Kaon Physics Status and Prospects

Francesca Bucci
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• CP-Violation
  • Leptonic and Semileptonic decays
  • Rare Decays, SM and Beyond
  • Lepton Universality and Flavour Violation
  • Exotics
• Re(\\varepsilon'/\\varepsilon) is one of the important actors of 1990s particle physics
• A non-zero value of Re(\\varepsilon'/\\varepsilon) signals the direct CP violation in the decay of the neutral kaon
• It was demonstrated that Re(\\varepsilon'/\\varepsilon) is different from zero beyond doubt
\[ \frac{\varepsilon'}{\varepsilon}_{Exp} = (16.6 \pm 2.3) \cdot 10^{-4} \]

World average from NA48 and KTeV

- Precise theoretical prediction difficult because of strong interplay of QCD and EW penguin contributions

- SM prediction is still debated:

\[ \frac{\varepsilon'}{\varepsilon}_{Th} = (1.9 \pm 4.5) \cdot 10^{-4} \]

Buras, Gorbahn, Jager, Jamin
arXiv 1507.06345

\[ \frac{\varepsilon'}{\varepsilon}_{Th} = (15 \pm 7) \cdot 10^{-4} \]

Gisbert, Pich
arXiv 1712.06147

- Waiting for lattice QCD to clarify the SM prediction
The prediction in the SM is:

$$\text{BR}(K_S \rightarrow \pi^0\pi^0\pi^0) = |\epsilon|^2 \times \frac{\tau_S}{\tau_L} \text{BR}(K_L \rightarrow \pi^0\pi^0\pi^0) \approx 3 \times 10^{-9}$$

Currently the best limit is provided by the KLOE Collaboration:

$$\text{BR}(K_S \rightarrow \pi^0\pi^0\pi^0) \leq 2.6 \times 10^{-8} \text{ at } 90\% \text{ C.L.}$$


A deviation from the predicted value would be a sign of CP violation beyond the complex phase present in the CKM matrix.
Since we are discussing $K_S$
LHCb as \( \mathcal{K}_0^S/\Sigma \) factory

- \( 10^{13} \mathcal{K}_0^S / \text{fb}^{-1} \) inside LHCb acceptance
- \( \mathcal{K}_0^S \) decays in LHCb characterized by decay vertices separated from the interaction point
- Candidates required to decay in the VELO region (~40%)
- Trigger limitations will be overcome thanks to the LHCb upgrade
LHCb: $K^0_s \rightarrow \mu^+\mu^-$

- SM prediction: $\text{BR}(K_s \rightarrow \mu\mu) = (5.1 \pm 1.5) \times 10^{-12}$
- Analysis performed on full Run-I data

More interesting region can be achieved by LHCb upgrade with trigger improvements
LHCb: $K^0_S \rightarrow \pi^0 \mu^+ \mu^-$ feasibility study

- Most precise measurement was performed by the NA48 experiment
  \[ \text{BR}(K^0_S \rightarrow \pi^0 \mu^+ \mu^-) = 2.9^{+1.5}_{-1.2} \times 10^{-9} \]  
- Improvements on BR($K^0_S \rightarrow \pi^0 \mu^+ \mu^-$) measurement would lead to better prediction for BR($K^0_L \rightarrow \pi^0 \mu^+ \mu^-$)

Excellent prospects for the LHCb upgrade
LHCb: evidence of $\Sigma^+ \rightarrow p\mu^+\mu^-$

- The HyperCP collaboration found evidence for $\Sigma^+ \rightarrow p\mu^+\mu^-$ decays
- 3 events clustered at $m_{\mu^+\mu^-} = 214$ MeV/c$^2$
- This suggested the existence of a new neutral particle
- LHCb analysis performed on full Run-I data [LHCb-CONF-2016-013]

No bumpy feature in $m_{\mu^+\mu^-}$

From the subset of events with available normalization

$\text{BR}(\Sigma^+ \rightarrow p\mu^+\mu^-) < 6.3 \times 10^{-8}$ at 95% C.L.
Outline

• CP-Violation
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• Exotics
Leptonic K decays and $V_{us}$

$V_{us}$ can be obtained from leptonic decays

$$\frac{|V_{us}|}{|V_{ud}|} \frac{f_K}{f_\pi} = \left( \frac{\Gamma(K \rightarrow l\nu(\gamma))}{\Gamma(\pi \rightarrow l\nu(\gamma))} \frac{m_{\pi^\pm}}{m_{K^\pm}} \right)^{1/2} \frac{1 - m_{\mu^2}/m_{\pi^\pm}^2}{1 - m_{\mu^2}/m_{K^\pm}^2} \left( 1 - \frac{1}{2} \delta_{EM} - \frac{1}{2} \delta_{SU(2)} \right)$$

Using typical inputs:
Blucher and Marciano, PDG2017

$$\frac{\Gamma(K \rightarrow \mu\nu(\gamma))}{\Gamma(\pi \rightarrow \mu\nu(\gamma))} = 1.3367(29)$$

$$\frac{f_{K^+}}{f_{\pi^+}} = 1.1933(29) \quad N_f = 2 + 1 + 1$$

$V_{us} = 0.2253(7)$
Semileptonic K decays and $V_{us}$

$V_{us}$ can also be determined from semileptonic kaon decays

$$|V_{us}|f_+(0) = \sqrt{\frac{BR(K \rightarrow \pi l \nu)}{\tau}} \cdot \frac{192\pi^3}{G_F^2 M_K^5 S_{EW}(1 + \delta^l_K + \delta^l_{SU2}) C^2 I^K_l}$$

<table>
<thead>
<tr>
<th>$K^0$</th>
<th>BR($K_{e3}$) [%]</th>
<th>BR($K_{\mu3}$) [%]</th>
<th>$\tau$ [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDG '04</td>
<td>39</td>
<td>27</td>
<td>51</td>
</tr>
<tr>
<td>PDG '08</td>
<td>40</td>
<td>27.5</td>
<td>52</td>
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<tr>
<td>FlaviaNet '10</td>
<td>39</td>
<td>27</td>
<td>51</td>
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</table>

<table>
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<tr>
<th>$K^\pm$</th>
<th>BR($K_{e3}$) [%]</th>
<th>BR($K_{\mu3}$) [%]</th>
<th>$\tau$ [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDG '04</td>
<td>4.8</td>
<td>3.2</td>
<td>12.35</td>
</tr>
<tr>
<td>PDG '08</td>
<td>5</td>
<td>3.3</td>
<td>12.4</td>
</tr>
<tr>
<td>FlaviaNet '10</td>
<td>5.2</td>
<td>3.4</td>
<td>12.35</td>
</tr>
</tbody>
</table>

Experimental input changing $\sim$5% in some cases...

Input from many experiments:
BNL865, KTeV, ISTRA+, KLOE, NA48, NA48/2
Semileptonic K decays and $V_{us}$

$|V_{us}|f_+(0)$ from world data

- $K_L e^3$
- $K_L \mu^3$
- $K_S e^3$
- $K^\pm e^3$
- $K^\pm \mu^3$

$|V_{us}|f_+(0) = 0.21654(41)$ $\chi^2/\text{ndf} = 1.54/4$ (82%)

M. Moulson, CKM 2016

For $f_+(0) = 0.9704(32)$, $N_f = 2+1+1$:

$V_{us} = 0.2231(4)_{\text{ex}} (7)_{\text{latt}}$
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K → πνν decays and CKM matrix

The very small hadronic error makes these decays special

\[
\text{BR}\left( K^+ \rightarrow \pi^+ \nu\nu \right) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[ \frac{|V_{cb}|}{0.0407} \right]^{2.8} \cdot \left[ \frac{\gamma}{73.2^\circ} \right]^{0.74}
\]

Buras et al., JHEP 1511

\[
\text{BR}\left( K_L \rightarrow \pi^0 \nu\nu \right) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[ \frac{|V_{ub}|}{3.88 \times 10^{-3}} \right]^2 \cdot \left[ \frac{|V_{cb}|}{0.0407} \right]^{2.8} \cdot \left[ \frac{\gamma}{73.2^\circ} \right]^{0.74}
\]

Precision of prediction limited by CKM parameters

Knowledge of \( \gamma, V_{cb} \) and \( V_{ub} \) will be improved by LHCb and Belle II

Overconstrain UT triangle to reveal possible NP

SM prediction

\[
\text{BR}\left( K^+ \rightarrow \pi^+ \nu\nu \right) = (8.4 \pm 1.0) \times 10^{-11}
\]

Experimental status

\[
\text{BR}\left( K^+ \rightarrow \pi^+ \nu\nu \right) = \left( 17.3^{+11.5}_{-10.5} \right) \times 10^{-11}
\]
**K→πνν decays and New Physics**

Extensions to the SM to which K→πνν are sensitive include

**Simplified Z and Z’ models**

Buras, Buttazzo, Knegjens, JHEP 1511

**LFU violation models**

Bordone, Buttazzo, Isidori, Monnard arXiv:1705.10729

K→πνν are the only kaon decays with ν_τ in the final state
The NA62 Experiment for $K^+ \rightarrow \pi^+ \nu \nu$

"In-flight" technique

SPS proton
400 GeV
$10^{12}$ p/s

Secondary Beam
75 GeV/c, $\Delta p/p \sim 1\%$
$K(6\%), \pi(70\%), p(23\%)$

Decay region
60 m length
$K^+$ decay rate $\sim 5$ MHz
Vacuum $O(10^{-6})$ mbar
NA62: Data taking

- 2014 Pilot run
- 2015 Commissioning run
- Full detector installation completed in September 2016
- First dataset to look for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay in 2016
- Continuous data-taking until the end of 2018

Plan to run after the CERN LS2 to complete the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ measurement
NA62: Kinematics

\[ m_{\text{miss}}^2 = (p_K - p_\pi)^2 \]
NA62: Signal region definition

Missing mass resolution for single track events

Protects against mis-reconstruction

Three different ways to reconstruct \( m^2_{\text{miss}} \):
- \( m^2_{\text{miss}} \) (STRAW, GTK)
- \( m^2_{\text{miss}} \) (RICH, GTK)
- \( m^2_{\text{miss}} \) (STRAW, Beam)
Selection criteria

• single track decay topology
• $\pi^+$ identification
• photon rejection
• multi-track rejection

Performance

• $\sigma_t \sim O(100 \text{ ps})$
• $\sigma(m^2_{\text{miss}}) = 1 \cdot 10^{-3} \text{ GeV}^4/c^2$
• $\mu^+$ mis-id = $1 \cdot 10^{-8}$ (64% $\varepsilon_{\pi^+}$)
• $\pi^0$ rejection = $3 \cdot 10^{-8}$
One candidate event in Region II with background expectation of 0.15±0.09

Event in box has $m_{\text{miss}}^2$ (STRAW, Beam) outside the signal region

$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 1.4 \times 10^{-10}$ 95% C.L.

$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 2.8^{+4.4}_{-2.3} \times 10^{-11}$ 68% C.L.
• The 2017 run has been very successful: \(~ 3 \cdot 10^{12}\) K\(^+\) decays have been collected
• Data taking is underway and will continue until the CERN LS2
• By the end of 2018 NA62 should have accumulated about 20 SM signal events
• To reach ultimate sensitivity NA62 plans to continue data taking after LS2
The KOTO Experiment for $K_L \to \pi^0 \nu \nu$

Aims at the first observation of $K_L \to \pi^0 \nu \nu$ at the J-PARK HEF

CsI calorimeter and hermetic veto system

First physics run (20kW) in May 2013 (100h before stop)
KOTO: Result of the first physics run

\[ \sim 2.3 \times 10^{11} K_L \]

One event was observed consistent with bkg expectation

- \[ \text{BR}(K_L \rightarrow \pi^0 \nu \nu) < 5.1 \times 10^{-8} \text{ (90\%C.L.)} \]
- \[ \text{BR}(K_L \rightarrow \pi^0 X^0) \ (M_X=\pi^-) < 3.7 \times 10^{-8} \text{ (90\%C.L.)} \]
KOTO: Lesson from the 2013 run

Main bkg due to halo neutrons hitting directly the calorimeter

charged pions from $K_L \rightarrow \pi^0\pi^+\pi^-$ decays hitting the downstream beam pipe

halo neutrons interacting with NCC material
KOTO: Preliminary results on 2015 data

Upgrade of the detector during the two years of beam break

No signal candidate observed

<table>
<thead>
<tr>
<th>Rec. $\pi^0 P_T$ (MeV/c)</th>
<th>Rec. $\pi^0 Z_{vtx}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>Expected</td>
</tr>
<tr>
<td>324.4±2.7</td>
<td>0.27±0.15</td>
</tr>
<tr>
<td></td>
<td>0.11±0.06</td>
</tr>
<tr>
<td>0.40±0.18</td>
<td>0.54±0.16</td>
</tr>
<tr>
<td>1.40±0.15</td>
<td></td>
</tr>
</tbody>
</table>

BR($K_L \rightarrow \pi^0 \nu\nu$) <3.0×10^{-9} (90% C.L.)

Koji SHIOMI, ICHEP 2018@Seul

Current upper limit improved by one order of magnitude

2016-2018 data analysis in ongoing
K→πνν prospects

KOTO ‘15/’16 run ~ 2018

KOTO upgrade SM > 2021

SM (SES)

NA62 $\mathcal{O}(10\%) \geq 2018$

BR($K^+ \rightarrow \pi^+\nu\bar{\nu}$)

Current Grossman-Nir Limit

Excluded by E391a

Excluded by E877/E849

BR($K_L \rightarrow \pi^0\nu\bar{\nu}$)
The K\textsubscript{L}EVER experiment for $K_{\text{L}} \rightarrow \pi^0\nu\nu$

Main detector/veto system:
- **UV/AFC** Upstream veto/Active final collimator
- **LAV1-25** Large-angle vetoes (25 stations)
- **MEC** Main electromagnetic calorimeter
- **SAC** Small-angle vetoes
- **CPV** Charged particle veto
- **PSD** Pre-shower detector

Target sensitivity:
- **5 years starting Run4**
- ~60 SM $K_{\text{L}} \rightarrow \pi^0\nu\nu$
- **S/B ~ 1**
- $\delta \text{BR}/\text{BR}(K_{\text{L}} \rightarrow \pi^0\nu\nu) \sim 20\%$
KLEVER: Status and timeline

Project timeline – target dates:

2017-2018  Project consolidation and proposal
  • Participation in Physics Beyond Colliders
  • Beam test of crystal pair enhancement
  • Input to European Strategy for Particle Physics
  • Expression of Interest to CERN SPSC

2019-2021  Detector R&D

2021-2025  Detector construction
  • Possible K12 beam test if compatible with NA62

2024-2026  Installation during LS3

2026-       Data taking beginning Run 4

Expression of Interest to SPSC

• Actively seeking new collaborators
• Institutes interested so far: Birmingham, Bristol, Charles U., Comenius U., Dubna, Ferrara, Florence, Frascati, George Mason U., Glasgow, La Sapienza, Luovain, Mainz, Moscow INR, Naples, Perugia, Pisa, Protvino, Sofia, Tor Vergata, Turin
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Hints of lepton non-universality have emerged from the analysis of B decays. In kaon physics the best test at the moment comes from:

\[ R_K = \frac{\Gamma(K^+ \rightarrow e^+\nu)}{\Gamma(K^+ \rightarrow \mu^+\nu)} \]

Most precise determination obtained by NA62

\[ R_K = (2.488 \pm 0.010) \times 10^{-5} \]

0.4% precision

NA62 prospects: expected uncertainty 0.2% (better hermetic vetoing, resolution and PID)

TREK stopped K proposal: expected uncertainty 0.25%
### NA62 Sensitivity for LFNV decays

\[ 10^{13} K^+ \rightarrow \text{single event sensitivity (SES)} \sim 10^{-12} \]
\[ 10^{11} \text{tagged } \pi^0 \rightarrow \text{SES} \sim 10^{-10} \]

<table>
<thead>
<tr>
<th>Mode</th>
<th>UL at 90% CL</th>
<th>Experiment</th>
<th>NA62 acceptance*</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K^+ \rightarrow \pi^+\mu^+e^- )</td>
<td>(1.3 \times 10^{-11} )</td>
<td>BNL 777/865</td>
<td>(<del>10%</del>)</td>
</tr>
<tr>
<td>( K^+ \rightarrow \pi^+\mu^-e^+ )</td>
<td>(5.2 \times 10^{-10} )</td>
<td>BNL 865</td>
<td>(<del>10%</del>)</td>
</tr>
<tr>
<td>( K^+ \rightarrow \pi^-\mu^+e^+ )</td>
<td>(5.0 \times 10^{-10} )</td>
<td>BNL 865</td>
<td>(<del>5%</del>)</td>
</tr>
<tr>
<td>( K^+ \rightarrow \pi^-e^+e^- )</td>
<td>(6.4 \times 10^{-10} )</td>
<td>BNL 865</td>
<td>(<del>5%</del>)</td>
</tr>
<tr>
<td>( K^+ \rightarrow \pi^-\mu^+\mu^- )</td>
<td>(1.1 \times 10^{-9} )</td>
<td>NA48/2</td>
<td>(<del>20%</del>)</td>
</tr>
<tr>
<td>( K^+ \rightarrow \mu^-\nu\mu^+e^+ )</td>
<td>(2.0 \times 10^{-8} )</td>
<td>Geneva Saclay</td>
<td>(<del>2%</del>)</td>
</tr>
<tr>
<td>( K^+ \rightarrow e^-\nu\mu^+\mu^- )</td>
<td>no data</td>
<td></td>
<td>(<del>10%</del>)</td>
</tr>
<tr>
<td>( \pi^0 \rightarrow \mu^+\mu^- )</td>
<td>(3.6 \times 10^{-10} )</td>
<td>KTeV</td>
<td>(<del>2%</del>)</td>
</tr>
<tr>
<td>( \pi^0 \rightarrow \mu^-e^+ )</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

* From fast Monte Carlo simulation with flat phase-space distribution. Includes trigger efficiency.
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HNLs from kaon decays at NA62

HNLs with mass \( m_N < (m_K - m_e) \) can be produced in \( K^+ \) decays: \( K^+ \rightarrow l^+N \) \((l=e,\mu)\)

- NA62 analysis based 2015 data equivalent \( \sim 3 \times 10^8 K^+ \) decays in FV
- Search for bump in the missing mass distribution \( m_{\text{miss}} = (p_K - p_l)^{1/2} \)
- No hypothesis on decay mechanism, only production

\[ \text{Phys. Lett. B778, 137 (2018)} \]

Improved sensitivity w.r.t. on the previous limits from HNL production searches over the whole mass range considered for \( |U_{e4}|^2 \), and above 300 MeV/c\(^2\) for \( |U_{\mu4}|^2 \).
Beam defining collimators (TAX1 and TAX2) 
\( \sim 11 \lambda_1 \) Cu-based can be used as a dump

Easy switch between \( K^+ \) beam and proton dump mode with TAXes

**10^{18} PoT/nominal year**: 10^{12}PoT/s on spill, 100 days/year, 60% run efficiency

**10^{15} D_{(s)}, 10^{14} K, 10^{18} \pi^0/\eta/\eta'/\Phi/\rho/\omega** with ratios 6.4/0.68/0.07/0.03/0.94/0.95 (B mesons too)
NA62-Dump sensitivity for HNLs

NA62 sensitivity with $10^{18}$ PoT in dump mode

- Assume to detect all two-track final states, including open channels
- Assume zero background
- Separately address 3 extreme coupling scenarios

Scenario 1: $U^2_e$ enhanced

$U^2_e : U^2_\mu : U^2_\tau = 52 : 1 : 1$

Scenario 2: $U^2_\mu$ enhanced

$U^2_e : U^2_\mu : U^2_\tau = 1 : 16 : 3.8$

Scenario 3: $U^2_\tau$ enhanced

$U^2_e : U^2_\mu : U^2_\tau = 0.061 : 1 : 4.3$

*Window of opportunity to search for HNL above the K mass in the near future*
NA62-Dump sensitivity for ALPs $\rightarrow \gamma\gamma$

NA62 sensitivity with $10^{18}$ PoT in dump mode

- Only prospect of a strictly predominant coupling to photons is shown
- Predominant ALPs production mechanism via Primakov production
- Search for ALPs $\rightarrow \gamma\gamma$ in NA62 FV, account for geometrical acceptance
- Assume zero background, evaluate 90%-CL exclusion plot

![Graph showing ALP-$\gamma$ coupling and ALP mass range](image)

NA62 projections with $10^8$ PoT

- JHEP 1602, 018 (2016)
- JHEP 1712, 094 (2017)
- arXiv:1708.05776
NA62-Dump sensitivity for Dark scalar/γ

NA62 sensitivity with $10^{18}$ PoT

- Dominant production mode is from B mesons produced in the dump
- Assume all two tracks final states
- DP production (meson decays, bremsstrahlung) in Be target
- Search for DP-decay to $ee$, $μμ$ in the NA62 FV
- Projection is conservative

---

**DM never thermalizes through mixing**

**SN1987a**

**BBN (t > 1 sec)**

**LHCb & Belle $B \rightarrow K \mu\mu$**

**LHCb $B \rightarrow K^{+}\ell\ell$**

**LUX & Super CDMS**

**NEWS**

**K → X (based on K949 data)**

**DM never thermalizes through mixing**

**NA62-BD**

**SHIP**

**SN**

**Excluded regions**

- **Belle II, 50 ab$^{-1}$, 2024**
- **LHCb, 15 fb$^{-1}$, 2020**
- **HFS, 2018-2020**
- **APEX, 2018+**
- **SeaQuest, 2017-2019**
- **VEPP, proposed**
- **Mu3e, 2017+**
- **MESA, 2020+**
- **SHIP, 2026++**

**ALP mass [GeV/c$^2$]**

**DP mass [MeV/c$^2$]**

**DP-γ coupling [GeV$^{-1}$]**

**DS-Higgs coupling**
Conclusions

• After more than 70 years, kaons are still providing important tools to build the SM of particle physics and to see beyond it (CPV, LU, LVF, Exotics, ...)
• The interplay between theory and experiment is very strong and mutually motivating (CKM, \( \varepsilon'/\varepsilon \), Rare decays, LQCD)
• There are compelling questions and ambition to address them

Thanks for your attention