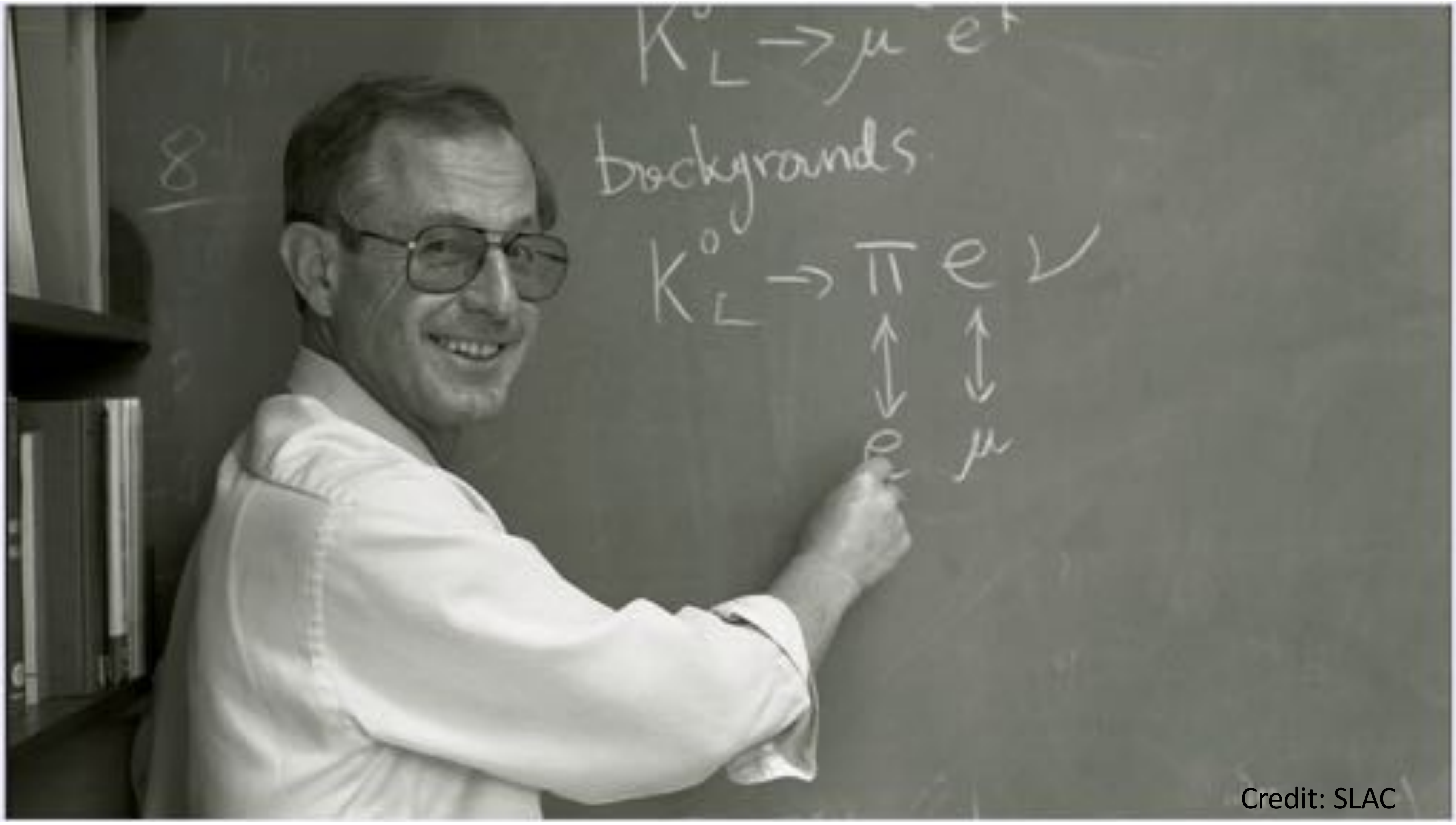


Stanisław Jerzy Wójcicki @ SLAC (ca. 1983)

My personal preamble

- I first met Stan in 1982 at Fermilab when I was a graduate student at U-of-R on E701 (A (search for neutrino oscillations in the neutrino narrow band beam).

- After my 1st postdoc (SLAC E140/E141), I took a 2nd postdoc with Stan on the BNL E791.

- E791 turned into E871 (... and E888 in between).

- At the end of E871, I returned to neutrinos at FNAL (joined MINOS in 1995).

→ I continuously worked or collaborated with Stan since Nov 1, 1986.

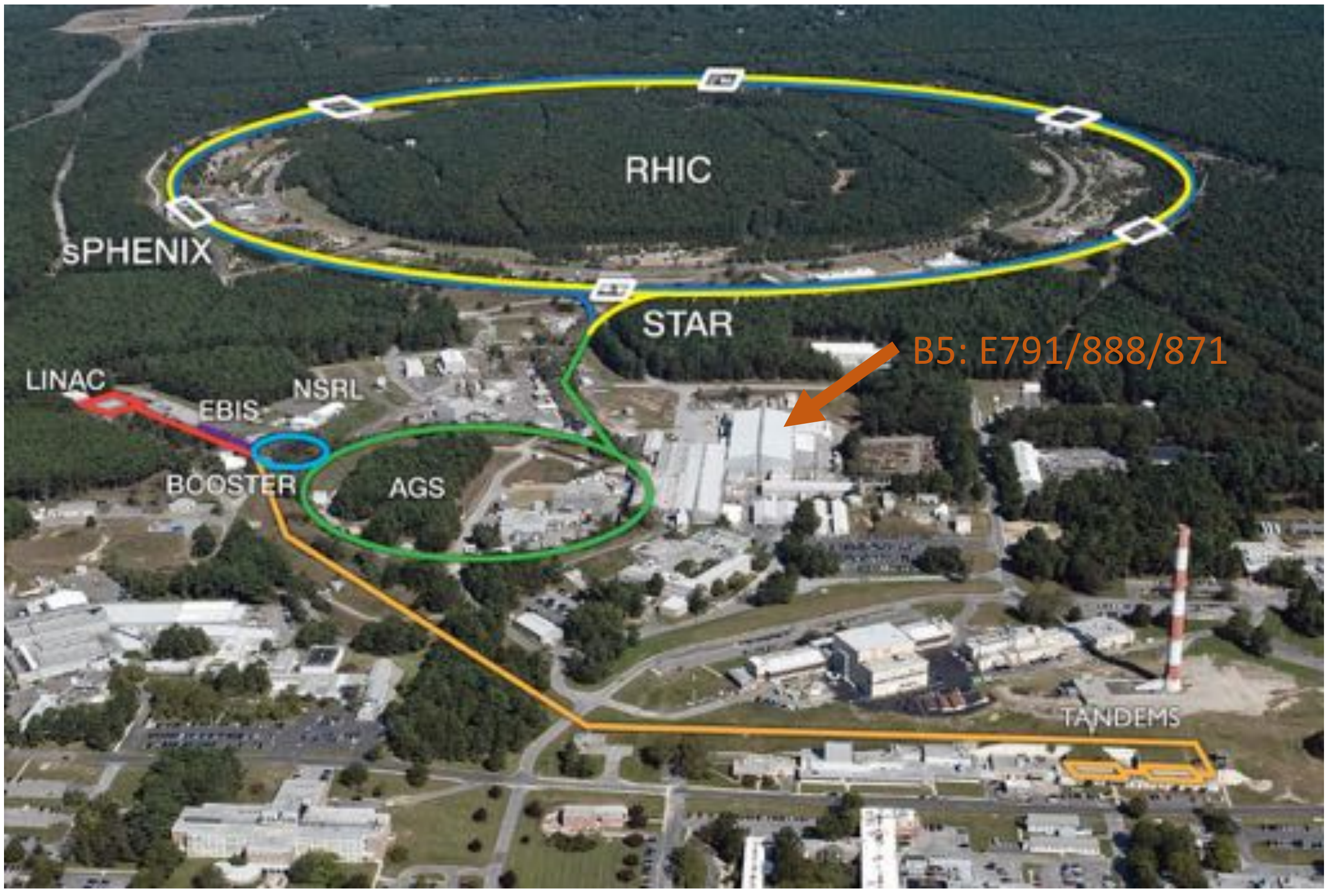
A few in a trillion

An abbreviated* story about a search for rare kaon decays
by BNL experiments 791 and 871
(1983-1996)

Karol Lang
University of Texas at Austin

The Stanley Wojcicki Scientific Symposium
Stanford, November 10, 2023

*and biased



RHIC
sPHENIX
STAR
B5: E791/888/871
LINAC
EBIS
NSRL
BOOSTER
AGS
TANDEMS

US kaon "industry" of that era

Search for Forbidden/New Processes/Particles	Test Higher Order (Suppressed) EW Interactions
$K_L \to \mu e$ (BNL E791)	$K_L \to \mu^+\mu^-/e^+e^-$ (BNL E871)
$K^+ \to \pi^+\mu^+e^-$ (BNL E865)	$K^+ \to \pi^+\nu\bar{\nu}$ (BNL E787)
$K^+ \to \pi^+X^0$ (BNL E787)	$K^+ \to \pi^+l^+l^-$ (BNL E787)

CP origins

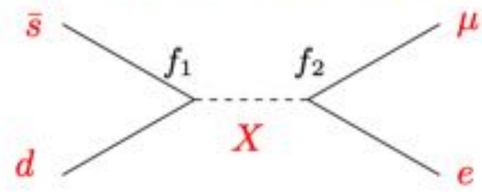
$K_L \to \pi^0 l^+ l^-$
(KTeV)

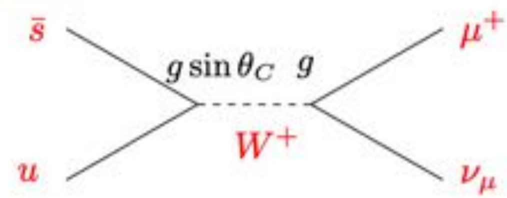
\+ CERN program
\+ KEK program

Physics Motivation for $K_L^0 \to \mu^\pm e^\mp$

- Standard Model is incomplete
- No known gauge symmetry responsible for lepton flavor conservation (LFC)
- Many extensions predict violation of LFC, e.g.:
  - horizontal gauge interactions → Cahn & Harrari (1980)
  - left-right symmetry → Langacker *et al.* (1988)
  - technicolor → Dimopoulos & Ellis (1981)
  - compositeness → Patti & Stremnitzer (1986)
  - supersymmetry → Mukhopadhyaya & Raychaudhuri (1990)

- $K_L^0 \to \mu^\pm e^\mp$ probes high energy scales:





$K_L^0 \to \mu^\pm e^\mp$ $\qquad$ $K^+ \to \mu^+ \nu_\mu$

$$\frac{\Gamma(K_L \to \mu e)}{\Gamma(K^+ \to \mu^+ \nu_\mu)} \simeq \left[\frac{f_1 f_2 / M_X^2}{g^2 \sin\theta_C / M_W^2}\right]^2$$

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

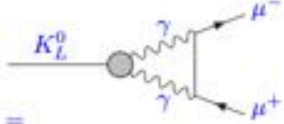
Before: $\mathrm{B}(K_L^0 \to \mu^\pm e^\mp) < 3.3 \times 10^{-11}$

BNL E791 $\quad (M_X > 92\ \mathrm{TeV})$

Physics Motivation for $K_L^0 \to \mu^+\mu^-$

- "Historical" FCNC decay mode (GIM mechanism)

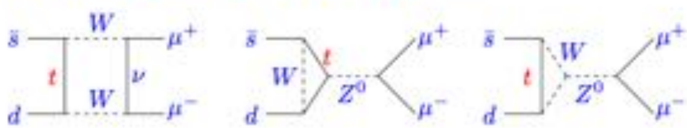
$$B(K_L^0 \to \mu^+\mu^-) = (ImA)^2 + (ReA)^2 = |A_{\gamma\gamma}|^2 + |A_{SD} + A_{LD}|^2$$



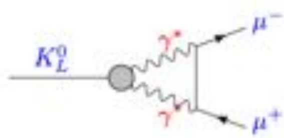
$(ImA)^2 = |A_{absorptive}|^2 = |A_{\gamma\gamma}|^2 =$

$B(K_L^0 \to \gamma\gamma) \times QED(\gamma\gamma \to \mu^+\mu^-) = (7.07 \pm 0.18) \times 10^{-9}$
(unitarity bound)

$(ReA)^2 = |A_{dispersive}|^2 = |A_{SD} + A_{LD}|^2 =$



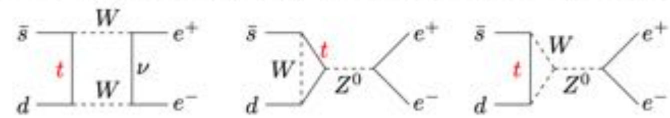
but also (theoretically challenging) long distance:



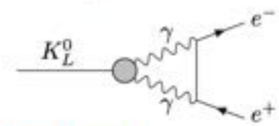
- Extract CKM from $B(K_L^0 \to \mu^+\mu^-)_{SD} = f(V_{td}, V_{ts}, m_{charm}, m_{top})$

Motivation for $K_L^0 \to e^+e^-$

- Short-distance as $K_L^0 \to \mu^+\mu^-$, with additional helicity suppression



- Also dominated by the long distance contributions:



Lower Limit (Unitarity Bound):

$$B_{LD}(K_L^0 \to \gamma\gamma \to e^+e^-) \approx 3 \times 10^{-12}$$

- Recent calculations within the framework of χPT suggest:

$$B(K_L^0 \to e^+e^-) \approx (9 \pm 0.5) \times 10^{-12}$$

G. Valencia, Nucl. Phys. **B517**,339(1998)
D. Gomez Dumm and A. Pich, Phys. Rev. Lett. **80**,4633(1998) and hep-ph/9810523

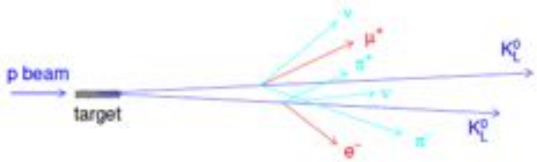
- $A_{absorptive} \approx 1/3 A_{total}$ in contrast to $K_L^0 \to \mu^+\mu^-$ where $A_{absorptive} \approx A_{total}$

- "close the discovery window" - previous limit:

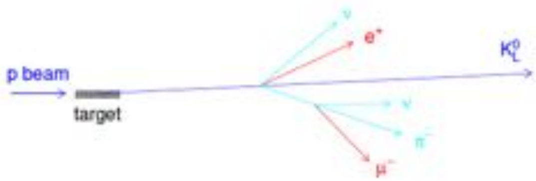
$$B(K_L^0 \to e^+e^-) < 4.1 \times 10^{-11} \quad \text{(BNL E791)}$$

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

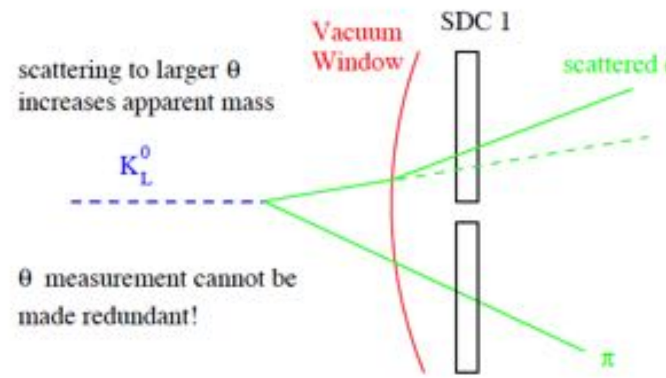
- accidental pileup of
  $K_L^0 \to \pi^\pm e^\mp \nu$ ~38%
  $K_L^0 \to \pi^\pm \mu^\mp \nu$ ~27%



- $K_L^0 \to \pi^\pm e^\mp \nu$
  $\pi \to \mu\nu$
  kinematic limit for
  $M_{\mu^\pm e^\mp} =$
  $M_K - 8.4\ MeV/c^2$
  (4% of all K_L^0 decays have $\mu^\pm e^\mp$ signature)

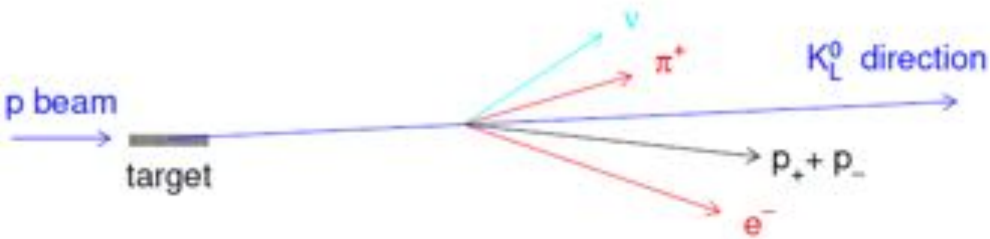


- upstream $K_L^0 \to \pi^\pm e^\mp \nu$ &
  $\pi \to \mu$ or misid & large electron scatter
  (7.5% of K_L^0 decay in the vacuum region
  vacuum window + first SDC = $0.34\% X_0$)



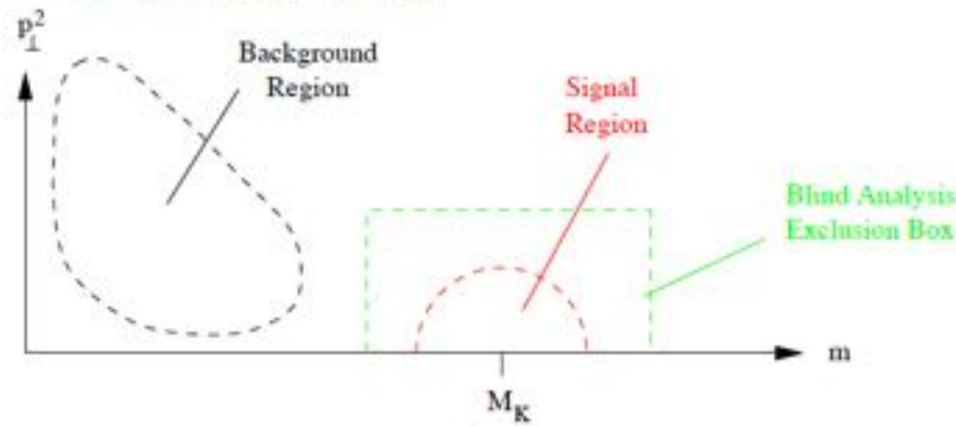
Measurement Principles

- reconstruct two-body (left & right) final state tracks
- measure momenta and angles → M_K & p_T



- redundant particle identification (muons, electrons):
  - lead glass + Cherenkov
  - muon range finder

- bias-free selection of events



- normalize to $K_L^0 \to \pi^+\pi^-$

BNL E791 (1983-1989)

VOLUME 63, NUMBER 20 PHYSICAL REVIEW LETTERS 13 NOVEMBER 1989

New Experimental Limits on $K_L^0 \to \mu e$ and $K_L^0 \to ee$ Branching Ratios

UCI

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UCLA

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University of California, Los Angeles, California 90024

G. W. Hart, W. W. Kinnison, D. M. Lee, R. J. McKee, E. C. Milner, G. H. Sanders, and H. J. Ziock
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

Penn

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University of Pennsylvania, Philadelphia, Pennsylvania 19104

Stanford

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Stanford University, Stanford, California 94309

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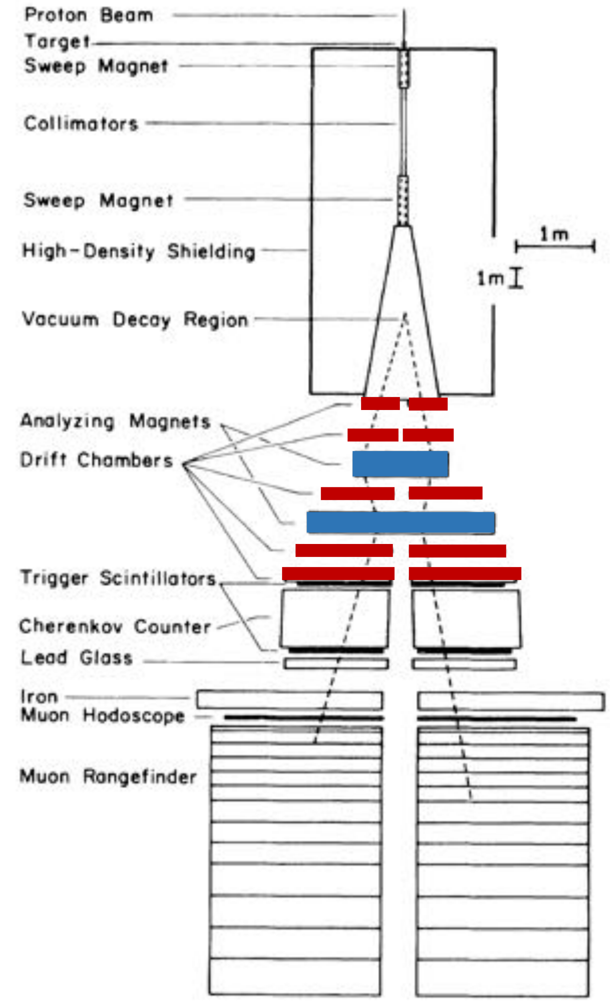
L. B. Auerbach, P. Buchholz, V. L. Highland, W. K. McFarlane, and M. Sivertz[f]
Temple University, Philadelphia, Pennsylvania 19122

W&M

M. D. Chapman, M. Eckhause, J. F. Ginkel, A. D. Hancock, D. Joyce,[g] J. R. Kane, C. J. Kenney, W. F. Vulcan, R. E. Welsh, R. J. Whyley,[h] and R. G. Winter
College of William and Mary, Williamsburg, Virginia 23185

(Received 7 August 1989)

A search for the decays $K_L^0 \to \mu e$ and $K_L^0 \to ee$ has produced no examples of either process. When normalized to the decay $K_L^0 \to \pi^+\pi^-$, the 90%-C.L. upper limits on the branching ratios are $B(K_L^0 \to \mu e) < 2.2\times10^{-10}$ and $B(K_L^0 \to ee) < 3.2\times10^{-10}$.

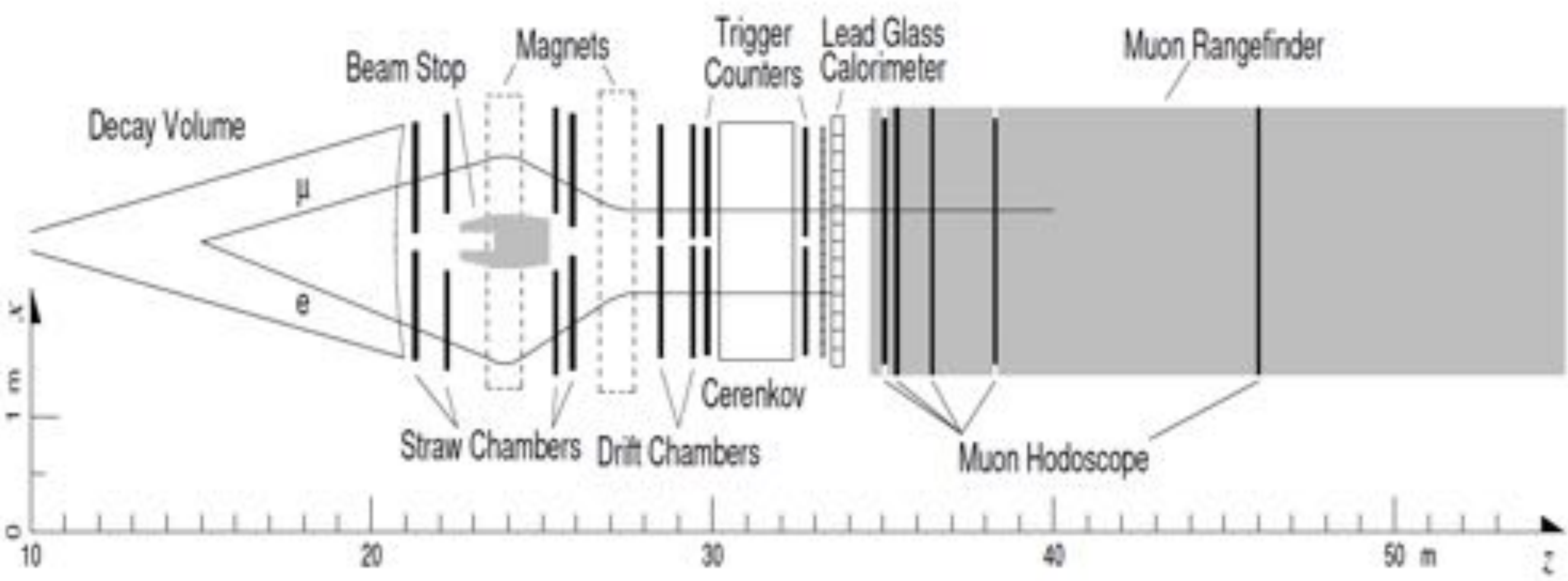


E791 lessons

- Need better rejection of background
- Need higher acceptance
- Need higher rates

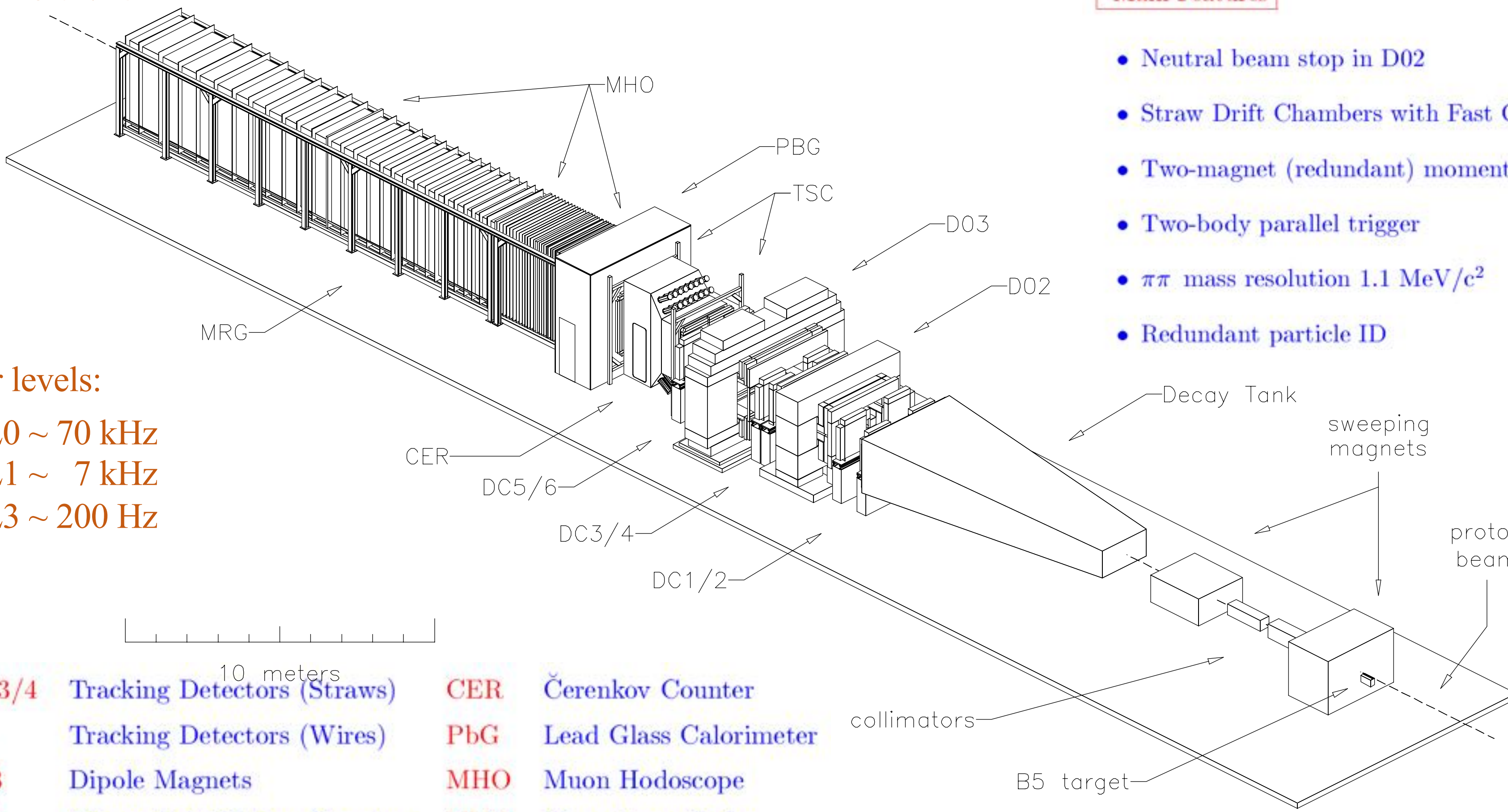
BNL E871

- Stan proposed two new and radical ideas:
  - a beam stop (needed R&D)
  - (upstream) straw drift chambers (needed R&D)



E871 Apparatus Layout

1.5 x 10^{13} protons 24 GeV over 1.2-1.6 s
2 x 10^{8} K_L per spill (2<p_K< 16 GeV/c
n/K_L ratio 8+/- 3



Main Features

- Neutral beam stop in D02
- Straw Drift Chambers with Fast Gas
- Two-magnet (redundant) momentum measurement
- Two-body parallel trigger
- $\pi\pi$ mass resolution 1.1 MeV/c^2
- Redundant particle ID

Trigger levels:

L0 ~ 70 kHz
L1 ~ 7 kHz
L3 ~ 200 Hz

DC 1/2/3/4	Tracking Detectors (Straws)	CER	Čerenkov Counter
DC 5/6	Tracking Detectors (Wires)	PbG	Lead Glass Calorimeter
D02/D03	Dipole Magnets	MHO	Muon Hodoscope
TSC 1/2	Trigger Scintillation Counters	MRG	Muon Rangefinder

BNL E871 COLLABORATION

Dave Ambrose, Charles Allen, Pat Coffey, Scott Graessle,
Gerry Hoffmann, Marek Hamela, Karol Lang, Marty Marcin,
Jim McDonough, Andy Milder, Chau Nguyen, Peter Riley,
Jack Ritchie, Vassilis Vassilakopoulos, Brent Ware, Steve Worm

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Nobu Kanematsu, Bill Molzon

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Casey Hartman, Mike Hebert, George Irwin, Dale Ouimette,
Marize Pommot-Maia, Allan Schwartz, Stan Wojcicki

Stanford University

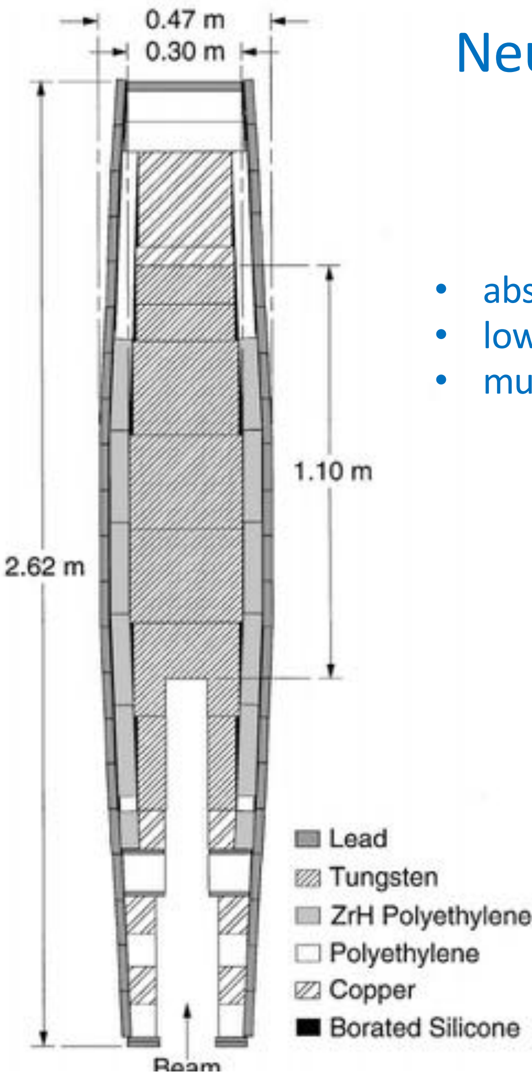
Morty Eckhause, Dale Hancock, Chris Hoff, John Kane,
Yunan Kuang, Rob Martin, Bob Welsh, Elliot Wolin

College of William and Mary

Phil Rubin

University of Richmond

- graduate students
- early contributions; also Steve Kettel (BNL)



Neutral beam stop

- absorb high energy neutrons
- lower rates downstream
- must be narrow (acceptance)

Material	Density (g/cm^3)	Elemental composition	(%)
Tungsten Heavimet	17.95	Tungsten	94.20
		Nickel	4.35
		Iron	0.85
		Cobalt	0.50
		Copper	0.10
"Stiff" lead	11.4	Lead	97.0
		Antimony	3.0
Copper	8.96	Copper	99.9
Borated zirconium Hydride polyethylene	3.67	Zirconium	85.0
		Carbon	8.9
		Hydrogen	3.4
		Oxygen	2.2
		Boron	0.5
FLEX/BORON	1.64	Silicon	26.9
		Boron	25.4
		Oxygen	24.2
		Carbon	20.1
		Hydrogen	2.8
Lithiated poly	1.06	Carbon	83.7
		Hydrogen	8.8
		Lithium	7.5
Borated poly, 0.5%	0.84	Carbon	83.1
		Hydrogen	14.2
		Oxygen	2.2
		Boron	0.5
Borated poly, 5.0%	0.93	Carbon	61.2
		Oxygen	22.2
		Hydrogen	11.6
		Boron	5.0

A compact beam stop for a rare kaon decay experiment

J. Belz[a,1], M. Diwan[b,2], M. Eckhause[c], C.M. Guss[a,3], A.D. Hancock[c], A.P. Heinson[d,4], V.L. Highland[a,5], G.W. Hoffmann[e], G.M. Irwin[b], J.R. Kane[c], S.H. Kettell[a,2], Y. Kuang[c,6], K. Lang[e], J. McDonough[e,7], W.K. McFarlane[a,8], W.R. Molzon[d], P.J. Riley[e], J.L. Ritchie[e], A.J. Schwartz[b,9], B. Ware[e,10], R.E. Welsh[c], R.G. Winter[c,5], M. Witkowski[c,11], S.G. Wojcicki[b], S.D. Worm[e,12,*], A. Yamashita[c,13]

[a] Temple University, Philadelphia, PA 19122, USA
[b] Stanford University, Stanford, CA 94309, USA
[c] College of William and Mary, Williamsburg, VA 23187, USA
[d] University of California, Irvine, CA 92717, USA
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Received 12 August 1998

gammas

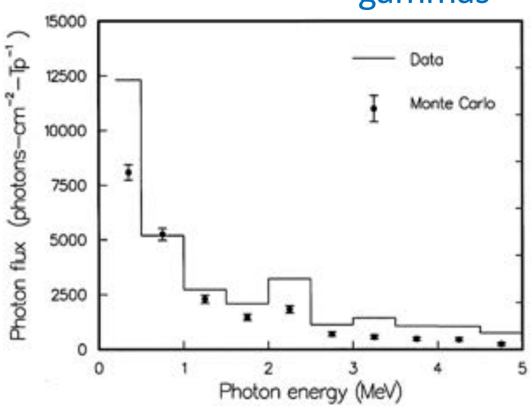


Fig. 13. Comparison of the photon flux predicted by the Monte Carlo simulation and the liquid scintillator measurements upstream of the shielded beam stop.

neutrons

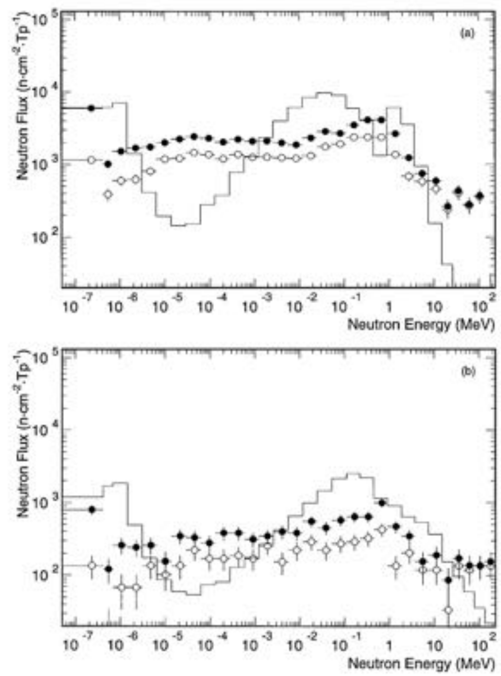
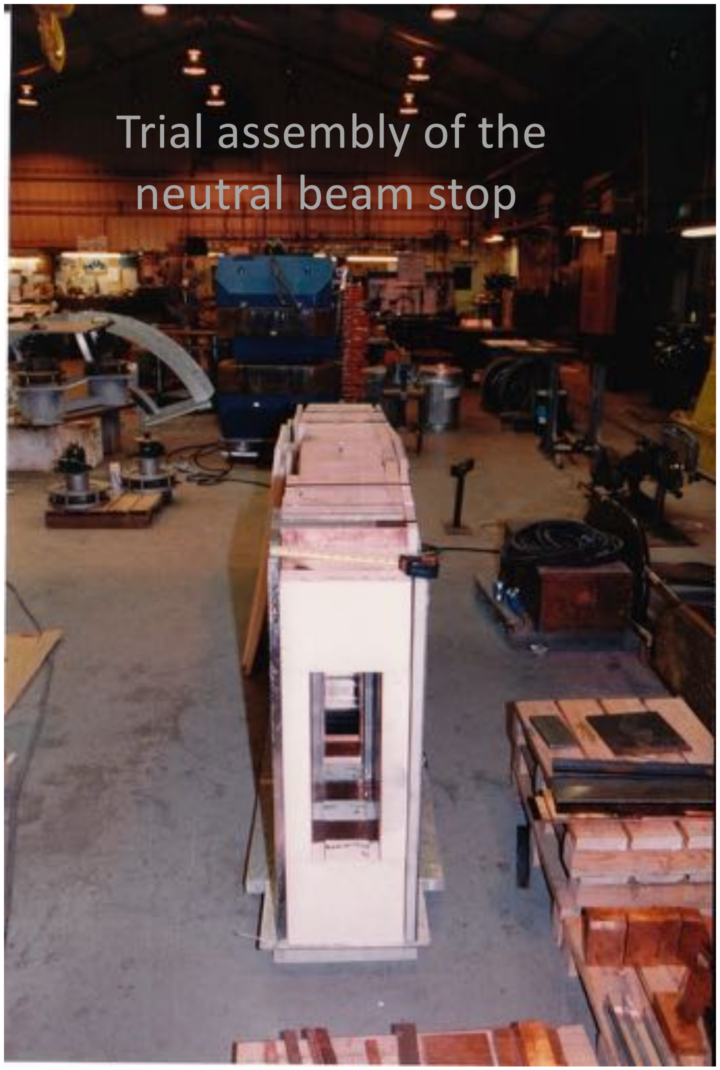
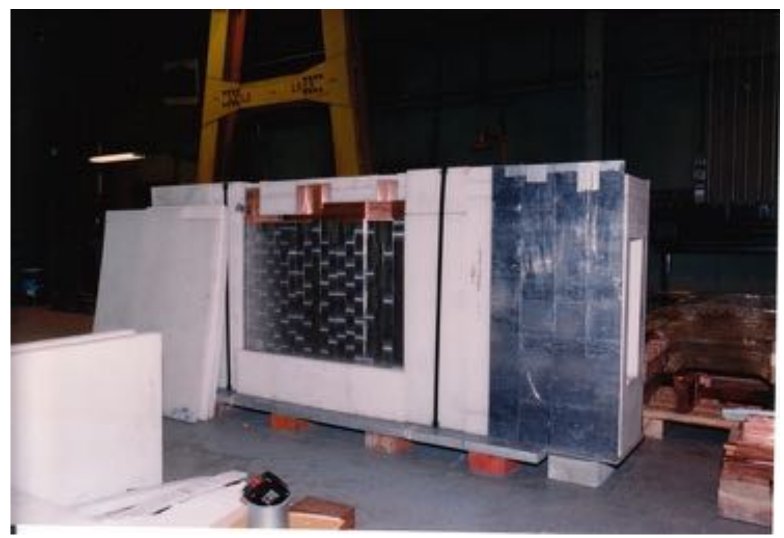


Fig. 12. Neutron flux from the Monte Carlo simulation and the Bonner sphere measurements for the shielded beam stop (configuration 3), both upstream (a) and downstream (b) of the beam stop. The solid line is the Bonner sphere result. The Monte Carlo predictions for neutrons emerging from the beam stop are shown for two cases: with (solid dots) and without (open circles) rescattering.

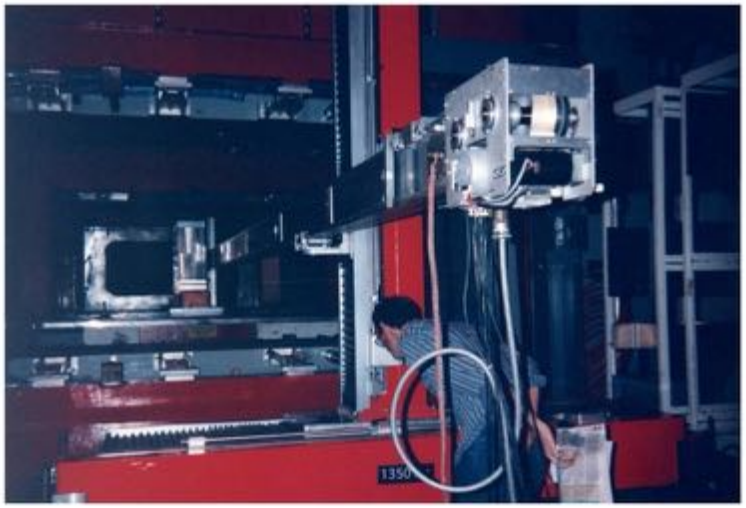


Trial assembly of the neutral beam stop

Steve Worm

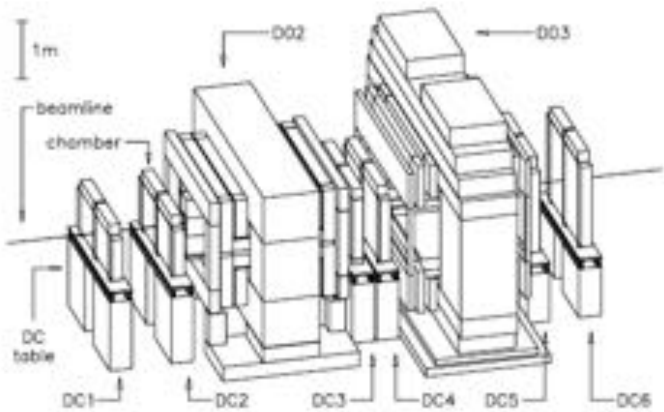


Precision magnet mapping



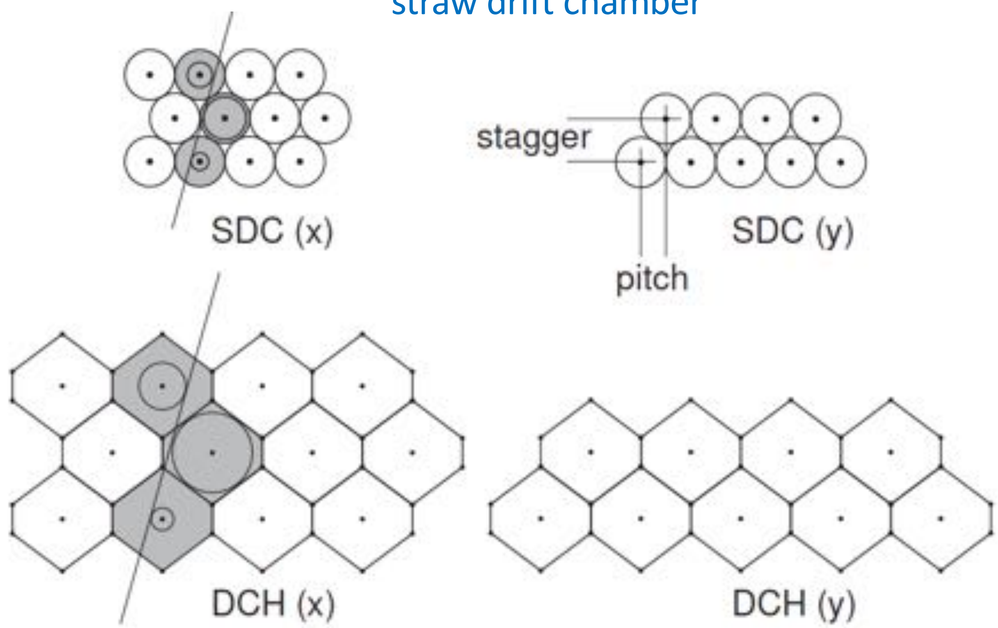
Neutral beam stop in the magnet

Tracking System & Magnetic Spectrometer



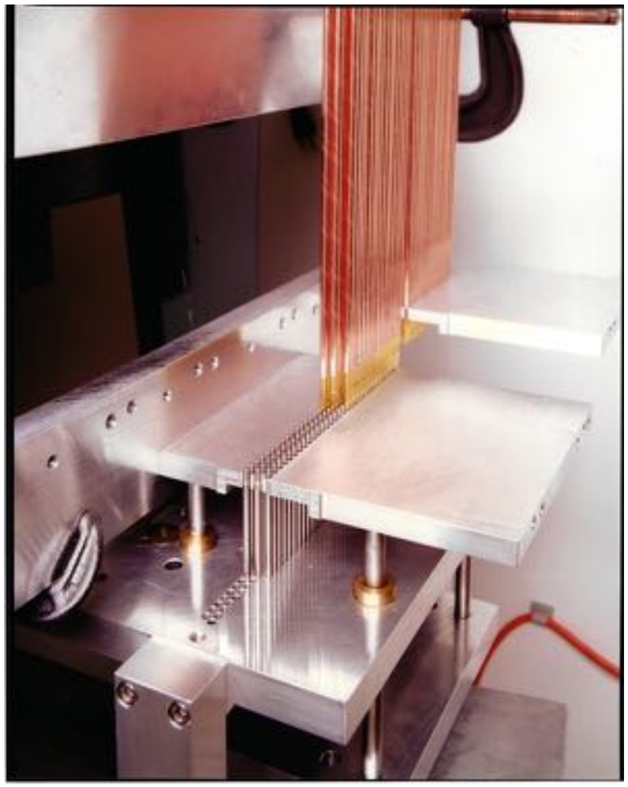
- Two momentum analyzing magnets for $\pi \to \mu\nu$ rejection
- Magnets tuned to give parallel tracks downstream
- 4 pairs of straw drift chambers with $CF_4 - C_2H_6$ (50 – 50) ($r = 5\ mm$, $\sigma = 160\mu$, $\epsilon = 96\%/\text{wire}$)
- 2 pairs of conventional drift chambers $Ar - C_2H_6$ (50 – 50) ($r = 10\ mm$, $\sigma = 120\mu$, $\epsilon = 98\%/\text{wire}$)
- Three sublayers in x view to minimize ambiguities
- $\sigma_{\pi\pi} = 1.1\ MeV/c^2$

straw drift chamber



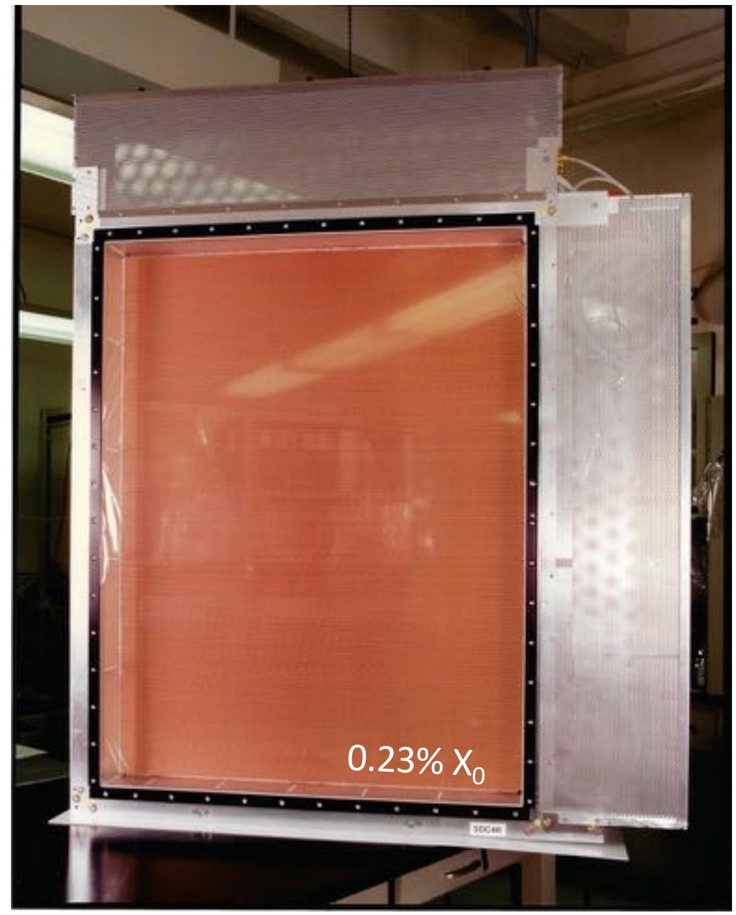
drift chamber (drift cells lines are "to guide your eyes")

Copperized Mylar straws



Texas crew members

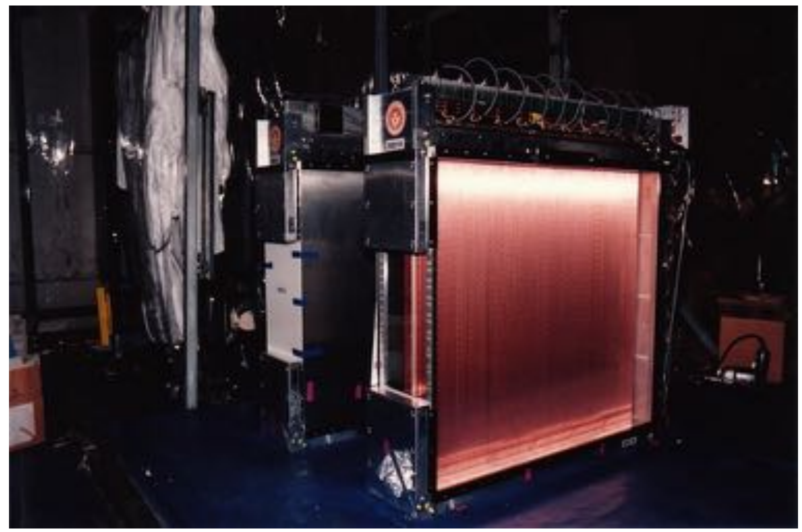
Straw Drift Chamber 4R



BNL B5 beamline:
between vacuum window and the magnet

BNL B5 beamline:
downstream vacuum window


Mike Hebert
Casey Hartman
Mark Backman



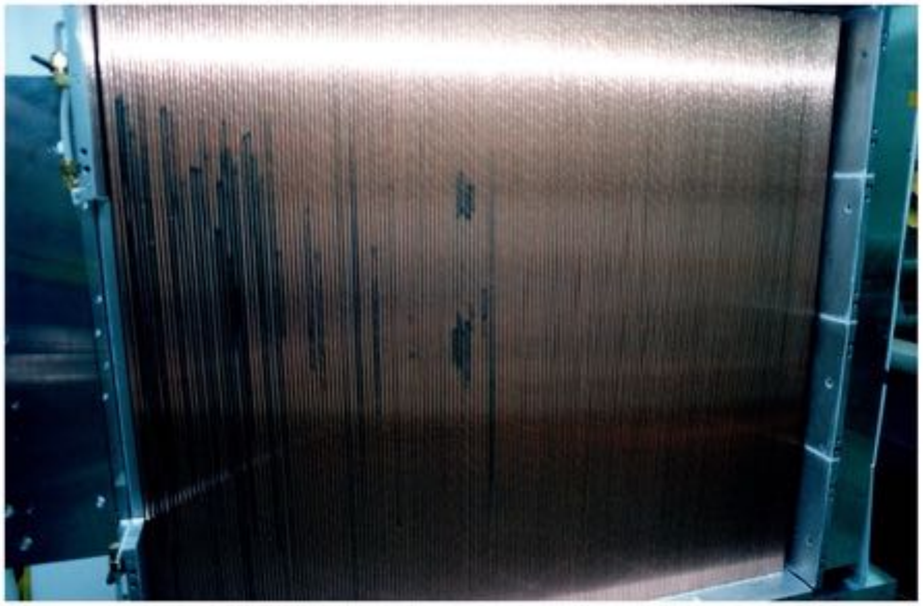

Vassilis Vassilakopoulos

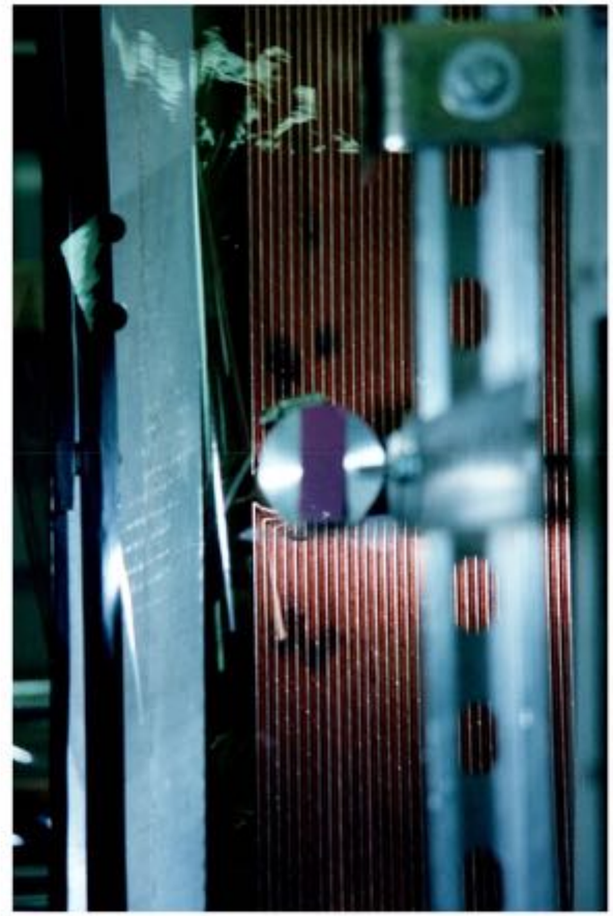

Straws FE


Casey Hartman

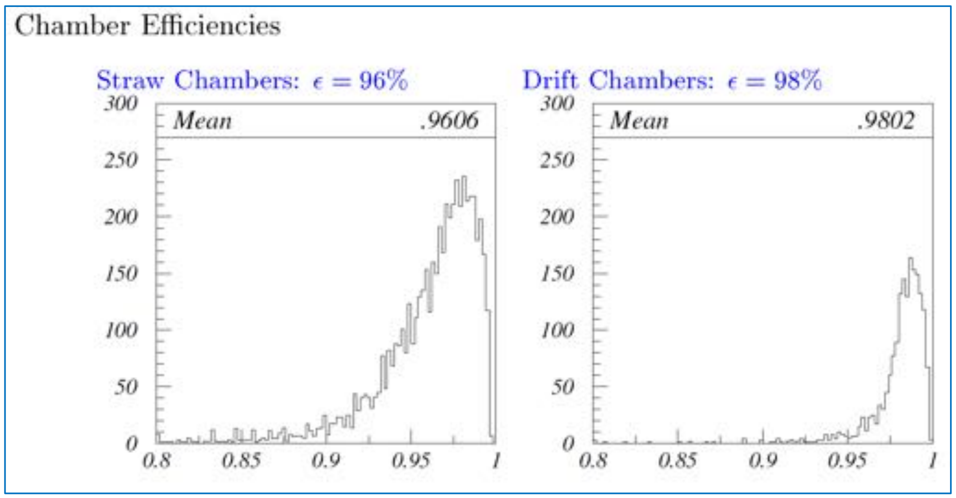
1993 test run with prototypes

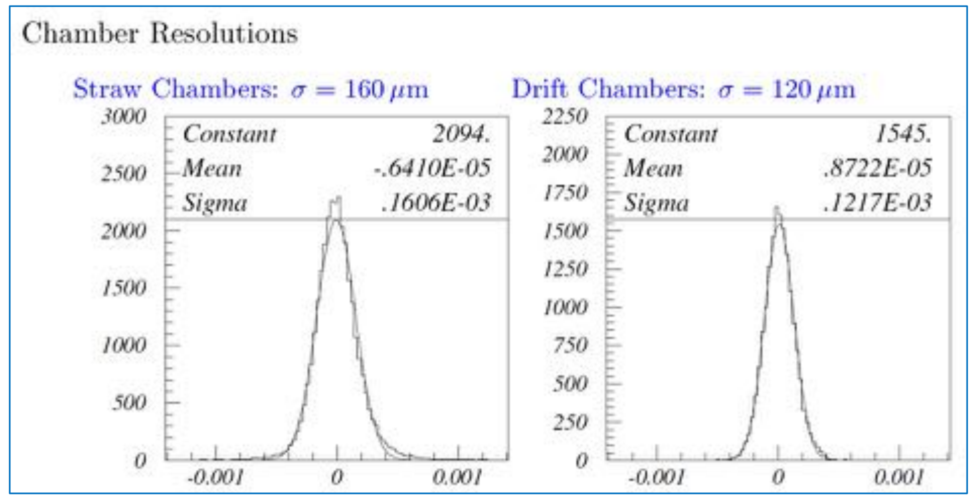
"discovered" plasma chemistry

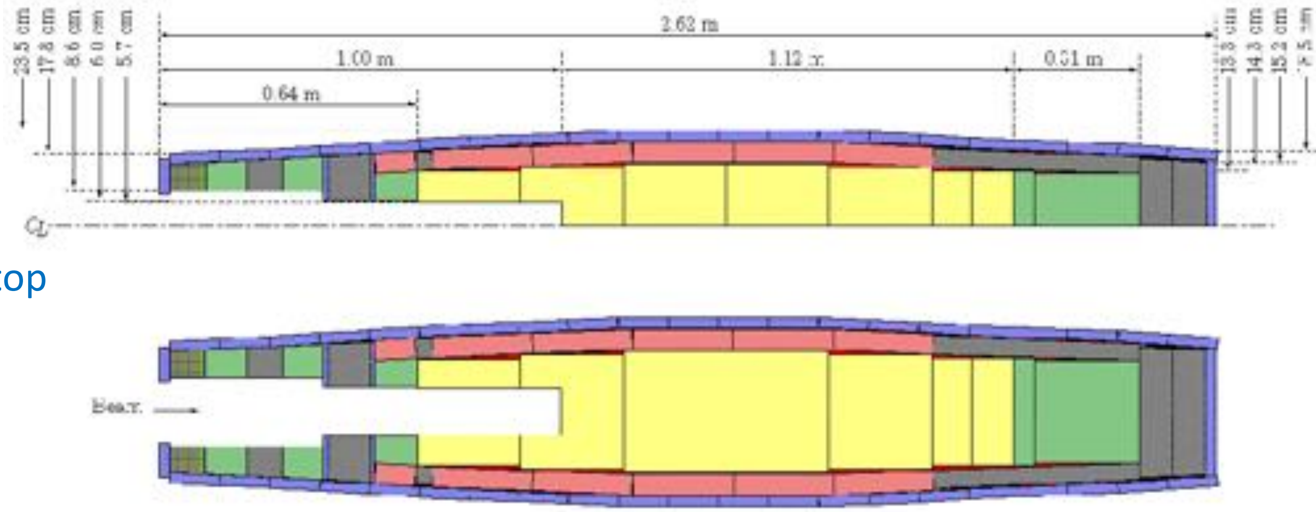




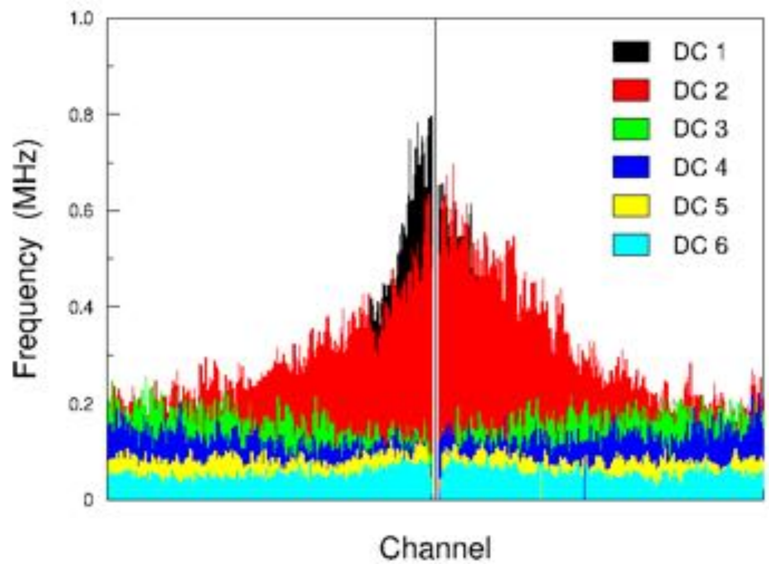
Tracking Chamber Performance







the beam stop



SDC/DC rates with the beam

Next to the last day of the 1995 run (Run 1,~22 weeks) ...

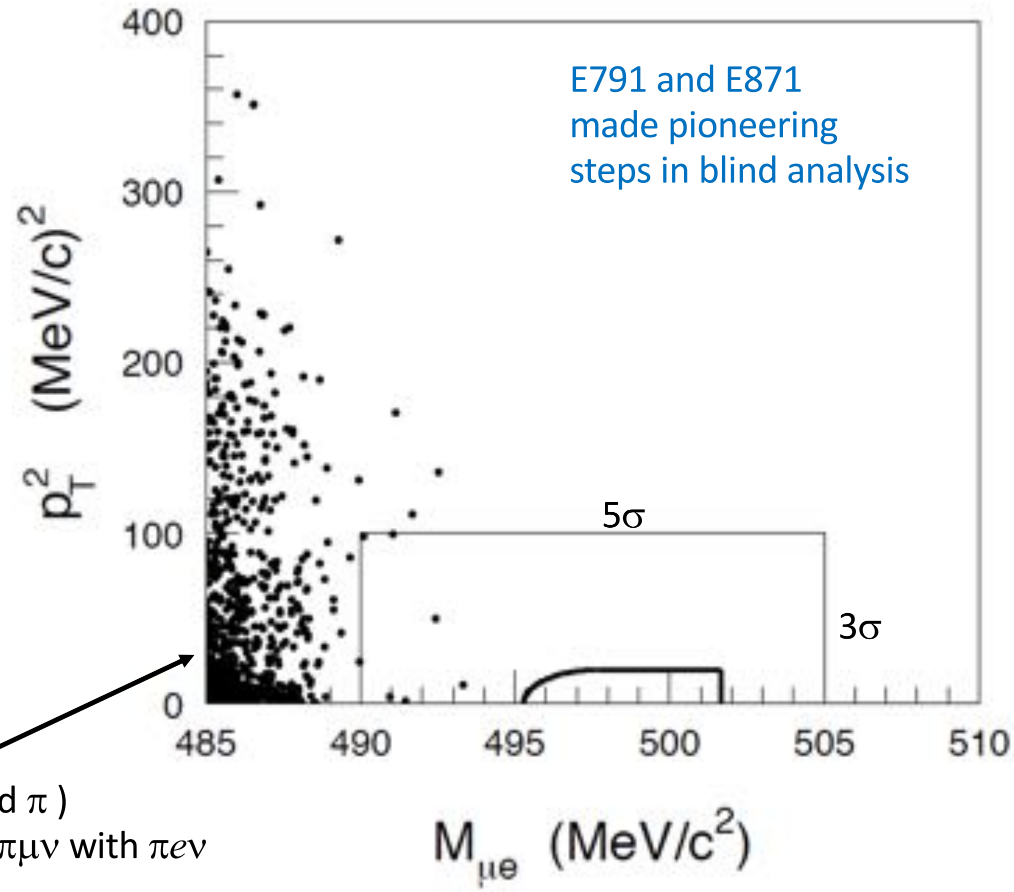
By then, Mel Schwartz became the BNL HEP Director
... and graciously supported the reconstruction of straw system.

Much reconstruction and analysis between this and the next slide ...

$K_L^0 \to \mu^\pm e^\mp$ **Final Results**

ΔL=2

- expected bkg in the signal region: 0.11 events
- NO CANDIDATES
- $B(K_L^0 \to \mu^\pm e^\mp) < 4.7 \times 10^{-12}$ (90% CL)



Phys.Rev.Lett. 81:5734-5737,1998

- "μ" (mis-id π)
- pile up of πμν with πeν

One in a billion

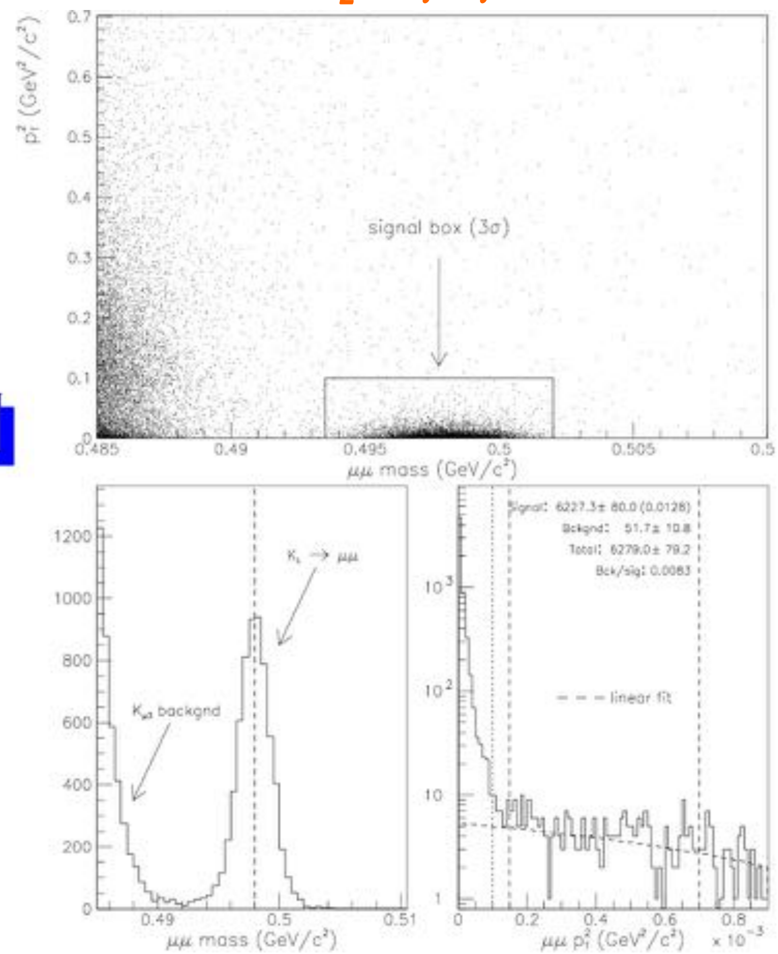
$K_L^0 \rightarrow \mu^+\mu^-$

$K_L^0 \rightarrow \mu^+\mu^-$: Final Event Counting

$$\Gamma(K_L^0 \rightarrow \mu^+\mu^-)/\Gamma(K_L^0 \rightarrow \pi^+\pi^-) = (3.474 \pm 0.057) \times 10^{-6}$$

$$B(K_L^0 \rightarrow \mu^+\mu^-) = (7.18 \pm 0.17) \times 10^{-9}$$

$\times 10^{-3}$



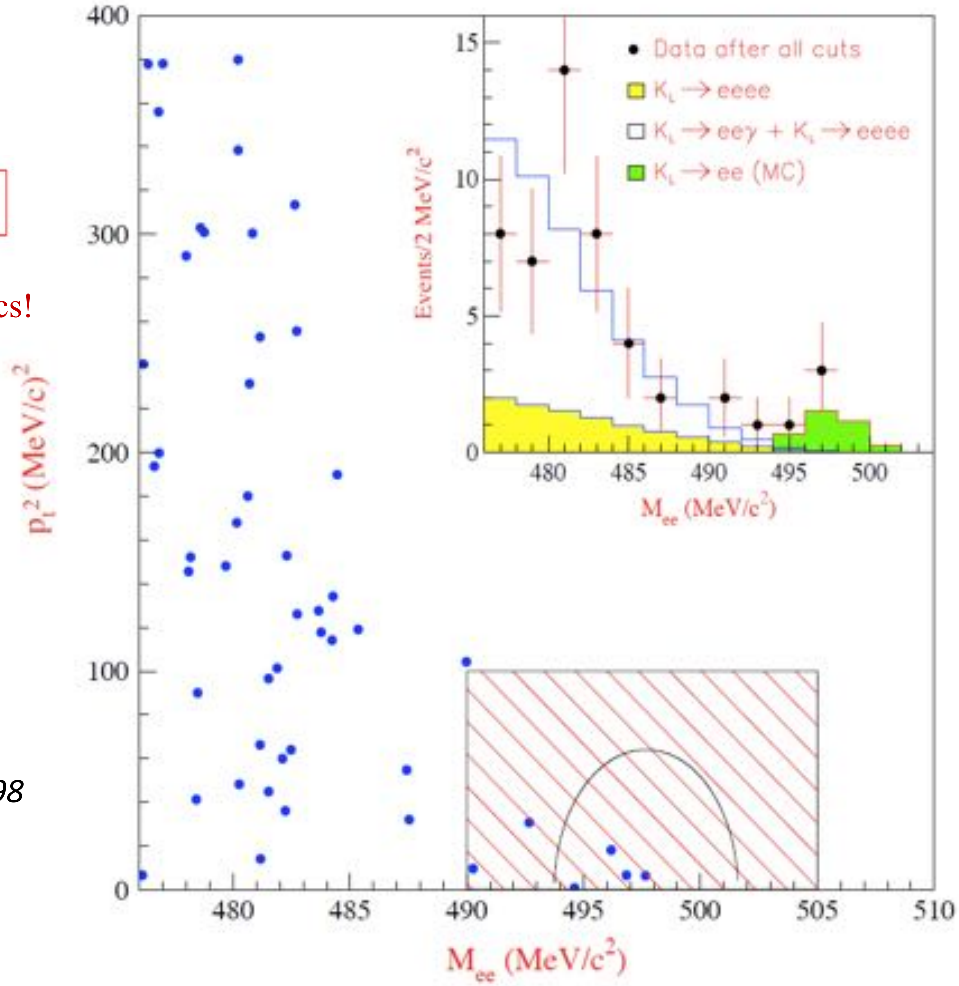
Phys.Rev.Lett. 84:1389-1392,2000

One in a trillion $K_L^0 \rightarrow e^+ e^-$

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

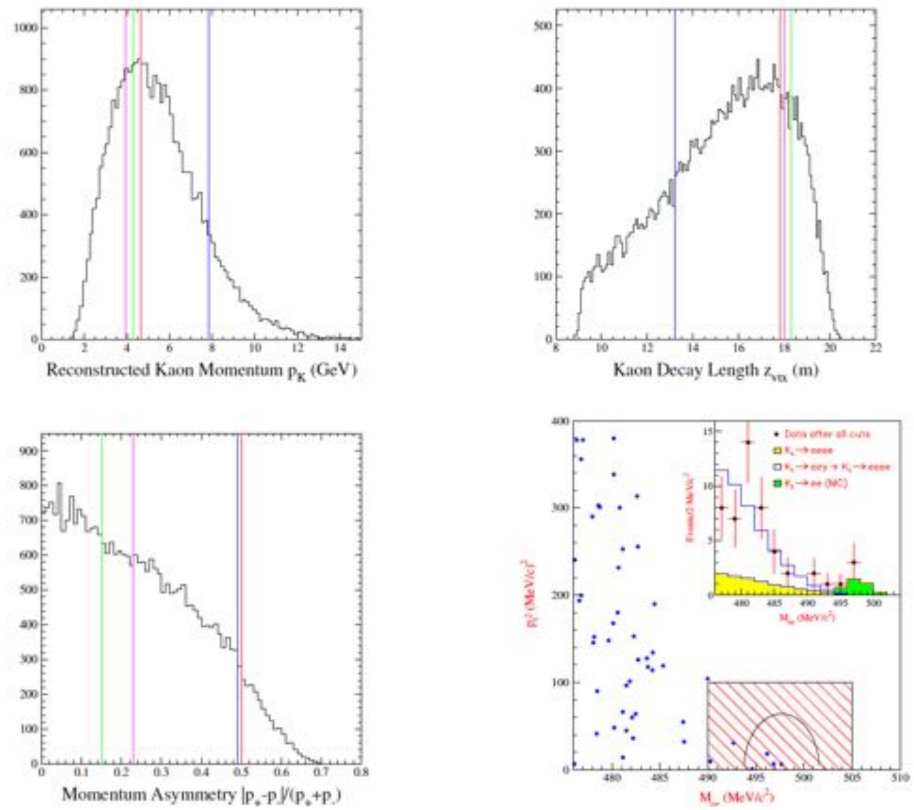
Rarest decay ever observed in particle physics!

Phys.Rev.Lett.81:4309-4312,1998



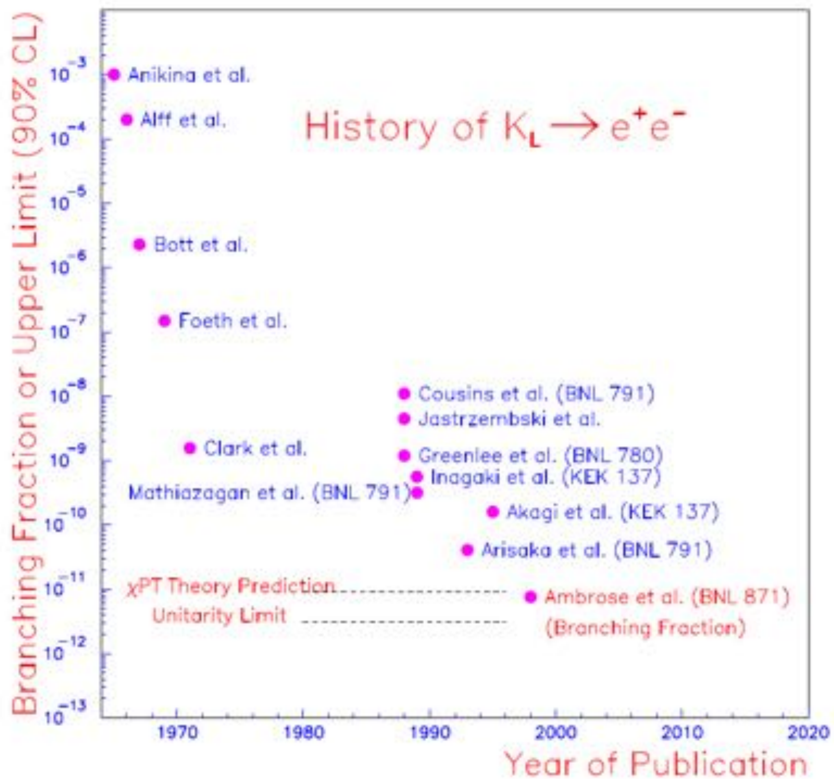
$K_L^0 \rightarrow e^+e^- \ldots$

the four events were "nicely" sampling all phase-space parameters...



The E871 legacy

Rarest decay ever observed
in particle physics!



- 1988: BNL E871 observes 4 candidates

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

- consistent with χPTpredictions

Summary

- We have pioneered instrumentation and analysis
- We have overcome many challenges due to:
  - ✓ natural physics processes
  - ✓ man-made calamities (there were more ...)

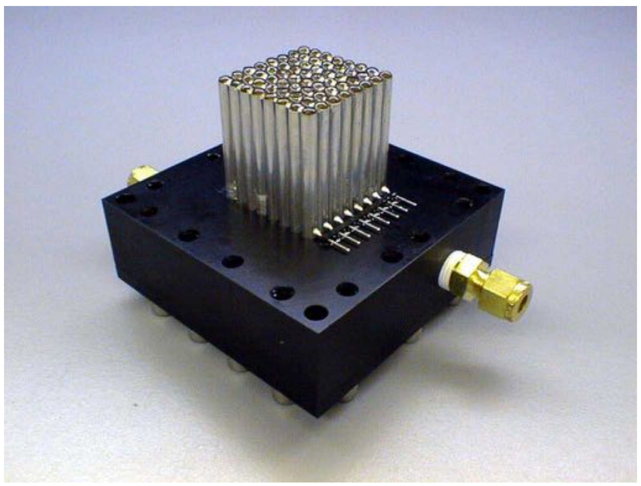
- Without Stan's intellectual and personal leadership
  we would not have succeeded!

Stanford, 2010

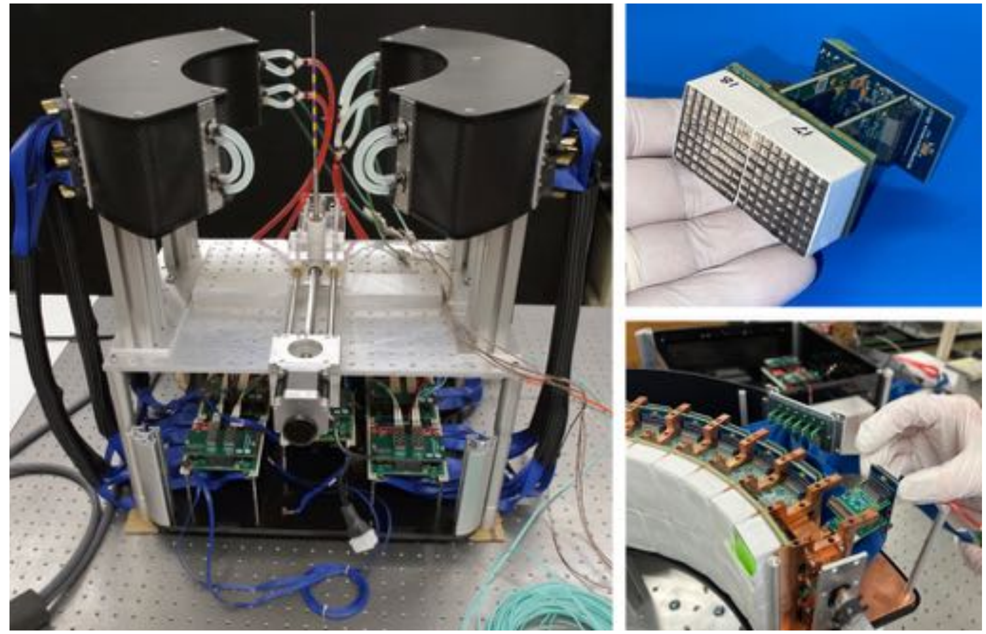
credit: K. Ecklund

Among my personal spinoffs :

1998 Xe "straw" PET scanner



2023 LYSO/SiPM PET scanner for proton therapy



Phys. Med. Biol. **68** (2023) 125001 https://doi.org/10.1088/1361-6560/acd29e

Physics in Medicine & Biology

IPEM
Institute of Physics and Engineering in Medicine

PAPER

The first PET glimpse of a proton FLASH beam

F Abouzahr[1], J P Cesar[1], P Crespo[2,3], M Gajda[1], Z Hu[4], W Kaye[5], K Klein[1], A S Kuo[1], S Majewski[1,6], O Mawlawi[7], A Morozov[2], A Ojha[1], F Poenisch[8], J C Polf[5], M Proga[1], N Sahoo[8], J Seco[9,10], T Takaoka[11], S Tavernier[12], U Titt[4], X Wang[8], X R Zhu[8] and K Lang[1]

Extras

Main Features of E871 in Numbers

- data taking periods: 1995 and 1996 runs
- beam
  - $p_{AGS} = 24\, GeV/c$, 1.5×10^{13} pot / 1.2–1.6 spill
    $\sim 40\%$ duty cycle
  - 2×10^8 K_L^0 /spill, $2 \leq p_K \leq 16\ GeV/c$
    $n/K_L^0 = 8 \pm 3$
  - Pt target 1.4 λ, $3.75°$ wrt collimators
    neutral beam solid angel: 4×16 mrad^2
  - decay volume: 11 m long, 7.5 % K_L^0 decays
- spectrometer
  - 2 spectrometer dipoles: $p_T^{kick} = 418$ and 216 MeV/c
  - beam stop
  - $r = 5\ mm$ straw drift chambers with fast $CF_4 - H_2C_6$ $(50 - 50)\%$
  - redundant PID for e and μ
- trigger + daq
  - multi-level two-body parallel trigger
    average throughput: L0: 70 kHz / L1: 7 kHz / L3: 200 Hz
  - parallel readout: front-end → Dual Port Memories (DPM)
  - 8 CPU/DPM's L3 software trigger
  - fast (200 ns) conversion time front-end electronics

$\Gamma(e^{\pm}\mu^{\mp})/\Gamma_{total}$ Γ_{34}/Γ

Test of lepton family number conservation.

VALUE (units 10^{-11})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*
<0.47	90		AMBROSE	98B	B871
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<9.4	90	0	AKAGI	95	SPEC
<3.9	90	0	ARISAKA	93	B791
<3.3	90	0	[1] ARISAKA	93	B791

[1] This is the combined result of ARISAKA 93 and MATHIAZHAGAN 89.

$\Gamma(e^{+}e^{-})/\Gamma_{total}$ Γ_{24}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-10})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*
$\mathbf{0.087^{+0.057}_{-0.041}}$		4	AMBROSE	98	B871
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.6	90	1	AKAGI	95	SPEC
<0.41	90	0	[1] ARISAKA	93B	B791

[1] ARISAKA 93B includes all events with <6 MeV radiated energy.

$\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ $\qquad\Gamma_{23}/\Gamma_8$

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-6})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
3.48 ±0.05 OUR AVERAGE					
3.474±0.057	6210	AMBROSE	00	B871	
3.87 ±0.30	179	[1] AKAGI	95	SPEC	
3.38 ±0.17	707	HEINSON	95	B791	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3.9 ±0.3 ±0.1	178	[2] AKAGI	91B	SPEC	In AKAGI 95
3.45 ±0.18 ±0.13	368	[3] HEINSON	91	SPEC	In HEINSON 95
4.1 ±0.5	54	INAGAKI	89	SPEC	In AKAGI 91B
2.8 ±0.3 ±0.2	87	MATHIAZHA...	89B	SPEC	In HEINSON 91

[1] AKAGI 95 gives this number multiplied by the PDG 1992 average for $\Gamma(K^0_L \to \pi^+\pi^-)/\Gamma(\text{total})$.

[2] AKAGI 91B give this number multiplied by the 1990 PDG average for $\Gamma(K^0_L \to \pi^+\pi^-)/\Gamma(\text{total})$.

[3] HEINSON 91 give $\Gamma(K^0_L \to \mu\mu)/\Gamma_{\text{total}}$. We divide out the $\Gamma(K^0_L \to \pi^+\pi^-)/\Gamma_{\text{total}}$ PDG average which they used.

VOLUME 63, NUMBER 20 PHYSICAL REVIEW LETTERS 13 NOVEMBER 1989

New Experimental Limits on $K_L^0 \to \mu e$ and $K_L^0 \to ee$ Branching Ratios

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(Received 7 August 1989)

A search for the decays $K_L^0 \to \mu e$ and $K_L^0 \to ee$ has produced no examples of either process. When normalized to the decay $K_L^0 \to \pi^+\pi^-$, the 90%-C.L. upper limits on the branching ratios are $B(K_L^0 \to \mu e) < 2.2 \times 10^{-10}$ and $B(K_L^0 \to ee) < 3.2 \times 10^{-10}$.

40

VOLUME 81, NUMBER 26 PHYSICAL REVIEW LETTERS 28 DECEMBER 1998

New Limit on Muon and Electron Lepton Number Violation from $K_L^0 \to \mu^\pm e^\mp$ Decay

D. Ambrose,[1] C. Arroyo,[2] M. Bachman,[3] D. Connor,[3] M. Eckhause,[4] S. Graessle,[1] A.D. Hancock,[4] K. Hartman,[2] M. Hebert,[2] C.H. Hoff,[4] G.W. Hoffmann,[1] G.M. Irwin,[2] J.R. Kane,[4] N. Kanematsu,[3] Y. Kuang,[4] K. Lang,[1] R. Lee,[3] R.D. Martin,[4] J. McDonough,[1] A. Milder,[1] W.R. Molzon,[3] M. Pommot-Maia,[2] P.J. Riley,[1] J.L. Ritchie,[1] P.D. Rubin,[5] V.I. Vassilakopoulos,[1] R.E. Welsh,[4] and S.G. Wojcicki[2]

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(Received 25 September 1998)

The most sensitive experiment to date to search for the muon and electron lepton number violating decay $K_L^0 \to \mu^\pm e^\mp$ has detected no events consistent with this process. Based on this result, the 90% confidence level upper limit on the branching fraction is $B(K_L^0 \to \mu^\pm e^\mp) < 4.7 \times 10^{-12}$. [S0031-9007(98)07985-X] 175

VOLUME 84, NUMBER 7 PHYSICAL REVIEW LETTERS 14 FEBRUARY 2000

Improved Branching Ratio Measurement for the Decay $K_L^0 \to \mu^+\mu^-$

D. Ambrose,[1] C. Arroyo,[2] M. Bachman,[3] D. Connor,[3] M. Eckhause,[4] S. Graessle,[1] A.D. Hancock,[4] K. Hartman,[2] M. Hebert,[2] C.H. Hoff,[4] G.W. Hoffmann,[1] G.M. Irwin,[2] J.R. Kane,[4] N. Kanematsu,[3] Y. Kuang,[4] K. Lang,[1] R. Lee,[3] R.D. Martin,[4] J. McDonough,[1] A. Milder,[1] W.R. Molzon,[3] M. Pommot-Maia,[2] P.J. Riley,[1] J.L. Ritchie,[1] P.D. Rubin,[5] V.I. Vassilakopoulos,[1] R.E. Welsh,[4] and S.G. Wojcicki[2]

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(Received 24 August 1999)

We report results from Experiment 871, performed at the BNL AGS, of a measurement of the branching ratio $K_L^0 \to \mu^+\mu^-$ with respect to the CP-violating mode $K_L^0 \to \pi^+\pi^-$. This experiment detected over 6200 candidate $\mu^+\mu^-$ events, a factor of 6 more than that seen in all previous measurements combined. The resulting branching ratio $\Gamma(K_L^0 \to \mu^+\mu^-)/\Gamma(K_L^0 \to \pi^+\pi^-) = (3.474 \pm 0.057) \times 10^{-6}$ leads to a branching fraction $B(K_L^0 \to \mu^+\mu^-) = (7.18 \pm 0.17) \times 10^{-9}$, which is consistent with the current world average, and reduces the uncertainty in this decay mode by a factor of 3. 93

VOLUME 81, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1998

First Observation of the Rare Decay Mode $K_L^0 \to e^+e^-$

D. Ambrose,[1] C. Arroyo,[2] M. Bachman,[3] P. de Cecco,[3] D. Connor,[3] M. Eckhause,[4] K.M. Ecklund,[2] S. Graessle,[1] A.D. Hancock,[4] K. Hartman,[2] M. Hebert,[2] C.H. Hoff,[4] G.W. Hoffmann,[1] G.M. Irwin,[2] J.R. Kane,[4] N. Kanematsu,[3] Y. Kuang,[4] K. Lang,[1] R. Lee,[3] R.D. Martin,[4] J. McDonough,[1] A. Milder,[1] W.R. Molzon,[3] M. Pommot-Maia,[2] P.J. Riley,[1] J.L. Ritchie,[1] P.D. Rubin,[5] V.I. Vassilakopoulos,[1] C.B. Ware,[1] R.E. Welsh,[4] S.G. Wojcicki,[2] E. Wolin,[4] and S. Worm[1]

(BNL E871 Collaboration)

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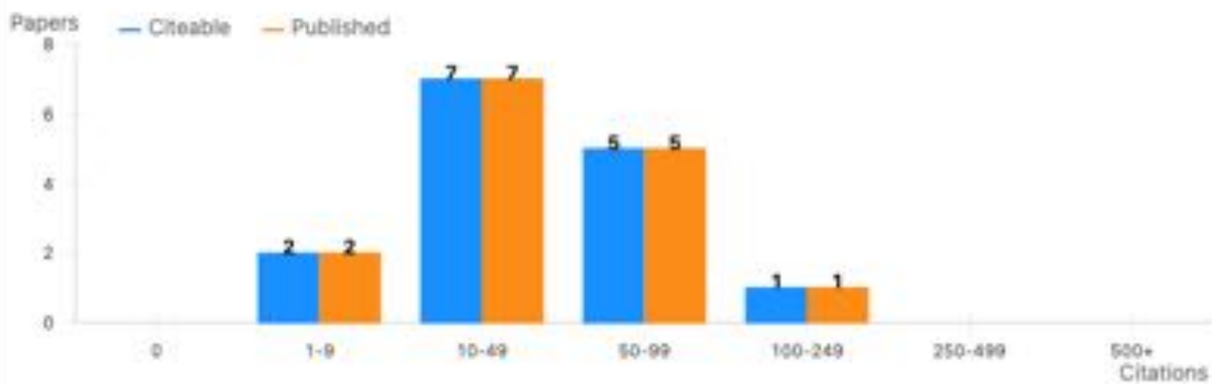
(Received 1 September 1998)

In an experiment designed to search for and study very rare two-body decay modes of the K_L^0, we have observed four examples of the decay $K_L^0 \to e^+e^-$, where the expected background is 0.17 ± 0.10 events. This observation translates into a branching fraction of $8.7^{+5.7}_{-4.1} \times 10^{-12}$, consistent with recent theoretical predictions. This result represents by far the smallest branching fraction yet measured in particle physics. [S0031-9007(98)07665-0] 69

Citation Summary

Exclude self-citations

	Citeable	Published
Papers	15	15
Citations	762	762
h-index	12	12
Citations/paper (avg)	50.8	50.8



VOLUME 76, NUMBER 18 PHYSICAL REVIEW LETTERS 29 APRIL 1996

Search for the Weak Decay of an *H* Dibaryon

J. Belz,[6,*] R.D. Cousins,[3] M.V. Diwan,[5,†] M. Eckhause,[8] K.M. Ecklund,[5] A.D. Hancock,[8] V.L. Highland,[6,‡] C. Hoff,[8] G.W. Hoffmann,[7] G.M. Irwin,[5] J.R. Kane,[8] S.H. Kettell,[6,†] J.R. Klein,[4,§] Y. Kuang,[8] K. Lang,[7] R. Martin,[8] M. May,[1] J. McDonough,[7] W.R. Molzon,[2] P.J. Riley,[7] J.L. Ritchie,[7] A.J. Schwartz,[4] A. Trandafir,[6] B. Ware,[7] R.E. Welsh,[8] S.N. White,[1] M.T. Witkowski,[8,||] S.G. Wojcicki,[5] and S. Worm[7]

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(Received 8 December 1995)

We have searched for a neutral H dibaryon decaying via $H \to \Lambda n$ and $H \to \Sigma^0 n$. Our search has yielded two candidate events from which we set an upper limit on the H production cross section. Normalizing to the inclusive Λ production cross section, we find $(d\sigma_H/d\Omega)/(d\sigma_\Lambda/d\Omega) < 6.3 \times 10^{-6}$ at 90% C.L., for an H of mass $\approx 2.15\ \mathrm{GeV}/c^2$. [S0031-9007(96)00050-6]

PACS numbers: 14.20.Pt, 13.85.Rm, 25.40.Ve

RAPID COMMUNICATIONS

Rapid Communications are intended for important new results which deserve accelerated publication, and are therefore given priority in the editorial office and in production. A Rapid Communication in **Physical Review D** *should be no longer than five printed pages and must be accompanied by an abstract. Page proofs are sent to authors, but because of the accelerated schedule, publication is generally not delayed for receipt of corrections unless requested by the author.*

Search for diffractive dissociation of a long-lived *H* dibaryon

J. Belz,[6,*] R. D. Cousins,[3] M. V. Diwan,[5,†] M. Eckhause,[8] K. M. Ecklund,[5] V. L. Fitch,[4] A. D. Hancock,[8] V. L. Highland,[6,‡] C. Hoff,[8] G. W. Hoffmann,[7] G. M. Irwin,[5] J. R. Kane,[8] S. H. Kettell,[6,†] J. R. Klein,[4,§] Y. Kuang,[8] K. Lang,[7] R. Martin,[8] M. May,[1] J. McDonough,[7,||] W. R. Molzon,[2] P. J. Riley,[7] J. L. Ritchie,[7] A. J. Schwartz,[4] A. Trandafir,[6] B. Ware,[7] R. E. Welsh,[8] S. N. White,[1] M. T. Witkowski,[8,¶] S. G. Wojcicki,[5] and S. Worm[7]

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(Received 14 July 1995)

We have searched for long-lived H dibaryons (six-quark *uuddss* states) in a neutral beam produced by 24.1 GeV/*c* *p*-Pt collisions. The signature was exclusive $\Lambda^0\Lambda^0$ production from diffractive dissociation of H's striking a plastic scintillator. We observed 40 $\Lambda^0\Lambda^0$ events with a background of 3.2 events, but see no evidence of H dissociation. Using our additional observation of 187 ± 39 $\Lambda^0 K_S^0$ events produced by coherent diffractive dissociation of neutrons from carbon for normalization, we place an upper limit of 1 mb/sr on the production of H's with lifetimes $\gtrsim 10^{-8}$ s.

PACS number(s): 13.85.Rm, 14.20.Pt, 25.40.Ve

PHYSICAL REVIEW C VOLUME 56, NUMBER 2 AUGUST 1997

Addendum to "Search for the weak decay of an *H* dibaryon"

J. Belz,[6,*] R. D. Cousins,[3] M. V. Diwan,[5,†] M. Eckhause,[8] K. M. Ecklund,[5] A. D. Hancock,[8] V. L. Highland,[6,‡] C. Hoff,[8] G. W. Hoffmann,[7] G. M. Irwin,[5] J. R. Kane,[8] S. H. Kettell,[6,†] J. R. Klein,[4,§] Y. Kuang,[8] K. Lang,[7] R. Martin,[8] M. May,[1] J. McDonough,[7,||] W. R. Molzon,[2] P. J. Riley,[7] J. L. Ritchie,[7] A. J. Schwartz,[4] A. Trandafir,[6] B. Ware,[7,||] R. E. Welsh,[8] S. N. White,[1] M. T. Witkowski,[8,¶] S. G. Wojcicki,[5] and S. Worm[7,**]

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(Received 14 March 1997)

We have performed an additional analysis to clarify the interpretation of two candidate events which were the result of a search for an H dibaryon. [S0556-2813(97)03308-6]

PACS number(s): 14.20.Pt, 13.85.Rm, 25.40.Ve

ELSEVIER Nuclear Instruments and Methods in Physics Research A 428 (1999) 239–262

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.nl/locate/nima

A compact beam stop for a rare kaon decay experiment

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Received 12 August 1998

Abstract

We describe the development and testing of a novel beam stop for use in a rare kaon decay experiment at the Brookhaven Alternating Gradient Synchrotron. The beam stop is located inside a dipole spectrometer magnet in close proximity to straw drift chambers and intercepts a high-intensity neutral hadron beam. The design process, involving both Monte Carlo simulations and beam tests of alternative beam-stop shielding arrangements, had the goal of minimizing the leakage of particles from the beam stop and the resulting hit rates in detectors, while preserving maximum acceptance for events of interest. The beam tests consisted of measurements of rates in drift chambers, scintillation counter hodoscopes, a gas threshold Cherenkov counter, and a lead glass array. Measurements were also made with a set of specialized detectors which were sensitive to low-energy neutrons, photons, and charged particles. Comparisons are made between these measurements and a detailed Monte Carlo simulation.

Available online at www.sciencedirect.com

SCIENCE DIRECT•

ELSEVIER Nuclear Instruments and Methods in Physics Research A 522 (2004) 274–293

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.com/locate/nima

A straw drift chamber spectrometer for studies of rare kaon decays

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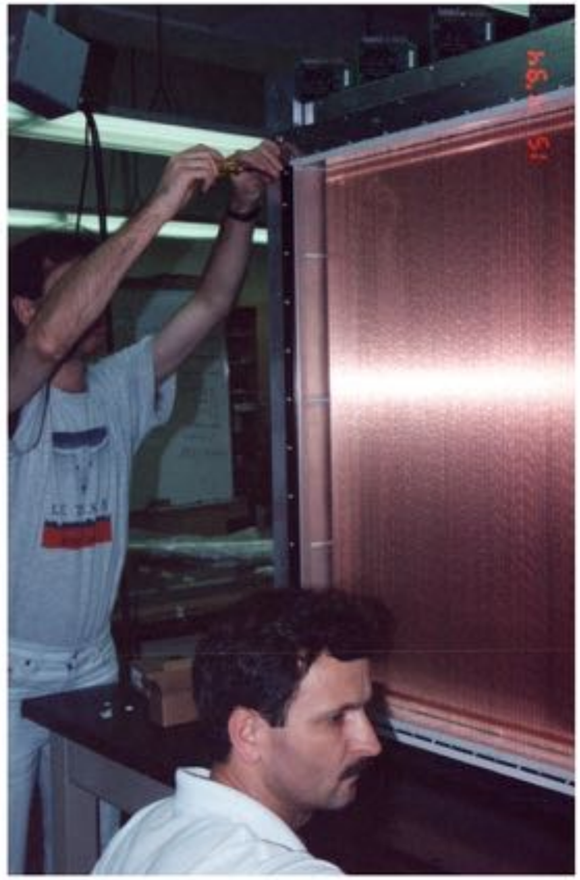
BNL E871 Collaboration

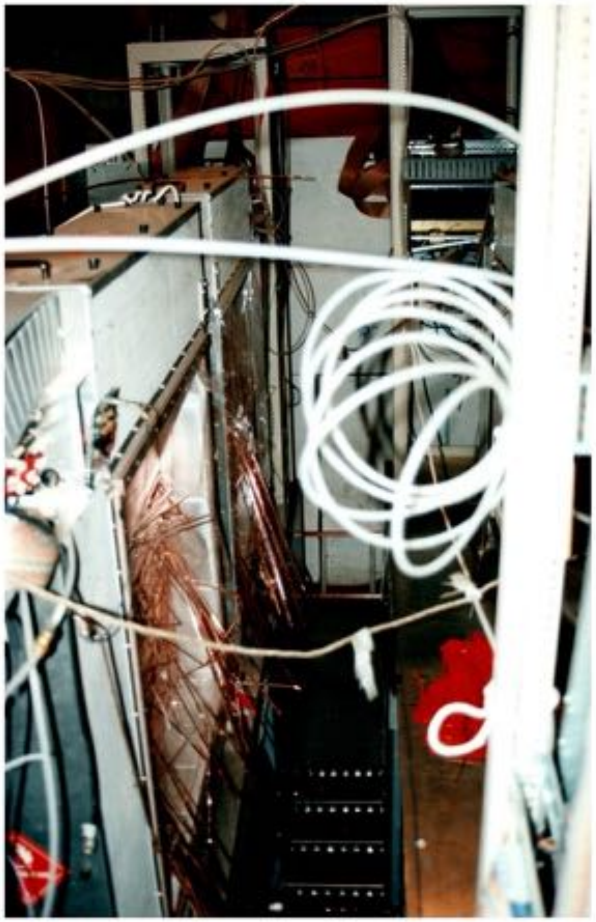
Received 25 August 2003; received in revised form 5 November 2003; accepted 10 November 2003

Abstract

We describe the design, construction, readout, tests, and performance of planar drift chambers, based on 5-mm-diameter copperized Mylar and Kapton straws, used in an experimental search for rare kaon decays. The experiment took place in the high-intensity neutral beam at the Alternating Gradient Synchrotron of Brookhaven National Laboratory, using a neutral beam stop, two analyzing dipoles, and redundant particle identification to remove backgrounds.



Marek Hamela



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