Neutral pion form factor measurement at NA62

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on behalf of the NA48/2 and NA62 collaborations

Outline:
1) The NA48/2 and NA62-\(R_K\) experiments at CERN
2) \(\pi^0\) transition form factor measurement from \(\pi^0\) Dalitz decays
3) A related result: search for the dark photon in \(\pi^0\) decays
4) Summary
Kaon experiments at CERN

Jura mountains

SPS

NA48/NA62: centre of the LHC

France

Switzerland

LHC

NA48/1

1997: $\varepsilon'/\varepsilon$: $K_L+K_S$

1998: $K_L+K_S$

1999: $K_L+K_S$ $K_S$ HI

2000: $K_L$ only $K_S$ HI

2001: $K_L+K_S$ $K_S$ HI

2002: $K_S$/hyperons

2003: $K^+/K^-$

2004: $K^+/K^-$

2007: $K^{+}_L/K^{+}_{\mu_2}$ tests

2008: $K^{+}_e/K^{+}_{\mu_2}$ tests

2014: pilot run

2015+: data taking

Earlier: NA31

NA48 discovery of direct CPV

NA48/2

NA62

$R_K$ phase

Geneva airport

KAON decay in flight experiments.
NA62: currently ~200 participants, ~30 institutions

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NA48/2 and NA62-R$_K$ experiments

2003–2007: charged kaon beams, the NA48 detector

Narrow momentum band $K^\pm$ beams: $P_K = 60$ (74) GeV/c, $\delta P_k / P_K \sim 1%$ (rms).

- Maximum $K^\pm$ decay rate $\sim 100$ kHz;
- **NA48/2**: six months in 2003–04;
- **NA62-R$_K$**: four months in 2007.

**Principal subdetectors:**

- Magnetic spectrometer (4 DCHs)
  4 views/DCH: redundancy $\Rightarrow$ efficiency;
  $\delta p/p = 0.48% \oplus 0.009% p$ [GeV/c] (in 2007)

- Scintillator hodoscope (HOD)
  Fast trigger, time measurement (150ps).

- Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi-homogeneous;
  $\sigma_E/E = 3.2%/E^{1/2} \oplus 9%/E \oplus 0.42%$ [GeV];
  $\sigma_x = \sigma_y = 4.2mm/E^{1/2} \oplus 0.6mm$ (1.5mm@10GeV).
**π⁰ Dalitz decay: π⁰_D→e⁺e⁻γ**

Kinematic variables:

\[ x = \frac{(p_e^+ + p_e^-)^2}{m_{π^0}^2}, \quad y = \frac{2 p_{π^0}.(p_e^+ - p_e^-)}{m_{π^0}^2(1 - x)} \]

Differential decay width:

\[ \frac{1}{\Gamma(π^0_{2γ})} \frac{d^2Γ(π^0_D)}{dx dy} = \frac{α}{4π} \frac{(1 - x)^3}{x} \left(1 + y^2 + \frac{r^2}{x}\right) \left(1 + δ(x, y)\right) |F(x)|^2 \]

Radiative corrections

Transition form factor:

\[ F(x) \approx 1 + ax \]

π⁰ decay studies at NA48/2 and NA62 experiments:

- High intensity K± decay in flight experiments.
- Intensive sources of tagged π⁰, mainly via K±→π±π⁰ decays (BR=21%).
- **NA48/2**: three-track trigger; **NA62-R_K**: electron (e±) trigger.
  Both experiments collected large samples of π⁰_D decays.
Radiative corrections are a key issue: larger correction to $d\Gamma/dx$ spectrum than TFF Mikaelian and Smith, PRD5 (1972) 1763: 
~5% correction to $d\Gamma/dx$ slope

Husek, Kampf and Novotny, PRD92 (2015) 054027: further ~0.5% correction to $d\Gamma/dx$ slope

$\frac{d^2\Gamma}{dx dy} = \left(\frac{d^2\Gamma}{dx dy}\right)_0 (1 + \delta(x, y))$

Radiative corrections: $\delta(x, y)$

✓ Husek et al. (2015) computation is used in this analysis;
✓ Crucially, radiative photon emission is simulated.
Transition form factor

Differential decay width:

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

- VMD expectation: TFF slope \( a \approx 0.03 \)
  [L.G. Landsberg, Phys. Rept. 128 (1985) 301]
- Enters hadronic contribution to \((g-2)_\mu\)
  [Knecht, EPJ Web Conf. 118 (2016) 01017]
  [Nyffeler, arXiv:1602.03398]
- Influences the \(\pi^0 \to e^+e^-\) decay rate
  [Husek et al., EPJ C74 (2014) 3010]
- Comparison of TFF slope predictions to a model-independent measurement: important test of the models.
- A difficult measurement: narrow \(q^2\) region accessible \(\to\) small effect.
Kaon decays in the fiducial decay region: \(~2 \times 10^{10}\).

Source of \(\pi^0\) considered: \(K^\pm \rightarrow \pi^\pm \pi^0\) decay (BR=21%).

Reconstructed \(\pi^0_D\) decay candidates, \(x = (m_{ee}/m_\pi)^2 > 0.01\): \(N(K_{2\pi D})=1.05 \times 10^6\).

Despite \(~10\) times smaller sample wrt NA48/2, good for spectrum study:

- minimum bias trigger: low systematics due to trigger efficiency;
- low beam intensity: low systematics due to accidentals.

Reconstructed \(K^\pm\) mass

Reconstructed \(x = (m_{ee}/m_\pi)^2\)

Selection optimized to increase acceptance at high \(x\).
NA62-R\(_K\) preliminary result:

\[ a = (3.70 \pm 0.53\text{\,stat} \pm 0.36\text{\,syst}) \times 10^{-2} \]

\[ \chi^2/\text{ndf} = 52.5/49, \quad p\,-\text{value} = 0.34 \]

First observation (5.8\(\sigma\)) of non-zero TFF slope in the time-like momentum transfer region.

[final result & paper in preparation]
World data: $\pi^0$ TFF slope measurement with $\pi^0_D$ decays

**Geneva-Saclay (1978)**
Fischer et al.

- 30k events

**Saclay (1989)**
Fonvieille et al.

- 32k events

**SINDRUM I @ PSI (1992)**
Meijer Drees et al.

- 54k events

**TRIUMF (1992)**
Farzanpay et al.

- 8k events

**NA62 (2016)**
(preliminary)

- 1M events

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**TFF expectations from theory:**

- **Chiral perturbation theory**
  [Kampf et al., EPJ C46 (2006) 191]
  \[ a = (2.90 \pm 0.50) \times 10^{-2} \]

- **Dispersion theory**
  [Hoferichter et al., EPJ C74 (2014) 3180]
  \[ a = (3.07 \pm 0.06) \times 10^{-2} \]

- **Two-hadron saturation model**
  [Husek et al., EPJ C75 (2015) 586]
  \[ a = (2.92 \pm 0.04) \times 10^{-2} \]

**CELLO measurement:**

Extrapolation of space-like momentum ($\gamma\gamma \rightarrow \pi^0$) region data fit to VMD model:

\[ a = (3.70 \pm 0.53_{\text{stat}} \pm 0.36_{\text{syst}}) \times 10^{-2} \]

**NA62-R_K preliminary result:**

\[ a = (3.70 \pm 0.53_{\text{stat}} \pm 0.36_{\text{syst}}) \times 10^{-2} \]
Two exclusive selections

\( \bar{K}^\pm \rightarrow \pi^\pm \pi^0_D \) selection:
- \(|m_{\gamma ee} - m_K| < 20 \text{ MeV}/c^2\);
- \(|m_{\gamma ee} - m_{\pi^0}| < 8 \text{ MeV}/c^2\);
- no missing momentum.

\( \bar{K}^\pm \rightarrow \pi^0_D \mu^\pm \nu \) selection:
- \( m_{\text{miss}}^2 = (P_K - P_\mu - P_{\pi^0})^2 \) compatible with zero;
- \(|m_{\gamma ee} - m_{\pi^0}| < 8 \text{ MeV}/c^2\);
- missing total and transverse momentum.

Reconstructed \( \pi^0_D \) decay candidates:
- \( N(\bar{K}^2\pi) = 1.38 \times 10^7 \),
- \( N(\bar{K}_{\mu 3D}) = 0.31 \times 10^7 \),
- total \( = 1.69 \times 10^7 \).

\( \bar{K}^\pm \) decays in fiducial region:
\( N_K = (1.57 \pm 0.05) \times 10^{11} \).
NA48/2: search for DP signal

UL on the number of DP candidates

UL on BR($\pi^0 \rightarrow \gamma A'$) at 90% CL

BR($A' \rightarrow e^+e^-$) = 1 assumed

Local signal significance never exceeds 3$\sigma$: no DP signal observed.

The obtained limits are background limited: 2–3 orders of magnitude above single event sensitivity.

DP mass scan:
- prompt decay chain $\pi^0 \rightarrow \gamma A'$, $A' \rightarrow e^+e^-$;
- range: 9 MeV/c$^2$ ≤ $m_{A'}$ ≤ 120 MeV/c$^2$;
- mass step 0.5$\sigma_m$, signal window ±1.5$\sigma_m$;
- DP mass hypotheses tested: 404;
- global fit for the background shape.
NA48/2: dark photon exclusion

\[ \mathcal{B}(\pi^0 \to \gamma A') = 2\varepsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \mathcal{B}(\pi^0 \to \gamma \gamma) \]

- Improvement on the existing limits in the \( m_{A'} \) range \( 9-70 \text{ MeV/c}^2 \).
- Most stringent limits are at low \( m_{A'} \) (kinematic suppression is weak).
- Sensitivity limited by irreducible \( \pi^0_D \) background: upper limit on \( \varepsilon^2 \) scales as \( \sim(1/N_K)^{1/2} \), modest improvement with larger data samples.
- If DP couples to quarks and decays mainly to SM fermions, it is ruled out as the explanation for the anomalous \( (g-2)_\mu \).
- Sensitivity to smaller \( \varepsilon^2 \) with displaced vertex analysis: to be investigated.
Kaon decay in flight experiments at CERN provide large samples of tagged neutral pions.

A preliminary result: [paper in preparation]
- TFF slope: \( a = (3.70 \pm 0.64) \times 10^{-2} \).
- First observation of non-zero TFF slope in the time-like region.
- Triggered progress in radiative corrections to \( \pi^0_D \) decays, which is crucial for this measurements.
  [Husek et al., PRD92(2015)054027]

Final result: dark photon search in \( \pi^0 \) decays [PLB746 (2015) 178]
- Improved limits (down to \( \varepsilon^2 = 2 \times 10^{-7} \)) in the 9–70 MeV/c\(^2\) mass range.
- The whole region favoured by \((g-2)_{\mu}\) is excluded now, assuming DP decays into SM fermions only.