Recent QCD results from NA48/2

Giuseppina Anzivino
University of Perugia and INFN
on behalf of the NA48/2 Collaboration

QCD 18
Montpellier, July 2-6, 2018
Outline

➔ NA48: a brief history
➔ The NA48/2 experiment
➔ Precise measurement of $K^\pm \rightarrow \pi^0 \ell^\pm \nu$ ($K_{\ell3}$) Form Factors
➔ First observation of the rare decay $K^\pm \rightarrow \pi^\pm \pi^0 e^+e^-$
➔ Summary
Kaons at CERN

NA48
Main goal: Search for direct CPV
Measurement of $\varepsilon'/\varepsilon$
Beams: $K_L / K_S$

NA48/1
Main goal: Rare $K_S$ decays and hyperon decays, CPV tests
Beams: $K_S$

NA48/2
Main goal: Search for direct CPV
Charge asymmetry measurement
Beams: $K^+ / K^-$

NA31 (1984-1990)
First evidence of direct CPV
Beams: $K_L / K_S$

NA62

NA62 - $R_K$
Main goal: Test of $\mu$-$e$ universality $R_K$ measurement
Beams: $K^+ / K^-$

NA62
Main goal: Rare kaon decays, measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
Beam: $K^+$

4-7-2018
Giuseppina Anzivino@QCD18
The NA48/2 experiment at CERN

Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Wien ~ 100 participants, 15 institutions, 8 countries

4-7-2018  Giuseppina Anzivino@QCD18
400 GeV proton beam on a beryllium target
60 ± 3 GeV Kaon momentum (~7x10^{11} ppp)
Simultaneous, unseparated focused beams

Similar acceptance for K^+ and K^- decays
flux ratio K^+ / K^- = 1.8
Main detector components:

- **Magnetic spectrometer (4 DCHs):**
  4 views: redundancy ⇒ efficiency
  \[ \sigma(p)/p = 1.02\% + 0.044\% \ p [\text{GeV}/c] \]
  + dipole magnet (257 MeV/c kick)

- **Hodoscope:** fast trigger and precise time measurement (150ps)

- **Liquid Krypton e.m. calorimeter:**
  High granularity, quasi–homogeneous
  \( 10 \text{ m}^3 \ (\sim 22 \text{ t}), 1.27 \text{ m (27 } X_0) \)
  \[ \sigma(E)/E = 3.2\% /\sqrt{E} + 9\% /E + 0.42\% [\text{GeV}] \]

- **Hadron calorimeter, photon vetos, muon and veto counters**
Measurement of
$K^\pm \rightarrow \pi^0 \ell^\pm \nu (K_{\ell 3})$ Form Factors
**K_{l3} form factors - theory**

- The kaon semileptonic decays $K^\pm \rightarrow \pi^0 l^\pm \nu (K_{l3})$ contribute to the precise determination of the CKM matrix element $|V_{us}|$.

- Defining the kinematic factors $A$, $B$ and $C$, the differential decay width can be written:

\[
A = m_K \left( 2E_l^* E_\nu^* - m_K \left( E_{\pi, \text{max}}^* - E_\pi^* \right) \right) + m_l^2 \left( \frac{\left( E_{\pi, \text{max}}^* - E_\pi^* \right)}{4 - E_\nu^*} \right)
\]

\[
B = m_l^2 \left( E_\nu^* - \left( \frac{E_{\pi, \text{max}}^* - E_\pi^*}{2} \right) \right)
\]

\[
C = m_l^2 \left( \frac{E_{\pi, \text{max}}^* - E_\pi^*}{4} \right)
\]

\[
\frac{d^2\Gamma(K_{l3})}{dE_l^*dE_\pi^*} = \rho(E_l^*, E_\pi^*) = N \left( A |f_+(t)|^2 + B f_+(t) f_-(t) + C |f_-(t)|^2 \right)
\]
**K_{l3} form factors - theory**

- $K_{l3}$ decays are described by two form factors $f_+(t)$ and $f_-(t)$, which enter in the matrix element.
- $f_+(t)$ and $f_-(t)$ are vector form factors.
- The scalar form factor, $f_0(t)$ is given by

$$f_0(t) = f_+(t) + \frac{t}{(M_K^2 - M_\pi^2)} f_-(t)$$

The FF can be parameterized in several ways:

<table>
<thead>
<tr>
<th>FF parameterization</th>
<th>$f_+(t, \text{ parameters})$</th>
<th>$f_0(t, \text{ parameters})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadratic (linear for $f_0(t)$)</td>
<td>$1 + \lambda' t/m^2_\pi + \frac{1}{2} \lambda''(t/m^2_\pi)^2$</td>
<td>$1 + \lambda'<em>0 t/m^2</em>\pi$</td>
</tr>
<tr>
<td>Pole</td>
<td>$M^2_V / (M^2_V - t)$</td>
<td>$M^2_S / (M^2_S - t)$</td>
</tr>
<tr>
<td>Dispersive *</td>
<td>$\exp(\Lambda_+ + H(t)) t/m^2_\pi$</td>
<td>$\exp(\ln C - G(t)) t/(m^2_K - m^2_\pi)$</td>
</tr>
</tbody>
</table>

**Data selection**

**Common cuts**
- $\gamma$ isolation: distance $> 15$ cm from charged track extrapolation
- $\pi^0$ reconstruction
  - $2 \gamma$ in time (5 ns) on LKr, with distance $> 20$ cm and total energy $> 15$ GeV
  - Neutral vertex: compatibility with beam axis and decay region
  - 1 good track in time with the $\pi^0$ (<10 ns), no extra charged tracks in 8 ns

**$K_{e3}$ dedicated cuts**
- Track Momentum $> 5$ GeV/c
- $E/P > 0.9$

**$K_{\mu3}$ dedicated cuts**
- Track Momentum $> 10$ GeV/c
- $E/P < 0.1$
- Signal in MUV
- Cuts to remove $\pi^\pm \pi^0 \pi^0$ and $\pi^\pm \pi^0$ with pion decay in flight
Data samples and background

- runs with dedicated trigger configuration
  - 16 runs, 4 days in 2004
  - trigger: 1 track + energy in LKr (E > 10 GeV)
- Events selected
  - $4.28 \times 10^6$ $K_e^3$
  - $2.91 \times 10^6$ $K_\mu^3$
- Small or negligible background contamination

<table>
<thead>
<tr>
<th>Decay</th>
<th>BR (%)</th>
<th>$F_e(10^{-3})$</th>
<th>$F_\mu(10^{-3})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^\pm \rightarrow \pi^\pm \pi^0 (K2\pi)$</td>
<td>20.66</td>
<td>0.270</td>
<td>0.264</td>
</tr>
<tr>
<td>$K^\pm \rightarrow \pi^\pm \pi^0\pi^0 (K3\pi)$</td>
<td>1.761</td>
<td>0.286</td>
<td>1.833</td>
</tr>
<tr>
<td>$K^\pm \rightarrow \pi^\pm \pi^0_D (K2\pi D)$</td>
<td>1.174</td>
<td>0.049</td>
<td>0.000</td>
</tr>
<tr>
<td>$K^\pm \rightarrow \pi^\pm \pi^0 g (K2\pi\gamma)$</td>
<td>0.02750</td>
<td>0.004</td>
<td>0.044</td>
</tr>
<tr>
<td>$K^\pm \rightarrow \mu^\pm \pi^0 \nu(K\mu3)$</td>
<td>0.03353</td>
<td>0.004</td>
<td>0.000</td>
</tr>
</tbody>
</table>

$F_eF_e$ estimated background contamination in $K_e^3$ and $K_\mu^3$ samples
Pion and leptons energy in the kaon rest frame

- Bin size at least 20 events per bin in the whole allowed region, 5x5 MeV cells
- Background tails and radiative corrections outside the kinematic limits are not considered in the fit
Fit procedure

✓ The experimental Dalitz plot is corrected for simulated background
✓ For each fit iteration, the Dalitz plot is filled with MC simulated ($\lambda_{gen}$) reconstructed centre-of-mass pion and lepton energies
✓ To obtain a simulated sample with a different set of FF ($\lambda$) for another parameterization, each event is weighted with:

$$w(\vec{\lambda}) = w_R(E_l, E_\pi) \frac{\rho(\vec{\lambda}, E_l, E_\pi)}{\rho(\vec{\lambda}_{gen}, E_l, E_\pi)}$$

✓ where $\rho$ is the non radiative density Dalitz formula
✓ Then, the most probable FF ($\lambda$) are obtained minimizing

$$\chi^2 = \sum_{bins} \frac{(\omega_{i,\text{data}} - N \cdot \omega_{i,\text{MC}})^2}{\sigma_{i,\text{data}}^2 - N^2 \cdot \sigma_{i,\text{MC}}^2}$$

✓ $\omega_{i,\text{data}}$ and $\omega_{i,\text{MC}}$ are the contents of experimental data in the i-th bin and the reweighted bin contents from MC, respectively.
## Results $K_{e3}$

<table>
<thead>
<tr>
<th></th>
<th>Quadratic parameterization ($10^{-3}$)</th>
<th>Pole parameterization (MeV)</th>
<th>Dispersive parameterization ($10^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\lambda'_+$</td>
<td>$\lambda''_+$</td>
<td>$M_V$</td>
</tr>
<tr>
<td>Central value</td>
<td>22.52</td>
<td>1.60</td>
<td>896.8</td>
</tr>
<tr>
<td>Statistical error</td>
<td>0.78</td>
<td>0.30</td>
<td>3.4</td>
</tr>
<tr>
<td>Systematic error</td>
<td>1.29</td>
<td>0.39</td>
<td>7.6</td>
</tr>
<tr>
<td>Total error</td>
<td>1.51</td>
<td>0.49</td>
<td>8.3</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
<td>609.4/687</td>
<td>609.3/688</td>
<td>609.1/688</td>
</tr>
<tr>
<td>correlation coeff.</td>
<td>-0.927</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
## Results $K_{\mu 3}$

<table>
<thead>
<tr>
<th></th>
<th>Quadratic parametrization ($10^{-3}$)</th>
<th>Pole parametrization (MeV)</th>
<th>Dispersive parametrization ($10^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\lambda'<em>+ \quad \lambda''</em>+ \quad \lambda'_0$</td>
<td>$M_V \quad M_S$</td>
<td>$\Lambda_+ \quad \ln C$</td>
</tr>
<tr>
<td>Central value</td>
<td>22.52 \quad 1.60 \quad 14.33</td>
<td>896.8 \quad 1196.4</td>
<td>23.55 \quad 186.68</td>
</tr>
<tr>
<td>Stat. error</td>
<td>0.78 \quad 0.30 \quad 1.11</td>
<td>3.4 \quad 18.1</td>
<td>0.50 \quad 5.12</td>
</tr>
<tr>
<td>Syst. error</td>
<td>1.29 \quad 0.39 \quad 1.25</td>
<td>7.6 \quad 28.8</td>
<td>0.97 \quad 9.23</td>
</tr>
<tr>
<td>Total error</td>
<td>1.51 \quad 0.49 \quad 1.67</td>
<td>8.3 \quad 34.0</td>
<td>1.10 \quad 10.55</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
<td>391.2/384</td>
<td>388.0/385</td>
<td>385.8/385</td>
</tr>
<tr>
<td>corr. coeff.</td>
<td>-0.969 ($\lambda'<em>+, \lambda''</em>+$)</td>
<td></td>
<td>0.320</td>
</tr>
<tr>
<td></td>
<td>0.851 ($\lambda'_+, \lambda'_0$)</td>
<td></td>
<td>0.408</td>
</tr>
<tr>
<td></td>
<td>-0.810 ($\lambda''_+, \lambda'_0$)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Combined $K_{e3}$ and $K_{\mu3}$ results

<table>
<thead>
<tr>
<th></th>
<th>Quadratic parametrization $(10^{-3})$</th>
<th>Pole parametrization (MeV)</th>
<th>Dispersive parametrization $(10^{-3})$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\lambda'_+$</td>
<td>$\lambda''_+$</td>
<td>$\lambda'_0$</td>
</tr>
<tr>
<td>Central value</td>
<td>23.35</td>
<td>1.73</td>
<td>14.90</td>
</tr>
<tr>
<td>Stat. error</td>
<td>0.75</td>
<td>0.29</td>
<td>0.55</td>
</tr>
<tr>
<td>Syst. error</td>
<td>1.23</td>
<td>0.41</td>
<td>0.80</td>
</tr>
<tr>
<td>Total error</td>
<td>1.44</td>
<td>0.50</td>
<td>0.97</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
<td>1004.6/1073</td>
<td></td>
<td></td>
</tr>
<tr>
<td>corr. coeff.</td>
<td>-0.954 ($\lambda'<em>+ , \lambda''</em>+$)</td>
<td>0.076 ($\lambda'_+ , \lambda'_0$)</td>
<td>-0.035 ($\lambda''_+ , \lambda'_0$)</td>
</tr>
</tbody>
</table>
Results - plots

- Ke3 and Kµ3 combined fit
- Results for quadratic fit: $\lambda'_+, \lambda''_+, \lambda'_0$
- Parameter correlation (1 $\sigma$ contours)
- Comparison with results from previous experiments
First observation of the $K^\pm \rightarrow \pi^\pm\pi^0e^+e^-$ decay
The $K^\pm \rightarrow \pi^\pm \pi^0 e^+ e^-$ decay - motivation

- Test of Chiral Perturbation Theory
- Proceeds through virtual photon exchange $K^\pm \rightarrow \pi^\pm \pi^0 \gamma^* \rightarrow \pi^\pm \pi^0 e^+ e^-$
- The differential decay rate is described in terms of three components: Inner Bremsstrahlung (IB), Direct Emission (DE (M,E)) and Interference (INT)
- Never observed so far

$$\frac{d^3 \Gamma}{dE_\gamma^* dT_c dq^2} = \frac{d^3 \Gamma_{IB}}{dE_\gamma^* dT_c dq^2} + \frac{d^3 \Gamma_{E}}{dE_\gamma^* dT_c dq^2} + \frac{d^3 \Gamma_{M}}{dE_\gamma^* dT_c dq^2} + \frac{d^3 \Gamma_{int}}{dE_\gamma^* dT_c dq^2}$$

[H. Pichl, EPJ C20 (2001) 371]
**Event selection for signal and normalization**

**Signal:** \( \pi^\pm \pi^0 e^+e^- \rightarrow \pi^\pm \gamma \gamma e^+e^- \)

- 3 charged tracks (2 “same sign” + 1 “opposite sign”), forming a vertex
- 2 photon clusters in LKr forming a \( \pi^0 \) pointing to the same decay vertex
- No PID from LKr, only kinematics \( \rightarrow \) no LKr acceptance cuts on tracks

**Normalization:** \( \pi^\pm \pi^0_D \rightarrow \pi^\pm e^+e^-\gamma \)

- Very abundant: \( \text{BR}(\pi^\pm \pi^0_D) \times \text{BR}(\pi^0_D) = 22.66 \% \times 1.174 \% = 2.425 \times 10^{-3} \)
- similar topology, only 1 photon
- similar cuts as for the signal

---

Trigger:
- L1 : > 1 HOD quadrant
- L2 : DCH track based kinematics

4-7-2018

Giuseppina Anzivino@QCD18
Event selection - cuts for signal

- Assign electron mass to the “opposite-sign” track
- The $\pi^0$ candidate is reconstructed from two photons pointing at the three-track vertex
- The kaon candidate is reconstructed from the $\pi^\pm\pi^0e^+e^-$ system
- Loose cuts are applied on the reconstructed $M(\pi^0)$ and $M(K^\pm)$

\[ |M_{\pi^0} - M^{PDG}_{\pi^0}| < 15 \text{ MeV }/ c^2 \]
\[ |M_{K^+} - M^{PDG}_{K^+}| < 45 \text{ MeV }/ c^2 \]
**Background evaluation**

**Main backgrounds to signal, use specific cuts to suppress**

\[
\begin{align*}
K_{3\pi D} & \left( K^\pm \rightarrow \pi^\pm \pi^0 \pi^0_D \right) & 1 \gamma \text{ lost} & M^2 \left( \pi^+ \pi^0 \right) > 0.12 \text{ GeV}^2 / c^4 \\
K_{2\pi D} & \left( K^\pm \rightarrow \pi^\pm \pi^0_D \right) & 1 \text{ extra } \gamma & \left| M \left( e^+ e^- \gamma \right) - M_{\text{PDG}} \left( \pi^0 \right) \right| > 7 \text{ MeV} / c^2
\end{align*}
\]

\[
\left( M \left( \pi^0 \right) - 0.42 \cdot M \left( K^\pm \right) + 73.2 \text{ MeV} / c^2 \right) < 6 \text{ MeV} / c^2 \quad \text{combined cut on masses}
\]

**Main backgrounds to normalization**

\[
K_{\mu 3D} \left( K^\pm \rightarrow \mu^\pm \nu \pi^0_D \right); \quad K_{e 3D} \left( K^\pm \rightarrow e^\pm \nu \pi^0_D \right)
\]

Residual background: 5.7%, estimated from simulation using the number of kaon decays from normalization with mis-ID of e or \( \mu \): 0.15%, estimated using MC + radiative corrections
Results

Data sample: $\sim 1.7 \times 10^{11}$ kaon decays (K$^+$ and K$^-$), collected in 2003-2004

Final spectra for signal and normalization channels

Signal: $\pi^\pm(\pi^0 \to \gamma\gamma)e^+e^-$

Normalization: $\pi^\pm(\pi^0_D \to \gamma e^+e^-)$
**Branching ratio measurement**

\[
BR\left(K^\pm \rightarrow \pi^\pm \pi^0 e^+ e^-\right) = \frac{N_S - N_{BS}}{N_N - N_{BN}} \times \frac{A_N}{A_S} \times \frac{\varepsilon_{L1N} \times \varepsilon_{L2N}}{\varepsilon_{L1S} \times \varepsilon_{L2S}} \times BR\left(K^\pm \rightarrow \pi^\pm \pi^0\right) \times BR\left(\pi^0_D\right)
\]

- \(A_S\) is the weighted average of IB, DE, INT acceptances using expected relative contributions
- radiative correction taken into account using PHOTOS

<table>
<thead>
<tr>
<th>Signal</th>
<th>Normalization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Candidates (N_S)</td>
<td>5076</td>
</tr>
<tr>
<td>Background (N_{SB})</td>
<td>289</td>
</tr>
<tr>
<td>Accepted (rad) (A_S)</td>
<td>0.666(1) %</td>
</tr>
<tr>
<td>L1 efficiency (S)</td>
<td>99.73(1) %</td>
</tr>
<tr>
<td>L2 efficiency (S)</td>
<td>99.46(1) %</td>
</tr>
</tbody>
</table>
Branching ratio - result

The preliminary result for the BR:

\[
BR\left( K^\pm \rightarrow \pi^\pm \pi^0 e^+ e^- \right) = \left( 4.22 \pm 0.06 \, _{\text{stat}}^{\pm 0.04} \, _{\text{syst}}^{\pm 0.13} \, _{\text{ext}}^{\pm 0.06} \right) \times 10^{-6}
\]

✓ Error dominated by external error on BR (\(\pi^0_D\))

✓ Result is in agreement with ChPT [EPJ C72 (2012)]

✓ Without radiative and isospin breaking corrections
  ✓ BR(IB) = 4.19 \times 10^{-6}

✓ With isospin breaking
  ✓ BR(IB) = 4.10 \times 10^{-6}

First observation!
Summary

Kℓ3 Form Factors

- FF have been measured by NA48/2 using \(4.3 \times 10^6 K_e^3\) and \(2.9 \times 10^6 K_\mu^3\) events collected in 2004
- Improved vertex definition, analysis almost insensitive to beam shape
- The combined \(K_e^3\) and \(K_\mu^3\) result is fully compatible with previous measurements, with improved precision
- This allow to decrease the contribution of Kℓ3 FF on \(|V_{us}|\) error

\[K^\pm \rightarrow \pi^\pm \pi^0 e^+ e^-\]

- \(~5000\) candidate events with 5\% background
- decay observed for the first time
- The preliminary BR measurement is in perfect agreement with ChPT-based theoretical prediction
- Uncertainty is dominated by external error

Both results close to be published