Recent results and prospects from NA62

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on behalf of the NA62 collaboration

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

Outline

- Measurement of the $\pi^0$ transition form factor from 2007 data
- Status and prospects for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
NA62 high-intensity facility to study rare kaon decays

Kaon Physics at CERN SPS

'82-'92 NA31: Direct CPV in $K^0_{L,S}$

'97-'01 NA48: Direct CPV in $K^0_{L,S}$

'02 NA48/1: $K_s$ rare decays

'03-'04 NA48/2: $K^{\pm}$ CP violation, semileptonic, low energy QCD

'07-'08 NA62: lepton universality $K^\pm_{e2}/K^\pm_{\mu2}$ (using the NA48 apparatus)

2014- NA62: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
Other physics opportunities can be studied at NA62

- **Standard Kaon Physics**
  - $\chi$PT studies: $K^+ \to \pi^+ \gamma\gamma$, $K^+ \to \pi^+ \pi^0 e^+ e^-$, $K^+ \to \pi\pi l^+\nu$
  - Lepton Universality studies: $R_K = \Gamma(K^+ \to e^+\nu)/\Gamma(K^+ \to \mu^+\nu)$

- **LFV/LNV in Kaon decays**
  - $K^+ \to \pi^+ \mu^+\mu^-$, $K^+ \to \pi^- \mu^+ e^+$, $K^+ \to \pi^- l^+ l^+$

- **Heavy neutrino searches**
  - $K^+ \to l^+ \nu_H$
  - $\nu_H$ (from K, D decays) $\to \pi^\pm l^\mp$

- **$\pi^0$ decays**
  - $\pi^0 \to$ invisible, $\pi^0 \to 3\gamma$ ($4\gamma$), $\pi^0 \to \gamma U$

- **Dark sector searches**
  - Long living dark photon (from prompt mesons decays) $\to l^+ l^-$
  - Long living axion-like (produced in beam-dump config.) $\to \gamma \gamma$
NA62 2007 data taking using the NA48 apparatus

- Main goal: \( R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2}) \)  

- Simultaneous \( K^\pm \) beams,  
  \( P_K = (74.0 \pm 1.4) \) GeV/c

- Main trigger: electron from \( K_{e2} \)  
  → efficient for \( \pi_0^D \) decays

Main detectors:

- Liquid Krypton EM calorimeter  
  high granularity, quasi-homogeneous  
  \( \sigma_E/E = 3.2%/E^{1/2} \oplus 9%/E \oplus 0.42% \)

- Scintillator hodoscope (2 planes)  
  fast trigger, \( \sigma_t = 150 \) ps

- Magnetic spectrometer (4 DCHs)  
  4 views/DCH: redundancy ⇒ efficiency  
  \( \sigma_p/p = 0.48% \oplus 0.009%p \) (\( p \) in GeV/c)
\( \pi^0 \) transition form factor (TFF)

\( K^\pm \) decaying in flight are used as a high-statistics source of tagged neutral pions to study the \( \pi^0 \) Dalitz decay: \( K^+ \rightarrow \pi^+ \pi^0 \rightarrow \pi^+ (\gamma e^+ e^-) \)

The Transition Form Factor \( F(x) \) describes the hadronic contribution at decay vertex

Kinematic variables \( x, y \)

\[
x = \frac{(P_{e+} + P_{e-})^2}{m^2_{\pi^0}} \leq x \leq 1
\]

\[
y = \frac{2P_{\pi^0} \cdot (P_{e+} - P_{e-})}{m^2_{\pi^0} (1 - x)}
\]

\(|y| \leq \beta = \sqrt{1 - r^2/x}

The \( \pi^0 \) TFF enters predictions for the hadronic \( \gamma \gamma \) scattering contribution to \( (g - 2)_\mu \)
Dalitz $x$ spectrum in $\pi^0$ decays

$$\frac{1}{\Gamma(\pi^0_{2\gamma})} \frac{d\Gamma(\pi^0_D)}{dx} = \frac{2\alpha}{3\pi} \frac{(1-x)^3}{x} \left(1 + \frac{r^2}{2x}\right) \sqrt{1 - \frac{r^2}{x}} \left[1 + \delta(x)\right] \left(1 + ax\right)^2$$

Radiative correction

$$\delta(x) = \delta_{\text{virt}}(x) + \delta_{\text{brem}}(x) + \delta_{\gamma \text{ IR}}(x)$$

[Mikaelian and Smith, Phys. Rev D 5 (1972) 1763]

$\alpha = \text{TFF slope parameter}$
Data selection

- 3 charged tracks originating from a common vertex
- one photon in the LKr calorimeter
- full kinematic closure; \( x > 0.01 \)

1.05 \times 10^6 fully reconstructed \( \pi^0 \rightarrow \gamma e^+e^- \) candidates
Theoretical predictions:

- \( a = (2.90 \pm 0.50) \times 10^{-2} \) Chiral Perturbation Theory \([K. Kampf et al., EPJ C46(2006) 191]\)
- \( a = (3.07 \pm 0.06) \times 10^{-2} \) Dispersion Theory \([M. Hoferichter et al., EPJ C74(2014) 3180]\)
- \( a = (2.92 \pm 0.04) \times 10^{-2} \) Two-hadron saturation \([T. Husek et al., EPJ C75(2015) 586]\)

\[ a = (3.70 \pm 0.53_{\text{stat}} \pm 0.36_{\text{syst}}) \times 10^{-2} \]
The $K \to \pi \nu \bar{\nu}$ decay

- FCNC loop processes forbidden at tree level in the SM

- Highest CKM suppression $\Rightarrow$ very sensitive to New Physics

- Theoretically clean: short distance dynamics, no hadronic uncertainties.


\[
B(K^+ \to \pi^+ \nu \bar{\nu}) = (8.39 \pm 0.30) \cdot 10^{-11} \left( \frac{|V_{cb}|}{0.0407} \right)^{2.8} \left( \frac{\gamma}{73.2^\circ} \right)^{0.74} = (8.4 \pm 1.0) \cdot 10^{-11}
\]

\[
B(K_L \to \pi^0 \nu \bar{\nu}) = (3.36 \pm 0.05) \cdot 10^{-11} \left( \frac{|V_{ub}|}{0.00388} \right)^2 \left( \frac{\sin \gamma}{\sin 73.2^\circ} \right)^2 = (3.4 \pm 0.6) \cdot 10^{-11}
\]

- **Experimental measurements**

\[
B(K^+ \to \pi^+ \nu \bar{\nu}) = (17.3^{+11.5}_{-10.5}) \cdot 10^{-11} \quad [\text{Phys.Rev.D77(2008)052003, Phys.Rev.D79(2009)092004}]
\]

\[
B(K_L \to \pi^0 \nu \bar{\nu}) < 2.6 \cdot 10^{-8} \ (90\% \ C.L.) \quad [\text{Phys.Rev.D81 (2010) 072004}]
\]
\( K \to \pi \nu \bar{\nu} \) NP sensitivity (complementary to LHC)

- Models with \( Z' \) gauge boson contribution to FCNC at tree level, sensitive to mass scales beyond those explored by LHC [Buras et al., JHEP 11 (2015) 166]

- Best probe of MSSM non-MFV (still not excluded by recent LHCb data) [Tanimoto and Yamamoto, PTEP 2015, 053B07; Isidori et al., JHEP 08 (2006) 064]


Some theoretical predictions for \( K^+ \to \pi^+ \nu \bar{\nu} \) and \( K_L^0 \to \pi^0 \nu \bar{\nu} \):

- \( Z' \) model, \( M_{Z'} = 500 \) TeV
- Littlest Higgs with T parity
- Randall-Sundrum
The NA62 experiment for $K \to \pi \nu \bar{\nu}$

Primary Goal

- Measurement of $B(K^+ \to \pi^+ \nu \bar{\nu})$ with 10% accuracy by collecting $O(100)$ events over 2 years of data taking

Technique: in-flight $K^+$ decay $\rightarrow$ High momentum kaon

Requirements (with $B \approx B_{SM} \sim 8 \cdot 10^{-11}$)

- Statistics:
  - $10^{13}$ $K^+$ decays (in 2 years)
  - $\sim 10\%$ acceptance
  $\rightarrow$ Kaon beam intensity

- Systematics:
  - $> 10^{12}$ background rejection
  - $< 10\%$ precise background measurement
  $\rightarrow$ Signal purity
NA62 apparatus

Detectors for the Secondary Beam
- Kaon ID (KTAG)
- Beam Tracker (GTK)
- Beam guard ring (CHANTI)

Secondary Beam
- SPS proton
  - 400 GeV
  - $10^{12}$ p/s
  - 3.5 s spill
- Momentum selection & collimation

Kaon Decays
- $\Delta p/p \sim 1\%$
- X,Y Divergence <100$\mu$rad
- K(6%), $\pi$(70%), p(23%)
- Total rate: 750 MHz
- Beam size: 6.0$\times$2.7 cm$^2$

Detectors for decay products
- Charged particle tracker (STRAWs)
- Charged particle time stamping (RICH)
- Photon detector (E.M. Calorimeters)
- Particle ID (RICH, Hadronic Calorimeter)

Decay volume
- Upstream
- Downstream

X, Y Divergence <100$\mu$rad
- K(6%), $\pi$(70%), p(23%)
- Total rate: 750 MHz
- Beam size: 6.0$\times$2.7 cm$^2$

E.M. calorimeters (large angles)
- Hadron calorimeter
- LKr

E.M. calorimeters (small angles)
- Straw Spectrometer
$K \rightarrow \pi \nu \bar{\nu}$ analysis strategy

**Signal signature:**
- incoming $K^+$
- outgoing $\pi^+$ in time with the $K^+$
- nothing else

**Background:** other $K^+$ decays; beam activity

**Experimental principles:**
1. Precise kinematic reconstruction
   \[ m_{\text{miss}}^2 = (P_K - P_\pi)^2 \]
2. PID: upstream $K$, downstream $e/\mu/\pi$
3. Hermetic $\gamma$ detection
4. Sub-ns timing

**Key analysis requirements:**
- Two signal regions in $m_{\text{miss}}^2$
- $15 \text{ GeV/c} < p_\pi < 35 \text{ GeV/c}$
- $65 \text{ m long decay region}$

Expect 45 SM signal events/year, <10 background
Experimental status

- **Beam** commissioned up to nominal intensity
- **Tracking detectors:**
  - Beam tracker (GTK) *partially commissioned*
  - Straw spectrometer *commissioned*
- **Čerenkov detectors:**
  - Beam Kaon ID (KTAG) *commissioned*
  - RICH *commissioned*
- **E.M. calorimeters:** large (LAVs) and small angles *commissioned*
- **Hadronic calorimeters:** MUV1, MUV2, muon veto MUV3 *commissioned*
- **Trigger:**
  - L0 *commissioned*
  - L1/L2 *partially commissioned*
- **Data samples for data quality studies**
  - Low intensity data taken with a minimum bias trigger
  - Samples at half and full intensity taken with a calorimeter trigger
Signal topology and Kaon ID

One track selection (OTS)

▶ Single downstream track
  • matching energy in calorimeters

▶ Beam track matching:
  • the downstream track
  • a $K^+$ signal in KTAG (Kaon ID)

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NA62 results and prospects

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Track origin in the fiducial region

Not Kaon ID

Beam scattering
Kinematics: upstream (GTK) and downstream (STRAWs) spectrometers

Goal: \((10^4 \div 10^5)\) suppression factor for the main kaon decay modes

Resolution on \(m_{\text{miss}}^2\) close to design

\(\sim 10^3\) kinematic suppression in 2015
Downstream PID: RICH + calorimeters

Goal: $\sim 10^7 \pi/\mu$ separation, mainly to suppress $K^+ \rightarrow \mu^+\nu$

RICH - after one track selection

- $80\% \pi^+$ efficiency in RICH with $\sim 10^2 \mu$ suppression
- Simple cut-based analysis on calorimeters $\Rightarrow (10^4 \div 10^6) \mu$ suppression with $(90\% \div 40\%) \pi^+$ efficiency. Room for improvements.
**Photon rejection: e.m. calorimeters**

**Goal:** $\sim 10^8$ rejection for $\pi^0$s from $K^+ \rightarrow \pi^+ \pi^0$

- Calorimeter (forward)
- Calorimeter (small angles)
- Calorimeters (large angles)

- Measured on data using $K^+ \rightarrow \pi^+ \pi^0$
- Selected kinematically
  - $P_{\pi^+} < 35$ GeV/c $\Rightarrow E_{\pi^0} > 40$ GeV
  - $O(10^6)$ rejection already obtained
  - 2015 measurement statistically limited
Conclusions

- Preliminary world best measurement of the $\pi^0$ form factor slope
  \[ a = (3.70 \pm 0.53_{\text{stat}} \pm 0.36_{\text{syst}}) \times 10^{-2} \] (NA62 2007 data)

- Commissioning of NA62 for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is almost completed

- Preliminary study of data taken at low intensity
  - Physics sensitivity for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is in line with design
  - Analysis of data taken at higher intensity is ongoing
  - A further compelling physics program is going to be addressed

- NA62 resumed data taking in May 2016 for a $\sim 200$ days run