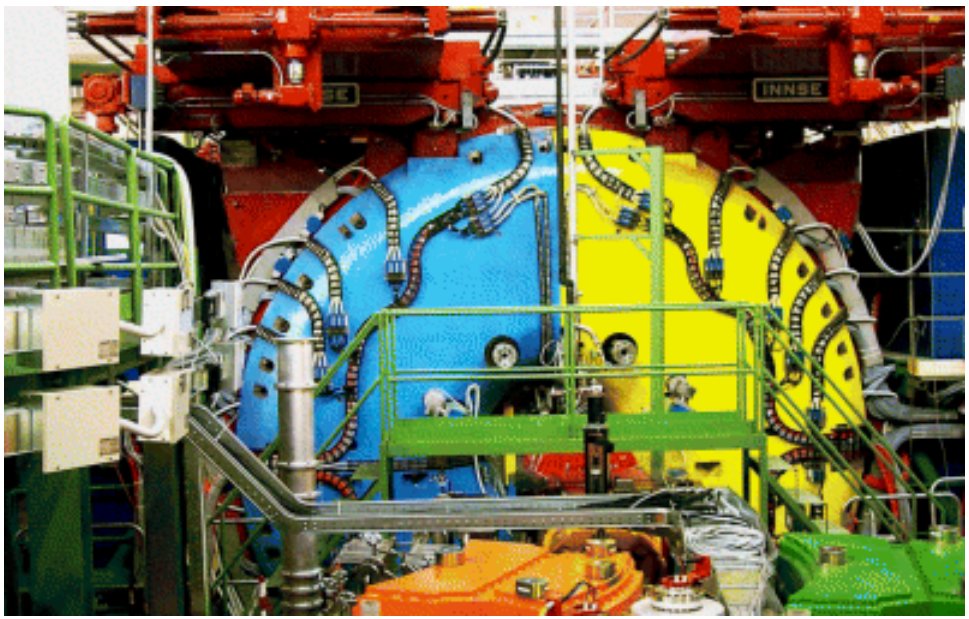
Recent results from KLOE at DAΦNE

Antonio Di Domenico* **on behalf of the KLOE collaboration**
***Università di Roma "La Sapienza" and INFN, Italy**



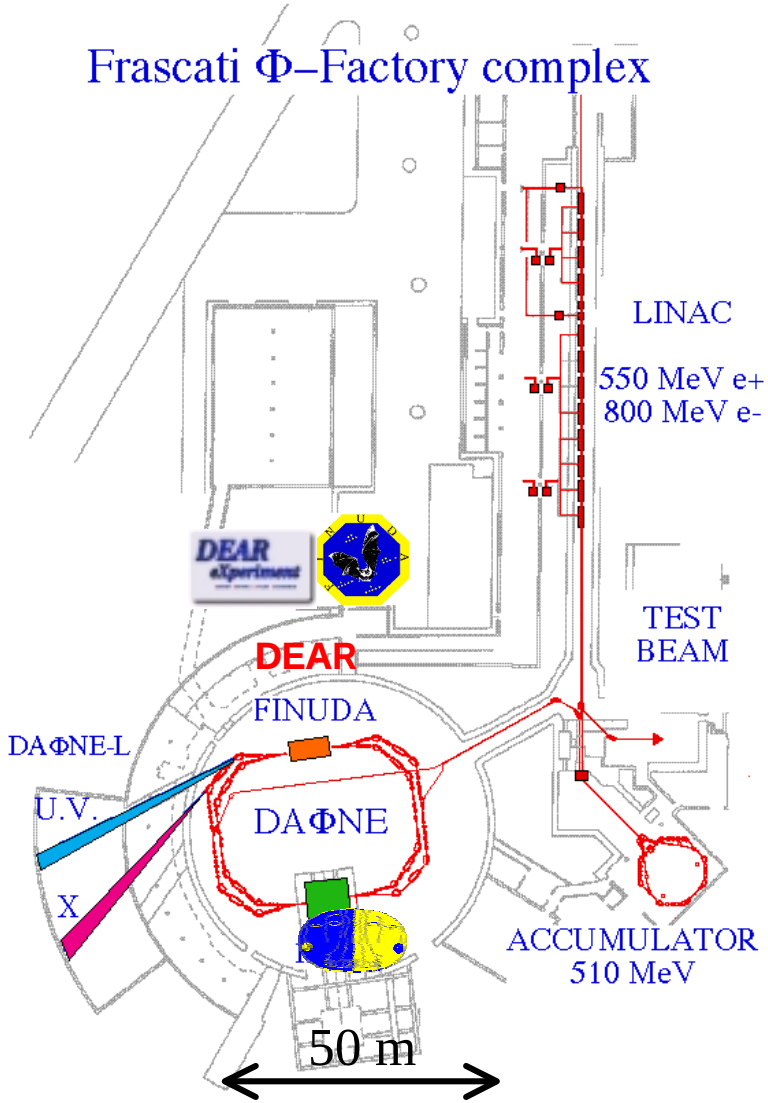
The Fifth KEK Topical Conference - Frontiers in Flavor Physics
November 20-22, 2001 - KEK, Tsukuba, Japan

DAΦNE : the Frascati Φ - factory

Design parameters

- Beam energy : 510 MeV
- Max number of bunches : 120
- Bunch spacing : 2.7 ns
- Bunch current : 40 mA
- Single bunch luminosity : $4 \cdot 10^{30}$ cm^{-2} s^{-1}

$L = 5 \cdot 10^{32}$ cm^{-2} s^{-1}



KLOE and DAΦNE mission

Study CP violation in the $K^0 - \overline{K}^0$ system measuring Re ε'/ε to $O(10^{-4})$ and Im ε'/ε to $O(10^{-3})$

- $e^+e^- \to \phi$ $\sigma_\phi \sim 3\ \mu b$
  $W = m_\phi = 1019$ MeV

- $BR(\phi \to K^+K^-) = 49.2\%$
- $BR(\phi \to K^0\overline{K}^0) = 33.8\%$
- $BR(\phi \to \pi^+\pi^-\pi^0) = 15.5\%$
- $BR(\phi \to \eta\gamma) = 1.3\%$

Neutral kaons produced in a pure quantum $J^{PC} = 1^{--}$ state:

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

$$= \frac{N}{\sqrt{2}}\left[\left|K_S(\vec{p})\right\rangle\left|K_L(-\vec{p})\right\rangle - \left|K_L(\vec{p})\right\rangle\left|K_S(-\vec{p})\right\rangle\right]$$

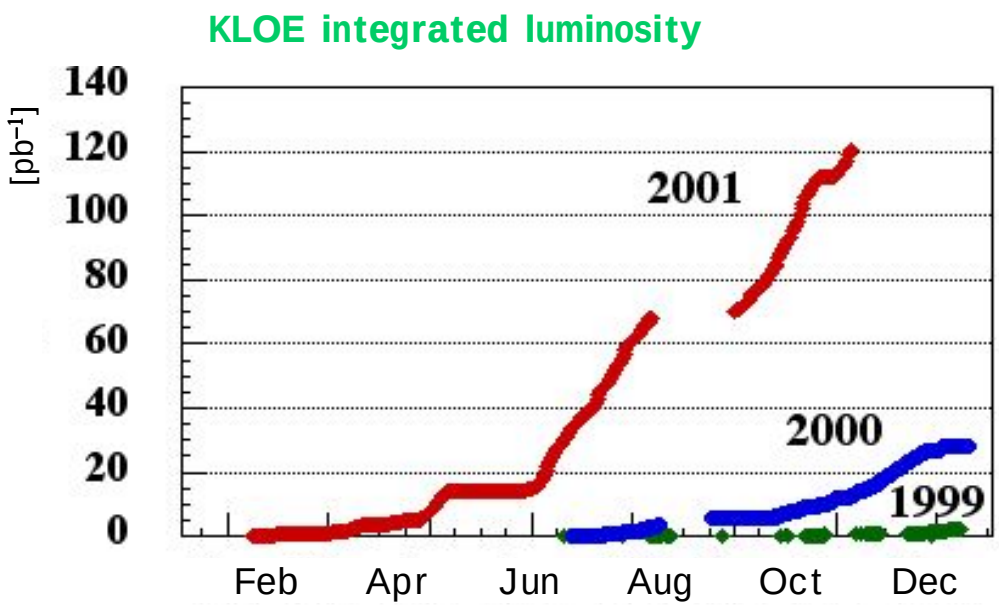
$p_K = 110$ MeV $\lambda_S = 6$ mm $\lambda_L = 3.5$ m

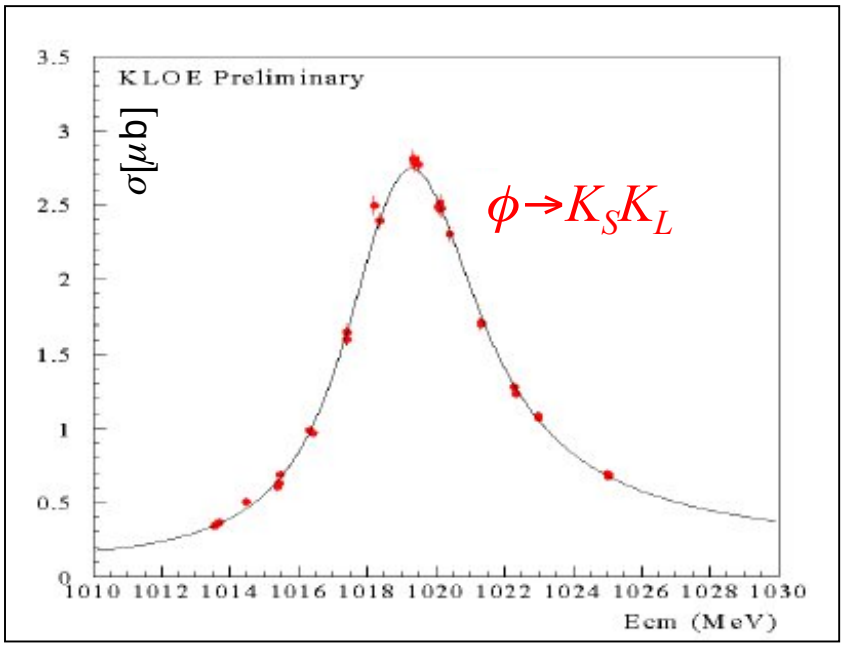
Two complementary ways to measure ε'/ε:

- Double ratio: $$1 - 6\,\mathrm{Re}(\varepsilon'/\varepsilon) = \frac{BR(K_L \to \pi^0\pi^0)/BR(K_L \to \pi^+\pi^-)}{BR(K_S \to \pi^0\pi^0)/BR(K_S \to \pi^+\pi^-)}$$

- Quantum interferometry: from the measured decay intensity $I(K_S K_L \to \pi^+\pi^-, \pi^0\pi^0, \Delta t)$ as a function of the difference of times of the two decays $\Delta t = t_{\pi+\pi-} - t_{\pi 0 \pi 0}$ it is possible to evaluate Re ε'/ε and Im ε'/ε

DAΦNE performance



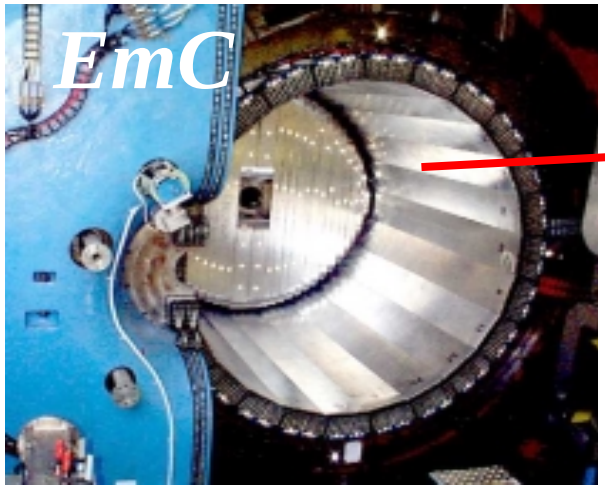


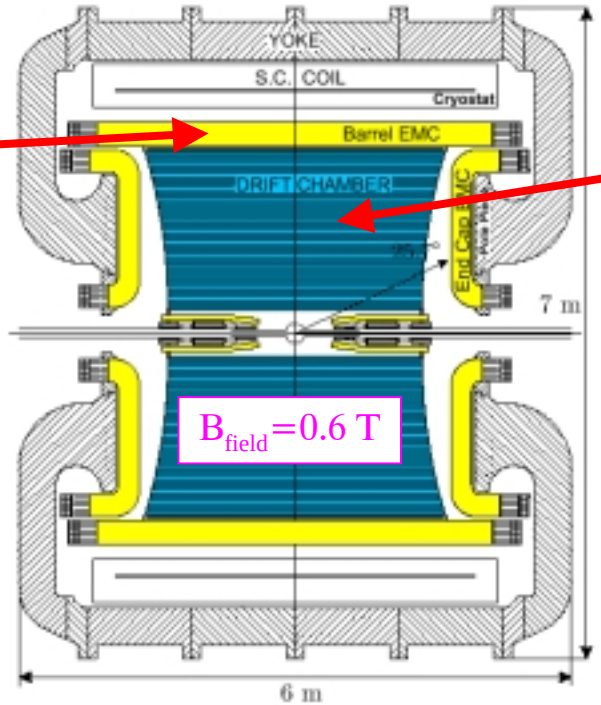
Daϕne and KLOE energy scan calibration

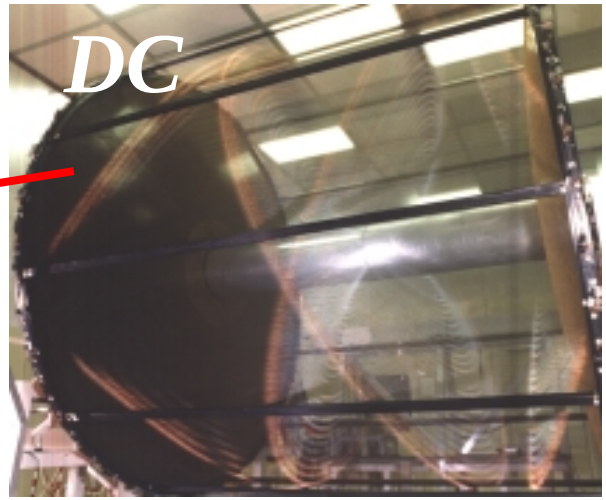
Present day performance:

	peak	average
$L(cm^{-2}\ s^{-1})$	$4.8 \cdot 10^{31}$	$3 \cdot 10^{31}$
$\int_{day} L\ dt\ \ (pb^{-1})$	2.5	1.4

The KLOE detector







Lead/scintillating fiber
4880 PMTs
98% coverage of solid angle

4 m diameter × 3.3 m length
90% helium, 10% isobutane
12582/52140 sense/total wires
All-stereo geometry

$\sigma_E/E = 5.7\% / \sqrt{E}(\mathrm{GeV})$

$\sigma_t = 54\ \mathrm{ps} / \sqrt{E}(\mathrm{GeV}) \oplus 50\ \mathrm{ps}$

(finite bunch-length contribution subtracted)

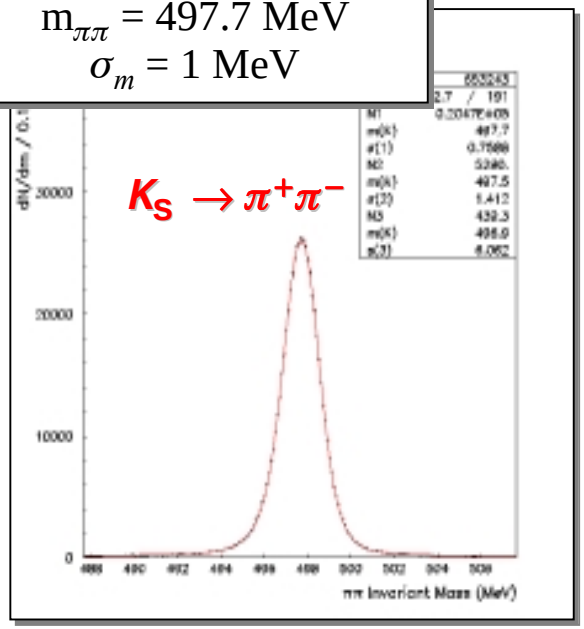
$\sigma_p/p = 0.4\ \%$ (tracks with $\theta > 45°$)

$\sigma_\phi = 150\ \mu\mathrm{m}$

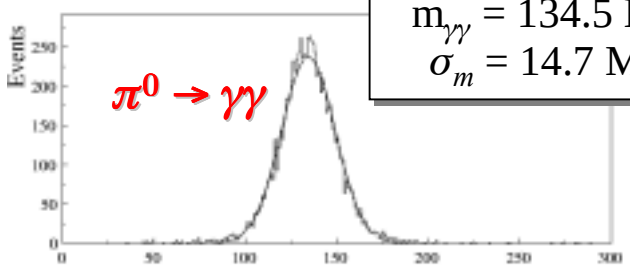
$\sigma_z = 2\ \mathrm{mm}$

KLOE detector performance

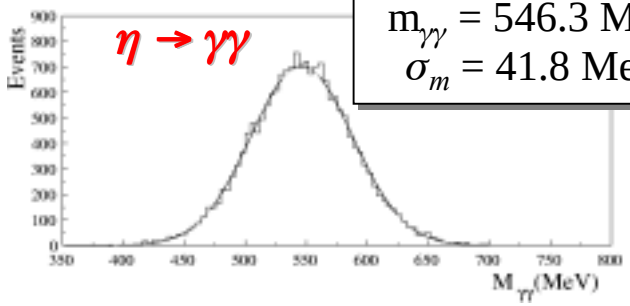
$m_{\pi\pi}$ = 497.7 MeV
σ_m = 1 MeV



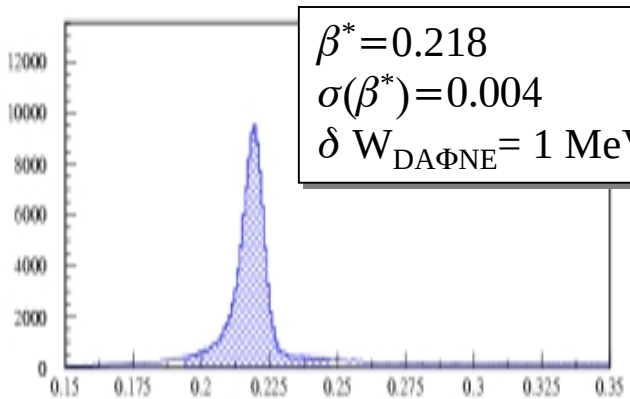
$m_{\gamma\gamma}$ = 134.5 MeV
σ_m = 14.7 MeV



$m_{\gamma\gamma}$ = 546.3 MeV
σ_m = 41.8 MeV

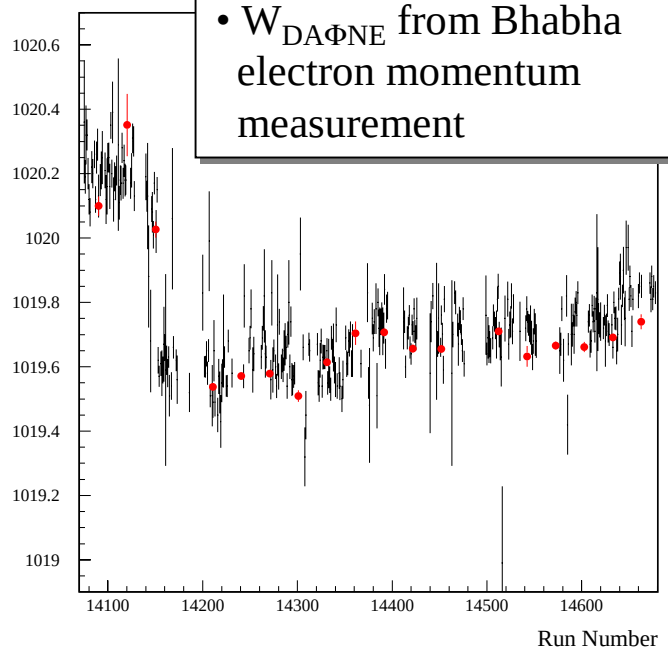


β^*=0.218
$\sigma(\beta^*)$=0.004
δ $W_{DA\Phi NE}$= 1 MeV



β^*=K_L velocity in the ϕ rest frame

- $W_{DA\Phi NE}$ from the velocity measurement of K_L interacting in the EmC
- $W_{DA\Phi NE}$ from Bhabha electron momentum measurement



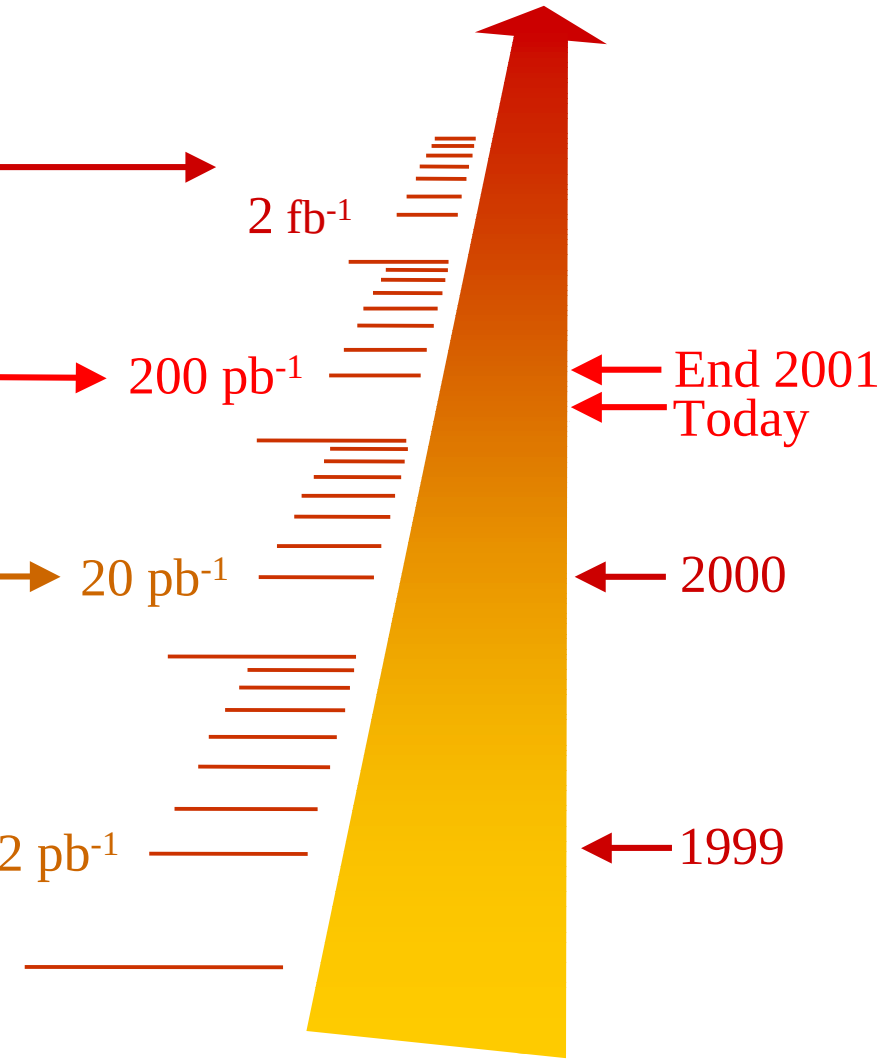
KLOE physics program

ε'/ε to $O(10^{-4})$ via double ratio
Semileptonic asymmetry (CPT test)
Interferometry

Improve K_S and ϕ physics,
rare K_S decays, $K_L \to 2\pi$,
$K_L \to \gamma\gamma$, $K^{\pm}$ decays
$\sigma(e^+e^- \to \pi^+\pi^-)$ to < 1 % (stat)

K_S physics
- $BR(K_S \to \pi^+\pi^-)/BR(K_S \to \pi^0\pi^0)$
- $BR(K_S \to \pi e \nu)$

ϕ radiative decays
- $\phi \to f_0\gamma$, $a_0\gamma$
- $\phi \to \eta'\gamma$, $\eta\gamma$



Tagging of K_S decays

Clean K_S tagging by time-of-flight identification of K_L interacting in the EmC ("K_L crash")

Selection cuts:

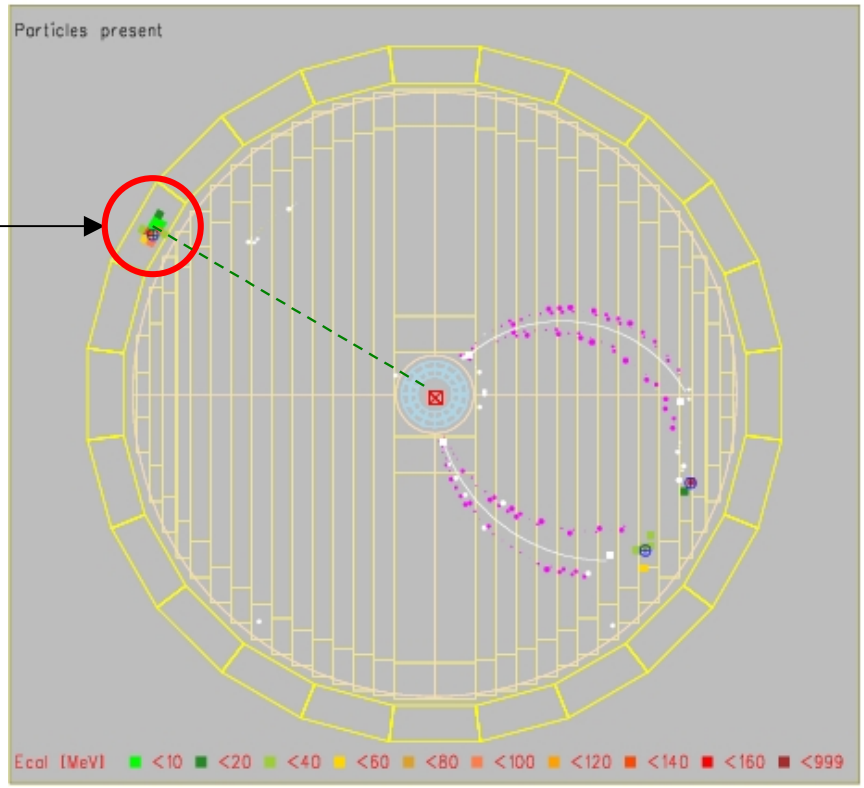
- $E_{clus} \geq 200$ MeV
- $|\cos(\theta_{clus})| \leq 0.7$
- $0.195 \leq \beta^* \leq 0.2475$

(β^* = K_L velocity in the ϕ rest frame)

Given the two body ϕ decay, the position of the K_L cluster provides the K_S momentum (useful in semil. decays)

40% of time , K_L crash triggers by itself

Facilitates determination of trigger efficiency



17 pb^{-1} = 5.4M K_L crash candidates

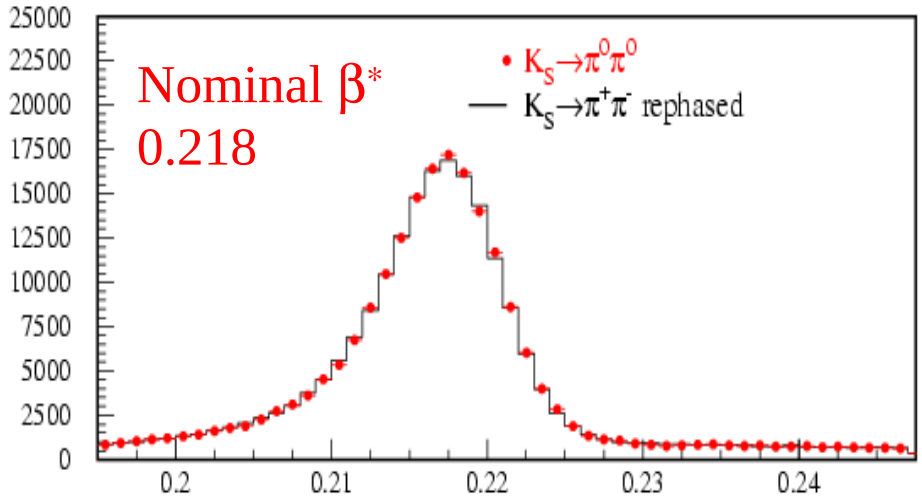
T_0 fixing

- The trigger is synchronized with the bunch crossing frequency
- The absolute time zero of the event is fixed a posteriori using the fastest cluster with

  $E_{cluster} > 50$ MeV

  $|\cos\theta| > 0.945$
- photon hypothesis used at the first reconstruction stage
- Tag efficiency is slightly dependent on the K_S decay due to the different t_0 determination: from γ's in $K_S \rightarrow \pi^0\pi^0$

  from pions clusters in $K_S \rightarrow \pi^+\pi^-$



β^* = velocity of K_L in rest frame of ϕ

after correction for pion velocities

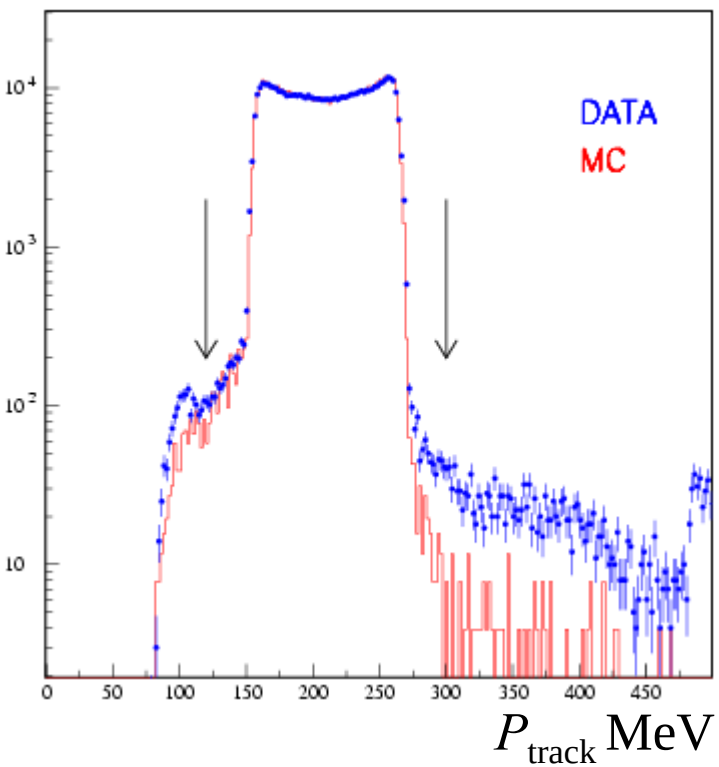
$K_S \to \pi^+\pi^-$

Selection:

K_L crash and 2 tracks from IP

Acceptance and loose p cuts:

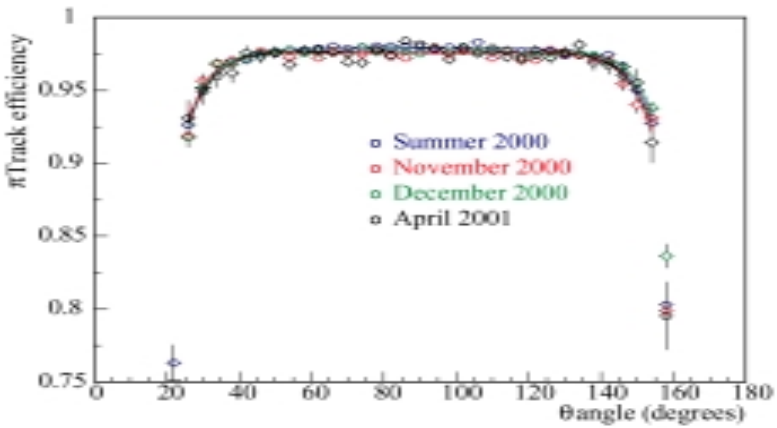
correction from MC



Efficiency evaluation:

Conditional single-track reconstruction efficiency from $K_S \to \pi^+\pi^-$ data, used to weight MC

ε(sel and rec) = (58.9 ± 0.2) %



Single-particle t_0 and trigger efficiencies from data:

$K_S \to \pi^+\pi^-$ also $K_L \to \pi^+\pi^-\pi^0$, $\phi \to \pi^+\pi^-\pi^0$

plugged into MC

$\varepsilon(t_0$ and trig) = (97.6 ± 0.05) %

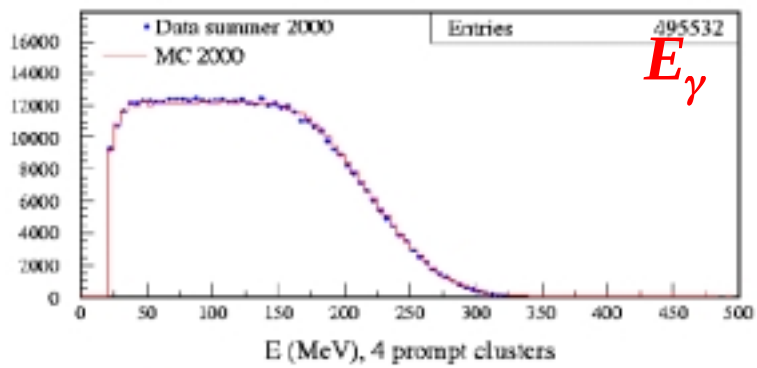
$K_S \to \pi^0\pi^0$

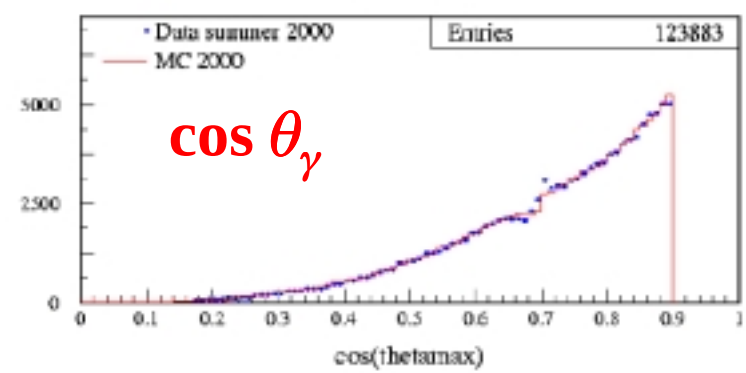
Selection:

K_L crash and ≥3 *prompt* photons (i.e. photons from IP: $|T-R/c| < 5\sigma_t$)

Acceptance (θ) and E cuts—

correction from MC

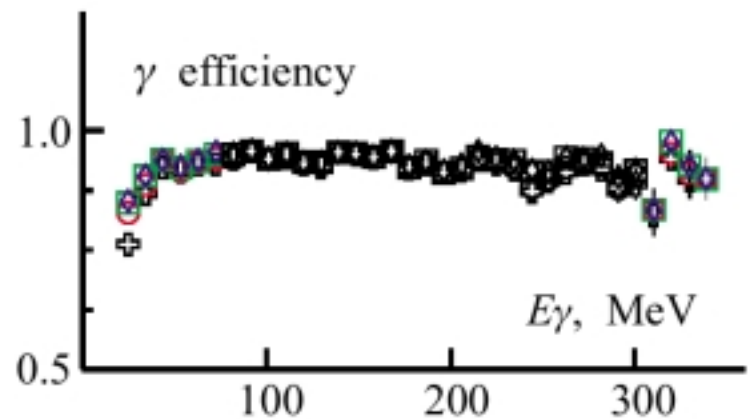




Efficiency evaluation:

Photon detection efficiency from data using $\phi \to \pi^+\pi^-\pi^0$ events

ε(sel and rec) = (90.1 ± 0.5)%



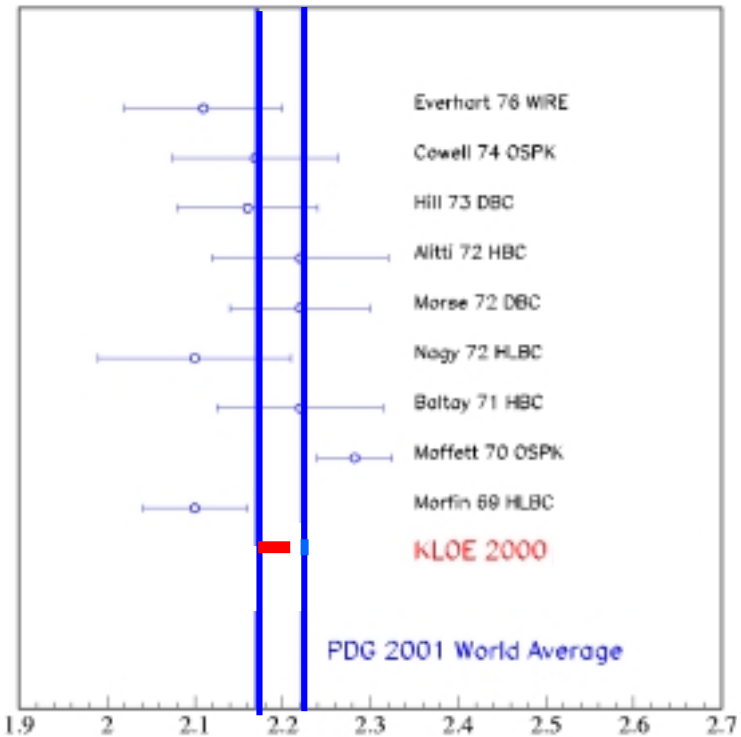
Trigger efficiency estimated by measuring probability of having 0,1 triggering clusters from data

$\varepsilon(t_0$ and trig) = (99.78 ± 0.04)%

BR($K_S \to \pi^+\pi^-$)/BR($K_S \to \pi^0\pi^0$)

KLOE 2000 data **$2.192 \pm 0.003_{stat} \pm 0.016_{syst}$**

PDG 2000 $2.197 \pm 0.026_{stat} \pm 0.013_{syst}$



Contribution to systematic error	%
$K_S \to \pi^0\pi^0$ selection	0.5
$K_S \to \pi^+\pi^-$ selection	0.2
trigger and t_0	0.06
Cosmic veto	0.3
tag bias	0.4
Overall systematic error	0.7

Work on $d\Gamma(K_S \to \pi^+\pi^-\gamma)/dE_\gamma$ in progress

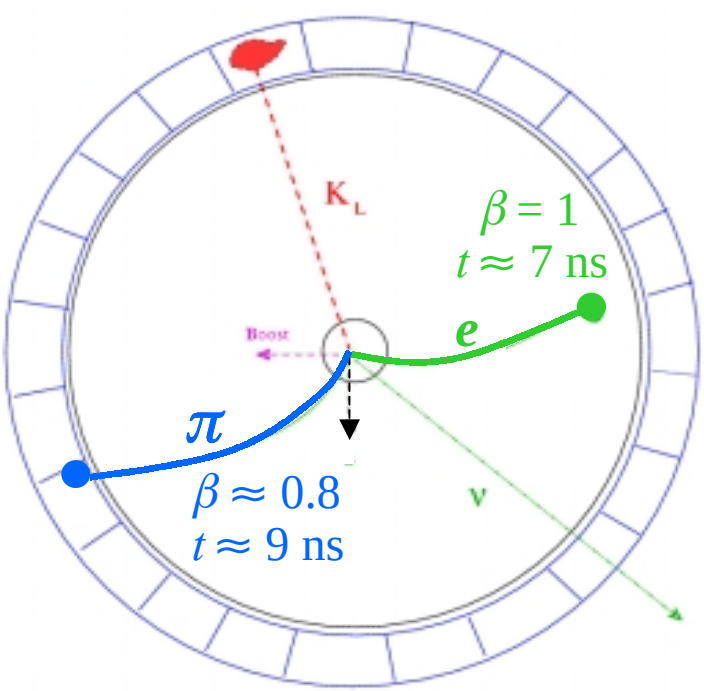
Analysis of $K_S \to \pi e \nu$ decays

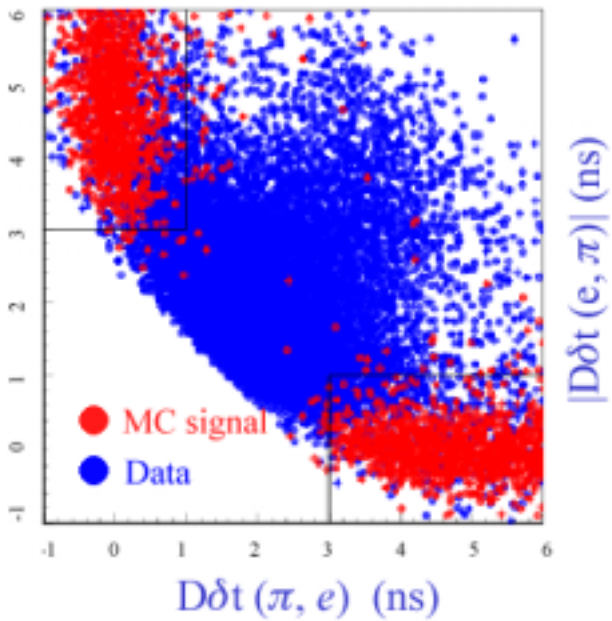
K_L crash and vertex at IP

2 tracks with associated EmC clusters

Preselection cuts on $M_{\pi\pi}$, P^*

Acceptance and selection efficiency from MC





π/e identification using time-of-flight

Cuts on $D\delta t(\pi, e)$, (e, π), (π, π), *e.g.*:

$D\delta t(\pi,e) \equiv [t_1 - t_2] - [T_1(\pi)^{exp} - T_2(e)^{exp}]$

Efficiency from $K_L \to \pi e \nu$ decays near origin

High-purity sample (> 99.7 %), isolable by kinematic cuts

Analysis of $K_S \to \pi e \nu$ decays

Single-particle t_0, track-cluster, and trigger efficiencies from data using:

$K_L \to \pi e \nu$ near origin

$\phi \to \pi^+\pi^-\pi^0, K_S \to \pi^+\pi^-$

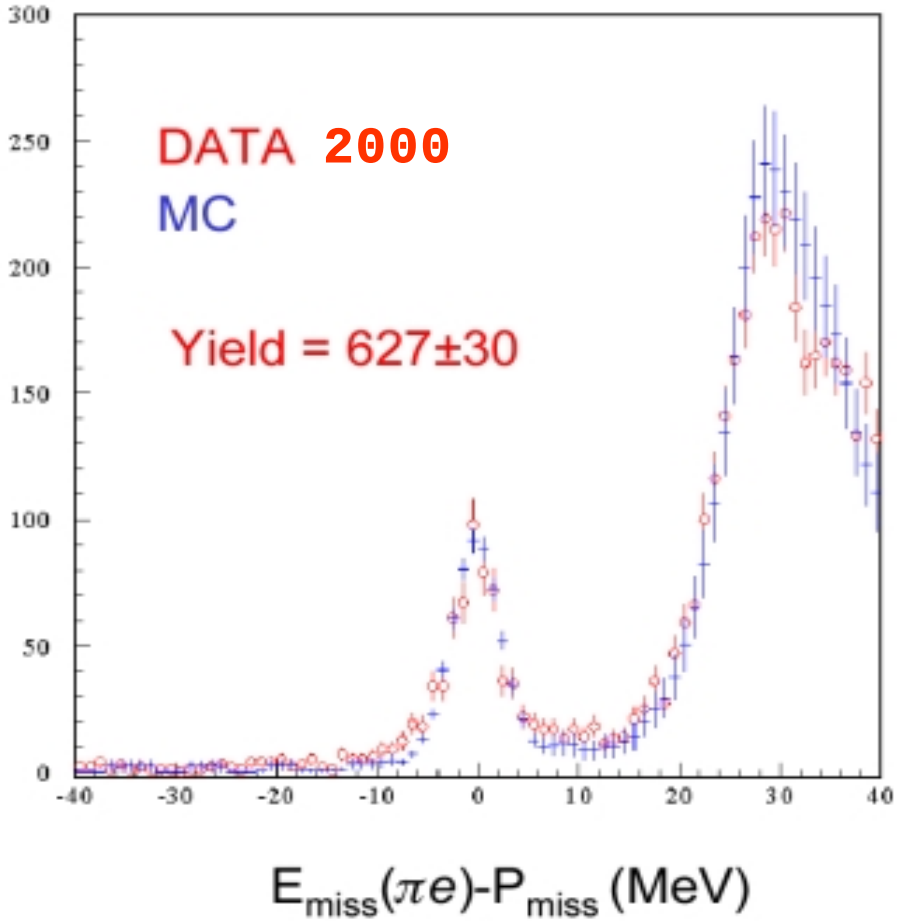
MC-weighted to get overall correction

Overall selection efficiency:

(21.9 ± 0.7)%

Fit to $E_{miss} - P_{miss}$ spectrum using MC spectra for signal and $\pi^+\pi^-$ background

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



BR($K_S \to \pi e \nu$)

KLOE 2000 data	$\mathbf{(6.79 \pm 0.33_{stat} \pm 0.20_{syst}) \cdot 10^{-4}}$
CMD-2 1999, 75 ± 13 evts.	$(7.2 \pm 1.4) \cdot 10^{-4}$
$\Gamma(K_S \to \pi e \nu) = \Gamma(K_L \to \pi e \nu)$	$(6.70 \pm 0.07) \cdot 10^{-4}$

Main contributions to the total error	%
Statistics	4.9
Tracking efficiency	2.0
vertex efficiency	2.0
preselection	0.5
Track topology cuts	0.4
Cluster $\cdot t_0 \cdot$ trigger	0.7
TOF selection	0.8
Tag bias	0.6
Total	5.9

$\phi \to \eta'\gamma, \eta\gamma$

Precise measurements of BR($\phi \to \eta'\gamma$) and BR($\phi \to \eta\gamma$) provide for:

- Probe of hidden strangeness and gluonium content of η'
- Determination of $\eta - \eta'$ mixing angle

$$\phi \to \eta'\gamma \to \pi^+\pi^-\eta\gamma \to \pi^+\pi^-3\gamma$$

$$\phi \to \eta\gamma \to \pi^+\pi^-\pi^0\gamma \to \pi^+\pi^-3\gamma$$

Event selection

3 prompt photons with $E > 7$ MeV, $\theta > 21°$

Vertex near IP

Preliminary kinematic fit

Constraints: conservation of total E, $\mathbf{p}$; $\beta = 1$ for each γ

Simple kinematic cuts to eliminate background:

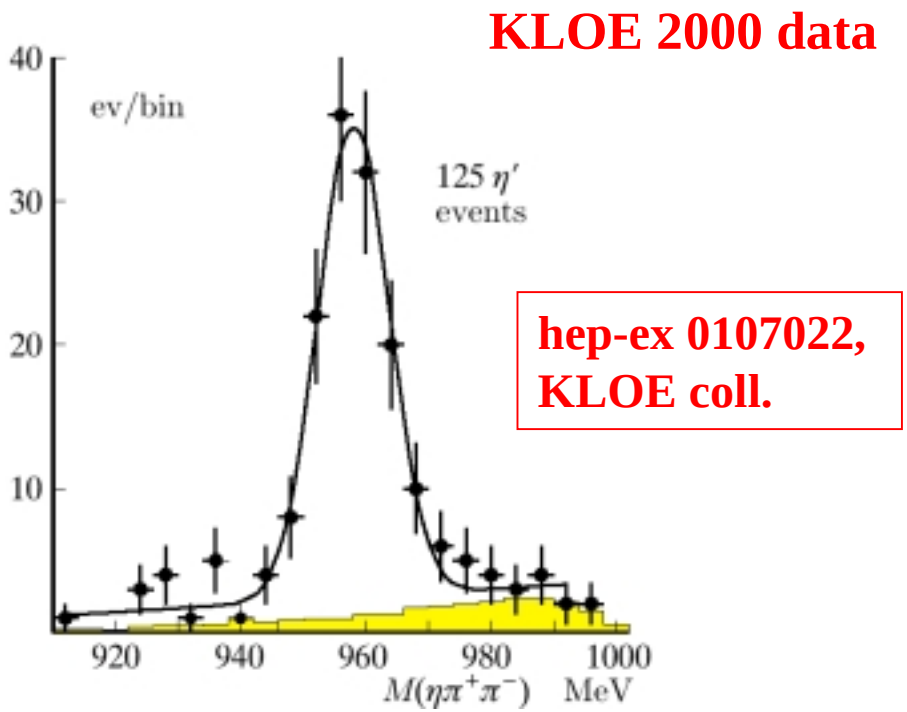
$\phi \to \pi^+\pi^-\pi^0$ with extra γ

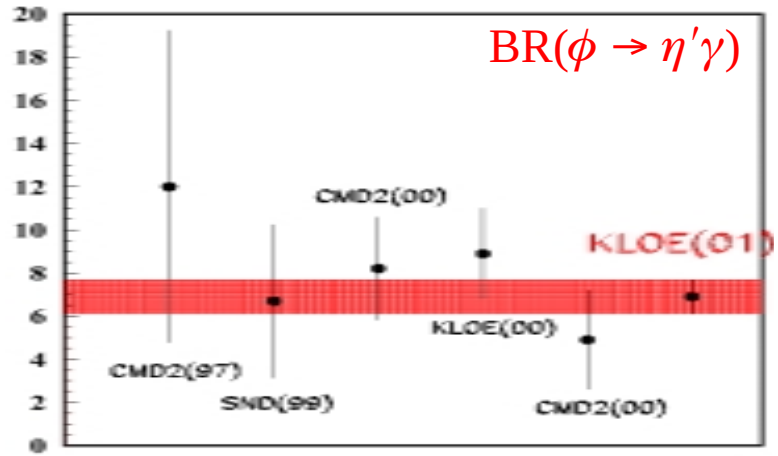
$\phi \to K_S K_L \to \pi^+\pi^- \pi^0 \pi^0$ with γ lost

Only surviving background to $\phi \to \eta'\gamma$ (at level of MC statistics) is from $\phi \to \eta\gamma$

Cuts on γ's energy spectrum: radiative photon energy very different in the η, η' cases

$\phi \to \eta'\gamma, \eta\gamma$





$$BR(\phi \to \eta'\gamma)/BR(\phi \to \eta\gamma) = (5.3 \pm 0.5_{stat} \pm 0.3_{syst}) \cdot 10^{-3}$$

$$BR(\phi \to \eta'\gamma) = \text{with PDG value for } \phi \to \eta\gamma \quad (6.8 \pm 0.6_{stat} \pm 0.5_{syst}) \cdot 10^{-5}$$

Measurement of $BR(\phi \to \eta'\gamma)/BR(\phi \to \eta\gamma)$ gives most accurate determination of pseudoscalar mixing angle to date:

$$\varphi_P = 40.0^{+1.7}_{-1.5} \quad \text{(flavor basis)}$$

$$\theta_P = -14.7^{+1.7}_{-1.5} \quad \text{(octet-singlet basis)}$$

Disfavors significant gluonium content for the η'

$\phi \to \pi^0\pi^0\gamma\ (f_0\gamma)$ and $\phi \to \eta\pi^0\gamma\ (a_0\gamma)$

Composition of f_0 and a_0 mesons uncertain

Precise measurements of BR($\phi \to f_0\gamma$) and BR($\phi \to a_0\gamma$) may distinguish between various models: $q\bar{q}q\bar{q}$ state, $K\bar{K}$ molecule, ordinary $q\bar{q}$ meson

Detect 5γ final states $\left\{ \begin{array}{l} \phi \to f_0\gamma \to \pi^0\pi^0\gamma \to 5\gamma \\ \phi \to a_0\gamma \to \eta\pi^0\gamma \to 5\gamma \end{array} \right.$

Background to $\phi \to f_0\gamma$	S/B
Resonant:	
$\phi \to \rho^0\pi^0 \to \pi^0\pi^0\gamma$	3.7
$\phi \to a_0\gamma \to \eta\pi^0\gamma \to \gamma\gamma\pi^0\gamma$	3.5
continuum:	
$e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$	0.6
misreconstructed 3,7 γ :	
$\phi \to \pi^0\gamma$	0.10
$\phi \to \eta\gamma \to \pi^0\pi^0\pi^0\gamma$	0.02

Background to $\phi \to a_0\gamma$	S/B
Resonant:	
$\phi \to \rho^0\pi^0 \to \eta\pi^0\gamma$	5.3
$\phi \to \rho^0\pi^0 \to \pi^0\pi^0\gamma$	1
$\phi \to f_0\gamma \to \pi^0\pi^0\gamma$	0.27
continuum:	
$e^+e^- \to \omega\pi^0 \to \eta\pi^0\gamma$	7
$e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$	0.14
misreconstructed 3,7 γ :	
$\phi \to \eta\gamma \to \gamma\gamma\gamma$	6.1×10^{-3}
$\phi \to \eta\gamma \to \pi^0\pi^0\pi^0\gamma$	7.5×10^{-3}

$\phi \to \pi^0\pi^0\gamma$ ($f_0\gamma$) and $\phi \to \eta\pi^0\gamma$ ($a_0\gamma$)

Preselection common to the two analyses:

- 5 prompt photons in EmC with energy > 7 MeV coming from the IP
- Acceptance cut: $21^o < \vartheta_{\mathbf{EmC}} < 159^o$

Further analysis steps:

- First kinematic fit (4-momentum conservation, T – R/c = 0 for each photon and *no* mass constraints on intermediate resonances)
- Photon pairing (best combination χ^2 for $\pi^0\pi^0\gamma$, $\eta\pi^0\gamma$, $\omega\pi^0$, $\eta\gamma$, $\pi^0\gamma$ hypothesis)
- Second kinematic fit *with* mass constraints on intermediate resonances without any assumption on the f_0 and a_0 mass
- Final cuts on χ^2 and kinematic variables to reject backgrounds

$\phi \to \pi^0\pi^0\gamma\ (f_0\gamma)$ and $\phi \to \eta\pi^0\gamma\ (a_0\gamma)$

KLOE 2000 data

hep-ex 0107024, KLOE coll.

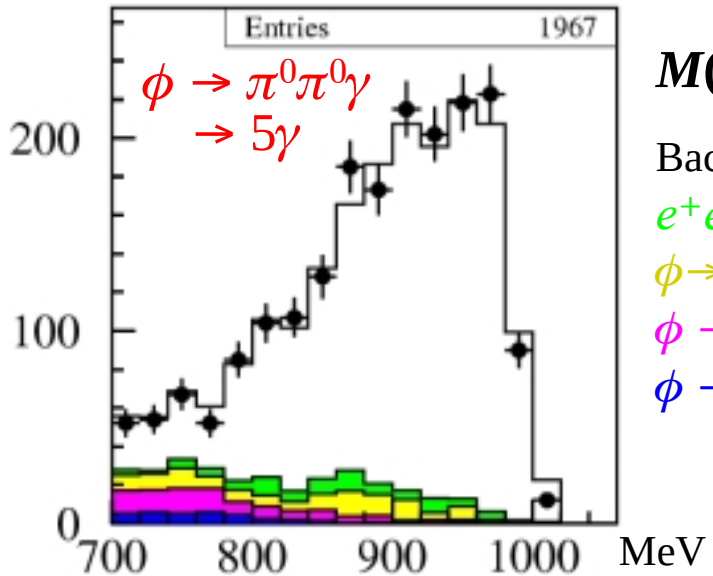
$\phi \to f_0\gamma \to \pi^0\pi^0\gamma$ BR($M_{\pi\pi}$ > 700 MeV) = $(7.9 \pm 0.2_{stat}) \cdot 10^{-5}$

$\phi \to a_0\gamma \to \eta\pi^0\gamma$ BR = $(5.8 \pm 0.5_{stat}) \cdot 10^{-5}$

BR($\phi \to f_0\gamma$)/BR($\phi \to a_0\gamma$) = $4.1 \pm 0.4_{stat}$

systematic error under study: it should not exceed 10%

Favorable comparison with prediction for f_0, a_0 compact $q\bar{q}$ or $q\bar{q}q\bar{q}$ states with significant virtual $K\bar{K}$ component F. Close and A. Kirk, PLB515,13(2001)



***M*($\pi^0\pi^0$)**

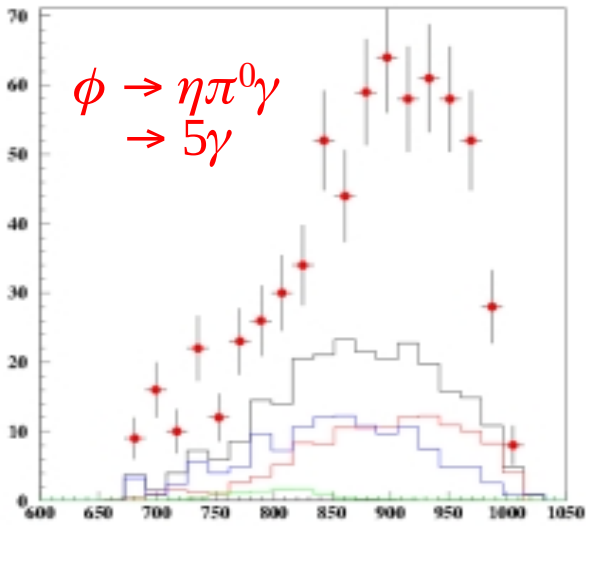
Backgrounds:

$e^+e^- \to \omega\pi^0$

$\phi \to \eta\gamma$

$\phi \to \rho\pi^0$

$\phi \to a_0\gamma$



***M*($\eta\pi^0$)**

Backgrounds:

$\phi \to \pi^0\pi^0\gamma$

$e^+e^- \to \omega\pi^0$

$\phi \to \eta\gamma$

Total

Conclusions

- ✓ DAFNE performance has improved considerably during the first two years of KLOE data taking
- ✓ The KLOE detector is performing well
- ✓ From the analysis of 2000 data we have measured and studied:

  $\mathrm{BR}(K_S \to \pi^+\pi^-)/\mathrm{BR}(K_S \to \pi^0\pi^0)$, $\mathrm{BR}(K_S \to \pi e\, \nu)$

  $\phi \to f_0\gamma \to \pi^0\pi^0\gamma$, $\phi \to a_0\gamma \to \eta\pi^0\gamma$, $\phi \to \eta\gamma$, $\phi \to \eta'\gamma$
- ✓ From the analysis of 2001 data we continue previous items and study:
  - rare K_S decays
  - $K_L \to 2\pi$, $K_L \to \gamma\gamma$ decays, $K^{\pm}$ decays
  - $\sigma(e^+e^- \to \pi^+\pi^-)$ by radiative return to < 1% statistical error