# RECENT NA48 RESULTS ON RARE KAON DECAYS

**Gianmaria Collazuol**
Scuola Normale Superiore
and INFN Pisa

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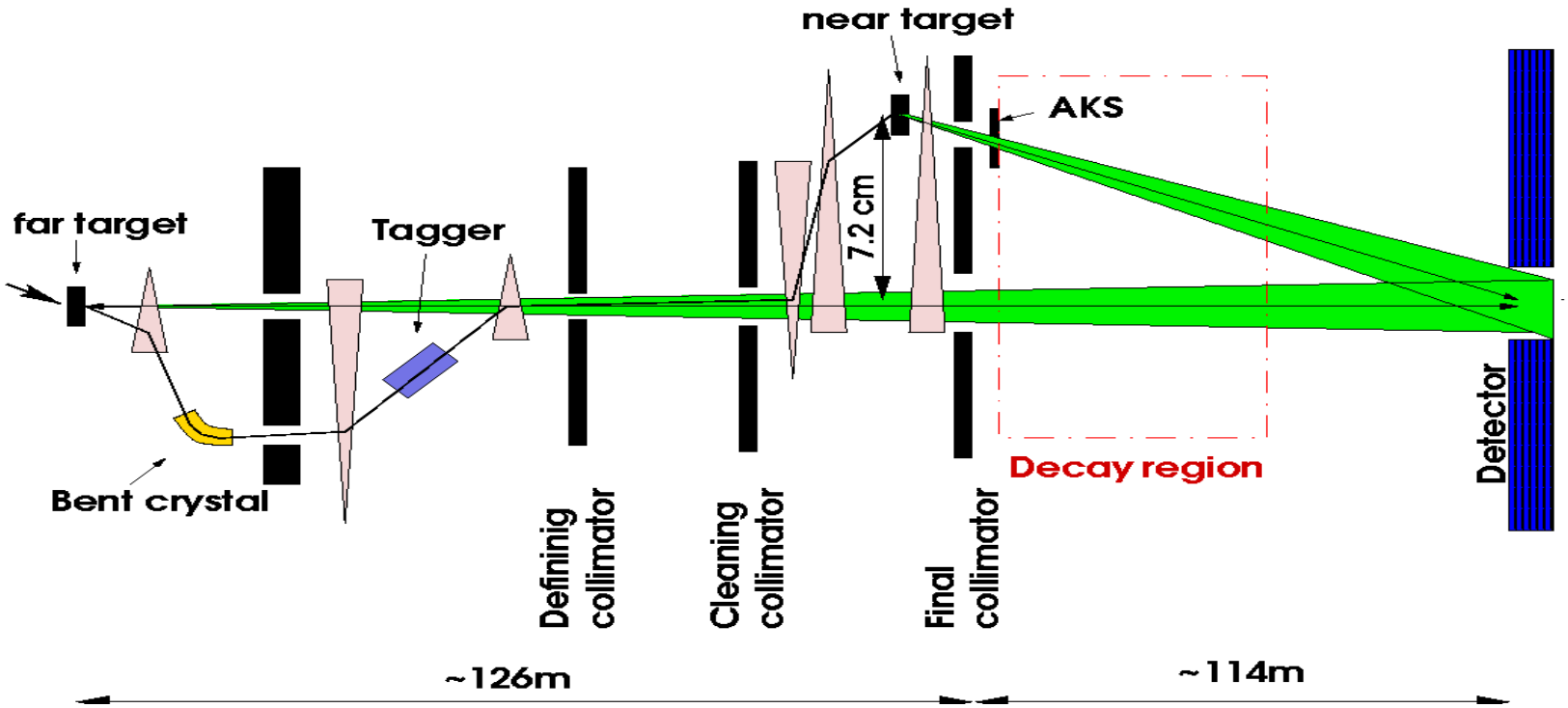
*On Befalf of the NA48 collaboration*
*Cambridge,Chicago,CERN,Dubna,Edinburgh*
*Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa,Saclay,*
*Siegen, Torino, Warsaw, Wien*

# Outlook

- Introduction
- First Observation of the decay $K_S \to \pi^0 ee$
- Search for CP(T) violation in $K_S \to 3\pi^o$ decays
- Conclusions

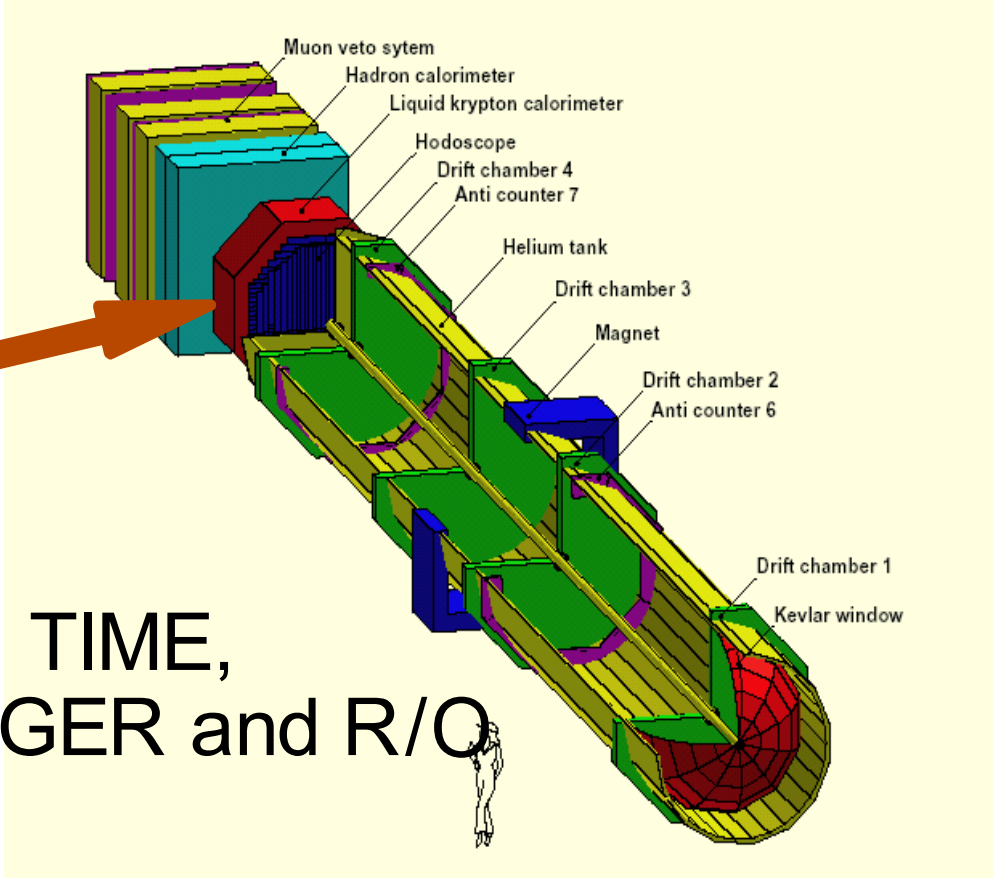
# NA48 neutral beam lines




Multi-stage collimation and high vacum in decay region and beam pipe:
→ neutron and gamma interactions kept at low level

# NA48 Central Detector

Lkr Calorimeter:
status of the art
for high resolution in
ENERGY, POSITION, TIME,
and remarkable TRIGGER and R/O
capabilities



# NA48 data taking periods

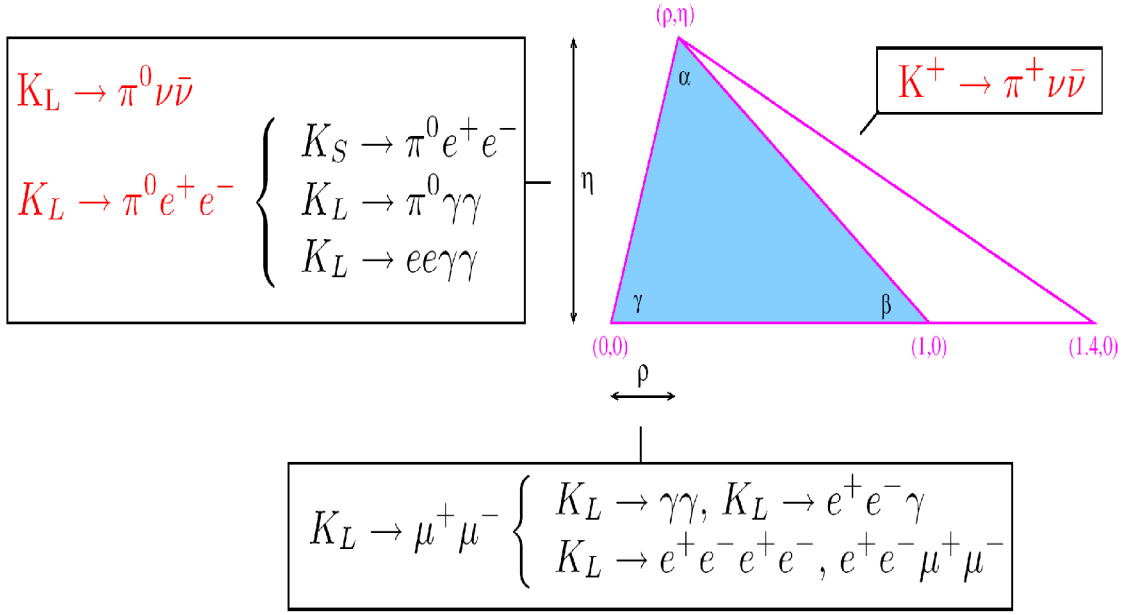
No spectrometer

| Run | Beam | Physics goals |
|---|---|---|
| 1997 | $K_L+K_S$ | $\varepsilon'/\varepsilon$ |
| 1998 | $K_L+K_S$ | $\varepsilon'/\varepsilon$<br>Rare $K_L$ decays |
| 1999 | $K_L+K_S$ | $\varepsilon'/\varepsilon$<br>Rare $K_L$ decays |
| | $K_L$ | Ke3/K$\mu$3 |
| | HI $K_S$ | $K_S$/hyperon decays |
| 2000<br>NA48<br>NA48/1 | $K_L$ | $\varepsilon'/\varepsilon$ checks<br>Neutral $K_L$ decays |
| | $\eta$ | $\varepsilon'/\varepsilon$ checks |
| | HI $K_S$ | Neutral $K_S$ decays<br>$\eta_{000}$ |

| Run | Beam | Physics goals |
|---|---|---|
| 2001 | $K_L+K_S$ | $\varepsilon'/\varepsilon$<br>Ke3/K$\mu$3 |
| 2002<br>NA48/1 | HI $K_S$ | Rare $K_S$ decays<br>Hyperon decays |
| 2003<br>NA48/2 | $K^+/K^-$ | Direct CP-v in<br>$K^{\pm}\rightarrow(3\pi)^{\pm}$<br>Rare $K^{\pm}$ decays |

# Measurement of $K_S \to \pi^o ee$

Unitarity triangle in the Kaon system

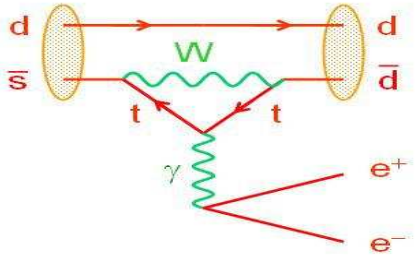



- $K \to \pi\nu\nu$ are theoretically clean, but experimentally very hard
- $K \to \pi ll$ are experimentally more constrained

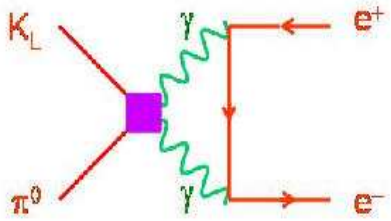
# $K_S \to \pi^o ee$ has three components

Complete re-analysis of the decay: Buchalla, D'Ambrosio, Isidori (BDI) hep-ph/0308008

- Direct CP-Violation (Short Distance)
  - SM fit: Im $\lambda_t = (1.36 \pm 0.12)\ 10^{-4}$
  - $BR(K_L \to \pi^o ee)_{CPV\text{-}dir} = (2.4 \pm 0.2) \times 10^{-12} \times (\mathrm{Im}\ \lambda_t / 10^{-4})^2 = (3.2 \pm 0.4) \times 10^{-12}$




- Indirect CP-Violation
  - $BR(K_L \to \pi^o ee)_{CPV\text{-}ind} \sim 1/330\ BR(K_S \to \pi^o ee)$




- CP-Conserving contribution
  - Need model ind. 3 par. fit (Gabbiani, Valencia, PRD 64 2001)
  - They fix the 3 counterterms from $K_L \to \pi^0\gamma\gamma$ and $K_S \to \gamma\gamma$
  - $BR(K_L \to \pi^o ee)_{CPC} < 3 \times 10^{-12}$ (conservative, BDI)

# $K_S \to \pi^o ee$ CPV components interfere

- $BR(K_L \to \pi^o ee)_{CPV} =$
  $[15.3\ |a_s|^2 \ \pm\ 6.8\ a_s\ (\mathrm{Im}\ \lambda_t / 10^{-4}) \ + 2.8\ (\mathrm{Im}\ \lambda_t / 10^{-4})^2\ ] \times\ 10^{-12}$

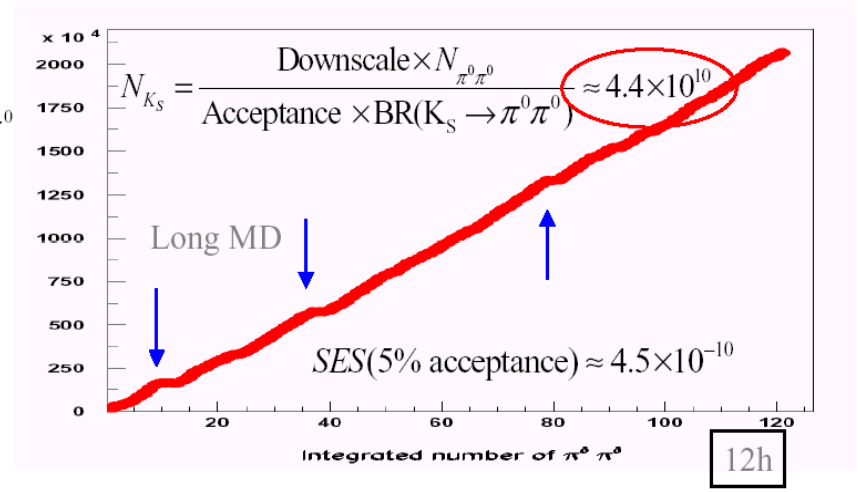
- $BR(K_S \to \pi^o ee) \ = 5.2\ |a_s|^2 \times 10^{-9}$

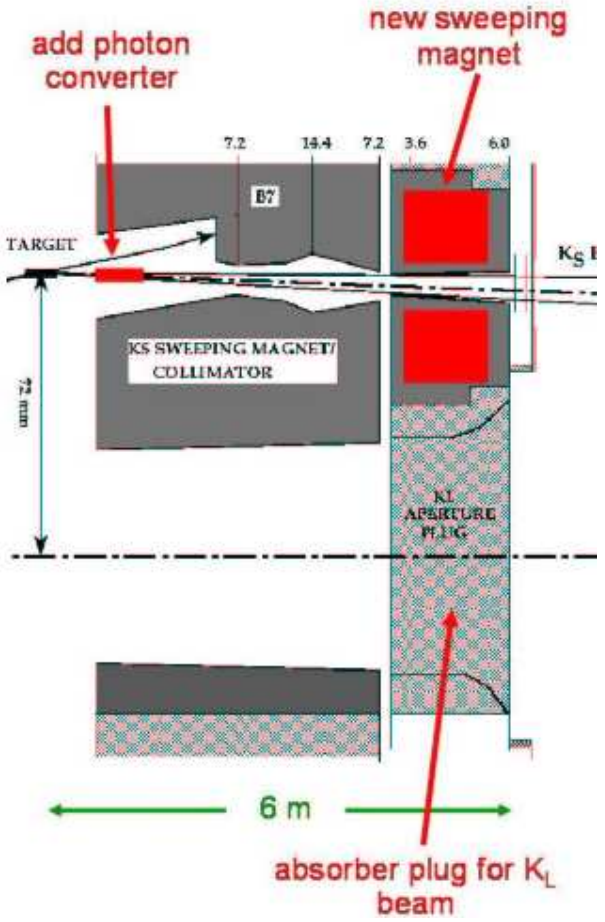
$BR(K_S \to \pi^o ee)$ and $BR(K_L \to \pi^o \gamma\gamma)$ determine whether it is possible to extract $\eta$ from a measurement of $BR(K_L \to \pi^o ee)$

Current limit: $BR(K_L \to \pi^o ee) < 5.1 \times 10^{-10}$ KTEV, PRL 86 397

# NA48/1: ~90 days data taking in 2002

- Run 2002: modified beam line
- 5 x $10^{12}$ protons/burst
- 2 x $10^{5}$ $K_s$ / burst
- ~4.4 x $10^{10}$ $K_s$ decays in fid. vol.



# Run 2002: Trigger for $\pi^o$ee events

- Level 1
  - Hits multiplicity in first DCH compatible with 1 track
- Level 2
  - Energy in EM CALO > 30 GeV
  - Energy center of gravity < 15 cm from beam axis
  - Fid. Vol. < 6 Ks lifetimes from final collimator
  - Hits multiplicity in first DCH compatible with 1 track
- Level 3
  - Software trigger: data volume reduction x 2.5

Trigger efficiency ~99.0% (measured using $\pi^o\pi^o_D$)

# Run 2002: R/O (upgraded)

- New DCH R/O:
  No dead time due to high multiplicity events
- Lkr CALO R/O:
  Compression of events gain x 2
- Events/burst ~ 50000
- Total data volume:
  ~ 50 TBytes

# $K_s \to \pi^o ee$ Data Analysis

- Selection of events with 2 clusters and 2 tracks within 2.5 ns
- Veto on additional tracks, clusters, hits in μ detector and energy deposition in Hadron CALO
- NEUTRAL VERTEX:
  - by imposing $m_{ee\gamma\gamma} = m_K$
  - ➔ extraction of $m_{\gamma\gamma}$
- CHARGED VERTEX:
  - By intersecting K and ee pair lines of flight
  - ➔ extraction of $m_{ee\gamma\gamma}$
- Kinematical analysis of events with $m_{\gamma\gamma}$ and $m_{ee\gamma\gamma}$
  - SIGNAL REGION: $\pm 2.5\ \sigma_{m_\pi}$ x $\pm\ 2.5\ \sigma_{m_K}$
  - CONTROL REGION: $\pm 6.0\ \sigma_{m_\pi}$ x $\pm\ 6.0\ \sigma_{m_K}$

  ($\sigma_{m_\pi}$=1.0 MeV/$c^2$ and $\sigma_{m_K}$ = 4.6 MeV/$c^2$)

# $K_S \to \pi^o ee$ Blind Analysis

1. Signal and Control regions masked
2. Selection tuning to reject BACKGROUND
3. Look at Control region
4. Accurate BKG evaulation
5. Look at Signal region

# $K_S \to \pi^o ee$ Background rejection

Most dangerous background sources:

1. $K_S \to \pi^o \pi^o$ with pion Dalitz decays or gamma conversions

2. $K_{L,S} \to ee\gamma\gamma$ (Greenlee) background

3. Overlap of 2 decays (close in time)

# $K_S \to \pi^o ee$ Background rejection (1)

$K_S \to \pi^o \pi^o$ with pion Dalitz decays or gamma conversions
especially when both pions decay $ee\gamma$

i. Rejection of small invariant mass ee pairs

accept if: $m_{ee} > 0.165$ MeV/$c^2$ (10 $\sigma$ away from $m_\pi$)

ii. Rejection of small invariant mass $\gamma$e pairs

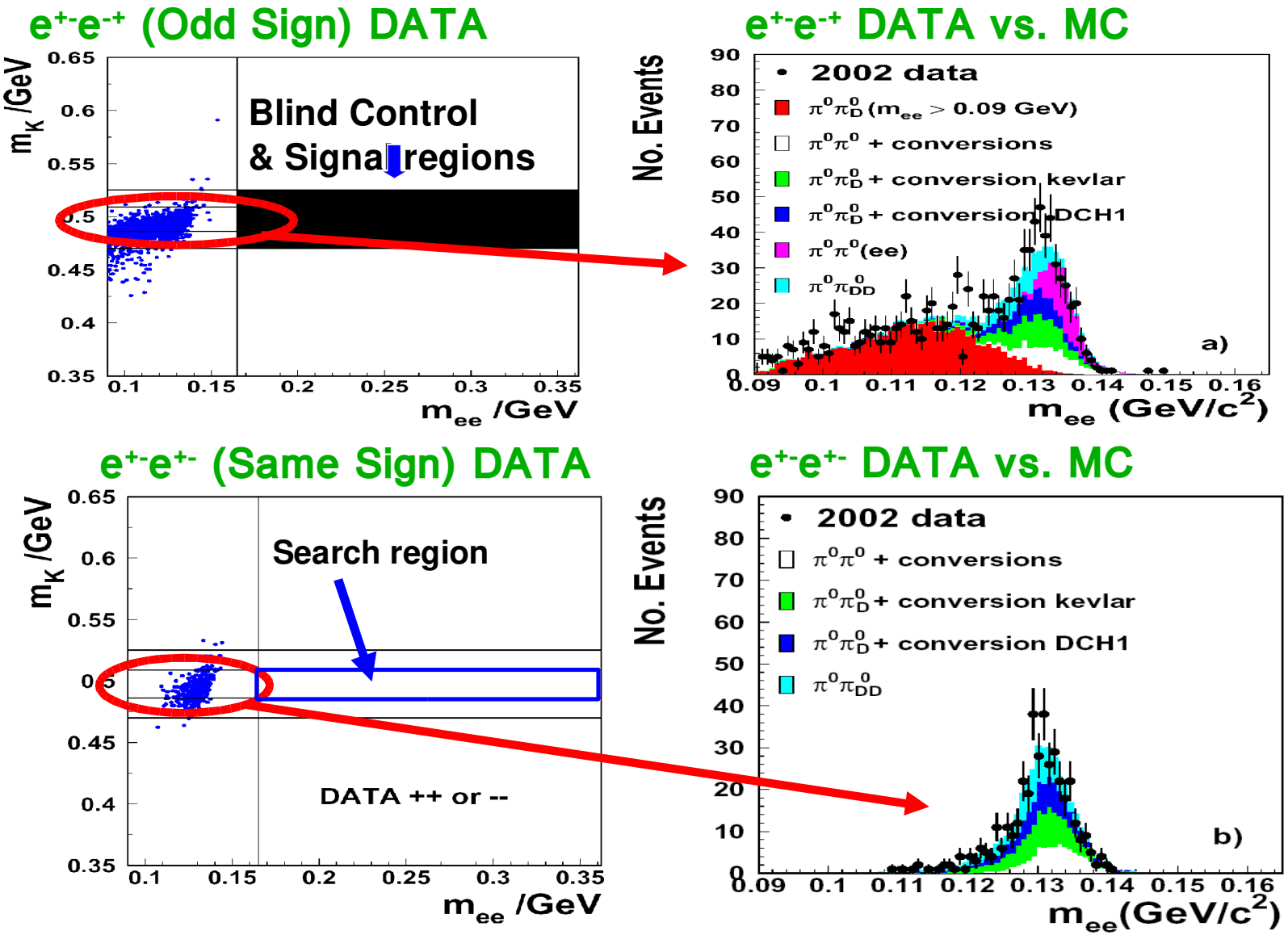
accept if: $m_{(e\gamma)1} > 0.165$ MeV/$c^2$ OR $m_{(e\gamma)2} > 0.165$ MeV/$c^2$

iii. Important check: events with SAME SIGN ee pairs

- No events found in DATA control region
- From Monte Carlo $\rightarrow$ 0.007 events expected in signal region

# $K_S \to \pi^o ee$ Background rejection (1)

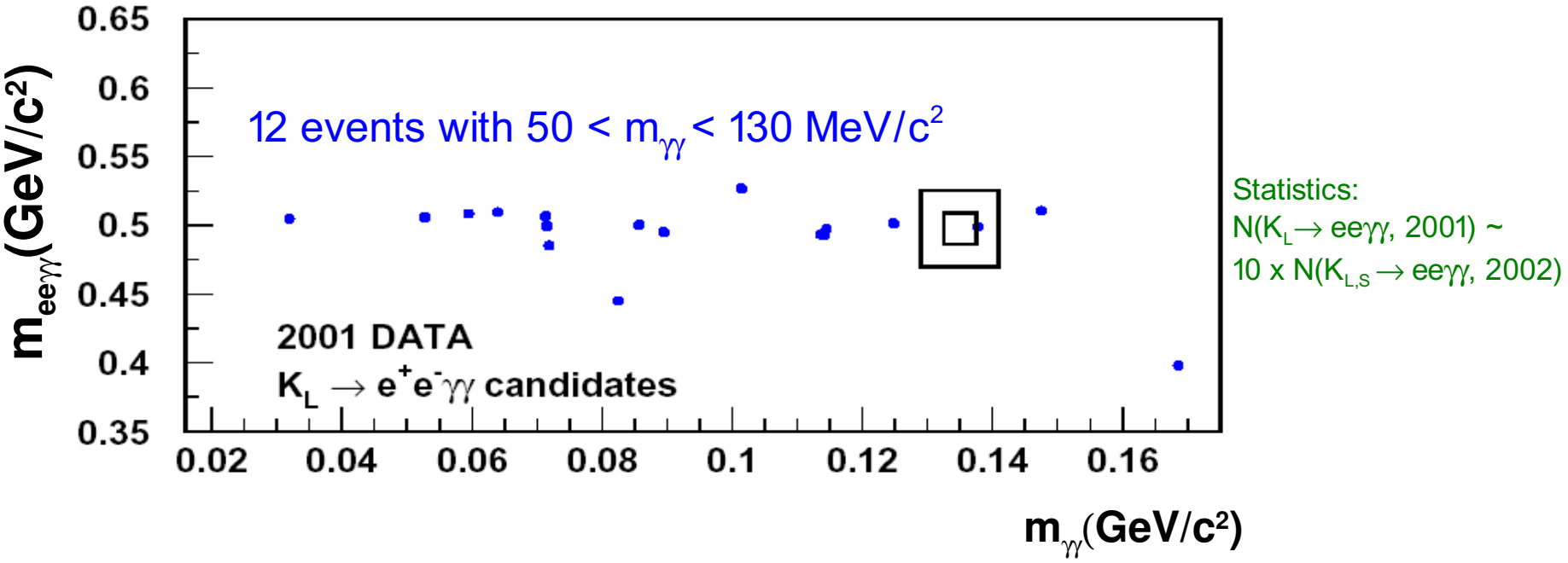
$K_s \to \pi^o \pi^o$ with pion Dalitz decays or gamma conversions



# $K_S \to \pi^o ee$ Background rejection (2)

## $K_{L,S} \to ee\gamma\gamma$ (Greenlee) background

- Measured using NA48 $K_L$ data from 2001
- Strongly suppressed by $m_{ee} > 0.165$ MeV/$c^2$ selection




Statistics:
$N(K_L \to ee\gamma\gamma, 2001) \sim$
$10 \times N(K_{L,S} \to ee\gamma\gamma, 2002)$

1 event in control region (24 $\sigma_{m_{\gamma\gamma}}$) $\to$ 0.075 in signal region (5 $\sigma_{m_{\gamma\gamma}}$)

# $K_S \to \pi^o ee$ Background rejection (3)

## Overlap of 2 decays (close in time)

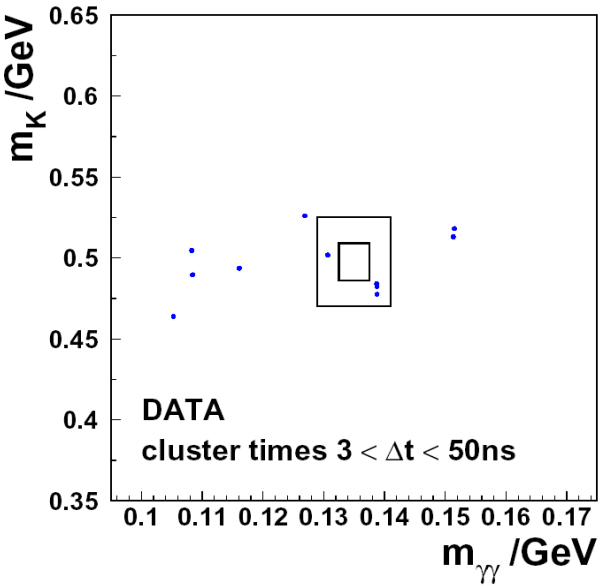
- Example:

  $p+Be \to K_L + X$ in time with $p+Be \to K_S + X$

  $\to \pi e \nu$ $\to \pi^o(\pi^o)$

  $\to \pi$ releases its energy in EM CALO

- Probability measured with decays well separated in time




3 events found in the control region
within a time interval of 47 ns

$\to$ 0.069 in the signal region

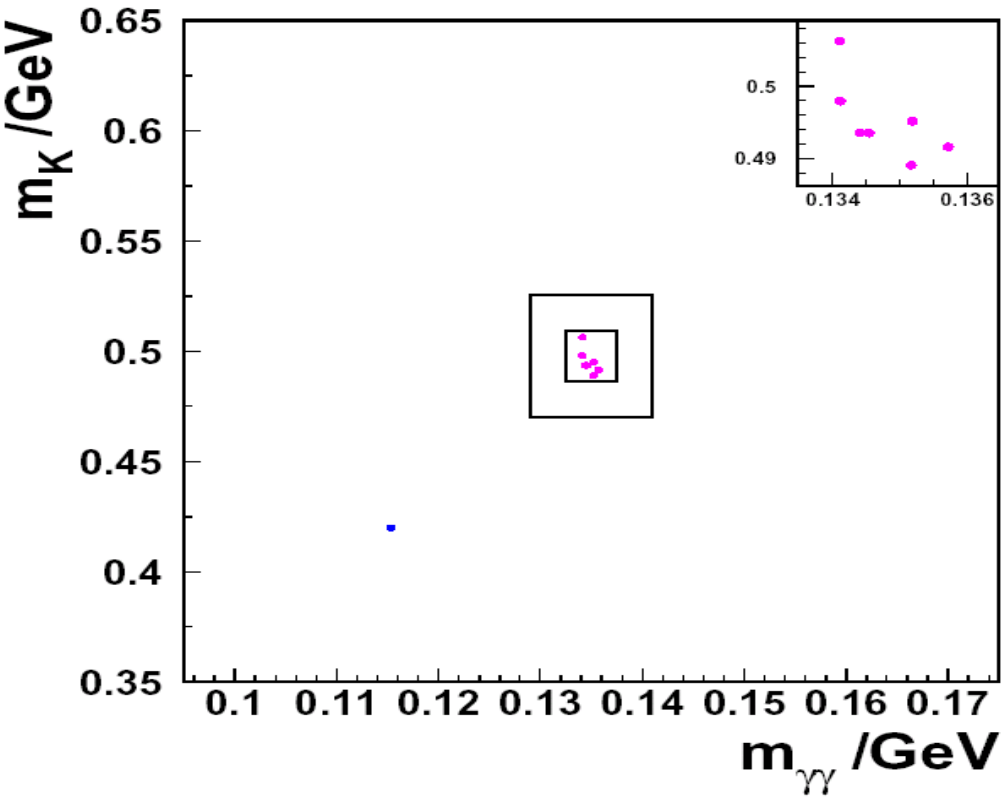
# $K_S \to \pi^o ee$ Background Summary

| Source | Control Region | Signal region |
|---|---|---|
| $K_S \to \pi^o_D \pi^o_D$ | 0.03 | 0.007 |
| $K_{L,S} \to ee\gamma\gamma$ | 0.11 | 0.075 |
| $\pi e\nu + 2\pi^o(\pi^o)$ | 0.19 | 0.069 |
| Total | $0.33^{+0.18}_{-0.11}$ | $0.15^{+0.05}_{-0.04}$ |

Many other sources investigated and found to be negligible

(e,g neutral cascade decays)

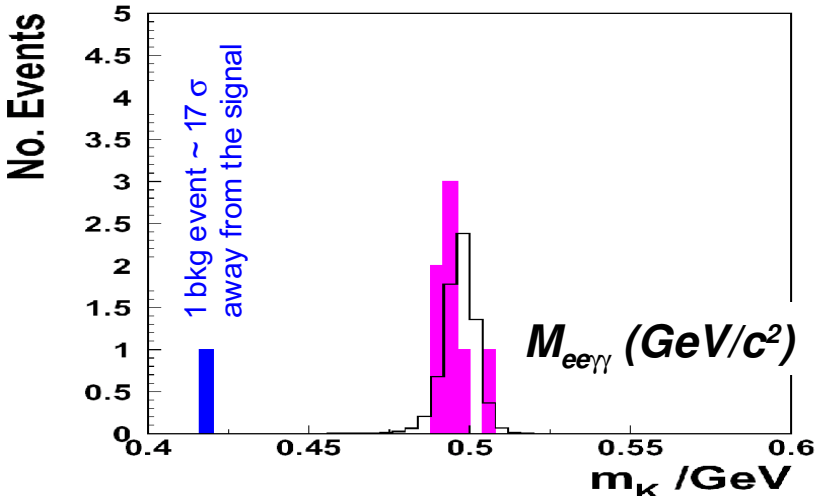
# First Observation of $K_S \to \pi^o ee$

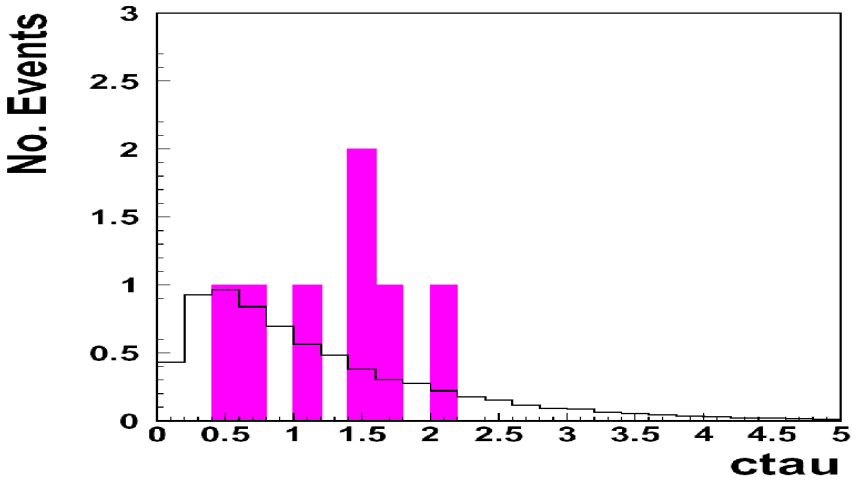


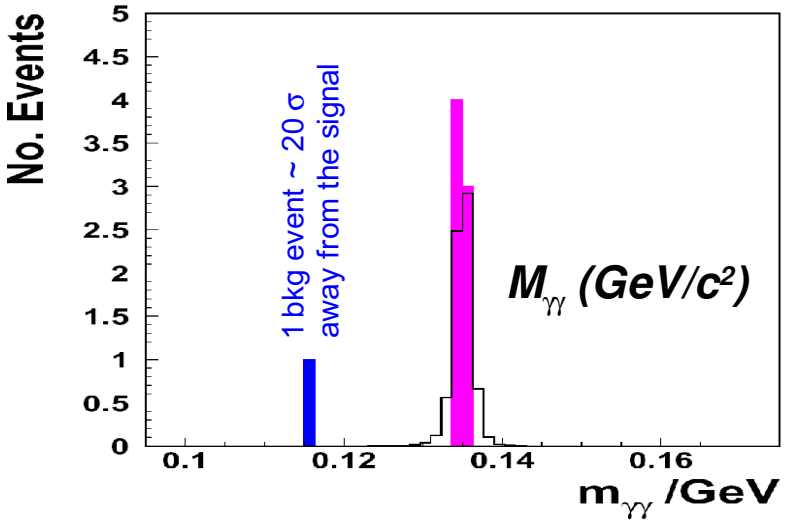

- 7 events found in the signal region
- 0 events found in the control region (***)
- 0.15 bkg events expected
- probability that all 7 events are bkg ~ $10^{10}$

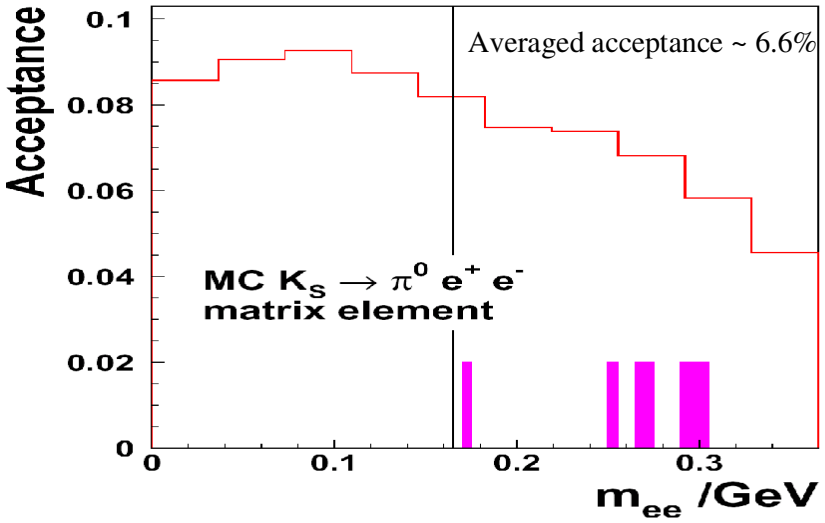
(***) No accumulation of events near the signal region, even relaxing other selections.

# How the 7 $K_S \to \pi^o ee$ events look ?



# $K_S \to \pi^o ee$ Branching Ratio

- Measured branching ratio:

**BR($K_S \to \pi^o ee$, $m_{ee}$>165 MeV/$c^2$) = ($3.0^{+1.5}_{-1.2}$(stat) ± 0.2(syst))×$10^{-9}$**

- Full branching ratio, extrapolating to all $m_{ee}$

(assuming vector interaction and unity form factor)

**BR($K_S \to \pi^o ee$) = ($5.8\ ^{+2.8}_{-2.3}$ (stat) ± 0.3($_{syst}$) ± 0.8(theor))×$10^{-9}$**

- Remarkable agreement with L. Sehgal prediction:

~5.5 ×$10^{-9}$ NP B19 (1970)

- In the notation of D'Ambrosio et al. JHEP 08 (1998 004):

$BR(K_S \to \pi^0 ee) \sim 5\ |a_s|^2 \ \to$

**$|a_s| = 1.08\ ^{+0.26}_{-0.21}$**

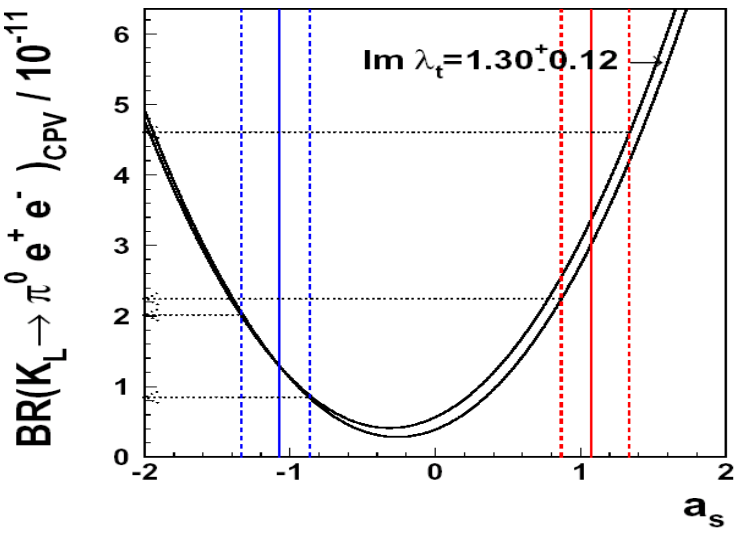
**PRELIMINARY**

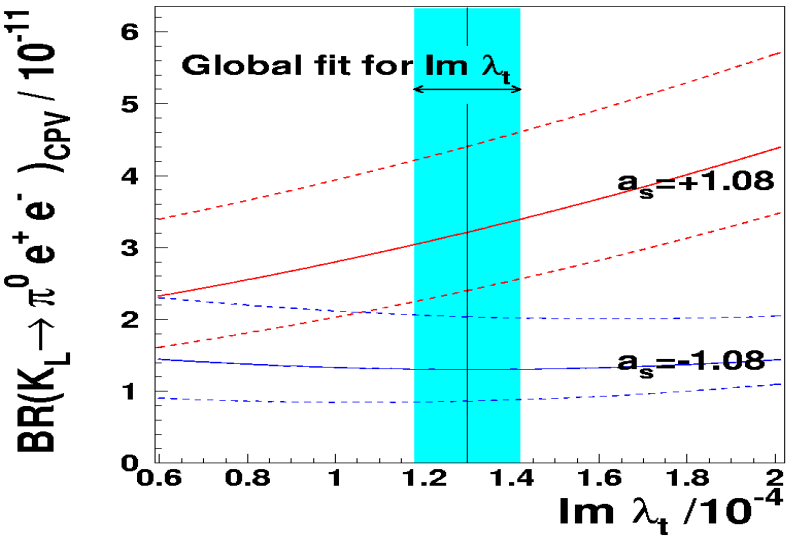
# Implications for $K_L \to \pi^o ee$

Measurement of |as| allows $BR(K_L \to \pi^o ee)$ to be predicted as a function of Im $\lambda_t$ to within a sign ambiguity:

INDIRECT INTERFERENCE DIRECT

$$BR(K_L \to \pi^o ee)_{CPV} = (17.7 \pm 9.5 + 4.7) \times 10^{-12}$$




=> expected $BR(K_L \to \pi^o ee)_{CPV} = 1 - 4 \times 10^{-11}$

# $K_S \to \pi^o \mu\mu$
# NA48/I preliminary result very soon

- Ratio BR($K_S \to \pi^o \mu\mu$)/BR($K_S \to \pi^o ee$) ~ 0.24

  well predicted from chiral PT

- Expected ~3 events in the box
- Dominant bkg from overlapping events
- Bkg from $K_L \to \pi^+ \pi^- \pi^o$ where pions decay in flight is

  minimized by kinematical constraints

# Search for CP(T) violation in $K_S \to 3\pi^o$ decays

- In the kaon system $K_S \to 3\pi^o$ is the CP violating mode ($CP(3\pi^0) = -1$) corresponding to $K_L \to 2\pi^o$

- The equivalent of $\eta_{oo}$ for $3\pi^o$ is:

$$\eta_{ooo} = \frac{A(K_S \to \pi^0\pi^0\pi^0)}{A(K_L \to \pi^0\pi^0\pi^0)} = \epsilon - \delta + i\frac{\Im(A_1)\exp(i\delta_1) - \Im(A_3)\exp(i\delta_3)}{\Re(A_1)\exp(i\delta_1) - \Re(A_3)\exp(i\delta_3)}$$

- It is equally allowed in the SM (where $\eta_{ooo} \sim \varepsilon$) but much more difficult to be investigated experimentally.

# Search for CP violation in $K_S \to 3\pi^o$ decays current limits

| | | | | |
|---|---|---|---|---|
| $\eta_{000}$ | Barmin et al. | 1983 | Bubble ch. | Re $\eta_{000}$=-8 ± 18 × $10^{-2}$<br>Im $\eta_{000}$=-5 ± 27 × $10^{-2}$ |
| | CPLEAR | 1998 | ppbar→$K^+K_0$bar$\pi^-$<br>$K^-K_0\pi^+$ | Re $\eta_{000}$=18 ± 14± 6 × $10^{-2}$<br>Im $\eta_{000}$=15 ± 20 ± 3 × $10^{-2}$ |
| | Novosibirsk SND | 1999 | Tagged $K_s$<br>ee→$\phi$→$K_SK_L$ | BR($K_S \to 3\pi^0$)<1.4 $10^{-5}$ 90%CL |

# NA48 search for $K_S \to 3\pi^o$ decays

NA48 data taking in year 2000 with no Drift Chambers

great opportunity to exploit the excellent energy resolution of the Lkr calorimeter and the high vaucum in the beam line

DOUBLE RATIO Method:

1) Two beams run not simultaneously: "KS beam" (NEAR) and "KL beam" (FAR) where a $K^o$-$K^o$bar incoh. mixture is produced by 400 GeV/c protons on Be

2) Look for $K_S$ - $K_L$ interference by analyzing in bins of energy the intensity of $3\pi^0$ decays from NEAR BEAM as a function of the proper time

3) Measure the acceptance using the $3\pi^0$ decays from the FAR beam

4) Apply Monte Carlo small acceptance corrections to take into account the slight geometrical difference between NA48 KS and KL beams

5) Fit the DOUBLE RATIO = (data-near/data-far)/(MC-near/MC-far)

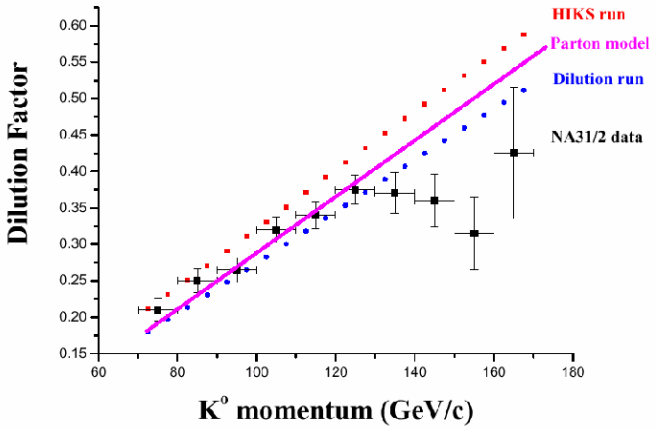
# NA48 search for $K_S \to 3\pi^o$ decays

The fit functions in the double ratio are:

$$f(E,t) = \frac{NEAR}{FAR} =$$
$$A(E)\left[1 + \left|\eta_{000}\right|^2 e^{(\Gamma_L - \Gamma_S)t} + 2D(E)e^{\frac{1}{2}(\Gamma_L - \Gamma_S)t}\left(\mathrm{Re}\eta_{000}\cos\Delta mt - \mathrm{Im}\eta_{000}\sin\Delta mt\right)\right]$$

Where D(E) is the energy dependent DILUTION function, measured by NA31:

$$D(E) = \frac{N(K^o) - N(\bar{K}^o)}{N(K^o) + N(\bar{K}^o)}$$



# NA48 search for $K_S \to 3\pi^0$ decays

NEAR and FAR target runs:

- SAME TRIGGER and DETECTOR
- SIMILAR ACCIDENTAL ACTIVITY (by tuning intensity)

Data samples:

- Near-target run

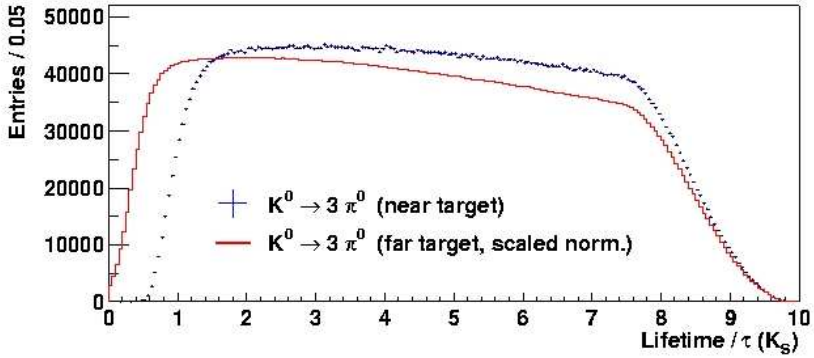
  $3\pi^0$ data: 6.5 x $10^6$

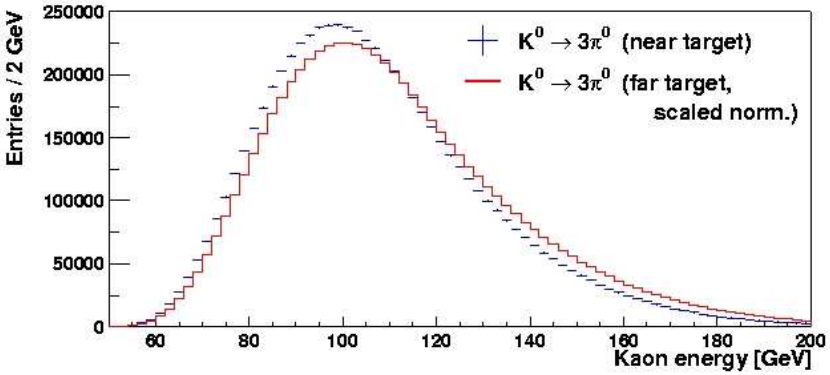
  $K_L \to 3\pi^0$ MC: 66 x $10^6$

- Far-target run

  $K_L \to 3\pi^0$ data: 154.7 x $10^6$

  $K_L \to 3\pi^0$ MC: 66 x $10^6$



# NA48 search for $K_S \to 3\pi^0$ decays

Simultaneous fit in 20 energy bins: free parameters = $Re(\eta_{000})$, $Im(\eta_{000})$, 20 normalization

Fit result (correlation $\rho = 0.8$):

$Re(\eta_{000}) = 0.026 \pm 0.010_{stat}$

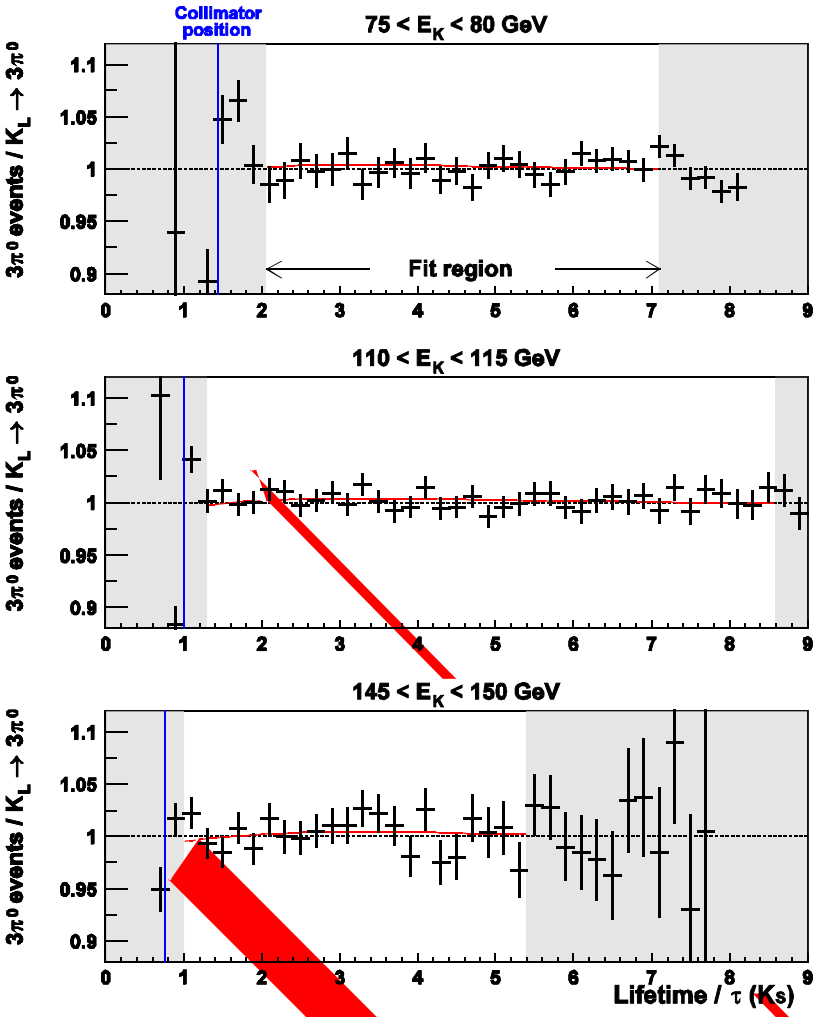
$Im(\eta_{000}) = 0.034 \pm 0.010_{stat}$

Check: fit far-target data/MC ($\eta_{000} = 0$)

$Re(\eta_{000}^{\text{far target}}) = 0.01 \pm 0.40$

$Im(\eta_{000}^{\text{far target}}) = 0.49 \pm 0.38$

| Systematics | $Re(\eta_{000})$ | $Im(\eta_{000})$ |
|---|---|---|
| Acceptance | ± 0.003 | ± 0.008 |
| Accidental activity | ± 0.001 | ± 0.006 |
| Energy scale | ± 0.001 | ± 0.001 |
| $K^0K^0$ dilution | ± 0.003 | ± 0.004 |
| Fit | ± 0.001 | ± 0.002 |
| Total | ± 0.005 | ± 0.011 |



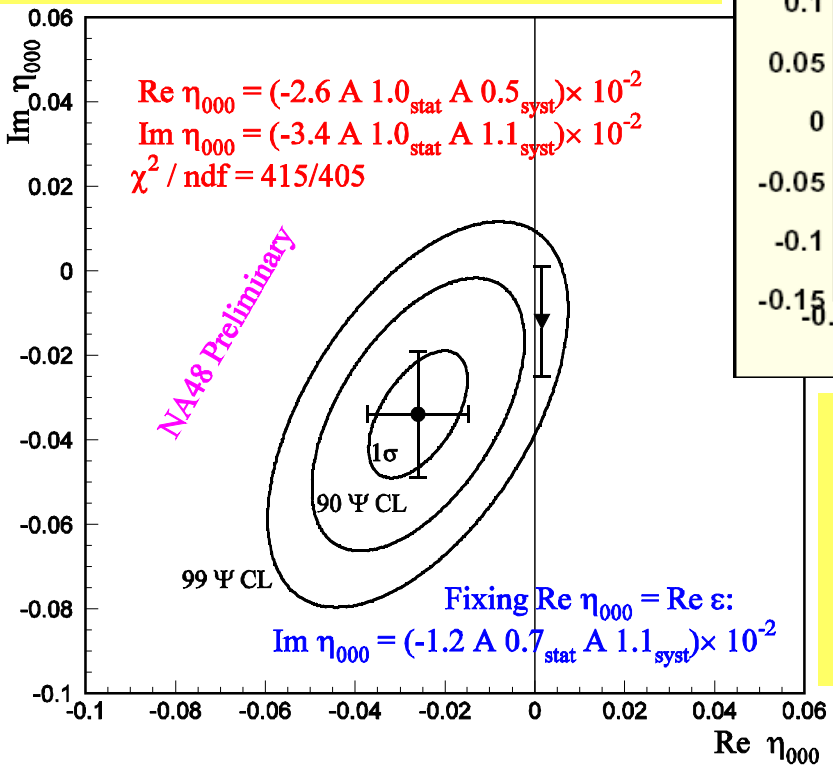
# $K_S \to 3\pi^o$ results on CP violation

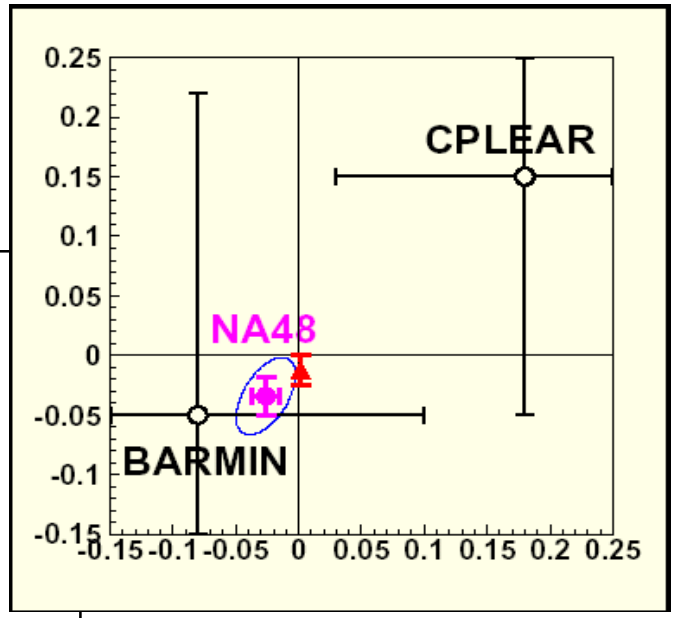
Preliminary NA48 result:

$Re(\eta_{000}) = 0.026 \pm 0.010_{stat} \pm 0.005_{sys}$

$Im(\eta_{000}) = 0.034 \pm 0.010_{stat} \pm 0.011_{sys}$

$BR(K_S \to 3\pi^0) < 1.4 \times 10^{-6}$ 90% CL




If $Re(\eta_{000}) = Re(\varepsilon)$

(assuming CPT conservation and $\Delta I = 3/2$ suppression):

$Im(\eta_{000}) = 0.012 \pm 0.007_{stat} \pm 0.011_{sys}$

$BR(K_S \to 3\pi^0) < 3.0 \times 10^{-7}$ 90% CL

SM prediction $BR(K_S \to 3\pi^0) \sim 3.0 \times 10^{-9}$

# $K_S \to 3\pi^o$ results on CPT violation

The Bell-Steinberger unitarity relation:

$$\Re\,\epsilon - i\,\Im\,\delta = \frac{1}{2\,(i\,\Delta\,m + 1/2\,(\Gamma_S + \Gamma_L))} \sum A^x(K_S \to f)\,A(K_L \to f)$$

where $K_S = K_1 + (\epsilon - \delta)\,K_2$
$K_L = K_2 + (\epsilon + \delta)\,K_1$

allows to test CPT in the KS-KL mixing.
So far the uncertainty on the test was dominated by the error on $A(K_S \to 3\pi^o)$. After NA48 measurement:

$$\mathrm{Im}\,\delta = (-1.2 \pm 3.0) \times 10^{-5} \quad \text{(now limited by } \eta_{+-}\text{)}$$

Assuming no CPT violation in decay:

$$M(K^0) - M(K^0\mathrm{bar}) = (-1.7 \pm 4.2) \times 10^{-19}\ \mathrm{GeV}/c^2$$

# Conclusions

A state of the art Lkr electromagnetic calorimeter
and high intensity kaon beam lines
have been allowing NA48 to address
various kaon rare decay studies.
This talk illustrated the preliminary results on :

THE FIRST OBSERVATION OF THE $K_S \to \pi^o ee$ DECAY:

$$BR(K_S \to \pi^o ee) = (5.8\ ^{+2.8}_{-2.3\ stat} \pm 0.3_{sys} \pm 0.8_{th}) \times 10^{-9}$$

THE SEARCH FOR CP(T) VIOLATION IN THE $K_S \to 3\pi^o$ DECAY:

$$Re(\eta_{000}) = 0.026 \pm 0.010_{stat} \pm 0.005_{sys}$$

$$Im(\eta_{000}) = 0.034 \pm 0.010_{stat} \pm 0.011_{sys}$$

$$Im\ \delta = (-1.2 \pm 3.0) \times 10^{-5}$$