Kaons @ CERN: Recent Results and Prospects

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on behalf of the NA62 and NA48/2 Collaborations

PASCOS 2012
Mérida, 3-8 June 2012
Outline

- Kaon physics at CERN \( \rightarrow \) NA48/n & NA62 brief history
- This talk → two main topics:
  - Chiral Perturbation Theory tests
    - \( K^\pm \rightarrow \pi^\pm\gamma\gamma \) decay NEW result
  - Tests of SM and search for New Physics
    - The \( K^+ \rightarrow \pi^+\nu\bar{\nu} \) decay
- Summary and Outlook

The NA62 Collaboration:
Birmingham, Bratislava, Bristol, CERN, Dubna, Fairfax, Ferrara, Firenze, Frascati, Glasgow, Liverpool, Louvain, Mainz, Merced, Moskow, Napoli, Perugia, Pisa, Protvino, Roma I, Roma II, San Luis Potosi, SLAC, Sofia, Torino

The NA48/2 Collaboration:
Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Vienna
NA48
Main goal: Search for direct CPV
Measurement of $\epsilon'/\epsilon$
Beams: $K_L + K_S$

NA48/1
Main goal: Rare $K_S$ decays and hyperon decays, CPV tests
Beams: $K_S$

NA48/2
Main goal: Search for direct CPV
Charge asymmetry measurement
Beams: $K^+ + K^-$

NA62
Main goal: Measurement of the decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
Beam: $K^+$

1997
1998
1999
2000
2001
2002
2003
2004
2005
2013

NA48/n history

4-6-2012
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High energy scales

Flavour sector probing extremely high energy scales: precision frontier *complementary* to LHC energy frontier

Study processes suppressed in SM, sensitive to New Physics

RARE DECAYS

Four main reasons

1) study explicit Violations of SM, such as LFV
2) probe the flavour sector by means of FCNC
3) test of fundamental symmetries such as CP and CPT
4) study of strong interaction at low energy in exclusive processes
NEW

NA48/2 and NA62
Chiral Perturbation Theory tests

$K^\pm \rightarrow \pi^\pm \gamma\gamma$
\[ K^\pm \rightarrow \pi^\pm \gamma \gamma - \text{introduction} \]

- Decay spectrum and rate strongly depend on the single \( \hat{c} \) parameter \( O(1) \)
- The \( M_{\gamma \gamma} \) spectrum has a pronounced cusp-like behaviour at \( 2m_\pi \) threshold

Unitarity corrections effects can increase the BR at low \( \hat{c} \) with a non-zero rate at \( m_{\gamma \gamma} \rightarrow 0 \)

Stringent test of ChPT

Experimental status

- BNL E787: 31 candidates, \( \text{BR} = (1.10 \pm 0.32) \times 10^{-6} \) (full kinematic range)
- New measurement NA48/2 and NA62

\[ [\text{Ecker, Pich, de Rafael, Phys. NPB 303 (1988), 665}] \]

\[ [\text{D'Ambrosio and Portolés, PLB 386 (1996), 403}] \]

\[ 4-6-2012 \quad \text{Giuseppina Anzivino@PASCOS 12} \]
NA48/2 Data set - 2004 (3 days)

mass spectrum

ChPT O(p⁶) fit

ChPT O(p⁴):  
\[ \hat{c} = 1.36 \pm 0.33 \text{ stat} \pm 0.07 \text{ syst} = 1.36 \pm 0.34 \]

ChPT O(p⁶):  
\[ \hat{c} = 1.67 \pm 0.39 \text{ stat} \pm 0.09 \text{ syst} = 1.67 \pm 0.40 \]

- **K_{\pi\gamma\gamma} candidates**: 147
- **K_{2\pi(\gamma)} background**: 11.0 ± 0.8
- **K_{3\pi} background**: 5.9 ± 0.7
- **K_{\pi\gamma\gamma} signal**: 130 ± 12
NA62 Data set – 2007 (3 months / downscaled trigger)

**mass spectrum**

![Graph showing mass spectrum](image)

- $K_{\pi\gamma\gamma}$ candidates: 175
- $K_{2\pi(\gamma)}$ background: $11.1 \pm 1.0$
- $K_{3\pi}$ background: $1.3 \pm 0.3$
- $K_{\pi\gamma\gamma}$ signal: $163 \pm 13$

**ChPT O(p⁶) fit**

![Graph showing ChPT fit](image)

- ChPT O(p⁴):
  \[ \hat{c} = 1.71 \pm 0.29_{\text{stat}} \pm 0.06_{\text{syst}} = 1.71 \pm 0.30 \]

- ChPT O(p⁶):
  \[ \hat{c} = 2.21 \pm 0.31_{\text{stat}} \pm 0.08_{\text{syst}} = 2.21 \pm 0.32 \]
Combined 2004 & 2007 - Fit results

ChPT $O(p^4)$: \( \hat{c} = 1.56 \pm 0.22_{\text{stat}} \pm 0.07_{\text{syst}} = 1.56 \pm 0.23 

ChPT $O(p^6)$: \( \hat{c} = 2.00 \pm 0.24_{\text{stat}} \pm 0.09_{\text{syst}} = 2.00 \pm 0.26 

\[
\text{BR} = (1.01 \pm 0.06) \times 10^{-6}
\]

- very low systematic uncertainties
- ChPT $O(p^4)$ vs $O(p^6)$ models cannot be discriminated within the current experimental sensitivity

\[\text{preliminary}\]
From NA48/2

- Precision measurement of \( K^\pm \rightarrow \pi^0\pm \nu (K_{l3}) \) form factors
  - provide the most accurate and theoretically cleanest way to access \(|V_{us}|\)

\[
\begin{array}{c|ccc}
\text{Quadratic (} \times 10^{-3} \text{)} & \lambda^+ & \lambda'' & \lambda_0 \\
\hline
K_{\mu 3}^\pm K_{e3}^\pm \text{ combined} & 26.98 \pm 1.11 & 0.81 \pm 0.46 & 16.23 \pm 0.95 \\
\hline
\text{Pole (MeV/c}^2\text{)} & m_V & m_S \\
\hline
K_{\mu 3}^\pm K_{e3}^\pm \text{ combined} & 877 \pm 6 & 1176 \pm 31 \\
\end{array}
\]

- NA48/2 is the first experiment which measured both \( K_{e3} \) and \( K_{\mu 3} \).
- high precision preliminary results, competitive with other measurements
- Results for \( K_{e3} \) and \( K_{\mu 3} \) from NA48/2 in good agreement.

- First observation of the decay \( K^\pm \rightarrow \pi^\pm \pi^0 e^+ e^- \)
  - Sensitivity to CPV and NP,
  - \( \sim 4500 \) events in the signal region

- Measurement of the \( K^+ \rightarrow e^+ \nu \gamma (SD+) \) decay
  - ChPT test to NLO in ChPT [O(p4) and O(p6)]
  - Model-independent form factor extraction allows comparison with theoretical predictions
  - \( K^+ \rightarrow e^+ \nu \gamma (SD+) \) candidates \( \sim 10000 \)

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 NA62 (R<sub>K</sub> phase - 2007) Test of µ-e universality

- In the SM $K_{e2}$ strongly helicity suppressed (V-A coupling)
- measure:
  \[
  R_K = \frac{\Gamma(K^\pm \rightarrow e^\pm \nu_e)}{\Gamma(K^\pm \rightarrow \mu^\pm \nu_\mu)} = (2.477 \pm 0.001) \times 10^{-5}
  \]
  [V. Cirigliano and I. Rosell, PRL99 (2007) 231801]

- Beyond the SM the presence of LFV terms, charged Higgs mediated, introduces extra contribution to the SM amplitude, enhancing the decay rate

**NA62 final result**

\[
R_K = (2.488 \pm 0.010) \times 10^{-5}, \quad \delta R_K / R_K = 0.40\%
\]

World Ke2 statistics increased by 1 order of magnitude
In agreement with SM expectation, but \( \sim 1 \sigma \) above further precision $R_K$ measurements
- Partial data set (40%): PLB 698 (2011) 105
- Full data set: paper close to be submitted

Clark et al. (1972)
Heard et al. (1975)
Heintze et al. (1976)
KLOE (2009)
* PDG 2010
NA62 (2011) full data set

PDG 2008
July 2011 average
NA62
Measurement of the ultra-rare decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$
Ultra-rare kaon decays & CKM

The Unitarity Triangle describes in the \((\rho, \eta)\) plane the CKM matrix

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} =
\begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\bar{\rho} - i\bar{\eta}) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \bar{\rho} - i\bar{\eta}) & -A\lambda^2 & 1
\end{pmatrix}
\]

The “Standard” Unitarity Triangle

\(V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0\)

The “Kaon” Unitarity Triangle

\(V_{us}^* V_{ud} + V_{cs}^* V_{cd} + V_{ts}^* V_{td} = 0\)

\(K^+ \rightarrow \pi^+ \nu\bar{\nu}\)

\(|V_{ts}^* V_{td}|\)

\(K_L \rightarrow \pi^0 \nu\bar{\nu}\)

\(\text{Im} (V_{ts}^* V_{td}) \propto \eta\)

the holy grail

Alternative way to measure the Unitarity Triangle parameters with smaller theoretical uncertainty
**$K \rightarrow \pi \nu \nu$ in the SM . . .**

- FCNC process forbidden at tree level \( \Rightarrow \) room for NP up to \(10 \times \)SM
- Short distance contribution dominated by $Z$ penguin and $W$ box diagrams
- “Super-clean” theoretically
  - hadronic matrix element can be extracted from measured quantities (Ke3)
- Very small BR due to the CKM top coupling
  - \( A \sim (m_t/m_W)^2 |V_{ts}V_{td}| \approx \lambda^5 \)
- Measurement of $|V_{td}|$ complementary to those from B-B mixing and $B \rightarrow \rho \gamma$
- $\delta \text{BR/BR} = 10\% \rightarrow \delta |V_{td}|/|V_{td}| = 7\%$.

<table>
<thead>
<tr>
<th>BR $\times 10^{10}$</th>
<th>SM Prediction</th>
<th>Experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+ \nu \bar{\nu}$</td>
<td>0.781 ± 0.075 ± 0.029 [1]</td>
<td>1.73 $^{+1.15}_{-1.05}$ [2]</td>
</tr>
<tr>
<td>$K^0 \rightarrow \pi^0 \nu \bar{\nu}$</td>
<td>0.243 ± 0.039 ± 0.006 [1]</td>
<td>&lt; 260 (@90% CL) [3]</td>
</tr>
</tbody>
</table>


7 events: twice as large as, but still consistent with SM expectation
Several SM extensions predict sizable deviations for the BR
Possibility to distinguish among different models

Concrete NP models predicting high deviations from MFV
Randall-Sudrum,
Littlest Higgs with T-parity,
SM 4th generation
**NA62 - Experimental principles**

- **Goal**: 10% precision Branching Ratio measurement
- **O(100) K^+ → π^+ν̅ν** events in two years of data taking

**Statistics**
- $\text{BR(SM)} \sim 7.8 \times 10^{-11}$
- Acceptance: 10%
- K decays: $10^{13}$

**Systematics**
- $\geq 10^{12}$ background rejection
- $\leq 10\%$ precision on background measurement

**Kaon intensity & signal efficiency**
- High momentum $K^+$ beam

**Signal purity & detector redundancy**
- Decay in-flight technique

**Very challenging experiment**
- Weak signal signature

**Huge background**

**Dilution factors**

<table>
<thead>
<tr>
<th>Decay</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+\nu$ (K_{µ2})</td>
<td>63.5%</td>
</tr>
<tr>
<td>$\pi^+\pi^0$ (K_{π2})</td>
<td>20.7%</td>
</tr>
<tr>
<td>$\pi^+\pi^+\pi^-$</td>
<td>5.6%</td>
</tr>
<tr>
<td>$\pi^0e^+\nu$ (K_{e3})</td>
<td>5.1%</td>
</tr>
<tr>
<td>$\pi^0\mu^+\nu$ (K_{µ3})</td>
<td>3.3%</td>
</tr>
</tbody>
</table>

**Constraints**

- $m^2_{\text{miss}} = (P_K - P_\pi)^2$
Experiment layout & sensitivity

- 400 GeV/c SPS primary protons
- 75 GeV/c kaons unseparated hadron beam
- \((p/\pi^+/K^+)(\Delta p/p \pm 1\%)\)
- 750 MHz → 50 MHz kaons → 6 MHz decays
- \(4.8 \times 10^{12} K^+\) decays/y → SES \(\sim 10^{-12}\)

Signal

<table>
<thead>
<tr>
<th>Signal</th>
<th>45 evt/y</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K^+ \rightarrow \pi^+\pi^0)</td>
<td>4.3%</td>
</tr>
<tr>
<td>(K^+ \rightarrow \mu^+\nu)</td>
<td>2.2%</td>
</tr>
<tr>
<td>(K^+ \rightarrow \pi^+\pi^+\pi^-)</td>
<td>&lt; 4.5%</td>
</tr>
<tr>
<td>(K^+ \rightarrow \pi^+\pi^0\gamma)</td>
<td>(\sim 2)%</td>
</tr>
<tr>
<td>(K^+ \rightarrow \mu^+\nu\gamma)</td>
<td>0.7%</td>
</tr>
<tr>
<td>total background</td>
<td>&lt; 13.5%</td>
</tr>
</tbody>
</table>
Background and kinematics

92% Bkg separated from signal by kinematic cuts
8% not separated

missing mass

\[ m^2_{\text{miss}} = (P_K - P_\pi)^2 \] defines low bkg signal regions separated by \( K^+ \rightarrow \pi^+\pi^0 \)

- high resolution \( m^2_{\text{miss}} \) reconstruction
- measure precisely kaon and pion momenta
- keep multiple scattering as low as possible

Gigatracker (Kaon)
Straw chambers (pion)

Veto and PID

\[ K^+ \rightarrow \pi^+\pi^0 \] background
Reject offline decays with \( \gamma \)
\( K^+ \) identification in the had beam
10\(^{-3}\) \( \pi-\mu \) separation

Photon veto system
Particle Identification
Tracking detectors

Gigatracker
- measurement of time, coordinates and momentum of individual particles
- three Si-pixel station before the decay volume
- $\sigma(t) \sim 150$ ps on single track (test beam)

Straw chamber spectrometer
- measurement of coordinates and momentum of charged particles originating from decay
- 4 chambers + magnet
- $\sigma(P_{\pi})/P_{\pi} \sim 0.3\% \oplus 0.007\% \times P_{\pi}$ (GeV/c)
- $\sigma(dX/dZ)/(dX/dZ) \sim 45-15$ $\mu$rad
CEDAR - Differential Cherenkov counter
- Filled with Hydrogen gas
- Positive identification of Kaons in a 800 MHz hadron beam
- Excellent time resolution O(100 ps)
- Sustain rate O(MHz/mm²)

Photon Veto System
- several subsystems, among them:
  - Large angle (8.5-50 mrad) Lead glass blocks
  - Inefficiency <10⁻⁴ for 100 MeV < E_\gamma < 35 GeV
  - Small angle (1-8 mrad) “shashlyk” calorimeters
  - Inefficiency <10⁻³ for E_\gamma > 10 GeV
Veto & PID detectors/2

RICH - Ring Imaging Cherenkov counter
- Filled with Neon at atm pressure
- Separate $\pi-\mu$ in $15 < p < 35$ GeV/c with a $\mu$ suppression factor better than $5 \times 10^{-3}$
- Measure pion crossing time with a resolution $< 100$ ps
- Provide a L0 trigger for charged tracks

Vessel:
- $\sim 18$ m long, $4 \rightarrow 3.4$ m diameter

Mirror Mosaic
- (17 m focal length)

Muon detector
- 3 planes MUV 1,2,3 + iron
- MUV 1+MUV 2 reach a factor of $10^6$ in muon rejection (combined with the RICH)
- MUV 3 for trigger purposes

Beam Pipe

volume $\sim 200$ m$^3$
Summary and outlook

Precision physics complementary to high-energy approach for NP search

- New measurement of the $K^+ \rightarrow \pi^+ \gamma \gamma$ from NA48/2 and NA62
  - new precise experimental data on ChPT parameters
  - ChPT $O(p^4)$ vs $O(p^6)$ models cannot be discriminated within the current experimental sensitivity

- The $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay: very challenging experiment
  - collect 0(100) events & provide a 10% BR measurement
  - key points: excellent resolutions, hermetic coverage, PID
  - construction well advanced, first technical run in October 2012
  - 2013 - complete detector and installation
  - 2014 (?) data taking with full detector (CERN accelerator schedule)
  - The high performances of the detectors can also be the building blocks for a further physics program

- Many other results at the frontier of precision physics

A very rich program in the near future
NA62 Penguins at work