The NA62 Experiment at CERN

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Beach 2010 - Perugia 24/06/2010
The $K \to \pi \nu \bar{\nu}$ decays: a clean theoretical environment

- NA62 Physics goal: study of the $K^+ \to \pi^+ \nu \bar{\nu}$ decay mode

- FCNC loop processes: $s \to d$ coupling and highest CKM suppression

Very clean theoretically: SD contributions dominate, hadronic matrix element related to precisely measured quantities

- **SM predictions (main uncertainties from CKM matrix elements):**
  \[ BR(K^+ \to \pi^+ \nu \bar{\nu}) = (8.5 \pm 0.7) \times 10^{-11}, \quad BR(K_L \to \pi^0 \nu \bar{\nu}) = (2.6 \pm 0.4) \times 10^{-11} \]

- **Experimental results:**
  \[ BR(K^+ \to \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10} \ [E787, E959] \]
  \[ BR(K_L \to \pi^0 \nu \bar{\nu}) \leq 2.6 \times 10^{-8} \ [E391a] \]
NP and The $K \to \pi \nu \bar{\nu}$ decays

(courtesy by C. Smith)

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

- $SU(2)_L$ breaking: $SM: v_u^2 Y_u^{32} Y_u^{31} \sim m_t^2 V_{ts} V_{td}$
- $MSSM: v_u^2 A_u^{32} A_u^{31} \sim m_t^2 \times O(1)$?
- $MFV: v_u^2 A_u^{32} A_u^{31} \sim m_t^2 V_{ts} V_{td} |A_0 a_2^* - \cot \beta \mu|^2$.

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

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Buras,Ewerth,Jager,Rosiek '04

Isidori, Mescia, Paradisi, Trine, C.S. '06

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

$B_d \to \mu^+\mu^-$

$\Delta M_{B_d}$

$B_d \to X_S \ell^+\ell^-$
The NA62 Experiment

Experimental Principles of NA62

- **Goal:** 10% precision branching ratio measurement
  
  \[ O(100) K^+ \rightarrow \pi^+ \nu \bar{\nu} \text{ events} \]

- **Requirements**
  
  ➔ **Statistics:**
  
  • BR(SM) \( \sim 8.5 \times 10^{-11} \)
  • Acceptance: 10%
  • K decays: \( 10^{13} \)

  ![Kaon intensity - Signal efficiency]

  ![Signal purity & Detector Redundancy]

- **Principles:**
  
  ➔ "High" momentum K\(^+\) beam

  ➔ Decay in-flight technique

- **% level Systematics**
  
  ➔ **Systematics**
  
  • \( \geq 10^{12} \) background rejection (i.e. \( \leq 10\% \) background)
  • \( \leq 10\% \) precision background measurement
Experimental Principles of NA62

- **Signal signature:**

- **Background:**
  - All the $K^+$ decay modes.
  - Accidental charged particles (beam particle interactions).

**Experimental technique:**

1. Kinematic rejection
2. Precise timing
3. Vetoes
4. Particle Identification
Detector Layout

- SPS primary protons @ 400 GeV/c ⇒ Unseparated secondary charged beam
- 75 GeV/c ($\Delta P/P \sim 1\%$)
- $p/\pi/K$ (positron free, fraction of K $\sim 6\%$)
- Area @ beam tracker 16 cm$^2$
- Integrated average rate @ beam tracker 750 MHz
- Kaon decays/year $4.8 \times 10^{12}$

Need ~same amount of protons as NA48
1) Kinematic Rejection

- Background from $K^+$ decays: $m_{\text{miss}}^2 = (P_K - P_\pi)^2$

- **Two signal regions** with a minimum of background, separated by the $K^+ \rightarrow \pi^+ \pi^0$

- **Background** from 1) Kinematic resolution 2) Decays “not constrained”.

- **Requirements**: low mass / high resolution trackers
  - tracking in vacuum, $\sigma \sim 100 \mu$m per coordinates

Gigatracker (kaon) Straw chambers (pion)
2) Precise Timing

- Needed for $K\pi$ matching
  - Possible mismatches induce loss of kinematic rejection power

- **Difficulty**: recognize kaons in a $\sim$GHz environment

- **Detectors involved**:
  - **CEDAR**: $\sigma(t) \sim 100$ ps
  - **Gigatracker**: $\sigma(t) \sim 200$ ps / station
  - **RICH**: $\sigma(t) < 100$ ps
Gigatracker

- Requirements:
- High space resolution: 300x300 $\mu$m pixels
- Low $X/X_0$: 200 $\mu$m sensor + 100 $\mu$m chip
  (<0.5% $X/X_0$ per station)
- Excellent time resolution: sophisticated RO chip bump bonded on the sensor (0.13 $\mu$m technology)

24/06/09  
Giuseppe Ruggiero
Straw Chamber Spectrometer

- 4 straw chambers in vacuum + 1 magnet (NA48 magnet, 256 MeV/c $P_t$ kick)

- 4 views per chamber (XYUV)
- 4 staggered layers of tubes per view
- 9.6 mm mylar tubes
- 2.1 m long
- Total $X/X_0 \sim 0.1\%$ per view

- 6 cm "radius" beam hole displaced in the bending plane according to the 75 GeV/c beam path
Straw Chamber Spectrometers R&D

- Placed in vacuum on the beam.
- Resolution from 2007 test beam (blue points). 2010 test beam just in this week.

Graph:

\[ \text{RMS} < 100 \, \mu\text{m} \]
Kinematic rejection capabilities

Performance of the new tracking system (Geant4 MC):
- $\sigma(P_K)/P_K \sim 0.2\%$, $\sigma(dX,Y/dZ) \sim 16 \mu$rad
- $\sigma(P_\pi)/P_\pi \sim 0.3\% \pm 0.007\% P_\pi$, $\sigma(dX,Y/dZ) \sim 45 - 15 \mu$rad

2-body rejection power
- $10^4 (K^+\rightarrow\pi^+\pi^0)$, $10^5 (K^+\rightarrow\mu^+\nu)$

Sources of inefficiency:
- MS non gaussian tails
- $K\pi$ mis-match

\[ \sigma(m^2_{miss}) \text{ GeV}^2/c^4 \]

\[ m^2_{miss} \text{ GeV}^2/c^4 \]
3) Photon Vetoes

- **Principle:**
  - Detectors designed to reject $K^+ \rightarrow \pi^+\pi^0$ together with the kinematic rejection.

- **Detectors:**
  - EM calorimeters (LAV, LKr, SAC)
  - 0-50 mrad

- **Key points:**
  - Analysis request: $P(\pi^+)<35 \text{ GeV/c} \Rightarrow P(\pi^0)> 40 \text{ GeV/c}$ it can hardly be missed in calorimeters!
  - $\geq 1 \text{ GeV}$ photons hit the liquid Kripton calorimeter.
  - $10^{-5}$ inefficiency of the liquid Kripton calorimeter for $\geq 10 \text{ GeV}$ photons.

- **Rejection Capability:**
  - $2 \div 3.5 \times 10^{-8} \pi^0$ rejection inefficiency from $K^+ \rightarrow \pi^+\pi^0$
NA48 Liquid Kripton em calorimetry inefficiency

- Inefficiency measured on data
- NA48 data @ 75 GeV
  - $K^+ \rightarrow \pi^+\pi^0$ selected using kinematic only

<table>
<thead>
<tr>
<th>E (GeV)</th>
<th>Inefficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 – 5.5</td>
<td>&lt; 10^{-3}</td>
</tr>
<tr>
<td>5.5 – 7.5</td>
<td>&lt; 10^{-4}</td>
</tr>
<tr>
<td>7.5 – 10</td>
<td>&lt; 5x10^{-5}</td>
</tr>
<tr>
<td>&gt; 10</td>
<td>&lt; 8x10^{-6}</td>
</tr>
</tbody>
</table>
Large Angle Veto (LAV)

- **OPAL lead glass:**
  - 12 rings in vacuum
    - 5 staggered planes per ring
- Blocks tested @ BTF (Frascati):
  - Inefficiency @ 471 MeV $e^+$:
    - $\sim 10^{-4}$ on the whole surface
- First ring built and tested in 2009 at CERN SPS
3) Muon Vetoes

- **Principle:**
  - Detectors designed to reject $K^+ \rightarrow \mu^+ \nu(\gamma)$ together with the kinematic rejection.

- **Detector**
  - Sampling hadronic calorimeter with scintillator planes

- **Key points:**
  - Sensitivity to MIP
  - EM/Hadronic showers separation (LKr/Hadronic calorimeter)

- **Rejection Capability:**
  - $O(10^{-5})$ muon rejection inefficiency.

Still not enough against the $K^+ \rightarrow \mu^+ \nu(\gamma)$ background
4) Particle Identification

Against $K^+$ decays:

Principle:
- Detectors designed to reject $K^+ \rightarrow \mu^+\nu(\gamma)$ together with the kinematic rejection and MUV

Detector:
- RICH for $\pi/\mu$ separation

Performances:
- $\sim 10^{-3} / 10^{-2}$ muon mis-identification probability up to 35 GeV/c

Redundancy
- Kinematic rejection, muon rejection, positron rejection.

Against accidentals:

Principle:
- Veto of events with $\pi^+/\text{protons}$ interacting with the beam tracker or with the residual gas in the decay volume.

Detector:
- CEDAR for $K^+$ identification.
**RICH**

- **Purposes:**
  - $\pi/\mu$ separation
  - Event time

**Radiator:** Ne (1 atm)

- $P_{\pi} > 15$ GeV/c (Cerenkov threshold).

**Test beam 2007**

- ECN3 (NA48 cavern) @ CERN
- 200 GeV hadron beam (pion/K)
- Full length prototype (0.5 m radius)
- 96 PMT Hamamatsu R7400

**Results** [NIM A 593, 2008]

- $N_{\text{hits}} \sim 17/\text{event}$
- $\Delta t_{\text{event}} \sim 70$ ps
- $\Delta \theta_c \sim 50 \mu \text{rad}$ (biased by PM Geometry)
Rich Test Beam '09

- Full length prototype tested on a charged beam at CERN SPS
- ~400 PMT installed
- HPTDC + TELL1 for readout
  (project developed within the collaboration in the framework of the Trigger R&D)
NA62 Sensitivity: signal acceptance

- Simulation of the NA62 apparatus
  - interactions in the trackers simulated using GEANT4
- Most important cut in the analysis:
  \[ 15 < P_{\pi} < 35 \text{ GeV/c} \]
  - For photon and muon rejection
  - RICH operational reasons
- Acceptance: \(~14.4\%\)
  - 3.5\% "region 1", 10.9\% "region 2"
  - 50\% loss due to \(P_{\pi}\) cut
  - Expected detector inefficiencies considered

To be reduced because of losses due to dead time, additional inefficiencies...

The NA62 experiment matches the goal of 10\% acceptance
## NA62 Sensitivity

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal: <strong>K^+ → π^+νν</strong> [ flux = 4.8 \times 10^{12} \text{ decay/year} ]</td>
<td><strong>55 evt/year</strong></td>
</tr>
<tr>
<td><strong>K^+ → π^+π^0</strong> [ η_{π^0} = 2\times10^{-8} (3.5\times10^{-8}) ]</td>
<td><strong>4.3% (7.5%)</strong></td>
</tr>
<tr>
<td><strong>K^+ → µ^+ν</strong></td>
<td><strong>2.2%</strong></td>
</tr>
<tr>
<td><strong>K^+ → e^+π^+π^−ν</strong></td>
<td>( ≤3% )</td>
</tr>
<tr>
<td><strong>Other 3 – track decays</strong></td>
<td>( ≤1.5% )</td>
</tr>
<tr>
<td><strong>K^+ → π^+π^0γ</strong></td>
<td>~2%</td>
</tr>
<tr>
<td><strong>K^+ → µ^+νγ</strong></td>
<td>~0.7%</td>
</tr>
<tr>
<td><strong>K^+ → e^+(µ^+) π^0ν, others</strong></td>
<td>negligible</td>
</tr>
<tr>
<td><strong>Expected background</strong></td>
<td>( ≤13.5% (≤17%) )</td>
</tr>
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Conclusions

• NA62 is approved and financed.

• With 2(+1) years of data taking NA62 will provide a 10% measurement of the BR of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

  • x50 Kaon flux with respect to NA48 with ~same amount of protons from SPS.

  • Key points: Excellent resolutions, hermetic coverage, strong particle ID.

  • The R&D is close to the end and the construction is already started.

• The high performances of the detectors can also be the building blocks for a further rich physics program.
Spares
Trigger system

- Sub-detectors R/O and integrated L0 trigger:
  - TELL1/TDC project
    - RICH, MUD, LAV, Straws
    - Gigatracker, LKr, CEDAR: dedicated projects for R/O and L0 trigger
- L0 processor:
  - receives O(40 MB/s), takes a decision delivered to all the detectors.
- L1 (subdetectors), L2 (event) triggers: online farm. Output O(kHz).
**TELL1/TDC R&D**

- LHCb TELL1 as underlying carrier board
- High integration TDC daughter card with HPTDCs developed (512ch/TELL1)
- Linear fast preamp/discriminator gives PH information with time-over-threshold
- Local processing and power storage
- TELL1/TDC based R/O system tested successfully during the '09 RICH test

**Graphical Data**

![Graph](image)

- Leading: 1 event
- Trailing: 1 event

**Statistics**

<table>
<thead>
<tr>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>99</td>
<td>67.32</td>
<td>7.855</td>
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</tbody>
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Ruggiero