Dec 1999

LNF Frascati

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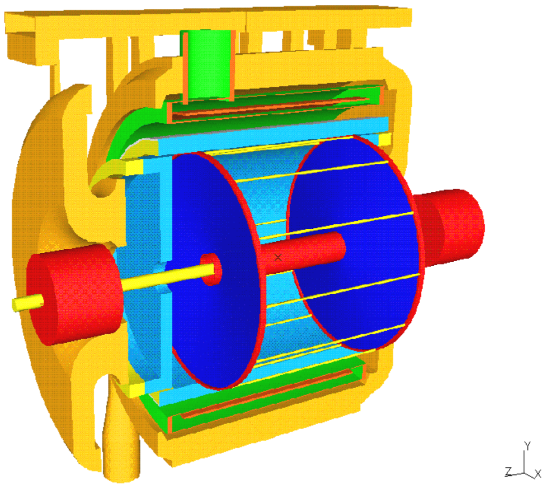
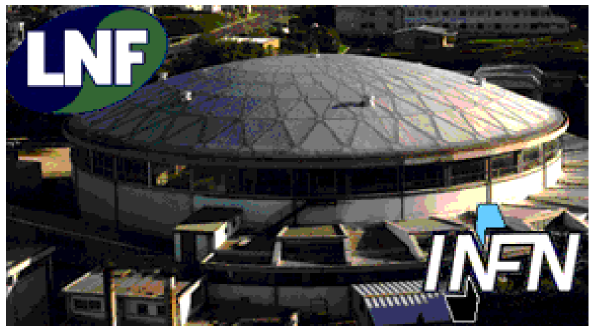
INFN - Pisa

Status report on KLOE/DAΦNE

at Frascati National Laboratory (LNF)





Frascati (ROME)

The DAΦNE machine

DAΦNE : $e^+ e^-$ collisions at

high luminosity ($L = 5 \times 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$)

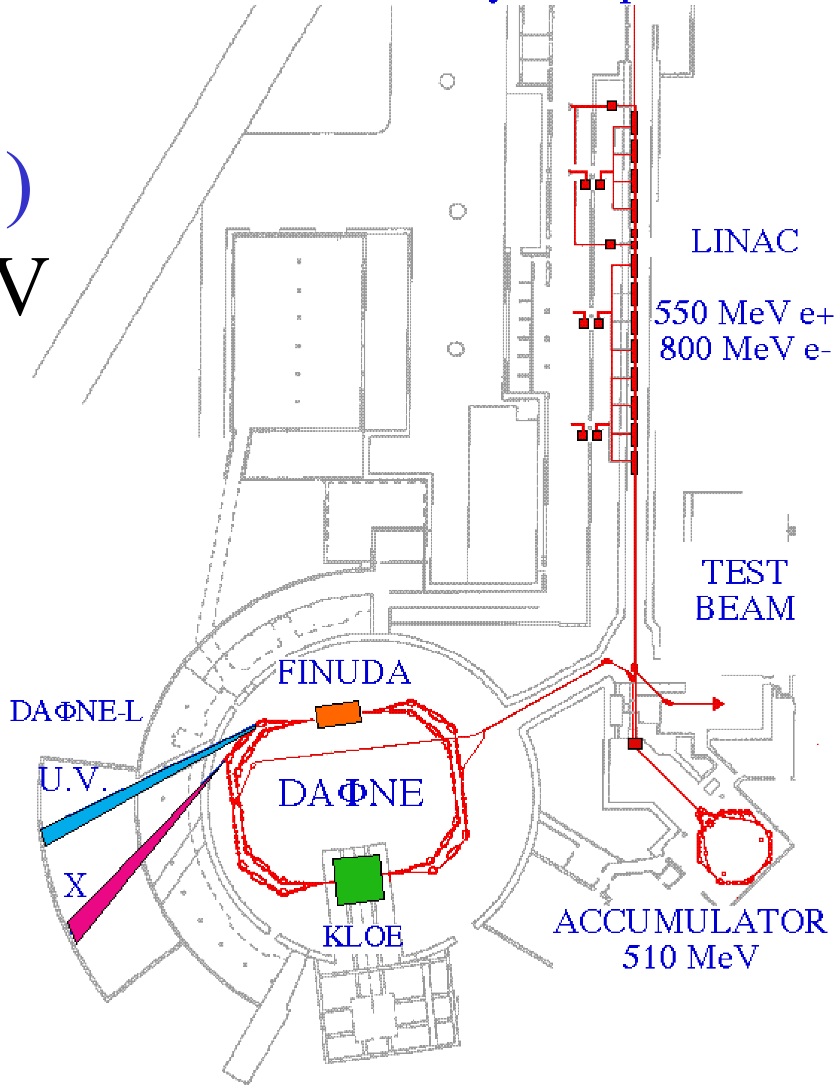
at the Φ peak : $E = M_{\Phi} = 1.02$ GeV

$\sigma(\Phi) \approx 3.3\ \mu b$

Φ decay products:

$K^+ K^-$	49.1%
$K_L K_S$	34.3%
$\rho\pi$	12.9%
$\pi^+\pi^-\pi^0$	2.5%
$\eta\gamma$	1.3%

Frascati Φ–Factory complex



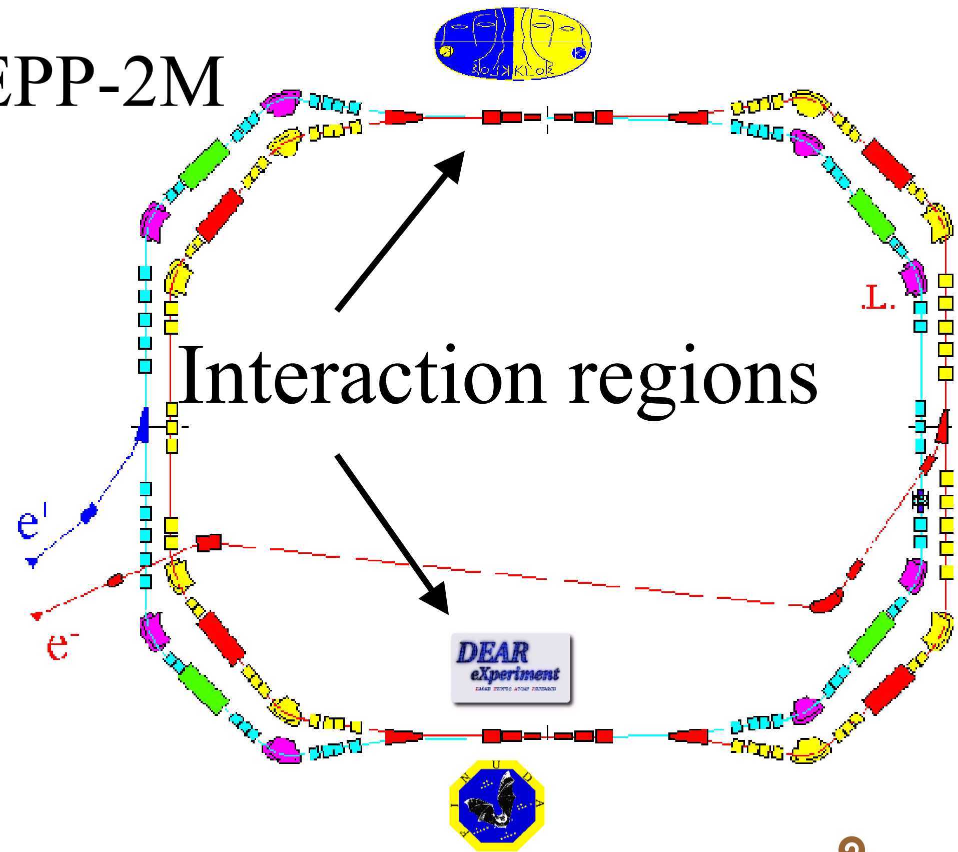
The DAΦNE machine

- 9×10^{10} particles/*single bunch*

  $L_{1b} = 1 \rightarrow 4 \times 10^{30}\ cm^{-2}s^{-1} \approx$ VEPP-2M

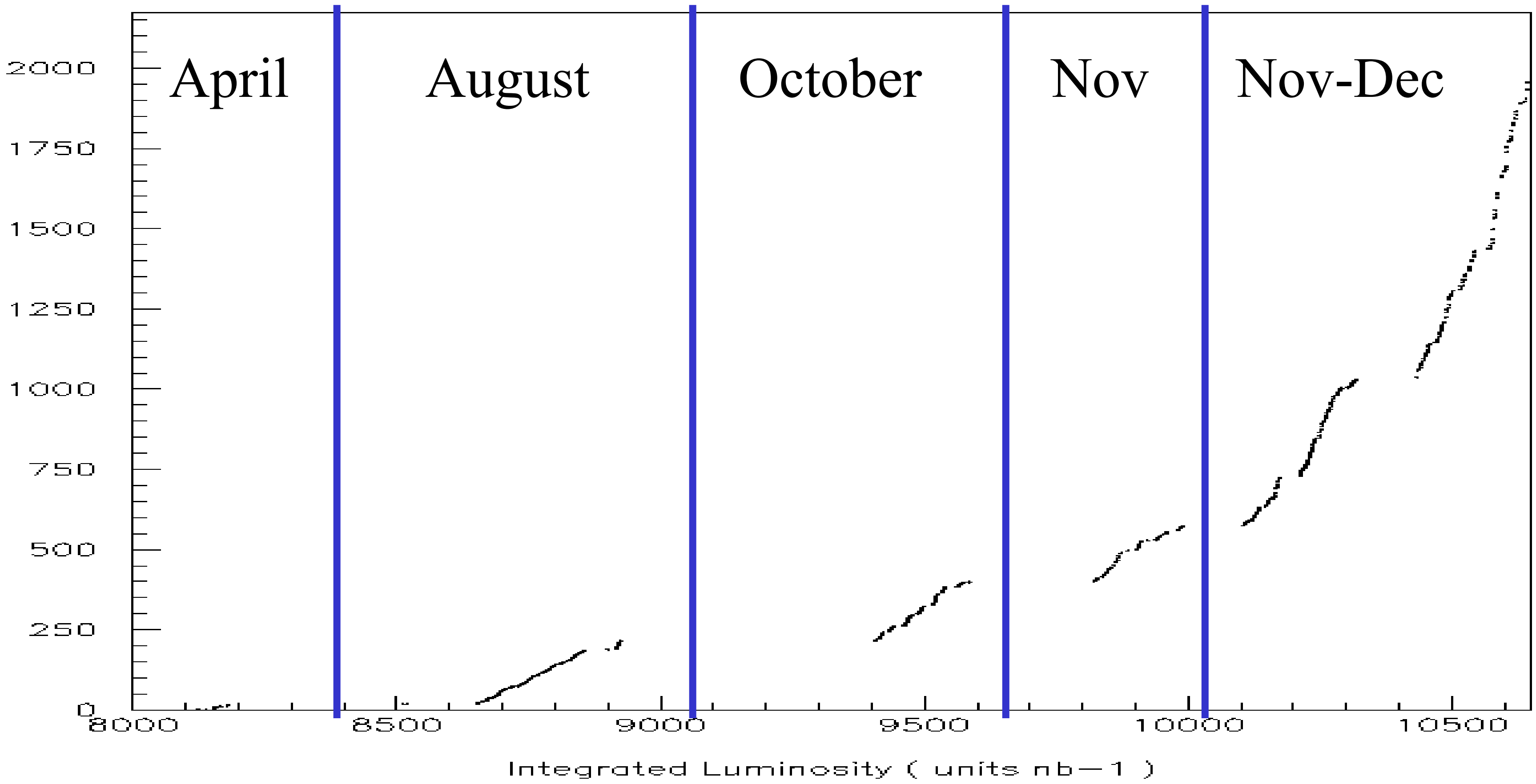
- $20 \rightarrow 120$ *bunches*
  - 5 A/beam
  - RF = 368 MHz
  - P $\approx 10^{-9}$ torr
  - 2 indipendent rings

- intersection at ≈ 25 mrad

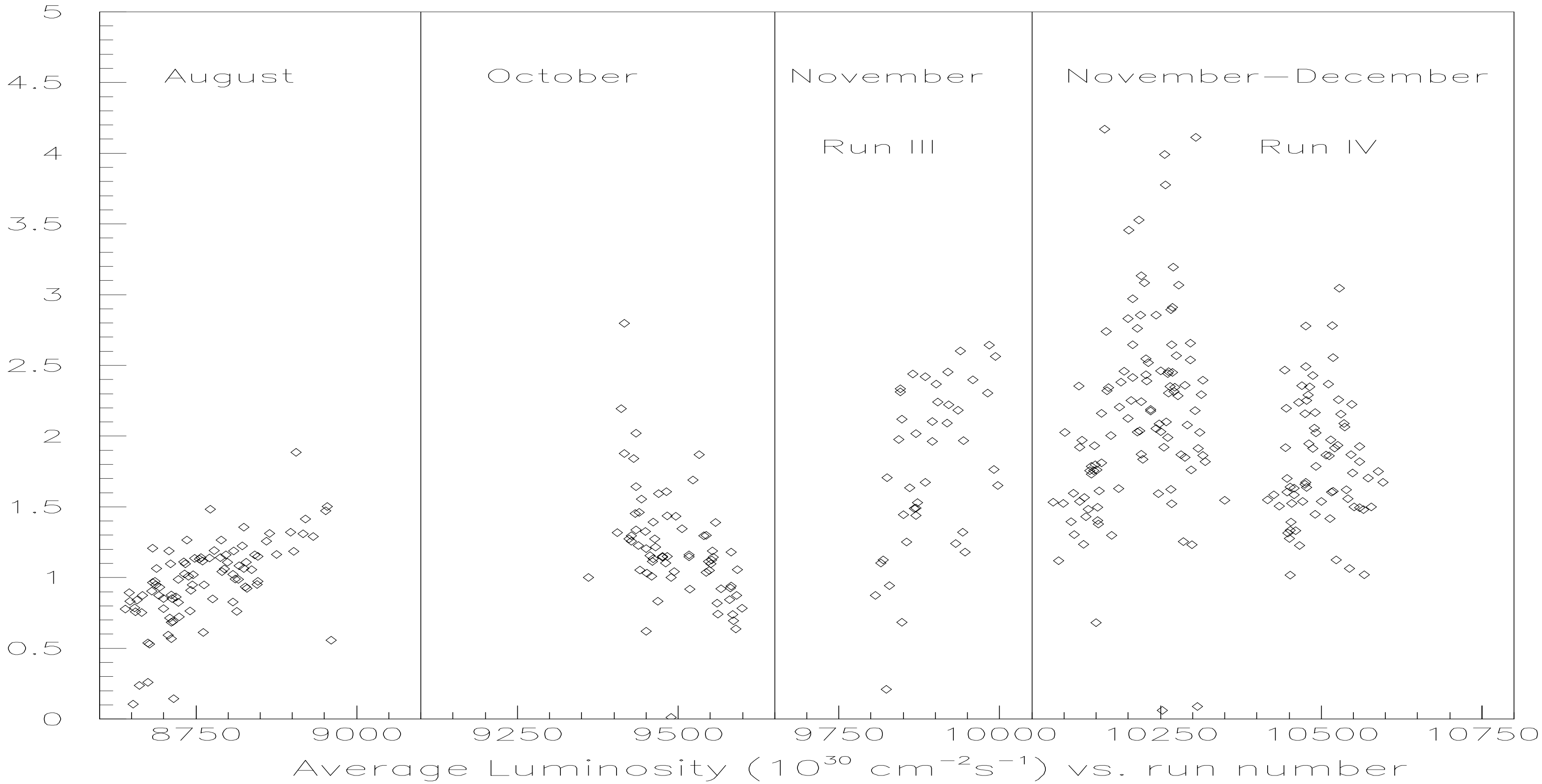


$L \sim 2 \times 10^{31} \rightarrow 4.8 \times 10^{32}\ cm^{-2}s^{-1}$

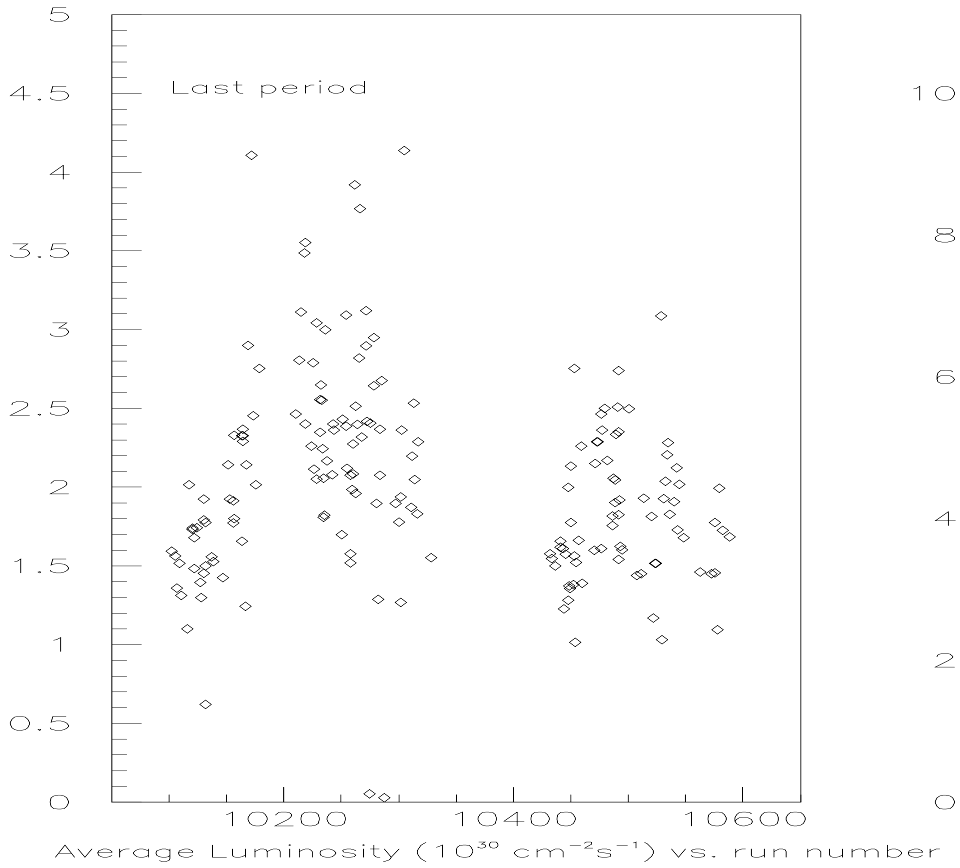
Integrated Luminosity vs. run

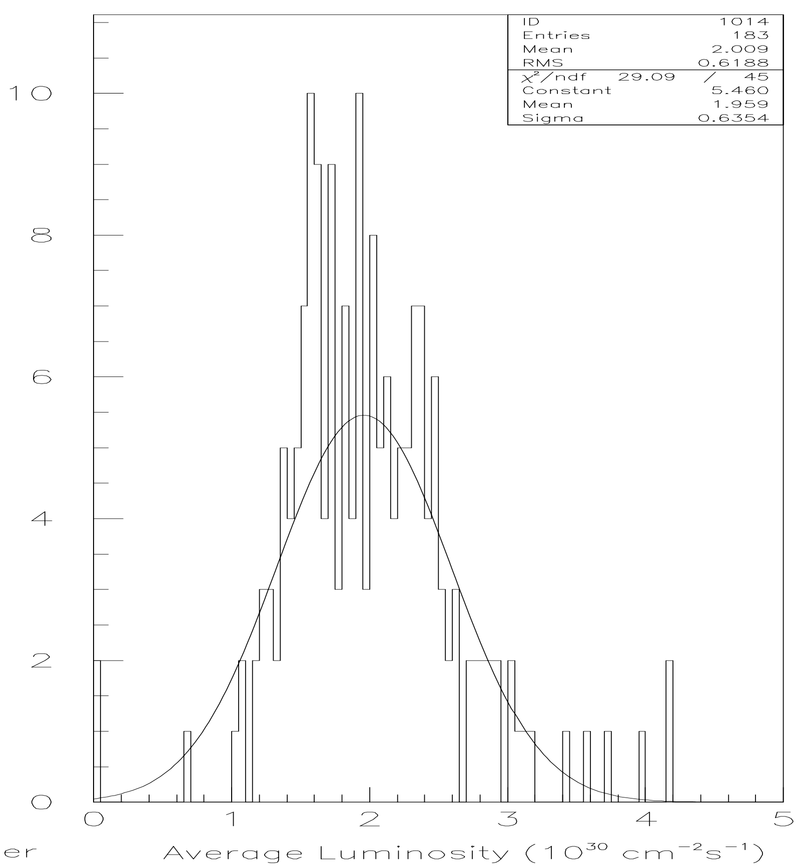


Average Luminosity per run vs. run



Average Luminosity, last period





Beam lifetimes in Nov-Dec running period

$\tau^{+} = \tau^{-} \sim$ 60 minutes in collision

τ = 180 m not colliding

τ_{Lum} = 30 m

During 20 day run: <Lum> ~ $Lum_{peak}/4$

Improvements require:

- topping up with DC on → harden DC
- topping more frequently → improve DaΦne
- raise τ^{+}, τ^{-} in collision to 180 τ_{Lum} = 90 m

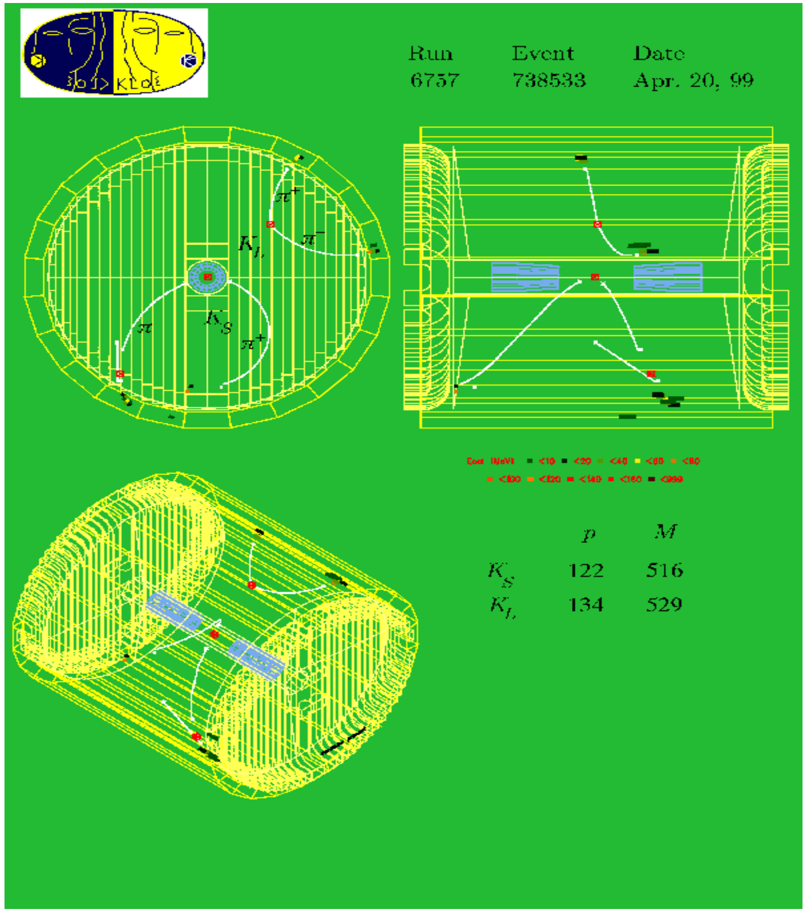
➡ Factor 2-3 easily gained

➡ **Both for KLOE and DAFNE the present running period is a very useful experience**

Kaon production at a ϕ factory

Pure and monochromatic KK beams from

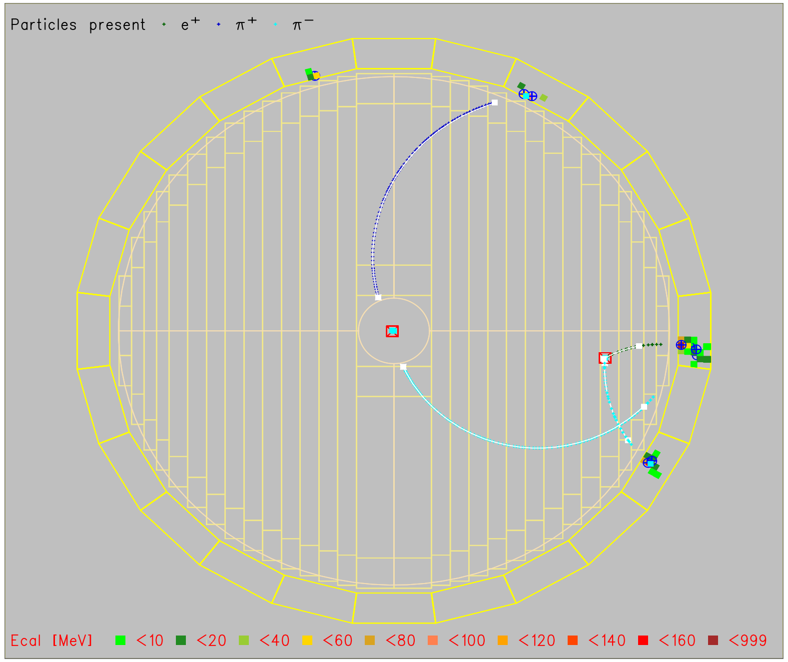
$$e^+e^- \rightarrow \phi \rightarrow \mathbf{K_S}\ \mathbf{K_L}$$

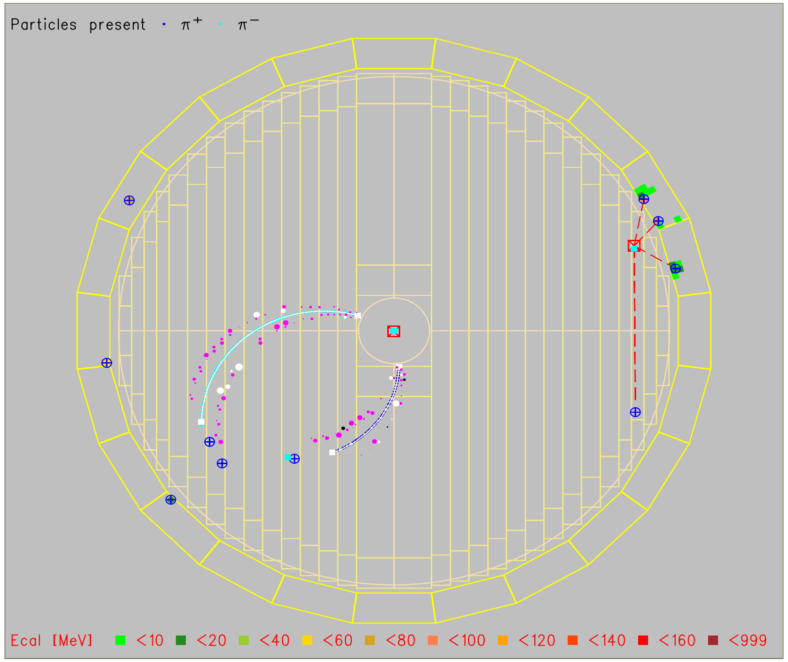


- $P_S \sim - P_L$ (ϕ boost = 13 MeV)
- M_ϕ = 1020 MeV P_K = 110 MeV/c
  - ➙ Efficient tagging
- KK pair has the ϕ quantum numbers ($J^{CP}=1^{--}$)
  - ➙ interferometric studies
- with β = 0.218
  - ➙ λ_S = 0.6 cm
  - ➙ λ_L = 340 cm

Tagging at KLOE

☛ ***KSTAG*** = identif. of a $K_L \rightarrow$ charged vertex or K_L cluster in EMC (~ indipendent from K_S decay mode)





☛ ***KLTAG*** = identif. of a $K_S \rightarrow \pi^+\pi^-$ vertex (~ indipendent from K_L decay mode)

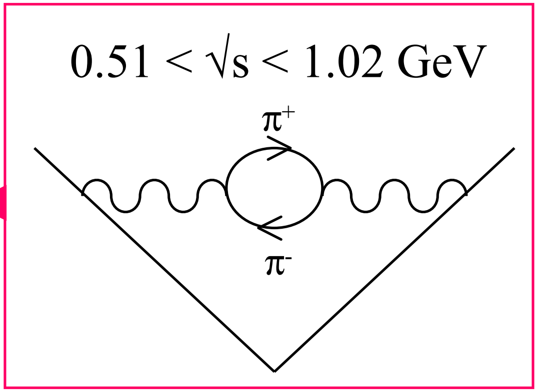
The KLOE physics program
(not only CP; not only kaons)

☛ KAON physics :

- ➥ CP violation studies (**interferometry** + **double ratio**)
- ➥ rare K_S (K_L) decays ($K_S \to \pi l \nu$, K_S (K_L) $\to \pi ee, \pi\mu\mu, \pi\nu\nu$)
- ➥ CPT limits $K_S \to \pi^+e^-\nu$ / $\pi^-e^+\nu$ vs $K_L \to \pi^+e^-\nu$ / $\pi^-e^+\nu$
- ➥ kaon form factors ($K_L \to \pi l \nu$, $K^+ \to \pi^0 l^+ \nu$)
- ➥ ...

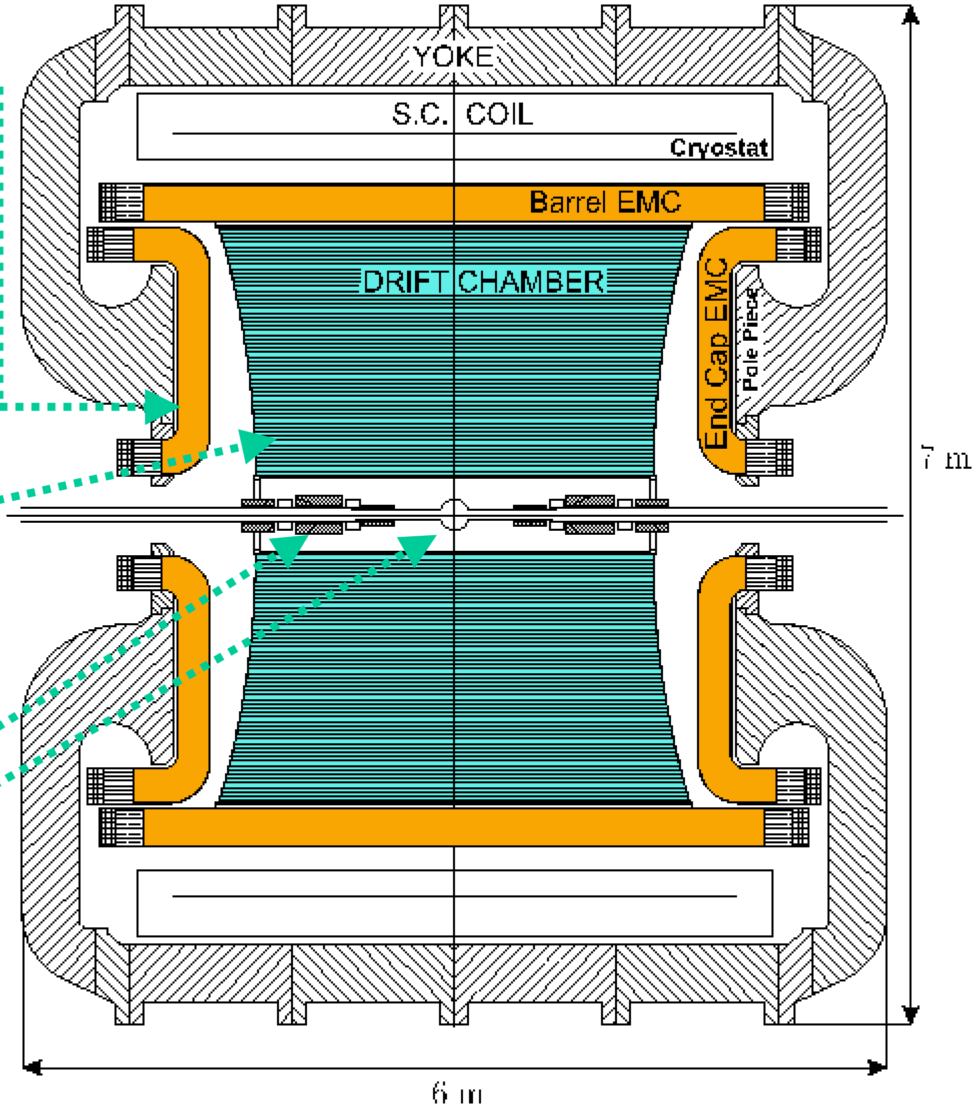
☛ NON KAON physics :

- ➥ radiative ϕ decays ($\phi \to \eta\gamma$, $\eta'\gamma$, $f^0\gamma$, $a^0\gamma$, ...)
- ➥ σ_{HAD} vs $\sqrt{s}$ ($e^+e^- \to \pi^+\pi^-$ after ISR) for g-2 predictions
- ➥ regeneration measurements at low momenta
- ➥ ...



The KLOE apparatus

- ***Lead - Scintillating fibers* calorimeter**
  - excellent resolution to reconstruct K_L neutral vertex with ToF technique
  - must detect photons down to 20 MeV
  - hermetic coverage to discriminate between $K_L \rightarrow 2\pi^0$ and $K_L \rightarrow 3\pi^0$ events
- ***Helium* Drift Chamber**
  - large volume for K_L decays
  - transparency (8mm *C-fiber* walls < 0.1 X_0)
- **Two quadrupole calorimeters**
  - to avoid γ losses in $K_L \rightarrow 3\pi^0$ events
- **Beryllium beam pipe**
  - sphere with radius 10 cm (~16 λ_S)



Interferometric measurements at KLOE

☛ The KK pair is produced in a well defined quantum state $J^{PC}=1^{--}$:

$$f_1 \xleftarrow[K_S,K_L]{t_1} \Phi \xrightarrow[K_L,K_S]{t_2} f_2 \qquad \Delta t = t_1 - t_2$$

☛ The probability of observing final states f_1, f_2 as a function of Δt is:

$$I(f_1, f_2, \Delta t) = \frac{1}{2\Gamma}\,|\langle f_1|K_s\rangle\langle f_2|K_s\rangle|^2 \times$$

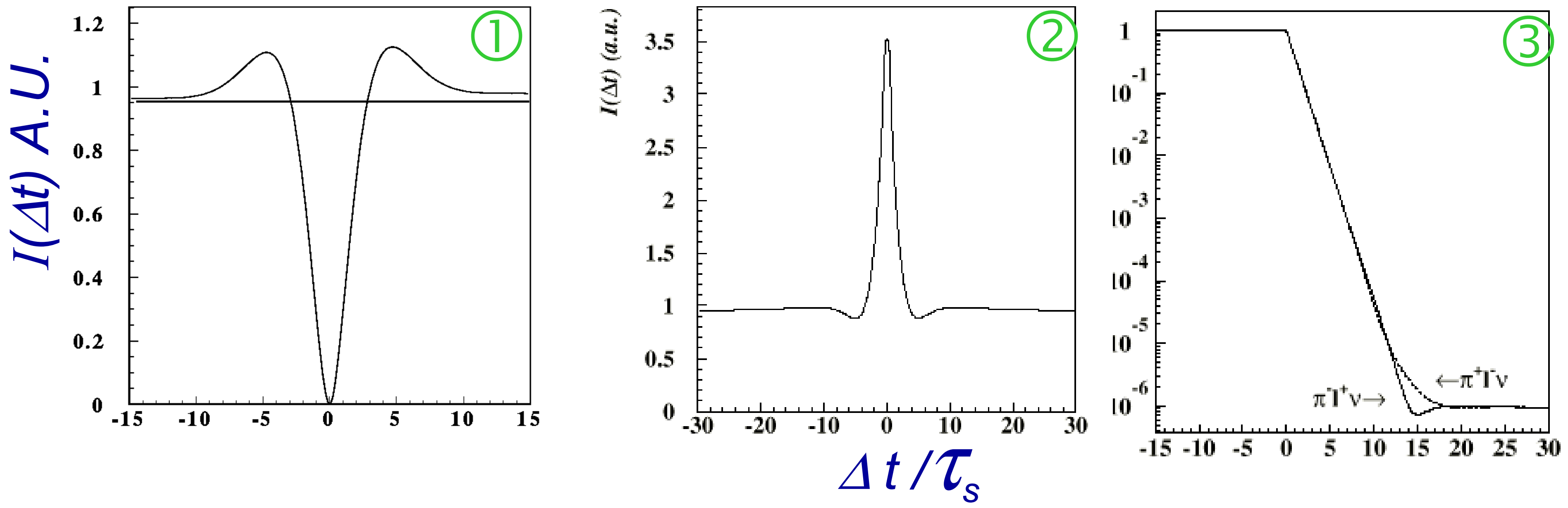
$$\left[|\eta_1|^2 e^{-\Gamma_L \Delta t} + |\eta_2|^2 e^{-\Gamma_S \Delta t} - 2|\eta_1||\eta_2| e^{-\Gamma \Delta t/2} \cos(\Delta m\, \Delta t + \Delta\varphi)\right]$$

$$\frac{\langle f_i | K_L \rangle}{\langle f_i | K_S \rangle} = \eta_i\, e^{i\varphi_i} \qquad \Delta m = M_L - M_S \qquad \Delta\varphi = \varphi_1 - \varphi_2$$

Interferometric measurements at KLOE

Informations on KAON system parameters from:

- ✓ identical final states → Δm Γ_S Γ_L
- ✓ $\pi^+\pi^-$, $\pi^0\pi^0$ ① → $\Re(\varepsilon'/\varepsilon)$ $\Im(\varepsilon'/\varepsilon)$
- ✓ $\pi^+ \ ^-\nu$, $\pi^- \ ^+\nu$ ② → $\Re(\delta_{CPT})$ $\Im(\delta_{CPT})$
- ✓ $\pi \quad \nu$, $\pi\pi$ ③ → T and CPT, Δm, $|\eta_{\pi\pi}|$, $\varphi_{\pi\pi}$



Double ratio

KLOE aims to **O(10 $^{-4}$)** accuracy in direct **CP** violation detection through the double ratio:

$$\mathbf{R} = \frac{BR(K_L \to \pi^+\pi^-)/BR(K_S \to \pi^+\pi^-)}{BR(K_L \to \pi^0\pi^0)/BR(K_S \to \pi^0\pi^0)} = 1 + 6\Re(\varepsilon'/\varepsilon)$$

Experimentally:

$$N^{obs} = Bkg_{L,S}^{\pm,0} + N_{KK} \times \varepsilon_{L,S}^{tag} \times BR_{L,S}^{\pm,0} \times \left\langle \varepsilon_{L,S}^{\pm,0} \right\rangle \times {}_{FV}\, g(\mathbf{l} - \mathbf{l}')I(\mathbf{l})d\mathbf{l}d\mathbf{l}'$$

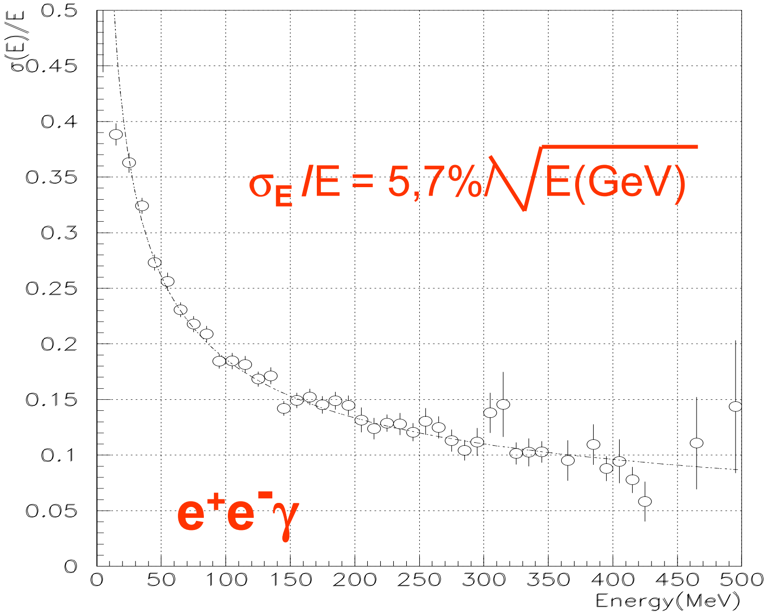
- **N_{KK} = $\boldsymbol{L}_{int} \times \sigma_\phi \times BR(\phi \to K_S K_L)$** and **$\varepsilon_{L,S}{}^{tag}$** drop out identically in the double ratio
- Trigger and reconstruction efficiencies, geometric acceptance and background contamination have to be checked at the level of few 10^{-4}

Statistics : ~ 2 years of data taking @ $L = 5 \times 10^{32} cm^{-2} s^{-1}$ ($4 \times 10^{10} \phi$)

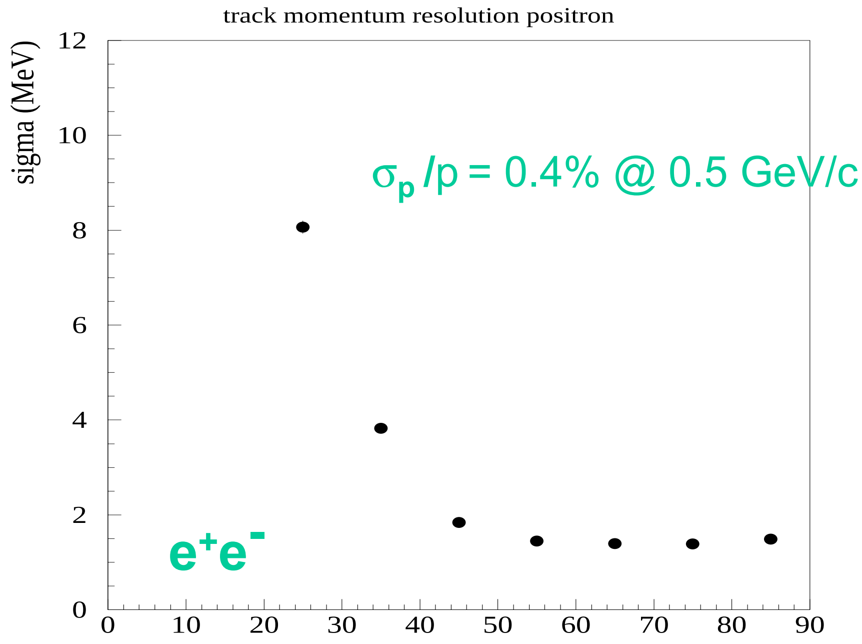
Backgrounds

Signal	Bkg	rel BR	
$K_L \to 2\pi^0$	$K_L \to 3\pi^0$	230	(1)
$K_L \to \pi^+\pi^-$	$K_L \to \pi\mu\nu$	130	(2)

1. **EMC coverage ~ 98% + low energy γ eff. + good resolution**



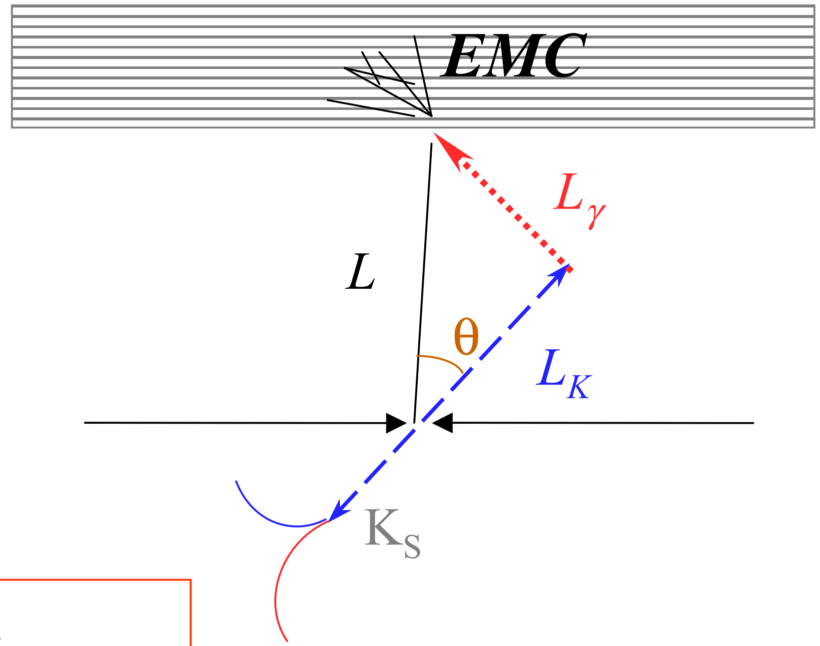
2. **DC: good momentum resolution (+EMC $\pi\mu$ separation)**



Reconstruction of the K_L neutral vertex

Given the K_L flight direction from the K_S momentum balance, the K_L decay vertex is determined from the total time of flight $t_K + t_\gamma$:

$$\begin{cases} L_\gamma^2 = L^2 + L_K^2 - 2LL_K \cos\vartheta \\ ct = L_K / \beta_K + L_\gamma \end{cases}$$



- weighted average over all γ's
- δL_K = 0.5 cm with 4 γ's and

  $\sigma_t = 55\ \text{ps} / \sqrt{E(\text{GeV})}$

Measured σ_t from γγ events

$\sigma_t = 74\ \text{ps} / \sqrt{E(\text{GeV})}$

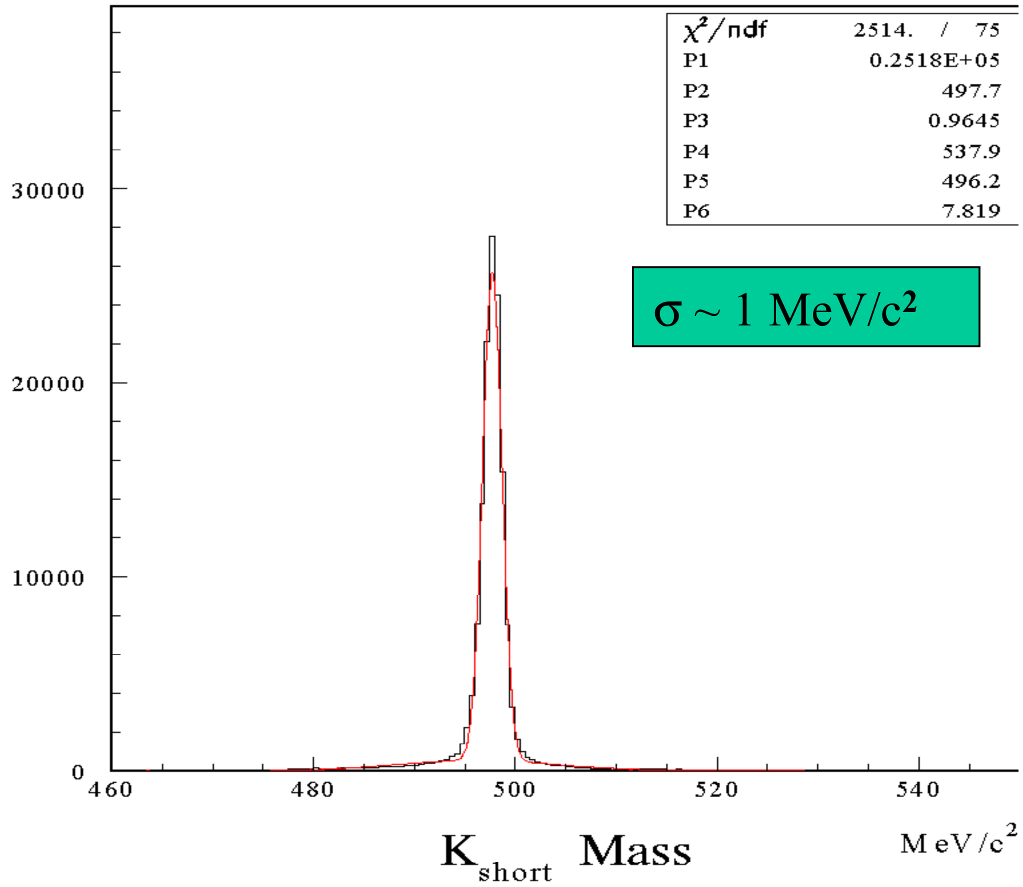
K_L *tag* with $K_S \to \pi^+\pi^-$ *signal*

Expected: $N_\phi \cdot BR(\phi \to K_S K_L, K_S \to \pi^+\pi^-) \cdot \varepsilon_{trig}(data) \cdot \varepsilon_{rec}(MC) =$ 179000

What we get : $N(K_S \to \pi^+\pi^-) =$ 170000

selection criteria:

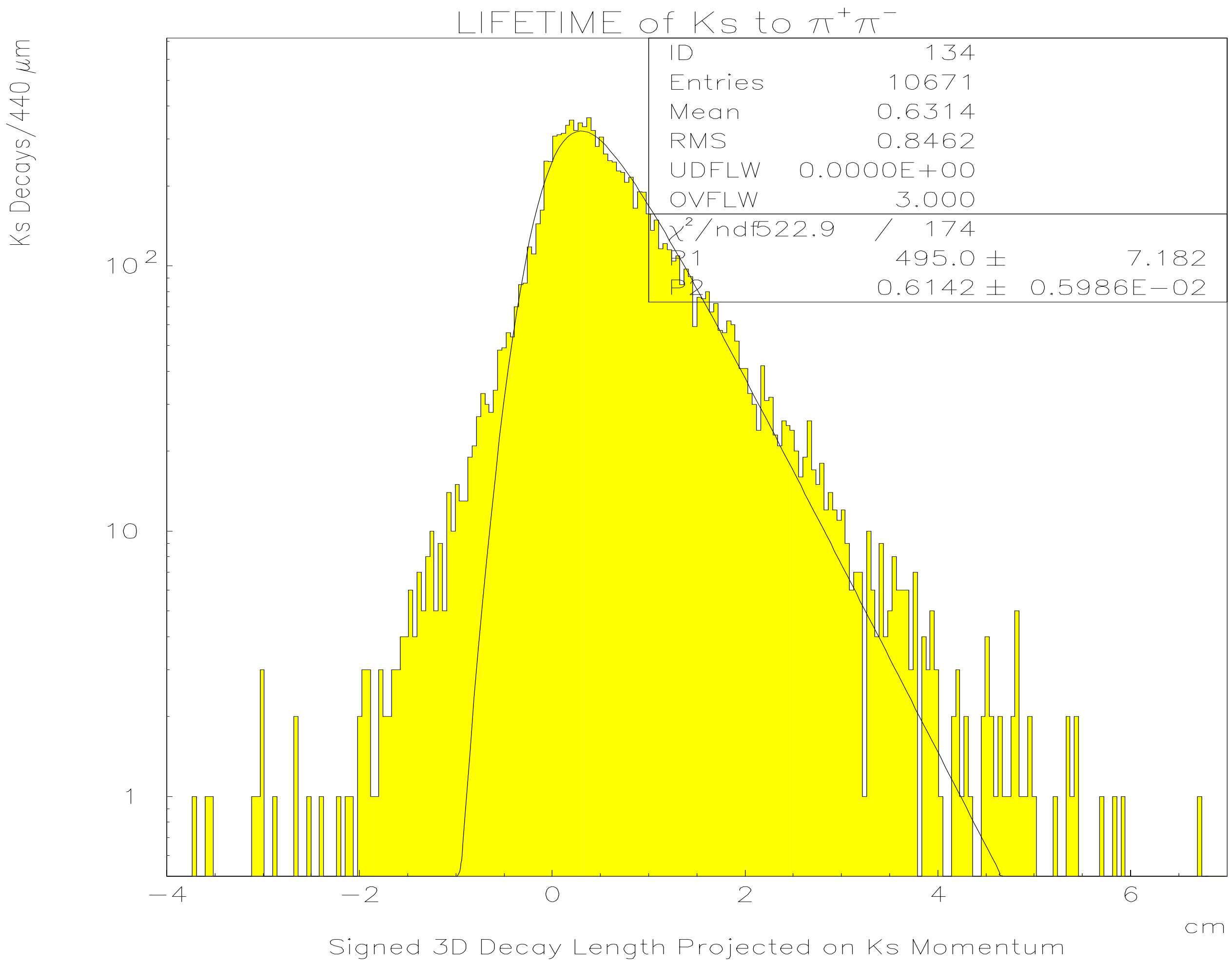
- 1 vertex with ***r*** < 5 cm from I.P.
- 2 opposite charged tracks connected
- 50 < P_{TOT} < 170 MeV/c
- 400 < M_{INV} < 600 MeV/c²



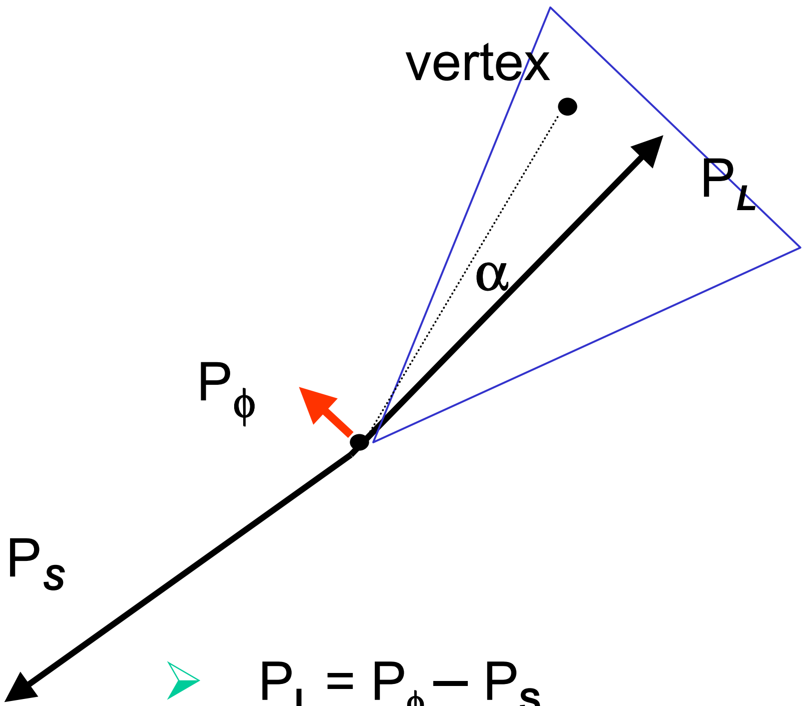
$K_S \rightarrow \pi^+ \pi^-$: lifetime

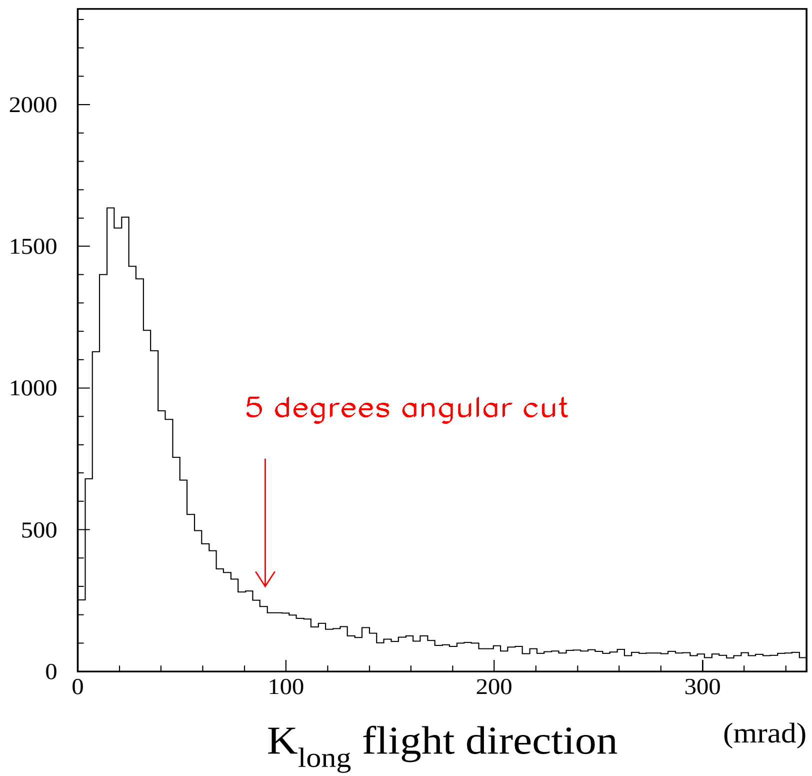
$\lambda_S = 6.1 \pm 0.6$ mm

Decay length distribution unfolded using the measured vertexing accuracy



K_L charged decay: selection

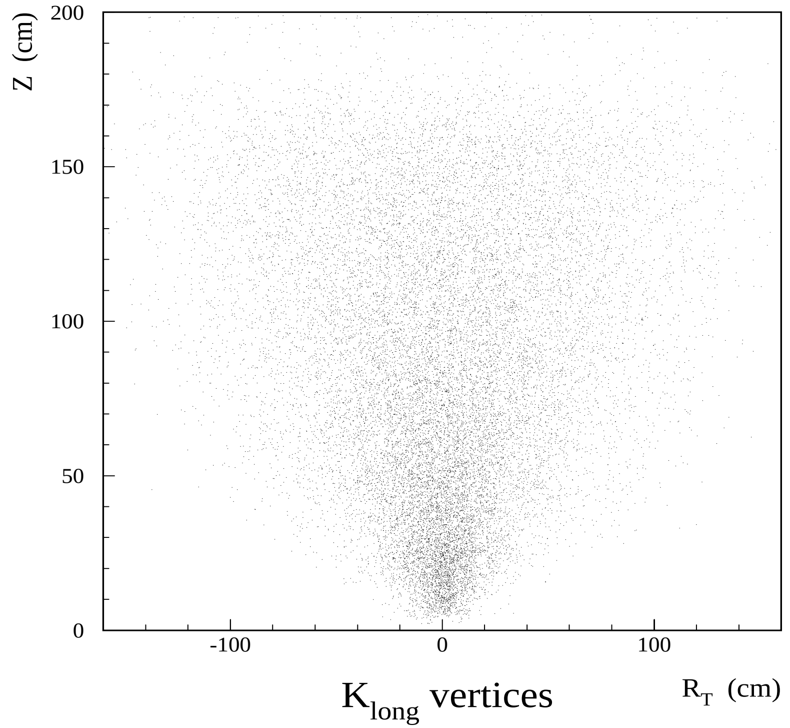


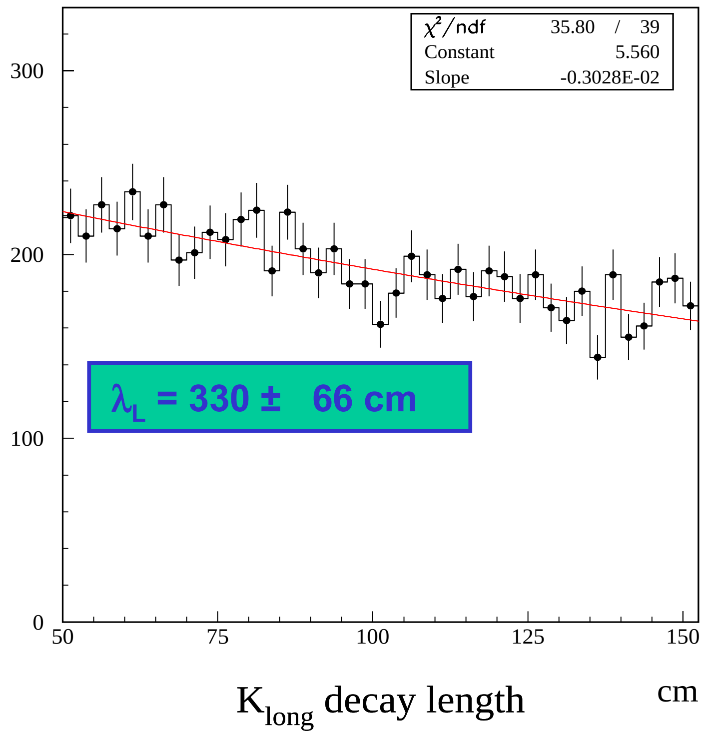


- $P_L = P_\phi - P_S$
- primary vertex = K_S flight direction @ y = 0
- 1 vertex in a 5^o cone with r > 5 cm

K_L charged decay: lifetime

20000 charged vertices with r > 5 cm



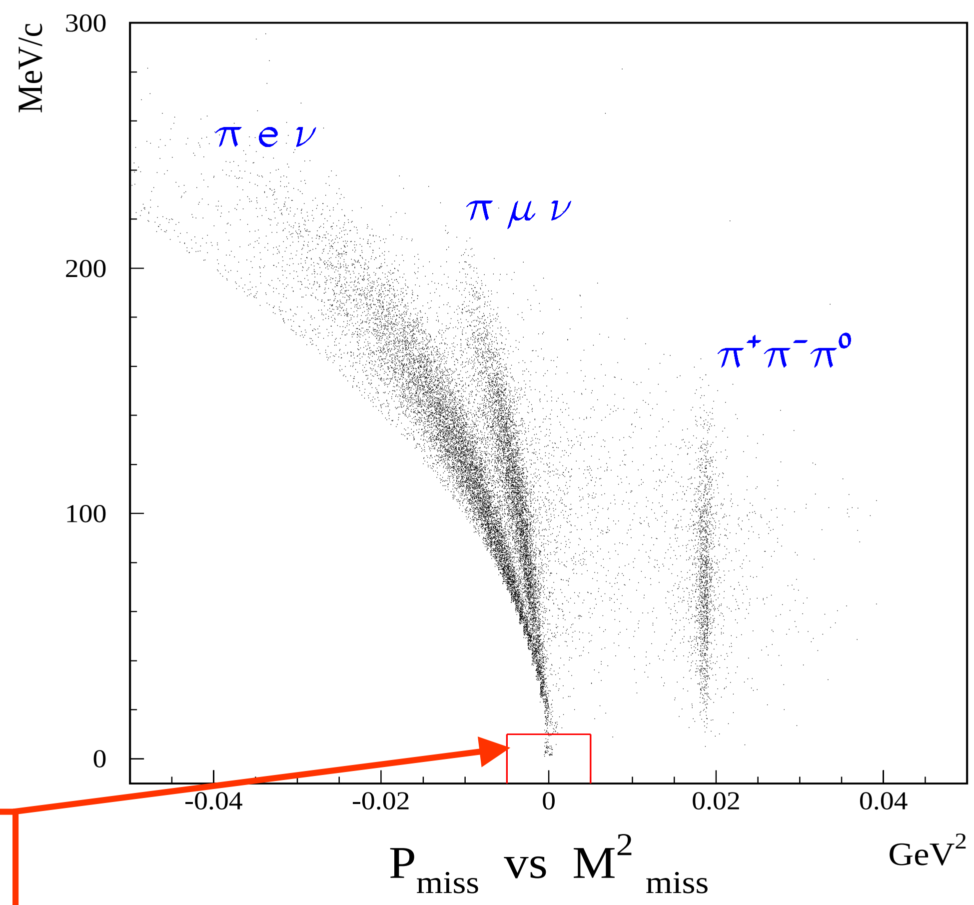


K_L charged decay: K_{l3} vs $\pi^+\pi^-\pi^0$

P_L and charged tracks momenta are used to build P_{miss} and M^2_{miss}

$M^2_{miss} =$
- $\to 0$ $(K_L \quad \pi^+\pi^-)$
- $\to < 0$ $(K_{l3}$, in $\pi\pi$ hyp$)$
- $\to m_\pi^2$ $(K_L \quad \pi^+\pi^-\pi^0)$

If the $\pi\pi$ hypothesis is used in the M^2_{miss} computation, we get a negative value for semileptonic decays.



CP violation region
$P_{miss} = M^2_{miss} = 0$

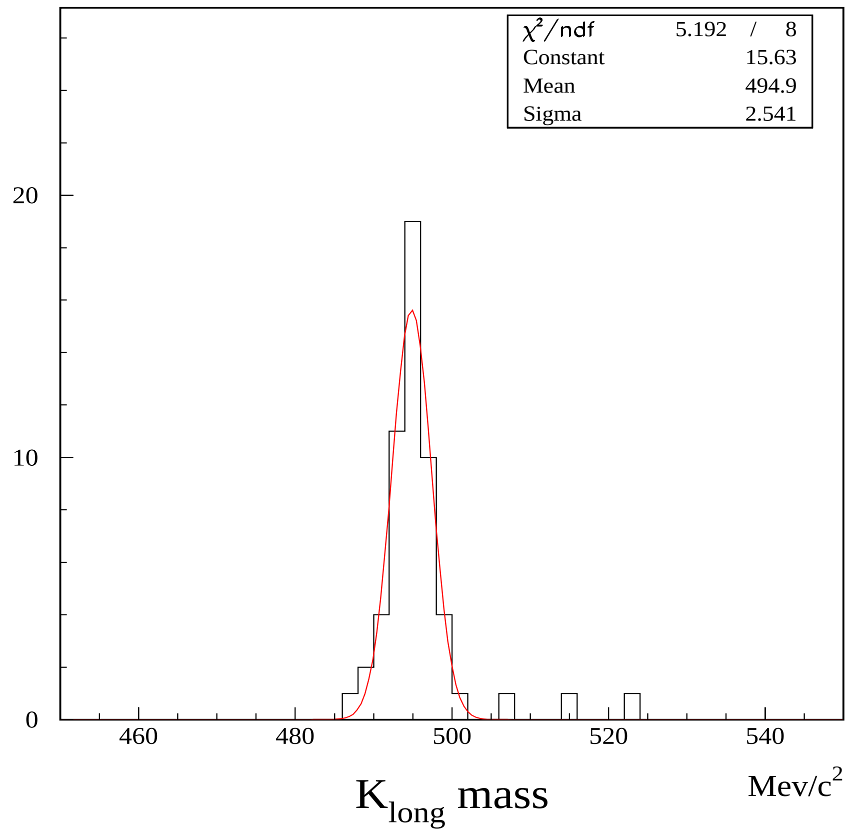
CP violation signal : 1

- P_{miss} < 10 MeV/c
- $|M_{miss}(\pi\pi)|$ < 70 MeV

55 events selected

(52 expected in the hypothesis of equal efficiencies for all charged vertices)

The cut on M_{miss} is very loose but the signal has a narrow peak ~ 2.5 MeV



K_L charged decay: K_{l3} vs $K_L^{2\pi}$ (1)

For semileptonic decays and $\pi^+\pi^-$ events ($\pi^+\pi^-\pi^0$ ruled out by a cut on M^2_{miss}) we can impose directly:

$$M^2_{miss}\,(m_x, m_\pi, P_L, p_1, p_2) = 0$$

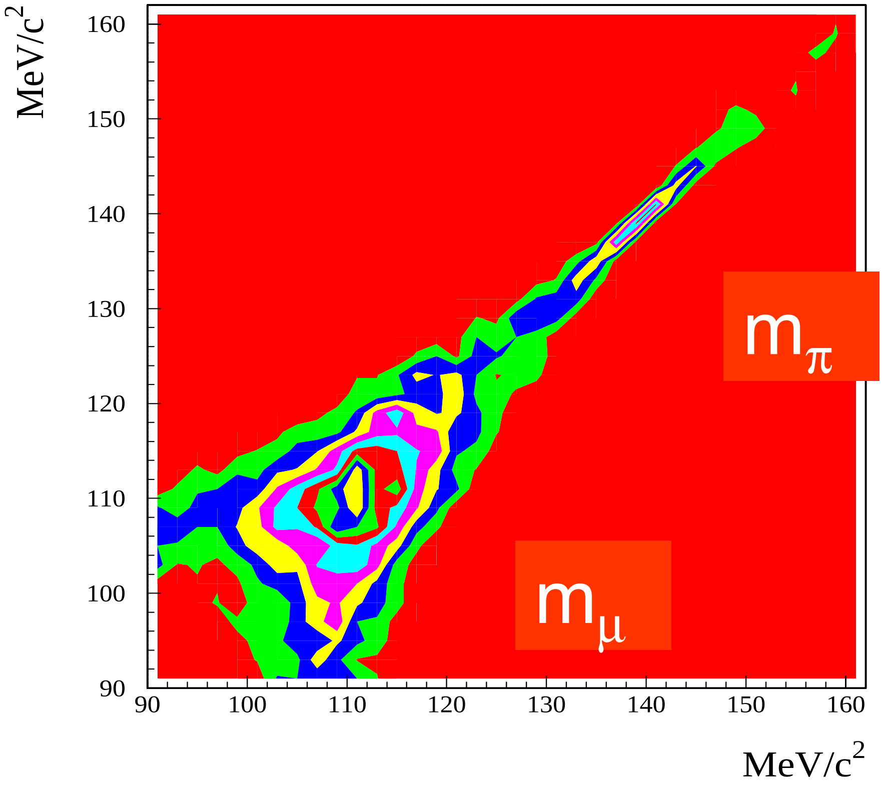
Two solutions (m_{x1} or m_{x2}) are calculated for m_x trying the π hypothesis on both the charged momenta; one of the two solutions should give:

m_x → m_e if K_{e3}

m_x → m_μ if $K_{\mu3}$

m_x → m_π if $\pi^+\pi^-$

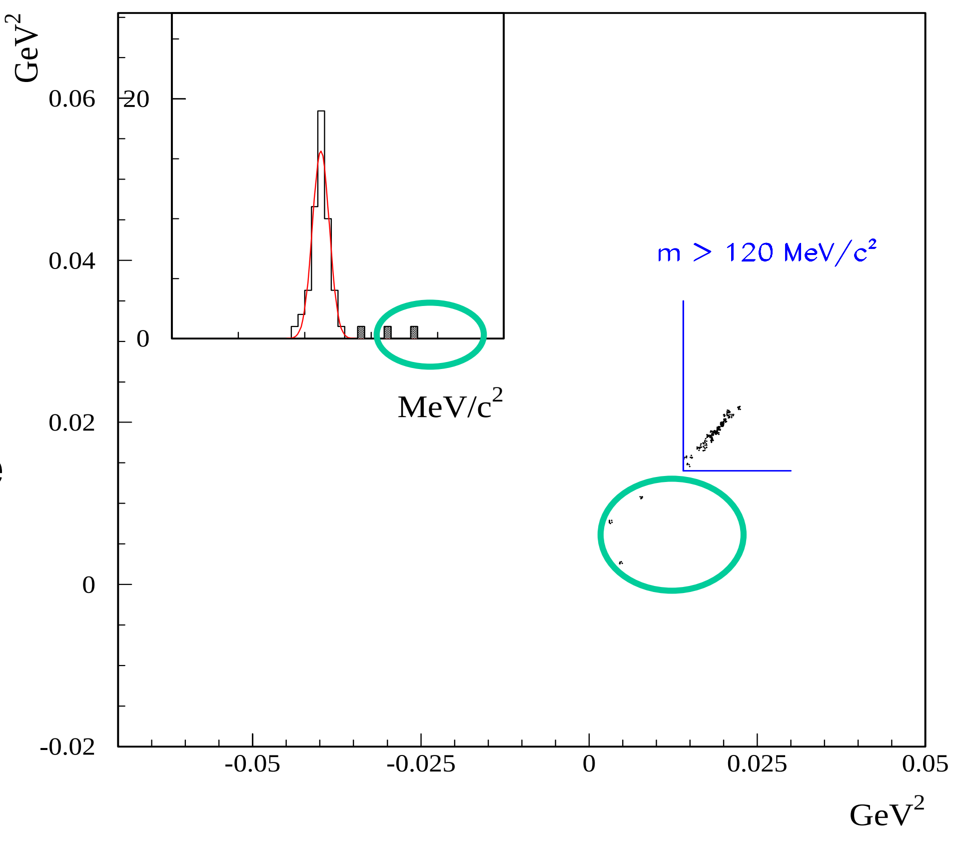
m_{x1} vs m_{x2}



K_L charged decay: K_{l3} vs $K_L^{2\pi}$ (2)

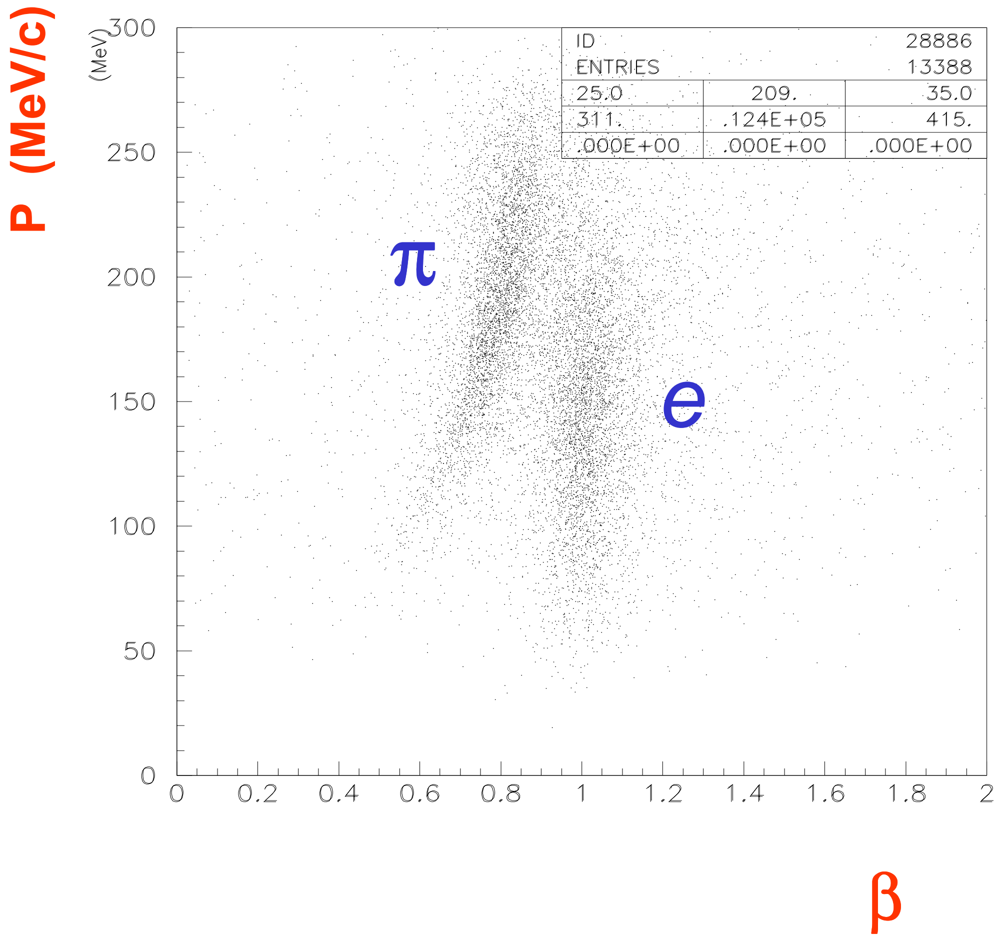
- Applying the mass calculation to the 2π events selected with the cut on P_{miss} and $M^2_{miss}(\pi\pi)$ results in a slightly better background rejection power.
- This is because, in the π hypothesis, the missing mass and the missing momentum, for semileptonic decays, partly overlap the signal region at (P_{miss}, M_{miss}) ~ (0,0)

m_{x1} vs m_{x2}



K_{e3} decay: momentum vs β

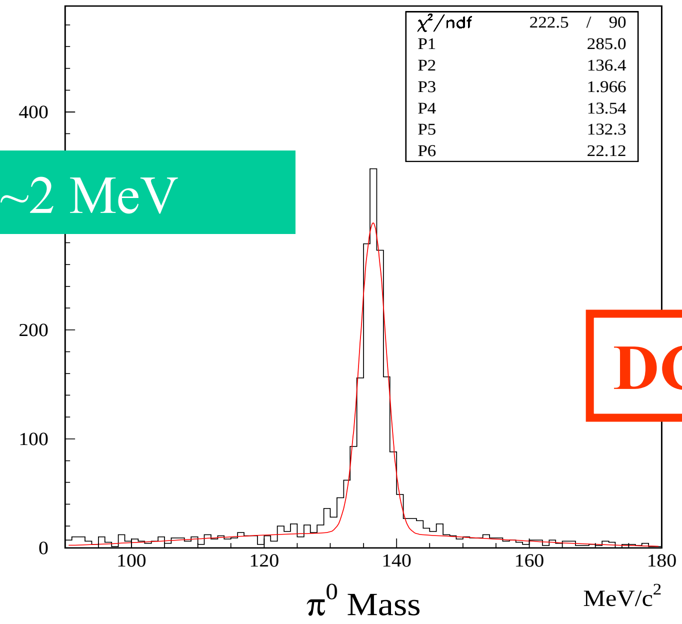
Calorimeter ToF can greatly help in discriminating between pions end leptons, representing an independent constraint to select a clean sample of 2π   events.



K_L charged decays: $\pi^+\pi^-\pi^0$

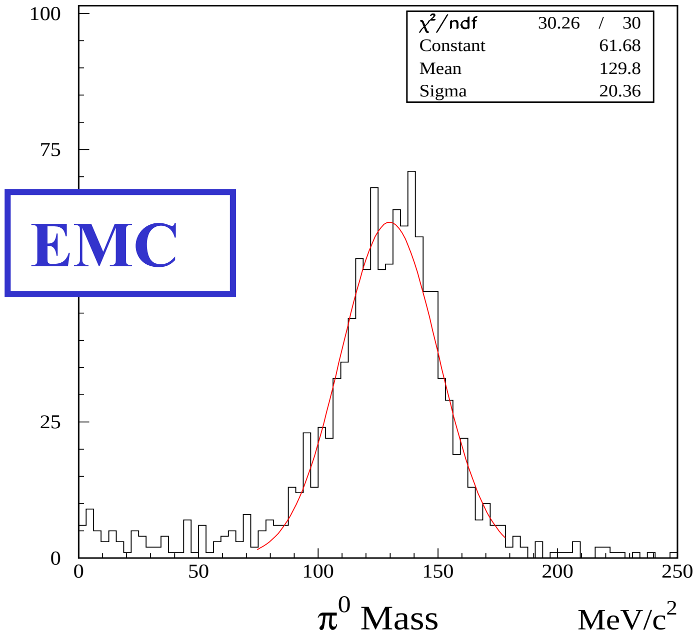
The π^0 peak is easily isolated from K_{l3} in the the M_{miss} distribution

σ~20 MeV



σ~2 MeV

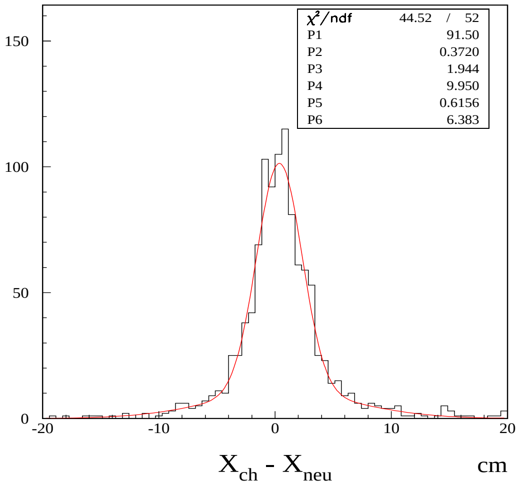
DC

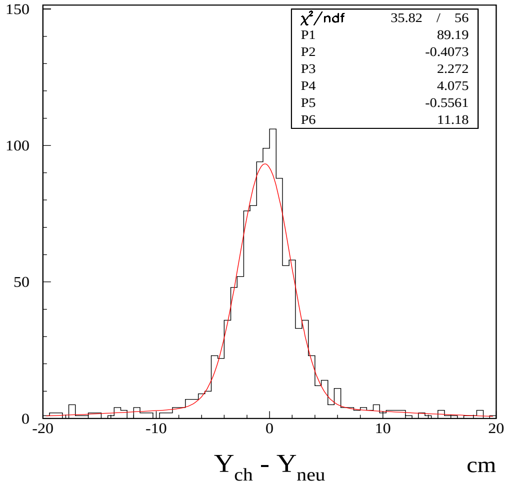


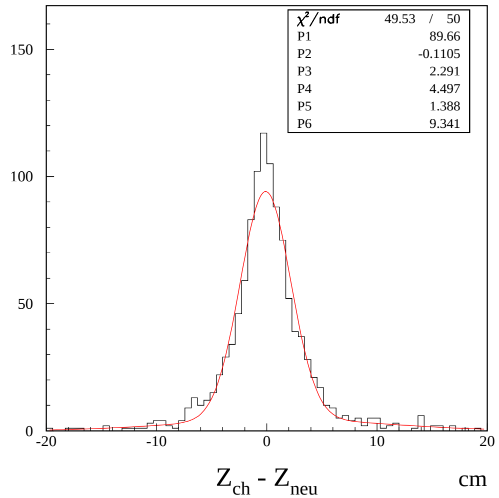
EMC

The π^0 signal is present also in the M_{inv} from the 2γ in EMC

$K_L \to \pi^+\pi^-\pi^0$: charged vs neutral vertex







$<\Delta x> \sim$ 4 mm	$\sigma_x \sim$ 1.9 cm
$<\Delta y> \sim$ - 4 mm	$\sigma_y \sim$ 2.3 cm
$<\Delta z> \sim$ - 1 mm	$\sigma_z \sim$ 2.3 cm

Worse neutral vertex resolution because:

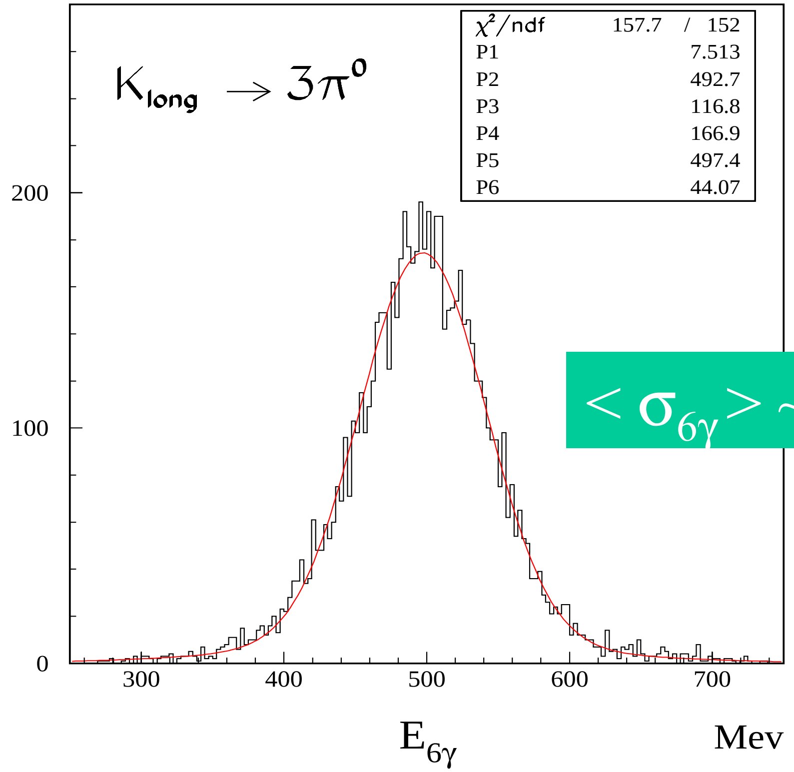
- in $K_L \to \pi^+\pi^-\pi^0$ there are less γ than in $K_L \to \pi^0\pi^0$
- γ energy in $K_L \to \pi^+\pi^-\pi^0$ is lower than in $K_L \to \pi^0\pi^0$

K_L neutral decay: $\pi^0\pi^0\pi^0$

- Selected neutral decays with 6 clusters in EMC

- The total energy of the 6 γ's is measured with the expected 10% resolution.

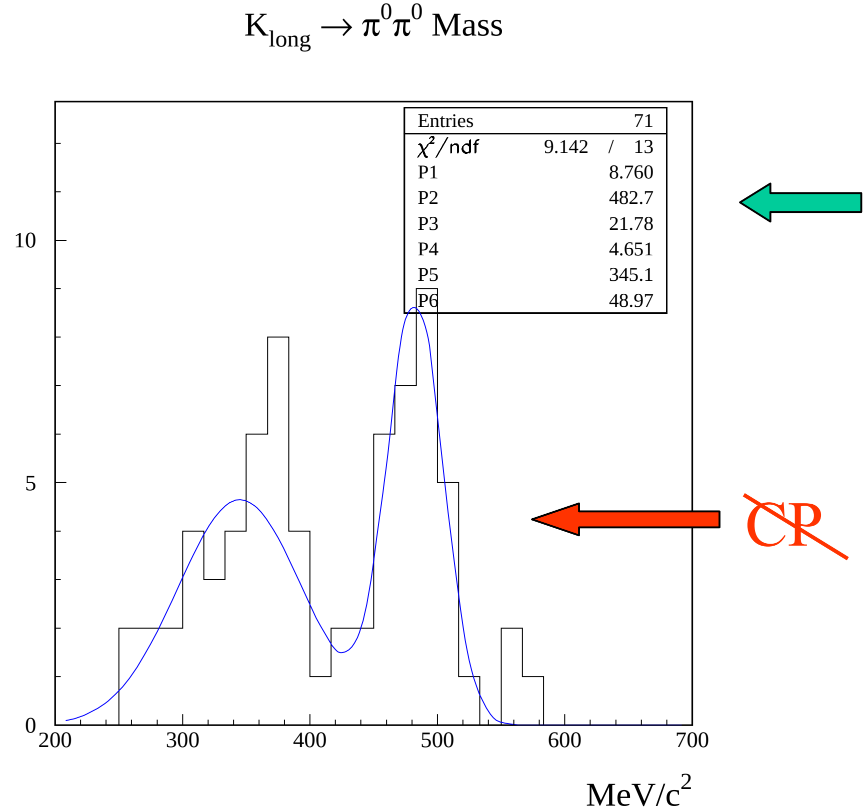
- Calibration of the mean value is still in progress



$< \sigma_{6\gamma} > \sim 44$ MeV

CP violation signal : 2

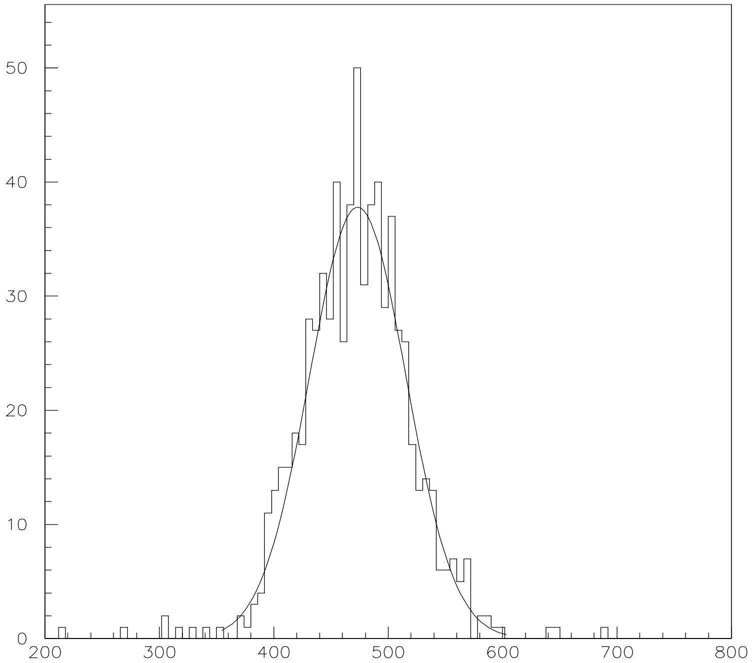
- Selected neutral K_L decays with 4 EMC clusters.
- Loose collinearity cut between the K_L flight path and the momentum of the $\pi^0\pi^0$ system
- Cut on the two π^0 invariant mass reconstructed



K_S neutral decay: $\pi^0\pi^0$

$M_{inv}(4\gamma)$ = 475 MeV

σ_{Minv} = 42 MeV



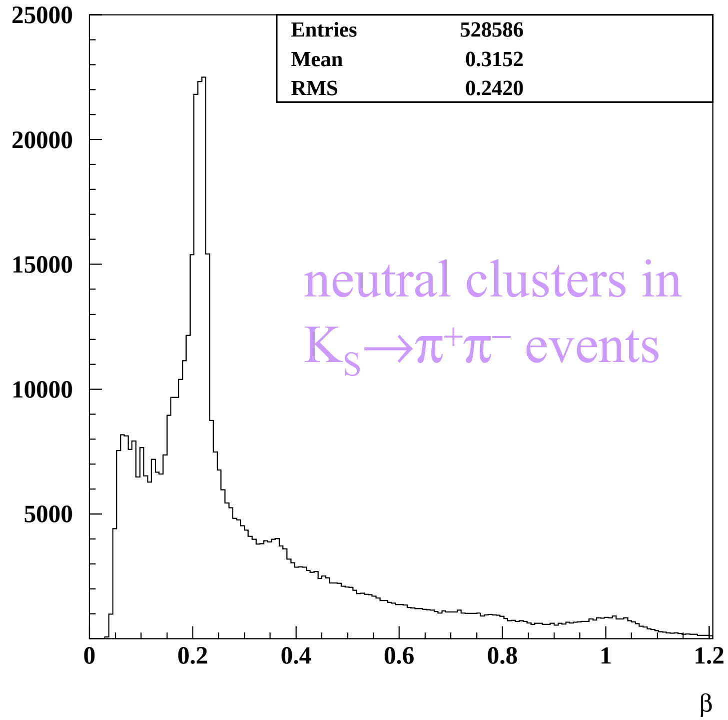
MeV/c²

Selection algorithm

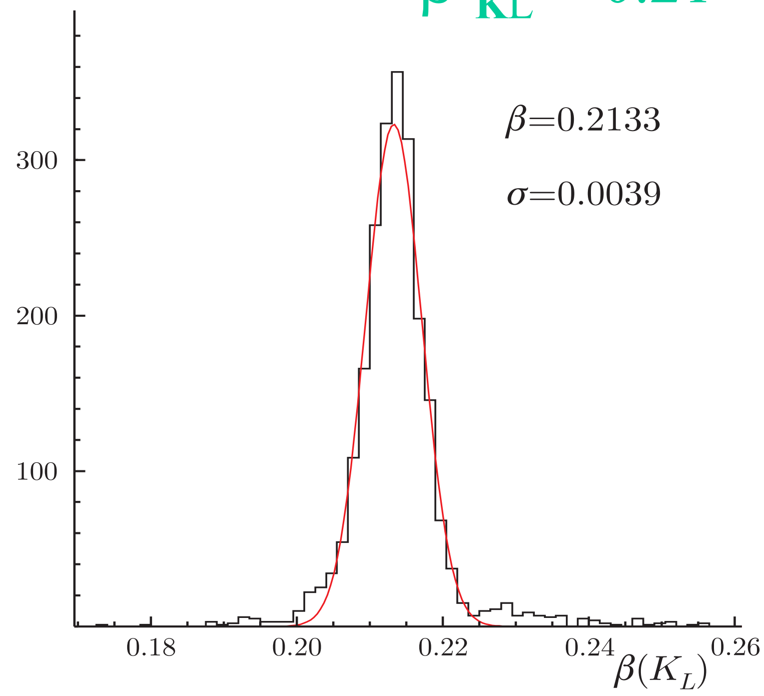
- 4 prompt photons $(0.9 < \beta < 1.2)$
- no tracks associated
- $\theta > 21°$ (machine bkg rejection)
- $390 < M_{inv} < 600$ MeV/c^2

low background contamination on real data ($\cong$1%)

K_L crash events



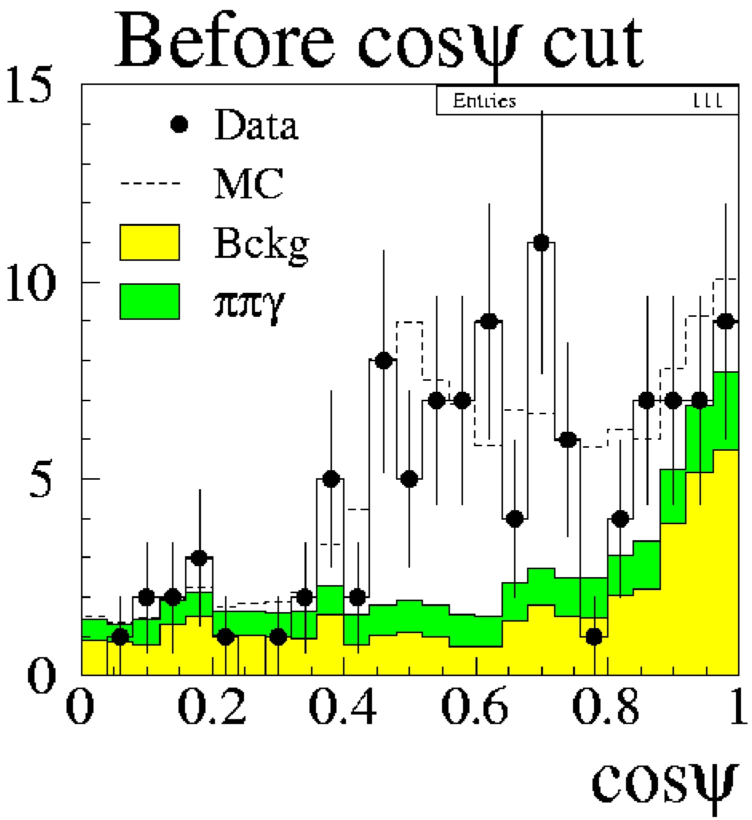
$\beta^*_{KL} = 0.21$

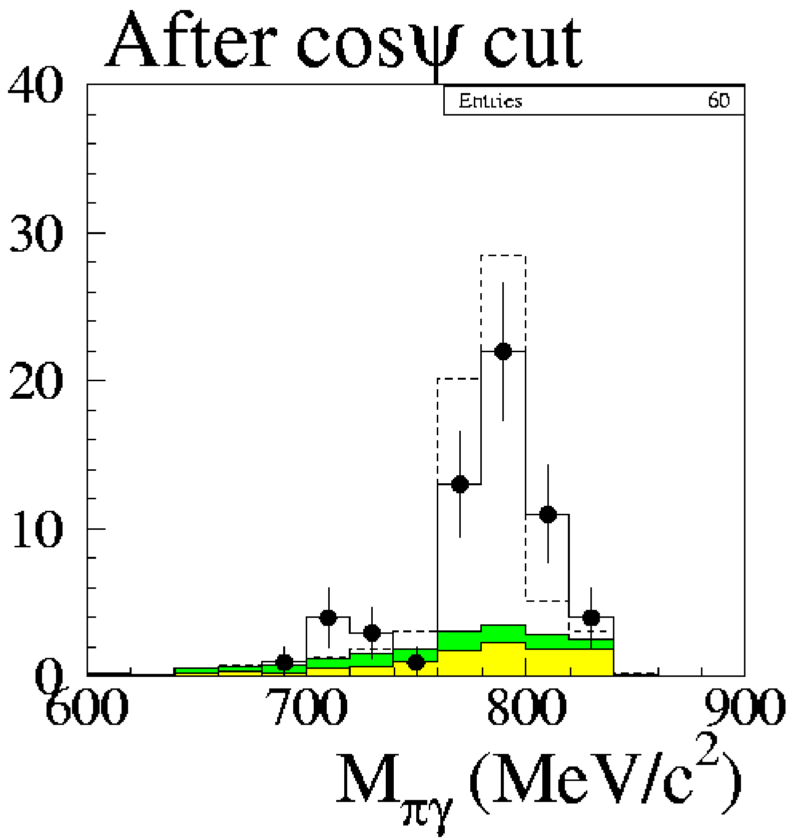


- The K_L interacting in the calorimeter can be tagged by a K_S detected and a neutral cluster on EMC opposite to the K_S flight direction
- The reconstructed β^*_{KL} in the CM is mainly affected by the machine energy spread:

$$\delta E_\Phi \sim 1 \text{ MeV} \rightarrow \delta\beta_{KL} \sim 0.004$$

$e^+e^- \rightarrow \omega\pi^0 \rightarrow \pi^0\pi^0\gamma$

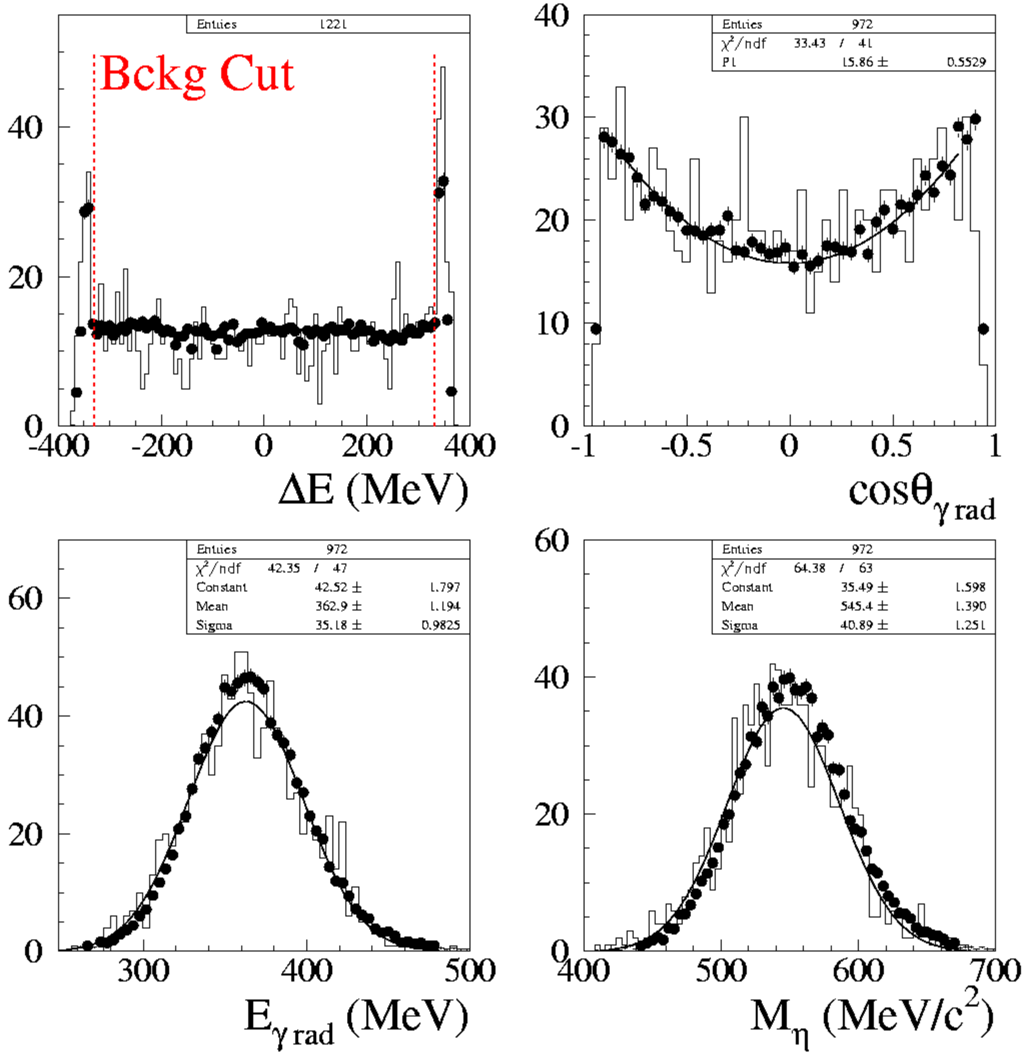




$$\sigma = (0.54 \pm 0.09\ (\text{stat.} + \text{bckg.}) \pm 0.05\ (\text{syst.})\ )\ \text{nb}$$

$$\sigma_{SND} = (0.64 \pm 0.08)\ \text{nb}$$

$\Phi \to \eta\gamma \to \gamma\gamma\gamma$



— Dati (120 nb^{-1})

● MC

E_{rad} = 363 MeV

M_η = 545 MeV/c^2

σ_η = 42 MeV/c^2

$Nev_{\chi 2} = 972 \pm 31$

$Nev_{bck} \approx 0$

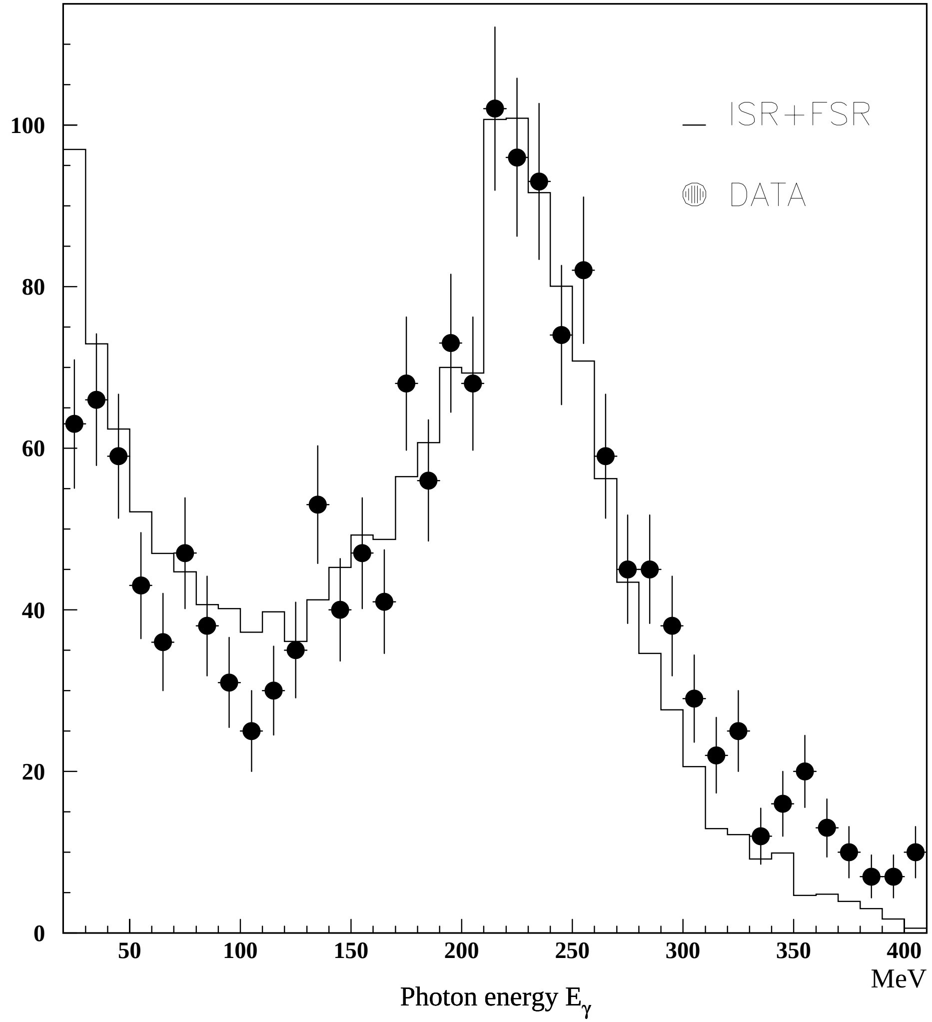
$e^+e^- \to \pi^+\pi^-\gamma$ events

Possible sources:

❶ initial state radiation

❷ final state radiation

❸ $\phi \to f_0\gamma \to \pi^+\pi^-\gamma$



Summary and Outlook

The roll-in of KLOE in December 1998 was the successful end of years of constructions and testing

In 1999, with more than 2 pb^{-1} of data, we are showing that the KLOE detector fully satisfies expectations

The first CP violating events have been identified and studies on systematics just started

Other non-CP analysis (radiatives, $K^{\pm}$,…) in progress

⇒ We are ready for real luminosity data to perform our approved program

Reconstruction overview: Nov. 24 -- Dec. 10

Collected statistics: runs 10106 - 10582 processed

===> ~200 runs ~3000 files

Integrated Luminosity: 966.5 nb^{-1}

Reconstr. Luminosity: 965.9 nb^{-1} ==> 99.94 %

1292.6 last score

Average Luminosity	2.0 x 10^{30} $cm^{-2}s^{-1}$
Average value for $\sigma(e^+e^-$ $\phi)$	2.86--3.06 μb
Total golden Bhabhas	5.6 10^6
Total K_S $\pi^+\pi^-$ (K_L tags)	0.46 10^6

Present analysis activities (not a complete list)

- ϕ radiative decays:
  - ☛ $\phi \to \eta\gamma + \pi^0\gamma \to 3\gamma$
  - ☛ $\phi \to \eta\gamma \to \pi\pi\pi\gamma$
  - ☛ $\phi \to \eta'\gamma$
  - ☛ $\phi \to \omega\gamma$
  - ☛ $\phi \to f_0\gamma$
- $\phi \to (\rho\pi + \pi\pi\pi)$
- $e^+e^- \to \pi^+\pi^-\gamma$ final state

Reconstruction overview: Nov. 24 -- Dec. 10

Average fraction of tracked sample	~15%
Average CPU time / triggers	0.03 s
max.	~10 s
Average CPU time per tracked evt.	0.25 s
max.	~50 s

Delivered Luminosity

☛ $L_{1b} = 1.5\times10^{29}$ @ 20mA/*bunch*

☛ $L_{MAX} = 2\times10^{30}$ @ 200mA/*beam*

☛ Average beam life time ~ 1h

☛ currently 100nb^{-1}/day collected

3pb^{-1} expected by the end of 1999

☛ 100 pb^{-1} *should* be collected in first months of 2000, $\Re(\varepsilon'/\varepsilon) \sim 10^{-3}$, *if* the DAΦNE upgrade program succeds (new kickers will be installed in jan-feb)

Fiducial volumes

- Systematics on double ratio R from boundaries determination and resolution smearing
- K_S : sphere with radius $R_S > 16\ \lambda_s$ error from FV_S cut negligible
- K_L : cylinder of $30 < R_L < 150$ cm, $|z_L| < 125$ cm 30 % of K_L decays

➥ The difference between charged and neutral FV_L affects directly the double ratio

➥ events when the neutral and charged vertex coincide ($K^{\pm} \to \pi^{\pm}\pi^0$, $K_L \to \pi^+\pi^-\pi^0$) are used to monitor misalignments

➥ gaussian smearing of the FV_L edge is negligible if $\sigma_{vert} \sim 1$ cm ($\sigma^2 / 2\lambda^2_L$)