Latest NA62 results on the search for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$
and prospects for a neutral pion Dalitz decay measurement

Tom Bache (University of Birmingham, UK)
Outline

Introduction to NA62
- History of kaon physics at CERN
- Physics motivation
- NA62 beam and detector layout

The $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ decay
- Latest analysis improvements
- Results from data taken in Run 1

The $\pi^0 \rightarrow e^+e^-\gamma$ decay
- Theory
- Experimental status
- Prospects for a measurement at NA62

Conclusions and the future of NA62
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The \( \pi^0 \rightarrow e^+e^-\gamma \) decay

The \( K^+ \rightarrow \pi^+\nu\bar{\nu} \) decay

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NA62 and kaon physics at CERN

1980s
NA31
First evidence of direct CPV

1997-2001
NA48
Discovery of direct CPV

2002
NA48/1
Rare decay studies

2003-2004
NA48/2
Precision measurements

2007-2008
NA62-\(R_K\)
\[ R_K = \frac{\Gamma(K_{e2})}{\Gamma(K_{\mu2})} \]

2015-2018
NA62 Run 1
(2015-2018)
Main goal: \(B(K^+ \rightarrow \pi^+ \nu \bar{\nu})\)
LNV/LFV searches, HNL, precision and rare decay measurements...

2021-L53
NA62 Run 2
(2021-L53)

~200 participants, 30 institutes, 14 countries

K_L/K_S beam
K_S/hyperon beam
K^+/K^- beam
K^+ beam

T. Bache - UoB Seminar
12/01/2022
Physics case: $BR(K^+ \rightarrow \pi^+ \nu\bar{\nu})$

The decay is a $s \rightarrow d \nu\bar{\nu}$ transition: flavour changing neutral current process (GIM mechanism) with high CKM suppression. Precise measurement would help constrain the unitarity triangle as well as a variety of new physics models (new sources of flavour violation, lepton flavour non-universality, leptoquark plus more).

It has a theoretically clean prediction (short distance contributions).

Standard model prediction (updated in 2021 which decreased the uncertainty by a factor 2.4 [arXiv:2109.11032]):

$$BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (8.60 \pm 0.42) \times 10^{-11}$$

The main uncertainty is from the $\gamma$ CKM parameter knowledge.
**BR(\(K^+ \to \pi^+ \nu\bar{\nu}\)) beyond the SM**


Constraints from existing measurements (correlations model dependent):

---

**Z'(5 TeV) in Constrained MFV**

**LFU violation**

They used a decay at rest technique.

Had the sensitivity to observe 1 SM signal event.

They observed 7 and used a statistical reweighting procedure to take into account the background.

BNL measurement:

$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$
**BR\((K^+ \to \pi^+ \nu \bar{\nu})\) at NA62**

**Strategy:**
- Decay in flight technique \((P_K = 75 \text{ GeV}/c)\).
- Kinematic analysis with \(m_{\text{miss}}^2 = (P_K - P_\pi)^2\) as the main kinematic variable.
- Require:
  - Charged particle identification \((K^+ \text{ and } \pi^+)\).
  - Muon and photon rejection.
  - Pion momentum range \([15,45]\) GeV/c.
- Signal and control kinematic regions are blinded during the analysis.

**Require:**
- Timing resolution \(O(100\text{ps})\).
- Kinematic rejection \(O(10^4)\) of \(K^+ \to \pi^+\pi^0\) and \(K^+ \to \mu^+\nu\).
- Muon rejection \(> 10^7\) (mainly from \(K^+ \to \mu^+\nu\)).
- \(\pi^0\) rejection \(> 10^7\) (mainly from \(K^+ \to \pi^+\pi^0\) with \(\pi^0 \to \gamma\gamma\)).
NA62 beam and detector layout

- **KTAG** (upstream Cherenkov detector) tags kaons in the beam \((\sigma_T \sim 70\text{ps})\)
- **GTK** (silicon pixel spectrometer) tracks the beam
- **CHANTI** (plastic scintillator) rejects inelastic scattering background
- **STRAW** (magnetic spectrometer) tracks \(K^+\) decay products
- **RICH** (downstream Cherenkov detector) provides PID \((\pi^+ / \mu^+ / e^+)\) and timing \((\sigma_T \sim 70\text{ps})\)
- **LKr** (ECAL) provides PID and photon veto

Protons from CERN SPS impinge on beryllium target.

Leads to an unseparated beam consisting of \(K^+, \pi^+\) and protons entering NA62.

6\% of the beam is \(K^+\).

Beam rate \(\sim 500\) MHz at decay region entrance \(\Rightarrow K^+\) decay rate \(\sim 5\) MHz in the decay region.

Beam momentum = 75 GeV/c (\(\pm 1\%\))
NA62 beam and detector layout
NA62 data taking periods

Run 1 comprises of 3 years of data taking between 2016 and 2018.

- 408 days in total.
- $\sim 6 \times 10^{12}$ $K^+$ decays.

Run 2 started in July 2021 and will continue until the start of LS3 (2024).

- Expect to collect $O(10^{13})$ $K^+$ decays.
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Conclusions and the future of NA62
Result from 2016+2017 analysis consistent with background expectation [JHEP 11 (2020) 042]:

\[ \text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 1.78 \times 10^{-10} @ 90\% \text{ CL} \]
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ selection

**πνν trigger:**
- L0 (hardware): charged particle present, muon and photon veto.
- L1 (software): $K^+$ ID, additional photon veto, track reconstruction.

**Minimum-bias trigger** (used for $K^+$ flux, efficiencies and background estimation):
- L0 (hardware): charged particle present

**πνν selection steps:**
- Reconstruction of $K^+$ and $\pi^+$ tracks
- $K^+ - \pi^+$ matching
- Reconstruction of decay vertex
- $\pi^+$ ID and $\mu^+ / \gamma$ rejection
- Multi-track rejection
- Kinematics ($m_{miss}^2$ vs $p_\pi$)

\[
m_{miss}^2 = (P_K - P_\pi)^2
\]
Several improvements were made in the 2018 analysis, with respect to the 2017 one. The aim was to increase the signal efficiency whilst keeping the same signal/background:

- New collimator installed on the beam line to remove background from upstream of the decay volume.
- BDT approach applied for estimation of upstream background (allowed certain geometrical cuts to be relaxed).
- PID conditions optimised in bins of $\pi^+$ momentum and BDT used for calorimeter PID.
- Photon rejection optimised by taking into account correlations with $Z_{vtx}$ and $\pi^+$ momentum.
Improvements in 2018 analysis

Collimator was installed part way through the 2018 run so 2018 sample split into “old-coll” and “new-coll” subsamples
➢ Different selections used for each subsample.

Track extrapolation to the collimator in sample of upstream events (data):

Red boxes = collimator coverage.
Blue boxes = last beam line dipole.
Black boxes = cut regions and background validation.
Final improvement was the enlargement of the second signal region, made possible due to optimised kinematic cuts.

In 2016/2017, both signal regions went up to a $\pi^+$ momentum of 35 GeV/c.

In 2018, R2 could be increased to 45 GeV/c.
2018 data after signal selection

Control and signal regions still blinded!
The number of expected $K_{\pi\nu\nu}$ events is:

$$N_{\pi\nu\nu}^{\text{exp}} = N_{\pi\pi} \varepsilon_{\text{trigger}} \varepsilon_{RV} \frac{A_{\pi\nu\nu} BR(\pi\nu\nu)}{A_{\pi\pi} BR(\pi\pi)}$$

where $N_{\pi\pi}$ is the number of $K^+ \to \pi^+ \pi^0$ events (normalisation channel), $\varepsilon_{\text{trigger}}$ and $\varepsilon_{RV}$ are the trigger and random veto efficiency and $A_{\pi\nu\nu}$ and $A_{\pi\pi}$ are the signal and normalisation acceptances.

Can define the single event sensitivity as:

$$SES = \frac{BR(\pi\nu\nu)}{N_{\pi\nu\nu}^{\text{exp}}}$$

i.e. the branching ratio if one signal event was observed.

### Table

<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>$\varepsilon_{\text{PNN}}$</td>
<td>0.89 ± 0.05</td>
<td>0.89 ± 0.05</td>
</tr>
<tr>
<td>$\varepsilon_{\text{trig}}$</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>

Total number of expected $K_{\pi\nu\nu}$ events = $7.58 \pm 0.40 \pm 0.75_{\text{ext}}$
Single event sensitivity (2018)

The number of expected $K_{\pi\nu\nu}$ events is:

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

where $N_{\pi\pi}$ is the number of $K^+ \rightarrow \pi^+ \pi^0$ events (normalisation channel), $\epsilon_{\text{trigger}}$ and $\epsilon_{RV}$ are the trigger and random veto efficiency and $A_{\pi\nu\nu}$ and $A_{\pi\pi}$ are the signal and normalisation acceptances.

Can define the single event sensitivity as:

$$SES = \frac{BR(\pi\nu\nu)}{N_{\pi\nu\nu}^{exp}}$$

i.e. the branching ratio if one signal event was observed.

<table>
<thead>
<tr>
<th>SES error budget</th>
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<tbody>
<tr>
<td>Trigger efficiency</td>
<td>5%</td>
</tr>
<tr>
<td>MC acceptance</td>
<td>3.5%</td>
</tr>
<tr>
<td>Random veto</td>
<td>2%</td>
</tr>
<tr>
<td>Background (normalisation)</td>
<td>0.7%</td>
</tr>
<tr>
<td>Instantaneous intensity</td>
<td>0.7%</td>
</tr>
<tr>
<td>Total</td>
<td>6.5%</td>
</tr>
</tbody>
</table>

By design, some systematics cancel: PID, detector inefficiencies, kaon ID, beam related acceptance losses.
**Total expected background (2018)**

<table>
<thead>
<tr>
<th>Background</th>
<th>2018 data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0$</td>
<td>0.75(4)</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+\nu$</td>
<td>0.49(5)</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^-e^+\nu$</td>
<td>0.50(11)</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^+\pi^-$</td>
<td>0.24(8)</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\gamma\gamma$</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^0l^+\nu$</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Upstream</td>
<td>3.30$^{+0.98}_{-0.73}$</td>
</tr>
<tr>
<td>Total</td>
<td>5.28$^{+0.99}_{-0.74}$</td>
</tr>
</tbody>
</table>

Background expectations validated in control regions using a blind procedure.

Expected SM signal = $7.58 \pm 0.40_{syst} \pm 0.75_{ext}$
2018 data before unblinding
2018 data after unblinding

17 events observed!

NA62 Preliminary
Run 1 results

Maximum likelihood fit conducted using signal and background expectation in sub-samples based on different hardware configurations.

The sub-samples (categories):
- 2018_S1 ~20% of the 2018 dataset, integrated over momentum.
- 2018_S2 ~80% of the 2018 dataset, 5 GeV/c wide bins from 15-45 GeV/c.
- 2016 and 2017 datasets, integrated over momentum, added as separate categories.

NA62 Run 1 (2016+2017+2018) result (68% CL):

\[ BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4\,\text{stat}} \pm 0.9\,\text{syst}) \times 10^{-11} \] (3.4σ significance and within 1σ of SM)
Comparison with world data

**Graphical Description**

- **BR(K^+ → π^+π^-)**
  - Logarithmic scale ranging from $10^{-4}$ to $10^{-11}$
  - Data points for different experiments:
    - **Camerini**
    - **Klems**
    - **Cable**
    - **Asano**
    - **E787**
    - **E787+E949**
    - **NA62** Preliminary

- **Year of Publication**
  - Spanning from 1960 to 2020

**Legends**

- **Experimental upper limit @ 90 % CL**
- **Experimental measurement**
- **Theoretical prediction**

**References**

- [JHEP 06 (2021) 093]
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The $\pi^0$ Dalitz decay

- In 1951 at the University of Birmingham, the $\pi^0$ Dalitz ($\pi_0^D$) decay was hypothesised by Richard Dalitz.

- Instead of decaying to two real photons (most common way), one photon is virtual and produces an electron-positron pair:

\[ \pi^0 \to e^+e^-\gamma \]

- The decay rate depends on the electromagnetic transition form factor $F(x)$, given by QCD in the SM. A form factor describes the underlying physics of the interaction by providing the momentum dependence of the matrix element. It can be measured by comparing the point-like ($p - l$) QED calculation to the rate observed in real life.

\[ \frac{d\Gamma}{dq^2} = \left. \frac{d\Gamma}{dq^2} \right|_{p-l} |F(q^2)|^2 \]

$q =$ four-momentum transfer

<table>
<thead>
<tr>
<th>Decay</th>
<th>PDG branching ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0 \to \gamma\gamma$</td>
<td>$98.823 \pm 0.034$</td>
</tr>
<tr>
<td>$\pi^0 \to e^+e^-\gamma $</td>
<td>$1.174 \pm 0.035$</td>
</tr>
<tr>
<td>$\pi^0 \to e^+e^-e^+e^-$</td>
<td>$(3.34 \pm 0.16) \times 10^{-5}$</td>
</tr>
<tr>
<td>$\pi^0 \to e^+e^-$</td>
<td>$(6.46 \pm 0.33) \times 10^{-8}$</td>
</tr>
</tbody>
</table>
The $\pi^0$ Dalitz decay

- Convenient to introduce two kinematic variables ($M_{ee}$ is the $e^+e^-$ invariant mass; $p$ are four momenta):

$$x = \left( \frac{M_{ee}}{m_{\pi^0}} \right)^2 = \frac{(p_{e+} + p_{e-})^2}{m_{\pi^0}^2}, \quad y = \frac{2p_{\pi^0} \cdot (p_{e+} - p_{e-})}{m_{\pi^0}^2 (1 - x)}$$

- The leading order decay rate is then given by:

$$\frac{d^2\Gamma^{LO}(\pi^0_D)}{dxdy} = \Gamma(\pi^0 \rightarrow \gamma\gamma) \frac{\alpha}{4\pi} \frac{(1 - x)^3}{x} \left(1 + y^2 + \frac{r^2}{x}\right) |\mathcal{F}(x)|^2$$

- But what about next-to-leading order? Require radiative corrections, leading to a correction $\delta$ to the LO term:

$$\frac{d^2\Gamma(\pi^0)}{dxdy} = \frac{d^2\Gamma^{LO}(\pi^0_D)}{dxdy} (1 + \delta(x, y))$$

- Three sources of radiative corrections have been investigated thus far: virtual, one-photon-irreducible and bremsstrahlung. The radiative correction function $\delta$ can be split into components depending on their origin:

$$\delta = \delta^{\text{virt}} + \delta^{1\gamma IR} + \delta^{BS}$$
Types of radiative correction

- Virtual

- One-photon irreducible

- Bremsstrahlung
Size of the radiative corrections

At the extremes of the $x$ and $y$ distributions, the radiative corrections can alter the LO decay rate by up to 40%.

Hence very important to account for correctly!
Size of the radiative corrections

The virtual and bremsstrahlung calculations were completed in the 1970s.

But the one-photon-irreducible component was not included until 2015 (motivated by a new precision $\pi_D^0$ form factor measurement at NA62) [Phys. Rev. D 92, 054027] [J. Phys. Lett. B. (2017) 02042].

The new radiative corrections led to a new SM $B(\pi_D^0)$ with a 0.05% relative uncertainty:

$$B(\pi_D^0)_{SM} = (1.1836 \pm 0.0006)\%$$

This is very precise compared to the current PDG value that has a 3% relative uncertainty:

$$B(\pi_D^0)_{PDG} = (1.174 \pm 0.035)\%$$
Most recent $B(\pi^0_D)$ measurement

There has actually been a more precise measurement of $B(\pi^0_D)$ but it is excluded from the PDG average.

It was published by the KTeV collaboration in 2019 [Phys. Rev. D 100, 032003], based on data taken in 1999:

$$B(\pi^0_D)_{KTeV} = (1.1559 \pm 0.0116)\%$$

This measurement has a 1% uncertainty and is $2.4\sigma$ from the SM calculation.

It was excluded from the PDG average because the measurement was done in the kinematic range $M_{ee} > 15$ MeV/c and then extrapolated to the full $M_{ee}$ range using the radiative corrections published in 1972 that excluded the one-photon irreducible component (and no error on this extrapolation was accounted for).

Interestingly, using the NA62 Monte Carlo decay generators that include the full radiative corrections, we can correct the KTeV result (this only corrects the extrapolation, not any MC acceptance effects):

$$B(\pi^0_D)_{KTeV, full rad corr} = (1.1749 \pm 0.0118)\%$$

which is within $1\sigma$ of the SM calculation.
Motivation for a new $B(\pi^0_D)$ measurement

Lots of motivations!
- Since the most recent theoretical advances of the SM $B(\pi^0_D)$ calculation, there has not been an experimental branching ratio measurement that includes the most recent radiative corrections.

- It is used as normalisation for several rare $\pi^0$ decay measurements:
  - Dominates uncertainty on $B(\pi^0 \rightarrow e^+e^-e^+e^-)$
  - Largest source of uncertainty on $B(\pi^0 \rightarrow e^+e^-)$

- It is also starting to limit measurements in the rare kaon sector:
  - $K^+ \rightarrow \pi^+ee^-$
  - $K^\pm \rightarrow \pi^\pm\pi^0e^+e^-$
  - $K_{L,S} \rightarrow \pi^+\pi^-e^+e^-$

Can NA62 produce a new, precise, measurement of $B(\pi^0_D)$ that includes all radiative corrections?
**$B(\pi_D^0)$ analysis strategy at NA62**

Best decay chain to use at NA62: $K^+ \to \pi^+\pi^0$ ($\sim 20\%$ BR) with $\pi^0 \to e^+e^-\gamma$ ($\sim 1\%$ BR).

The $\pi_D^0$ decay is not rare meaning statistics shouldn’t be a problem! Hence want to reduce systematics as much as possible.

- Normalise the measurement using $K^+ \to \pi^+\pi^0$ with $\pi^0 \to \text{anything}$. The signal selection can thus be a stricter version of the normalisation selection, leading to systematics cancellation.
- Use as few detectors as possible in the analysis.
- Use the minimum-bias trigger (requires a signal in the NA48-CHOD, akin to the presence of a charged particle; has a downscaling of 400 in Run 1).

Notation used in the following slides:

$$\epsilon = \frac{N_{\pi_D^0}}{N_\pi^0} = \text{ratio between the number of } \pi_D^0 \text{ events (signal) and the number of } \pi^0 \text{ events (normalisation).}$$
$B(\pi^0_D)$ analysis strategy at NA62

- To actually do the measurement, vary $B(\pi^0_D)$ in the MC and calculate the expected value of $\epsilon$ given some value of $B(\pi^0_D)$:
  \[ \text{Exp}(\epsilon) = \frac{N_{\pi^0_D}}{N_{\pi^0}} \]
  - Plot $\text{Exp}(\epsilon)$ against $B(\pi^0_D)$ and perform a linear fit.
  - Using the fit, find the measured $B(\pi^0_D)$ given the measured value of $\epsilon$ from data, as shown by the solid line on the plot:
    \[ \epsilon_{data} = \frac{N^\text{data}_{\pi^0_D}}{N^\text{data}_{\pi^0}} \]
  - Statistical error on the measured $\epsilon$ is converted to a statistical error on $B(\pi^0_D)$. 

Plot shown for demonstration only!
**B(π⁺D⁰) analysis selection**

### Normalisation ($K^+ \rightarrow \pi^+ \pi^0_{\text{everything}}$) selection:
- Reconstruction of exactly one $\pi^+$ track that crosses the beam axis within the decay volume
- $K^+ - \pi^+$ time matched
- $\pi^+$ ID and $\mu^+$ rejection
- Kinematics ($m_{\text{miss}}^2 = (P_K - P_{\pi})^2$; also defines signal region)

### Signal ($K^+ \rightarrow \pi^+ \pi^0_D$) selection:
- Reconstruction of exactly one $\pi^+$ track that crosses the beam axis within the decay volume
- $K^+ - \pi^+$ time matched
- $\pi^+$ ID and $\mu^+$ rejection
- Kinematics ($m_{\text{miss}}^2 = (P_K - P_{\pi})^2$; also defines signal region)
- Decay vertex has three tracks, one of which is the $\pi^+$ found in the normalisation selection
- Other two tracks:
  - $e^\pm$ ID
  - Separated at STRAW (to remove $\gamma$ that undergo conversion in the STRAW gas)
  - In-time with the $\pi^+$ track

N.B. No reconstruction of the photon is carried out in an attempt to reduce the number of detectors used in the analysis.
Due to the high intensity nature of NA62 and the (relatively, compared to other measurements conducted) large branching ratio we’re trying to measure, pileup plays a very important role in the analysis.

Without any pileup treatment, find very poor data/MC agreement.

To properly simulate pileup, inject randomly chosen MC events from a difference MC sample at the reconstruction stage. This sample contains a beam that is not forced to decay (hence includes decays, inelastic scattering, kaons that pass straight through...).

This provides a much better pileup simulation than the traditional approach of injecting hits into the detectors.
For the $B(\pi^0_D)$ measurement, we need (at least) two data points in order to perform the linear fit. Let’s stick with only two for now...

What value for $B(\pi^0_D)$ should be used for each point?

- Want to minimise the distance between the points so that the linear approximation holds.
- Want to minimise extrapolation.

Hence, have one point at the PDG $B(\pi^0_D)$. Where is best for the second point?
MC samples

With one point at the PDG $B(\pi^0_D)$. Where is best for the second point?

➢ Can estimate the $B(\pi^0_D)$ and its uncertainty for different positions by scaling the $N_{\pi^0_D}$ observed.

➢ Systematic error on $B(\pi^0_D)$ from the fit uncertainties stops reducing once we reach $B(\pi^0_D) \sim 0.02$ (approx. twice the PDG value).

➢ To keep in-line with the linear approximation, use 0.02 as the second data point.
MC samples

- The MC sample used is a combination of the 6 main $K^+$ decay modes (with $\pi^0\gamma\gamma$ and $\pi^0_D$ too) (more details on this in back-up).

- With this MC sample, only $\sim 0.2\%$ of the events will be $K^+ \rightarrow \pi^+ \pi^0_D$ decays due to suppression by the branching ratio.

- Also have suppression by the signal acceptance.

- This means that to obtain a 1% statistical error on a single data point, we require 1 billion MC events
  - With the current NA62 MC samples, we have 800M already available.
  - Leads to a systematic uncertainty on $B(\pi^0_D)$ from the fit of $\sim 1\%$.
Expected statistical and systematic errors

Statistical error from data on $B(\pi^0_D)$ is expected to be sub-dominant
➢ With $10^{12}$ $K^+$ decays in Run 1, expect $O(10^5)$ $\pi^0_D$ decays in the final signal sample $\Rightarrow \sigma_{stat} \sim 0.3\%$.

Systematic errors expected to be dominant
➢ Assuming 1 billion MC events are available, the systematic error from the fit uncertainties is expected to be $\sim 1\%$.
➢ This analysis is also unusual in that the signal and normalisation decays have different numbers of charged particles in the final state. The track reconstruction efficiency (three tracks vs. one track) is thus expected to play a vital role. Initial studies suggest a systematic error of $\sim 0.5\%$.
➢ Also $e\pm$ PID, trigger... (expected to be less than that above but studies in progress)

$A B(\pi^0_D)$ measurement at NA62 should hence be able to improve on the 3% PDG precision.
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Conclusions and the future of NA62
Conclusions

NA62 has collected $6 \times 10^{12}$ $K^+$ decays in flight during Run 1, with multiple world leading analyses taking place.

Summary of this talk:

➢ 20 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ candidates observed in Run 1, corresponding to a signal significance of 3.5$\sigma$ [JHEP 06 (2021) 093].
➢ A $B(\pi^0_D)$ measurement at NA62 should be able to incorporate the most up-to-date radiative corrections as well as improve on the current PDG average.

Large variety of other measurements have been/are being conducted at NA62:

➢ Rare decay and precision measurements (e.g. $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ [ICHEP 2020 proceedings]).
➢ Exotic searches of e.g. HNL in $K^+ \rightarrow l^+ N$ [PLB 807 (2020) 135599, PLB 816 (2021) 136259].
➢ Searches for forbidden decays e.g. LFV and LNV [Phys. Rev. Lett. 127, 131802 (2021)].

NA62 Run 2 started in July 2021 and will continue until LS3. Improvements relative to Run 1:

➢ Higher intensity (70% -> 100%).
➢ 4th GTK station added.
➢ Three new veto counters placed upstream or downstream of decay region.
Back-up
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ opened signal regions
\( K^+ \rightarrow \pi^+ \nu \bar{\nu} \) opened signal regions
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ re-interpreted as $K^+ \rightarrow \pi^+ X$

Peak search performed, looking for peak at $m_X^2$. 

[Ref: JHEP 06 (2021) 093]
\[ K^+ \rightarrow \pi^+ \nu \bar{\nu} \text{ re-interpreted as } K^+ \rightarrow \pi^+ X \]

Interpretation if X is a dark-sector scalar, S, which mixes with the Higgs boson according to the mixing parameter \( \sin^2 \theta \).
$\pi^0_D$ analysis signal regions

Normalisation

Signal

WIP: figures produced with ~40% of total MC available
Pileup effects

Both features caused by detector deadtime, causing the selected track to be associated with a hit at an earlier time. Without simulation of this pileup effect, find very poor data/MC agreement.

Altered $\pi^0$ selections used to produce these plots.
How much MC is required and what type of MC is required?

Traditionally in NA62, one MC sample contains one decay mode, the analysis is run on that one decay mode and then multiple MC samples are combined by normalising them with respect to each other using the acceptances and branching ratios.

However, the normalisation ($\pi^0$) and signal ($\pi^0_D$) decays are included in the MC sample used to inject pileup at the reconstruction stage (they have to be to obtain a proper simulation).

- This means that there are normalisation/signal decays present in non-signal MC samples (e.g. $\pi^0_D$ events pass the selection in a $K^+ \rightarrow \mu^+ \nu$ sample), leading to a large over-estimate in the acceptance, making it impossible to correctly normalise each MC sample correctly with respect to each other after running the analysis.

Normalisation decays present in other MC samples.
MC samples in $\pi^0_D$ analysis

Hence need to combine all the MC samples required into a single sample, in the correct proportions (based on BR). This is equivalent to normalising before we run the analysis, rather than after.

- However, this has the negative side-effect of limiting the statistical precision.
- This mixture of MC samples will be referred to as “mixed MC”.
- Colour in histograms now represents the true decay mode that was selected (rather than the sample type) and there are no problems with normalisation.