Recent results from NA48/2 (LFV, DP) and NA62 (Neutral Pion Form Factor) 

On behalf of the NA62 collaboration

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XIIIth International Conference on Heavy Quarks and Leptons, 24-05-2016
NA48/2 - NA62_{R_K} experiment

Lepton Number Violating (LNV) decay $K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm$

Search for resonances in $K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm$ and $K^\pm \rightarrow \pi^\pm \mu^+ \mu^-$

Dark Photon (DP) searches in $\pi^0$ decay

$\pi^0$ electromagnetic transition form factor (TFF) measurement
CERN NA48/NA62 experiments

Jura mountains

Geneva airport

SPS

LHC

Experiments history

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<th>Earlier</th>
<th>Experiment</th>
<th>Year(s)</th>
<th>Description</th>
</tr>
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<td>NA31</td>
<td></td>
<td></td>
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<tr>
<td>NA48</td>
<td>((K_S/K_L))</td>
<td>1997</td>
<td>(Re(\varepsilon'/\varepsilon)) Discovery of direct CPV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2001</td>
<td></td>
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<tr>
<td>NA48/1</td>
<td>((K_S/)hyperons))</td>
<td>2002</td>
<td>Rare (K_S) and hyperon decays</td>
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<tr>
<td>NA48/2</td>
<td>((K^+/K^-))</td>
<td>2003-2004</td>
<td>Direct CPV, Rare (K^+/K^-) decays</td>
</tr>
<tr>
<td>NA62_{R_K}</td>
<td>((K^+/K^-))</td>
<td>2007-2008</td>
<td>(R_K = K^\pm/e^-_2/K^\pm/\mu^-_2)</td>
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<tr>
<td>NA62</td>
<td>((K^+))</td>
<td>2014</td>
<td>(K^+ \rightarrow \pi^+\nu\bar{\nu}), Rare (K^+) and (\pi^0) decays</td>
</tr>
</tbody>
</table>

Kaon decay in flight experiment

NA62: currently \(~200\) participants, \(29\) institutions from \(13\) countries
Experimental Setup (NA48/2 – NA62\( _{Rk} \))

- **Principal subdetectors**
  - Scintillator hodoscope (HOD)
  - Low-level trigger, time measurement (150 ps)
  - Magnetic spectrometer (4DHCs)
    - 4 views/DCH high efficiency
    - \( \sigma_p/p = 1.02\% \oplus 0.044\% \cdot p \) [GeV/c] NA48/2
      \[ = 0.48\% \oplus 0.009\% \cdot p \] [GeV/c] NA62\( _{Rk} \)
  - Liquid Krypton EM calorimeter (LKr)
    - High granularity, quasi-homogeneous
    - \( \sigma_E/E = (3.2/\sqrt{E} \oplus 9/E \oplus 0.42)\% \) [E in GeV]
    - \( \sigma_x = \sigma_y = (4.2/\sqrt{E} \oplus 0.6) \) mm [E in GeV]
      \[ (1.5 \text{ mm @ 10 GeV}) \]

**NA48/2**
- \( P_K = 60 \pm 3 \) GeV/c
- 3-track vertex trigger
- Simultaneous \( K^+ / K^- \) beam

**NA62\( _{Rk} \)**
- \( P_K = 74 \pm 2 \) GeV/c
- \( K_{e2} \) trigger
- Alternate \( K^+ / K^- \) beam
LNV in the $K^\pm \to \pi \mu \mu$ decays

- **Majorana Neutrinos**
  - Asaka-Shaposhnikov model ($\nu$MSM) [PLB 620 (2005) 17]:
    three sterile neutrinos $N_i$ in the SM to explain Dark Matter ($N_1$, $O$(keV))
    + Baryon Asymmetry and low $\nu$ mass ($N_{2,3}$, $O$(100 MeV – few GeV))
  - Effective vertices with $W^\pm, Z$ and SM leptons with $U$ mixing matrix
  - Production of $N_{2,3}$ in $K^\pm$ decays and $N_{2,3}$ decay for $m_{2,3} < m_K - m_\mu$
    $$K^\pm \to \mu^\pm N, \quad N \to \pi^\pm \mu^\mp$$
  - $\text{BR}(K^\pm \to \mu^\pm N) \times \text{BR}(N \to \pi^\mp \mu^\pm) \sim |U_{\mu 4}|^4$

- **Inflatons**
  - Shaposhnikov-Tkachev model [PLB 639 (2006) 414]:
    $\nu$MSM + real scalar field (inflaton $\chi$) with scale-invariant couplings to explain
    universe homogeneity and isotropy on large scales/structures on smaller scales
  - $\chi$-Higgs mixing ($\theta$), $\chi$-Higgs coupling $\to$ universe reheating, $\tau_\chi \sim (10^{-8} - 10^{-12})$
  - Production in Kaon decays:
    $$m_\chi < 354 \text{ MeV}/c^2 \text{ and } \text{BR}(K^\pm \to \pi^\pm \chi) = 1.3 \times 10^{-3} \left(\frac{2|\vec{p}_\chi|}{M_K}\right) \theta^2$$

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**Blind analysis:**

- Selection based on simulation of $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ and $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ (background, similar topology)
- 3-track vertex topology, 2 same-sign muons, 1 odd-sign pion, no missing momentum
- First-order cancellation of systematic effects
- Control region: $M_{\pi\mu\mu} < 480$ MeV/$c^2$
- Signal region: $|M_{\pi\mu\mu} - M_K| < 5$ MeV/$c^2$

**Results:**

- Event in Signal Region: $N_{obs} = 1$
- Expected background from MC:
  
  $N_{exp} = 1.163 \pm 0.867_{stat} \pm 0.021_{ext} \pm 0.116_{syst}$
- From Rolke-Lopez statistical method:
  
  $BR(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}) < 8.6 \times 10^{-11}$ @ 90% CL

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LNC: Opposite-Sign Muon Sample

Selection
- Similar to same-sign
  - 3-track vertex, 2 opposite-sign muons, 1 pion, no missing momentum
  - First-order cancellation of systematic effects
  - Signal region: $|M_{\pi\mu\mu} - M_K| < 8 \text{ MeV}/c^2$

Results
- Event in Signal Region: 3489 $K^\pm \rightarrow \pi^\pm \mu^+ \mu^-$ candidates
- Background: $(0.36 \pm 0.10)\%$
- Search for resonances in $M_{\pi\mu}$ and $M_{\mu\mu}$ invariant masses
  - step=$0.5\sigma(M_{res})$ and window=$\pm2\sigma(M_{res})$
  - Limit using Rolke-Lopez from $N_{obs}$ and $N_{exp}$ for each hypothesis
LNV and LNC: Resonances searches

- Search for $K^\pm \rightarrow \mu^\pm N_4 (N_4 \rightarrow \pi^\mp \mu^\pm)$ decays, 284 mass hypotheses
  - 2 possibilities for $M(\pi^\mp \mu^\pm)$, closest to $M_{res}$ chosen
  - Never exceeds $+3\sigma$: no signal observed and UL(BR)$\sim 10^{-10}$ for $\tau < 100$ ps

- Upper limit on $\text{BR}(K^\pm \rightarrow \mu^\pm N_4)\text{BR}(N_4 \rightarrow \pi^\mp \mu^\pm)$
  - $UL(BR) = \frac{UL(N_{sig})}{N_{K*Acceptance}}$

- Statistical significance
  - $z = \frac{(N_{obs} - N_{exp})}{\sigma(N_{obs}) \oplus \sigma(N_{exp})}$

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LNV and LNC: Resonances searches

- **Search for** $K^\pm \to \mu^\pm N_4 (N_4 \to \pi^\mp \mu^\pm)$ **decays**, 284 mass hypotheses
  - 2 possibilities for $M(\pi^\mp \mu^\pm)$, closest to $M_{res}$ chosen
  - Never exceeds $+3\sigma$: no signal observed and UL(BR)$\sim 10^{-10}$ for $\tau < 100$ ps

- **Search for** $K^\pm \to \mu^\pm N_4 (N_4 \to \pi^\pm \mu^\mp)$ **decays**, 280 mass hypotheses
  - Never exceeds $+3\sigma$: no signal observed and UL(BR)$\sim 10^{-9}$ for $\tau < 100$ ps

- **Upper limit on**
  \[ BR(K^+ \to \mu^+ N_4) BR(N_4 \to \pi^\mp \mu^\pm) \]

  \[ UL(BR) = \frac{UL(N_{sig})}{N_K \times Acceptance} \]

- **Statistical significance**
  \[ Z = \frac{(N_{obs} - N_{exp})}{\sigma(N_{obs}) \oplus \sigma(N_{exp})} \]

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LNV and LNC: Resonance searches

- **Search for** \( K^\pm \rightarrow \mu^\pm N_4 (N_4 \rightarrow \pi^\mp \mu^\mp) \)** decays, **284 mass hypotheses**
  - 2 possibilities for \( M(\pi^\mp \mu^\mp) \), closest to \( M_{\text{res}} \) chosen
  - Never exceeds +3\( \sigma \): no signal observed and UL(BR)~\( 10^{-10} \) for \( \tau < 100 \) ps

- **Search for** \( K^\pm \rightarrow \mu^\pm N_4 (N_4 \rightarrow \pi^\pm \mu^\mp) \)** decays, **280 mass hypotheses**
  - Never exceeds +3\( \sigma \): no signal observed and UL(BR)~\( 10^{-9} \) for \( \tau < 100 \) ps

- **Search for** \( K^\pm \rightarrow \pi^\pm X (X \rightarrow \mu^+ \mu^-) \)** decays, **267 mass hypotheses**
  - Never exceeds +3\( \sigma \): no signal observed and UL(BR)~\( 10^{-9} \) for \( \tau < 100 \) ps

- **Upper limit on**
  \[
  \text{BR}(K^\pm \rightarrow \mu^\pm N_4) \times \text{BR}(N_4 \rightarrow \pi^\mp \mu^\mp) 
  \]
  \[
  \text{UL}(\text{BR}) = \frac{\text{UL}(N_{\text{sig}})}{N_{K\text{*Acceptance}}}
  \]

- **Statistical significance**
  \[
  z = \frac{(N_{\text{obs}} - N_{\text{exp}})}{\sqrt{\sigma(N_{\text{obs}}) + \sigma(N_{\text{exp}})}}
  \]

\[z \text{ vs. } M_{\text{res}}\]
Dark Photon Searches


- QED-like interactions with SM fermions
  $$\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$

- Coupling constants and charges generated through kinetic mixing between QED and the new U(1) gauge bosons
  $$\mathcal{L}_{mix} = -\frac{\epsilon}{2} F_{\mu\nu}^{QED} F_{\mu\nu}^{dark}$$

- Motivations:
  - Possible explanation for positron excess in cosmic rays (PAMELA, FERMI, AMS-02) by dark matter annihilation
  - Possible solution to the muon g-2 anomaly

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**Production**

Batell, Pospelov and Ritz, [PRD80 (2009) 095024]

- $\text{BR}(\pi^0 \to \gamma A') = 2\varepsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \text{BR}(\pi^0 \to \gamma\gamma)$
- Mixing parameter $\varepsilon$ and dark photon mass $m_{A'}$
- Loss of sensitivity as $m_{A'}$ approaches the $m_{\pi^0}$ threshold
- For $\varepsilon^2 > 10^{-7}$ and $m_{A'} > 10 \text{ MeV}/c^2$ mean free path is negligible and prompt decay is assumed
- Signature similar to $\pi_D$
  $\pi_D^0 \to \gamma e^+ e^-$; $\pi^0 \to \gamma A'$
  $\Downarrow e^+ e^-$

**Decay**

Batell, Pospelov and Ritz, [PRD79 (2009) 115008]

- Accessible in $\pi^0$ decay, assuming only into SM fermions
  $\Gamma_{A'} \approx \Gamma(A' \to e^+ e^-)$
  $\approx \alpha \varepsilon^2 m_{A'}/3$
- Hadronic decay contribution $m_{A'} > 2m_{\pi^0}$
- **NA48/2 data**: $\sim 2 \times 10^{11} K^\pm$ decays in the fiducial region
- **$\pi/\mu/e$ separation using $E/p$**
- **Selection for $K^\pm \rightarrow \pi^\pm \pi^0_D$**
  - Three-track vertex topology
  - $|m_{\pi\gamma e e} - m_K| < 20 \text{ MeV}/c^2$
  - $|m_{\gamma e e} - m_{\pi^0}| < 8 \text{ MeV}/c^2$
  - No missing momentum
- **Selection for $K^\pm \rightarrow \pi^0_D \mu^\pm \nu$**
  - $|m_{\gamma e e} - m_{\pi^0}| < 8 \text{ MeV}/c^2$
  - No missing mass

- **Sensitivity determined by irreducible $\pi^0$ Dalitz decay (1.2%)**
- **Acceptance for both signature depending on $m_{A'}$ up to 4.5%**
Scan for narrow peaks in $e^+e^-$ invariant mass spectrum

- $\sigma_{m_{ee}} = 0.011 \times m_{ee}$
- Range: $9 \text{ MeV}/c^2 \leq m_{A'} < 120 \text{ MeV}/c^2$
- Variable DP mass step: $\approx 0.5\sigma(m_{A'})$
- Mass-window: $\pm 1.5\sigma(m_{A'})$
- Limits from $N_{obs}$ and $N_{exp}$ for each of the 404 $m_{A'}$ hypotheses

Local signal significance never exceeds $3\sigma$:
- no DP signal is observed.
Improvement on the existing limits in the $m_{A'}$ range $9 - 70$ MeV/$c^2$

Most stringent limits are at low $m_{A'}$ (kinematic suppression is weak)

Sensitivity limited by the irreducible $\pi^0_D$ background, ULs are 2-3 orders of magnitude above SES.

Upper limit on $\varepsilon^2$ scales as $\sim (1/NK)^{1/2}$: modest improvement with larger samples

If DP couples to quarks and decays mainly to SM fermions, it is ruled out as the explanation for the anomalous $(g - 2)_\mu$
\( \pi^0 \) TFF: Dalitz Decay

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

- **Kinematic variables**
  
  \[ x = \frac{(p_{e^+} + p_{e^-})^2}{m_{\pi^0}^2}, \quad y = \frac{2p_{\pi^0} \cdot (p_{e^+} - p_{e^-})}{m_{\pi^0}^2 (1-x)} \]

- **Differential decay width**
  
  \[ \frac{1}{\Gamma(\pi^0_{2\gamma})} \frac{d^2\Gamma(\pi^0_D)}{dxdy} = \frac{\alpha}{4\pi} \frac{(1-x)^3}{x} \left( 1 + y^2 + \frac{r^2}{x} \right) \left( 1 + \delta(x, y) \right) |F(x)|^2 \]

- **Form factor varies slowly:**
  
  \[ \text{Approximation } F(x) \approx 1 + ax \]

- **Slope measured from Dalitz decays from** \( K^\pm \rightarrow \pi^\pm \pi_D^0 \)
  
  \[ \text{Expectation from VMD: } a \approx 0.03 \]
  
  \[ \text{Enters hadronic light-by-blight scattering contribution to } (g - 2)_\mu \]
  
  A. Nyffeler [arXiv:1602.03398]

  \[ \text{Model independent measurement: important test of the theory models} \]
Corrections from NLO differential width encoded in $\delta(x, y)$


Corrections of same magnitude as TFF

New generator with radiative correction and simulation of bremsstrahlung photon.
Select pure $\pi_D^0$ sample from
- 3-track vertex topology
- One photon candidate and max three well reconstructed tracks
- Identification by reconstructed kinematics
  - $115 \text{ MeV}/c^2 < M_{ee\gamma} < 145 \text{ MeV}/c^2$
  - $465 \text{ MeV}/c^2 < M_{\pi^+\pi^0} < 510 \text{ MeV}/c^2$
  - Dalitz variable $y < 1; \quad 0.01 < x < 1$
- Reconstructed Kaon compatible with beam properties and offline L2 and L3 trigger conditions

Build $x$ Dalitz distribution for data and MC (equal population bins)

For each TFF slope value hypothesis, reweight simulated events ($a_{sim} = 0.032$)

$$w(a) = \frac{(1 + ax_{true})^2}{(1 + a_{sim}x_{true})^2}$$

Minimise $\chi^2(a)$ of Data/Simulation wrt. $a$
\( \pi^0 \) TFF: Preliminary Result

**Data sample**
- Kaon decays: \( \sim 2 \times 10^{10} \)
- Fully reconstructed \( \pi^0_D \) events in the signal region \( (x > 0.01) \): \( 1.05 \times 10^6 \)

**Uncertainties**

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<thead>
<tr>
<th>Source</th>
<th>( \delta a \times 10^{-2} )</th>
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<tbody>
<tr>
<td>Statistical – Data</td>
<td>0.49</td>
</tr>
<tr>
<td>Statistical – MC</td>
<td>0.20</td>
</tr>
<tr>
<td>Beam momentum spectrum simulation</td>
<td>0.30</td>
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<tr>
<td>Spectrometer momentum scale</td>
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<tr>
<td>Spectrometer resolution</td>
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<tr>
<td>LKr non-linearity and energy scale</td>
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<tr>
<td>Particle mis-ID</td>
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<tr>
<td>Accidental background</td>
<td>0.08</td>
</tr>
<tr>
<td>Neglected ( \pi^0_D ) sources in MC</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**Fit result illustration**
- Data / MC(a=0) ratio
- 20 equal population bins
- Points in bin barycenters

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

\[
= (3.70 \pm 0.64) \times 10^{-2}
\]

\( \chi^2/\text{n.d.f.}: 52.5/49, \) p-value: 0.34
**Theory expectations**

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

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

- T. Husek et al., EPJ C75 (2015) 12, 586. Two-hadron saturation (THS) model:
  \[ a = (2.92 \pm 0.04) \times 10^{-2} \]

**CELLO measurement:**

- H. J. Behrend et al., Z. Phys. C49 (1991), 401. Extrapolation of space-like momentum region data fit to VMD model:
  \[ a = (3.26 \pm 0.26_{\text{stat}}) \times 10^{-2} \]
Summary

- **LNV decay @ NA48/2**
  - $BR(K^\pm \to \pi^\mp \mu^\mp \mu^\pm) < 8.6 \times 10^{-11}$ at 90% CL

- **Majorana Neutrinos and Inflaton @ NA48/2**
  - $K^\pm \to \mu^\pm N_4(N_4 \to \pi^\mp \mu^\pm)$: UL(BR) of the order of $10^{-10}$ for $\tau < 100$ ps
  - $K^\pm \to \mu^\pm N_4(N_4 \to \pi^\pm \mu^\mp)$: UL(BR) of the order of $10^{-9}$ for $\tau < 100$ ps
  - $K^\pm \to \pi^\pm \chi(\chi \to \mu^+ \mu^-)$: UL(BR) of the order of $10^{-9}$ for $\tau < 100$ ps

- **Dark Photon searches @ NA48/2**
  - Improved limits on DP mixing $\epsilon^2$ in the mass range $9 - 70$ MeV/$c^2$
  - The whole region favoured by $(g - 2)_\mu$ is excluded

- **$\pi_D^0$ electromagnetic TFF slope @ NA62$_{RK}$**
  - $a = (3.70 \pm 0.53_{stat} \pm 0.36_{syst}) \times 10^{-2}$
  - Preliminary model independent result
  - ~1 million fully reconstructed $\pi_D^0$ decays
  - Improves TFF precision in the time-like momentum region

Nicolas Lurkin, HQL2016, 24-05-2016