$K^+ \rightarrow \pi^+ \nu \nu$: first NA62 results

Silvia Martellotti* on behalf of NA62 Collaboration

(*INFN Laboratori Nazionali di Frascati & CERN)

Laboratori Nazionali di Frascati. 2018, April 18th.
Outline

- Theoretical introduction to the $K \rightarrow \pi \nu \nu$ rare decays
- NA62 experiment at the CERN SpS
  - Aim and strategy for the $\text{BR}(K^+ \rightarrow \pi^+ \nu \nu)$ measurement
  - Detector overview
  - Results with 2016 data
  - Prospects
The $K^+ \rightarrow \pi^+ \nu\nu$ decay is extremely suppressed

**Flavor-changing neutral current quark transition $s \rightarrow d \nu\nu$.**

Forbidden at tree level, dominated by short-distance dynamics (GIM mechanism).

Is characterized by a theoretical cleanness in the SM prediction of the $\text{BR}(K^+ \rightarrow \pi^+ \nu\nu)$: loops and radiative corrections are under control.

**Highly suppressed & Very well predicted**  
**Excellent laboratory complementary to LHC**

Stringent test of the SM and possible **evidence for New Physics**
### Past measurement and prediction

**Current theoretical prediction:**

\[
\text{BR}(K^+ \to \pi^+ \nu \bar{\nu})_{\text{SM}} = (8.4 \pm 1.0) \times 10^{-11}
\]

\[
\text{BR}(K_L \to \pi^0 \nu \bar{\nu})_{\text{SM}} = (3.4 \pm 0.6) \times 10^{-11}
\]

- Main contribution to the errors comes from the uncertainties on the SM input parameters
- Intrinsic theoretical uncertainties (1-3%) slightly larger for the charged channel because of the corrections from lighter-quark contributions

**Experimental status:**

\[
BR(K^+ \to \pi^+ \nu \bar{\nu})_{exp} = (17.3^{+11.5}_{-10.5}) \times 10^{-11}
\]

Only measurement obtained by E787 and E949 experiments at BNL with **stopped kaon decays (7 candidates)**

- Gap between theoretical precision and large experimental error motivates a strong experimental effort. **Significant new constraints can be obtained.**

Neutral decay \(K_L \to \pi^0 \nu \bar{\nu}\) has never been measured
Measurement of BR of charged ($K^+ \rightarrow \pi^+\nu\nu$) and neutral ($K_L \rightarrow \pi^0\nu\nu$) modes can determine the **unitarity triangle** independently from B inputs.

\[
\delta(\text{BR}) / \text{BR} = 10\% \text{ would lead to } \delta(|V_{td}|) / |V_{td}| = 7\%
\]

**Example of CKM constraints:**
- BR($K^+ \rightarrow \pi^+\nu\nu$) to ±10%
- BR($K_L \rightarrow \pi^0\nu\nu$) to 15%
New Physics from $K\rightarrow\pi\nu\nu$ decays

- **Simplified Z, Z’ models** [Buras, Buttazzo, Knegjens, JHEP 1511 (2015) 166]
- **Littlest Higgs with T-parity** [Blanke, Buras, Recksiegel, EPJ C76 (2016) no.4 182]
- **Custodial Randall-Sundrum** [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- **LFU violation models** [Isidori et al., Eur. Phys. J. C (2017) 77]
- **Constraints from existing measurements** (correlations model dependent)

Z’ (5 TeV) in constrained MFV

---

![Graphs and diagrams related to New Physics from $K\rightarrow\pi\nu\nu$ decays]
New Physics from $K \to \pi \nu \nu$ decays

$K \to \pi \nu \nu$ is uniquely sensitive to high mass scales.

**NP may simply occur at a higher mass scale**

→ Null results from direct searches at LHC so far

**Indirect probes to explore high mass scales become very interesting!**

Es: Tree-level flavor changing $Z'$ LH+RH couplings

- Some fine-tuning around constraint from $\varepsilon_K$
- $K \to \pi \nu \nu$ sensitive to mass scales up to 2000 TeV (up to tens of TeV even if LH couplings only)
- Order of magnitude higher than for $B$ decays

Buras et al., JHEP 1411

$m_{Z'} = 500$ TeV
The **CERN-SPS secondary beam line** already used for the NA48 experiment can deliver the required $K^+$ intensity.

In the North Area the SpS extraction line is providing a secondary charged hadron beam:

- 400 GeV/c primary proton beam
- $3 \times 10^{12}$ protons/pulse
- 40 cm beryllium target
- **75 GeV/c** unseparated hadrons beam: $\pi^+, K^+ (6\%)$, **protons** ($\Delta p/p \pm 1\%$)
- $4.8 \times 10^{12} K^+$ decays/year
NA62 Experiment
NA62 Apparatus

270 m long downstream of the beryllium target. Useful $K^+$ decays are detected in a 65 m long fiducial volume.

Each detector sends $\sim 10$ MHz of raw input data to the Level 0 trigger (FPGA) that selects 1 MHz of events. L1 and L2 triggers (software) guarantee a maximum of 10 kHz of acquisition rate.

Approximately cylindrical shape around the beam axis for the main detectors. Diameter varies from 20 to 400 cm.
Design criteria: kaon intensity, signal acceptance, background suppression

Kaons with high momentum. **Decay in flight technique.**

Signal signature: $K^+ \text{ track} + \pi^+ \text{ track}$

<table>
<thead>
<tr>
<th>Decay</th>
<th>BR</th>
<th>Main Rejection Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \to \mu^+ \nu_\mu(\gamma)$</td>
<td>63%</td>
<td>$\mu$-ID + kinematics</td>
</tr>
<tr>
<td>$K^+ \to \pi^+\pi^0(\gamma)$</td>
<td>21%</td>
<td>$\gamma$-veto + kinematics</td>
</tr>
<tr>
<td>$K^+ \to \pi^+\pi^+\pi^-$</td>
<td>6%</td>
<td>multi-track + kinematics</td>
</tr>
<tr>
<td>$K^+ \to \pi^+\pi^0\pi^0$</td>
<td>2%</td>
<td>$\gamma$-veto + kinematics</td>
</tr>
<tr>
<td>$K^+ \to \pi^0 e^+\nu_e$</td>
<td>5%</td>
<td>$e$-ID + $\gamma$-veto</td>
</tr>
<tr>
<td>$K^+ \to \pi^0 \mu^+\nu_\mu$</td>
<td>3%</td>
<td>$\mu$-ID + $\gamma$-veto</td>
</tr>
</tbody>
</table>

**Keystones**

- $O(100 \text{ ps})$ Timing between sub-detectors
- $O(10^4)$ Background suppression from kinematics
- $O(10^7)$ $\mu$-suppression ($K^+ \to \mu^+\nu$)
- $O(10^7)$ $\gamma$-suppression (from $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$)
Most discriminating variable:

\[ m_{\text{miss}}^2 = (P_{K^+} - P_{\pi^+})^2 \]

Where the daughter charged particle is assumed to be a pion.

Theoretical \( m_{\text{miss}}^2 \) distribution for signal and backgrounds of the main \( K^+ \) decay modes: (signal is multiplied by a factor \( 10^{10} \)).

2 signal regions, on each side of the \( K^+ \rightarrow \pi^+ \pi^0 \) peak (to eliminate 92% of the \( K^+ \) width).

Main background sources:
- \( K^+ \rightarrow \pi^+ \pi^0 \), \( K^+ \rightarrow \mu^+ \nu \) non gaussian resolution and radiative tails
- \( K^+ \rightarrow \pi^+ \pi^+ \pi^- \) non gaussian resolution tails
- decays with neutrino in final state

Main background contributions
## NA62 Timescale

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>Pilot Run</td>
</tr>
<tr>
<td>2015</td>
<td>Commissioning</td>
</tr>
<tr>
<td>2016</td>
<td>Commissioning + Physics Run</td>
</tr>
<tr>
<td>2017</td>
<td>Physics Run (ongoing)</td>
</tr>
<tr>
<td>2019-2020</td>
<td>LS2 Long shutdown 2</td>
</tr>
</tbody>
</table>

### 2016:
- 40% of nominal intensity: $13 \times 10^{11}$ proton on target
- $\sim 1 \times 10^{11}$ $K^+$ decays useful for $\pi\nu\nu$

### 2017:
- 60% of nominal intensity: $20 \times 10^{11}$ proton on target
- $> 3 \times 10^{12}$ $K^+$ decays collected
**Beam ID & Tracking**

**KTAG:** Differential Čerenkov counter blind to all particles but kaons of appropriate momentum (75 GeV, K+ rate: ~45 MHz). $\sigma_t \sim 70 \, \text{ps}$, efficiency > 99%.

*Steel vessel, 4.5 m long, filled with compressed nitrogen.*

**GTK:** GigaTrakker Spectrometer for K$^+$ momentum and timing measurement. $\sigma_t \sim 100 \, \text{ps}$, $\sigma_{dx,dy} \approx 0.016 \, \text{mrad}$, $\Delta P/P < 0.4\%$.

*750 MHz beam environment. 3 stations of 18000 silicon pixels (140 KHz/pixel).*

**CHANTI:** Charged particle veto to reduce the background induced by inelastic interactions.

*6 stations of X-Y plastic scintillator bars coupled with optical fibers. Efficiency > 99%.*
**Secondary particle ID & Tracking**

**STRAW:** Spectrometer with STRAW tubes for secondary particle momentum measurement.

4 chambers (4 layers < 0.5 $X_0$) in vacuum, 7168 STRAW tubes. Magnet provides a 270 MeV/c momentum kick in the horizontal plane. $\sigma_t \sim 6$ ns, $\sigma_{dx,dy} \sim 130$ μm.

**CHOD:** Charged Hodoscope of plastic scintillator to provide fast signal of the beam.

Old CHOD $\sigma_t \sim 250$ ns, CHOD $\sigma_t \sim 1$ ns

**RICH:** Ring Imaging Cherenkov detector for the secondary particle identification.

17 m long tank. Neon gas (1 atm). Downstream: mosaic of 20 spherical mirrors.

Upstream: ~2000 PMTs. $\mu/\pi$ separation $\sim 10^2$, $\sigma_t$ of a ring < 100 ps

---

NA62: Secondary ID & Tracking

Fiducial decay region

MAGNET

STRAW CHAMBERS

CHOD

Old CHOD (NA48)
Photon Veto

**LAV:** Large Angle Veto. 12 stations to veto $\gamma$ with angles $8.5 < \theta < 50 \text{ mrad}$.

4 or 5 rings of lead glass crystals read out by PMTs. First 11 stations are in vacuum. $\sigma_t \sim 1 \text{ ns, } 10^{-3}$ to $10^{-5}$ inefficiency (on $\gamma$ down to 150 MeV).

**IRC/SAC:** Inner Ring Calorimeter and Small Angle Calorimeter. To veto $\gamma$ with angles <1 mrad.

*Shashlik calorimeters. Lead and plastic scintillator plates.* $\sigma_t < 1 \text{ ns, } 10^{-4}$ inefficiency.

**LKr:** NA48 LKr Calorimeter: to veto $\gamma$ with angles $1 < \theta < 8.5 \text{ mrad}$ and for PID.

*Ionization chamber + liquid Krypton, 2x2 cm$^2$ cells.* $\sigma_t \sim 500 \text{ ps (E}_{\text{clusters}} > 3 \text{ GeV}), \sigma_t \sim 1 \text{ ns (hadronic and MIP clusters)}, \sigma_{dx,dy} \sim 1 \text{ mm, } 10^{-5}$ inefficiency ($E_\gamma > 10 \text{ GeV}$).
Muon Veto

**MUV3:** Efficient fast Muon Veto (reduction factor > 10) used in the hardware trigger level. Placed after an iron wall. 1 plane of 148 5cm thick scintillator tiles. Muon Rate: 10 MHz. $\sigma_t \sim 500$ ps, efficiency $\sim 99.5\%$

**MUV1/2:** Hadronic calorimeters for the $\mu/\pi$ separation.

2 modules of iron-scintillator plate sandwiches. Readout with LKr electronics.

Cluster reco at $\sim 20$ ns from $T_{track}$, and at $\pm 150$ mm from the expected impact point.
First data declared good for πνν. 4 weeks of Data taking. <60’000 good spills

**Trigger streams**

**PNN Trigger**
Hardware L0: RICH, CHOD, MUV3 (Veto), LKr (E < 20 GeV).
Software L1: KTAG, LAV (Veto), STRAW (momentum < 50 GeV/c).

**Control Trigger**
Hardware L0: CHOD

**Offline Analysis**

**Data Sample**

- Bad data based on detector performances identified on spill by spill basis
- Signal selection tuned on MC, 10% PNN data, control data
- The analysis is mostly cut based

**K⁺ → π⁺π⁰, K⁺ → μ⁺ν, K⁺ → π⁺π⁺π⁻ samples for background estimation**

**Blind analysis procedure:** signal and control regions kept masked for the whole analysis
Analysis steps

- Selection
- Evaluation of the single event sensitivity
- Background estimation and validation
- Un-blinding of signal regions and interpretation of the results
Analysis steps

Selection

- $K^+$ decays with a single charged particle in final state
- Particle ID: $\pi^+$
- Photon & Multiple charged particle rejection
- Kinematic Selection of Signal Regions
K\(^+\)-\(\pi^+\) matching

- KTAG – GTK – RICH time matching:
  - Kaon decay time (\(t_{\text{decay}}\))
- GTK – STRAW Spectrometer spatial matching (CDA)
- 75% \(K^+\) reconstruction and ID efficiency
- <1% \(K^+\) mis-tag if \(K^+\) track present, dependent on beam intensity

\[
K^+ \rightarrow \pi^+ \pi^+ \pi^- \text{ control sample}
\]

\(\sigma \approx 1.4 \text{ mm} \)

\[
K^+ \rightarrow \pi^+ \pi^+ \pi^- \text{ control sample}
\]

\(\sigma \approx 110 \text{ ps} \)

- No activity in CHANTI
- \(110 < Z_{\text{vertex}} < 165 \text{ m} \)
- \(15 < P_{\pi^+} < 35 \text{ GeV/c} \)
  (to leave at least 40 GeV of missing energy)
Kinematics

\[ m^2_{\text{miss}} \equiv m^2_{\text{miss}} (\text{GTK, STRAW}) = (P_K - P_\pi)^2 \] with \( m_\pi \) hypothesis.
3 different ways to compute $m^2_{\text{miss}} = (P_K - P_\pi)^2$:
- $m^2_{\text{miss}} \equiv m^2_{\text{miss}} (\text{GTK, STRAW})$
- $m^2_{\text{miss}} (\text{RICH}) \equiv m^2_{\text{miss}} (\text{GTK, RICH})$
- $m^2_{\text{miss}} (\text{beam}) \equiv m^2_{\text{miss}} (\text{beam, STRAW})$

Additional power for background suppression

- $K^+ \rightarrow \pi^+ \nu \nu$ MC
- $K^+ \rightarrow \pi^+ \pi^0$ control data

$K^+ \rightarrow \mu^+ \nu$ control data
**π⁺ Particle identification**

**in Calorimeters**
- Electromagnetic calo (LKr),
- Hadronic calo (MUV1,2)
- Scintillator pads (MUV3)

*MUV3+BDT classifier using: energy, energy sharing, clusters shape*

\[0.6 \cdot 10^{-5} \mu^+ \text{ efficiency} \text{ vs } 77\% \pi^+ \text{ efficiency}\]

**in RICH**

*Track driven Likelihood particle ID discriminant*

*Particle mass using track momentum*

*Momentum measurement under mass hypothesis (velocity - spectrometer)*

\[2.5 \cdot 10^{-3} \mu^+ \text{ efficiency} \text{ vs } 75\% \pi^+ \text{ efficiency}\]
Photon rejection

- Timing coincidence of signals in LKr, LAV, SAV not associated to $\pi^+$ and $t_{\text{decay}}$
- Not coincidences of signals in LKr and hodoscopes not associated to $\pi^+$, in time with $t_{\text{decay}}$
- Typical timing coincidences: $\pm 3 \div \pm 5$ ns; energy dependent time cut in LKr

![Control data (downscaled 400)](image1)

![PNN data](image2)

- Before rejection
- After rejection

- Fraction of surviving $K^+ \rightarrow \pi^+\pi^0$ (15 – 35 GeV momentum range): $\sim 2.5 \cdot 10^{-8}$
- High suppression of $K^+ \rightarrow \pi^+\pi^+\pi^-$, $K^+ \rightarrow \pi^+\pi^-e^+\nu$ with Multi-Charge cuts
MC Signal after selection

Signal acceptance: 4%

\[ K^+ \rightarrow \pi^+\nu\bar{\nu} \text{ MC} \]
Data after selection

\[ \pi^+ \pi^+ \pi^- \text{ region} \]

\[ \mu^+ \nu \text{ control region} \]

\[ \pi^+ \pi^0 \text{ region} \]

\[ \pi^+ \pi^0 \text{ control region} \]
Analysis steps

- Selection
- Evaluation of the single event sensitivity
- Background estimation and validation
- Un-blinding of signal regions and interpretation of the results
Single Event Sensitivity (SES)

\[ SES = \frac{1}{N_K \sum_j (A_{\pi\nu\nu}^j \cdot \epsilon_{RV}^j \cdot \epsilon_{trig}^j)} \]

\( j = \pi^+ \) momentum bin

- number of \( K^+ \) decays
- signal acceptance
- random veto efficiency
- trigger efficiency

Normalization: \( K^+ \rightarrow \pi^+\pi^0 \) from control data.
Same \( \pi^+\nu\nu \) selection with \( \gamma \), multiplicity rejection not applied; \( m_{\text{miss}}^2 \) cuts modified

\[ N_K = \frac{N_{\pi\pi} \cdot D}{A_{\pi\pi} \cdot BR_{\pi\pi}} \]

\( N_{\pi\pi} = \) number of \( K^+ \rightarrow \pi^+\pi^0 \) (\( \sim 6 \times 10^6 \))
\( D = \) control trigger downscaling (400)
\( A_{\pi\pi} = \) normalization acceptance (\( \sim 0.1 \) from MC)

\[ N_K = (1.21 \pm 0.02_{\text{syst}}) \times 10^{11} \]

systematic uncertainty:
- discrepancies in data/MC
- variation of the measured \( K^+ \) flux as a function of \( P_{\pi^+} \)
**Signal Acceptance & Trigger Efficiency**

![Graph showing the acceptance and trigger efficiency as a function of $P_{\pi^+}$](image)

### Everything is computed separately in 4 bins of $P_{\pi^+}$, 5 GeV/c wide

- **Signal acceptance ($\sim4\%$)**
  - Computed with MC
  - Particle ID and losses due to $\pi^+$ interaction in the detector material included (main sources of systematic error)

### PNN Trigger efficiency

- Computed using control data and $K^+ \rightarrow \pi^+\pi^0$ control sample
  - L0 efficiency $\sim90\%$, weakly dependent on $P_{\pi^+}$, losses due mainly to LKr and MUV3 veto conditions
  - L1 efficiency $>97\%$
Single Event Sensitivity (SES)

Random veto

- Signal efficiency losses due to random activity in the veto detectors
- Estimated on data using a $K^+ \rightarrow \mu^+\nu$ sample (ratio of events selected before and after the $\gamma$ and multiplicity cuts)
- Is flat as a function of $P_{\pi^+}$, but depends on the instantaneous intensity

Single event sensitivity

<table>
<thead>
<tr>
<th>Number of $K^+$ decays</th>
<th>$N_K = (1.21 \pm 0.02) \times 10^{10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance $K^+ \rightarrow \pi^+\nu\bar{\nu}$</td>
<td>$A_{\pi\nu\bar{\nu}} = 4.0 \pm 0.1$</td>
</tr>
<tr>
<td>PNN trigger efficiency</td>
<td>$\epsilon_{trig} = 0.87 \pm 0.2$</td>
</tr>
<tr>
<td>Random Veto</td>
<td>$\epsilon_{RV} = 0.76 \pm 0.04$</td>
</tr>
<tr>
<td>SES</td>
<td>$(3.15 \pm 0.01_{stat} \pm 0.24_{syst}) \cdot 10^{-10}$</td>
</tr>
<tr>
<td>Expected SM $K^+ \rightarrow \pi^+\nu\bar{\nu}$</td>
<td>$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$</td>
</tr>
</tbody>
</table>

Error on the SM BR
Analysis steps

- Selection
- Evaluation of the single event sensitivity
- Background estimation and validation
- Un-blinding of signal regions and interpretation of the results
Background estimation

\[ N_{\text{bkg}}^{\text{exp}}(R1/R2) = \sum_j \left[ N(bkg)_j \cdot f_j^{\text{kin}}(R1/R2) \right] \]

- Expected background events in region 1/2
- \( \pi^+ \) momentum bin
- bkg events after \( \pi\nu\nu \) selection
- Fraction of events in region 1/2

Calculated for the main background decays:
\( K^+ \to \pi^+\pi^0(\gamma), K^+ \to \mu^+\nu(\gamma), K^+ \to \pi^+\pi^+\pi^-, K^+ \to \pi^+\pi^-\) e\(^+\)\nu

under the assumption that particle identification, \( \gamma \) and multiplicity rejection are independent from the cuts on \( m^2_{\text{miss}} \)

- Fraction of background events entering signal regions through the reconstructed tails of the corresponding \( m^2_{\text{miss}} \) peak
- is modeled on control samples selected on data and eventually corrected for biases induced by selection criteria using MC simulation
Data control sample of $K^+ \rightarrow \pi^+ \pi^0(\gamma)$ selected tagging the $\pi^0$ with the two $\gamma$'s in the LKr

MC sample of $K^+ \rightarrow \pi^+ \pi^0(\gamma)$ selected as in data

The $\pi^0$ tagging suppresses almost completely the radiative part

MC sample of $K^+ \rightarrow \pi^+ \pi^0(\gamma)$ selected as $\pi\nu\nu$ without applying $\gamma$ and multiplicity rejection

$\pi^0 \gamma$ rejection of the radiative tail in R2 estimated from MC:

- single photon detection efficiency applied to each of the 3 photons in the final state
- $\times 30$ than single $\pi^0$ rejection

The radiative part accounts for about 13% of the total background and dominates the systematic uncertainty
$K^+ \rightarrow \pi^+\pi^0(\gamma)$ background

<table>
<thead>
<tr>
<th></th>
<th>$\pi^+\pi^0$</th>
<th>$\pi^+\pi^0(\gamma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>$0.022 \pm 0.004_{stat} \pm 0.002_{syst}$</td>
<td>0</td>
</tr>
<tr>
<td>R2</td>
<td>$0.037 \pm 0.006_{stat} \pm 0.003_{syst}$</td>
<td>$0.005 \pm 0.005_{syst}$</td>
</tr>
</tbody>
</table>

Expected $K^+ \rightarrow \pi^+\pi^0(\gamma)$
background in $P_{\pi^+}$ bins
compared to the expected
number of SM $K^+ \rightarrow \pi^+\nu\nu$ events

Residual PNN trigger $\pi^+\pi^0$
events gather at low $P_{\pi^+}$

$$N_{\pi\pi(\gamma)}^{expected} = 0.064 \pm 0.007_{stat} \pm 0.006_{syst}$$
$K^+ \rightarrow \mu^+ \nu(\gamma)$ background

- Data control sample of $K^+ \rightarrow \mu^+ \nu(\gamma)$ selected tagging $\mu^+$ in MUV3
- MC sample of $K^+ \rightarrow \mu^+ \nu(\gamma)$ selected as in data
- MC sample of $K^+ \rightarrow \mu^+ \nu(\gamma)$ selected as $\pi \nu \nu (\gamma$ veto, multiplicity rejection) without muon-ID (to test the effect of the $\mu$-ID on the tails)

*The radiative contribution is included in the measured tails*

- RICH potentially correlates particle ID and kinematics if events enter in signal region because of momentum mis-measurement is STRAW
- The effect on background is estimated on data comparing RICH performances measured on $K^+ \rightarrow \mu^+ \nu(\gamma)$ events in $\mu^+ \nu$ peak and signal region
\( K^+ \rightarrow \mu^+ \nu(\gamma) \) background

<table>
<thead>
<tr>
<th></th>
<th>( \mu^+ \nu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>0.019 ± 0.003_{stat} ± 0.003_{syst}</td>
</tr>
<tr>
<td>R2</td>
<td>0.0012 ± 0.0002_{stat} ± 0.0006_{syst}</td>
</tr>
</tbody>
</table>

Expected \( K^+ \rightarrow \mu^+ \nu(\gamma) \) background in \( P_{\pi^+} \) bins compared to the expected number of SM \( K^+ \rightarrow \pi^+ \nu\bar{\nu} \) events.

The background depends on \( P_{\pi^+} \) as both tails and particle ID steeply increase at higher momentum because of kinematics and RICH performances.

\[
N_{\mu\nu(\gamma)}^{expected} = 0.020 \pm 0.003_{stat} \pm 0.003_{syst}
\]
Background estimation validation

Validation: event expected in the control regions

<table>
<thead>
<tr>
<th></th>
<th>$\pi^+\pi^0$</th>
<th>$\mu^+\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR1</td>
<td>$0.52 \pm 0.08_{\text{stat}} \pm 0.03_{\text{syst}}$</td>
<td></td>
</tr>
<tr>
<td>CR2</td>
<td>$0.94 \pm 0.14_{\text{stat}} \pm 0.05_{\text{syst}}$</td>
<td>$1.02 \pm 0.16_{\text{stat}}$</td>
</tr>
</tbody>
</table>
$K^+ \rightarrow \pi^+\pi^+\pi^-$ background

- Data control sample of $K^+ \rightarrow \pi^+\pi^+\pi^-$ selected tagging $\pi^+\pi^-$ pair
- MC sample of $K^+ \rightarrow \pi^+\pi^+\pi^-$ selected as in data

Multiplicity rejection and kinematics cuts turn out to be very effective against $K^+ \rightarrow \pi^+\pi^+\pi^-$ decays (one order of magnitude lower than the other two)

$$f^{kin}(R2) \leq 10^{-4}$$

- Kinematic rejection factor corrected for biases induced by the control sample selection using MC

$$N_{\pi\pi\pi}^{expected} = 0.002 \pm 0.001_{stat} \pm 0.002_{syst}$$
$K^+ \rightarrow \pi^+\pi^-e^+\nu$ background

- Expected in signal region 2
- Branching ratio $4.25 \times 10^{-5}$
- Kinematics is strongly correlated with topology: different method
- Background estimated using MC ($\sim 4 \times 10^8$ events generated)
- Validated using different control samples $K^+ \rightarrow \pi^+\pi^-e^+\nu$ - enriched
- The statistics of the MC sample is the limiting factor of the final estimation

$$N_{\pi\pi e\nu}^{expected} = 0.018^{+0.024}_{-0.017} \mid_{stat} \pm 0.009_{syst}$$
**Upstream background**

- $\pi^+$ from a decay upstream of the decay region matching a $\pi^+$ from the beam.
- $\pi^+$ from beam particle interactions in GTK matching a $K^+$.
- $\pi^+$ from interaction of a $K^+$ with material in the beam (prompt particle or decay product).

$p\nu\nu$-like data sample enriched for upstream events: position of $\pi^+$ at the entrance of the decay region.

The position of the $\pi^+$ indicates their origin upstream or via interactions in GTK stations and drive the choice of a **geometrical cut covering the central aperture of the dipole**

$$|X_{\text{track}}| > 100 \text{ mm, } |Y_{\text{track}}| > 500 \text{ mm}$$
Upstream background

Distribution of the time coincidence between KTAG-RICH and GTK-KTAG. Suggest an accidental source for these events

- Cut 1: \(K^+ - \pi^+\) matching
- Cut 2: box cut

**Bifurcation technique is adopted**

The combinations of Cut1 and Cut2 defines 4 samples:

If all the samples contain the same type of events and Cut1 and Cut2 are independent:

\[
A_{exp} = B \cdot \frac{C}{D}
\]

Procedure validated using different sets of values for Cut1 – Cut2

\[
N_{upstream}^{exp} = 0.050^{+0.090}_{-0.030} \text{ \textit{stat}}
\]

(statistics limit the accuracy)
### Expected events summary

<table>
<thead>
<tr>
<th>Process</th>
<th>Expected events in R1+R2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ (SM)</td>
<td>$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$</td>
</tr>
<tr>
<td><strong>Total Background</strong></td>
<td><strong>$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$</strong></td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0(\gamma)$ IB</td>
<td>$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+\nu(\gamma)$ IB</td>
<td>$0.020 \pm 0.003_{stat} \pm 0.003_{syst}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^-e^+\nu$</td>
<td>$0.018^{+0.024}<em>{-0.017}</em>{stat} \pm 0.009_{syst}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^+\pi^-$</td>
<td>$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$</td>
</tr>
<tr>
<td>Upstream Background *</td>
<td>$0.050^{+0.090}<em>{-0.030}</em>{stat}$</td>
</tr>
</tbody>
</table>

* The upstream background is relevant. In 2016 data analysis tight geometrical cuts are employed to keep it under control causing up to 30-40% signal acceptance reduction

- In the final part of 2017 data-taking a copper plug was inserted in to the last dipole (corresponding to the aperture of the final collimator) to mitigate this issue
- The installation of a new final collimator which extends further transversally that will improve our immunity to upstream interaction is foreseen in mid June 2018
Analysis steps

- Selection
- Evaluation of the single event sensitivity
- Background estimation and validation
- Un-blinding of signal regions and interpretation of the results
Result

Figure showing a plot of $m^2_{\text{miss}}$ [GeV$^2$/c$^4$] against $\pi^+$ momentum [GeV/c]. The plot includes data points and shaded regions indicating $K^+ \rightarrow \pi^+\nu\bar{\nu}$ MC.
Result

![Graph showing a plot of $m_{\text{miss}}^2$ vs. $\pi^+$ momentum [GeV/c]. The graph includes data points and shaded regions for $K^+ \rightarrow \pi^+\nu\bar{\nu}$ MC.](image-url)
Result

1 event in R2
**Result**

- **HV intervention**

- **Result**

  - 1 event in R2

  - Likelihood value under different mass hypothesis

  - $P_{\pi^+} = 15.3 \text{ GeV}$
### Preliminary Results

<table>
<thead>
<tr>
<th>Event Observed</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>SES</td>
<td>$(3.15 \pm 0.01_{stat} \pm 0.24_{syst} \cdot 10^{-10})$</td>
</tr>
<tr>
<td>Expected Background</td>
<td>$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$</td>
</tr>
<tr>
<td>Expected SM $K^+ \to \pi^+ \nu \bar{\nu}$</td>
<td>$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$</td>
</tr>
</tbody>
</table>

\[ BR(K^+ \to \pi^+ \nu \bar{\nu}) < 11 \times 10^{-10} \text{ @ 90\% CL} \]
\[ BR(K^+ \to \pi^+ \nu \bar{\nu}) < 14 \times 10^{-10} \text{ @ 95\% CL} \]

\[
BR(K^+ \to \pi^+ \nu \bar{\nu})_{SM} = (0.84 \pm 0.10) \times 10^{-10}
\]
\[
BR(K^+ \to \pi^+ \nu \bar{\nu})_{exp} = (1.73^{+1.15}_{-1.05}) \times 10^{-10}
\]

- Present result is from cut based analysis
- Full probability based analysis is under development
The new NA62 decay in flight technique to measure BR(K^+ \rightarrow \pi^+\nu\nu) works!
- 1 event observed in 2016 data
- BR(K^+ \rightarrow \pi^+\nu\nu) < 14 \times 10^{-10} @ 95\% CL

Processing of the 2017 data is on-going
- 20 times more than the present statistics
- upstream background reduction expected
- improvements on reconstruction efficiency

2018 data taking on going
- 218 days including stops
- studies to improve signal acceptance on going (MVA approach)

20 SM events expected before LS2

Running after 2018 to be approved
- condition for ultimate sensitivity under evaluation
Thank you for the attention from the NA62 Collaboration!

28 institutions, ~200 participants,

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