The Fermilab Kaon Physics Research Program in the Littenberg Era

R. Tschirhart
Littenberg Symposium
BNL
June 24th 2016

The Fermilab Kaon Physics Research Program

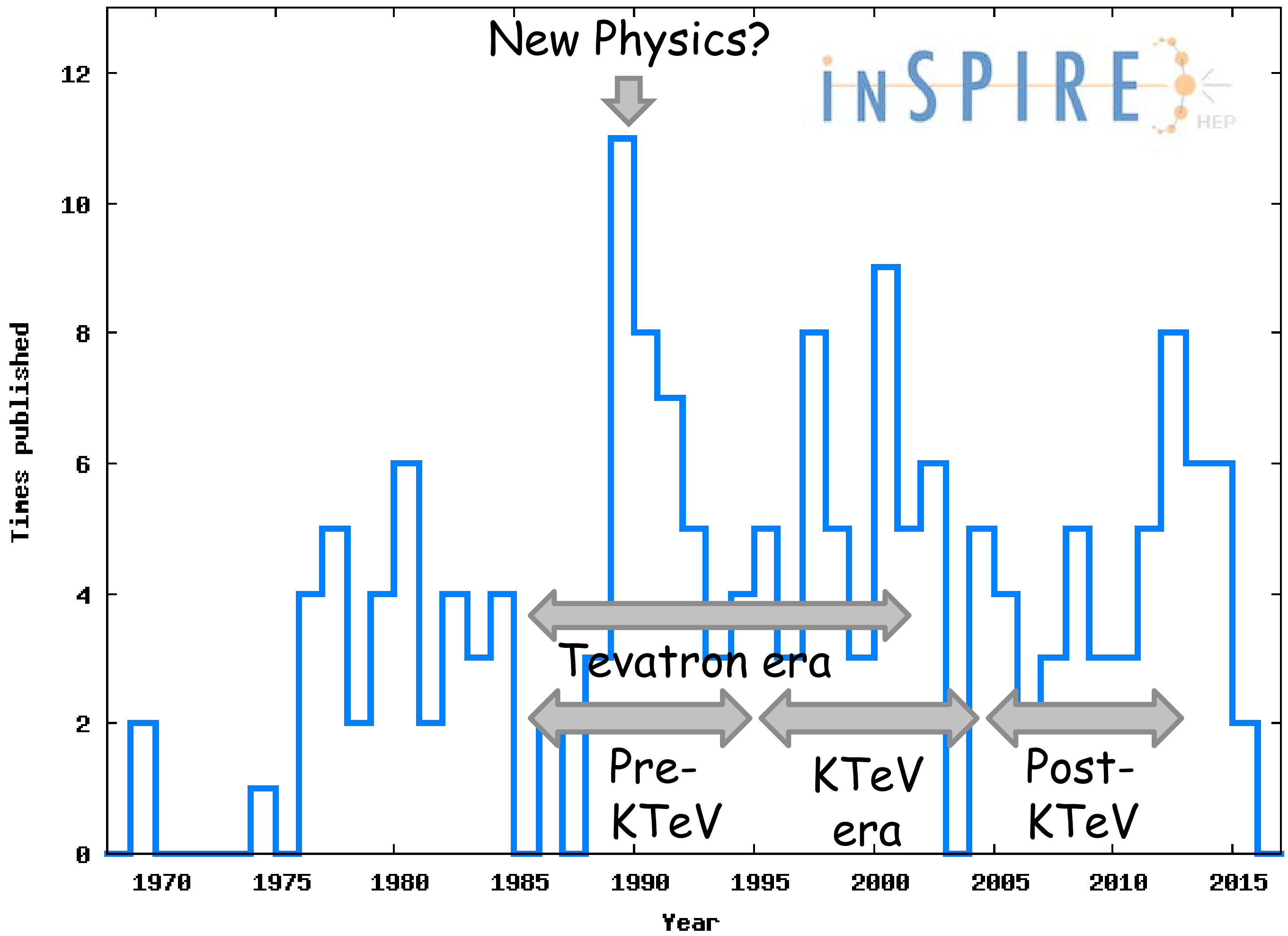
- **1985-1995:** The Tevatron enabled high energy (30-70 GeV), high flux neutral kaon beams with a K_L/n ratio near unity. Experiments: E617*, E731, E773, E799.

- **1995-2005:** The KTeV era; exploiting these beams with the revolution in computing and high precision calorimetry and instrumentation. Emergence of blind analyses.

- **2005-2015:** The KAMI, CKM, and ORKA $K \to \pi \nu \bar{\nu}$ initiatives advance but ultimately do not succeed. Important contributions to the KOTO and NA62 experiments in Japan and Europe which continue.

*Based on 400-GeV Main Ring beam, data taken 1982; Published 1985

Littenberg Publications



-1989-

March 1989: Tim Berners-Lee issued a proposal to the management at CERN for a system called "Mesh" that later became the World Wide Web.

November 1989:
Fall of the
Berlin Wall

December 1989:
Taylor Swift born…eventual revenge of the World Wide Web.

CP-violating decay $K^0_L \to \pi^0 \nu\bar{\nu}$

Laurence S. Littenberg
Phys. Rev. D 39, 3322 – Published 1 June 1989

PHYSICAL REVIEW D VOLUME 39, NUMBER 11 1 JUNE 1989

CP-violating decay $K_L^0 \to \pi^0 \nu\bar{\nu}$

Laurence S. Littenberg
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973
(Received 6 January 1989)

The process $K_L^0 \to \pi^0 \nu\bar{\nu}$ offers perhaps the clearest window yet proposed into the origin of *CP* violation. The largest expected contribution to this decay is a direct *CP*-violating term at $\approx \text{few} \times 10^{-12}$. The indirect *CP*-violating contribution is some *3 orders of magnitude* smaller, and *CP*-conserving contributions are also estimated to be extremely small. Although this decay has never been directly probed, a branching ratio upper limit of $\sim 1\%$ can be extracted from previous data on $K_L^0 \to 2\pi^0$. This leaves an enormous range in which to search for new physics. If the Kobayashi-Maskawa (KM) model prediction can be reached, a theoretically clean determination of the KM product $\sin\theta_2 \sin\theta_3 \sin\delta$ can be made.

CP-violating decay $K^0_L \to \pi^0 \nu\bar{\nu}$

Laurence S. Littenberg
Phys. Rev. D 39, 3322 – Published 1 June 1989

Abstract:

"The process $K^0_L \to \pi^0 \nu\bar{\nu}$ offers perhaps the clearest window yet proposed into the origin of CP violation. The largest expected contribution to this decay is a direct CP-violating term at few × 10^{-12} . The indirect CP-violating contribution is some 3 orders of magnitude smaller, and CP-conserving contributions are also estimated to be extremely small. Although this decay has never been directly probed, a branching ratio upper limit of ~1% can be extracted from previous data on $K^0_L \to \pi^0 \pi^0$. This leaves an enormous range in which to search for new physics. If the Kobayashi-Maskawa (KM) model prediction can be reached, a theoretically clean determination of the KM product $\sin\theta_2 \sin\theta_3 \sin\delta$ can be made."

Context and Prejudice: Flavor Physics circa 1989…

- Neutrino mixing out of reach??
- What *is* CP violation? Why is it so small? A new super-weak force??
- The top quark is elusive…..very high mass; does it even exist?
- *If* the top quark exists and is heavy…new high mass particles can compete in virtual loops in flavor changing neutral currents.
- But…B meson's are reconstructed only by the handful. Factories??
- K mesons can be produced in large numbers, but how can we possibly measure the rare $K_L \rightarrow \pi^0\pi^0$ neutral mode decay with sufficient precision to search for direct matter anti-matter asymmetries??

…and in 1989, "sage" advice to Postdocs…

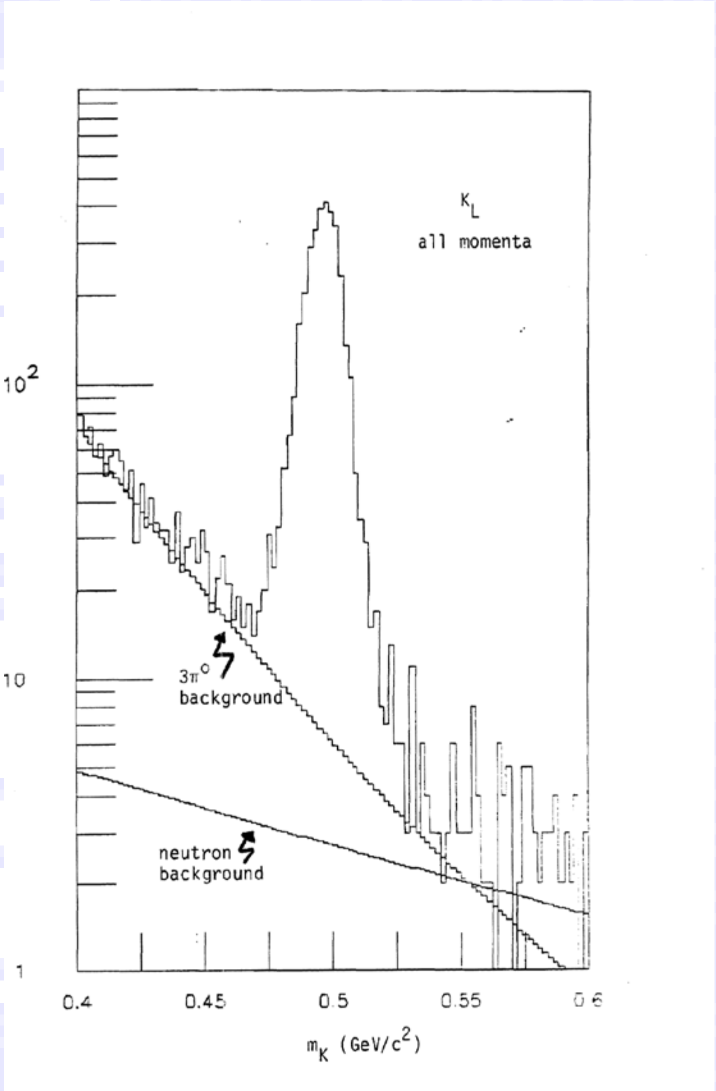
- Neutrinos are boring
- The future is the Superconducting Super Collider
- Cosmology will never move errors from the exponent to the mantissa
- CP-violation will be a rich Garden of Eden in the Quark Sector; with bountiful new physics
- Oh, and don't worry, senior faculty will be retiring soon…

Early Days of the Fermilab Program: The E617 Cauldron of Cronin, Telegdi and Winstein.

U Chicago war room, circa 1980

First Fermilab Crack at Direct* CP Violation with E617

- Introduction of double-beam technique with an alternating regenerator in the beam to serve as a K_S source.
- 400 GeV Main Ring run, 1982
- Aiming for >50,000 $K^0_L \rightarrow 2\pi^0$ events, got 3100 events.
- 6% mass resolution
- 1984 PhD Bernstein.

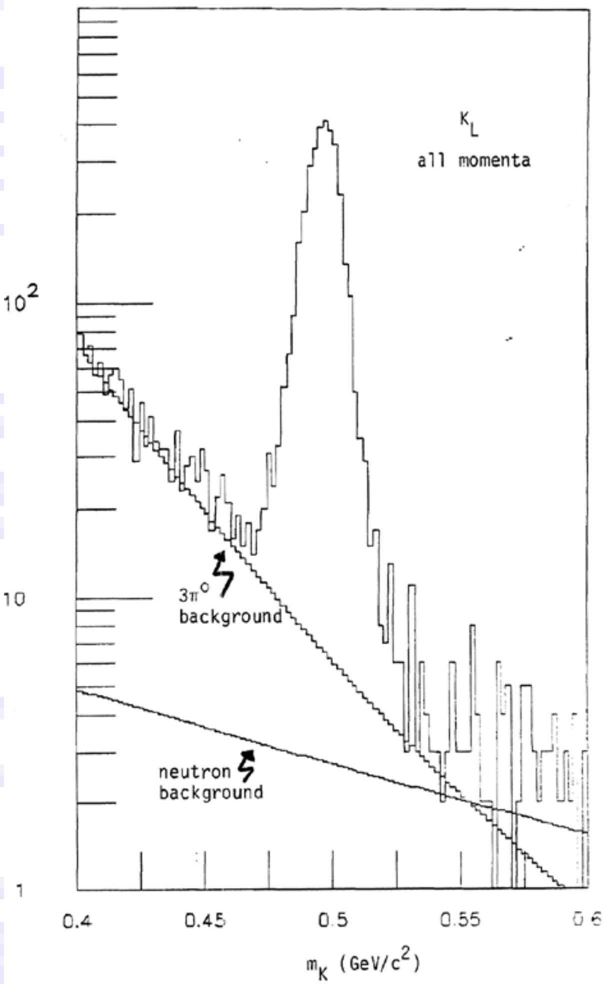


R. H. Bernstein Thesis, 1984

*$Re(\varepsilon'/\varepsilon) = 1/6[\, 1 - \Gamma(K_L \rightarrow \pi^+\pi^- / K_s \rightarrow \pi^+\pi^-)/\Gamma(K_L \rightarrow \pi^0\pi^0 / K_S \rightarrow \pi^0\pi^0)\,]$

First Fermilab Crack at Direct* CP Violation with E617

- Introduction of double-beam technique with an alternating regenerator in the beam to serve as a K_S source.

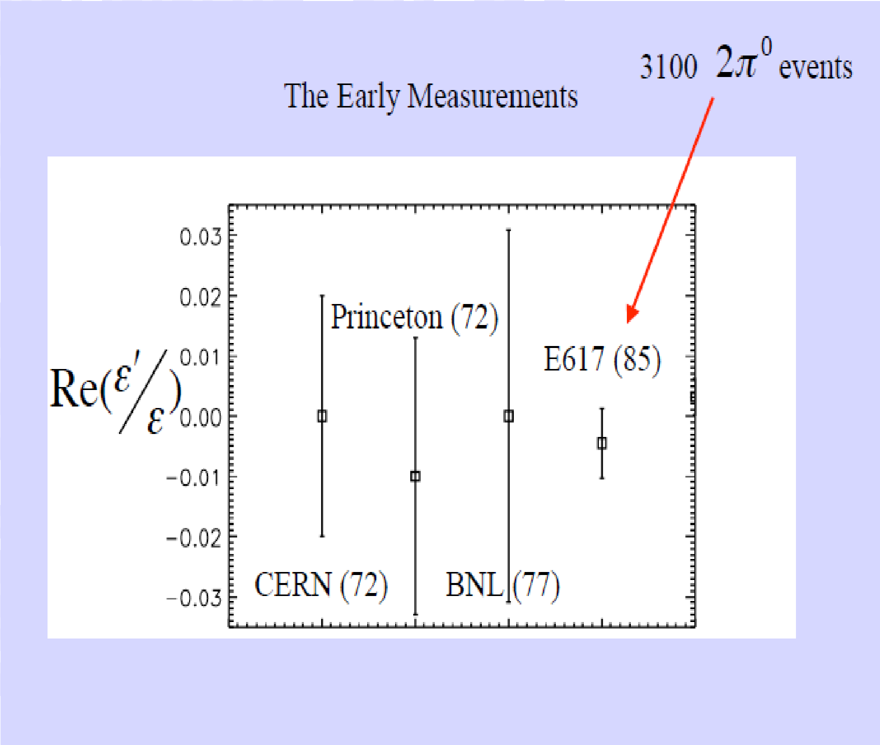


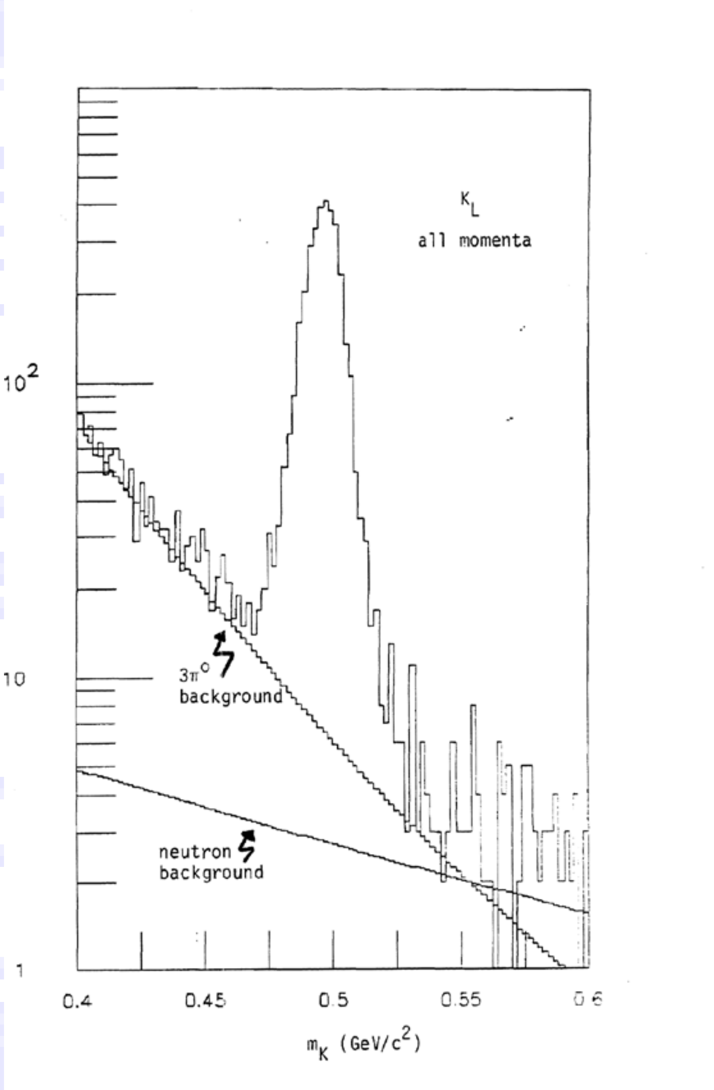
R. H. Bernstein Thesis, 1984

$^*Re(\varepsilon'/\varepsilon) = 1/6[\,1 - \Gamma(K_L\rightarrow\pi^+\pi^-/K_S\rightarrow\pi^+\pi^-)/\Gamma(K_L\rightarrow\pi^0\pi^0/K_S\rightarrow\pi^0\pi^0)\,]$

First Fermilab Crack at Direct* CP Violation with E617

- Introduction of double-beam technique with an alternating regenerator in the beam to serve as a K_S source.



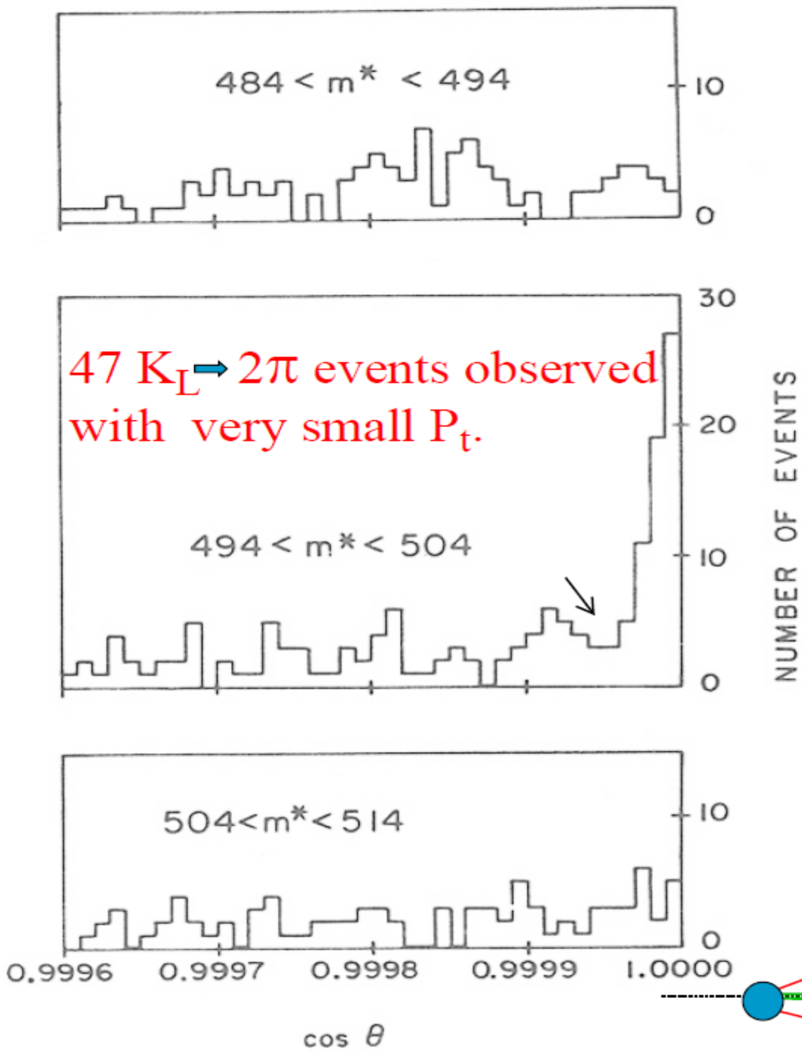


R. H. Bernstein Thesis, 1984

*$Re(\epsilon'/\epsilon) = 1/6[\ 1 - \Gamma(K_L \to \pi^+\pi^-/K_S \to \pi^+\pi^-)/\Gamma(K_L \to \pi^0\pi^0/K_S \to \pi^0\pi^0)\ ]$

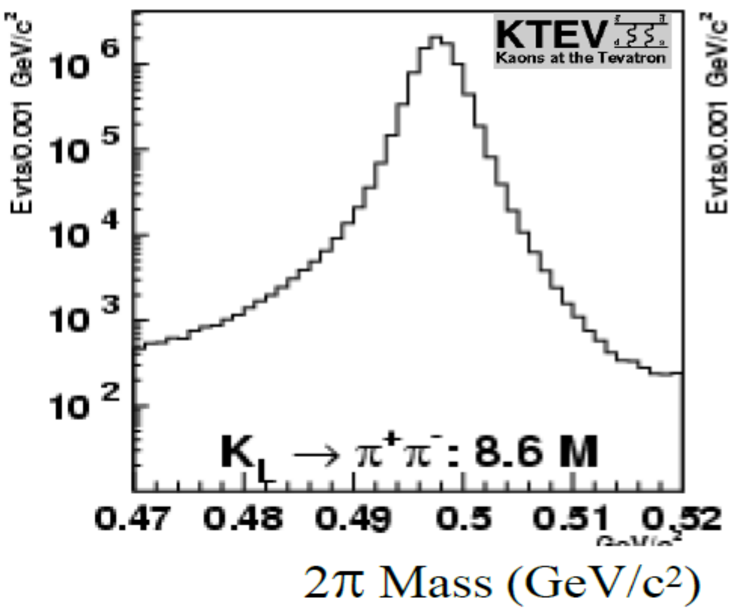
Context of E617…half-way between 1964 and 2004

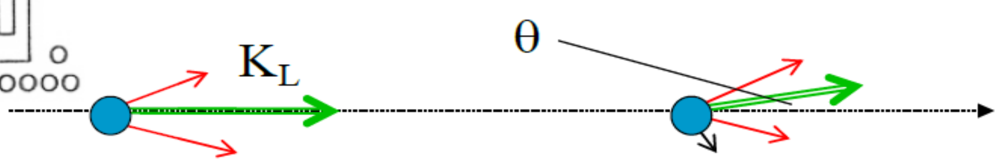
1964



~2004

~20 Million CP $K_L \rightarrow 2\pi$ Observed by the KTeV Experiment.





Kaons at the TeVatron

- The KTeV experiment was primarily a comprehensive study of neutral kaon decays, data collected 1995-2005.

- The research program yielded 32 PhD theses and 50 physics publications, most notably the establishment of matter/antimatter asymmetry in particle decay amplitudes.

- This rich research program was largely driven by intense beams of in-flight neutral kaon decays reconstructed with a high-speed , high-resolution spectrometer.

Helen T. Edwards
May 27,1936 - June 21, 2016

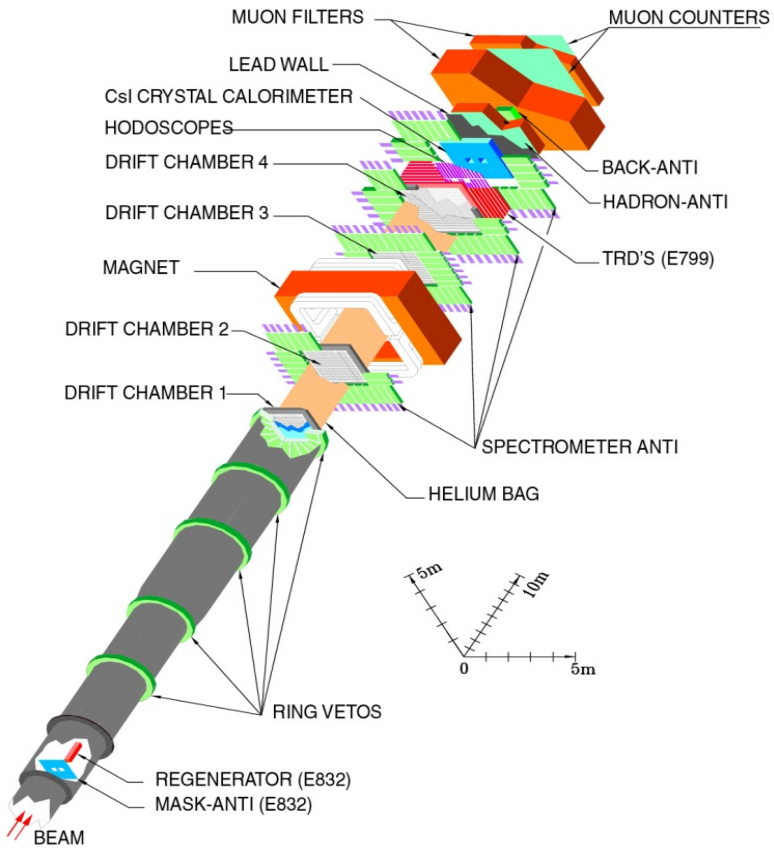
KTeV was the culimanation of the high-energy in-flight program at Fermilab

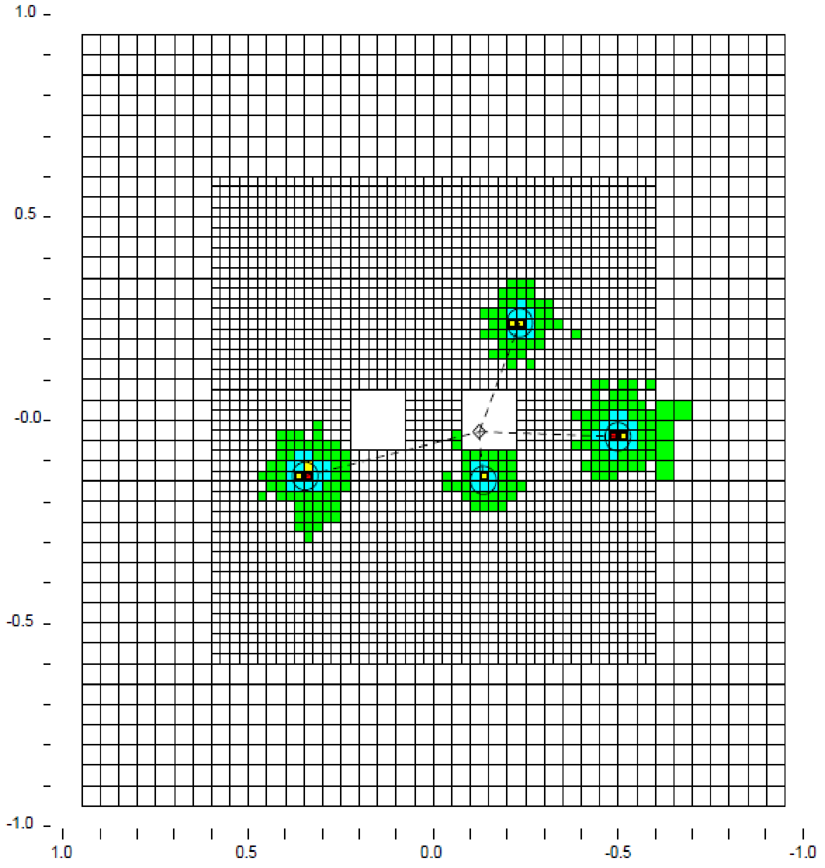
University of Chicago Group, circa 1997

Enabling Collaboration!

1996 KTeV Collaboration meeting at the University of Arizona.
75 collaborators, 32 PhD students, 50 science publications.

Unprecedented photon calorimetry and Trigger & DAQ

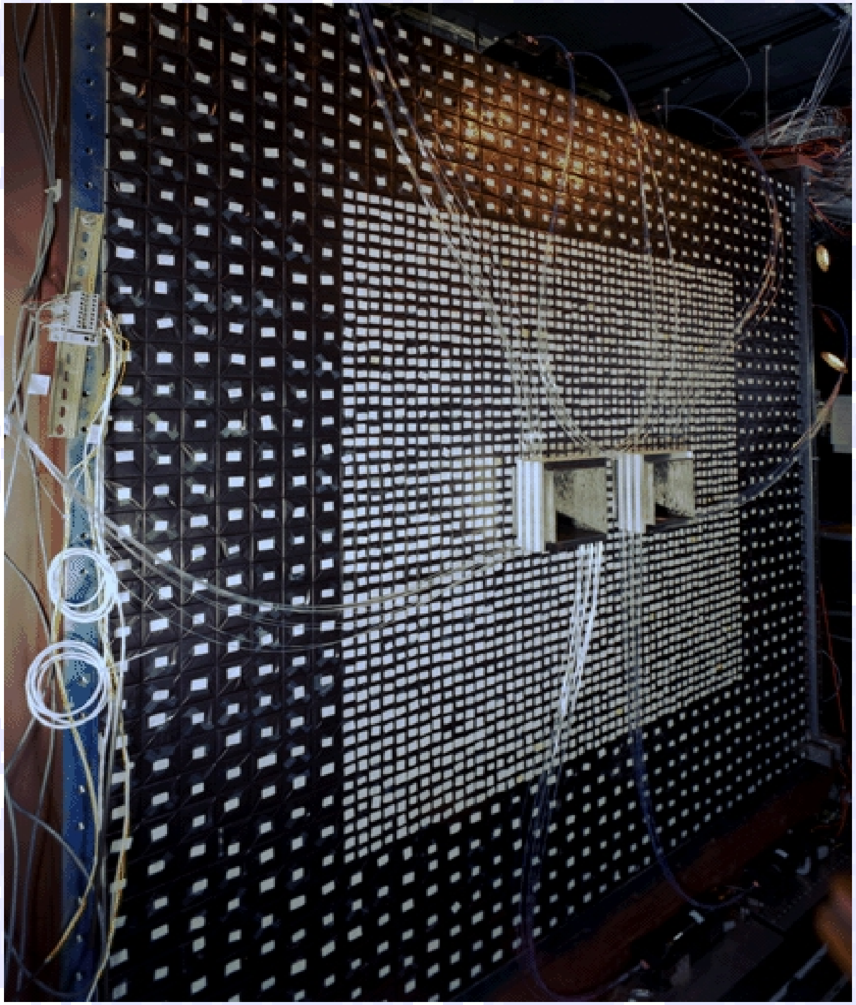




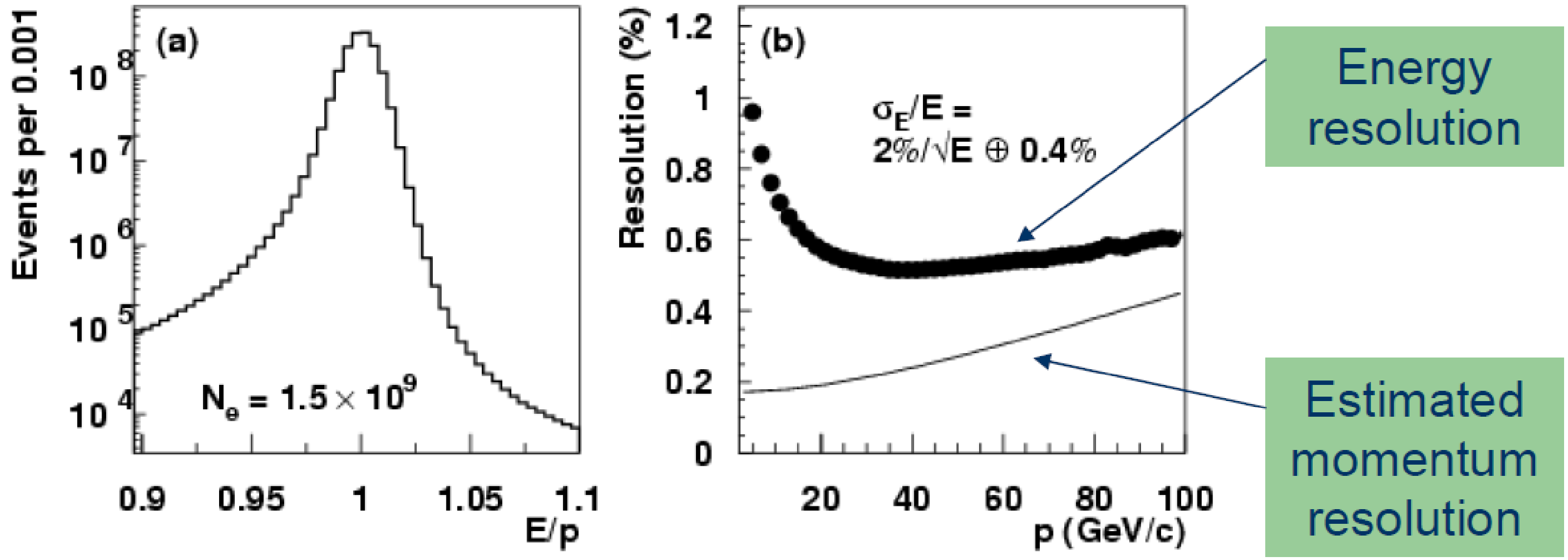
Beam view of $K^0 \rightarrow \pi^0 \pi^0$ in CsI calorimeter

KTeV Pure CsI Calorimeter

- 3100 crystals, 1.9mx1.9m
- 27 X_0 deep (50cm)
- 90% of light has 20-nsec component
- Pioneering application of the “QIE” pipelined charge integrating encoder broadly used in the field.

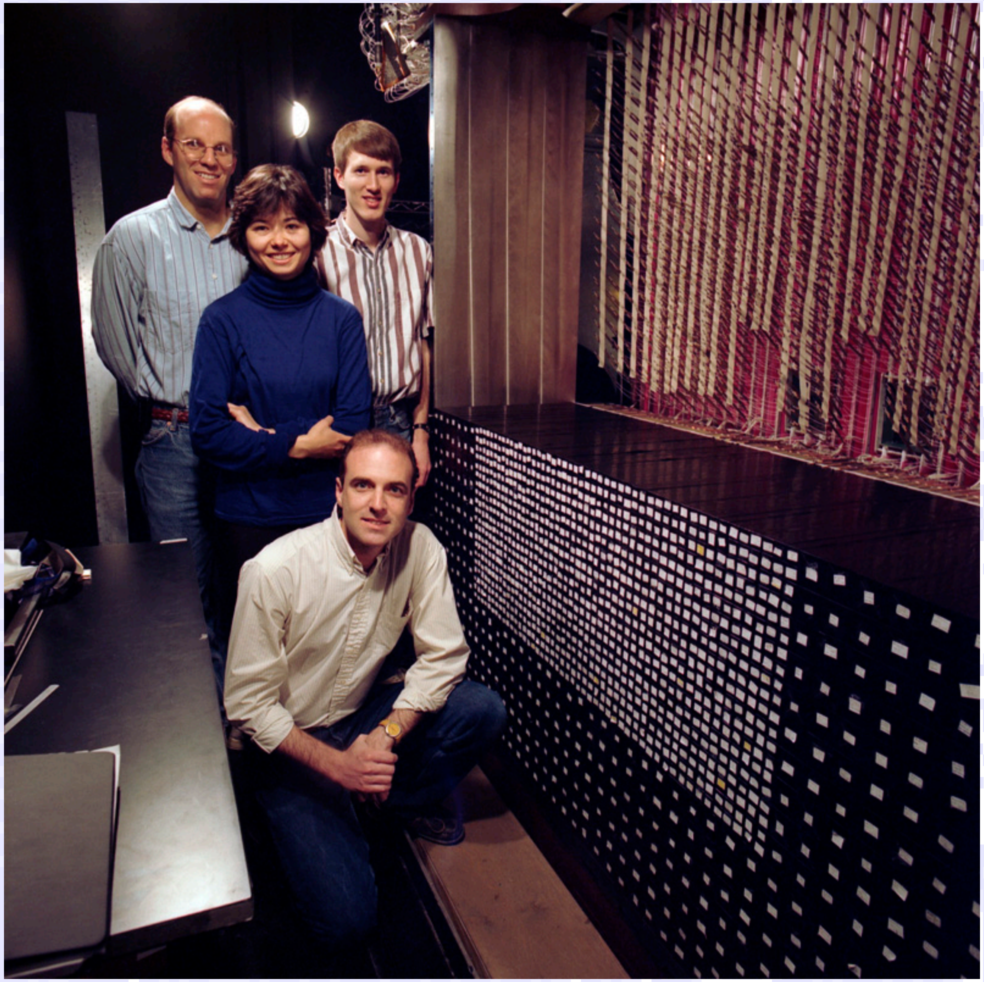


Delivered EM-calorimetry performance better than 1% resolution over full physics energy range: *Best in the field*

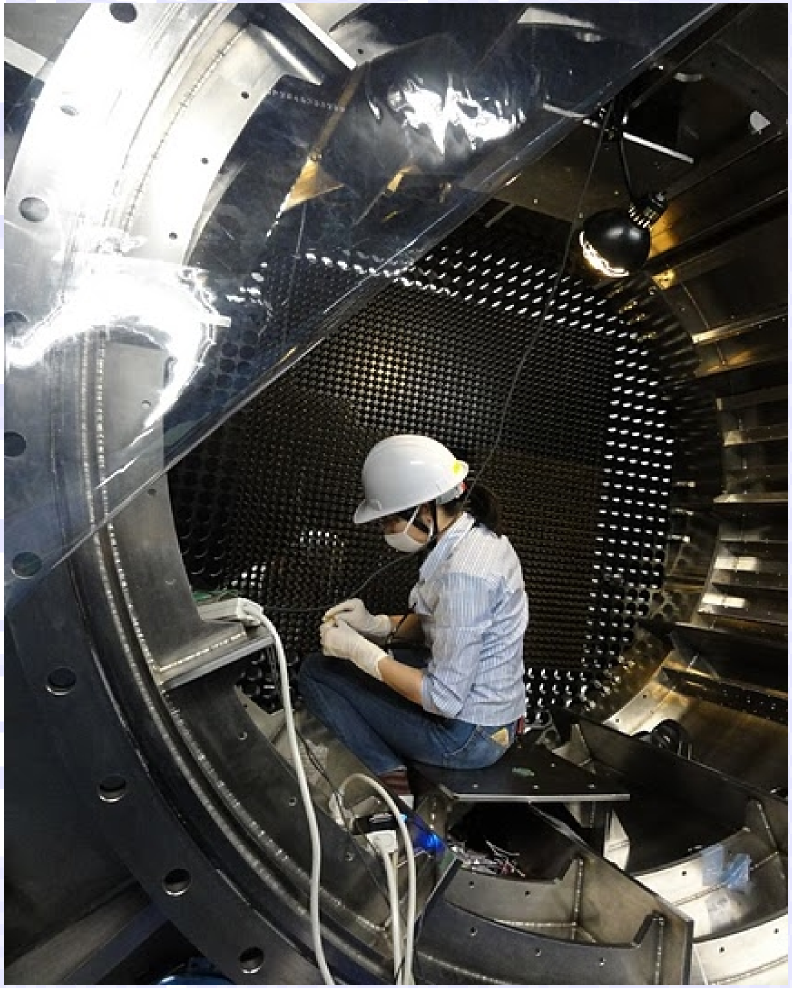


- Calibration based on 1.5 billion Ke3 electrons
- Final E/p resolution after all corrections: ~0.6%

KTeV CsI Crystals and PMTs continuing great science in the JPARC KOTO $K_L \rightarrow \pi^0 \nu \bar{\nu}$ adventure

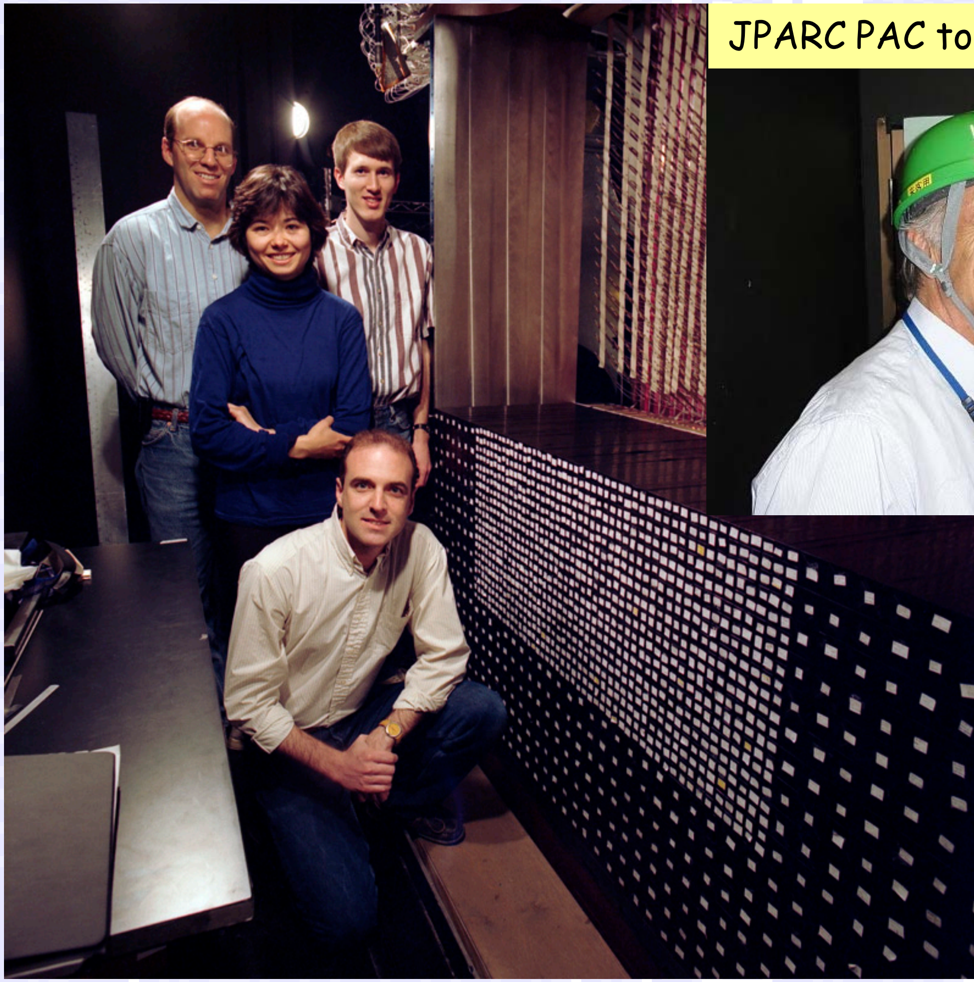


KTeV Calorimeter assembly

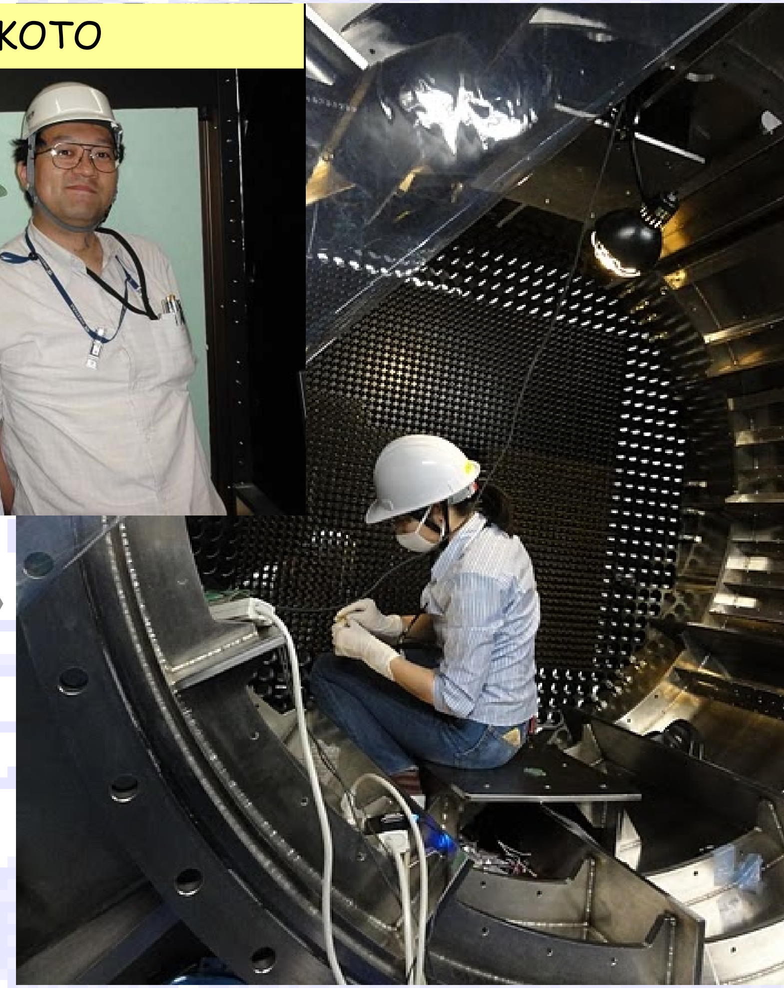


KOTO Calorimeter assembly

KTeV CsI Crystals and PMTs continuing great science in the JPARC KOTO $K_L \to \pi^0 \nu\bar{\nu}$ adventure



JPARC PAC tour of KOTO



KTeV Calorimeter assembly

KOTO Calorimeter assembly

KOTO experiment

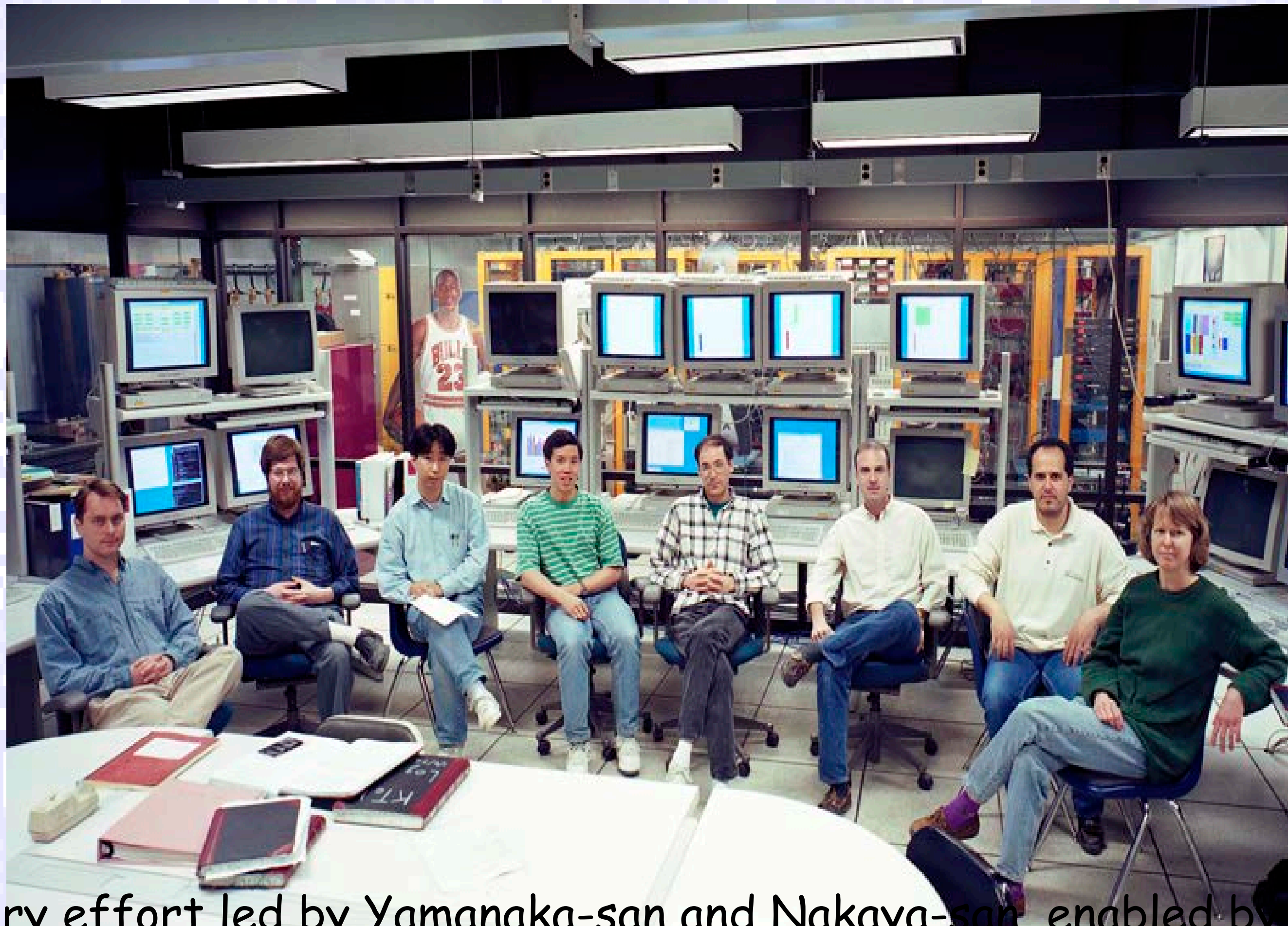
- KOTO (J-PARC E14)

  to search for new physics beyond the SM

  with the decay $K_L \to \pi^0 \nu \bar{\nu}$
- KOTO collaboration Japan-Korea-Russia-Taiwan-US

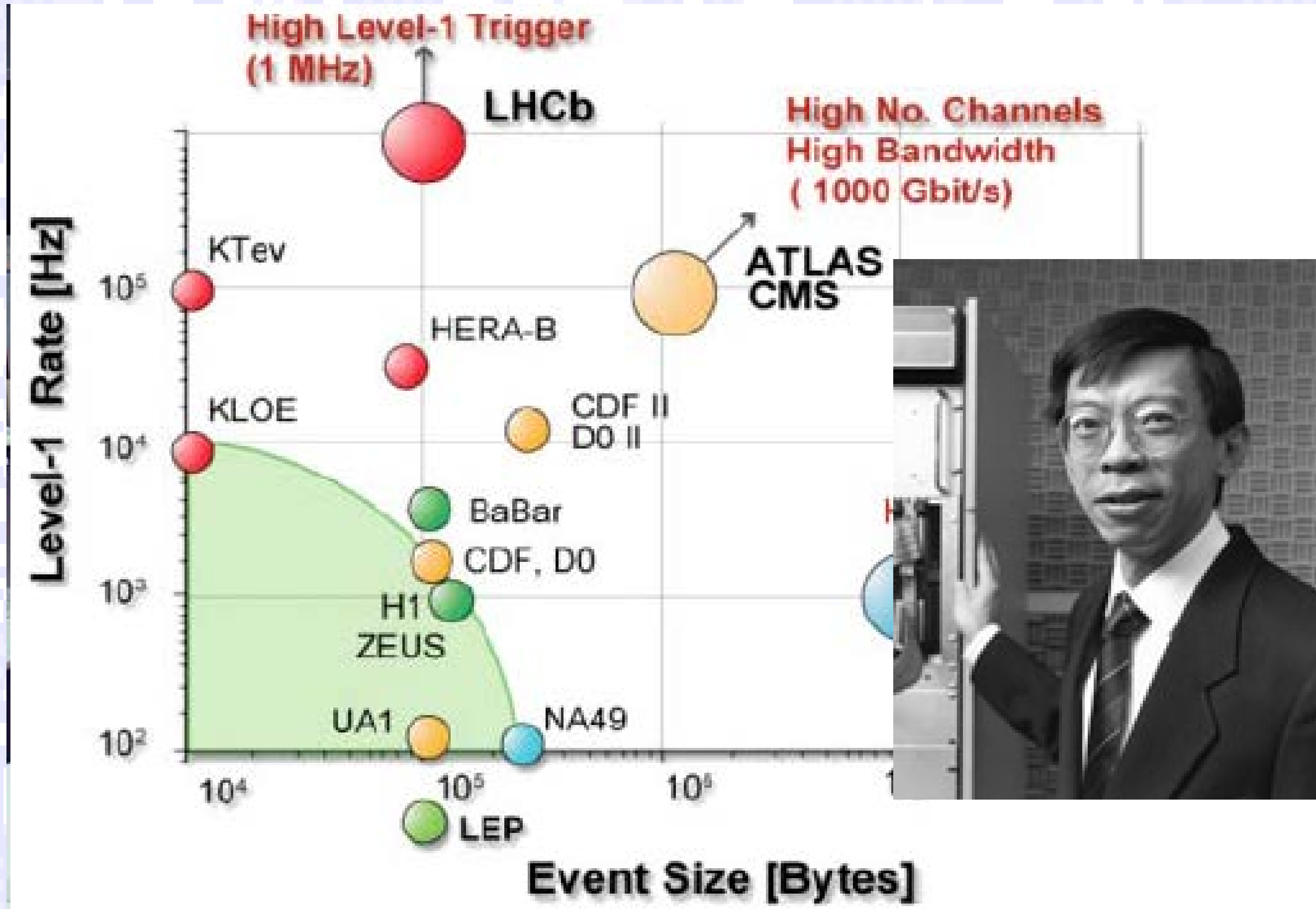
Nanjo-san, JPARC PAC, July 2015, Tokai

KTeV was the first major experiment to *filter out most* events online based on *full reconstruction of events in software…now standard of the field*



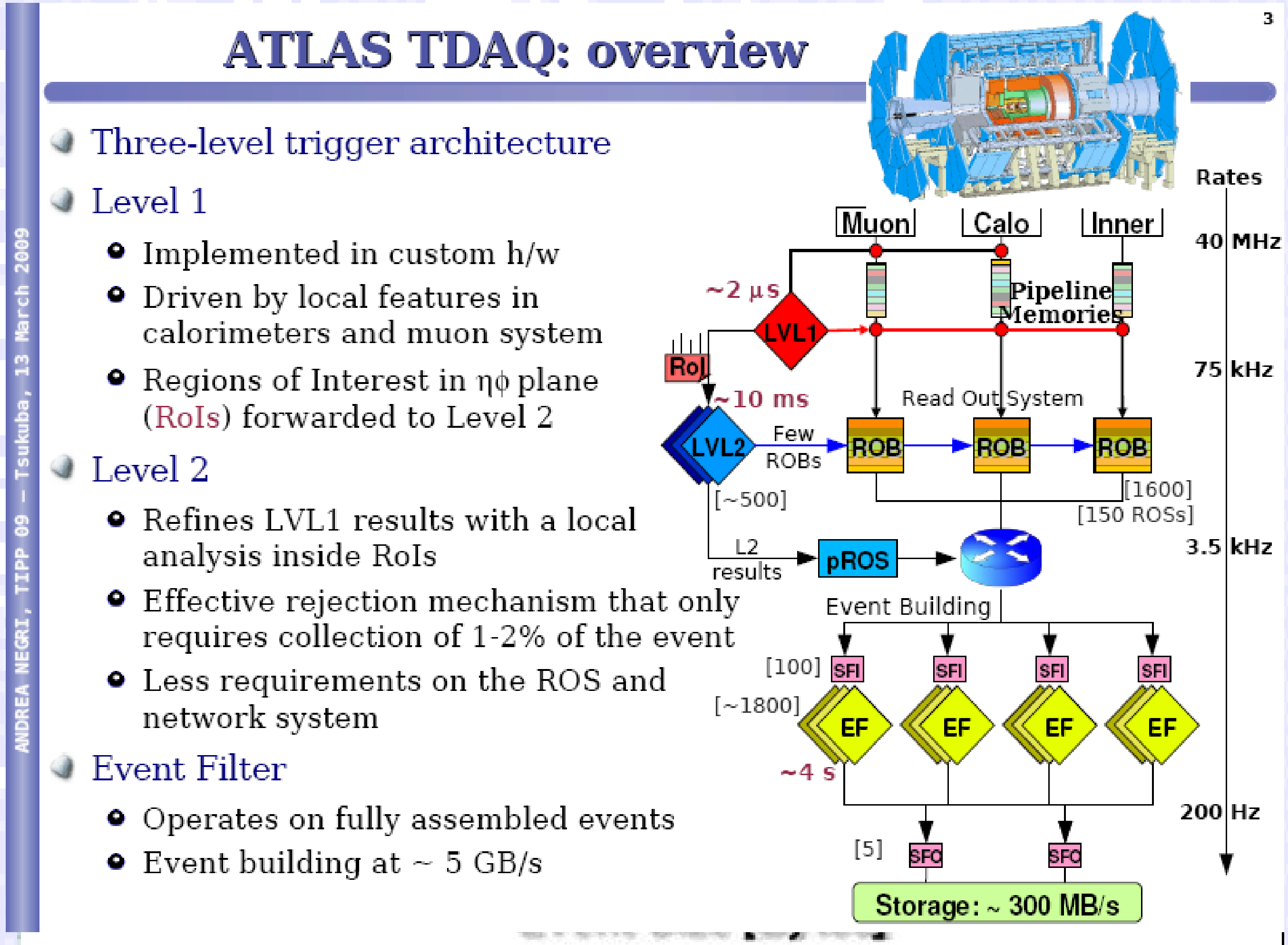
Level-3 Visionary effort led by Yamanaka-san and Nakaya-san, enabled by the Level-2 muscle provided by Yah Wah and colleagues.

KTeV was the first major experiment to *filter out most* events online based on *full reconstruction of events in software…now standard of the field*



Level-3 Visionary effort led by Yamanaka-san and Nakaya-san, enabled by the Level-2 muscle provided by Yah Wah and colleagues.

KTeV was the first major experiment to *filter out most* events online based on *full reconstruction of events in software…now standard of the field*



Level-3 Visionary effort led by Yamanaka-san and Nakaya-san, enabled by the Level-2 muscle provided by Yah Wah and colleagues.

Yamanaka and Wah opening the door to new rare decay physics….

Yamanaka-san near the summit of Mauna Kea; Oct 2010.

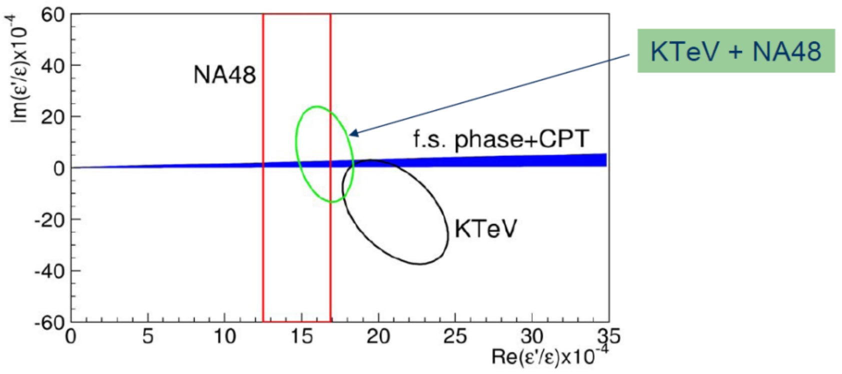
Highlights of KTeV Science…

- Re(ε'/ε) = (1.66 ± 0.26)×10^-3*

$$\Rightarrow \frac{\Gamma(K^0\to\pi^+\pi^-) - \Gamma(\overline{K}^0\to\pi^+\pi^-)}{\Gamma(K^0\to\pi^+\pi^-) + \Gamma(\overline{K}^0\to\pi^+\pi^-)} = (5.04 \pm 0.22) \times 10^{-6}\ {}^{**}$$

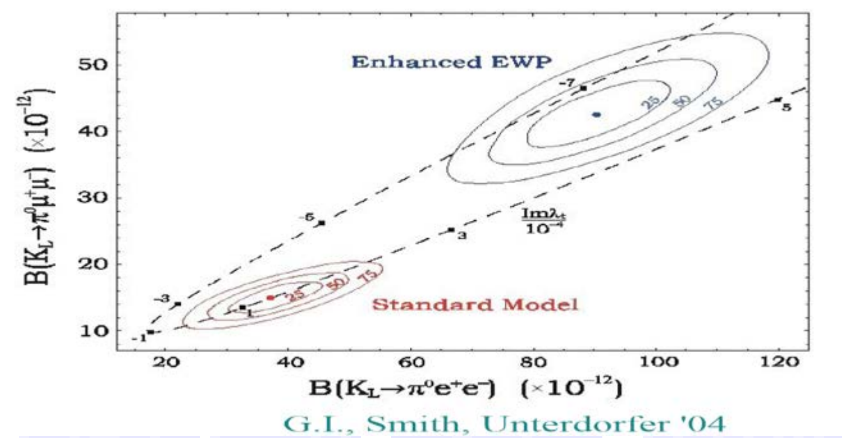
Matter/Antimatter asymmetry in a decay amplitude established, Superweak model excluded.

Large component of this asymmetry might arise from New Physics.



- $K_L \to \pi^0 ee, \pi^0\mu\mu$

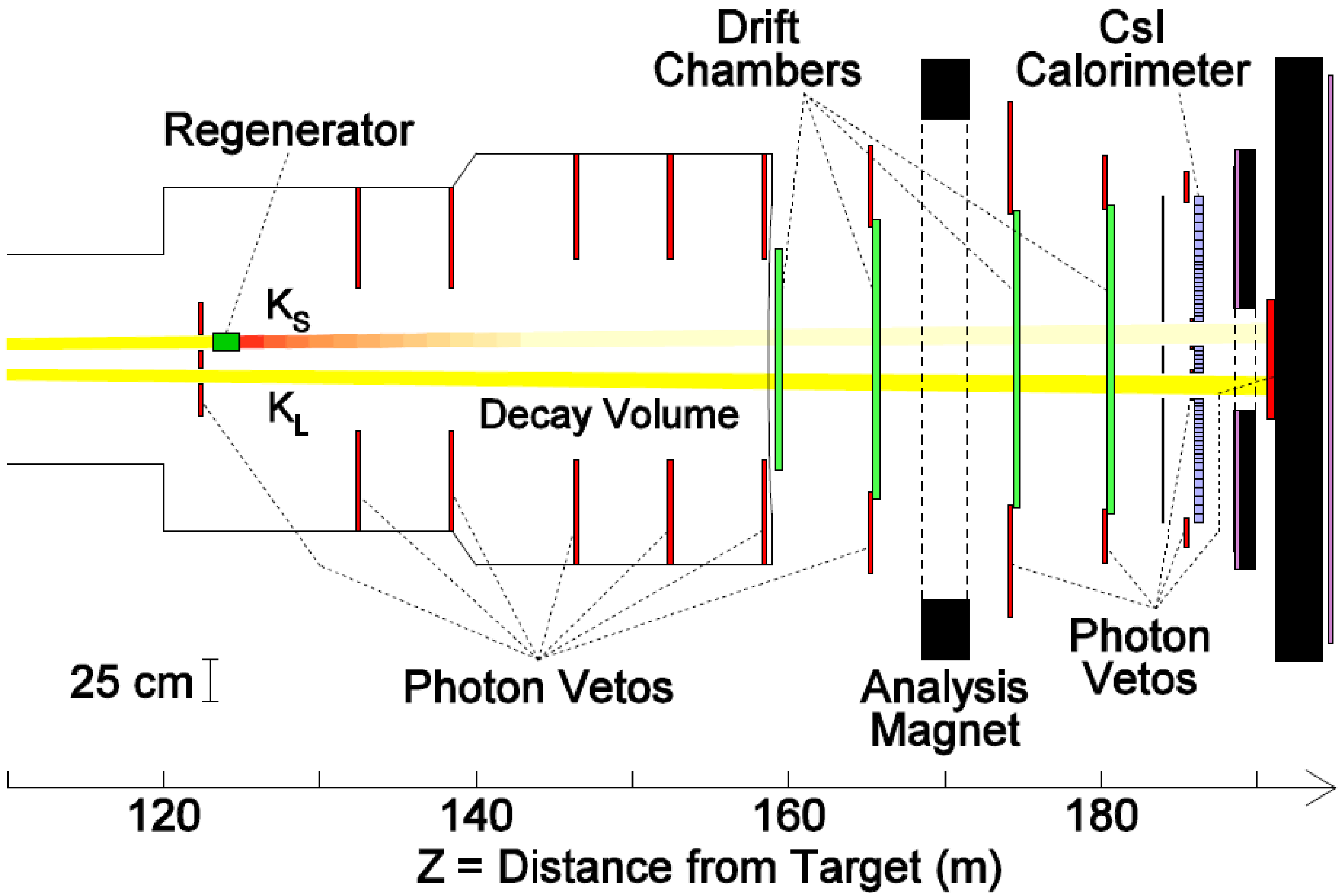
KTeV limited these rates to x8 and x25 the Standard model rates (10^{-11} level) for the ee and μμ modes…. fertile hunting ground for new physics models.



* PDG, **J Imazoto

KTeV Experiment: K_S beam made from an incident K_L beam.

KTEV
Kaons at the Tevatron



K_L Beam passes through 2m of plastic scintillator, which induces a ~3% *coherent* K_S component in the downstream amplitude.

$$K_{Down} = K_L + \rho K_S$$

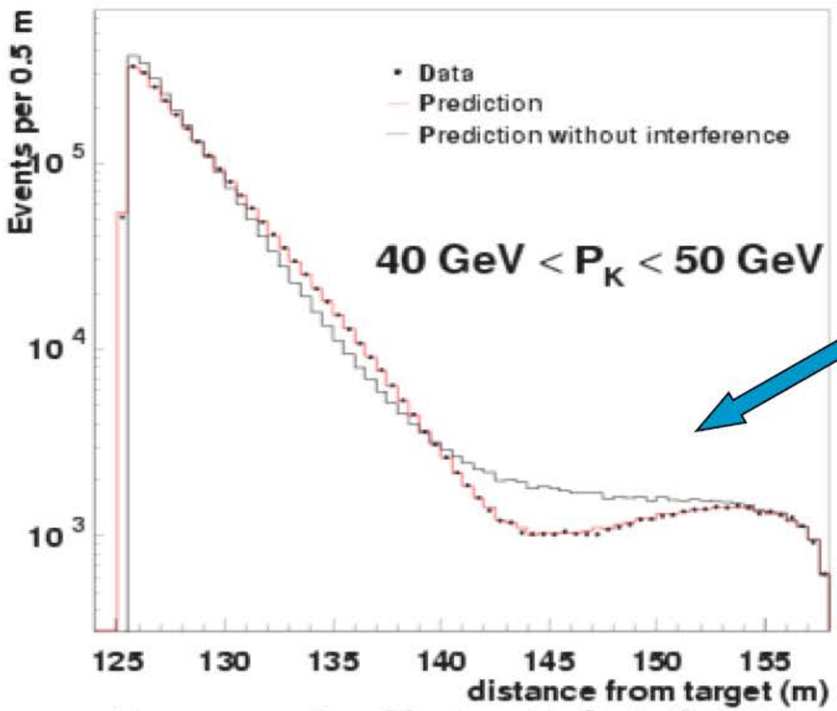
K_L and K_S in the Regenerator Beam.

KTEV Kaons at the Tevatron

The regenerator beam is a coherent super-position of K_S and K_L. Must account for K_L component to extract correct value of $\mathrm{Re}(\epsilon'/\epsilon)$.

K_{Reg} shape depends on:

- τ_S, Δm, ϕ_η.
- Attenuation in the regenerator.

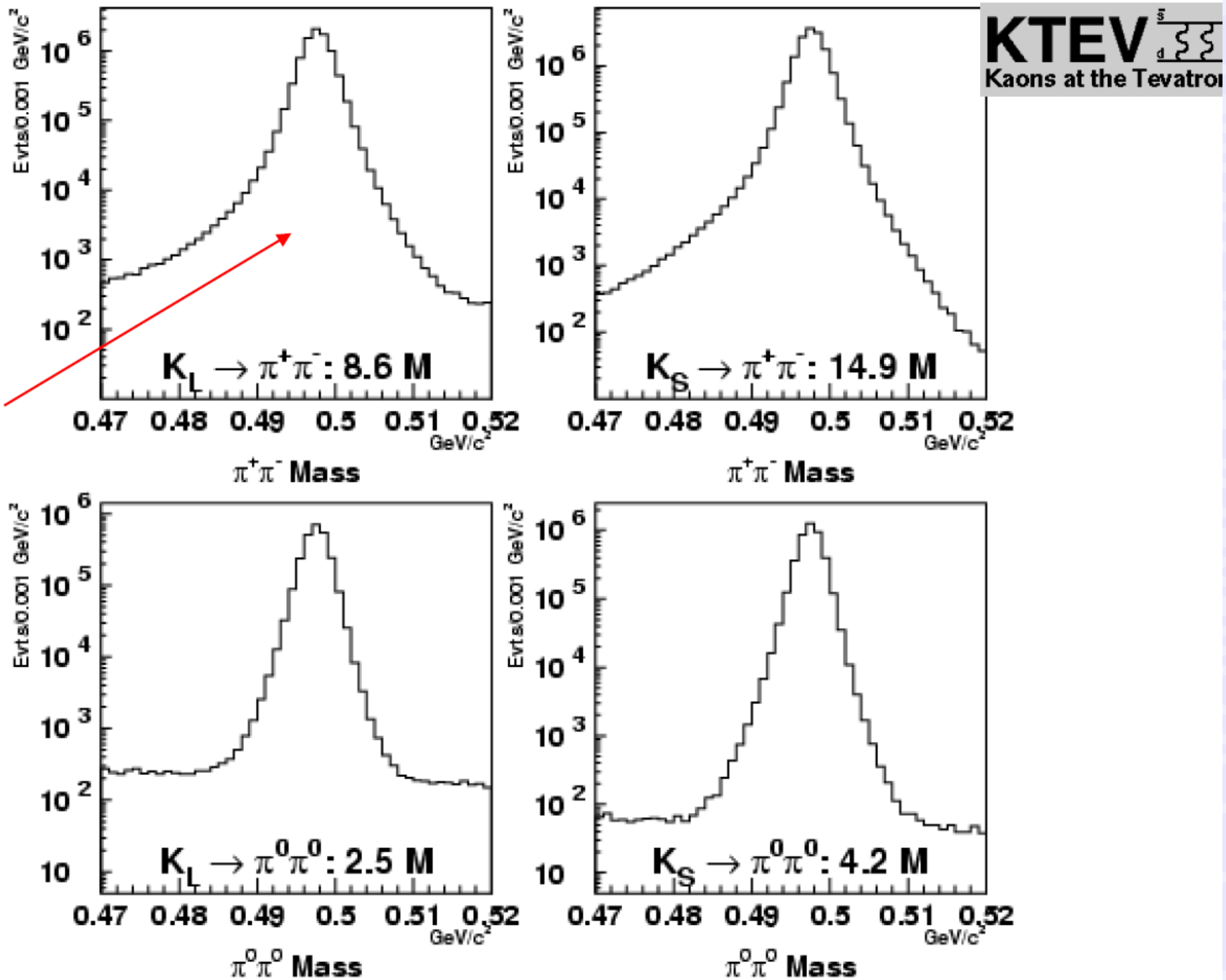


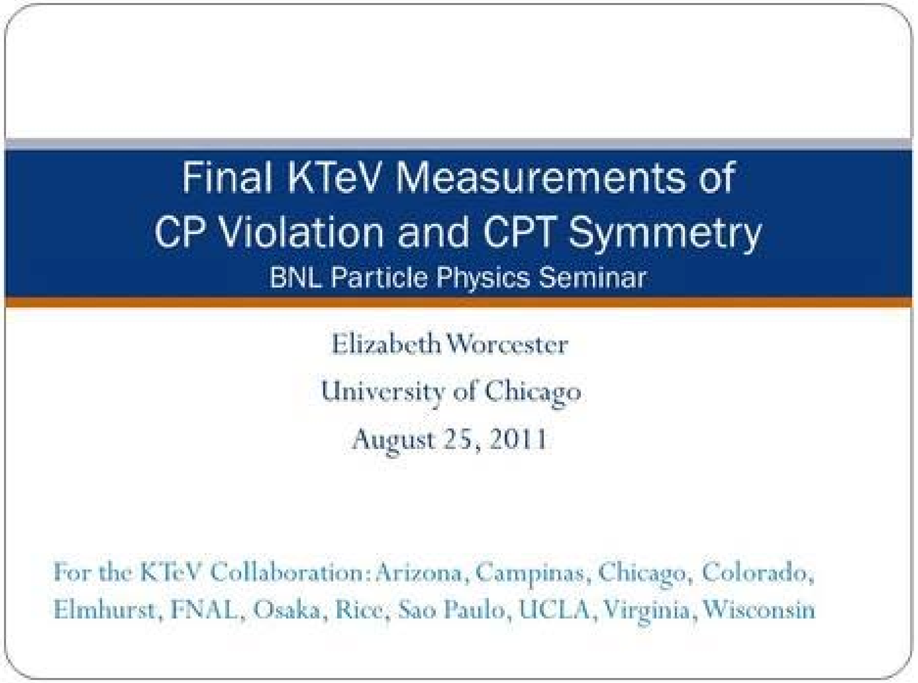
Regenerator Vertex Z distribution

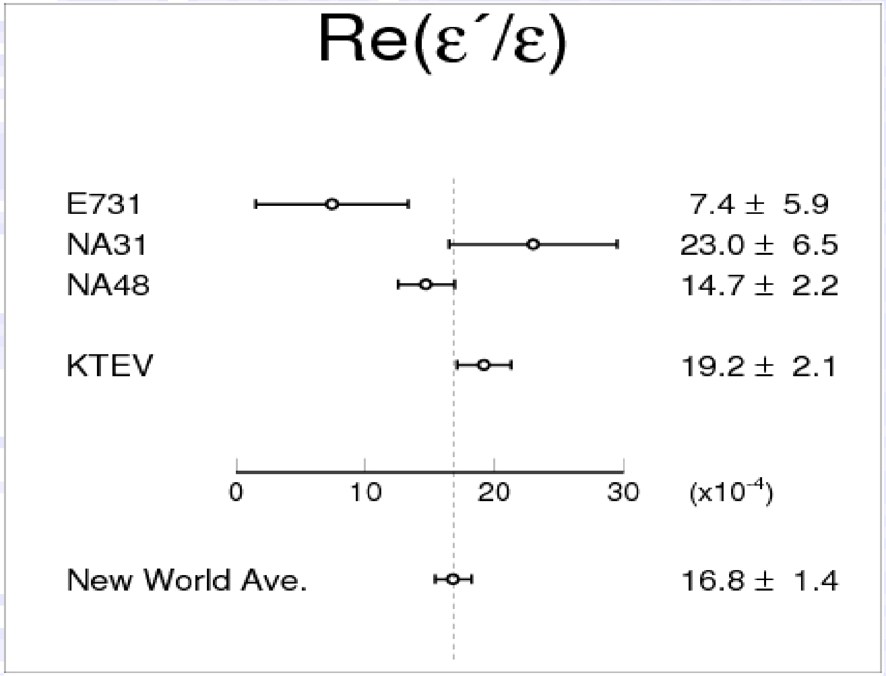
Quantum coherence over 30m!

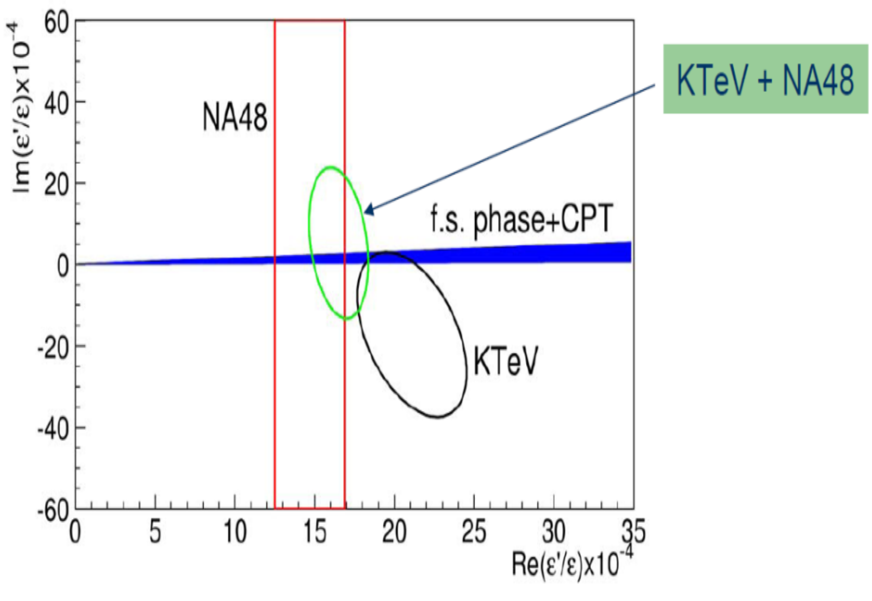
Raw $K^0 \rightarrow \pi\pi$ Statistics: $\sigma(\varepsilon'/\varepsilon) = 1.7\text{x}10^{-4}$

CPV first found with 47 $K_L \rightarrow \pi^+\pi^-$ events!









Phys. Rev. D 83, 092001 (2011).

Epsilon-Prime* Strikes Back!

Is new physics hiding in plain sight?? Renewed prospects of a precise determination of Re (ε'/ε)* in the Standard Model.

*Re (ε'/ε) = 1/6[1 - $\Gamma(K_L \to \pi^+\pi^- / K_S \to \pi^+\pi^-) / \Gamma(K_L \to \pi^0\pi^0 / K_S \to \pi^0\pi^0)$]

Epsilon-Prime* Strikes Back!

Is new physics hiding in plain sight?? Renewed prospects of a precise determination of Re (ε'/ε)* in the Standard Model.

*Re (ε'/ε) = 1/6[1 - $\Gamma(K_L \rightarrow \pi^+\pi^- / K_s \rightarrow \pi^+\pi^-)/\Gamma(K_L \rightarrow \pi^0\pi^0 / K_S \rightarrow \pi^0\pi^0)$]

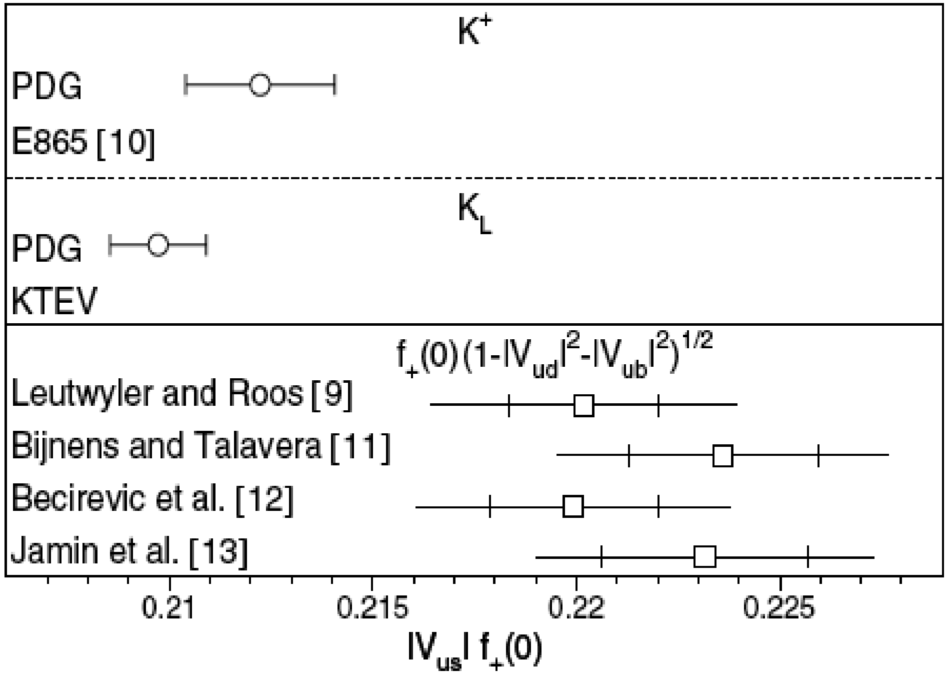
Epsilon-Prime* Strikes Back!

Is new physics hiding in plain sight?? Renewed prospects of a precise determination of Re (ε'/ε)* in the Standard Model.

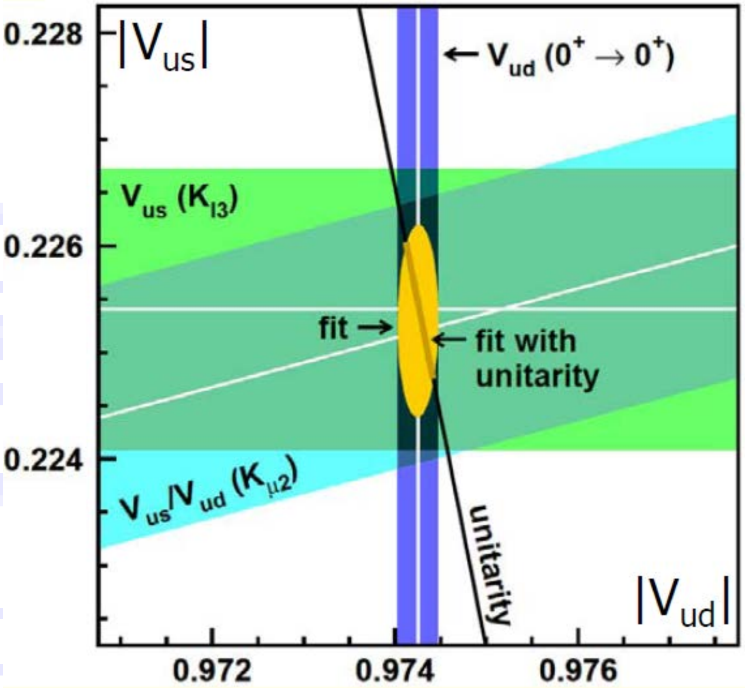
*Re $(\varepsilon'/\varepsilon) = 1/6[\ 1 - \Gamma(K_L\rightarrow\pi^+\pi^-/K_s\rightarrow\pi^+\pi^-)/\Gamma(K_L\rightarrow\pi^0\pi^0/K_S\rightarrow\pi^0\pi^0)\ ]$

Serendipity: Resolution of the $V_{ud}/V_{us}/V_{ub}$ non-Unitarity tension by precision measurement of $K_L \rightarrow \pi e \nu$ decays.

2004: $|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2 < 1$??



2010: KTeV,BNL-865,NA48,KLOE

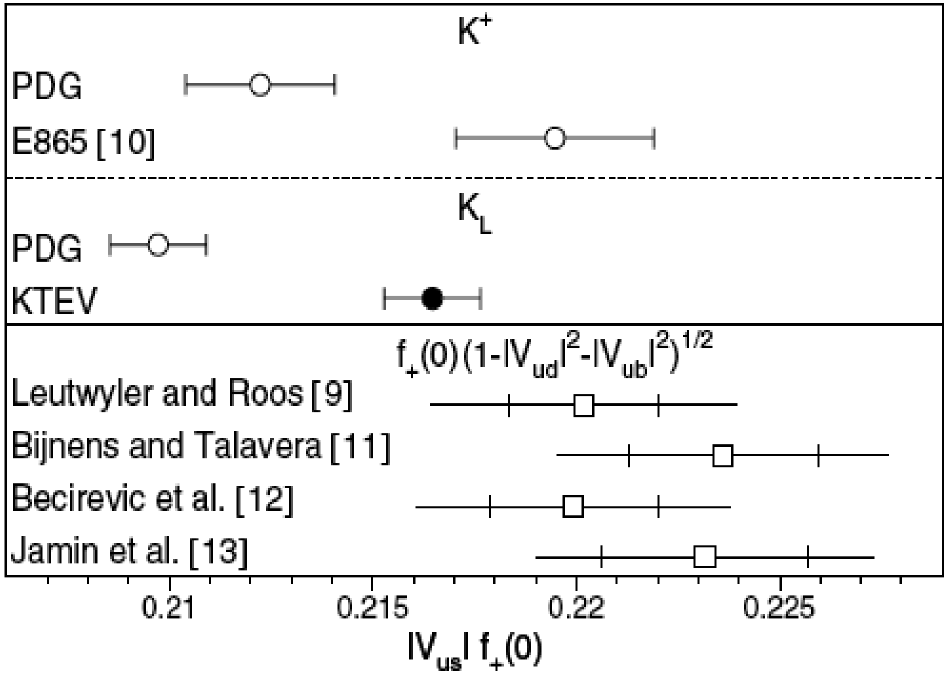


Enrico Lunghi, LME-2010, Fermilab

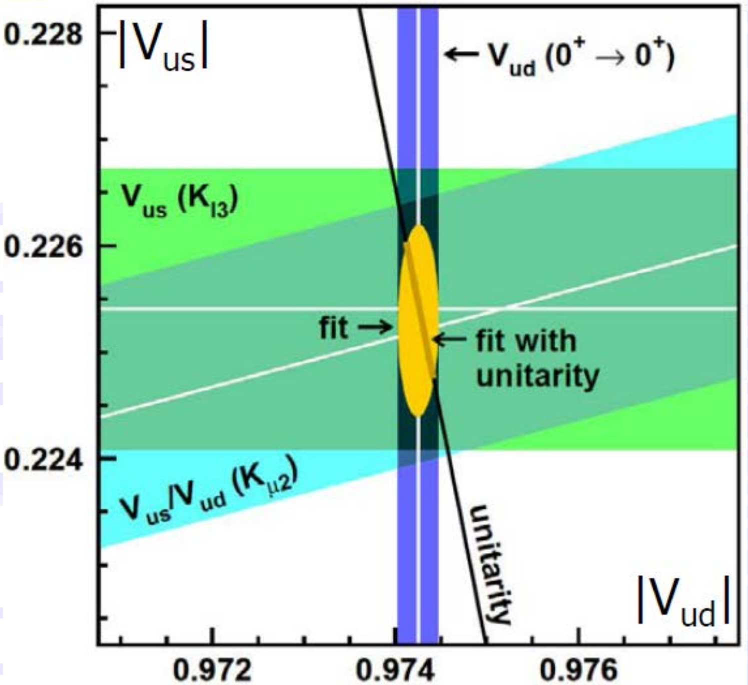
New Physics models squeezed out beyond the 5 TeV scale

Serendipity: Resolution of the $V_{ud}/V_{us}/V_{ub}$ non-Unitarity tension by precision measurement of $K_L \rightarrow \pi e \nu$ decays.

2004: $|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2 < 1$??



2010: KTeV,BNL-865,NA48,KLOE

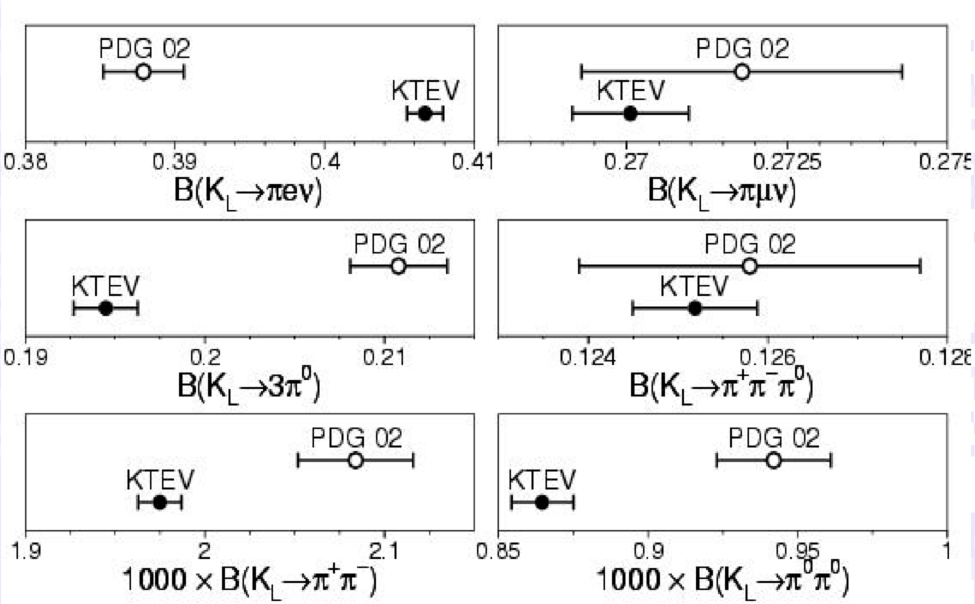


Enrico Lunghi, LME-2010, Fermilab

New Physics models squeezed out beyond the 5 TeV scale

KTeV and BNL-865 Resolve the Unitarity Tension of the CKM matrix,

followed by important contributions from NA48@CERN and KLOE@Frascati



Phys. Rev. D 70, 092006 (2004).

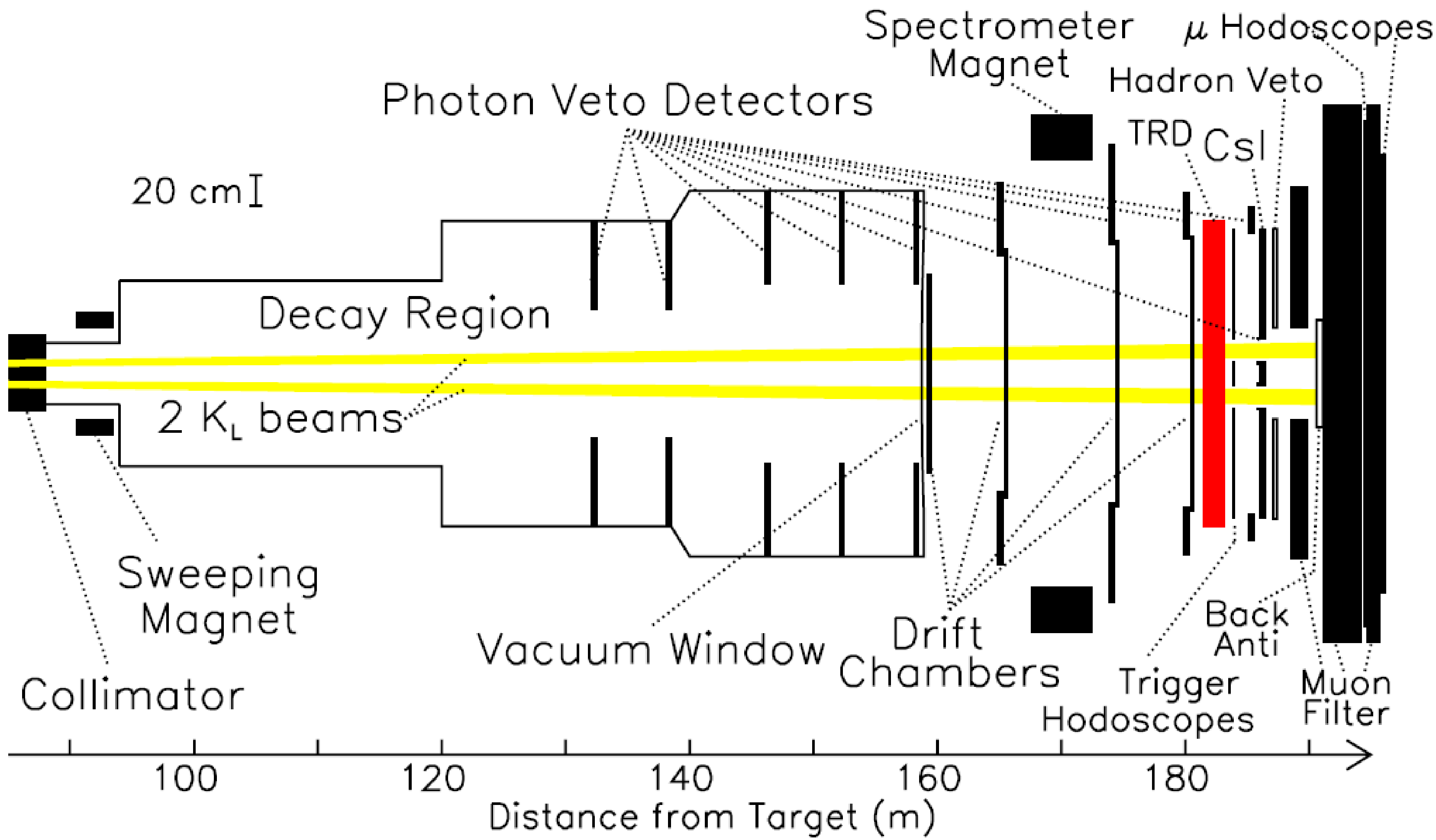
R. Kessler ,E. Blucher, S. Glazov,
University of Chicago

KTeV Rare Decay Program (★); Manifest in the PSI Littenberg Summer School Lectures August 18th-24th 2002

TABLE 1. *Rare K decay modes under recent or on-going study.*

$K^+ \to \pi^+ \nu\bar{\nu}$	★ $K_L \to \pi^0 \nu\bar{\nu}$	★ $K_L \to \pi^0 \mu^+ \mu^-$	★ $K_L \to \pi^0 e^+ e^-$
$K^+ \to \pi^+ \mu^+ \mu^-$	$K^+ \to \pi^+ e^+ e^-$	$K_L \to \mu^+ \mu^-$	$K_L \to e^+ e^-$
$K^+ \to \pi^+ e^+ e^- \gamma$	$K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$	★ $K_L \to e^\pm e^\mp \mu^\pm \mu^\mp$	$K^+ \to \pi^+ \pi^0 \gamma$
★ $K_L \to \pi^+ \pi^- \gamma$	★ $K_L \to \pi^+ \pi^- e^+ e^-$	$K^+ \to \pi^+ \pi^0 e^+ e^-$	$K^+ \to \pi^0 \mu^+ \nu \gamma$
★ $K_L \to \pi^0 \gamma\gamma$	$K^+ \to \pi^+ \gamma\gamma$	$K^+ \to \mu^+ \nu \gamma$	$K^+ \to e^+ \nu e^+ e^-$
$K^+ \to \mu^+ \nu e^+ e^-$	$K^+ \to e^+ \nu \mu^+ \mu^-$	★ $K_L \to e^+ e^- \gamma$	★ $K_L \to \mu^+ \mu^- \gamma$
★ $K_L \to e^+ e^- \gamma\gamma$	★ $K_L \to \mu^+ \mu^- \gamma\gamma$	★ $K_L \to e^+ e^- e^+ e^-$	★ $K_L \to \pi^0 e^+ e^- \gamma$
$K^+ \to \pi^+ \mu^+ e^-$	★ $K_L \to \pi^0 \mu^\pm e^\mp$	$K_L \to \mu^\pm e^\mp$	$K^+ \to \pi^- \mu^+ e^+$
$K^+ \to \pi^- e^+ e^+$	$K^+ \to \pi^- \mu^+ \mu^+$	$K^+ \to \pi^+ X^0$	★ $K_L \to e^\pm e^\pm \mu^\mp \mu^\mp$
$K^+ \to \pi^+ \gamma$	★ $K_L \to \pi^0 \pi^0 e^+ e^-$		
$\pi^+ \to \pi^0 e^+ \nu_e$	$\pi^+ \to e^+ \nu_e$	$\pi^+ \to e^+ \nu_e \gamma$	$\pi^+ \to e^+ \nu_e e^+ e^-$
$\pi^+ \to e^+ \nu_e \nu\bar{\nu}$	★ $\pi^0 \to e^+ e^-$	★ $\pi^0 \to e^+ e^- e^+ e^-$	$\pi^0 \to \nu\bar{\nu}$
$\pi^0 \to \gamma \nu\bar{\nu}$	$\pi^0 \to 3\gamma$	★ $\pi^0 \to \mu e$	

KTeV Detector in the Rare-Decay Configuration



Designed for State-of-the-Art Sensitivity to $K^0_L \to \pi^0 ee$ and $K^0_L \to \pi^0 \mu\mu$

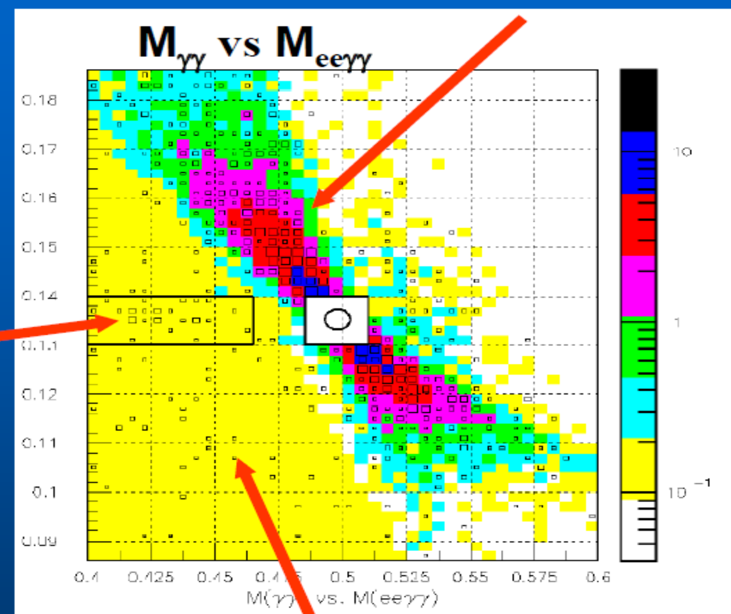
Backgrounds for $K_L \to \pi^0 e^+ e^-$

- Other backgrounds come from a kaon decay modes such as $K_L \to \pi^0\pi^0\pi^0_D$.
- The most significant and dangerous background comes from $K_L \to ee\gamma\gamma$ decays.

$K_L \to \pi^0\pi^0\pi^0_D$,

$\pi^{\pm}e^{\mp}\nu + \pi^0_{ACC}$

$K_L \to ee\gamma\gamma$



$K_L \to \pi^0\pi^0\pi^0$, $\pi^{\pm}e^{\mp}\gamma\nu + \gamma_{ACC}$

$e^+\gamma X$

$e^- X$

γX

- The normalization mode is $K_L \to \pi^0\pi^0_D$

June 26th 2003 R. Tschirhart

From Kaon-2013 Littenberg Presentation

Phys. Rev. Lett. 84, 5279-5282 (2000).

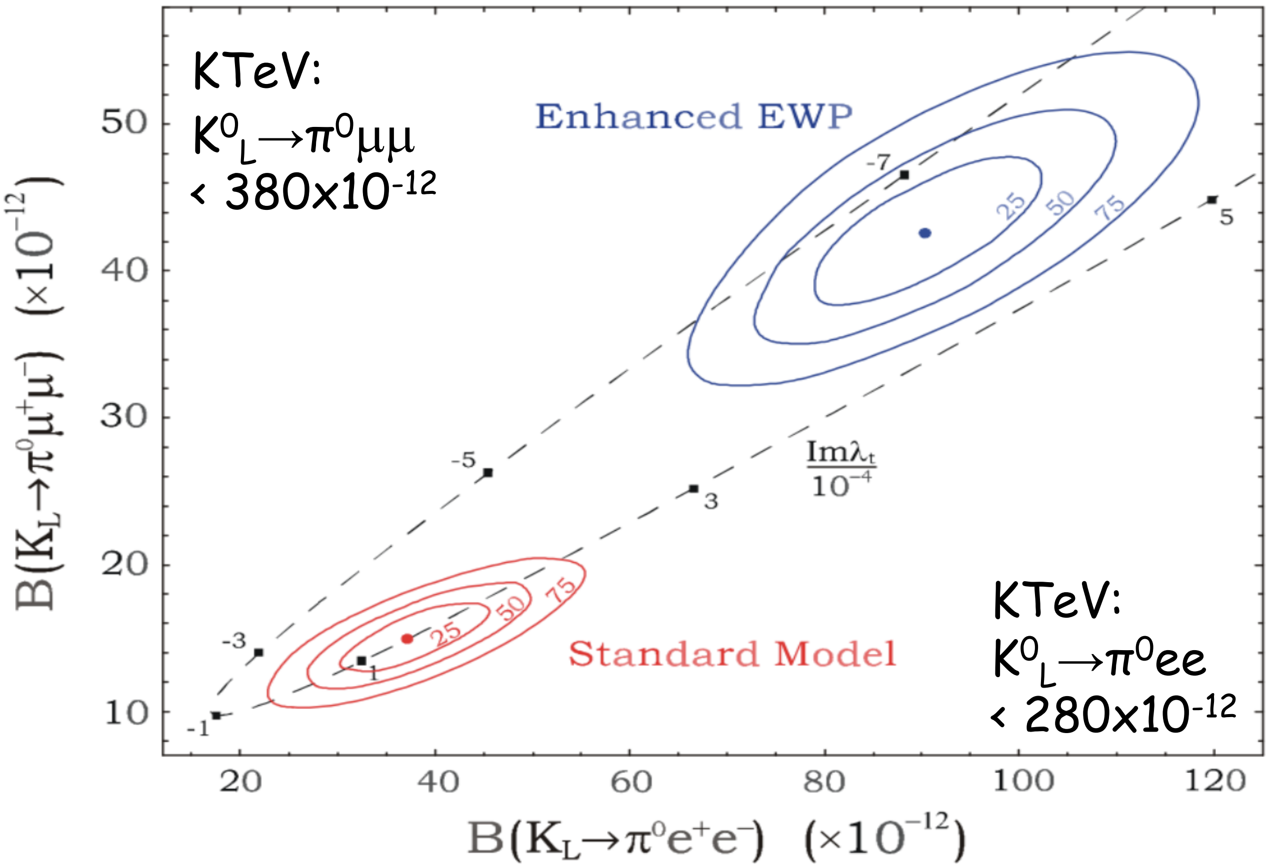
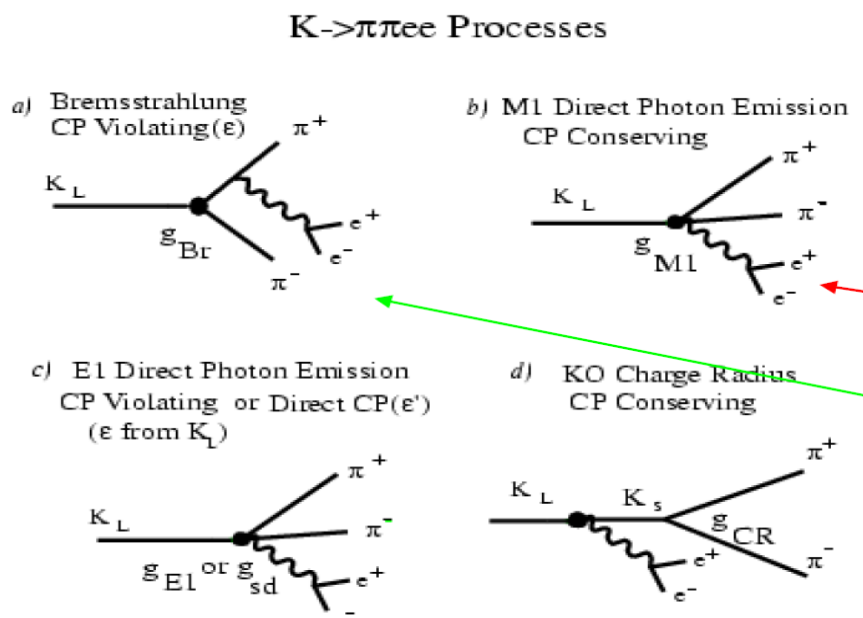


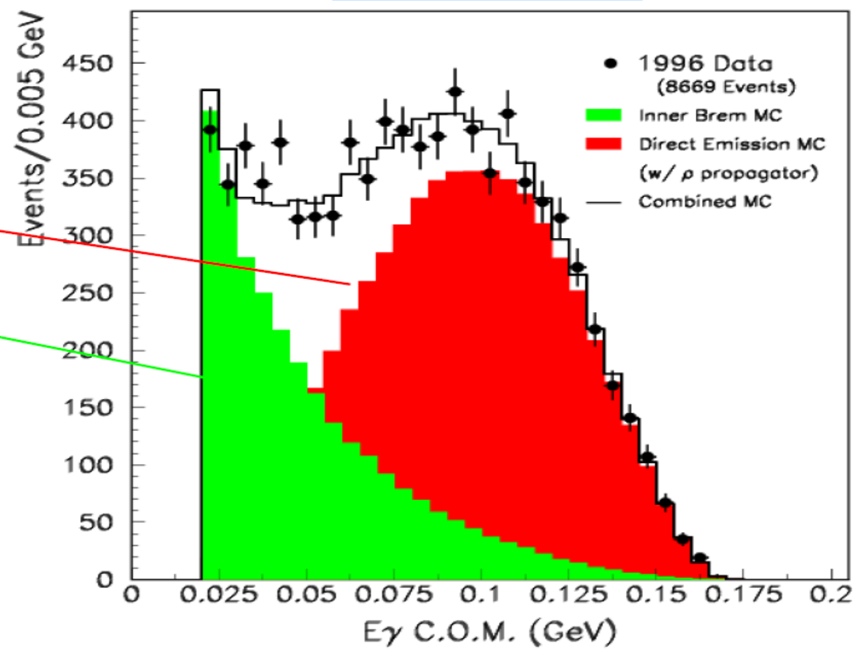
Figure 4: From Ref. [17], 25%, 50% and 75% confidence-level regions for the Standard Model (assuming positive interference) and the enhanced-electroweak-penguin model of Ref. [12], taking into account all the present uncertainties..

Phys. Rev. Lett. 93, 021805 (2004).

$K_L \to \pi^+\pi^-e^+e^-$, Another T-odd laboratory…

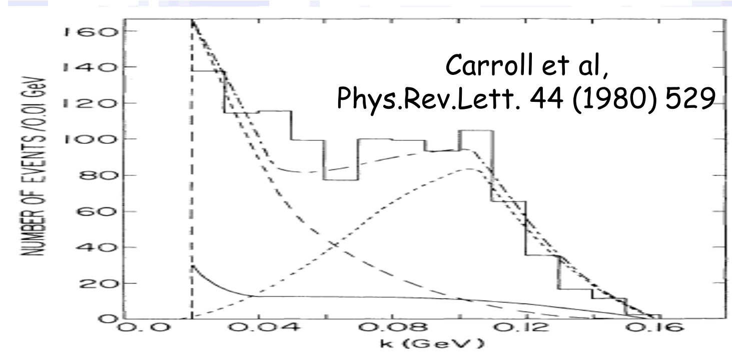


$K_L \to \pi\pi\gamma$

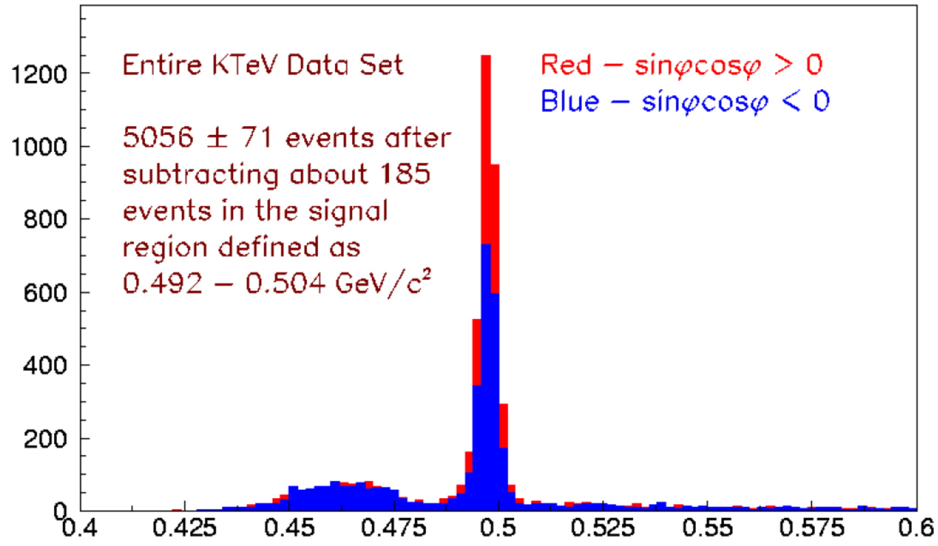


Asymmetry = 13.6 +- 1.4 +- 1.5 %
g_{CR} (coupling of the CP conserving charge radius process)
= 0.163 +- 0.014 +- 0.023
$\langle r^2_{K0} \rangle$ (K^0 charge radius) = (-0.077 +- 0.007 +- 0.011)fm^2
$|g_{E1}|/|g_{M1}|$ < 0.04 (90% CL)
$|g_{M1}|$ = 1.11 +- 0.12 +- 0.08
a_1/a_2 = (-0.744 +- 0.027 +- 0.032) GeV^2/c^2

Published in Phys. Rev. Lett. 96, 101801 (2006).



Rare Decay Serendipity
High Detector Acceptance

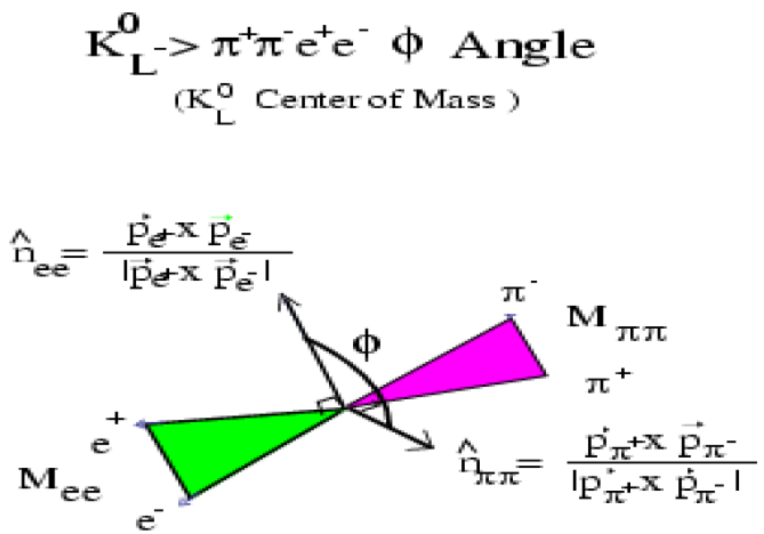


$BR(K_L \to \pi^+\pi^-e^+e^-) = 3.6\times10^{-7}$

Asymmetry = 13.6 +- 1.4 +- 1.5 %
g_{CR} (coupling of the CP conserving charge radius process)
= 0.163 +- 0.014 +- 0.023
$\langle r^2_{K0}\rangle$ (K^0 charge radius) = (-0.077 +- 0.007 +- 0.011)fm^2
$|g_{E1}|/|g_{M1}|$ < 0.04 (90% CL)
$|g_{M1}|$ = 1.11 +- 0.12 +- 0.08
a_1/a_2 = (-0.744 +- 0.027 +- 0.032) GeV^2/c^2

Published in Phys. Rev. Lett. 96, 101801 (2006).

T-odd Observable



$$\hat{z} = \frac{\vec{p}_{\pi^+} + \vec{p}_{\pi^-}}{|\vec{p}_{\pi^+} + \vec{p}_{\pi^-}|}$$

$$\sin\phi\cos\phi = (\hat{n}_{ee} \times \hat{n}_{\pi\pi})\cdot \hat{z}(\hat{n}_{ee} \cdot \hat{n}_{\pi\pi})$$

What High Performance Calorimetry brings to Rare Decays

$K^0_L \rightarrow \pi^0\pi^0(\pi^0 \rightarrow ee)$

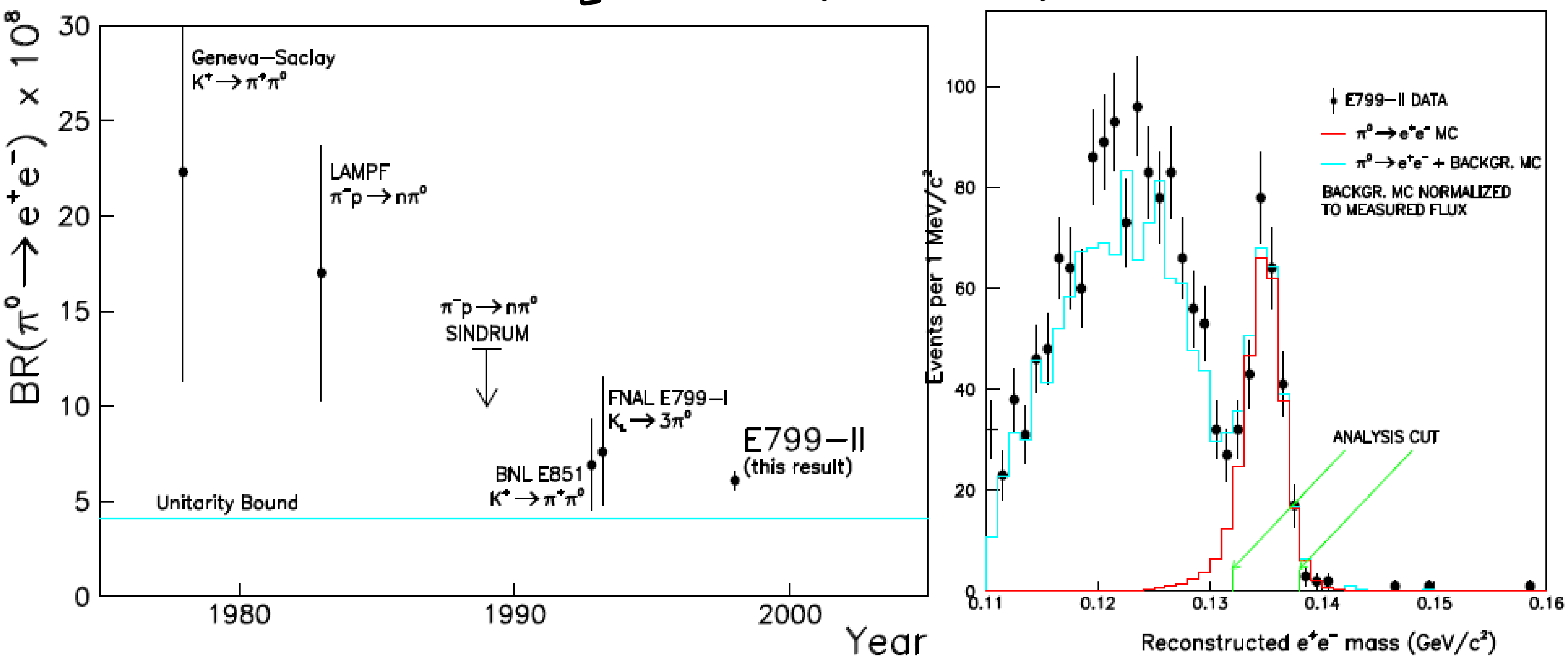


FIGURE 7. **Left:** history of $\pi^0 \rightarrow e^+e^-$ measurements from Ref. [35]. Horizontal line is the absorptive contribution from $\pi^0 \rightarrow \gamma\gamma$. **Right:** Reconstructed m_{ee} distribution for $\pi^0 \rightarrow e^+e^-$ candidates from Ref. [35].

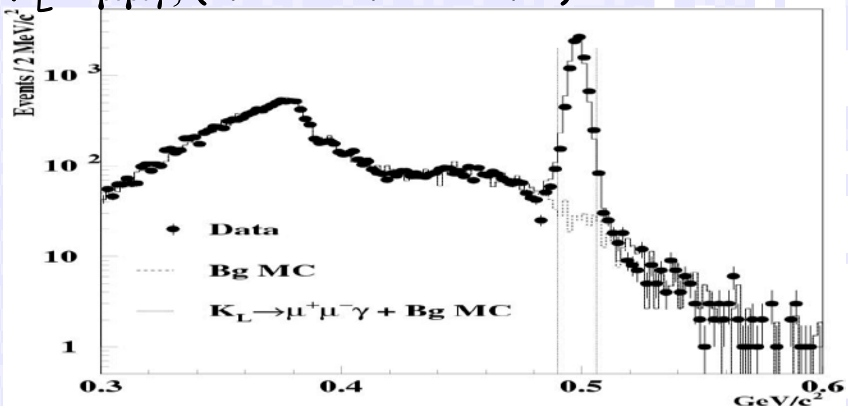
BR($\pi^0 \rightarrow ee$) = (6.44 +- 0.25 +- 0.22) x 10^{-8}

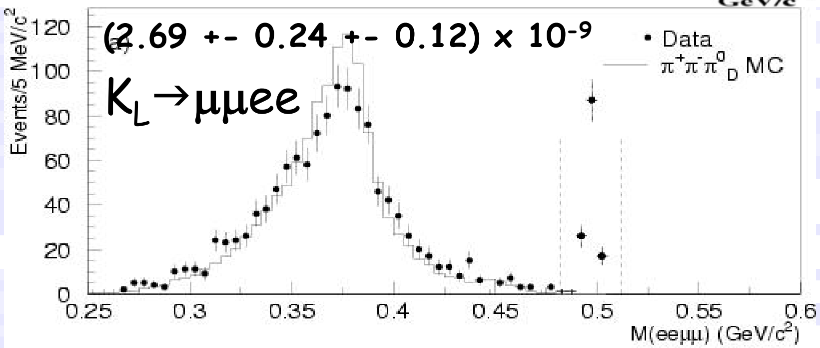
Littenberg, 2003 Review

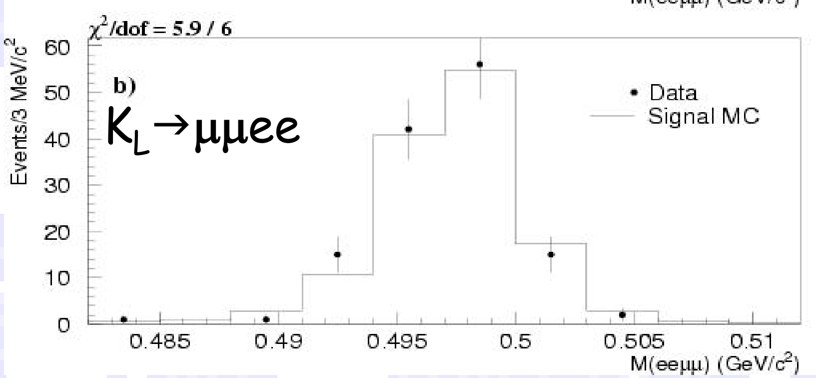
Published in Phys. Rev. D 75, 012004 (2007).

Tour-de-Force of $K_L \to \gamma\gamma^*$ and $K_L \to \gamma^*\gamma^*$ daughters…

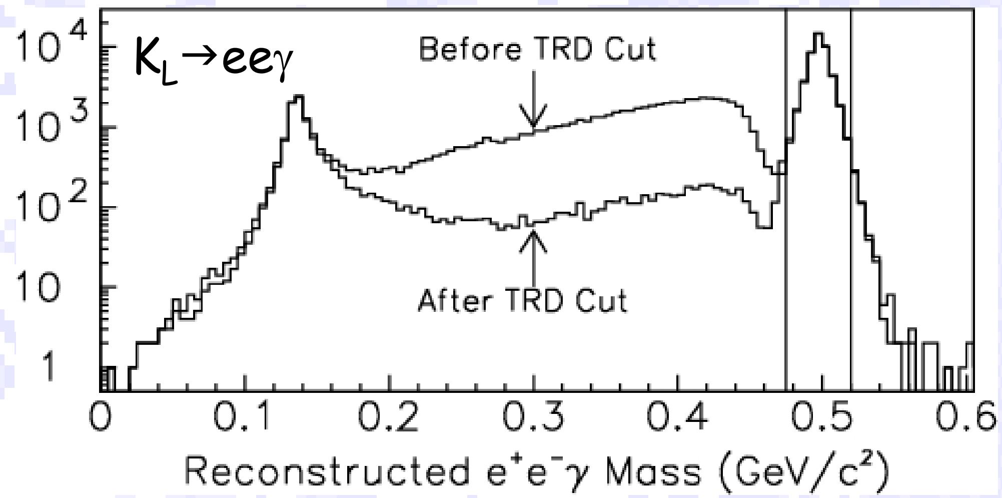
$K_L \to \mu\mu\gamma$, (3.62 +- 0.04 +- 0.08) x 10^{-7}

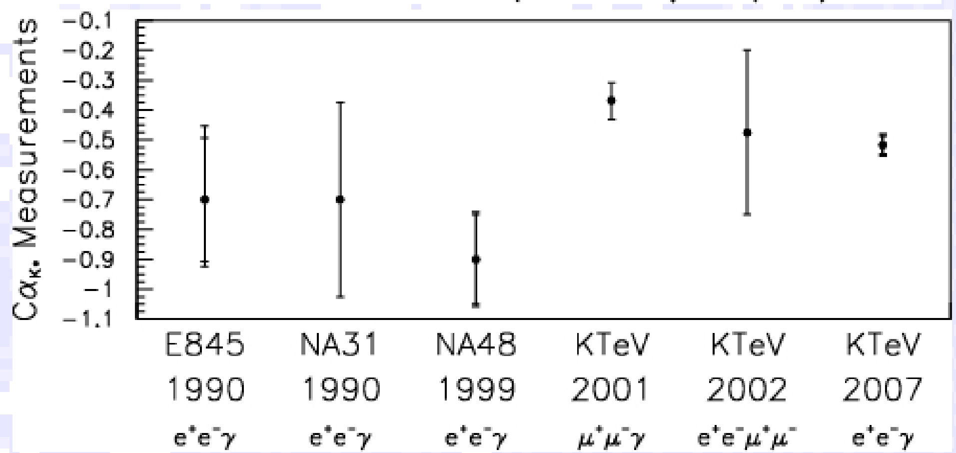






Phys. Rev. Lett. 99, 051804 (2007).
Phys. Rev. Lett. 87, 071801 (2001).
Phys. Rev. Lett. 90, 141801 (2003).





Tour-de-Force of $K_L \to \gamma\gamma^*$ and $K_L \to \gamma^*\gamma^*$ daughters…

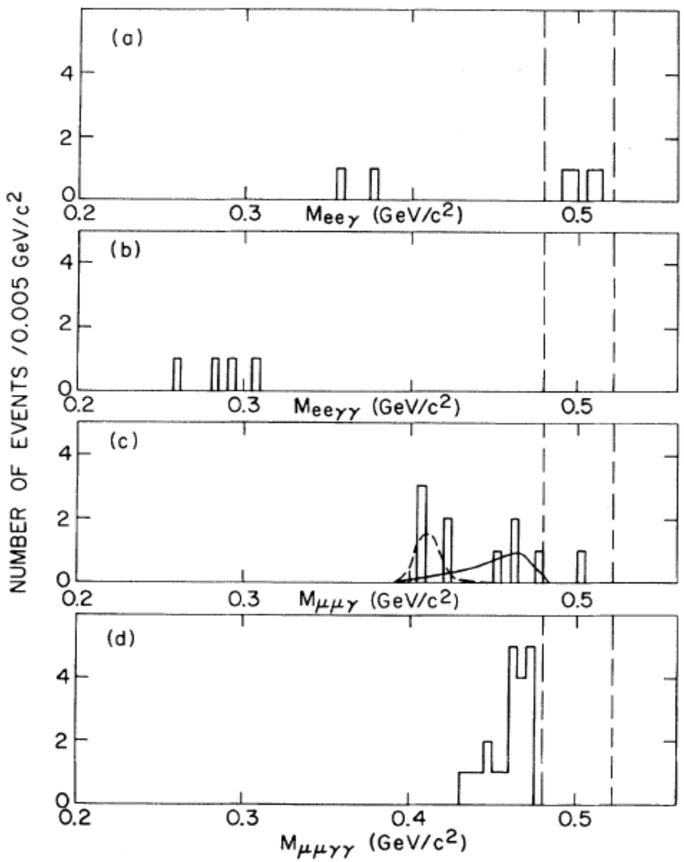
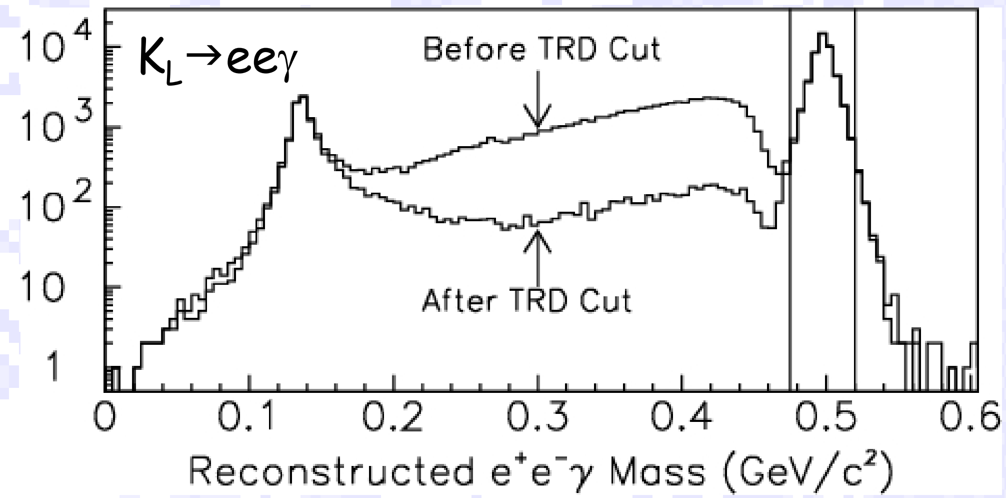
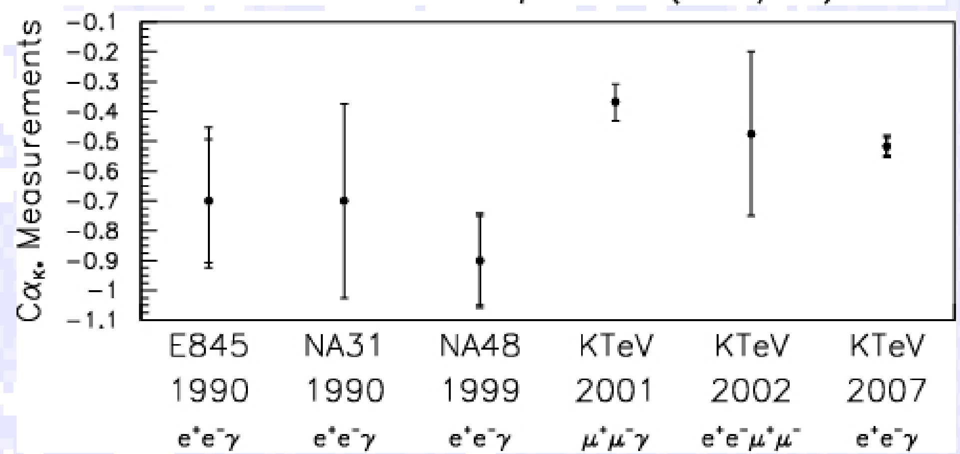


FIG. 2. Effective-mass spectra for events subject to all cuts except in mass. Vertical lines show mass cuts. (a) $e^+e^-\gamma$, (b) $e^+e^-\gamma\gamma$, (c) $\mu^+\mu^-\gamma$ (dashed line is expected $K_L{}^0 \to \pi^+\pi^-\pi^0$ background, solid line is sum of expected $K_L{}^0 \to \pi^\pm\mu\nu\gamma$ and $K_L{}^0 \to \pi^\pm\mu\nu$ backgrounds), and (d) $\mu^+\mu^-\gamma\gamma$.

Carroll et al,
Phys. Rev. Lett. 44, 525 – Published 25 February 1980

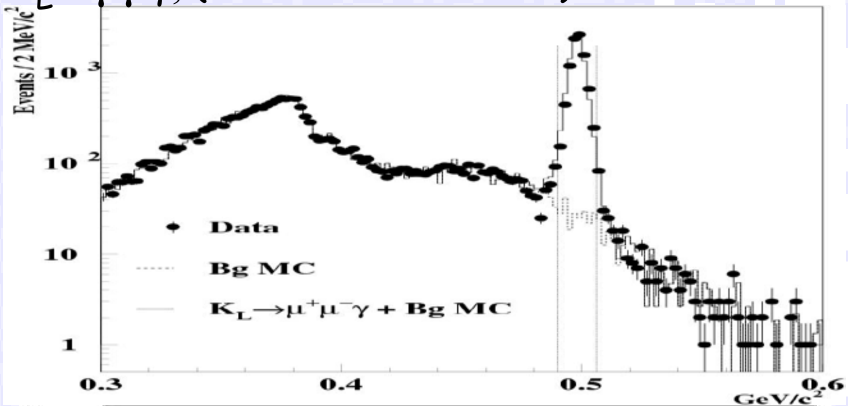
Phys. Rev. Lett. 99, 051804 (2007).
Phys. Rev. Lett. 87, 071801 (2001).
Phys. Rev. Lett. 90, 141801 (2003).



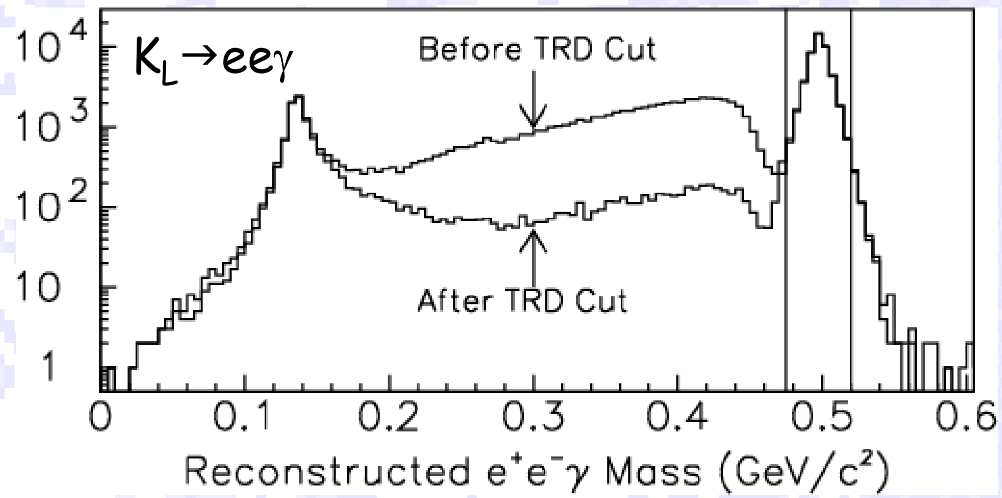


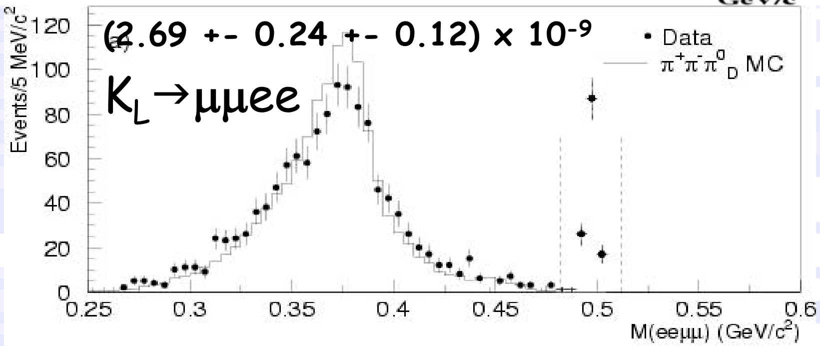
Tour-de-Force of $K_L \to \gamma\gamma^*$ and $K_L \to \gamma^*\gamma^*$ daughters…

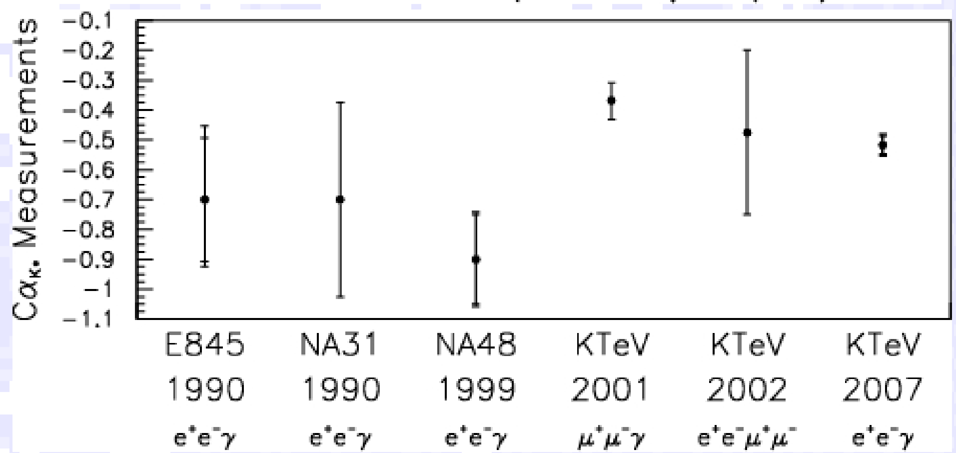
$K_L \to \mu\mu\gamma$, $(3.62 \pm 0.04 \pm 0.08) \times 10^{-7}$

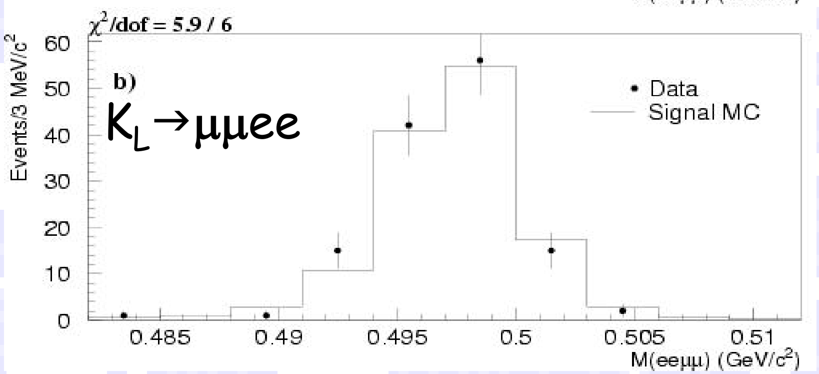


Phys. Rev. Lett. 99, 051804 (2007).
Phys. Rev. Lett. 87, 071801 (2001).
Phys. Rev. Lett. 90, 141801 (2003).







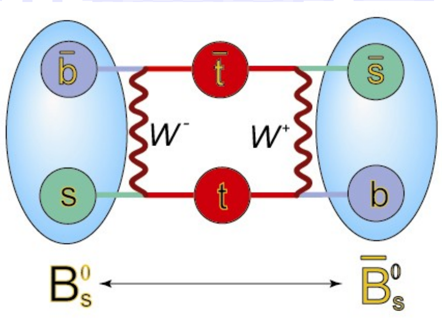


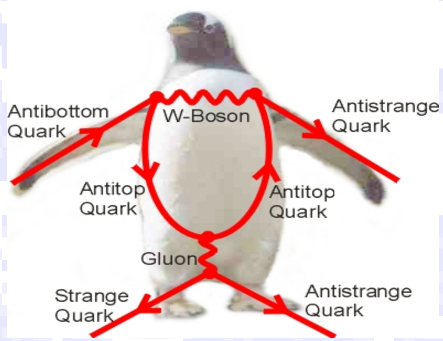
The KTeV Legacy

- Established decay-amplitude matter-antimatter asymmetries together with our CERN colleagues.
- Probed many, many rare-decays that have cranked up the tension on the "flavor problem".
- Substantially advanced the state of the art in precision calorimetry and data acquisition in High Energy Physics.
- Developed next generation leaders for the field.

1990's Brought Clear Emergence of the "Flavor Problem"

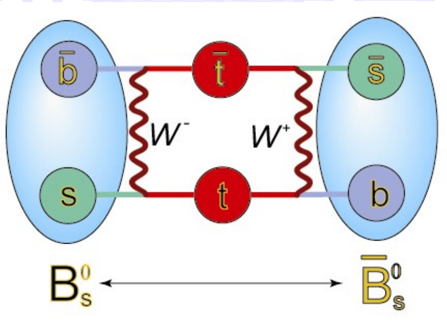
Why don't we see the *Terascale Physics we expect* affecting the flavor physics we study today??

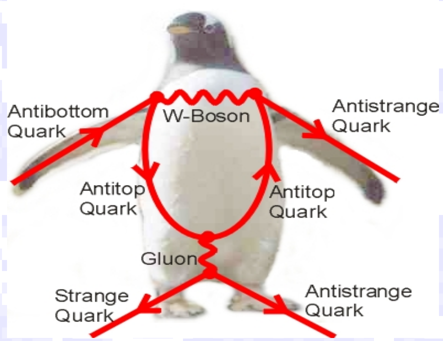




1990's Brought Clear Emergence of the "Flavor Problem"

Why don't we see the *Terascale Physics we expect* affecting the flavor physics we study today??





The Post-KTeV Era: Next Generation Rare Decays to Crack the Flavor Problem

2001

Kaons at the Main Injector (KAMI) proposed

Charged Kaons at the Main Injector (CKM) proposed and granted scientific approval

BTeV, CKM and RSVP cancelled in the inaugural P5 process

The Mu2e experiment advances in the second P5 process

ORKA proposed and granted scientific approval

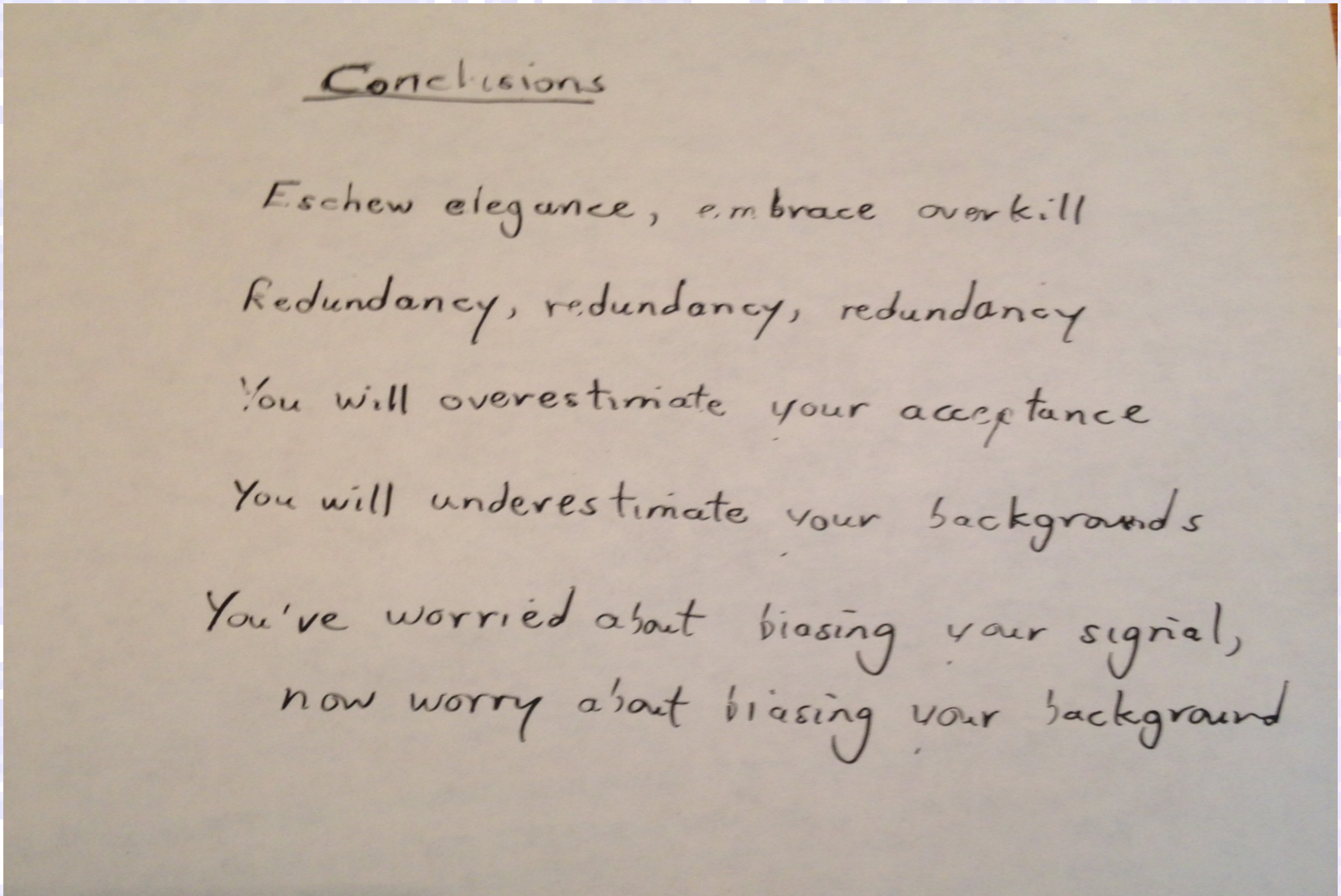
ORKA and Project-X kaons cancelled by the P5 process

2016

Mu2e continues; Project likely to succeed

Amalfi Coast, June 2013

Laur's advice towards developing the Fermilab Rare Decay Program for the post KTeV era..



Laur's advice towards developing the Fermilab Rare Decay Program for the post KTeV era..

- Eschew elegance, embrace overkill.
- Redundancy, Redundancy, Redundancy.
- You will over-estimate your acceptance
- You will under-estimate your backgrounds
- You are worried about biasing your signal;
- Now worry about biasing your backgrounds....

-Laur Littenberg, rare-decay workshop at Fermilab in the 90's

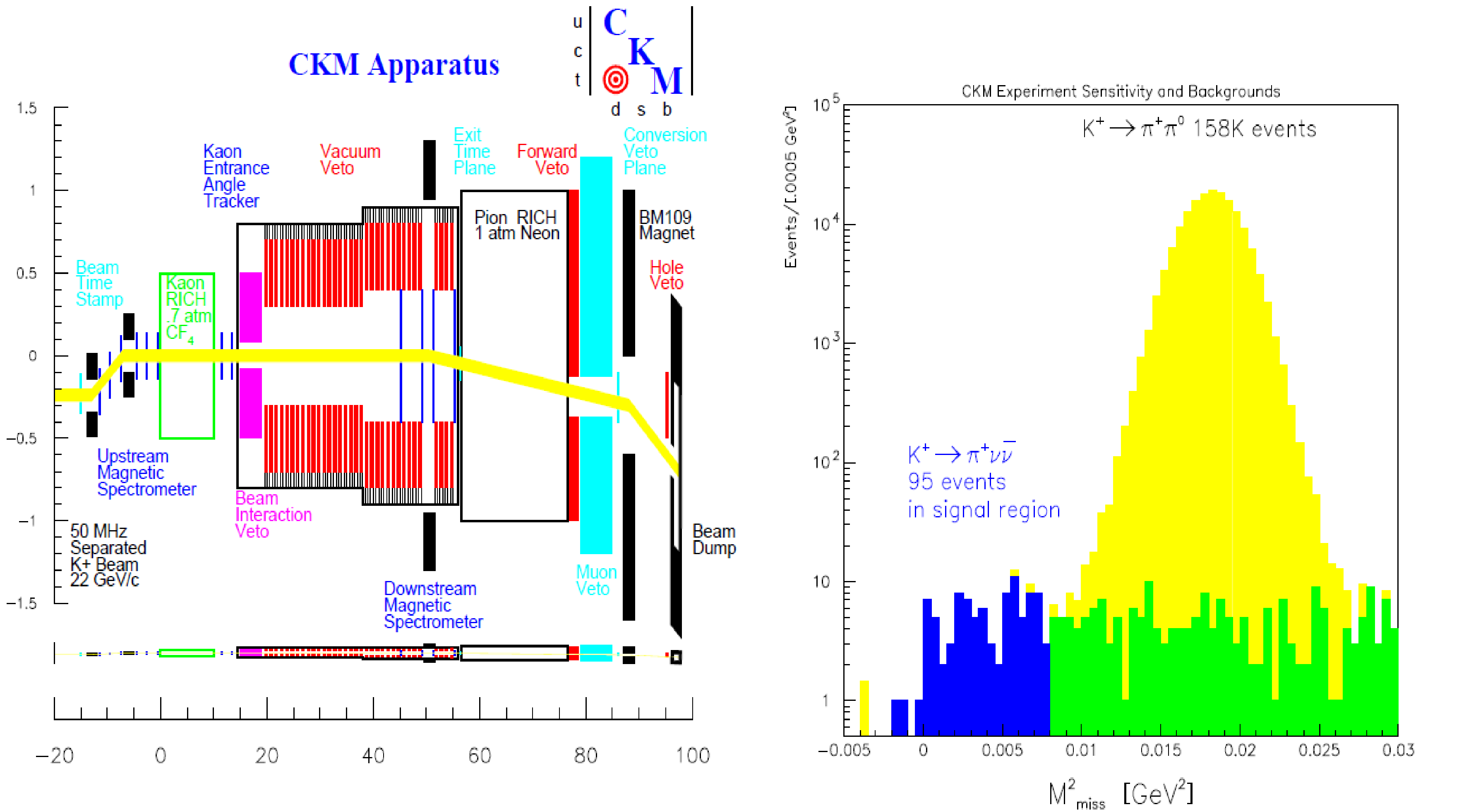
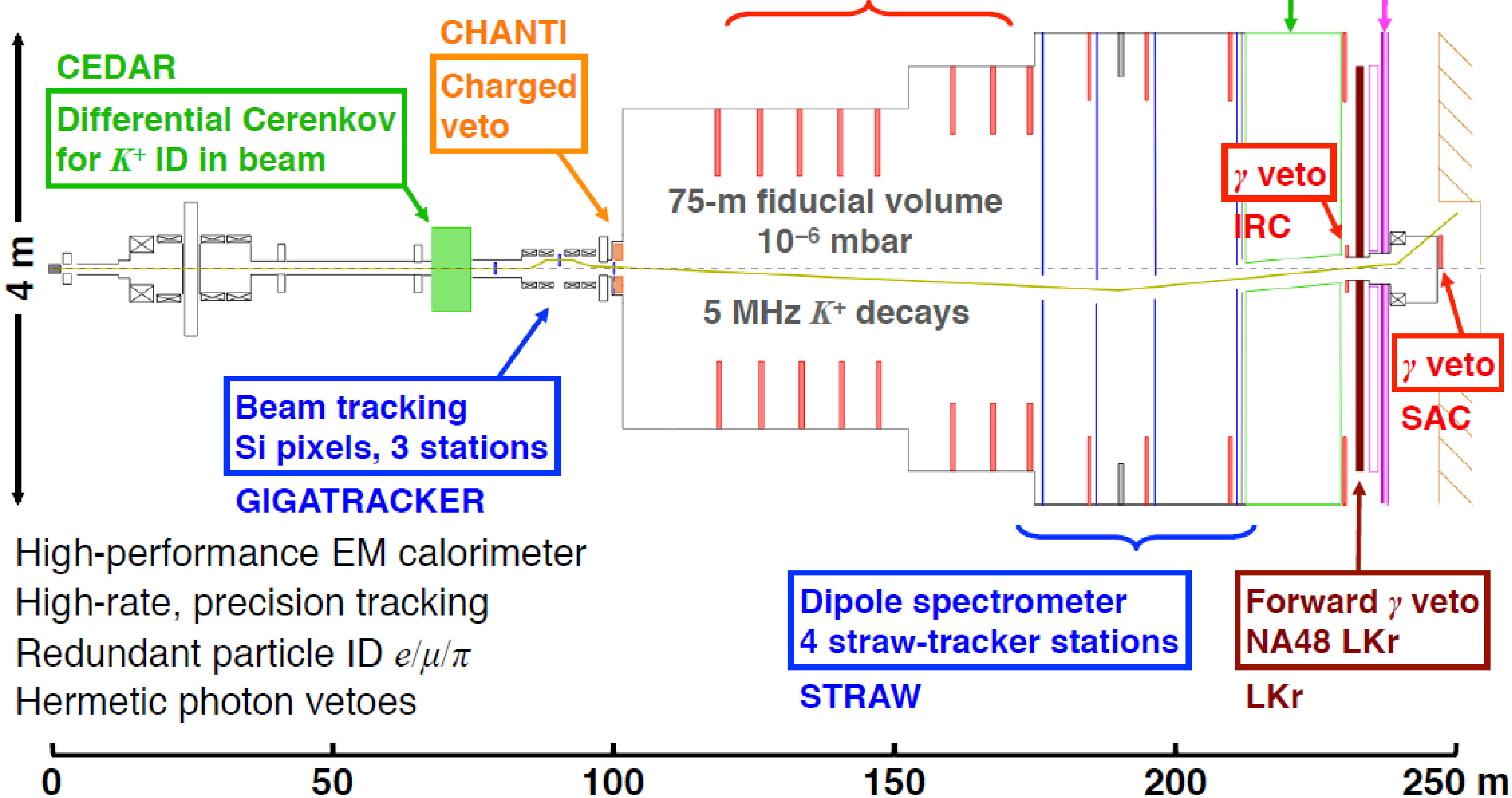


FIGURE 13. **Left:** apparatus of the CKM experiment at FNAL. **Right:** expected signal and background.

The NA62 experiment at the SPS

75 GeV secondary positive beam
750 MHz total beam rate
50 MHz K^+ into experiment



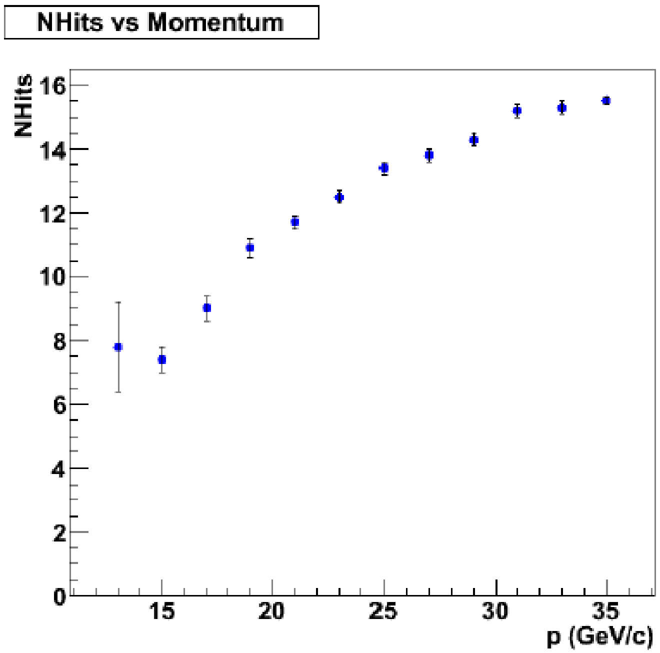
High-performance EM calorimeter
High-rate, precision tracking
Redundant particle ID $e/\mu/\pi$
Hermetic photon vetoes

Forbidden pion and kaon decays in NA62 – M. Moulson (Frascati) – KAON 2013 – Ann Arbor, MI – 29 April 2013 13

Back in the lab frame!

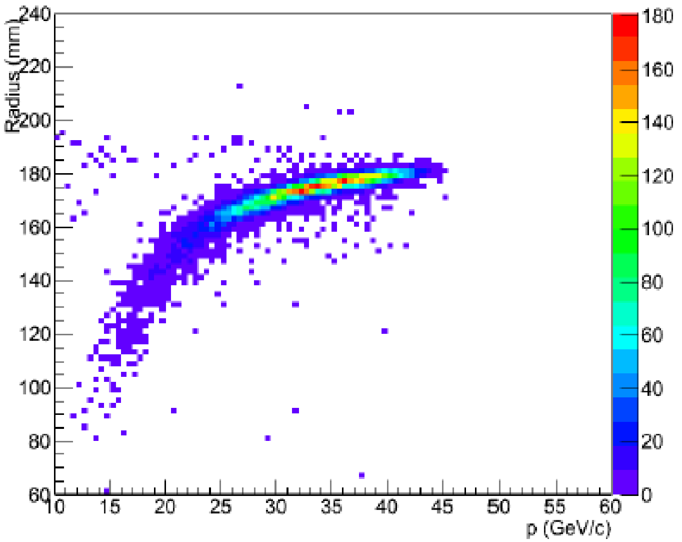
A. Ceccucci , Chiral Dynamics Pisa, July 2, 2015

RICH PERFORMANCE



Number of hits per ring as a
Function of particle momentum

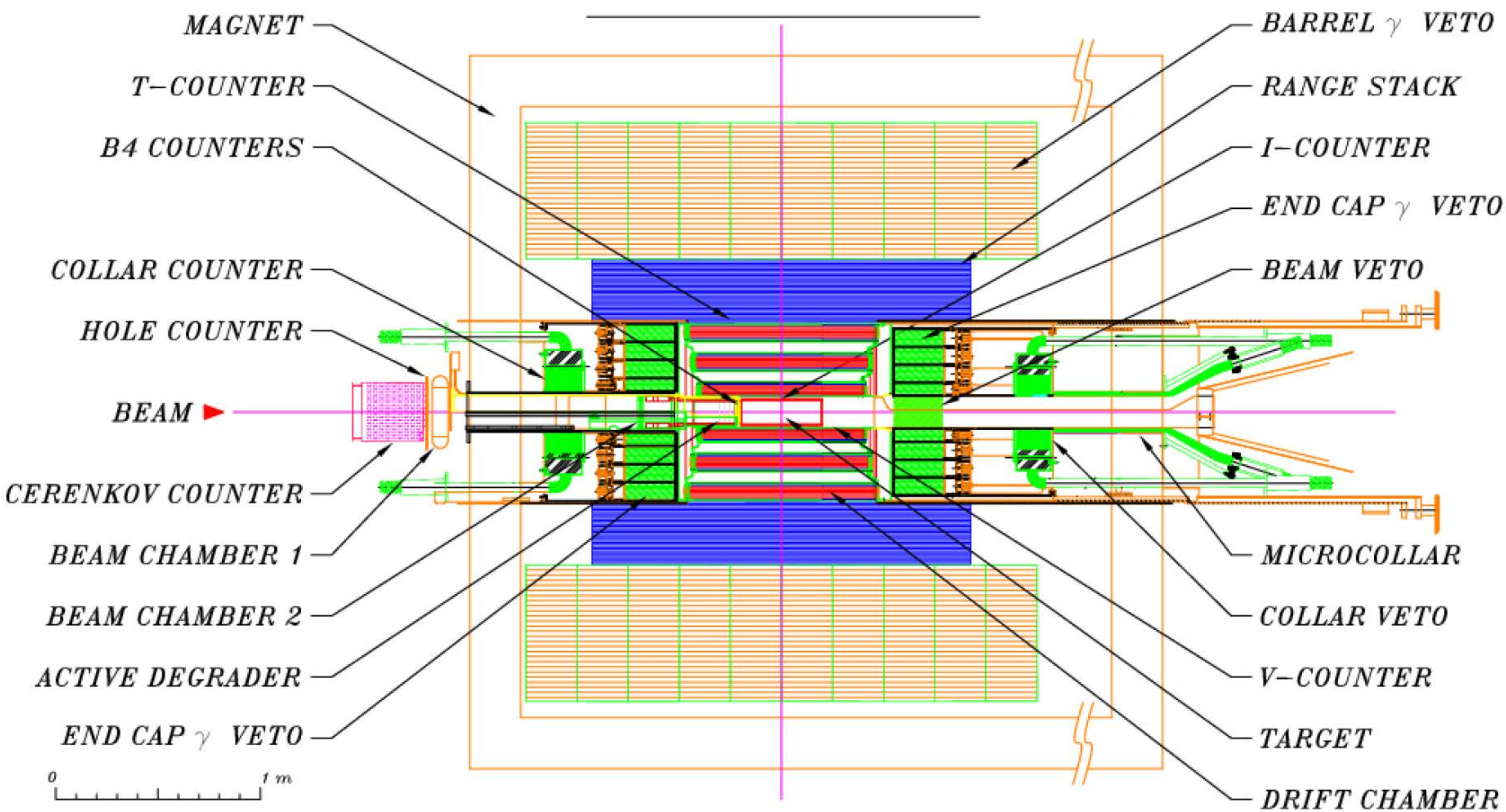
High-Speed Precision
"*Velocity Spectrometer*"



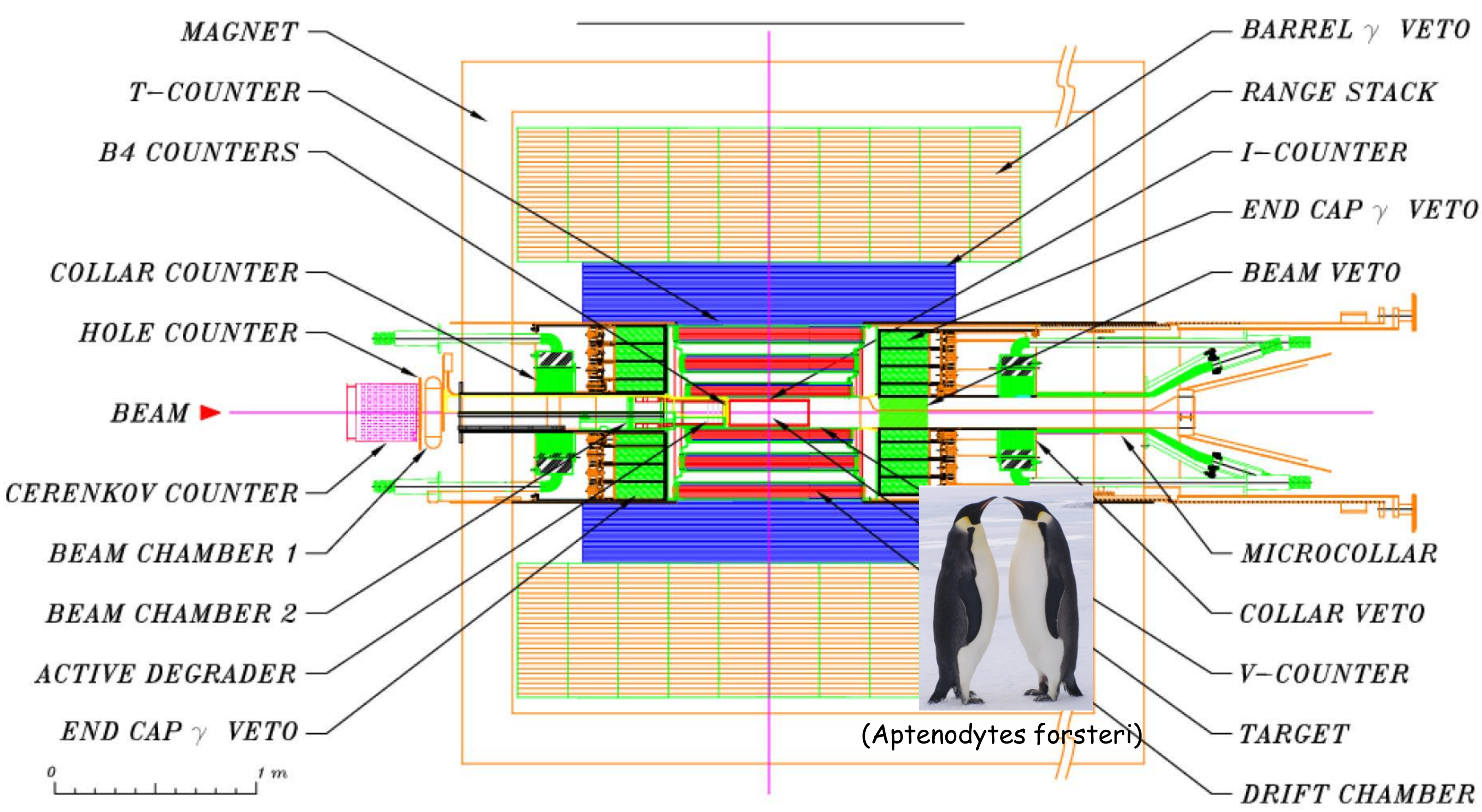
Cherenkov ring radius vs. particle momentum for $\pi^+\pi^0$ events (w/o spectrometer information)

A. Ceccucci , Chiral Dynamics Pisa, July 2, 2015

ORKA is a 4th Generation Detector - x100 sensitivity - x10 from kaon flux, x10 from detector



ORKA is a 4th Generation Detector - x100 sensitivity - x10 from kaon flux, x10 from detector

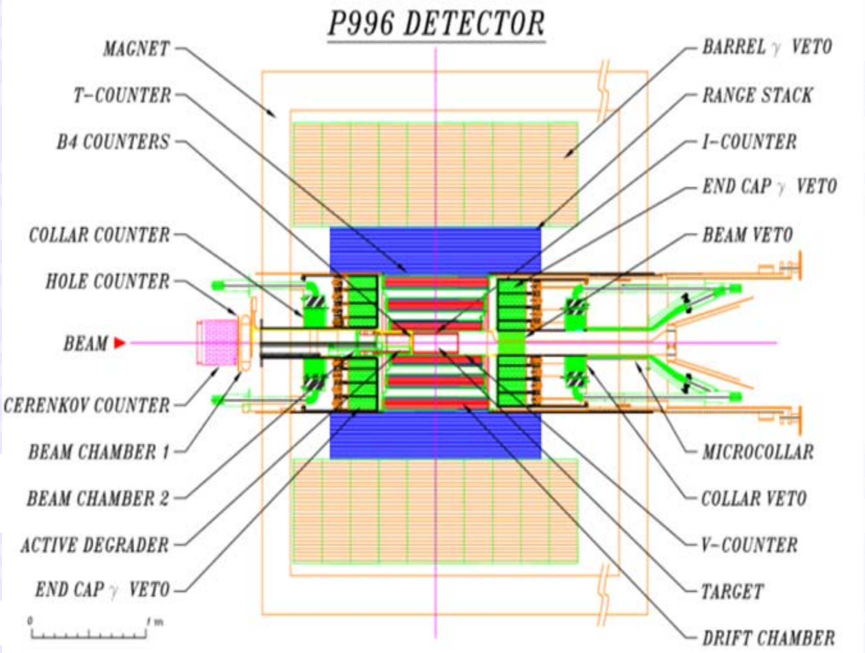


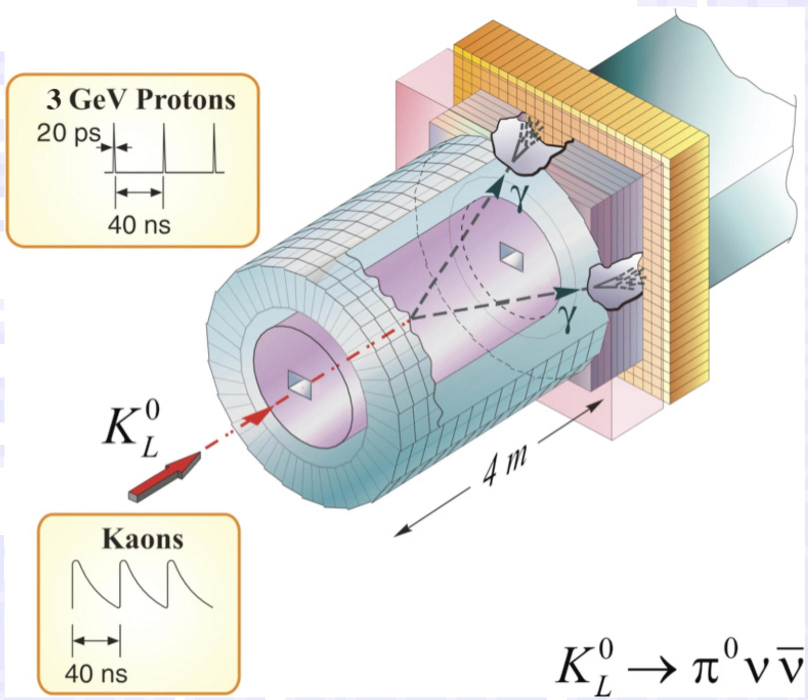
(Aptenodytes forsteri)

Laur and Colleagues made Leading Contributions towards Understanding the: Definitive Measurement of $K \rightarrow \pi\nu\bar{\nu}$

In the Project-X era the Fermilab ORKA experiment could have precisely measure the rate and form-factor of $K^+ \rightarrow \pi\nu\bar{\nu}$.

The Project-X era presented an opportunity to measure the holy grail of kaon physics with precision: $K_L \rightarrow \pi\nu\bar{\nu}$.

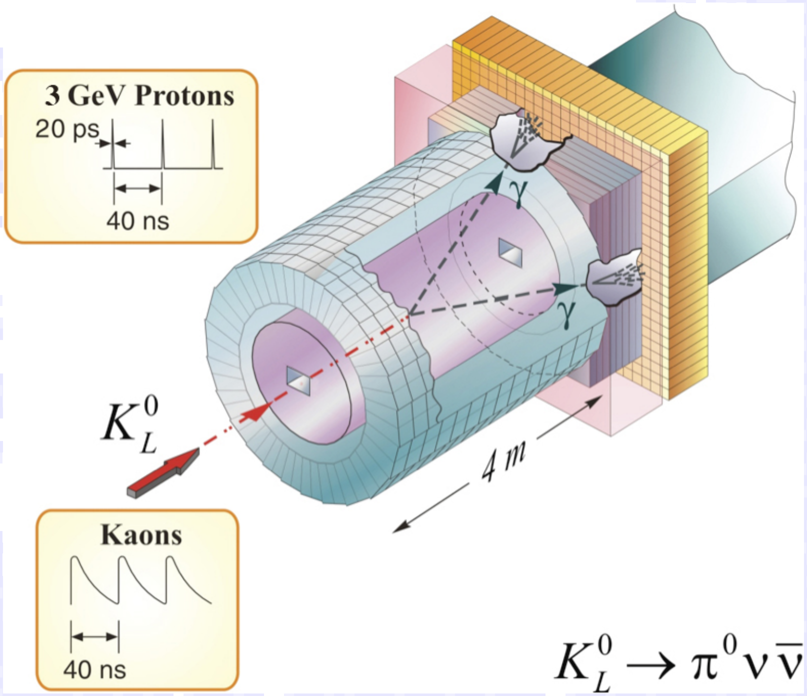




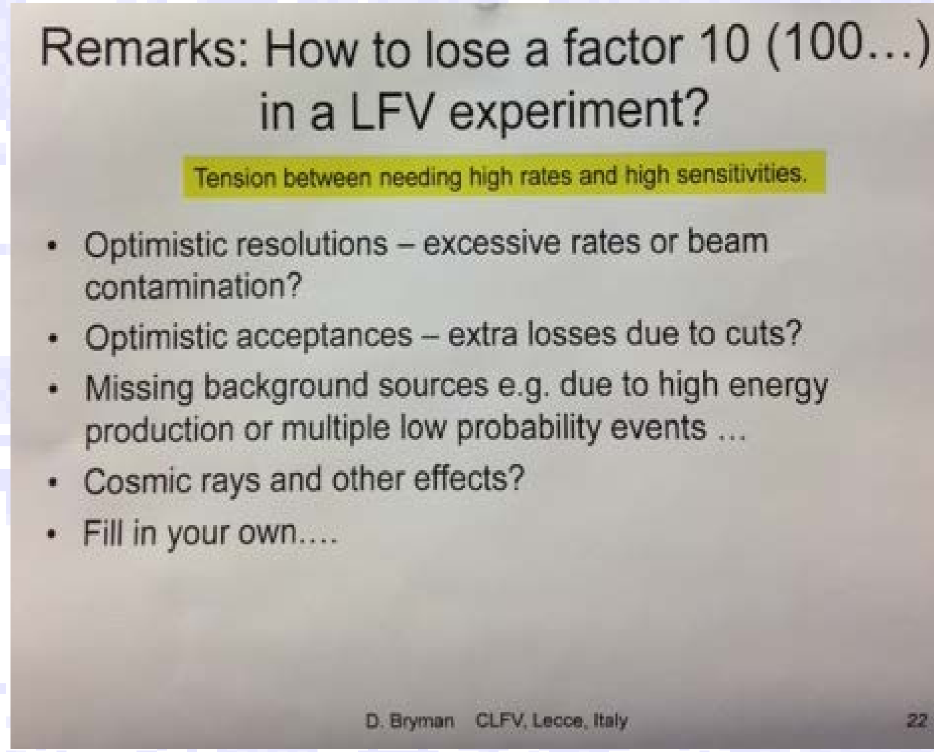
Laur and Colleagues made Leading Contributions towards Understanding the: Definitive Measurement of $K \rightarrow \pi\nu\bar{\nu}$

In the Project-X era the Fermilab ORKA experiment could have precisely measure the rate and form-factor of $K^+ \rightarrow \pi\nu\bar{\nu}$.

The Project-X era presented an opportunity to measure the holy grail of kaon physics with precision: $K_L \rightarrow \pi\nu\bar{\nu}$.



Legacy of Littenberg/Bryman guidance for the next generation rare decay program at Fermilab…



Posted above the Mu2e Project Manager's desk

“Sage” advice to Postdocs Today…

- Flavor Physics is boring
- The future is neutrinos
- Collider physics is over after the LHC
- Cosmology will be a rich Garden of Eden with bountiful new physics
- Oh, and don’t worry, senior faculty will be retiring soon…

Advice from a real Sage* Regarding the Future of Rare Decay Physics…

- "Don't worry too much about what others will or won't do.

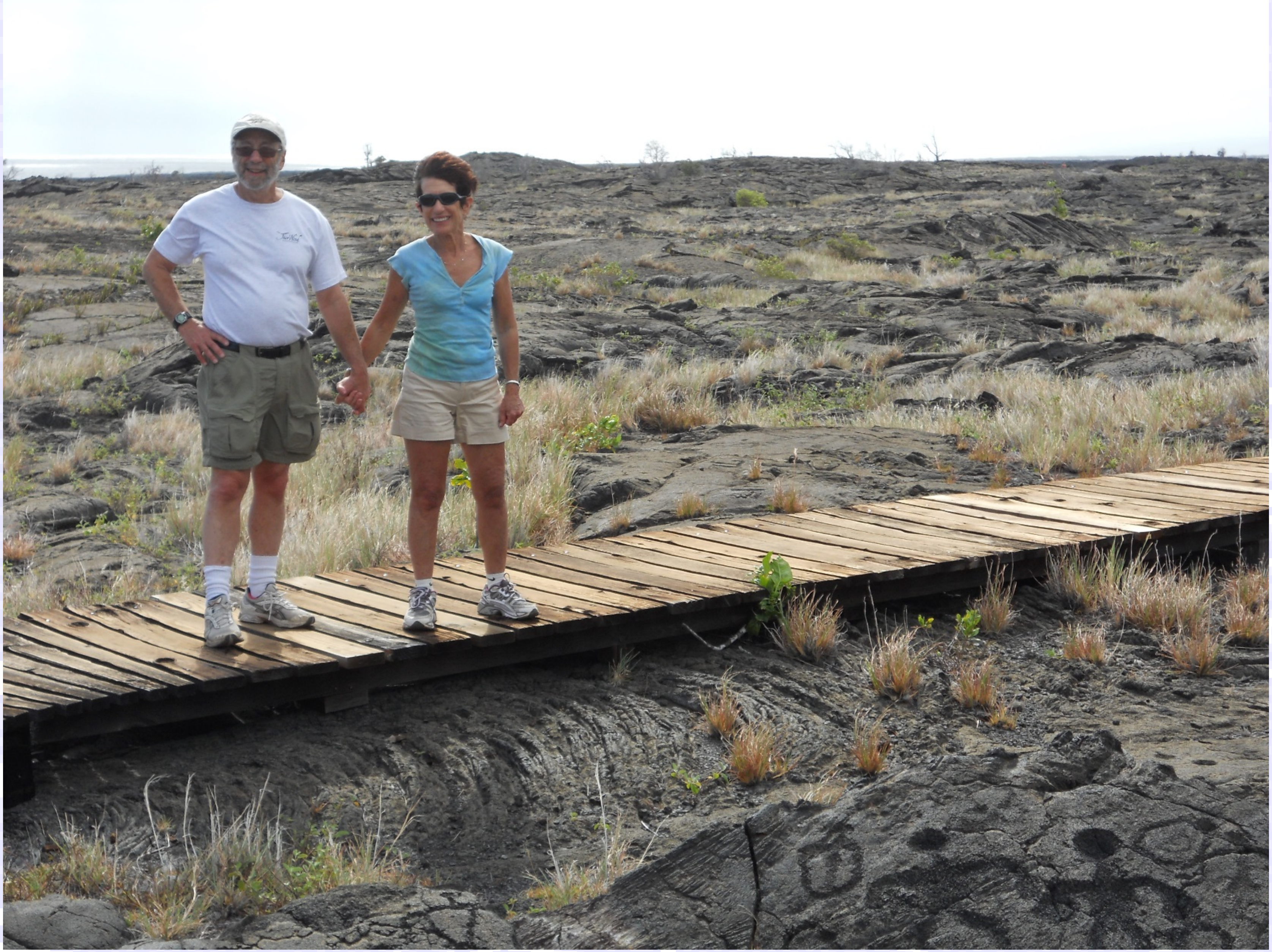
- If you are going to do it, don't scrimp!

- Allow enough running time (years) for development, mid-course corrections, upgrades, and learning as you go."

*Littenberg, Villars 2004; as CERN considers it future.

Amalfi coast, June 2013

Amalfi coast, June 2013



Hawaii; Oct 2010

Spares

$K^0_L \to \pi^0 ee$, $K^0_L \to \pi^0 \mu\mu$ and related backgrounds

- K_L ->p^0 e^+ e^- BR < 2.8 x 10^{-10} (90%CL) .
  Published in Phys. Rev. Lett. 93, 021805 (2004).

- K_L ->p^0 m^+ m^- BR < 3.8 x 10^{-10} (90% CL)
  Published in Phys. Rev. Lett. 84, 5279-5282 (2000).

- K_L ->p^0 n n-bar BR <5.9 x 10^{-7} (90% CL)
  Published in Phys. Rev. D 61, 072006 (2000).

- K_L ->e^+ e^- g g

BR(Egamma*>5MeV) = (5.84 +- 0.15 +- 0.32) x 10^{-7} ,
based on 1543 events including 56+-8 background events.
Published in Phys. Rev. D 64, 012003 (2001).

- K_L->mu^+mu^-g g

BR($M_{gamma\ gamma}$ > 1MeV/c^2) = (10.4 +7.5 -5.9 +- 0.7) x 10^{-9},
Published in Phys. Rev. D 62, 112001 (2000).

Other Rare Kaon Decays Probed by KTeV…

- K_L->$pi^0pi^0e^+e^-$

BR < 6.6 x 10^{-9} (90% CL)
Published in Phys. Rev. Lett. 89, 211801 (2002).

- K_L->$pi^0pi^0mu^+mu^-$

BR(K_L->$pi^0pi^0mu^+mu^-$) < 9.2 x 10^{-11} (90% CL)
BR(K_L->$pi^0pi^0X^0$ -> $pi^0pi^0mu^+mu^-$) < 1.0 x 10^{-10} (90% CL)
Published in Phys. Rev. Lett. 107, 201803 (2011).

- K_L->pi^0pi^0gamma

BR < 2.32 x 10^{-7} (90% CL)
Published in Phys. Rev. D 78, 032014 (2008).

- K_L ->e^+e^- e^+e^-

BR = (4.16 +- 0.13 +- 0.13 +- 0.17 (ext syst)) x 10^{-8}
Published in Phys. Rev. Lett. 86, 5425-5429 (2001).

The Dalitz Decays…

- **$K_L \to e^+e^-\gamma$**

$BR/BR(K_L \to pi^0pi^0pi^0_D)$ = (1.3302 +- 0.0046 +- 0.0102) x 10^{-3},
CalphaK* = -0.517 +- 0.030(fit) +- 0.022(syst.)
$alpha_{DIP}$ = -1.729 +- 0.043(fit) +- 0.028(syst.)
Published in Phys. Rev. Lett. 99, 051804 (2007).

- **$K_L \to \mu^+\mu^-\gamma$**

BR = (3.62 +- 0.04 +- 0.08) x 10^{-7} ,
$alpha_{K*}$ = -0.160 +0.026-0.028,
Published in Phys. Rev. Lett. 87, 071801 (2001).

- **$K_L \to e^+e^-\mu^+\mu^-$**

BR=(2.69 +- 0.24 +- 0.12) x 10^{-9} ($(M_{eemm}/M_K)^2$ > 0.95) ,
Form factor $alpha_{DIP}$ = -1.59 +- 0.37.
BR(lepton flavor violation) < 4.12 x 10^{-11} .
Published in Phys. Rev. Lett. 90, 141801 (2003).

Following BNL measurements and searches of Carrol et al:
Published in Phys.Rev.Lett. 44 (1980) 525

Other Rare Decays Probed by KTeV…

- **K_L->pi$^+$e$^-$nu e$^+$e$^-$**

BR(KL->pi^{+-}e^{-+}nu e$^+$e$^-$; M_{ee}>5MeV/c^2, E^*_{ee} > 30MeV)
= (1.285 +- 0.041) x 10^{-5},
Published in Phys. Rev. Lett. 99, 081803 (2007)

- **K_L ->pi^0 e$^+$ e$^-$ gamma**

BR = (1.62 +- 0.14 +- 0.09) x 10^{-8}
Published in Phys. Rev. D 76 052001(2007).

- **K_L->pi^{0}mu e**

BR < 7.6 x 10^{-11} (90% CL)
Published in Phys. Rev. Lett. 100, 131803 (2008)

- **K_L->pi^{0}pi^{0}mu e**

BR < 1.7 x 10^{-10} (90% CL)
Published in Phys. Rev. Lett. 100, 131803 (2008)

Rare pion decays probed by KTeV

- **$pi^0 \to e^+ e^-$**

BR($pi^0 \to e^+e^-$, $(Mee/Mpi^0)^2 > 0.95$) = $(6.44 \pm 0.25 \pm 0.22) \times 10^{-8}$
Published in Phys. Rev. D 75, 012004 (2007).

- **$pi^0 \to e^+ e^- e^+ e^-$**

BR(pi0 ->4e) BR(pi0->gg)/BR(pi0->eeg)^2 = 0.2329 +- 0.0015 +- 0.0010,
BR(pi0->4e; x>0.9) = $(3.26 \pm 0.18) \times 10^{-5}$,
Published in Phys. Rev. Lett. 100, 182001 (2008)

- **$pi^0 \to mu\ e$**

BR < 3.6×10^{-10} (90% CL)
Published in Phys. Rev. Lett. 100, 131803 (2008)