KLOE results in kaon physics and prospects for KLOE-2

Eryk Czerwiński on behalf of KLOE and KLOE-2 collaborations

Novosibirsk, 22.09.2011
Overview

► kaon physics at $\phi$ factory
► DA$\Phi$NE collider and KLOE detector
► KLOE results
► ongoing analyses
► KLOE-2 project at upgraded DA$\Phi$NE
kaon physics at $\phi$ factory

- DA$\Phi$NE collider and KLOE detector
- KLOE results
- ongoing analyses
- KLOE-2 project at upgraded DA$\Phi$NE
Why $\varphi$ resonance?

- $\text{BR}(\varphi \rightarrow K^+K^-) = 49.2\%$
- $\text{BR}(\varphi \rightarrow K^0\bar{K}^0) = 33.8\%$
- neutral kaon pairs produced in a pure quantum state ($J^{PC}=1^{--}$)
  
  $$|i\rangle \propto \frac{1}{\sqrt{2}} \left( |K_L, p\rangle |K_s, -p\rangle - |K_L, -p\rangle |K_s, p\rangle \right)$$
  
- detection of one kaon guarantees the presence of a second one with known momentum and direction (tagging)
► kaon physics at $\varphi$ factory

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► KLOE-2 project at upgraded DA$\Phi$NE
DAΦNE (Double Annular Factory for Nice Experiments)

1999-2007:

\[ \mathcal{L}_{\text{peak}} = 1.4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \]

\[ \int \mathcal{L} dt = 8.5 \text{ pb}^{-1}/\text{day} \]

\[ L_{\text{peak}} = 1.4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \]

Integrated luminosity:

- **2005**: 1256 pb\(^{-1}\)
- **2004**: 734 pb\(^{-1}\)
- **2002**: 320 pb\(^{-1}\)
- **2001**: 172 pb\(^{-1}\)

\( e^+e^- \) collider with two storage rings and two interaction points
KLOE (K LOng Experiment)

**Drift chamber**
- gas mixture: 90% He + 10% C$_4$H$_{10}$
- $\delta p_t / p_t < 0.4\%$ ($\theta > 45^\circ$)
- $\sigma_{xy} \approx 150$ $\mu$m ; $\sigma_z \approx 2$ mm

**Electromagnetic calorimeter**
- lead/scintillating fibers
- 98% solid angle coverage
- $\sigma_E / E = 5.7\% / \sqrt{(E(\text{GeV}))}$
- $\sigma_t = 57$ ps / $\sqrt{(E(\text{GeV}))} \pm 100$ ps
- PID capabilities

Data taking ended on March 2006
- 2.5 fb$^{-1}$ on tape @ $\sqrt{s} = M_\phi$
  (8×10$^9$ $\phi$=> 6.6×10$^9$ kaon pairs)
- ~10 pb$^{-1}$ @ 1010, 1018, 1023, 1030 MeV
- 250 pb$^{-1}$ @ 1000 MeV

22.09.2011

Eryk Czerwiński - PhiPsi2011
Neutral kaons beams (1/2)

\[ K_S \rightarrow \pi^+\pi^- \]

\[ K_L \rightarrow 2\pi^0 \]

\[ K_L \text{ tagged by } K_S \rightarrow \pi^+\pi^- \text{ vertex at IP} \]
Neutral kaons beams (2/2)

$K_S \rightarrow \pi^- e^+ \nu$

$K_L$ "crash" $\beta = 0.22$ (TOF)

$K_S$ tagged by $K_L$ interaction in EmC

UNIQUE
kaon physics at $\phi$ factory

DA$\Phi$NE collider and KLOE detector

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ongoing analyses

KLOE-2 project at upgraded DA$\Phi$NE
## KLOE papers - kaon physics

<table>
<thead>
<tr>
<th>Equation</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau(K_S) = 89.562 \pm 0.029_{\text{stat}} ^{+0.043}_{-\text{syst}} \text{ps}$</td>
<td></td>
<td>EPJC 71 (2011)</td>
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<tr>
<td>$R_k = (2.493 \pm 0.025_{\text{stat}} ^{+0.019}_{-\text{syst}}) \times 10^{-5}$</td>
<td></td>
<td>EPJC 64 (2009)</td>
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<tr>
<td>$</td>
<td>V_{us}</td>
<td>f_+(0) = 0.2157(6)$</td>
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<tr>
<td>$</td>
<td>V_{us}</td>
<td>= 0.2237(13)$</td>
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<tr>
<td>$1 -</td>
<td>V_{ud}</td>
<td>^2 -</td>
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<tr>
<td>$\tau^+ = 12.347(30)$</td>
<td></td>
<td>JHEP 01 (2008)</td>
</tr>
<tr>
<td>$\text{BR}(K^+ \to \pi^0 e^+\nu) = 0.04965(5)$</td>
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<td>PLB 666 (2008)</td>
</tr>
<tr>
<td>$\text{BR}(K^+ \to \pi^+\pi^0(\gamma)) = 0.2065(9)$</td>
<td></td>
<td>PLB 666 (2008)</td>
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<tr>
<td>$\lambda^+ ' = (25.6 \pm 1.5_{\text{stat}} ^{+0.9}_{-\text{syst}}) \times 10^{-3}$</td>
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<td>JHEP 12 (2007)</td>
</tr>
<tr>
<td>$\lambda^+ '' = (1.5 \pm 0.7_{\text{stat}} ^{+0.4}_{-\text{syst}}) \times 10^{-3}$</td>
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<td>JHEP 12 (2007)</td>
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<td>$\lambda_0 = (15.4 \pm 1.8_{\text{stat}} ^{+1.3}_{-\text{syst}}) \times 10^{-3}$</td>
<td></td>
<td>JHEP 12 (2007)</td>
</tr>
<tr>
<td>$\lambda_+ ' = (25.5 \pm 1.8) \times 10^{-3}$</td>
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<td>PLB 636 (2006)</td>
</tr>
<tr>
<td>$\lambda_+ '' = (1.4 \pm 0.8) \times 10^{-3}$</td>
<td></td>
<td>PLB 636 (2006)</td>
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<tr>
<td>$\text{BR}(K_S \to \pi e\nu) = 7.046(91) \times 10^{-4}$</td>
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<td>PLB 636 (2006)</td>
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<tr>
<td>$\text{Re}(\varepsilon) = (159.6 \pm 1.3) \times 10^{-5}$</td>
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<td>JHEP12 (2006)</td>
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<tr>
<td>$\text{Im}(\delta) = (0.4 \pm 2.1) \times 10^{-5}$</td>
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<td>PLB 662 (2006)</td>
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<td>$\text{BR}(K^+ \to \mu^+\nu) = 0.6366(17)$</td>
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<td>PLB 632 (2006)</td>
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<tr>
<td>$\text{BR}(K_S \to \pi^+\pi^-)/\text{BR}(K_S \to \pi^0\pi^0) = 2.2549(54)$</td>
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<td>EPJC 48 (2006)</td>
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<tr>
<td>$\xi_{00} = (1.0 \pm 2.1_{\text{stat}} ^{+0.4}_{-\text{syst}}) \times 10^{-6}$</td>
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<td>PLB 642 (2006)</td>
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<tr>
<td>$\text{BR}(K_{e3}) = 0.4008(15)$</td>
<td></td>
<td>PLB 632 (2006)</td>
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<tr>
<td>$\text{BR}(K_{\mu3}) = 0.2699(14)$</td>
<td></td>
<td>PLB 632 (2006)</td>
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<tr>
<td>$\tau_L = 50.92(30) \text{ ns}$</td>
<td></td>
<td>PLB 626 (2005)</td>
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</table>
Lifetime of $K_S$ (recent result)


$$\tau(K_S) = 89.562 \pm 0.029_{\text{stat}} \pm 0.043_{\text{syst}} \, \text{ps}$$

Systematic source | Absolute value [ps]
--- | ---
cuts & FV | 0.024
fit range | 0.012
$p'_K$ calibration | 0.033
kaon mass | 0.004
efficiency | 0.005
total | 0.043

Last input for $V_{US}$
Quantum interferometry

\[ |i\rangle \propto \frac{1}{\sqrt{2}} (|K_L, p\rangle |K_S, -p\rangle - |K_L, -p\rangle |K_S, p\rangle) \]

K_S and K_L are entangled states: \( \varphi \)-factory is a unique environment to study quantum interference.

\[ \xi = 0 \rightarrow \text{QM} \]
\[ \xi > 0 \rightarrow \text{decoherence} \]

\( |\psi\rangle = \frac{1}{\sqrt{2}} (|K_{L}, p\rangle |K_{S}, -p\rangle + |K_{L}, -p\rangle |K_{S}, p\rangle) \)

PLB 642 (2006) 315
\( \xi_{00} = (1.4 \pm 9.5_{\text{STAT}} \pm 3.8_{\text{Syst}}) \times 10^{-7} \)
Short summary

KLOE has performed:
✓ measurements of all relevant parameters for charged and neutral kaons: BR’s, lifetimes, form factors.
✓ SM test in the flavor sector through precise measurements of $V_{us}$ and $R_K = \frac{\Gamma(K \to e\nu)}{\Gamma(K \to \mu\nu)}$
✓ CPT and quantum mechanics tests with the analysis of the QM interference of neutral kaons, $K_S$ semileptonic decays, unitary (Bell-Steinberger relation)

Details about kaon physics at KLOE can be found e.g. Riv. Nuovo Cim. Vol. 31, N 10, 531 (2008)
e-Print: arXiv:0811.1929 [hep-ex]
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Ongoing analyses

\[ K^+ \rightarrow \pi^+ \pi^+ \pi^- \] closes the measurements of \( K^\pm \) main Brs (systematics underway)

\[ K_S \rightarrow \pi^0 \pi^0 \pi^0 \] an update with whole statistics of KLOE previous measurement (Phys. Lett. B 619 (2005) 61) (systematics underway)

interferometry with
\[ K_SK_L \rightarrow \pi^+ \pi^- \pi^+ \pi^- , K_SK_L \rightarrow \pi^+ \pi^- \pi^0 \pi^0 , K_SK_L \rightarrow \pi^+ \pi^- \pi \ell \nu \]

\[ K_S \rightarrow \pi \nu \] an update with whole statistics of KLOE previous Measurement (Phys. Lett. B 535 (2002) 37)

\[ K_S \text{ regeneration} \]
Preliminary result from $K_S \rightarrow \pi^0\pi^0\pi^0$

Best sensitivity from KLOE [PLB619(2005)61] so far
450 pb$^{-1} \Rightarrow BR(K_S \rightarrow 3\pi^0) < 1.2 \times 10^{-7}$ @90% C.L.

Updated analysis:
$E_C > 129$ MeV
$0.196 \leq \beta_{cr} \leq 0.25$
$\chi^2_{fit} < 35$
$\Delta E/\sigma_E \geq 1.7$
$12.1 \leq \chi^2_{2\pi} \leq 60$
$\chi^2_{3\pi} \leq 4.6$
$R_{\min} > 65$cm

$\varepsilon_{3\pi} = 0.053 \pm 0.003$

$N_{3\pi^0} \leq 2.44/\varepsilon_{3\pi^0} = 12.84$ at 90 % C.L.

Normalized to $N_{2\pi^0} = 9062000/\varepsilon_{3\pi^0} = 136457576$

$BR(K_S \rightarrow 3\pi^0) < 2.9 \times 10^{-8}$ @90% C.L.
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DAΦNE upgrade (2/2)

$\mathcal{L}_{\text{new}} \sim 3 \times \mathcal{L}_{\text{old}}$ achieved with the same circulating currents as in the past

$\int \mathcal{L} dt = 1 \text{ pb}^{-1}/\text{hour}$

A new collision scheme worked out with:

➢ larger crossing angle
➢ reduced beam size at the crossing point
➢ sextupole pairs for crab-waist configuration of beam interaction

KLOE-2 is starting data campaign at upgraded DAΦNE
Detector upgrade for first KLOE-2 run ($\approx 5$ fb$^{-1}$ in 1 year): 2+2 detector stations for leptons in $e^+e^-\rightarrow e^+e^-\gamma\gamma\rightarrow e^+e^-X$

High Energy Taggers (HET)
- $E>400$ MeV
- 11m from IP
- scintillators + PMTs
- $\sigma_E \sim 2.5$ MeV
- $\sigma_T \sim 200$ ps

Low Energy Taggers (LET)
- $E=160-230$ MeV
- inside KLOE detector
- LYSO+SiPM
- $\sigma_E < 10\%$ for $E>150$ MeV

See talk of F. Nguyen in gamma gamma physics session for details
Major detector upgrades (late 2012) for second KLOE-2 run:

**Inner Tracker**
- 4 layers of cylindrical triple GEM
- better vertex reconstruction near IP
- larger acceptance for low $p_t$ tracks

**QCALT**
- $W$ + scintillator tiles + SiPM/WLS
- QUADS instrumentation for $K_L$ decays

**CCAL**
- LYSO + APD
- increase acceptance for $\gamma$'s from IP (21° → 8°)
QM, CPT tests with neutral kaons

\[ I(\pi^+\pi^-, \pi^+\pi^-; \Delta t) \text{ (a.u.)} \]

- **Black hist:** \( \sigma(\Delta t) \approx 1\,\tau_s \)
  - (KLOE)
- **Red hist:** \( \sigma(\Delta t) \approx 0.3\,\tau_s \)
  - (expected at KLOE-2)
- **Blue curve:** ideal

○ sensitivity with the present KLOE resolution \( (\sigma(\Delta t) \approx 1.0\,\tau_s) \)

● sensitivity with improved resolution \( (\sigma(\Delta t) \approx 0.3\,\tau_s \text{ expected at KLOE-2}) \)
KLOE-2 physics program

Goal: ~20 fb$^{-1}$ in the next 3-4 years to extend the KLOE physics program at DAΦNE upgraded in luminosity (approved)

- γγ physics:
  - existence (and properties) of $\sigma/f_0(600)$;
  - study of $\Gamma(S/PS \rightarrow \gamma\gamma)$;
  - PS transition form factor;

- light meson spectroscopy:
  - properties of scalar/vector mesons;
  - rare $\eta$ decays;
  - $\eta'$ physics;

- kaon physics:
  - test of CPT (and QM) in correlated kaon decays;
  - test of CPT in $K_S$ semileptonic decays;
  - test of SM (CKM unitarity, lepton universality);
  - test of ChPT ($K_S$ decays);

- dark forces searches:
  - light bosons @ $O(1 \text{ GeV})$;

- hadronic cross section:
  - $\alpha_{em}(M_Z)$ and $(g-2)$.

Summary

► A φ-factory is the ideal place to study both charged and neutral kaons, where they are copiously produced in a clean environment.

► KLOE measured with high precision all relevant parameters for charged and neutral kaons: BR’s, lifetimes, form factors. Several test of the standard model, discrete symmetries and quantum mechanics were performed.

► KLOE-2 is going to continue the physics program of KLOE, with special emphasis on CPT, QM tests and KS physics.

► KLOE-2 data taking campaign is starting.
Koniec?
Fine?
The End?
NO!
A new beginning!