Search for $K^+ \rightarrow \pi^+\nu\nu$ at

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on behalf of the NA62 Collaboration

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Outlines

- Theoretical introduction to the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ rare decay
- The NA62 experiment at CERN SPS: aim and strategy
- Experimental setup
- Data quality from 2015 data
- Conclusions
Theoretical Motivations

- **FCNC loop process**

  ![Diagram of FCNC loop process]

- **BR suppressed** by hierarchical structure of the CKM matrix

  \[
  BR(K^+ \to \pi^+ \nu \bar{\nu}) = k_m \left[ 1 + \Delta_{EM} \left( \frac{S}{\chi^5} X(x_t) \right)^2 + \left( \frac{\rho \lambda_c}{\chi} (P_c + \delta P_{c,u}) + \frac{\rho \lambda_t}{\chi} X_t \right)^2 \right] 
  \]

  Hadronic matrix element from Ke3 via isospin rotation

  ∆EM = k_m (1 + |V_{td}|^2)

  Charm contributes to theory errors

  Loops favor top contribution

  \[ x_q \equiv m_q^2/m_W^2 \]

  \[ \lambda = V_{us} \]

  \[ \lambda_c = V_{cs}^* V_{cd} \]

  \[ \lambda_t = V_{ts}^* V_{td} \]

- BR suppression by hierarchical structure of the CKM matrix

  \[
  B_{SM}(K^+ \to \pi^+ \nu \bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11} 
  \]

  \[
  B_{SM}(K_L \to \pi^0 \nu \bar{\nu}) = (3.00 \pm 0.30) \times 10^{-11} 
  \]

  [JHEP 1511 (2015) 033]

  Very clear SM prediction

  Extraction of V_{td} without hadronic uncertainties

  and...
Sensitive probe to New Physics

Deviation from $\mathcal{B}_{\text{SM}} \to$ signal of New Physics process

Present experimental knowledge

Experimental status

<table>
<thead>
<tr>
<th></th>
<th>SM prediction ($\times 10^{-11}$)</th>
<th>Experiment ($\times 10^{-11}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+\nu\bar{\nu}$</td>
<td>9.11 ± 0.72</td>
<td>$17.3^{+11.5}_{-10.5}$</td>
</tr>
<tr>
<td>$K^0 \rightarrow \pi^0\nu\bar{\nu}$</td>
<td>3.00 ± 0.30</td>
<td>&lt;2600</td>
</tr>
</tbody>
</table>

PAST:

Stopped kaon technique

E787 E949  @ BNL  

NOW

NA62 in-flight-decay technique → 10% precision
NA62 at CERN SPS

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna (JINR), Fairfax, Ferrara, Florence, Frascati, Glasgow, Liverpool, Louvain-la-Neuve, Mainz, Merced, Moscow (INR), Naples, Perugia, Pisa, Prague, Protvino (IHEP), Rome I, Rome II, San Luis Potosi, SLAC, Sofia, TRIUMF, Turin, Vancouver (UBC)

- ✔ '06 Proposal
- ✔ '09-'12 R&D and construction for πνν
- ✔ '12 technical run
- ✔ '14-'15 commissioning runs
- ✔ '16 run started in May
- □ Physics runs ('16-'18)
Analysis strategy

**Measuring the \( B(K^+ \rightarrow \pi^+\nu\nu) \) with 10% precision**

**Ultra rare decay \( O(10^{-11}) \)**

- High intensity beam → \( 10^{13} \) decays in two years of data taking
- Large signal acceptance → 10%
- Large background rejection → \( 10^{12} \)

**Clear signal signature: \( K^+ \) track + \( \pi^+ \) track**

- Precise timing → 100-150 ps
- Kinematics cut → low mass tracking
- High efficiency photon and muon vetos
Analysis strategy

Large background rejection $\rightarrow 10^{12}$

$M_{\text{miss}}^2 = (P_K - P_\pi)^2$

92% separated by kinematic cut

<table>
<thead>
<tr>
<th>Decay</th>
<th>BR</th>
<th>Rejection Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \mu^+\nu$</td>
<td>63%</td>
<td>$\mu$-ID + kinematics</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0$</td>
<td>21%</td>
<td>$\gamma$-veto + kinematics</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^+\pi^-$</td>
<td>6%</td>
<td>multi-tracks + kinematics</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0\pi^0$</td>
<td>2%</td>
<td>$\gamma$-veto + kinematics</td>
</tr>
<tr>
<td>$K^+ \rightarrow e^+\pi^0\nu$</td>
<td>5%</td>
<td>e-ID + $\gamma$-veto</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+\pi^0\nu$</td>
<td>3%</td>
<td>$\mu$-ID + $\gamma$-veto</td>
</tr>
</tbody>
</table>

Decay | event/year |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0$ [SM] (flux $4.5\times10^{12}$)</td>
<td>45</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+\nu$</td>
<td>1</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^+\pi^-$</td>
<td>$&lt; 1$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^-e^+\nu +$ other 3 tracks decays</td>
<td>$&lt; 1$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0\gamma$(IB)</td>
<td>1.5</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+\nu\gamma$(IB)</td>
<td>0.5</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^0\mu^+(\mu^+)\nu$, others</td>
<td>negligible</td>
</tr>
<tr>
<td>Total background</td>
<td>$&lt; 10$</td>
</tr>
</tbody>
</table>
NA62 experimental setup

High intensity Beam

Secondary beam from SPS: 750 MHz

75 GeV/c with $\delta p/p = 1\%$

Composition:

- **6% $K^+$**
- **23% $p$**
- **70% $\pi^+$**

Beam and detector commissioned up to nominal intensity (2015)
NA62 experimental setup

**Trackers**

**GTK**

3 station of Si-Pixel detector (60.8x27mm²)
Low material budget: 0.5 $X_0$
Momentum Resolution $\sim \delta p/p = 0.2\%$
Fast Timing: $\sigma = 200$ ps (hit time resolution)
From 2015: $\sigma \sim 230-250$ ps

**STRAW**

Low material budget: $< 0.5\%$ $X_0$ (per chamber)
Vertical magnetic field: $P_{T_{kick}} = 270$ MeV/c
Angular resolution $< 60$ $\mu$rad
Momentum resolution $\sim \delta p/p = 1\%$
From 2015: $\sigma \sim 5$ ns

All Station 2015 Under commissioning
NA62 experimental setup

Particle ID

**KTAG**

45 MHz K⁺

Fast Timing: σ < 100 ps

0.1% mis-ID → from 2015 data

**RICH**

**Vessel:** 17m long & Ø 4 m

Neon gas @ ~1atm

**Mirrors:** curvature 34m

Reflectivity > 90%

Pion ID efficiency ~80%

Muon mis-ID ~ 1%

@ 15 < p < 35 GeV/c from 2015 data
**NA62 experimental setup**

**Vetoing for photons and muons**

**Photon veto system**
- **LAVs**: 8.5-50 mrad, \( \varepsilon = 10^{-4} \) \( E_\gamma > 200 \) MeV
- **LKr**: 1-8.5 mrad, \( \varepsilon = 10^{-5} \) \( E_\gamma > 10 \) GeV
- **IRC&SAC**: <1 mrad, \( \varepsilon = 10^{-4} \) \( E_\gamma > 5 \) GeV
- **Target**: \( \pi^0 \) rejection \( O(10^8) \)

**Muon veto system**
- **MUV1&MUV2**: hadronic calorimeter
- **MUV2**: iron-scintillator plate sandwiches
- **MUV3**: Efficient fast \( \mu \)-veto

26/07/2016
Signal topology and Kaon ID

2015 Data sample: Low intensity data taken with a minimum bias trigger (this talk)
Samples at half and full intensity taken with a calorimeter trigger

Single Track Selection
Beam Track: matching kaon in KTAG
Matching Kaon – Downstream track

Beam track: no matching
Kaon in KTAG

2015 Data sample: Low intensity data taken with a minimum bias trigger (this talk)
Samples at half and full intensity taken with a calorimeter trigger

2015 Data
Downstream Particle Identification

**GOAL:** \( O(10^7) \) π/μ separation, to reject \( K^+ \rightarrow \mu^+ \nu \)

Pure sample of pion and muon selected using kinematics cuts

**RICH**

Best π/μ separation

@ \( 15 < P_\pi < 35 \text{ GeV/c} \)

\( O(10^2) \) μ suppression

80% π⁺ efficiency in 2015.

**CALORIMETERS**

\( 10^4 - 10^6 \) μ⁺ suppression for 90% - 40% π⁺ efficiency in 2015 using a cut analysis.
Photon rejection

**Technique:** EM calorimeters exploiting correlation between $\gamma$s' from $\pi^0$

**GOAL:** $O(10^8)$ rejection $\pi^0$ from $K^+ \to \pi^+\pi^0$

$P_{\pi^+} < 35 \text{ GeV/c} \rightarrow E_{\pi^0} > 40 \text{ GeV}$

Measured on data using $K^+ \to \pi^+\pi^0$
selected kinematically

$O(10^6)$ $\pi^0$ rejection already obtained.
More statistics needed to push the study at the design sensitivity.
Kinematics

Goal: $O(10^4)$ suppression factor of the main kaon decay modes

Single track selection + Kaon ID + vertex cut

Resolution close to the design

$O(10^3)$ suppression factor from 2015 data.

26/07/2016
Further opportunities

<table>
<thead>
<tr>
<th>Decay</th>
<th>Physics</th>
<th>Present limit (90% C.L.) / Result</th>
<th>NA62</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+\mu^+e^-$</td>
<td>LFV</td>
<td>$1.3 \times 10^{-11}$</td>
<td>$0.7 \times 10^{-12}$</td>
</tr>
<tr>
<td>$\pi^+\mu^-e^+$</td>
<td>LFV</td>
<td>$5.2 \times 10^{-10}$</td>
<td>$0.7 \times 10^{-12}$</td>
</tr>
<tr>
<td>$\pi^-\mu^+e^+$</td>
<td>LNV</td>
<td>$5.0 \times 10^{-10}$</td>
<td>$0.7 \times 10^{-12}$</td>
</tr>
<tr>
<td>$\pi^-\mu^+e^+$</td>
<td>LNV</td>
<td>$6.4 \times 10^{-10}$</td>
<td>$2 \times 10^{-12}$</td>
</tr>
<tr>
<td>$\pi^-\mu^-\mu^+$</td>
<td>LNV</td>
<td>$1.1 \times 10^{-9}$</td>
<td>$0.4 \times 10^{-12}$</td>
</tr>
<tr>
<td>$\mu^-\nu e^+e^+$</td>
<td>LNV/LFV</td>
<td>$2.0 \times 10^{-8}$</td>
<td>$4 \times 10^{-12}$</td>
</tr>
<tr>
<td>$e^-\nu \mu^+\mu^+$</td>
<td>LNV</td>
<td>No data</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td>$\pi^+X^0$</td>
<td>New Particle</td>
<td>$5.9 \times 10^{-11}$ $m_{X^0} = 0$</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td>$\pi^+\chi\chi$</td>
<td>New Particle</td>
<td>$-$</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td>$\pi^+\pi^-e^-\nu$</td>
<td>$\Delta S \neq \Delta Q$</td>
<td>$1.2 \times 10^{-8}$</td>
<td>$10^{-11}$</td>
</tr>
<tr>
<td>$\pi^+\pi^-\mu^-\nu$</td>
<td>$\Delta S \neq \Delta Q$</td>
<td>$3.0 \times 10^{-6}$</td>
<td>$10^{-11}$</td>
</tr>
<tr>
<td>$\pi^+\gamma$</td>
<td>Angular Mom.</td>
<td>$2.3 \times 10^{-9}$</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td>$\mu^+\nu_h,\nu_h \rightarrow \nu\gamma$</td>
<td>Heavy neutrino</td>
<td>Limits up to $m_{\nu_h} = 350$ MeV</td>
<td>$&gt;&gt;2$ better</td>
</tr>
<tr>
<td>$R_K$</td>
<td>LU</td>
<td>$(2.488 \pm 0.010) \times 10^{-5}$</td>
<td>$10^5$ events</td>
</tr>
<tr>
<td>$\pi^+\gamma\gamma$</td>
<td>$\chi$PT</td>
<td>$&lt; 500$ events</td>
<td>$O(10^6)$</td>
</tr>
<tr>
<td>$\pi^0\pi^0 e^+\nu$</td>
<td>$\chi$PT</td>
<td>660000 events</td>
<td>$O(10^5)$</td>
</tr>
<tr>
<td>$\pi^0\pi^0 \mu^+\nu$</td>
<td>$\chi$PT</td>
<td>$-$</td>
<td>$O(10^5)$</td>
</tr>
</tbody>
</table>
Conclusions

- Commissioning of the detector has been completed
- Physics sensitivity for $K^+ \rightarrow \pi^+ \nu \nu$ measurement in line with the design:
  - **Time resolution** close to the design
  - **Kinematics** Resolution close to the design. Prospects to reach the designed signal – background separation.
  - **Pion – muon ID** Separation with RICH close to expectations. Study of the separation with calorimeters on going. Results from simple cut analysis promising.
  - **Photon veto:** 2015 measurement statistically limited

**NA62 started to collect data in April 2016 and will continue in 2017 and 2018**
Thanks for your attention