Recent Results on Radiative Kaon decays from NA48 and NA48/2.

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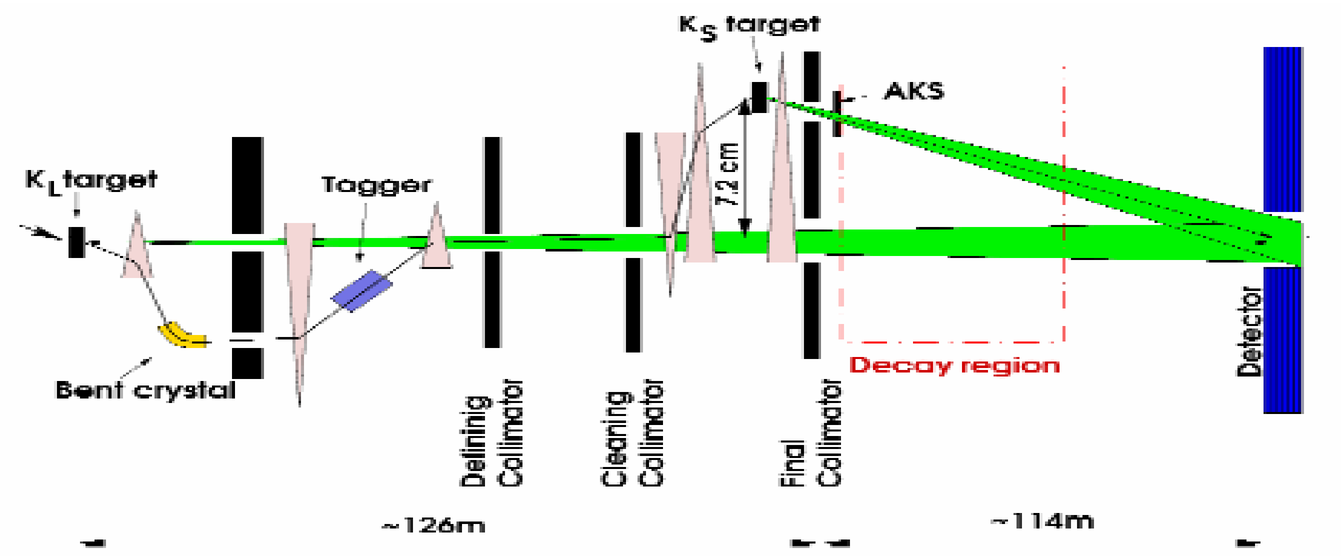
Overview

- Branching fraction of radiative decay $K_L \to \pi^+ e^- \nu\gamma$ ($K_L e3\gamma$) with respect to $K_L e3$
  - Introduction
  - Selection and reconstruction
  - Results
- The radiative decay $K^\pm \to \pi^\pm \pi^0 \gamma$
  - Introduction
  - Selection and reconstruction
  - Trigger
  - Background sources
  - Results
- Summary and Conclusions

The $K_L e3\gamma$ decay. Introduction

- Dedicated run: 2 days in 1999 with only K_L beam



- 100 10^6 triggers recorded amounting to 2 TB

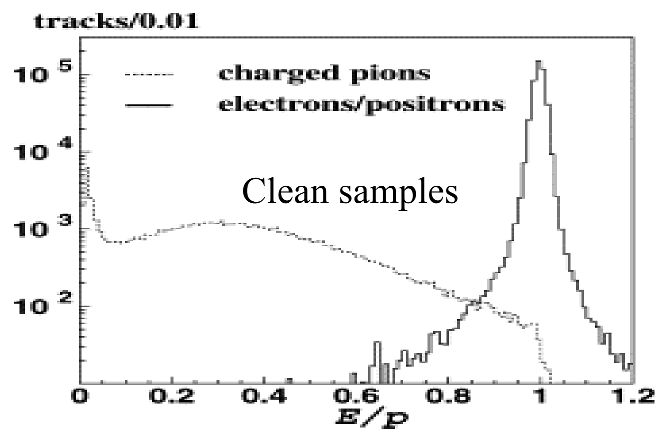
The $K_L e3\gamma$ decay. Introduction

- Method: measure ratio of $R=BR(K_L e3\gamma) / BR(K_L e3)$
- Two possible components for $K_L e3\gamma$, IB and DE
  - IB comes from bremsstrahlung of electron
  - DE comes from weak vertex
- Due to small electron mass IB dominates
- IB has collinear and infrared singularities. Impose cuts on E^*_γ and $\theta^*_{e\gamma}$

  $R= BR(Ke_L 3\gamma, E^*_\gamma >30$ MeV, $\theta^*_{e\gamma} >20^0) / BR(K_L e3)$
- Where $BR(K_L e3)$ includes any number of gammas

Ratio of BR($K_L e3\gamma$)/ BR($K_L e3$). Selections.

- Common to both channels:
  - Two tracks from a good vertex. Distance between tracks @ LKr> 25 cm.
  - Pion-electron separation based on E/p. Final requirement 0.93<E/p<1.1 for electrons, E/p<0.90 for pions
  - Both of the possible p_K solutions must lie within (80,160) GeV/c
  - Cuts against $K_L \to \pi^+ \pi^- \pi^0$ and MUV against Kμ3. Negligible background remains for $K_L e3$

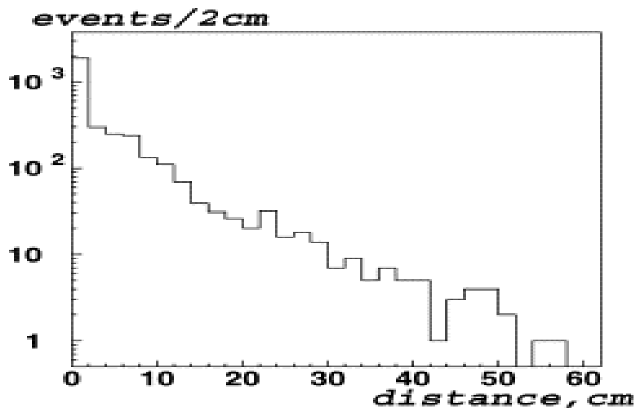


Select electron sample using hard cuts on E/p for pion

Select pion sample from K2π or cutting hard on E/p for electron

Ratio of BR($K_L e3\gamma$)/ BR($K_L e3$). Selections.

- Specific to $K_L e3\gamma$
  - Require one cluster in time with E>4 GeV/c^2
  - Hadronic showers can produce satellite clusters faking the radiated gamma. Distance between pion track at LKr and γ > 55 cm
  - Distance γ-e > 6 cm
  - Background dominated by Ke4 ~ 0.7 %
  - $E^*\gamma$>30 MeV and $\theta^*_{e\gamma}>20^0$ for both solutions



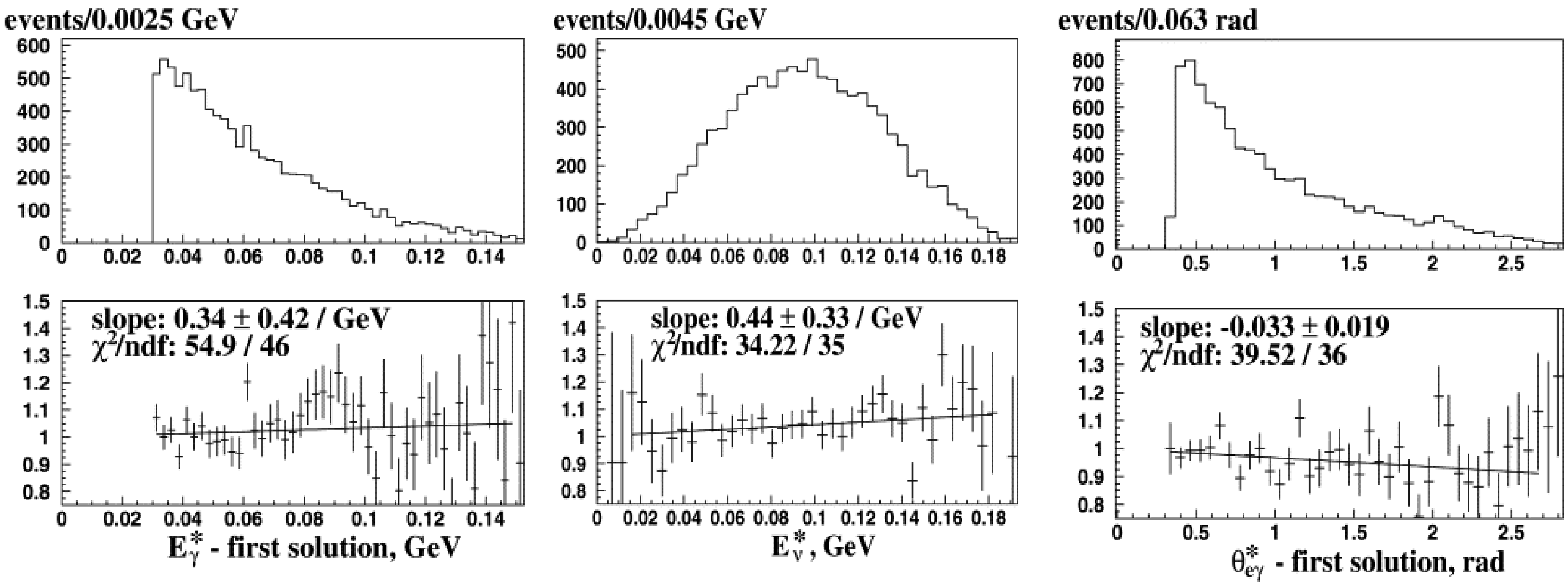
Select $K \rightarrow \pi^+ \pi^-$:

Distance between tracks at Lkr $d_{\pi\pi}$ > 80 cm

Cluster energy E> 4 GeV

The $K_L e3\gamma$ decay. Data-MC comparison

- MC includes radiative corrections, virtual and real.
  Real: obtained using PHOTOS package.
  Virtual: Angular distribution of $\theta^*_{e\gamma}$ used to weight MC accordingly to data
- Good agreement in relevant variables after weighting procedure

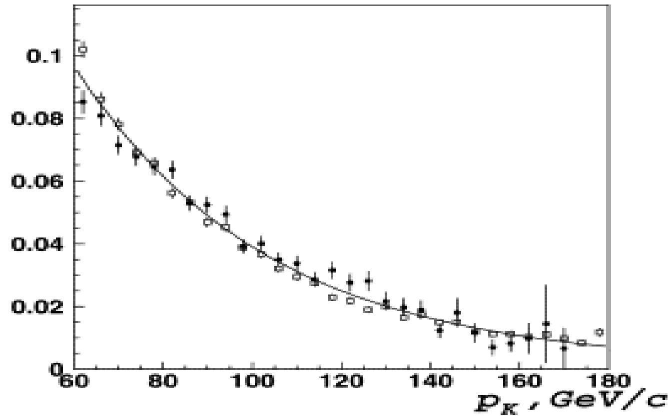


The $K_L e3\gamma$ decay. Systematic checks

- Radiative corrections:
  - Rejection of more than one hard photon must be accounted for in MC
  - Correction of ~0.05% due to differences in number of γ between data and MC
  - Requiring any number of hard γ agrees within 0.2%
- Summary on systematic checks:

Source	$\triangle R/R$
K_L spectrum	$^{+6}_{-3} \cdot 10^{-3}$
$K_{e3\gamma}$ selection	$\pm 5 \cdot 10^{-3}$
γ accidentals	$^{+2}_{-1} \cdot 10^{-3}$
Background uncertainties	$^{+4}_{-3} \cdot 10^{-3}$
K_{e3} selection	$\pm 5 \cdot 10^{-3}$
Form-factor uncertainties	$\pm 1 \cdot 10^{-3}$
TOTAL	$^{+11}_{-9} \cdot 10^{-3}$

- Main source of systematic uncertainty is knowledge of kaon spectrum
  - Measurements from K2π and K3π and 'diagonal solutions' of $K_L e3$
  - Difference in acceptance ratio quoted a systematic uncertainty



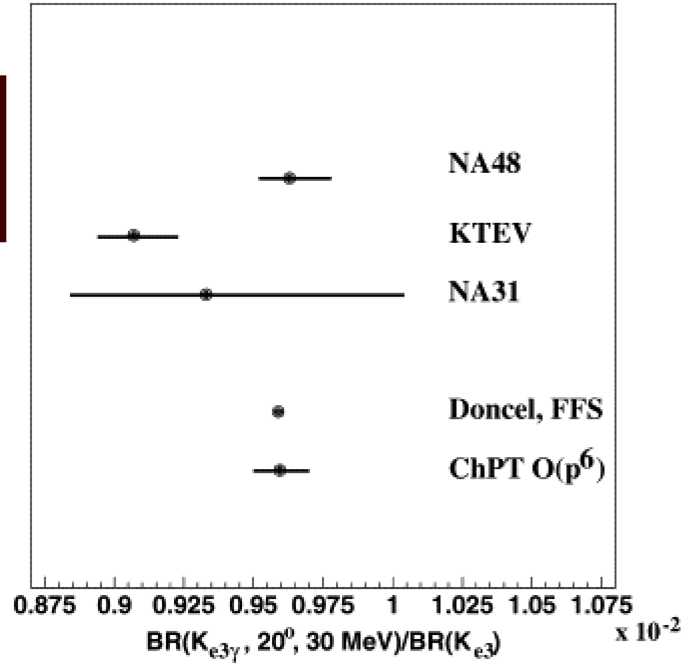
The $K_L e3\gamma$ decay. Results

- Final sample19000 $K_L e3\gamma$ and 5.6 10^6 $K_L e3$ events

$$BR(K_L e3\gamma, E^*_\gamma > 30\ MeV, \theta^*_{e\gamma} > 20^0) / BR(K_L e3) = (0.964 \pm 0.008_{stat}\ {}^{+0.011}_{-0.009\ syst})\%$$

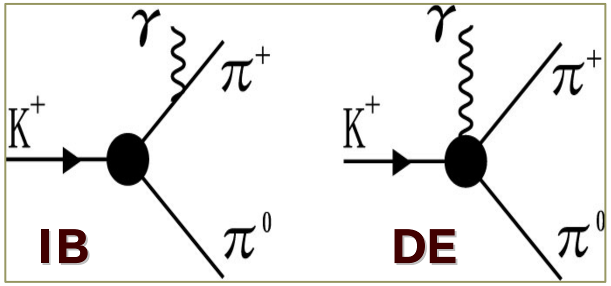
- Good agreement with theoretical predictions
- At a variance with another experimental results

PL B605 (2005) 247



The $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$ decay. Introduction

- Two amplitudes:
  - Inner Bremsstrahlung (IB)
    - Calculable: QED corrections to $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}$
    - Suppressed by m_{π} and $\Delta I=1/2$
  - Direct Emission (DE)
    - Insight on weak vertex structure
    - Electric (E) from L^4 ChPT lagrangian and loops L^2 (non predictable)
    - Magnetic (M) has contributions from chiral anomaly (calculable) and also direct contributions (non predictable)
- Interference (INT) possible between IB and electric part of DE
  - Measuring at the same time DE and INT gives measurement of both M and E
  - In addition CPV could appear in INT



PDG values for $55 < T^*_{\pi} < 90$ MeV

BR(IB): $(2.75 \pm 0.15)\cdot 10^{-4}$

BR(DE): $(4.4 \pm 0.8)\cdot 10^{-6}$

INT: not measured

The $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$ decay. Introduction

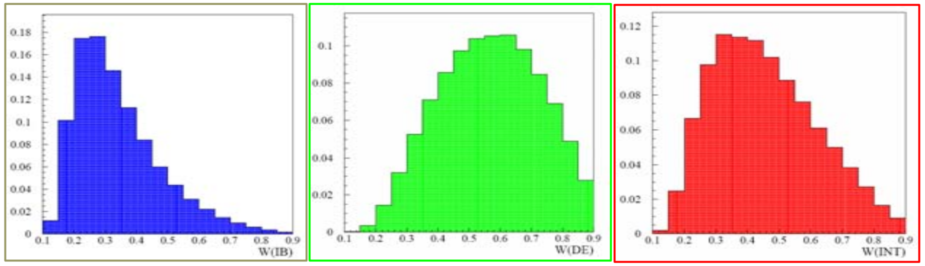
- Two Dalitz plot variables: W and T^*_π

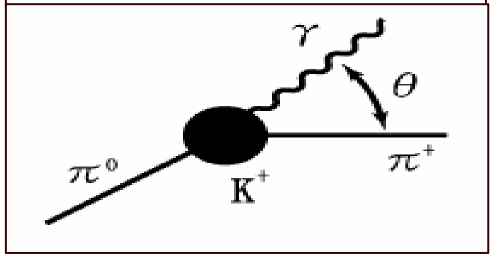
$$W^2 = \frac{(p_K p_\gamma)(p_\pi p_\gamma)}{m_\pi^2 m_K^2}$$

(Lorentz invariant definition)

In K rest frame

$$W^2 = \frac{E_\gamma^2 (E_\pi - P_\pi \cos\theta_{\pi\gamma})}{m_K m_\pi^2}$$





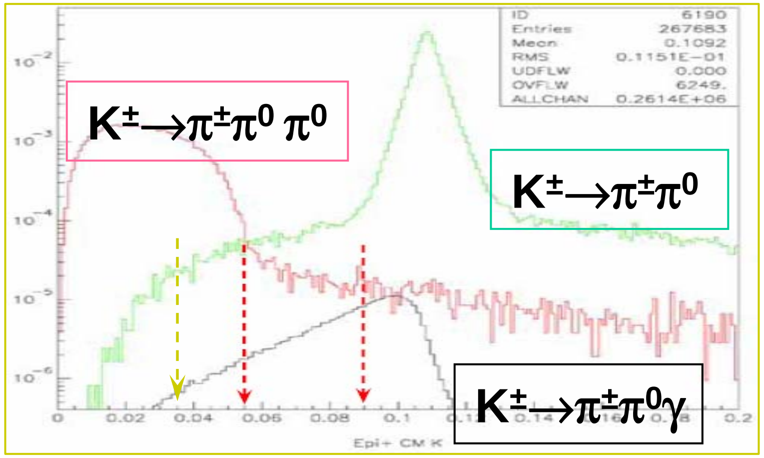
- Matrix element shows separation in W^2 of components

$$\frac{d\Gamma^\pm}{dW} \simeq \left(\frac{d\Gamma^\pm}{dW}\right)_{IB}\left[1 + 2\left(\frac{m_\pi}{m_K}\right)^2 W^2 |E| cos((\delta_1 - \delta_0) \pm \phi) + \left(\frac{m_\pi}{m_K}\right)^4 W^4 (|E|^2 + |M|^2)\right]$$

IB **INT** **DE**

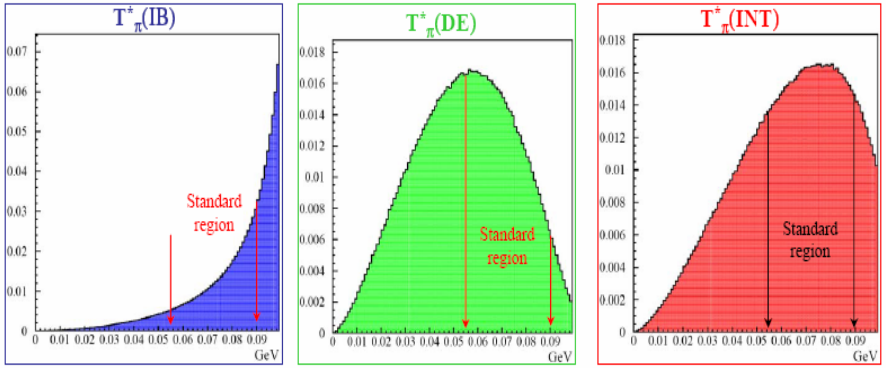
The $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$ decay. Introduction

- Previous measurements:
  - $55 < T^*_{\pi} < 90$ MeV to avoid background from $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$ and $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}$



- In NA48/2 cut at trigger level at $\sim T_{\pi}^* < 90$ MeV

- NA48/2: Enlarged T^*_{π} lower cut from 55 MeV to 0 MeV
  - Gain sensitivity to DE and INT
  - But must keep background from $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi$ under control !



The $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$ decay. Introduction

- Previous measurements:
  - INT found to be compatible with zero

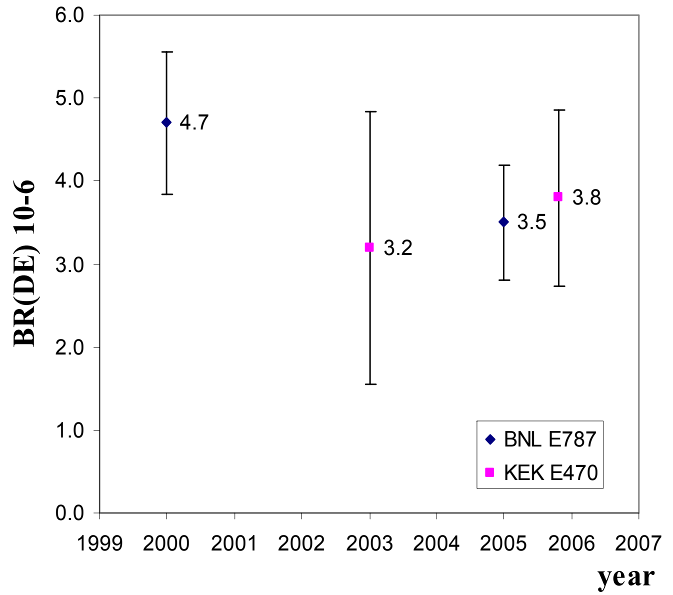
$$\text{INT}=(-0.58^{+0.91}_{-0.83})\% \text{ of IB}$$ **KEK E470**

$$\text{INT}=(-0.4 \pm 1.6)\% \text{ of IB}$$ **BNL E787**

  - Set INT to zero and fit only to DE

Experiment	year	# of events	DE BR 10^{-6}
Abrams [5]	1972	2100	$15.6 \pm 3.5 \pm 5.0$
Smith [18]	1976	2461	23 ± 32
Bolotov [19]	1987	140	$20.5 \pm 4.6^{+3.9}_{-2.3}$
E787 [20]	2000	19836	$4.7 \pm 0.8 \pm 0.3$
E470 [21]	2003	4434	$3.2 \pm 1.3 \pm 1.0$
E787 [22]	2005	20571	$3.5 \pm 0.6^{+0.3}_{-0.4}$
E470 [23]	2005	10154	$3.8 \pm 0.8 \pm 0.7$

Recent history of BR(DE)



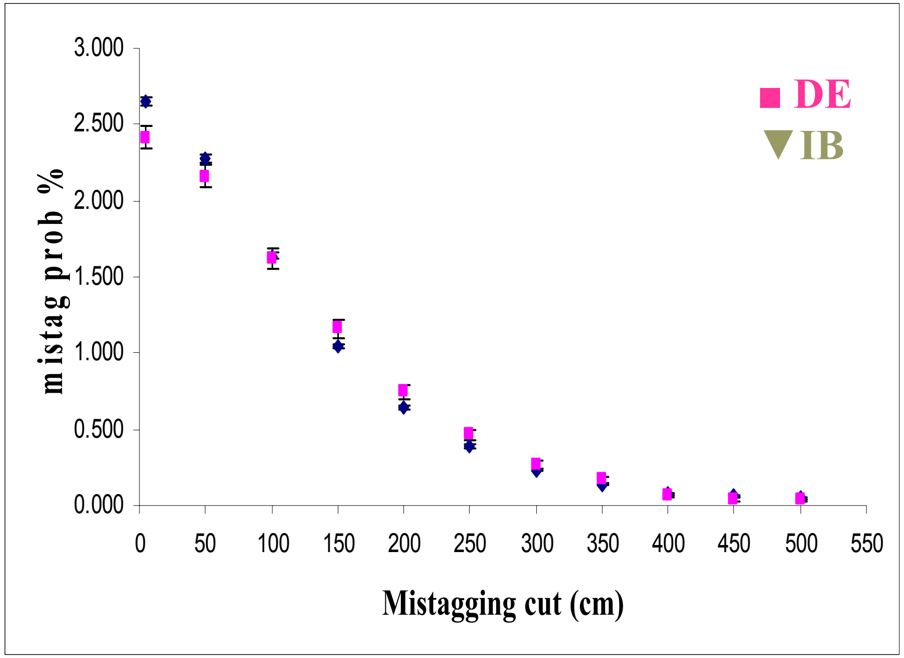
- NA48/2 has analyzed > 5 times more events !

The $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$ decay. Reconstruction

- Select 1 track and any number of clusters.
- Require 3 gammas with $E\gamma > 3$ GeV outside 35 cm radius from π at LKr. Gammas 10 cm away from other clusters
- Charged vertex (zvc): Calculate the kaon decay point as the position where the π track intersects the beam line
- Selecting the γ pairing for the π^0
  - Three combinations are possible
  - Choosing the wrong combination for the π^0 (misstagging) →choosing the wrong odd gamma → Distorts E γ → distorts W.
  - Two possible methods used: Select the combination giving the best π^0 invariant mass or combination giving the best kaon invariant mass
- Neutral vertex (zvn): From imposing π^0 mass to γ pairs. Must be in agreement with charged vertex (within 400 cm)

The $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$ decay. Reconstruction

- Miss tagging problem
  - Miss tagged events move to large W
  - This could induce a DE component if difference between Data-MC
  - Must keep miss tagging probability as small as possible
- Simply demanding compatibility between zvc and best zvn gives 2.5% miss tagging
- Solution: Reject events with a second solution for neutral vertex close to best one
- Require |zvn (second)-zvn (best)| Δ_{zvn}> xx cm

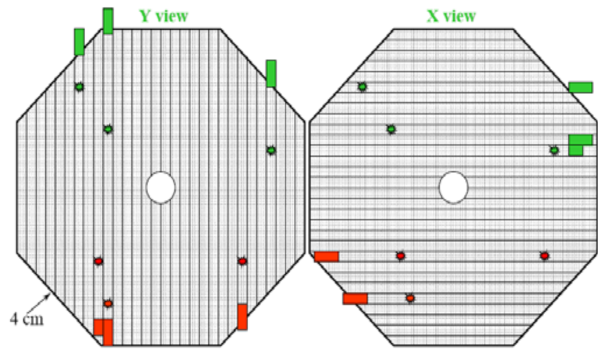


- Evaluation of miss tagging probability with MC. Probability of choosing wrong solution < $1.2 10^{-3}$ at Δ_{zvn}=400 cm

The $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ decay. Trigger

- L1 trigger
  - Require one track and LKr information (peaks) compatible with at least 3 clusters
  - This introduces an energy dependence → distortion of W distribution
  - Correction found using all 3 γ events ($K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ with γ lost) and applied to MC

L1 requires $n_x>2$ or $n_y>2$



- L2 trigger (rejects $K^{\pm} \to \pi^{\pm}\pi^{0}$)
  - Using DCH information and assuming 60 GeV kaon along z axis on-line processors compute a sort of missing mass of the K-π system
  - Cut events compatible with missing mass compatible with π^0. Equivalent to T^*_{π} <90 MeV cut
  - To keep away of edge resolution effects require T^*_{π} <80 MeV in analysis

The $K^{\pm}\rightarrow \pi^{\pm}\pi^{0}\gamma$ decay. Background

- Most dangerous are $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0}$ and $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}$

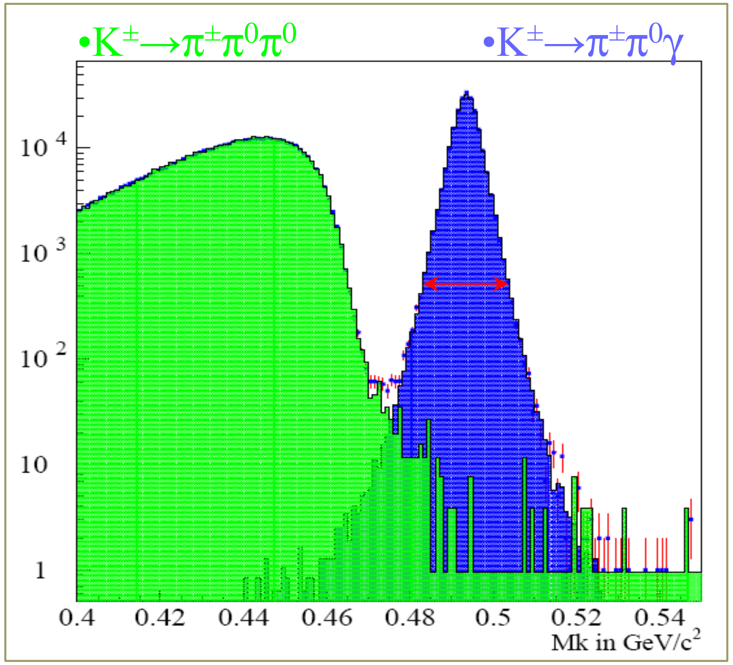
Channel, BR	Mechanism	Cuts
$K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0}$ $(1.73 \pm 0.04)\%$	One γ lost Overlapping of two γ	Cog, mass cut ??? Dangerous!!
$K^{\pm}\rightarrow\pi^{\pm}\pi^{0}$ $(21.13 \pm 0.14)\%$	Accidental clusters Clusters from π shower	Time cuts, mass cut Min dist $\pi\gamma$, mass cut $T_{\pi}^{*} < 80$ MeV

- Channels with ν easier to reject
  - Smaller BR
  - Mass and cog cuts, particle ID
  - Time cuts for non-radiative

Channel, BR	Channel, BR (cut)
$K^{\pm}\rightarrow e^{\pm}\pi^{0}\nu$ (Ke3) $(4.87 \pm 0.06)\%$	$K^{\pm}\rightarrow e^{\pm}\pi^{0}\nu\gamma$ (Ke3γ) $^{*}(2.65 \pm 0.20)10^{-4}$
$K^{\pm}\rightarrow \mu^{\pm}\pi^{0}\nu$ (Kμ3) $(3.27 \pm 0.06)\%$	$K^{\pm}\rightarrow \mu^{\pm}\pi^{0}\nu\gamma$ (Kμ3γ) $^{*}< 6.1 10^{-5}$

The $K^{\pm}\rightarrow \pi^{\pm}\pi^{0}\gamma$ decay. Background

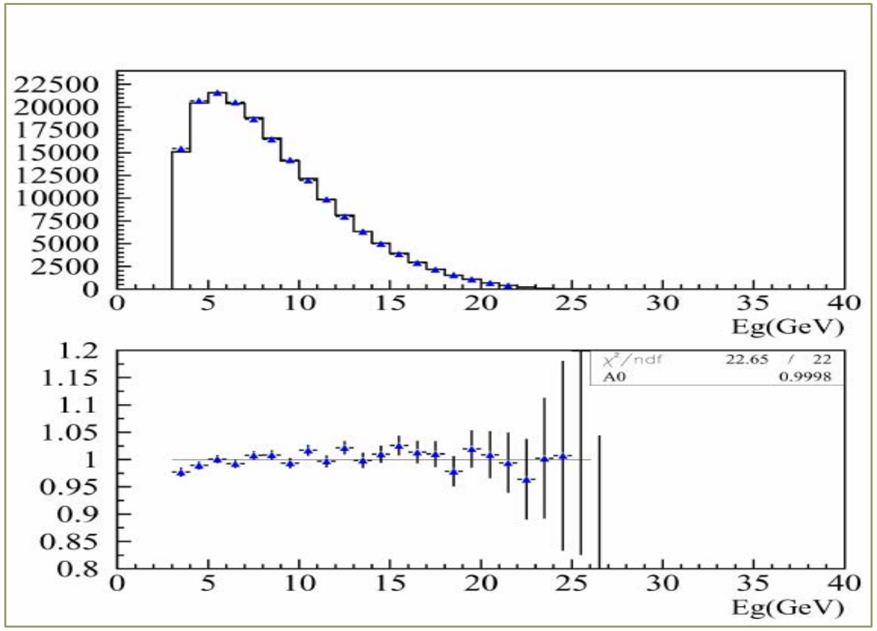
- Cut on overlapping gammas (allows avoiding $T^*_{\pi} > 55$ MeV)
  - For every of the 3 gammas in the event assume that its energy E_i is really the overlap of two gammas of energies $E_i = x$ and $E' = (1-x) E_i$
  - Solve for sharing fraction (x) imposing that the two π^0 must come from same vertex position. As $z\pi^0_1 = z\pi^0_2$ solve for x and get $z\pi^0$
  - Reject event if reconstructed $z\pi^0$ is compatible with charged z (within 400 cm)
- In addition need to use MUV detector to avoid missreconstruction of track momentum due to $\pi\rightarrow\mu$ decay in flight
- After cuts the background estimation is < 1% of DE

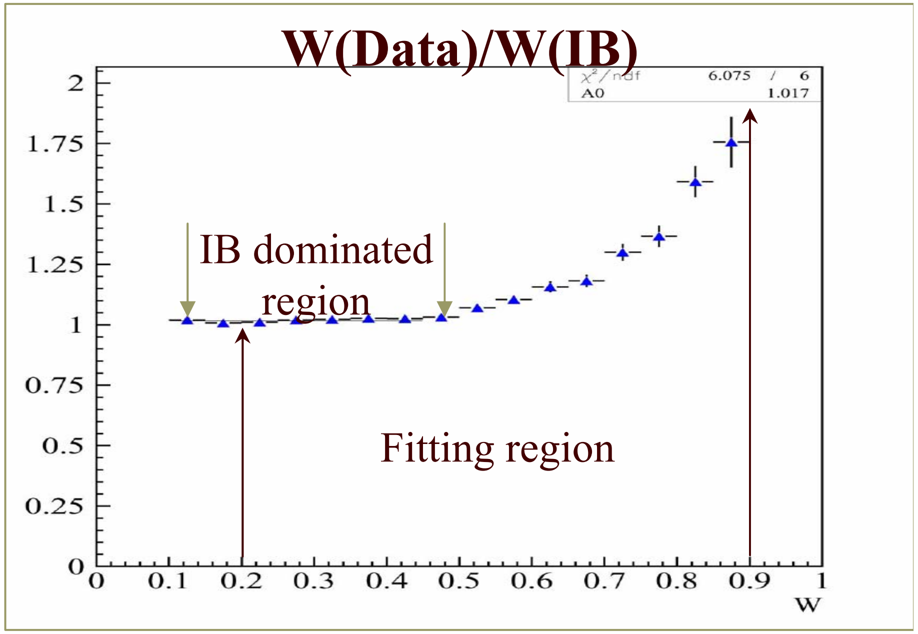


All physical background can be explained in terms of $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0}$

The $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$ decay. Data-MC

- After trigger efficiency correction good agreement MC-Data for Eγ, in particular for Eγ >5GeV (used for final result)
- W(Data)/W(MC-IB) is in good agreement for IB dominated region and clearly shows DE



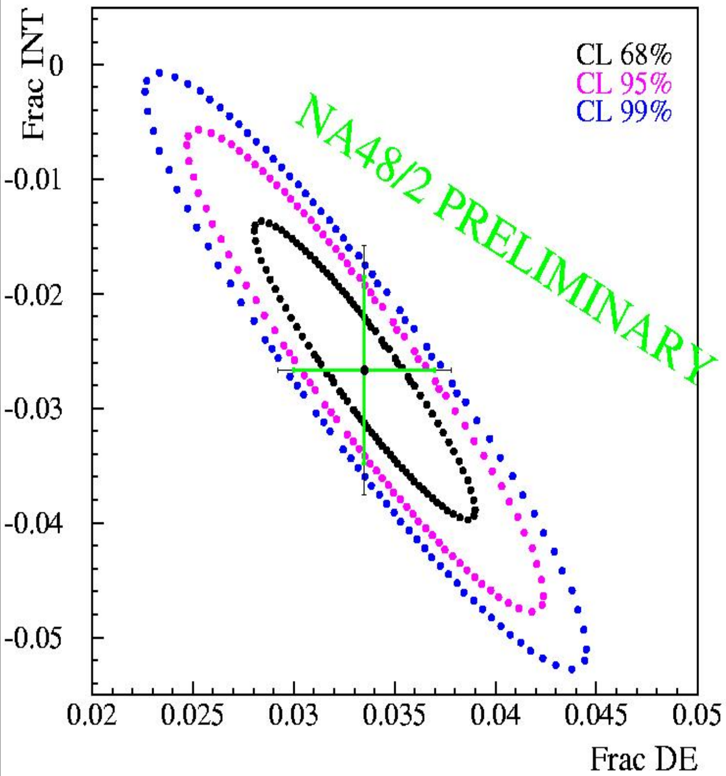


The $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$ decay. Results

- Use extended ML for 0.2<W<0.9
- Based on 124 10^3 events
- Systematic checks:
  - Trigger efficiency dominates (trigger improved for 2004)
  - Neutral energy scale, fitting procedure, miss tagging
- First evidence of INT!

NA48/2 Preliminary: 2003 data
$0<T^*_{\pi}<80$ MeV

Frac(DE) = $(3.35 \pm 0.35_{stat} \pm 0.25_{syst})$ %
Frac(INT) = $(-2.67 \pm 0.81_{stat} \pm 0.73_{syst})$ %

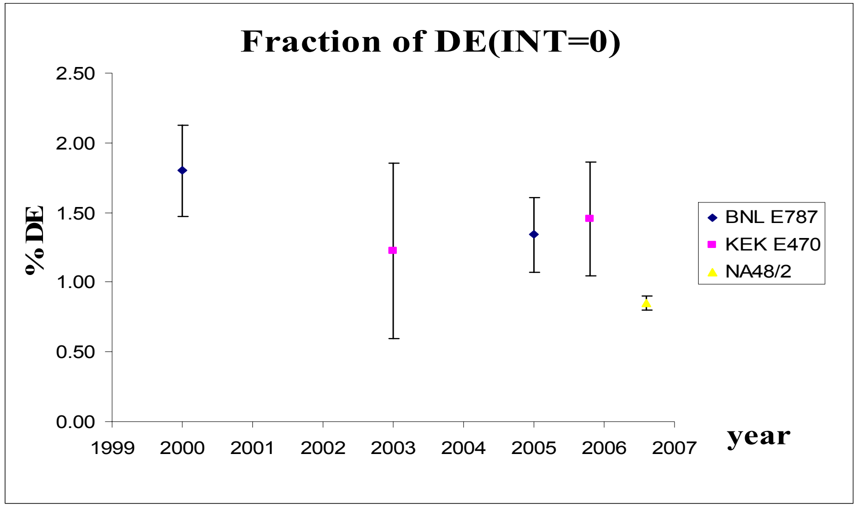


High correlation -0.92

The $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$ decay. Results

- For comparison: Setting INT=0, fitting between $0<T^{*}_{\pi}<80$ MeV and extrapolating to $55<T^{*}_{\pi}<90$ MeV

$\text{Frac(DE)} = (0.85 \pm 0.05_{stat} \pm 0.02_{syst})$ %



Summary and conclusions

- The branching ratio of $K_L e3\gamma$ decay has been measured with respect to $K_L e3$ decay with accuracy. Result in agreement with theory

$$BR(K_L e3\gamma, E^*_\gamma > 30\ \text{MeV}, \theta^*_{e\gamma} > 20^0) / BR(K_L e3) = (0.964 \pm 0.008_{stat}\ {}^{+0.011}_{-0.009\ syst})\%$$

- 124 10^3 $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$ events used to extract DE and INT in $0 < T^*_\pi < 80$ MeV. First evidence for non zero INT term has been found

NA48/2 Preliminary: 2003 data

Frac(DE) = $(3.35 \pm 0.35_{stat} \pm 0.25_{syst})$ %
Frac(INT) = $(-2.67 \pm 0.81_{stat} \pm 0.73_{syst})$ %

SPARE

ALGORITHM TO REJECT OVERLAPPING GAMMAS

- Overlapping gammas would give right kaon mass.
- For any of the 3 gammas with energies E1, E2, E3 do the following:
- Assume that the gamma with energy E1 is really the overlap of two gammas of energies E=xE1 and E'=(1-x)E1
- Suppose E comes from a pi01 together with cluster 2 and E' was coming from pi02 with cluster 3. Then the vertices would be:

- Zpi01=(Dist12*E*E2)1/2/Mp0 =(Dist12*xE1*E2)1/2/Mp0
- Zpi02=(Dist13*E'*E3)1/2/Mp0 =(Dist13*(1-x)E1*E3)1/2/Mp0

- 3. As Zpi01=Zpi02 we can solve for x and get Zpi0

- 4. We reject the event if |Zpi0-Zcharged| < 500 cm

- Thanks to this cut we can extend region to 0<T<80 MeV keeping the needed rejection.

SPARE

Effect	Syst. DE	Syst. INT
Energy scale	+0.09	-0.21
Fitting procedure	0.02	0.19
LVL1 trigger	±0.17	±0.43
Mistagging	_	±0.2
LVL2 Trigger	±0.17	±0.52
Resolutions difference	<0.05	<0.1
LKr non linearity	<0.05	<0.05
BG contributions	<0.05	<0.05
TOTAL	**±0.25**	**±0.73**