Recent results from E865:

Test of the Lepton Family Conservation

in the charged kaon decay

$$K^+ \to \pi^+\mu^+e^-$$

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Sep 4, 2003

Outline

Lepton Family Violating Decay

$$K^+ \to \pi^+\mu^+e^-$$

- Motivation
- Experimental Setup
- Analysis
- Conclusion

Motivation

Standard Model and $K^+ \to \pi^+\mu^+e^-$

$$\text{Quarks}: \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

Generation Mixing (CKM) -established fact

$$\text{Leptons}: \begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

Same mechanism did not allow family mixing due to (m_ν=0)

Recent Results in Neutrino physics (Neutrino oscillations) $\to$ lepton family mixing

Lepton Family Numbers $L_e \quad L_\mu \quad L_\tau$:

$$L_l = +1 \quad for \quad l^- \quad and \quad \nu_l$$
$$L_l = -1 \quad for \quad l^+ \quad and \quad \overline{\nu_l}$$
$$L_l = 0 \quad for \quad nonleptonic \quad particles$$

K^+ (0) $\to \pi^+$ (0) μ^+ (L_μ=-1) e^- ($L_e = 1$)

Standard Model: $K^+ \to \pi^+\mu^+e^-$ allowed $< O(10^{-53})$

Unobservable Level

"Why look for this decay?"

Possible Experimental Outcome:

- Observed LFV $\to$ NEW PHYSICS
- No signal $\to$ Expensive disappointment?

  Valuable result for the theory

  Standard Model extensions, like:

  - Supersymmetry
  - Extended Technicolor and Horizontal Gauge Theories
  - Leptoquarks

  Allowed LFV at a much higher rate as high as 10^{-10}

$\mu^+ \to e^+ \gamma$	$<1.2 \times 10^{-11}$
$\mu^- Ti \to e^- Ti$	$<6.1 \times 10^{-13}$
$B^0 \to \mu e$	$<1.2 \times 10^{-7}$
$K^+ \to \pi^+ \mu^+ e^-$	$< 2 \times 10^{-10}$ (Before E865)
$K_L^0 \to \mu^\pm e^\mp$	$< 4.7 \times 10^{-12}$

All searches are complimentary

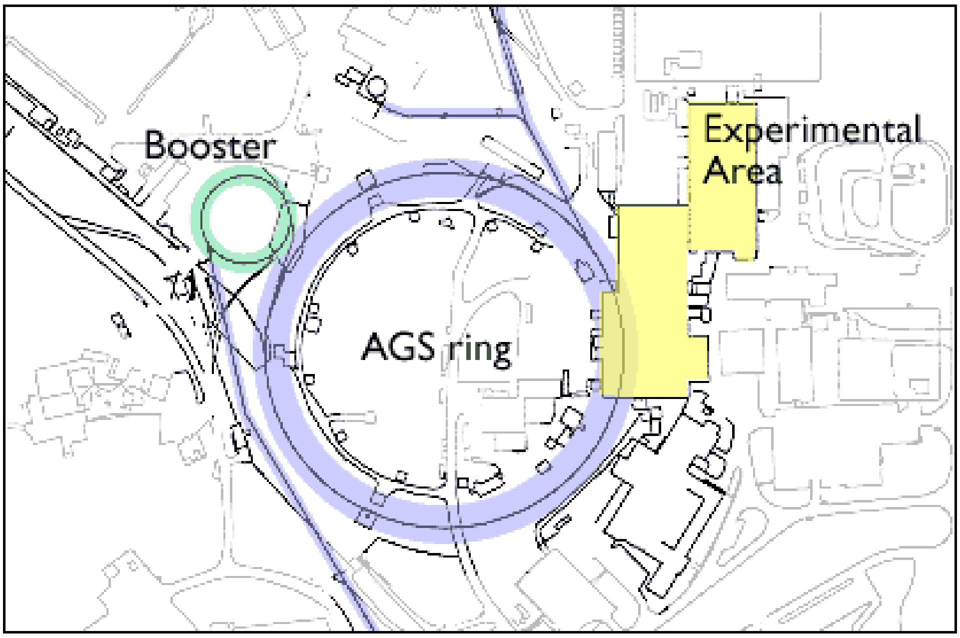
Experiment E865 at BNL (Started in 1995)

Goal: Single Event Sensitivity $O(10^{-12})$

Experimental Setup

Main considerations:

- Kaons must be produced in copious amount
- Effective detection of the decay products
- Suppression of Background processes



The Alternating Gradient Synchrotron complex

	Protons	Kaons[1]
Momentum (GeV/c)	24	6
Rate per 2.8 s spill[2]	1×10^{13}	2×10^{8}
Rate per hour	7×10^{15}	1.4×10^{11}

[1] K^+/π^+=0.05 and K^+/p=0.1
[2] Cycle time=5.1 s

Detector Requirements

- Detector parts should be able to handle high rates
- Particle Identification:

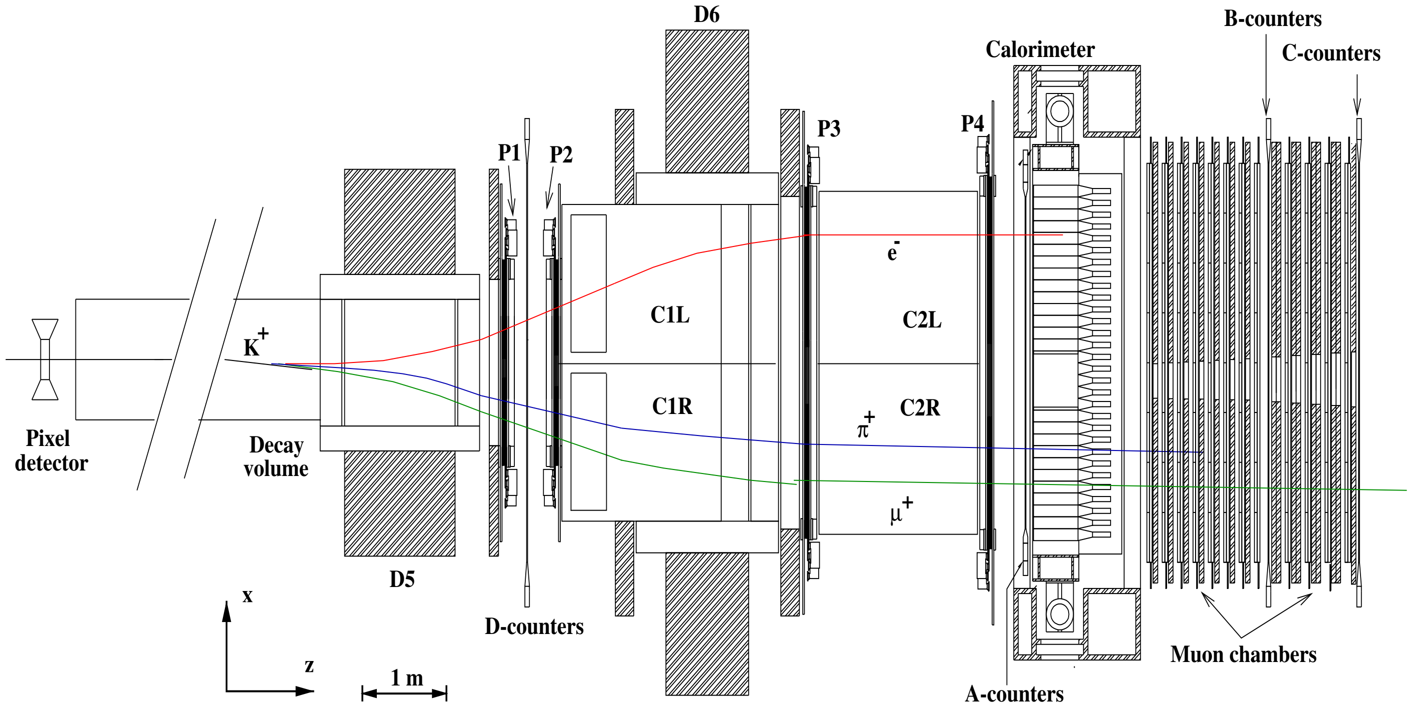
Background from Kaon decays ($O(10^{-13})$):

Decay Mode	Misidentification	Branching
$K^+ \to \pi^+\pi^+\pi^-$ $\pi^+ \to \mu^+\nu_\mu$	$\underline{\pi^- \text{ as } e^-}$	8×10^{-3}
$K^+ \to \pi^0\pi^+$ $\pi^0 \to e^+e^-\gamma$	$\underline{e^+ \text{ as } \pi^+}$ π^+ as μ^+	2.5×10^{-3}
$K^+ \to \pi^0\mu^+\nu$ $\pi^0 \to e^+e^-\gamma$	$\underline{e^+ \text{ as } \pi^+}$	4×10^{-4}

Veto π^- Veto e^+ π^+ from μ^+

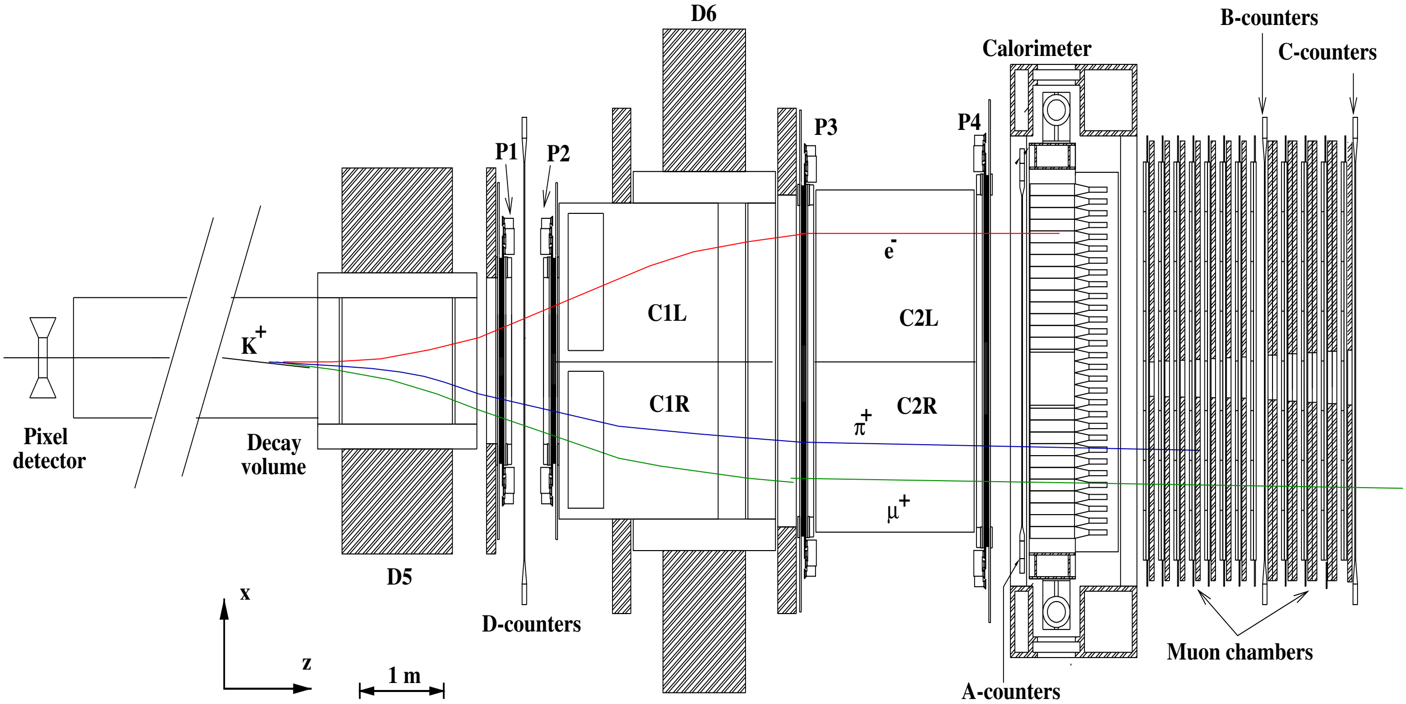
- Accurate kinematic reconstruction
- Good timing resolution for accidental events suppression
- Effective triggering system (accommodate high rate)

Detector View from the Top



Spectrometer	4 MWPC (P1...P4) - Position Detectros
	Dipole Magnets(D5,D6) $P_T = \pm 255$MeV/c
Čerenkov Counters	γ_t=60 (C1L,C2L) γ_t=35(C1R,C2R)
	e^+, e^- - producing light
EM Calorimeter	600 modules (15 Rad length)
	σ_E=6.8% $\sqrt{E(\mathrm{GeV})}$
Muon Chambers	24 Iron Plates and proportional chambers
	$P_\mu > 0.8$ GeV/c reaches B-counter
Trigger Hodoscopes	D,A,B,C-counters (Triggering, time)
Beam hole	inactive region in the center for beam passage

Trigger System



Level	Description	Rate
T0	3 coincidences between A-counter, Calorimeter and 2 D-counter hits . Combination consistent with 3 charged body decay kinematics	≈0.4MHz
T1	Information from each čerenkov counter and B-counter (μ^+) PME=C1L·C2L·MU	≈1.3kHz
T2	Small vertical separation between e^+ e^-	≈0.6kHz
T3	Rejects events with two many or two few PWC hits	≈0.6kHz

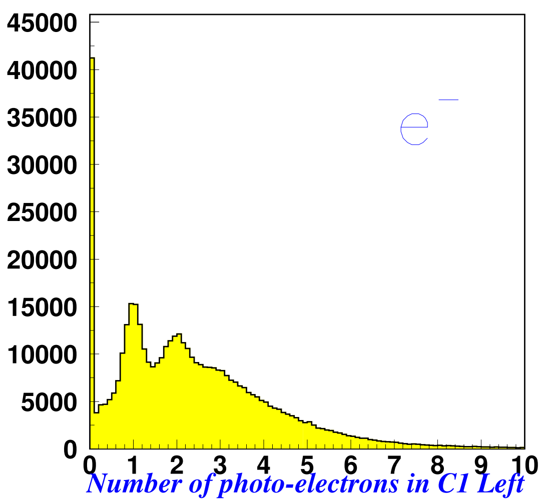
Analysis strategy

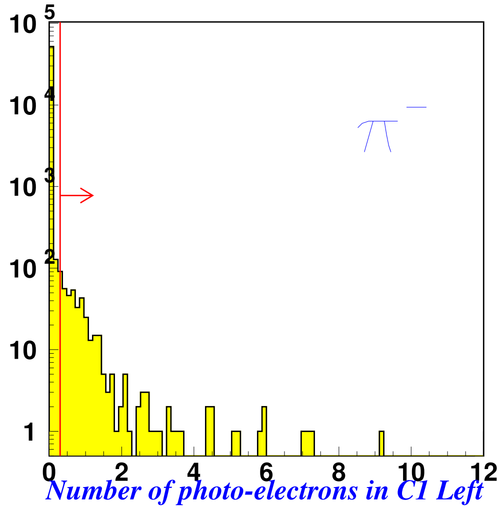
Five months of collecting data yielded 2 TBytes of raw data. Effective analysis procedure becomes crucial.

- PASS1 - First FILTERING PROCESS (90 tapes)
  Basic requirements:
  - 3 or more hits in the calorimeter.
  - 2 positive tracks and 1 negative track
  - track's miss distance from the vertex < 10 cm
  - Total 3 track momentum < 8 GeV/c
- PASS2 - Loose PID cuts (20 tapes)
- PASS3 - Blind Analysis
  Signal region is not examined until backgrounds are properly understood, estimated and suppressed.
  Final pass through the data with all final cuts applied.
- **Likelihood analysis** for surviving events

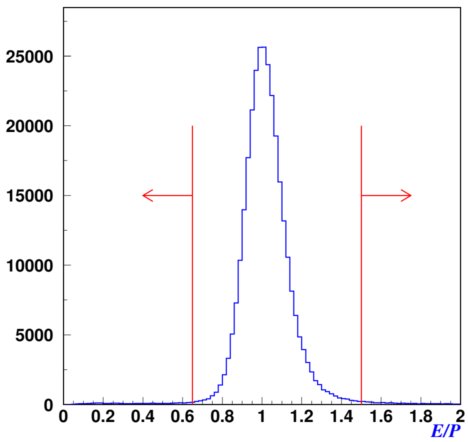
Particle Identification

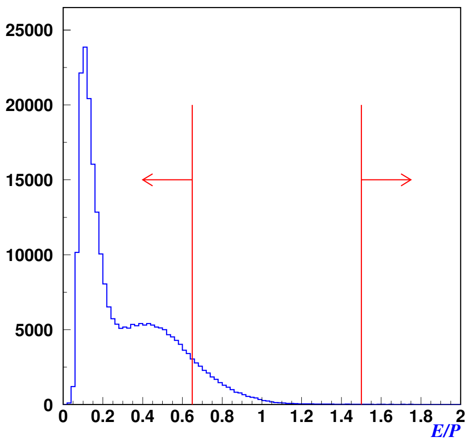
- Electron CONCERN : π^{-} as e^{-}
  - Light in both Čerenkov counters



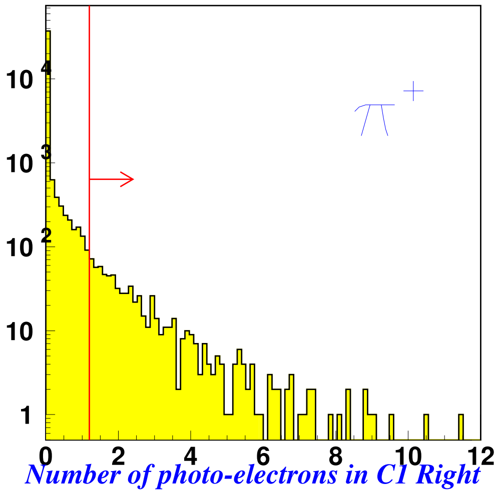


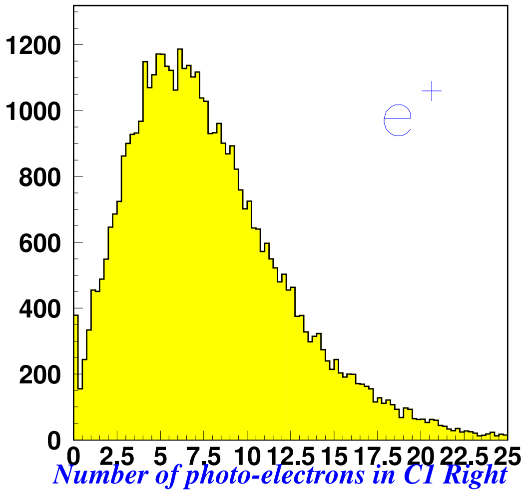
  - 0.65 $<$ Energy/Momentum ratio $<$ 1.5





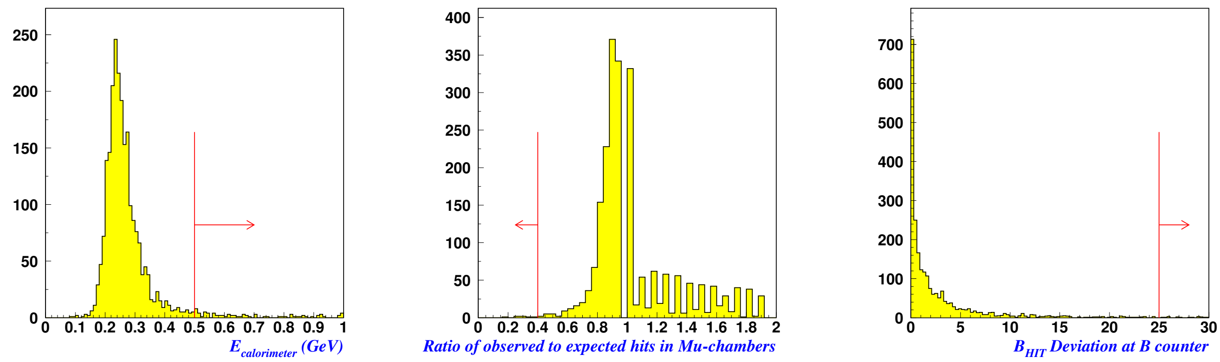
- Pion
  - Less then 1.2 p.e.'s in both Čerenkov counters





  - Energy/Momentum ratio < 0.9

- # Muon
  - Less then 1.2 p.e.'s in both Čerenkov counters
  - Energy in the Calorimeter $<$ 0.45 GeV
  - Range in the muon system consitent with momentum
  - Hit in the B-counter consistent with the track



Background from other K^+ decays depends on the PID:

Achieved PID efficiencies

e^- efficiency 0.767 $\pm$ 0.03

π^+ efficiency 0.804 $\pm$ 0.01

μ^+ efficiency 0.79 $\pm$ 0.01

P(π^- as e^-)=(8.7$\pm$2.6)$\times 10^{-6}$

P(e^+ as π^+)=(1.1$\pm$0.1)$\times 10^{-5}$

P(π^+ as μ^+)=0.066$\pm$0.001

* Likelihoods were not utilized yet.

Pass3

- Backgrounds suppression (PID and Kinematic selection)
- High ($\approx 90\%$ per cut) efficiency for signal events

event selection criteria:

- Sum of Track's $\chi^2 < 25$

- Normalized vertex miss distance $S < 2.35$ cm

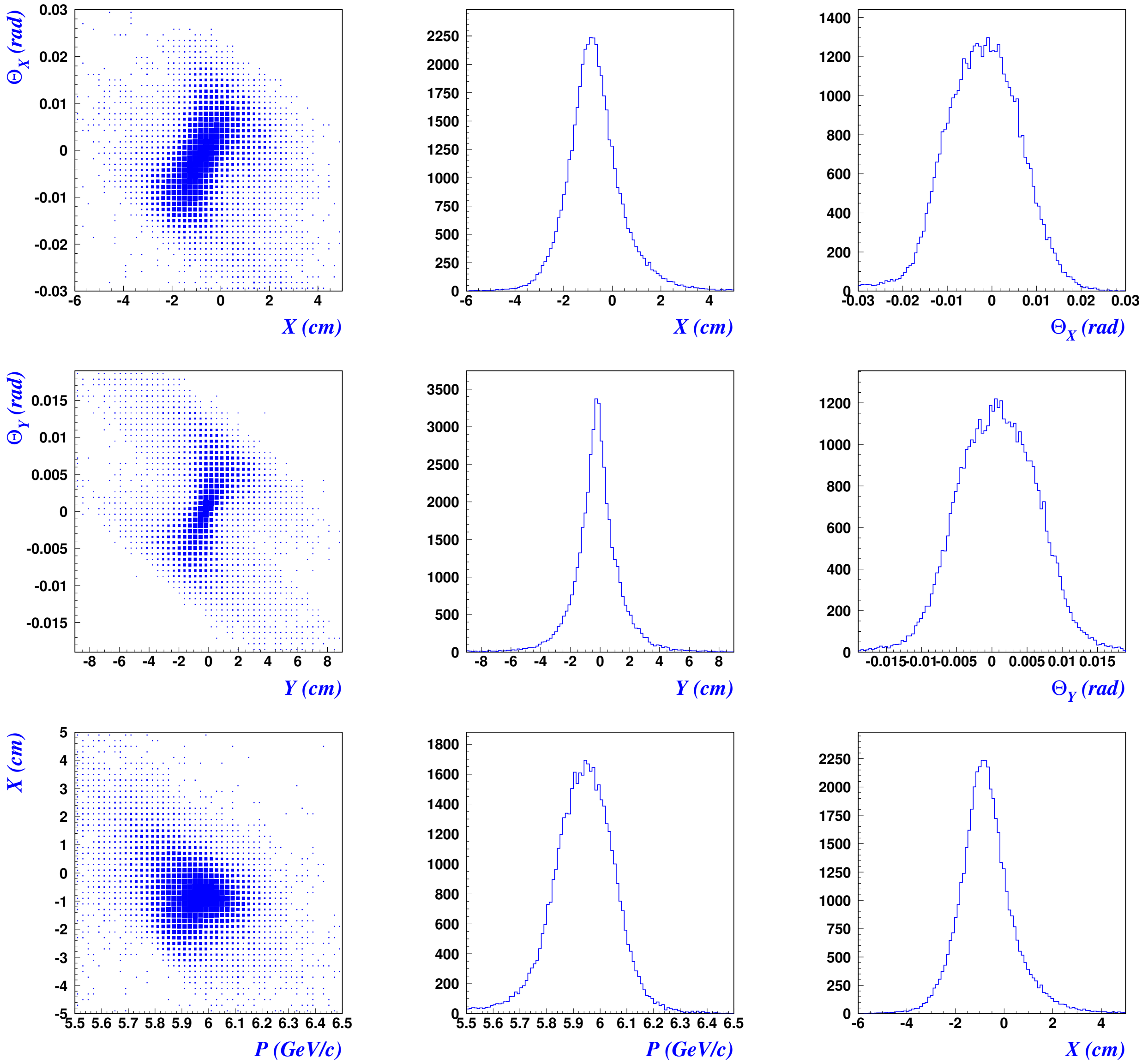
- Extra calorimeter clump time > 1 ns

- No gamma clumps within 2 ns

- Target likelihood (will be discussed)

- Time difference between e^-, π^+, μ^+ (will be discussed)

Kaon distributions at the Production Target for $K_{\pi\pi\pi}$



The Likelihood was calculated that the momentum vector at the target coincides with the $K_{\pi\pi\pi}$ distribution, approximated by: $\mathcal{L} = \mathcal{L}_1(X, \theta_X)\mathcal{L}_2(Y, \theta_Y)\mathcal{L}_3(P, X)$

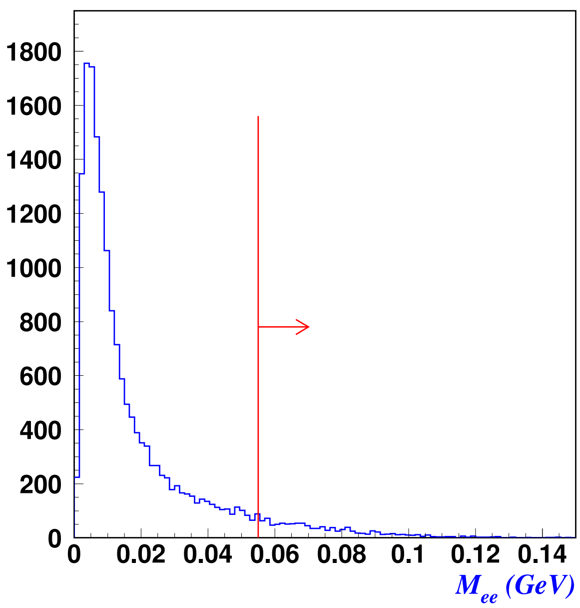
Predicting the K_{Dal} background level

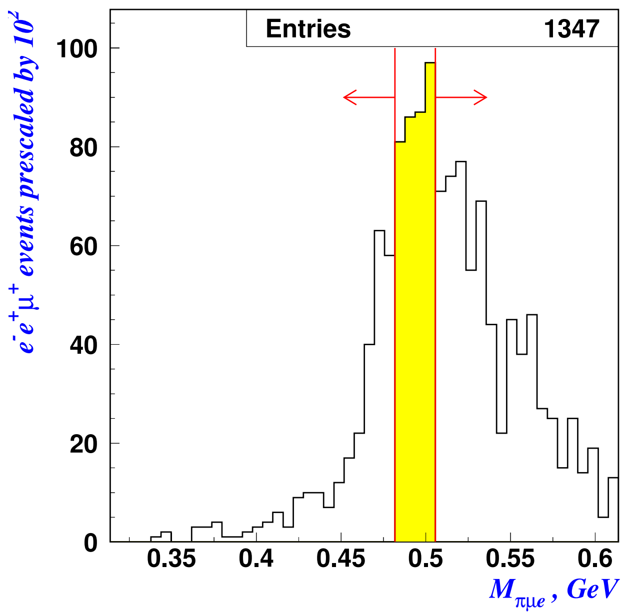
Background from $K^+ \to \pi^0\mu^+\nu$, $K^+ \to \pi^0\pi^+$ with $\pi^0 \to e^+e^-\gamma$

$$N(K_{DAL})^{BG} = N(ee\mu) \times P(e^+ \text{ as } \pi^+)$$
$$P(e^+ \text{ as } \pi^+) = (2.5 \pm 0.5) \times 10^{-6} \text{ (From PID Analysis)}$$

Cuts designed to suppress K_{Dal} Background:

- $M_{ee} > 0.055$ GeV (e^+e^- from a π^0 decay have Low M_{ee})
- N_γ=0 .or. $T_\gamma > 2$ns





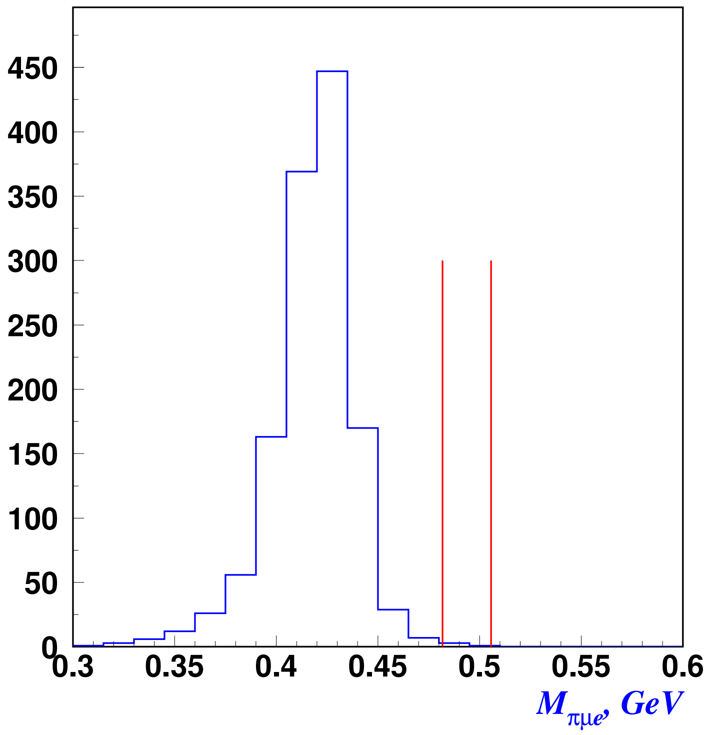
$N(K_{DAL})^{BG} = 3.51 \times 10^4 \times P(e^+$ as $\pi^+)$=0.09 ± 0.01 events

Predicting the K_{Tau} background level

Background from $K^+ \to \pi^+\pi^+\pi^-$, with $\pi^+ \to \mu^+\nu_\mu$

$$N(K_{\pi\pi\pi})^{BG} = N(\pi\pi\mu) \times P(\pi^- \text{ as } e^-)$$
$$P(\pi^- \text{ as } e^-) = (2.4 \pm 1.4) \times 10^{-6} \text{ (From PID Analysis)}$$

K_{Tau} background kinematic rejection - Low $M_{\pi\mu e}$



$N(K_{\pi\pi\pi})^{BG} = 5.25 \times 10^4 \times P(\pi^- \text{ as } e^-)$ =0.1 ± 0.1 events

Accidental background

ACCIDENTAL EVENTS

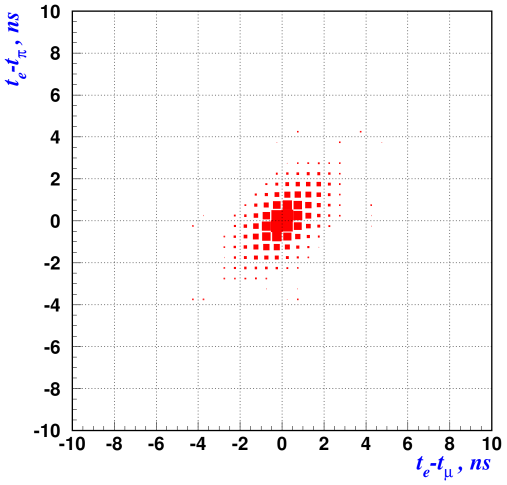
- Reconstructed Kaon momentum is no longer constrained by the momentum of the beam kaons (6 GeV/c).
- Quality of the reconstructed vertex is poor.
- Target Likelihood is poor, since accidental event would rarely be tracked back to the target.
- Track times, determined by the time of Shower and hodoscope hits are inconsistent with each other for different tracks.
- Presence of extra clumps in the calorimeter, since accidental event is a superposition of several decays (Kaon, or beam background).
- Correct PID for π^+, μ^+, and e^-
- 2+1 or 1+1+1 mechanism
- Possibly some combinations are favoured ($e\mu + \pi$,$e\pi + \mu$,$e + \pi\mu$)

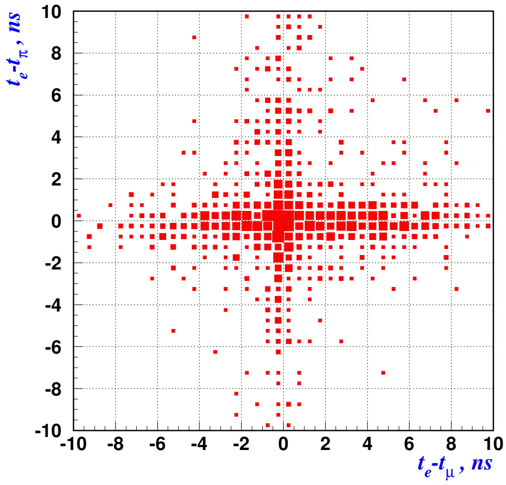
Ways to select accidental events:

- OUT of TIME
- Reconstructed Kaon momentum $P_{\mathrm{KAON}} > 6.9$ GeV/c
  $P_{beam} = 5.9$ GeV/c with a $\sigma_P = 0.1$ GeV/c

Track times correlation

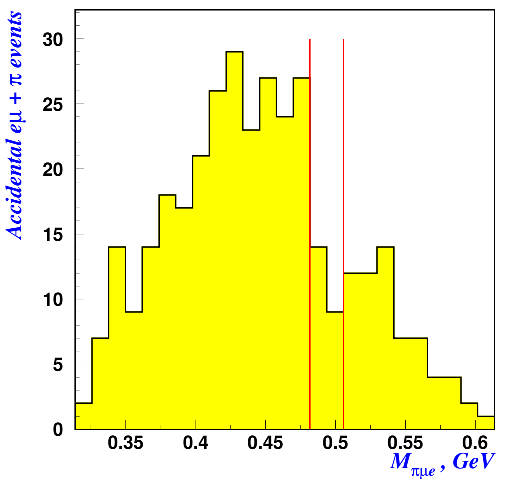
$t_e - t_\pi$ and $t_e - t_\mu$

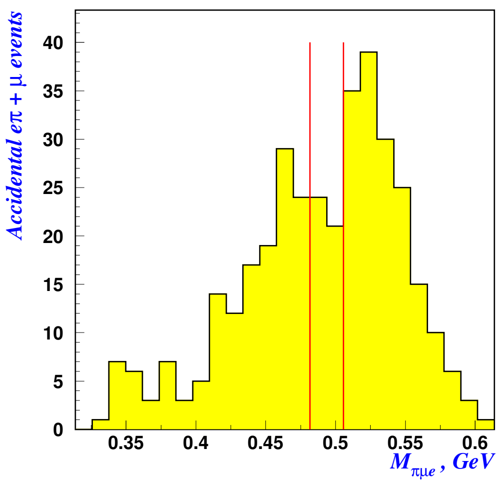




$K_{\pi\pi\pi}$ events

$P_{\mathrm{KAON}} > 7$ GeV/c





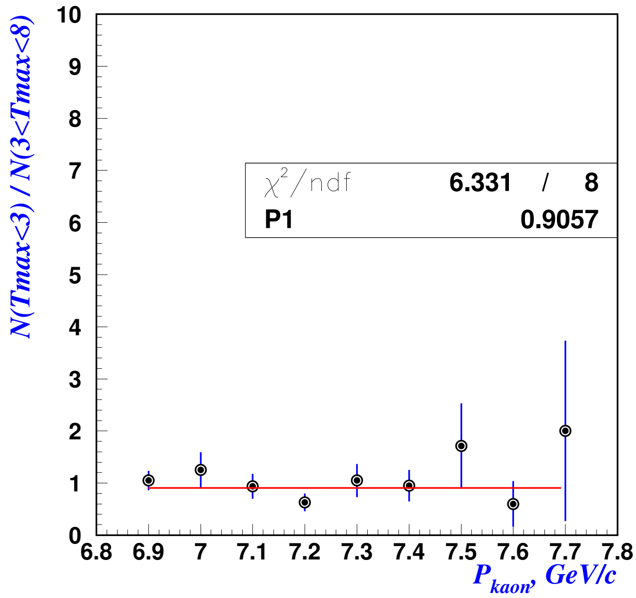
$$\frac{e^-\mu^+ + \pi^+}{\approx 40\%}$$

$$\frac{e^-\pi^+ + \mu^+}{\approx 60\%}$$

Predicting Accidental Background

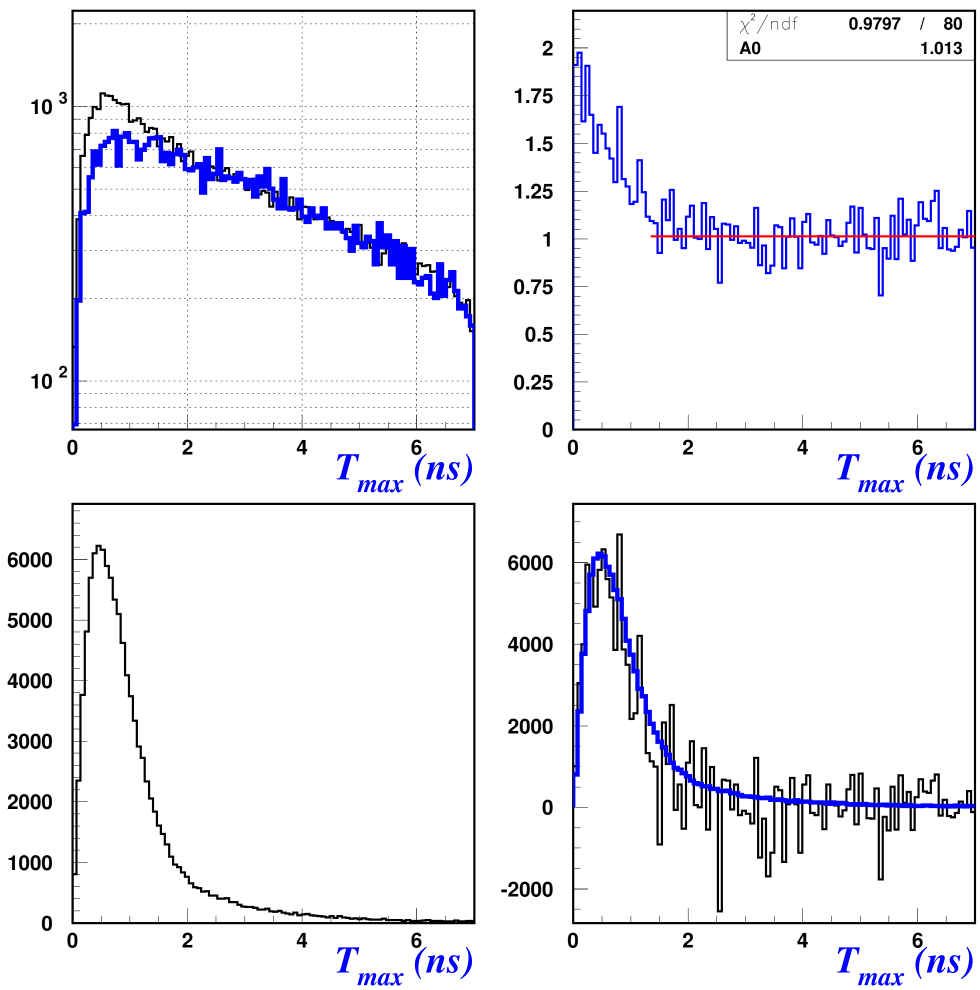
- Select OUT OF TIME $K^+ \to \pi^+ \mu^+ e^-$ candidates (Accidentals) (track's time is more then 3 ns (3σ) from the other two tracks)
- Project OUT OF TIME events into the IN TIME signal region. (Ratio $R{=}N(IN\ TIME)/N(OUT\ OF\ TIME)$ is extracted using High Momentum ($P_{KAON} > 6.9$ GeV/c) events

Time distribution of events with high kaon momentum can be different?



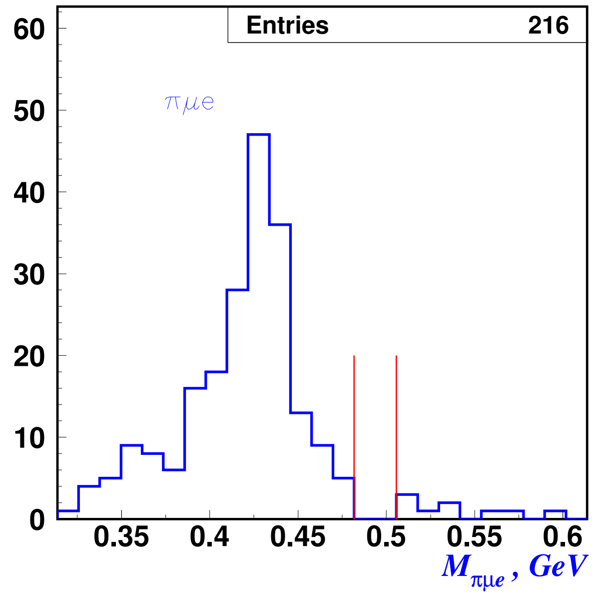
Projection factor used to estimate the level of accidental background in the signal region from the number of the out-of-time accidentals versus the Kaon momentum

Time distribution of High Momentum Events

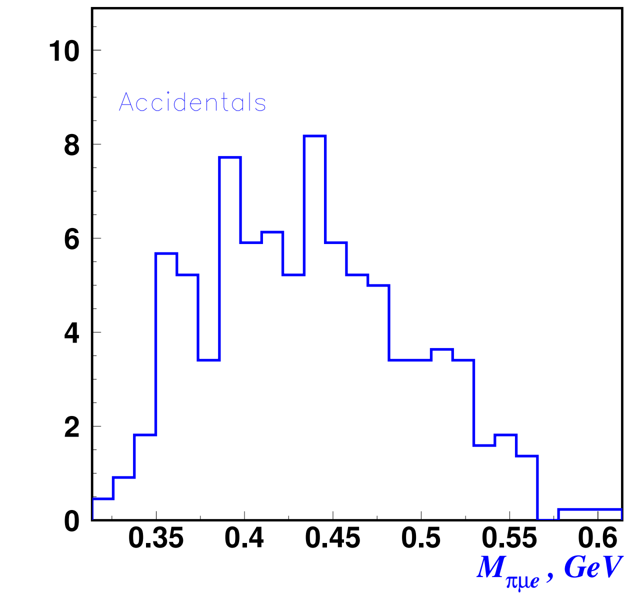


Top Left: $K_{\pi\mu e}$ candidates (thin line) and high momentum accidentals (bold line). **Top Right:** Ratio of time distribution for $K_{\pi\mu e}$ candidates and high momentum accidental events. **Bottom Left:** Time distribution of good $K_{\pi\pi\pi}$ events. **Bottom Right:** Difference between time distributions of $K_{\pi\mu e}$ candidates and high momentum accidentals (thin line) and time distribution of good $K_{\pi\pi\pi}$ events (bold line).

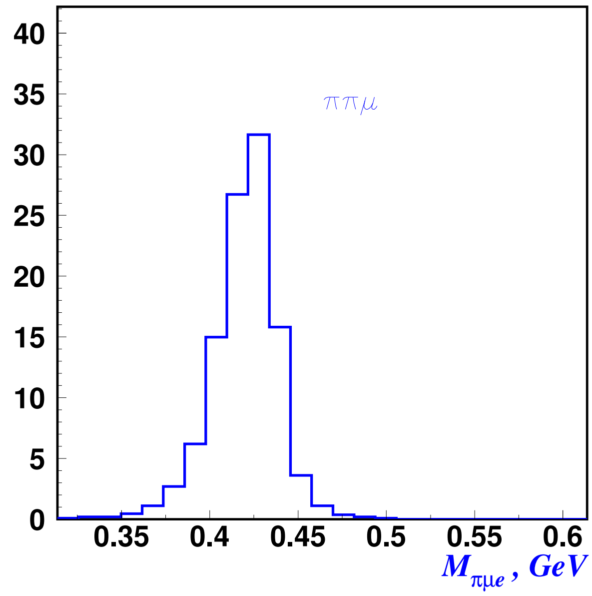
$M_{\pi\mu e}$ spectrum for backgrounds and observed $\pi\mu e$ candidates



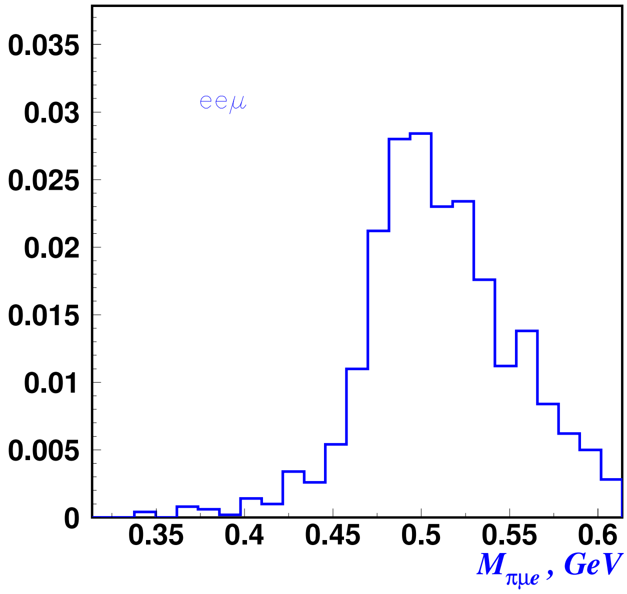
$K_{\pi\mu e}$ candidates



Accidental background

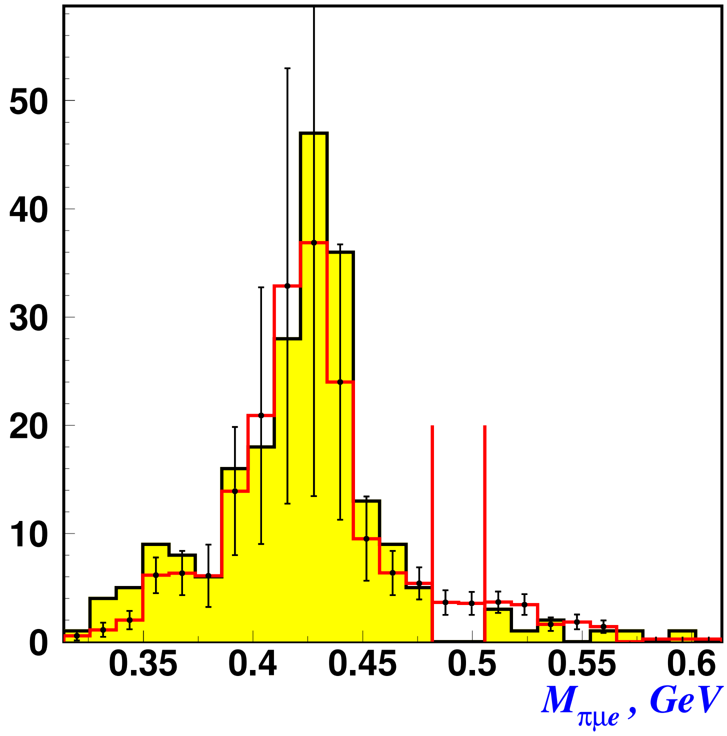


K_{Tau} background



K_{Dal} background

Adding backgrounds



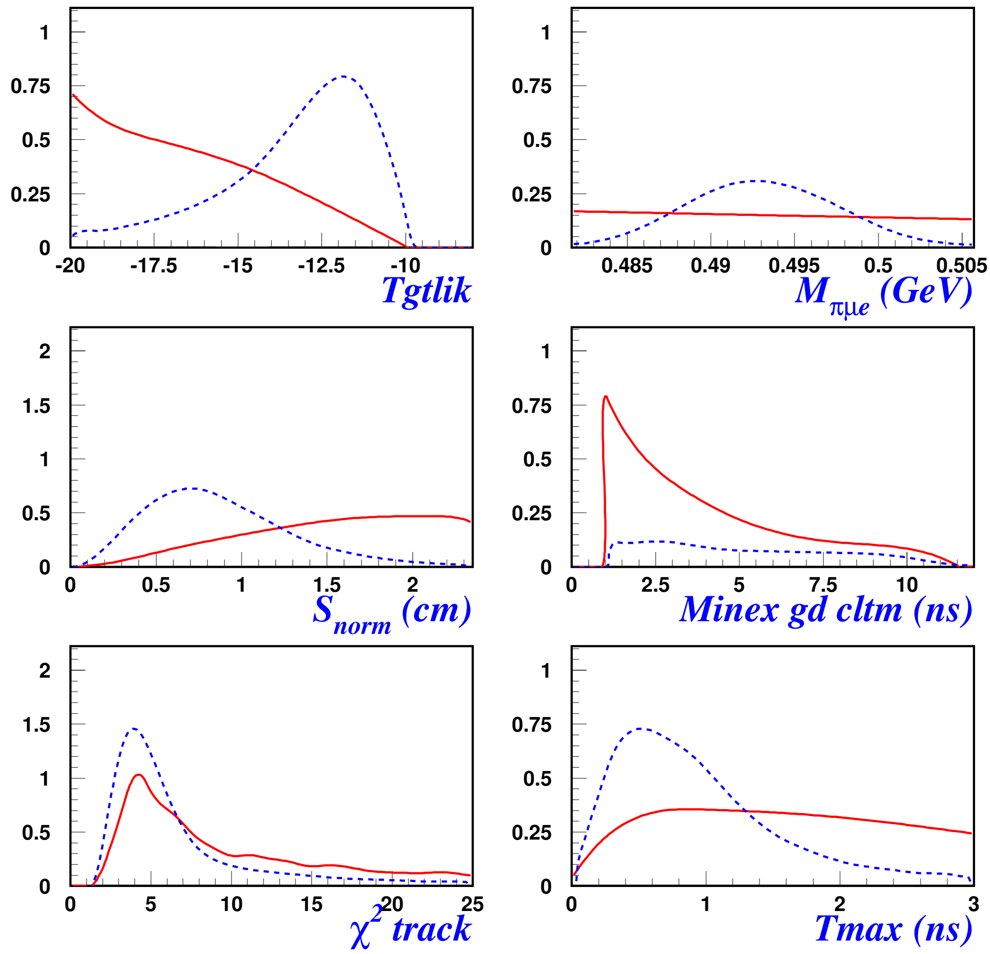
Filled histogram - observed $K^+ \to \pi^+ \mu^+ e^-$ candidate events
Ticks with errors - predicted background level

- Misidentification probabilities and background estimates are confirmed
- Dominating Background is accidental
- Estimated Level 8.2 events
- General Likelihood using independent kinematic variables

General Likelihood for $K^+ \to \pi^+\mu^+e^-$

$$\mathcal{L}_{\pi\mu e}(x_1 ... x_6) = \prod_{i=1}^{6} P_i^{\pi\mu e}(x_i)$$

$$\mathcal{L}_{Acc}(x_1 ... x_6) = \prod_{i=1}^{6} P_i^{Acc}(x_i)$$

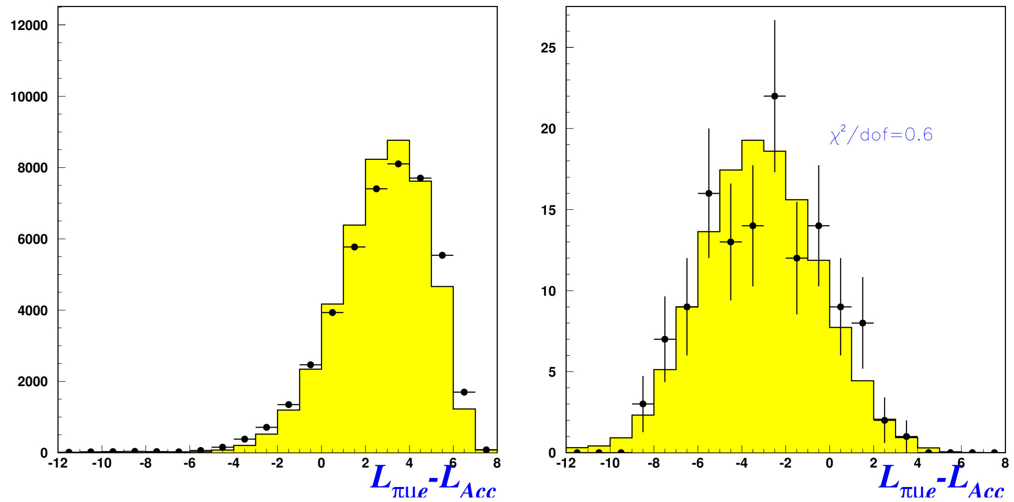


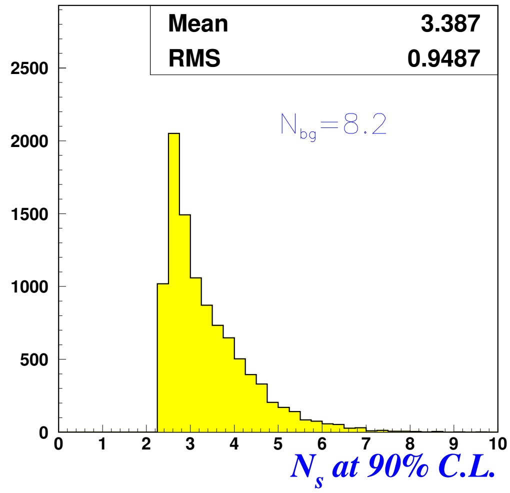
Probability Density Functions $P_i(x_i)$ created for $K_{\pi\mu e}$ and accidental background

Predicting the likelihood efficiency

Log Likelihood templates $L = L_{\pi\mu e} - L_{Acc} = \log \mathcal{L}_{\pi\mu e} - \log \mathcal{L}_{Acc}$

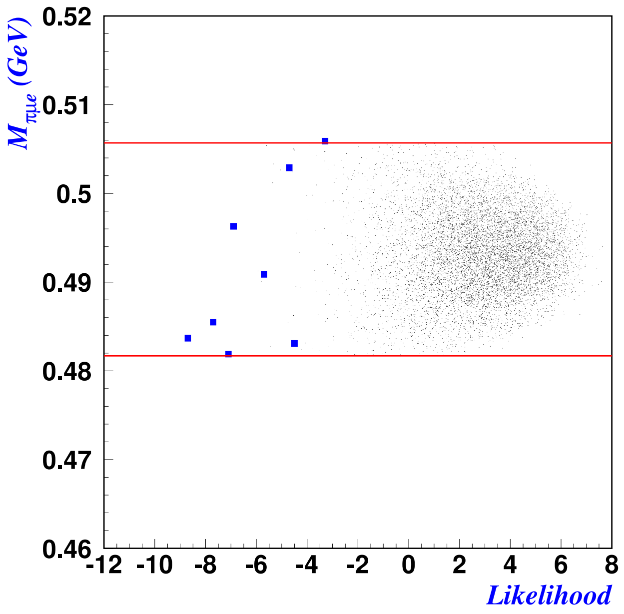
$K_{\pi\mu e}$ Accidental background

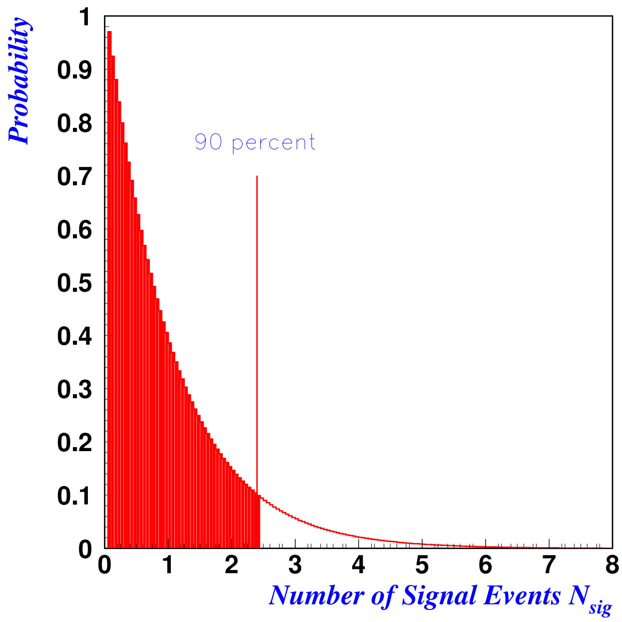




Assuming NO SIGNAL EVENTS Likelihood would yield:
Upper 90% C.L. on $N(\pi\mu e)^{max}$ = 3.4$\pm$1

EXAMINING the SIGNAL REGION (Mass versus Likelihood)





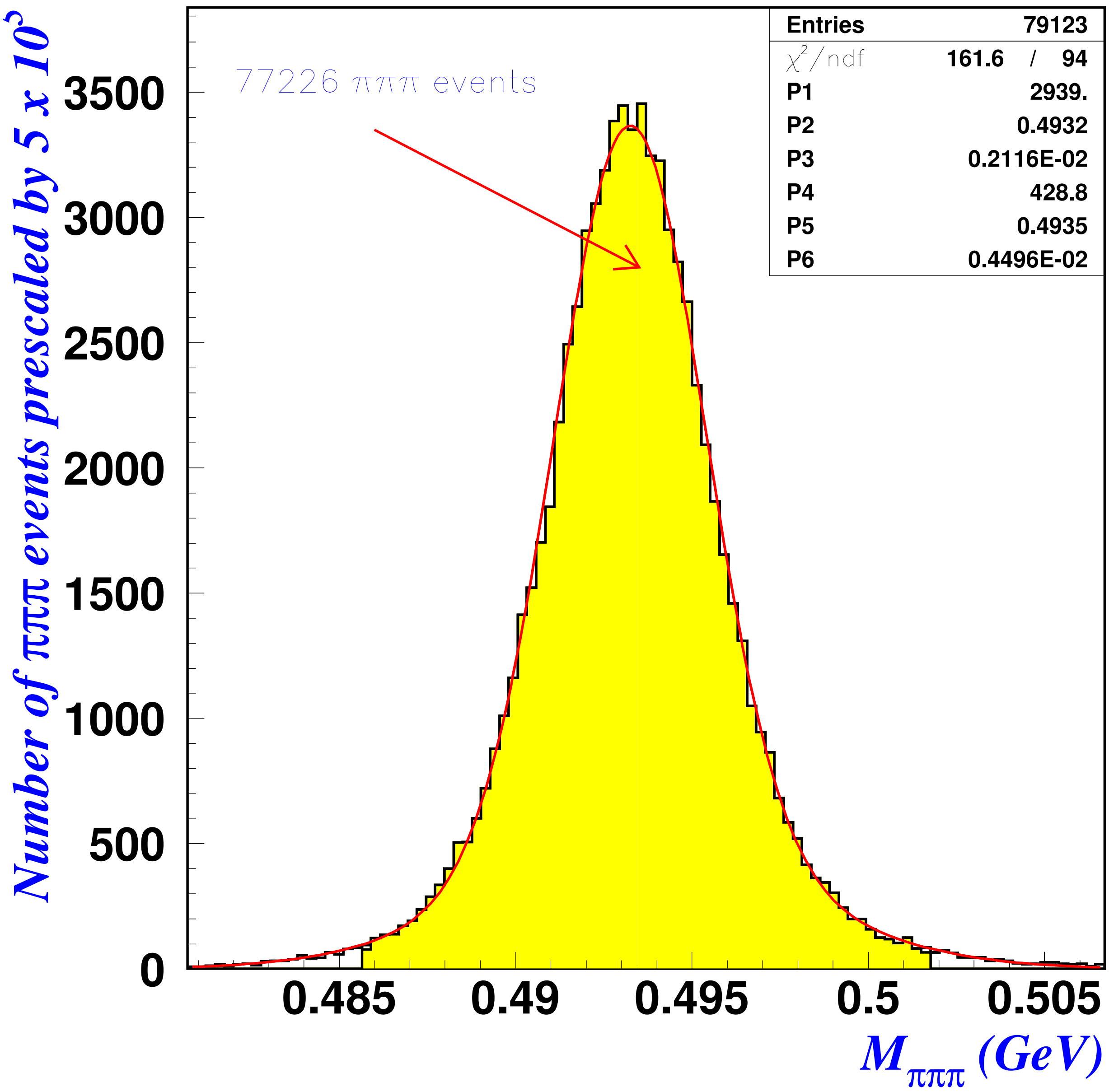
$N(\pi\mu e)^{90\%}$ = 2.4 events

$$BR(\pi\mu e) = BR(\pi\pi\pi) \cdot \frac{N(\pi\mu e)}{N(\pi\pi\pi)} \cdot \frac{Acc(\pi\pi\pi)}{Acc(\pi\mu e)} \cdot C \qquad (1)$$

where:

BR	- denotes branching ratio
$N(\pi\mu e)$	- the 90% CL number of $K_{\pi\mu e}$ events
$N(\pi\pi\pi)$	- number of $K_{\pi\pi\pi}$ events
Acc	- acceptance of the detector system
C	- correction factor accounting for efficiency differences between ($K_{\pi\pi\pi}$) and ($K_{\pi\mu e}$) selection.

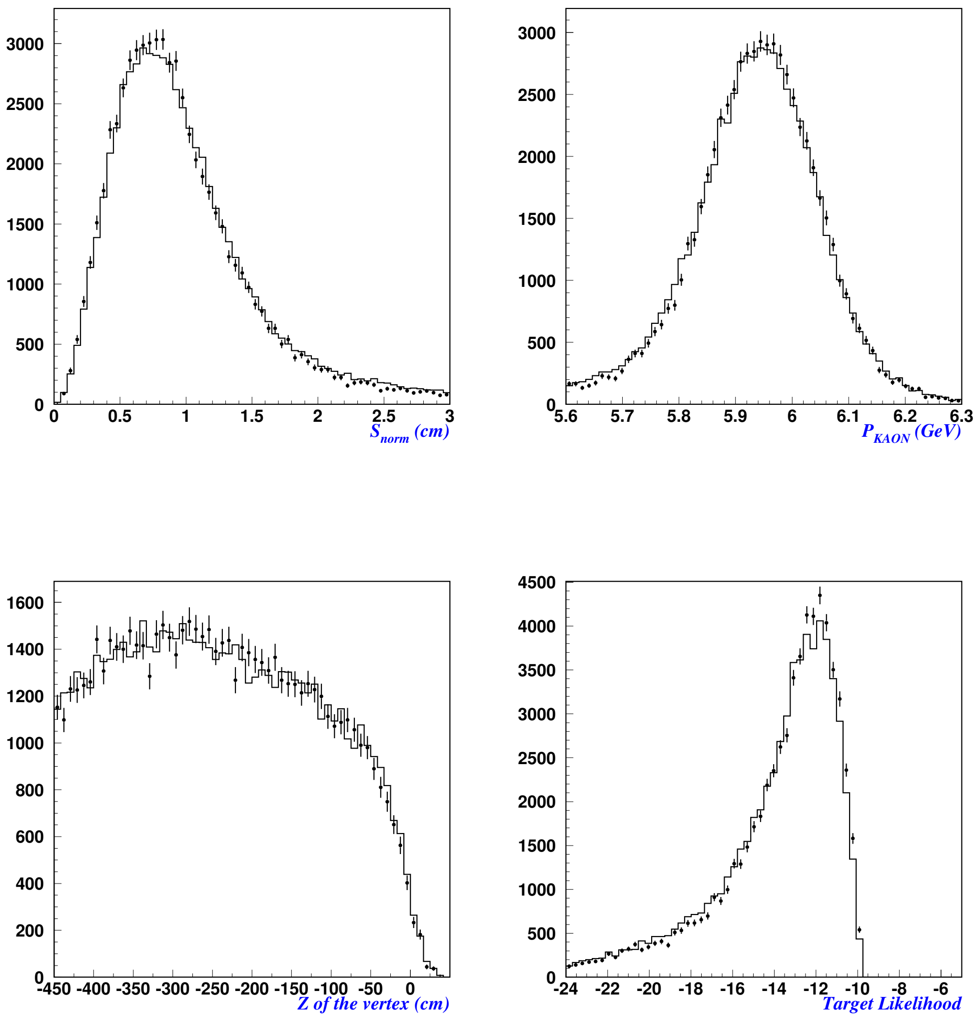
Number of $K_{\pi\pi\pi}$ events



N($\pi\pi\pi$) =77226 $\times$ 50 $\times$ 10^4 = 3.86 $\times 10^{10}$ events

Acceptance Ratio Calculation

- Monte Carlo Simulation using GEANT3
- Detector efficiencies determined from the Data



DATA (dots with errors) and MC(histogram) comparison for $K_{\pi\pi\pi}$ decay

Acc($\pi\pi\pi$)	Acc($\pi\mu e$)	Acc($\pi\pi\pi$)/Acc($\pi\mu e$)
0.126(1)	0.068(1)	1.86(2)

Correction Factor Calculation

$$C = \frac{\prod_{i=1}^{n} \epsilon_i^{\pi\pi\pi}}{\prod_{j=1}^{n} \epsilon_j^{\pi\mu e}} \to \frac{1}{\prod_{j=1}^{7} \epsilon_j^{\pi\mu e}} \quad (2)$$

Description	*Value*
π^+ detection (e^+ veto)	0.781 ± 0.004
μ^+ detection	0.79 ± 0.01
e^- detection	0.745 ± 0.003
e^+e^- invariant mass $M_{e^+e^-} > 55$ MeV	0.919 ± 0.007
require e^- to be on the left side	0.926 ± 0.008
require π^+ to be on the right side	0.891 ± 0.008
reject π^+ from $K^+ \to \pi^0\pi^+$ decay	0.865 ± 0.009

C=3.32 $\pm$ 0.08

Result

AN UPPER LIMIT at 90 % CL

$$BR(\pi\mu e) < BR(\pi\pi\pi) \cdot \frac{N(\pi\mu e)^{90\%}}{N(\pi\pi\pi)} \cdot \frac{Acc(\pi\pi\pi)}{Acc(\pi\mu e)} \cdot C \qquad (3)$$

The value of the factors on the right hand side are:

$$\begin{aligned} BR(\pi\pi\pi) &= 0.0558 \pm 0.0003 \\ N(\pi\mu e)^{90\%} &= 2.4 \\ N(\pi\pi\pi) &= 3.86 \times 10^{10} \\ \frac{Acc(\pi\pi\pi)}{Acc(\pi\mu e)} &= 1.86 \pm 0.02 \\ C &= 3.32 \pm 0.08 \end{aligned}$$

$$\boxed{BR(\pi\mu e) < 2.4 \times 9.0 \times 10^{-12} = 2.2 \times 10^{-11}} \qquad (4)$$

Previous experiments and E865 results from 95, 96 years showed that:

$$BR(\pi\mu e) < 2.8 \times 10^{-11}$$

Combining our result with the previous one leads to the new upper limit on $K_{\pi\mu e}$ branching ratio:

$$BR(\pi\mu e) < \mathbf{1.2 \times 10^{-11}}$$

CONCLUSION

- The limit on the LFV via decay $K_{\pi\mu e}$ is improved by one order of magnitude (2$\times 10^{-10} \to 1.2 \times 10^{-11}$)

- Possible Extension theories “phase space” is reduced

- Rate of the decay probes the mass scale of hypothetical new interaction field:
$M_X >$ 80 TeV (for Horizontal Gauge)
$M_{LQ} >$ 270 TeV (for Leptoquarks)

- No New Physics yet

- Future searches for LFV :
$\mu^+ \to e^+\gamma \; O(10^{-14})$
$\mu^- N \to e^- N \; O(10^{-16})$