Kaons as high precision probes at CERN: From NA48 to P-326

M.S. Sozzi
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Joint meeting of Pacific Region Particle Physics Communities
October 30th 2006
• **Appetizer**: fast forward from the past  
  Direct CPV, $\eta$ mass, $K_s$ rare decays

• **Main course**: recent achievements  
  CPV in $K \rightarrow 3\pi$ decays  
  Radiative decays  
  $Ke4$ decays  
  $\pi\pi$ scattering lengths  
  Semileptonics  
  Leptonics

• **Dessert**: the future program  
  Towards ultra-rare decays

• **Doggy bag**…
Once upon a time in Geneva...

**NA48** [ɛn ɛi fɔrˈtɛ āt]: *n.*
1. International collaboration (b. 1989) of 120–odd physicists formed by Cagliari, Cambridge, Edinburgh, Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Siegen, Torino, Warsaw universities, CERN, JINR Dubna, LAL Orsay, CEA Saclay and HEPHY Vienna to work on a particle physics experiment searching for direct CP violation in kaons at CERN

PROPOSAL FOR
A PRECISION MEASUREMENT OF $\varepsilon'/\varepsilon$ IN CP VIOLATING $K^0 \rightarrow 2\pi$ DECAYS

CERN/SPSC/90-22
SPSC/P253
20 July 1990

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The NA48 detector

Main detector components:

- **Magnetic spectrometer (4 DCHs):**
  4 views: redundancy ⇒ efficiency
  \( \sigma_{p/p} = 1.0\% + 0.044\% \, p \, [GeV/c] \)

- **Hodoscope**
  Fast trigger
  Precise time measurement (150ps)

- **Liquid Krypton EM calorimeter (LKr)**
  High granularity, quasi-homogeneous
  \( \sigma_{E/E} = 3.2\%/\sqrt{E} + 9%/E + 0.42\% \, [GeV] \)
  \( e/\pi \) discrimination

- **Hadron calorimeter, photon vetos,**
  muon veto counters
The story so far...

<table>
<thead>
<tr>
<th>Year</th>
<th>Experiment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>NA48: $\varepsilon'/\varepsilon$</td>
<td>The quest for direct CP violation</td>
</tr>
<tr>
<td>1998</td>
<td>NA48: $\varepsilon'/\varepsilon$</td>
<td>Rare $K_L$ decays</td>
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<td>1999</td>
<td>NA48/1: $K_S$</td>
<td>Rare $K_s$ decays, Hyperon decays</td>
</tr>
<tr>
<td>2000</td>
<td>NA48/2: $K_L$, $K_S$</td>
<td>Direct CP violation searches, Study of $\pi\pi$ interactions</td>
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<td>2001</td>
<td>NA48/2: $K_S$</td>
<td>Rare $K^\pm$ decays</td>
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<td>NA48/2: $K^\pm$</td>
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3 experiments in 1: a multi-purpose kaon laboratory
**NA48: Direct CP violation: $\varepsilon'/\varepsilon$**

1999: proof of direct CP violation (after 36 years!) at $>7\,\sigma$

World average: \[ \text{Re}(\varepsilon'/\varepsilon) = (16.3 \pm 2.3) \cdot 10^{-4} \]

\[ \frac{\Gamma (K^0 \to \pi^+\pi^-) - \Gamma (\bar{K}^0 \to \pi^+\pi^-)}{\Gamma (K^0 \to \pi^+\pi^-) + \Gamma (\bar{K}^0 \to \pi^+\pi^-)} = (5.04 \pm 0.82) \times 10^{-6} \]

**BREAKING NEWS !!!**

Italo Mannelli (Pisa), Heinrich Wahl (CERN) and Bruce Winstein (Chicago) receive the 2007 Panofsky Prize of the American Physical Society, for their leading role in a series of experiments on precision experiments with kaons
**NA48: η mass**

No sensitivity to absolute E scale (normalization to π⁰ mass)

\[ M_\eta = (547.843 \pm 0.030 \pm 0.041) \text{ MeV}/c^2 \]


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**NA48/1: K_\Bar{S} decays**

December 10, 1999

CERN/SPSC 2000-002

SPSC/P253 ADD.2

**ADDENDUM 2 TO P253**

A high sensitivity investigation of K_\Bar{S} and neutral hyperon decays using a modified K_\Bar{S} beam.

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**Highlight:**

First measurements of K_\Bar{S} → π⁰ℓ⁺ℓ⁻

\[ BR = (5.8^{+2.8}_{-2.3} \pm 0.8) \times 10^{-9} \]


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**Outcome:** indirect CPV dominates in K_L → π⁰ℓ⁺ℓ⁻

\[ BR = (2.8^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9} \]

ADDENDUM III
(to Proposal P253/CERN/SPSC)
for a Precision Measurement of Charged Kaon Decay Parameters with an
Extended NA48 Setup

(1) Search for direct CPV asymmetries in K→3π decays
(2) Extraction of ππ scattering lengths from Ke4 decays
(3) High sensitivity study of rare decays (and TV, CPV)

Data taking completed (2003 and 2004, 110 days)
10^{11} K^± through experiment, ~ 200 TB of data recorded

New beam line with two achromatic magnet quadruplets
with K magnetic spectrometer:
MICROMEGA TPC
(0.7% resolution) at 2×10^7 particles/s
<100 ps time resol.
NA48/2 beams

$P_K$ spectra
$60 \pm 3$ GeV/c

2 ÷ 3 M K/spill ($\pi/K \sim 12$)
$\pi$ decay products stay in pipe
$K^+/K^-$ flux $\approx 1.8$

$\sim 7 \times 10^{11}$ ppp

Beams coincide within $\sim 1\text{mm}$ all along 114m decay volume, always in vacuum

10$^{11}$ K decays per year collected

Momentum selection
Focusing
$\mu$ sweeping

Defining collimators
Protecting collimator
Cleaning collimator

KABES 1
KABES 2
KABES 3

Final collimator

Decay volume

Keylar window

Magnet

Target

0º prod. angle

1cm

not to scale

10 cm

50

100 200

250 m

Vacuum tank

He tank + spectrometer
(Direct) CP violation in $K_{\pi^3}$

**Kinematics:**

\[ s_i = (P_{K} - P_{\pi_i})^2 \quad i=1,2,3 \quad (3=\text{odd } \pi) \]
\[ s_0 = (s_1 + s_2 + s_3)/3 \]
\[ u = (s_3 - s_0)/m_\pi^2 = 2m_K (m_K/3 - E^*_{\text{odd}})/m_\pi^2 \]
\[ v = (s_2 - s_1)/m_\pi^2 = 2m_K (E^*_1 - E^*_2)/m_\pi^2 \]

**Matrix element:**

\[ |M(u,v)|^2 \sim 1 + gu + hu^2 + kv^2 \]

\[ K^\pm \rightarrow \pi^\pm \pi^+ \pi^- \ (\tau) \quad g = -0.2154 \pm 0.0035 \]
\[ K^\pm \rightarrow \pi^\pm \pi^0 \pi^0 \ (\tau') \quad g = 0.652 \pm 0.031 \]
\[ |h|, |k| \ll |g| \]

**Potential benefits:**

- Potentially large effects (isospin)
- Simple selection
- Low backgrounds
- No absolute $K$ flux measurement: compare only Dalitz plot shapes

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**K± asymmetries: status**

**THEORY:**

SM contribution: many theoretical computations from several groups

- Large uncertainties (~1 order of magnitude)
  - esp. for “neutral”

Rate asymmetries further suppressed

Some enhancements possible beyond SM

- $A_g \sim 10^{-5}$
  - Compatible with SM
- $A_g > 1 \cdot 10^{-4}$
  - SUSY / New Physics

**Data Points:**

- Smith et al. (1975) (“neutral”)
- Ford et al. (1970) (“charged”)
- HyperCP prelim. (2000) (“charged”)
- TNF (2004) (“neutral”)

**Note:**

- $A_g$ values are given in the range of $10^{-5}$ to $10^{-6}$.
The experimental method

Exploit maximal cancellations

- **Simultaneous** $K^+$ and $K^-$ beams, superimposed in space, with narrow momentum spectra
- Detect asymmetry only from slopes of ratios of normalized $u$ distributions
- **Equalize** averaged $K^+$ and $K^-$ acceptances by frequently alternating polarities of relevant magnets

Project Dalitz plot onto $u$–axis
Neglect asymmetries in quadratic slopes

If acceptance is equal for $K^+$ and $K^-$

$$R(u) = \frac{N^+(u)}{N^-(u)} \approx n \cdot \frac{1+g_+u}{1+g_-u} \approx n \cdot (1+\Delta g u)$$

from which $Ag = \Delta g/2g$ is extracted

Any imperfection has to be charge-asymmetric AND non-flat in $u$ to induce an effect
Acceptance cancellation

Detector left-right asymmetry cancels in 4 ratios of $K^+$ over $K^-$ u distributions:

\[
\begin{align*}
R_{US} &= \frac{N(A+B+K+)}{N(A+B-K-)} \\
R_{UJ} &= \frac{N(A+B-K+)}{N(A+B+K-)} \\
R_{DS} &= \frac{N(A-B+K+)}{N(A-B-K-)} \\
R_{DJ} &= \frac{N(A-B-K+)}{N(A-B+K-)}
\end{align*}
\]

(same deviation by spectrometer in numerator and denominator)

- Beam line (achromat) polarity (A) reversed on *weekly* basis
- Spectrometer magnet polarity (B) reversed on *daily* or *3h* basis

Analysis does not rely on Monte Carlo
More cancellations

Fit with **quadruple ratio:**

\[ R = \frac{N(A+B+K+)}{N(A+B-K-)} \frac{N(A+B-K+)}{N(A+B+K-)} \frac{N(A-B+K+)}{N(A-B-K-)} \frac{N(A-B-K+)}{N(A-B+K-)} \]

Cancel global time instabilities

Cancel beam differences

\[ R = n \cdot (1 + 4 \Delta g u) \]

The fit result is sensitive only to **time variation** of **left-right asymmetries** of experimental conditions on a time-scale of \( \sim 1 \) subsample.
$K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$

**Final sample 2003+2004:**

$3.1 \times 10^9$ events selected ($K^+/K^- \approx 1.8$)

- **Even pion in beam pipe**
- **Odd pion in beam pipe**

- **No significant background**
- **Magnetic spectrometer only**

- **$K^+$:** $2.00 \times 10^9$ events
- **$K^-$:** $1.11 \times 10^9$ events

$\sigma_M = 1.7 \text{ MeV}/c^2$
**K^± → π^±π^+π^- asymmetry results**

**PRELIMINARY** based on full statistics accumulated in the 2003 and 2004 runs

\[ A_g = (1.3 \pm 1.5_{\text{stat}} \pm 0.9_{\text{trig}} \pm 1.4_{\text{syst}}) \times 10^{-4} \]

\[ A_g = (1.3 \pm 2.3) \times 10^{-4} \]

**Measurements of A_g**

- Factor ~20 higher precision than previous measurements
- Statistical uncertainties dominate
- No CPV found
- Compatible with SM estimates
- Design goal reached
- Systematics finalized soon
- New physics window closed


\[ A_g \times 10^4 \]

- Ford et al. (1970)
- HyperCP (2000)
- preliminary 2003
- final 2003
- prelim. 2003+2004
- NA48/2 (superseding)
$K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$

**Final sample 2003+2004:**

$0.91 \times 10^8$ events selected ($K^+ / K^- \approx 1.8$)

No significant background

$\pi \rightarrow \mu \nu$

$Z_{ij} \approx \frac{1}{m_{\pi^0}} \sqrt{E_i E_j} d_{ij}^2$

Vertex

$LKr$

EM calorimeter only
$K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ asymmetry results

PRELIMINARY
based on full statistics accumulated in the 2003 and 2004 runs

$A_g = (2.1 \pm 1.6_{\text{stat}} \pm 1.0_{\text{syst}} \pm 0.2_{\text{ext}}) \times 10^{-4}$

$A_g = (2.1 \pm 1.9) \times 10^{-4}$

Statistics much lower than for “charged” mode
But more favourable Dalitz-plot distribution
Quadratic slope cannot be neglected

- Factor $\sim 10$ higher precision than previous measurements
- Statistical uncertainties dominate
- No CPV found
  Compatible with SM estimates
- Design goal reached
  Systematics finalized soon

New physics window closed

Measurements of $A_g$

Smith et al. (1975)
TNF (2004)
final 2003
prelim. 2003+2004


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$K^\pm \to \pi^\pm \pi^\mp \pi^\mp$ Dalitz plot

Experiment designed for asymmetry measurements
Still, unprecedented statistics allows improvement in slope measurements
*Deliberately ignore* non-analytic (see later) and radiative effects
Full MC tuning, agreement to $10^{-3}$ level

\[ \frac{d\Gamma}{du dv} \sim C(u,v) \times (1 + gu + hu^2 + kv^2) \]

Naïve Coulomb correction

Preliminary results from partial 2003 statistics (0.47×10^9 events)
- \( g = -21.131 \pm 0.010 \pm 0.005 \)
- \( h = 1.829 \pm 0.017 \pm 0.031 \)
- \( k = -0.467 \pm 0.005 \pm 0.009 \)

“Naïve” slopes (comparable with PDG)
Systematics dominated by $\pi$ mom. resolution
\( K^\pm \rightarrow \pi^\pm \pi^+ \pi^- \) Dalitz plot

One order of magnitude improvement in precision

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Kaons at CERN: from NA48 to P-326
\[ K^\pm \rightarrow \pi^+\pi^0\gamma \]

\[ \text{BR} \sim 3 \cdot 10^{-4} \quad \text{IB dominates, DE measured, interference term not yet} \]

\[ W^2 = \left( \frac{P_K^* \cdot P_{\gamma}^*}{m_K} \right) \left( \frac{P_{\gamma}^* \cdot P_{\gamma}^*}{m_{\gamma}} \right) \]

\[ \frac{d\Gamma^\pm}{dW} \simeq \left( \frac{d\Gamma^\pm}{dW} \right) \left[ 1 + 2 \left( \frac{m_{\pi}}{m_K} \right)^2 W^2 |E| \cos\left( (\delta_1 - \delta_0) \pm \phi \right) + \left( \frac{m_{\pi}}{m_K} \right)^4 W^4 (|E|^2 + |M|^2) \right] \]

INT term could give CPV asymmetry

\[ |\varepsilon'_{+\gamma}| \ll 10^{-4} \]

\[ A_t = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ - \Gamma^-} \propto \varepsilon'_{+\gamma} \tan(\Delta \delta) \]

\[ \Gamma^\pm = \int dE_\gamma \left[ \left. \frac{\partial \Gamma}{\partial E_\gamma} - \frac{\partial \Gamma}{\partial E_\gamma} \right|_{IB} \right] \]
$\bar{K}^+ \to \pi^\pm \pi^0 \gamma$

Background $(3\pi) < 1\%$ of DE

NA48/2 (2006) preliminary: (30% sample)
First indication of INT
Systematics from trigger efficiency (improved in 2004)

\[
\text{Frac}(DE)_{0 < T_\pi^* < 80\,\text{MeV}} = (3.35 \pm 0.35_{\text{stat}} \pm 0.25_{\text{syst}})\% \\
\text{Frac}(INT)_{0 < T_\pi^* < 80\,\text{MeV}} = (-2.67 \pm 0.81_{\text{stat}} \pm 0.73_{\text{syst}})\%
\]

$p = 0.92$
$K^+ \rightarrow \pi^+\pi^-e^\pm\nu$ (Ke4) decays

**Form factors**

\[
F = F_s e^{i\delta_0} + F_p e^{i\delta_1} \cos \theta + \text{d-wave...}
\]

\[
G = G_p e^{i\delta_1} + \text{d-wave...}
\]

\[
H = H_p e^{i\delta_1} + \text{d-wave...}
\]

Keep only s- and p- waves (small $q^2$) and rotate by $\delta_1 \rightarrow 5$ form factors

(30% of sample) $\sim 370000$ events with 0.5% background

10 independent fits on equal-population bins in 5–dim space (each $M_{\pi\pi}$ bin)

“Classical” way to extract well-predicted difference of s-wave $\pi\pi$ scattering lengths (predicted by QCD at 2% – quark condensate)

Theoretical input required

Cabibbo–Maksymovicz variables:

$M^2_{\pi\pi}$, $M^2_{e\pi\pi}$, $\cos \theta_{\pi\pi}$, $\cos \theta_e$, $\phi$

**Diagram:**

Entries per 0.005 GeV/c²

- $K_{e4}$ data
- $K_{e4}$ MC
- Background

$M_{K_{e4}}$ (GeV/c²)

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Ke4 results

New NA48/2 preliminary (350K events):

\[ a_0^0 = 0.256 \pm 0.008 \pm 0.007 \pm 0.018 \]

(and \( a_0^2 = -0.031 \pm 0.015 \pm 0.015 \pm 0.009 \) using U.B.)
$K^\pm \rightarrow \pi^0\pi^0e^\pm\nu$

Only 1 form factor in this case
2–3% background.
New NA48/2 preliminary measurement (9600 events):

$$BR\left(K_{e4}^{00}\right) = (2.587 \pm 0.026_{\text{stat}} \pm 0.019_{\text{syst}} \pm 0.029_{\text{ext}}) \cdot 10^{-5}$$

Form factors consistent with charged Ke4 (37K events)
ππ scattering in K→3π decays

NA48/2: K± → π±π0π0 events

Experimental M_{oo}^2 distribution for 23 x 10^6 K± → π±π0π0 decays

Stimulated much theoretical work:
Cabibbo et al., Gamiz et al., Colangelo et al.

M_{0} = 1 + \frac{1}{2} g_{0} u + \frac{1}{2} h' u^2

“A threshold cusp” (Wigner 1948)

Unperturbed matrix element:

Final state pion scattering effect:

Sudden change of slope (“cusp”) at M_{oo} = 2m_π

2M(π^±)

M(π^0π^0)

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Kaons at CERN: from NA48 to P-326

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ππ scattering lengths

The magnitude of the discontinuity (cusp) is directly related to the \((a_0^0 - a_0^2)\) difference in \(\pi\pi\) scattering lengths.

Using Cabibbo–Isidori 2nd order expansion (and assuming \(k=0\)), from the unconstrained fit:

\[
(a_0 - a_2) m_\pi = 0.268 \pm 0.010_{\text{stat}} \pm 0.004_{\text{syst}} \pm 0.013_{\text{ext}}
\]

\[a_2 m_\pi = 0.041 \pm 0.022_{\text{stat}} \pm 0.014_{\text{syst}}\]

(20% of total statistics)

New approach, potentially very powerful, alternative to Ke4 and pionium (DIRAC expt)

Evidence for pionium formation, sensitivity to higher–order effects…

Radiative effects require improved theoretical framework


[see Cabibbo, Isidori, JHEP 0503 (2005) 21]
\( \pi\pi \) scattering lengths: improvements

Unperturbed matrix element:

\[
M_0 = 1 + \frac{1}{2} g_0 u + \frac{1}{2} h' u^2 + \frac{1}{2} k' v^2 + \ldots
\]

and \( k' \approx 0 \) was assumed (following PDG)

NA48/2 preliminary (2003 data):

Evidence for a non–zero \( k' \)

\[
k' = 0.0097 \pm 0.0003 \text{ stat} \pm 0.0008 \text{ syst}
\]

Significative changes in \( g_0 \) and \( h' \)

No change in \( a_0^0 \)–\( a_0^2 \) and \( a_0^2 \)
**ππ scattering lengths: improvements**

Non-relativistic lagrangian framework developed (Colangelo et al.)

- Allows systematic improvement and inclusion of radiative effects
- Allows fitting the whole Dalitz plot
- Includes quadratic terms at second order

![Comparison between the two representations](image1.png)

![Graph showing scattering lengths](image2.png)

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**WORK IN PROGRESS...**
**Kℓ3 decays: \( V_{us} \) and form factors**

After the “semileptonic revolution” the \( V_{us} \) issue seems solved
More results expected
(K\(^\pm\), K\(_S\), radiative)

K\(\mu3\) form factors:

2.6M K\(_L\)→πμν decays

\[
\hat{\lambda}_+ = 0.0260 \pm 0.0007^{\text{stat}} \pm 0.0010^{\text{syst}} \\
\hat{\lambda}_0 = 0.0120 \pm 0.0008^{\text{stat}} \pm 0.0015^{\text{syst}}
\]

NA48 preliminary
**Kℓ2 decays: unexpected fame**

Masiero et al. (2006): \( R_K = \frac{\Gamma(K^{\pm} \rightarrow e^{\pm}\nu)}{\Gamma(K^{\pm} \rightarrow \mu^{\pm}\nu)} \)
as the most sensitive probe of SUSY LFV effects: effects can reach 2–3% (!)

**SM:** \( R_K = (2.472 \pm 0.001) \times 10^{-5} \)

**PDG:** \( R_K = (2.45 \pm 0.11) \times 10^{-5} \)

**NA48/2 preliminary** (byproduct, 1 month run)

\( R_K = (2.416 \pm 0.043 \pm 0.024) \times 10^{-5} \)

A new run would have the potential to reach sub–percent accuracy.
$K \rightarrow \pi \nu \nu$: the (new) "holy grail"

- $Z(\gamma)$ penguin and box diagrams
- Top in loop, sensitivity to $V_{td}$
- Small theoretical uncertainty (also true BSM)

\[
B(K^+ \rightarrow \pi^+ \nu \nu) \approx 1.0 \times 10^{-10} \ A^4 \left( \eta^2 + (\rho_0 - \rho)^2 \right) = (8.0 \pm 1.1) \times 10^{-11}
\]

\[
B(K_L \rightarrow \pi^0 \nu \nu) = 2.2 \times 10^{-10} \left( \frac{\text{Im}(V_{ts}^* V_{td})}{\lambda^5} \ X(x_t) \right)^2 = (2.8 \pm 0.4) \times 10^{-11}
\]

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\[ \text{Today} \]

100 events
Mean=SM

\[ \text{Tomorrow} \]

100 events
Mean=E787/E949

\[ \text{E787/E949: BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.47^{+1.30}_{-0.89} \times 10^{-10} \]
**$K^+ \rightarrow \pi^+\nu\bar{\nu}$: P-326 proposal**

- At CERN SPS
- Decay *in flight*  
  (75 GeV unseparated $K^+$ beam)
- Loosely based on NA48 detector  
  (incl. LKr calorimeter)
- Background rejection:  
  - PID($\pi/\mu$) by RICH  
  - High $E\pi^0$, low ineff.  
  - Missing mass cut
- $K^+$ tracking in 1 GHz
- Expect 80 SM events in 2 years
### $K^+ \rightarrow \pi^+ \nu \bar{\nu}$: P-326 yield/yr

<table>
<thead>
<tr>
<th>Source</th>
<th>Total</th>
<th>Region I</th>
<th>Region II</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal (SM)</strong></td>
<td>65</td>
<td>16</td>
<td>49</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi^0$</td>
<td>$2.7 \pm 0.2$</td>
<td>$1.7 \pm 0.2$</td>
<td>$1.0 \pm 0.1$</td>
</tr>
<tr>
<td>$K_{\mu2}$</td>
<td>$1.2 \pm 0.3$</td>
<td>$1.1 \pm 0.3$</td>
<td>$&lt; 0.1$</td>
</tr>
<tr>
<td>$K_{e4}$</td>
<td>$2 \pm 2$</td>
<td>Negligible</td>
<td>$2 \pm 2$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi^+ \pi^-$ and other 3-tracks</td>
<td>$1 \pm 1$</td>
<td>Negligible</td>
<td>$1 \pm 1$</td>
</tr>
<tr>
<td>$K_{\pi2\gamma}$</td>
<td>$1.3 \pm 0.4$</td>
<td>Negligible</td>
<td>$1.3 \pm 0.4$</td>
</tr>
<tr>
<td>$K_{\mu2\gamma}$</td>
<td>$0.4 \pm 0.1$</td>
<td>$0.2 \pm 0.1$</td>
<td>$0.2 \pm 0.1$</td>
</tr>
<tr>
<td>$K_{e3}$, $K_{\mu3}$, others</td>
<td>Negligible</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total bkg</strong></td>
<td>$9 \pm 3$</td>
<td>$3.0 \pm 0.2$</td>
<td>$6 \pm 3$</td>
</tr>
</tbody>
</table>
**$K^+ \rightarrow \pi^+ \nu \bar{\nu}$: P-326 status**

CERN, Dubna, Ferrara, Firenze, Frascati, Mainz, Merced, Moscow, Napoli, Perugia, Protvino, Pisa, Roma, Saclay, San Luis Potosi, Sofia, Torino

and **looking for more collaborators**...

SPS used as **LHC injector** (it will run in the future)
No flagrant time overlap with CNGS
Fully compatible with rest of CERN fixed target program
Conservative beam request

R&D endorsed by CERN Research Board on December 2005

Test beams Oct–Nov 2006

Aims to complete R&D by the end of **2007**...

... to start data taking in **2011**
Outlook

A 17-year long enterprise
8 years of data-taking
A wide range of physics topics:
  CP violation, CPT tests,
  $K_L$, $K_S$, $K^\pm$ rare decays, chiral perturbation theory,
  hyperon physics, hadronic physics,
  exotic searches, meson masses

35 physics papers and 20 technical papers so far
120 physicists, 90+ Ph.D. students

A new challenge ahead
for everybody who wants to join!
Spare slides
**K → πℓ̅ℓ**

**Experimental problems:**

\[ \text{BR} \approx 10^{-11}, \] few (or no) kinematic constraints, backgrounds with BR x 10^7

| \( K_L \rightarrow π^0e^+e^- \) | \( 10^{-11} \) (CPV\(_{\text{dir}}\) 3·10^{-12}) | < 2.8 ·10^{-10} (FNAL KTeV) | CPC+CPV, eeγγ bkg. 3 ev. (2.05 bkg) |
| \( K_L \rightarrow π^0μ^+μ^- \) | \( 10^{-11} \) (CPV\(_{\text{dir}}\) 1·10^{-12}) | < 3.8 ·10^{-10} (FNAL KTeV) | CPC+CPV 2 ev. (0.87 bkg) |
| \( K^+ \rightarrow π^+νν^- \) | \( 8·10^{-11} \) (at 7%) | \( 1.47^{+1.30}_{-0.89} \) · 10^{-10} (BNL E787+E949) | Dedicated expt. 3 evt. (bkg. 0.45) |
| \( K_L \rightarrow π^0νν^- \) | \( 2.8·10^{-11} \) (at 2%) | < 5.9 ·10^{-7} (KTeV, Dalitz decay) | CPV dir “Nothing to nothing” |

Dedicated experiments required
$K_L \rightarrow \pi^0 \ell^+ \ell^-$

KTeV limits (90% CL):

- **CP-allowed**: not predicted, derived from $K_L \rightarrow \pi^0 \gamma \gamma$ (NA48/KTeV)
- **Indirect CP violating**: not predicted, measured by $K_S \rightarrow \pi^0 \ell^+ \ell^-$ (NA48/1)
- **Direct CP violating**: predicted and proportional to CKM phase

Combinatorial situation: 3 contributions

BR($K_L \rightarrow \pi^0 e^+ e^-$) $< 2.8 \times 10^{-10}$
BR($K_L \rightarrow \pi^0 \mu^+ \mu^-$) $< 3.8 \times 10^{-10}$

$BR(K_L \rightarrow \pi^0 e^+ e^-)_{CPV} \approx 10^{-12} \left[ 15.3 a_S^2 - 6.8 a_s \text{Im}(\lambda_t) \times 10^{-4} + 2.8 \text{Im}(\lambda_t)^2 \times 10^{-8} \right]$ $\lambda_t = V_{ts}^* V_{td}$

$|a_s| \approx 1 \div 1.5$ measured by $K_S$ (sign ?)
### $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ CPV slope asymmetry

**Theoretical predictions**

<table>
<thead>
<tr>
<th>Standard Model</th>
<th>L.Maiani, N.Paver (95)</th>
<th>$(2.3\pm0.6)\times10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Bel’kov (95)</td>
<td></td>
<td>$&lt; 4\times10^{-4}$</td>
</tr>
<tr>
<td>G.D’Ambrosio, G.Isidori (98)</td>
<td></td>
<td>$&lt;10^{-5}$</td>
</tr>
<tr>
<td>E.Shabalin (01)</td>
<td></td>
<td>$&lt; 3\times10^{-5}$</td>
</tr>
<tr>
<td>E.Gamiz, J.Prades, I.Scimemi (03)</td>
<td></td>
<td>$(-2.4\pm1.2)\times10^{-5}$</td>
</tr>
<tr>
<td>E.Shabalin (05)</td>
<td></td>
<td>$&lt; 8\times10^{-5}$</td>
</tr>
<tr>
<td><strong>New physics</strong></td>
<td>G.D’Ambrosio, G.Isidori, G.Martinelli (00)</td>
<td>up to $10^{-4}$</td>
</tr>
<tr>
<td>E.Shabalin (98) [WHDM]</td>
<td></td>
<td>$\sim 4\times10^{-4}$</td>
</tr>
<tr>
<td>I.Scimemi (04)</td>
<td></td>
<td>$&gt; 3\times10^{-5}$</td>
</tr>
</tbody>
</table>
**Time-stability & control**

Physics asymmetry

Control quantities cancelling in the result
quadruple ratio components rearranged
(smallness proves second order effects are negligible)

\[ R_{LR}(u) = R_S/R_J \]

\[ R_{UD}(u) = R_U/R_D \]

Control of setup
time-variable biases

Control of differences of the two beam paths

\[ \chi^2/\text{ndf} = 10.0/8 \]
(results consistent)

Monte Carlo
(reproduces apparatus asymmetries)
### Ke4 form factor results

#### $K^\pm \rightarrow p^+p^-e^\mp n$

<table>
<thead>
<tr>
<th>Form Factor</th>
<th>Value</th>
<th>Stat Error</th>
<th>Sys Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f'_s/f_s$</td>
<td>$0.169 \pm 0.009$</td>
<td>$0.034$</td>
<td>$0.009$</td>
</tr>
<tr>
<td>$f''_s/f_s$</td>
<td>$-0.091 \pm 0.009$</td>
<td>$0.031$</td>
<td>$0.009$</td>
</tr>
<tr>
<td>$f_p/f_s$</td>
<td>$-0.047 \pm 0.006$</td>
<td>$0.008$</td>
<td>$0.006$</td>
</tr>
<tr>
<td>$g'_p/f_s$</td>
<td>$0.891 \pm 0.019$</td>
<td>$0.020$</td>
<td>$0.019$</td>
</tr>
<tr>
<td>$g''_p/f_s$</td>
<td>$0.111 \pm 0.031$</td>
<td>$0.032$</td>
<td>$0.031$</td>
</tr>
<tr>
<td>$h_p/f_s$</td>
<td>$-0.411 \pm 0.027$</td>
<td>$0.038$</td>
<td>$0.027$</td>
</tr>
</tbody>
</table>

#### $K^\pm \rightarrow p^0p^0e^\mp n$

<table>
<thead>
<tr>
<th>Form Factor</th>
<th>Value</th>
<th>Stat Error</th>
<th>Sys Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f'_s/f_s$</td>
<td>$0.129 \pm 0.036$</td>
<td>$0.020$</td>
<td>$0.020$</td>
</tr>
<tr>
<td>$f''_s/f_s$</td>
<td>$-0.040 \pm 0.034$</td>
<td>$0.020$</td>
<td>$0.020$</td>
</tr>
</tbody>
</table>

$a_0^0 = 0.256 \pm 0.008_{\text{stat}} \pm 0.007_{\text{syst}} \pm 0.018_{\text{theo}}$

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M.S. Sozzi

Kaons at CERN: from NA48 to P-326

DPF2006 – Oct 30th 2006
**Cusp in \( K^\pm \to \pi^\pm \pi^0\pi^0: \) results**

The scattering length difference:

\[
(a_0-a_2)m_+ = 0.268 \pm 0.010_{\text{stat}} \pm 0.004_{\text{syst}} \pm 0.013_{\text{ext}}
\]

and

\[
(a_2)m_+ = -0.041 \pm 0.022_{\text{stat}} \pm 0.014_{\text{syst}}
\]

If correlation between \( a_0 \) and \( a_2 \) (universal band) is used:

\[
(a_0-a_2)m_+ = 0.264 \pm 0.006_{\text{stat}} \pm 0.004_{\text{syst}} \pm 0.013_{\text{ext}}
\]

From same fit slope parameters are obtained (assuming \( k=0! \)):

\[
g_0 = 0.645 \pm 0.004_{\text{stat}} \pm 0.009_{\text{syst}}
\]

\[
h' = -0.047 \pm 0.012_{\text{stat}} \pm 0.011_{\text{syst}}
\]

**Main systematic uncertainties:** acceptance, trigger efficiency, fit interval

**NA48/2 measurements of \( \pi\pi \) scattering lengths from Ke4 Charged decays:**

- scattering lengths extracted in a model dependent way (input \( a_0^2 = f(a_0^0) \))
- use Universal Band function

**NA48/2 Preliminary (370k decays)**

\[
a_0^0 = 0.256 \pm 0.008_{\text{stat}} \pm 0.007_{\text{syst}} \pm 0.018_{\text{theo}}
\]

**Previous published results:**

- CERN/PS Geneva-Saclay (30k decays)
  \[
a_0^0 = 0.253 \pm 0.037_{\text{stat+sys}} \pm 0.014_{\text{theo}}
\]

- BNL E865 (400k decays)
  \[
a_0^0 = 0.229 \pm 0.012_{\text{stat}} \pm 0.004_{\text{sys}} \pm 0.014_{\text{theo}}
\]