Latest Results from NA48 and NA48/1

Mark Slater
University of Cambridge

Rencontres de Moriond
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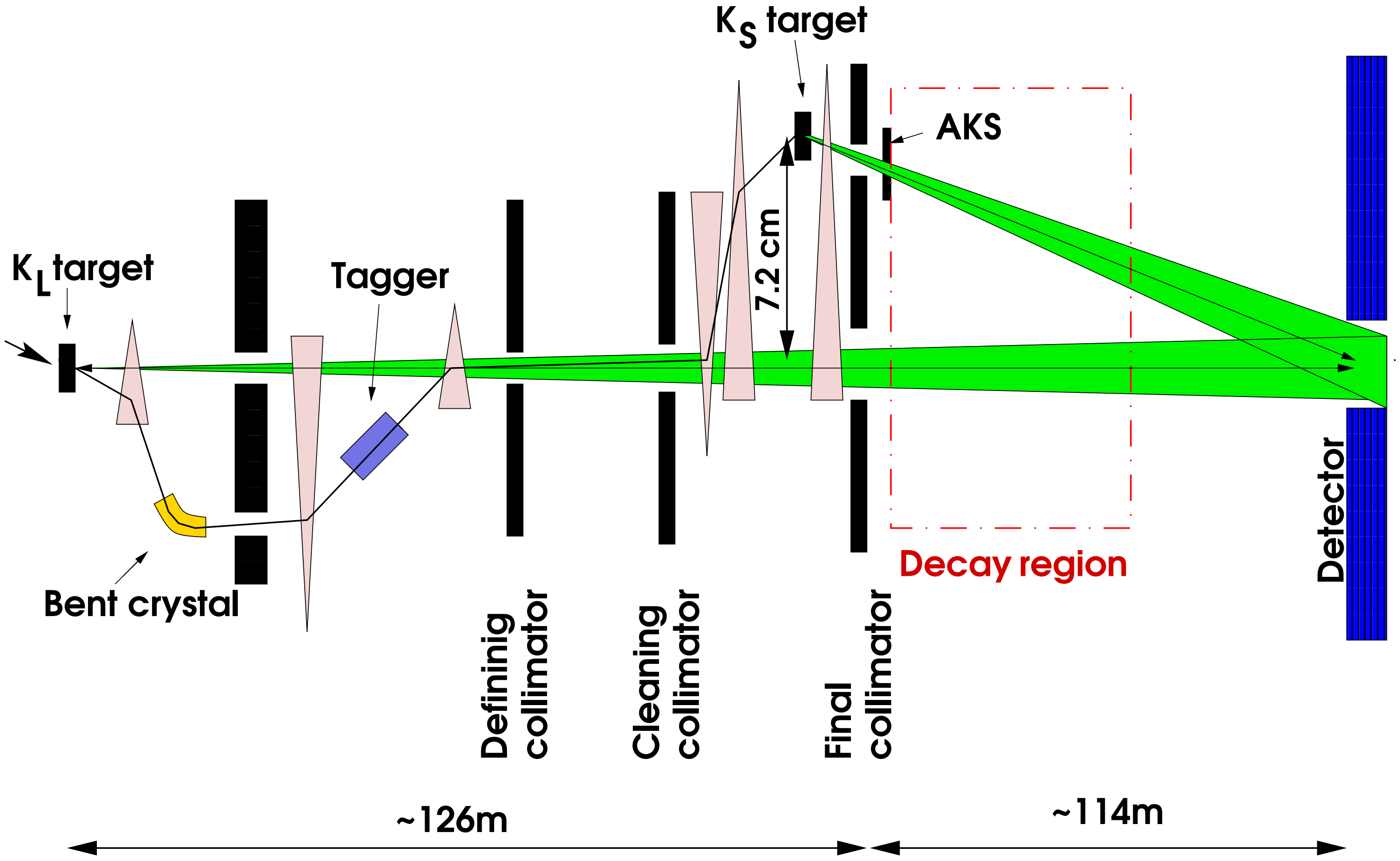
On behalf of the NA48 and NA48/1 Experiments :
Cambridge, Chicago, CERN, Dubna, Edinburgh
Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Saclay,
Siegen, Torino, Warsaw, Wien

Outline

- The NA48 beamline and detector
- Physics motivation for $K_S \to \pi^0 l^+ l^-$searches
- First observation of $K_S \to \pi^0 e^+ e^-$
- First observation of $K_S \to \pi^0 \mu^+ \mu^-$
- Interpretation of $K_S \to \pi^0 l^+ l^-$ Results
- Branching Ratio, Form Factor and Asymmetry measurements of:
  - $K_L \to \pi^\pm e^\mp \nu \gamma$
  - $K_L \to \pi^0 \pi^\pm e^\mp \nu$
  - $\Xi \to \Lambda \gamma$
- Conclusions

The NA48 simultaneous K_S and K_L beams

Used for $\mathrm{Re}(\varepsilon'/\varepsilon)$ measurement until 2001



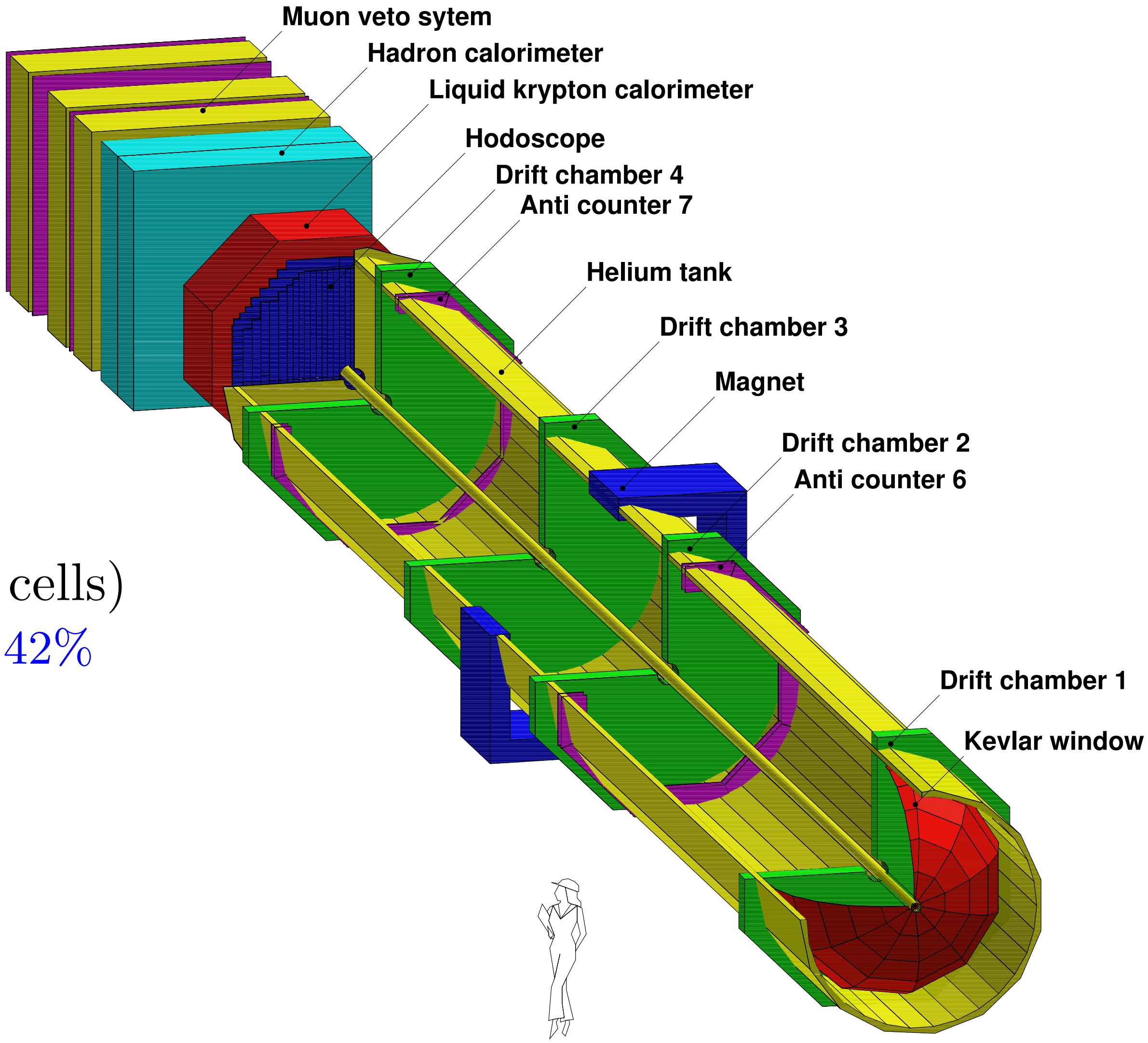
In 2002: K_S target only

NA48 Detector

- Magnetic spectrometer :
  charged particles
  $\sigma(p)/p \simeq 0.5\ \% \oplus 0.009\ p[GeV/c]\ \%$
  ($P_{\perp}{}^{kick} \sim 265$ MeV/c)

- Liquid Krypton EM calorimeter :
  photons and electrons
  high granularity (13212 2×2 cm^2 cells)
  $\sigma(E)/E = 3.2\%/\sqrt{E} \oplus (9\%)/E \oplus 0.42\%$
  $\sigma(t) \simeq 265$ ps for 50 GeV e^-

- Muon System :
  $\sigma(t) \simeq 350$ ps
  25cm $\times$ 25cm cells

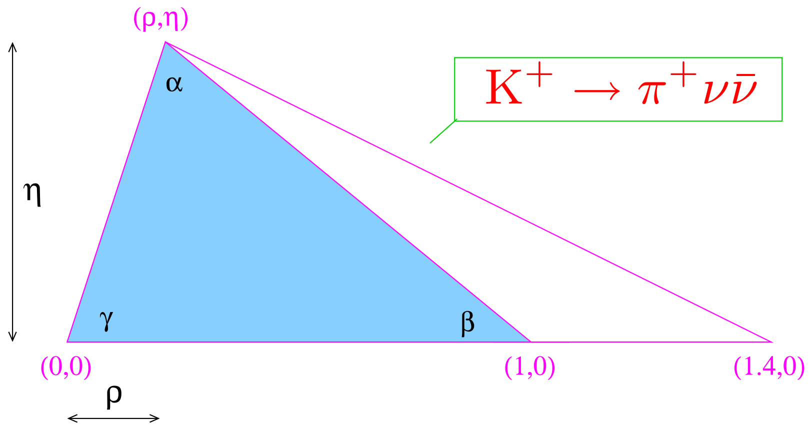


$K_S \to \pi^0 l^+ l^-$: *Physics Motivation*

Parameters of the unitarity triangle can be determined using rare Kaon decays:

$\mathrm{K_L} \to \pi^0 \nu \bar{\nu}$

$$K_L \to \pi^0 l^+ l^- \left\{ \begin{array}{l} K_S \to \pi^0 l^+ l^- \\ K_L \to \pi^0 \gamma\gamma \\ K_L \to l^+ l^- \gamma\gamma \end{array} \right.$$



$$K_L \to \mu^+ \mu^- \left\{ \begin{array}{l} K_L \to \gamma\gamma,\ K_L \to e^+ e^- \gamma \\ K_L \to e^+ e^- e^+ e^-,\ e^+ e^- \mu^+ \mu^- \end{array} \right.$$

$K_L \to \pi^0 l^+ l^-$ contains:

- a CP conserving part — $\mathrm{BR}(K_L \to \pi^0 \gamma\gamma)$
- a direct CP violating part — determines η
- an indirect CP violating part, — $\mathrm{BR}(K_S \to \pi^0 l^+ l^-)$

Analysis Strategy for $K_S \to \pi^0 e^+ e^-$ *and* $K_S \to \pi^0 \mu^+ \mu^-$

Branching ratios predicted to be $\sim 10^{-9}$

$\rightarrow$ Only a few events expected

"Blind Analysis" procedure employed $\rightarrow$ signal and control regions masked:

Signal Region: $2.5\sigma_{m_K} \times 2.5\sigma_{m_{\pi^0}}$
Control Region: $6.0\sigma_{m_K} \times 6.0\sigma_{m_{\pi^0}}$

Backgrounds were studied using both data and MC simulation

$\rightarrow$ Fix cuts

$\rightarrow$ Unmask control region

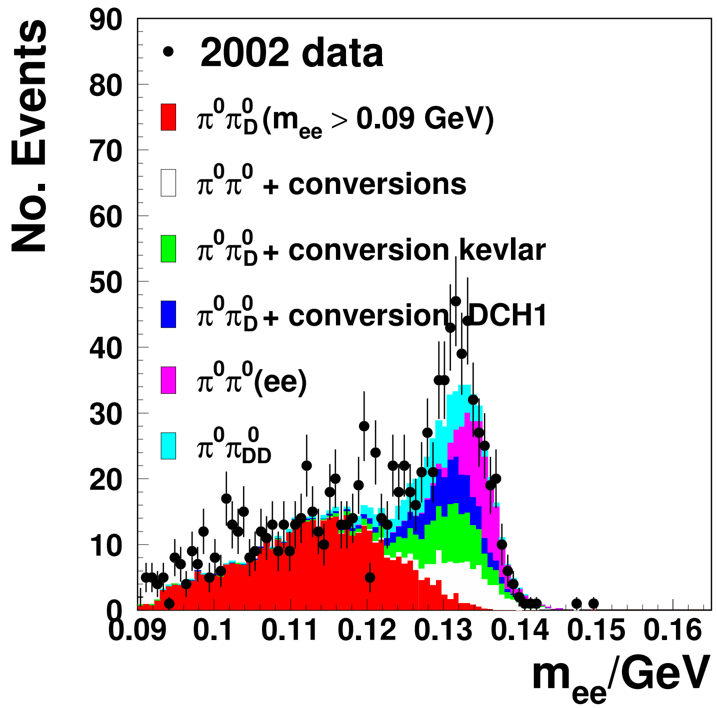
$\rightarrow$ Unmask signal region

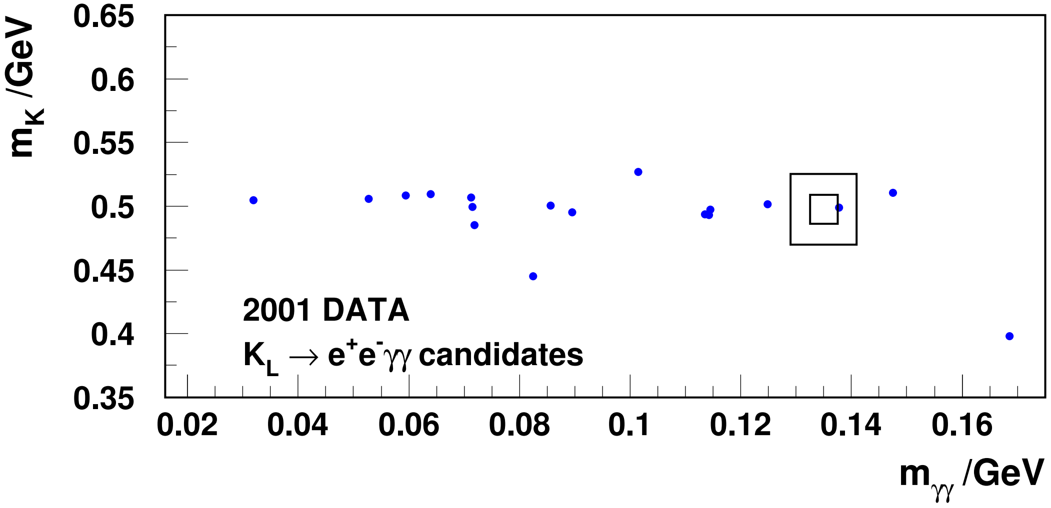
Backgrounds to the Search for $K_S \rightarrow \pi^0 e^+ e^-$

Significant background from Dalitz decays and conversions

Background simulated in Monte Carlo:
$\rightarrow$ Reasonable Agreement

Removed by a conservative cut:
$m_{ee} > 0.165$ GeV





Irreducible background from $K_L \rightarrow ee\gamma\gamma$

Estimated to be $\sim$ 0.075 events using 2001 K_L data

Further Backgrounds to the Search for $K_S \to \pi^0 e^+ e^-$

Further background contributions from Ξ^0 decays:

- $\Xi^0 \to \Lambda(p\pi^-)\pi^0$
- $\Xi^0 \to \Lambda(pe^-\nu)\pi^0$
- $\Xi^0 \to \Sigma^+(p\pi^0)e^-\nu$

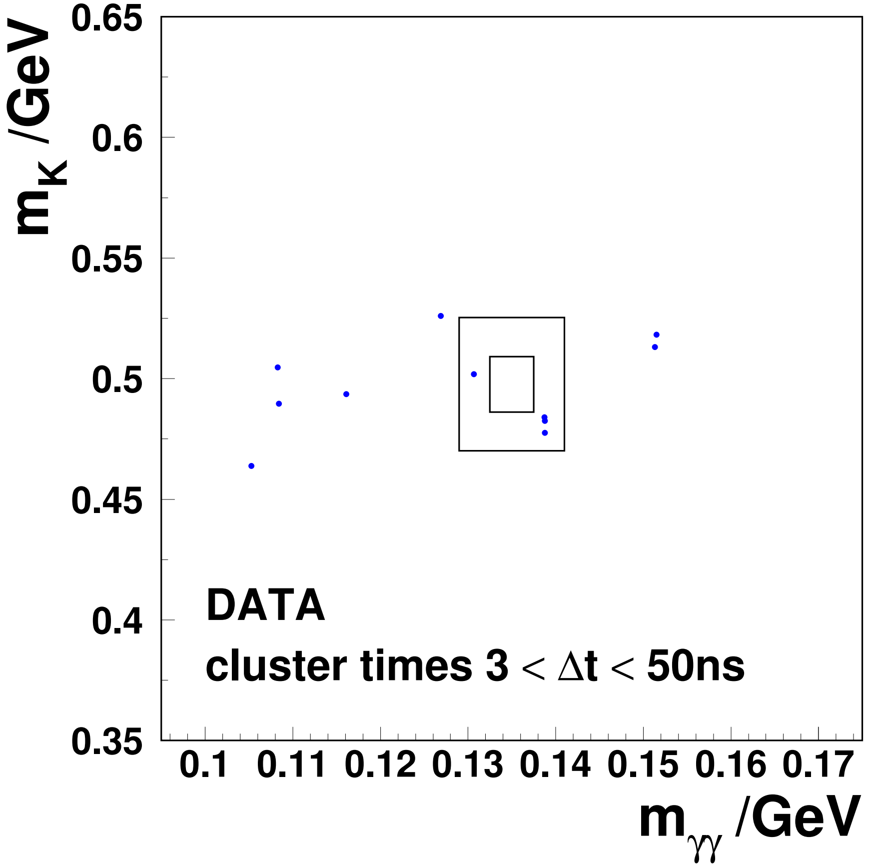
Removed by a Momentum Asymmetry cut

Accidental Backgrounds

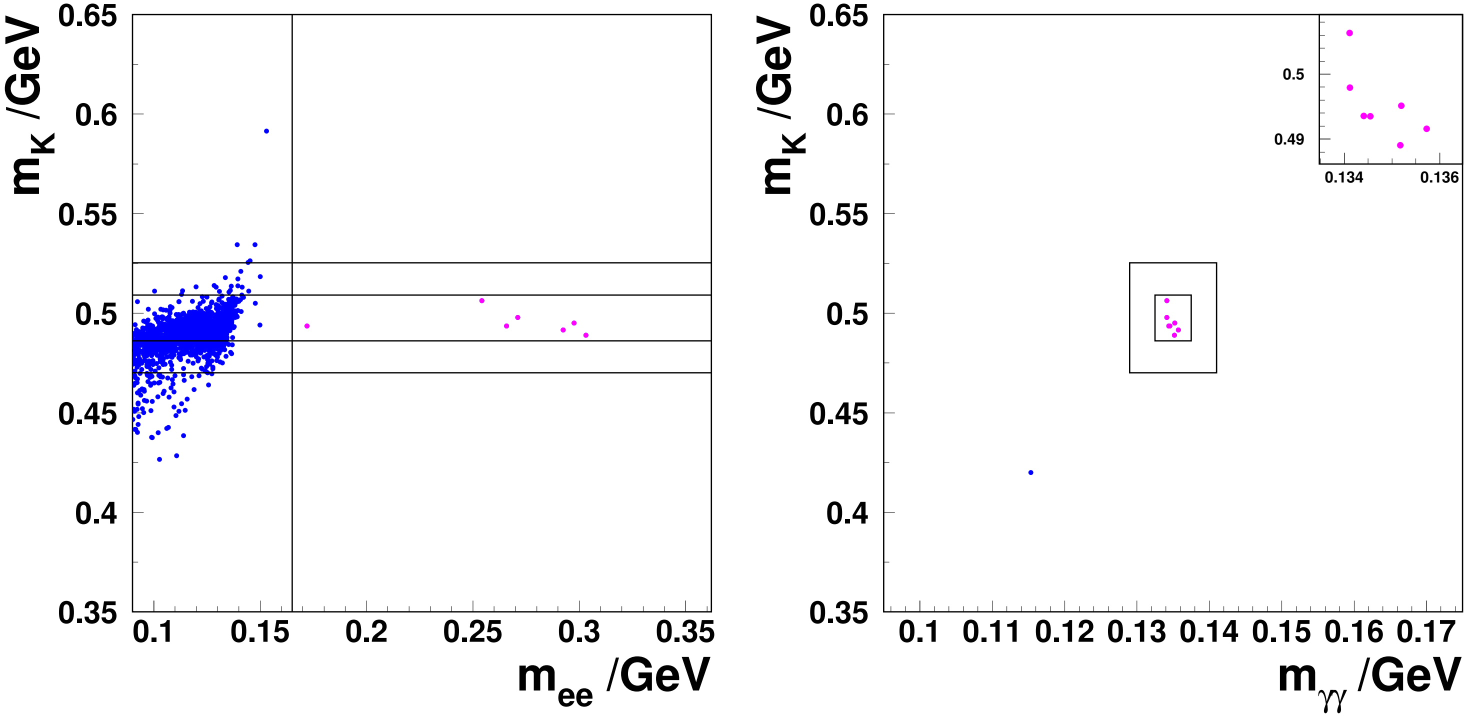
Background from fragments of two overlapping decays, e.g. $K_L \to \pi^\pm e^\mp \nu + K_S \to \pi^0\pi^0$

Estimated by extrapolating from the control region in the time sidebands

$\to$ 0.069 expected events



The Result



7 events found with a background of $0.15^{+0.05}_{-0.04}$

$\rightarrow$ presence of signal well established

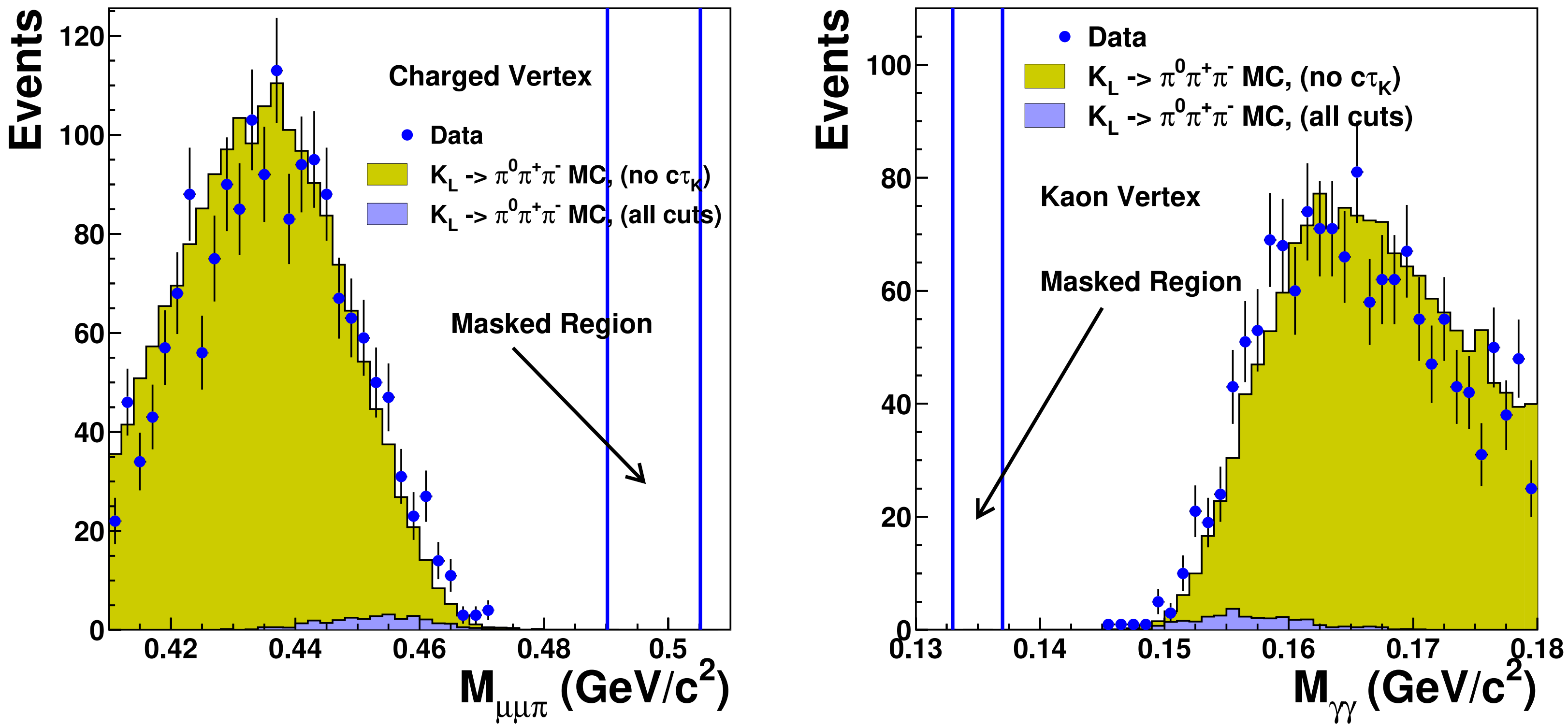
This leads to the result (using unit form factor):

$$BR(K_S \rightarrow \pi^0 e^+ e^-) = (5.8^{+2.8}_{-2.3}(stat) \pm 0.3(syst) \pm 0.8(theory)) \times 10^{-9}$$

[PLB576 (2003)]

Physical Background to the Search for $K_S \to \pi^0\mu^+\mu^-$

Background from $K_L \to \pi^0\pi^+\pi^-$ studied using Monte Carlo:



$\sim 22 \times 2002$ statistics was generated

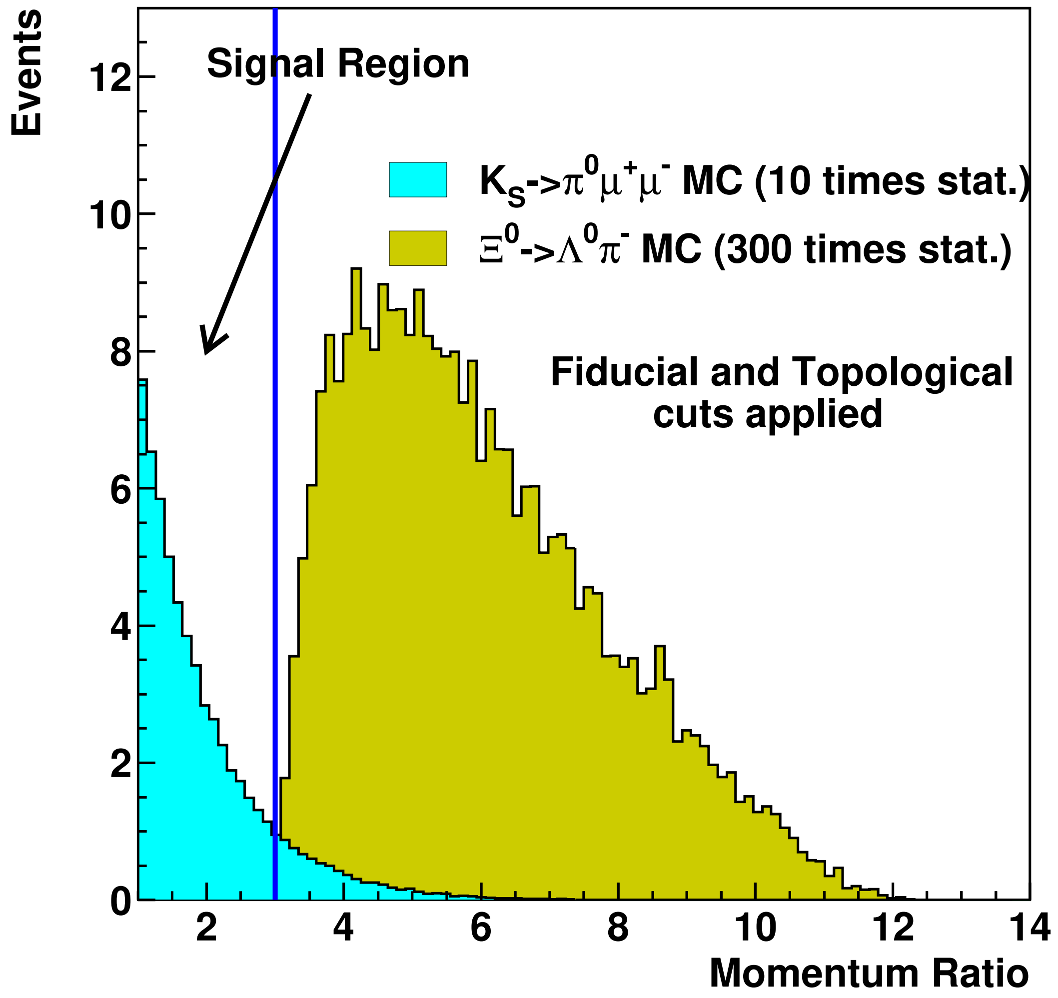
$\rightarrow$ No MC events found in signal region

$\rightarrow \leq 0.019$ events expected

Further Physical Backgrounds to the Search for $K_S \rightarrow \pi^0\mu^+\mu^-$

As with $K_S \rightarrow \pi^0 e^+ e^-$, there is a background contribution from Hyperon decays

Removed by a similar Momentum Asymmetry cut



The background $K_L \rightarrow \mu^+\mu^-\gamma\gamma$ is also present, (Greenlee)

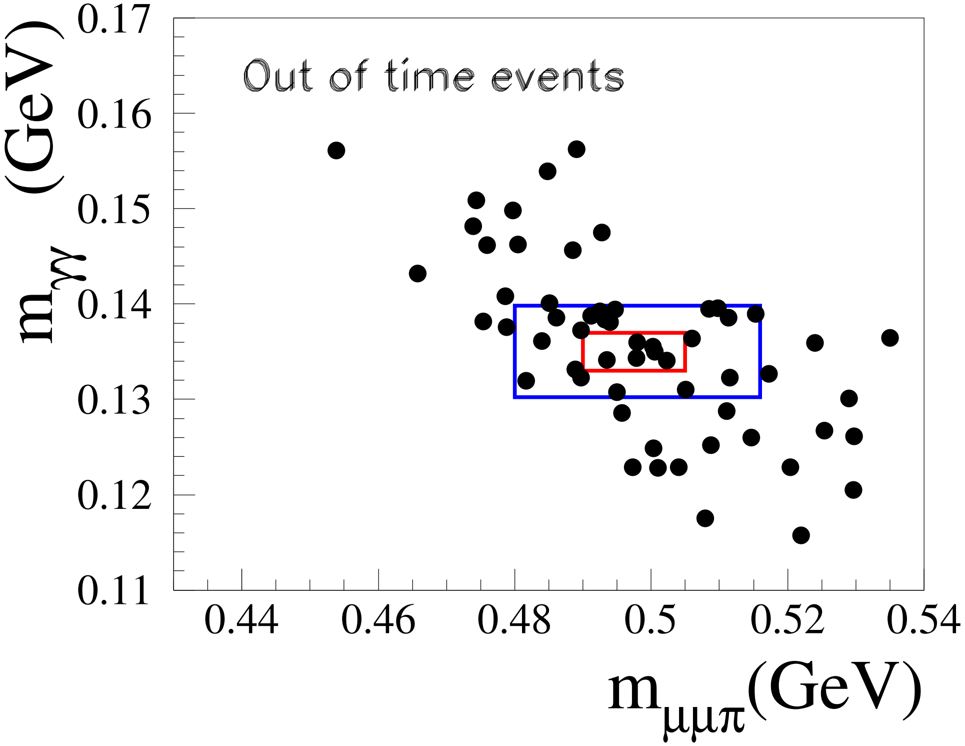
Studied with Monte Carlo

$\rightarrow 0.04 \pm 0.04$ events expected

Accidental Background to the Search for $K_S \to \pi^0\mu^+\mu^-$

Dominated by:

- $K_L \to \pi^{\pm}\mu^{\mp}\nu + K_S \to \pi^0\pi^0$
- $K_S \to \pi^+\pi^- + K_S \to \pi^0\pi^0$



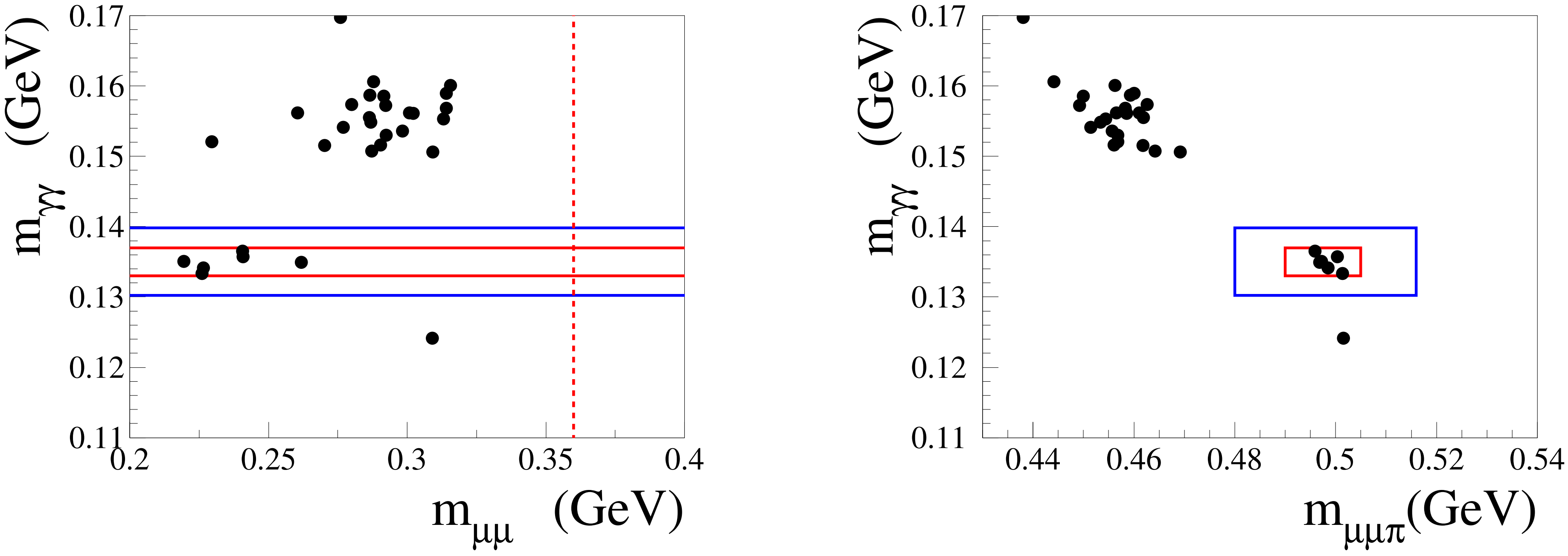
Examine the time sidebands and extrapolate into the signal region

$\to$ 6 events found *Out of Time*

Events present in OT signal region so no extrapolation from Control region required

$\to$ $0.18^{+0.18}_{-0.11}$ events expected

The Result



6 events found with a background $0.22^{+0.19}_{-0.12}$

$\rightarrow$ presence of signal well established

This leads to the result, (using unit form factor):

$$BR(K_S \rightarrow \pi^0\mu^+\mu^-) = (2.9^{+1.4}_{-1.2}(stat) \pm 0.2(syst)) \times 10^{-9}$$

Interpretation of the $K_S \to \pi^0 l^+ l^-$ Measurements

Chiral Perturbation Theory predicts the $K_S \to \pi^0 l^+ l^-$ branching ratios:

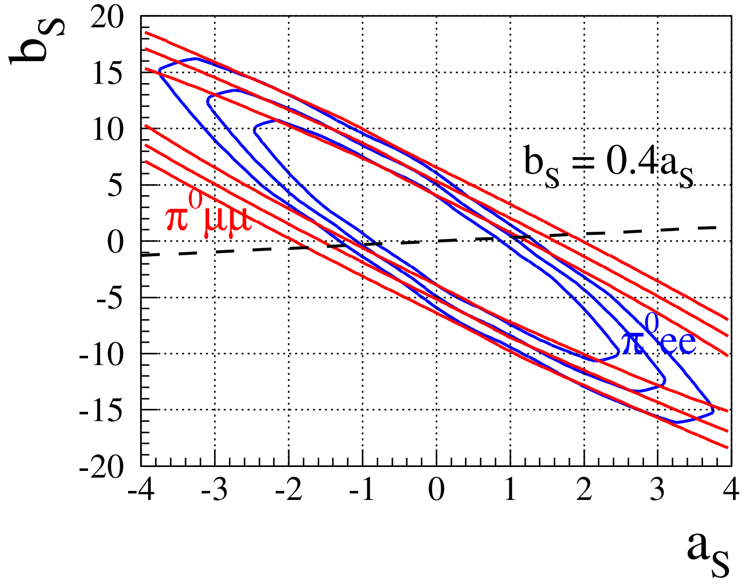
$$BR(K_S \to \pi^0 e^+ e^-) = [0.01 - 0.76 a_S - 0.21 b_S + 46.5 a_S^2 + 12.9 a_S b_S + 1.44 b_S^2] \times 10^{-10}$$
$$BR(K_S \to \pi^0 \mu^+ \mu^-) = [0.07 - 4.52 a_S - 1.50 b_S + 98.7 a_S^2 + 57.7 a_S b_S + 8.95 b_S^2] \times 10^{-11}$$

Assuming the Vector Meson Dominance (VMD) Model ($b_S/a_S = 0.4$), $|a_S|$ can be extracted for both channels:

$$BR(K_S \to \pi^0 e^+ e^-) \simeq 5.2 \times 10^{-9} a_S^2 \quad \Rightarrow |a_S|_{\pi^0 ee} = 1.06^{+0.26}_{-0.21} \pm 0.07$$
$$BR(K_S \to \pi^0 \mu^+ \mu^-) \simeq 1.2 \times 10^{-9} a_S^2 \quad \Rightarrow |a_S|_{\pi^0 \mu\mu} = 1.55^{+0.38}_{-0.32} \pm 0.05$$

Combining both $K_S \to \pi^0 l^+ l^-$ results in a log-likelihood fit:

$\rightarrow$ Curves compatible with each other and VMD



Implications for $K_L \to \pi^0 l^+ l^-$

Measurement of $|a_S|$ allows $BR(K_L \to \pi^0 l^+ l^-)$ to be predicted:

$$BR(K_L \to \pi^0 l^+ l^-)_{CPV} \times 10^{12} = C_{IND} \pm C_{INT}\left(\frac{Im(\lambda_t)}{10^{-4}}\right) \pm C_{DIR}\left(\frac{Im(\lambda_t)}{10^{-4}}\right)^2$$

Where:

- C_{DIR} — Direct CPV component
- $C_{IND} \sim BR(K_S \to \pi^0 l^+ l^-)$ — Indirect CPV component
- $C_{INT} \sim \sqrt{BR(K_S \to \pi^0 l^+ l^-)}$ — Interference Term
- $Im(\lambda_t) = -A^2 \lambda^5 \eta$ — Measures CP violation in Kaon system

Taking $Im(\lambda_t)$ from PDG World Average $(1.36 \pm 0.12) \times 10^{-4}$

$$BR(K_L \to \pi^0 e^+ e^-)_{CPV} \times 10^{12} \simeq 17_{\text{indirect}} \pm 9_{\text{interference}} + 5_{\text{direct}}$$
$$BR(K_L \to \pi^0 \mu^+ \mu^-)_{CPV} \times 10^{12} \simeq 9_{\text{indirect}} \pm 3_{\text{interference}} + 1_{\text{direct}}$$

$K_L \rightarrow \pi^{\pm}e^{\mp}\nu\gamma$ *Branching Ratio Measurement*

Precise measurement of $BR(K_L \rightarrow \pi^{\pm}e^{\mp}\nu\gamma)$ has been made using data taken from 1999

Current leading measurement by KTeV of
$BR(K^0 \rightarrow \pi^{\pm}e^{\mp}\nu\gamma)/BR(K^0 \rightarrow \pi^{\pm}e^{\mp}\nu) = 0.908 \pm 0.008^{+0.0013}_{-0.012}\%$
$\rightarrow$ Disagrees with theory

Measurement is highly dependent on how radiative corrections are modelled
$\rightarrow$ Attempt to develop a Model Independent method

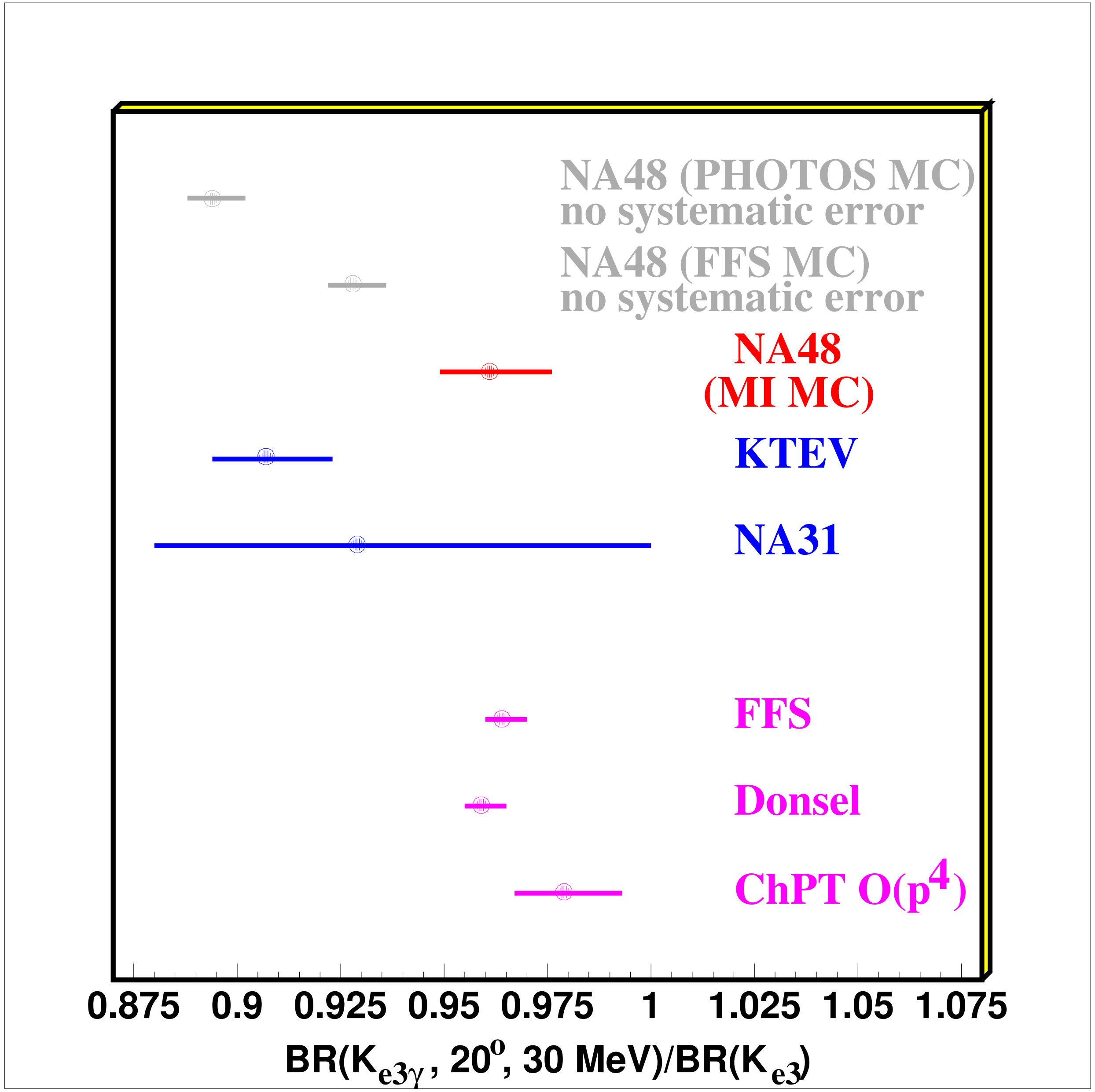
Initial Monte Carlo generation was performed using the PHOTOS package
$\rightarrow$ Not very good agreement with data

Weight MC with E^*_γ and $\theta^*_{e\gamma}$ distributions from data
$\rightarrow$ Good agreement for all variables

Ratio of $BR(K^0 \rightarrow \pi^{\pm}e^{\mp}\nu\gamma)/BR(K^0 \rightarrow \pi^{\pm}e^{\mp}\nu)$:

$$R = 0.962 \pm 0.007^{+0.012}_{-0.011}\%$$

$K_L \rightarrow \pi^{\pm} e^{\mp} \nu \gamma$ *Branching Ratio Measurement*



$K_L \to \pi^0\pi^\pm e^\mp\nu$ *Branching Ratio and Form Factor Measurements*

Good test of Chiral Perturbation Theory (CHPT) predictions for long-distance meson interactions

Measurement of form factors allows the determination of CHPT parameters

Background

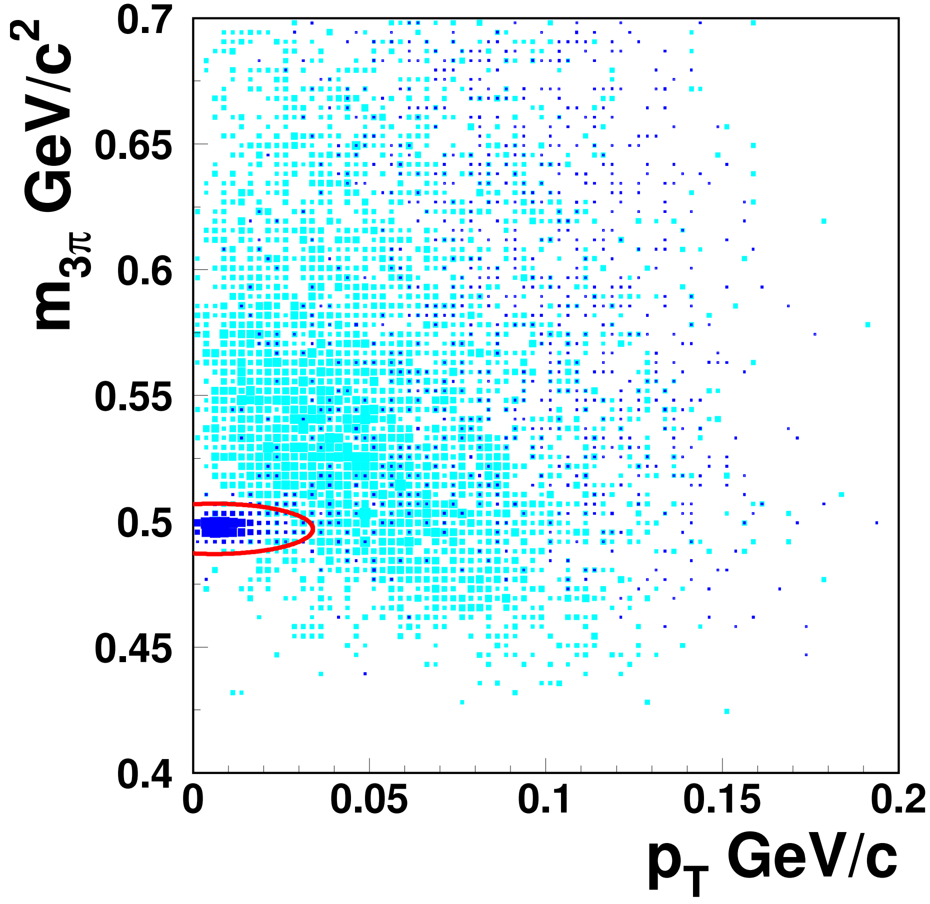
Significant background from $K_L \to \pi^0\pi^+\pi^-$

$\rightarrow$ Pion mis-id'd as electron

Neural network used to distinguish pions/electrons

Took into account geometric characteristics of showers and tracks

$\rightarrow$ Background reduced to 1.13%



$K_L \to \pi^0\pi^\pm e^\mp\nu$ *Branching Ratio and Form Factor Measurements*

Matrix Element assumed to have V-A structure

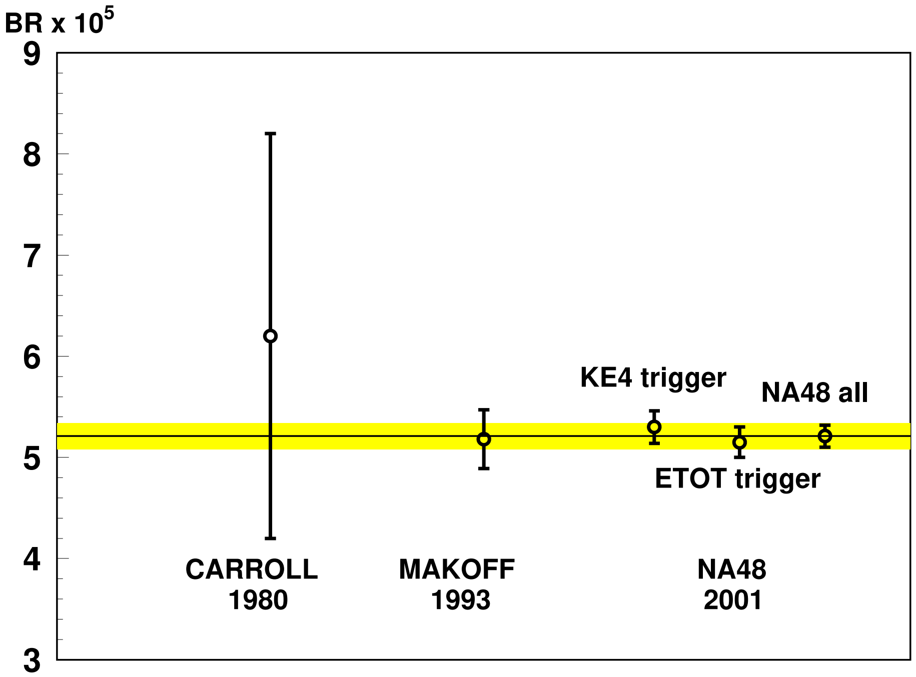
Parameterised with 4 variables:

- $\bar{f}_s$, $\bar{f}_p$, λ_g: (Axial-Vector Component)
- $\bar{h}$: (Vector Component)

Performing a simultaneous fit yields:

- $\bar{f}_s = 0.052 \pm 0.006_{stat} \pm 0.002_{syst}$
- $\bar{f}_p = -0.051 \pm 0.011_{stat} \pm 0.005_{syst}$
- $\lambda_g = 0.087 \pm 0.019_{stat} \pm 0.006_{syst}$
- $\bar{h} = -0.32 \pm 0.12_{stat} \pm 0.07_{syst}$

5464 events ($10\times$ previous measurement) were found with a background of 62 events



This leads to the Branching Ratio:

$$BR(K_L \to \pi^0\pi^\pm e^\mp\nu) = (5.21 \pm 0.07_{stat} \pm 0.09_{syst}) \times 10^{-5}$$

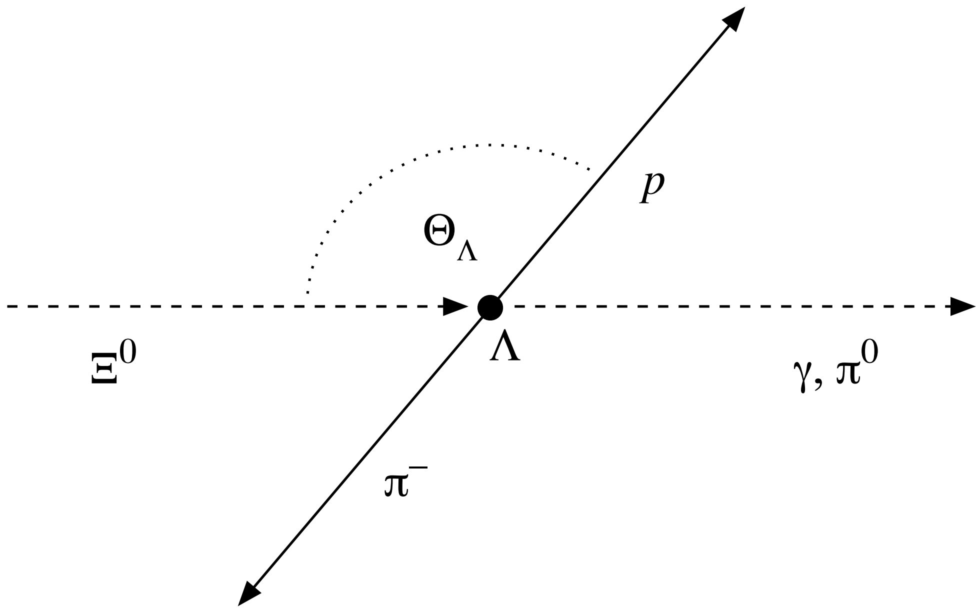
$\Xi \to \Lambda\gamma$ *Branching Ratio and Asymmetry Measurements*

730 $\Xi \to \Lambda\gamma$ events were recorded with a background of 58.2 ± 7.8 events

Asymmetry was measured using angle between Ξ^0 and p, Θ_Λ

Effect of background on the asymmetry was measured in the sidebands

Isotropic MC used to correct for acceptance effects



Asymmetry has been measured as:
$\alpha(\Xi \to \Lambda\gamma) = -0.78 \pm 0.18_{stat} \pm 0.06_{syst}$
(First Evidence for non-zero Asymmetry)

Branching Ratio has also been measured:

$BR(\Xi \to \Lambda\gamma) = (1.16 \pm 0.05_{stat} \pm 0.06_{syst}) \times 10^{-3}$

Much larger statistical sample (from 2002 run) is currently under analysis...

Conclusions

First observations of the decays $K_S \to \pi^0 e^+ e^-$ and $K_S \to \pi^0 \mu^+ \mu^-$ have been made:

$$BR(K_S \to \pi^0 e^+ e^-) = (5.8^{+2.8}_{-2.3}(stat) \pm 0.3(syst) \pm 0.8(theory)) \times 10^{-9}$$
$$BR(K_S \to \pi^0 \mu^+ \mu^-) = (2.9^{+1.4}_{-1.2}(stat) \pm 0.2(syst)) \times 10^{-9}$$

Branching Ratios for the following have been measured:

$$BR(K_L \to \pi^\pm e^\mp \nu \gamma) = 0.960 \pm 0.07^{+0.012}_{-0.011}\%$$

$$BR(K_L \to \pi^0 \pi^\pm e^\mp \nu) = (5.21 \pm 0.07_{stat} \pm 0.09_{syst}) \times 10^{-5}$$

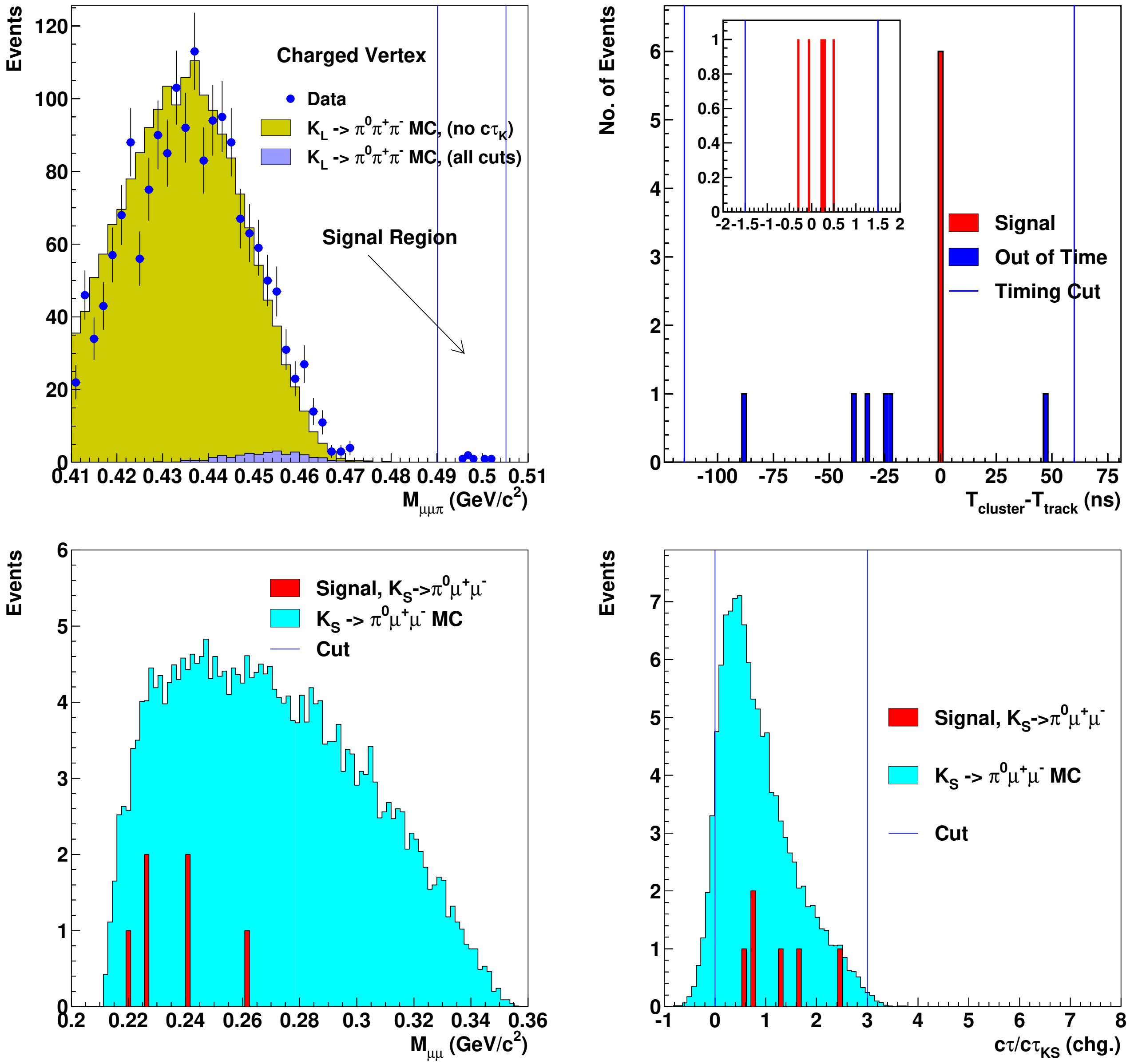
$$BR(\Xi \to \Lambda\gamma) = (1.16 \pm 0.05_{stat} \pm 0.06_{syst}) \times 10^{-3}$$

The Asymmetry of the $\Xi \to \Lambda\gamma$ decays has also measured:

$$\alpha(\Xi \to \Lambda\gamma) = -0.78 \pm 0.18_{stat} \pm 0.06_{syst}$$

Spares

$K_S \rightarrow \pi^0\mu^+\mu^-$ *candidates*



$\Xi \to \Lambda\gamma$ *Branching Ratio and Asymmetry Measurements*