Results and Status of NA62
with emphasis on new physics searches

Babette Döbrich (CERN) for the collaboration

KIT, Flavor & DM 24/09/18
$K \rightarrow \pi \nu \bar{\nu}$: motivation and state of art

- ultra-rare FCNC decay, theory prediction:
  \[(K \rightarrow \pi \nu \bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}\]
  Buras et al. JHEP 1511, 33
**$K \to \pi \nu \bar{\nu}$: motivation and state of art**

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- **experiment at BNL, E949 (2008), stopped Kaons:**
  $${\text{BR}}(K \to \pi \nu \bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11} \text{ } \text{Phys. Rev. D 79, 092004}$$

- **NA62 primary goal:** measurement of $${\text{BR}}(K \to \pi \nu \bar{\nu})$$ with 10% signal acceptance (decay in flight) $\Rightarrow \sim 10^{13} K^+$ in fiducial volume
\[ K \rightarrow \pi \nu \bar{\nu} : \]

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  \( \Rightarrow \sim 10^{13} K^+ \) in fiducial volume

- BR correlated with flavor observables & sensitive to new physics, e.g.  
  **flavored axion models**  
NA62 rationale

A Kaon’s life:
- $\text{BR}(K \rightarrow \pi^+\pi^0) \simeq 0.21$
- $\text{BR}(K \rightarrow \mu^+\nu) \simeq 0.64$
- $\text{BR}(K \rightarrow \pi^+\pi^-\pi^+) \simeq 0.06$

Detector system
- Kaon: KTAG, GTK, CHANTI
- Pion: STRAW, CHOD, RICH
- $\gamma$ Vetoes: LAV, IRC, SAC, LKr
- MUV system: $\mu$ & Hadron

unseparated 750 MHz beam at GTK3
(6.6 % Kaons at 75 GeV, 1 % bite)
NA62 rationale II & requirements

- $m_{\text{miss}}^2 = (P_K - P_\pi)^2$
- $10^{12}$ background rejection!
- kinematic $\mathcal{O}(10^4)$
- high-efficiency veto: $\mathcal{O}(10^8)$
  rejection of $\pi^0$ for $E(\pi^0) > 40\text{GeV}$
- particle ID $\mu$ vs $\pi$: rejection of $\mathcal{O}(10^7)$ for $15 < p_{\pi^+} < 35\text{GeV}$
- timing subdetectors $\mathcal{O}(100\text{ps})$
2016 data: $\sim 10^{11} K^+$ useful for analysis

- $K^+$ decay into single charged track, $\pi^+$ PID, $\gamma$ & multi-track rejection
- Performances: GTK-KTAG-RICH timing: $O(100\text{ps})$, $\gamma$/multi-track rejection: $3 \times 10^{-8}$, overall $\pi^+$ ID: 64%
### Single Event Sensitivity and background budget

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

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

<table>
<thead>
<tr>
<th>Number of (K^+) Decays</th>
<th>(N_{K} = (1.21 \pm 0.02) \times 10^{11})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance (K^+ \rightarrow \pi^+\nu\bar{\nu})</td>
<td>(A_{\pi\nu\nu} = 0.040 \pm 0.001)</td>
</tr>
<tr>
<td>PNN trigger efficiency</td>
<td>(\epsilon_{\text{trig}} = 0.87 \pm 0.02)</td>
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<tr>
<td>Random trigger veto</td>
<td>(\epsilon_{RV} = 0.76 \pm 0.04)</td>
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<tr>
<th>SES</th>
<th>((3.15 \pm 0.01_{\text{stat}} \pm 0.24_{\text{syst}}) \times 10^{-10})</th>
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<tr>
<td>Expected SM (K^+ \rightarrow \pi^+\nu\bar{\nu})</td>
<td>(0.267 \pm 0.001_{\text{stat}} \pm 0.020_{\text{syst}} \pm 0.032_{\text{ext}})</td>
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<th>Process</th>
<th>Expected events in R1+R2</th>
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<tr>
<td>(K^+ \rightarrow \pi^+\nu\bar{\nu}) (SM)</td>
<td>(0.267 \pm 0.001_{\text{stat}} \pm 0.020_{\text{syst}} \pm 0.032_{\text{ext}})</td>
</tr>
<tr>
<td>Total Background</td>
<td></td>
</tr>
<tr>
<td>(K^+ \rightarrow \pi^+\pi^0(\gamma)) IB</td>
<td>(0.064 \pm 0.007_{\text{stat}} \pm 0.006_{\text{syst}})</td>
</tr>
<tr>
<td>(K^+ \rightarrow \mu^+\nu(\gamma)) IB</td>
<td>(0.020 \pm 0.003_{\text{stat}} \pm 0.003_{\text{syst}})</td>
</tr>
<tr>
<td>(K^+ \rightarrow \pi^+\pi^-e^+\nu) IB</td>
<td>(0.018^{+0.024}<em>{-0.017</em>{\text{stat}}} \pm 0.009_{\text{syst}})</td>
</tr>
<tr>
<td>(K^+ \rightarrow \pi^+\pi^+\pi^-)</td>
<td>(0.002 \pm 0.001_{\text{stat}} \pm 0.002_{\text{syst}})</td>
</tr>
<tr>
<td>Upstream Background</td>
<td>(0.050^{+0.090}<em>{-0.030</em>{\text{stat}}})</td>
</tr>
</tbody>
</table>

- \(N_K\) computed from \(K^+ \rightarrow \pi^+\pi^0\) on control trigger stream \((D = 400)\), w/o \(\gamma\) and multiplicity rejection and modified \(m^2_{\text{miss}}\)-cut
- **Expected number of events from 2016 data**: \(BR_{\text{SM theory}}/\text{SES}\)
- Validation of background expectations in control regions, see e.g. [https://indico.cern.ch/event/714178/](https://indico.cern.ch/event/714178/) for details
Unblinding of signal regions: 1 event observed in 2016 data

- Processing of 2017 data ongoing (20-fold present statistics)
- 2018: data taking ongoing → prospect of some mitigation of upstream background

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<th>Events Observed</th>
<th>SES</th>
<th>Expected Background</th>
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<td>1</td>
<td>$(3.15 \pm 0.01_{\text{stat}} \pm 0.24_{\text{syst}}) \times 10^{-10}$</td>
<td>$0.15 \pm 0.09_{\text{stat}} \pm 0.01_{\text{syst}}$</td>
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$BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) < 11 \times 10^{-10}$ @ 90% CL

$BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) < 14 \times 10^{-10}$ @ 95% CL

Expected limit: $BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) < 10 \times 10^{-10}$ @ 95% CL

For comparison: $BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) = 2.8^{+1.4}_{-2.3} \times 10^{-10}$ @ 68% CL

$BR(K^+ \rightarrow \pi^+\nu\bar{\nu})_{SM} = (0.84 \pm 0.10) \times 10^{-10}$

$BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$

BNL E949/E787 Kaon Decay at Rest
NA62 beyond $\pi \nu \bar{\nu}$

protons on target (POT) \(\searrow\)
\(\leftarrow\) beam collimator (TAX) ‘open’

⇒ $K^+$ to detector \(\downarrow\)

main measurement:
BR $\mathcal{O}(10^{-10})$: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

\(\leftarrow\) beam collimator closed
⇒ exotics to detector \(\downarrow\)

with much reduced backgrounds

3) dedicated data-taking e.g. axion $\rightarrow \gamma \gamma$

some examples will follow!

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NA62 beyond $\pi\nu\bar{\nu}$

protons on target (POT) ↘

beam collimator (TAX) ‘open’

⇒ $K^+$ to detector ↓

main measurement:
BR $\mathcal{O}(10^{-10})$: $K^+ \to \pi^+\nu\bar{\nu}$

1) Kaon decay with exotic

2) parasitically: e.g. exotic $\to l^+l^-$ + exotic away from beamline can produce exotics

∧ beam collimator closed → dump ⇒ exotics to detector ↓ with much reduced backgrounds

3) dedicated data-taking e.g. axion $\to \gamma\gamma$

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NA62 beyond $\pi \nu \bar{\nu}$

protons on target (POT) can produce exotics

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$\text{BR} \mathcal{O}(10^{-10}): K^+ \rightarrow \pi^+ \nu \bar{\nu}$

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$\Rightarrow$ $K^+$ to detector $\downarrow$

$+$ exotic away from beamline
NA62 beyond $\pi\nu\bar{\nu}$

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can produce exotics

\(\leftarrow\) beam collimator closed \(\rightarrow\) dump

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1) Kaon decay with exotic: results

Trigger band width shared by $\pi^+\bar{\nu}\nu$
+ other Kaon & non-Kaon modes

example Kaon: $K^+ \rightarrow N + l^+$,

N: ‘stable’ Heavy Neutrino

2015 data: PLB 778 137 (2018)

based on $\sim 3 \times 10^8$ Kaon decays
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from 2016 data:

invisibly decaying Dark Photon $K^+ \rightarrow \pi^0\pi^+$ with $\pi^0 \rightarrow A' + \gamma$

(prelim: paper in preparation)

search peak in missing mass of $m_{\text{miss}}^2 = (P_K - P_\pi - P_\gamma)^2$
2+3) Exotic from dumped-beam: prospects

1. Parasitic to $\pi \nu \bar{\nu}$: invisible Dark Photons, heavy Neutrinos... as seen before

2. Trigger Parasitic to $\pi \nu \bar{\nu}$: $\mu \pi + \mu \mu$ away from beamline: 2017: $\mathcal{O}(10^{17})$ POT, sizable statistics $\mathcal{O}(10^{18})$ POT possible this year

3. dump-mode: sizable statistics $\mathcal{O}(10^{18})$ reserved for future, but some channels discovery potential with moderate statistics (e.g. ALP $\mathcal{O}(10^{16})$)

⇒ In the following: "long-lived" prospects at $\mathcal{O}(10^{18})$ POT

Under study / definition, interaction/synergy with the Physics Beyond Collider CERN initiative
ALPs coupled to photons

\[ \mathcal{L}_{\text{axion}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \frac{a}{f_{\gamma}} F_{\mu\nu} \tilde{F}_{\mu\nu}. \]

ALP = Axion-like particle (name derives from QCD axion) 
good properties 
as dark matter mediator
see e.g. 1709.00009

- Assume $10^{18}$ 400-GeV POT
- projection based on Primakov production and 0 background
Dark Photons

\[ \mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - \frac{\epsilon}{2 \cos \theta_W} F'_{\mu \nu} B_{\mu \nu}, \]

minimistic NP:

Extra U(1) mixing

kinematically with EM or hypercharge

Sensitivity expected to be higher than shown:
1. including direct QCD production of \( A' \)
2. Including \( A' \) production in the dump (here, only target)

- Assume \( 10^{18} \) 400-GeV POT
- Study DP production (meson decays, bremsstrahlung) from interaction on target, search for \( ee, \mu \mu \)
- Assume zero background, expected 90%-CL exclusion plot
Dark Scalars

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

in this model we assume \( \lambda = 0 \)

- real singlet scalar coupled with Higgs

Assume \( 10^{18} \) 400-GeV POT

- sensitivity to hidden scalars charged decays search for \( ee, \mu\mu, \pi\pi, KK \) two-track final states originating at the TAX

- assume zero background, expected 90%-CL exclusion plot

NA62 projected sensitivity dominated by beauty production
Heavy Neutral Leptons

\[ \mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \sum F_\alpha I (\bar{L}_\alpha H) N_I \]

- e.g. $\nu$MSM $\rightarrow$ neutrino masses, (warm) DM candidate and baryon asymmetry
- separately address 3 extreme coupling scenarios [Shaposhnikov, Gorbunov arXiv:0705.1729]
- Assume $10^{18}$ 400-GeV POT: search for two-track final states originating at the TAX sensitivity includes open channels, assuming 0 background
- assume zero background, evaluate expected 90%-CL exclusion plot
Background rejection NA62: 2016 data $\mathcal{O}(10^{15})$ POT

- **Track quality** (association with CHOD, LKr hits in time) + **acceptance** (CHOD, LKr, MUV3)

- **Vertex quality:** two-track-distance $< 1$ cm, vertex-position $105 < z < 165$ m

- Further veto (rhs): $E_{\text{LKr, additional}} < 2$ GeV; IRC, SAC, LAV no hits with $\pm 5$ ns, CHANTI no candidate within $\pm 5$ ns

- No events in signal region at TAX even with standard $K^+$ beam at $\mathcal{O}(10^{15})$ POT, background rejection OK for $\mathcal{O}(10^{15})$ POT in standard conditions and $4 \times \mathcal{O}(10^{15})$ in dump
Thanks for listening :-)

- $\pi \nu \bar{\nu}$ expected about 20 SM events from the 2017+2018 sample
- Kaon in-flight-decay technique validated
- methods to improve signal efficiency under study
- 2018: Processing on parallel with data-taking
- the analysis of 2017+2018 sample should provide: ESPP input

In addition,
- before LS2: $\pi \nu \bar{\nu}$-parasitic triggers/searches + short dedicated beam-dump runs
- after LS2, $\mathcal{O}(10^{18})$POT would provide sensitivity to various weakly coupled particles
Constraints from past experiments: ALP-example

\[ N_{\text{det}} \sim \]
\[ N_{\text{pot}} \frac{\sigma_a}{\sigma_p} \left[ \exp \left( -\frac{D}{\gamma \beta \tau} \right) - \exp \left( -\frac{D + L}{\gamma \beta \tau} \right) \right] \]

- decay length \( \gamma \beta \tau \), ALP lifetime \( \Gamma = \tau^{-1} = g_{a\gamma}^2 m_a^3 / (64\pi) \)

### exclusion through dumps

- **CHARM** 400 GeV, \( N_{\text{pot}} = 2.4 \times 10^{18} \) on copper, \( D = 480m, L = 35m \) (off-axis: 7-12 mrad)

- **NuCal** 70 GeV, \( N_{\text{pot}} = 1.7 \times 10^{18} \) on iron, \( D = 64m, L = 23m, \) on-axis 0-15 mrad

- **SLAC141** 9 GeV, \( N_{\text{eot}} = 2 \times 10^{15} \) on tungsten, \( D = 35m \)

- **SLAC137** 20 GeV, \( N_{\text{eot}} = 2 \times 10^{20} \) on aluminum, \( D = 200m \)

Plot from 1512.03069 with updates from 1709.00009

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