Physics Beyond the Standard Model with the NA62 experiment at CERN

Paolo Massarotti (massarotti@na.infn.it)
UniversitÀ degli studi di Napoli Federico II and INFN Napoli
on behalf of the NA62 collaboration

BSM 2023, Hurghada
Outline

- The NA62 experiment
- Experimental setup
- NA62 main goal: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
- Hidden sector
  - $K^+ \rightarrow \pi^+ e^+ e^- e^+ e^-$
  - $A' \rightarrow l^+ l^-$
- LFV
  - $K^+ \rightarrow \mu^- \nu e^+ e^+$
- Conclusions
NA62 experiment at CERN

NA62 is located in the North Area at CERN:

- Fixed target experiment with kaon decay-in-flight

- Main goal: $\text{BR}(K^+ \rightarrow \pi^+ \nu\bar{\nu})$ with 10% precision

- Primary beam: 400 GeV/c protons from SPS

- Secondary beam: 75 GeV/c positive charged particle (6% K+)

NA62 collaboration: ~ 200 participants from ~ 30 institution:
Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Sofia, Torino, TRIUMF, Vancouver UBC

Timeline

<table>
<thead>
<tr>
<th>Period</th>
<th>Description</th>
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<tr>
<td>2009 – 2014</td>
<td>Construction and installation</td>
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<tr>
<td>2014 – 2015</td>
<td>Technical runs</td>
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<td>2016 – 2018</td>
<td>Physics runs</td>
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<tr>
<td>2021 – 2023</td>
<td>Physics runs</td>
</tr>
</tbody>
</table>
NA62 beam and detector

**SPS Beam**
- 400 GeV/c protons
- 3.5s spill

**Secondary positive beam**
- 75 GeV/c momentum, 1% bite
- 100 μrad divergence (RMS)
- 60x30 mm² transverse size
- $K^+(6\%)/\pi^+(70\%)/p(24\%)$
- 750 MHz at GTK3

**Decay Region and Detectors**
- Fiducial region 60 m
- $K^+$ decay rate $\sim$ 5 MHz
- Vacuum $\mathcal{O} 10^{-6}$ mbar
- Si pixel beam tracker + Straw tracker
- LKr Calorimeter from NA48
- Cerenkov counter for K id RICH for $\pi/\mu$ id

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NA62 beam and detector

SPS Beam
400 GeV/c protons
3.5s spill

Secondary positive beam
75 GeV/c momentum, 1% bite
100 µrad divergence (RMS)
60x30 mm² transverse size
K⁺(6%)/π⁺(70%)/p(24%)
750 MHz at GTK3

Decay Region and Detectors
Fiducial region 60 m
K⁺ decay rate ~ 5 MHz
Vacuum $\mathcal{O} 10^{-6}$ mbar
Si pixel beam tracker + Straw tracker
LKr Calorimeter from NA48
Cerenkov counter for K id RICH for $\pi/\mu$ id
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$
Precise SM predictions: \[\text{BR}(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}\]
\[\text{BR}(K_L \rightarrow \pi^0\nu\bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}\]

\[\text{BR}(K^+ \rightarrow \pi^+\nu\bar{\nu})\] and \[\text{BR}(K_L \rightarrow \pi^0\nu\bar{\nu})\] can discriminate among different NP scenarios

✅ Models with CKM-like flavour structure

✅ Custodial Randall-Sundrum

✅ MSSM analyses
[Blazek, Mataki, Int.J.Mod.Phys. A29 (2014) no.27],
[Isidori et al. JHEP 0608 (2006) 064]

✅ LFU violation models

✅ Leptoquarks

✅ Simplified Z, Z' models

✅ Littlest Higgs with T-parity
Experimental Strategy

Performances
- Kinematic suppression $O(10^4)$
- Muon suppression $O(10^7)$
- $\pi^0$ suppression $O(10^7)$
- Timing between sub-detectors $O(100 \text{ ps})$

Selection
- $K^+, \pi^+$ track reconstruction
- Track matching, vertex reconstruction
- $\pi^+$ identification, $\mu^+$ rejection
- Multi-track rejection, photon veto
- Kinematics ($m^2_{\text{miss}}, p_\pi$)

Analysis
- Momentum range: $15 < p_\pi < 45 \text{ GeV/c}$
- Signal regions blinded during the analysis
- Data-driven background estimate
- 7 categories depending on hardware and momentum
### RUN1 summary

\[
N_{\pi\nu\nu}^{exp} \approx N_{\pi\pi} \epsilon_{\text{trigger}} \epsilon_{RV} \frac{A_{\pi\nu\nu}}{A_{\pi\pi}} \frac{Br(\pi\nu\nu)}{Br(\pi\pi)} \quad \text{S.E.S.} = \frac{Br(\pi\nu\nu)}{N_{\pi\nu\nu}^{exp}}
\]

<table>
<thead>
<tr>
<th></th>
<th>2016 data</th>
<th>2017 data</th>
<th>2018 S1 data</th>
<th>2018 S2 data</th>
</tr>
</thead>
<tbody>
<tr>
<td>SES \times 10^{10}</td>
<td>3.15 \pm 0.24</td>
<td>0.39 \pm 0.02</td>
<td>0.54 \pm 0.04</td>
<td>0.14 \pm 0.01</td>
</tr>
<tr>
<td>(A_{\pi\nu\nu} \times 10^{2})</td>
<td>4 \pm 0.4</td>
<td>3 \pm 0.3</td>
<td>4 \pm 0.4</td>
<td>6.4 \pm 0.6</td>
</tr>
<tr>
<td>Expected SM signal</td>
<td>0.27 \pm 0.04</td>
<td>2.16 \pm 0.13</td>
<td>1.56 \pm 0.10</td>
<td>6.02 \pm 0.39</td>
</tr>
<tr>
<td>Expected background</td>
<td>0.15 \pm 0.090</td>
<td>1.46 \pm 0.30</td>
<td>1.11^{+0.40}_{-0.22}</td>
<td>4.31^{+0.91}_{-0.72}</td>
</tr>
<tr>
<td>Observed events</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>15</td>
</tr>
</tbody>
</table>

[PLB 791 (2019) 156-166]  [JHEP 11 (2020) 042]  [JHEP 06 (2021) 093]
Single Event Sensitivity: $(0.839 \pm 0.053_{\text{syst}}) \times 10^{-11}$

Expected SM signal events: $10.01 \pm 0.42_{\text{syst}} \pm 1.19_{\text{ext}}$

Expected background events: $7.03^{+1.05}_{-0.82}$

Observed events: 20

Significance: $3.4\sigma$

$\text{Br}(K^+ \to \pi^+ \nu \bar{\nu}) = (10.6^{+4.0}_{-3.5\text{ stat}} \pm 0.9_{\text{syst}}) \cdot 10^{-11} (3.4 \sigma \text{ significance})$
$K^+ \rightarrow \pi^+ e^+ e^- e^+ e^-$
Searches for production of dark-sector in meson decays have been focused on the production of a single particle, which is either invisible or decays into lepton or photon pairs (not on the pair-production of dark states)

**Two-fold interest in the context of dark sector:**

- A short-lived QCD axion:
  - plausible explanation for the “17 MeV anomaly” in the mass spectra of the $e^+e^-$ pairs produced in the de-excitation of $^{8}$Be, $^{4}$He and $^{12}$C nuclei
    - assuming $m_a = 17 \text{ MeV}/c^2$, $B(K^+ \rightarrow \pi^+a) > 2 \times 10^{-8}$ is predicted
      - [Phys. Rev. D105 (2022) 015017]

- Dark scalar $S$, and a dark photon $A'$ with masses satisfying the condition $m_S \geq 2m_{A'}$ and $K^+ \rightarrow \pi^+S$, $S \rightarrow A'A'$, $A' \rightarrow e^+e^-$
  - [Phys. Rev. D105 (2022) 015017]
The data sample analysed is obtained from $8.3 \times 10^5$ SPS spills recorded in 2017–2018; $K^+ \rightarrow \pi^+ e^+ e^- e^- (K_{\pi 4e})$ rate is normalised to decay $K^+ \rightarrow \pi^+ \pi^0_{DD} (K_{2\pi DD})$ which allows a first order cancellation of detector and trigger inefficiencies.

- **STRAW information only, to avoid loss in signal acceptance:**
  - vertices are reconstructed by extrapolating STRAW tracks backward
  - 5 tracks,
  - $p_{track}$ in the range 5–45 GeV/c.
  - each pair of tracks should be separated by at least 15 mm in each STRAW chamber plane, to suppress photon conversions and fake tracks

- **Invariant mass $m_{\pi 4e}$ used to distinguish between signal and bkg**
  - Three assignments of the $\pi^+$ mass to one of the positively charged tracks are considered. The mass assignment corresponding to the minimal value of $|m_{\pi 4e} - m_K|^2$ is chosen
The data sample analyzed is obtained from $8.3 \times 10^5$ SPS spills recorded in 2017–2018. $K^+ \rightarrow \pi^+ e^+ e^- e^+ e^-$ ($K_{\pi 4e}$) rate is normalised to decay $K^+ \rightarrow \pi^+ \pi^0_{DD}$ ($K_{2\pi DD}$) which allows a first order cancellation of detector and trigger inefficiencies.

**Discriminating kinematic variable and blind analysis strategy**
- Signal region kept masked until the completion and validation of the background evaluation

**For $K_{\pi 4e}$**
- $|m_{4e} - m_{\pi 0}|^2 > 10\text{MeV}/c^2$
- consistency of the two reconstructed $e^+e^-$ mass for each X mass hypothesis $|m_{ee} - m_X| < 0.02m_X$
- $p_{\pi} > 10\text{GeV}/c$.

**For $K_{2\pi DD}$** $|m_{4e} - m_{\pi 0}|^2 < 10\text{MeV}/c^2$
Uniform phase space assumed for $K^+$ decays, isotropic decays of dark states

No data observed in the Signal Region

Upper limits at 90% CL at the level of $10^{-9}$ for the branching ratios of two prompt decay chains involving pair-production of hidden-sector mediators.

The QCD axion is excluded as a possible explanation of the 17 MeV anomaly

[Physics Letters B 846 (2023) 138193]
\[ A' \rightarrow l^+ l^- \]
New U(1) gauge-simmetry
A’ vector mediator field
interaction between A_μ‘ and the SM hypercharge B_μν via kinetic-mixing

In the mass range < 700 MeV/c^2, DP decay width dominated by l^+ l^- final states
In 2021, NA62 collected $1.40 \pm 0.28 \times 10^{17}$ POT.
A’→l⁺l⁻ selection

Signal selection

- l⁺l⁻ vertex reconstructed within the NA62 decay region and pointing back to the proton beam interaction point at the TAXes
- CR and SR masked until the analysis strategy is frozen
- Bkg estimated selecting single tracks in a data sample orthogonal to the one used for the analysis
- A’→μ⁺μ⁻ result also interpreted in terms of the emission of axion-like particles in a model-independent approach, improving on previous limits for masses below 280 MeV/c²
A’→l⁺l⁻ results

90% CL upper limits exploring new regions of the parameter space $\epsilon, M_{A'}$

1 event observed in the SR corresponing to 2.4$\sigma$ global significance

[JHEP 09 (2023) 035]
\[ K^+ \rightarrow \mu^- \nu e^+ e^+ \]
Search for LFV and LNV @ NA62

A large dataset of $K^+$ decays to lepton pairs in 2016–2018, using dedicated trigger.

- UL of the branching ratios of the LNV decays
  - $K^+ \rightarrow \pi^- (\pi^0) e^+ e^+ \quad \text{[Phys. Lett. B 830 (2022) 137172]}$
  - $K^+ \rightarrow \pi^- \mu^+ \mu^+ \quad \text{[Phys. Lett. B 797 (2019) 134794]}$
  - $K^+ \rightarrow \pi^- \mu^+ e^+ \quad \text{[Phys. Rev. Lett. 127 (2021) 131802]}$

- UL of the branching ratios of the LFV decays
  - $K^+ \rightarrow \pi^+ \mu^- e^+ \quad \text{[Phys. Rev. Lett. 127 (2021) 131802]}$
  - $\pi^0 \rightarrow \mu^- e^+ \quad \text{[Phys. Rev. Lett. 127 (2021) 131802]}$

$K^+ \rightarrow \mu^- \nu e^+ e^+$ decay is forbidden in the SM by either lepton number (LN) or lepton flavour (LF) conservation, depending on the flavour of the emitted neutrino.

Current UL of the decay branching fraction is $2.1 \times 10^{-8}$ at 90% CL

$K^+ \rightarrow \mu^- \nu e^+e^+$ selection

$K^+ \rightarrow \mu^- \nu e^+e^+$ rate ($K_{\mu\text{vvee}}$) is normalised to decay $K^+ \rightarrow \pi^+e^+e^-$ ($K_{\pi\text{ee}}$) which allows a first order cancellation of detector and trigger inefficiencies.

Common selection

- Three-track vertices extrapolating STRAW tracks into the FV with $6 < P < 44$ GeV/c

- PID is based on the ratio $E/p$
  - $\pi$ is identified by $E/p < 0.85$,
  - $\mu$ is identified by $E/p < 0.2$
  - $e$ is identified by $0.9 < E/p < 1.1$

- For $K_{\pi\text{ee}}$
  - $|p_{\text{vtx}} - p_{\text{beam}}| < 2$ GeV/c,
  - $470 < m_{\pi\text{ee}} < 505$ MeV/c$^2$,

- For $K_{\mu\text{vvee}}$
  - $p_{\text{beam}} - p_{\text{vtx}} > 10$ GeV/c,
  - $-0.006 \text{ GeV}^2/c^4 < m_{\text{miss}}^2 < 0.004 \text{ GeV}^2/c^4$
$K^+ \rightarrow \mu^- \nu e^+e^+$ result

$K^+ \rightarrow \pi^+e^+e^-$ invariant mass

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

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

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

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

$\text{Br}(K^+ \rightarrow \mu^- \nu e^+e^+) < 8.1 \times 10^{-11}$ at 90% CL

[Physics Letters B 838 (2023) 137679]
Conclusions

\[ K^+ \rightarrow \pi^+ \nu \bar{\nu} \]
✓ Run1 measurement compatible with the SM within one standard deviation
✓ The most precise measurement of the BR obtained so far

\[ K^+ \rightarrow \pi^+ a a, \ a \rightarrow e^+ e^- \ \text{and} \ K^+ \rightarrow \pi^+ S, \ S \rightarrow A'A', \ A' \rightarrow e^+ e^- \ \text{UL have been set} \]

\[ \text{[JHEP 06 (2021) 093]} \]

\[ K^+ \rightarrow \mu^- \nu e^+ e^+ \ \text{UL have been set} \]

\[ \text{[Physics Letters B 838 (2023) 137679]} \]

\[ \text{A'} \rightarrow \ell^+ \ell^- \ \text{in beam-dump mode UL have been set, exploring new regions of the parameter space} \]

\[ \text{[JHEP 09 (2023) 035]} \]

NA62 will take data until LS3. Stay tuned!!!!!
Theoretical error budget
Buras. et. al., JHEP11(2015)033

$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$

- FCNC loop processes: $s \rightarrow d$ coupling and highest CKM suppression
- Theoretically clean: Short distance contribution
- Hadronic matrix element measured with $K_{l3}$ decays

$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \left( \frac{|V_{cb}|}{0.0407} \right)^{2.8} \left( \frac{\gamma}{73.2^\circ} \right)^{0.74} = (8.4 \pm 1.0) \times 10^{-11}$$

- Experimental result collecting 7 events: [Phys. Rev. D 79, 092004 (2009)]

$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11} \quad \text{(BNL “kaon decays at rest”)$$
**K^+ → π^+ν̅ν and the LFU violation**

Measurement of $K^+ → π^+ν̅ν$ together with $B^+ → K^{*+}ν̅ν$ can probe the Lepton-Flavour Universality

- An interactions responsible for LFU violations can couple mainly to the third generation of left-handed fermions;

- $K^+ → π^+ν̅ν$ is the only kaon decays with third-generation leptons (the τ neutrinos) in the final state;

- A deviations from the Standard Model predictions in $K^+ → π^+ν̅ν$ branching ratios should be closely correlated to similar effects in $B^+ → K^{*+}ν̅ν$. 

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Signal Selection

- Two signal regions kept blinded
- In order to evaluate the background from K decays, the tails of the distribution are extrapolated into the signal regions.
- The control regions are kept blinded too, to validate the procedure.

**Selection criteria**
- single track decay topology
- $\pi^+$ identification
- photon rejection
- multi-track rejection

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>BR</th>
<th>Main rejection tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \mu^+\nu(\gamma)$</td>
<td>63%</td>
<td>$\mu$-ID + kinematics</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0(\gamma)$</td>
<td>21%</td>
<td>$\gamma$-veto + kinematics</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^-\pi^+$</td>
<td>6%</td>
<td>multi + kinematics</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0\pi^0$</td>
<td>2%</td>
<td>$\gamma$-veto + kinematics</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^0e^+\nu_e$</td>
<td>5%</td>
<td>e-ID + $\gamma$-veto</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^0\mu^+\nu_\mu$</td>
<td>3%</td>
<td>$\mu$-ID + $\gamma$-veto</td>
</tr>
</tbody>
</table>
Single Event Sensitivity (SES)

\[ N_{\pi\nu\nu}^{\text{exp}} \approx N_{\pi\pi}\epsilon_{\text{trigger}}\epsilon_{\text{RV}} \frac{A_{\pi\nu\nu}}{A_{\pi\pi}} \frac{Br(\pi\nu\nu)}{Br(\pi\pi)} \rightarrow \text{S.E.S.} = \frac{Br(\pi\nu\nu)}{N_{\pi\nu\nu}^{\text{exp}}} \]

- **Photon + multiplicity rejection**
- **Photon rejection**
- **LKr veto**
- **LAV veto**
- **IRC+SAC veto**

**Graphical Representation**

- Random veto: efficiency loss due to beam activity

- **K^+ \rightarrow \pi^+\pi^0** normalization signal
- Cancellation of systematic effects
- Random Veto: efficiency loss due to beam activity

<table>
<thead>
<tr>
<th></th>
<th>Subset S1</th>
<th>Subset S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_{\pi\pi} \times 10^{-7})</td>
<td>3.14</td>
<td>11.6</td>
</tr>
<tr>
<td>(A_{\pi\pi} \times 10^2)</td>
<td>7.62 ± 0.77</td>
<td>11.77 ± 1.18</td>
</tr>
<tr>
<td>(A_{\pi\nu\nu} \times 10^2)</td>
<td>3.95 ± 0.40</td>
<td>6.37 ± 0.64</td>
</tr>
<tr>
<td>(\epsilon_{\text{trig}})</td>
<td>0.89 ± 0.05</td>
<td>0.89 ± 0.05</td>
</tr>
<tr>
<td>(\epsilon_{\text{RV}})</td>
<td>0.66 ± 0.01</td>
<td>0.66 ± 0.01</td>
</tr>
<tr>
<td>(SES \times 10^{10})</td>
<td>0.54 ± 0.04</td>
<td>0.14 ± 0.01</td>
</tr>
<tr>
<td>(N_{\pi\nu\nu}^{\text{exp}})</td>
<td>1.56 ± 0.10 ± 0.19_{\text{ext}}</td>
<td>6.02 ± 0.39 ± 0.72_{\text{ext}}</td>
</tr>
</tbody>
</table>

\[ \text{SES_{Run1}} = (0.839 \pm 0.054) \times 10^{-11} \]
Background from Kaon Decay

Control $\pi^+ \pi^0$ data to study $m^2_{\text{miss}}$ distribution

Expected $K^+ \rightarrow \pi^+ \pi^0$ events in signal region

$$N^\text{exp}_{\pi\pi} (SR) = N_{\pi\pi} f_{\text{kin}}(SR)$$

Data in $\pi^+ \pi^0$ region after $\pi^+ \nu\bar{\nu}$ selection

Fraction of $\pi^+ \pi^0$ in signal region, measured on control data

- $K^+ \rightarrow \mu^+ \nu_\mu$ and $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ backgrounds: similar procedure
- $K^+ \rightarrow \pi^+ \pi^- e^+ \nu_e$ evaluated with MC simulations
Upstream background

- Pions produced upstream the fiducial volume
  - Early $K^+$ decay or interaction with the beam spectrometer material
  - only a $\pi^+$ enters the fiducial decay region
  - there is an in-time pileup beam particle (in GTK)
  - the upstream $\pi^+$ is scattered in the first STRAW chamber.

- Kaon-pion association and geometrical variables
- Data driven background estimation
2016 – 2017 data tacking results

**2016**

1 events observed

SES = $3.15 \times 10^{-10}$

$\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 14 \times 10^{-10} \atop @ 90\% \text{ CL}$


**2017**

2 events observed

SES = $0.389 \times 10^{-10}$

$\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 1.7 \times 10^{-10} \atop @ 90\% \text{ CL}$

[J. High Energ. Phys. 2020, 42 (2020)]
2018 data tacking results
Control regions: main decays

<table>
<thead>
<tr>
<th>Decay</th>
<th>Subset S1</th>
<th>Subset S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+\pi^0$</td>
<td>$0.23 \pm 0.02$</td>
<td>$0.52 \pm 0.05$</td>
</tr>
<tr>
<td>$\mu^+\nu$</td>
<td>$0.19 \pm 0.06$</td>
<td>$0.45 \pm 0.06$</td>
</tr>
<tr>
<td>$\pi^+\pi^-e^+\nu$</td>
<td>$0.10 \pm 0.03$</td>
<td>$0.41 \pm 0.10$</td>
</tr>
<tr>
<td>$\pi^+\pi^+\pi^-$</td>
<td>$0.05 \pm 0.02$</td>
<td>$0.17 \pm 0.08$</td>
</tr>
<tr>
<td>$\pi^+\gamma\gamma$</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td>$\pi^0 l^+\nu$</td>
<td>$&lt; 0.001$</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td>Upstream</td>
<td>$0.54^{+0.39}_{-0.21}$</td>
<td>$2.76^{+0.90}_{-0.70}$</td>
</tr>
<tr>
<td>Total</td>
<td>$1.11^{+0.40}_{-0.22}$</td>
<td>$4.31^{+0.91}_{-0.72}$</td>
</tr>
</tbody>
</table>
2018 data tacking results

5.3 background + 7.6 SM signal events expected
2018 data tacking results

5.3 background + 7.6 SM signal events expected, 17 events observed
## Search for LNV and LNV @ NA62

<table>
<thead>
<tr>
<th>Previous UL @90% CL</th>
<th>NA62 UL @90% CL</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(K^+ \to \pi^- \mu^+ \mu^+)</td>
<td>(8.6 \times 10^{-11})</td>
<td>(4.2 \times 10^{-11})</td>
<td>2017 data</td>
<td>PLB 797 (2019) 134794</td>
</tr>
<tr>
<td>(K^+ \to \pi^- e^+ e^+)</td>
<td>(6.4 \times 10^{-10})</td>
<td>(5.3 \times 10^{-11})</td>
<td>Run1 data</td>
<td>PLB 830 (2022) 137172</td>
</tr>
<tr>
<td>(K^+ \to \pi^- \pi^0 e^+ e^+)</td>
<td>no limit</td>
<td>(8.5 \times 10^{-10})</td>
<td>Run1 data</td>
<td>PLB 830 (2022) 137172</td>
</tr>
<tr>
<td>(K^+ \to \pi^- \mu^+ e^+)</td>
<td>(5.0 \times 10^{-10})</td>
<td>(4.2 \times 10^{-11})</td>
<td>2017+2018 data</td>
<td>PRL 127 (2021) 131802</td>
</tr>
<tr>
<td>(K^+ \to \pi^- \mu^- e^+)</td>
<td>(5.2 \times 10^{-10})</td>
<td>(6.6 \times 10^{-11})</td>
<td>2017+2018 data</td>
<td>PRL 127 (2021) 131802</td>
</tr>
<tr>
<td>(\pi^0 \to \mu^- e^+)</td>
<td>(3.4 \times 10^{-9})</td>
<td>(3.2 \times 10^{-10})</td>
<td>2017+2018 data</td>
<td>PRL 127 (2021) 131802</td>
</tr>
</tbody>
</table>

\[\text{Factor 2 improvement} \quad \text{Factor 12 improvement} \quad \text{Factor 12 improvement} \quad \text{Factor 8 improvement} \quad \text{Factor 13 improvement}\]

\[\text{LNF: } K^+ \rightarrow \pi^- e^+ e^+\]

\[\text{LNV: } K^+ \rightarrow \pi^- \mu^+ \mu^+\]

\[\text{LNV/LFV: } K^+ \rightarrow \pi^- \mu^+ e^+\]

\[\text{LFV: } K^+ \rightarrow \pi^+ \mu^- e^+\]