Tests of Chiral Perturbation theory with KLOE

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Chiral Perturbation Theory

Chiral Perturbation Theory (ChPT) is the low-energy effective field theory of strong interactions.

For process involving the *s* quark $\rightarrow$ SU(3) version of ChPT

Assumptions

- spontaneous breaking of $SU(3)_L \times SU(3)_R$ symmetry of $\mathcal{L}_{QCD}$ in the chiral limit $\Rightarrow$ $q\bar{q}$ condensate
- Goldstone modes $\Rightarrow$ octet of pseudoscalar mesons (π, K, η)

Chiral Perturbation Theory

SU(3) version of ChPT

- ✓ write the Chiral Lagrangian in terms of the Goldstone boson fields
- ✓ add the soft breakings terms induced by the quark masses

Lagrangian not renormalizable + infinite number of arbitrary constants

low energy limit

expansion up to a given order in powers of pseudoscalar momenta and quark masses

finite number of constants to be determined experimentally

Testing ChPT with kaons

Since their discovery K mesons have represented one of the most powerful
sources of information on fundamental interactions.

In the framework of ChPT kaon decays play a twofold role:

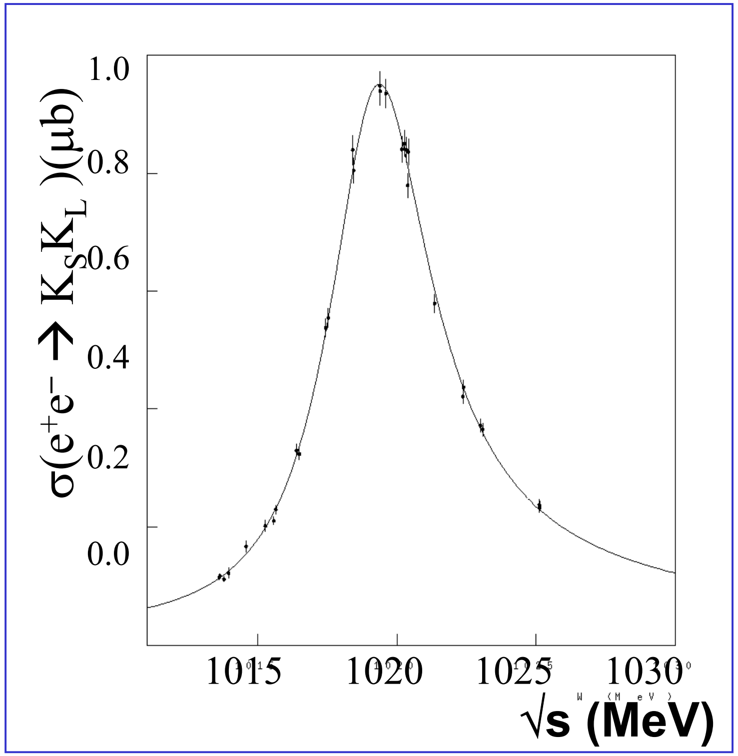
- **semileptonic decays** allow us to investigate the strong sector of the chiral Langrangian

  low energy coupling constants are known ⇨ *precise & interesting tests of the theory*

- **non-leptonic and radiative non-leptonic decays** allow us to investigate the chiral realization of the four-quark effective hamiltonian for weak interactions

Kaon Physics at the Φ - factory DAΦNE

$$e^+e^- \rightarrow \phi(1020)$$



ϕ decays:

$BR(\phi \rightarrow K^+K^-) = 49.2\%$

$BR(\phi \rightarrow K^0\bar{K}^0) = 33.8\%$

$BR(\phi \rightarrow \rho\pi) = 15.4\%$

$BR(\phi \rightarrow \eta\gamma) = 1.3\%$

$$\vec{P}_\Phi = \vec{P}_K + \vec{P}_{\bar{K}}$$

- $P_{K0} \approx$ **110 MeV/c**
- $P_{K\pm} \approx$ **125 MeV/c**

- very clean environment
- pure $K_S K_L$ and K^+K^- beams almost monochromatic ($P_\phi \approx 13$ MeV/c)
- kaon momentum precisely known thanks to kinematics enclosure of the event

⇒ ***tagging***

The tagging

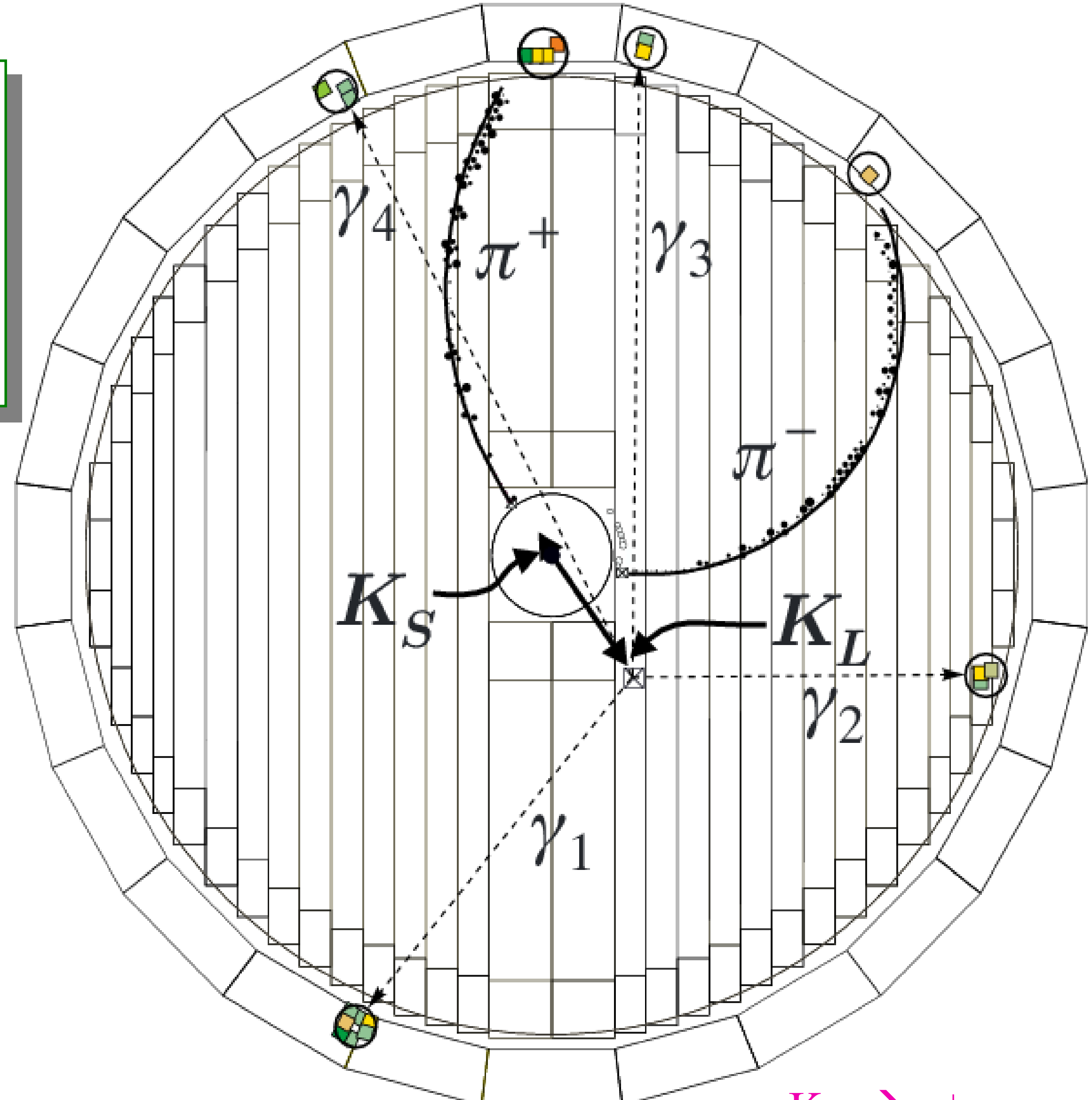
Neutral kaons are produced in a pure quantum state ($J^{PC}=1^{--}$) :

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

(contamination from K_SK_S,K_LK_L < 10^{-9})

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

and the same stands for K^+K^-



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

$K_L \rightarrow \pi^0\pi^0$

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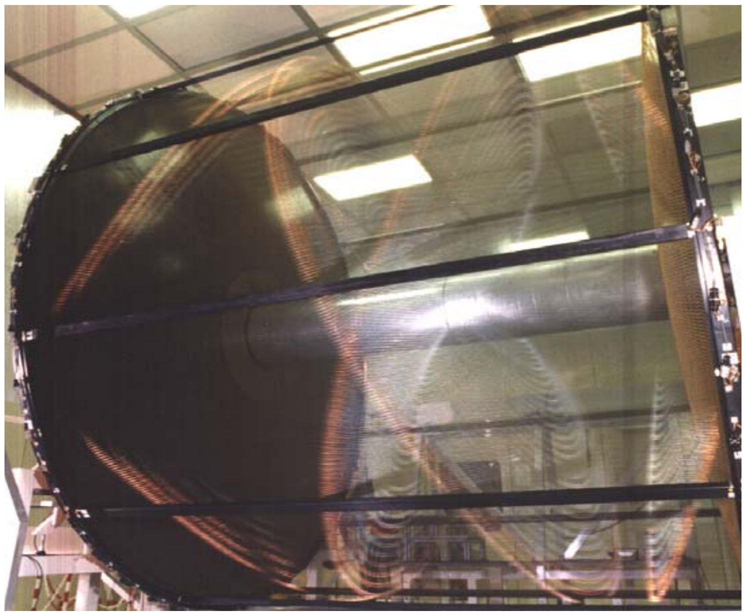
The KLOE detector

Drift Chamber

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



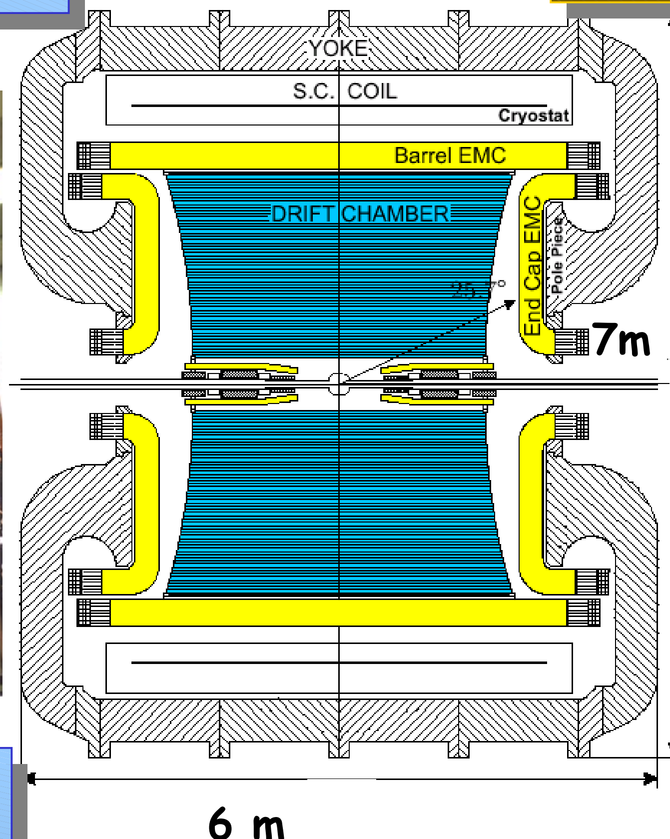
$\sigma_{r\phi}$ = 150 mm σ_z = 2 mm

σ_V = 3 mm σ_p/p = 0.4 %

λ_S = 0.6 cm

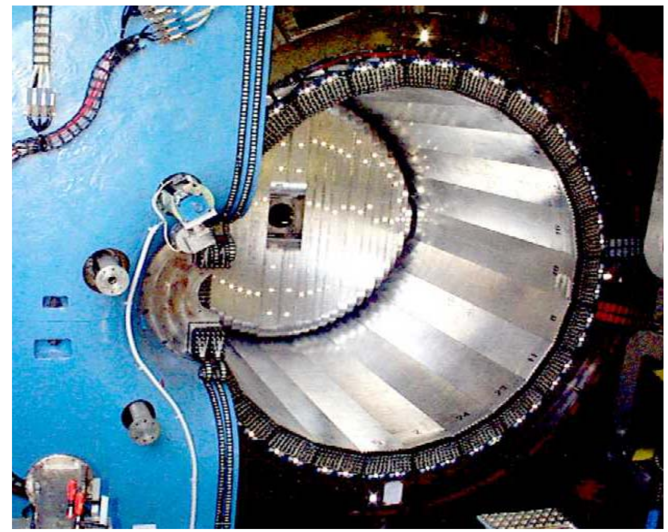
λ_L = 340 cm

$\lambda_\pm$ = 95 cm



Electromagnetic Calorimeter

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



$\sigma_E/E = 5.4\%/\sqrt{E(\mathrm{GeV})}$

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

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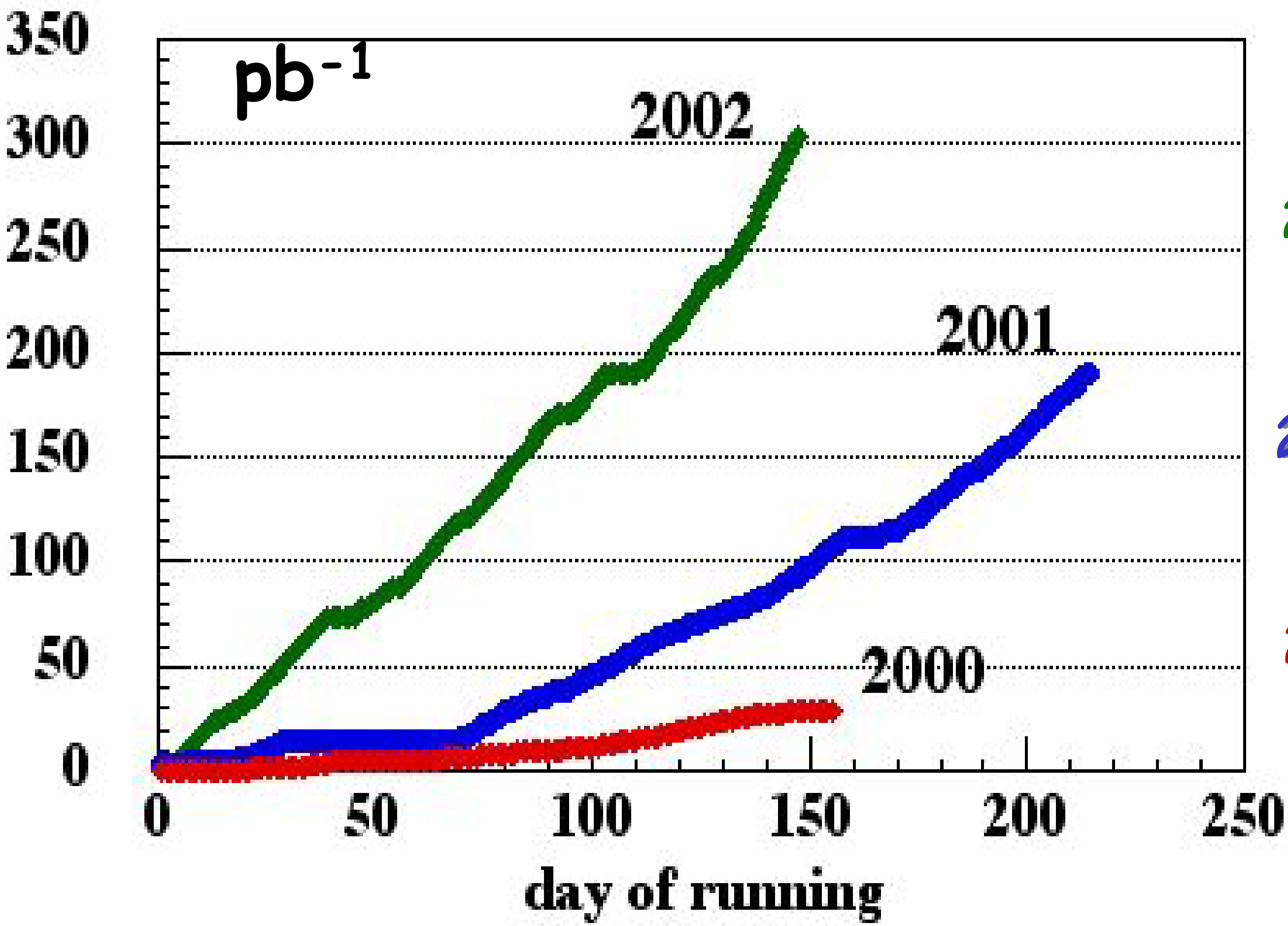
KLOE Integrated Luminosity



2002 (300 pb^{-1} → 9x 10^8 ϕ) analysis in progress

2001 (190 pb^{-1} → 5.7 × 10^8 ϕ) analysis in progress

2000 (20 pb^{-1} → 7.5 × 10^7 ϕ) published results

1.5×10^6 K^+K^-/pb^{-1}

10^6 K_LK_S/pb^{-1}

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+2002 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(500 pb^{-1})

on tape analysis progress

....

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

Outline

Among the various tests of ChPT accessible at KLOE
I will focus on:

1) $\Gamma(K_S \rightarrow \pi^+\pi^- (\gamma))/\Gamma(K_S \rightarrow \pi^0\pi^0)$
   Isospin (I=0 and 2) amplitudes and the $\pi\pi$ phase-shifts
2) $Br(K_L \rightarrow \gamma\gamma) / Br(K_L \rightarrow 3\pi^0)$
   high order corrections in ChPT and theoretical prediction of $K_L \rightarrow \mu^+\mu^-$
3) K_{l3} decays
   BR's , kaon form factors and V_{us} for charged and neutral kaons
4) K_{l4} decays
   phase shift of the $\pi\pi$ elastic scattering and strength of the $q\bar{q}$ condensate
5) $\eta \rightarrow \pi^0\gamma\gamma$
   high order corrections in ChPT

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

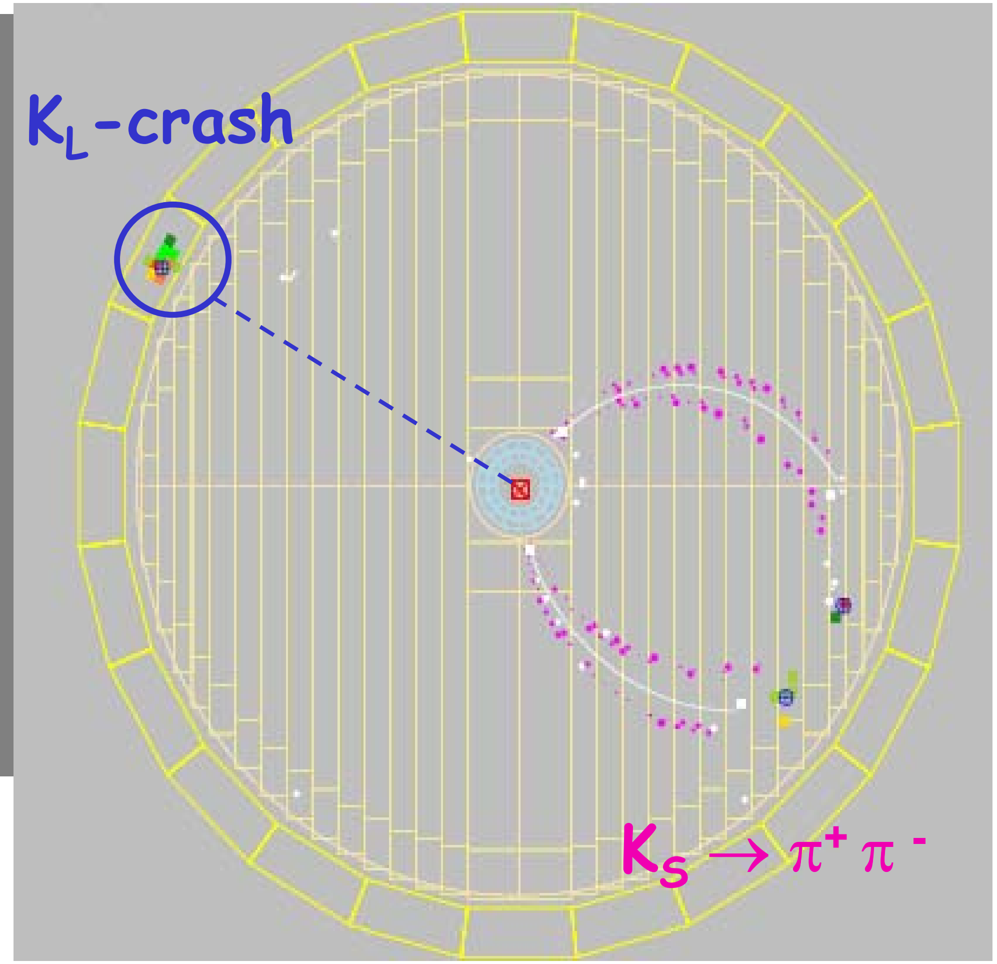
K_S analysis at KLOE

K_S tagging

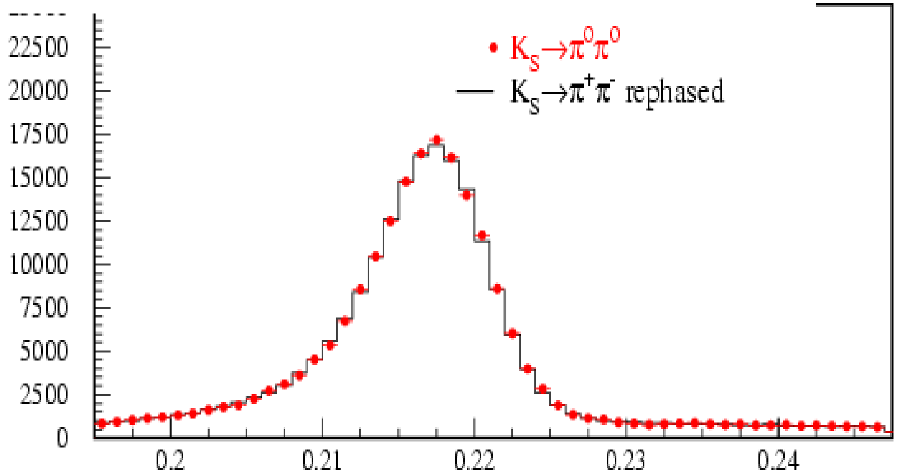
- time of flight identification of K_L interacting in the EmC ("K_L-crash")
- selected as a calorimeter cluster with:

  a) $E_{CLU} > 200$ MeV
  b) $|\cos(\theta_{CLU})| < 0.7$
  c) $0.195 \le \beta^* \le 0.2475$

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



β^* distribution of "K_L-crash"



- K_S **momentum** from K_L cluster position
- Tagging efficiency $\varepsilon_{tag,total} \sim$ **30%**

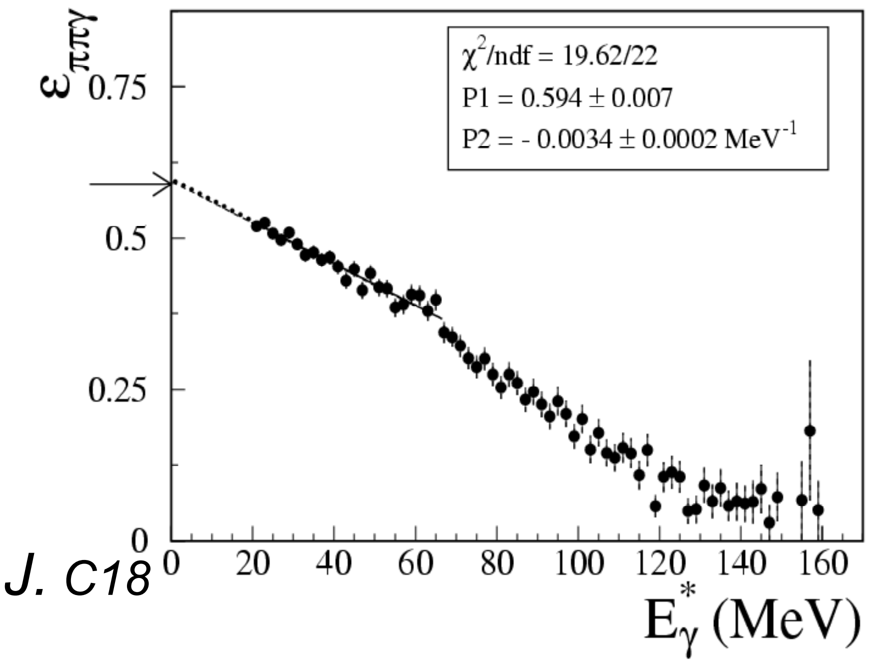
$\Gamma(K_S \to \pi^+\pi^-(\gamma))/\Gamma(K_S \to \pi^0\pi^0)$

Motivations

first step towards Re(ε'/ε) and 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
- 2 tracks from IP reaching EMC(*) and acceptance cuts
- no γ required in EMC
  $\Rightarrow$ ***fully inclusive measurement***
- $\varepsilon_{\pi\pi(\gamma)}(E^*_\gamma)$ from MC folded to theoretical γ spectrum from *Cirigliano et al., Eur. Phys. J.* C18



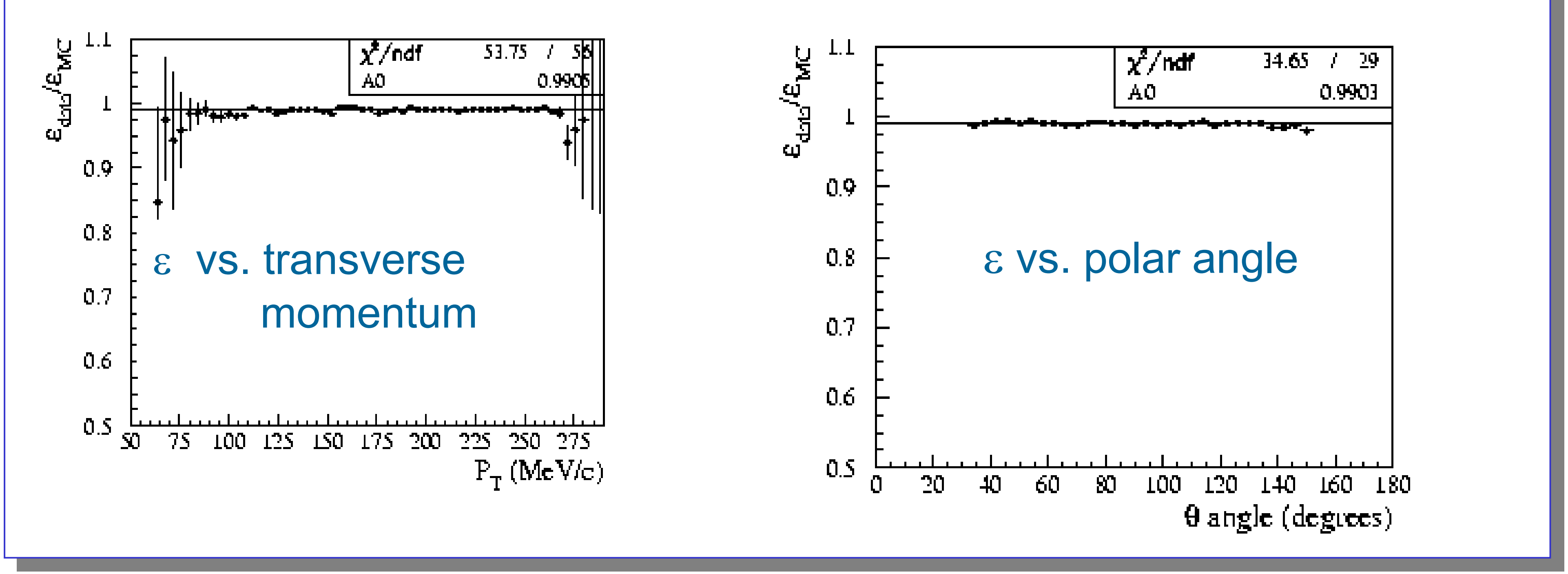
$K_S \to \pi^0\pi^0$ selection

K_L-crash .and. $\geq$ 3 neutral "prompt" clusters: $|t-R/c| < 5\sigma_t$ .and. $E_\gamma > 20$ MeV

Efficiency evaluation : $K_S \to \pi^+\pi^- (\gamma)$

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

data/MC comparison



ε_{+-} **(sel and rec) = (57.6 ± 0.2) %**

- ***single-particle t_0 and trigger efficiencies*** from data, plugged into MC

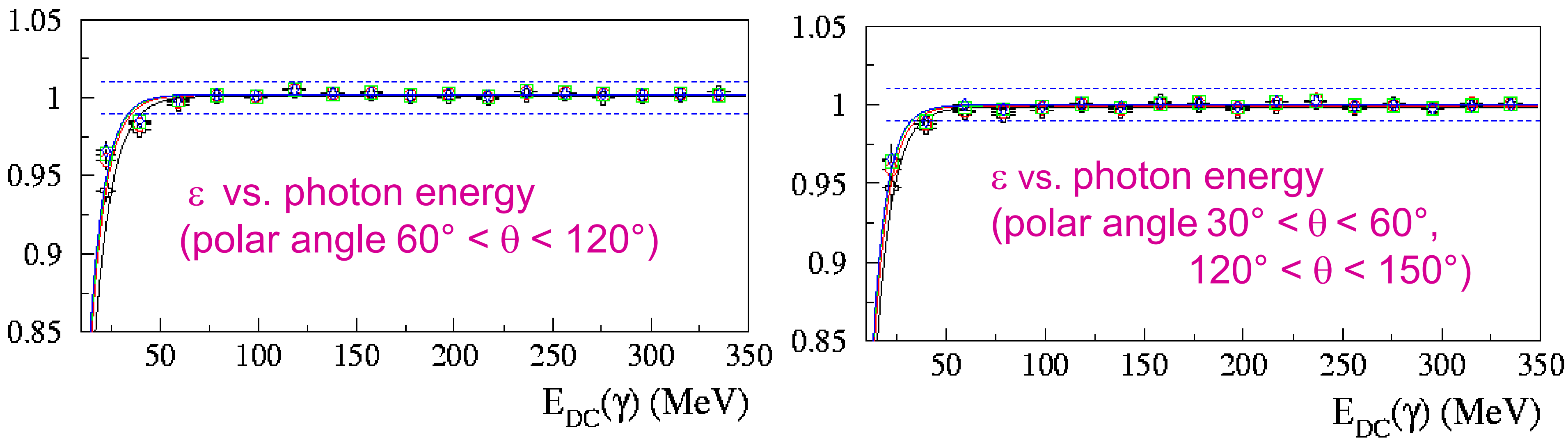
ε_{+-} **(t_0 and trig) = (97.9 ± 0.03) %**

$K_S \to \pi^+\pi^-$ from $K_L \to \pi^+\pi^-\pi^0$ –tagged sample and $\phi \to \pi^+\pi^-\pi^0$

Efficiency evaluation : $K_S \to \pi^0\pi^0$

- ***photon detection efficiency*** from data using $\phi \to \pi^+ \pi^- \pi^0$ events.

data/MC comparison



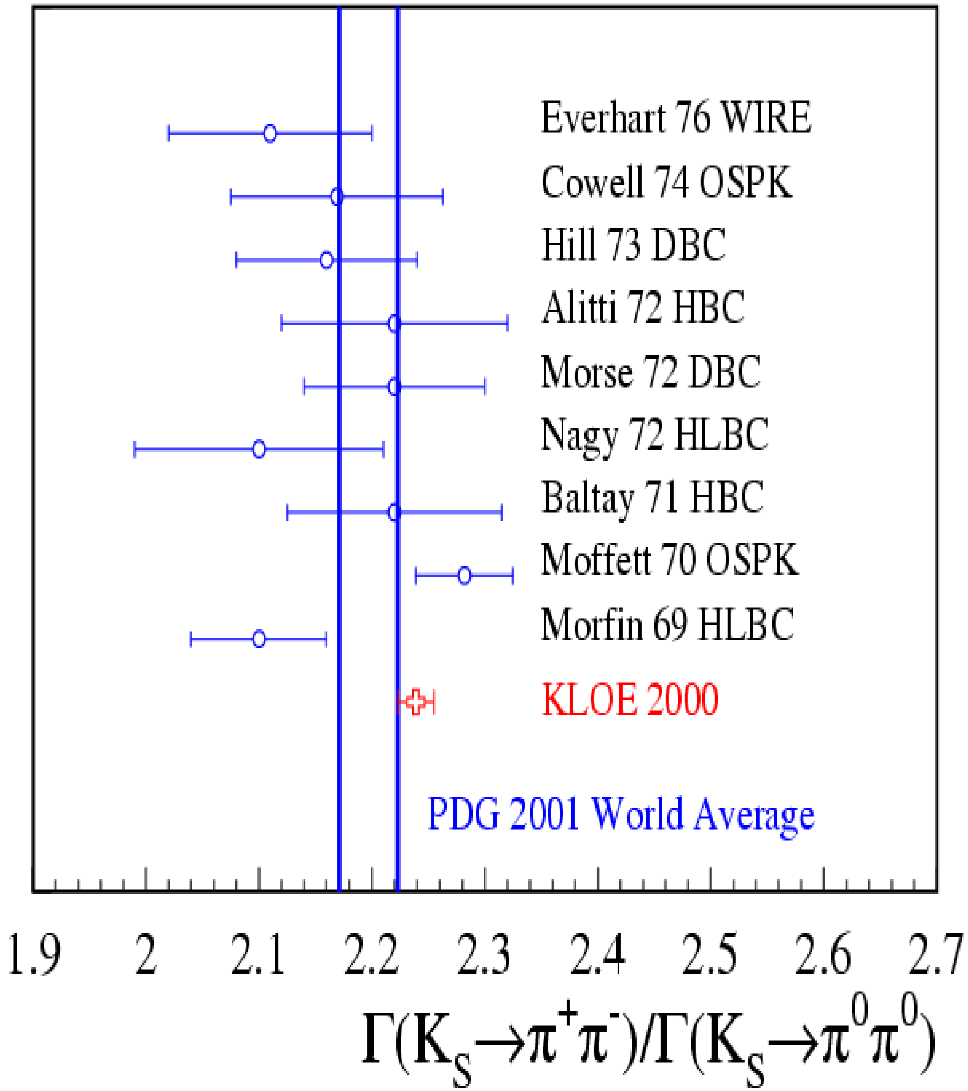
$\varepsilon_{00}(\text{sel}) = (90.1 \pm 0.2)\%$

- ***single-particle t_0 and trigger efficiencies*** from data, plugged into MC

ε_{00} (t_0 and trig) = $(99.86 \pm 0.04)\%$

$K_S \to \pi^0\pi^0$ from $K_L \to \pi^+\pi^-\pi^0$ –tagged sample

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



KLOE 2000 data *Phys. Lett. B 538 (2002), 21*

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

PDG 2000 average

$R = 2.197 \pm 0.026$

(without clear indication of E^*_γ)

Near future goals

- reach 0.1% systematic uncertainty on R [< 2·10-4 on Re(ε′/ε)]
- measure absolute branching ratios
- E_γ^* spectrum

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

Both the isospin (I=0 and 2) amplitudes and the pp phase-shifts can be estimated from the measured **K** $\to \pi\pi$ branching ratios:

Transition amplitudes

$$A(K_1 \to \pi^+\pi^-) = \sqrt{\frac{2}{3}} A_0 e^{i\delta_0} + \sqrt{\frac{1}{3}} A_2 e^{i\delta_2}$$

$$A(K_1 \to \pi^0\pi^0) = \sqrt{\frac{1}{3}} A_0 e^{i\delta_0} - \sqrt{\frac{2}{3}} A_2 e^{i\delta_2}$$

$$A(K^+ \to \pi^+\pi^0) = \sqrt{\frac{3}{4}} A_2 e^{i\delta_2}$$

Decay rates

$$\Gamma(\pi^+\pi^-) = \frac{2}{3}A_0^2 + \frac{1}{3}A_2^2 + \frac{2\sqrt{2}}{3} A_0 A_2 \cos(\delta_0 - \delta_2)$$

$$\Gamma(\pi^0\pi^0) = \frac{1}{3}A_0^2 + \frac{2}{3}A_2^2 - \frac{2\sqrt{2}}{3} A_0 A_2 \cos(\delta_0 - \delta_2)$$

$$\Gamma(\pi^+\pi^0) = \frac{3}{2}A_2^2$$

$$K_1 = \frac{|K^0\rangle + |\overline{K}^0\rangle}{\sqrt{2}} \cong K_S$$

$$\left(\frac{A_0}{A_2}\right)^2 = \frac{3\Gamma_S}{4\Gamma^+} - 1 = \frac{3}{4}\frac{1}{\tau_S}\frac{\tau^+}{BR(K^+ \to 2\pi)} - 1 = (22.2 \pm 0.07)^2$$

$$R = \frac{\Gamma(K_1 \to \pi^+\pi^-)}{\Gamma(K_1 \to \pi^0\pi^0)} = \frac{\rho_\pm}{\rho_{00}}\left[2 + 6\sqrt{2}\frac{A_2}{A_0}\cos(\delta_0 - \delta_2)\right]$$

δ_0–δ_2 situation

1) O(p²) ChPT prediction $\delta_0-\delta_2 = (45\pm6)^o$

2) $\pi\pi$ scattering $\delta_0-\delta_2 = (45.2 \pm1.3 \pm1.5)^o$

3) BR's from PDG $\delta_0-\delta_2 = (56.7\pm3.8)^o$ ← *inconsistent with 1) and 2)*

4) KLOE measurement of $\Gamma(K_S\rightarrow \pi^+\pi^-)/\Gamma(K_S\rightarrow\pi^0\pi^0)$ $\delta_0-\delta_2 = (48\pm3)^o$

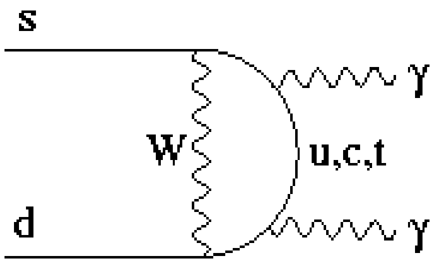
⇒ *Using the KLOE measurement the estimate of $\delta_0-\delta_2$ from $K \rightarrow \pi\pi$ BR's is consistent with 1) and 2)*

2) $Br(K_L \rightarrow \gamma\gamma) / Br(K_L \rightarrow 3\pi^0)$

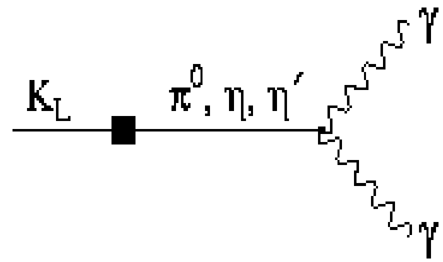
$K_L \rightarrow \gamma\gamma$

ChPT

- $O(p^6)$ amplitude and long-distance contribution are dominant



Short-distance contribution

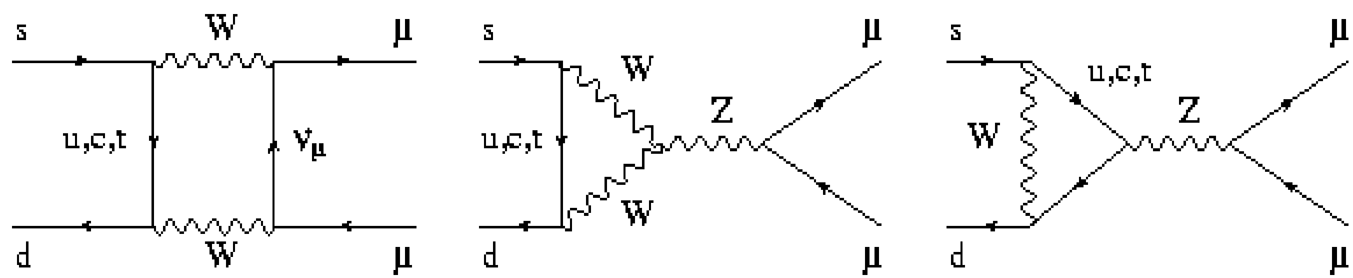


Long-distance contribution

very sensitive to chiral corrections, in particular $\eta-\eta'$ mixing

- prediction of $BR(K_L \rightarrow \mu+\mu-)$

$$BR = \left|\Im m A\right|^2 + \left|\Re e A\right|^2$$



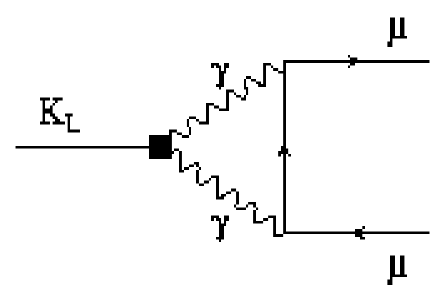
Short-distance contribution

$\propto BR(K_L \rightarrow \gamma\gamma)$
model independent

$$\Re e A_{LONG} + \Re e A_{SHORT}$$

$\propto BR(K_L \rightarrow \gamma\gamma)$
model dependent

dominated by ***t*** quark
$\Rightarrow$ extraction V_{td}



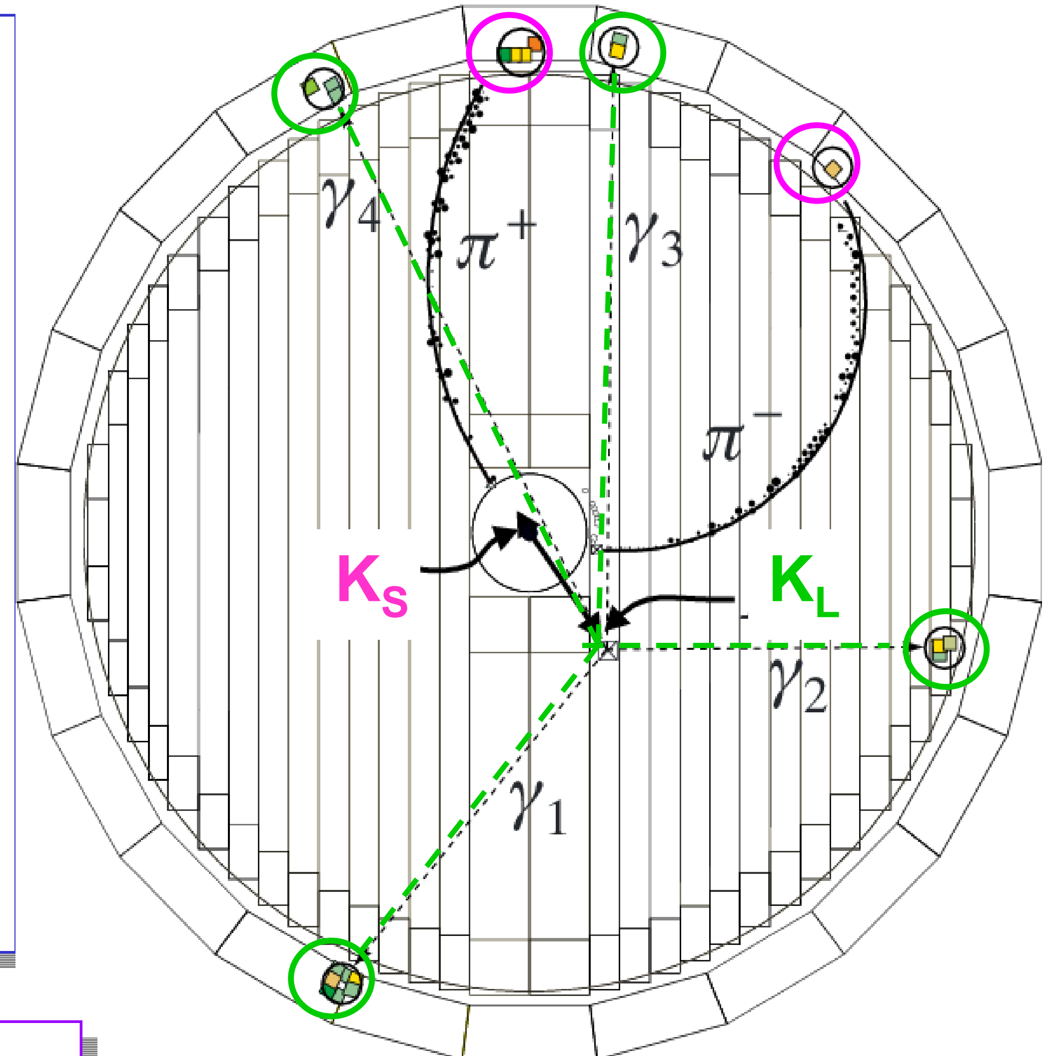
Long-distance contribution

K_L tagging at KLOE

K_L tagging

- identification of $K_S \rightarrow \pi^+\pi^-$ events
- single vertex in K_S fiducial volume

  $r_T < 4$ cm and $|z| < 8$ cm
- two and only two tracks of opposite charge connected to the vertex
- $50 < p_{KS} < 170$ MeV/c in ϕ ref. frame
- $400 < M_{KS} < 600$ MeV/c^2



- **K_L momentum** from K_S and ϕ momenta
- Tagging efficiency $\varepsilon_{tag,total}$ **~ 75%**

$K_L \rightarrow \pi^0\pi^0$

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

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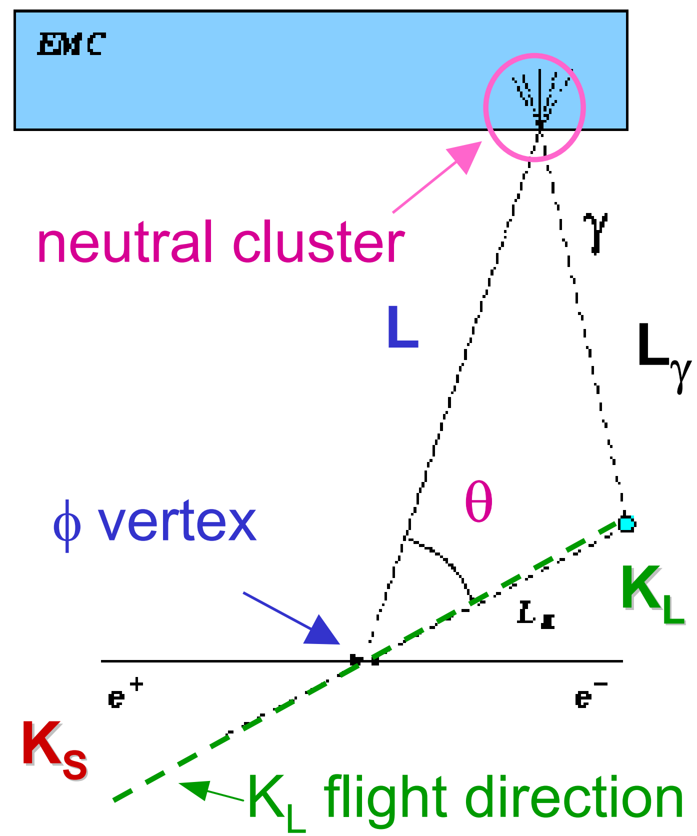
$K_L \to \gamma\gamma$

Strateg y

- BR($K_L \to \gamma\gamma$) from $\Gamma(K_L \to \gamma\gamma)/\Gamma(K_L \to 3\pi^0)$ (ΔBR($K_L \to 3\pi^0$)/BR~ 1.3%)
- K_L tagging from $K_S \to \pi^+\pi^-$ events
- neutral vertex in: 30< r_T < 170 cm and | z | < 140 cm
- selection for $K_L \to \gamma\gamma$ and $K_L \to 3\pi^0$ events

Neutral vertices reconstructed applying the time of flight triangle to cluster not attached to tracks:

$$\left.\begin{aligned} L^2 + L_K^2 - 2LL_K\cos\theta &= L_\gamma^2 \\ L_K/\beta_K + L_\gamma &= ct_\gamma \end{aligned}\right\} \quad L_K = \frac{\sum_{i=1}^{NCLU} E_i \cdot l_{Ki}}{\sum_{i=1}^{NCLU} E_i}$$



$K_L \rightarrow \gamma\gamma$ selection

- look for a neutral vertex with 2 γ's attached
- pre-selection to reject the most dangerous background from $K_L \rightarrow 3\pi^0$ events (BR~21%)

  E_γ > 100 MeV

  E_{tot} > 350 MeV

  ψ > 160° (2 γ's angle in plane $\perp$ to p_{KL})

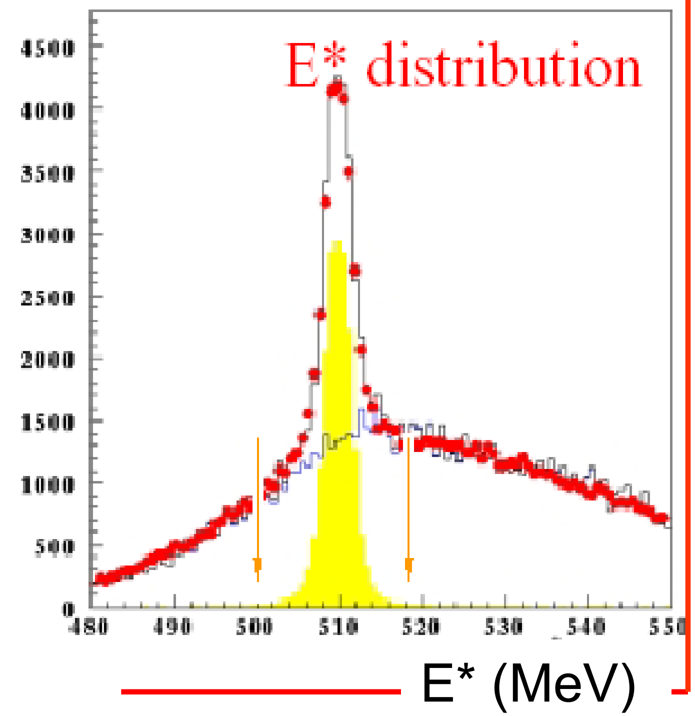
- selection cuts on:

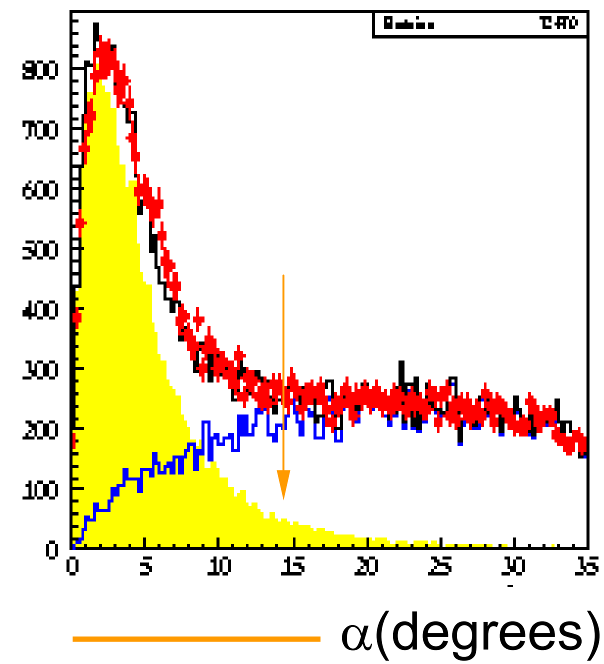
  a) E* the total energy of the 2 γ's:

  (E* - 510)< 5 σ**

  b) α the angle between the K_L momentum reconstructed from 2 γ's and the K_L momentum from K_S and ϕ

  α < 15°





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$K_L \rightarrow 3\pi^0$ selection

- neutral vertex with > 3 γ's attached
- cluster energy $E_\gamma > 20$ MeV .and. at least one cluster with $E_\gamma > 80$ MeV (*)
- distance from any another cluster > 40 cm

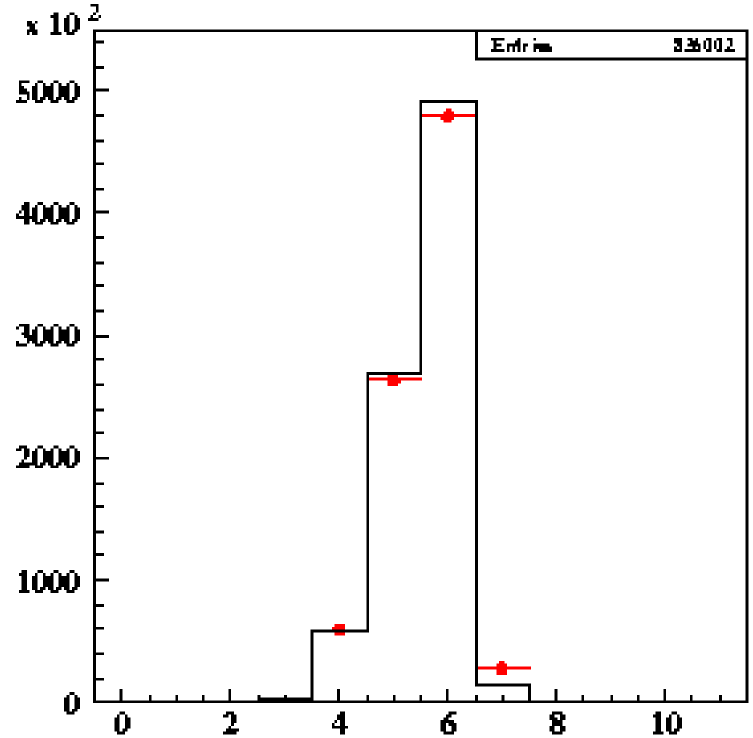
Background comes from:

- $K_L \rightarrow \pi^0\pi^+\pi^-$ and no track-to-cluster association
- $K_L \rightarrow 2\pi^0$
- machine background (*)

Main sources of inefficiencies are:

- geometrical acceptance
- merging with other clusters or splitting
- accidental association to a charged track

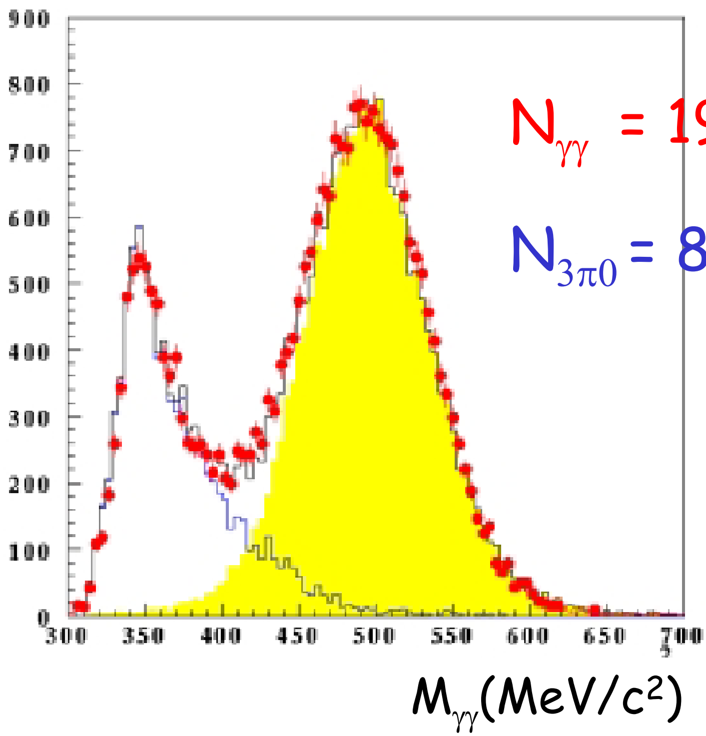
changes the weight of the relative population in



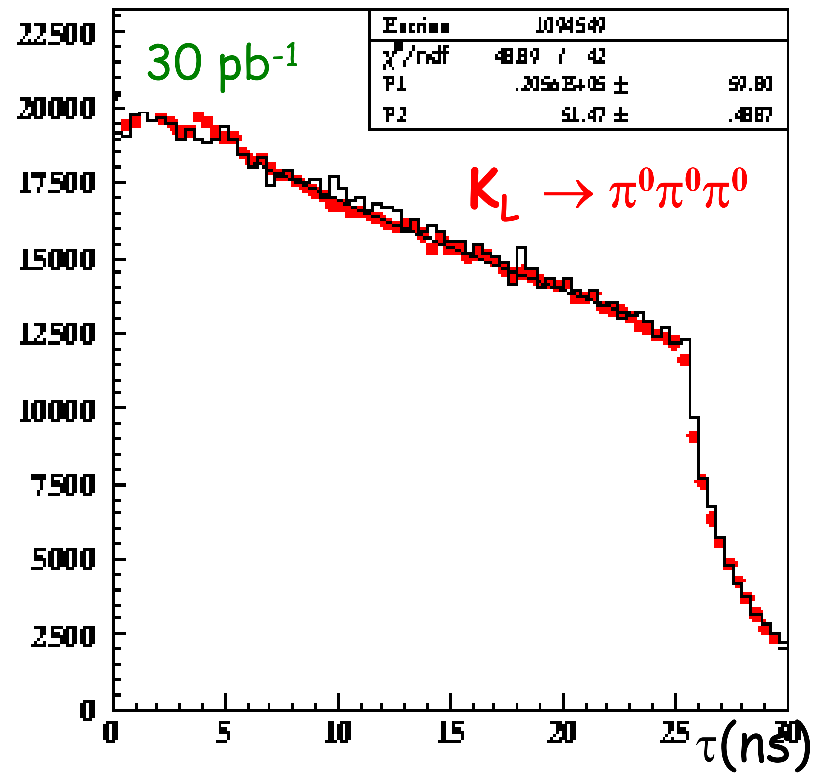
# of neutral clusters

$R=\Gamma(K_L \to \gamma\gamma)/\Gamma(K_L \to \pi^0\pi^0\pi^0)$

- 312 pb^{-1} analized (2001+2002 data)
- efficiencies estimated mainly from data



K_L lifetime



KLOE τ_L = 51.5 ± 0.5 ns

PDG τ_L = 51.7 ± 0.4 ns

Results

KLOE: $R = (2.797 \pm 0.028_{stat} \pm 0.025_{syst})\times 10^{-3}$

NA48: $R = (2.81 \pm 0.01_{stat} \pm 0.02_{syst})\times 10^{-3}$

PDG : $R = (2.77 \pm 0.08)\times 10^{-3}$

$K_S \to \gamma\gamma$

Significant test of ChPT:

- its branching ratio is unambiguously predicted at $O(p^4)$ order:

$$BR^{(4)}(K_S \to \gamma\gamma) = 2.1\times10^{-6}$$

- higher order effects are predicted to be ~20% of $O(p^4)$ value

$BR^{EXP}(K_S \to \gamma\gamma)$ vs $BR^{(4)}(K_S \to \gamma\gamma)$ ⇒ $O(p^6)$ loop contribution estimation

Experimental situation

$$BR^{EXP}(K_S \to \gamma\gamma) = (2.78 \pm 0.06_{stat} \pm 0.04_{syst})\times10^{-6}$$

NA48 from $\Gamma(K_S \to \gamma\gamma)/\Gamma(K_S \to 2\pi^0)$

- significantly higher than $BR^{(4)}(K_S \to \gamma\gamma)$
- higher order corrections increase the decay rate by ~30%

To subtract the background coming from $K_L \to \gamma\gamma$ NA48 has to evaluate it from the measurement of the ratio $R=\Gamma(K_L \to \gamma\gamma)/\Gamma(K_L \to \pi^0\pi^0\pi^0)$

$K_S \rightarrow \gamma\gamma$ with KLOE

- Pre-selection to reject the most dangerous background $K_S \rightarrow 2\pi^0$ (BR~31%)
  - K_L-crash
  - 2 "prompt" clusters $|t-R/c| < 5\sigma_t$
  - $E_\gamma > 220$ MeV
- Selection
  - $M_{\gamma\gamma} > 400$ MeV/c^2 invariant mass on the 2 γ's
  - coskk < -0.9 and -0.95< cos12 < -0.85

    coskk angle between K_S direction from K_L-crash and K_S direction from 2 γ's

    cos12 angle between the 2 γ's

$\varepsilon_{tot} \approx 20\%$

$N_{\gamma\gamma} \sim 70$ expected with 500 pb^{-1} but S/B=1/4 $\Rightarrow$ *More statistics is needed*

Thanks to the tagging we will have systematic uncertainties totally different from those of NA48

3) K_{l3} decays

V_{us} from K_{l3} decays

$$\Gamma(K_{e3}) = \frac{G_F^2 m_K^5}{192\pi^3} C_K^2 |V_{us}|^2 |f_+^{K\pi}(0)|^2 I_K(m_K^2, m_\pi^2, m_\ell^2, \tilde{f}_+^{K\pi}(q^2))$$

measuring

$$BR(K_{l3})/\tau_K$$

provided by the theory

measuring q^2 evolution of the form factor:

$$f_+^{K\pi}(q^2) = f_+^{K\pi}(0) \cdot \left(1 + \frac{\lambda_+^{K\pi}}{m_\pi^2} q^2\right)$$

The observable is: $|V_{us}||f_+(0)|$

V_{us} from K_{l3} decays

Ignoring phase space and form factor differences:

$\Gamma(K_L \to \pi e \nu) = \Gamma(K_S \to \pi e \nu) = 2\,\Gamma(K^{\pm} \to \pi^0 e^{\pm} \nu)$

But:

$$2 \times (2\Gamma^+ - \Gamma^0)/(2\Gamma^+ + \Gamma^0) = (3.66 \pm 0.06)\%$$

⇒ **SU(2) (and SU(3)$_F$) symmetry breaking effect**

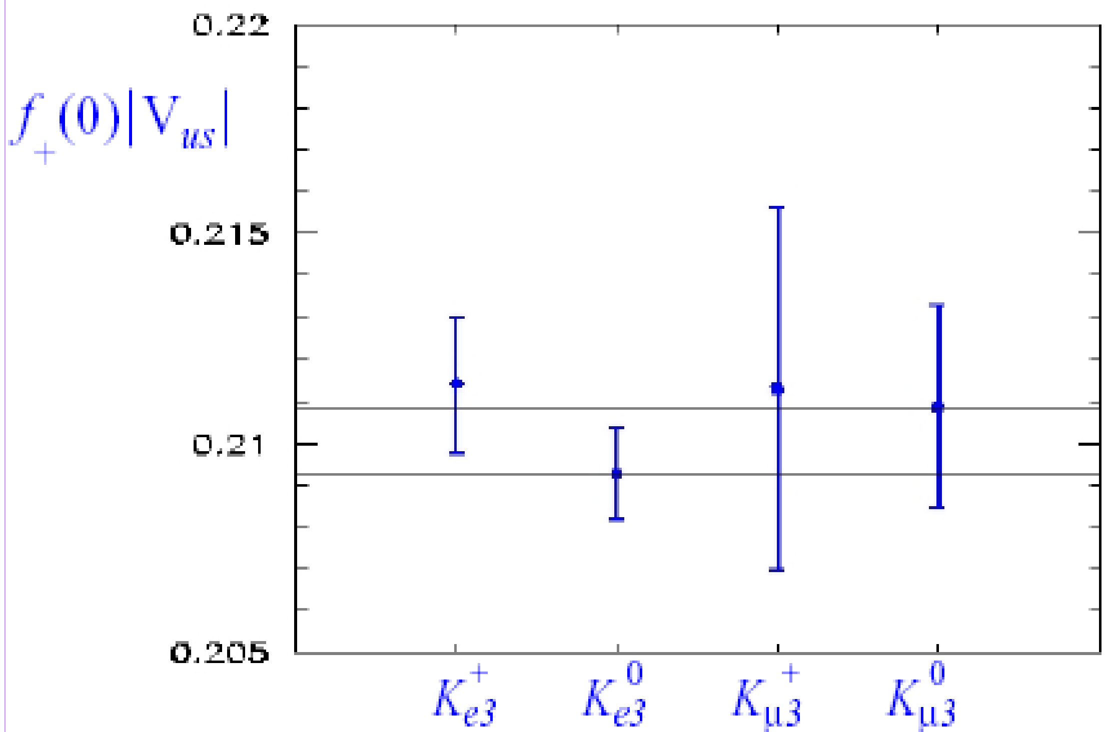
To extract V_{us} from the experimental observable we need:

- SU(2) and SU(3)$_F$ symmetry breaking corrections
- radiative corrections

V_{us}= 0.2196 ± 0.0026 (PDG '02) $\Delta V_{us}/V_{us}$ = 1.18%

Status of K_{l3} decays: theoretical corrections

Applying previous corrections to all the K_{l3} modes we have:



- $|V_{us}|_{Kl3} = 0.2187 \pm 0.0020$

  Calderon-Lopez Castro

  Phys Rev D65 (2002)

- Large spread after IB corrections

  γ inclusive measurement ???

- Clear prescription for radiative corrections from *Cirigliano et al., Eur. Phys. J. C 23 (2002)*
- *Applied to K^+_{e3} gives the result:* $|V_{us}|_{K^+_{e3}} = 0.2207 \pm 0.0024$

Status of K_{l3} decays: experimental situation

$\frac{\Delta BR}{BR}(\%)$	$\frac{\Delta\tau}{\tau}(\%)$	$\frac{\Delta\Gamma}{\Gamma}(\%)$	$\frac{\Delta\lambda_+}{\lambda_+}(\%)$	$\frac{\Delta\lambda_0}{\lambda_0}(\%)$
K^+_{e3}				
1.2	0.2	1.22	4.5	-
$K^+_{\mu3}$				
2.5	0.2	2.5	12.2	19.7
K^0_{e3}				
0.7	0.8	1.06	4.7	—
$K^0_{\mu3}$				
0.9	0.8	1.20	14.7	24.0

Contributions to the relative accuracy on V_{us}

$$\frac{\Delta|V_{us}|}{|V_{us}|} = 0.5\left(\frac{\Delta BR_{K_{e3}}}{BR_{K_{e3}}} + \frac{\Delta\tau}{\tau}\right) + 0.05\frac{\Delta\lambda_+}{\lambda_+} + \frac{\Delta f_+(0)}{f_+(0)}$$

$K^{\pm}_{e3}$ 0.59% 0.22% 0.86%

$\Gamma(K_{l3})$ inclusive measurement with both $K^{\pm}$ and K^0

Measuring Γ(e3) at KLOE

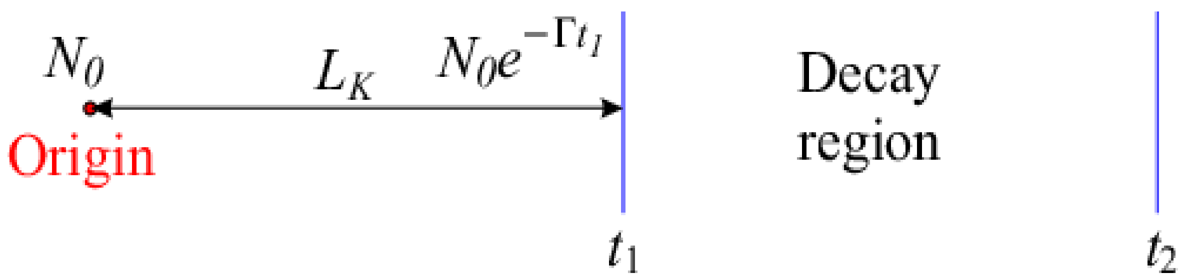
Traditional method

- measurement of $\Gamma = 1/\tau$
- measurement of **BR(e3)**

$$\Gamma(e3) = BR(e3) \times \Gamma$$

$$\frac{\delta\,\Gamma(e3)}{\Gamma(e3)} = \sqrt{\left(\frac{\delta\tau}{\tau}\right)^2 + \left(\frac{\delta(BR(e3))}{BR(e3)}\right)^2}$$

KLOE method



$$\Gamma(e3) = (\Delta N_{e3} / \Delta t)/N_{KL}$$

- by the tag count the number of *K produced*, N_{KL}
- count the number N_{e3} of semileptonic decays in the decay region

Γ is a correction & $\delta\tau/\tau$ dependence reduced by a factor ≈ 5

Measuring V_{us} at KLOE

$$\frac{\Delta|V_{us}|}{|V_{us}|} = 0.5\left(\frac{\Delta BR_{K_{e3}}}{BR_{K_{e3}}} + \frac{\Delta\tau}{\tau}\right) + 0.05\frac{\Delta\lambda_+}{\lambda_+} + \frac{\Delta f_+(0)}{f_+(0)}$$

from experiments **from theory**

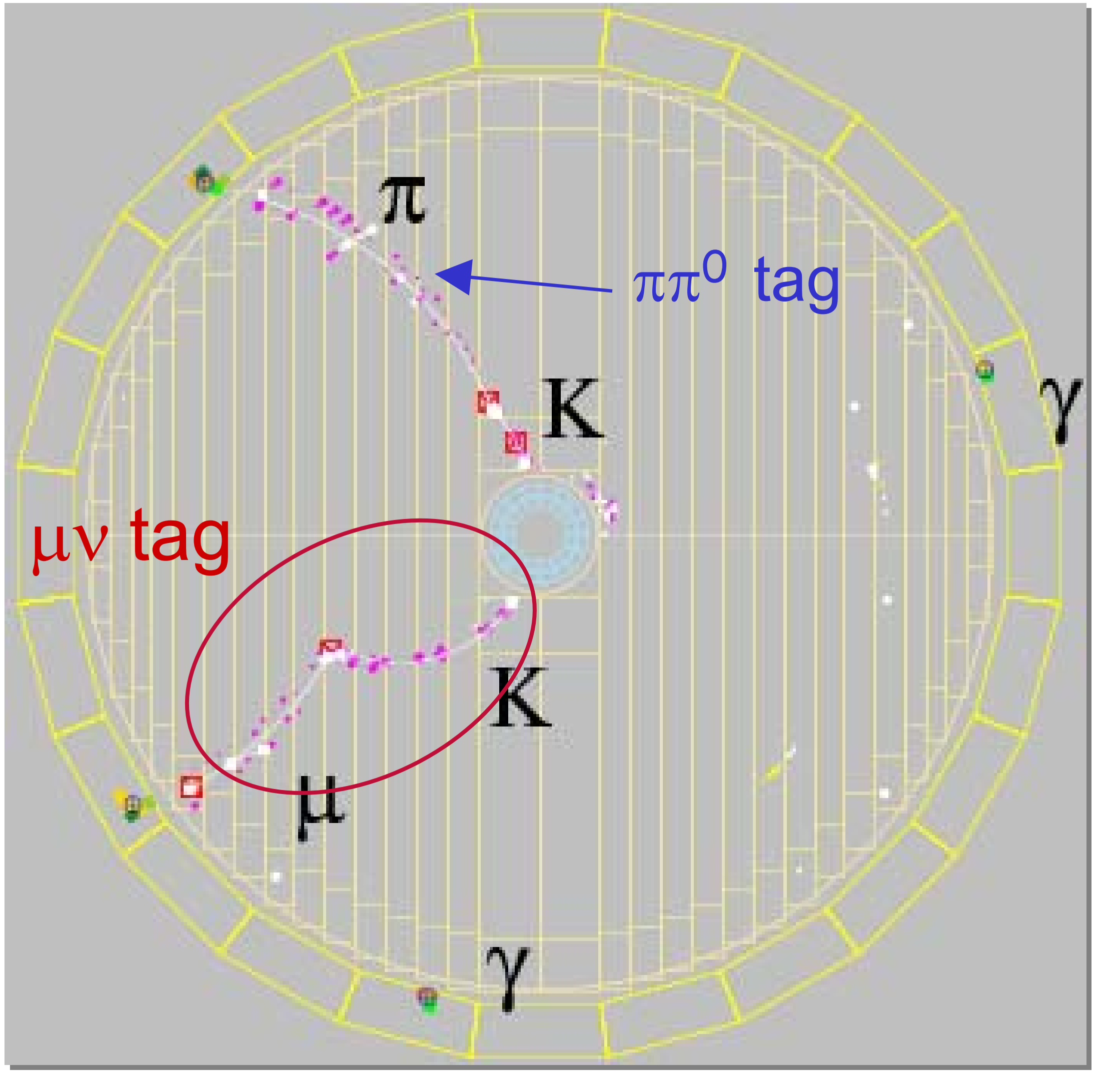
KLOE with the **same detector** and using **both charged and neutral kaons**

can **improve the experimental contribution to V_{us} accuracy** measuring:

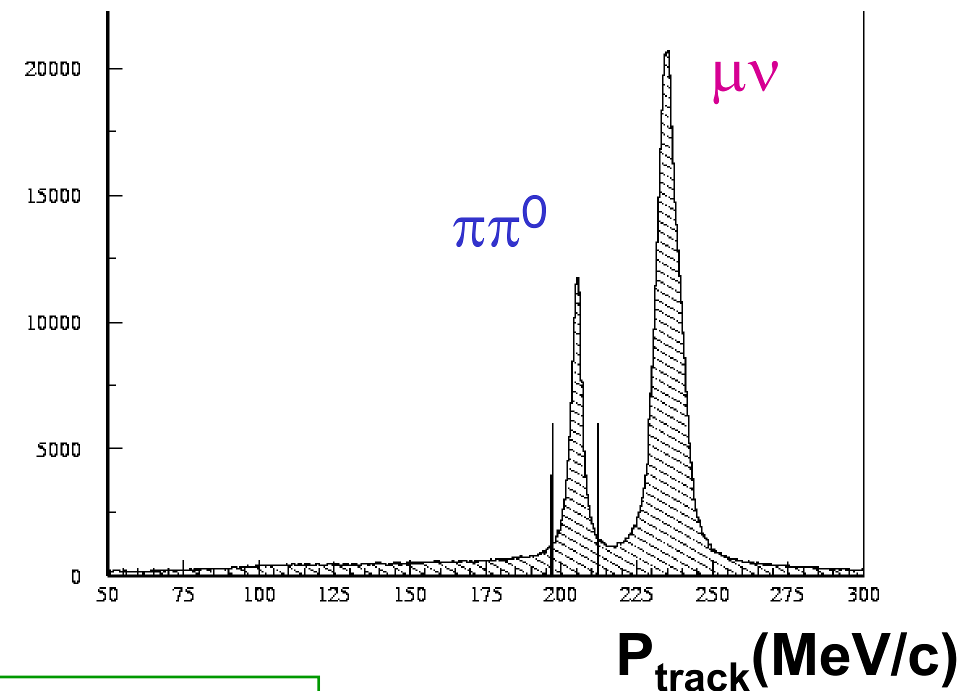
- absolute branching ratios or directly the partial decay width
- form factor slopes λ_+ and λ_0
- τ_{KL}

K_{l3} decays from charged kaons

Tag is provided by $K\rightarrow\mu\nu$, $K\rightarrow\pi\pi^0$ (BR~85%)selected using only DC information:



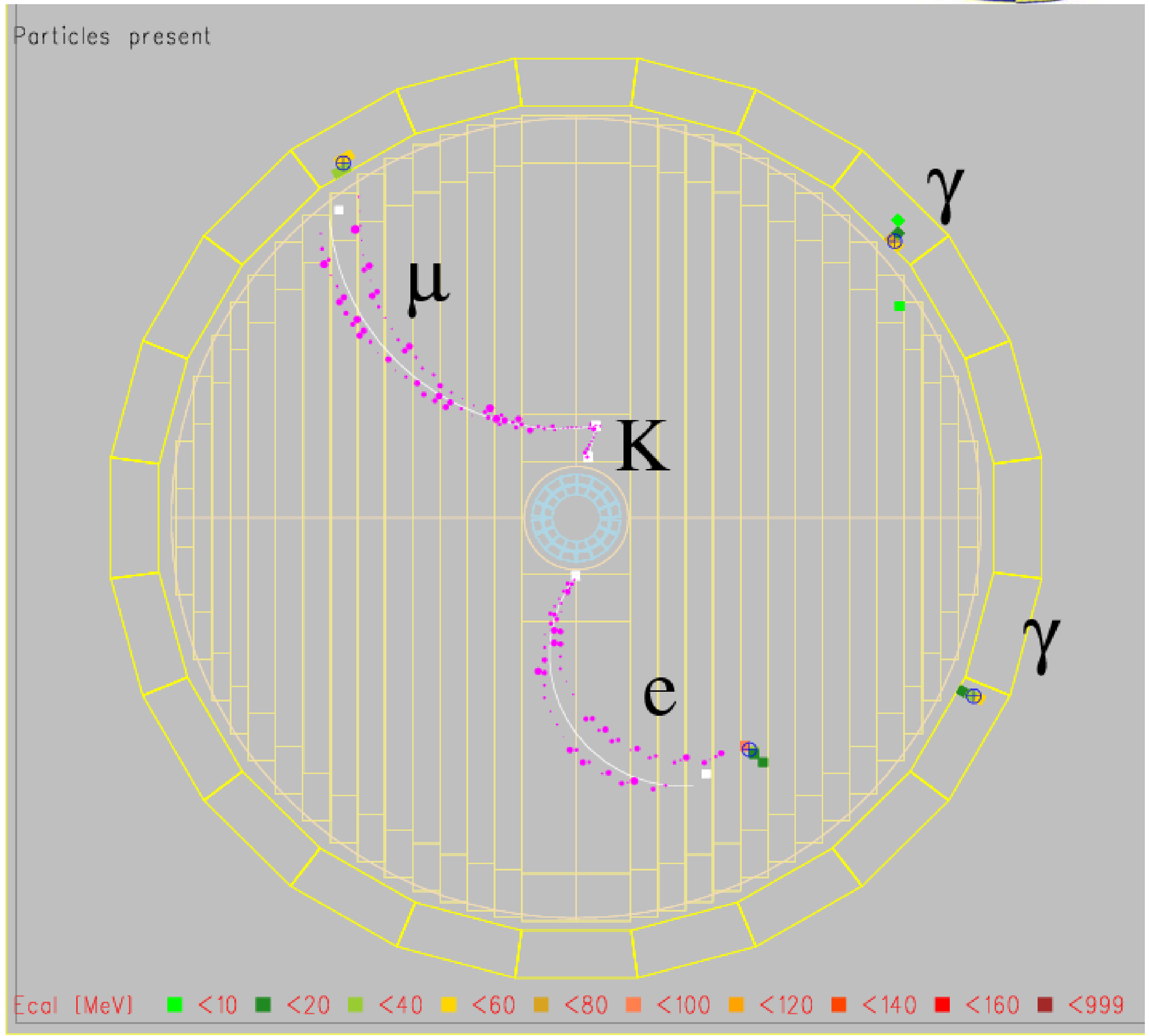
- K from IP ($70 < p_K < 130$ MeV/c)
- decay in fiducial volume
- "right" p_K-$p_{daughter}$ at vertex
- p_{track} in K ref. frame



$$\varepsilon^{TAG}_{\pi\pi^0} \approx \varepsilon^{TAG}_{\mu\nu}$$ from data using only EMC information

$K^{\pm}_{e3}$ signal selection

- ✓ Tag on one side
- ✓ Vertex in DC
- ✓ ToF selection
- ✓ π^0 in EMC



17 pb^{-1}

	$K^{\pm}_{e3}$ (yield)	$\varepsilon_{sele}(K^{\pm}_{e3})(\%)$
$K^{\pm}_{\mu}$ TAG	21 662	34.4 ± 0.6
$K^{\pm}_{\pi\pi^0}$ TAG	3 872	32.7 ± 1.3

Preliminary

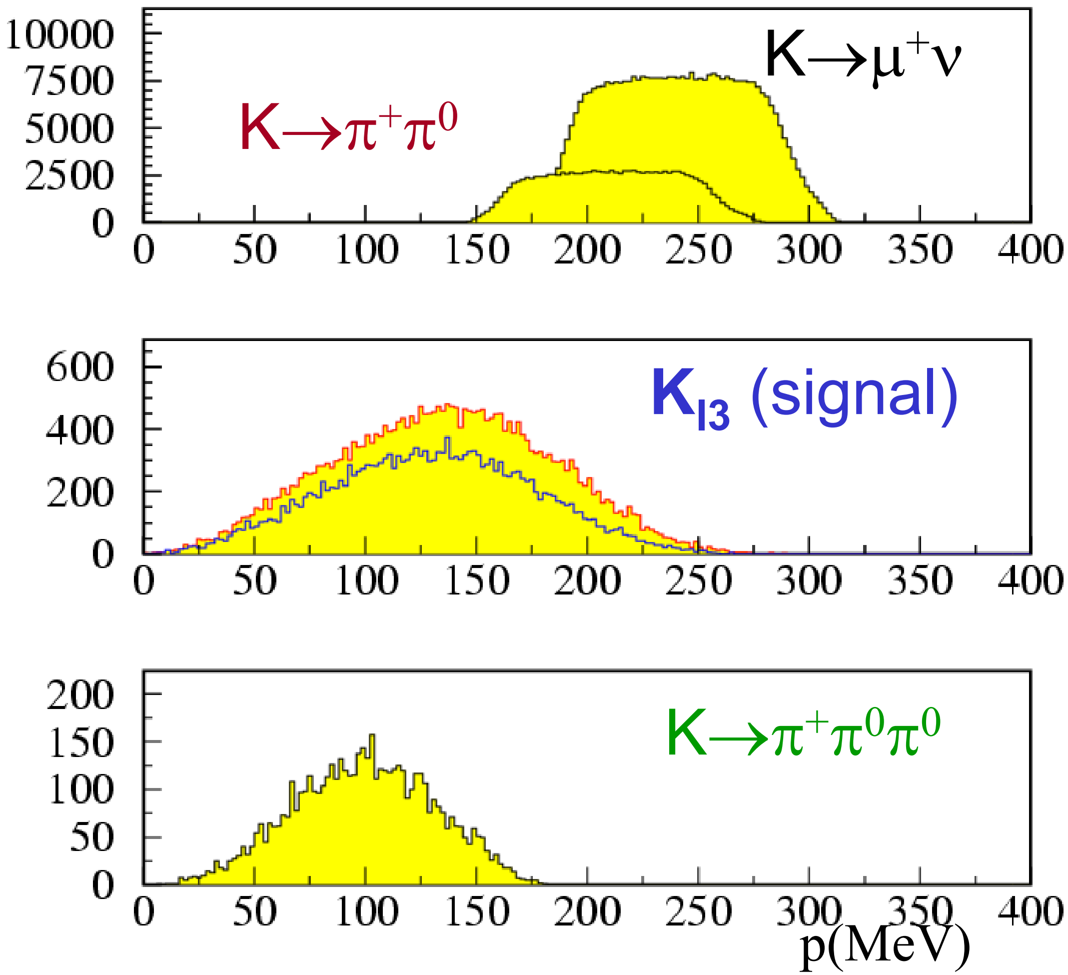
$$N_{K^{\pm}_{e3}} \approx 2000/\text{pb}^{-1} \Rightarrow \underbrace{0.4\times10^6}_{} + \underbrace{0.6\times10^6}_{}$$

200 pb^{-1} (2001 run) ≈**300 pb^{-1}** (2002 run)

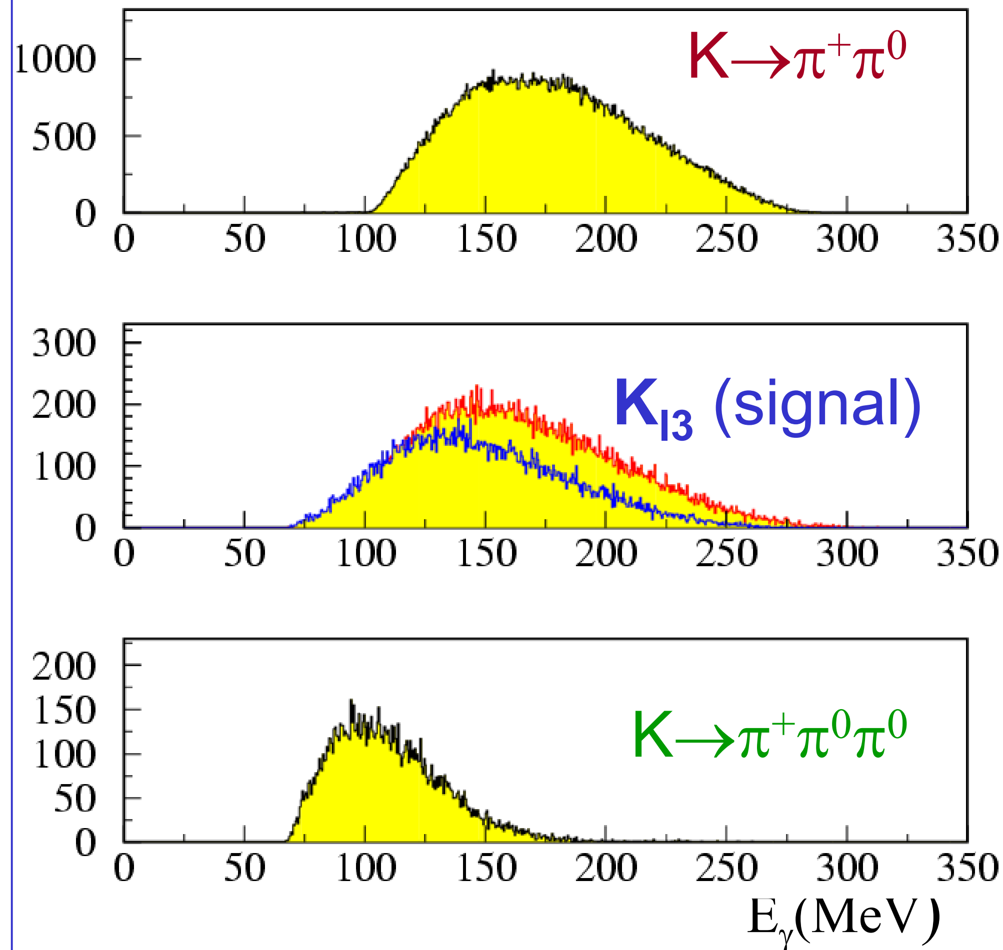
$K^{\pm}_{e3}$ signal efficiency

Most of the efficiencies can be evaluated directly from data using control samples ⇒ method used for $\Gamma(K_S \to \pi^+\pi^-(\gamma))/\Gamma(K_S \to \pi^0\pi^0)$

Track + Vertex fit



π^0 cluster



K_{l3} decays from neutral kaons

Tag is provided by $K_s \to \pi^+\pi^-$ decays selected using only DC information:

- single vertex in K_S fiducial volume

  $r_T < 4$ cm and $|z| < 8$ cm

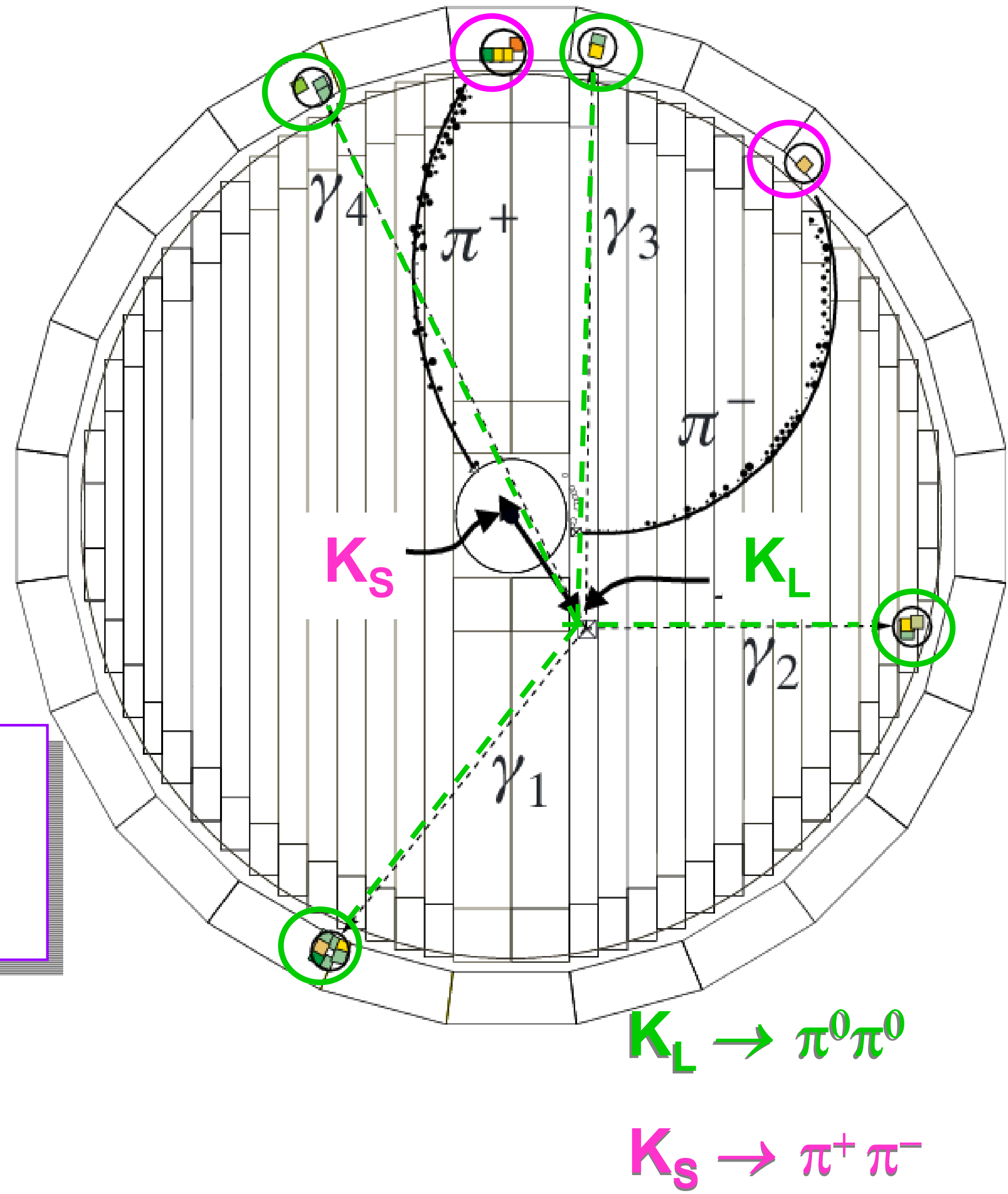
- two and only two tracks of opposite charge connected to the vertex

- $50 < p_{KS} < 170$ MeV/c in ϕ ref. frame

- $400 < M_{KS} < 600$ MeV/c^2

- **K_L momentum** from K_S and ϕ momenta
- Tagging efficiency $\varepsilon_{tag,total} \sim$ **75%**

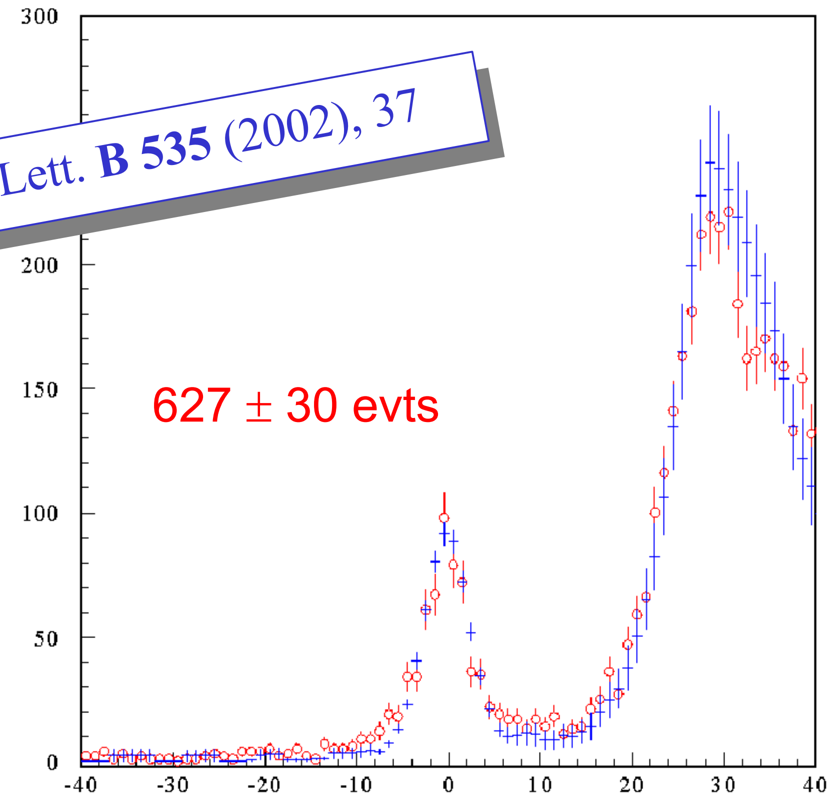
$\varepsilon_{tag,total}$ can be estimated from data using a sample with "K_L – crash" and two tracks



K^0_{e3} signal selection

- ✓ Tag on one side
- ✓ Vertex in DC fiducial volume
- ✓ Invariant mass cut
- ✓ ToF selection

➢ Procedure already used for $K_S \rightarrow \pi^{\pm} e^{\pm} \nu$:



KLOE 2000 data:

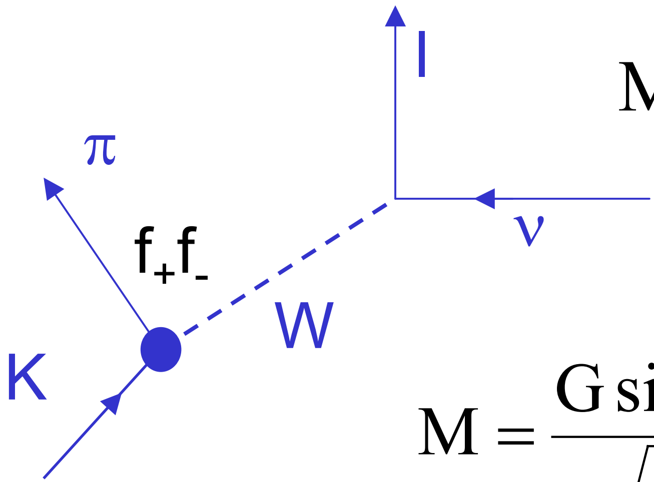
$BR(K_S \rightarrow \pi^{\pm} e^{\pm} \nu) = (6.79 \pm 0.33_{stat} \pm 0.16_{syst}) \times 10^{-4}$

$$N_{K^0_{e3}} \approx 3\times10^4/\mathrm{pb}^{-1} \Rightarrow 6\times10^6 + 9\times10^6$$ (~1.5x 10^4 $K_S \rightarrow \pi^{\pm} e^{\pm} \nu$)

200 pb^{-1} (2001 run) — **≈300 pb^{-1}** (2002 run)

E. De Lucia

K_{l3} the form factors



$$M = \frac{G\sin\theta}{\sqrt{2}} \underbrace{\langle \pi | J_\mu^{had} | K \rangle}_{f_+(t)P_\mu + f_-(t)q_\mu} u_l \gamma^\mu (1-\gamma_5) u_\nu$$

$t = q^2 = (P^K - P^\pi)^2$

$P_\mu = P_\mu^K + P_\mu^\pi$

$q_\mu = P_\mu^K - P_\mu^\pi$

$$M = \frac{G\sin\theta}{\sqrt{2}} \left\{ f_+(t) P_\mu \bar{u}_\nu \gamma^\mu (1-\gamma_5) u_l + \underline{\underline{m_l}} f_-(t) u_l (1-\gamma_5) u_\nu \right\}$$

event density: $\rho(E_\mu, E_\pi) = \frac{d^2\Gamma}{dE_\pi dE_\mu} = \frac{|M|^2}{8M(2\pi)^3} \propto Af_+^2(t) + Bf_+(t)f(t) + Cf^2(t)$

$$f(t) = f_+(t) + \frac{t}{M_K^2 - m_\pi^2} f_-(t)$$

linear expansion of the $f_i(t)$:

$$f_+(t) = f_+(0)(1 + \lambda_+ t/m_\pi^2)$$

$$f(t) = f(0)(1 + \lambda_0 t/m_\pi^2)$$

$\Rightarrow \rho(E_\mu, E_\pi, \lambda_+, \lambda_0)$

λ_+ ***and*** λ_0 can be measured from fit of the Dalitz plot distribution

Measuring λ_+

K^0_{e3}

$$\lambda_+ = 0.0245 \pm 0.0012_{stat} \pm 0.0022_{syst}$$ (CPLEAR) 3.6×10^5 events

6×10^6 @KLOE (200 pb^{-1}) $\sigma_{stat} \approx O(10^{-4})$

$K^\pm_{e3}$

$$\lambda_+ = 0.0293 \pm 0.0015_{stat} \pm 0.002_{syst}$$ (ISTRA+) 1.3×10^5 events

$$\lambda_+ = 0.0278 \pm 0.0017_{stat} \pm 0.0015_{syst}$$ (KEK-E246) 10^5 events

4×10^5 @KLOE (200 pb^{-1}) $\sigma_{stat} \approx O(10^{-3})$

⇒ ***KLOE*** can improve the actual measurements of λ_+ using both **K^0_{e3}** and **$K^\pm_{e3}$** decays

Measuring λ_0

$K^0_{\mu3}$

$$\lambda_0 = 0.019 \pm 0.004$$ (Donaldson et al.) $1.6\text{x}10^6$ events

6x10⁶ → $6\text{x}10^6$

@KLOE (200 pb^{-1})

$\sigma_{stat} \approx O(10^{-4})$

$K^{\pm}_{\mu3}$

$$\lambda_0 = 0.0209 \pm 0.004_{stat} \pm 0.002_{syst}$$ (ISTRA+) $1.1\text{x}10^5$ events

$$\lambda_0 = 0.022 \pm 0.005_{stat} \pm 0.004_{syst}$$ (KEK-E246) $4.1\text{x}10^4$ events

$4\text{x}10^5$

@KLOE (200 pb^{-1})

$\sigma_{stat} \approx O(10^{-3})$

KLOE can improve the actual measurements of λ_0 using both **$K^0_{\mu3}$** and **$K^{\pm}_{\mu3}$** decays

4) Kl4 decays

K_{e4} decays

The **ππ scattering** at low energy is the simplest possible hadronic interaction

- promising ground for studying the strength of the $q\bar{q}$ **condensate**
- test the hypothesis that the quark condensate is the leading order parameter of the spontaneous broken chiral symmetry

- **πN $\rightarrow$ $\pi\pi$ N**

  High statistics available but extraction of $\pi\pi$ amplitude is **model dependent**

- **Ke4 decays**

  no additional strongly interacting particles in the final state

  - **very precise predictions from ChPT** (*but* BR(Ke4) 3.91×10^{-5})

K_{e4} decays

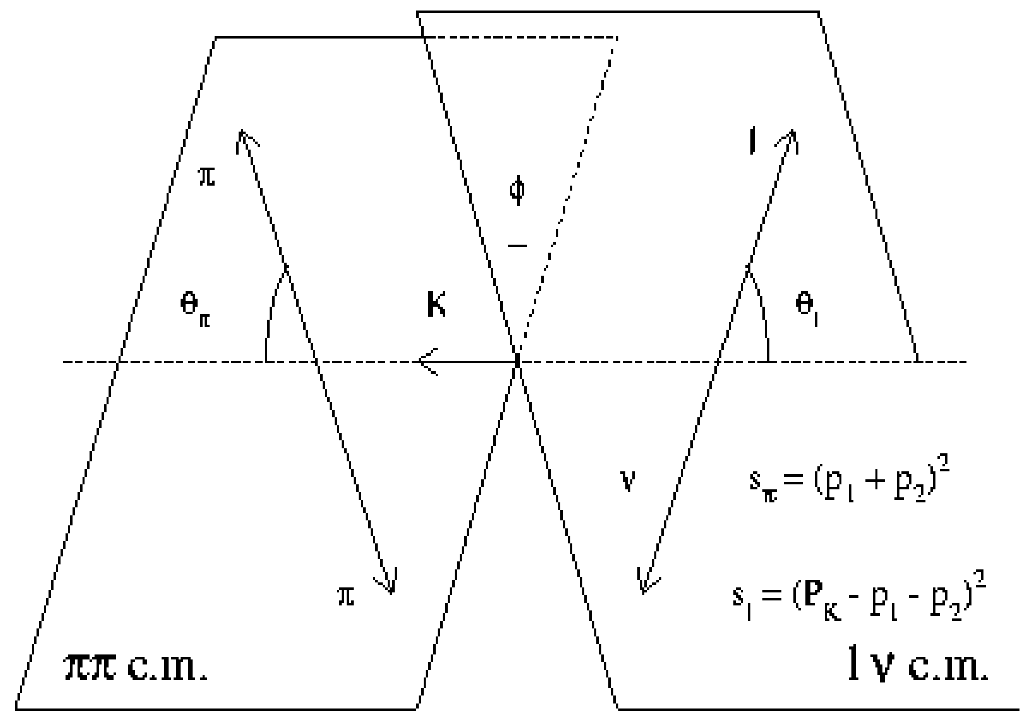
$$d\Gamma = G_F^2 |V_{us}|^2 N(s_\pi, s_e) J_5(s_\pi, s_e, \vartheta_\pi, \vartheta_e, \phi) ds_\pi ds_e d\cos\vartheta_\pi d\cos\vartheta_e d\phi$$

- J_5 is a simple function of $\vartheta_e \phi$ and of 9 intensities $I_i(s_\pi, s_e, \vartheta_\pi, F, G, H, R)$

full kinematics described by 5 variables

- performing the partial wave expansion of the form factors F,G,H,R in the variable ϑ_π :

- the amplitudes are functions of s_π, s_e
- the phases coincide with the phase shift of the $\pi\pi$ elastic scattering δ_l^I and are functions of s_π



K_{e4} decays

The observable is the phase difference:

$$\delta(s_\pi) = \delta_0^0(s_\pi) - \delta_1^1(s_\pi) \qquad 4M^2_\pi < s_\pi < M^2_K$$

To extract it from data we can use the Pais-Treiman method:

- $d^2\Gamma/d\cos\theta_e\, d\phi$ event distribution in s_π bins
- fit the event distribution with the 9 intensities I_i
- neglecting all the waves higher than S and P we have:

$$\tan(\delta_0^0 - \delta_1^1) = \frac{1}{2}\frac{\int_{-1}^{1} I_7 d\cos\theta_\pi}{\int_{-1}^{1} I_4 d\cos\theta_\pi}$$

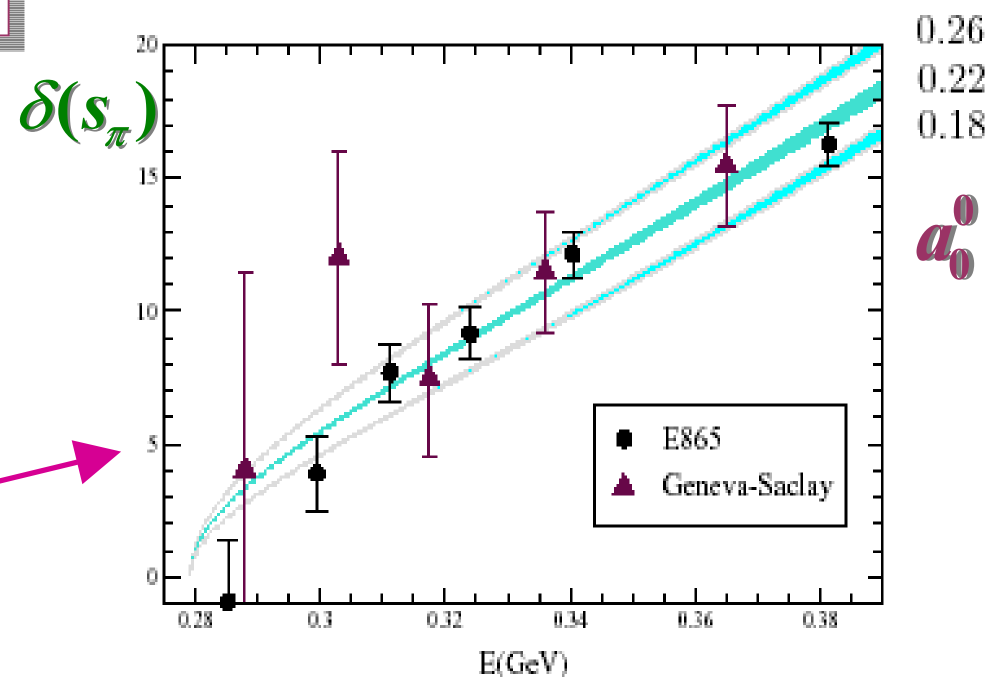
K_{e4} decays theoretical predictions

Predictions are made on the S-wave scattering length a_0^0 (dominant wrt a_0^2)

ChPT prediction $a_0^0 = 0.220 \pm 0.005$

Need to relate δ to a_0^0:

- expansion by Basdevant et al.
  but introduces new parameters
- Roy equations
  phenomenological description



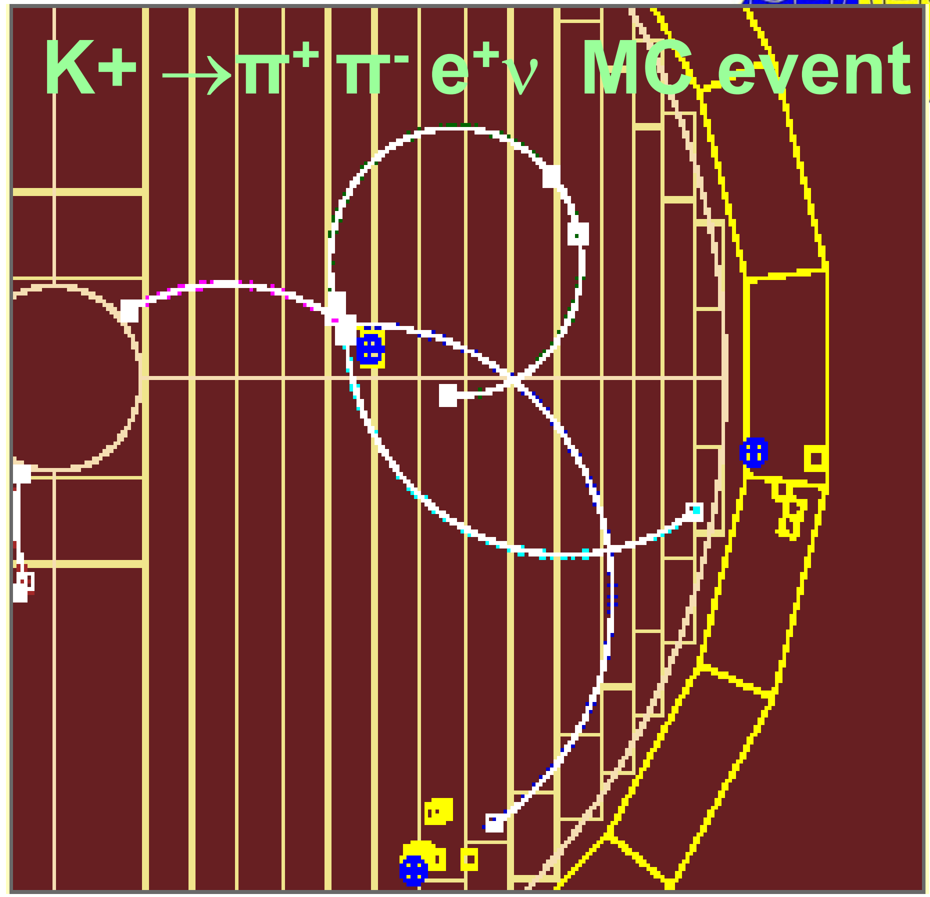
Experimental situation (from $K^{\pm}_{e4}$)

Rosselet et al. (1977) $a_0^0 = 0.26 \pm 0.05$ ~3×10^4 events

E865 Coll. (2000) $a_0^0 = 0.228 \pm 0.012$ ~3×10^5 events

K_{e4} decays at KLOE

- ✓ Tag on one side using $K \rightarrow \mu\nu$ decays
  simpler reconstruction of the 4 tracks
- ✓ Vertex in DC fiducial volume
- ✓ 4 tracks attached to the vertex
  $p_T < 200$ MeV/c $\Rightarrow$ spiralling tracks
- ✓ ToF selection
- ✓ main backgroung **K+** $\rightarrow \pi^+ \pi^- \pi^+$



Need optimization of:

- pattern recognition and track fit procedure for very low momenta
- Vertex fit with 4 tracks

(everything optimized for CP events)

more statistics is needed to enter into the game!!

$N^{tag}_{K\pm e4} \approx 1.5 \times 10^4$ but

Totally different systematic uncertainties at KLOE thanks to the unique feature of the tagging

5) $\eta \to \pi^0\gamma\gamma$

$\eta \to \pi^0 \gamma\gamma$: **theory**

This decay is a window on rather high order corrections in Ch

- Leading term $O(p^2)$ is absent
- tree-level amplitude $O(p^4)$ is also zero
- loop contributions $O(p^4)$ plays a very minor role:

$$\Rightarrow \Gamma^{(4)}(\eta \to \pi^0\gamma\gamma) = 4 \div 7 \mathrm{x} 10^{-3} \ \text{eV}$$

- chiral expansion starts from $O(p^6)$

Theoretical predictions of $\Gamma(\eta \to \pi^0\gamma\gamma)$ eV

VDM	0.30 ± 0.16	(Ng-Peters)
V+A resonance	0.47 ± 0.20	(Ko)
q-box diagram	0.70 ÷ 0.92	(Ng-Peters, Nemoto et al.)
ChPT	0.42 ± 0.20	(Ametller et al.)
ChPT	0.58 ± 0.30	(Bellucci-Bruno)

$\eta \to \pi^0 \gamma\gamma$: experiments

Experimental situation

GAMS-2000 (1981)	$6\times10^5\ \eta$	38 events	$BR(\eta \to \pi^0\gamma\gamma) = (9.5 \pm 2.3)\times10^{-4}$
GAMS-2000 (1984) reanalysis			$BR(\eta \to \pi^0\gamma\gamma) = (7.1 \pm 1.4)\times10^{-4}$ $\Gamma(\eta \to \pi^0\gamma\gamma) = 0.84 \pm 0.18$ eV
~~SND(2001)~~	~~$2.6\times10^5\ \eta$~~	~~170 events~~ (7signal + 163 bckg)	~~$BR(\eta \to \pi^0\gamma\gamma) = (2.1^{+3.8}_{-1.9})\times10^{-4}$~~
~~Crystal Ball (2001)~~ preliminary	~~$2\times10^7\ \eta$~~	~~500 events~~	~~$BR(\eta \to \pi^0\gamma\gamma) = (3.2 \pm 0.9)\times10^{-4}$~~ $\Gamma(\eta \to \pi^0\gamma\gamma) = 0.38 \pm 0.11$ eV

No agreement between GAMS-2000 and Crystal Ball

measures of E_γ and of $\gamma\gamma$ invariant mass spectra are needed

$\Rightarrow$ different shapes for different models

$\eta \to \pi^0 \gamma\gamma$ with KLOE

- Tag η decays from $\phi \to \eta\gamma$ asking for a photon with $E\gamma$ = 363 MeV

  available statistics:

$$N_{\eta}^{tag} \approx 2x10^7$$ same as Crystal Ball

- the selection looks for 5 "prompt" γ in the final state:

- photon pairing and kinematic fit with mass constraint in the hypothesis:

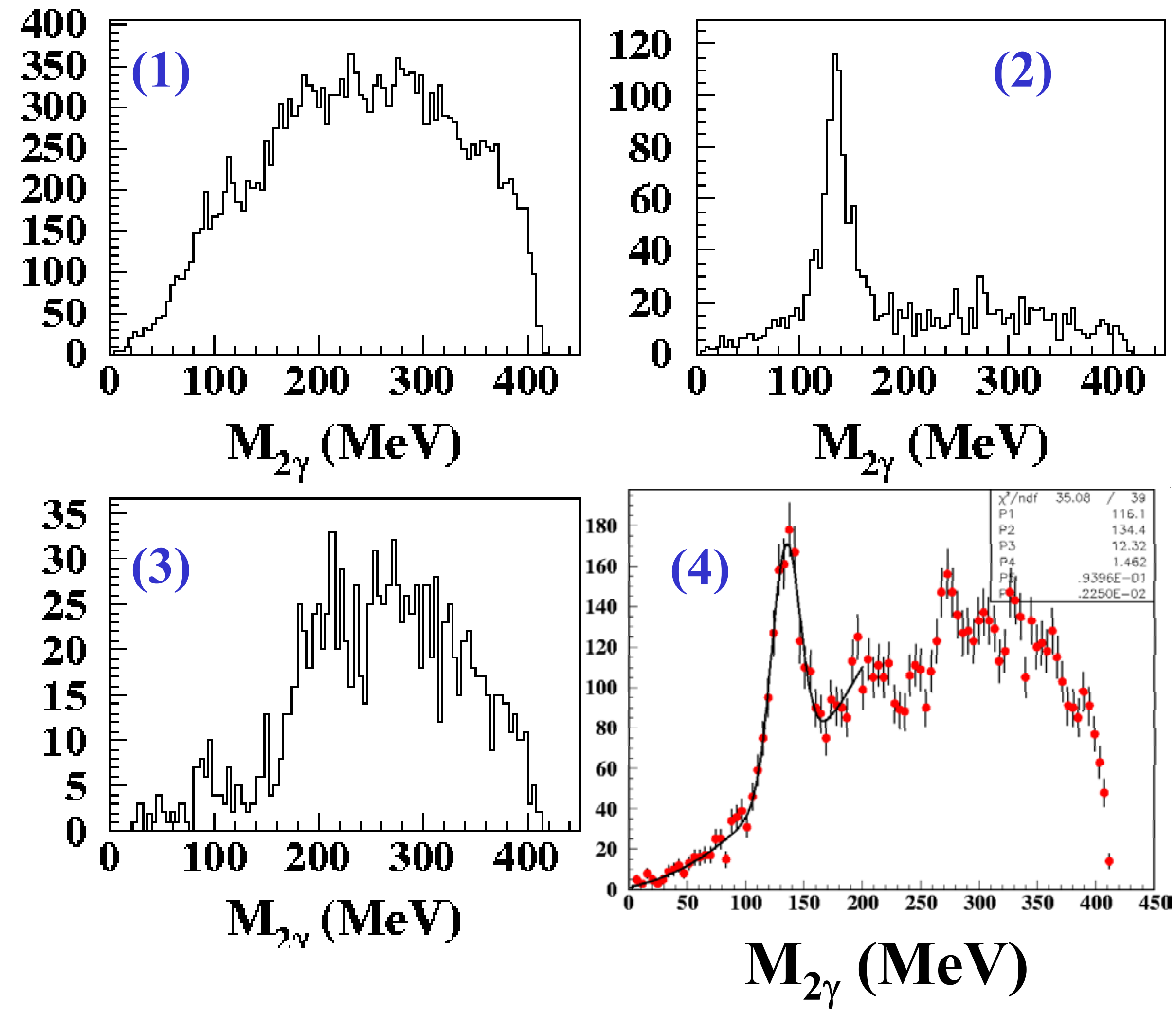
1. $\pi^0\pi^0\gamma$ $(f_0 \to \pi^0\pi^0)$
2. $\eta\pi^0\gamma$ $(a^0 \to \eta\pi^0)$
3. $\omega\pi^0 \to \pi^0\pi^0\gamma$ $(M(\pi^0\gamma)=M(\omega))$
4. $\eta\gamma \to 3\gamma$
5. $\eta\gamma \to \pi^0 \gamma\gamma\gamma$

$\eta \to \pi^0 \gamma\gamma$ with KLOE

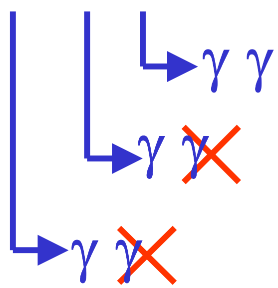
After $\pi^0\pi^0\gamma$ and $\eta\pi^0\gamma$ rejection:

(1)Signal (MC)
(2) Residual $\pi^0\pi^0\gamma$ (MC)
(3) $\eta\gamma \to \pi^0\pi^0\pi^0\gamma$ (MC)
(4) Data

$M_{2\gamma}$ $\gamma\gamma$ invariant mass spectra



Cutting the π^0 peak does not help with (3)
$\phi \to \eta\gamma \to \pi^0\pi^0\pi^0\gamma$



$\Rightarrow$ only one π^0 is reconstructed

Still no clear signal of $\eta \to \pi^0\gamma\gamma$ crucial to improve $\phi \to \eta\gamma \to \pi^0\pi^0\pi^0\gamma$ rejection both using QCAL (γ lost) and shower shape variables (merging)

Conclusions

KLOE can perform many tests of Chiral Perturbation Theory

- Totally different systematic uncertainties wrt other experiments thanks to the unique feature of the tagging

- First results from:
  - $\delta_0 - \delta_2$ measurement using $K \rightarrow \pi\pi$
  - $\Gamma(K_L \rightarrow \gamma\gamma)/\Gamma(K_L \rightarrow \pi^0\pi^0\pi^0)$ measurement

- With the available statistics relevant contribution to:
  - K_{l3} decays for the measurement of V_{us}
  - $\eta \rightarrow \pi^0\gamma\gamma$

- With more luminosity the following items will be accessible:
  - Ke4 decays
  - $K_S \rightarrow \gamma\gamma$

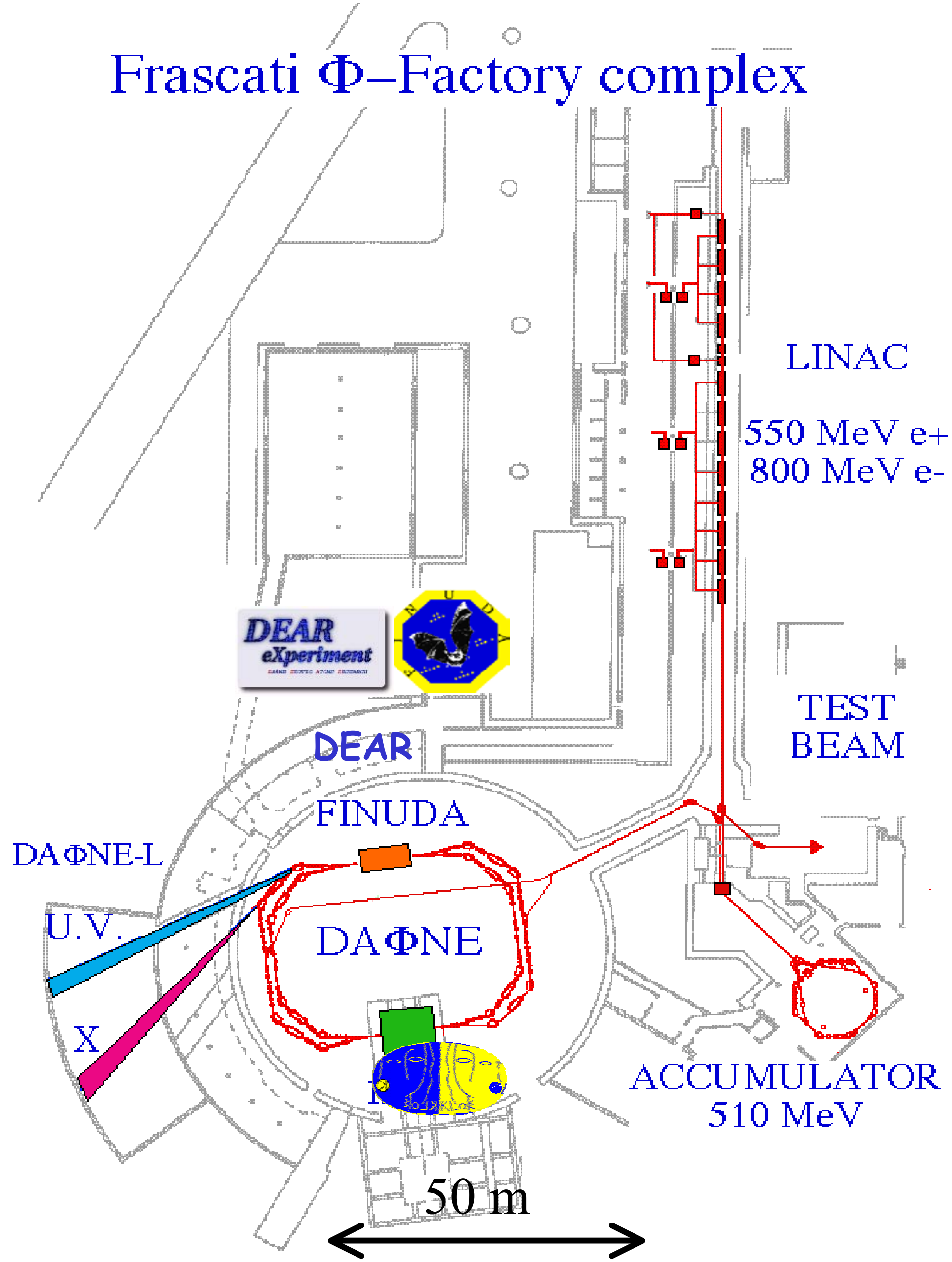
DAΦNE parameters

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}

↓

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



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

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): $(7.2 \pm 1.4) \times 10^{-4}$

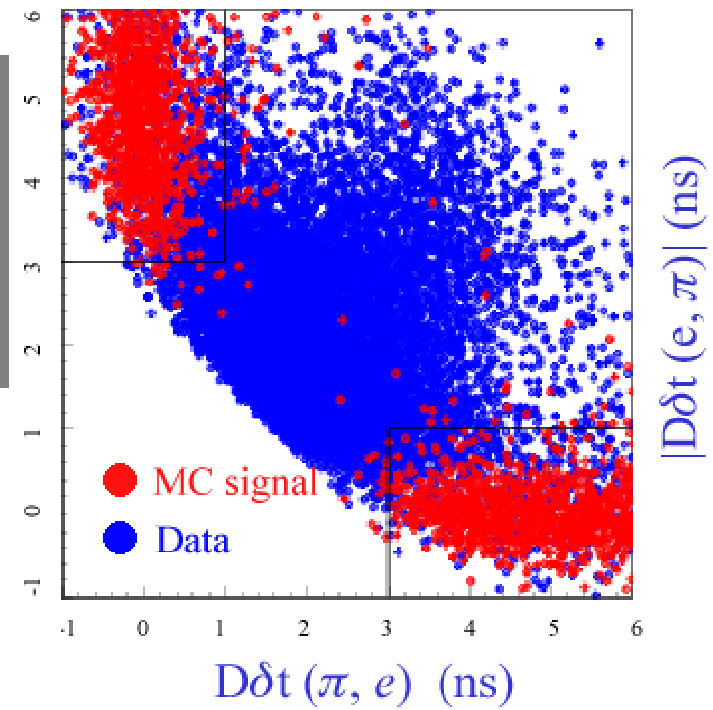
Selectio

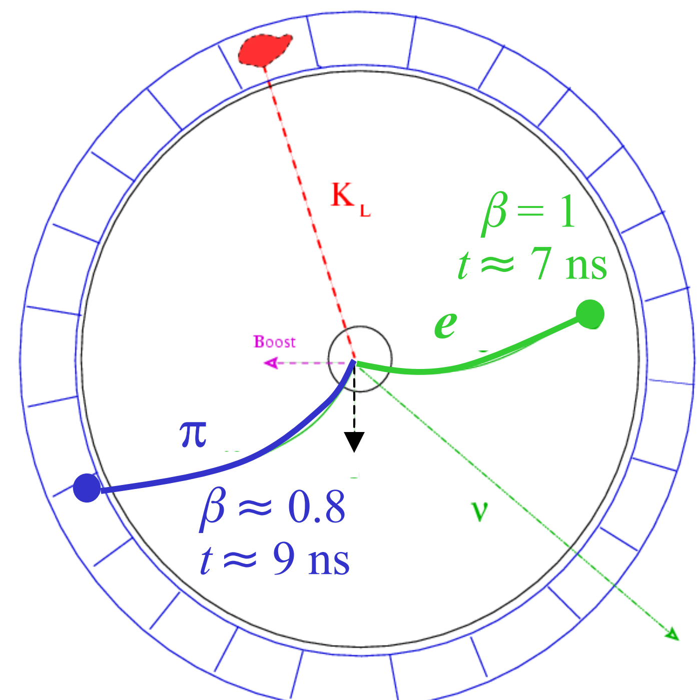
- K_L-crash.and.charged vertex at IP (r<8cm , |z|<10cm) .and.2 tracks with associated EmC clusters
- invariant mass of the tracks in π hp $M_{\pi\pi} < 490$ MeV/c^2 (against background from $K_S \to \pi^+\pi^-$)
- π/e identification using time-of-flight
- $E_{miss} - |p_{miss}|$

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

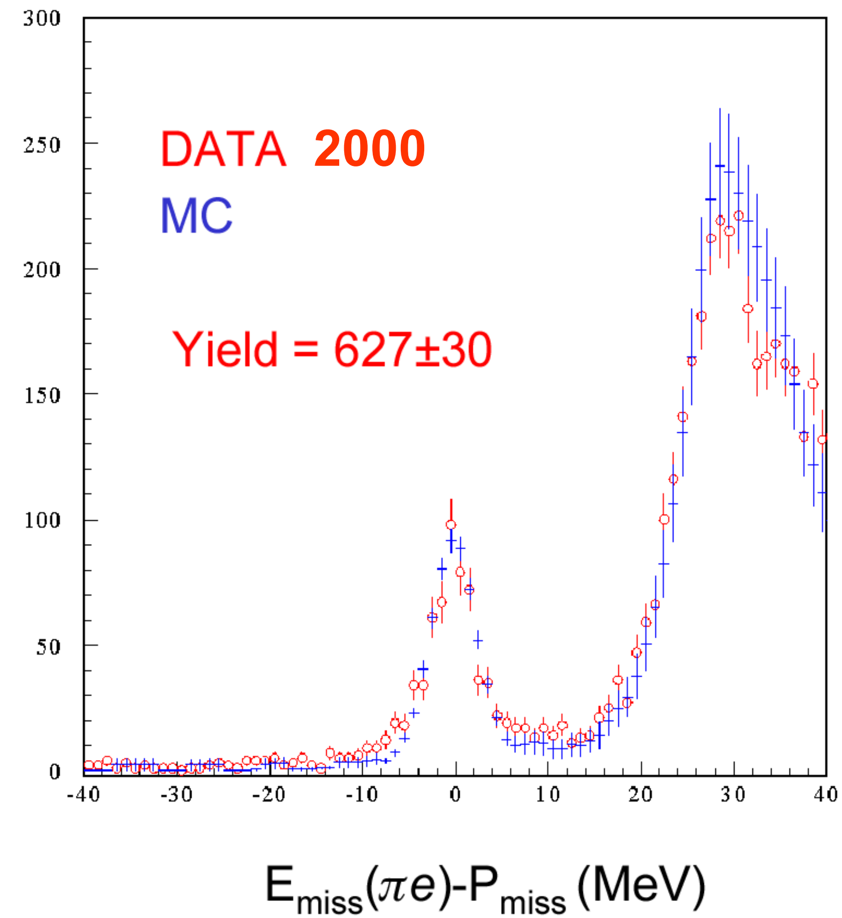
- ✓ **Vertex reconstruction, fiducial cuts and $M_{\pi\pi}$ efficiency** from MC but also from data $K_L \to \pi e \nu$ near I.P. (high-purity sample (> 99.7 %), by kinematic cuts) and $K_S \to \pi^o \pi^o$ to scale MC
  Tracking efficiency for MC and data from $K_S \to \pi^+\pi^-$

- ✓ **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($K_S \to \pi^{\pm} e^{\pm} \nu$)

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

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

Using PDG:

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

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 !!