Prospects for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ observation at CERN-NA62

Cristina Biino * - INFN Torino

SUSY 2015 – Lake Tahoe, 23-29 August 2015

*On behalf of the NA62 Collaboration:
CERN, Ferrara, Firenze, LNF, Napoli, Perugia, Pisa, Roma1, Roma2, Torino, UC Louvain, Sofia, Bucharest, Prague, Mainz, Birmingham, Bristol, Glasgow, Liverpool, TRIUMF, UBC, IHEP, INR, JINR, George Mason, SLAC, UC Merced, BU, BNL, San Luis Potosi
The $K^+\rightarrow \pi^+\nu\bar{\nu}$ decay is a FCNC process, in the SM is forbidden at tree level and dominated by short distance dynamics.

- Very clean theoretical scenario
  - No hadronic uncertainties
  - Electroweak amplitude is largely dominated by top quark loops
  - Dependence on the product of CKM matrix elements $V_{ts}^* V_{td}$

- SM prediction takes into account:
  - 1 loop contributions at the leading order
  - NLO QCD correction to top quark contributions
  - NLO electroweak corrections to both top and charm contributions
  - NNLO QCD corrections to charm contributions
  - Isospin breaking and non-perturbative effects

Box and penguin, one loop diagrams at leading order

Z-penguin

W-box
Short-distance contribution (top quark) dominance → theoretically clean dependence on the product of CKM matrix elements $V_{ts}V_{td}^*$.

- $K \rightarrow \pi \nu\nu$ is one of the few processes that can be used to verify accurately the SM Unitary.

SM suppression and proportionality to powers of $V_{ts}V_{td}^*$ allows:
  - stringent test of the SM
  - high sensitivity to New Physics (NP)

Complementary to LHC
Theoretical prediction

Golden modes:

\[ K \rightarrow \pi \nu \bar{\nu} \]

\[
\begin{align*}
BR(K_L \rightarrow \pi^0 \nu \bar{\nu}) &= (3.00 \pm 0.30) \times 10^{-11} \\
BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) &= (9.11 \pm 0.72) \times 10^{-11}
\end{align*}
\]

| \( |V_{cb}| \)  | 9.9%  |
| \( \delta P_{c,u} \) | 2.9% |
| \( P_c^{SD}(X) \)     | 6.7% |
| \( X_t \)             | 1.8% |
| other                   | 0.9% |

Error budget

\[ P_c = P_c^{SD}(X) + X_t + \text{other} + \gamma \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

| \( |V_{cb}| \)  | 9.9%  |
| \( \delta P_{c,u} \) | 2.9% |
| \( P_c^{SD}(X) \)     | 6.7% |
| \( X_t \)             | 1.8% |
| other                   | 0.9% |

\[ Error \text{ budget} \]

\[ P_c = P_c^{SD}(X) + X_t + \text{other} + \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]

\[ |V_{cb}| \]

\[ |\delta P_{c,u}| \]

\[ P_c^{SD}(X) \]

\[ X_t \]

\[ \text{other} \]

\[ \gamma \]
Measurement of charged $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay and neutral $K_L \rightarrow \pi^0 \nu \bar{\nu}$ modes can discriminate different NP scenarios.


**RSc:** Randall-Sundrum mechanism [M.Blanke et al., JHEP 0903 (2009) 108]


**MFV:** Minimal Flavor Violation [W.Altmannshofer et al., Nucl.Phys. B830]


Probe of MSSM non-MFV, not yet excluded by LHC [G. Isidori et al., JHEP 0608 (2006) 088]

Measurement of $|V_{td}|$ complementary to measurements from B-B mixing

$\delta(BR)/BR = 10\%$ implies $\delta(|V_{ts}|)/|V_{td}| = 7\%$
• $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$ (from 7 events)


• $\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 2600 \times 10^{-11}$

### Experimental vs. Theoretical Status

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

Gap between theoretical precision and large experimental errors!

**NA62 aims at ~10% precision measurement of the BR($K^+ \to \pi^+ \nu \bar{\nu}$) in 2 years of data taking**
Experimental requirements

**NA62 goal:** measure $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ with 10% accuracy

$\Rightarrow$ O(100) SM events + systematics control at % level

- Assuming a 10% signal acceptance and a $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ 
  $\sim 10^{10}$ at least $10^{13}$ Kaon decays are required
- Rejection factor for dominant kaon decays of the order of $10^{12}$ (for background <20%)
- Systematics: <10% precision background measurement

**NA62 design criteria:** Kaon beam intensity, signal acceptance, background suppression

- Technique: high momentum Kaons and in flight decay

★ Signal signature: one beam $K^+$ track fully matched with one final state $\pi^+$ track
★ Basic ingredients: precise timing & kinematic cuts

$P_{K^+}$

$P_{\pi^+}$

$\theta_{K\pi}$

$P_{\nu}$

$P_{\bar{\nu}}$

C. Biino – SUSY 2015
Kinematically discriminating variable:  
\[ m_{\text{miss}}^2 = (P_K - P_\pi)^2 \]
where the particle from the decay is assumed to be a pion.

2 signal regions, on each side of the $K^+ \rightarrow \pi^+\pi^0$ peak, are used to remove contributions from more than 90% of main $K^+$ background decays.
Na62 experimental strategy

### Background suppression:

<table>
<thead>
<tr>
<th>K decay background</th>
<th>BR</th>
<th>Rejection tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>K⁺ → μ⁺ ν</td>
<td>0.6355</td>
<td>μ-ID + kinematics</td>
</tr>
<tr>
<td>K⁺ → π⁺ π⁰</td>
<td>0.2066</td>
<td>γ-veto + kinematics</td>
</tr>
<tr>
<td>K⁺ → π⁺ π⁺ π⁻</td>
<td>0.0559</td>
<td>π⁻-ID + multi-track + kinematics</td>
</tr>
<tr>
<td>K⁺ → π⁺ π⁰ π⁰</td>
<td>0.0176</td>
<td>γ-veto + kinematics</td>
</tr>
<tr>
<td>K⁺ → π⁰ e⁺ ν</td>
<td>0.0507</td>
<td>e-ID + kinematics + γ-veto</td>
</tr>
<tr>
<td>K⁺ → π⁰ µ⁺ ν</td>
<td>0.0335</td>
<td>μ-ID + kinematics + γ-veto</td>
</tr>
<tr>
<td>K⁺ → π⁺ π⁻ e⁺ ν</td>
<td>4.257 × 10⁻⁵</td>
<td></td>
</tr>
</tbody>
</table>

- Beam tracking
- Photon veto
- Muon veto
- π/μ/e identification

\[ P_{π⁺} < 35 \text{ GeV/c to ensure} \quad P_{π⁰} > 40 \text{ GeV/c} \quad \sim 92\% \Rightarrow \sim 8\% \]
### Decay and Event Rate per Year

<table>
<thead>
<tr>
<th>Decay</th>
<th>event/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+ \nu \bar{\nu} (*)$</td>
<td>45</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi^0$</td>
<td>5</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>$K^+ \rightarrow \pi^+ \pi^- e^+ \nu + \text{other 3 track decays}$</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>$K^+ \rightarrow \pi^0 e^+ (\mu^+) \nu + \text{others}$</td>
<td>negligible</td>
</tr>
<tr>
<td><strong>Total background</strong></td>
<td>&lt; 10</td>
</tr>
</tbody>
</table>

(*) [SM] (flux $4.5 \times 10^{12}$ $K^+$ decay/year)
The NA62 experiment at CERN

Jura mountains

NA48 / NA62

SPS

France

LHC

Switzerland

~200 participants from 30 institutions

2005 Proposal
2009 Approved
2010 Technical design
2012 Technical run (partial layout)
2014 Pilot Run
2015-18 Physics Runs
The NA62 beam and detector

- CERN SPS 400 GeV/c primary proton beam on a Be target
- Secondary un-separated positive hadron beam (6% K⁺); momentum 75 (±1%) GeV/c
- Nominal beam intensity: 750 MHz (~45 MHz K⁺ decays in the fiducial volume)

**High intensity and fast timing**

**High performance e.m. calorimeter**

**High rate precision and low mass tracking**

**Redundant particle ID**

**Hermetic photon veto**
The NA62 detector
First Look at 2014 Data Quality

( no GTK, 3 out of 4 Straw ch., no RICH mirror alignment, no photon rejection)

- Events with only 1 track in the straw detector (40ns time window)
- $10^2$ muon rejection at trigger level
First Look @2014 Data: Missing Mass

Requiring K-ID from KTAG in time with the spectrometer track
Requiring decay vertex in fiducial region

$P_{\text{reco}} < 35 \text{ GeV/c}$

Requiring $K^+ \rightarrow \pi^+ \pi^0$

Region I

$K^+ \rightarrow \mu^+ \nu$

Region II

$K^+ \rightarrow \pi^+ \pi^+ \pi^-$

Entries 10897
Mean 0.02742
RMS 0.0321

$K^+ \rightarrow \pi^+ \pi^0$
The rare $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay

$BR_{\text{theor}} = (9.11 \pm 0.72) \times 10^{-11}$ \hspace{1cm} $BR_{\text{exp}} = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$

- Gap between theoretical precision and large experimental error
- Sensitive probe to New Physics
- Motivations for a strong experimental effort

- NA62: a substantial upgrade of the previous CERN experiments, designed to measure the BR with 10% precision
- NA62 successful pilot run in 2014
- Data taking starting: NA62 ready for physics and planning to collect the world largest sample of $K^+$

NA62 marks CERN’s return to the exploration of the Standard Model using high-intensity Kaon beams.

Kaons are partner of LHC in the quest for physics beyond the SM.
Extra material
Charged Kaon Beams: different exp. techniques.

“Stopped” → work in Kaon frame, high Kaon purity (electromagneto-static-separators); compact detectors

“In-Flight” → decays in vacuum (no scattering, no interactions) ; RF separated or unseparated beams; extended decay regions

<table>
<thead>
<tr>
<th>Exp</th>
<th>Machine</th>
<th>Meas. or UL 90% CL</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argonne</td>
<td>&lt; 5.7 x 10^{-5}</td>
<td>Stopped, HL Bubble chamber</td>
<td></td>
</tr>
<tr>
<td>Bevatron</td>
<td>&lt; 5.6 x 10^{-7}</td>
<td>Stopped, Spark chamber</td>
<td></td>
</tr>
<tr>
<td>KEK</td>
<td>&lt; 1.4 x 10^{-7}</td>
<td>Stopped, π⁺ μ⁺ e⁺</td>
<td></td>
</tr>
<tr>
<td>E787</td>
<td>(1.57 ± 1.75 -0.82 ) x 10^{-10}</td>
<td>Stopped</td>
<td></td>
</tr>
<tr>
<td>E949</td>
<td>(1.73 ± 1.15 -1.05 ) x 10^{-10}</td>
<td>Stopped</td>
<td></td>
</tr>
<tr>
<td>NA62</td>
<td>SPS</td>
<td>In-Flight, unseparated.</td>
<td></td>
</tr>
</tbody>
</table>
### Beyond the baseline

<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>$\pi^-e^+e^+$</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>$\mu^-ve^+e^+$</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>$5.9 \times 10^{-11}$</td>
<td>$m_{X^0} = 0$</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>$1.2 \times 10^{-3}$</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>$\mu^+\nu\nu$</td>
<td>Heavy neutrino</td>
<td>Limits up to $m_{\nu_h} = 350$ MeV</td>
<td></td>
</tr>
</tbody>
</table>

| $R_K$           | LU       | $(2.488 \pm 0.010) \times 10^{-5}$ | $>\times 2$ better |
| $\pi^+\gamma\gamma$ | $\chi$PT | $<$ 500 events                  | $10^5$ events       |
| $\pi^0\pi^0\gamma\gamma$ | $\chi$PT | $66000$ events                 | $O(10^6)$          |
| $\pi^0\pi^0\mu^+\nu$ | $\chi$PT | $-$                             | $O(10^5)$          |
New Physics Sensitivity

- **Z’ gauge boson mediating FCNC at tree level**
  

- **Littlest Higgs with T-parity**
  

- **Custodial Randall-Sundrum**
  
  [M. Blanke et al., JHEP 0903 (2009) 108]

- **Best probe of MSSM non-MFV (still not excluded by LHC)**
  
  [G. Isidori et al., JHEP 0608 (2006) 088]
Recent $K^\pm$ experiments at CERN

<table>
<thead>
<tr>
<th>Experiment</th>
<th>NA48/2 ($K^\pm$)</th>
<th>NA62-R$_K$ ($K^\pm$)</th>
<th>NA62 ($K^+$; starting)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam momentum, GeV/c</td>
<td>60</td>
<td>74</td>
<td>75</td>
</tr>
<tr>
<td>RMS momentum bite, GeV/c</td>
<td>2.2</td>
<td>1.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Spectrometer thickness, $X_0$</td>
<td>2.8%</td>
<td>2.8%</td>
<td>1.8%</td>
</tr>
<tr>
<td>Spectrometer $p_T$ kick, MeV/c</td>
<td>120</td>
<td>265</td>
<td>270</td>
</tr>
<tr>
<td>$M(K^\pm \rightarrow \pi^\pm\pi^\mp\pi^-)$ resolution, MeV/c$^2$</td>
<td>1.7</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>$K^\pm$ decays in fiducial volume</td>
<td>$2 \times 10^{11}$</td>
<td>$2 \times 10^{10}$</td>
<td>$1.2 \times 10^{13}$</td>
</tr>
<tr>
<td>Main trigger</td>
<td>multi-track; $K^\pm \rightarrow \pi^\pm\pi^0\pi^0$</td>
<td>$e^\pm$</td>
<td>$K_{\pi\pi\pi}$ + ...</td>
</tr>
</tbody>
</table>

Kaon beams: sources of large clean tagged $\pi^0$ samples.

- In a $K^\pm$ beam, ratio of number of decays $\pi^0/K^\pm \approx 1/3$.
- Principal $\pi^0$ source: $K^\pm \rightarrow \pi^\pm\pi^0$ (known as $K_{2\pi}$).
- Best data on many rare/forbidden $\pi^0$ decays come from $K$ experiments.