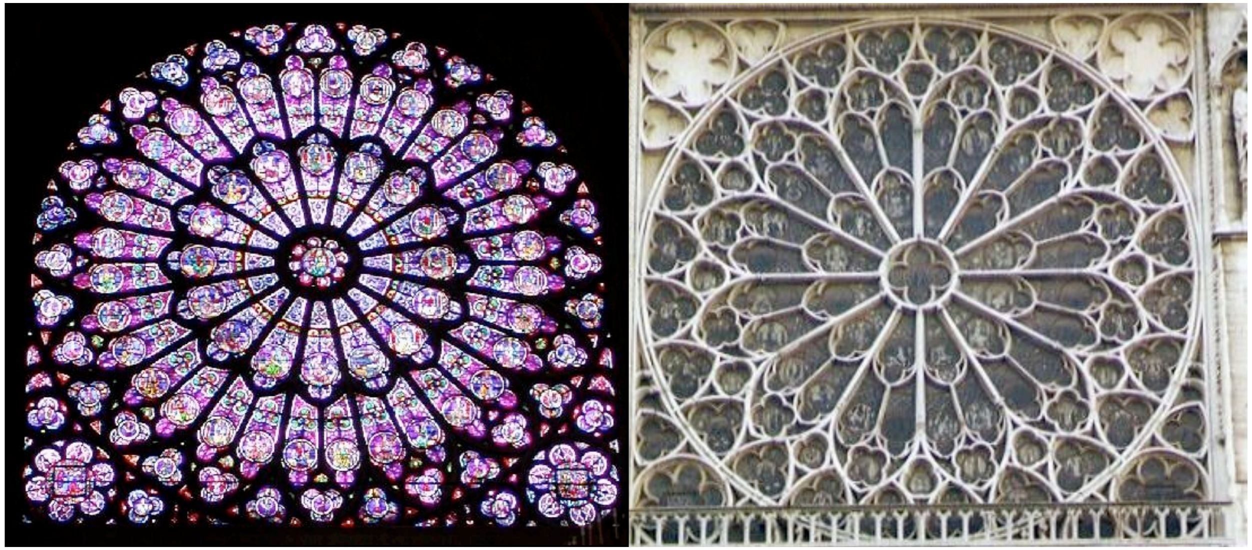
Highlights of the KLOE experiment at DAΦNE

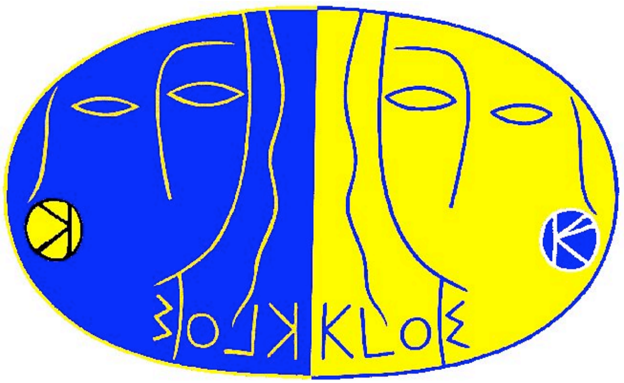
Strange mesons: a guided tour in the land of symmetries



Filippo Ceradini - Dipartimento di Fisica, Università Roma Tre and INFN
Paris, 21 septembre 2006

table des matières

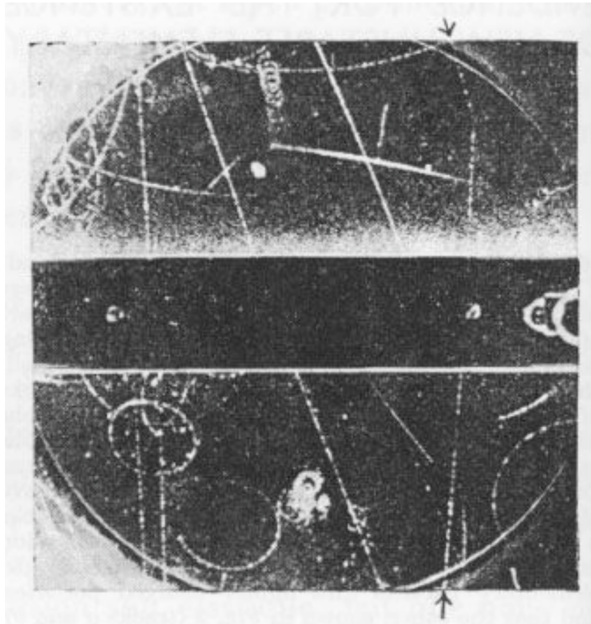
à bien regarder …



… elle n'est pas symmetrique

Strangeness: a new flavour of matter

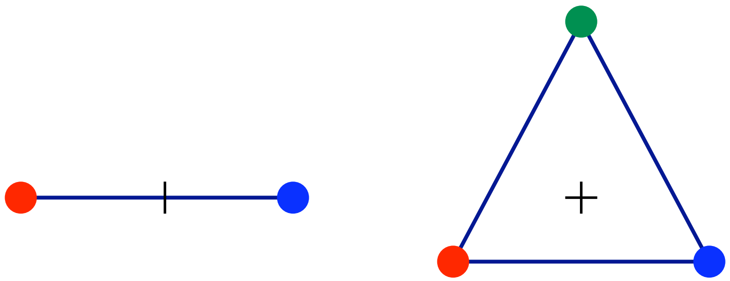
60 years ago: some strange things happen



the discovery of a new flavour of matter
not present in nuclei

Murray Gell-Mann and Kazuhito Nishijima
from isospin to flavour symmetry

from Pauli SU(2) to Gell-Mann SU(3)



strange mesons and P-symmetry

50 years ago: many new particles

$V^0_1 \rightarrow p\,\pi^-$ $V^0_2 \rightarrow \pi^+\pi^-$

$\theta^+ \rightarrow \pi^+\pi^0$ $\tau^+ \rightarrow \pi^+\pi^+\pi^-$

the τ-θ puzzle

same mass, same lifetime, but they decay to different P eigenstates

1956 - Tsung Dao Lee and Chen Ning Yang show the way out: Parity is not a good symmetry in weak decays, make three experiments and convince yourself

from the Nobel lecture

The situation that the physicist found himself in at that time has been likened to a man in a dark room groping for an outlet. He is aware of the fact that in some direction there must be a door which would lead him out of his predicament. But in which direction?

That direction turned out to lie in the faultiness of the law of parity conservation for the weak interactions. But to uproot an accepted concept one must first demonstrate why the previous evidence in its favor were insufficient. Dr. Lee and I examined this question in detail, and in May 1956 we came to the following conclusions: (A) Past experiments on the weak interactions had actually no bearing on the question of parity conservation. (B)

strange mesons and CP eigenstates

but two neutral mesons are observed with very different lifetimes, they decay to different CP eigenstates

1955 - Murray Gell-Mann and Abraham Pais: if CP is a good symmetry, then short- and long-lived neutral *K* mesons are combinations of strangeness

$$K_1 = \frac{K^0 + \overline{K^0}}{\sqrt{2}} \qquad K_2 = \frac{K^0 - \overline{K^0}}{\sqrt{2}}$$

1955 - Abraham Pais and Oreste Piccioni show how to prove it: observe regeneration of K_S in a K_L beam and strangeness oscillations

1960 - the first measurements of $|m(K_L) - m(K_S)|$

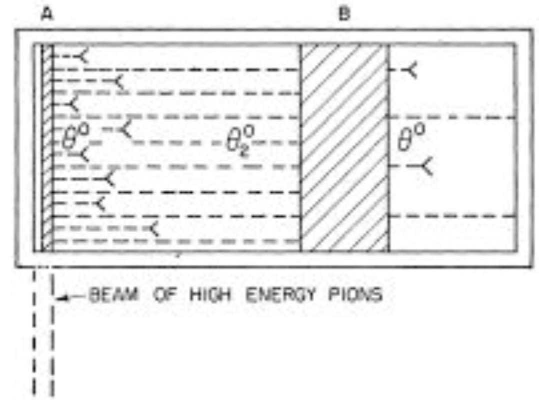


FIG. 1. Schematic diagram showing the regeneration of θ_1^0 events in a multiplate cloud chamber. The symbol ---< indicates the decay: $\theta_1^0 \to \pi^+ + \pi^-$.

PHYSICAL REVIEW VOLUME 124, NUMBER 4 NOVEMBER 15, 1961

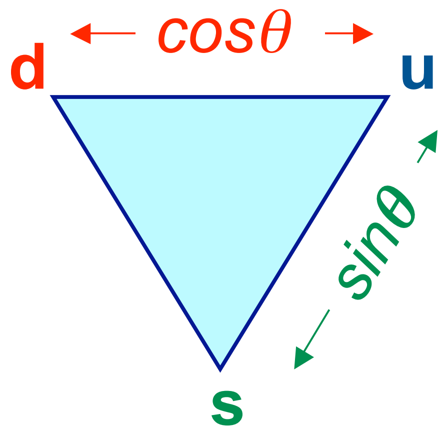
Regeneration of Neutral *K* Mesons and Their Mass Difference*

R. H. Good,† R. P. Matsen,‡ F. Muller,§ O. Piccioni,|| W. M. Powell, H. S. White, W. B. Fowler,** and R. W. Birge††
Lawrence Radiation Laboratory, University of California, Berkeley, California

$\Delta m \sim 1/2\ \hbar/\tau_s$

strange mesons and flavour symmetry

40 years ago - Nicola Cabibbo: the angle of strangeness and the universality of Fermi coupling



two lepton families

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$

but one quark family

$$\begin{pmatrix} u \\ d\, cos\theta + s\, sin\theta \end{pmatrix}$$

$\mu \rightarrow \nu_\mu\, e\, \bar{\nu}_e$ ⟹ Fermi constant

axial current

$$\frac{K \rightarrow \mu\, \bar{\nu}_\mu}{\pi \rightarrow \mu\, \bar{\nu}_\mu} \approx \frac{G^2 sin^2\theta}{G^2 cos^2\theta}$$

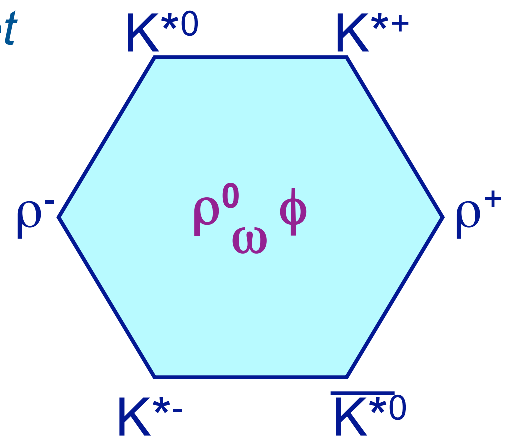
vector current

$$\frac{K \rightarrow \pi^0\, e\, \bar{\nu}_e}{\pi \rightarrow \pi^0\, e\, \bar{\nu}_e} \approx \frac{G^2 sin^2\theta}{G^2 cos^2\theta}$$

strange mesons and quarkonium

1962 - the discovery of the ϕ meson

the $J^P = 1^-$ $q\bar{q}$ nonet



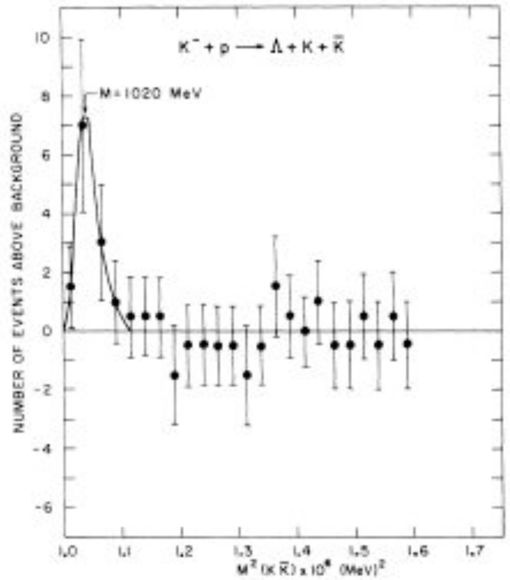


FIG. 4. The (effective mass)^2 distribution for $K\bar{K}$ from the channel $\Lambda K\bar{K}$ for those events above phase space.

the SU(3) flavour-neutral eigenstates

$$|8\rangle_a = \frac{u\bar{u} - d\bar{d}}{\sqrt{2}} \qquad |8\rangle_s = \frac{u\bar{u} + d\bar{d} - 2s\bar{s}}{\sqrt{6}} \qquad |1\rangle = \frac{u\bar{u} + d\bar{d} + s\bar{s}}{\sqrt{3}}$$

but fortunately $|8\rangle_s$ and $|1\rangle$ mix to make the ϕ an almost pure $s\bar{s}$ state: it mainly decays to strange mesons

$\phi \rightarrow$

K^+K^-	49.2 %
$K_L K_S$	34.0 %
$\pi^+\pi^-\pi^0$	15.3 %
$\eta\gamma$	1.30 %

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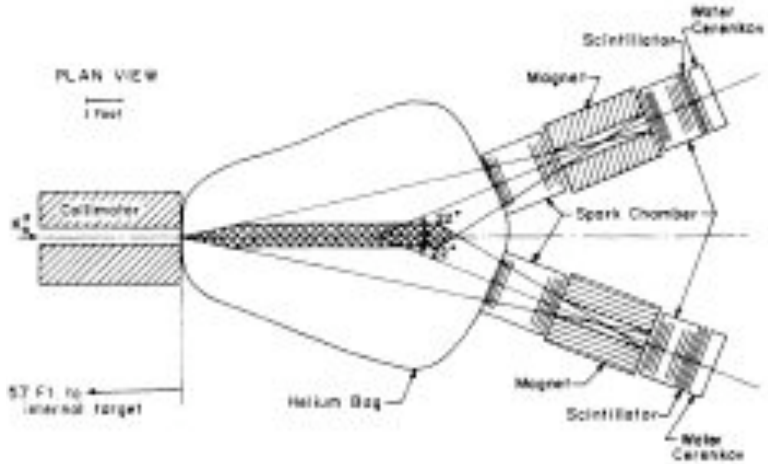
strange mesons and CP-symmetry

40 years ago: but also $K_L \rightarrow \pi^+\pi^-$!
and also CP-symmetry is violated

then $K_S \neq K_1$ and $K_L \neq K_2$

$$K_S = \frac{(1+\epsilon)K^0 + (1-\epsilon)\overline{K^0}}{\sqrt{2(1+|\epsilon|^2)}} \qquad K_L = \frac{(1+\epsilon)K^0 - (1-\epsilon)\overline{K^0}}{\sqrt{2(1+|\epsilon|^2)}}$$



strange mesons and matter-antimatter symmetry

… and should observe $K_L \rightarrow \pi^- e^+ \nu \neq K_L \rightarrow \pi^+ e^- \bar{\nu}$

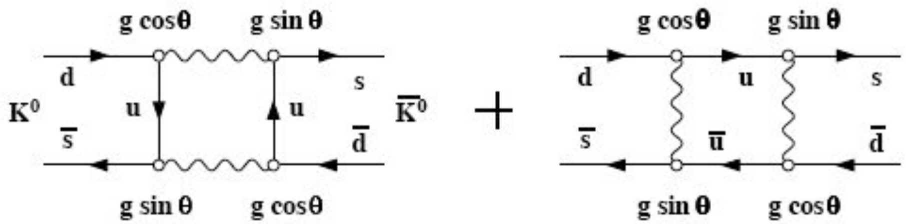
$$\frac{\Gamma(K_L \rightarrow \pi^- e^+ \nu) - \Gamma(K_L \rightarrow \pi^+ e^- \bar{\nu})}{\Gamma(K_L \rightarrow \pi^- e^+ \nu) + \Gamma(K_L \rightarrow \pi^+ e^- \bar{\nu})} = \frac{2\mathcal{R}\epsilon}{1+|\epsilon|^2} \simeq 2\mathcal{R}\epsilon$$

you can tell a friend from another world what is your definition of positive/negative electric charge

strange mesons and more flavours

but Δm is too small to be accounted for with only three flavours

$$\Delta m = \frac{\langle K^0 + \overline{K^0} | H_W | K^0 + \overline{K^0} \rangle}{2} + \frac{\langle K^0 - \overline{K^0} | H_W | K^0 + \overline{K^0} \rangle}{2} = 2 \langle d\bar{s} | H_W | s\bar{d} \rangle$$



Sheldon Glashow, John Iliopoulos and Luciano Maiani:
a fourth flavour to prevent flavour changing neutral current

$$\begin{pmatrix} u \\ d\ \cos\theta + s\ \sin\theta \end{pmatrix} \oplus \begin{pmatrix} c \\ -\ d\ \sin\theta + c\ \cos\theta \end{pmatrix}$$

give the correct value for Δm if $m_c \sim 1.5$ GeV

strange mesons and quark mixing

but CP violation cannot be accounted for with only four flavours

1973 - Makoto Kobayashi and Toshihide Maskawa: if ~~CP~~ then need a complex matrix, extend Cabibbo mixing to three quark families

$$\mathbf{V_{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Wolfenstein, 1983

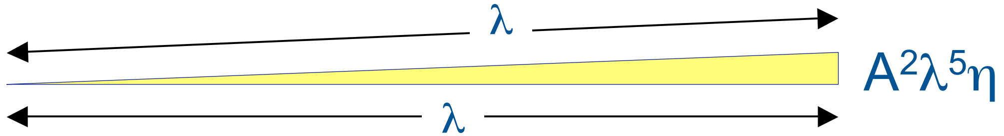
if no other families, then V_{CKM} is a unitary matrix: $\sum_i V^*_{ij} V_{ik} = \delta_{jk}$

9 constraints, *e.g.* **the first row**: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

1988 - Cecilia Jarlskog: six unitarity triangles, all of them have the same area

$J = Im(V^*_{ij} V_{ik} V^*_{lm} V_{ln}) \approx A^2\lambda^6\eta$; $\sqrt{J}$ measures the size of ~~CP~~ effects

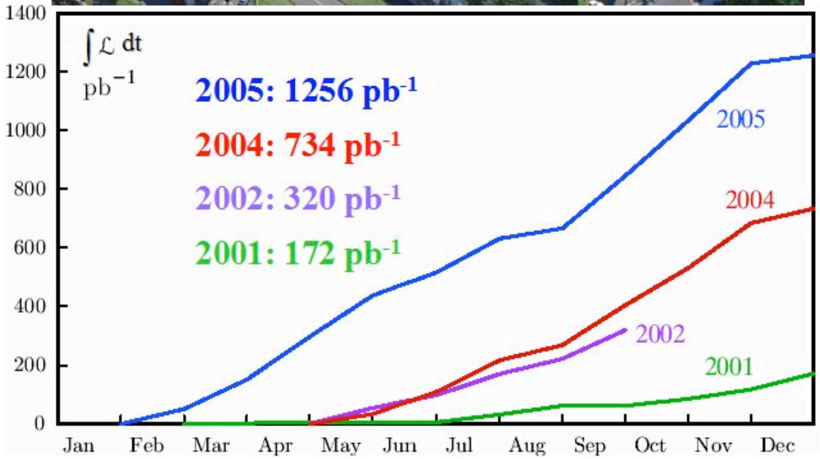
the strange triangle: $V^*_{ud}V_{cd} + V^*_{us}V_{cs} + V^*_{ub}V_{cb} = 0$



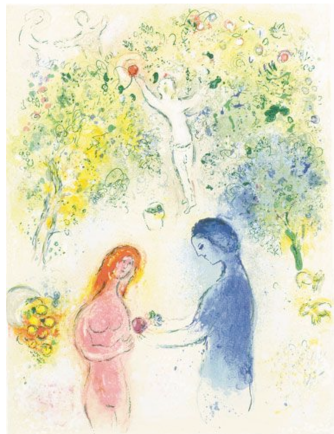
DAΦNE and KLOE

~ 1990: many proposals around the world to build a ϕ factory …

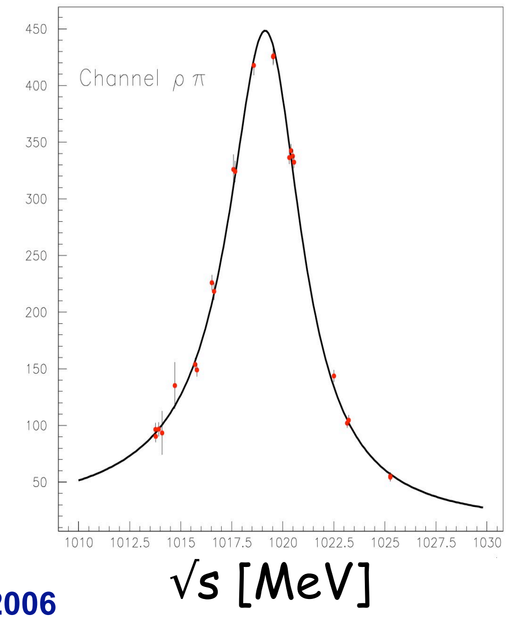
Double Annular ring For Nice Experiments



Daphnis and Chloe by Marc Chagall



The ϕ resonance by KLOE



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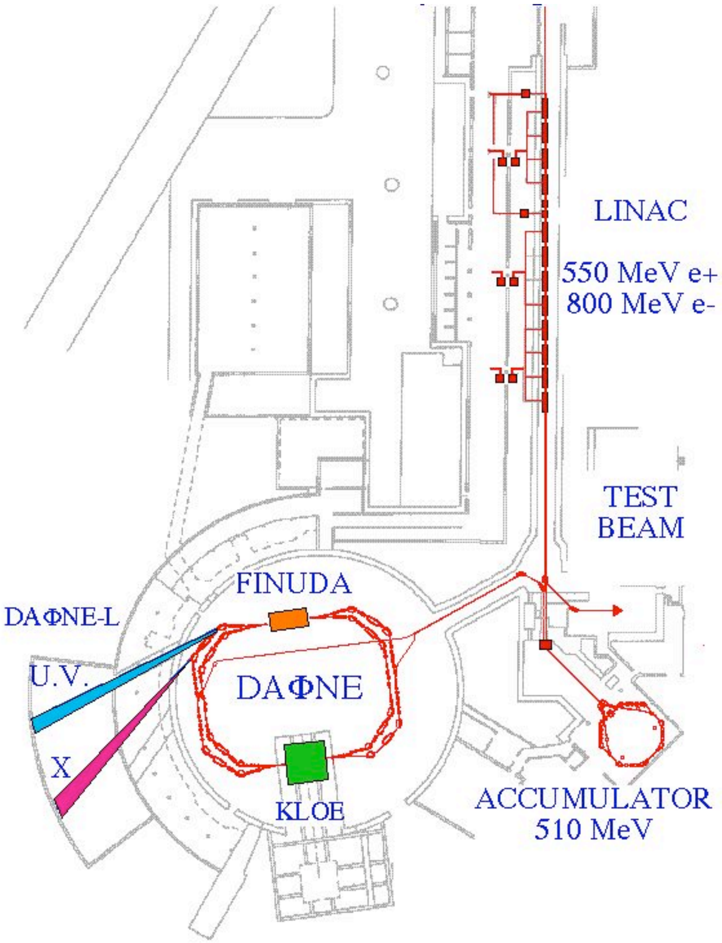
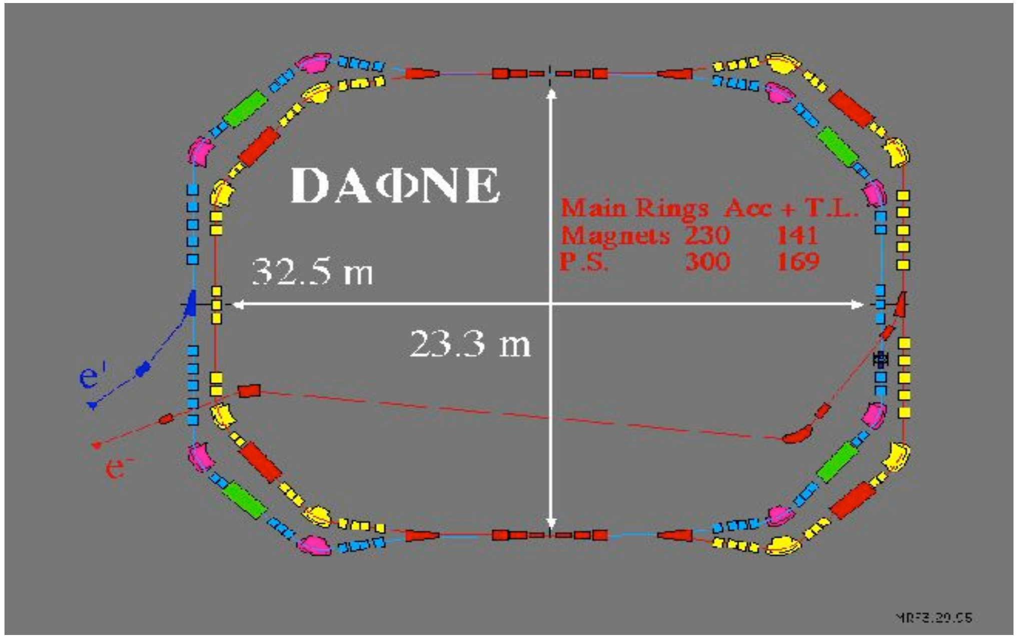
the Frascati ϕ factory

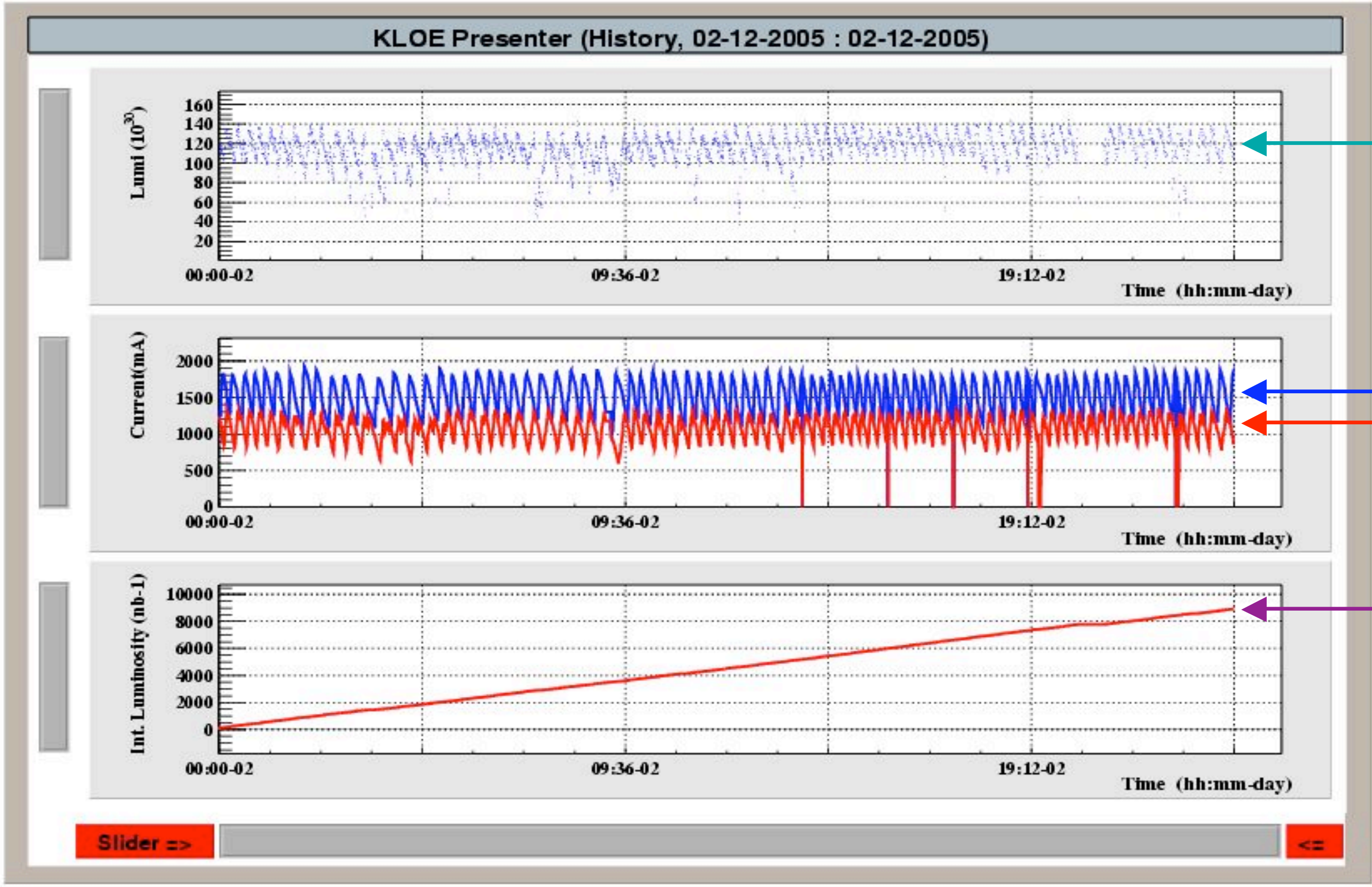


- e^+e^- collider $\sqrt{s} = M_\varphi = 1019.4$ MeV
- 2 interaction regions (KLOE – DEAR/FINUDA)
- separate e^+, e^- rings to minimize beam-beam interactions
- crossing angle: 12.5 mrad $\rightarrow p_T \sim 13$ MeV/c



KLOE data taking

DAΦNE 24h performance in topping-up mode, december 05



$L = 1.2\ 10^{32}\ cm^{-2}\ s^{-1}$

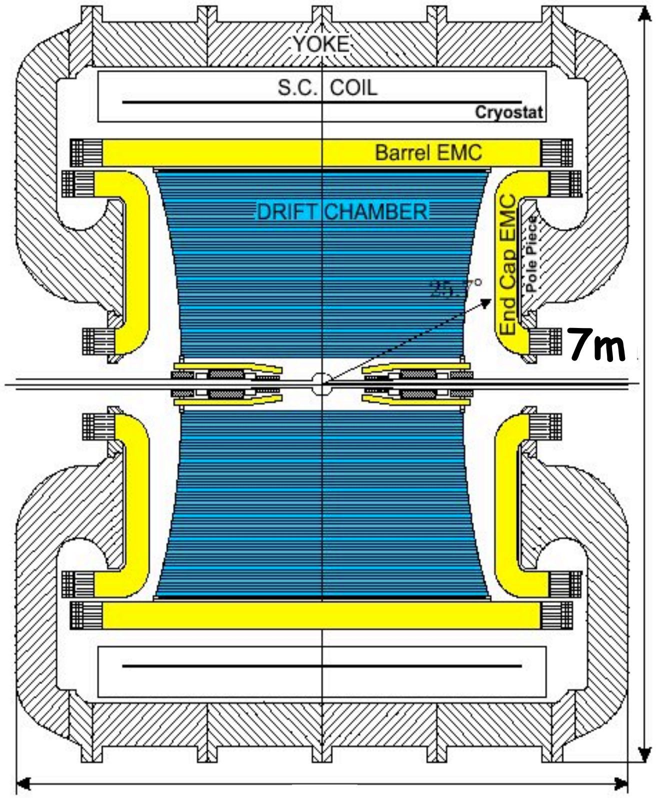
e^- 1.6 A

e^+ 1.1 A

$\int Ldt = 8\ pb^{-1}$

the KLOE experiment

K LOng Experiment



Large decay volume λ_L = 3.5 m

Maximum trasparency

Unbiased trigger

Tracking
Vertexing
Calorimetry
Time of flight

Spherical **beam pipe**, 10 cm ∅, 0.5 mm thick, in Be-Al alloy, to minimize regeneration, scattering, γ conversion

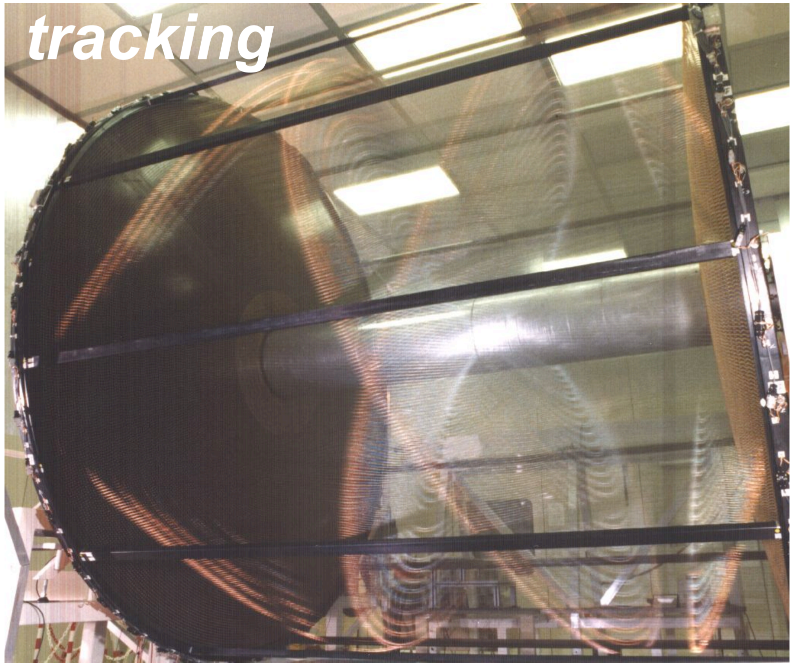
Permanent-magnet **low-β quadrupoles** instrumented, to increase the hermeticity for γ detection

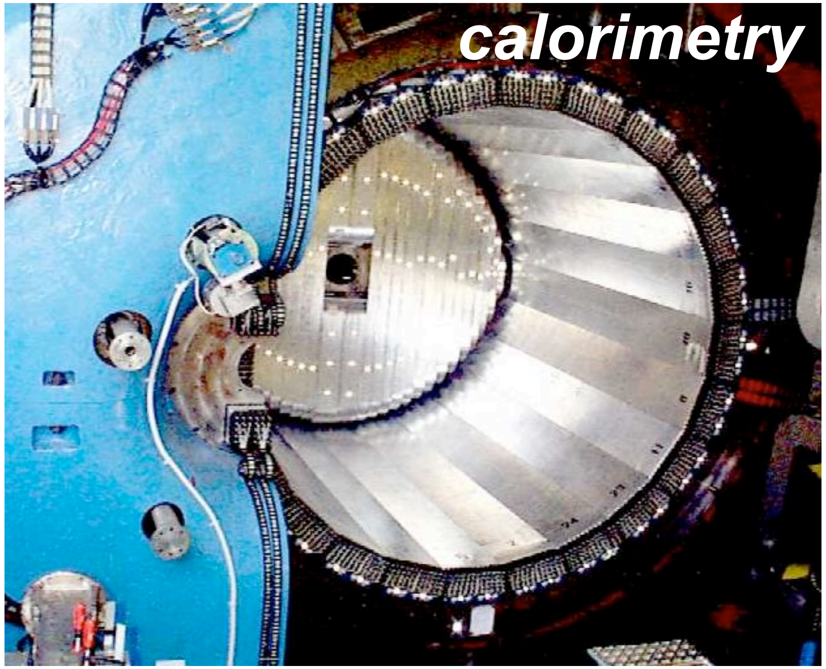
Tracking: large volume drift chamber, 4 m ∅, L=3.4 m, with carbon-fiber frame, filled with low-density gas (90%He + 10%i-C_4H_{10}), 12582 all-stereo squared cells (wires: tungsten 25 μm ∅ + aluminum 50 μm ∅)

Calorimeter: 0.5 mm lead - 1 mm ∅ scintillating fibers, 15 X_0 thick, finely segmented in 2 × 2440 cells

Superconducting coil, B = 0.52 T

the KLOE detectors





$\sigma_p / p = 0.4\%$ for tracks $\theta > 45°$
$\sigma_{r\varphi} = 0.150$ mm, $\sigma_z = 2$ mm
$\sigma_{vertex} \sim 3$ mm
$\sigma(m_{\pi\pi}) \sim 1$ MeV

$\varepsilon > 95\%$ for $E_\gamma > 20$ MeV
$\sigma_E / E = 0.057/\sqrt{E}$ (GeV)
$\sigma_t = 54$ ps $/ \sqrt{E}$ (GeV) $\oplus$ 50 ps
$\sigma_{shower} = 1.3$ cm $/ \sqrt{E}$ (GeV)
$\sigma_{vertex}(\gamma\gamma) \sim 1.5$ cm ($K_L \rightarrow \pi^+\pi^-\pi^0$)

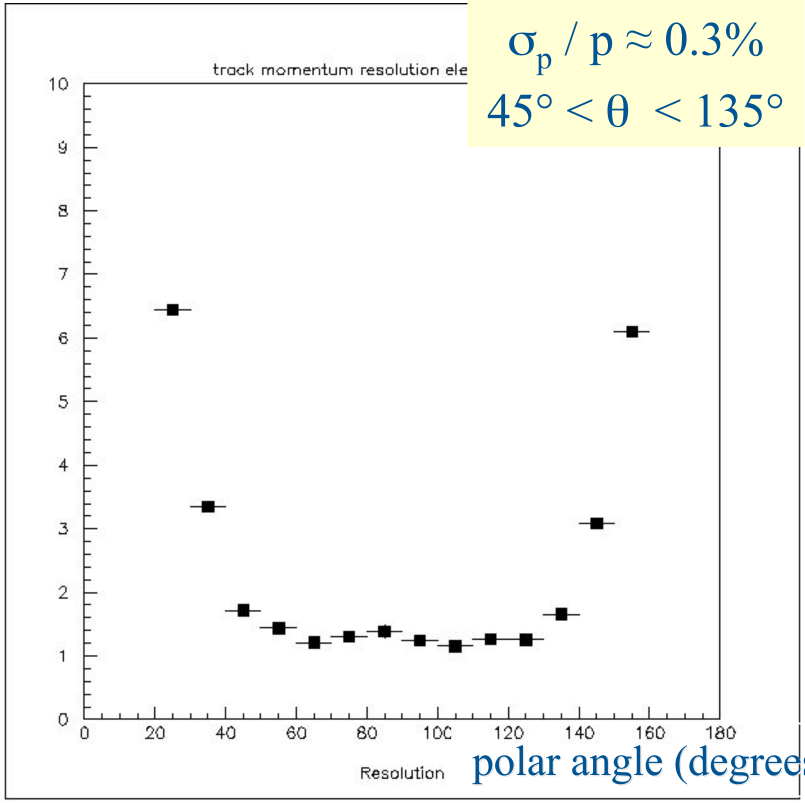
tracking in the drift chamber

drift chamber resolution $\sigma_{r\varphi} \approx 150\ \mu m$

Bhabha scattering events

$\sigma_p / p \approx 0.3\%$

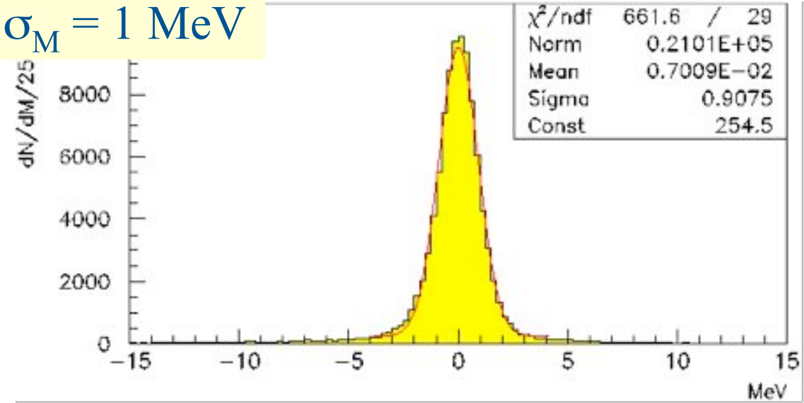
$45° < \theta < 135°$



polar angle (degrees)

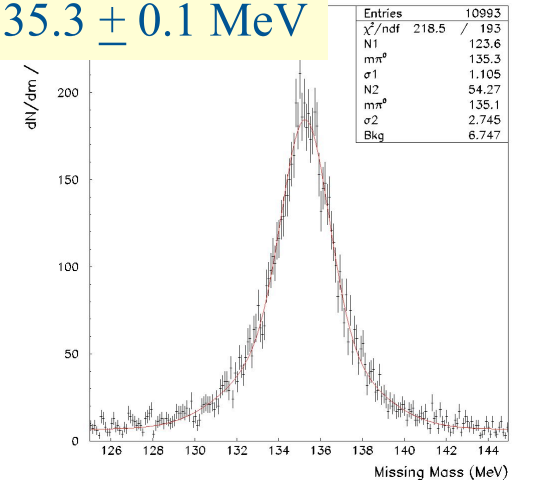
$K_S \rightarrow \pi^+\pi^-$

$\sigma_M = 1$ MeV



$K_L \rightarrow \pi^+\pi^-\pi^0$

$M(\pi^0) = 135.3 \pm 0.1$ MeV



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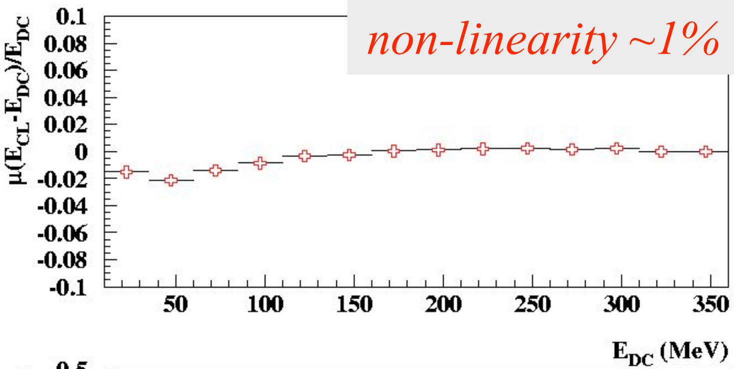
measuring photons

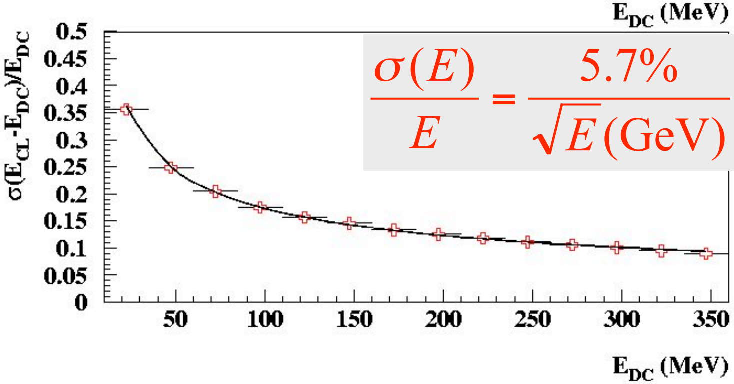
Energy resolution

$\phi \to \pi^+\pi^-\pi^0$ E_γ from tracking

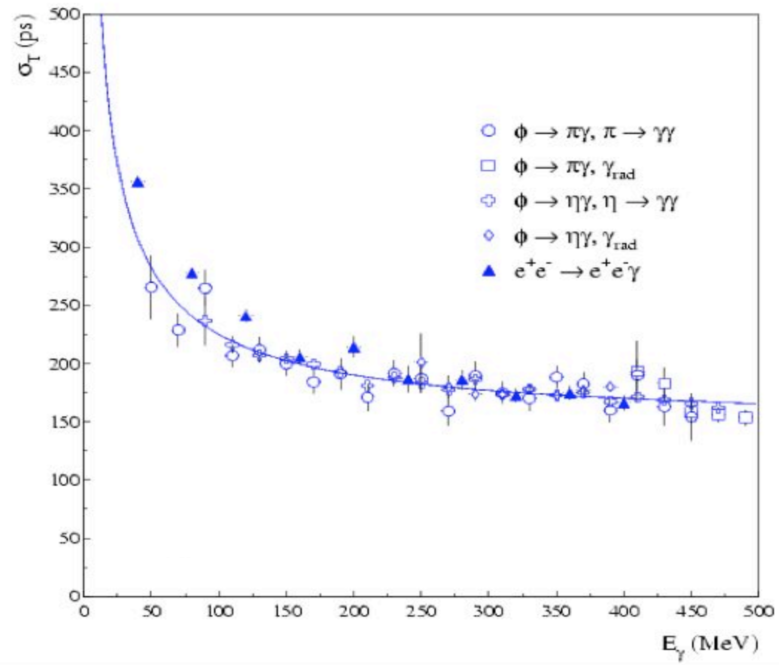
non-linearity ~1%



$$\frac{\sigma(E)}{E} = \frac{5.7\%}{\sqrt{E(\mathrm{GeV})}}$$



Time resolution



$\sigma(t) = 54\ \mathrm{ps} / \sqrt{(E/\mathrm{GeV})} \oplus 120\ \mathrm{ps} \oplus 40\ \mathrm{ps}$

bunch structure

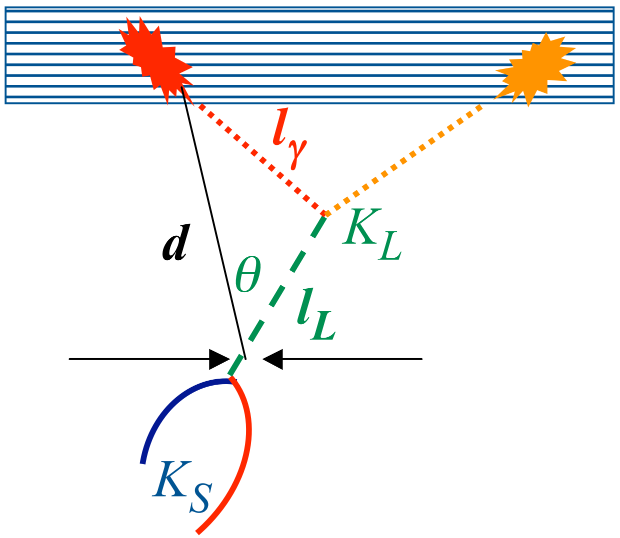
miscalibration term

measuring photons

the photon decay triangle

$$l_\gamma^2 = d^2 + l_L^2 - 2d\, l_L \cos\theta$$

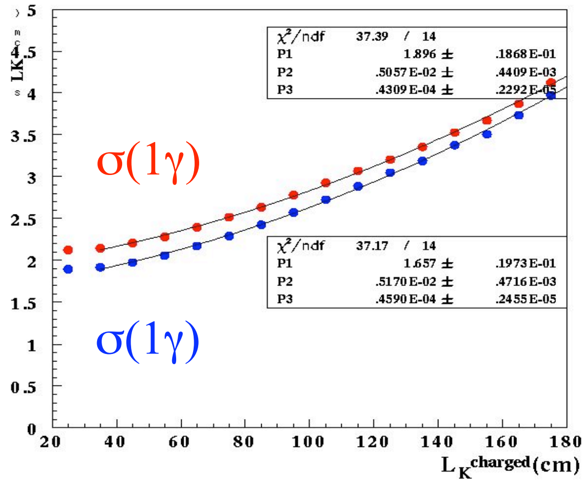
$$ct_\gamma = l_L / \beta_L + l_\gamma$$



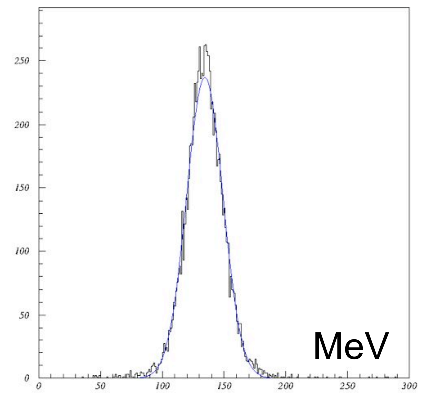
neutral vertex space resolution

$K_L \rightarrow \pi^+\pi^-\pi^0$

$\sigma(l_{\pi\pi} - l_\gamma)$



γγ mass resolution



M = 134.5 MeV

$\sigma_M \approx 14$ MeV

the trigger

as unbiased as possible

bunch crossing period is 2.7 ns << particle propagation

large time spread: L/c of prompt photon ≈ 7 ns, L/βc of *K* ≈ 30 ns

Level-1 initiates the read-out of the calorimeter

energy deposits in the calorimeter

OR multiplicity and topology of drift cells hit in a narrow time window

AND Level-2 confirmation after 2 μs: stop to the drift chamber

cosmic ray rate ≈ 3 kHz: cosmic ray "soft" **VETO**

from the outermost layer of the calorimeter

downscaled for checks

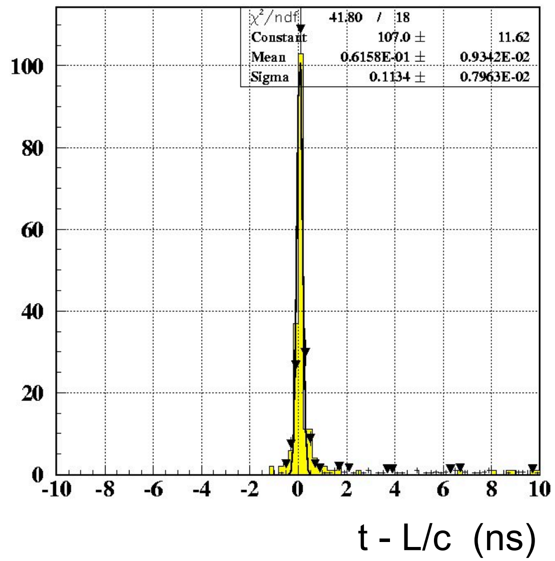
t_0 of the event found off-line from the event topology

typical data acquistion rate ≈ 2.5 kHz

- 1/2 machine background
- 1/4 cosmic rays
- 1/4 e^+e^- collisions

off-line filter for rejection of background and cosmics

Bhabha scattering events

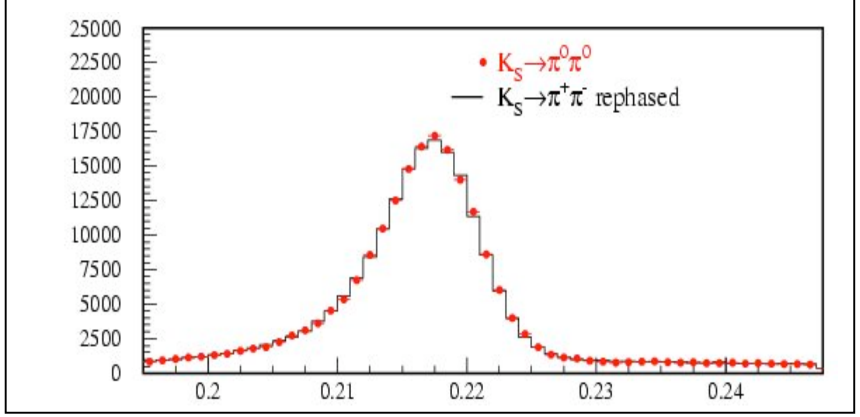


measuring the DAΦNE parameters

monitoring on-line

- Bhabha scattering events
- $e^+e^- \to \gamma\gamma$ events
- β^* of K_L interactions
- $\phi \to K_L K_S$ decays
- $K_S \to \pi^+\pi^-$ opening angle

β^*_K after correction for pion velocities



e^+e^- c.m. energy: $\sigma_E \approx 10$ keV

beam-beam energy spread: $\delta E \approx 0.3$ MeV

e^+e^- transverse momentum: $\sigma_{PT} \approx 0.1$ MeV/c

beam-beam luminous point: $\sigma_{\Delta x}$, $\sigma_{\Delta z} \approx 0.1$ mm

luminosity: $\delta L / L \approx 2\%$ $\Rightarrow$ 0.6% off-line

$\int Ldt \approx 2.4$ fb^{-1} of data on disk, $\approx 1/5$ analysed so far

$\phi \to K\, K$ decays

the ϕ decay at rest provides monochromatic and pure kaon beams

$$K^+ K_L \longleftarrow \phi \longrightarrow K^- K_S$$

pure $J^{PC} = 1^{--}$ state

$$\frac{1}{\sqrt{2}}\left(|K, -\mathbf{p}\,\rangle|\bar{K}, +\mathbf{p}\,\rangle - |\bar{K}, +\mathbf{p}\,\rangle|K, -\mathbf{p}\,\rangle\right)$$

Tagging: observation of $K_{S,L}$ signals the presence of $K_{L,S}$; K^+ signals K^-

⇒ clean, normalized K^+ K^- K_L and K_S beams

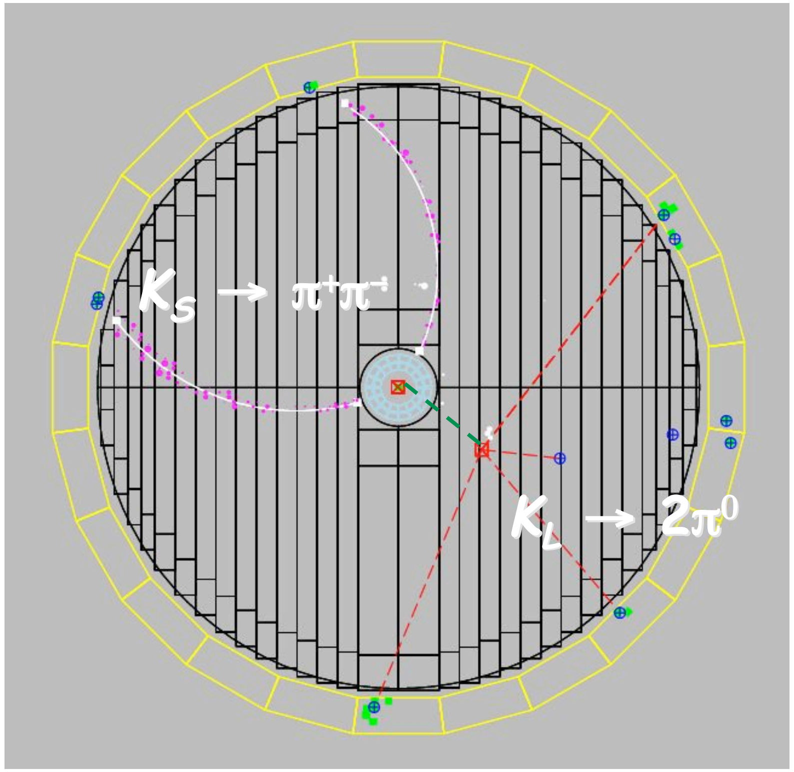
⇒ measurement of absolute branching ratios: $BR = N_{evt} / \varepsilon_{evt} N_{tag}$

$K^+ K^-$
$\beta^* = 0.245$
$p^* = 127$ MeV/c
$\lambda_\pm = 95$ cm

$K_L K_S$
$\beta^* = 0.216$
$p^* = 110$ MeV/c
$\lambda_S = 6$ mm; $\lambda_L = 3.4$ m

tagging of K_L or K_S beam

K_L tagged by $K_S \to \pi^+\pi^-$

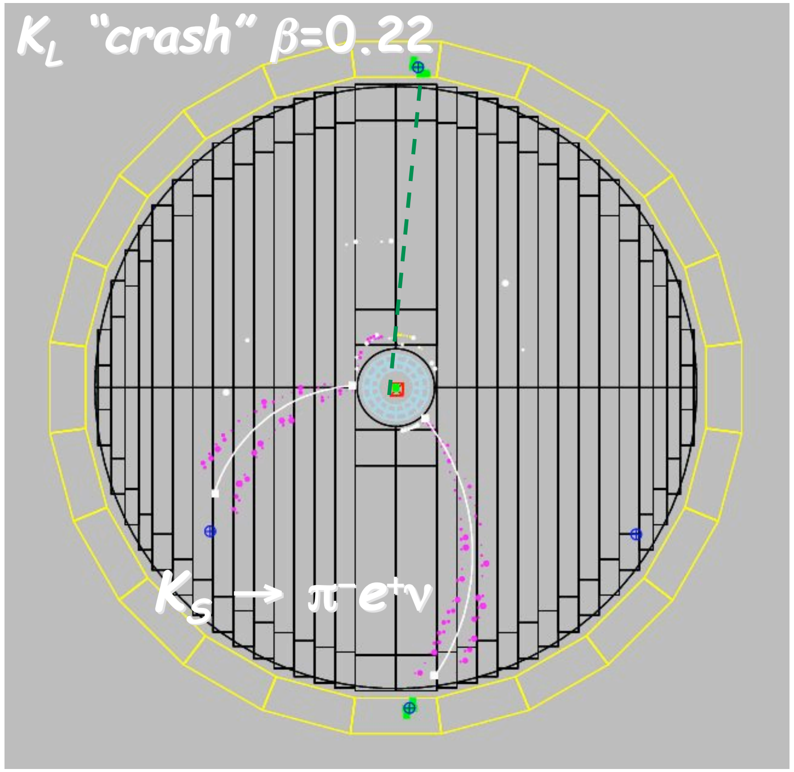


ε ~ **70%** geometry & vertex

K_L angular resolution ~ 1°

K_L momentum resolution ~ 1 MeV

K_S tagged by K_L interaction



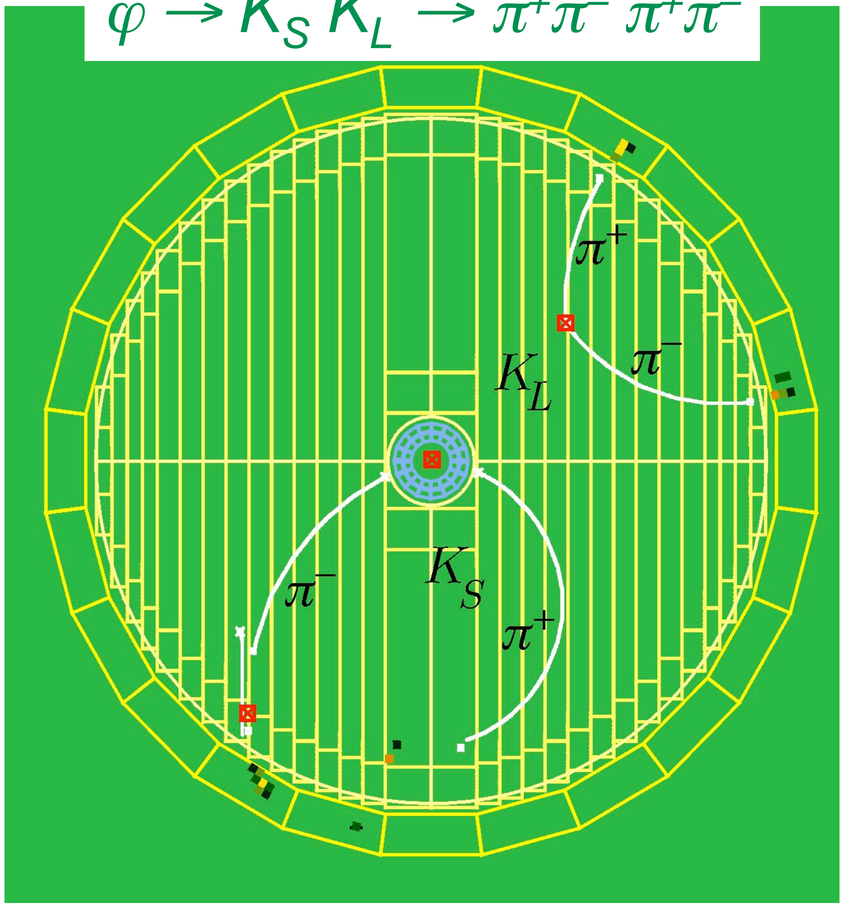
ε ~ **30%** geometry & energy cut

K_S angular resolution ~ 1°

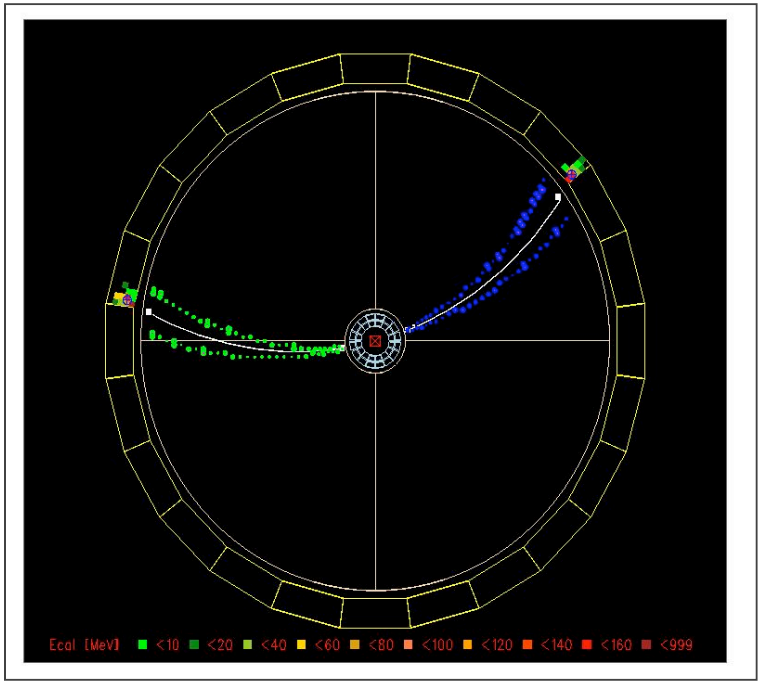
K_S momentum resolution ~ 1 MeV

the first CP-violating event

during the commissioning of DAΦNE, photo of the month in 1999



a Bhabha scattering event



tagging K_L decays

K_S - tag

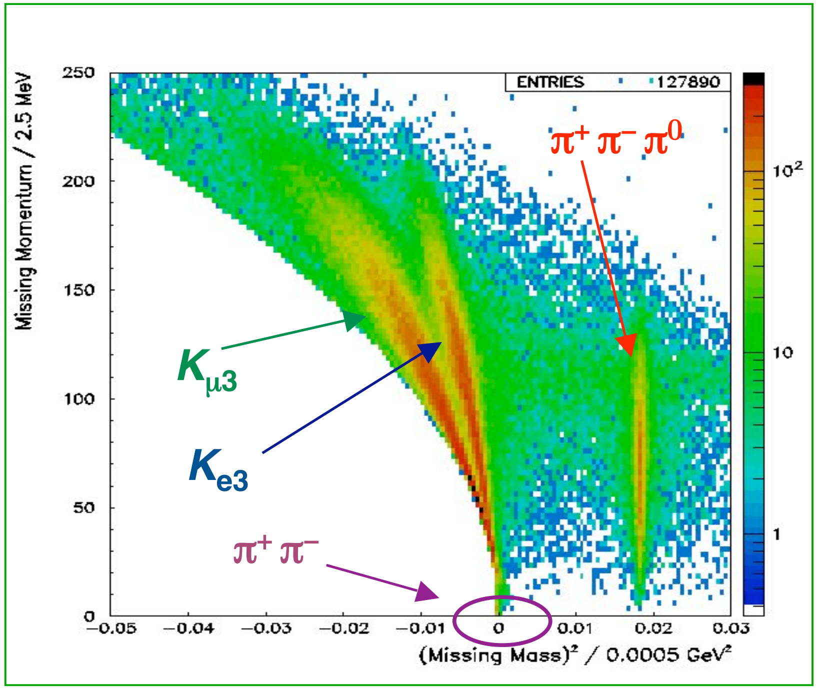
- two tracks with opposite curvature
- that form a vertex
- in a small cylinder around the crossing point
- $\boldsymbol{p}_1 + \boldsymbol{p}_2 \approx 110$ MeV/c
- $M_{12} \approx M_K$ assigning the π mass to the tracks

K_L

- two tracks with opposite curvature
- that form a vertex
- in a decay fiducial volume
- along the direction opposite to $\boldsymbol{p}_{12}$

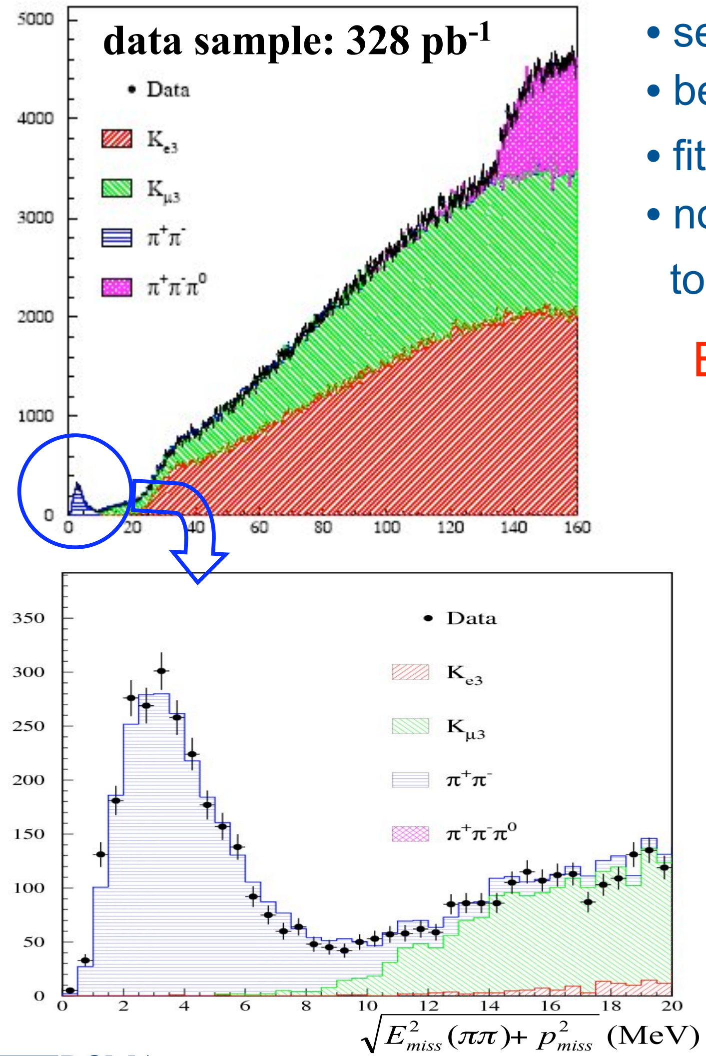
assigning to both tracks the π mass:
the missing momentum × missing mass plot
clearly separates the main decays

using only the tracking information



then π–μ–e identification done by time-of-flight, shower shape and dE/dx

$K_L \to \pi^+\pi^-$



- select all K_L decays
- best discriminating variable for $K_L \to \pi^+\pi^-$ $\sqrt{E^2_{miss}(\pi\pi) + p^2_{miss}}$
- fit the distribution to Monte Carlo shapes
- normalize to the decay $K_L \to \pi\mu\nu$ to reduce systematics due to tag bias

$BR(K_L \to \pi^+\pi^-) = (1.963 \pm 0.012 \pm 0.017) \times 10^{-3}$

using the KLOE results for $BR(K_S \to \pi^+\pi^-)$ and τ_L and the world average for τ_S *and* $Re(\varepsilon'/\varepsilon)$

$|\eta_{+-}| = (2.219 \pm 0.013) \times 10^{-3}$

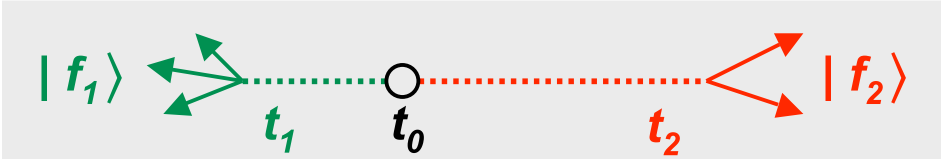
$|\varepsilon| = (2.284 \pm 0.014) \times 10^{-3}$

In this 2006 edition of the *Review of Particle Physics*, the values of $|\epsilon|$, $|\eta_{+-}|$, and $|\eta_{00}|$ decrease significantly as a result of the high precision measurements of K^0_L branching ratios from KTeV, KLOE, and NA48. These measurements reduce the branching ratio $\Gamma(K^0_L \to \pi^+\pi^-)/\Gamma(\text{total})$ by 5.5 percent, a 4.6σ decrease relative to the 2004 edition [21].

$\phi \to K_S\, K_L$ time evolution

an example of quantum interference

$$|\, i\,\rangle = \frac{1}{\sqrt{2}}\left[|K_S(\mathbf{p}), K_L(-\mathbf{p})\rangle - |K_L(\mathbf{p}), K_S(-\mathbf{p})\rangle\right]$$



time evolution of the system

$$\langle f_1 t_1, f_2 t_2|\, i\,\rangle = \frac{1}{\sqrt{2}}\left[\langle f_1 t_1|K_S(\mathbf{p})\rangle\langle f_2 t_2|K_L(-\mathbf{p})\rangle - \langle f_1 t_1|K_L(\mathbf{p})\rangle\langle f_2 t_2|K_S(-\mathbf{p})\rangle\right]$$

$$= \frac{1}{\sqrt{2}}\left(\langle f_1|K_S\rangle\langle f_2|K_S\rangle\ \eta_2\ e^{-im_S t_1 - \Gamma_S t_1/2 - im_L t_2 - \Gamma_L t_2/2} - \langle f_2|K_S\rangle\langle f_1|K_S\rangle\ \eta_1\ e^{-im_S t_2 - \Gamma_S t_2/2 - im_L t_1 - \Gamma_L t_1/2}\right)$$

$$= \frac{\langle f_1|K_S\rangle\langle f_2|K_S\rangle}{\sqrt{2}}\left(\eta_2\ e^{-(\Gamma_S t_1 + \Gamma_L t_2)/2}\ e^{-i(m_S t_1 + m_L t_2)} - \eta_1\ e^{-(\Gamma_S t_2 + \Gamma_L t_1)/2}\ e^{-i(m_S t_2 + m_L t_1)}\right)$$

number of decays to the state f_1 at t_1 and f_2 at t_2

$$N(f_1 t_1, f_2 t_2) = \frac{|\langle f_1|K_S\rangle\langle f_2|K_S\rangle|^2}{2}\left(|\eta_2|^2 e^{-(\Gamma_S t_1 + \Gamma_L t_2)} + |\eta_1|^2 e^{-(\Gamma_S t_2 + \Gamma_L t_1)} - 2|\eta_1||\eta_2| e^{-(\Gamma_S + \Gamma_L)(t_2 + t_1)/2}\cos[\Delta m(t_2 - t_1) + \phi_2 - \phi_1]\right)$$

as a function of the relative delay $|\Delta t|$

$$N(f_1, f_2, \Delta t) = \int_{\Delta t \geq 0} N(f_1 t_1, f_2 t_2) d[t_1 + t_2] = \frac{|\langle f_1|K_S\rangle\langle f_2|K_S\rangle|^2}{2(\Gamma_S + \Gamma_L)}\left(|\eta_2|^2 e^{-\Gamma_S \Delta t} + |\eta_1|^2 e^{-\Gamma_L \Delta t} - 2|\eta_1||\eta_2| e^{-(\Gamma_S + \Gamma_L)\Delta t/2}\cos[\Delta m \Delta t + \phi_2 - \phi_1]\right)$$

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$\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^-$

different interference patterns for different decay modes

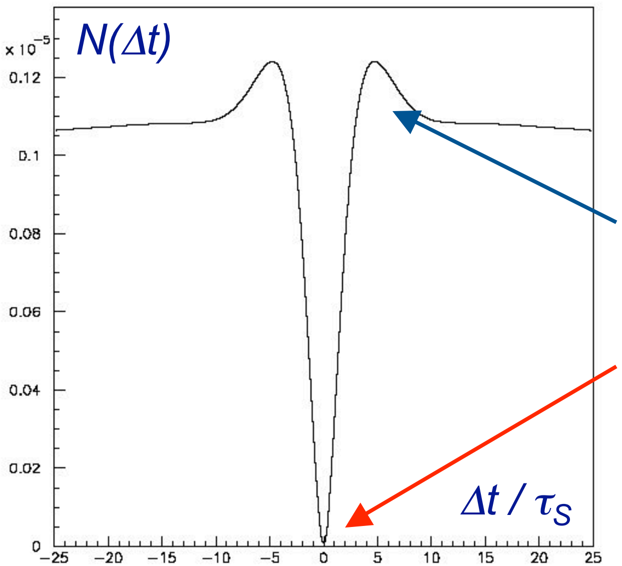
$f_1 = f_2 = \pi^+\pi^-$

$$N(t_1,t_2) = \frac{|\langle\pi^+\pi^-|K_S\rangle|^4|\eta_{+-}|^2}{2}\left(e^{-(\Gamma_S t_1+\Gamma_L t_2)} + e^{-(\Gamma_S t_2+\Gamma_L t_1)} - 2e^{-(\Gamma_S+\Gamma_L)(t_2+t_1)/2}\cos\Delta m(t_2-t_1)\right)$$

$$N(\Delta t) = \frac{|\langle\pi^+\pi^-|K_S\rangle|^4|\eta_{+-}|^2}{2(\Gamma_S+\Gamma_L)}\left(e^{-\Gamma_S\Delta t} + e^{-\Gamma_L\Delta t} - 2e^{-(\Gamma_S+\Gamma_L)\Delta t/2}\cos\Delta m\Delta t\right)$$

no decays with $\Delta t = 0$! a kaon can influence the other's fate without delay

an example of the Einstein-Podolsky-Rosen paradox



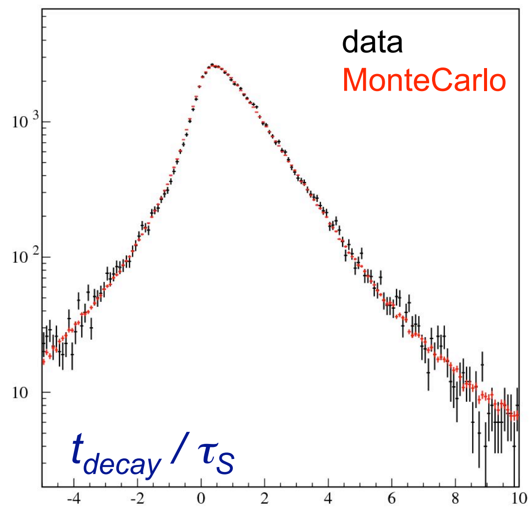
peak height and position sensitive to Δm

distructive quantum interference: no simultaneous decays in the same final state

$\tau_S = (0.9030 \pm 0.0056)\ 10^{-10}$ s

PDG: $(0.8935 \pm 0.0008)\ 10^{-10}$ s

K_S lifetime



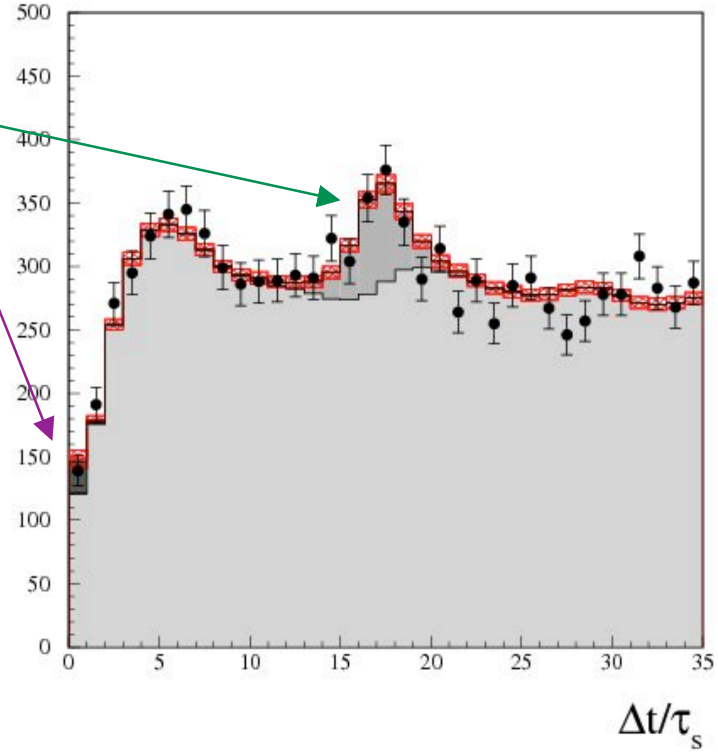
time resolution should be $\approx \tau_S$ ⟶ $\sigma = (1.15 \pm 0.02) \times \tau_S$

quantum coherence & CPT symmetry

data: 380 pb^{-1}, 7366 events

$K_L \rightarrow K_S$ coherent regeneration on the beam pipe

$e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$ non-resonant background



fitting the $\Delta t / \tau_S$ distribution with models

- CPT-violating parameter ω
- quantum decoherence parameter ζ

$$| i \rangle = \frac{1}{\sqrt{2}}\left(\left[|K^0,\overline{K^0}\rangle - |\overline{K^0},K^0\rangle\right] + \omega\left[|K^0,\overline{K^0}\rangle + |\overline{K^0},K^0\rangle\right]\right)$$

$| \omega | < 2.1\ 10^{-3}$ at 95% CL

$$N(\Delta t) \propto e^{-\Gamma_S \Delta t} + e^{-\Gamma_L \Delta t} - (1-\zeta) 2e^{-(\Gamma_S+\Gamma_L)\Delta t/2} \cos \Delta m \Delta t$$

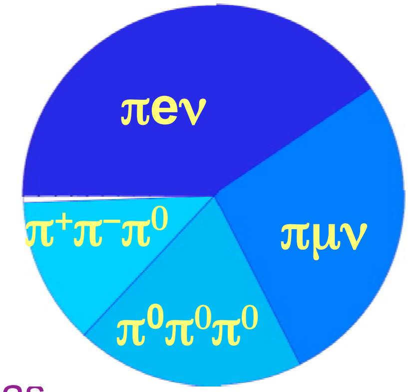
$\Delta m = (5.34 \pm 0.34)\ 10^9\ s^{-1}$

$\zeta_{00} < 0.5\ 10^{-5}$ at 95% CL

if Δm fixed at the PDG value $(5.290 \pm 0.016)\ 10^9\ s^{-1}$

dominant K_L decays

measurement of the absolute branching ratios



$$BR(K_L \to f) = \frac{N_f}{N_{tag}} \frac{1}{\epsilon_{rec}^{f} \, \epsilon_{FV}(\tau_L) \cdot \epsilon_{tag}^{f}/\epsilon_{tag}^{all}}$$

reconstruction efficiency

$K_L \to \pi e\nu, \pi\mu\nu$ $\varepsilon \approx 55\%$

$K_L \to \pi^+\pi^-\pi^0$ $\varepsilon \approx 40\%$

$K_L \to \pi^0\pi^0\pi^0$ $\varepsilon \approx 99\%$

integral over the fiducial volume

$\varepsilon(\tau_L) \approx 26\%$

tag bias,
ask for $K_S \to \pi^+\pi^-$
to trigger the event

328 pb^{-1}: 13 10^6 K_L tagged by $K_S \to \pi^+\pi^-$

- 1/4 for the measurement
- 3/4 to evaluate efficiencies

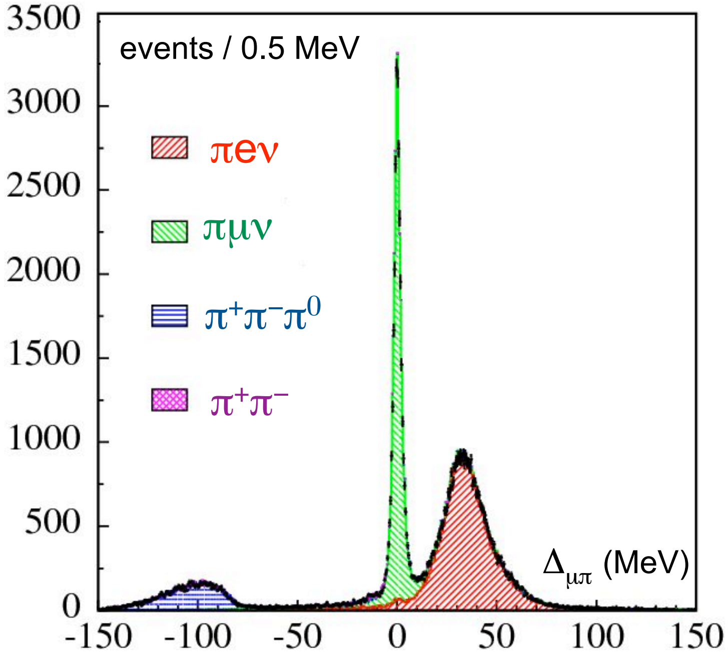
$\pi^0\pi^0\pi^0$

- energy-clusters vertex reconstructed by TOF
- ε_{rec} = 99%, background < 1%

$\pi e\nu$, $\pi\mu\nu$, $\pi^+\pi^-\pi^0$

- two-tracks vertex in the fiducial volume
- P.I.D. using shower shape and decay kinematics
- best discriminating variable: lesser of p_{miss}-E_{miss} in π-μ or μ-π hypothesis
- fit the MonteCarlo distribution including radiative processes

K_L decays

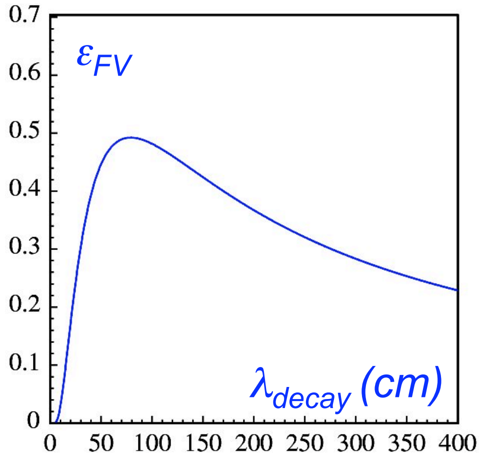


$\Delta_{\mu\pi}$ = lesser of p_{miss}-E_{miss} in π-μ or μ-π hypothesis

$BR(\pi e\nu + \pi\mu\nu + \pi^+\pi^-\pi^0 + \pi^0\pi^0\pi^0)_{KLOE}$

$+ BR(\pi^+\pi^- + \pi^0\pi^0)_{PDG04} = 1.0104 \pm 0.0076$

the efficiency depends on the lifetime and the error on the BR is dominated by the error on τ_L



- sum of all BR's
- constraint $\sum_i Br_i = 1$
- re-evaluate BR's
- evaluate the K_L lifetime

K_L branching ratios

absolute branching ratios fully inclusive for radiation

BR($K_L \to \pi e \nu(\gamma)$) = 0.4007 ± 0.0006 ± 0.0014

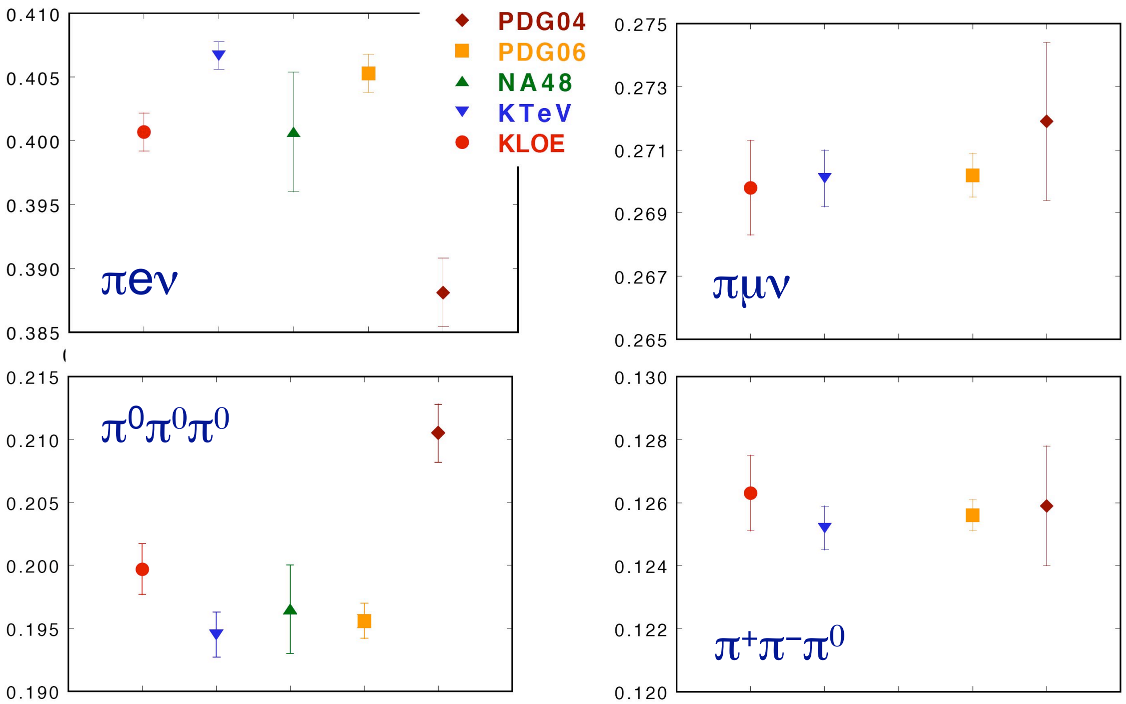
BR($K_L \to \pi \mu \nu(\gamma)$) = 0.2698 ± 0.0006 ± 0.0014

BR($K_L \to \pi^+\pi^-\pi^0(\gamma)$) = 0.1263 ± 0.0005 ± 0.0011

BR($K_L \to \pi^0\pi^0\pi^0$) = 0.1997 ± 0.0005 ± 0.0019

lifetime from normalization

τ_L = 50.72 ± 0.17 ± 0.33 ns



much has changed in the last years

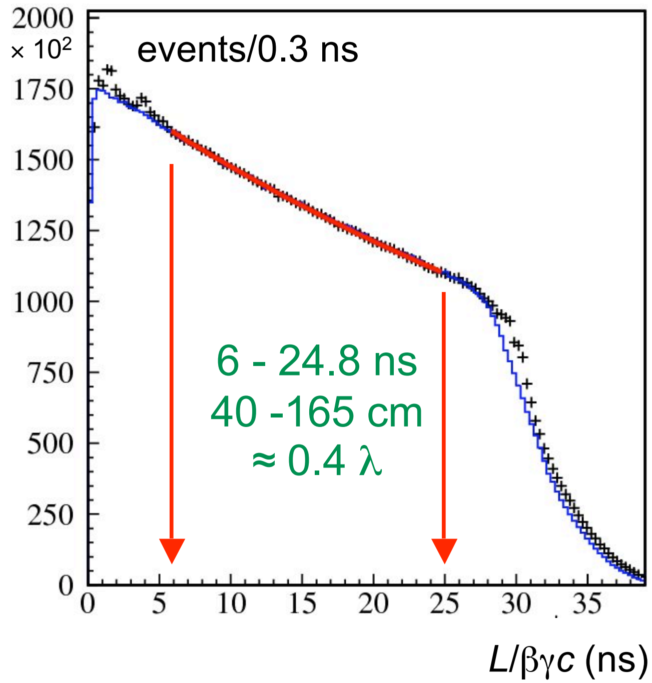
K_L lifetime

direct measurement of the K_L lifetime

- use the decay $K_L \to \pi^0\pi^0\pi^0$ tagged by $K_S \to \pi^+\pi^-$
- large acceptance ≈ 0.4 λ
- very high efficiency, ≈ constant along decay path
- use $K_L \to \pi^+\pi^-\pi^0$ to evaluate resolution and time scale

data: 400 pb^{-1}, 10^7 $K_L \to \pi^0\pi^0\pi^0$ events

τ_L = 50.92 ± 0.17 ± 0.25 ns



the two measurements are independent,
can make the average (considering correlations)

τ_L = 50.84 ± 0.23 ns

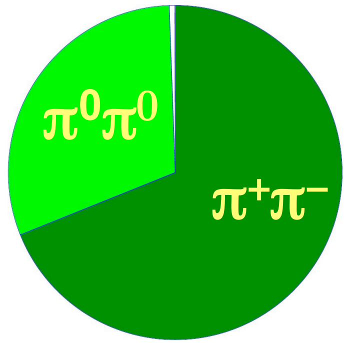
only an old precise measurement
Vosburg'72: τ_L = 51.54 ± 0.44 ns

K^0_L MEAN LIFE

VALUE (10^{-8} s)	EVTS	DOCUMENT ID		TECN
5.114±0.021 OUR FIT				
5.099±0.021 OUR AVERAGE				
5.072±0.011±0.035	13M	[13] AMBROSINO	06	KLOE
5.092±0.017±0.025	15M	AMBROSINO	05C	KLOE
5.154±0.044	0.4M	VOSBURGH	72	CNTR

dominant K_S decays

measurement of the absolute branching ratios



K_L - tag

- ≈ 50% of K_L interact in the calorimeter
- energy cluster with E > 200 MeV
- $\beta^* \approx 0.216$
- angular resolution ≈ 1°

$K_S \to \pi^+\pi^-$

- two tracks with opposite curvature
- that form a vertex close to the interaction region
- $120 < p < 300$ MeV/c, $30^o < \theta < 150^o$
- acceptance × efficiency ≈ 0.59

$K_S \to \pi^0\pi^0$

- at least three "prompt" clusters
- $| t - r/c | < 5\sigma_t$
- E > 20 MeV, $25^o < \theta < 155^o$
- acceptance × efficiency ≈ 0.85

data: 410 pb^{-1}, measure the ratio $K_S \to \pi^+\pi^-(\gamma)$ / $K_S \to \pi^0\pi^0$ = 2.2549 ± 0.0054

including semileptonic decays, $K_S \to \pi e\nu$, $\pi\mu\nu$, and normalizing $\sum_i Br_i = 1$

BR($K_S \to \pi^+\pi^-(\gamma)$) = (69.196 ± 0.051)%

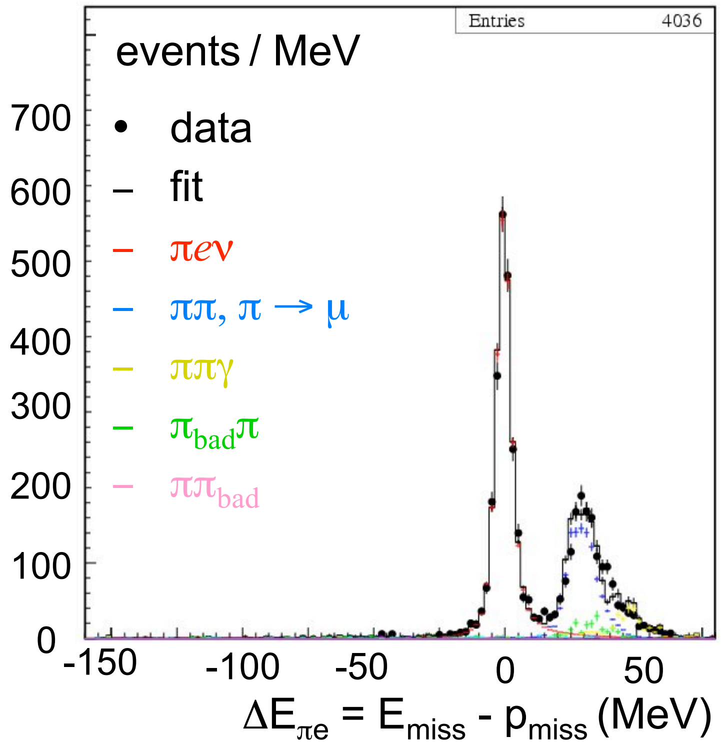
BR($K_S \to \pi^0\pi^0$) = (30.678 ± 0.051)%

K_S semileptonic decays

$K_S \to \pi e \nu$

- two tracks with opposite curvature
- that form a vertex close to the interaction region
- $M_{\pi\pi}$ < 490 MeV assigning the π mass
- e-π identification by time-of-flight
- fit the distribution of $E_{miss}(\pi e) - p_{miss}$

data: 410 pb^{-1},
normalization to $K_S \to \pi^+\pi^-(\gamma)$ in the same data set



BR($K_S \to \pi^- e^+ \nu$) = (3.528 ± 0.062) 10^{-4}

BR($K_S \to \pi^+ e^- \nu$) = (3.517 ± 0.058) 10^{-4}

BR($K_S \to \pi e \nu$) = (7.046 ± 0.091) 10^{-4}

charge asymmetry

$$A_S = \frac{N(K_S \to \pi^- e^+ \nu) - N(K_S \to \pi^+ e^- \nu)}{N(K_S \to \pi^- e^+ \nu) + N(K_S \to \pi^+ e^- \nu)} = (1.5 \pm 9.6 \pm 2.9)\ 10^{-3}$$

$A_L = (3.322 \pm 0.058 \pm 0.047)\ 10^{-3}$ KTeV
$A_L = (3.317 \pm 0.070 \pm 0.072)\ 10^{-3}$ NA48

- $A_S = A_L$ if CPT-symmetry and $\Delta S = \Delta Q$ hold
- $A_S \neq A_L$ signals CPT-violation in mixing and/or $\Delta S \neq \Delta Q$ in the decay

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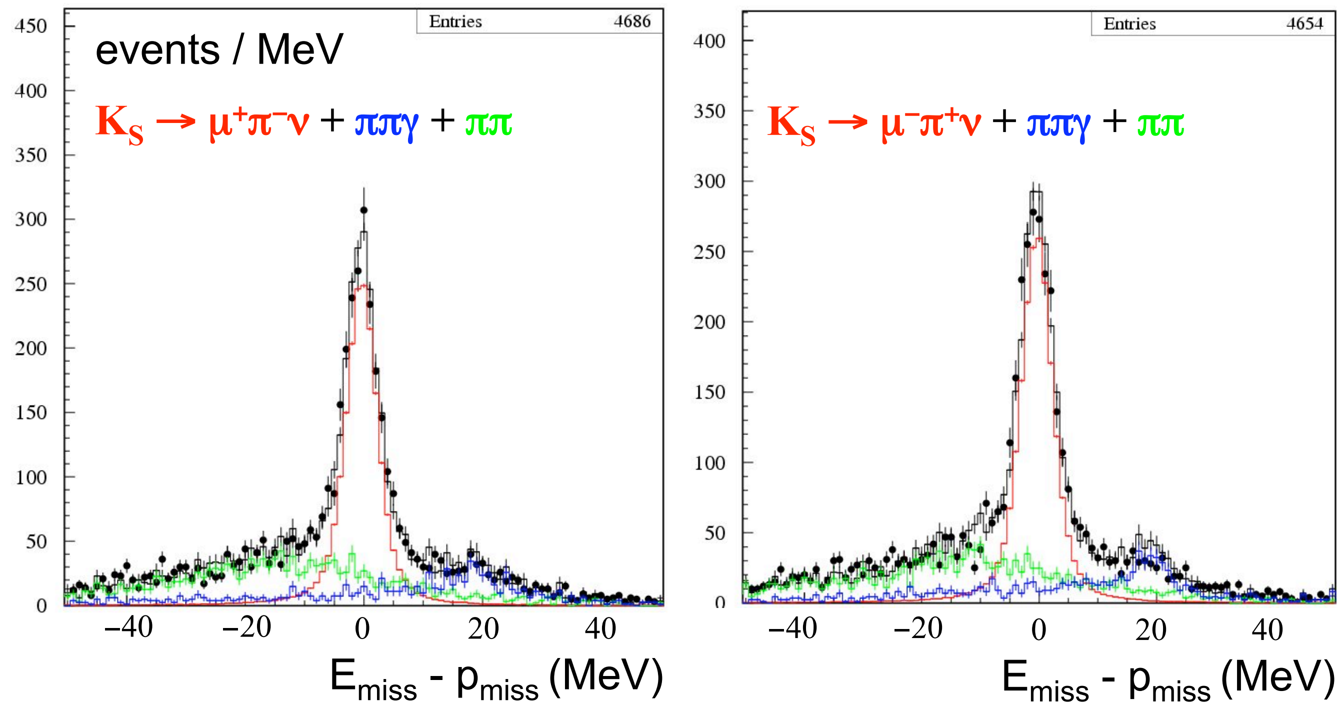
$K_S \to \pi\mu\nu$ first measurement

$K_S \to \pi\mu\nu$

- two tracks with opposite curvature
- that form a vertex close to the interaction region
- μ-π identification by time-of-flight
- fit the distribution of $E_{miss}(\pi\mu) - p_{miss}$

work in progress, should reach ≈ 3% statistical error with 410 pb^{-1}



search for $K_S \to \pi^0\pi^0\pi^0$

$K_S \to \pi^0\pi^0\pi^0$ pure CP-violating decay

defining $\eta_{000} = \dfrac{\langle \pi^0\pi^0\pi^0 | K_S \rangle}{\langle \pi^0\pi^0\pi^0 | K_L \rangle} = \varepsilon + \varepsilon'_{000}$ with $|\varepsilon'_{000}| << |\varepsilon|$

$\Rightarrow$ small branching ratio: $BR(K_S \to 3\pi^0) \approx |\eta_{000}|^2 \, BR(K_L \to 3\pi^0) \, \tau_S / \tau_L \approx 1.9 \; 10^{-9}$

best limit from NA48: $BR(K_S \to 3\pi^0) < 7.4 \; 10^{-7}$ at 90% CL

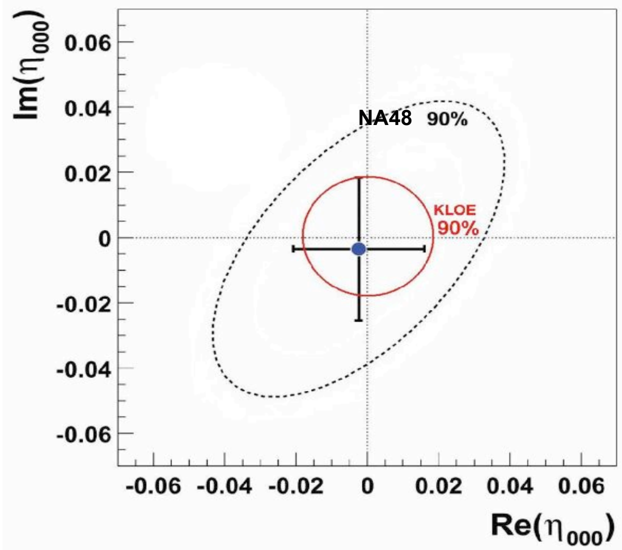
$K_S \to \pi^0\pi^0\pi^0$

- six neutral “prompt” clusters
- no tracks from interaction region
- kinematic fit: K-mass & energy-momentum conservation
- efficiency = 24%
- normalize to $K_S \to \pi^0\pi^0$ in the same data sample

450 pb^{-1}: find 2 events in the signal box
with $3.13 \pm 0.82 \pm 0.37$ expected background events

$BR(K_S \to \pi^0\pi^0\pi^0) < 1.2 \; 10^{-7}$ at 90% CL

$|\eta_{000}| < 0.018$ at 90% CL



kaon decays and CPT test

quantum field theory and Lorentz invariance and locality imply CPT-symmetry
i.e. mass and decay width of particle and antiparticle coincide, *but …*

there can be violations $O(E/M_P)$ from quantum gravity, $M_P \approx 10^{19}$ GeV

neutral kaons are the most sensitive probes to search for CPT-violating effects

CPLEAR

$$i\frac{d}{dt}\begin{pmatrix}K\\ \overline{K}\end{pmatrix} = \left(M - i\frac{\Gamma}{2}\right)\begin{pmatrix}K\\ \overline{K}\end{pmatrix}$$

if CPT then $M_{11} = M_{22}$, $\Gamma_{11} = \Gamma_{22}$
best test is $|M_{K^0} - M_{\overline{K}^0}| / M_K <$ few $\times 10^{-18}$

$$K_S = \frac{(1+\epsilon_S)K^0 + (1-\epsilon_S)\overline{K^0}}{\sqrt{2(1+|\epsilon_S|^2)}} \qquad K_L = \frac{(1+\epsilon_L)K^0 - (1-\epsilon_L)\overline{K^0}}{\sqrt{2(1+|\epsilon_L|^2)}}$$

$\varepsilon_S = \varepsilon + \delta$ $\quad \varepsilon \Rightarrow$ ~~CP~~

$\varepsilon_L = \varepsilon - \delta$ $\quad \delta \Rightarrow$ ~~CPT~~

$$\delta = \frac{(\Gamma_K - \Gamma_{\overline{K}})/2 + i(M_K - M_{\overline{K}})}{\Delta\Gamma} \cos\varphi_{SW}\, e^{i\varphi_{SW}}$$

$\Delta\Gamma = \Gamma_S - \Gamma_L \quad \Delta m = M_S - M_L$
$\tan\varphi_{SW} = 2\,\Delta m / \Delta\Gamma$ superweak phase

unitarity "Bell-Steinberger" relation

$$(\Gamma_S + \Gamma_L + i\,2\Delta m)\frac{Re(\epsilon) - i\,Im(\delta)}{1+|\epsilon|^2} = \sum_f \mathcal{A}_S^*(f)\mathcal{A}_L(f)$$

$\sum_f$ extended to **all** K_S and K_L decay amplitudes $\Rightarrow$ $Re(\varepsilon)$ and $Im(\delta)$
if $Im(\delta) \neq 0$ then CPT or unitarity is violated (or both)

CPT tests à la CPLEAR

semileptonic decay amplitudes

$\mathcal{A}(K^0 \to \pi^- \ell^+ \nu) = a + b$ $\quad$ $\mathcal{A}(\overline{K^0} \to \pi^+ \ell^- \overline{\nu}) = a^* - b^*$

$\mathcal{A}(K^0 \to \pi^+ \ell^- \overline{\nu}) = c + d$ $\quad$ $\mathcal{A}(\overline{K^0} \to \pi^- \ell^+ \nu) = c^* - d^*$

CPLEAR analysis♦: measurable quantities from asymmetries of decay rates

y = - b / a ~~CPT~~ & $\Delta S = \Delta Q$

$x_+ = c^* / a$ CPT & ~~$\Delta S = \Delta Q$~~

$x_- = - d^* / a$ ~~CPT~~ & ~~$\Delta S = \Delta Q$~~

$R_+(t) = R\left[K^0 \to (\pi^- \ell^+ \nu)_t\right]$ $\quad$ $\overline{R}_-(t) = R\left[\overline{K^0} \to (\pi^+ \ell^- \overline{\nu})_t\right]$

$R_-(t) = R\left[K^0 \to (\pi^+ \ell^- \overline{\nu})_t\right]$ $\quad$ $\overline{R}_+(t) = R\left[\overline{K^0} \to (\pi^- \ell^+ \nu)_t\right]$

with input from hadronic decays

Re(ε) = (1.65 ± 0.41) 10^{-3}

Re(δ) = (3.0 ± 3.3) 10^{-4}

Im(δ) = (-1.5 ± 2.3) 10^{-2}

Re(x_-) = (0.2 ± 1.3) 10^{-2}

Im(x_+) = (1.2 ± 2.2) 10^{-2}

Re(y) = (0.3 ± 3.0) 10^{-3}

and with the constraint of unitarity

Re(ε) = (1.649 ± 0.025) 10^{-3}

Im(δ) = (2.4 ± 5.0) 10^{-5}

limits on $|M_{11} - M_{22}|$, $|\Gamma_{11} - \Gamma_{22}|$ ♠

♦ *Physics Reports 374 (2003)*

♠ *see later*

CPT tests à la KLOE

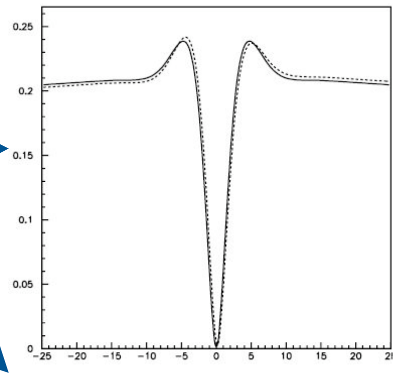
quantum interference of correlated decays

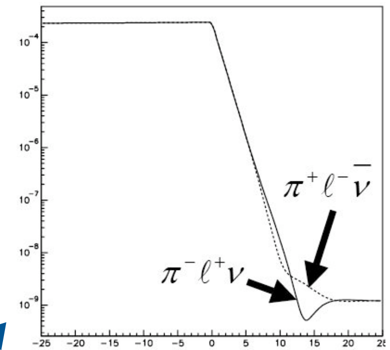
$\phi \to K_S K_L \to \pi^+\pi^- \pi^+\pi^-$ Δm ; Γ_S ; Γ_L

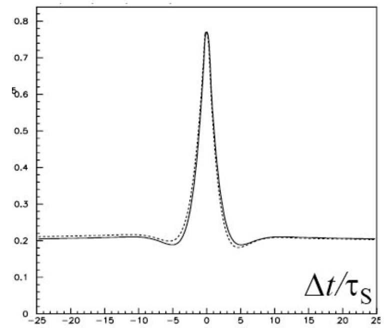
$\phi \to K_S K_L \to \pi^+\pi^- \pi^0\pi^0$ $Re(\varepsilon'/\varepsilon)$; $Im(\varepsilon'/\varepsilon)$

$\phi \to K_S K_L \to \pi\pi\, \pi l \nu$ $Re(\delta) + Re(x_-)$; $Im(\delta) + Im(x_+)$

$\phi \to K_S K_L \to \pi l \nu\, \pi l \nu$ $A_L = 2[\, Re(\varepsilon) - Re(\delta) - Re(y) - Re(x_-)\,]$







analyse more data, reach higher discriminating e–μ–π power,
for the time being … exploit

- new precise measurements of branching ratios
- new information on the charge asymmetry A_S

$$\frac{\Gamma(K_S \to \pi e \nu) - \Gamma(K_L \to \pi e \nu)}{\Gamma(K_S \to \pi e \nu) + \Gamma(K_L \to \pi e \nu)} = 2\, Re(x_+)$$

$A_S + A_L = 4\, [\, (Re(\varepsilon) - Re(y)\,]$

$A_S - A_L = 4\, [\, (Re(\delta) + Re(x_-)\,]$

$Re(x_+) = (\, -0.5 \pm 3.6\,)\, 10^{-3}$

$Re(\varepsilon) - Re(y) = (\, 1.2 \pm 2.5\,)\, 10^{-3}$

$Re(\delta) + Re(x_-) = (\, -0.5 \pm 2.5\,)\, 10^{-3}$

$Re(y) = (\, 0.4 \pm 2.5\,)\, 10^{-3}$

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CPT test: KLOE fit

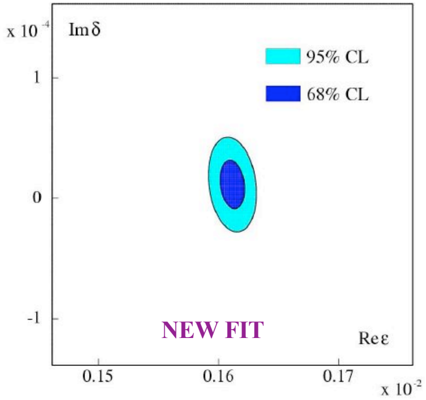
τ_S	PDG
τ_L	KLOE
$K_S \to \pi^+\pi^- / K_S \to \pi^0\pi^0$	KLOE
$BR(K_L \to \pi^+\pi^-)$	KTeV+KLOE
$BR(K_L \to \pi^0\pi^0)$	KTeV
$BR(K_L \to \pi e\nu)$	KLOE
$BR(K_L \to \pi^+\pi^-\pi^0)$	KLOE
$BR(K_L \to \pi^0\pi^0\pi^0)$	KLOE
$BR(K_S \to \pi^0\pi^0\pi^0)$	KLOE
$BR(K_S \to \pi e\nu)$	KLOE
A_L	KTeV+NA48
A_S	KLOE
η_{+-0}	CPLEAR
φ_{+-}	PDG
φ_{00}	PDG
φ_{SW}	PDG
$Im(x_+)$	CPLEAR+NA48+KLOE

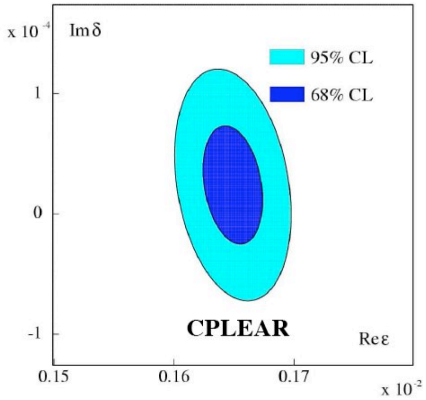
$Re(\varepsilon) = (1.61 \pm 0.01)\ 10^{-3}$

$Im(\delta) = (1.3 \pm 2.0)\ 10^{-5}$

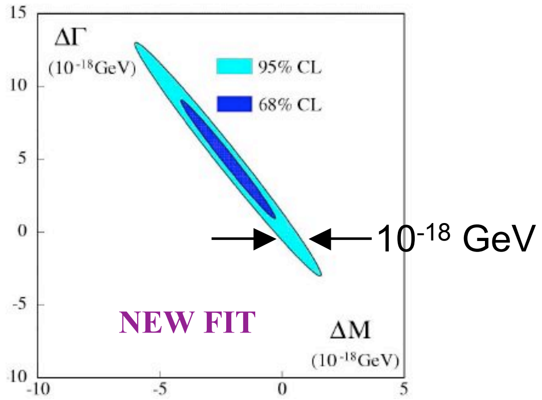
improves the CPLEAR fit

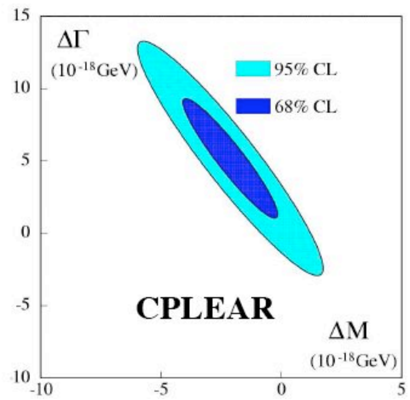
$Im(\delta) \otimes Re(\varepsilon)$





$\Delta\Gamma \otimes \Delta M$

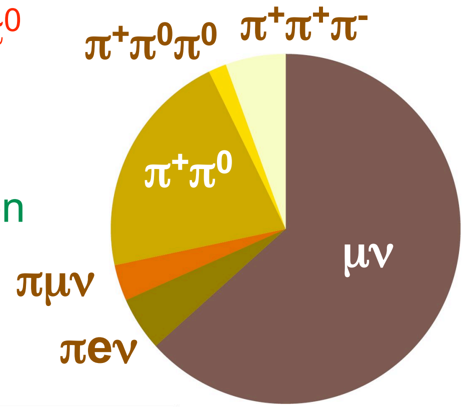


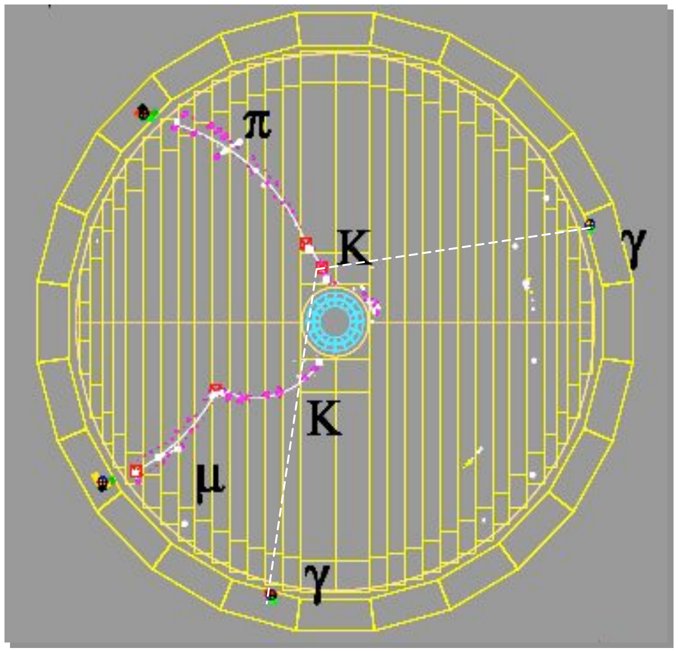


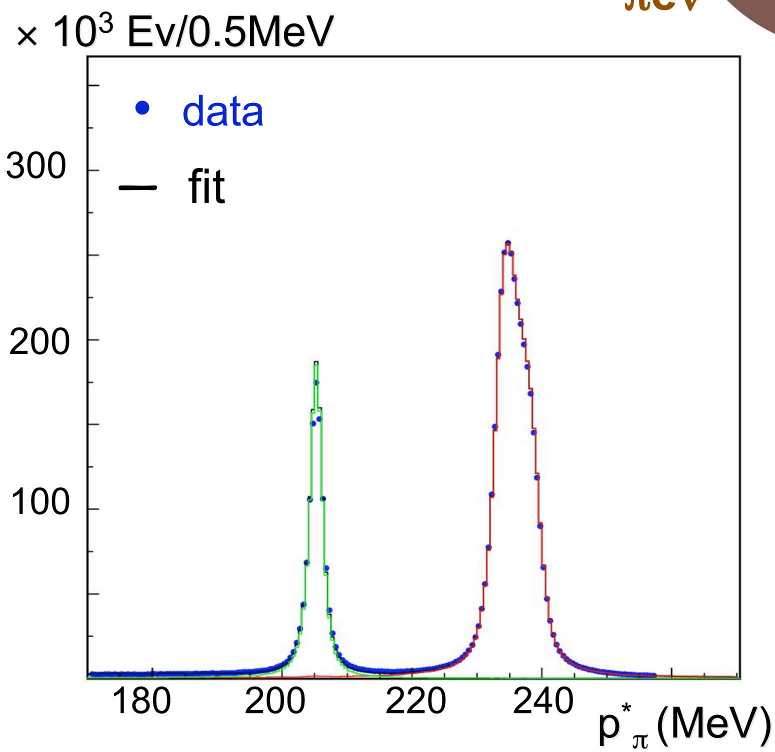
tagging $K^+ K^-$

identification of $K^+ K^-$ events by the decay $K^\pm \to \mu^\pm\nu$, $K^\pm \to \pi^\pm\pi^0$

- two tracks of the same curvature
- that form a secondary vertex "kink" in the fiducial volume
- two-body decay kinematics in the *K* frame: peak in the p* distribution
- tagging efficiency ≈ 36%



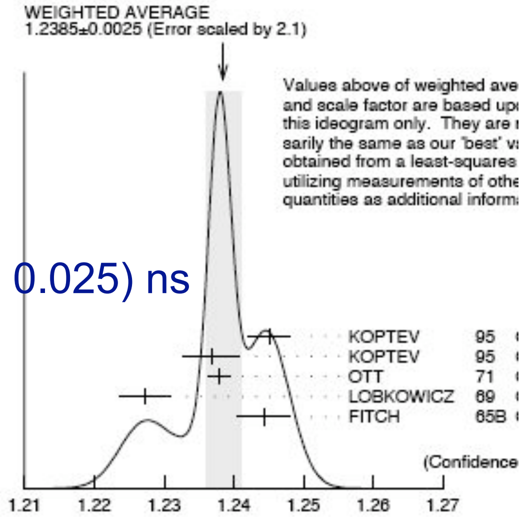




the $K^{\pm}$ lifetime

review of measurements: not so clear

- tag events with $K \rightarrow \mu\nu$ decay
- identify a kaon decay vertex in the fiducial volume
- use two different methods to measure $\tau_{\pm}$ to cross-check systematic errors

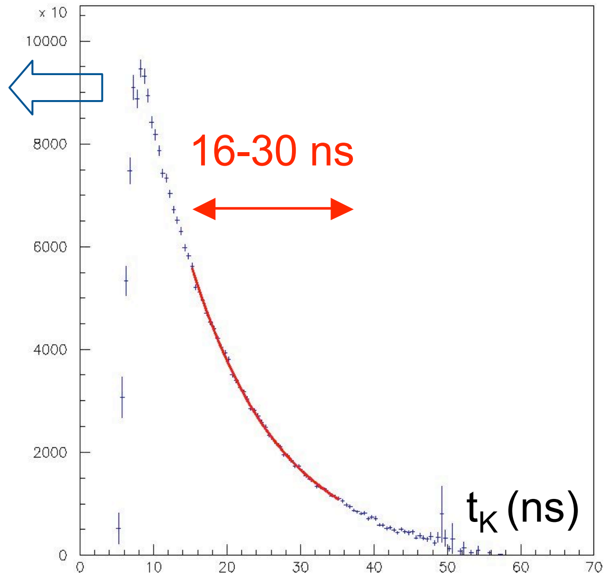


τ_{PDG} = (12.385 ± 0.025) ns

1[st] method: $\tau_{\pm}$ from the ***K* decay length**

- use all two-body decays
- measure the kaon decay length
- proper time $t_K = L / \beta\gamma c$
- fit of the t_K distribution

$\tau_{\pm}$ = (12.367 ± 0.034 ± 0.065) ns



2[nd] method: $\tau_{\pm}$ from the ***K* decay time**

use only $K^{\pm} \rightarrow X^{\pm}\pi^0$ decays

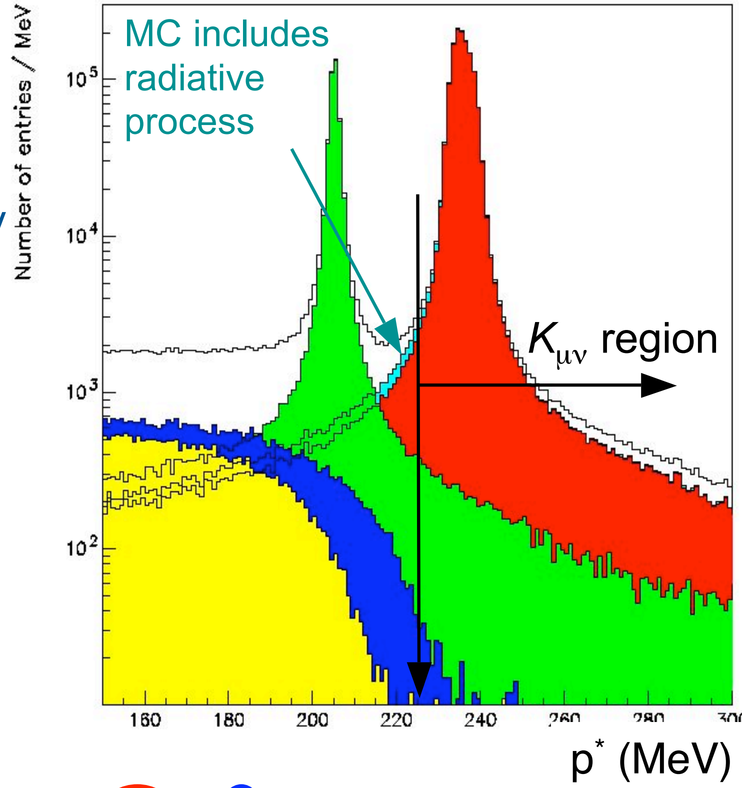
- use the tag to estimate the $\phi \rightarrow K^+K^-$ time, t_0, and the clusters time, t_γ
- decay time $t_K = (t_\gamma - R_\gamma/c - t_0)\ \gamma_K$
- fit of the t_K distribution

work in progress

$K \to \mu\nu(\gamma)$ decay

measurement of the absolute branching ratio

- tag = $K^- \to \mu^-\nu$, signal = $K^+ \to \mu^+\nu$
  to minimize effect of nuclear interactions
- 175 pb^{-1}, 1/3 for signal selection, 2/3 for efficiency
- subtraction of $\pi^+\pi^0$ identified background
- count events in 225–400 MeV window of the p* distribution (in the π mass hypothesis)
- efficiency ≈ 32%



result fully inclusive of radiation (accounted for in the Monte Carlo)

BR($K^+ \to \mu^+\nu(\gamma)$) = 0.6366 ± 0.0009 ± 0.0015

$\Gamma(\mu^+\nu_\mu)/\Gamma_{total}$

VALUE (units 10^{-2})	EVTS	DOCUMENT ID	TECN	CHG
63.44±0.14 OUR FIT Error includes scale factor of 1.2.				
63.60±0.16 OUR AVERAGE				
63.66±0.09±0.15	865k	[9] AMBROSINO 06A	KLOE	+
63.24±0.44	62k	CHIANG 72	OSPK	+

[9] Fully inclusive. Used tagged kaons from ϕ decays.

$$\frac{\Gamma(K^\pm \to \mu^\pm\nu(\gamma))}{\Gamma(\pi^\pm \to \mu^\pm\nu(\gamma))} = \frac{|V_{us}|^2}{|V_{ud}|^2}\,\frac{f_K^2}{f_\pi^2}\,\frac{m_K(1-m_\mu^2/m_K^2)^2}{m_\pi(1-m_\mu^2/m_\pi^2)^2}\,[1+\mathcal{O}(\alpha/\pi)]$$

imput from theory

$|V_{us}|$ = 0.2223 ± 0.0026

$K^{\pm}$ *semileptonic* decays

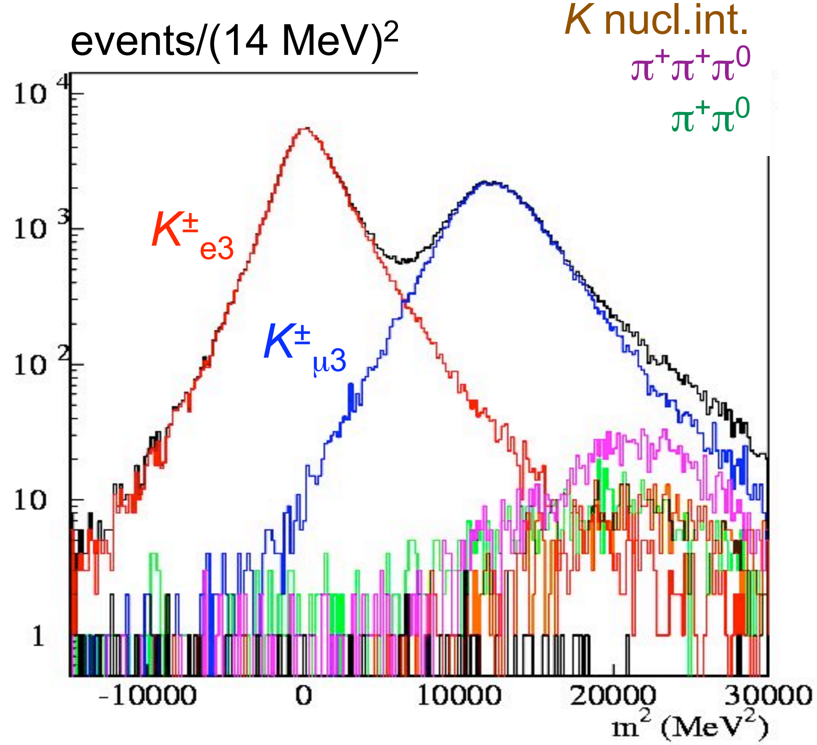
measurement of the absolute branching ratios

- 4 tag samples: $K^- \to \mu^-\nu$, $K^+ \to \mu^+\nu$, $K^- \to \pi^-\pi^0$, $K^+ \to \pi^+\pi^0$, analyzed independently to control systematics
- kinematical cuts to reject non-semileptonic decays
- time-of-flight for e-μ separation
- fit the $m^2_{\pi l}$ distribution

average of the 4 tag samples:

BR($K^{\pm}_{e3}$) = (5.047 ± 0.019 ± 0.039) 10^{-2}

BR($K^{\pm}_{\mu3}$) = (3.310 ± 0.016 ± 0.045) 10^{-2}



semileptonic decays and V_{us}

muon decay
$$\Gamma(\mu \to e\nu\bar{\nu}) = \frac{G^2 m_\mu^5}{768\pi^3}\,(\mathbf{1}+\mathbf{3})\left[1+\mathcal{O}(m_e^2/m_\mu^2)+\mathcal{O}(\alpha/\pi)\right]$$
V and *A*

kaon decay: Fermi super-allowed, $0^- \to 0^-$ only *V*, Cabibbo suppressed, $\approx |V_{us}|^2$

$$\Gamma(K \to \pi\ell\nu(\gamma)) = \frac{G^2 m_K^5}{768\pi^3}\, C_K^2\, |V_{us}|^2\, |f_+^{K\pi}(0)|^2\, I_K^\ell\, S_{ew}\, \left[1+\delta_{SU(2)}+\delta_{em}\right]$$

BR($K \to \pi l\nu$) / τ_K

Clebsh-Gordan isospin factor
C_K = 1 ($1/\sqrt{2}$) for K^0 ($K^\pm$)

$f^{K\pi}(t)$: $K \to \pi$ form factor
$t = (p_K - p_\pi)^2$

phase-space integral

short-distance electro-weak correction
$\approx 1 + (2\alpha/\pi)\, ln\, (M_Z / M_K)$

isospin-breaking +
long-distance e.m.
corrections (≈ %)

to be measured:
- branching ratios
- *K* lifetime
- *K* mass
- form factor *t* dependence

better if in the same experiment

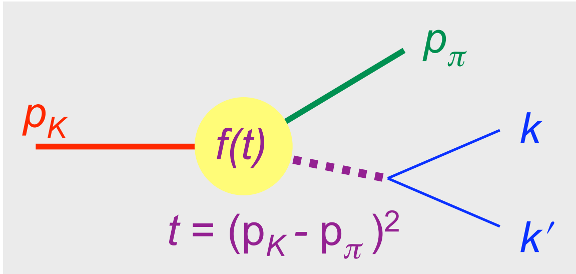
to be computed:
- form factor at $t = 0$
- ~~SU(2)~~, e.m., e.w. corrections

K form factors

definitions: two invariants → two form factors

$$\langle \pi | \bar{s}\gamma_\alpha u | K \rangle = \tilde{f}_+^{K\pi}(t)(p_K + p_\pi)_\alpha + \tilde{f}_-^{K\pi}(t)(p_K - p_\pi)_\alpha$$

$\approx m_{lepton}$



$$f_0^{K\pi}(t) = \tilde{f}_+^{K\pi}(t) + \frac{t}{m_K^2 - m_\pi^2}\,\tilde{f}_-^{K\pi}(t)$$

parametrization as power expansion

vector $f_+(t) = f_+(0)\left(1 + \lambda'_+ \frac{t}{m_\pi^2} + \lambda''_+ \frac{t^2}{2m_\pi^4} + \ldots\right)$ scalar $f_0(t) = f_+(0)\left(1 + \lambda'_0 \frac{t}{m_\pi^2} + \lambda''_0 \frac{t^2}{2m_\pi^4} + \ldots\right)$

or as a pole $f_+(t) = f_+(0)\,\frac{1}{1 - t/M_V^2}$ $f_0(t) = f_+(0)\,\frac{1}{1 - t/M_S^2}$ $\lambda' = (m_\pi/M)^2$ $\lambda'' = 2\,\lambda'^2$

the λ parameters are extracted from the event density function,
the integral I_K is computed as function of λ's

form factor parameters

data: 328 pb^{-1}, 2 10^6 $K_L \to \pi e \nu$ decays, analysis as before

- more stringent kinematic cuts, time-of-flight for $e-\mu-\pi$ separation
- to improve the resolution in momentum transfer t
- separate measurement for each charge state ($e^+\pi^-$, $e^-\pi^+$) to control systematics

linear expansion: $\lambda_+ = (28.6 \pm 0.5 \pm 0.4)\ 10^{-3}$

quadratic expansion: $\lambda'_+ = (25.5 \pm 1.5 \pm 1.0)\ 10^{-3}$

$\lambda''_+ = (1.4 \pm 0.7 \pm 0.4)\ 10^{-3}$

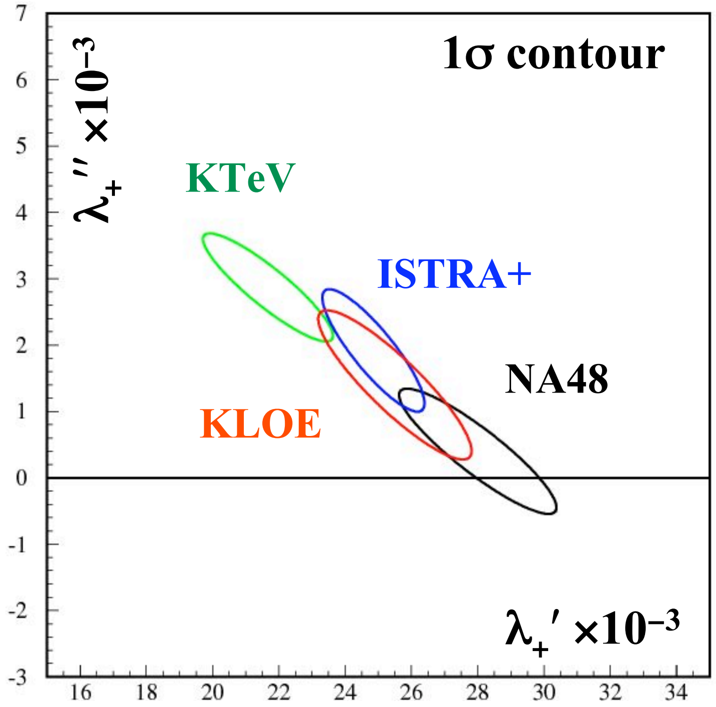
pole model: $M_V = 870 \pm 7$ MeV

KTeV: $M_V = 882.3 \pm 6.5$ MeV

NA48: $M_V = 859 \pm 18$ MeV

good consistency (beware of correlations)

$K_L \to \pi e \nu$



V_{us}

putting results together

form factor parameters × 10^3
$\lambda'_+ = 25.42 \pm 0.31$; $\lambda''_+ = 1.29 \pm 0.03$; $\lambda_0 = 15.87 \pm 0.95$ ⇨ *phase space integral $I_K(\lambda)$*

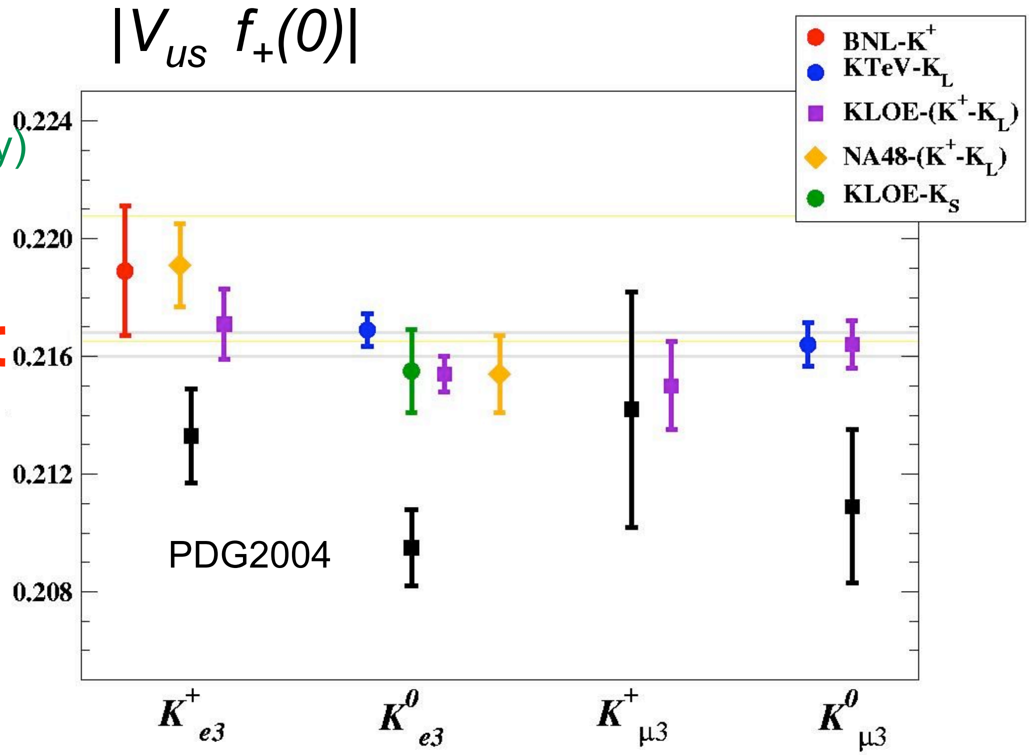
Leutwyler and Roos, χPT: $f_+(0) = 0.961 \pm 0.008$
lattice QCD: $f_+(0) = 0.960 \pm 0.009$

$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$
$V_{ud} = 0.9738 \pm 0.0003$ (nuclear β decay)
$V_{ub} = (3.6 \pm 0.7)\ 10^{-3}$
$V_{us}f_+(0) = 0.2185 \pm 0.0022$

experiments average
$V_{us}f_+(0) = 0.2164 \pm 0.0005$

$|V_{us}| = 0.2252 \pm 0.0019$

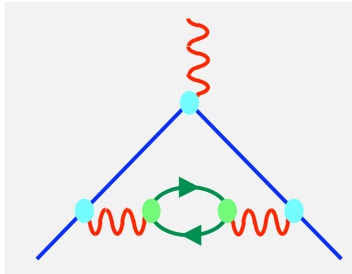
the long-lasted crisis of the CKM matrix unitarity is over



the muon anomaly

the muon anomalous magnetic moment

$$\vec{\mu} = g \frac{e\hbar}{2m} \vec{s}$$



experiment E821 at Brookhaven

$a_\mu = (g_\mu - 2)/2 = (116\ 592\ 080 \pm 60)\ 10^{-11}$

theory: $a_\mu = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had} + a_\mu^{new}$

the hadronic contribution is large

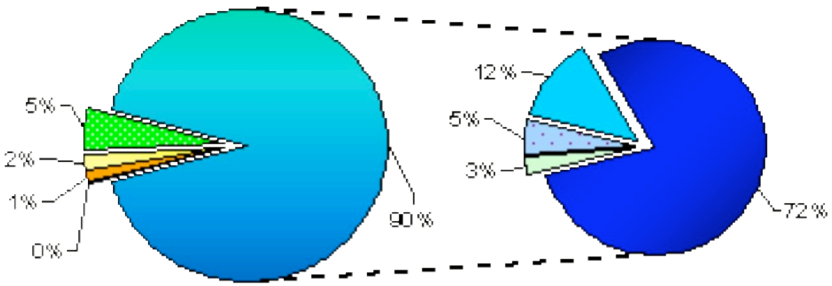
$a_\mu^{had} \approx 7000 \times 10^{-11}$

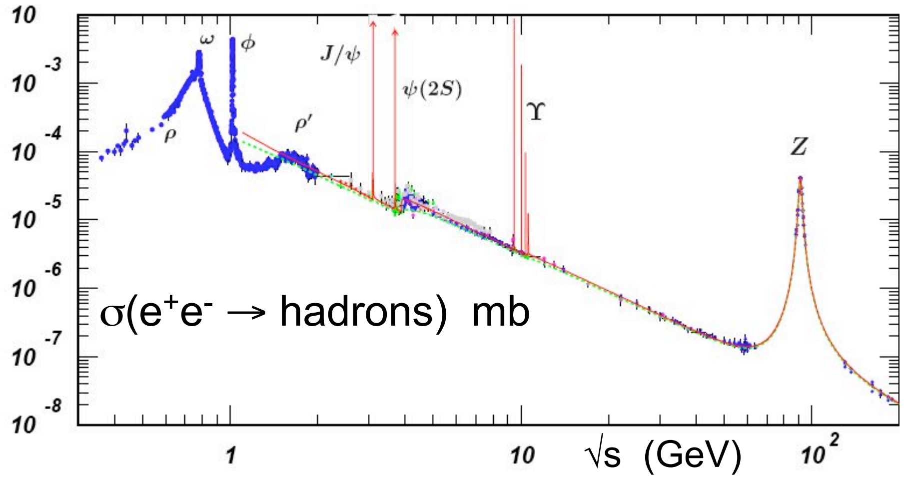
and gives the largest theory error

a_μ^{had} computed with the dispersion relation

$$a_\mu^{had} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} \sigma_{e^+e^- \to had}(s) K(s) ds$$

the kernel K(s) behaves ~ 1/s





2π	3π (+ω,φ)	4π	> 4π (+KK)	1.8 - 3.7	3.7 - 5 (+J/ψ, ψ)	5 - 12 (+ϒ)	12 - ∞

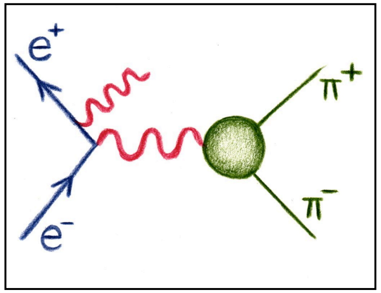
$e^+e^- \rightarrow \pi^+\pi^-\gamma$

measuring $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$

contribution to a_μ for $\sqrt{s}$ < 1 GeV ≈ **2/3**, mainly $e^+e^- \rightarrow \pi^+\pi^-$

DAΦNE is tuned at $\sqrt{s} = m_\phi$

KLOE: stay at the ϕ peak, use the ***radiative return*** method



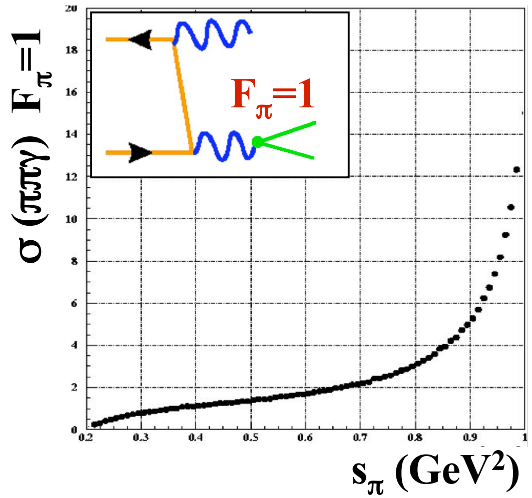
Initial State Radiation

- ***no γ tagging***: *photons* $\theta_\gamma < 15^o$ or $\theta_\gamma > 165^o$, *pions* $50^o < \theta_\pi < 130^o$
- small relative contribution of *FSR*
- reduced background contamination from $\phi \rightarrow \pi^+\pi^-\pi^0$
- measure differential cross section $e^+e^- \rightarrow \pi^+\pi^-\gamma$ as function of the $\pi\pi$ invariant mass
- extract $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ using the radiator function
- correct for final state radiation

main error in $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$

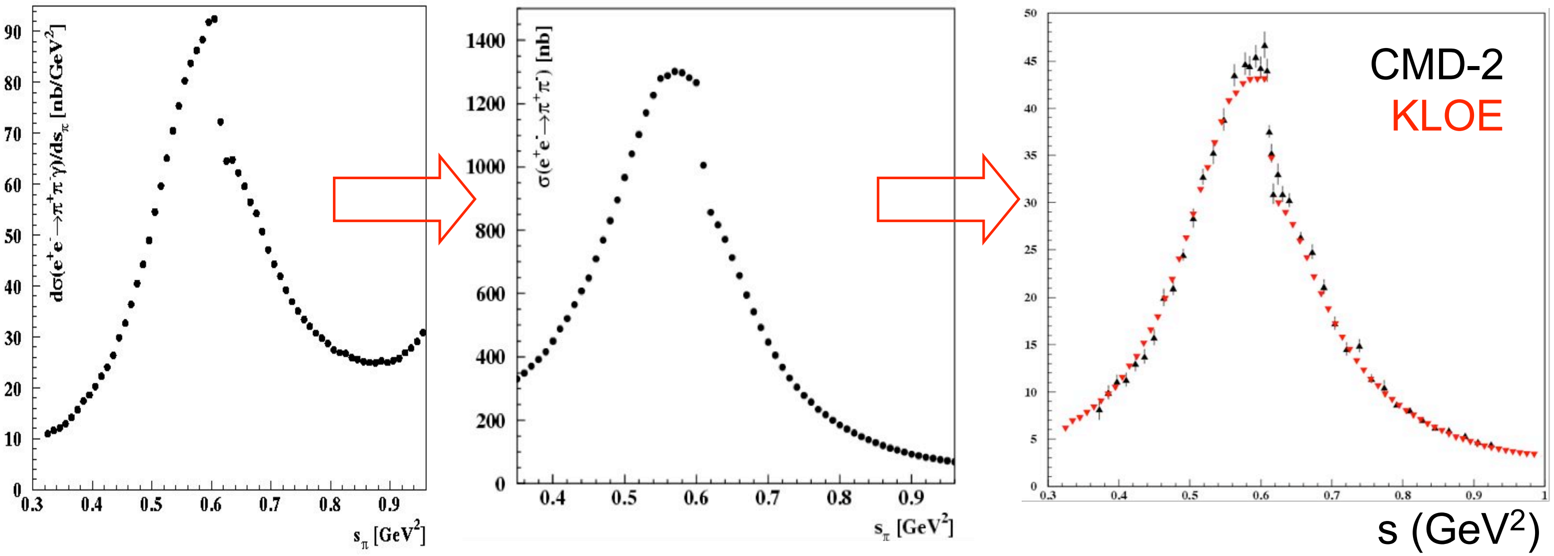
$$\sigma(e^+e^- \rightarrow \pi^+\pi^-) H(m^2_{\pi\pi}, s) = m^2_{\pi\pi} \left[\frac{d\sigma(\pi^+\pi^-\gamma)}{dm^2_{\pi\pi}} \right]_{ISR}$$

PHOKARA event generator used as radiator function



$e^+e^- \to \pi^+\pi^-$

$d\sigma(e^+e^- \to \pi^+\pi^- \gamma) / ds_{\pi\pi}$ $\sigma(e^+e^- \to \pi^+\pi^-)$ $|F_\pi(s)|^2$



statistical error of $\sigma(e^+e^- \to \pi^+\pi^-)$ is negligible,
systematic error is ±1.3%: 0.9% measurement $\oplus$ 0.9% from $H(s_{\pi\pi},s)$

two different methods: CMD-2: energy scan, KLOE: radiative return
fair agreement *(but at the peak ?)*, good agreement for a_μ^{had}

KLOE: $0.35 < s < 0.95$ $a_\mu^{had} = (3756 \pm 8_{stat} \pm 35_{syst} \pm 35_{\mathbf{theo}})\ 10^{-11}$

CMD-2: $0.37 < s < 0.93$ $a_\mu^{had} = (3786 \pm 27_{stat} \pm 23_{syst})\ 10^{-11}$

VEPP-4M
Novosibirsks

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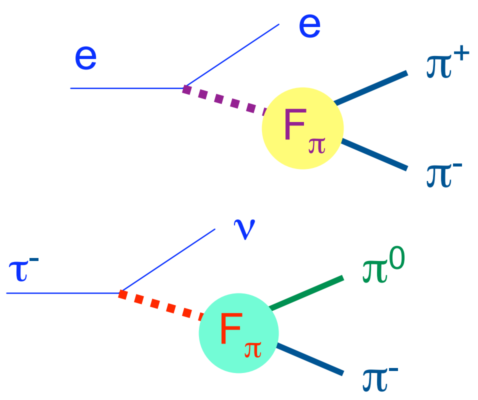
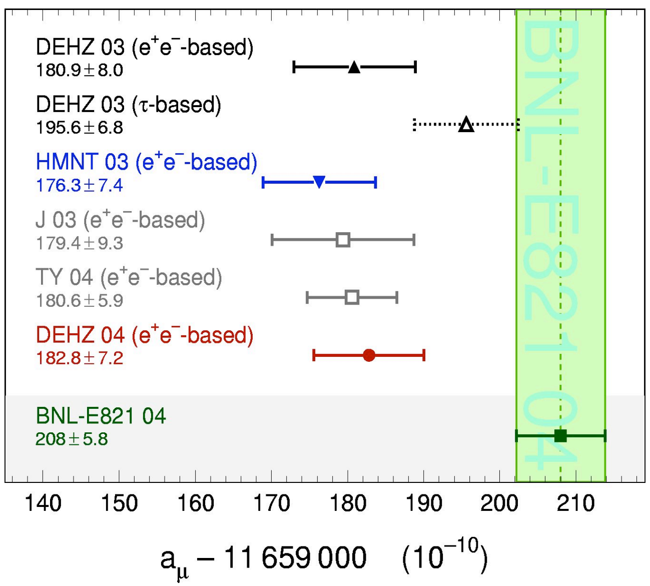
$e^+e^- \otimes \tau \rightarrow \nu$

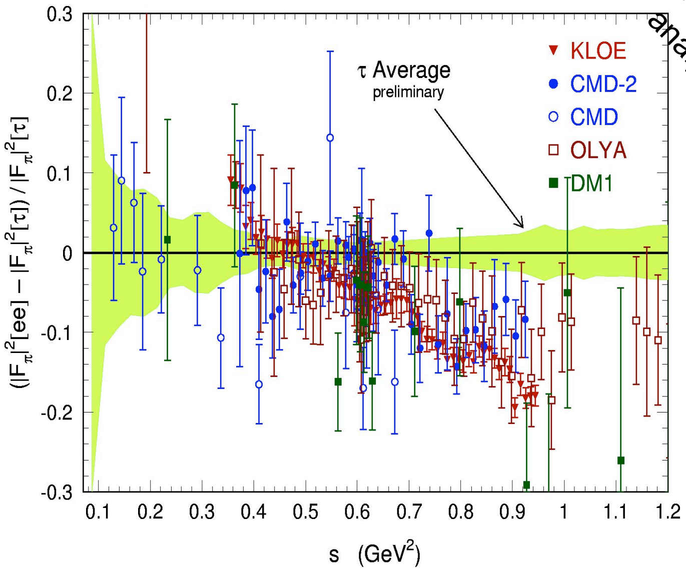


- analysis of τ decays agrees better with E821 result
- $\Delta a_\mu(\tau \rightarrow \nu) \approx 1\sigma$; $\Delta a_\mu(e^+e^-) \approx 3\sigma$
- systematic difference in e^+e^- and $\tau \rightarrow \nu$ data as function of s
- agreement among e^+e^- experiments, the trend is the same

a problem with isospin symmetry ?

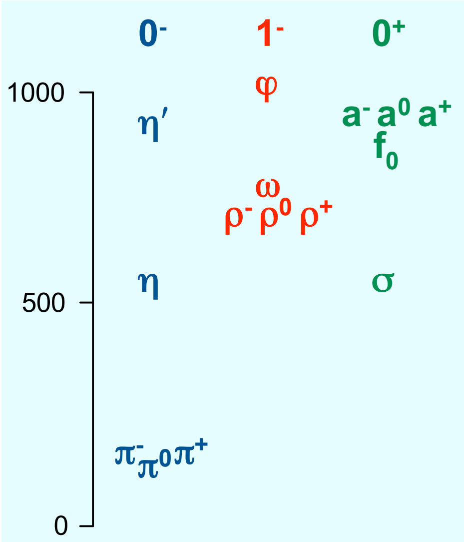
new results from KLOE, CMD2, SND coming soon

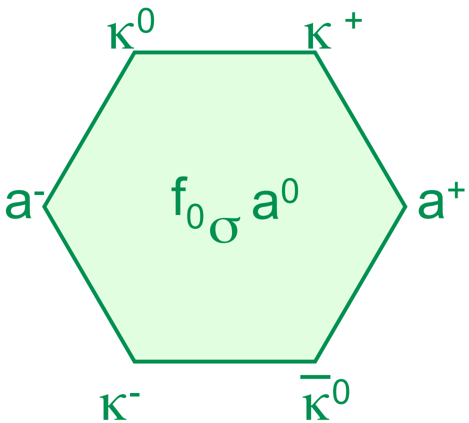




τ data from ALEPH, OPAL, CLEO
analysis of Davier, Höcker, Zhang

light mesons





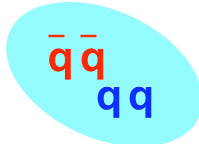
light mesons: $q\bar{q}$ pairs in the lowest state of angular momentum antisymmetric for interchange of colour, flavour, spin

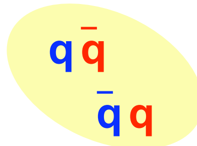
doesn't work for scalar mesons

- what is the structure of 0^+ mesons ?
- why an inverted mass spectrum ?
- do they obey the $SU(3)_{flavour}$ symmetry ?
- do κ and σ really exist ?

models

- bound state of two **diquarks**
- **molecule** of two pseudoscalar mesons





ϕ decays to scalar mesons, $\phi \to f_0\gamma$, $\phi \to a_0\gamma$

they are almost degenerate in mass close to the $s\bar{s}$ threshold

f_0 and a_0 should contain some hidden strangeness

σ should reveal itself in the $\pi\pi\gamma$ mass spectrum

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ϕ radiative decays

$1^- \to 0^-$ magnetic dipole transition $\phi \to \eta'\gamma$; $\phi \to \eta\gamma$; $\phi \to \pi^0\gamma$

$1^- \to 0^+$ electric dipole transition $\phi \to a_0\gamma$; $\phi \to f_0\gamma$; very broad resonances !

a_0 isospin $$|1,0\rangle = \frac{|\pi^+\pi^-\rangle - |\pi^-\pi^+\rangle}{\sqrt{2}}$$ antisymmetric, does not decay $\to \pi\pi$, but $\to \eta\pi^0$

f_0 $$|0,0\rangle = \frac{|\pi^+\pi^-\rangle - |\pi^0\pi^0\rangle + |\pi^-\pi^+\rangle}{\sqrt{3}}$$ decays in the three combinations with equal weight

$\phi \to a_0\gamma$ $a_0 \to \eta\pi^0$; $\eta \to \pi^+\pi^0\pi^-$ or $\gamma\gamma$; final state: 2 tracks + 5 photons OR 5 photons

- kinematic fit in the hypothesis $\eta\pi^0\gamma$,
- fit the $\eta\pi^0$ mass spectrum with the amplitude $\mathcal{A}(\phi \to a_0\gamma) + \mathcal{A}(\phi \to \rho^0\pi^0)$

$\phi \to f_0\gamma$ $f_0 \to \pi^0\pi^0$; final state: 5 photons

- kinematic fit in the hypothesis $\pi^0\pi^0\gamma$,
- fit the $\pi^0\pi^0$ mass spectrum with the amplitude $\mathcal{A}(\phi \to f_0\gamma) + \mathcal{A}(\phi \to \rho^0\pi^0) + \mathcal{A}(\phi \to \sigma\gamma)$

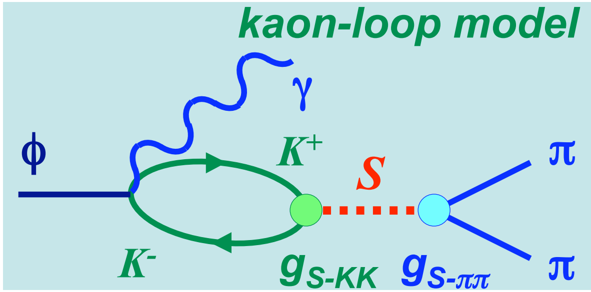
$f_0 \to \pi^+\pi^-$; final state: 2 tracks + 1 photon

- large background from ISR $\rho^0 \to \pi^+\pi^-$
- fit the $\pi^+\pi^-$ mass spectrum with the amplitude $\mathcal{A}_{IRS} + \mathcal{A}_{FRS} + \mathcal{A}_{cont}(\rho\pi\gamma) + \mathcal{A}(\phi \to f_0\gamma) + \mathcal{A}(\phi \to \sigma\gamma)$

scalar mesons

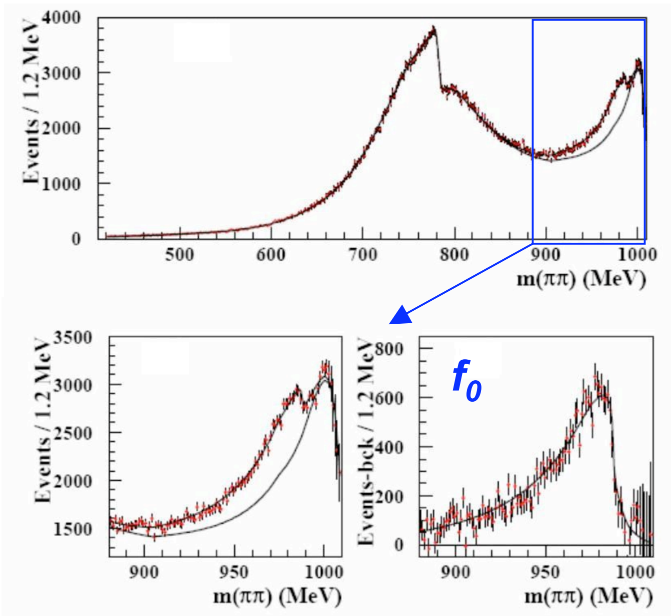
results, *very model-dependent*

$g^2_{aKK}/4\pi = 0.40 \pm 0.04\ \mathrm{GeV}^2$
$g^2_{aKK}/g^2_{a\eta\pi} = 0.55 \pm 0.07$
$BR(\phi \to a_0\gamma) = (0.74 \pm 0.07)\ 10^{-4}$



$g^2_{fKK}/4\pi = 2.79 \pm 0.12\ \mathrm{GeV}^2$	$g^2_{fKK}/4\pi = 2.76 \pm 0.13\ \mathrm{GeV}^2$
$g^2_{fKK}/g^2_{f\pi\pi} = 4.00 \pm 0.14$	$g^2_{fKK}/g^2_{f\pi\pi} = 2.66 \pm 0.10$
$BR(\phi \to \pi^0\pi^0\gamma) = (1.07 \pm 0.07)\ 10^{-4}$	$BR(\phi \to \pi^+\pi^-\gamma) = (2.1 \pm 0.4)\ 10^{-4}$
σ favoured in the fit	σ not needed in the fit

fit of the $\pi^+\pi^-$ mass spectrum with the kaon-loop model



- a_0 and f_0 strongly coupled to *KK*, f_0 more than a_0
- branching ratios relatively large
- no evidence for σ meson, neither excluded nor confirmed
- results consistent with the description of scalar mesons as bound states of diquarks

$$a^- = ds\,\bar{d}\bar{s} \qquad a^0 = \frac{us\,\bar{u}\bar{s} - ds\,\bar{d}\bar{s}}{\sqrt{2}} \qquad a^+ = us\,\bar{d}\bar{s}$$

$$f = \frac{us\,\bar{u}\bar{s} + ds\,\bar{d}\bar{s}}{\sqrt{2}}$$

$$\sigma = ud\,\bar{u}\bar{d}$$

pseudoscalar mesons

$\eta - \eta'$ mixing

in the SU(3) basis $|\pi_8\rangle = \frac{u\bar{u} - d\bar{d}}{\sqrt{2}}$ $|\eta_8\rangle = \frac{u\bar{u} + d\bar{d} - 2s\bar{s}}{\sqrt{6}}$ $|\eta_0\rangle = \frac{u\bar{u} + d\bar{d} + s\bar{s}}{\sqrt{3}}$

who are π^0 , η , η' ?

likely $\pi^0 = |\pi_8\rangle$ with no strange quark and

$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \begin{pmatrix} \cos\theta_P & \sin\theta_P \\ -\sin\theta_P & \cos\theta_P \end{pmatrix} \begin{pmatrix} \eta_8 \\ \eta_0 \end{pmatrix}$$

in the flavour basis $|N\rangle = \frac{u\bar{u} + d\bar{d}}{\sqrt{2}}$ $|S\rangle = s\bar{s}$ $\varphi_P = \theta_P + atan\sqrt{2}$

measure the decays $\phi \to \eta'\gamma$ and $\phi \to \eta\gamma$ selecting the same final state

$\eta' \to \eta\, \pi^+\pi^-$, $\eta \to \gamma\gamma$ $\quad$ $\eta \to \pi^+\pi^-\pi^0$, $\pi^0 \to \gamma\gamma$

$$\frac{BR(\phi \to \eta'\gamma)}{BR(\phi \to \eta\gamma)} = (4.76 \pm 0.22)\ 10^{-3}$$

$BR(\phi \to \eta'\gamma) = (6.19 \pm 0.30)\ 10^{-5}$

flavour basis: $\varphi_P = (41.5 \pm 0.7 \pm 0.6_{theo})^o$ SU(3) basis: $\theta_P = (-13.2 \pm 0.7 \pm 0.6_{theo})^o$

η forbidden decays

$\eta \to \gamma\gamma\gamma$ ~~C~~ even $\to$ odd $BR(\eta \to \gamma\gamma\gamma) < 1.6\ 10^{-5}$ 90% C.L.

$\eta \to \pi^+\pi^-$ ~~P~~ and ~~CP~~ odd $\to$ even $BR(\eta \to \pi^+\pi^-) < 1.3\ 10^{-5}$ 90% C.L.

best world limits

the puzzle of the η mass

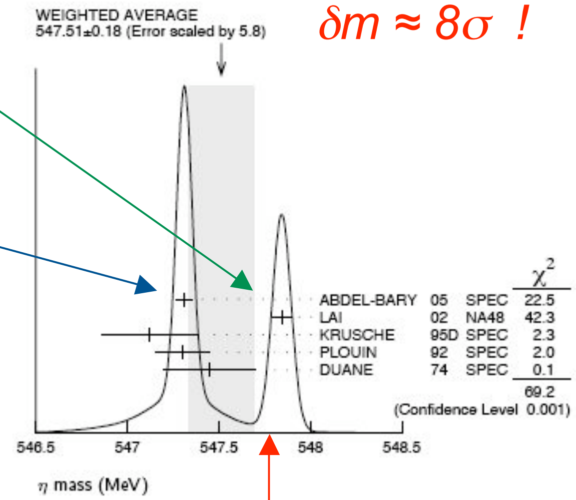
NA48 $\eta \to 3\pi^0$ decay, measure energies and angles

$m_\eta = 547\,843 \pm 30 \pm 41$ keV

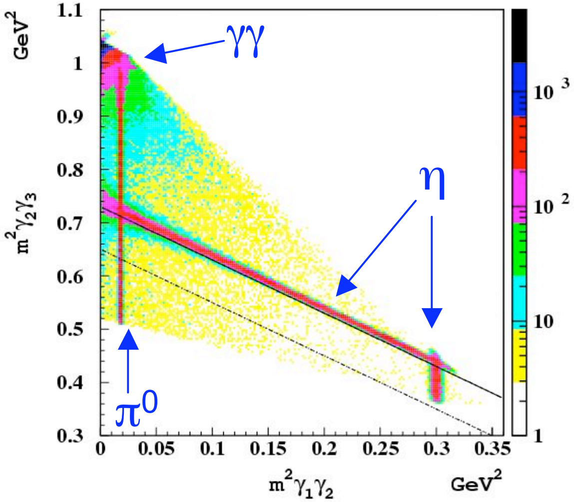
GEM reaction $p + d \to 3He + \eta$ close to threshold, measure missing mass

$m_\eta = 547\,311 \pm 28 \pm 32$ keV

$\delta m \approx 8\sigma$!



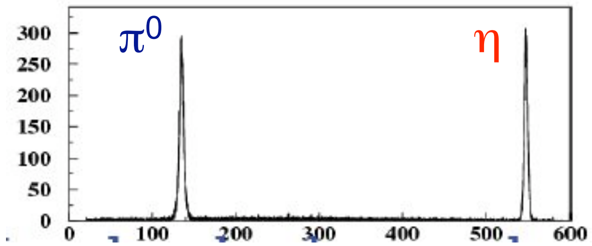
- select $\phi \to \eta\gamma$; $\eta \to \gamma\gamma$ from the 3γ Dalitz plot
- kinematic fit with the φ mass constraint
- energy calibration with $e^+e^-\gamma$; energy scale from m_ϕ



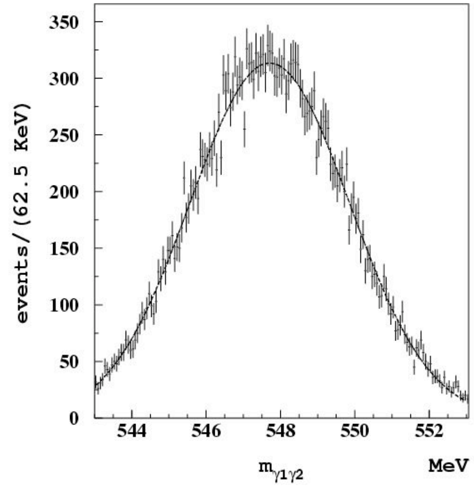
check:

$m(\pi^0) = 134990 \pm 6 \pm 30$ keV

$m(\pi^0)_{PDG} = 134976.6 \pm 0.6$ keV



$m_\eta = 547\,822 \pm 5 \pm 69$ keV



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the future

DAΦNE will run in 2006-07 for two other experiments: SIDDHARTA and FINUDA

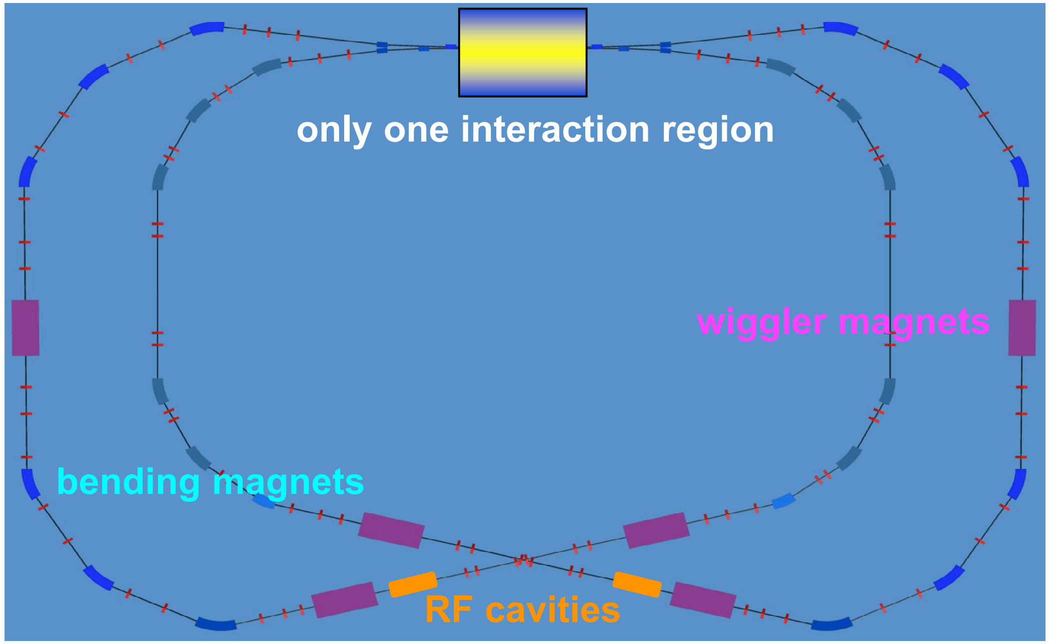
with periods of machine developments to increase the luminosity and the beam lifetime

plan (*to be approved*) to start in 2008 building a DAΦNE-2

- higher luminosity at the ϕ: ≈ 8 10^{32} $cm^{-2}s^{-1}$ ⇒ 10 fb^{-1} per year
- maximum energy, $\sqrt{s} \approx 2.5$ GeV

and start a new physics program in ≥ 2011 to reach ≈ 40 fb^{-1}

3×10^{10} ϕ
2×10^{9} tagged K_S
1×10^{9} tagged K_L
4×10^{8} η
…



expressions of interest presented at the Laboratory this spring:

Continuation of KLOE physics program at DAΦNE upgraded in luminosity and in energy

Measurement of the nucleon form factors in the time-like region

Study of deeply bound kaonic nuclear states at at DAΦNE-2

the program

study of the **time evolution of entangled kaon states**, reach the sensitivity to the Planck scale: interesting tests of CPT-symmetry and quantum mechanics

e–μ universality ($K \to e\nu$ / $K \to \mu\nu$) and the **mass of the μ-neutrino**

verify the **universality of the weak coupling** to leptons and quarks, test the unitarity of the CKM mixing matrix

measurement of **rare K_S decays** (charge asymmetry, $K_S \to \pi^+\pi^-\pi^0$, $K_S \to \pi^0\pi^0\pi^0$)

light mesons: structure of scalars (via γγ interaction), rare decays of pseudoscalars

improve and extend the measurement of **$\sigma(e^+e^- \to$ hadrons)**, muon anomaly, evolution of α_{em}

measure the **baryon electromagnetic form factors**, $e^+e^- \to p\bar{p}$, $n\bar{n}$, $\Lambda\bar{\Lambda}$

… and more

the KLOE detector has proven to well face the challenge, nevertheless ***something can be improved***

- add a **small precise tracker** for K_S decays and to improve the z coordinate
- add a **tagging system** for $e^+e^- \to e^+e^-\gamma\gamma$
- increase the **calorimeter read-out granularity**
- increase the **band-width of the data acquisition**
- reduce the magnetic field (easy)

a new exciting challenge, who wants to join is welcome

conclusion

1999: commissioning of DAΦNE and KLOE

2000: first data, 20 pb^{-1}, and first results

2001-05: KLOE has collected ≈ 2.4 fb^{-1} of data, with a remarkable efficiency

2006: short period off-resonance at $\sqrt{s}$ = 1 GeV for ≈ 0.2 fb^{-1}

about 1/5 of data analyzed so far: strong impact on many fundamental parameters

- the K^0 mass, the K_L lifetime, the K^+ lifetime,
- the absolute branching ratios for the main K_S and K_L decays
- the K_S and K_L weak form factors
- $|f_+(0)\ V_{us}|$
- the hadronic contribution to vacuum polarization for $\sqrt{s}$ < 1 GeV
- the structure of light scalar mesons
- … and more

many thanks to my KLOE friends

merci a vous pour l'aimable hospitalité

the KLOE friends

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appendix

Detector and data handling

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- The tracking detector of the KLOE experiment, N.I.M. A488 (2002) 51
- The trigger system of the KLOE experiment, N.I.M. A492 (2002) 134
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