Status and results of the NA48 experiment at CERN

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on behalf of the **NA48 COLLABORATION**:
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Perugia-Pisa-Saclay-Siegen-Torino-Vienna-Warsaw

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  - $\mathrm{K_L} \to e^+e^-\gamma\gamma$
  - $\mathrm{K_L} \to \pi^+\pi^-e^+e^-$

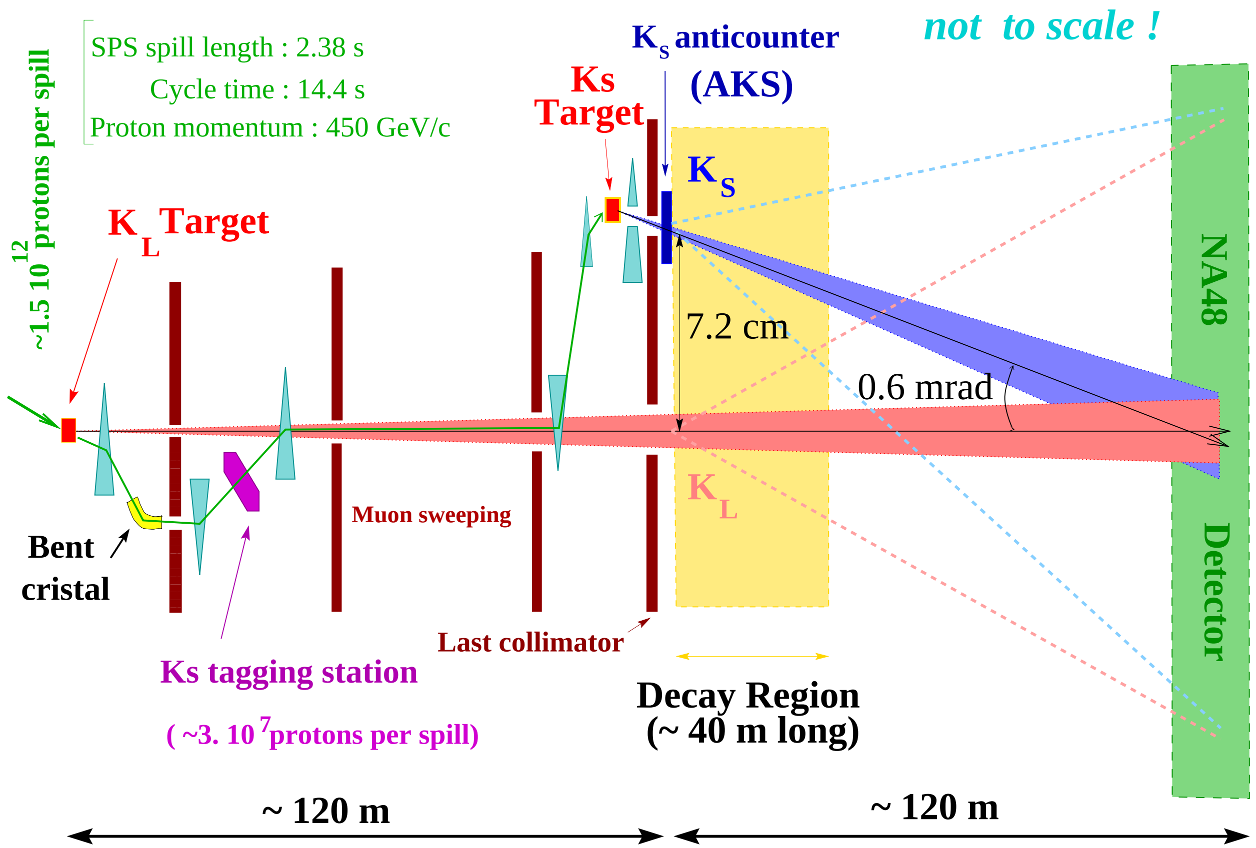
The NA48 experiment - The Measurement

- **Aim:**
  - measure the direct CP violation parameter $\mathrm{Re}(\varepsilon'/\varepsilon)$ in the $K_{\mathrm{L,S}} \to \pi\pi$ decays with accuracy $\sim 2 \times 10^{-4}$
  - technique of the double ratio R:

$$\mathrm{Re}(\varepsilon'/\varepsilon) \sim \frac{1}{6}\left\{1 - \frac{\Gamma(\mathrm{K_L} \to \pi^0\pi^0)}{\Gamma(\mathrm{K_S} \to \pi^0\pi^0)} \Big/ \frac{\Gamma(\mathrm{K_L} \to \pi^+\pi^-)}{\Gamma(\mathrm{K_S} \to \pi^+\pi^-)}\right\}$$

- **Method:**
  - produce simultaneous and almost collinear $\mathrm{K_L} + \mathrm{K_S}$ beams
  - tag the proton upstream of the $\mathrm{K_S}$ target
  - measure the 4 decays $K_{\mathrm{L,S}} \to \pi^0\pi^0$ $K_{\mathrm{L,S}} \to \pi^+\pi^-$ concurrently in the same detector and from the same decay region
  - use lifetime weighting technique
- **Statistics:**
  - Collect a few 10^6 $\mathrm{K_L} \to \pi^0\pi^0$ decays (limiting mode)
- **Previous measurementes:**
  - **NA31:** $(23 \pm 6.5) \times 10^{-4}$
  - **E731:** $(7.4 \pm 5.2 \pm 2.9) \times 10^{-4}$

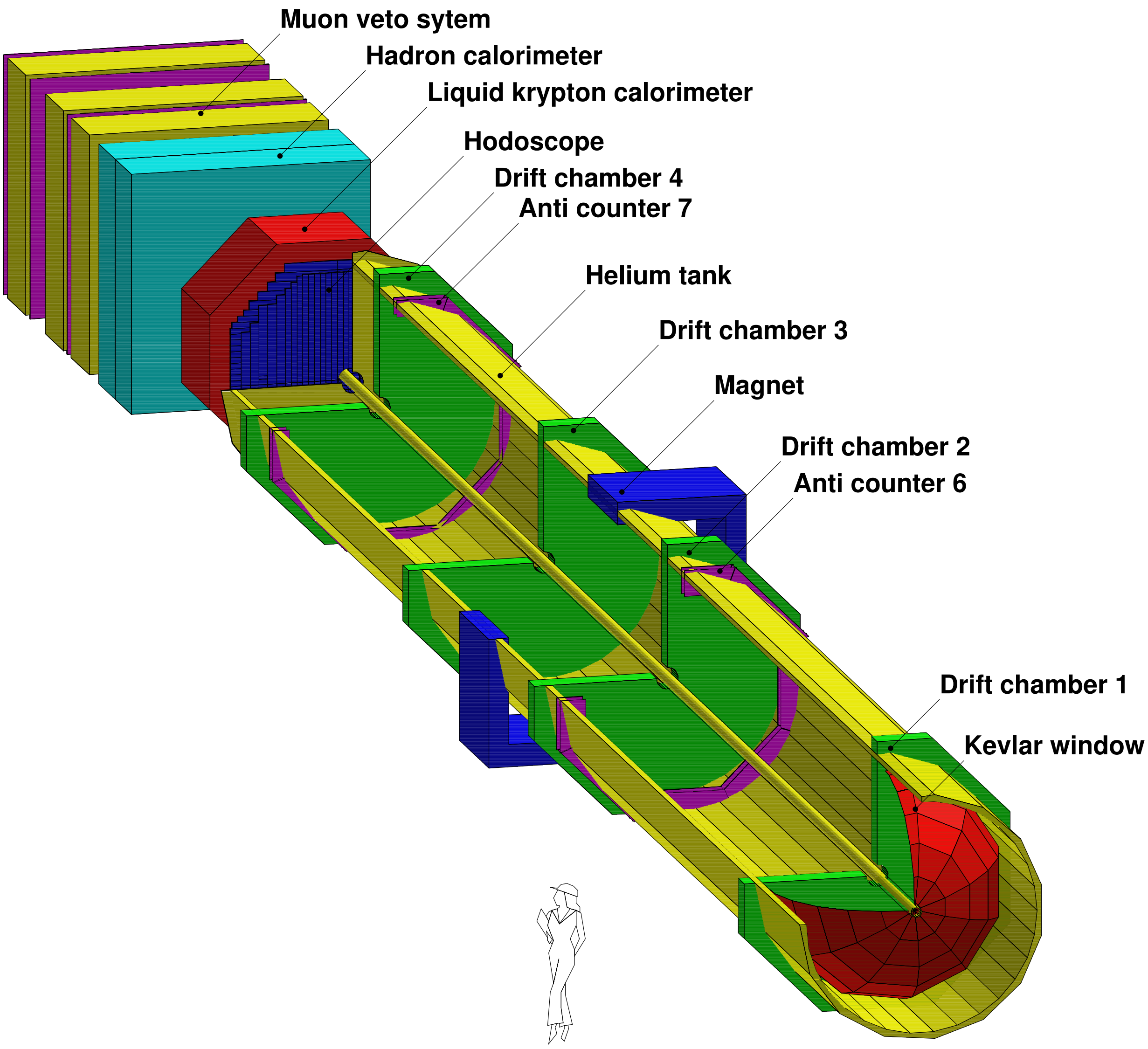
The NA48 experiment - The $K_{L,S}$ Beams



Two **simultaneous and almost collinear** neutral kaon beams converge towards the NA48 calorimeters with an angle of 0.6 mrad.

- $\mathrm{K_L}$ beam: SPS primary proton beam (450 GeV, 1.5×10^{12} ppp)
- $\mathrm{K_S}$ beam: protons splitted off the primary beam using a **bent crystal** (3×10^{7} ppp)

The NA48 experiment - The Detector



- **CHARGED DECAYS:**
  magnetic spectrometer and scintillator hodoscope
- **NEUTRAL DECAYS:**
  quasi-homogeneous Liquid Krypton e.m. calorimeter

The 1997 Data Taking – The Run

- First physics run: Sep/Oct 1997
- Installation and commissioning of the readout and neutral trigger electronics of the Liquid Kripton calorimeter ($\sim$ 13.000 channels)
- DAQ and triggering systems integration, online detector calibration and fine–tuning
- 42 days of $\mathrm{Re}(\varepsilon'/\varepsilon)$ data taking
- 2/3 nominal beam intensity ($\sim 1. \times 10^{12}$ ppp)
- 25 Tbytes of data written on tape

  $1.1 \times\ 10^{9}$ triggers, 12000 events/spill

  12 Mbytes/s transfer rate

- $\sim$ **650 000** $\mathrm{K_L} \rightarrow \pi^0\pi^0$ collected with

– energy: 70 GeV $< E_{\mathrm{K}} <$ 170 GeV

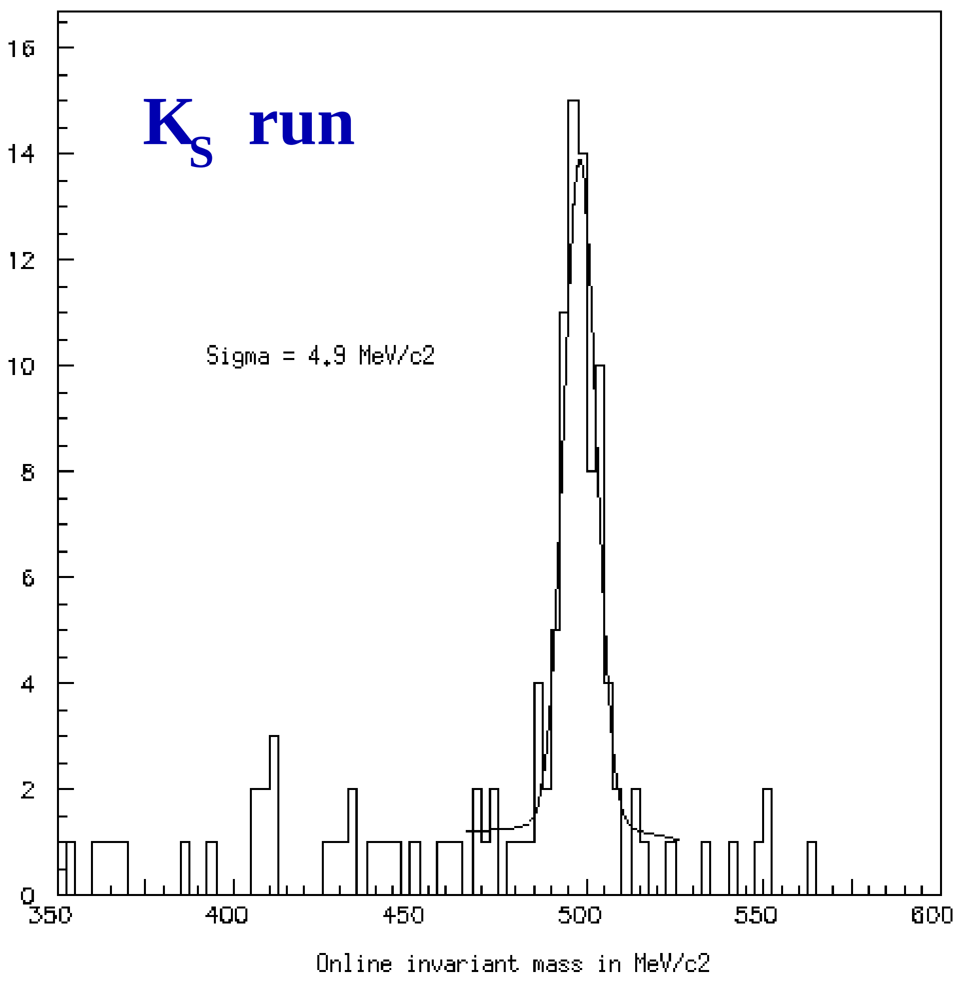
– lifetime: $0 < \tau < 4\ \tau_{\mathrm{S}}$

$\Rightarrow$ $4 - 5\ 10^{-4}$ **statistical error on** $\mathrm{Re}(\varepsilon'/\varepsilon)$

Detector Performance – The Trigger

The $\pi^+\pi^-$ Trigger in 1997

- **Level1:** digital system, combines informations from scintillator hodoscope (t_0) and calorimeters (E_{tot}), generate a decision every 25 ns
- **Level2:** farm of microprocessors based on drift chambers informations, calculates K mass and decay vertex position

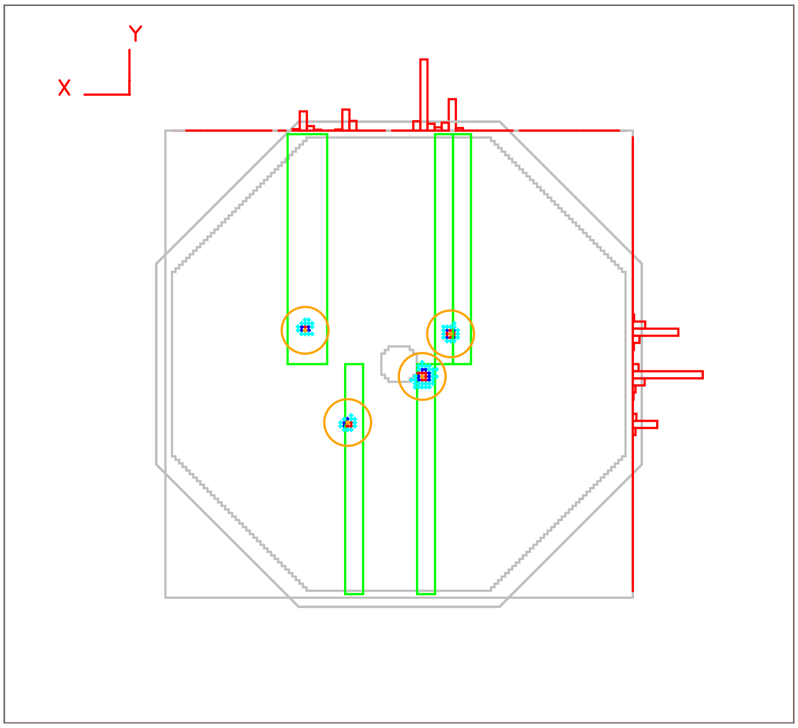


- **rates (Level2):**
  - input 70 KHz
  - output $\sim 2\ KHz$
- **efficiency (Level1 and Level2 combined):**
  - K_S : $(90.61 \pm 0.08)\%$
  - K_L : $(90.66 \pm 0.10)\%$
- **dead time** $\sim 1\ \%$ (applied to neutral)

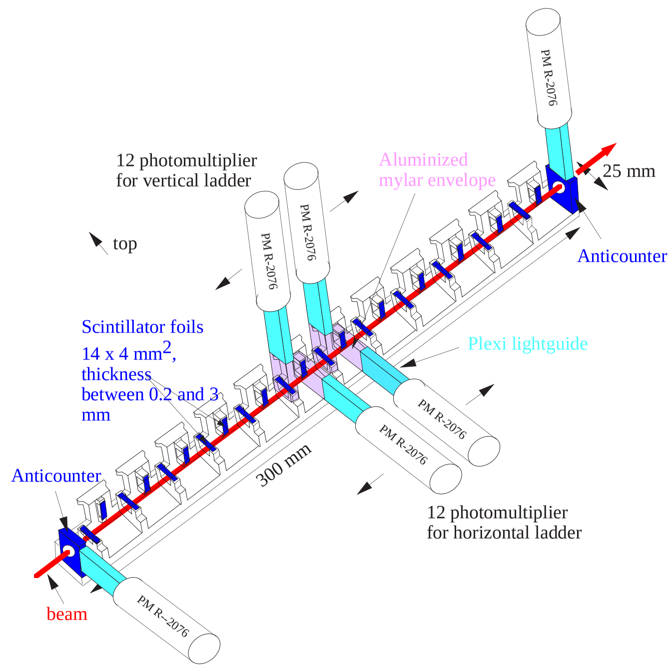
Detector Performance – The Trigger

The $\pi^0\pi^0$ Trigger

- reduce LKr calorimeter informations (40 MHz fast readout) to 64 vertical and 64 horizontal projections
- compute and cut on number of near–in–time clusters, E_{tot}, energy CoG, decay vertex position
- fully pipelined, deadtimeless, generate a decision every 25 ns
- **rates:**
  - input $\sim 1\ MHz$
  - output $\sim 2\ KHz$
- **efficiency** (K_L + K_S **combined**): $(99.79 \pm 0.06)\%$



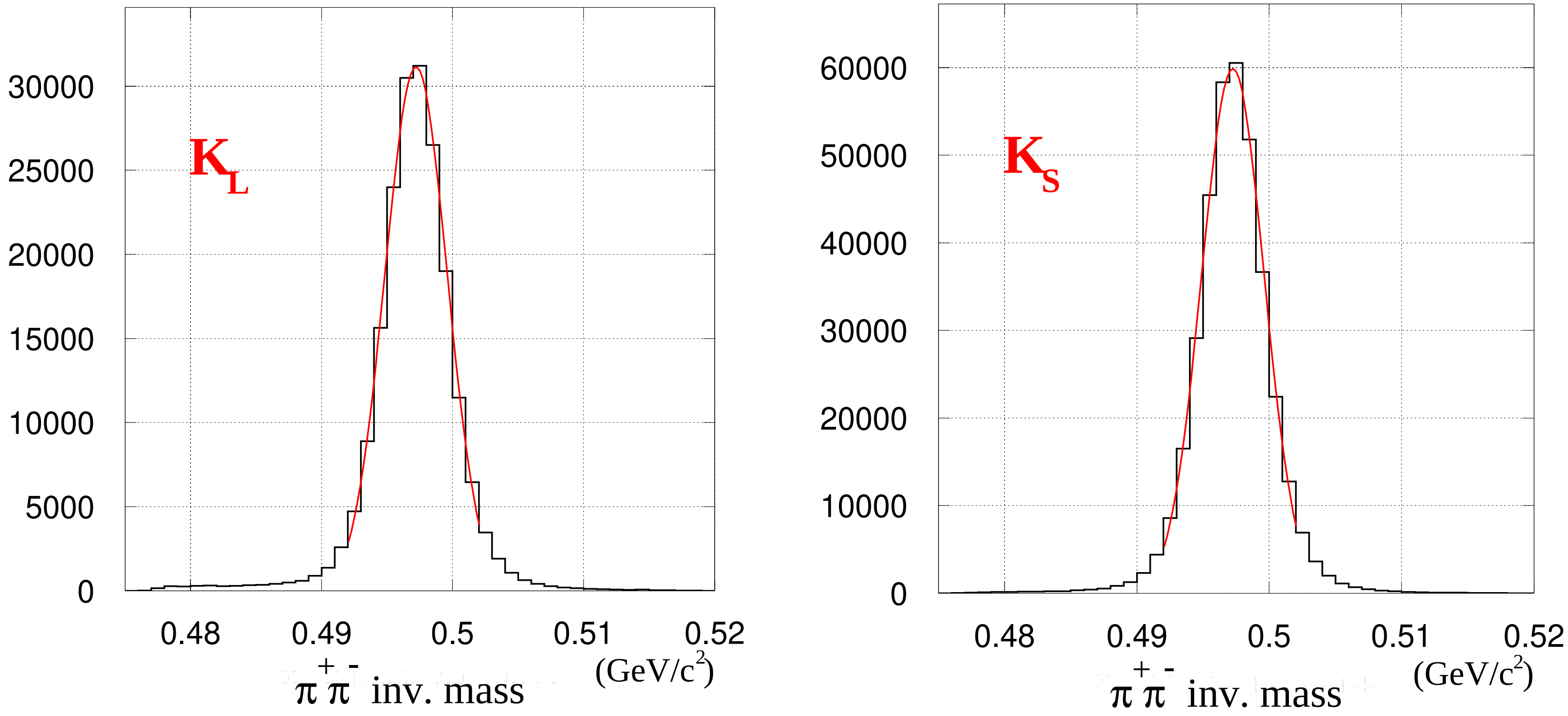
Detector Performance – The Tagger



- Two ladders of 12 staggered scintillators
- counter thickness: 200–3000 μm
- individual counter rate: 1–2 MHz
- high precision alignement: movement system of four remotely controlled motors (accuracy $\sim 1\ \mu m, 1\ mrad$)
- $0.01X_0$, 300-400 photoelectons light yield
- 8–bit 1 GHz Flash-ADC readout system
- single counter + electronics time resolution: $\sim 120\ ps$
- double pulse resolution: $\sim 4 - 5\ ns$
- **1997 run performances ($\pm 2\ ns$ time window):**
  - **time resolution:** $\sim 200\ ps$
  - **inefficiency:** $\sim 2 \times 10^{-4}$

Detector Performance – The Spectrometer

Mass resolution: $\sim 2.5\ \mathbf{MeV/c^2}$

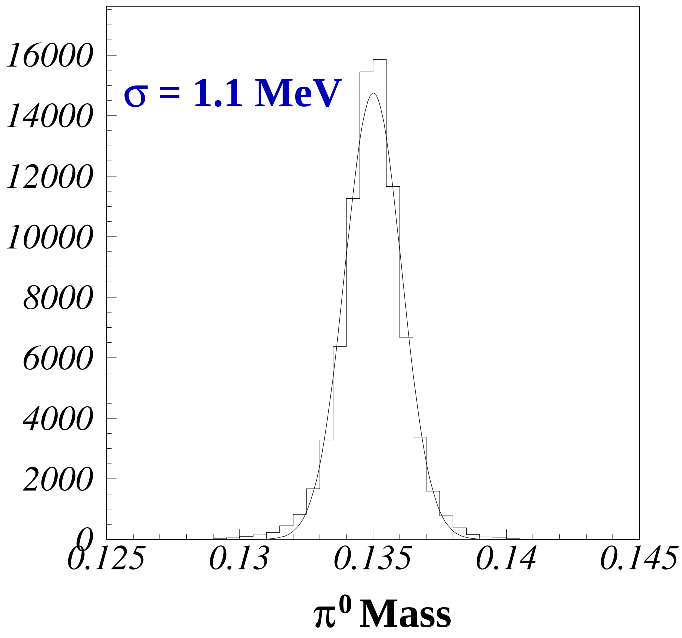


$$\frac{\sigma(\mathbf{P})}{\mathbf{P}} = 0.48\,\% \oplus 0.009\ \mathbf{P}[\mathbf{GeV/c^2}]\ \%$$

(from e^- scan at 25 and 100 GeV)

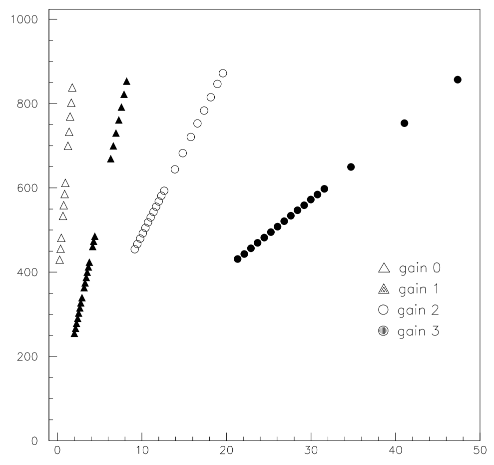
The Liquid Kripton Calorimeter

Detector Performance – The LKr Calorimeter



- **13212 cells ($2 \times 2\ cm^2$), asyncronous readout electronics, 40 MHz digital sampling**
- **stable operation at reduced HV (1.5 KV) due to capacitor problem**
  - $\sim 20\%$ increase of electronic noise
  - small space charge correction to the energy
- **1 column (4 cm wide) not connected to HV**

The LKr Calorimeter – Calibration

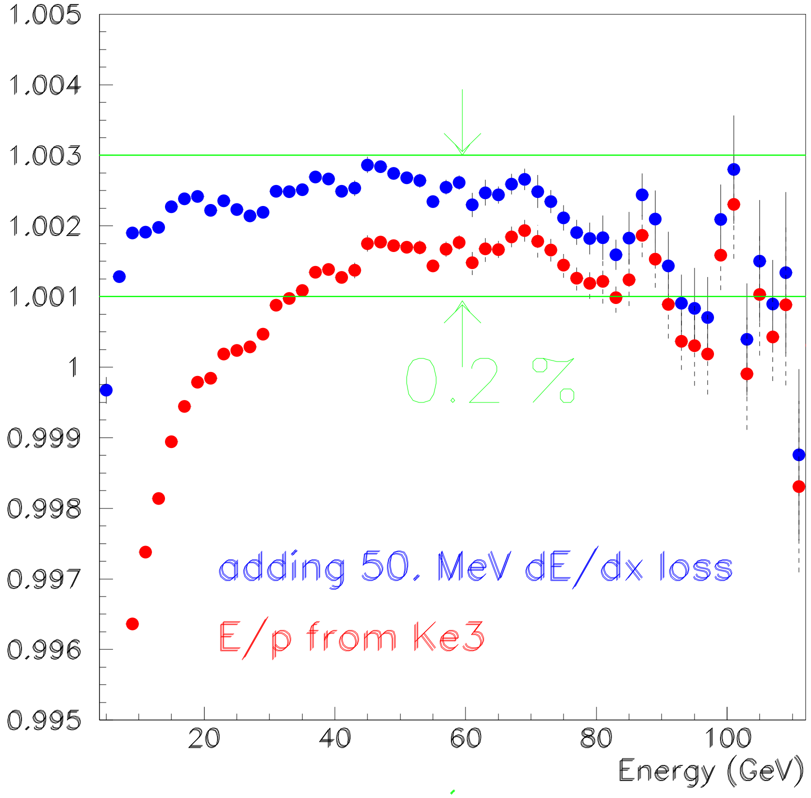


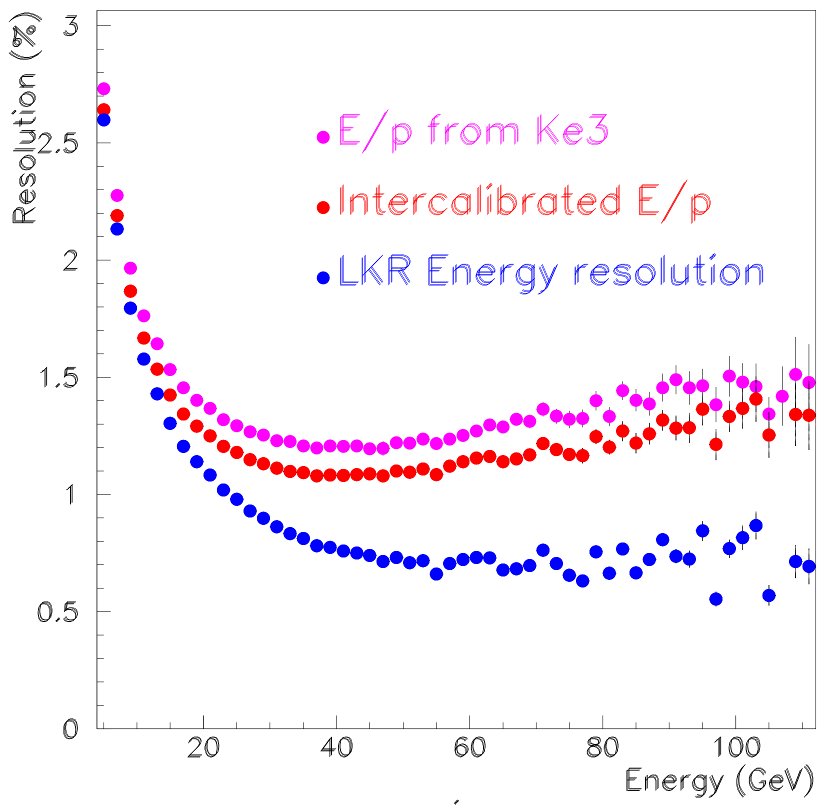
ADC counts vs Energy (GeV)

- FADC 10 bits resolution, 14 bits dynamic range obtained by means of 4 fast-switched gain ranges: $\sim 3.5\ MeV$ to $\sim 50\ GeV$ per cell
  (4 offsets + 4 slopes)×13212 channels = 105696 constants
- all gain stages (PA, TX, Shapers) monitored by precise charge injection
- improve (slightly) resolution with intercalibration factors (1 correction per cell) by E/p equalisation of electrons from K_{e3} decays
- absolute energy calibration: fit the steep rise of the K_S vertex distribution and adjust the value to the known position of the AKS counters
- regular check of the electronics chain, gain stability better than 0.1%

The LKr Calorimeter – Linearity and Resolution

With electrons from K_{e3}

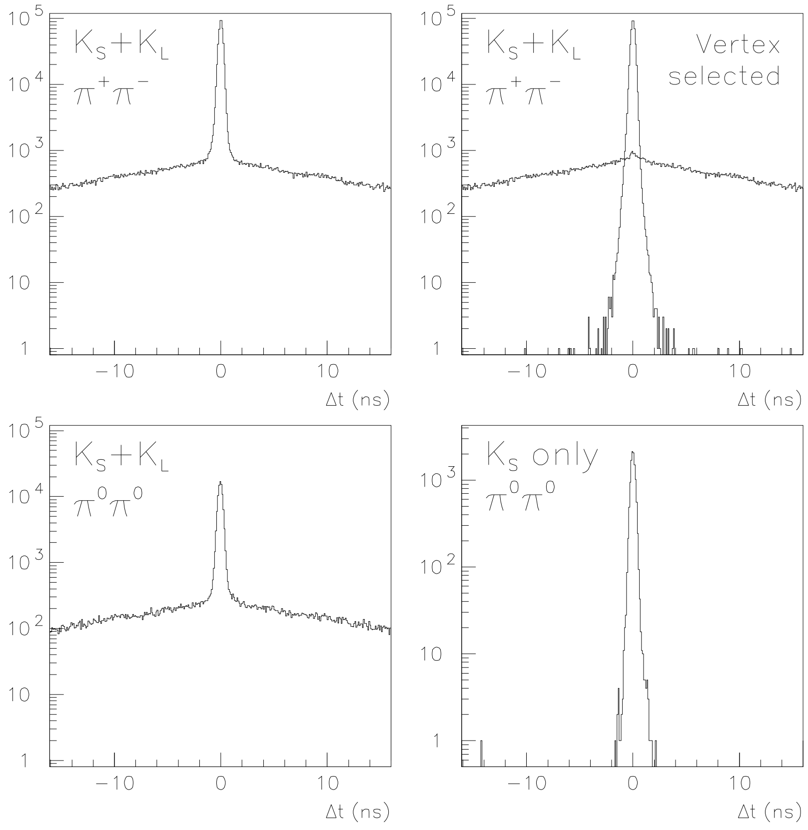




5 → 100 GeV: linear whithin ∼ 0.2%

$$\frac{\sigma(E)}{E} = \frac{3.5\%}{\sqrt{E}} \oplus \frac{110MeV}{E} \oplus 0.6\%$$

The 1997 Re(ε'/ε) analysis – The K_S tagging



t_{tag} = proton time in tagger

Charged mode : $\Delta t_C = t_{hod} - t_{tag}$

Neutral mode : $\Delta t_N = t_{LKr} - t_{tag}$

$K_S \equiv |\Delta_t| \leq 2$ns

$K_L \equiv |\Delta_t| > 2$ns

α_{SL} : $K_S \rightarrow K_L$ *transitions*

$\Rightarrow$ *tagging inefficiency : a few* 10^{-4}

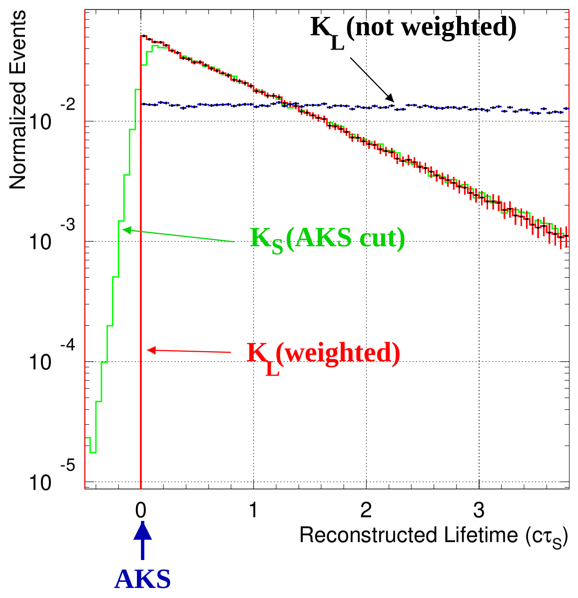
α_{LS} : $K_L \rightarrow K_S$ *transitions*

$\Rightarrow$ *accidental activity*

$\Rightarrow$ Re(ε'/ε) *dilution* $= (11.5 \pm 0.03)\%$

$$\delta(\mathrm{Re}(\varepsilon'/\varepsilon)) \sim \delta(\alpha_{LS}^{00} - \alpha_{LS}^{+-}) \sim 1.5 \times 10^{-4}$$

The 1997 Re(ε'/ε) analysis – Lifetime Weighting



- **Technique to reduce the acceptance correction**
  - lifetime weighting makes the $\mathrm{K_L}$ vertex distribution identical to the $\mathrm{K_S}$ distribution
  - weight applied to $\mathrm{K_L}$:

$$\exp\left(-\frac{(z_{\mathrm{REC}} - z_{AKS})m_{\mathrm{K}}}{c\tau_{\mathrm{S}}E_K(1-\tau_{\mathrm{S}}/\tau_{\mathrm{L}})}\right)$$

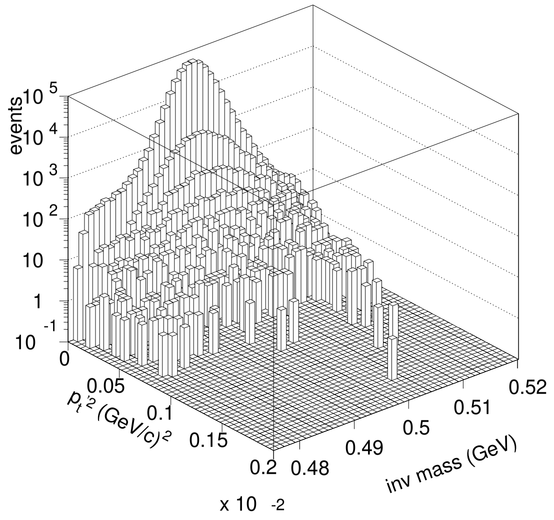
- The acceptances cancel out in the double ratio R for $\mathrm{K_S}$ and $\mathrm{K_L}$:

  $\Rightarrow$ acceptance corrections less than 0.5%

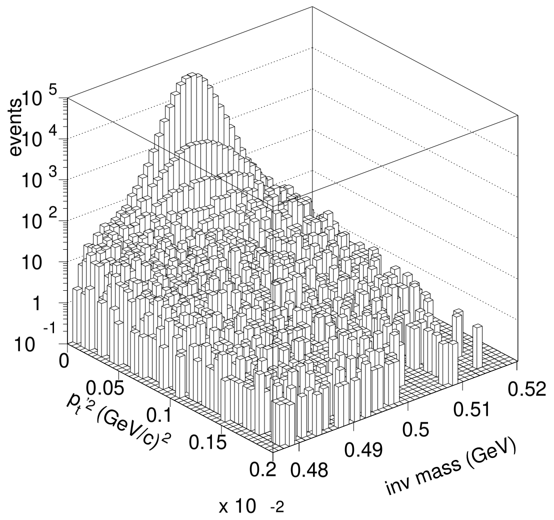
  $\Rightarrow$ increase of the statistical error (up to 40% for a decay region of $4\tau_{\mathrm{S}}$)

The Charged Background

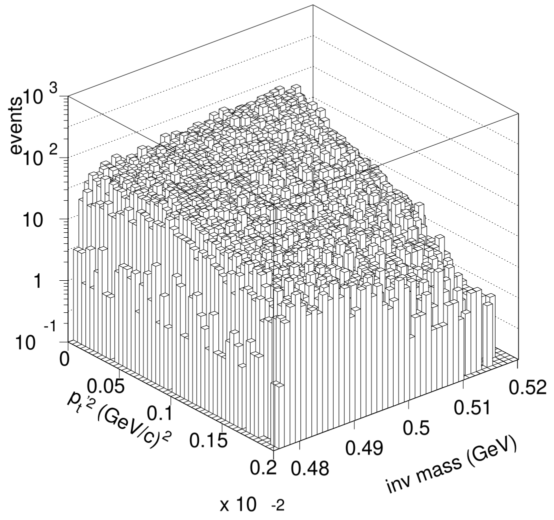
$K_S \rightarrow \pi^+\pi^-$



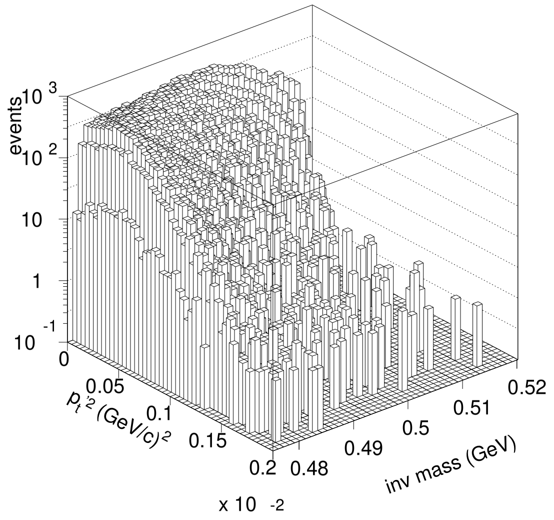
$K_L \rightarrow \pi^+\pi^-$ (+ background)



Identified K_{e3} (E/P)



Identified $K_{\mu3}$ (muon counters)

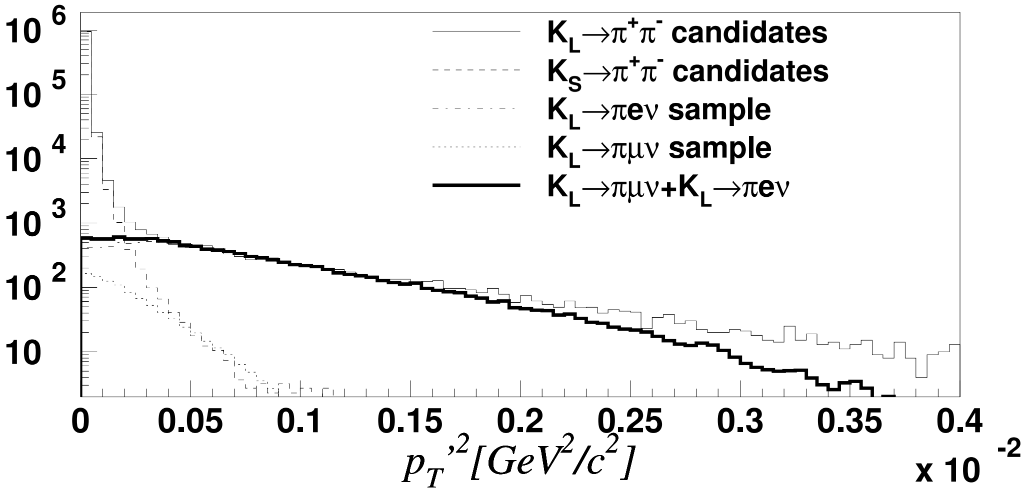


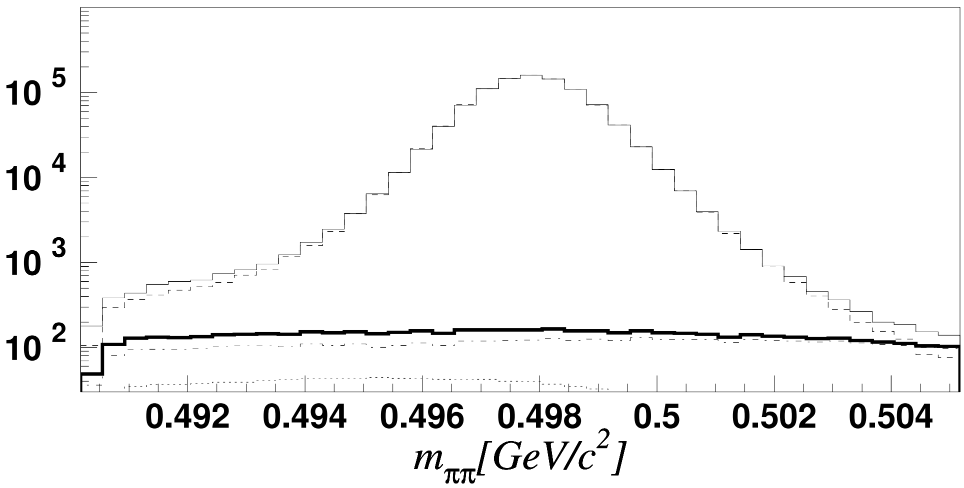
K_{e3} & $K_{\mu3}$ decays: **dominant background** to $K_L \rightarrow \pi^+\pi^-$

B.R.(K_{e3}) ~ 37.8% – B.R.($K_{\mu3}$) ~ 27.2%

⇒ background ~ 10^2 times more frequent than signal

The Charged Background – Estimation

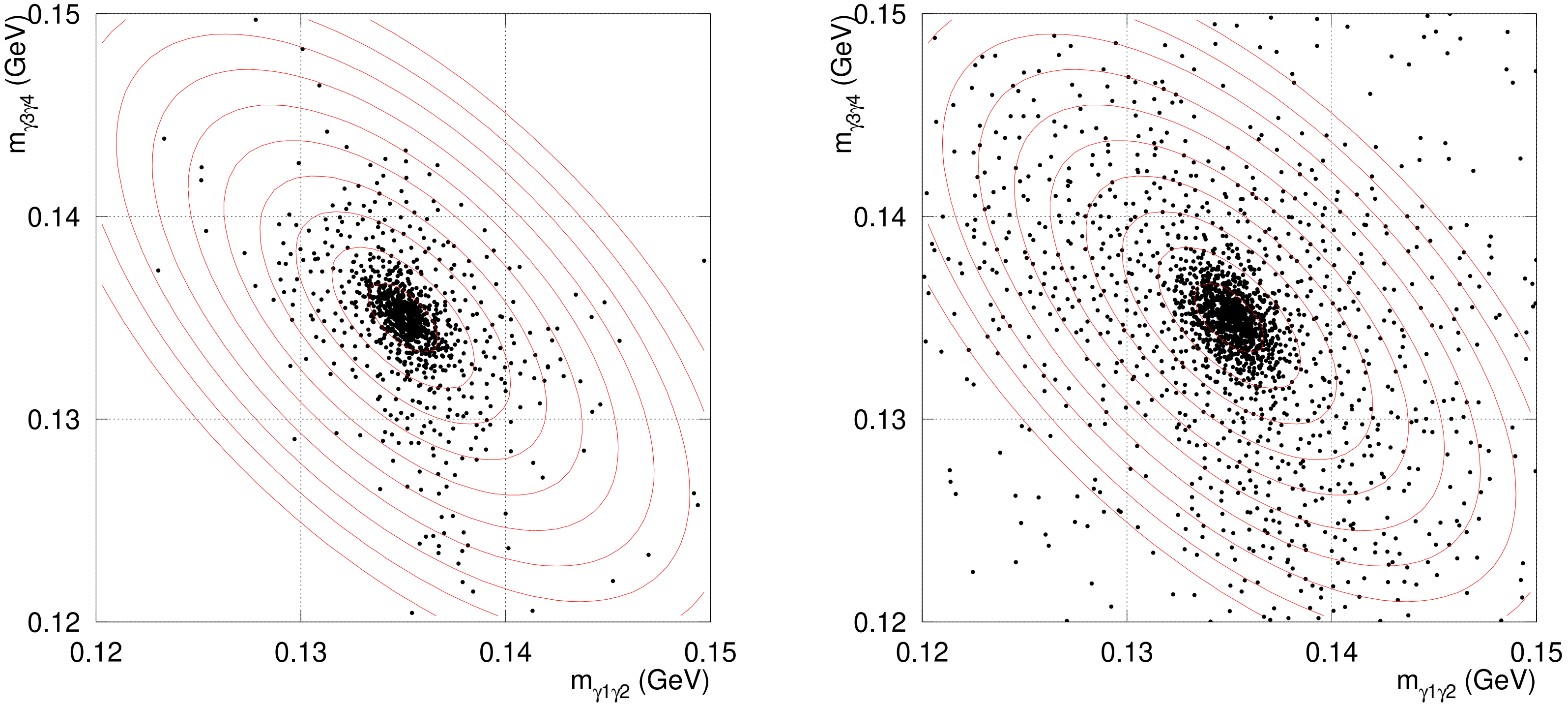




- background shape evaluated in the $(M_{\pi\pi}, P'^2_T)$ plane
- use selected samples of K_S, K_{e3} and $K_{\mu3}$ to fit the K_L distribution: $\alpha S(\pi^+\pi^-) + \beta B(K_{e3}) + \gamma B(K_{\mu3})$
- the remaining K_{e3} and $K_{\mu3}$ are evaluated in $(M_{\pi\pi}, P'^2_T)$ control regions and extrapolated to the signal region

  $\Rightarrow$ background below the $K_L \to \pi^+\pi^-$ peak:
  $\sim 3 \times 10^{-3}$ (statistical error 10 times smaller)

The 1997 Re(ε'/ε) analysis – The Neutral Background

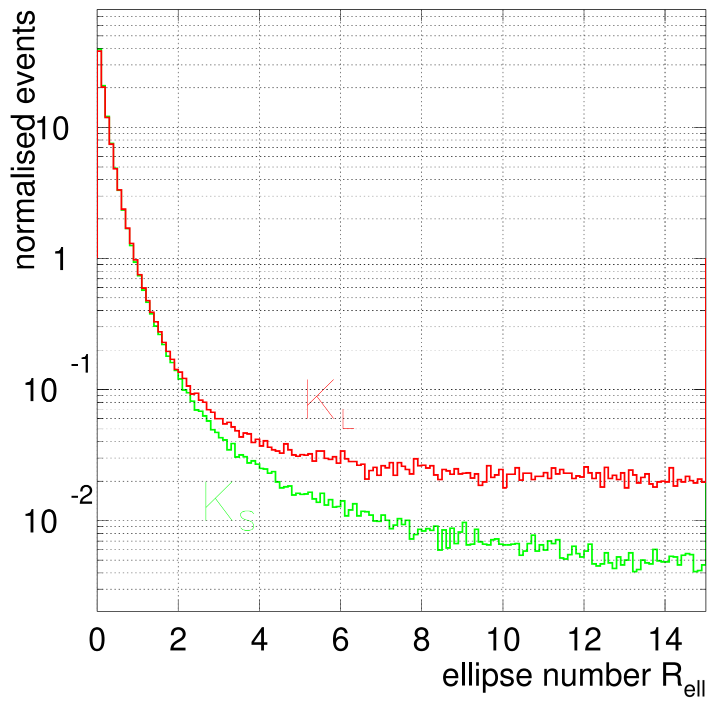


$K_S \to \pi^0\pi^0$ $\qquad\qquad$ $K_L \to \pi^0\pi^0$

Background to $\mathrm{K_L} \to \pi^0\pi^0$**:** $\mathrm{K_L} \to 3\pi^0$ **decays when 2 photons are missed**

$\Rightarrow$ **B.R.**$(\mathrm{K_{L\ 3\pi^0}}) \sim 21.6\%$ $\quad \Rightarrow \sim 220$ **times more frequent than signal**

The Neutral Background – Estimation



- **background reduction:**
  - require 4 in-time clusters and energy CoG
  - impose M_K to calculate the neutral decay vertex
  - photons paired to get the best $\pi^0\pi^0$ combination (best χ^2 to give $M_{\gamma\gamma} = M_{\pi^0}$)
- **subtract background** in elliptical χ^2 rings of the $(m_{\gamma_1\gamma_2}, m_{\gamma_3\gamma_4})$ plane
- $K_{3\pi^0}$ **background estimation:**
  - $\sim\ 3 \times 10^{-3}$ unweighted
  - $\sim\ 1 \times 10^{-3}$ weighted

The 1997 $\mathrm{Re}(\varepsilon'/\varepsilon)$ analysis – Conclusions

- **1997** $\mathrm{Re}(\varepsilon'/\varepsilon)$ **analysis almost completed**
- **good quality of the data: soon results**
- **statistical error of** $\sim 4-5\ 10^{-4}$
- **systematics error still limited by the statistics available to study each effect**
- **accuracy of 1997** $\mathrm{Re}(\varepsilon'/\varepsilon)$ **value comparable to previous experiments**

The 1998 Data Taking

- **Improvements:**

  LKr calorimeter: HV blocking capacitors replaced

  $\Rightarrow$ stable operation at 3 KV ($\sim$ 20% signal gain)

  $\Rightarrow$ $\sigma_{m_{\pi^0}} \leq 1 MeV/c^2$

  new light carbon fiber beam–pipe

  $\Rightarrow$ less showers in the beam–pipe

  $\Rightarrow$ 30% current reduction in drift chamber readout

  $\Rightarrow$ dead time reduction in drift chamber readout

  new charged trigger processors

  $\Rightarrow$ handle higher trigger rate (no downscaling)

  $\Rightarrow$ reduced dead time

  upgraded DAQ system: event–building PC farm

  $\Rightarrow$ handle 30% trigger rate increase

  $\Rightarrow$ $\sim$ 20 Mbytes/s trasfer rate

- **Achievements:**

  NA48 run from May to September 1998

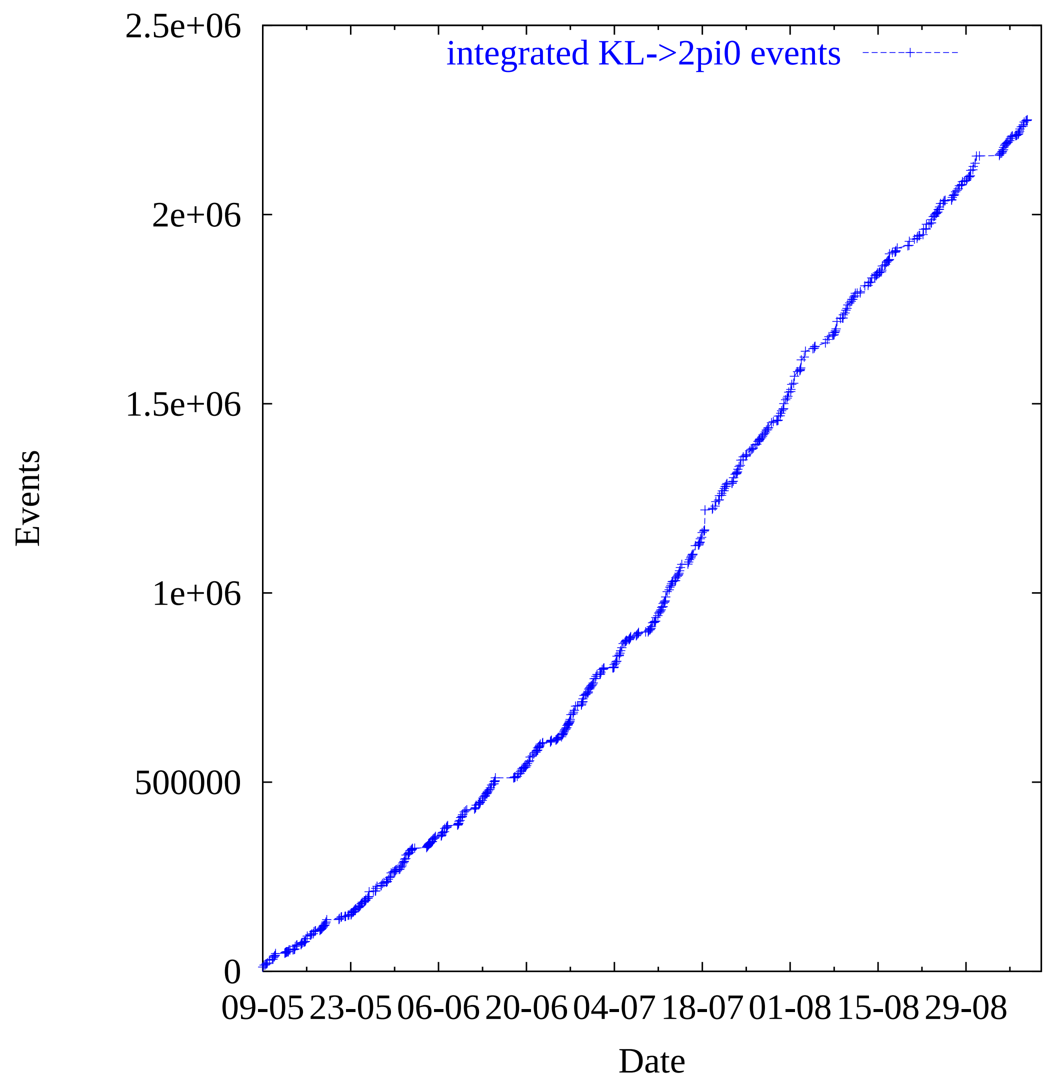
  $\Rightarrow$ nominal beam intensity (1.5×10^{12} ppp)

  $\Rightarrow$ 110 days of Re(ε'/ε) data taking

  $\Rightarrow$ $\sim 2 \times 10^6$ $K_L \rightarrow \pi^0\pi^0$ collected

  $\Rightarrow$ 65 Tbytes of data recorded **and** reprocessed

The 1998 Data Taking – Statistics



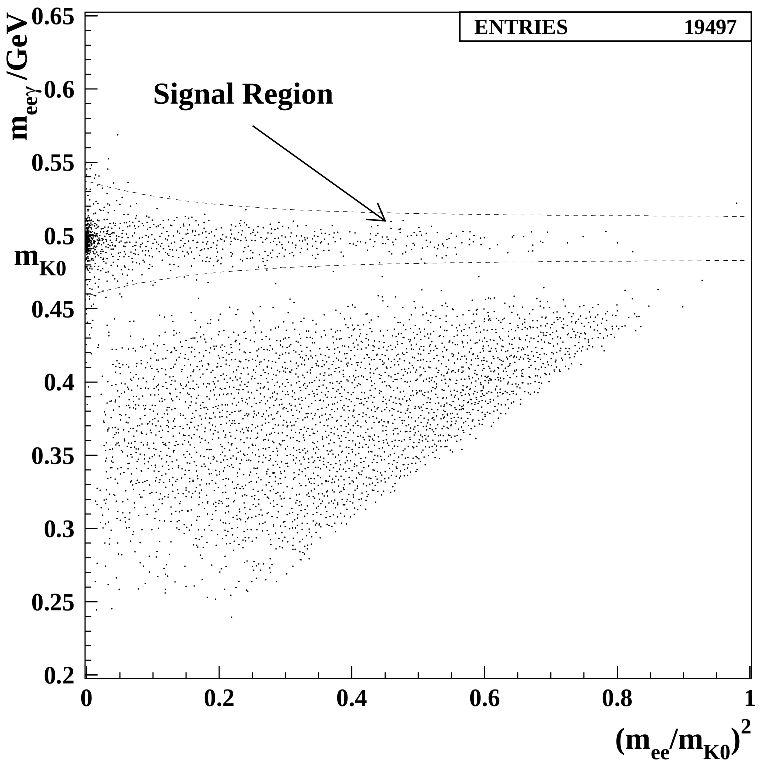
Collected $\sim 2 \times 10^6$ $\mathrm{K_L} \rightarrow \pi^0\pi^0$ **events with**

- $0 < c\tau < 3.5\ c\tau_s$
- $70 < E_K < 170 GeV$

Data Taking for $\mathrm{Re}(\varepsilon'/\varepsilon)$ **in 1999 (plus option for the year 2000, 120 days/year)**

The Rare Decays – $K_L \to e^+e^-\gamma$

1997 Data Results



- $K_L \to \gamma\gamma^*, \quad \gamma^* \to e^+e^-, \; \mu^+\mu^-$

⇒ precise measurement of the B.R. and of the parameter α_{K^*} for the $K\gamma\gamma^*$ form factor

- **DP**: $B.R. = (9.1 \pm 0.5) \times 10^{-6}$, $\alpha_{K^*} = -0.28 \pm 0.08$

1997 DATA – PRELIMINARY RESULTS

- signal well separated from the background: 6864 events
- main background: $K_S \to \pi^0\pi^0{}_D$, K_{e3} + *accidental* γ
- total background: 10.3 ± 1.5 events

The Rare Decays – $K_L \to e^+e^-\gamma$

1997 Data Results

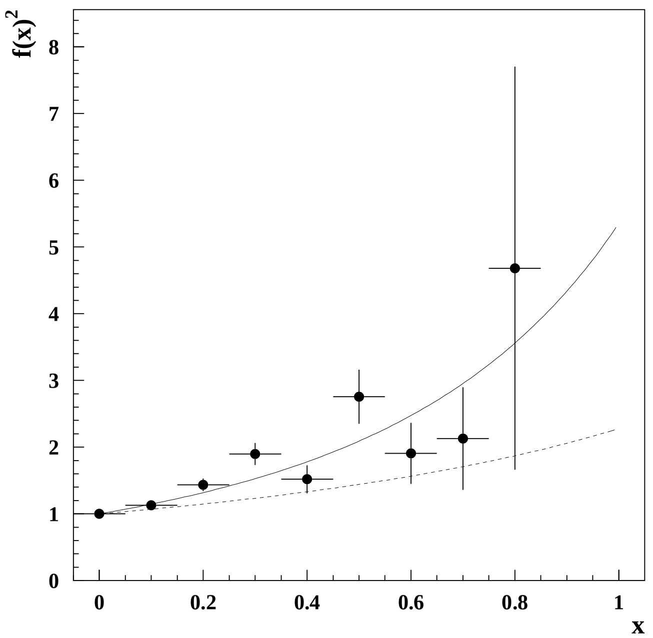


Figure: the form factor squared $f(x)^2$ vs $x = m_{ee}^2/m_K^2$ from the data (points), the fit with α_{K^*}=-0.30 (solid line), and with α_{K^*}=0.0 (dashed line)

- generate Montecarlo samples for different α_{K^*}'s
- χ^2 test on m_{ee} for each sample
- radiative corrections applied to the fit

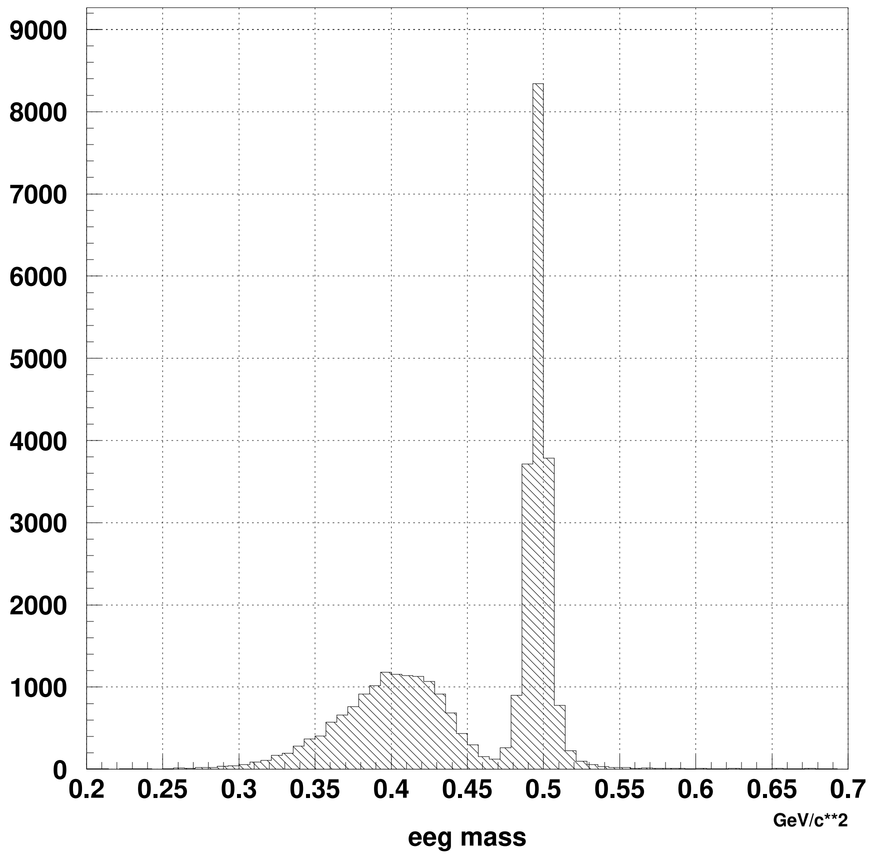
1997 DATA – PRELIMINARY RESULTS:

$$\boxed{\alpha_{K^*} = (-0.357 \pm 0.064^{+0.019}_{-0.014}}$$

$$\boxed{B.R. = (1.060 \pm 0.022 \pm 0.019 \pm 0.042) \times 10^{-5}}$$

The Rare Decays – $K_L \to e^+e^-\gamma$

1998 Data Results

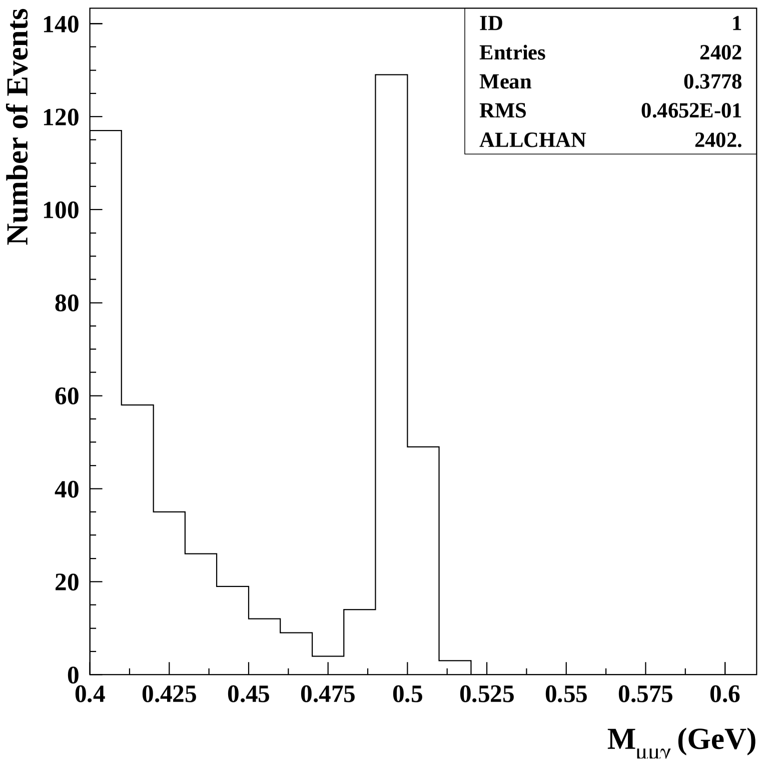


PRELIMINARY

$K_L \to e^+e^-\gamma$ **expectation with 1998 data:**

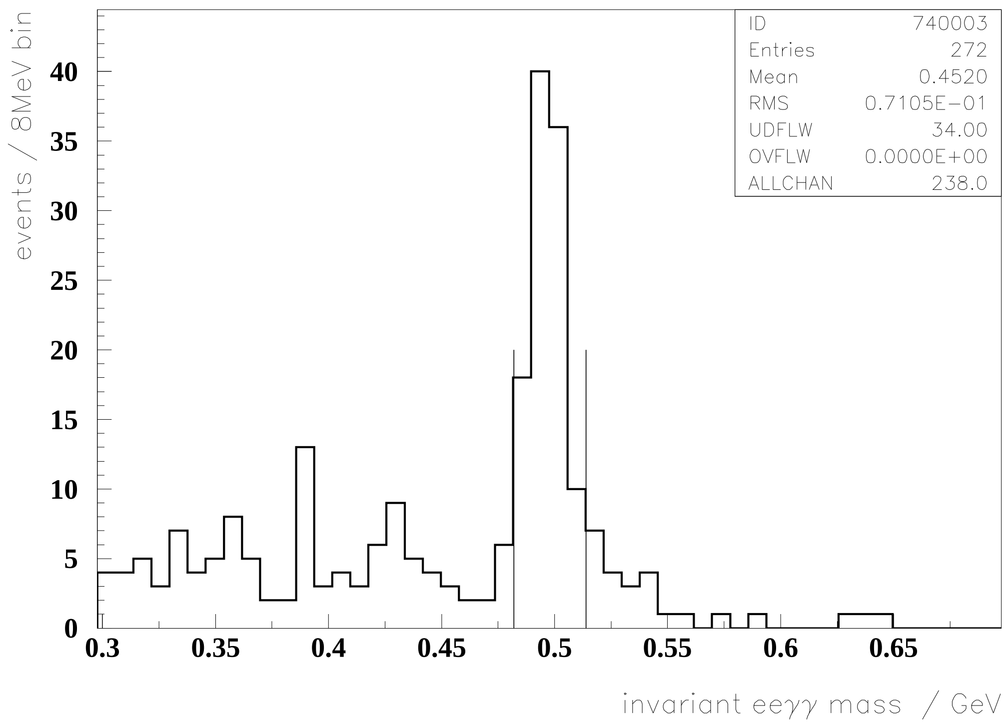
- data from real time reconstruction monitor histograms
- $\sim$ 18000 events in the peak
- $\sim \frac{2}{3}$ of available statistics

The Rare Decays – $K_L \to \mu^+\mu^-\gamma$



- $K_L \to \mu^+\mu^-\gamma$ expectation with 1998 data:
  - data from real time reconstruction monitor histograms ($\sim \frac{1}{13}$ of the total 1998 statistics)
  - expect more than 2000 events from the 1998 statistics
- Published Results (Z.Phys. C76, 653 (1997)):
  - B.R. $= (3.4 \pm 0.6_{stat} \pm 0.4_{syst}) \times 10^{-7}$
  - $\alpha_{K^*} = -0.04^{+0.24}_{-0.21}$
  - data taken in a short special run, $\sim 3 \times 10^6$ triggers
  - signal: 59 events, background: 14 events

The Rare Decays – $K_L \to e^+e^-\gamma\gamma$



1997 DATA RESULTS (PRELIMINARY)

- invariant mass distribution with 1997 data
- 106 $e^+e^-\gamma\gamma$ *events* in the peak

PRELIMINARY BRANCHING RATIO:

$$\boxed{BR(K_L \to e^+e^-\gamma\gamma) = (4.5 \pm 0.7 \pm 1.4) \cdot 10^{-7}}$$

Conditions: $E_\gamma > 5$ MeV and $m_{e\gamma} > 1$ MeV

The Rare Decays – $K_L \to \pi^+\pi^-e^+e^-$

1998 Data Results

- $K_L \to \pi^+\pi^-\gamma^*, \quad \gamma^* \to e^+e^-$

  $\Rightarrow$ large manifestation of indirect CP violation in the asymmetry between the $(\pi^+ - \pi^-)$ and the $(e^+ - e^-)$ planes
- **expected asymmetry** $\sim$ 14%
- main background: $K_L \to \pi^+\pi^-\pi^0{}_D$ with missing γ

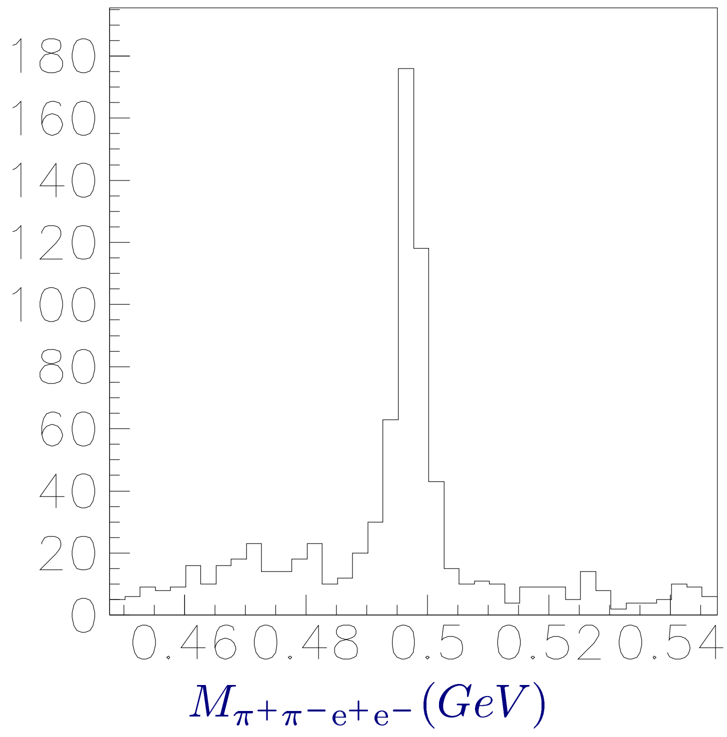
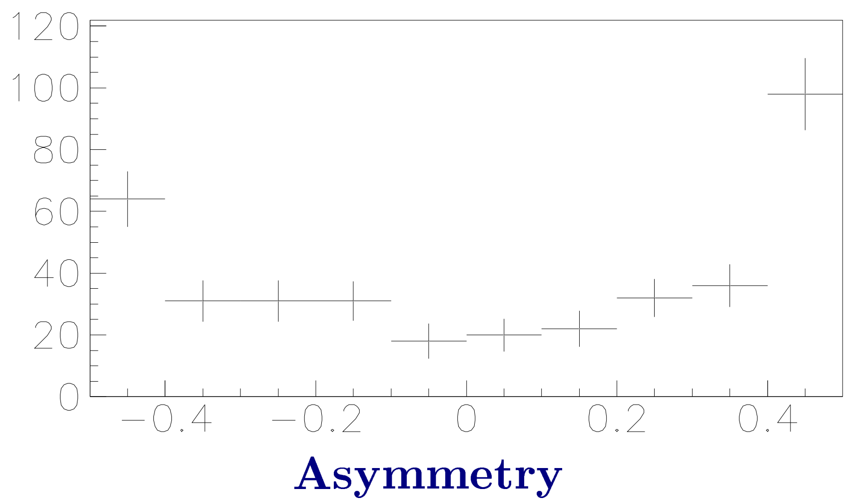


Figure: invariant mass distribution $M_{\pi^+\pi^-e^+e^-}$ ($\sim \frac{2}{3}$ of the statistics used) after all cuts and bakground subtraction: $\sim$ 380 *signal events* in the peak; $\sim$ 70 *background events* (extrapolated form side bands of mass distribution)

The Rare Decays – $K_L \rightarrow \pi^+\pi^-e^+e^-$

1998 Data Results



- **Figure** (PRELIMINARY): **raw** distribution of the interference term $cos\phi \cdot sin\phi$ (Asymmetry)
- ϕ = angle between the $(\pi^+ - \pi^-)$ and the $(e^+ - e^-)$ planes $\Rightarrow$ the asymmetry in this variable is violating both T and CP
- the above distribution has NOT been corrected for acceptance

1998 DATA – PRELIMINARY RESULTS

$$\boxed{B.R. = (3.13 \pm 0.23(stat)) \times 10^{-7}}$$

$\Rightarrow$ based on 240 $\pm$ 16 signal events ($\sim$ 90K bursts of data) with *signal/background* $\sim$ 6, systematics to be evaluated yet