Latest measurement of $K^+ \rightarrow \pi^+ \bar{\nu} \bar{\nu}$ with the NA62 experiment at CERN

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FROM THE INFRARED TO THE ULTRAVIOLET

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The main aim is the measurement of $\text{BR}(K\rightarrow\pi\nu\nu)$.

The physics program is much broader. Follow the talks by S. Ghinescu and P. Massarotti.
**K→πνν in the SM**

Measuring both $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $KL \rightarrow \pi^0 \nu \bar{\nu}$ provides the CKM unitarity triangle independently from measurements in B mesons sector.

### BR($K^+ \rightarrow \pi^+ \nu \bar{\nu}$)

<table>
<thead>
<tr>
<th>Error budget:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s(68%)$</td>
</tr>
<tr>
<td>$c(29%)$</td>
</tr>
<tr>
<td>$u(3%)$</td>
</tr>
</tbody>
</table>

**Experimental result before NA62:**

$$B(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{exp}} = (17.3^{+11.5}_{-10.5}) \cdot 10^{-11}$$


$K\rightarrow\pi\nu\nu$ for new physics

Search for New Physics at the EW scale with sizable coupling to SM particles via indirect effects in loops

- Custodial Randall-Sundrum
  [JHEP 0903 (2009) 108]
- LFU violation models
- MSSM scenarios:
  [JHEP 0608 (2006) 064]
  [Int.J.Mod.Phys A29 (2014) no.27, 1450162]
- Simplified $Z, Z'$ models
  [JHEP 1511 (2015) 166]
- Littlest Higgs with T-parity
Measurement strategy

Decay in flight technique:

\[ m_{miss}^2 = (p_K - p_\pi)^2 \]

- very good kinematic reconstruction
- time measurements
- \( K, \pi, \mu \) identification
- Hermetic detection of muons
- Hermetic detection of photons

### Decay Rates and Rejection Tools

<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>
About 20% of $K^+$ decay inside the fiducial volume
2 years running at high intensity we collected:
• $O(10^{13})$ $K^+$ decays in fiducial volume
NA62 apparatus

**LAV:** photon veto at large angles lead-glass blocks

**STRAW:** Downstream tracking

**RICH:** Ring imaging Cherenkov kinematics and particle ID

**GTK:** kaon tracking: 3 stations of silicon sensors

**KTAG:** Kaon identification Cherenkov counter filled with N2

**CHOD:** charged hodoscope

**LKr:** quasi-homogenous ionization chamber 27X0 deep

**MUV0, MUV3** plastic scintillators

**IRC, SAC:** lead and scintillator plates Shashlyk configuration

400 GeV protons

Robert Volpe, University of Rome "Tor Vergata"
Analysis principle

- Control data collected with a different trigger
- Data-driven background estimation
- Control regions to validate it
- Normalization to $K \rightarrow \pi^+ \pi^0$ decay
Normalization

Efficiencies not in common with $K \rightarrow \pi^+\pi^0$

$$N_{\pi\nu\nu} = N_{\pi\pi} \epsilon_{\text{trig}} \epsilon_{\text{RV}} \frac{A_{\pi\nu\nu}}{A_{\pi\pi}} \frac{BR(\pi\nu\nu)}{BR(\pi\pi)}$$

$\epsilon_{\text{RV}}$, Random Veto efficiency:
signal efficiency due to accidental activity

efficiency and normalization have been computed in bins of pion momentum and intensity

$N_{\pi\nu\nu} = 2.16 \pm 0.12 \pm 0.26_{\text{ext}}$
Background from $K^+$ decays

\[ K^+ \rightarrow \mu^+\nu \text{ and } K^+ \rightarrow \pi^+\pi^0 \]

\[ N_{\mu\nu}^{exp}(region) = \sum_j \left[ N(\mu\nu)_j \cdot f_j^{kin}(region) \right] \]

N\text{exp in the Signal (control) region}

Sample selected on background region with $\nu\nu$ trigger data to get the shape

Fraction of events in the signal (control) region, measured in control data

Validation in control regions

\[ N_{\pi\pi}^{exp}(region) = \sum_j \left[ N(\pi^+\pi^0)_j \cdot f_j^{kin}(region) \right] \]
Upstream background

Not only Kaon decays in decay region:

- $K^+$ decays/interacts in the achromat
- Secondary $\pi^+$ downstream
- Beam elements block additional particles
- $\pi^+$ scattering in straw chamber 1
- Pileup beam particle tagged as $K^+

Count events on data with inverted $K-\pi$ matching

Estimate the probability to occur from data/simulation
### Summary of expected Sig and Bkg

<table>
<thead>
<tr>
<th>Process</th>
<th>Expected events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+ \nu \bar{\nu}$</td>
<td>$2.16 \pm 0.12_{stat} \pm 0.26_{syst}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi^0(\gamma)$ IB</td>
<td>$0.29 \pm 0.03_{stat} \pm 0.03_{syst}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+ \nu_\mu(\gamma)$ IB</td>
<td>$0.11 \pm 0.02_{stat} \pm 0.03_{syst}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+ \nu_\mu (\mu^+ \rightarrow e^+ decay)$</td>
<td>$0.04 \pm 0.02_{syst}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi^- e^+ \nu_e$</td>
<td>$0.12 \pm 0.05_{stat} \pm 0.03_{syst}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi^+ \pi^-$</td>
<td>$0.02 \pm 0.02_{syst}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \gamma \gamma$</td>
<td>$0.005 \pm 0.005_{syst}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow l^+ \pi^0 \nu_l (l = e^+, \mu^+)$</td>
<td>negligible</td>
</tr>
<tr>
<td>Upstream background</td>
<td>$0.9 \pm 0.2_{stat} \pm 0.2_{syst}$</td>
</tr>
<tr>
<td><strong>Total background</strong></td>
<td>$1.5 \pm 0.2_{stat} \pm 0.2_{syst}$</td>
</tr>
</tbody>
</table>

$N_{\pi\nu\nu} = 2.16 \pm 0.12 \pm 0.26_{ext}$

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**Result from analysis of 2016 dataset:**

$$N_{\pi\nu\nu}^{exp}(SM) = 0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$$

Total background: $0.152^{+0.092}_{-0.033}|_{stat} \pm 0.013_{syst}$

1 event observed

$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 14 \times 10^{-10}$ at 95% CL
Results with 2016 and 2017 data

2016 and 2017:

\[ BR_{SM}(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (0.84 \pm 0.10) \times 10^{-10} \]

Observed UL at 90% CL:
\[ BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) < 1.85 \times 10^{-10} \]

Grossman-Nir bound

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**Note:**

Paper in preparation

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Exotics with $K^+ \rightarrow \pi^+ + \text{inv}$

Search for $K^+ \rightarrow \pi^+\pi^0$, $\pi^0 \rightarrow \text{inv}$

Search for $K^+ \rightarrow \pi^+X$, $X$ invisible

hidden sector searches
$K^+ \rightarrow \pi^+\pi^0, \ \pi^0 \rightarrow \text{inv}$

- $\pi^0 \rightarrow \nu\nu$ is not forbidden because of neutrino non-zero masses, but in the SM: 
  $\text{BR}(\pi^0 \rightarrow \nu\nu) \sim O(10^{-24})$, so any observation $\Rightarrow$ BSM physics
- The present experimental limit is $2.7 \times 10^{-7}$ at 90% C.L., from BNL experiments

The hermetic photon veto in NA62, essential for $\pi\nu\nu$ analysis, allows for the search in the Kaon decay

$K^+ \rightarrow \pi^+\pi^0(\gamma), \ \pi^0 \rightarrow \text{invisible}$

**Analysis strategy:**

$$\text{BR}(\pi^0 \rightarrow \text{invisible}) = \text{BR}(\pi^0 \rightarrow \gamma\gamma) \times \frac{N_s}{N_{\pi^0} \times \epsilon_{\text{sel}} \times \epsilon_{\text{trig}}}$$

The main background is $K^+ \rightarrow \pi^+\pi^0, \ \pi^0 \rightarrow \gamma\gamma$ with undetected photons

Using a counting experiment approach in the region:
25 < $p$ < 40 GeV and $m^2_{\text{miss}}$ in [0.012, 0.021] GeV$^2$/c$^4$

$$\text{BR}(\pi^0 \rightarrow \text{invisible}) \leq 4.4 \times 10^{-9} \text{ at 90% C.L.}$$

An improvement by a factor 60 wrt the previous experimental result
\[ K^+ \rightarrow \pi^+ X, \ X \text{ invisible} \]

Motivation: feebly interacting new particle foreseen in several models

**Dark scalar: mixing with the Higgs**

\[ \mathcal{L}_{\text{scalar}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - (\mu S + \lambda S^2) H^\dagger H \]

\[ \mu = \sin \theta \quad \lambda = 0 \]

JHEP05(2010)010, JHEP02(2014)123

**Pseudo-scalar**

Axion-like particles (ALPs)  
QCD axion, Axiflavon (m~0)

arxiv:1612.05492

**Analysis strategy:**

Use exactly the same selection, normalization and background evaluation of \( \pi \nu \nu \) analysis  
Generate signal with two body decay for 200 mass hypotheses to compute acceptance

**Few mass points after the full selection, normalized to unity**

- R1  
- R2

\[ m^2_{\text{miss}} \quad \text{[GeV}^2/\text{c}^4] \]

\[ m_X = 70 \text{ MeV}/c^2 \quad m_X = 154 \text{ MeV}/c^2 \]
\[ m_X = 168 \text{ MeV}/c^2 \quad m_X = 182 \text{ MeV}/c^2 \]
\[ m_X = 196 \text{ MeV}/c^2 \quad m_X = 210 \text{ MeV}/c^2 \]
\[ m_X = 224 \text{ MeV}/c^2 \quad m_X = 238 \text{ MeV}/c^2 \]
\[ m_X = 252 \text{ MeV}/c^2 \]

Paper in preparation
\[ K^+ \rightarrow \pi^+ X, \ X \text{ invisible} \]

**Bump hunting in \( m^2_{\text{miss}} \)**

No deviation from the SM have been observed, so: *setting upper limit*

- Shape analysis on \( m^2_{\text{miss}} \)
- Fully frequentist approach
- Profiled likelihood test statistic

**Background model**
- **shape**: Parameterized with polynomial functions in R1 and R2
- **Bkg yield** from \( \pi\nu\nu \) analysis, including \( K \rightarrow \pi\nu\nu \) from simulation and with SM BR

**Signal model**
- **shape**: Gaussian
- **Ns** from efficiency and normalization obtained in bins of \( p \) and intensity, as in \( \pi\nu\nu \) analysis

Sensitivity degrades at small \( m_X \) because of resolution.

In particular, for axion models, half of the signal is cut away
$K^+ \rightarrow \pi^+ X$, with $X$ decaying

If $X$ decays to visible SM particles

Probability that $X$ does not decay within the NA62 apparatus:

$$P = e^{-\left(\frac{\Delta L}{\beta\gamma c\tau}\right)}$$

Comparison with BNL result
A. V. Artamonov et al. (E949 Collaboration)
Phys. Rev. D 79, 092004

Small improvement for $m_X$ in 40-80 MeV
Improved of ~1 order of magnitude in Region2

Prospects with 2018 data: Improvements are expected from a dedicated analysis exploiting the two-body kinematics, and extending the signal regions, especially at low masses

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Conclusions

- With 2016 and 2017 data the upper limit at 90% CL
  \[ BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) < 1.85 \times 10^{-10} \]

- 2018 data analysis is ongoing

- The same analysis principle with 2017 dataset has been exploited to search for exotic physics:
  \[ BR(\pi^0 \rightarrow \text{invisible}) \leq 4.4 \times 10^{-9} \text{ at 90\% CL} \]

\[ BR(K^+ \rightarrow \pi^+X) < (0.5 - 2) \times 10^{-10} \text{ at 90\% CL for } m_X \text{ in [0,100] MeV} \]
\[ BR(K^+ \rightarrow \pi^+X) < (0.4 - 1.4) \times 10^{-10} \text{ at 90\% CL for } m_X \text{ in [160,260] MeV} \]

- 2018 data analysis is ongoing

Stay tuned and safe! Thank you

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Spares
Dark scalar, Higgs mixing

\[ \text{BR}(K^+ \rightarrow \pi^+ X) = f \times \frac{2|p_X|}{m_X} \times \sin^2 \theta \]

F. Bezrukov, D. Gorbunov, JHEP05(2010)010
Jackson D. Clarke, Robert Foot and Raymond R. Volkas, JHEP02(2014)123
NA62 apparatus

- very good kinematic reconstruction
- Precise time measurements

33x10^{11} ppp on T10 (750 MHz at GTK3)
Secondary beam: 75 GeV/c momentum
K^+ (6%)/\pi^+ (70%)/p(24%)

FV: Fiducial decay volume

\[ m^2_{\text{miss}} = (p_K - p_\pi)^2 \]

Target (T10)

CHANTI
Vetoing bkg from beam-GTK interactions

Kaon identification
Differential Cherenkov detector
\( \sigma(t) = 70 \text{ ps} \)

GTK
Kaon tracking
Si pixel, 3 stations
\( \sigma(t) = 200 \text{ ps}, \sigma(p)/p = 0.2\% \)

KTAG

120 m tube in vacuum
(500 m^3 at 10^{-6} mbar)

100 m
160 m

STRAW
Downstream tracking:
Dipole spectrometer
4 straw-tracker stations
\( \sigma(p)/p = 0.3\% \)

\( \checkmark \) Time resolution \( \sim 100 \text{ ps} \)
\( \checkmark \) \( \sigma(m^2_{\text{miss}}) = 10^{-3} \text{ GeV}^2/c^4 \)

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NA62 apparatus

background rejection: $K^+ \rightarrow \pi^+\pi^0$

Hermetic photon veto system (LAV, SAV, LKr)

Multiplicity rejection (LAV, SAV, LKr, CHOD, STRAW)

Large Angle Veto (LAV)
12 stations (lead glass blocks)
Covering angles $8.5 < \theta < 50 \text{ mrad}$

Small Angle Veto (SAV)
IRC: Inner Ring Calorimeter
Small Angle Calorimeter
Covering angles $< 1 \text{ mrad}$

LKr calorimeter
Photon detection
Covering angles $1 < \theta < 8.5 \text{ mrad}$

$\varepsilon(\pi^0) = 3 \times 10^{-8}$
NA62 apparatus

**background rejection:** $K \rightarrow \mu^+ \nu$

**Particle identification:**
To separate $\pi/\mu/e$

The RICH is used also to obtain an independent $p$ momentum measurement.

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**RICH**
Ring Imaging Cherenkov detector

- Neon 1 Atm
- $\pi/\mu/e$ separation

**MUV**
Muon veto system

- MUV1 & MUV2: Hadronic calorimeters for the $\mu/\pi$ separation
- MUV3: Efficient fast Muon Veto used in the hardware trigger level.

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**Multivariate analysis**
with MUV1, MUV2 and LKr info

2 algorithm for the RICH variables

- $\varepsilon(\mu^+) = 10^{-8}$
- $\varepsilon(\pi^+) = 64\%$

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JINST 12 P05025 (2017), arxiv:1703.08501
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Upstream background

\[ N_{upstream}^{bg} = N_{\pi^+}^{upstream} \cdot P_{preco\ pileup} \cdot P_{matching \ K-\pi} \]

Upstream enriched sample

NA62 Preliminary

NA62 Preliminary

NA62 Preliminary

NA62 Preliminary

data
Bkg: $K^+ \rightarrow \pi^+ \pi^- e^+ \nu$

MC simulation validated using data

Validation in the control region