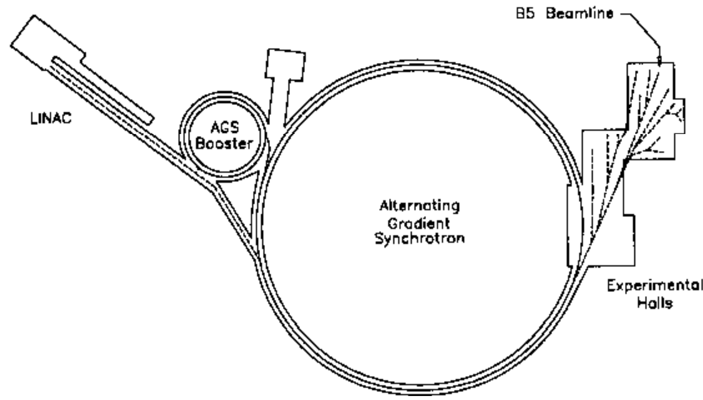
Rare Kaon Decays: Brookhaven E871



$\mathbf{K^0_L \to \mu^\pm e^\mp}$	lepton flavor violating
$\mathbf{K^0_L \to \mu^+\mu^-}$	GIM suppressed
$\mathbf{K^0_L \to e^+e^-}$	GIM, helicity suppressed

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Workshop on Heavy Quarks at Fixed Target
Fermi National Accelerator Laboratory
October 10-12, 1998

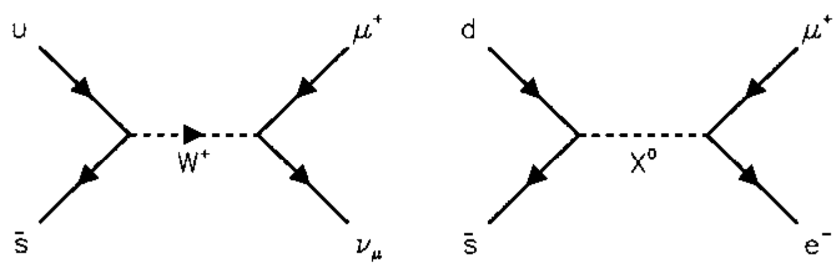
Theoretical Motivation: $K_L^0 \to \mu^\pm e^\mp$

- lepton flavor violation:
  - conservation *not* derived from gauge invariance
  - non-zero neutrino masses imply $B(K_L^0 \to \mu e) \sim 10^{-25}$
- allowed for in many extensions to Standard Model:
  - right-left symmetry ($B_{\mu e} \sim 10^{-15}$)
  - supersymmetry ($B_{\mu e} < 10^{-14}$)
  - technicolor ($B_{\mu e} > 10^{-10}$)
  - compositeness ($B_{\mu e} > 10^{-11}$)
- previous experimental limit: (BNL E791)

$$B(K_L^0 \to \mu e) < 3.3 \times 10^{-11}$$

- high-sensitivity searches probe high mass scales:

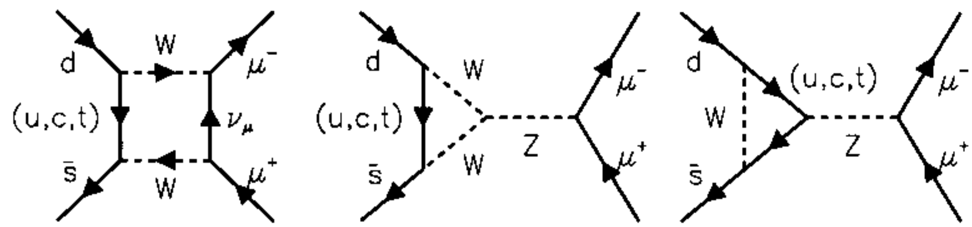
$$\frac{\Gamma(K_L^0 \to \mu e)}{\Gamma(K^+ \to \mu^+ \nu)} = \left[\frac{g_X^2/M_X^2}{g^2 sin\theta_c/M_W^2}\right]^2$$



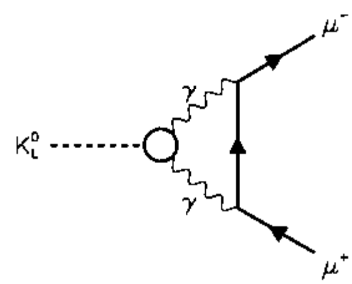
$$M_X \approx (220TeV)\left[\frac{10^{-12}}{B(K_L^0 \to \mu e)}\right]^{1/4}$$

Theoretical Motivation: $\mathbf{K^0_L \to \mu^+\mu^-}$

- led in part to GIM mechanism invoking *charm* quark



- residual rate dominated by absorptive two-photon intermediate state, giving "*Unitarity Bound*"



$$B(K^0_L \to \mu\mu)_{\gamma\gamma} = \left[\frac{\Gamma(K^0_L \to \gamma\gamma \to \mu\mu)}{\Gamma(K^0_L \to \gamma\gamma)}\right] \times B(K^0_L \to \gamma\gamma)$$

$$= (7.07 \pm 0.18) \times 10^{-9}$$

- total decay rate from dispersive, absorptive parts:

$$B(K^0_L \to \mu^+\mu^-) = |Re\mathcal{A}|^2 + |Im\mathcal{A}|^2$$

$$\Longrightarrow Re\mathcal{A} = \mathcal{A}_{SD} + \mathcal{A}_{LD}$$

- short-distance dispersive contribution:

$$|\mathcal{A}_{SD}|^2 \sim |ReV^*_{ts}V_{td}|^2 \implies Re(V^*_{ts}V_{td}) = -A^2\lambda^5(1-\rho)$$

- current world average: (PDG)

$$B(K^0_L \to \mu\mu) < (7.2 \pm 0.5) \times 10^{-9}$$

Theoretical Motivation: $\mathbf{K_L^0 \to e^+e^-}$

- short-distance physics is GIM *and* helicity suppressed:

$$\frac{B(K_L^0 \to ee)_{SD}}{B(K_L^0 \to \mu\mu)_{SD}} \approx \frac{B(K^+ \to e\nu)}{B(K^+ \to \mu\nu)} \approx \left(\frac{m_e}{m_\mu}\right)^2 \approx 2.4 \times 10^{-5}$$

- absorptive contribution also contains helicity suppressed "*Unitarity Bound*": ($\beta_\ell = \sqrt{1 - 4m_\ell^2/m_K^2}$)

$$\frac{B(K_L^0 \to \gamma\gamma \to ee)}{B(K_L^0 \to \gamma\gamma \to \mu\mu)} = \left(\frac{m_e}{m_\mu}\right)^2 \frac{\beta_e}{\beta_\mu} \frac{\left(ln\frac{1+\beta_e}{1-\beta_e}\right)^2}{\left(ln\frac{1+\beta_\mu}{1-\beta_\mu}\right)^2}$$

$$B(K_L^0 \to \gamma\gamma \to ee) \approx 3 \times 10^{-12}$$

- $\mathcal{A}_{LD}$ similarly enhanced over $\mathcal{A}_{SD}$
- recent Standard Model predictions: (χPT)

$$B(K_L^0 \to e^+e^-) = (9.0 \pm 0.5) \times 10^{-12}$$

  – Valencia, Nucl. Phys. **B517**, 339 (1998).
  – Dumm and Pich, Phys. Rev. Lett. **80**, 4633 (1998).

- previous experimental limit: (BNL E791)

$$B(K_L^0 \to ee) < 4.1 \times 10^{-11}$$

BNL E871: Collaboration

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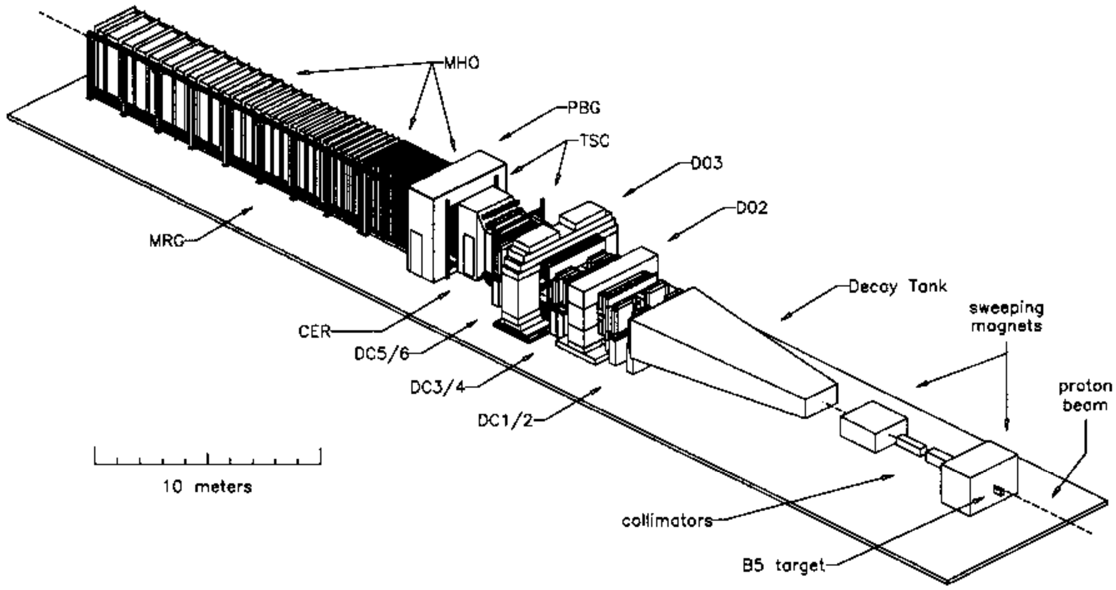
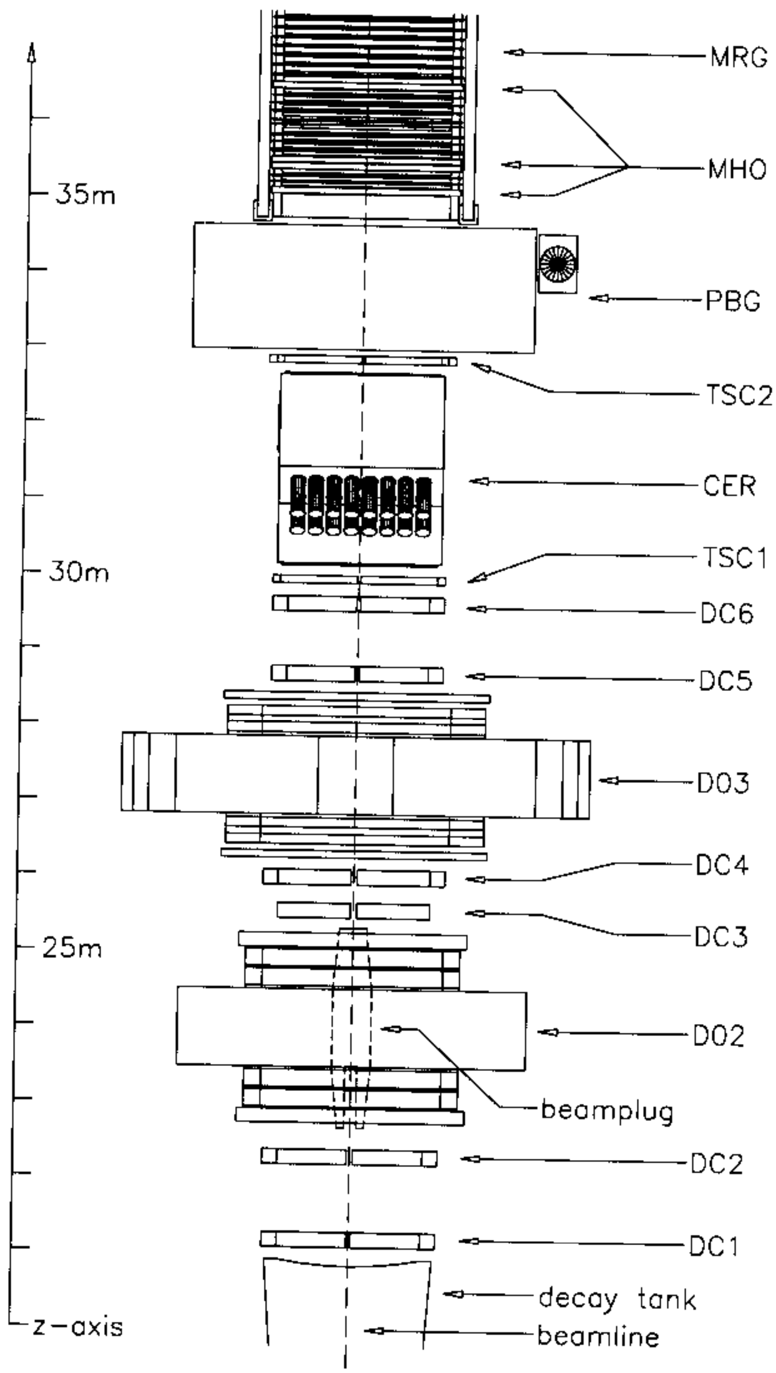
BNL E871: Overview

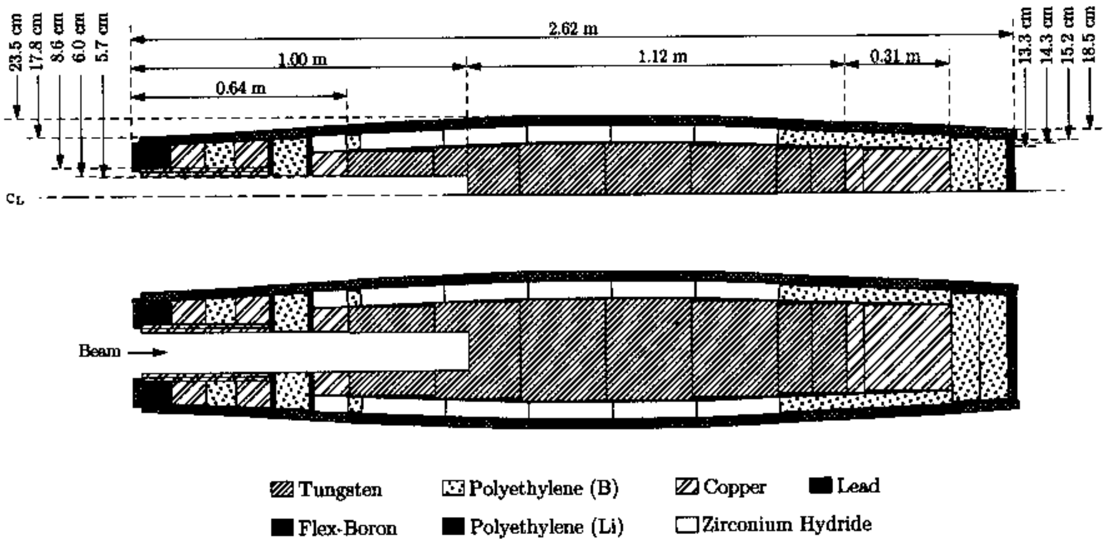


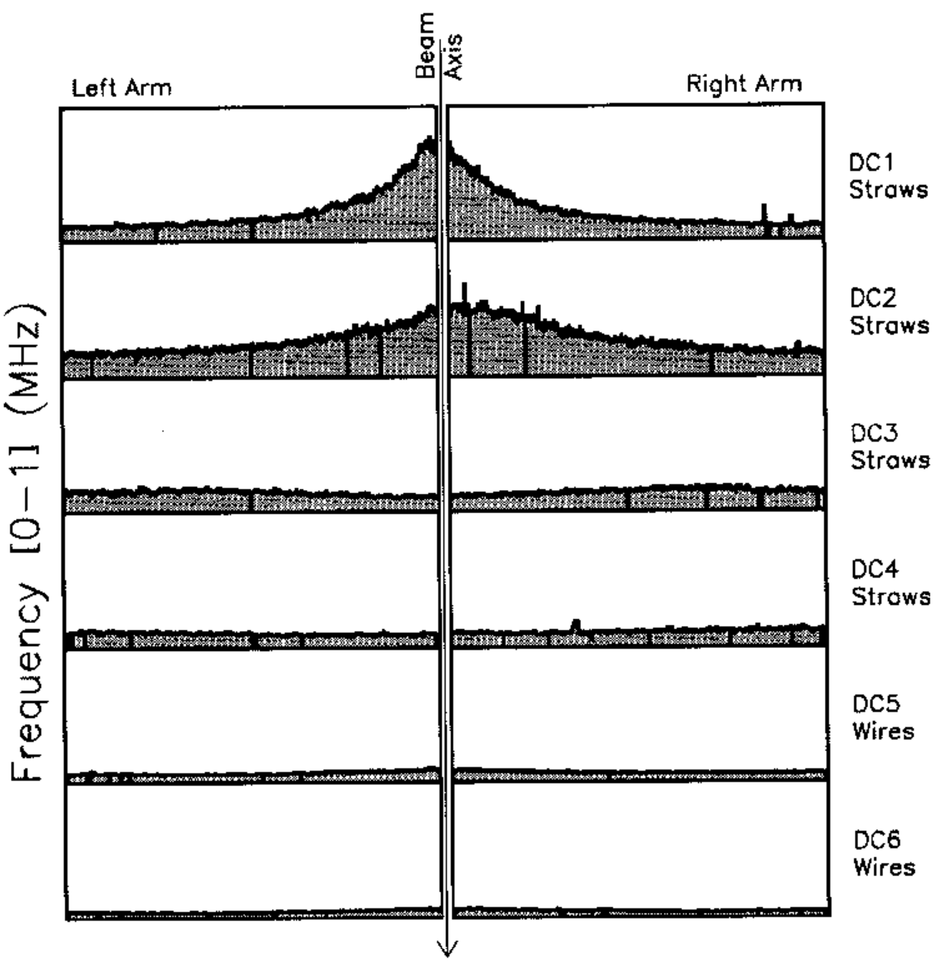
- upgrade to BNL E791: (1988-1990)
  - $K_L^0 \to \mu^\pm e^\mp$ (not observed) $B_{\mu e} < 3.3 \times 10^{-11}$
  - $K_L^0 \to e^+ e^-$ (not observed) $B_{ee} < 4.1 \times 10^{-11}$
  - $K_L^0 \to \mu^+ \mu^-$ (707 events) $B_{\mu\mu} = (6.86 \pm 0.37) \times 10^{-9}$
- AGS booster addition (15×10^{12} protons on target)
- neutral beam stop
- straw drift chambers
- parallel hardware trigger

BNL E871: Apparatus



Beam Plug and Detector Rates



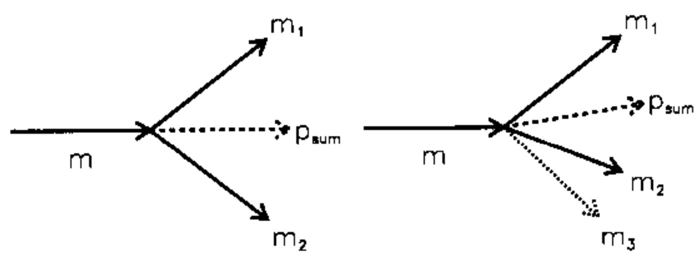


Dilepton Kaon Decays: Normalization and Backgrounds

- measure branching *ratio* with respect to $K_L^0 \rightarrow \pi^+\pi^-$:

$$\frac{B(K_L^0 \to \ell^+\ell^-)}{B(K_L^0 \to \pi^+\pi^-)} \sim \left(\frac{N_{\ell\ell}}{P \cdot N_{\pi\pi}}\right)\left(\frac{A_{\pi\pi}}{A_{\ell\ell}}\right)$$

- backgrounds from semileptonic ($K_{\ell 3}$) decays:
  - K_{e3} (39%): $K_L^0 \to \pi^\pm e^\mp \nu$, $\pi \to \mu\nu$
  - $K_{\mu 3}$ (27%): $K_L^0 \to \pi^\pm \mu^\mp \nu$, $\pi \to \mu\nu$
- select two-body decays through transverse momentum (p_T)



- dilepton invariant mass cut excludes most background:

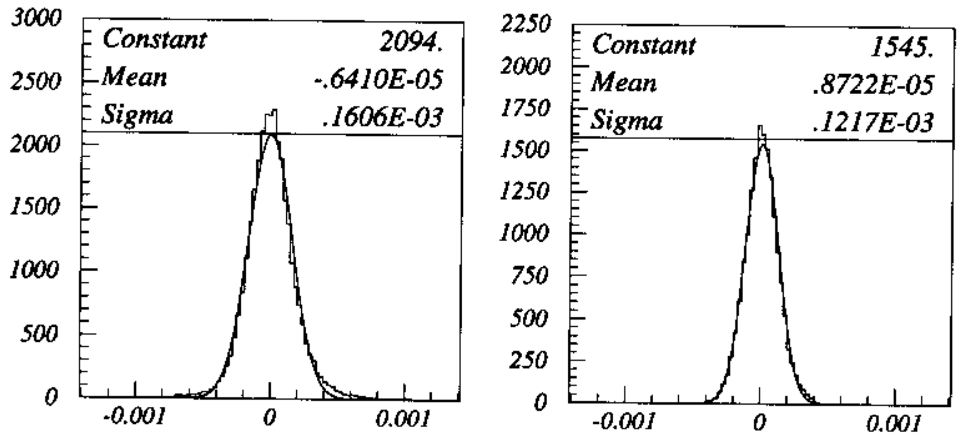
$$m^2 = m_1^2 + m_2^2 + 2(E_1E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2)$$

$$\Longrightarrow \quad m_{max}^2 = m_K^2 + m_\mu^2 - m_\pi^2$$

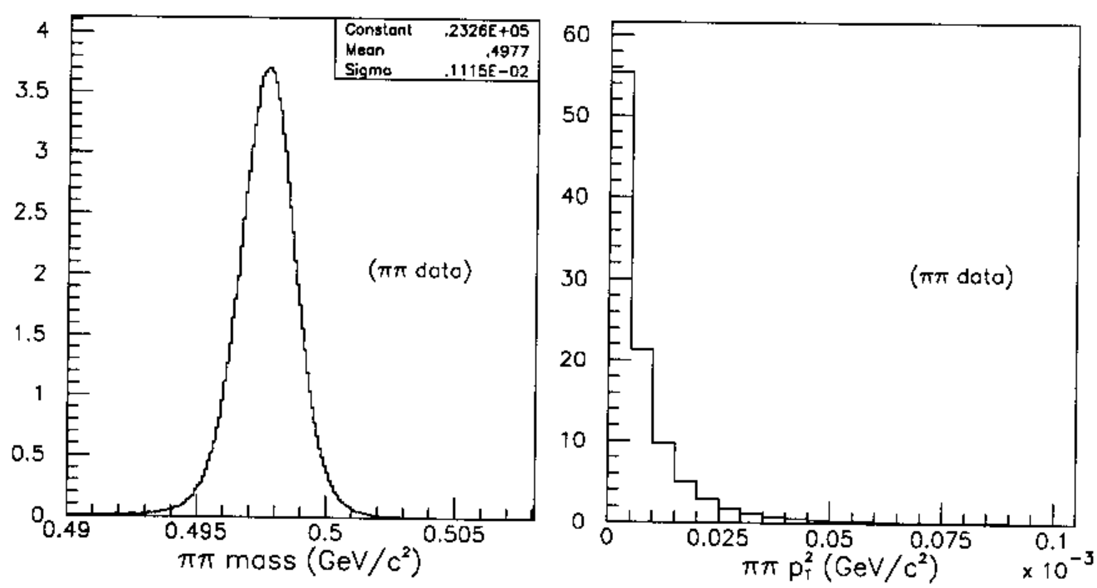
Background	Signal	$\mathbf{m_K^{max}}$ (GeV/c^2)
$K_{\mu 3}$	$\mu\mu$	0.489
	μe	0.478
	$\pi\pi$	0.506
K_{e3}	ee	0.478
	μe	0.489
	$\pi\pi$	0.517

Spectrometer Resolution

- single-wire DC resolutions of 120-160 μm



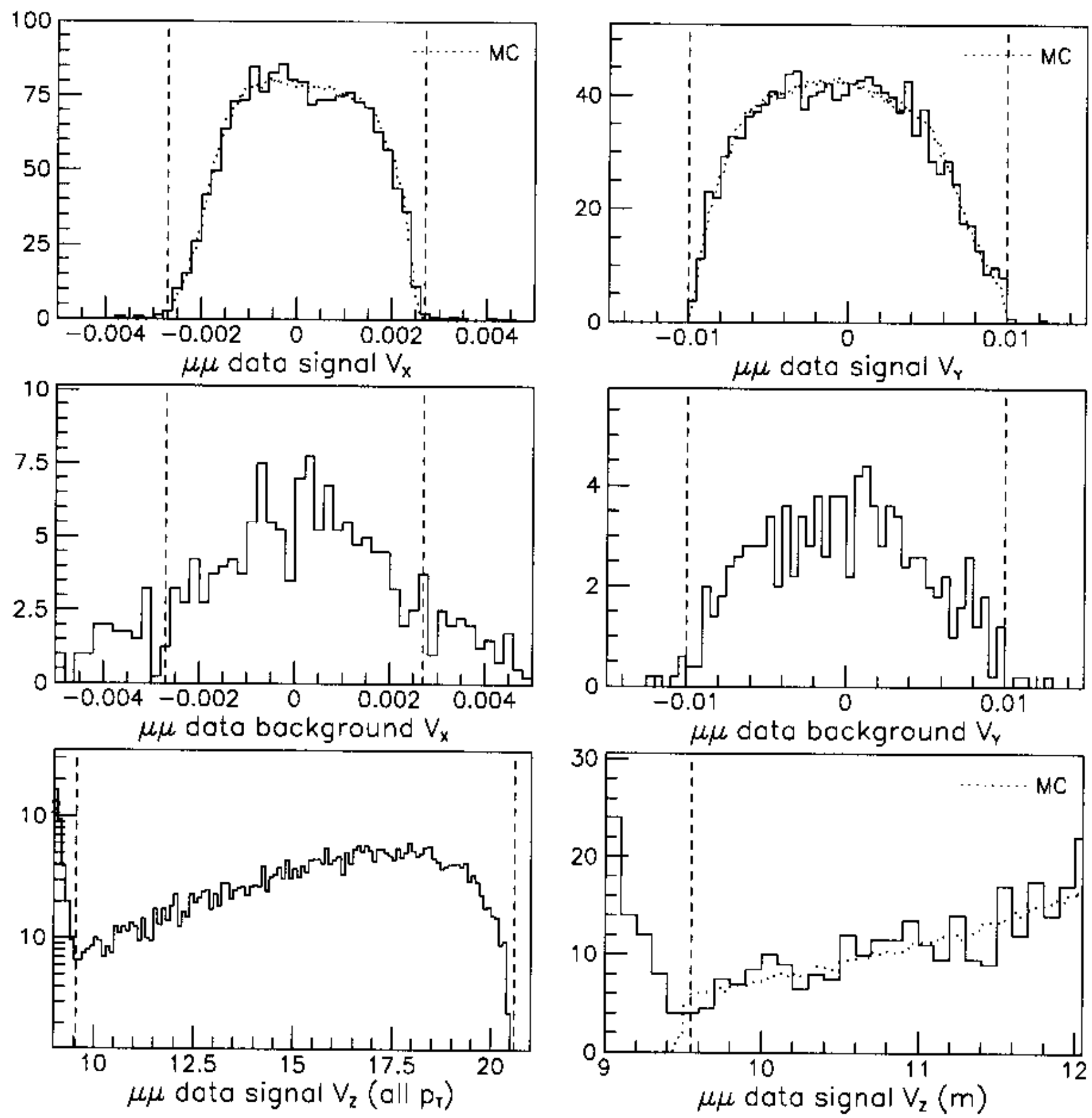
- two-body invariant mass resolutions:



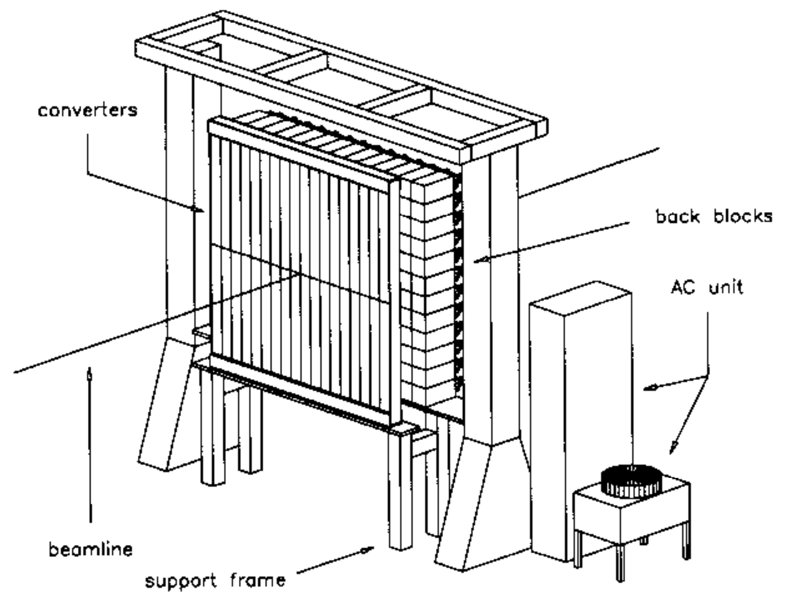
Decay mode	σ_m (Mev/c^2)
$\pi\pi$	1.11 (data)
$\mu\mu$	1.26 (MC)
μe	1.38 (MC)
ee	1.39 (MC)

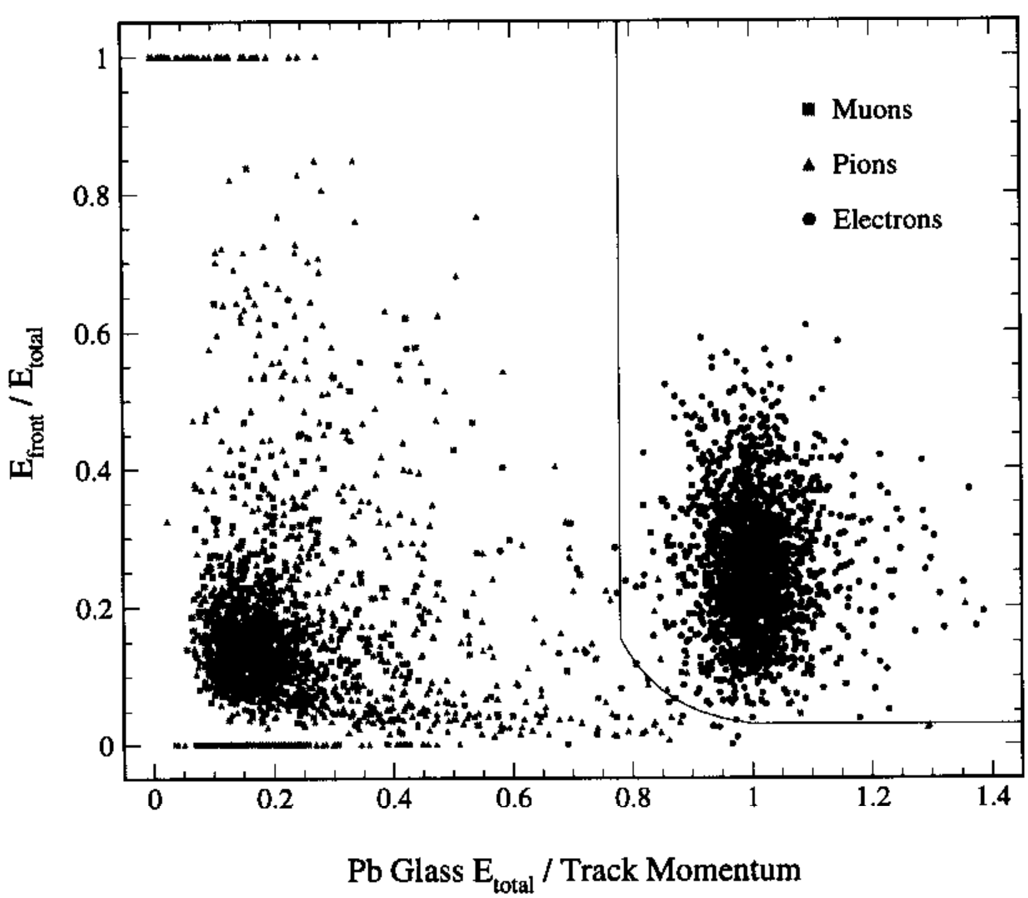
Event Reconstruction

- event and track quality cuts via χ^2
- decay vertex cuts:

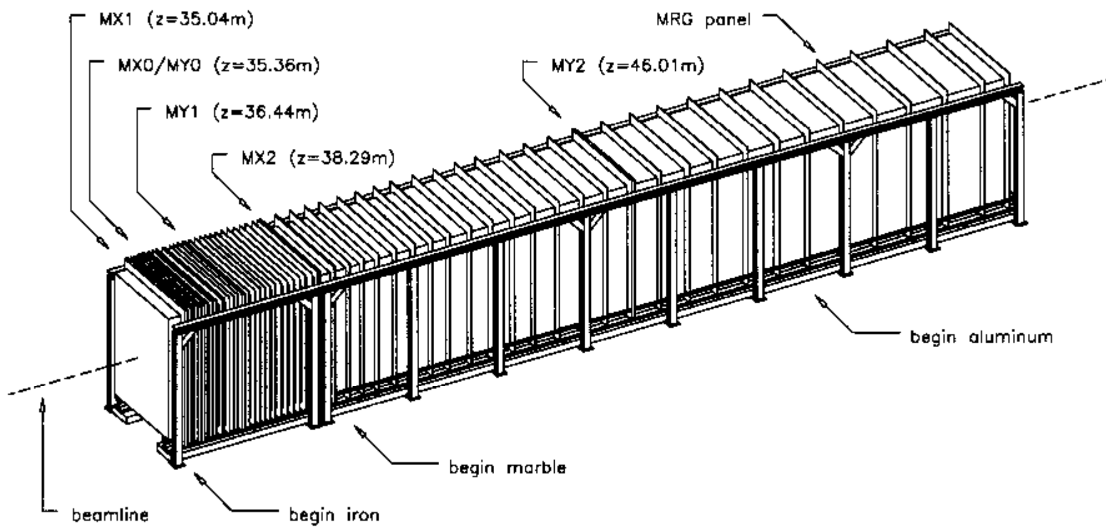


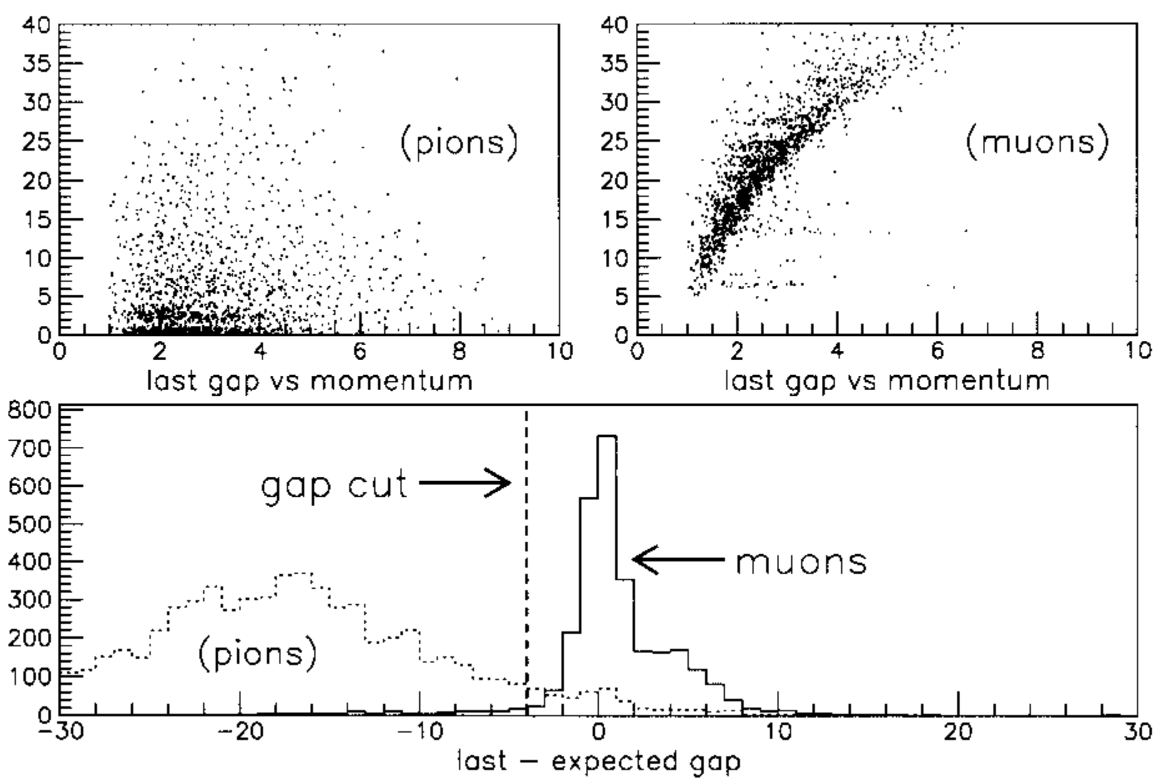
Electron Identification: PBG





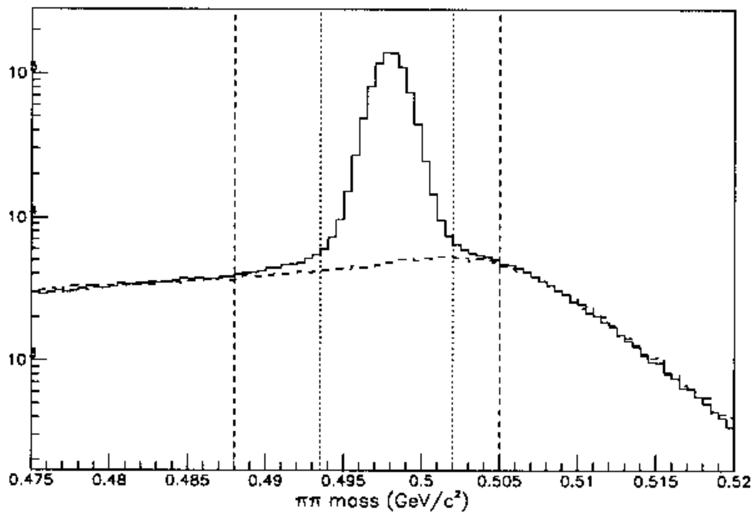
Muon Identification: Hodoscope and Rangefinder

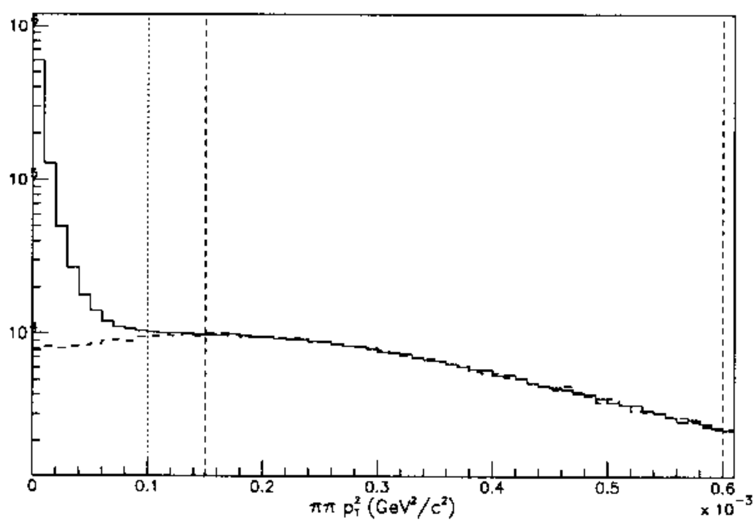




BNL E871: $K_L^0 \to \pi^{\pm}\pi^{\mp}$ Normalization

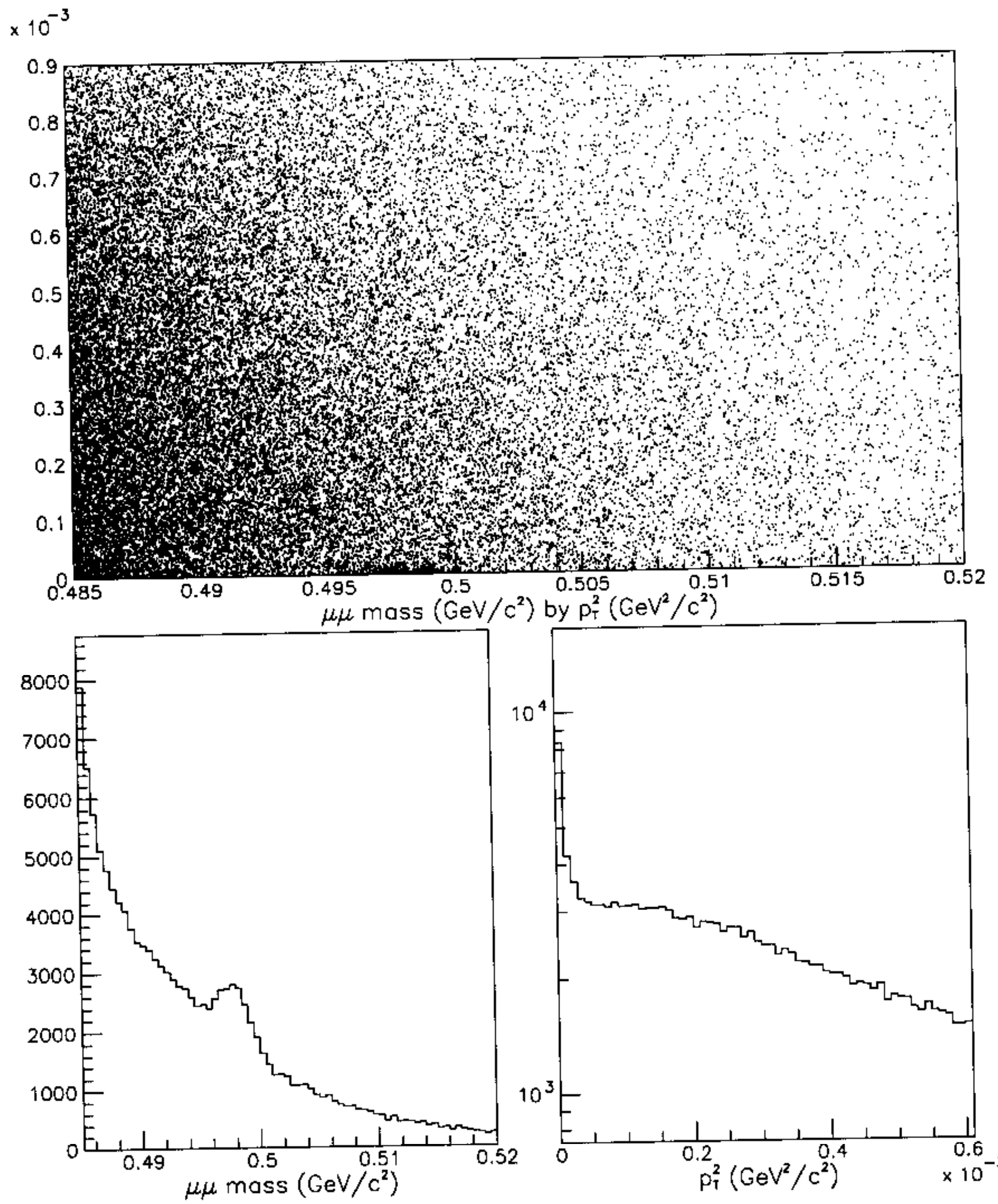
- K_{e3} background removed with electron veto
- remaining $K_{\mu 3}$ background easily simulated, subtracted:





- measured $\sim 800k$ events after hardware/software prescale of 2000

$K_L^0 \to \mu^+\mu^-$ (Minimal Cuts)

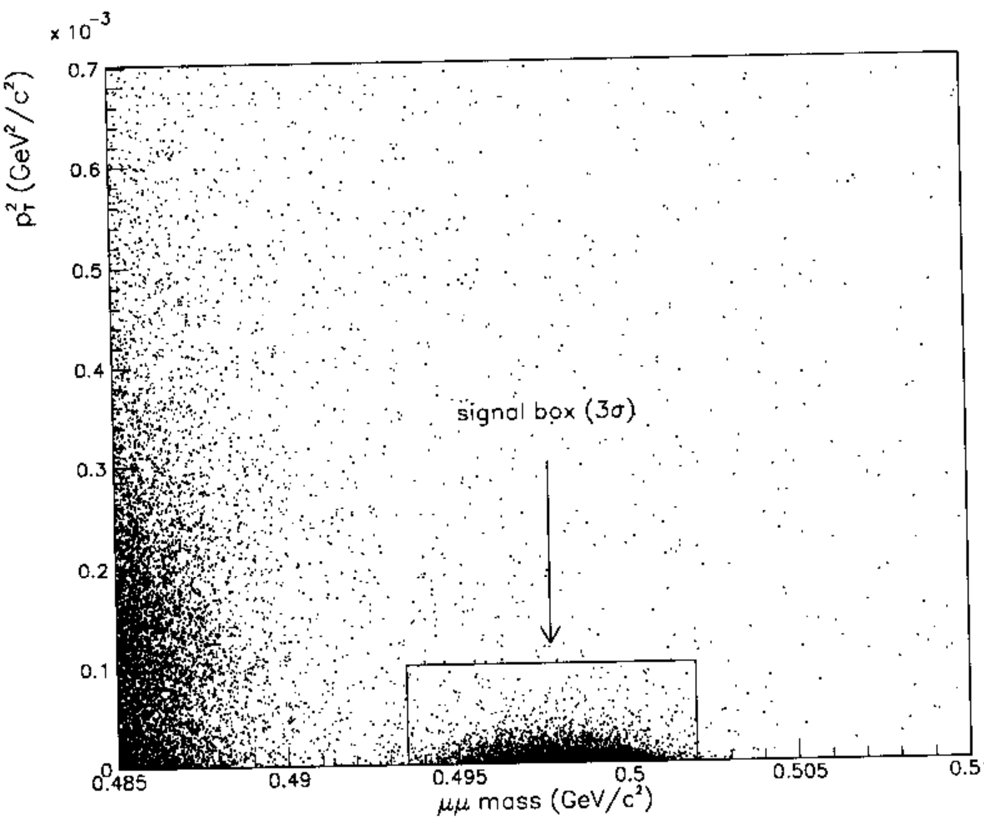


$\mathbf{K_L^0} \to \mu^+\mu^-$ Strategy

- blind analysis through hidden prescale:

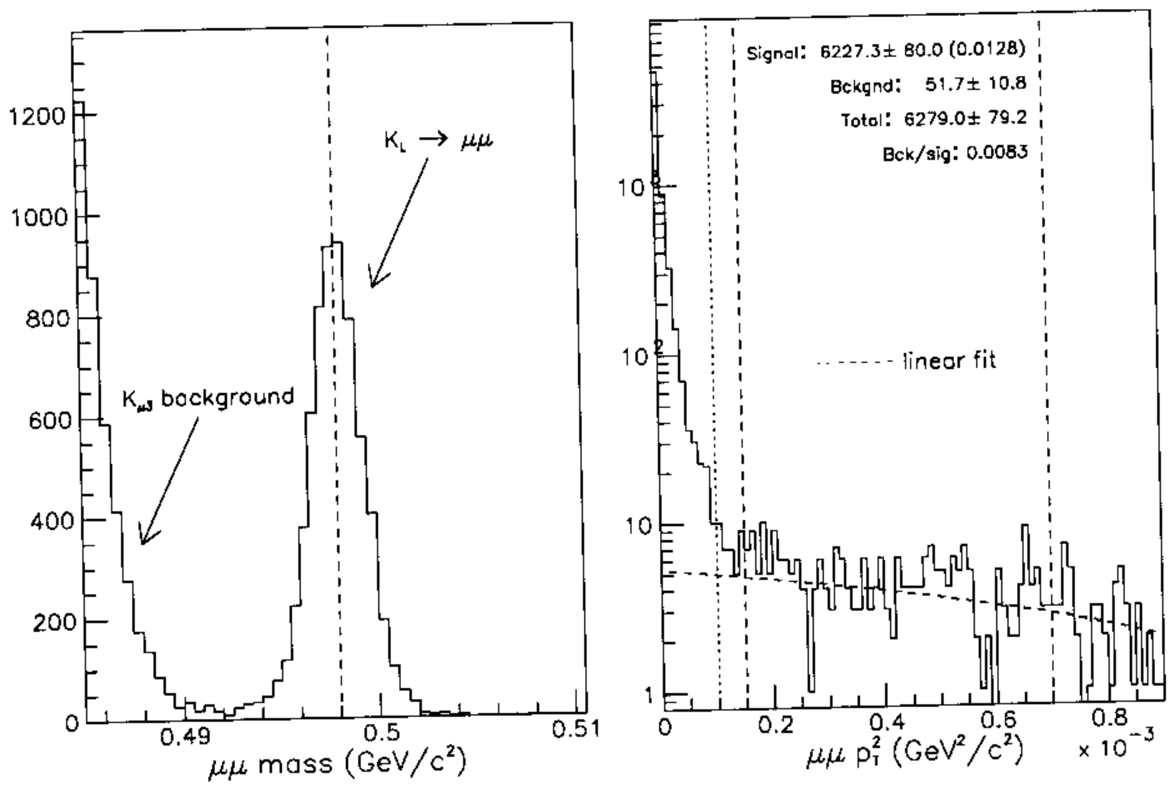
$$\frac{B(K_L^0 \to \mu\mu)}{B(K_L^0 \to \pi\pi)} = \left(\frac{N_{\mu\mu}}{P \cdot N_{\pi\pi}}\right)\left(\frac{A_{\pi\pi}}{A_{\mu\mu}}\right)\left(\frac{1}{\varepsilon_{\mu\mu}^{trig}}\right)\left(\frac{1}{\varepsilon_{\mu\mu}^{PID}}\right)\cdots$$

- measure correction terms within $\sim$ 0.1-0.2%
- loose kinematic, PID cuts give high efficiency, low systematics
- dominant backgrounds:
  - pile-up (suppressed with extra-track cut)
  - K_{e3} (removed with electron veto)



$\mathbf{K_L^0 \to \mu^+\mu^-}$ Results
(Preliminary)

- background subtraction:



- branching ratio:

$$\frac{B(K_L^0 \to \mu\mu)}{B(K_L^0 \to \pi\pi)} = (3.50 \pm 0.11) \times 10^{-6}$$

- using measured value for $K_L^0 \to \pi^+\pi^-$:

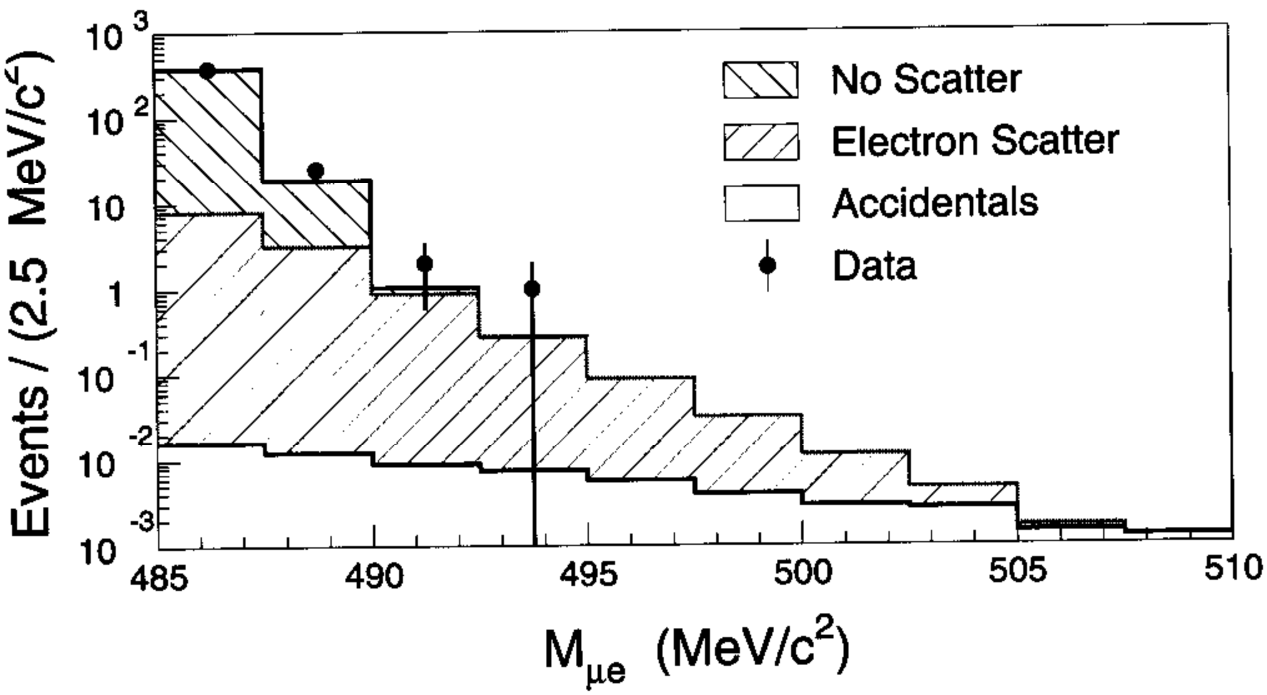
$$B(K_L^0 \to \pi^+\pi^-) = (2.067 \pm 0.35) \times 10^{-3}$$

branching fraction becomes: (preliminary)

$$B(K_L^0 \to \mu^+\mu^-) = (7.23 \pm 0.22) \times 10^{-9}$$

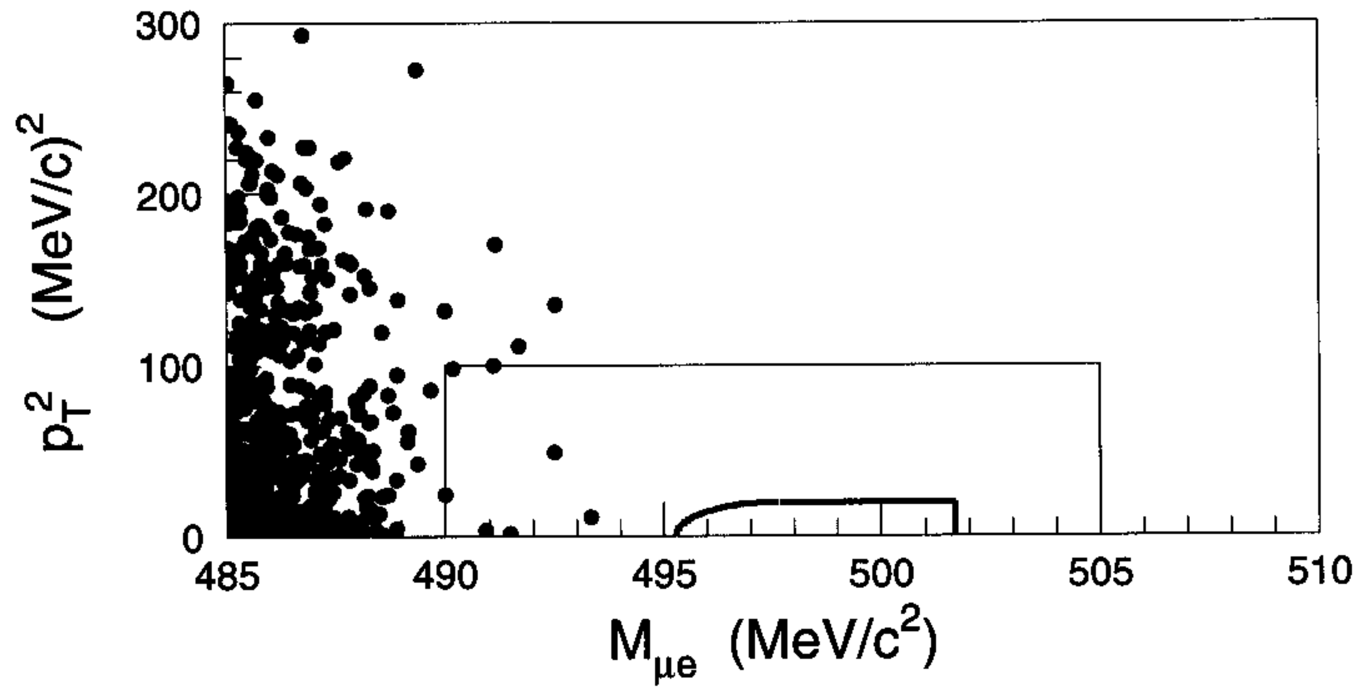
$K_L^0 \to \mu^\pm e^\mp$ Strategy

- perform *blind* analysis:
  - exclude signal region from view ($490 < m_{\mu e} < 505\, MeV/c^2, p_T < 10\, MeV/c$)
  - determine, fix cuts before revealing signal
- specific background cuts:
  - large scatters from vacuum window ($p_T^{\parallel}$ cut)
  - accidental, pile-up events (extra track cut)



- predicted background: 0.1 events

$K_L^0 \to \mu^{\pm}e^{\mp}$ Results

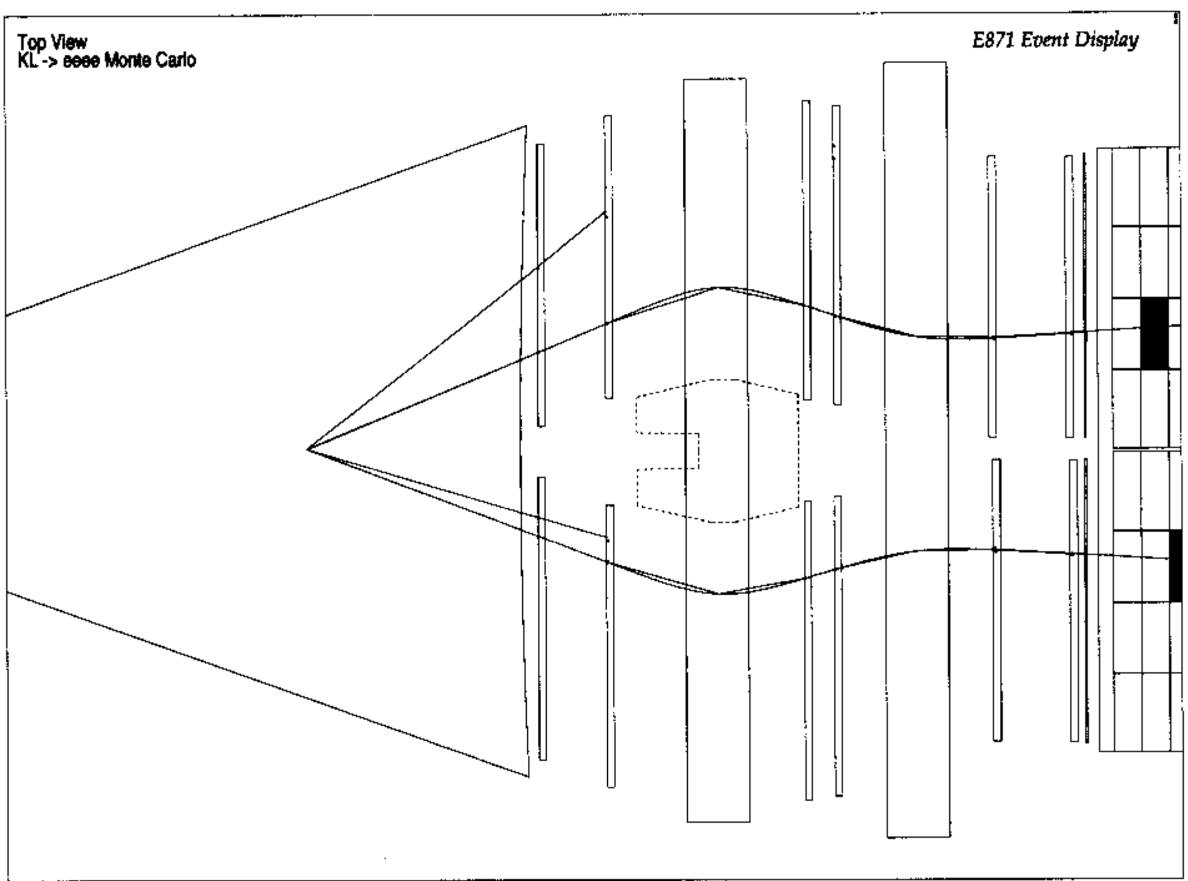


- no candidate events observed
- branching fraction: (90% CL)

$$B(K_L^0 \to \mu^{\pm}e^{\mp}) \ < \ 4.8 \times 10^{-12}$$

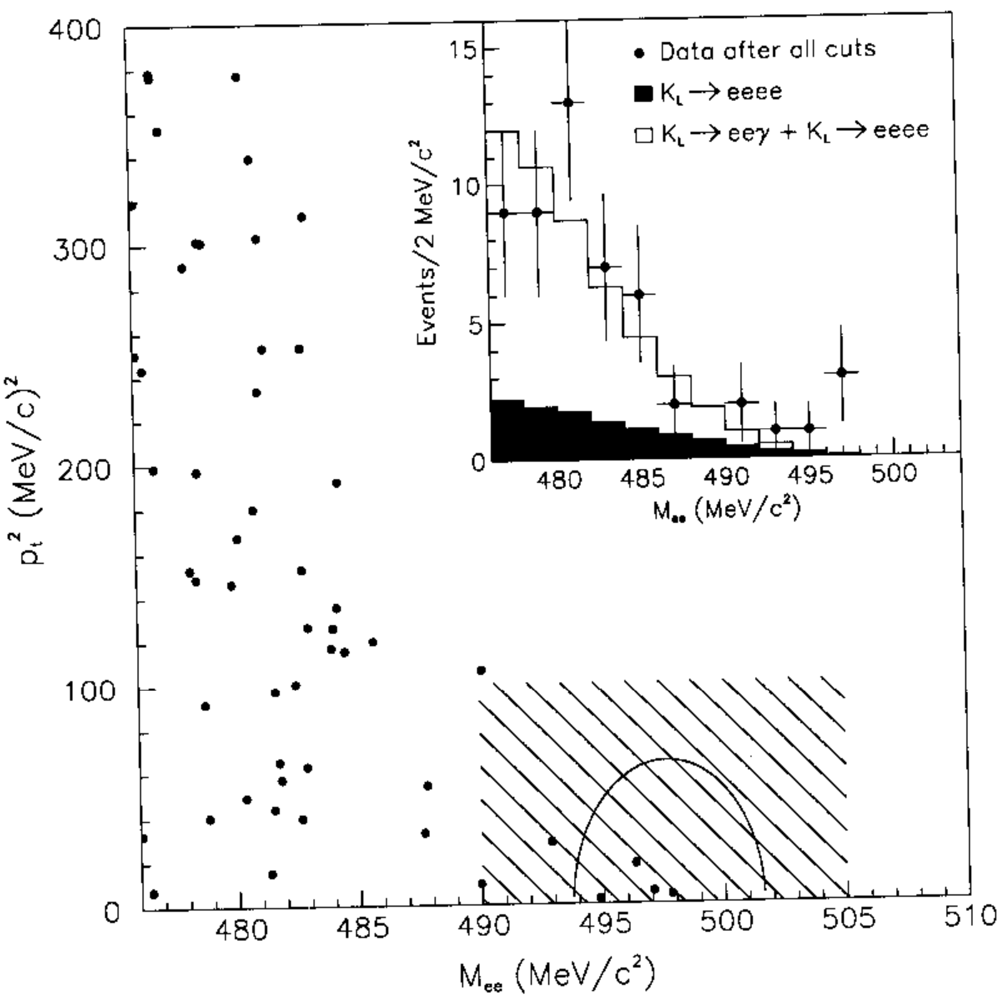
$\mathbf{K_L^0 \rightarrow e^+e^-}$ Strategy

- blind analysis and cuts similar to $K_L^0 \rightarrow \mu e$
- additional physics backgrounds:
  - $K_L^0 \rightarrow ee\gamma$ ($B_{ee\gamma} \approx 9 \times 10^{-6}$)
  - $K_L^0 \rightarrow eeee$ ($B_{4e} \approx 4 \times 10^{-8}$)
- $4e$ events suppressed with *stub* cut



- predicted total background after cuts: 0.2 events

$K_L^0 \to e^+e^-$ Results



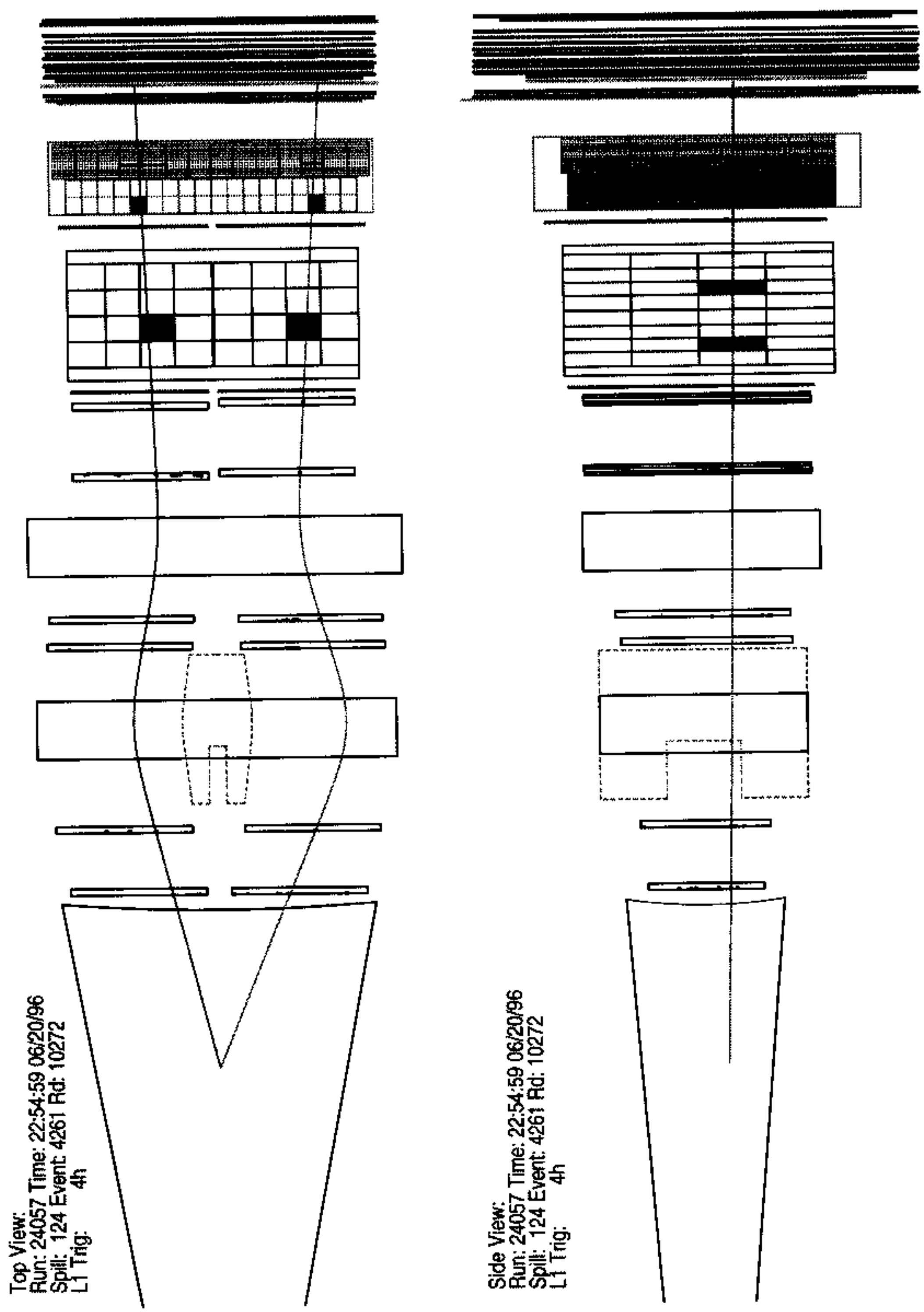
- observe four candidate events
- using measured value for $K_L^0 \to \pi^+\pi^-$, branching fraction becomes:

$$B(K_L^0 \to e^+e^-) = 8.7^{+5.7}_{-4.1} \times 10^{-12}$$

- consistent with Standard Model prediction:

$$B(K_L^0 \to e^+e^-) = (9.0 \pm 0.5) \times 10^{-12}$$

$K_L^0 \to e^+e^-$ Example Event



BNL E871: Summary of Results

- $\mathbf{K_L^0 \to \mu^\pm e^\mp}$
  - no candidate events observed
  - branching fraction: (90% CL)

$$B(K_L^0 \to \mu^\pm e^\mp) < 4.8 \times 10^{-12}$$

  - *most sensitive search to date*

- $\mathbf{K_L^0 \to \mu^+ \mu^-}$
  - over 6200 candidate events observed
  - branching fraction: (preliminary)

$$B(K_L^0 \to \mu^+ \mu^-) = (7.23 \pm 0.22) \times 10^{-9}$$

  - *will reduce uncertainty by over* $\frac{1}{3}$

- $\mathbf{K_L^0 \to e^+ e^-}$
  - four candidate events observed
  - branching fraction:

$$B(K_L^0 \to e^+ e^-) = 8.7^{+5.7}_{-4.1} \times 10^{-12}$$

  - *smallest branching fraction ever measured*