rightarrow e\nu / K \rightarrow \mu\nu$
- ✧ Prospects for **Lepton Flavour Violation** (LFV) searches:
  - ☑ NA62: Forbidden modes for LFV tests in K^+, π^0 decays
- ✧ Summary and Outlook

Kaon Physics: LFV/LNV searches

LFV/LNV transitions:

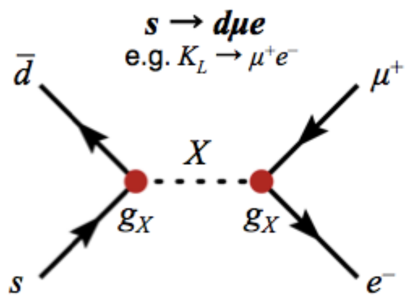
- Rates extremely suppressed in SM extensions including right-handed neutrino
- Larger rates predicted by Supersymmetry (MSSM with/without R-parity)
  [Eur.Phys.J.C22:715-726,2002]
- Any observable rate leads to evidence of NP

Kaon decays:

- SM at energy scale E~M_K provides simple and precise computations
- Event topology gives clean experimental signatures
- High intensity beam facilities
- Sensitivity to very small BRs

K decays are competitive in the search of LFV/LNV phenomena

Very high energy scales accessible, thus sensitivity to tree-level NP contributions



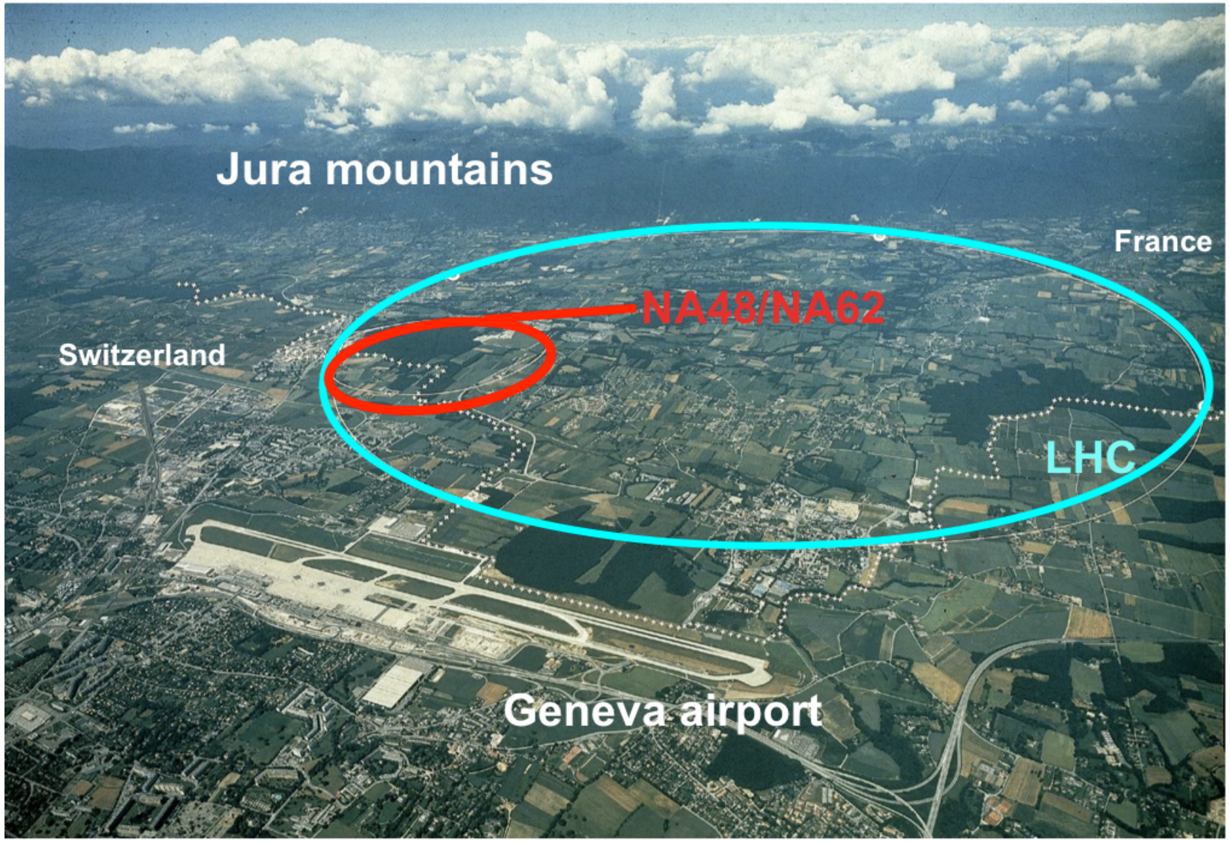
Example with dimensional argument:

$$\frac{\Gamma_{LFV}}{\Gamma_{LFC}} \sim O\left(\frac{g_X^2}{g_W^2} \cdot \frac{M_W^2}{M_X^2}\right)$$

$$for: g_X \sim g_W : BR \sim 10^{-12}$$
$$M_X \sim 100 TeV$$

Kaons at CERN SPS

NA48/NA62 a series of experiments, present-day CERN Kaon physics programme



NA62 primary goal:
Measure BR($K^+ \to \pi^+ \nu\bar{\nu}$) with 10% accuracy

NA48 discovery of direct CPV
- 1997: ε'/ε: K_L+K_S
- 1998: K_L+K_S
- 1999: K_L+K_S | K_S HI
- 2000: K_L only | K_S HI
- 2001: K_L+K_S | K_S HI

NA48/1
- 2002: K_S/hyperons

THIS TALK

NA48/2 rare K decays
- 2003: K^+/K^-
- 2004: K^+/K^-

NA62 (R_K phase)
- 2007: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$
- 2008: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$

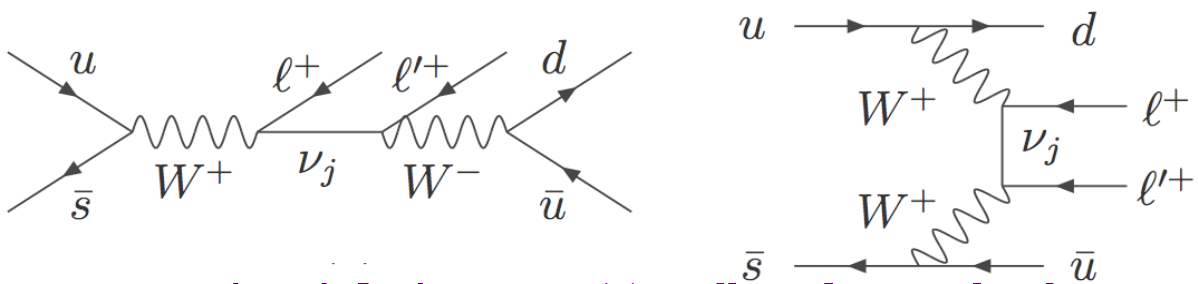
NA62
- 2007-2013: design & construction
- 2014-2016: $K^+ \to \pi^+ \nu\bar{\nu}$ data taking

The $K^{\pm} \rightarrow \pi^{\mp}\mu^{\pm}\mu^{\pm}$ decay

LNV in $K^{\pm} \rightarrow \pi^{\mp}\mu^{\pm}\mu^{\pm}$ decay:

- $|\Delta L| = 2$ transition mediated by ν exchange, if ν is **Majorana** particle;
- Coupling sensitive to effective ν mass (kinematically allowed if $\mathbf{m_\pi < m_\nu < m_K}$);
- Best way to search for $|\Delta L_\mu| = 2$ transitions

$$K^+ \rightarrow \pi^- \ell^+ \ell'^+, \text{ where } \ell^+\ell'^+ = e^+e^+, \mu^+e^+ \text{ or } \mu^+\mu^+$$

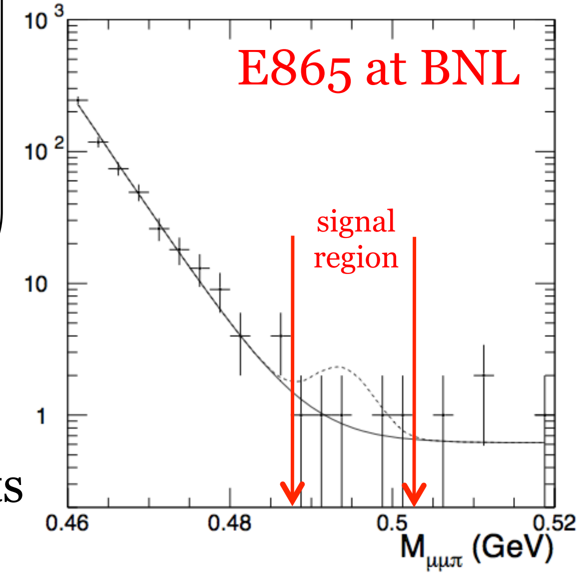


BSM R-parity violation: transition allowed at tree level at rates close the present experimental limit [PLB 491 (2000) 285]

Neutrino-less double beta ($0\nu 2\beta$) decay of nuclei & $\mu \rightarrow e$ conversions.

E865 data taking (1997) to study $K^+ \rightarrow \pi^+\mu^+\mu^-(K_{\pi\mu\mu})$:

- ☑ ~ 400 $K\pi\mu\mu$ events observed [Phys. Rev. Lett. 84, 2580 (2000)]
- ☑ background study used to estimate $K^+ \rightarrow \pi^-\mu^+\mu^+$ ($K_{\mu\mu\pi}$) events



Bkg estimation: fit with empirical function from $K_{\pi\mu\mu}$ analysis

$$\boxed{Br(K^+ \rightarrow \pi^-\mu^+\mu^+) < 3.0 \times 10^{-9} \text{ (90\%C.L.)}}$$

[Phys. Rev. Lett. 85 (2000) 2877]

NA48/2 Detector

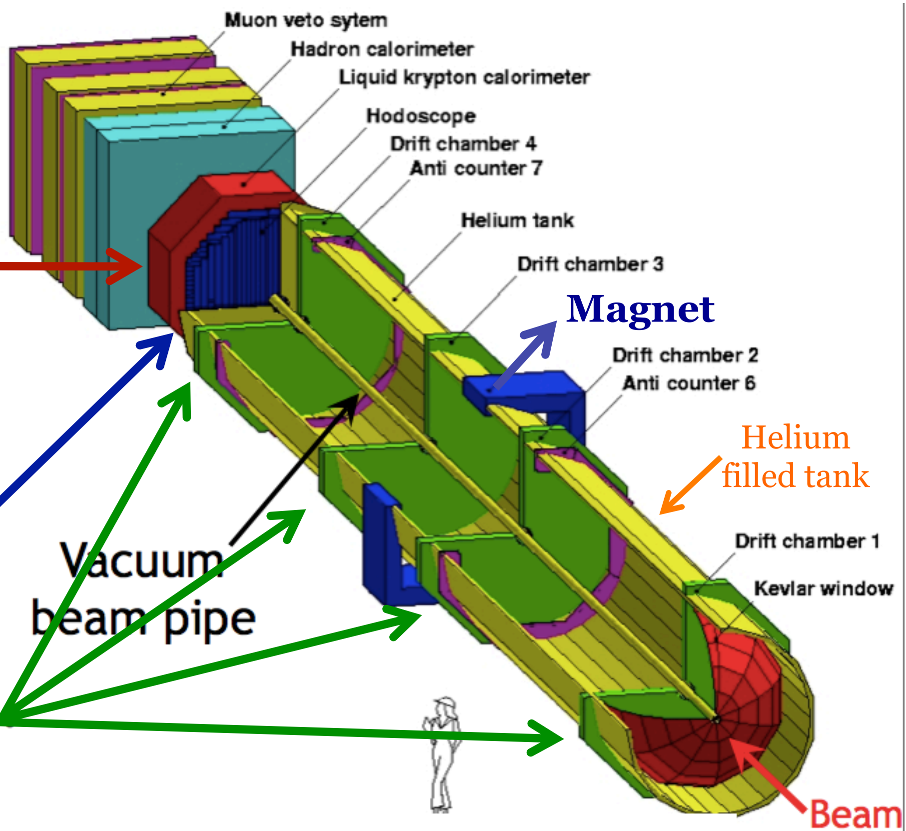
Data Taking: **2003-2004** (6 months)
Primary **SPS protons** (400 GeV/c) on Be target;
Unseparated secondary beam: (60 ± 3) GeV/c (rms);
Simultaneous $K^{\pm}$ highly collimated beams
~ **2×10^{11}** K decays in fiducial volume;

Main subdetectors :

Liquid Krypton EM calorimeter (LKr):
High granularity, quasi-homogeneous;
$\sigma_E/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\%$ [GeV]
$\sigma_x=\sigma_y=4.2/\sqrt{E} + 0.6$mm (1.5mm@10GeV)

Hodoscope (Hodo):
fast trigger, precise time measurement (150ps)

Spectrometer (4 DCHs + Magnet):
$P_\perp$ kick ~ 120 MeV/c
$\sigma_p/p = 1.02\% + 0.044\%\cdot p$ [GeV/c]



decay volume is upstream

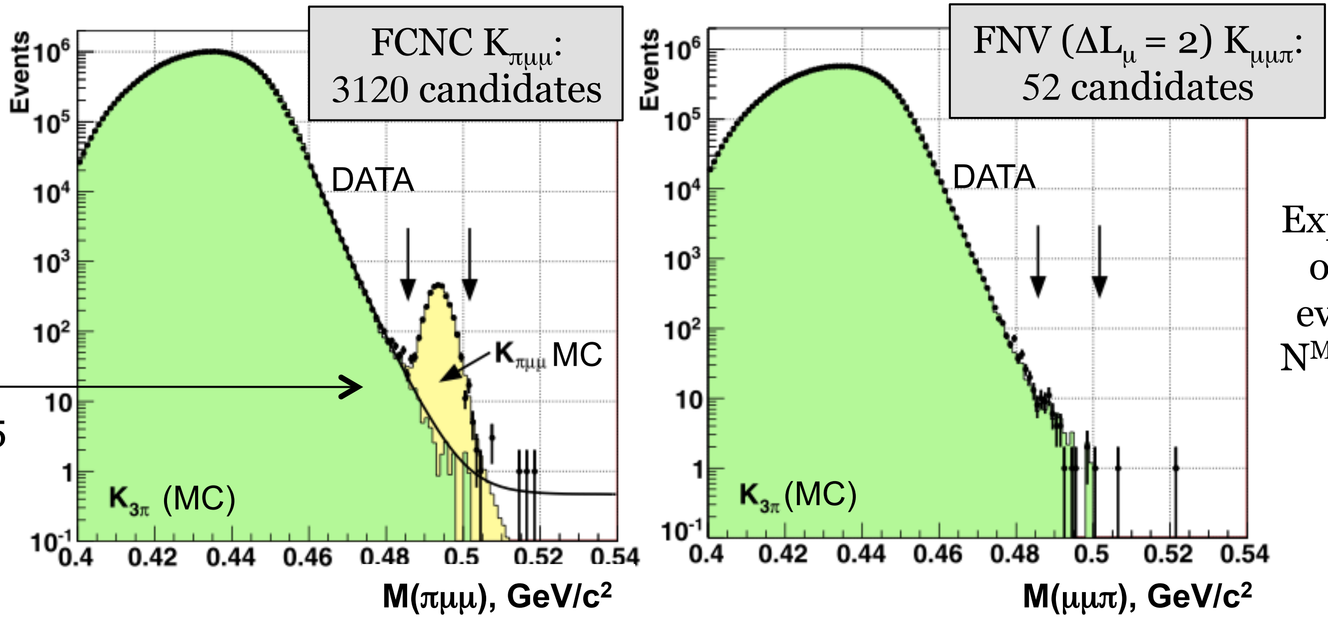
NA48/2: $K^\pm \to \mu^\pm \mu^\pm \pi^\mp$ Upper Limit

$K^\pm \to \pi^\pm \mu^\pm \mu^\mp$ ($K_{\pi\mu\mu}$) rate measured relative to $K^\pm \to \pi^\pm \pi^+ \pi^-$ ($K_{3\pi}$) normalization channel

- $K_{\pi\mu\mu}$ and $K_{3\pi}$ samples collected concurrently using same trigger (3-trk at Hodo)
- 3-track vertices reconstructed by extrapolation of DCH tracks (+ MUV hits for $K_{\pi\mu\mu}$)

Invariant mass distributions for correct vs wrong-sign events

Mass spectrum fit with empirical function as performed by E865



Expected number of background events from MC $N^{MC} = 52.6 \pm 19.8$

$BR(K^\pm \to \pi^\mp \mu^\pm \mu^\pm) < 1.1 \times 10^{-9}$ @ 90% CL [PLB 697(2011)107]

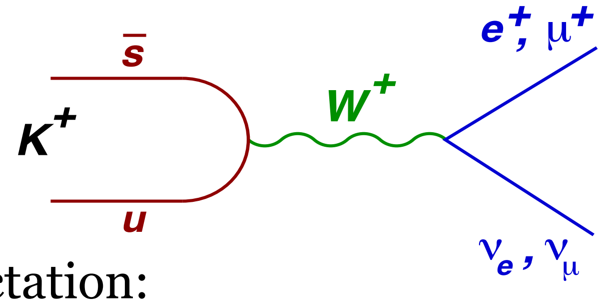
×3 improvement wrt previous measurement

Prospects for sensitivity enhancement wrt current experimental limit:

- × 10 with data re-analysis: improved MUV event reconstruction & bkg determination
- × 1000 with NA62 detector: ×50 kaon decays in FV, lower bkg contamination

NA62 (R_K phase): LFU test

A precise measurement of the ratio R_K of $K^{\pm}\rightarrow l^{\pm}\nu_l$ (K_{l2}) leptonic decays provides a stringent test of SM and indirect search for New Physics.



- Hadronic uncertainties cancel in the ratio $K_{e2}/K_{\mu2}$
- SM prediction: excellent sub-permille accuracy

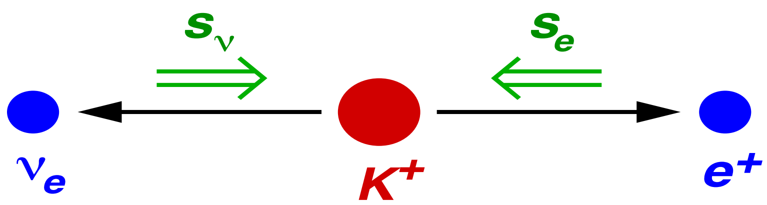
R_K is sensitive to lepton flavour violation and its SM expectation:

$$R_K = \frac{\Gamma(K^{\pm}\rightarrow e^{\pm}\nu)}{\Gamma(K^{\pm}\rightarrow \mu^{\pm}\nu)} = \underbrace{\frac{m_e^2}{m_\mu^2}}_{\text{Helicity suppression: } f\sim10^{-5}} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot \underbrace{(1+\delta R_K^{\text{rad.corr.}})}$$

Helicity suppression: f~10^{-5}

Radiative correction (few %) due to $K^+\rightarrow e^+\nu\gamma$ (IB) process, by definition included into R_K

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



Helicity suppression of R_K might enhance sensitivity to non-SM effects to an experimentally accessible level

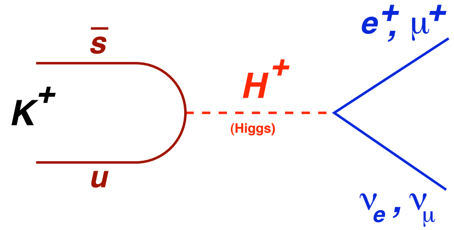
R_K^{SM} = $(2.477\pm0.001)\times10^{-5}$

Phys. Rev. Lett. 99 (2007) 231801

NA62 (R_K phase): beyond the SM

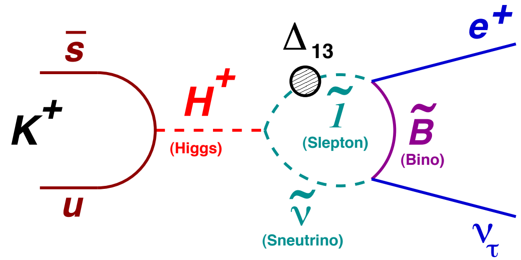
In MSSM the presence of LFV terms (charged Higgs coupling) introduces extra contributions to the SM amplitude, enhancing the decay rate.

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



Tree level

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



One-loop level

PRD 74 (2006) 011701,
JHEP 0811 (2008) 042

R-parity MSSM predicts up to ~1% effect: [Girrbach, Nierste, arXiv:1202.4906]

-> R_K enhancement experimentally accessible

Experimental status:

KLOE result (PDG 2010): $R_K = (2.493 \pm 0.031) \times 10^{-5}$ ($\delta R_K/R_K = 1.3\%$) (EPJ C64 (2009) 627)

NA62 (R_K phase) goal: measurement of R_K with accuracy better than 1%

NA62 (R_K phase) detector

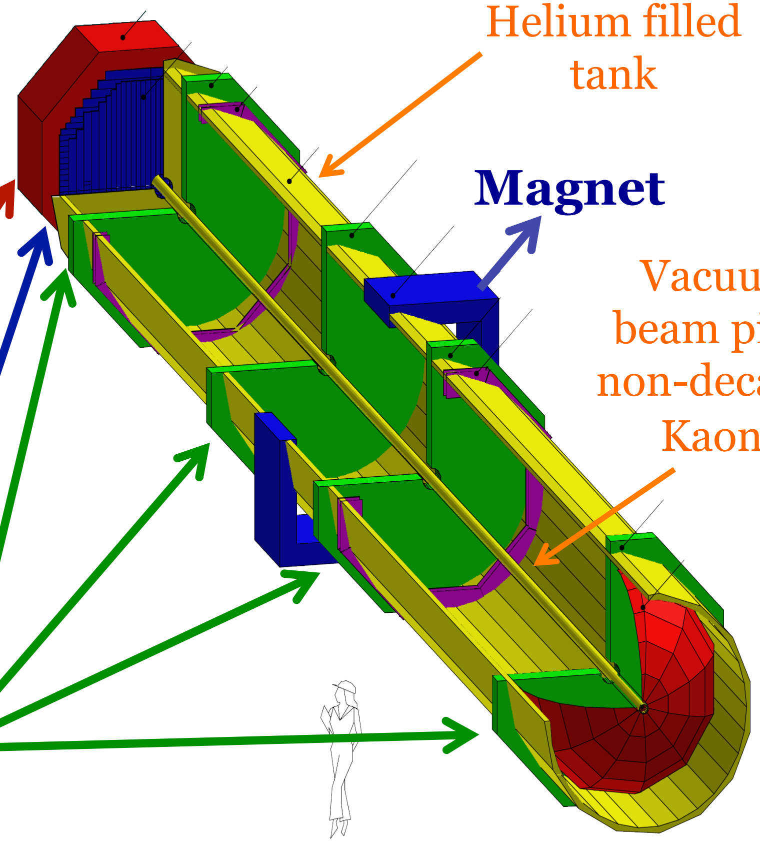
Data Taking: **2007-2008** (4 months)
Primary **SPS protons** (400 GeV/c) on Be target;
Unseparated secondary beam: (74 ± 2) GeV/c (rms);
~ **2×10^{10}** K decays in fiducial volume;

Main subdetectors
from its predecessor NA48/2:

Liquid Krypton EM calorimeter (LKr):
High granularity, quasi-homogeneous;
$\sigma_E/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\%$ [GeV]
$\sigma_x=\sigma_y=4.2/\sqrt{E} + 0.6$mm (1.5mm@10GeV)

Hodoscope:
fast trigger, precise time measurement (150ps)

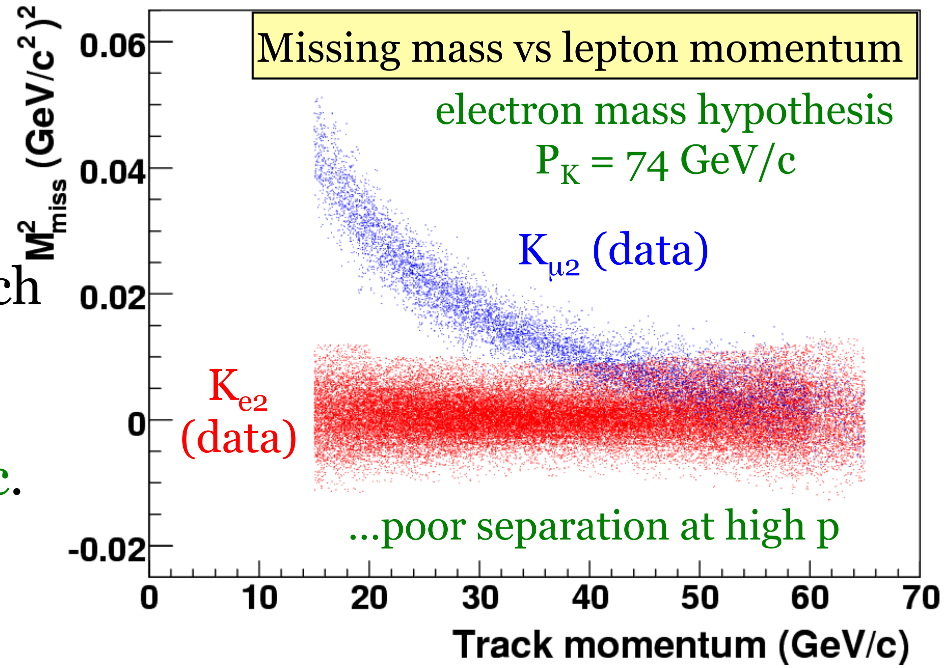
Spectrometer (4 DCHs + Magnet):
4 views/DCH ⇒ high efficiency;
$\sigma_p/p = 0.48\% + 0.009\%\cdot p$ [GeV/c]



K_{e2} & $K_{\mu2}$ Event Selections

Large common part (topological similarity)

- one reconstructed track;
- geometrical acceptance cuts;
- K decay vertex: closest distance of approach between track & kaon axis;
- veto extra LKr energy deposition clusters;
- track momentum: 13GeV/c < p < 65GeV/c.



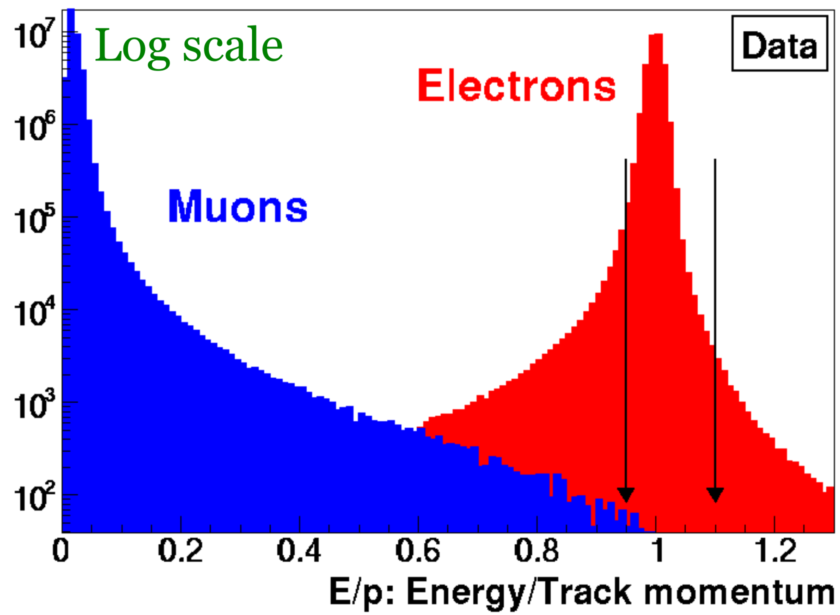
Kinematic identification

- 2 body decay $M^2_{miss} = (P_K - P_l)^2$ (kaon momentum measured with $K_{3\pi}$ decays)
- sufficient $K_{e2}/K_{\mu2}$ separation up to 25GeV/c

Particle Identification

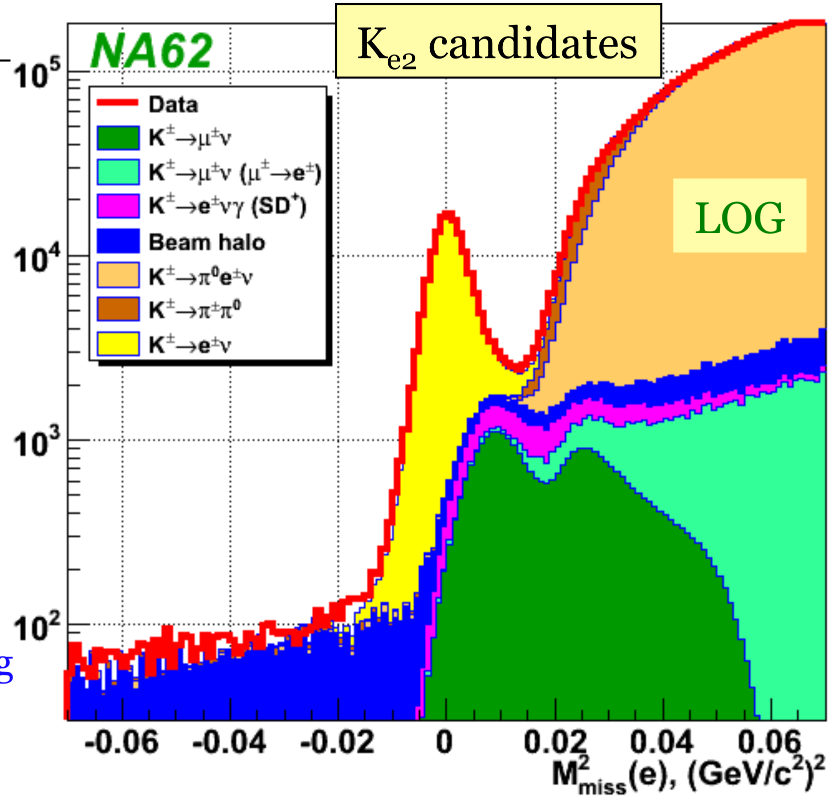
- E/p = (LKr energy deposit/track momentum)
- (0.9 to 0.95) < E/p < 1.10 for electrons
- E/p < 0.85 for muons

➔ Powerful $\mu^{\pm}$ suppression in $e^{\pm}$ sample: ~10^6



K_{e2} : NA62 Full Data Set

145,958 $K^+ \to e^+\nu$ candidates.
Electron ID efficiency: (99.28±0.05)%.
B/(S+B) = (10.95±0.27)%.

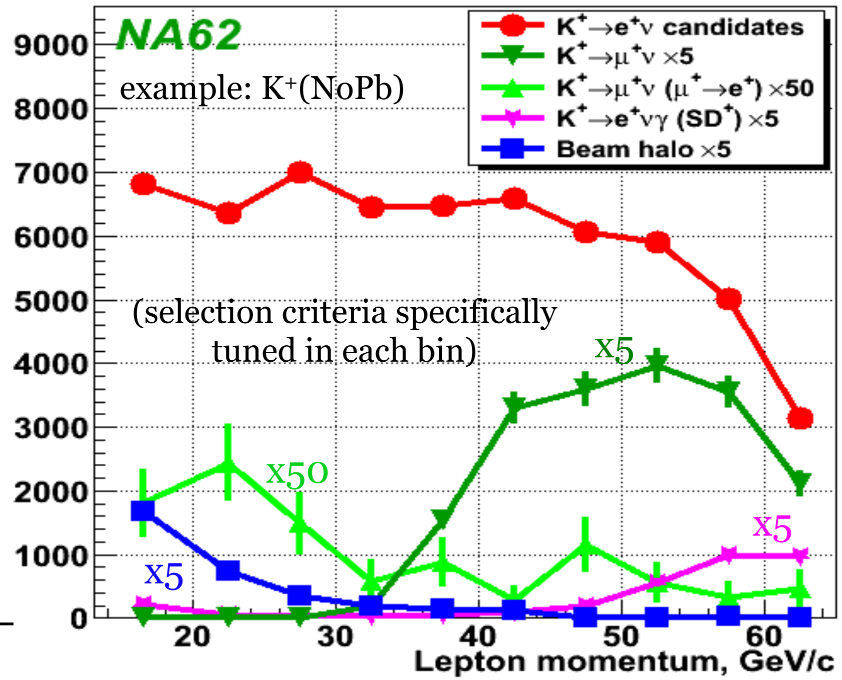


cf. KLOE:
13.8K candidates (K^+ and K^-), ~90% electron ID efficiency, 16% bkg

K_{e2} candidates and backgrounds in momentum bins

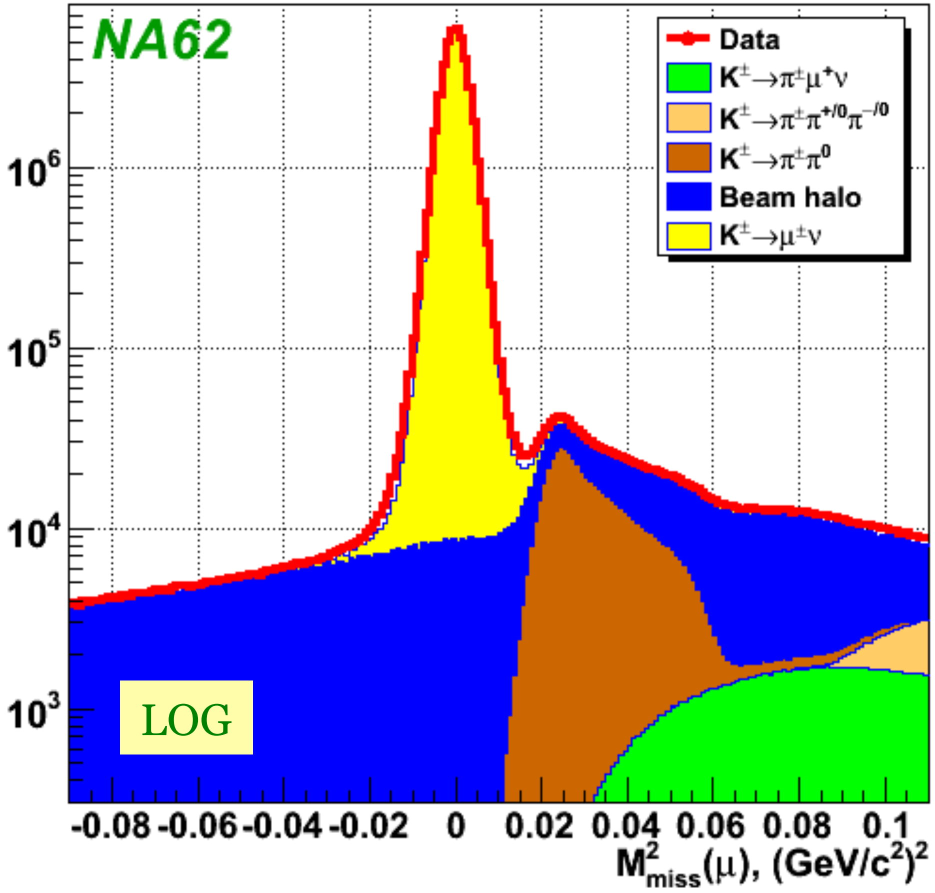
K_{e2} background sources:

▪ $K_{\mu 2}$	(5.64±0.20)%
▪ $K_{\mu 2}$ (μ decay)	(0.26±0.03)%
▪ $K_{e2\gamma}$ (SD$^+$)	(2.60±0.11)%
▪ Beam halo	(2.11±0.09)%
▪ K_{e3}	(0.18±0.09)%
▪ $K_{2\pi}$	(0.12±0.06)%
▪ Wrong sign K	(0.04±0.02)%
Total	**(10.95±0.27)%**

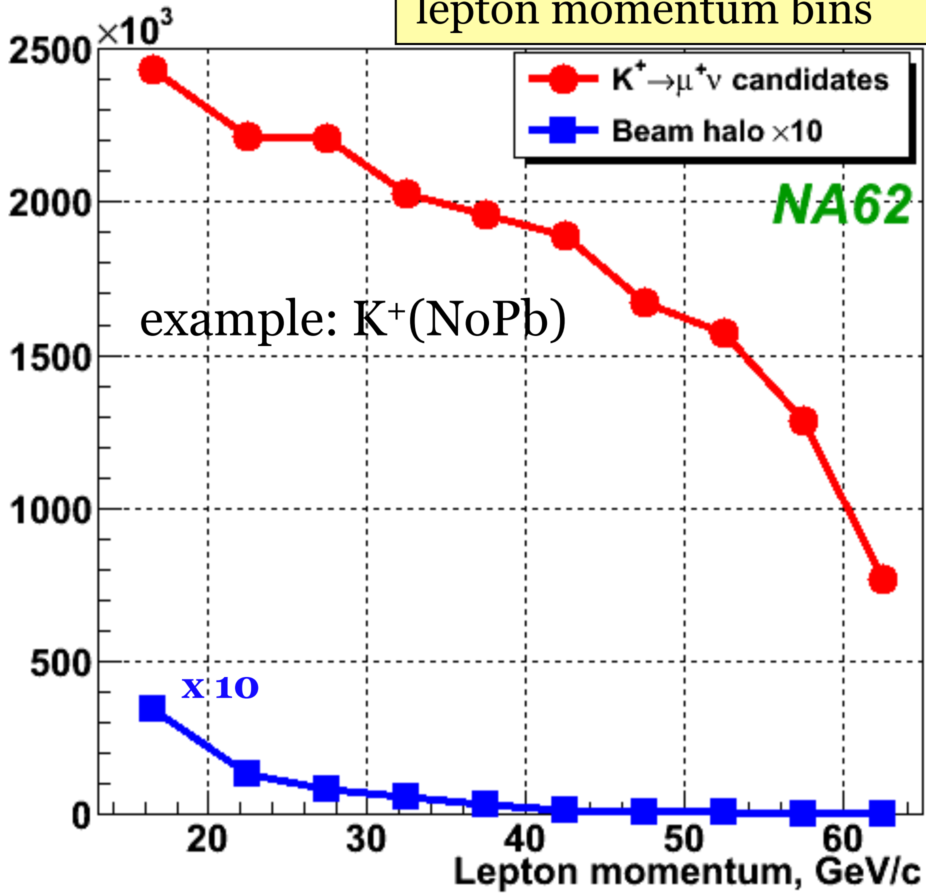


$K_{\mu 2}$: NA62 Full Data Set

$K_{\mu 2}$ candidates



$K_{\mu 2}$ candidates and bkg in lepton momentum bins



42.817M $K^+\to\mu^+\nu$ candidates
(pre-scaled trigger)

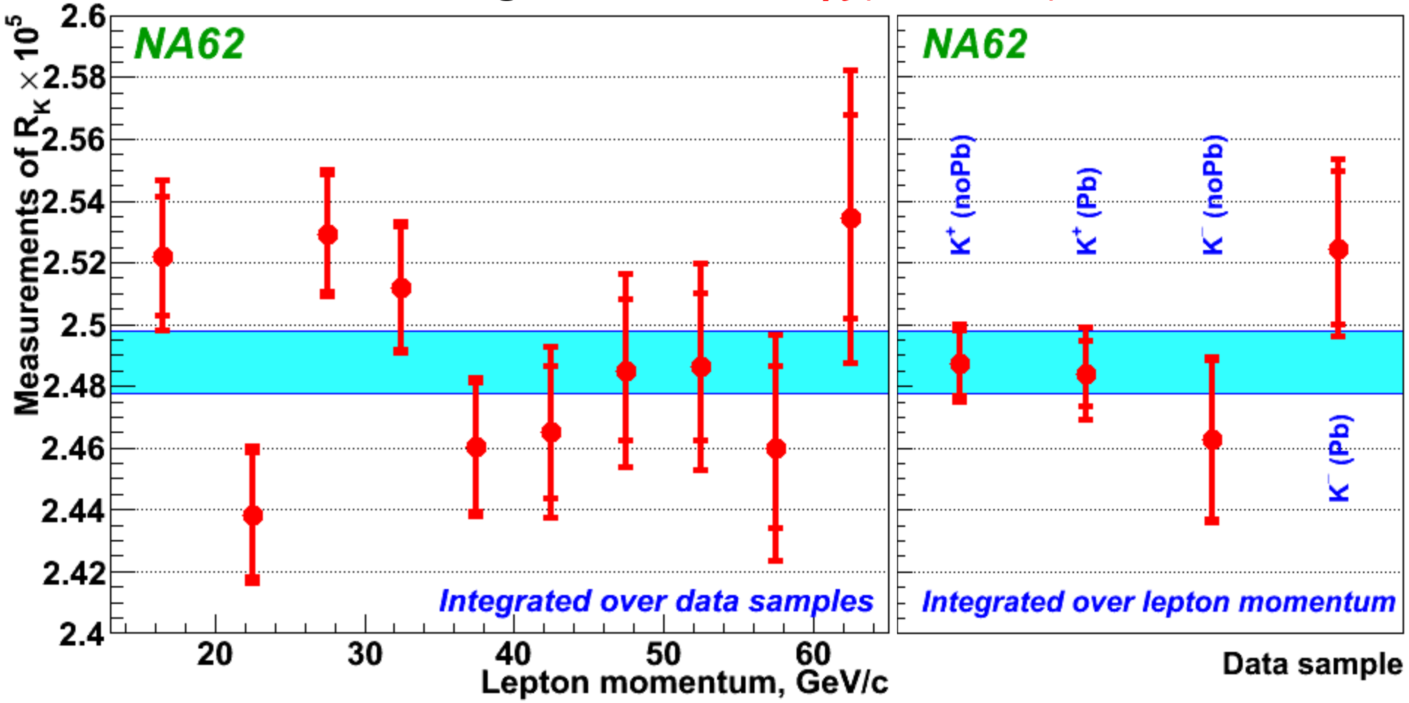
B/(S+B) = (0.50±0.01)%
Background dominated by beam halo

NA62 (R_K phase): Final Result

$$R_K = (2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^{-5}$$
$$= (2.488 \pm 0.010) \times 10^{-5}$$

[PLB 719 (2013) 326]

Fit over 40 measurements (4 data samples x 10 momentum bins) including correlations: $\chi^2/ndf=47/39$



Independent measurements in lepton momentum bins

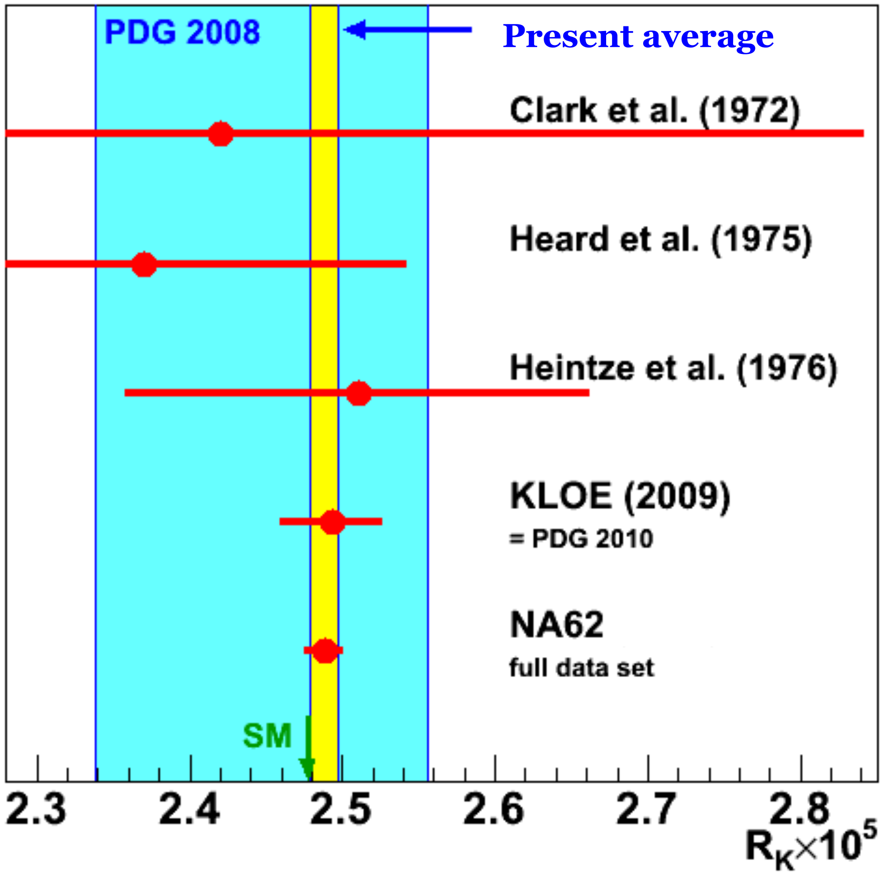
(systematic errors included, partially correlated)

Uncertainties
0.4% tot precision

Source	$\delta R_K \times 10^5$
Statistical	0.007
$K_{\mu 2}$	0.004
BR($K_{e2\gamma}$ SD$^+$)	0.002
Beam halo	0.002
$K^\pm \to \pi^0 e^\pm \nu$, $K^\pm \to \pi^\pm \pi^0$	0.003
Matter Composition	0.003
Acceptance	0.002
DCH alignment	0.001
Electron ID	0.001
LKr readout inef	0.001
1-track trigger	0.001
Total	**0.010**

R_K : World Average

R_K measurement currently in agreement with the Standard Model expectation at ~1.2σ.

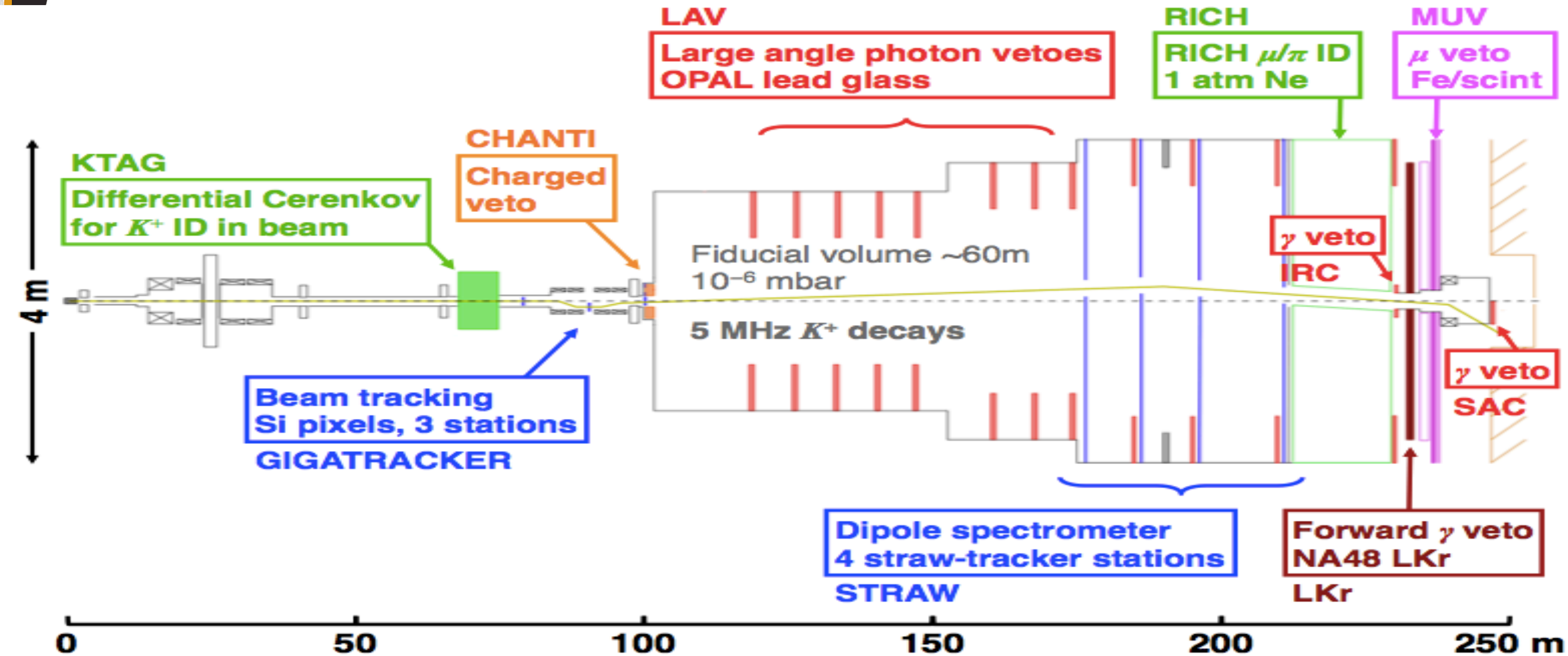


World average	$\delta R_K \times 10^5$	Precision
PDG 2008	2.447±0.109	4.5%
Present	2.488±0.009	0.4%

NA62 prospects: improve the uncertainty by a factor of ~ 2

Any significant enhancement with respect to the Standard Model would be evidence of new physics.

The NA62 Detector



Study of $\mathbf{K^+ \rightarrow \pi^+ \nu\bar{\nu}}$ with K+ decay-in-flight technique (talk from S.Venditti)

BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$)$_{SM}$ ~ 10^{-10} :

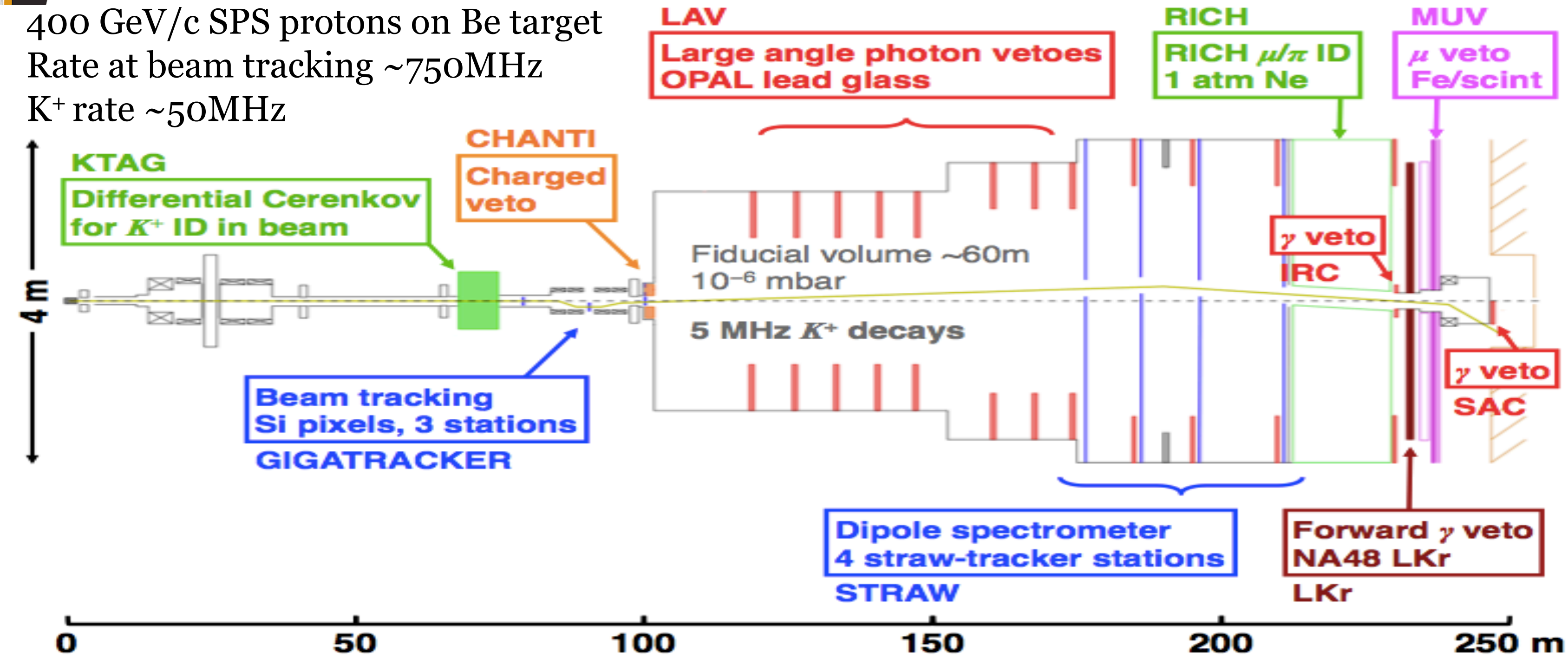
- ✓ Excellent probe for flavour sector in SM, complementary to B physics
- ✓ "Golden" mode for indirect search of NP

Primary NA62 goal: Detect ~100 $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ decays with S/B ~ 10

Secondary NA62 goals: Perform searches in rare & forbidden decays **(this talk) ->** Prospects for LFNV in K^+ and π^0 decays

The NA62 Detector

400 GeV/c SPS protons on Be target
Rate at beam tracking ~750MHz
K^+ rate ~50MHz



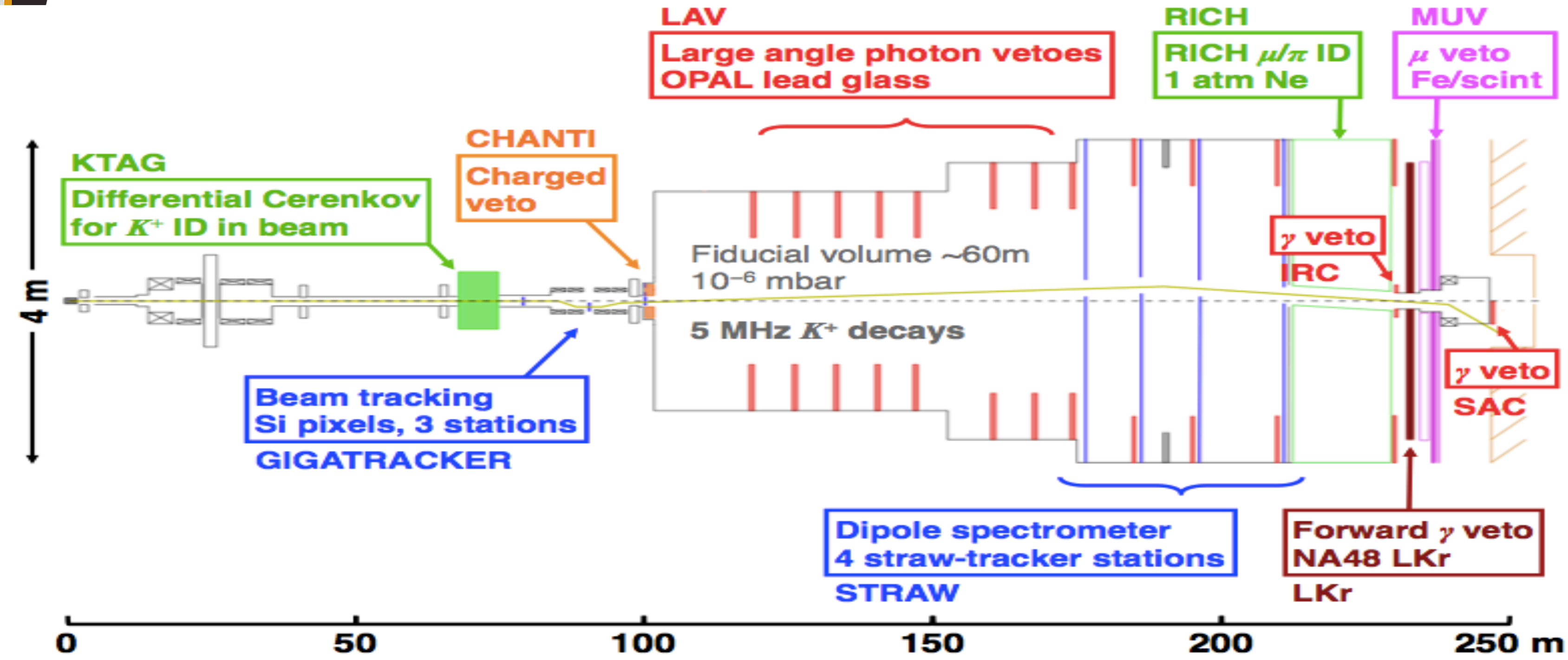
Improvements from NA48/2 to NA62:

✓Total K^+ decays in fiducial volume:	1.9×10^{11}	vs	1.2×10^{13}
✓Secondary hadron beam momentum:	(60 ± 3) GeV/c	vs	(75 ± 1) GeV/c
✓ Momentum $P_\perp$ kick from spectrometer:	120 MeV/c	vs	270 MeV/c
✓ ×2 better mass resolution (i.e. $M(\pi\pi\pi)$):	1.7MeV	vs	0.8 MeV

Main benefits for LFV/LNV searches:

Higher kaon flux - Improved mass reconstruction – Redundant PID – Hermetic Veto

The NA62 Detector



KTAG: non-destructive K^+ ID (σ_t ~100 ps, >99% K purity, 50 MHz operation)

GTK: fast beam tracking ($\delta P/P$~0.2%, ~750 MHz beam flux, σ_t < 200 ps/station)

STRAW: decay product tracking (operation in vacuum, $\delta P/P$<1%)

RICH: ID for daughter pions, muons (reduces μ bkg < 1% up to 35GeV, σ_t < 100 ps)

MUV: hadronic calorimeter and muon veto ($1-\varepsilon < 10^{-5}$ for ID of outgoing μ's)

LAV-LKr-IRC-SAC: hermetic γ veto (0-50 mrad, 5×10^{-8} rejection for $K\to\pi^+\pi^0$)

CHOD: charged hodoscope (scintillator, σ_t < 200 ps)

Prospects for LFNV Searches in K^+ and π^0 decays at NA62

High-intensity experiment allows LFV/LNV searches from K^+ and π^0 decays
Possible improvements on many experimental limits

Decay mode	Physics Interest	UL at 90% CL (Experiment)
$K^+ \to \pi^+ \mu^+ e^-$	LFV	$< 1.3 \times 10^{-11}$ (BNL E777/E865)
$K^+ \to \pi^+ \mu^- e^+$	LFV	$< 5.2 \times 10^{-10}$ (BNL E865)
$K^+ \to \pi^- \mu^+ e^+$	LFNV: $\Delta L_\mu = \Delta L_e = -1$	$< 5.0 \times 10^{-10}$ (BNL E865)
$K^+ \to \pi^- e^+ e^+$	LNV: $\lvert\Delta L_e\rvert = 2$	$< 6.4 \times 10^{-10}$ (BNL E865)
$K^+ \to \pi^- \mu^+ \mu^+$	LNV: $\lvert\Delta L_\mu\rvert = 2$	$< 1.1 \times 10^{-9}$ (NA48/2)
$K^+ \to \mu^- \nu_\mu e^+ e^+$	LNV: $\lvert\Delta L_e\rvert = 2$ or LFV	$< 2.8 \times 10^{-8}$ (Geneva-Saclay)
$K^+ \to e^- \nu_e \mu^+ \mu^+$	LNV: $\lvert\Delta L_\mu\rvert = 2$ or LFV	No Data
$\pi^0 \to \mu^\pm e^\mp$	LFV	$< 3.6 \times 10^{-10}$(KTEV)

- Total number of decays in fiducial volume: 1.2×10^{13} K^+ & 2.5×10^{12} π^0
- Expected Acceptance O(10%)

NA62 SINGLE-EVENT SENSITIVITY(*): ~ 10^{-12} ON K^+ DECAY ~ 10^{-11} ON π^0 DECAY

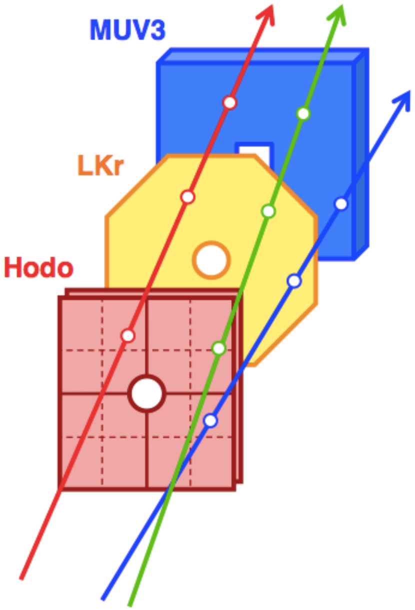
(*)computations: 1/(Acceptance * number of decays)

Trigger for LFNV in NA62

Preliminary studies on secondary NA62 triggers for LFNV decays:

- 3-tracks in the final states
- expected bandwith for 3-tracks trigger ~ 0.5 MHz
- total bandwith available for primary NA62 (level-0) trigger ~ 1 MHz
- trigger on 3-tracks decays not feasible in high rate environment of NA62

Possibility to use level-0 trigger conditions from calorimeters:



Definitions of level-0 trigger primitives:

Q_n	Hits in at least n Hodo quadrants
$LKR_n(x)$	At least n LKr clusters with energy $E > x$ GeV
MUV_n	Hits in at least n MUV3 pads

Level-0 triggers for LFNV searches:

ee pair	$Q_2 \cdot LKR_2(15)$
$e\mu$ pair	$Q_2 \cdot LKR_1(15) \cdot MUV_1$
$\mu\mu$ pair	$Q_2 \cdot MUV_2$

Lepton Pair Level-0 trigger: expected bandwidth ~ few ×10 kHz

Dominated by $K^+ \to \pi^+\pi^+\pi^-$ decays, can be included in NA62 DAQ system design

Summary and Outlook

Search for LNV at NA48/2:

✧Data taking 2003-2004;

✧**UL @ 90% CL: BR($K^{\pm}\rightarrow\pi^{\mp}\mu^{\pm}\mu^{\pm}$) < 1.1×10^{-9}** [PLB 697(2011)107];

✧Prospects of improvements with optimization studies and future detector.

Study of LFU at NA62 (R_K phase):

✧Data taking 2007-2008;

✧Largest sample of 0.15M $K^{\pm}\rightarrow e^{\pm}\nu$ decay candidates [PLB 719 (2013) 326];

✧**BR($K^{\pm}\rightarrow e^{\pm}\nu$)/BR($K^{\pm}\rightarrow\mu^{\pm}\nu$)=$(2.488\pm0.010)\times10^{-5}$ (0.4% precision)**

Future Prospects at NA62:

✧Experiment to measure BR(K^{+} -> $\pi^{+}\nu\bar{\nu}$) with a 10% precision well adapted to study rare/forbidden K^{+} and π^{0} decays;

✧Prospects for improvements on many LFV/LNV experimental limits.

"13th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon (MENU 2013)"

(Rome, September 30 - October 4)

SPARES

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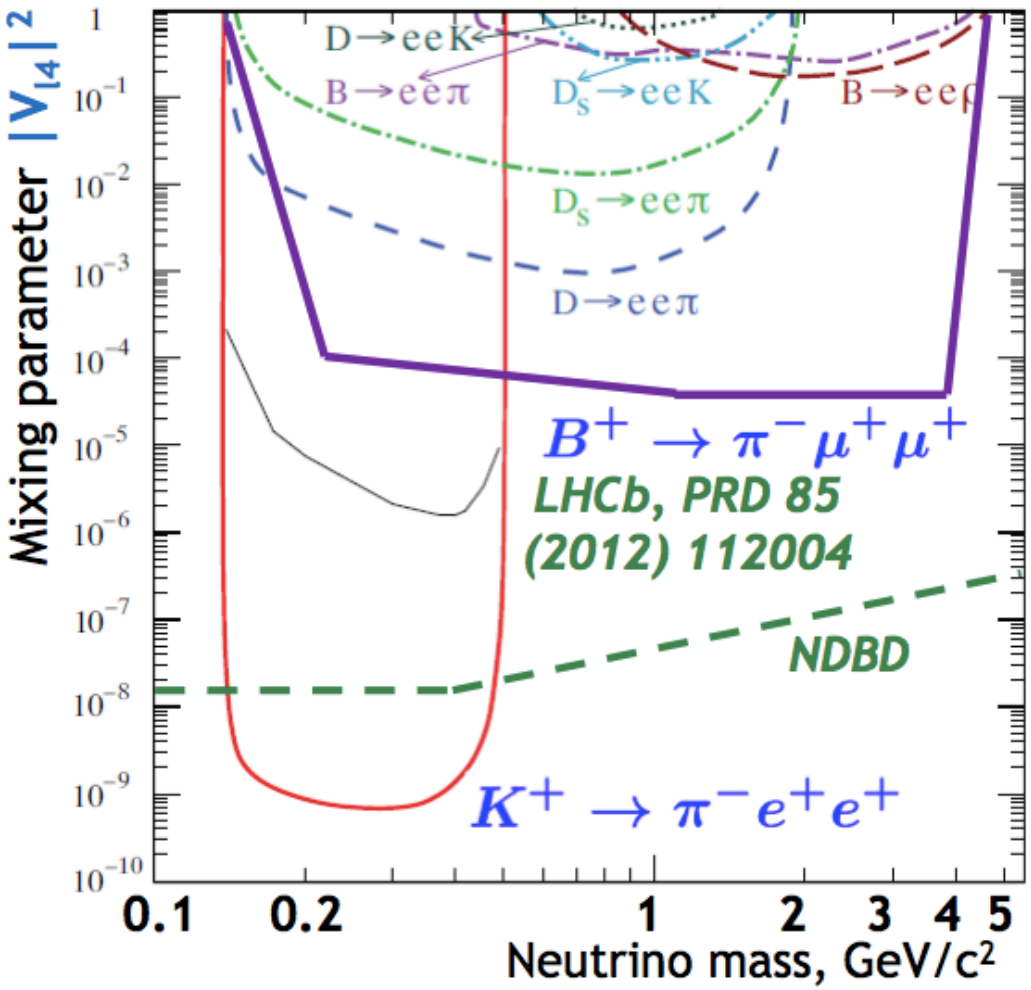
Majorana Neutrino Exclusion Regions



R_K Measurement Strategy

(1) $K_{e2}/K_{\mu2}$ candidates are collected concurrently:
- analysis does not rely on kaon flux measurement;
- several systematic effects cancel in the ratio (at first order);

(2) MC simulations used to a limited extent:
- Geometrical part of the acceptance correction and bkg estimation;

(3) PID, trigger, readout efficiencies and beam halo bkg measured directly from data;

Counting experiment - analysis in 10 lepton momentum bins:
(due to strong momentum dependence of backgrounds and event topology)

Signal events · *Particle ID eff* · *Trigger efficiency*

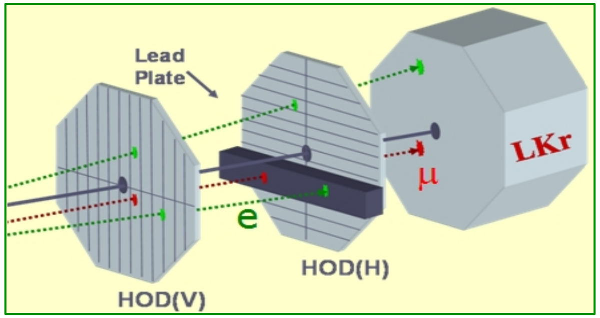
$$R_K = \frac{1}{D} \cdot \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu2}) - N_B(K_{\mu2})} \cdot \frac{f_\mu \cdot A(K_{\mu2}) \cdot \varepsilon(K_{\mu2})}{f_e \cdot A(K_{e2}) \cdot \varepsilon(K_{e2})} \cdot \frac{1}{f_{LKR}}$$

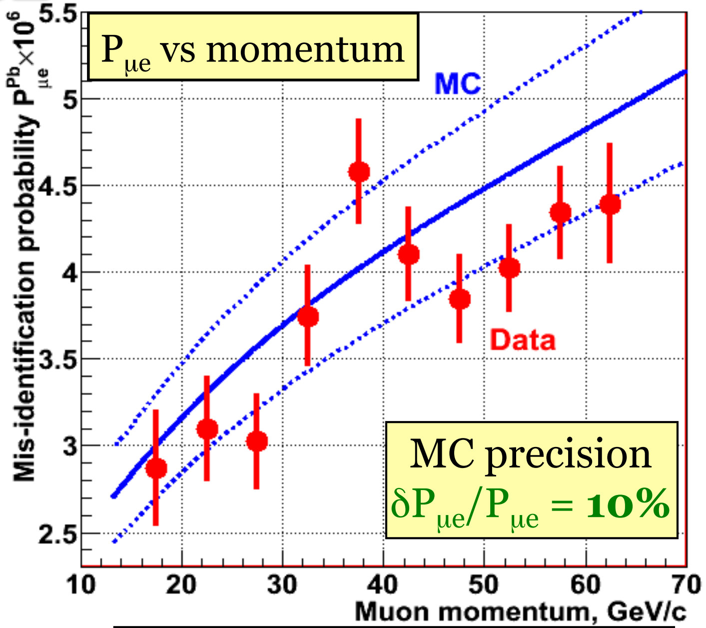
$K_{\mu2}$ downscaling · *Background events* · *Geometrical acceptance* · *Global LKr readout eff*

$K_{\mu 2}$ background in K_{e2} sample

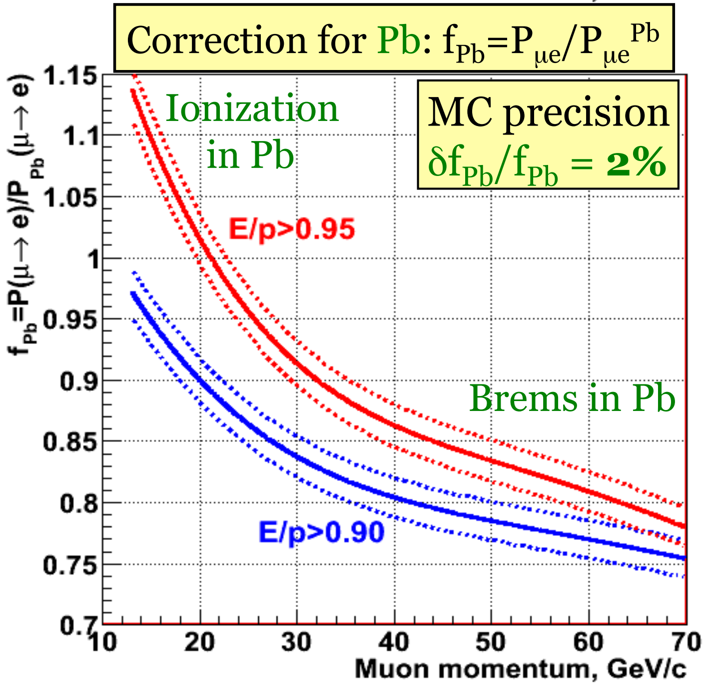
- **<u>The main background in the K_{e2} sample</u>** is due to catastrophic energy loss of muons in the LKr; ($E_{LKr}/p_{DCH} > 0.95$ ➔ misID events as K_{e2})
- **<u>To measure directly $P(\mu\rightarrow e)$</u>**: "lead wall" (~9.2 X_0) installed on ~20% LKr surface for ~50% of the run time;
- **<u>2 data samples</u>**: K^+(Pb), K^-(Pb)

$P(\mu\text{->}e) \sim (3\div5)\cdot10^{-6}$





- $K_{\mu 2}$ candidates, track traversing Pb, p > 30GeV/c, $E/p > 0.95$: electron contamination $< 10^{-8}$;
- The result agrees with Geant4 simulation;
- **<u>$P(\mu\rightarrow e)$ modified by the Pb wall</u>**: the correction f_{Pb} is evaluated with a dedicated Geant4-based simulation;



Result: B/(S+B) = (5.64±0.20)%

Uncertainties: limited control data sample (0.16%), MC correction δf_{Pb} (0.12%), M^2_{miss} vs P_{track} correlation (0.08%).

Beam Halo Background

Electrons produced by beam halo muons via $\mu \to e$ decay can be kinematically and geometrically compatible to genuine K_{e2} decays

Data-driven background measurement:

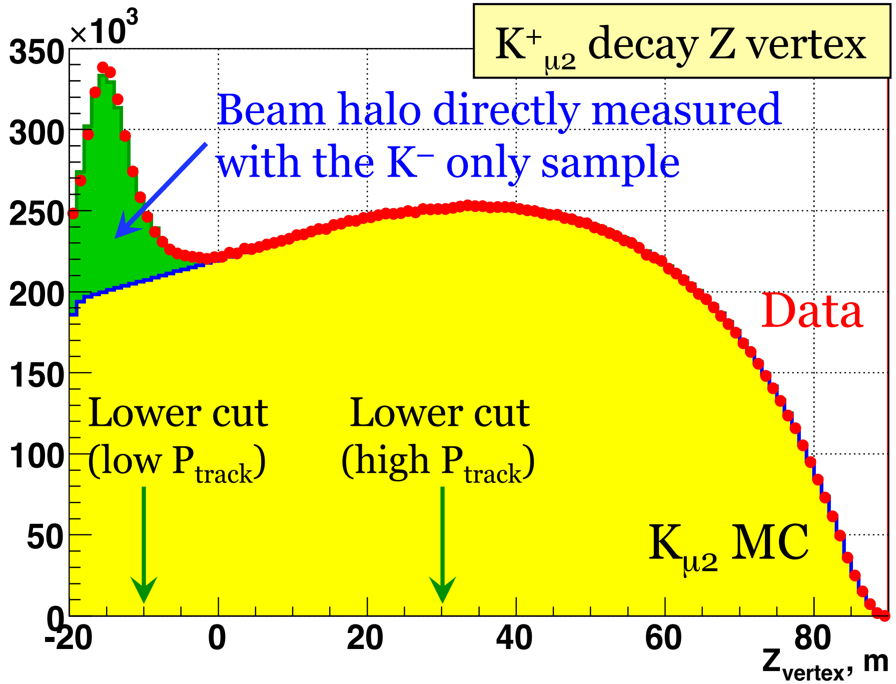
- Halo background much higher for K^-_{e2} (~20%) than for K^+_{e2} (~1%);
- Halo background in the $K_{\mu 2}$ sample is considerably lower;
- Control data samples: ~66% is K^+ only , ~7% is K^- only, ~27% has both;
- K^+ halo component is measured directly with the K^- sample and vice versa;

Background measured at 0.1-0.2% precision and strongly depends on decay vertex position and track momentum.

The selection criteria (esp. Z_{vertex}) are optimized to minimize the halo background.

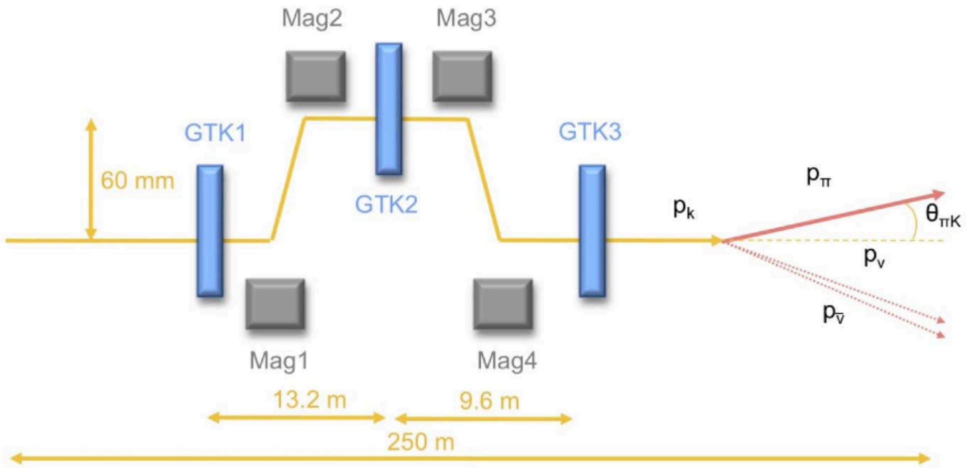
$$B/(S+B) = (2.11 \pm 0.09)\%$$

Uncertainties:
1) limited size of control sample;
2) π, K decays upstream vacuum tank.



Tracking Systems: GTK

Beam tracking: GigaTraKer (GTK)



Tracking of K^+ under the conditions:

➢high and non-uniform beam rate (750 MHz unseparated beam);

➢minimal amount of material on the beam line (< 1%X0);

➢excellent time resolution (~150 ps) match the pion tracking information from downstream detectors;

Spectrometer layout

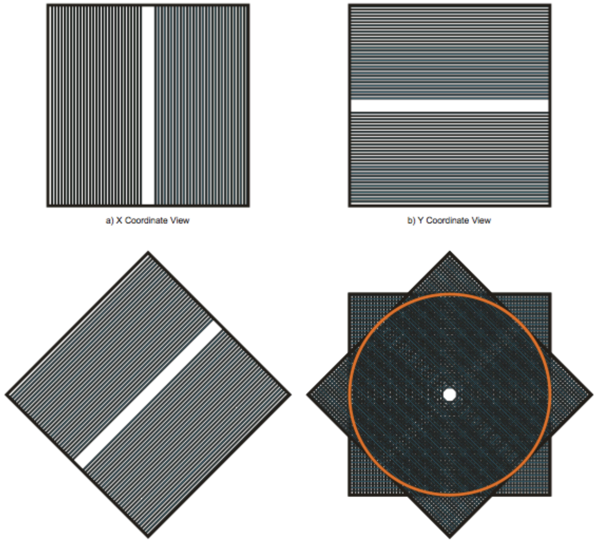
- 3 stations of hybrid silicon pixel detectors
- 4 achromat magnets (beam displacement ~60mm)
- 18, 000 pixels/station of size 300 × 300 μm²

Measurement of $\mathbf{P_K}$ momentum and position

Expected resolutions from simulations: $\sigma_p/p \sim 0.2\%$ and $\sigma_q = 16$ μrad

Tracking Systems: STRAW

Downstream tracking: STRAW



Tracking of secondary charged particles under the conditions:

- operation in vacuum;
- minimum amount of material (≤ 0.5%X0 for each chamber);
- spatial resolution $\sigma \leq 130\mu m$ (1 "View") to reconstruct precisely the intersection between the decay and parent particle;

Measurement of $\mathbf{P}_{\pi}$ momentum and position

Spectrometer layout

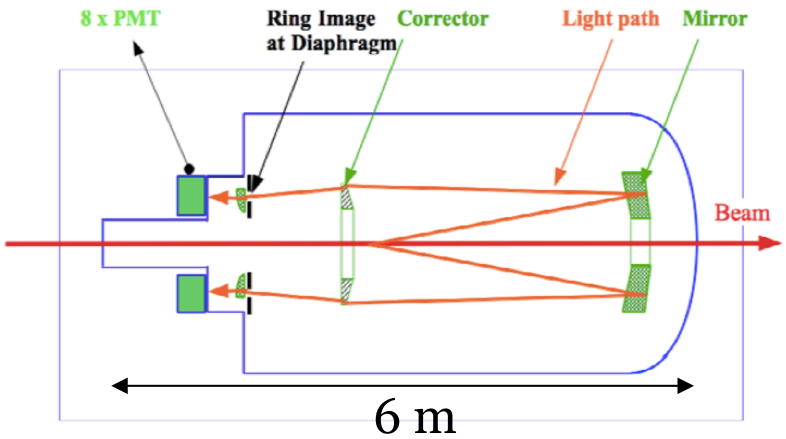
- high aperture dipole magnet (B-field ~ 0.36 T; $\Delta p_{\perp}$ = 270 MeV)
- 4 straw-tube chambers (2.1 m in diameter)
- 1,792 straw tubes/chamber (16 layers - 4 "Views")

One track: measurements of 2 couples of orthogonal coordinates (x,y ; u,v)
Each coordinate: combined info from four layers of straw tubes
Expected resolutions: $\sigma_p/p \sim 0.32\% \oplus 0.008\%\, p$ and $\sigma_{q(Kp)}$ = 20-50 μrad

Beam Timing - Kaon ID

Kaon ID to suppress background from beam particle interactions with material on the beam line

Beam Timing to match upstream info from GTK (~750MHz) with downstream π detection(~10MHz)



K^+ ID and tagging under the conditions:

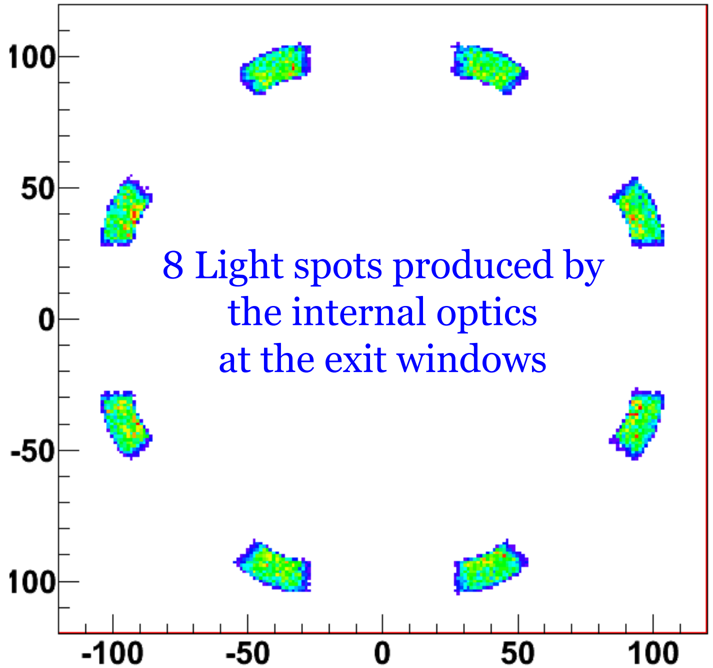
- High-intensity hadron beam (750 MHz);
- K beam composition ~ 6% (~50MHz);
- Cherenkov light yield ~ 250 γ /K (~ few MHz/mm²);
- Hydrogen gas (0.2% of X_0) at ~ 4 bar;

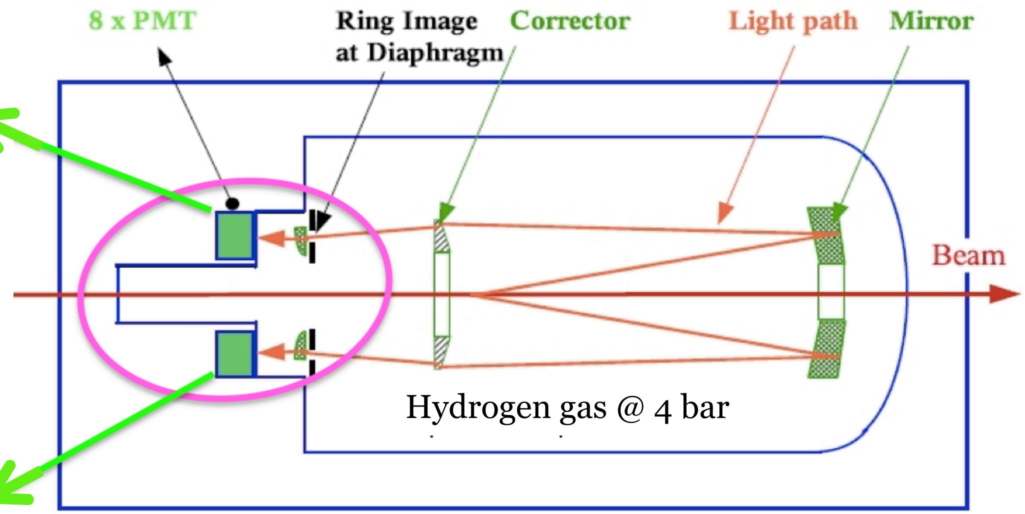
CEDAR/KTAG layout and principles

- Original counter used at CERN for SPS secondary beam diagnostics.
- Vessel filled with gas of controlled pressure;
- Internal optics axis precisely aligned with the beam axis;
- Only Cherenkov light from Kaons is transported by internal optics through the diaphragm (adjustable width) onto PMTs;

CEDAR/KTAG Upgrade

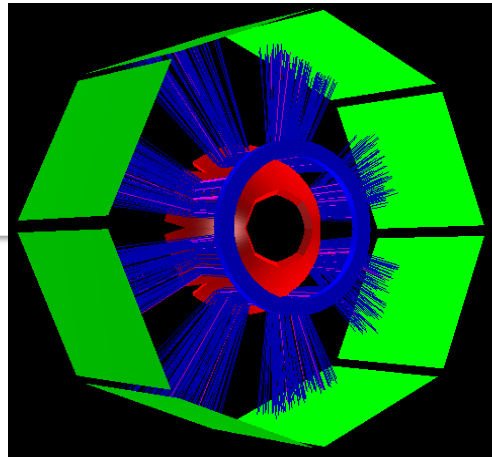
Photon detector and Readout upgrade to cope with huge illumination and required time performances (σ_t ~ 100 ps)





Old PMTs placed behind exit windows

Projection of Cherenkov light to new PMT planes

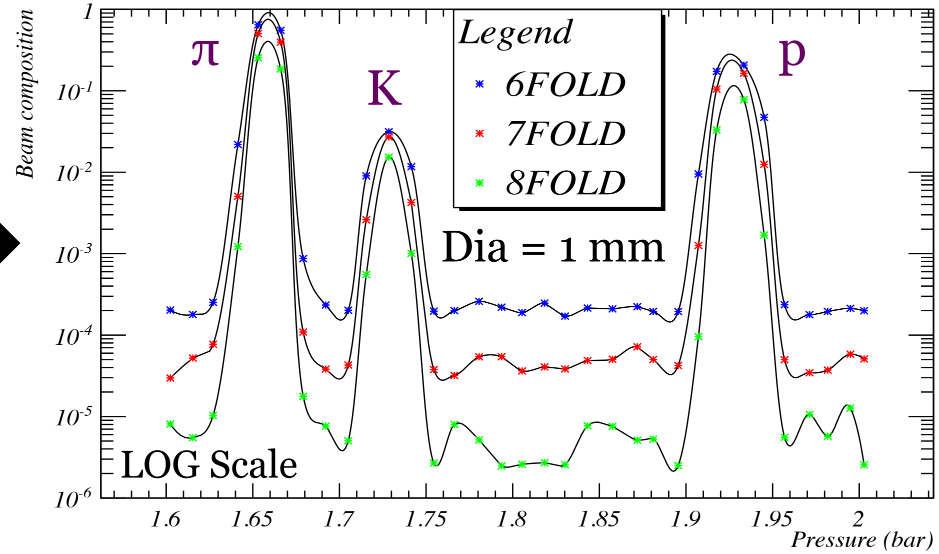


New KTAG concept: light spots enlarged to spread the photon rate on bigger areas

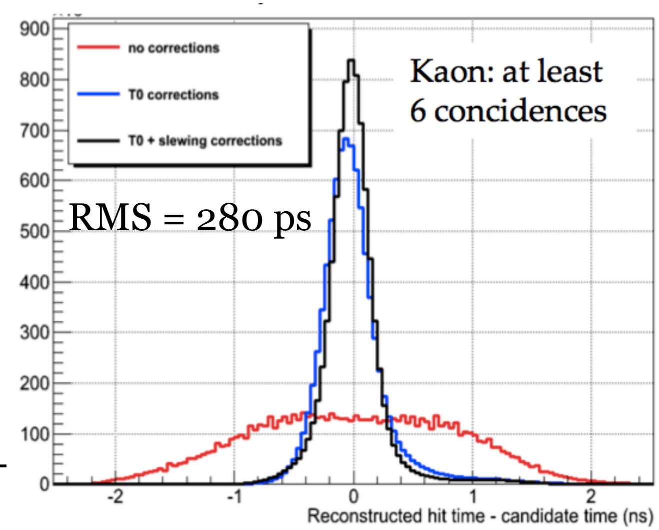
Exit windows
Additional mirrors
New PMT planes

CEDAR/KTAG Tests & Results

- ✓ Hadron beam @ 75 GeV (~40KHz)
- ✓ Beam composition from Pressure scan



Required resolution on K crossing time σ_t ~ 100ps

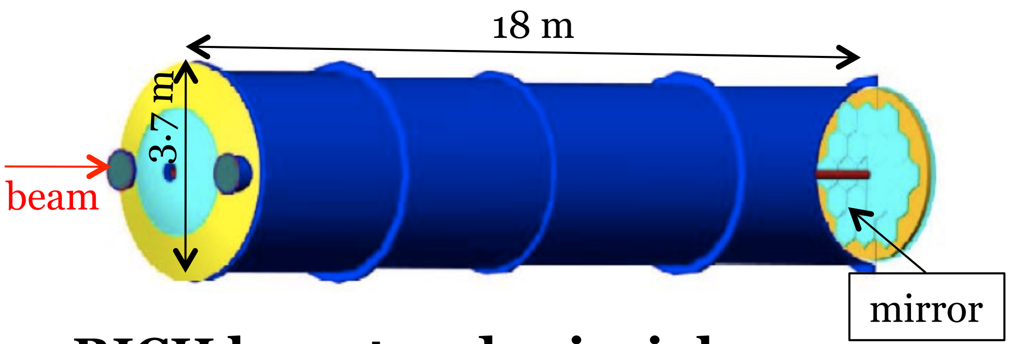


Half-Detector equipped: 4 light spots

(*)**UK** Responsibility

Pion ID: RICH

Downstream PID: Ring Image Cherenkov detector

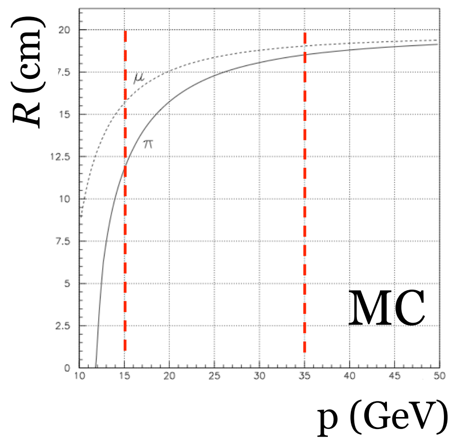


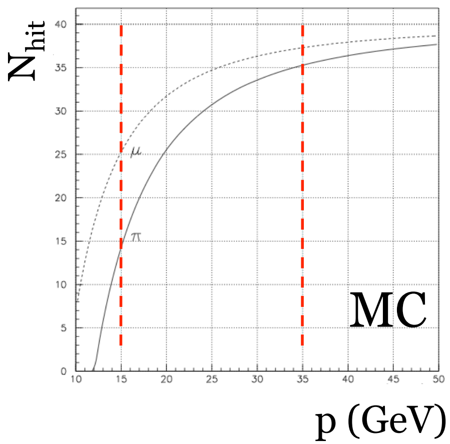
Requirements:

- π^+/μ^+ separation in the momentum range (15,35)GeV/c
- pion crossing time with σ_t < 100 ps

RICH layout and principles

- Radius of Cherenkov light ring $R \propto \beta$ of particle (i.e. its mass)
- Ne gas at 1 atm; $p_{threshold}$ = 12 GeV for π
- High granularity photon detector (2000 PMTs) -> $\sigma_t \sim \sigma_{PMT,\gamma} / \sqrt{N_{hit}}$



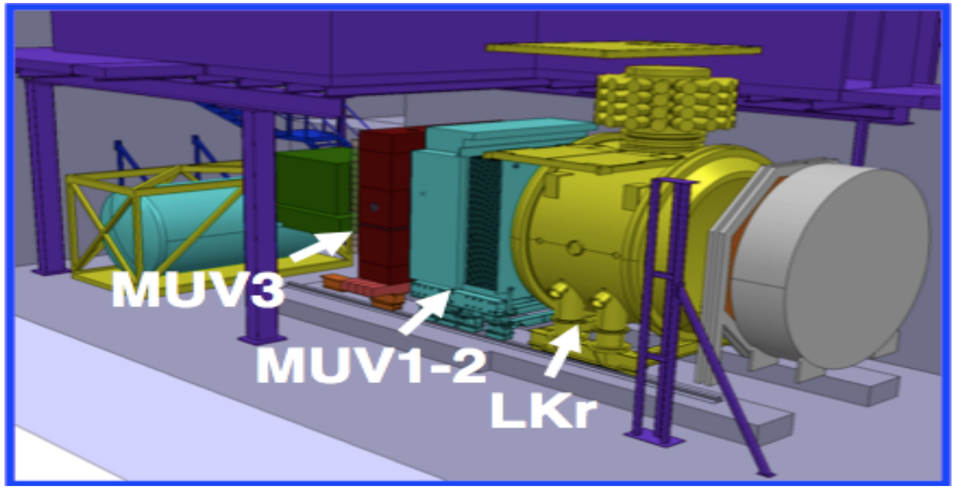


Needed for bkg rejection of $K^+ \rightarrow \mu^+\nu$
(BR($K^+ \rightarrow \mu^+\nu$) ~ 63%)

Provide:
- L0 trigger for charged particles
- μ suppression better than 1%

Muon Detector

Downstream PID: Muon Veto (MUV)



Needed for bkg rejection of $K^+ \rightarrow \mu^+\nu$

($BR(K^+ \rightarrow \mu^+\nu) \sim 63\%$)

Requirements:

- μ mis-ID as a π: suppression down to $\sim 10^{-5}$
- muon crossing time with $s_t < 1$ns

➢3 modules (MUV1-2-3) according to longitudinal position along the beam axis;

➢**MUV1-2**: iron-scintillation sandwich calorimeters for the measurement of deposited energies and shower shapes of incident particles;

➢**MUV1-2**: suppress muons undergoing "catastrophic" bremsstrahlung or pair production (depositing major fraction of energy in LKr downstream)

➢**MUV3**: scintillation counter to detect non-showering muons

➢**MUV3**: Fast Muon Veto used in L0 trigger (10MHz);

Photon Veto Systems - I

Photon Veto system: LAV, LKr, IRC, SAC

- Needed for bkg rejection of $K^+ \rightarrow \pi^+\pi^0$ (BR($K^+ \rightarrow \pi^+\pi^0$) ~ 21%);
- Hermetic photon coverage with 4 different detectors/technologies
- Required (average) inefficiency on the rejection of the $\pi^0 \rightarrow \gamma\gamma$ at level of 10^{-8};
- Kinematic cut on $p_\pi < 35$ GeV gives $\pi^0 \rightarrow \gamma\gamma$ with 40 GeV

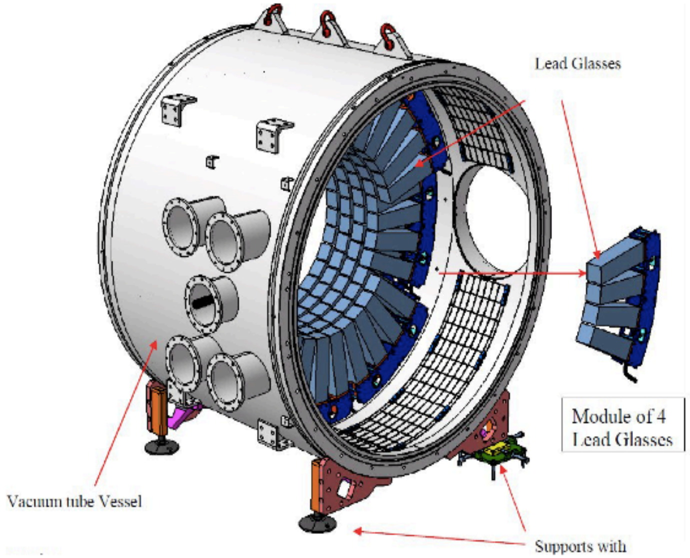
Simulations showed:

- $K^+ \rightarrow \pi^+\pi^0$ kinematic rejection (m^2_{miss}) ~ 10^{-4}
- 81.2% both γs in forward region (IRC and/or SAC)
- 18.6% 1γ in forward region, 1γ at large angle (IRC or SAC + LAV)
- 0.2% 1γ at large angle, 1 γ out of acceptance (LAV + lost)

LAV = Large Angle Veto
LKr = Liquid Kripton calorimeter
IRC = Inner Radius Calorimeter
SAC = Small Angle Calorimeter

Detector	θ [mrad]	Max. $1-\varepsilon$
LAV	8.5 - 50	10^{-4} at 200 MeV
LKr	1 - 8.5	10^{-3} at 1 GeV 10^{-5} at 10 GeV
IRC+SAC	< 1	10^{-4} at 5 GeV

Photon Veto Systems - II



-12 **LAV** stations distributed along the decay volume and covering the angular region: (8.5÷50) mrad;

- Photon energy range (10MeV÷30GeV);

- each **LAV**: 4/5 staggered layers of lead-glass crystals from OPAL EM barrel calorimeter;

- test beam with e^- at 200MeV showed $(1-\varepsilon) \sim 10^{-4}$

- **LKr** fundamental detector constructed for the studies of direct CP-violation in the neutral kaon system (NA48);

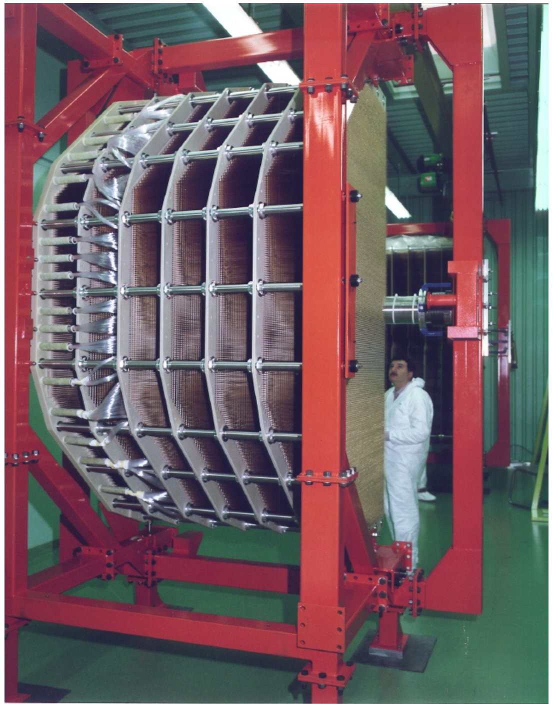
- quasi-homogeneous ionization chamber;

- Photon energy range (>1GeV);

- high energy (>10GeV) EM showers contained in compact detector (27 X_0);

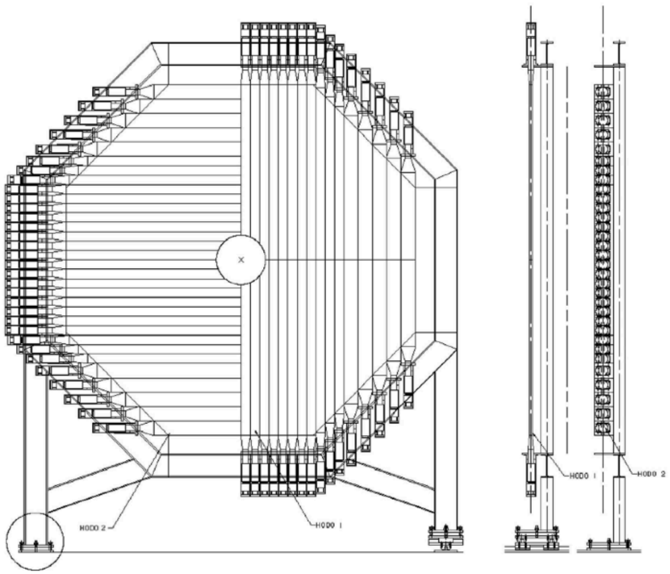
- 13, 248 readout cells with a transverse size of ~2×2 cm^2 each and no longitudinal segmentation;

- from studies with e^- at E>10GeV -> $(1-\varepsilon) \sim 8\times10^{-6}$



Charged Hodoscope: CHOD

Downstream counter



Detector layout

Tagging of secondary charged particles under the conditions:

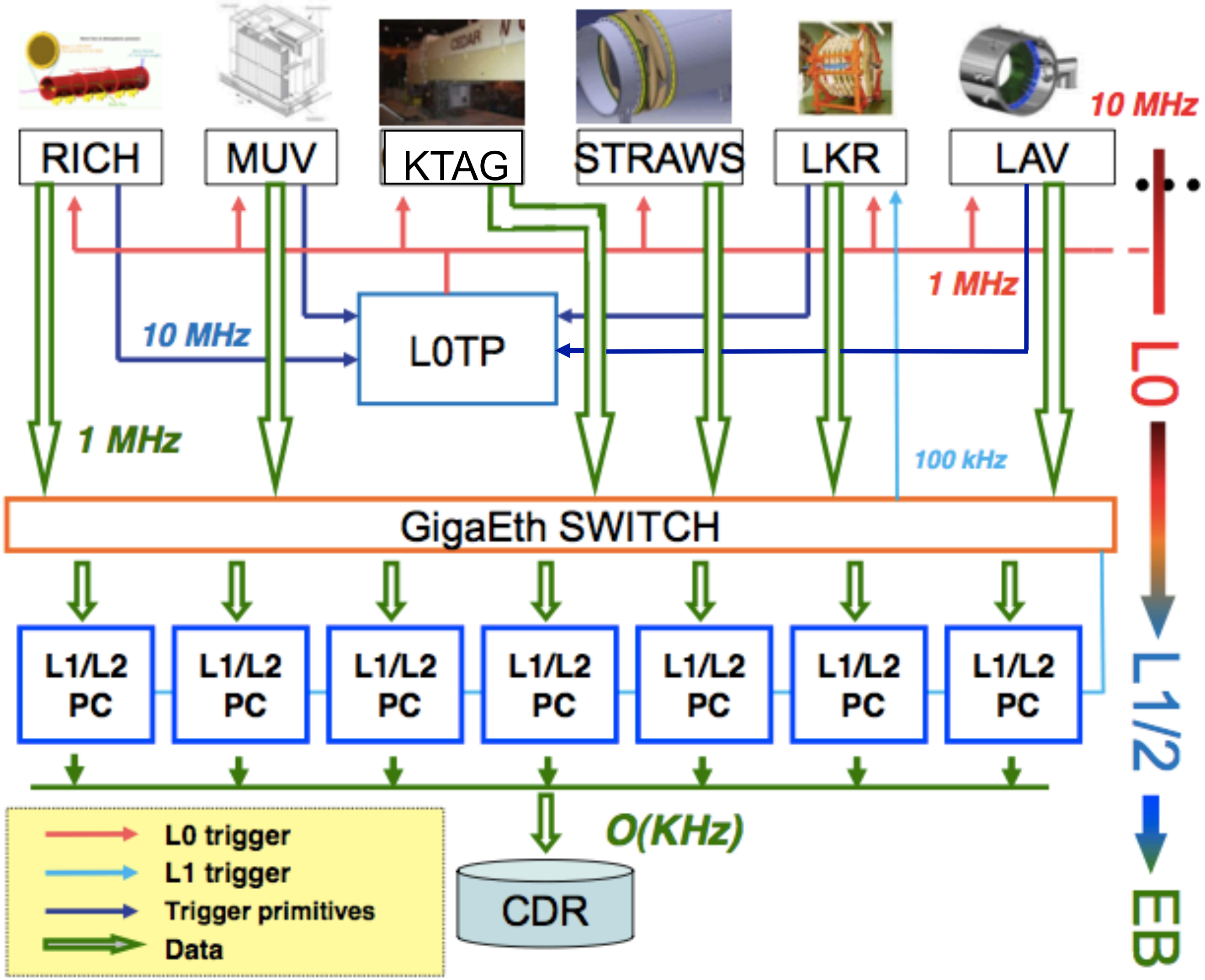
- minimum amount of material (~ 0.05X0 for each plane);
- time resolution σ_t ~ 200 ps;

Minimum bias trigger for decays with charged particles in the final state

- 128 plastic scintillation counters arranged in two planes (separated by 75 cm)
- counters disposed horizontally in the first plane and vertically in the second one.
- single counter: length: 60-121 cm, width 6.5-9.9 cm.

Each CHOD plane divided into 4 quadrants (made of 16 counters).
Each quadrant is sub-divided into 2 sub-quadrants;
16 total number of sub-quadrants - used to defined as many sets of fast logic signals for trigger purposes.

NA62 Trigger Technique: The TDAQ System



L0: Hardware synchronous level. 10 MHz to 1 MHz. Max latency 1 ms.

L1: Software level. "Single detector". 1 MHz to 100 kHz

L2: Software level. "Complete information level". 100 kHz to few kHz.