Kaon physics at CERN - Recent results from the NA48/2 and NA62 experiments

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for the NA48/2 and NA62 collaborations

Meson 2012, Cracow
### Topics covered in this talk:

- $K_{13}^{\pm}$ form factors measurement at NA48/2.
- ChPT test: New measurement of $K^{\pm} \rightarrow \pi^{\pm} \gamma \gamma$.
- Precision lepton flavour universality test: $K^{\pm} \rightarrow l^{\pm} \nu$.
- NA62: The ultra-rare decay $K^{+} \rightarrow \pi^{+} \nu \bar{\nu}$.

### RA48/NA62 at CERN

Ancestor: NA31

<table>
<thead>
<tr>
<th>Year</th>
<th>Run Type</th>
<th>Data</th>
</tr>
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<tbody>
<tr>
<td>1997</td>
<td>$\varepsilon'/\varepsilon$ run</td>
<td>$K_L + K_S$</td>
</tr>
<tr>
<td>1998</td>
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<td>$K_L + K_S$</td>
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<tr>
<td>1999</td>
<td>$\varepsilon'/\varepsilon$ run</td>
<td>$K_L + K_S$</td>
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<td>2000</td>
<td>$K_L$ only</td>
<td>$K_S$ High Intensity</td>
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<td>$\varepsilon'/\varepsilon$ run</td>
<td>$K_L + K_S$</td>
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<td>2002</td>
<td>$K_S$ High Intensity</td>
<td></td>
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<tr>
<td>2003</td>
<td>$K^+$ High Intensity</td>
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<tr>
<td>2004</td>
<td>$K^+$ High Intensity</td>
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<td>2007/08</td>
<td>$K_{T2}^+ / K_{T2}^-$ runs</td>
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<td>2007-2013</td>
<td>R&amp;D</td>
<td></td>
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<tr>
<td>2012</td>
<td>Start $K^+ \rightarrow \pi^+ \nu \bar{\nu}$</td>
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</table>
The NA48/2 and NA62 ($R_K$) beam line

Momentum selection
(60±3) GeV/c (NA48/2)
(74.0±1.4) GeV/c (NA62)

Simultaneous $K^+/K^-$ beams (2003–04);
mostly $K^+$ beam (2007)

Beams coincide within ~1mm

~$10^{12}$ protons per spill

The analyses presented in this talk are based on two data taking periods with minimum bias trigger configurations:
The NA48 detector

Magnetic spectrometer
- 4 drift chambers with central dipole magnet
- 4 views/chamber: redundancy → efficiency
- Magnet polarity periodically reversed
NA48/2: $\Delta p/p = 1.00\% \oplus 0.044\% \times p$
NA62: $\Delta p/p = 0.47\% \oplus 0.020\% \times p$

Liquid Krypton EM calorimeter (LKr)
- High granularity (13248 cells of $2 \times 2 \text{cm}^2$)
- Quasi-homogeneous, $\sim 7 \text{m}^3$ liquid krypton as active medium ($27 X_0$ deep)
  → fully contains $\gamma$’s up to 100 GeV
- $\sigma_E/E = 3.2\%/\sqrt{E} \oplus 9\% / E \oplus 0.42\% [\text{GeV}]
- Spatial resolution $\sim 1 \text{mm}$ (at 20 GeV)

Results from NA48/2 and NA62 – p. 4
Precision measurement of $K_{13}^{\pm}$ form factors
The kaon semileptonic decays

$K \rightarrow \pi l \nu \ (K_{l3})$ decays provide the most accurate and theoretically cleanest way to access $|V_{us}|$:

$$
\Gamma(K_{l3(\gamma)}) = \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f+(0)|^2 I_{K}^l (\lambda_{+0}) (1 + \delta_{SU(2)}^l + \delta_{EM}^l)^2
$$

**Experimental inputs:**
- $\Gamma(K_{l3(\gamma)})$ Branching ratios and kaon lifetimes.
- $I_{K}^l (\lambda_{+0})$ Phase space integral depending on the form factors.

**Theory inputs:**
- $S_{EW}$ Universal short distance EW corrections (1.0232 ± 0.0003).
- $f+(0)$ Form factor at zero momentum transfer.
- $\delta_{SU(2)}^l$ Form factor correction for isospin breaking (charged mode only).
- $\delta_{EM}^l$ Long distance EM effects.
**K_{13} form factors: Introduction**

$K_{13}$ decays are described by **two form factors** $f_{\pm}(t)$, and the **matrix element** can be written as:

$$M = \frac{G_F}{2} V_{us} (f_{+}(t)(P_K + P_{\pi})^\mu \bar{u}_l \gamma_\mu (1 + \gamma_5) u_\nu + f_{-}(t)m_l \bar{u}_l (1 + \gamma_5) u_\nu)$$

$t = q^2$ is the square of the four-momentum transfer to the lepton-neutrino system. $f_{-}(t)$ can only be measured in $K_{\mu3}$ decays because of $m_e << m_\mu$.

Usually form factors are re-formulated to express the **vector** and **scalar exchange contributions**:

- $f_{+}(t)$ is the **vector form factor**.
- $f_{0}(t)$ is the **scalar form factor** which can be described as a linear combination of $f_{\pm}(t)$:

$$f_{0}(t) = f_{+}(t) + \frac{t}{(m_K^2 - m_\pi^2)} f_{-}(t).$$

$f_{+}(0)$ cannot be measured directly $\Rightarrow$ the form factors are normalized to it:

$$\bar{f}_{+}(t) = \frac{f_{+}(t)}{f_{+}(0)}, \quad \bar{f}_{0}(t) = \frac{f_{0}(t)}{f_{+}(0)}.$$
Form factor parametrizations

1) Parametrizations using physical quantities are called class 1 parametrizations. They depend on free parameters with a physical meaning.

**Pole parametrization:**
Assumes the exchange of vector and scalar resonances $K^*$ with spin parity $1^-/0^+$ and masses $m_V/m_S$.

$f_+(t)$ can be described by $K^*(892)$, while for $f_0(t)$ no obvious dominance is seen:

$$\bar{f}_{+,0}(t) = \frac{m_{V,S}^2}{m_{V,S}^2 - t}$$

2) Parametrizations without a physical meaning are called class 2 parametrizations. They require more free parameters and are extensions in the momentum transfer $t$.

**Linear and quadratic parametrizations:**

$$\bar{f}_{+,0}(t) = \left[ 1 + \lambda_{+,0} \frac{t}{m_\pi^2} \right]$$  \hspace{1cm} \text{Linear}$$

$$\bar{f}_{+,0}(t) = \left[ 1 + \lambda'_{+,0} \frac{t}{m_\pi^2} + \frac{1}{2} \lambda''_{+,0} \left( \frac{t}{m_\pi^2} \right)^2 \right]$$  \hspace{1cm} \text{Quadratic}$$

More free parameters to be determined $\rightarrow$ Correlations!
No sensitivity to determine $\lambda'_0$ with current experiments $\rightarrow \bar{f}_+$ quadratic / $\bar{f}_0$ linear.
**K_{l3} Dalitz plots + corrections**

Data recorded 2004 in a special three days run with minimum bias trigger.

- $2.5 \times 10^6 \ K^\pm_{\mu3}$ candidates selected
- $4.0 \times 10^6 \ K^\pm_{e3}$ candidates selected

Very low background for both channels at per-mil level!

Applied corrections:
- Background subtraction
- Acceptance
- Radiative corrections

Reconstructed data Dalitz plot

Corrected Dalitz plot

Results from NA48/2 and NA62 – p. 9
### Preliminary results (1)

<table>
<thead>
<tr>
<th>Quadratic ($\times 10^{-3}$)</th>
<th>$\lambda'_+$</th>
<th>$\lambda''_+$</th>
<th>$\lambda_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\mu3}^\pm$</td>
<td>$26.3 \pm 3.0_{\text{stat}} \pm 2.2_{\text{syst}}$</td>
<td>$1.2 \pm 1.1_{\text{stat}} \pm 1.1_{\text{syst}}$</td>
<td>$15.7 \pm 1.4_{\text{stat}} \pm 1.0_{\text{syst}}$</td>
</tr>
<tr>
<td>$K_{e3}^\pm$</td>
<td>$27.2 \pm 0.7_{\text{stat}} \pm 1.1_{\text{syst}}$</td>
<td>$0.7 \pm 0.3_{\text{stat}} \pm 0.4_{\text{syst}}$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pole (MeV/$c^2$)</th>
<th>$m_\nu$</th>
<th>$m_\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\mu3}^\pm$</td>
<td>$873 \pm 8_{\text{stat}} \pm 9_{\text{syst}}$</td>
<td></td>
</tr>
<tr>
<td>$K_{e3}^\pm$</td>
<td>$879 \pm 3_{\text{stat}} \pm 7_{\text{syst}}$</td>
<td>$1183 \pm 31_{\text{stat}} \pm 16_{\text{syst}}$</td>
</tr>
</tbody>
</table>

**68% Confidence level contours**

- KTeV $K^0$
- KLOE $K^0$
- Istra+ $K^-$
- NA48 $K^0$
- NA48/2 $K^\pm$ preliminary

**68% Confidence level contours**

- FlaviaNet Fit $K_{\mu3}$ 2010
- FlaviaNet Fit $K_{e3}$ 2010
Preliminary results (2)

- **NA48/2** is the first experiment which measured both $K_{e3}^\pm$ and $K_{\mu3}^\pm$.
- Results for $K_{e3}^\pm$ and $K_{\mu3}^\pm$ from NA48/2 in good agreement.
- **NA48/2 preliminary result** with high precision, fully competitive to other measurements. Offers the combined result with the smallest error.

<table>
<thead>
<tr>
<th>Quadratic ($\times 10^{-3}$)</th>
<th>$\lambda'_\pm$</th>
<th>$\lambda''_\pm$</th>
<th>$\lambda_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\mu3}^\pm K_{e3}^\pm$ combined</td>
<td>26.98 ± 1.11</td>
<td>0.81 ± 0.46</td>
<td>16.23 ± 0.95</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pole (MeV/$c^2$)</th>
<th>$m_V$</th>
<th>$m_S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\mu3}^\pm K_{e3}^\pm$ combined</td>
<td>877 ± 6</td>
<td>1176 ± 31</td>
</tr>
</tbody>
</table>
ChPT tests:

A new measurement of

\[ K^\pm \rightarrow \pi^\pm \gamma\gamma \] decays
**K^± → π^±γγ**: Introduction

**ChPT description:**

\[ \mathcal{O}(p^4) \]

Loop diagrams

→ **cusp** at \( \pi^+\pi^- \) threshold: \( m_{\gamma\gamma} = 2m_{\pi^+} \)

(or \( z = (m_{\gamma\gamma}/m_K)^2 \approx 0.32 \)).


Rate and spectrum depend on a single unknown \( \mathcal{O}(1) \) parameter \( \hat{c} \).

\[ \mathcal{O}(p^6) \]

'Unitarity corrections' increase BR at low \( \hat{c} \) and result in a non-zero rate at \( m_{\gamma\gamma} \rightarrow 0 \).

[D'Ambrosio, Portoles, PLB386 (1996) 403]

**Experimental status:**

**BNL 787**: 31 candidates with 5 bkg. events, BR = \((1.10 \pm 0.32) \times 10^{-6}\).

[PRL79 (1997) 4079]

**NA48/2 main data set**: measurement hindered by trigger efficiency.

→ **New strategy**: use minimum bias trigger samples from NA48/2 and NA62.
Minimum bias data samples 2004+2007

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<thead>
<tr>
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</thead>
<tbody>
<tr>
<td><strong>K_{\pi\gamma\gamma} candidates</strong></td>
<td>147</td>
<td>175</td>
</tr>
<tr>
<td><strong>K_{2\pi(\gamma)} background</strong></td>
<td>11.0 ± 0.8</td>
<td>11.1 ± 1.0</td>
</tr>
<tr>
<td><strong>K_{3\pi} background</strong></td>
<td>5.9 ± 0.7</td>
<td>1.3 ± 0.3</td>
</tr>
<tr>
<td><strong>K_{\pi\gamma\gamma} signal</strong></td>
<td>130 ± 12</td>
<td>163 ± 13</td>
</tr>
</tbody>
</table>

Results from NA48/2 and NA62 – p. 14
\[ K^\pm \rightarrow \pi^\pm \gamma\gamma: \text{ChPT fits} \]

- Visible region is above the \( K^+ \rightarrow \pi^+ \pi^0 \) peak with \( m_{\gamma\gamma} = m_{\pi^0} \):
  \[ z > 0.2 \text{ or } m_{\gamma\gamma} > 220 \text{ MeV}/c^2. \]
- Cusp-like behaviour at \( 2m_\pi \) (\( z \approx 0.32 \)) is clearly observed.
\( K^\pm \rightarrow \pi^\pm \gamma \gamma \): Preliminary fit results

**Fit results for parameter \( \hat{c} \)**

<table>
<thead>
<tr>
<th>( \hat{c} = )</th>
<th>( \mathcal{O}(p^4) )</th>
<th>( \mathcal{O}(p^6) )</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NA48/2 2004</strong></td>
<td>1.36 ± 0.33(<em>{\text{stat}}) ± 0.07(</em>{\text{syst}}) = 1.36 ± 0.34</td>
<td>1.67 ± 0.39(<em>{\text{stat}}) ± 0.09(</em>{\text{syst}}) = 1.67 ± 0.40</td>
<td>1.56 ± 0.22(<em>{\text{stat}}) ± 0.07(</em>{\text{syst}}) = 1.56 ± 0.23</td>
</tr>
<tr>
<td><strong>NA62 2007</strong></td>
<td>1.71 ± 0.29(<em>{\text{stat}}) ± 0.06(</em>{\text{syst}}) = 1.71 ± 0.30</td>
<td>2.21 ± 0.31(<em>{\text{stat}}) ± 0.08(</em>{\text{syst}}) = 2.21 ± 0.32</td>
<td>2.00 ± 0.24(<em>{\text{stat}}) ± 0.09(</em>{\text{syst}}) = 2.00 ± 0.26</td>
</tr>
</tbody>
</table>

ChPT \( \mathcal{O}(p^6) \) combined BR fit: \( BR = (1.01 \pm 0.06) \times 10^{-6} \).

- All results presented here are preliminary! (E. Goudzovski @ FPCP, May 2012)
- The combined 2004+2007 results contain correlated uncertainties.
- PDG (= BNL E787): \( BR = (1.10 \pm 0.32) \times 10^{-6} \).
- In good agreement with NA48/2 preliminary result. (based on partial (40\%) data sample with 1164 \( K^\pm \rightarrow \pi^\pm \gamma \gamma \) candidates) (Cristina Morales-Morales @ Moriond QCD 2008)
$K^\pm \rightarrow \pi^\pm \gamma \gamma$: Fit results + conclusions

- Total number of candidates (from NA48/2 + NA62) = 322.
- Background contamination: $(9 \pm 1)$% due to $K^+ \rightarrow \pi^+ \pi^0(\pi^0)(\gamma)$ with photon fusion.
- Very low systematic uncertainties.
- ChPT $O(p^4)$ vs $O(p^6)$ models cannot be discriminated.
Precision lepton universality test through the ratio

\[ \frac{\Gamma(K^\pm \rightarrow e^{\pm}\nu)}{\Gamma(K^\pm \rightarrow \mu^{\pm}\nu)} \]
\[ R_K = \frac{\Gamma(K \rightarrow e\nu)}{\Gamma(K \rightarrow \mu\nu)} \] in the SM

- **Precision tests** → search for deviations from the SM in rare or forbidden processes

- **Leptonic meson decays:** \( P^+ \rightarrow l^+\nu \)
  Angular momentum conservation leads to helicity suppression of SM contribution

- Excellent sub-per-mil accuracy of SM prediction due to cancellation of hadronic uncertainties in the ratio \( R_K = K_{e2}/K_{\mu2} \)
  (similarly, \( R_\pi \) in the pion sector)

\[
R_K = \frac{\Gamma(K^\pm \rightarrow e^\pm\nu)}{\Gamma(K^\pm \rightarrow \mu^\pm\nu)} = \frac{m_e^2}{m_\mu^2} \cdot \left( \frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2} \right)^2 \cdot (1 + \delta R_K^{\text{rad.corr.}}) \\
= (2.477 \pm 0.001) \times 10^{-5} \quad \text{[Cirigliano, Rosell, PRL99 (2007) 231801]}
\]

- Radiative corrections \( \delta R_K^{\text{rad.corr.}} \) (few %) due to the IB part of the radiative \( K \rightarrow e\nu\gamma \) process (by definition included in \( R_K \))

- Measurements of \( R_K \) and \( R_\pi \) have long been considered as tests of lepton universality

- Strong helicity suppression of \( R_P \) enhances sensitivity to non-SM effects

Results from NA48/2 and NA62 – p. 19
$R_K = K_{e2}/K_{\mu2}$ beyond the SM

2HDM (incl. SUSY) - tree level:
$K^+ \to l^+\nu$ can proceed via exchange of charged Higgs $H^+$ instead of $W^+$
$\to$ ratio $R_K$ remains unchanged

Possible scenario, one loop level:

'Loop effects are predicted to lead to lepton flavour violating (LFV) couplings $lH^+\nu_\tau$
which give dominant contribution to $\Delta R_K$'

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

Up to $\sim 1\%$ effect possible in large (not extreme) $\tan \beta$ regime with relatively massive charged Higgs $\to$ experimentally accessible!

Example:
$\Delta_{13} = 5 \times 10^{-4}$, $M_H = 500$ GeV, $\tan \beta = 40$:
$R^{LFV}_K \approx R^{SM}_K (1 + 0.013)$

Analogous SUSY effects in pion decay are suppressed by factor $(m_{\pi}/M_K)^4 \approx 6 \times 10^{-3}$

However, large effects expected in B decays due to $(M_B/M_K)^4 \sim 10^4$

Results from NA48/2 and NA62 – p. 20
Measurement method

**K_{e2} and K_{µ2} candidates collected simultaneously**

- Measurement independent of kaon flux.
- A number of systematic effects cancel at first order in the ratio \( R_K \) (e.g. reconstruction/trigger efficiencies, time-dependent effects).

**A counting experiment in 10 independent bins of lepton momentum**

\[
R_K = \frac{1}{D} \cdot \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{µ2}) - N_B(K_{µ2})} \cdot \frac{A(K_{µ2}) \times f_µ \times \epsilon(K_{µ2})}{A(K_{e2}) \times f_e \times \epsilon(K_{e2})} \cdot \frac{1}{f_{LKr}}
\]

- \( N(K_{e2}), N(K_{µ2}) \): numbers of selected \( K_{12} \) candidates
- \( N_B(K_{e2}), N_B(K_{µ2}) \): numbers of background events
- \( A(K_{e2}), A(K_{µ2}) \): geometric acceptances (from MC)
- \( f_e, f_µ \): measured particle ID efficiencies (from data)
- \( \epsilon(K_{e2}) / \epsilon(K_{µ2}) > 99.9\% \)
- \( f_{LKr} = 0.9980 (3) \): \( E_{LKr} \) trigger efficiency
- \( D = 150 \): global LKr readout efficiency
- \( f_{LKr} = 0.9980 (3) \): downscaling factor of the \( K_{µ2} \) trigger

Main source of systematic uncertainty: \( N_B(K_{e2}) \).
**Ke2 and K_μ2 selection**

**Large common part** (topological similarity)
- One reconstructed track
- Geometrical acceptance cuts
- Decay vertex defined as closest distance of approach of track + nominal kaon axis
- Track momentum 13 - 65 GeV/c

**Kinematic separation**

Missing mass \( M_{miss}^2 = (P_K - P_l)^2 \)

- \( P_K \) average measured with \( K^\pm \rightarrow 3\pi \) decays
- \( \Rightarrow \) Sufficient \( Ke2/K_\mu2 \) separation only for lepton momenta < 30 GeV/c

**Particle identification**

- \( E/p \) : LKr energy deposit / track momentum
  - < 0.85 for muons, electrons: (0.90-0.95) <\( E/p < 1.10 \)
  - \( \rightarrow \) powerful \( \mu^\pm \) suppression in \( e^\pm \) sample (\( \sim 10^6 \))

Results from NA48/2 and NA62 – p. 22
**$K\mu_2$ background in $K_{e2}$ sample**

**Problem:**

'Catastrophic' energy loss of muons in LKr $\Rightarrow$ Muons with $E/p > 0.95$ identified as electrons ($P_{\mu e} \sim 3 \times 10^{-6}$ and momentum-dependent).

$P_{\mu e}/R_K \sim 10\% \Rightarrow K\mu_2$ decays represent the major background

**Solution:** Direct measurement of $P_{\mu e}$

$\Rightarrow$ Lead wall (9.2 $X_0$) in front of LKr: suppression of electron contamination from $\mu$-e decay.

$\Rightarrow$ Tracks traversing Pb with $p > 30\text{GeV/c} + E/p > 0.95 \rightarrow$ pure $\mu$ samples with catastrophic bremsstrahlung (electron contamination $< 10^{-8}$).

$P_{\mu e}$ is modified by the Pb wall (ionization losses + bremsstrahlung)

$\Rightarrow$ The correction is evaluated with a dedicated Geant4-based simulation.

Due to the Pb wall affecting the acceptances and the different background conditions

$\Rightarrow$ Divide the data addtionally into 4 samples:

$K^+(\text{Pb}), K^+(\text{noPb}) / K^-(\text{Pb}), K^-(\text{noPb})$

**Lead (Pb) wall**

- Thickness: $\sim 10 \times X_0$ (Pb + Fe)
- Width: 240 cm (= HOD size)
- Height: 18 cm (= 3 counters)
- Area: $\sim 20\%$ of HOD area
- Duration: $\sim 50\%$ of $R_K$ data taking

Results from NA48/2 and NA62 – p. 23
Ke2 candidates and background

145,958 K± → e±ν candidates
(99.28 ± 0.05) % electron ID efficiency
B/(S+B) = (10.95 ± 0.27) %
cf. KLOE: 13.8k candidates,
~ 90 % electron ID efficiency, 16 % bkg.

Results from NA48/2 and NA62 – p. 24
\( \mathbf{K}_{\mu_2} \) candidates and backgrounds

42.817M \( \mathbf{K}^\pm \rightarrow \mu^\pm \nu \) candidates with very low background
\( \mathbf{B}/(\mathbf{S}+\mathbf{B}) = (0.50 \pm 0.01) \% \)

\( \mathbf{K}_{\mu_2} \) trigger was pre-scaled by \( \mathbf{D} = 150 \)

The only significant background source is the beam halo.
NA62 final result

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

$R_K = (2.488 \pm 0.007_{\text{stat}} \pm 0.007_{\text{syst}}) \times 10^{-5}$
$= (2.488 \pm 0.010) \times 10^{-5}$ (0.40% precision!)

NA62 publications:
- Partial (40%) data set: PLB 698 (2011) 105.
- Full data set: paper to be submitted in summer 2012.

Uncertainties summary

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta R_K \times 10^5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>0.007</td>
</tr>
<tr>
<td>$K_{\mu 2}$</td>
<td>0.004</td>
</tr>
<tr>
<td>$K_{e2\gamma}$ ($SD^+$)</td>
<td>0.002</td>
</tr>
<tr>
<td>$K_{e3}$, $K_2\pi$</td>
<td>0.003</td>
</tr>
<tr>
<td>Beam halo</td>
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</tr>
<tr>
<td>Matter composition</td>
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<tr>
<td>Acceptance corr.</td>
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<tr>
<td>Electron ID</td>
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<tr>
<td>DCH alignment</td>
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<tr>
<td>1TRK trigger eff.</td>
<td>0.001</td>
</tr>
<tr>
<td>LKr readout eff.</td>
<td>0.001</td>
</tr>
<tr>
<td>Total</td>
<td>0.010</td>
</tr>
</tbody>
</table>

Results from NA48/2 and NA62 – p. 26
\( R_K \): world average and New Physics limits

KLOE and NA62 have significantly improved the precision in \( R_K \).

In agreement with SM expectation, but \( \sim 1\sigma \) above \( \rightarrow \) motivation for further precision \( R_K \) measurements.

<table>
<thead>
<tr>
<th>World average</th>
<th>( R_K \times 10^5 )</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDG 2008</td>
<td>( 2.447 \pm 0.109 )</td>
<td>4.5 %</td>
</tr>
<tr>
<td>PDG 2010</td>
<td>( 2.493 \pm 0.031 )</td>
<td>1.3 %</td>
</tr>
<tr>
<td>July 2011</td>
<td>( 2.488 \pm 0.009 )</td>
<td>0.4 %</td>
</tr>
</tbody>
</table>
The Holy Grail: NA62 and the ultra-rare decay

\[ K^+ \rightarrow \pi^+ \nu \bar{\nu} \]
**K → πν̅ν - The golden modes for kaons**

Why **K → πν̅ν decays** are among the few golden channels to search for New Physics:

1) They are extremely rare!

Loop-induced **FCNC processes**, transition described by **Z-penguin** and **box diagrams**:

![Diagram](image)

2) The SM prediction is exceptionally precise!

\[
\begin{align*}
BR(K^0 \to π^0ν̅ν) &= \kappa_L \text{Im}(V_{ts}^* V_{td})^2 X(m_t, m_W)/|V_{us}|^5 \\
BR(K^+ \to π^+ν̅ν) &= \kappa_+ (V_{ts}^* V_{td})^2 X(m_t, m_W)/|V_{us}|^5 + \text{charm contr.}
\end{align*}
\]

The hadronic matrix element can be extracted from the precisely measured K → πeν decay. **Charm contributions** in charged mode only, precision recently reduced by NNLO calculation.

The SM prediction is tiny!

(Brod et al., PRD83 (2011) 034030)

Uncertainty almost only from knowledge on |V_{ts}|!

3) In extensions of the SM, the decay remains similarly predictive!
**K → πν¯ν - The golden modes for kaons**

Furthermore, \( K^+ \rightarrow π^+ν\bar{ν} \) allows the measurement of \(|V_{td}|\) complementary to those from \( B - \bar{B} \) mixing and \( B \rightarrow ργ \) (and without requiring input from lattice QCD).

A precision in the branching ratio \( δBR/BR = 10\% \) would lead to \( δ|V_{td}|/|V_{td}| = 7\% \).

**Experimental situation** - far from theory precision

- \( BR(K^0 \rightarrow π^0ν\bar{ν}) < 2.6 \times 10^{-8} \) (90%CL) \( E931a \) (KEK) (PRD 81 (2010) 072004)
- \( BR(K^+ \rightarrow π^+ν\bar{ν}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10} \) \( E787/E949 \) (BNL) (PRL 101 (2008) 191802)

- BNL result based on 7 \( K^+ \rightarrow π^+ν\bar{ν} \) candidates (2.6 expected bkg.).
- Incoming kaons stopped in target

→ low signal efficiency (\( \sim 1\% \)) and significant background (\( \sim 30\% \)) due to \( π \) scattering.

**NA62@CERN aims to collect \( \mathcal{O}(100) \) \( K^+ \rightarrow π^+ν\bar{ν} \) decays with \( \sim 10\% \) background in 2 years of data taking using a novel decay-in-flight-technique.**

Results from NA48/2 and NA62 – p. 30
Principles of NA62 (1)

- $K^+$ decay-in-flight-technique to avoid the scattering and the backgrounds introduced by the stopping target.
  $\rightarrow$ long decay region

- High momentum to improve the background rejection.
  $\rightarrow$ unseparated hadron beam

Statistics:
To measure a $10^{-11}$ BR, you need a huge amount of kaon decays ($\mathcal{O}(10^{13})$ in total).
$\rightarrow$ Very high kaon intensity and good signal efficiency.

Systematics:
$\geq 10^{12}$ background rejection (i.e. $\sim 10\%$ precision bkg. measurement)
$\rightarrow$ Signal purity and detector redundancy.

Signal signature:
Only one charged track identified as a pion + nothing.

Background:
All the $K^+$ decay modes!
Kinematical background rejection

Reconstruction of missing mass:

\[ m_{\text{miss}}^2 \approx m_K^2 \left( 1 - \frac{p_\pi}{p_K} \right) + m_\pi^2 \left( 1 - \frac{p_K}{p_\pi} \right) - p_K p_\pi \theta_{\pi K}^2 \]

92% of total background kinematically constrained:
- Definition of the signal region
- \( K^+ \rightarrow \pi^+ \pi^0 \) ’needle’ forces to split it into two parts (Region I + Region II).

Kinematic rejection power:
- \( \sim 10^4 \) (\( K^\pm \rightarrow \pi^\pm \pi^0 \)), \( \sim 10^5 \) (\( K^\pm \rightarrow \mu^\pm \nu \)).

8% of total background not kinematically constrained:
- Radiative decays or decays with neutrino in final state.
- Span across the signal region.
- Rejection relies on excellent vetoes + PID.

Results from NA48/2 and NA62 – p. 32
1) **Precise timing** to associate the decay to the correct incoming parent particle ($K^+$) in a $\sim 800$ MHz hadron beam.

\[ \rightarrow \text{Beam tracker with } \sigma_t \sim 100 \text{ ps. (GigaTracker GTK: three Si pixel stations)} \]

2) **Kinematical rejection**

\[ \rightarrow \text{low mass / high resolution spectrometers operating in vacuum.} \]

- $K^+ \rightarrow \text{GTK} / \pi^+ \rightarrow \text{Straw spectrometer}$

3) **Excellent high efficiency vetoes**

- **$\gamma$ veto:** Mandatory to veto $\gamma$’s from $K^+ \rightarrow \pi^+ \pi^0$

With $p(K^+) = 75 \text{ GeV}/c$ and low momentum $\pi^+$ ($p(\pi^+) : 15-35 \text{ GeV}/c$)

\[ \rightarrow p(\pi^0) > 40 \text{ GeV}/c \rightarrow \text{cannot be missed at full angular coverage (} \sim 10^8 \text{ rejection !)} \]

**Components:** LargeAngleVeto (LAV, reusing OPAL lead glass blocks), NA48 LKr, SAV.

- **$\mu$ veto:** Extreme $\mu$ suppression of $10^{11}$ required (to kill main decay $K_{\mu 2}$).

\[ \rightarrow \text{No single detector can do this, several detector components must work together.} \]

4) **Particle identification**

- $K/\pi$ (CEDAR: Cherenkov kaon tagger).

- $\pi/\mu$ (RICH: 17m long, excellent time resolution of $\sim 70$ps (defines event time)).
The NA62 detector for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

- SPS primary protons @ 400 GeV/c.
- 75 GeV/c unseparated hadron beam (p/π/K), $(\Delta p/p \sim 1\%)$.
- 750 MHz $\rightarrow$ 50 MHz kaons (6%) $\rightarrow$ 6 MHz decays.
- $4.8 \times 10^{12}$ kaon decays per year.

**NA62 timeline:**
- First technical run in autumn 2012 including many parts of the experiment.
- 2013: Complete detector installation.
- 2014-?: Data taking with full detector (driven by CERN accelerator schedule).