The NA62 Project at CERN:
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at the SPS

Rencontres de Moriond EW,
March, 7-14, 2009

A. Ceccucci for the NA62 Collaboration:

Bern ITP, Birmingham, CERN, Dubna, Ferrara, Fairfax, Florence, Frascati,
IHEP, INR, Louvain, Mainz, Merced, Naples, Perugia, Pisa, Rome I,
Rome II, San Luis Potosi, SLAC, Sofia, TRIUMF, Turin
Flavor in the Era of the LHC*

• The current experimental manifestations of CP-Violation (K and B decays and mixing) are consistent with just one complex phase in the CKM matrix (“Standard Model”)

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“[These articles] confirm that flavour physics is an essential ingredient in the future of high-energy physics”

• Paradigm shift: we should determine the “true” CKM parameters from observables not affected by New Physics (e.g. B tree decays) and measure loop-induced, precisely predictable (SM), FCNC to detect patterns of deviation
Rare Kaon Decays

\( K_L \rightarrow \mu^+ \mu^- \): A theoretically pristine and experimentally almost unexplored opportunity

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

\( K_L \rightarrow \pi^0 \nu \bar{\nu} : \quad \bar{\eta} < 17 \)

\( K_L \rightarrow \pi^0 e^+ e^- : \quad \bar{\eta} < 3.3 \)

\( K_L \rightarrow \pi^0 \mu^+ \mu^- : \quad \bar{\eta} < 5.4 \)
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$: Physics Motivation

In the Standard Model:

$$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}(\gamma)) = k_+ (1 + \Delta_{EM}) \times \frac{|V_{ts}^* V_{td} X_t (m_t^2) + \lambda^4 \Re V_{cs}^* V_{cd} (P_c (m_c^2) + \delta P_{c,u})|^2}{\lambda^5}$$

- Charm
  - NNLO QCD [Buras, Gorbahn, Haisch, Nierste ’06]
  - EW Corrections to $P_c$ [Brod, Gorbahn ’08]
- Long Distance
  - $|\Delta E| < 1\%$ [Mescia, Smith ‘07]
  - $\delta P_{c,u} + 6\%$ [Isidori, Mescia, Smith ‘05]

- The SM Branching Ratio prediction is precise (~8%) and the intrinsic theory error is small
- The parametric error will be further reduced

[52% CKM, 17% $m_c$, 31% Theory]

[J. Brod @ CKM’08]
SM Prediction vs. Experiment

As reported by J. Brod, CKM '08

\[ B^{TH}(K^+ \rightarrow \pi^+ \nu \bar{\nu}(\gamma)) = (0.85 \pm 0.07) \times 10^{-10} \]

For \( m_c = (1286 \pm 13) \text{ MeV} \) [Kühn et al. '07]

\[ B^{EXP}(K^+ \rightarrow \pi^+ \nu \bar{\nu}(\gamma)) = (1.73^{+1.15}_{-1.05}) \times 10^{-10} \]

[E787, E949 '08]

And, for comparison:

\[ B^{TH}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) = (2.76 \pm 0.40) \times 10^{-11} \]

\[ B^{EXP}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) \leq 6.8 \times 10^{-8} \quad 90\% \text{ CL} \] [E391a '08]

Future: E14 (KOTO) @ J-PARC
**Kaon Rare Decays and NP**

(courtesy by Christopher Smith)

**C. The Z penguin (and its associated W box)**

\[ SU(2)_L \text{ breaking: } \begin{align*}
SM &: v_u^2 Y_u^{*32} Y_u^{31} \sim m_l^2 V_{ls} V_{td} \\
MSSM &: v_u^2 A_u^{*32} A_u^{31} \sim m_l^2 \times O(1) \\
MFV &: v_u^2 A_u^{*32} A_u^{31} \sim m_l^2 V_{ls} V_{td} |A_0 a_2 - \cot \beta f_t|^2
\end{align*} \]

- Relatively slow decoupling (w.r.t. boxes or tree).

**Buras, Ewerth, Jager, Rosiek '04**

**Isidori, Mescia, Paradisi, Trine, C.S. '06**
The CERN proton Complex is unique

The SPS is needed as LHC proton injector only part-time

For the reminder of the time it can provide 400 GeV/c protons for fast or slow extraction

Nota Bene: $\text{NAYY} \equiv \text{YYth}$
Experiment Performed at the North Area SPS Extraction site
Proposed Detector Layout

SPS primary p: 400 GeV/c
Unseparated beam:
• 75 GeV/c
• 800 MHz
• π/K/p (~6% K⁺)

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$

~11 MHz of $K^+$ decays

• Sensitivity is NOT limited by protons flux
• Needs ~same amount of protons on target as NA48

Moriond EW, 2009
A. Ceccucci
Principles of NA62

- **High momentum** kaon beam to improve the rejection of the $\pi^0$ induced backgrounds
- **Decay in-flight** to avoid the scattering and the backgrounds introduced by the stopping target

The experimental technique exploits:

1. **Precise timing** to associate the outgoing $\pi^+$ to the correct incoming parent particle ($K^+$)
2. **Kinematical Rejection** of two- and three-body backgrounds
3. **Vetoes** ($\gamma$ and $\mu$)
4. **Particle Identification** ($K/\pi$, $\pi/\mu$)

To achieve the required background suppression, these techniques have to be combined together and possible correlations have to be measured
1. Precise Timing

Unseparated beam, in-flight decay:

How do you associate the parent kaon to the daughter pion in a ~1 GHz beam?

$K^+$: Gigatracker (pixel detector) with very good time resolution (~100 ps)

$\pi^+$: RICH (Neon, 1 atm) read out by Photomultipliers

CEDAR (rate ~ 50 MHz)

Gigatracker (rate ~ 1 GHz)

RICH (rate ~ 10 MHz)

~120 m
GTK Station

**Requirements:**
- Track and time each beam particle
- Time resolution: 200 ps / station
- Material Budget: < 0.5 % $X_0$ / station
- Pattern: 300 x 300 $\mu$m²

**Two options for the Read-Out:**
- On-Pixel TDC
- End-of-Column TDC
2. Kinematic Rejection

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

<table>
<thead>
<tr>
<th>Decay</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \mu^+ \nu$ ($K_{\mu2}$)</td>
<td>0.64</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi^0$ ($K_{\pi2}$)</td>
<td>0.21</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi^+ \pi^-$</td>
<td>0.07</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi^0 \pi^0$</td>
<td></td>
</tr>
</tbody>
</table>

~92% of Kaon decays are kinematically constraint
Kinematical Rejection

K⁺→π⁺π⁰ selected on 2007 data using LKr information only
Look at the tails in the m²_miss reconstructed with the NA48 DCH

**Data vs. NA48MC:** reproducibility of non-gaussian tails within x²
K⁺→π⁺νν regions: background ~2×10⁻³

### OLD DCH: Data vs. MC

![OLD DCH: Data vs. MC](image)

### New Straw Tracker: MC

![New Straw Tracker: MC](image)
The Straw Trackers operated in vacuum will enable us to:
• Remove the multiple scattering due to the Kevlar Window
• Remove the acceptance limitations due to the beam-pipe
• Remove the helium between the chambers

• The Straw Tracker is essential to study ultra-rare-decays in flight
STRAW Prototype built in 2007

Ultrasound Welded mylar (linear weld, no glue!)
- 36 Al
- 12 (Cu+Au) mylar straws
Straw Prototype: Beam Test 2007

Residuals

RUN 20629, muons

RMS = 104 μm
σ = 45 μm

RUN 20650, pions

RMS = 100 μm
σ = 43 μm

RUN 20694, kaons

RMS = 122 μm
σ = 45 μm

Resolution (cm)

Thr = 6 fC, pions

Drift Distance (cm)

CO₂ (80%) CF₄ (10%) Isob. (10%)
3. Vetoes

- **Photon vetoes to reject** \( K^+ \rightarrow \pi^+ \pi^0 \)
  
  \( P(K^+) = 75 \text{ GeV/c} \)
  
  Requiring \( P(\pi^+) < 35 \text{ GeV/c} \)
  
  \( P(\pi^0) > 40 \text{ GeV/c} \) It can hardly be missed in the calorimeters

**Signature:**
- Incoming **high momentum** \( K^+ \)
- Outgoing **low momentum** \( \pi^+ \)

- **Muon Veto to reject** \( K^+ \rightarrow \mu^+ \nu \)
**LKr γ Detection Efficiency**
(Measured from data)

**LKr ineff. per γ (E_γ > 10 GeV):**
\[ \eta \sim 7 \times 10^{-6} \] (preliminary)

\[ K^+ \rightarrow \pi^+ \pi^0 \text{ selected kinematically} \]

\[ \pi^+ \text{ track and lower energy } \gamma \text{ are used to predict the position of the other } \gamma \]

\[ \begin{align*}
K^+ & \rightarrow \pi^+ \pi^0, \\
\gamma & \text{ selected with } E_\gamma > 10 \text{ GeV}, \\
\eta & \sim 7 \times 10^{-6} \text{ (preliminary)}
\end{align*} \]
Photon Anticounters

Mechanics
For the first full ring has been ordered
LAV prototype tested at CERN

20 blocks installed in the NA62 vacuum tube

Muons and kaons from 2/10 to 6/10

Validation of the operation in vacuum, cabling and support mechanics

Preliminary time resolution with kaons

$\sigma_t = 1.02$ ns
4. Particle Identification

- **K⁺** Positive identification (CEDAR)
- **π/μ** separation (RICH)
- **π/e** separation (E/P)

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<tr>
<td>$K^+ \to \pi^0 e^+ \nu$ ($K_{e3}$)</td>
<td>0.051</td>
</tr>
<tr>
<td>$K^+ \to \pi^0 \mu^+ \nu$ ($K_{\mu3}$)</td>
<td>0.034</td>
</tr>
<tr>
<td>$K^+ \to \mu^+ \nu \gamma$ ($K_{\mu2\gamma}$)</td>
<td>$6.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>$K^+ \to \pi^+ \pi^- e^+ \nu$ ($K_{e4}$)</td>
<td>$4.1 \times 10^{-5}$</td>
</tr>
<tr>
<td>$K^+ \to \pi^+ \pi^- \mu^+ \nu$ ($K_{\mu4}$)</td>
<td>$1.4 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
The RICH Detector

Neon Gas at atmospheric pressure

- Mirror Mosaic (17 m Focal Length)
- Vessel: 17 m long, 3 m dd
- Beam Pipe
- 2×1000 PMT (hex packing 18 mm side)
RICH Simulation: particles separation

\[ m_{rec}^2 = p^2 \left( \mathcal{G}_{max}^2 - \mathcal{G}_c^2 \right) \]

Momentum from the magnetic spectrometer

Muon suppression in \( \pi \) sample (15<p<35 GeV/c): \( 1.3 \times 10^{-3} \)
RICH-100: 2007 Test Beam results

N. of Events
- DATA □ MC

Ring Center X (mm)

N. of Events
- DATA □ MC

Ring Center Y (mm)

N. of Events
- DATA □ MC(All) □ MC(π⁻) □ MC(p) □ MC(K⁻)

$R_{fit} (\text{mm})$

$\Delta \theta_c \approx 50 \, \mu\text{rad}$
(biased by PM geometry)

$N_{\text{Hits}} \approx 17$

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

96 PMT
Hamamatsu R7400

17 m focal, 50 cm wide,
2.5 cm thick glass mirror
### NA62 Sensitivity

<table>
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<th>Decay Mode</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal:</strong> $K^+ \rightarrow \pi^+\nu\nu \ [ \text{flux} = 4.8 \times 10^{12} \text{ decay/year} ]$</td>
<td>55 $\text{evt/year}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0 \ [ \eta_{\pi^0} = 2 \times 10^{-8} (3.5 \times 10^{-8}) ]$</td>
<td>4.3% (7.5%)</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+\nu$</td>
<td>2.2%</td>
</tr>
<tr>
<td>$K^+ \rightarrow e^+\pi^+\pi^-\nu$</td>
<td>$\leq$3%</td>
</tr>
<tr>
<td><strong>Other 3 – track decays</strong></td>
<td>$\leq$1.5%</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0\gamma$</td>
<td>$\sim$2%</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+\nu\gamma$</td>
<td>$\sim$0.7%</td>
</tr>
<tr>
<td>$K^+ \rightarrow e^+(\mu^+)\pi^0\nu$, others</td>
<td>negligible</td>
</tr>
<tr>
<td><strong>Expected background</strong></td>
<td>$\leq$13.5% ($\leq$17%)</td>
</tr>
</tbody>
</table>

**Definition of “year” and running efficiencies based on NA48 experience**
Summary

• The physics case to study rare kaon decays at the SPS during the LHC era is very strong
• The $K^+ \rightarrow \pi^+ \nu\nu$ proposal has received recommendation for approval by the CERN SPS Committee.
• The experiment was approved by the CERN Research Board (December 5, 2008) "subject to the definition of resource sharing within the Collaboration. The experiment will continue to be known as NA62”
• The MoU is under discussion
• With ~50 times the kaon flux of NA48/2, the physics menu –in addition to the very rare decays- promises to be very rich ranging from the precision-tests of lepton universality to the study of the strong interaction at low energy (there should be good material for both EW and QCD Moriond sessions in 201X! )
SPARES
NA62 Seen from the CERN Management

Excerpt from the interview to Sergio Bertolucci
(Director of Research and Scientific Computing)

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...favouring the birth of smaller experiments is also important in maintaining a dynamic physics community. ‘Smaller’ does not mean ‘less challenging’. One good example is the NA62 experiment, which will look for rare kaon decays and which is in a very advanced stage of approval: it is extremely challenging, both in terms of the detector requirements and physics studies. In Spring 2009 we will hold a workshop to assess the situation and to encourage the submission of more proposals of this sort.