

## An Improved Limit on the Decay $K^+ \rightarrow \pi^+ \mu^+ e^-$

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TRIUMF

(on behalf of the E865 collaboration)

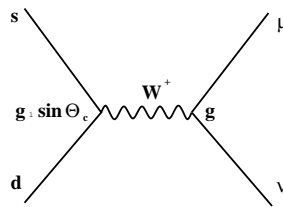
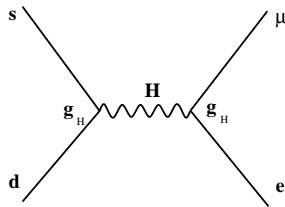
### OUTLINE:

- Motivation
- Experimental Setup
- Analysis
- Conclusion

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

$$K^+ (0) \rightarrow \pi^+ (0) \mu^+ (L_\mu=-1) e^- (L_e = 1)$$

- Observed LFNV  $\rightarrow$  **NEW PHYSICS**
- No signal  $\rightarrow$  **Valuable result for the theory**  
 Supersymmetry, Extended Technicolor and Horizontal Gauge Theories, and Leptoquarks allowed LFNV at a rate as high as  $10^{-10}$   
 Example: Horizontal Extended Technicolor Boson (H) couples LF



$$\frac{B(K^+ \rightarrow \pi^+ \mu^+ e^-)}{B(K^+ \rightarrow \pi^0 \mu^+ \nu)} = 16 \frac{1}{\sin^2 \theta_c} \left( \frac{g_H}{g} \right)^4 \left( \frac{M_W}{M_H} \right)^4, \quad (1)$$

$$M_H \approx 150 \text{ TeV} \left[ \frac{10^{-12}}{B(K^+ \rightarrow \pi^+ \mu^+ e^-)} \right]^{1/4} \quad (2)$$

Robert N. Cahn and Haim Harari. *Nucl. Phys.*, B176:135, 1980.

$$\text{BR}(K \pi \mu e) < 2.8 \times 10^{-11} \rightarrow M_H > 65 \text{ TeV}$$

## Some of the LFNV searches:

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

**E865 at BNL** (started in 1995)

**Goal:** Single Event Sensitivity for  $K_{\pi^+ \mu^+ e^-}$  of  $O(10^{-12})$

## The E865 Collaboration

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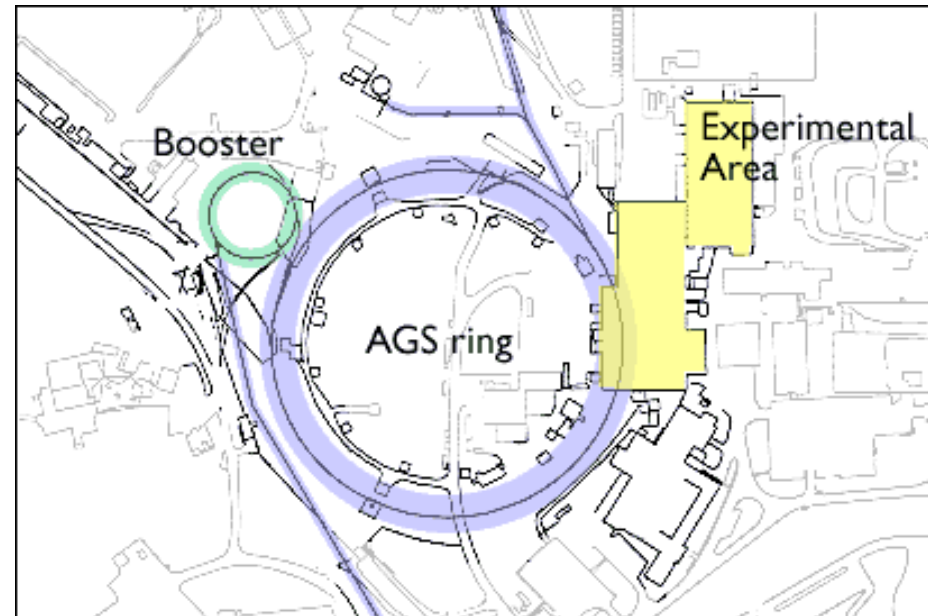
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## Experimental Setup

Kaons must be produced in copious amount



The Alternating Gradient Synchrotron complex

	Protons	Kaons <sup>1</sup>
Momentum (GeV/c)	24	6
Rate per 2.8 s spill <sup>2</sup>	$1 \times 10^{13}$	$2 \times 10^8$
Rate per hour	$7 \times 10^{15}$	$1.4 \times 10^{11}$

<sup>1</sup>  $K^+/\pi^+=0.05$  and  $K^+/p=0.1$

<sup>2</sup> Cycle time=5.1 s

## Detector Requirements

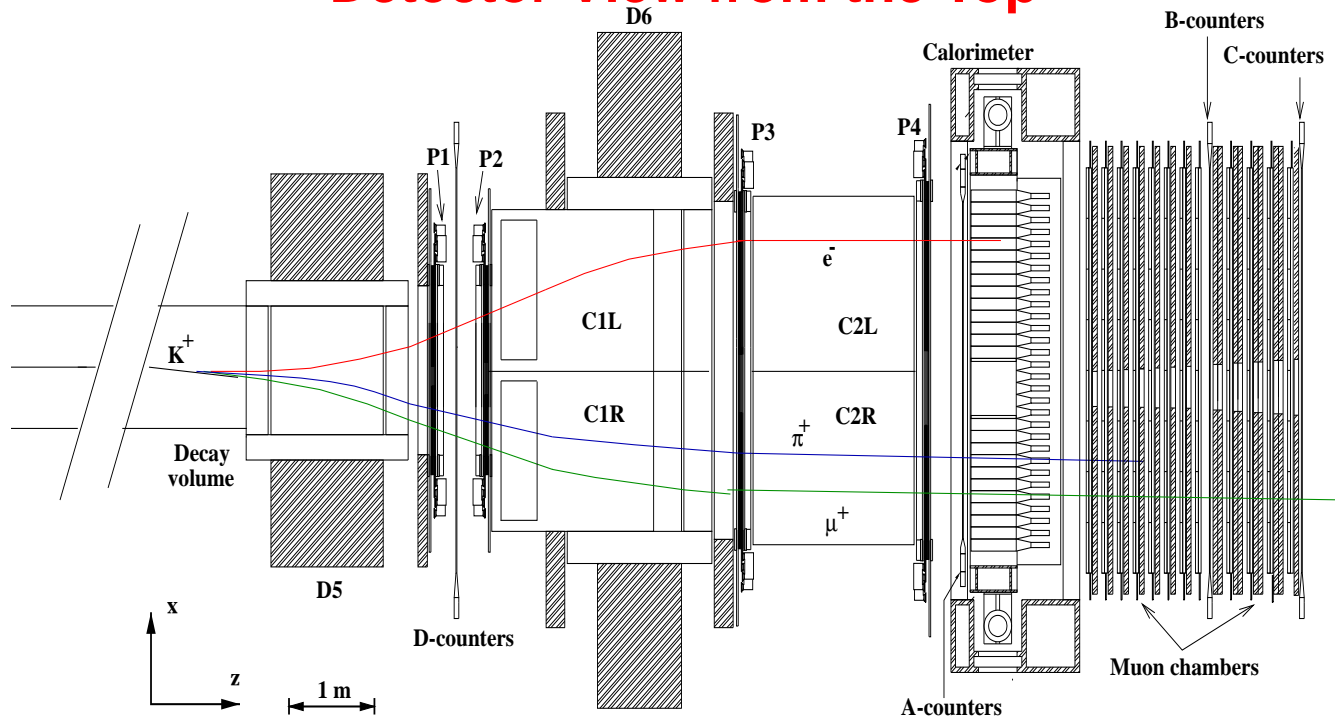
High Rate and good Particle Identification:  
Background from Kaon decays ( $O(10^{-13})$ ):

Decay Mode	Misidentification	Branching
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$ $\pi^+ \rightarrow \mu^+ \nu_\mu$	<u><math>\pi^-</math> as <math>e^-</math></u>	$8 \times 10^{-3}$
$K^+ \rightarrow \pi^0 \pi^+$ $\pi^0 \rightarrow e^+ e^- \gamma$	<u><math>e^+</math> as <math>\pi^+</math></u> $\pi^+$ as $\mu^+$	$2.5 \times 10^{-3}$
$K^+ \rightarrow \pi^0 \mu^+ \nu$ $\pi^0 \rightarrow e^+ e^- \gamma$	<u><math>e^+</math> as <math>\pi^+</math></u>	$4 \times 10^{-4}$

Veto  $\pi^-$    Veto  $e^+$     $\pi^+$  from  $\mu^+$

Accurate kinematic reconstruction

## Detector View from the Top



Spectrometer

4 MWPC (P1...P4) and Dipole Magnets(D5,D6)  $P_T = \pm 255 \text{ MeV}/c$

Čerenkov Counters

$\gamma_t=60$  (C1L,C2L)  $\gamma_t=35$ (C1R,C2R)  $e^+, e^-$  - producing light

EM Calorimeter

600 modules (15 Rad length)  $\sigma_E=6.8\% \sqrt{E(\text{GeV})}$

Muon Chambers

24 Iron Plates and proportional chambers  $P_\mu > 0.8 \text{ GeV}/c$  reaches B-counter

Trigger Hodoscopes

D,A,B,C-counters (Triggering, time)

Trigger

3 hits in A-counter and Calorimeter, consistent with 3 charged particle decay of a  $K^+$   
Particle ID of  $e^-$  and  $\mu^+$

## 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

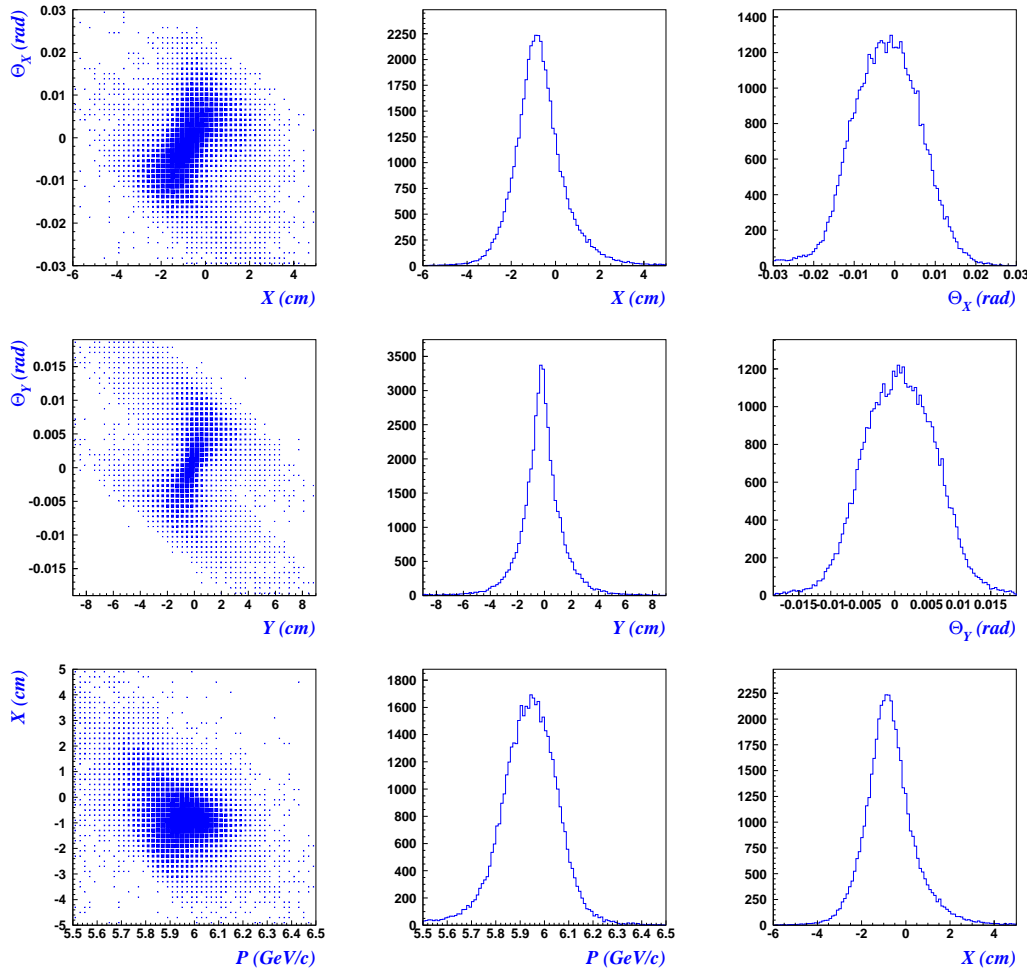
## Pass3

- 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  $e^-, \pi^+, \mu^+$  (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

$K^+ \rightarrow \pi^0 \mu^+ \nu$ ,  $K^+ \rightarrow \pi^0 \pi^+$  with  $\pi^0 \rightarrow e^+ e^- \gamma$

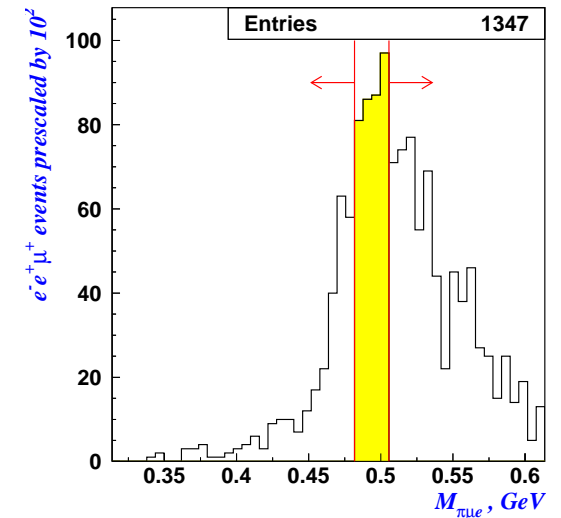
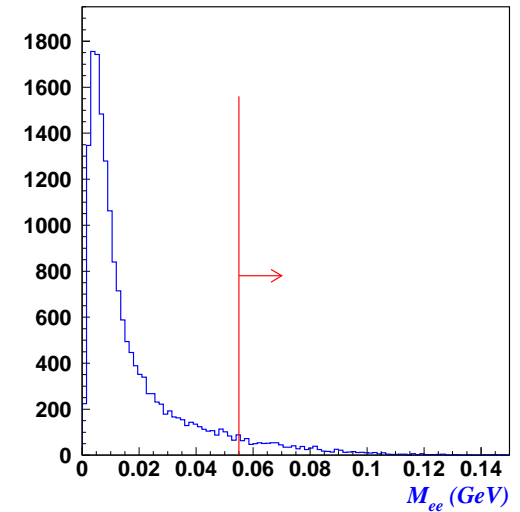
$$N(K_{DAL})^{BG} = N(ee\mu) \times P(e^+ \text{ as } \pi^+)$$

$$P(e^+ \text{ as } \pi^+) = (2.5 \pm 0.3) \times 10^{-6} \text{ (From PID Analysis)}$$

Cuts designed to suppress  $K_{Dal}$  Background:

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

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



## Predicting the $K_{Tau}$ background level

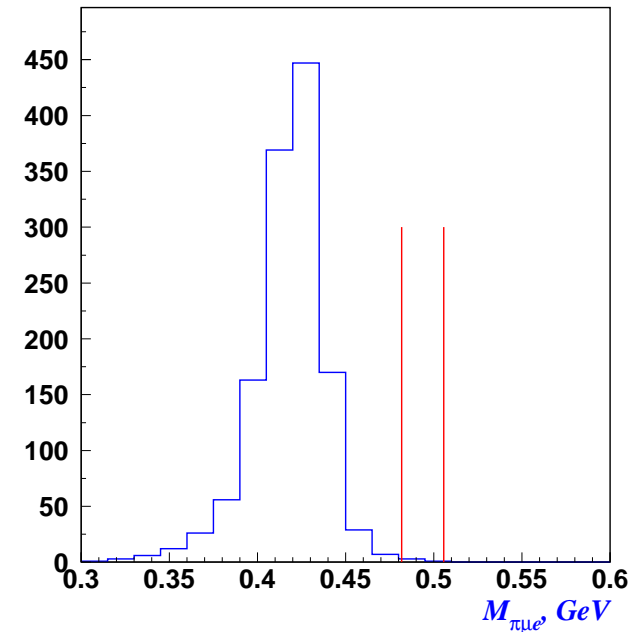
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$ , with  $\pi^+ \rightarrow \mu^+ \nu_\mu$

$$N(K_{\pi\pi\pi})^{BG} = N(\pi\pi\mu) \times P(\pi^- \text{ as } e^-)$$

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

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

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



## Accidental background

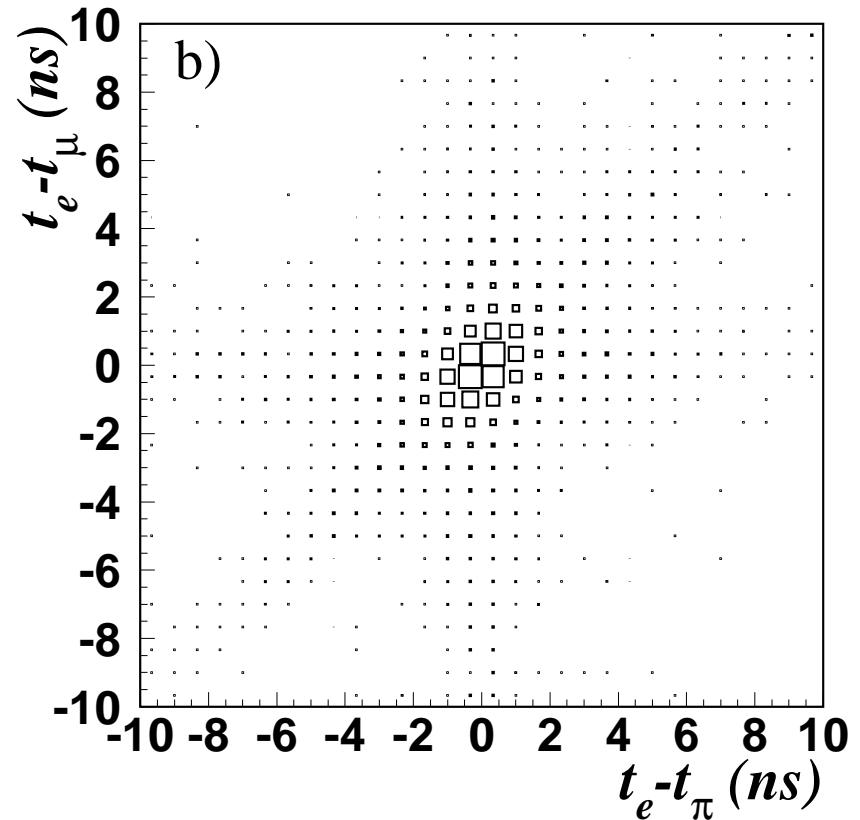
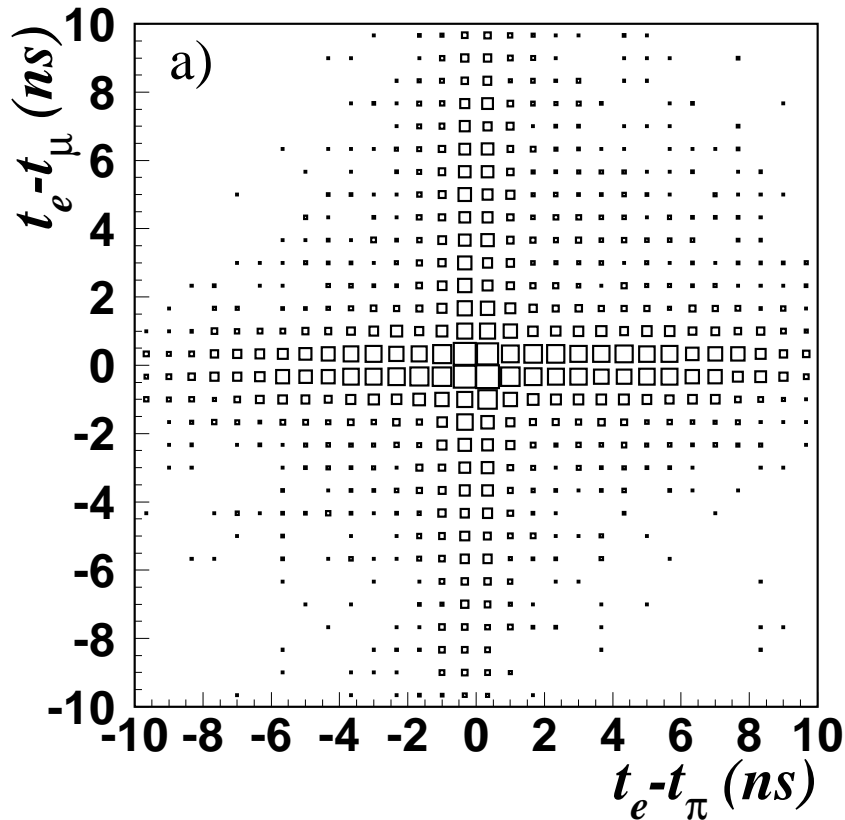
ACCIDENTAL EVENTS are characterized by:

- 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  $\pi^+$ ,  $\mu^+$ , and  $e^-$
- 2+1 or 1+1+1 mechanism. Possibly some combinations are favored ( $e\mu + \pi, e\pi + \mu, e + \pi\mu$ )

Ways to select accidental events:

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

## Track times correlation for Accidentals (a) and signal (b):

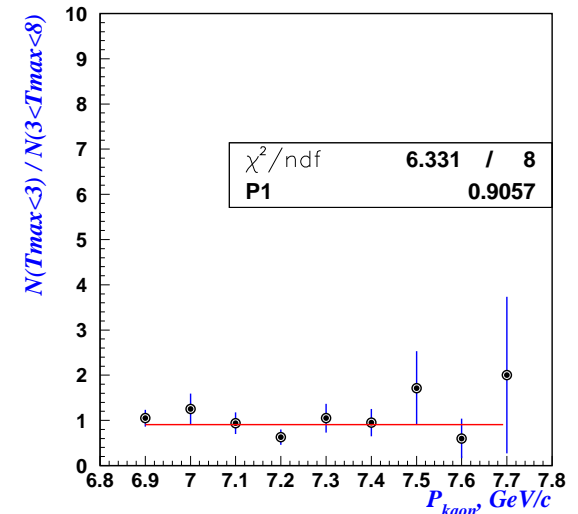


Two main accidental components:  $e^- \mu^+ + \pi^+$  ( $\approx 40\%$ )       $e^- \pi^+ + \mu^+$  ( $\approx 60\%$ )

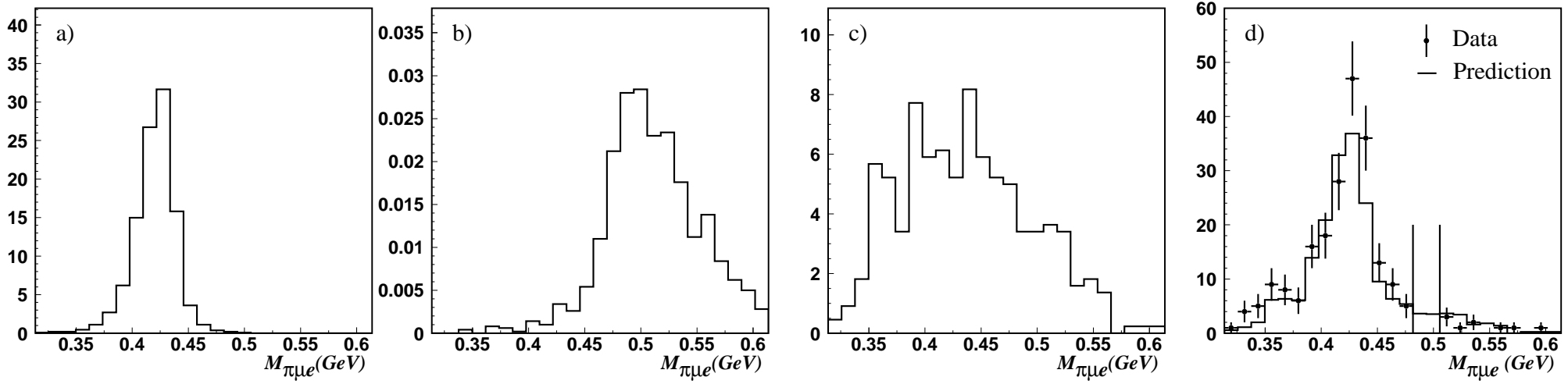
## Predicting Accidental Background

- Select OUT OF TIME  $K_{\pi\mu e}$  candidates (Accidentals)  
(track's time is more then 3 ns ( $3\sigma$ ) 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)

Checked that the time distribution of events with high kaon momentum is not 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

$M_{\pi\mu e}$  spectrum for backgrounds and observed  $\pi\mu e$  candidatesa)  $\pi^+ \mu^+ \pi^-$  ( $K_{\text{Tau}}$ ) backgroundb)  $e^+ \mu^+ e^-$  ( $K_{\text{Dal}}$ ) background

c) Accidental background

d) Data (Ticks with errors) and Background prediction (histogram)

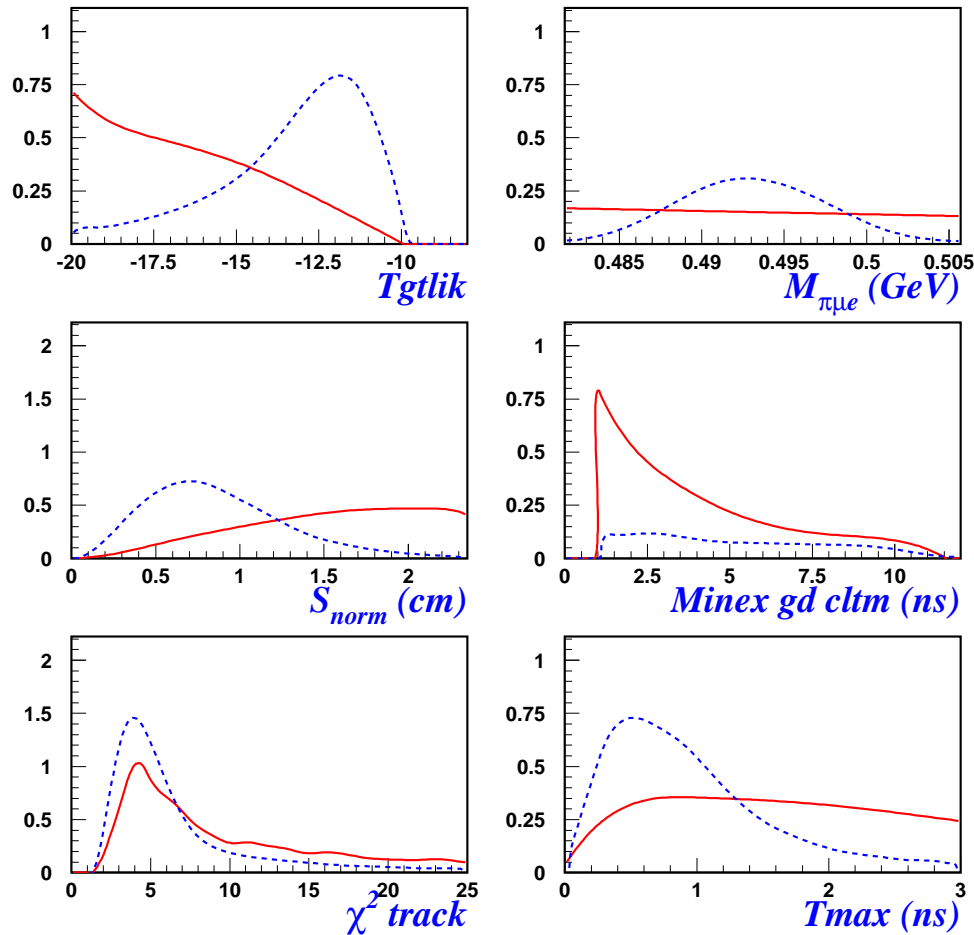
- Misidentification probabilities and background estimates are confirmed

- Dominating Background is Accidental (98%)

- Estimated Level  $8.2 \pm 1.9$  events

- **Final step:** General Likelihood using independent kinematic variables

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

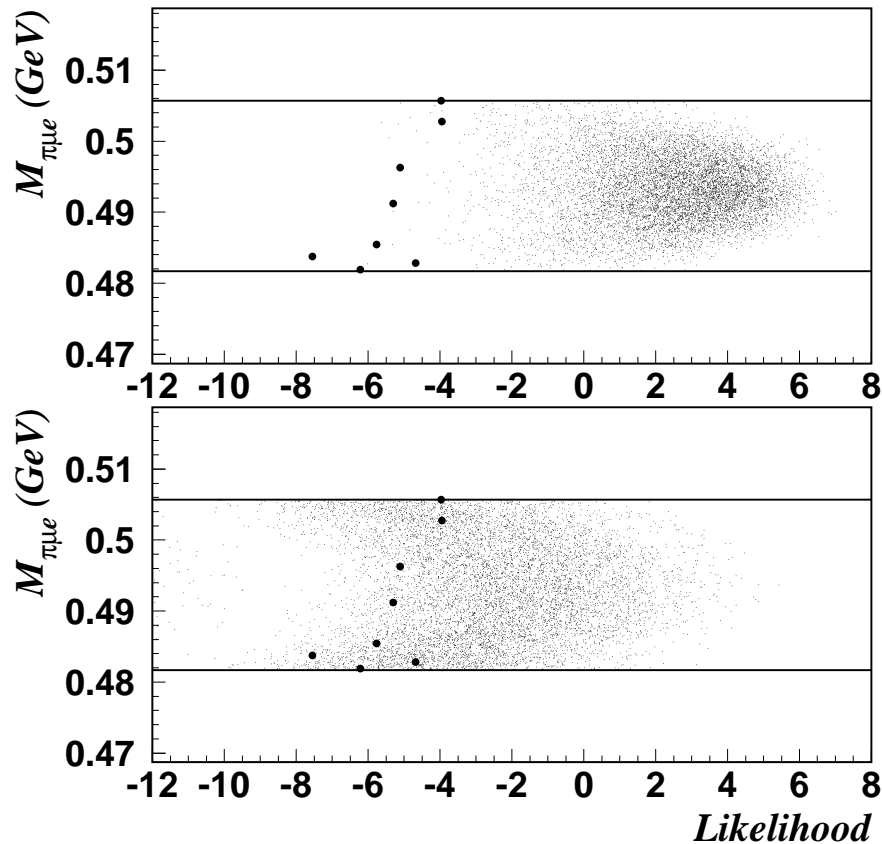


$$\mathcal{L}_{\pi\mu e}(x_1 \dots x_6) = \prod_{i=1}^6 P_i^{\pi\mu e}(x_i)$$

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

Probability Density Functions  $P_i(x_i)$  created for  $K_{\pi\mu e}$  and accidental background (Everything except  $M_{\pi\mu e}$  mass is from data)

## Signal region (Mass versus Likelihood)



Observed events are not consistent with the signal

Bayesian approach is used to determine the limit:

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

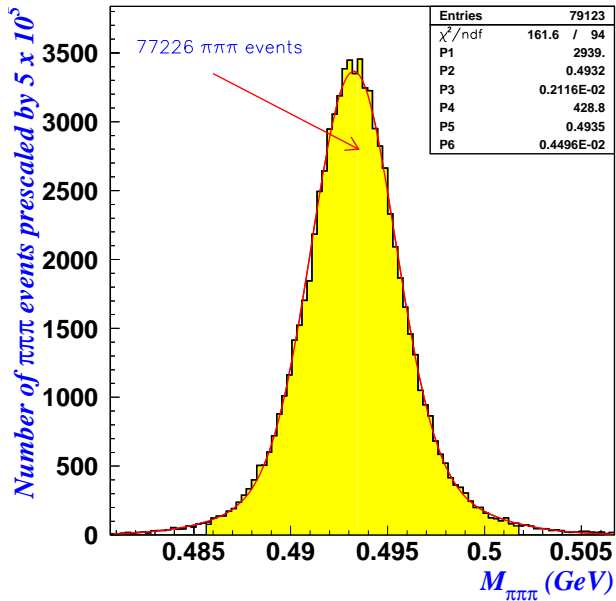
$$BR(\pi\mu e) = BR(\pi\pi\pi) \cdot \frac{N(\pi\mu e)}{N(\pi\pi\pi)} \cdot \frac{Acc(\pi\pi\pi)}{Acc(\pi\mu e)} \cdot C \quad (3)$$

where:

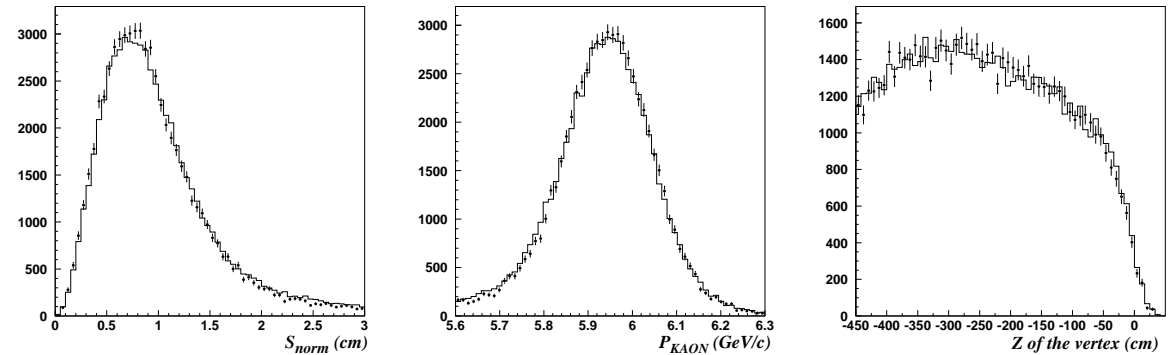
- $BR$  - denotes branching ratio
- $N(\pi\mu e)$  - the 90% CL number of  $K\pi\mu e$  events
- $N(\pi\pi\pi)$  - number of  $K\pi\pi\pi$  events
- $Acc$  - acceptance of the detector system
- $C$  - correction factor accounting for efficiency differences between  $(K\pi\pi\pi)$  and  $(K\pi\mu e)$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

## Normalization and Acceptance Ratio Calculation

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



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



DATA (ticks 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)

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

## Correction Factor

Description	Value
$\pi^+$ detection ( $e^+$ veto)	$0.781 \pm 0.004$
$\mu^+$ detection	$0.79 \pm 0.01$
$e^-$ detection	$0.745 \pm 0.003$
$M_{e^+e^-} > 55$ MeV	$0.919 \pm 0.007$
$e^-$ on the left side	$0.926 \pm 0.008$
$\pi^+$ on the right side	$0.891 \pm 0.008$
reject $\pi^+$ from $K^+ \rightarrow \pi^0 \pi^+$	$0.865 \pm 0.009$

$$C = 3.32 \pm 0.08$$

## Result:

$$BR(\pi\mu e) < BR(\pi\pi\pi) \cdot \frac{N(\pi\mu e)^{90\%}}{N(\pi\pi\pi)} \cdot \frac{Acc(\pi\pi\pi)}{Acc(\pi\mu e)} \cdot C \quad (4)$$

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

$$BR(\pi\mu e) < 2.4 \times 9.0 \times 10^{-12} = 2.2 \times 10^{-11} \quad (5)$$

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

(E777, and E865 results from 1995,1996)

R. Appel, *et al. Phys. Rev. Lett.*, 85:2450, 2000.

Combining 1998 result with the previous one leads to the new upper limit on  $K_{\pi\mu e}$  branching ratio:

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

## Conclusion

- The limit on the LFNV via decay  $K_{\pi\mu e}$  is improved by one order of magnitude ( $2 \times 10^{-10} \rightarrow 1.2 \times 10^{-11}$ )
- Possible Extension theories “phase space” is reduced
- Rate of the decay probes the mass scale of hypothetical new interaction field:  $M_H > 80$  TeV (for Extended Technicolor or Horizontal Gauge Models)
- No New Physics yet :(
- Future searches for LFNV:
  - $\mu^+ \rightarrow e^+ \gamma$   $O(10^{-14})$
  - $\mu^- N \rightarrow e^- N$   $O(10^{-16})$
- PRD article is being prepared