KLOE results on Kaon decays and Φ radiative decays

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for the KLOE Collaboration

Heavy Quarks and Leptons 2002, Vietri 27/5-1/6

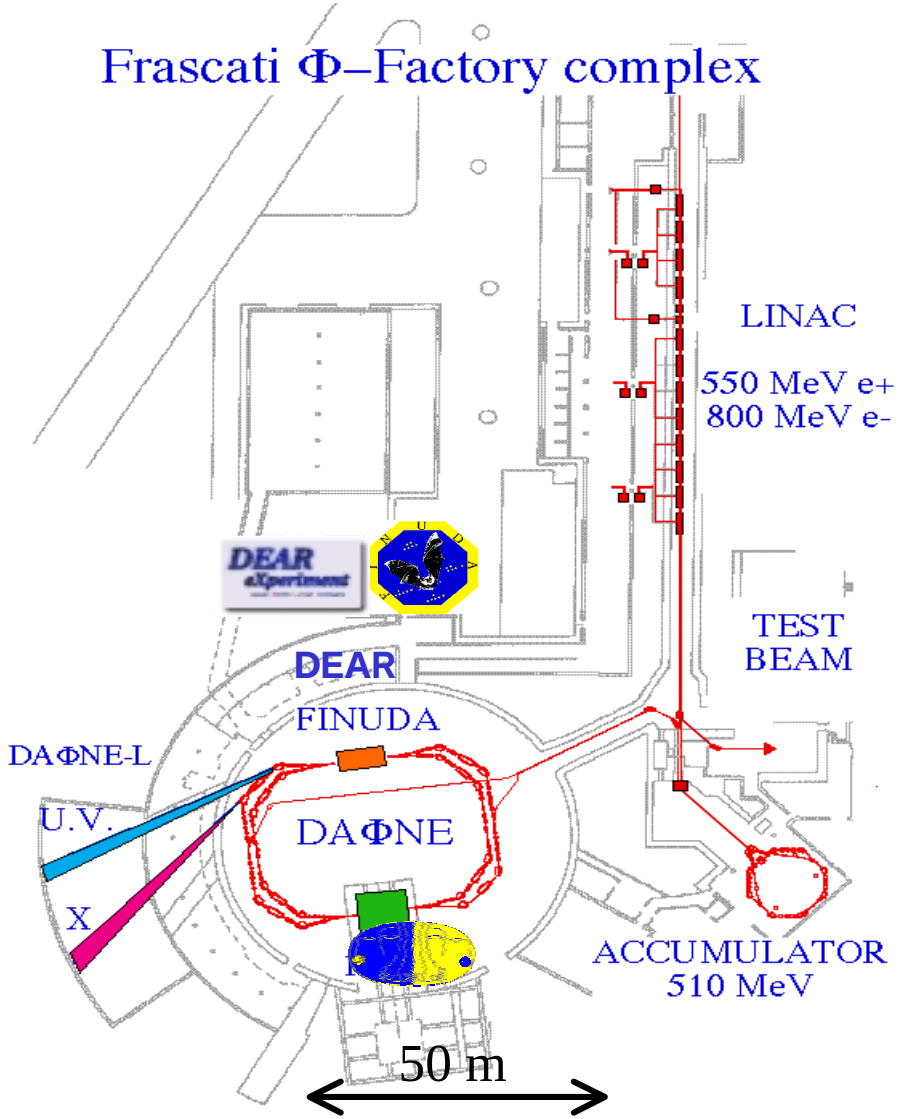
DAΦNE parameters

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}

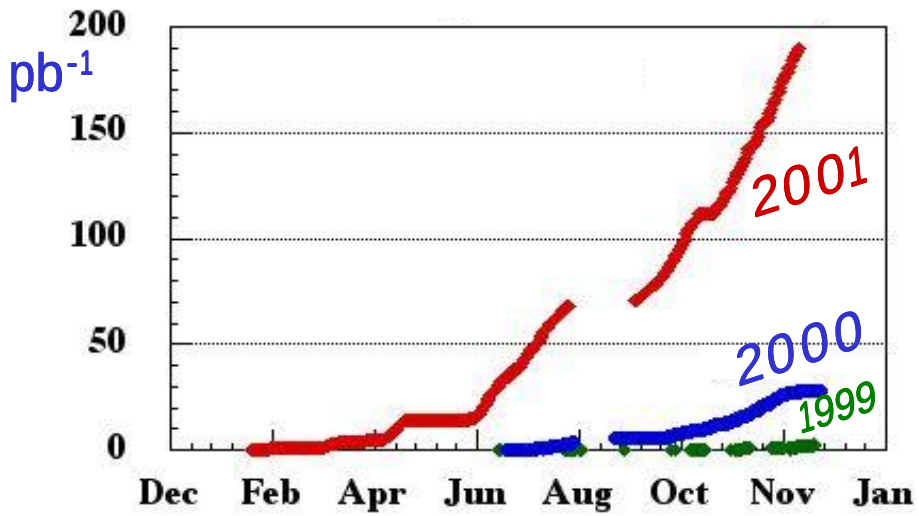
↓

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



DAΦNE Performance

KLOE Integrated Luminosity april '99 → december '01



(190 pb^{-1} ➔ 5.7 x 10^8 ϕ)
analysis in progress

(25 pb^{-1} ➔ 7.5 x 10^7 ϕ)
analysis completed

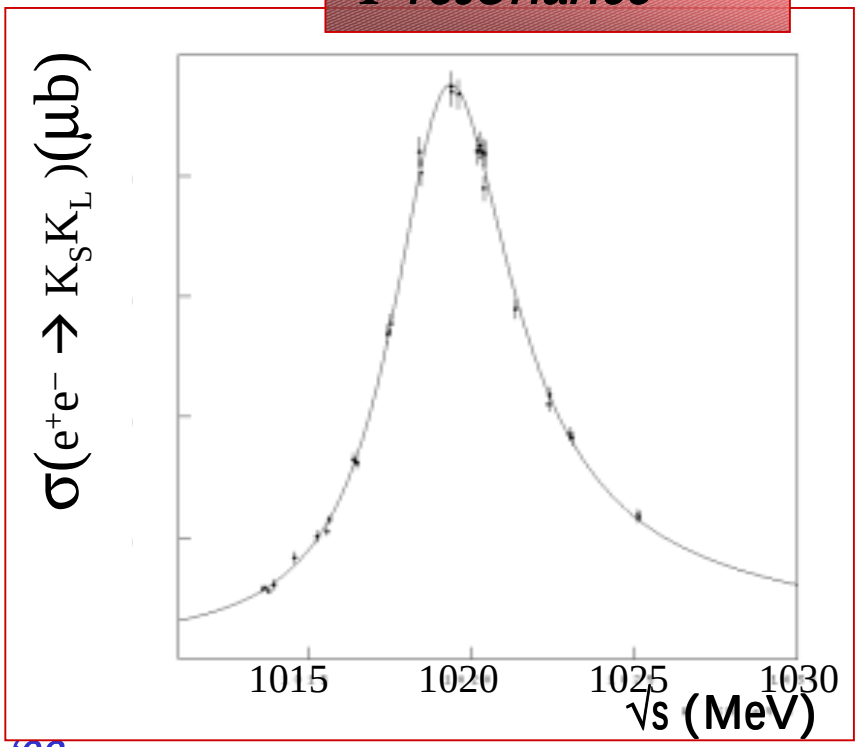
2001 day performance:	peak	average
L(cm^{-2} s^{-1})	$5 \cdot 10^{31}$	$3.5 \cdot 10^{31}$
$\int_{day} L\,dt$ (pb^{-1})	3	1.8

MAY '02 new data taking started

L(cm^{-2} s^{-1})	$4.6 \cdot 10^{31}$	$3.2 \cdot 10^{31}$
$\int_{day} L\,dt$ (pb^{-1})	2.5	2

machine background reduction of a factor 2÷3

Φ resonance



The KLOE detector

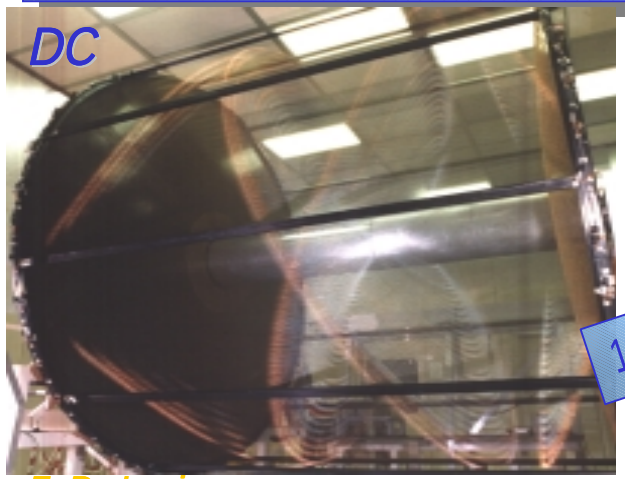
Neutral kaons are produced in a pure quantum state ($J^{PC}=1^{--}$) :

$$\sqrt{\ } \rightarrow K^0\overline{K}^0 \rightarrow K_S K_L$$

(contamination from $K_S K_S, K_L K_L < 10^{-9}$)

$p_K \cong 110$ MeV/c $\lambda_S = 6$ mm $\lambda_L = 3.4$ m

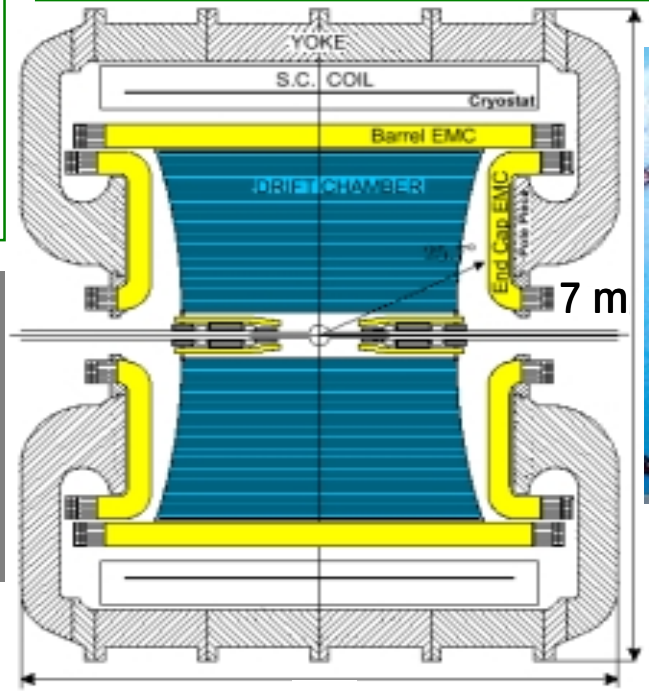
- 4 m diameter × 3.3 m length
- 90% helium, 10% isobutane
- 12582/52140 sense/tot wires
- All-stereo geometry

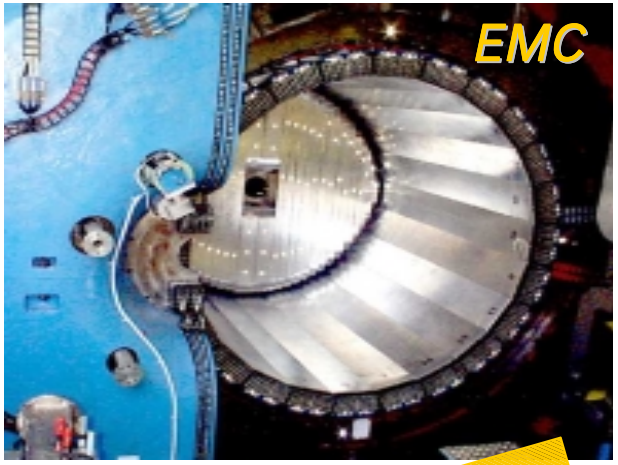


$155 < p_\pi < 265$

TAGGING

detection of a K_S (K_L) guarantees the presence of a K_L (K_S) with known momentum and direction



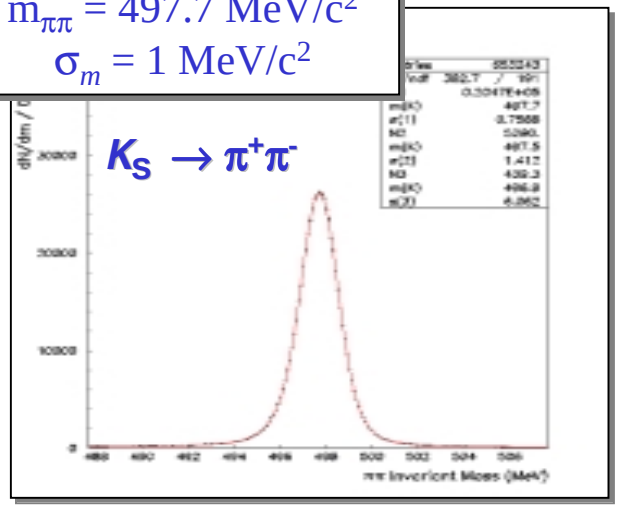


$20 < E_\gamma < 500$ MeV

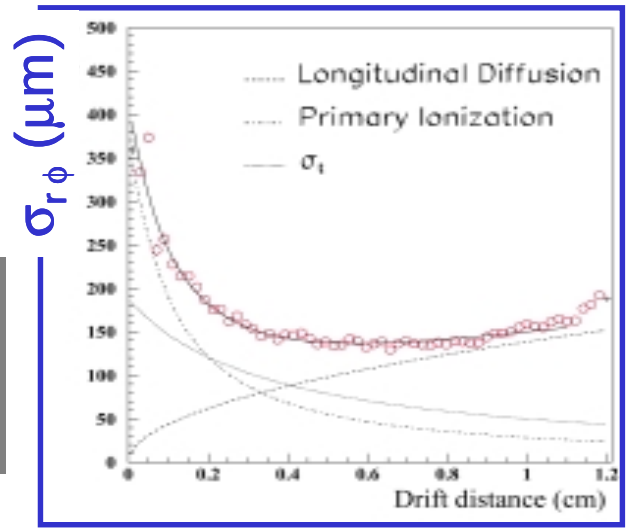
- Lead/scintillating fiber
- 98% coverage of solid angle
- 88 modules (barrel + end-caps)
- 4880 PMTs (two side read-out)

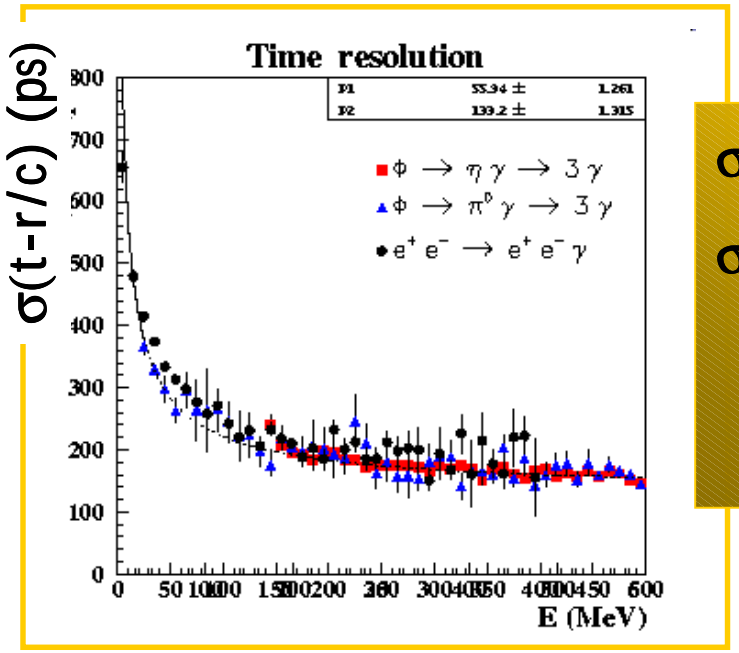
The KLOE detector performances

$m_{\pi\pi}$ = 497.7 MeV/c^2
σ_m = 1 MeV/c^2

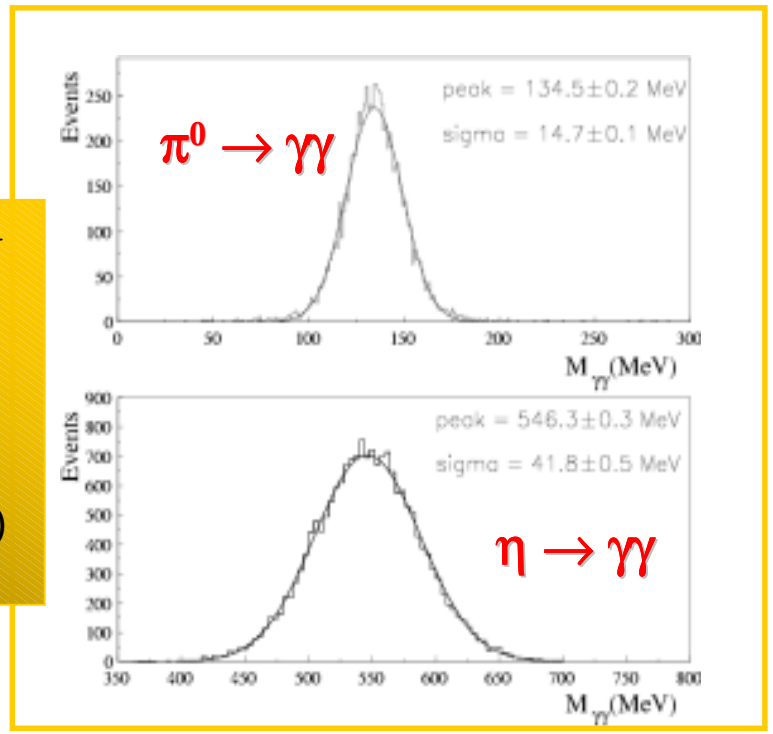


σ_p/p = 0.4 %
$\sigma_{r\phi}$ = 150 μm
σ_z = 2 mm
σ_V = 3 mm





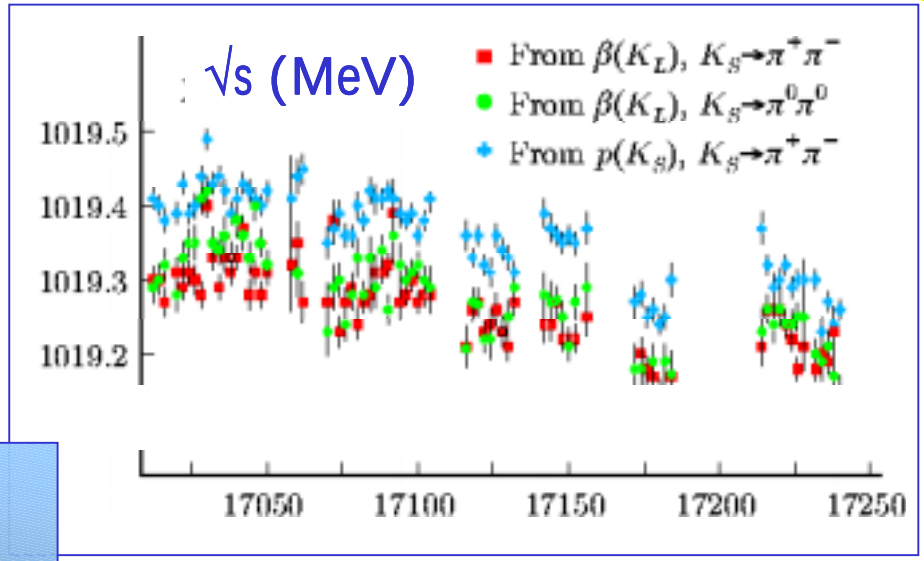
σ_E/E =5.4% /$\sqrt{E(GeV)}$
σ_t = 54 ps /$\sqrt{E(GeV)}$
⊕50 ps(cal)
⊕120 ps (coll.time)



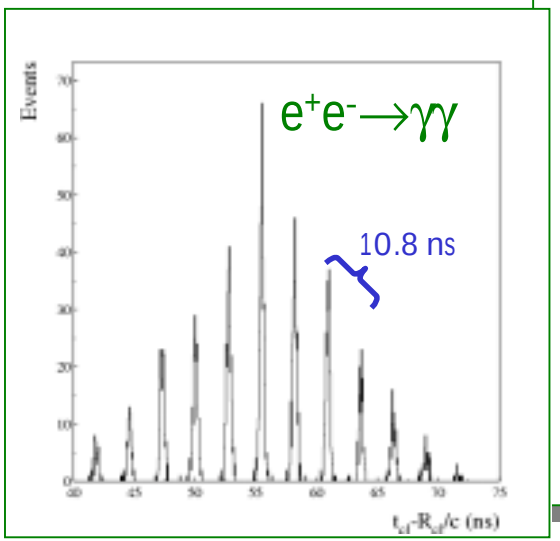
DAΦNE energy and bunch-crossing time

Energy

- $\sqrt{s}$ from the β of K_L interacting in the EmC
- $\sqrt{s}$ from K_S pions and Bhabha electrons momenta measurement



At current luminosity Dafne energy at 0.01% within 1 minute of data taking using K_L β, K_S energy and Bhabha scattering events



Bunch-crossing time

large spread of the trigger time with respect to the crossing time but the signal is synchronized with machine RF/4 (10.8 ns) at 50 ps level

Off-line determination of the bunch-crossing time T_0

hp: the fastest cluster with time t^{CLUS} in EMC is due to a prompt γ from I.P. with time of flight $t^{TOF} = R^{CLUS}/c$:

($E^{CLUS} > 50$ MeV and $\rho^{CLUS} > 60$ cm to avoid selection of "accidental" clusters)

The KLOE physics program

2000 statistics:

K_S physics :

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

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

ϕ radiative decays

$\phi \to f_0\gamma,\ a_0\gamma$

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

O(20 pb^{-1})

✓ first publications

2001 statistics:

- rare K_S decays
- K_L form factors, $K_L \to 2\pi$, $K_L \to \gamma\gamma$
- $K^{\pm}$ decays
- $\sigma(e^+e^- \to \pi^+\pi^-)$ via ISR
- η decays

O(200 pb^{-1})

on tape
analysis in progress

- ε'/ε via double ratio
- Semileptonic asymmetry (CPT test)
- $K_L K_S$ Interferometry

. . . .

Recent results in publication

Using a sample of 5×10^7 ϕ decays (2000 data):

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

  hep-ex/0204024 , accepted by *Phys.Lett.B*

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

  Phys.Lett. B 535 37 (2002)

- $BR(\phi \to \eta\, \pi^0 \gamma) \Rightarrow BR(\phi \to a_0 \gamma \to \eta\, \pi^0 \gamma)$

  Phys.Lett. B 536 209 (2002)

- $BR(\phi \to \pi^0 \pi^0 \gamma) \Rightarrow BR(\phi \to f_0 \gamma \to \pi^0 \pi^0 \gamma)$

  Phys.Lett.B 537 21 (2002)

- $BR(\phi \to \eta'\gamma)/BR(\phi \to \eta\gamma)$

  to be submitted to *Phys.Lett. B*

K_S analysis at KLOE

K_S tagging using time of flight identification of K_L interacting in the EmC ("K_L-crash") selected as a calorimeter cluster with:

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

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

$$\delta\beta = 0.004 \Rightarrow \delta W_{DA\Phi NE} = 1 \text{ MeV}$$

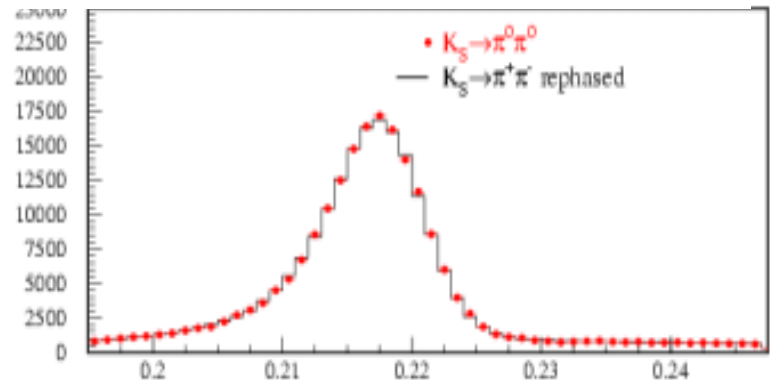
✓ relies on the measurement of β^* slightly dependent on K_S decay

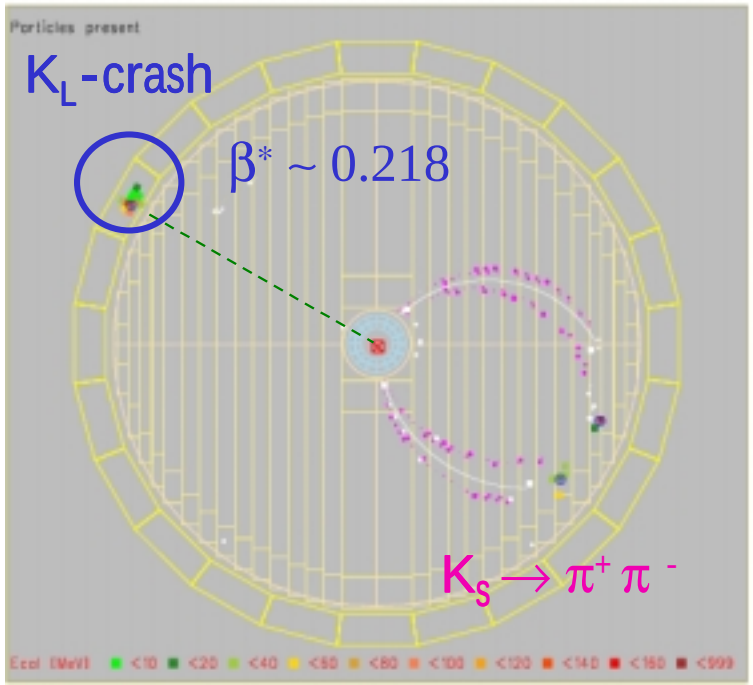
✓ easier determination of trigger efficiency
40% of times , K_L-crash triggers by itself

✓ K_S momentum from K_L cluster position

2000 data analysis = 5.4×10^6 K_L crash
2001 data on tape ~ 6×10^7 K_L crash

β^* after correction for different pion velocities and trigger latency





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

Motivations

- first step towards Re(ε′/ε)
- extraction of Isospin 0 and 2 amplitudes and phases from consistent treatment of soft γ in $K_S \to \pi^+\pi^-(\gamma)$

$K_S \to \pi^+\pi^-(\gamma)$ selection

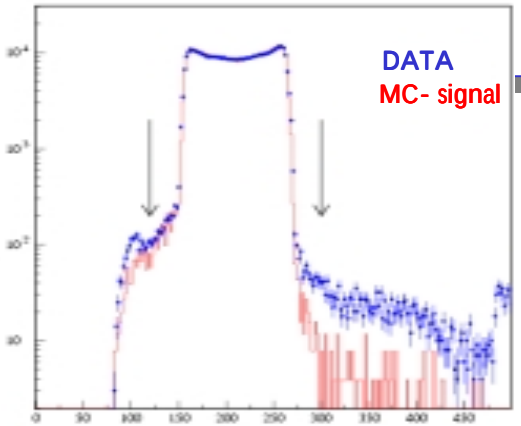
❖ K_L-crash .and. 2 tracks from IP reaching EMC(*)

❖ $120 < P_{track} < 300$ MeV/c .and. $30^o < \theta < 150^o$

fully inclusive measurement ⇒ no γ required in EMC

(*) acceptance depending on the photon energy E^*_γ

$\varepsilon_{\pi\pi(\gamma)}(E^*_\gamma)$ from MC folded to theoretical γ spectrum



P_{track} (MeV/c)

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

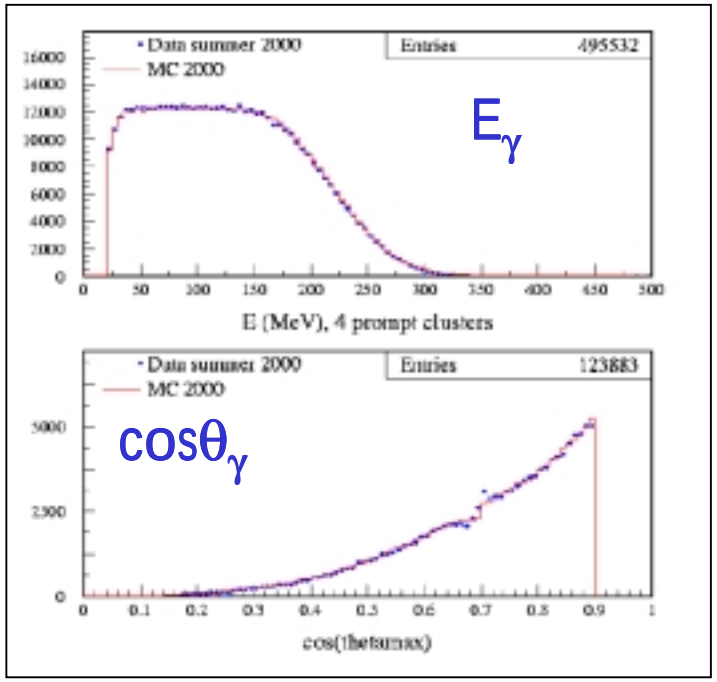
❖ K_L-crash .and. ≥ 3 neutral "prompt" clusters:

$|t^{CLUS} - R^{CLUS}/c| < 5\sigma_t$ .and.

$E^{CLUS} > 20$ MeV .and.

$\cos\theta < 0.9$

acceptance and *E* cuts correction from MC

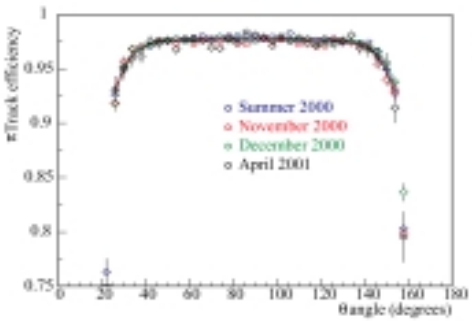


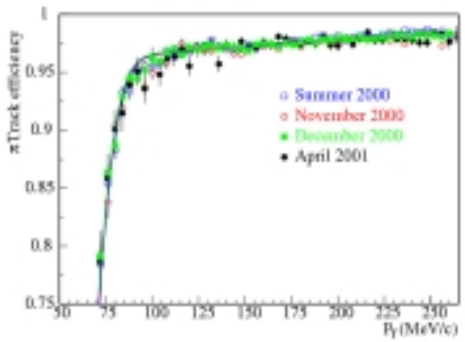
Efficiency evaluation

$K_S \to \pi^+\pi^-(\gamma)$

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

ε_{+-} (sel and rec) = (57.6 ± 0.2) %





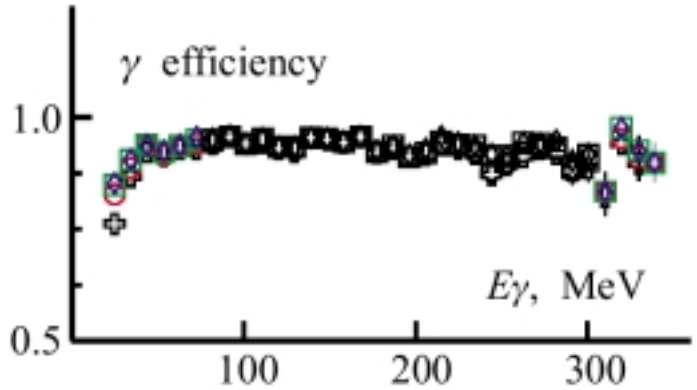
- ***single-particle t_0 and trigger efficiencies*** using data: *$K_S \to \pi^+\pi^-$ from $K_L \to \pi^+\pi^-\pi^0$ – tagged sample (t_0-independent), $\phi \to \pi^+\pi^-\pi^0$* and *$K_S \to \pi^+\pi^-$ with 2 trigger sectors fired by K_L-crash* plugged into MC

ε_{+-} (t_0 and trig) = (97.9 ± 0.03) %

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

- ***photon detection efficiency*** from data using $\phi \to \pi^+\pi^-\pi^0$ events. The overall selection efficiency (mostly acceptance):

ε_{00} = (90.1 ± 0.2)%



- ***t_0 and trigger efficiency*** using data: *$K_S \to \pi^0\pi^0$ from $K_L \to \pi^+\pi^-\pi^0$ –tagged sample (t_0-independent), $K_S \to \pi^0\pi^0$ with 2 trigger sectors fired by K_L-crash*

ε_{00} (t_0 and trig) = (99.86 ± 0.04)%

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

Result

$N_{ev}(K_S \to \pi^+\pi^-) = 1.098 \times 10^6$

$N_{ev}(K_S \to \pi^0\pi^0) = 0.788 \times 10^6$

KLOE 2000 data

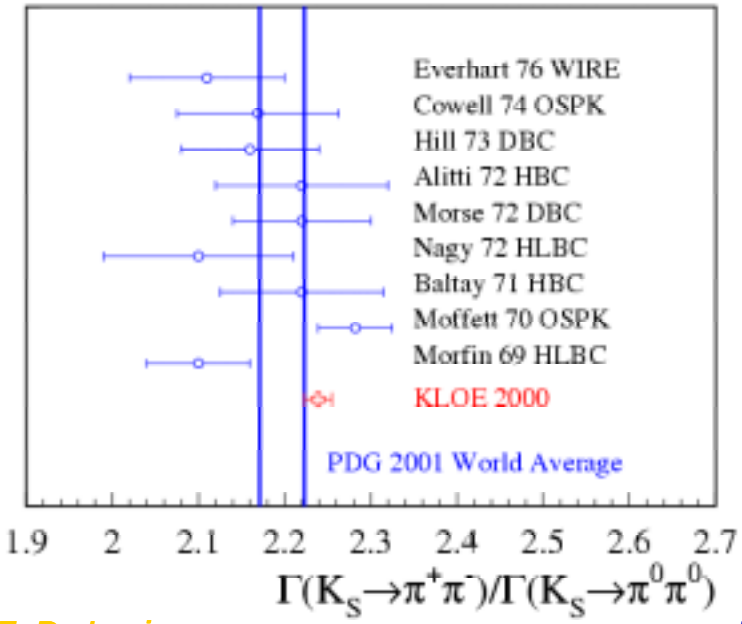
$2.239 \pm 0.003_{stat} \pm 0.015_{syst}$

PDG 2000 average

2.197 ± 0.026

(without clear indication of E^*_γ)

Statistical error (%)	0.14
Contribution to systematic error	%
$K_S \to \pi^0\pi^0 / K_S \to \pi^+\pi^-$ tag	0.55
photon counting	0.20
trigger and t_0	0.23
tracking	0.26
Overall systematic error	0.68



With 2001 data (180 pb^{-1}) improvement s on:

- absolute scale ➔ tagging efficiency bias
- statistics of control sub-samples
- E_γ^* spectrum

$BR(K_S \to \pi^{\pm} e^{\pm} \nu)$

Motivations

- if (CPT).and.(ΔS.eq. ΔQ) then

  $BR(K_S \to \pi^{\pm} e^{\pm} \nu) = BR(K_L \to \pi^{\pm} e^{\pm} \nu) \times \Gamma_L / \Gamma_S$

  from PDG values $= (6.704 \pm 0.071) \times 10^{-4}$

only one measurement (CMD-2 1999): $(7.2 \pm 1.4) \times 10^{-4}$

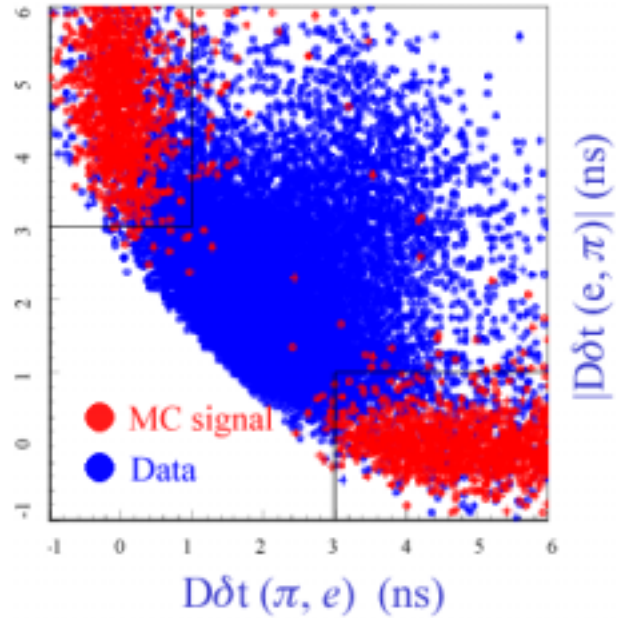
Selection

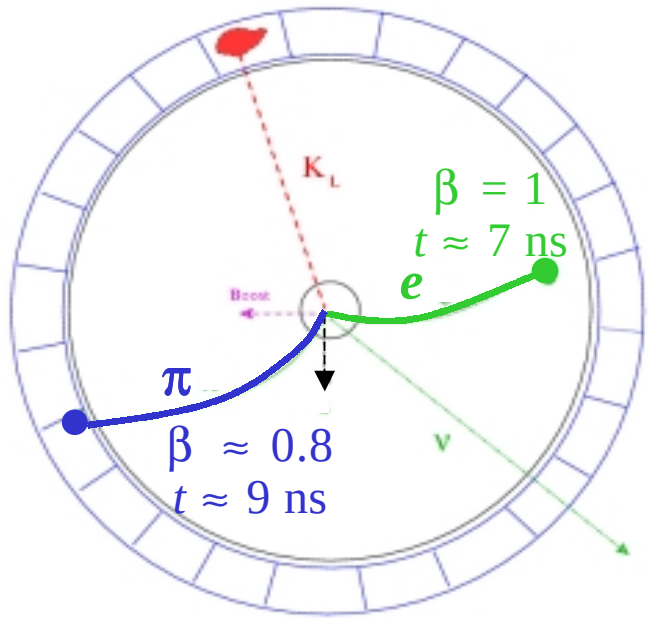
- ❖ K_L-crash.and.charged vertex at IP ($r<8$cm , $|z|<10$cm) .and.2 tracks with associated EmC clusters
- ❖ invariant mass of the tracks in π hp $M_{\pi\pi} < 490$ MeV/c^2 (against background from $K_S \to \pi^+\pi^-$)
- ❖ π/e identification using time-of-flight
- ❖ E_{miss} - $|p_{miss}|$

π/e identification using time-of-flight

$$D\delta t\,(\pi,e) = [t_1^{CLU} - t_2^{CLU}] - [L_1 / c\,\beta(\pi) - L_2 / c\,\beta(e)]$$

- ❖ $|D\delta t\,(\pi, \pi)| > 1.5$ ns to reject $K_S \to \pi^+\pi^-$
- ❖ Cuts on $D\delta t\,(\pi, e)$ and $D\delta t(e, \pi)$



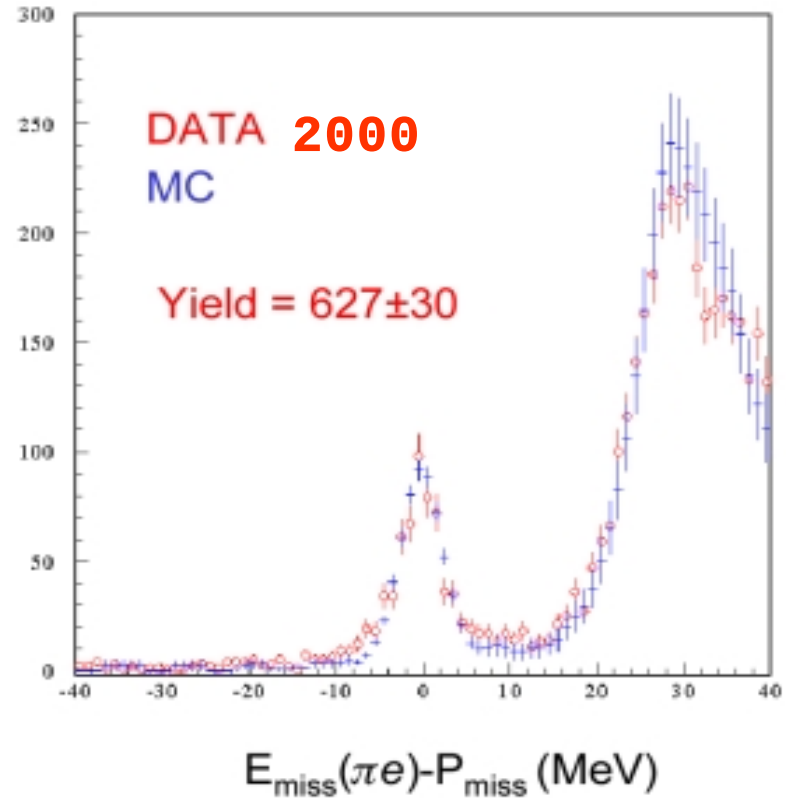


Efficiency evaluation

- ✓ Vertex reconstruction, fiducial cuts and $M_{\pi\pi}$ efficiency from MC but also from data $K_L \to \pi e \nu$ near I.P. (high-purity sample (> 99.7 %), by kinematic cuts) and $K_S \to \pi^0\pi^0$ to scale MC
  Tracking efficiency for MC and data from $K_S \to \pi^+\pi^-$
- ✓ Single-particle t_0, track-cluster, and trigger efficiencies from data using $K_L \to \pi e \nu$ near origin and $K_S \to \pi^+\pi^-$ but also $\phi \to \pi^+\pi^-\pi^0$. MC efficiency scaled accordingly
- ✓ Time of flight ID efficiency from $K_L \to \pi e \nu$ decays near origin and $K_S \to \pi^+\pi$

Overall selection efficiency:

(20.8± 0.4)%



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

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

$BR(K_S \rightarrow \pi^{\pm} e^{\pm} \nu)$

CPT and $\Delta S = \Delta Q$ predicts: $\Gamma(K_S \rightarrow \pi^{\pm} e^{\pm} \nu) = \Gamma(K_L \rightarrow \pi^{\pm} e^{\pm} \nu)$

and then: $BR(K_S \rightarrow \pi^{\pm} e^{\pm} \nu) = BR(K_L \rightarrow \pi^{\pm} e^{\pm} \nu) \times (\Gamma_L/\Gamma_S)$

Using PDG:

$$BR(K_S \rightarrow \pi^{\pm} e^{\pm} \nu) = (6.704 \pm 0.071) \times 10^{-4}$$

Result

KLOE 2000 data, $(6.79 \pm 0.33_{stat} \pm 0.16_{syst}) \times 10^{-4}$ 627 ± 30 evts

CMD-2 1999, $(7.2 \pm 1.4) \times 10^{-4}$ 75 ± 13 evts

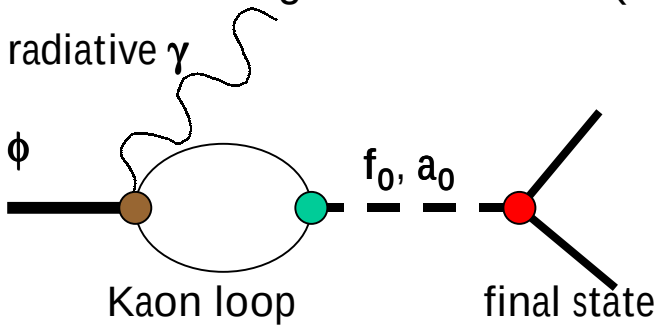
Main contributions to the total error	%
Statistics	4.9
Tracking + vertex efficiency	2.0
Cluster, t_0 , trigger	0.9
TOF selection eff	0.8
Tag eff	0.6
Total	5.9

lower with the 2001 data !!

Φ Radiative decays: $\phi \to (f_0\gamma)\ \pi^0\pi^0\gamma$; $\phi \to (a_0\gamma)\ \eta\pi^0\gamma$

Motivations

- various models for f_0 and a_0 mesons : *qqqq* state, *KK* molecule, ordinary *qq* meson.
- $\phi \to f_0\gamma$, $a_0\gamma$ BR and mass spectra sensitive to f_0 ,a_0 nature [*Achasov, Ivanchenko 1989*]: phenomenological framework (**kaon loop** model) ➡ coupling constants



- $g(\phi KK)$ — from $\Gamma(\phi \to K^+K^-)$
- $g(f_0KK)$ $g(a_0KK)$ — f_0 , a_0 model
- $g(f_0\pi\pi)$ $g(a_0\eta\pi)$ — $M(\pi^0\pi^0)$ $M(\eta\pi)$ spectra

a_0 analysis :

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

- $\gamma\gamma$ — 5γ final state
- $\pi^+\pi^-\pi^0$ — 2tracks + 5γ final state

first observation

f_0 analysis :

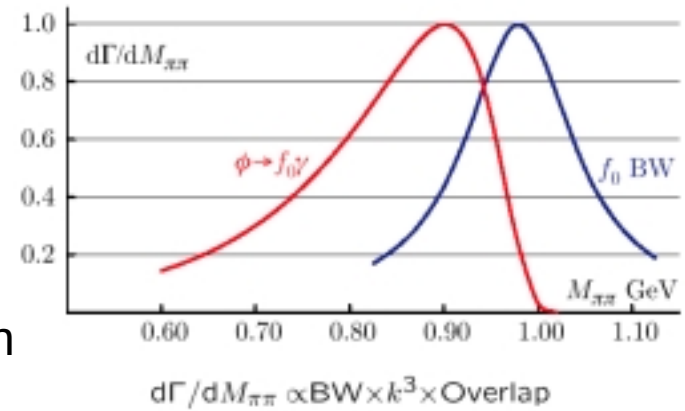
uses $\phi \to f_0\gamma \to (\pi^0\pi^0)\gamma$

5γ final state

Overlap = structure dependent function

k = f_0 momentum

Signal shape



Φ Radiative decays: $\phi \to f_0\gamma$, $a_0\gamma \to 5\gamma$ final state

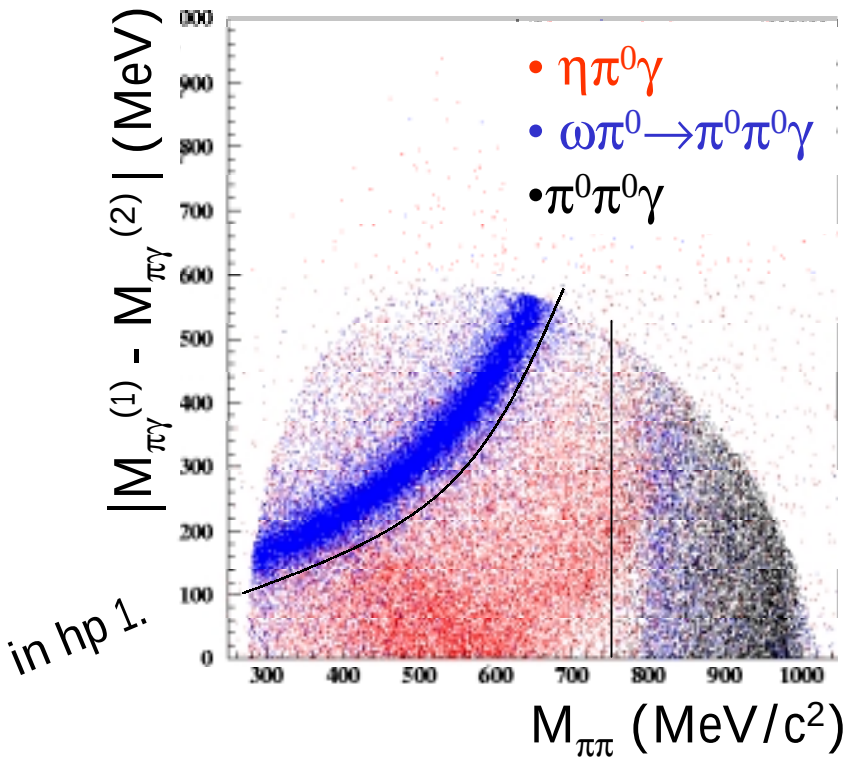
Selection

- 5 "prompt" γ with $E_\gamma > 7$ MeV
- $|\cos\vartheta| < 0.93$ (to avoid background from I.P.)
- $\Sigma_5 E_i > 700$ MeV to reject $\phi \to K_L K_S \to$ neutrals
- kinematic fit (4-mom. + |t-r/c| conservation)

Background sources

$e^+e^- \to \omega\pi^0$ $\omega \to \pi^0\gamma$
$\phi \to \pi^0\pi^0\gamma$
$\phi \to \eta\pi^0\gamma$ $\eta \to \gamma\gamma$
} 5γ final states

$\phi \to \eta\gamma$ $\eta \to \gamma\gamma$ 3γ final state
$\eta \to \pi^0\pi^0\pi^0$ 7γ final state



Photon pairing in the hypothesis

1. $\pi^0\pi^0\gamma$
2. $\eta\pi^0\gamma$
3. $\omega\pi^0 \to \pi^0\pi^0\gamma$ ($M(\pi^0\gamma)=M(\omega)$)
4. $\eta\gamma \to 3\gamma$ (rejecting events η and γ with E_γ=363 MeV)

⇒ **kinematic fit with mass constraint**

- for (2) η e π^0 mass
- for (1) e (3) two π^0

} χ^2 cut

Φ Radiative decays: $\phi \rightarrow \pi^0\pi^0\gamma\ (f_0\gamma)$

After χ^2 cut in $\pi^0\pi^0\gamma$ hp + $\Delta M_{\gamma\gamma}$ cut + background sub.

Results

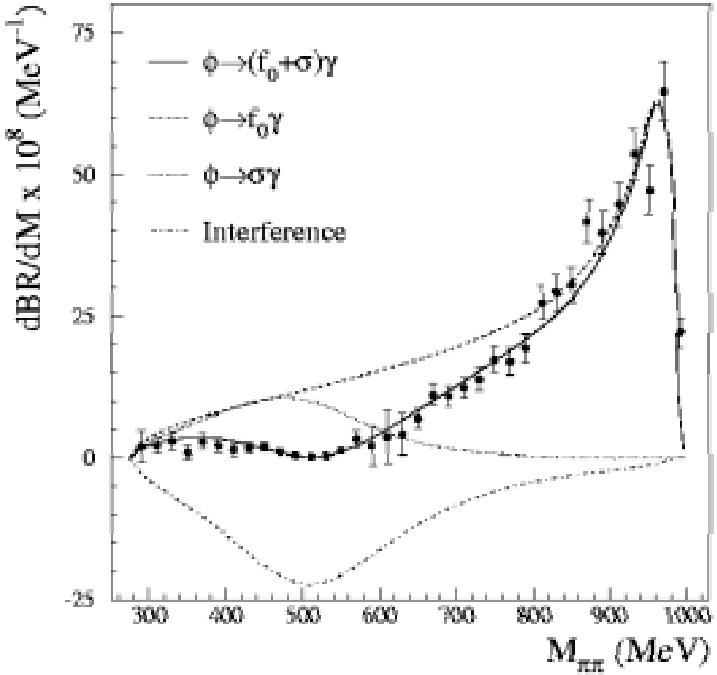
$N_{ev} = 2438 \pm 61$

$BR(\phi \rightarrow \pi^0\pi^0\gamma) = (1.09 \pm 0.03_{stat} \pm 0.05_{syst})\times10^{-4}$

(from the fit to the spectrum)

CMD-2 $(0.92 \pm 0.08 \pm 0.06)\times10^{-4}$

SND $(1.14 \pm 0.10 \pm 0.12)\times10^{-4}$



The fit to the $M_{\pi0\,\pi0}$ spectrum (kaon loop)

contributions from $\phi \rightarrow f_0\gamma$ and $\phi \rightarrow \sigma\gamma$ with "strong" destructive interference ($M_{\pi\pi} < 700$ MeV)

Negligible contribution from $\phi \rightarrow \rho^0\pi^0 \rightarrow \pi^0\pi^0\gamma$

$M(f_0) = 973 \pm 1$ MeV

$g^2(f_0KK)/4\pi = 2.79 \pm 0.12$ GeV^2

$g(f_0\pi\pi)/g(f_0KK) = 0.50 \pm 0.01$

$g(\phi\sigma\gamma) = 0.060 \pm 0.008$

$BR(\phi \rightarrow f_0\gamma \rightarrow \pi^0\pi^0\gamma) = (1.49 \pm 0.07)\times10^{-4}$

Φ Radiative decays: $\phi \rightarrow \eta\pi^0\gamma\ (a_0\gamma)$

➢Sample (a) from $\eta \rightarrow \gamma\gamma$ final state

Parabolic cut to reject $\omega\pi^0$ .and. $M_{\pi\pi} < 760$ MeV to reject f_0 .and. 3σ cut on M_η to reject $\phi \rightarrow \eta\gamma \rightarrow \pi^0\pi^0\pi^0\gamma$

Main background :$\pi^0\pi^0\gamma$.

($N_{ev} = 916$ $N_{bck} = 309 \pm 20$)

$BR(\phi \rightarrow \eta\pi^0\gamma) = (8.5 \pm 0.5_{stat} \pm 0.6_{syst})\times10^{-5}$

➢ Sample (b) from $\eta \rightarrow \pi^+\pi^-\pi^0$ final state

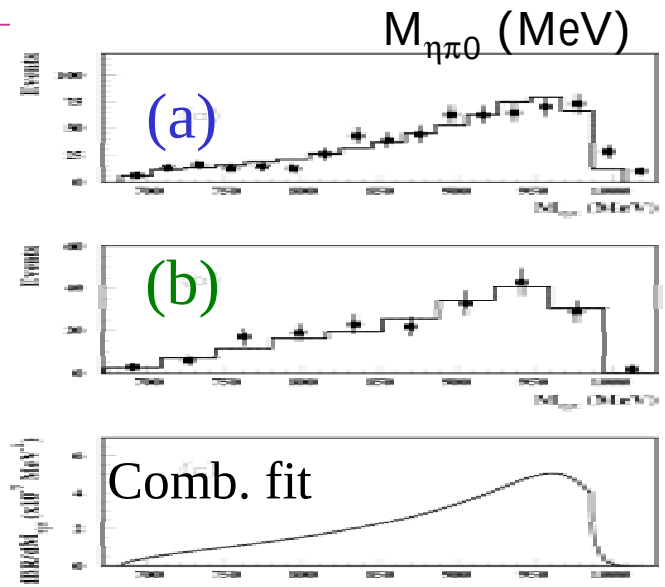
Neutral selection as for (a) .and. 1 vtx in I.P. + 2 tracks .and. $M_{inv}(\pi^+\pi^-) < 425$ MeV to reject $K_S \rightarrow \pi^+\pi$ .and.kinematic fit with mass constraint on η and π^0

Negligible background with the same topology .

($N_{ev} = 197$ $N_{bck} = 4 \pm 4$)

$BR(\phi \rightarrow \eta\pi^0\gamma) = (8.0 \pm 0.6_{stat} \pm 0.5_{syst})\times10^{-5}$

CMD-2	$(9.0 \pm 2.4 \pm 1.0) \times 10^{-5}$
SND	$(8.8 \pm 1.4 \pm 0.9) \times 10^{-5}$



Combined fit to the $M_{\eta\pi0}$ spectra

using PDG for a_0 mass (984.8 MeV)

$g^2(a_0KK)/4\pi = 0.40 \pm 0.04$ GeV^2

$g(a_0\eta\pi)/g(a_0KK) = 1.35 \pm 0.09$

$BR(\phi \rightarrow a_0\gamma \rightarrow \eta\pi^0\gamma) = (7.4 \pm 0.7)\times10^{-5}$

Summary of the results on f_0 and a_0

Within the context of the kaon-loop model with point-like coupling of scalars to kaon pairs, we have obtained:

f_0

	KLOE	4q model
$g^2_{f0KK}/(4\pi)$ (GeV^2)	2.79±0.12	"super-allowed" (few GeV^2)
$g_{f0\pi\pi}/g_{f0KK}$	0.50±0.01	0.3-0.5

a_0

$g^2_{a0KK}/(4\pi)$ (GeV^2)	0.40 ± 0.04	"super-allowed" (few GeV^2)
$g_{a0\eta\pi}/g_{a0KK}$	1.35 ± 0.09	0.91

- f_0 parameters compatible with 4q model
- a_0 parameters not well described by the 4q model

(2001 data ⇒ more accurate study of a_0)

Φ Radiative decays: $\phi \to \eta' \gamma$,$\eta\gamma$

Motivations

Precise measurements of **BR($\phi \to \eta'\gamma$)** and **BR($\phi \to \eta\gamma$)** and the determination of **η–η' mixing angle** probe hidden strangeness and gluonium content of η'

Used decay chains:

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

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

the topology is the same

Selection

- 3 "prompt" γ with $E_\gamma > 7$ MeV and $\theta > 21^o$ .and.
2 tracks vertex in IP
- Preliminary kinematic fit:
conservation of total E, p and $\beta = 1$ 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

- *negligible background but N(a)~N(b)/100*

Φ Radiative decays: $\phi \rightarrow \eta' \gamma$,$\eta\gamma$

Result

$N(b) = 50210 \pm 220$

$N(a) = 120 \pm 12_{stat} \pm 5_{bck}$

$R = BR(\phi \rightarrow \eta'\gamma)/BR(\phi \rightarrow \eta\gamma)$

KLOE 2000 data

$R = (4.70 \pm 0.47_{stat} \pm 0.31_{syst}) \times 10^{-3}$

From R we obtain the pseudoscalar mixing angle:

$\varphi_P = (41.8 \pm 1.7)^o$ [$\theta_P = (-12.9 \pm 1.7)^o$]

(flavor basis) (octet-singlet basis)

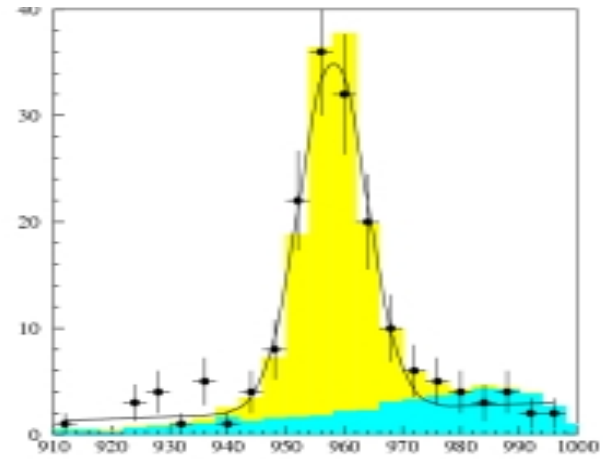
Using PDG value for $BR(\phi \rightarrow \eta\gamma)$ we obtain:

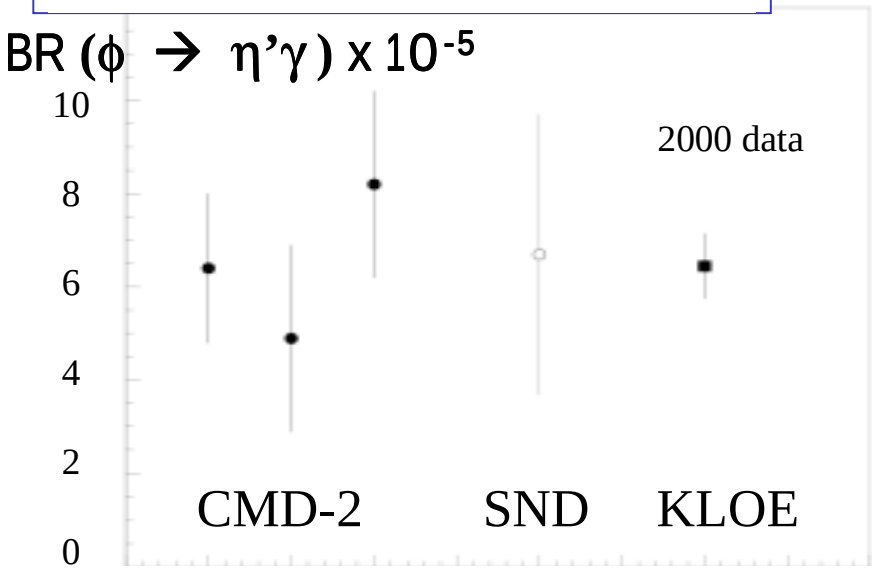
$BR(\phi \rightarrow \eta'\gamma) =$

$(6.10 \pm 0.61_{stat} \pm 0.43_{syst}) \times 10^{-5}$

most precise determination to date

Invariant mass spectrum of $\eta'\gamma$





➡ consistent with **the gluonium contents of the** $\eta' < 15\%$

Conclusions

- DAΦNE improved continuously during the first two years of KLOE data taking and improvements on the background are already visible in 2002 data taking
- The KLOE detector is performing well
- With 2000 data we measured:
  - $\Gamma(K_S \to \pi^+\pi^- (\gamma))/ \Gamma(K_S \to \pi^0\pi^0)$, $BR(K_S \to \pi e \nu)$
  - $\phi \to f_0\gamma \to \pi^0\pi^0\gamma$, $\phi \to a_0\gamma \to \eta\pi^0\gamma$
- With 2001 data we will improve the results and expect results from:
  - $K_L \to 2\pi$, $K^{\pm}$ decays, $K_L \to \gamma\gamma$ decays
  - Rare K_S decays (BR ~ 10^{-5})
  - $\sigma(e^+e^- \to \pi^+\pi^-)$ by ISR
  - η decays (6×10^6 η tag from $\phi \to \eta\gamma$ E_γ = 363 MeV photon)