Neutral Kaon Physics at Fermilab

- Context Leading Up to late 70s
- Fermilab E617/E731/KTeV
- Concluding Thoughts
- A Perspective with a Little Distance

Not a comprehensive review!

1964 INTERNATIONAL SCHOOL OF PHYSICS "ETTORE MAJORANA"

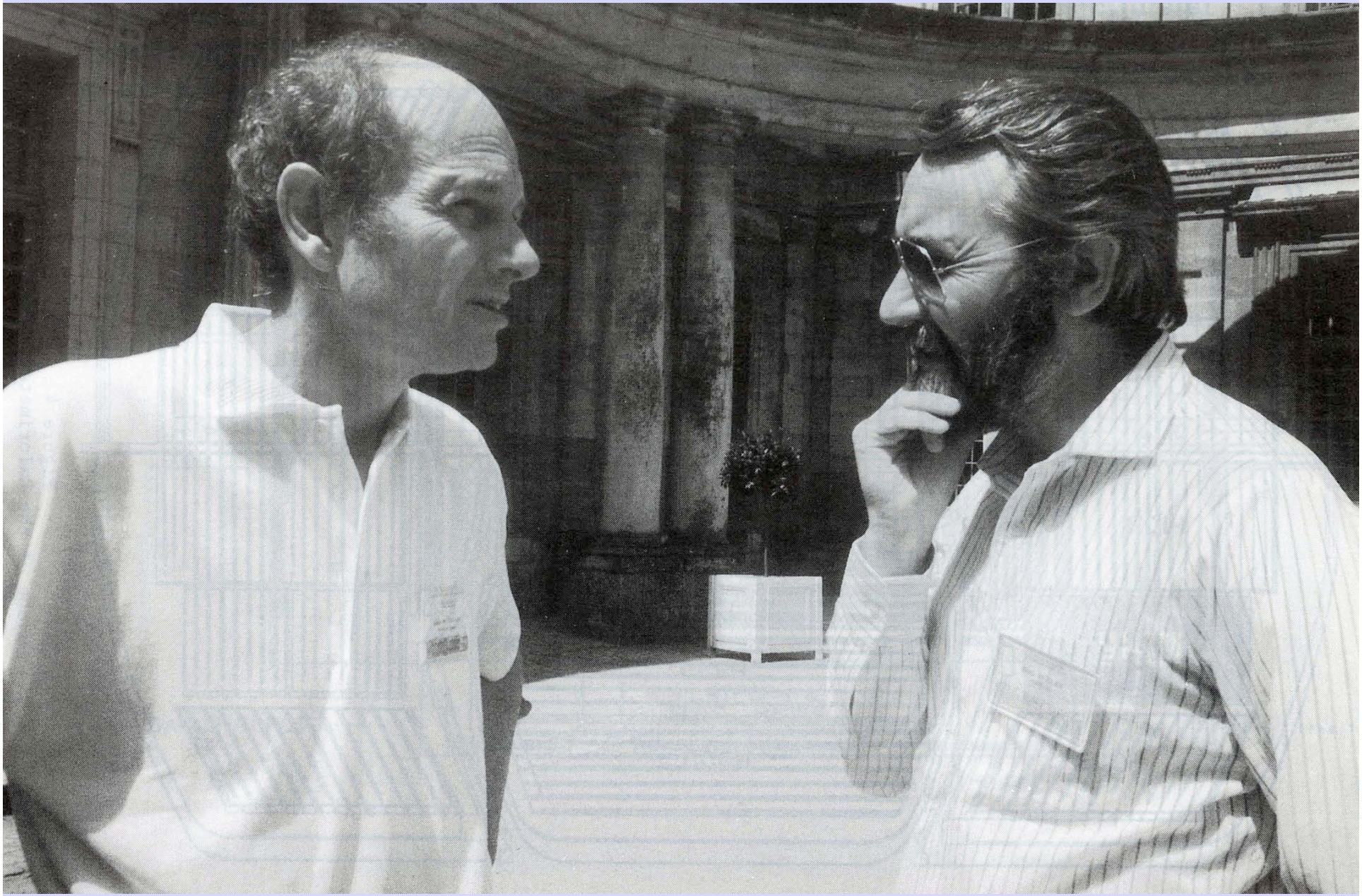
Symmetries in Elementary Particle Physics

Edited by
A. ZICHICHI

The programme of the school was greatly influenced by two remarkable discoveries: the Ω^- and the $K_2^0 \to \pi^+ \pi^-$. Both results encouraged a tremendous development in both theoretical and experimental work. At

CP Violation ca 1978

- 64 Discovery
- 67 CPV in early universe (Sakharov)
  Unconnected (like gravity)
- 71 FNAL K^0 Program approved (not for CPV)
- 76 First calculation of ε' in KM (EGN)
  KM provided a connection!
- 79 FNAL (E617), BNL & later CERN began programs
  Seeking a new phenomenon: direct CPV
  Elaboration of the predictions
  Everyone learned about kaons in school
  < 20 experimentalists (today about 2000)
  No WBS!



The Unique Laboratory of the Neutral Kaons

M_K	500 MeV
Δm	3.5×10^{-6} ev
ε	7×10^{-9} ev
$M_{K^0} - M_{\overline{K}^0}$	$< 3.5 \times 10^{-10}$ ev
ε'	???

Covers 20 orders of magnitude in scale

Experiments simultaneously sensitive to strong, electromagnetic, weak, CP violating & gravity forces

$$\eta_{+-} = \frac{amp(K_L \to \pi^+\pi^-)}{amp(K_S \to \pi^+\pi^-)}$$

$$\eta_{00} = \frac{amp(K_L \to 2\pi^0)}{amp(K_S \to 2\pi^0)}$$

$$1 + 6\frac{\varepsilon'}{\varepsilon} = \frac{\dfrac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)}}{\dfrac{\Gamma(K_L \to 2\pi^0)}{\Gamma(K_S \to 2\pi^0)}}$$

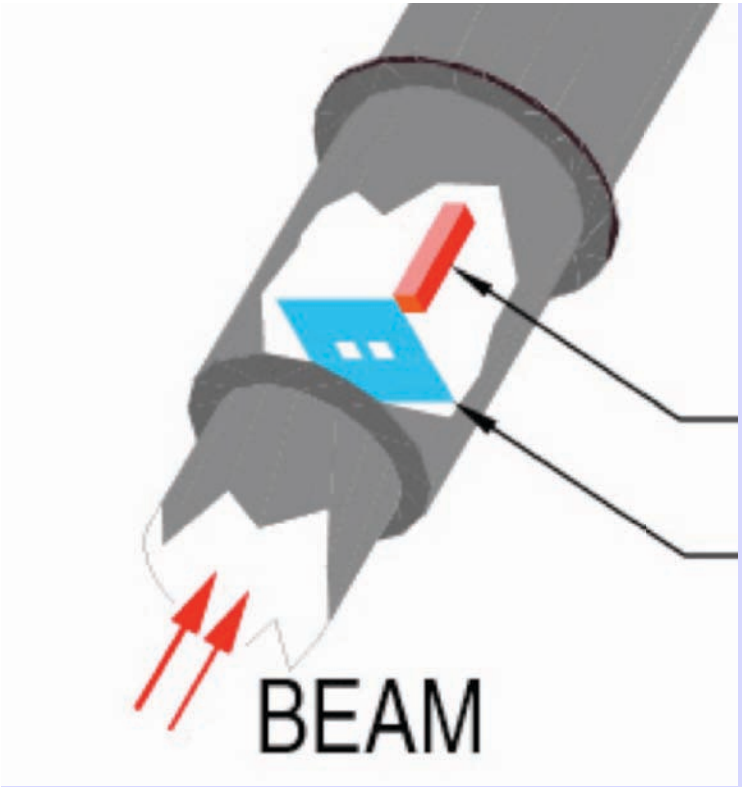
Is CP Violation purely in particle/anti-particle mixing: $K^0 \Leftrightarrow \overline{K}^0$

$\eta_{+-} = \eta_{00} = \varepsilon$: "Superweak Model"

Or is there also a "direct" component: ε' ?

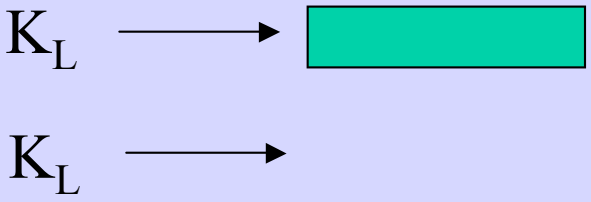
Primary Features of the Fermilab Approach

- Use of Regenerator to make K_S
  - Provides crucial checks and by-products
- Double Beam
  - Side-by-side K_S and K_L beams
    - Many potential systematic effects (nearly) cancel
- Precision em calorimetry
  - Lead glass, CsI
- Detailed Monte Carlo simulations
  - Beam and detector
  - Collection of high statistics decay modes
- Blind Analysis



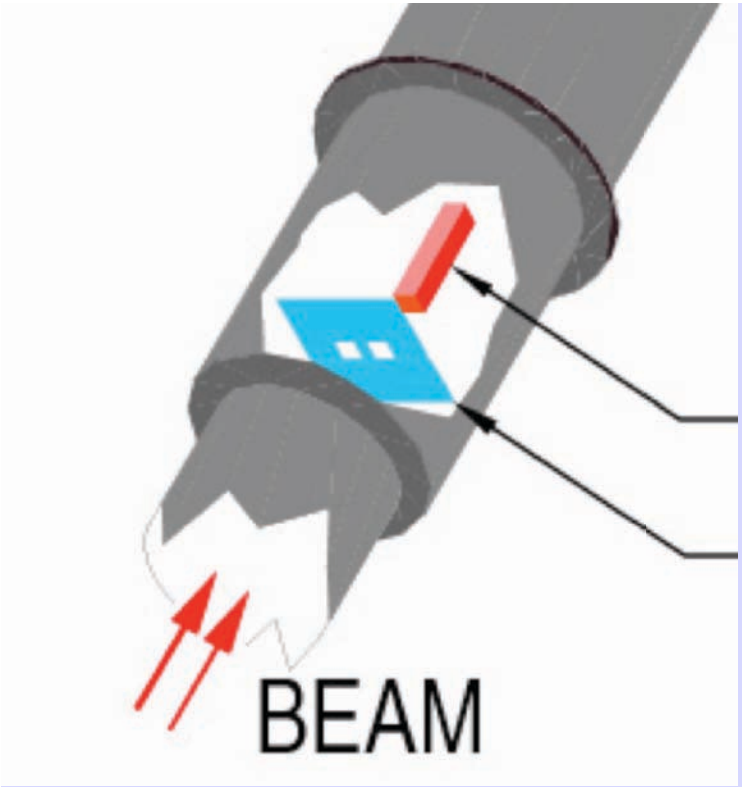
Double Beam
Regenerator to provide K_S
Tracking chambers $\pi^+\pi^-$
EM calorimeter $\pi^0\pi^0$

Measure $\frac{\rho}{\eta_\pm}, \frac{\rho}{\eta_{00}}$
Separately (later all 4 simultaneously)



$K_L + \rho K_S$
K_L
} $\pi^+\pi^-$ or $\pi^0\pi^0$

ρ=0.03



Double Beam
Regenerator to provide K_S
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EM calorimeter $\pi^0\pi^0$

Measure $\frac{\rho}{\eta_{\pm}}, \frac{\rho}{\eta_{00}}$

Separately (later all 4 simultaneously)

$K_L \longrightarrow$

$K_L \longrightarrow$ 

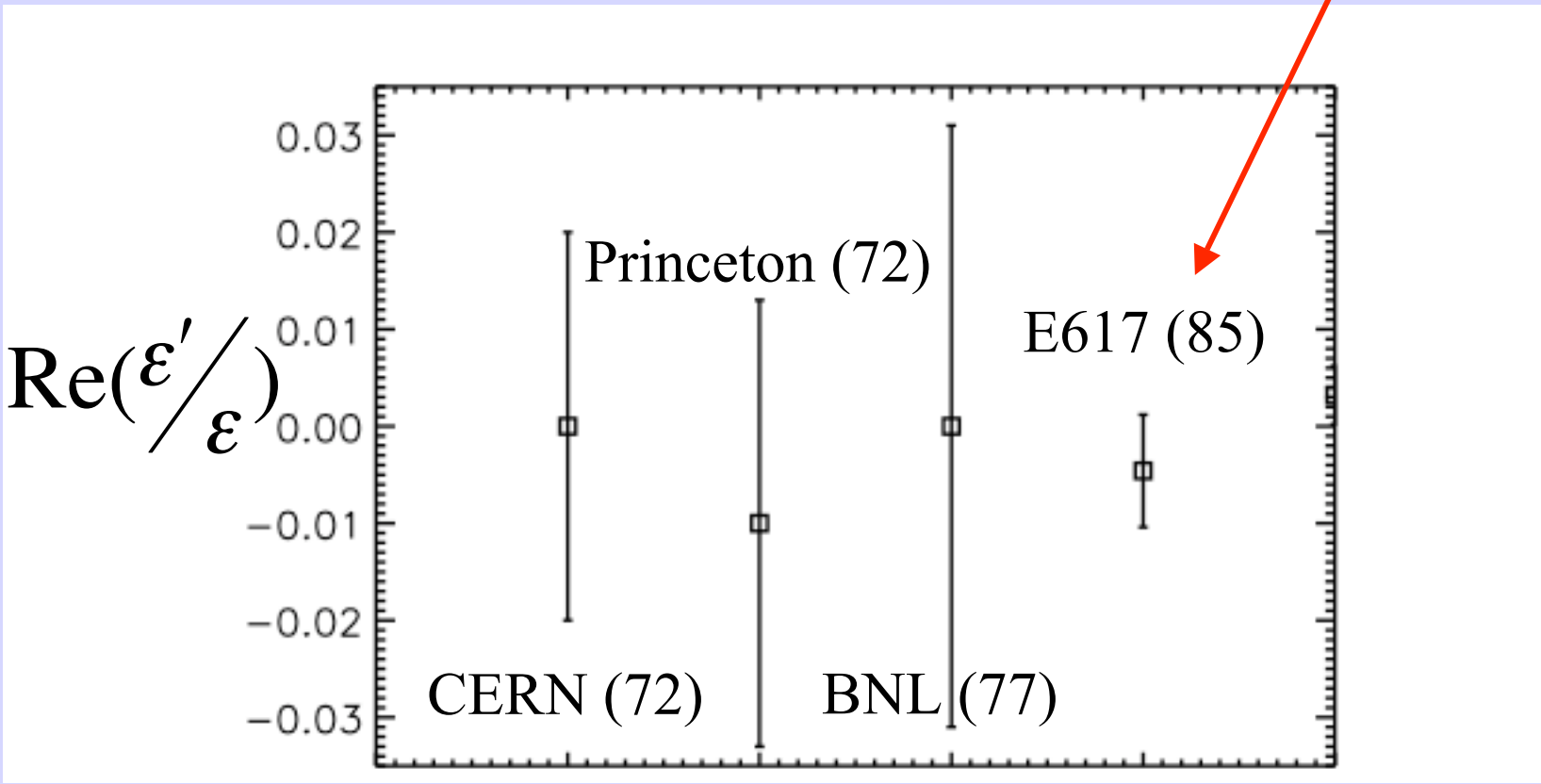
K_L
$K_L + \rho K_S$
} $\pi^+\pi^-$ or $\pi^0\pi^0$

ρ=0.03

Fermi/Marshall; Dicke Switching

The Early Measurements

3100 $2\pi^0$ events



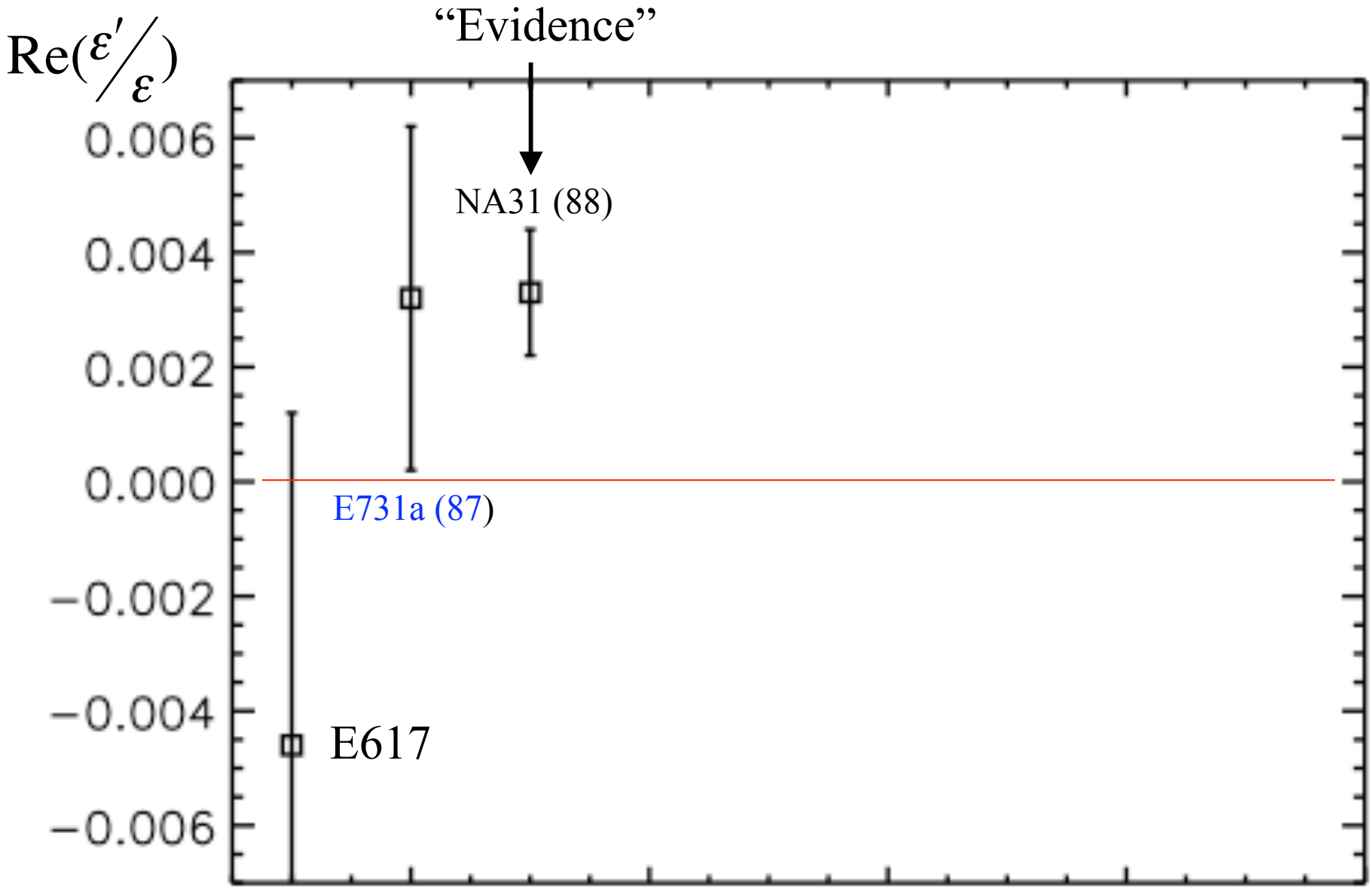
Subsequent Experiments

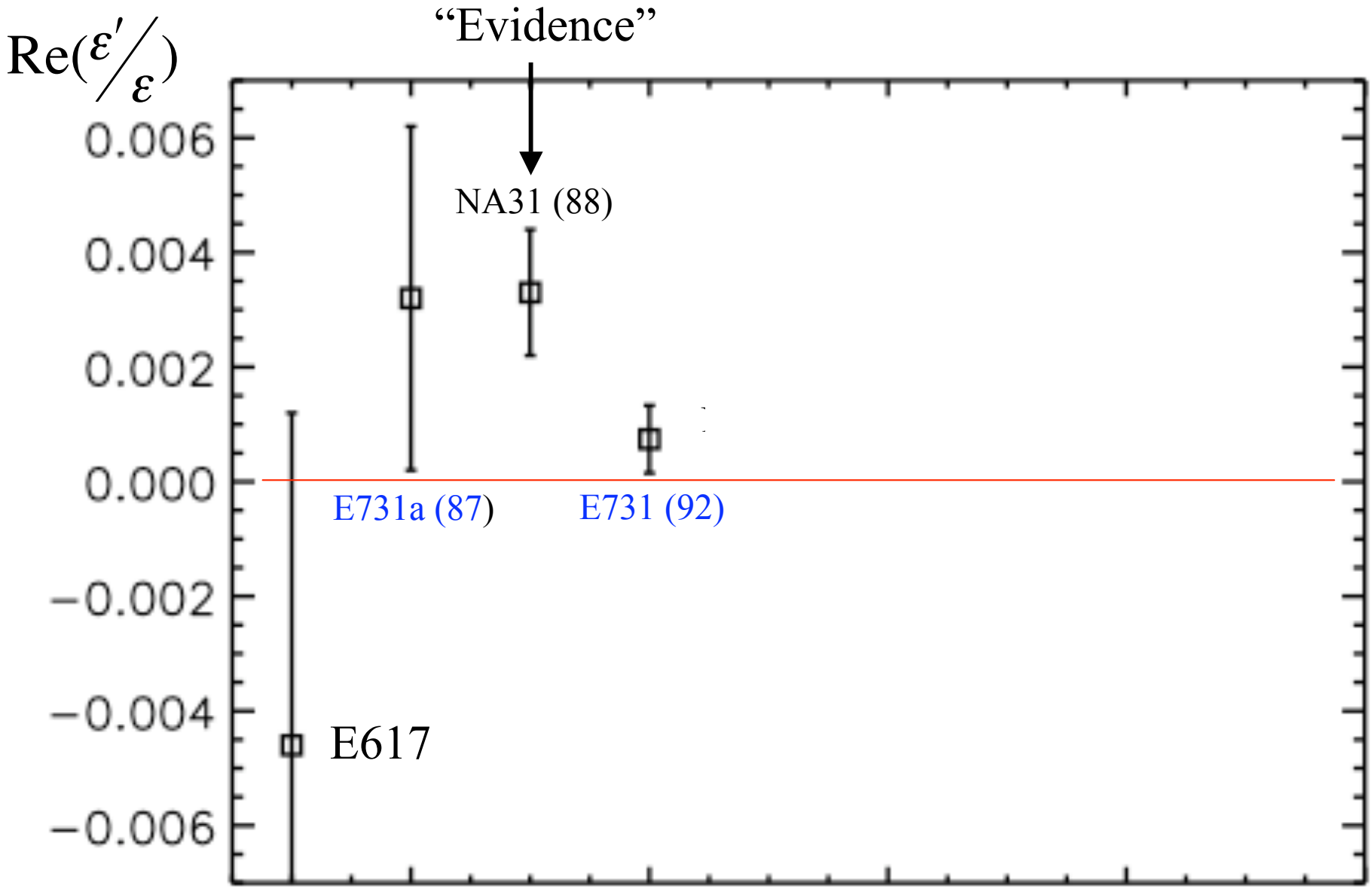
- FNAL
  - E731
  - E773
  - E799
  - KTeV
- CERN
  - NA31
  - NA48[1]
- "Collider" experiments:
  - CERN
  - Frascati

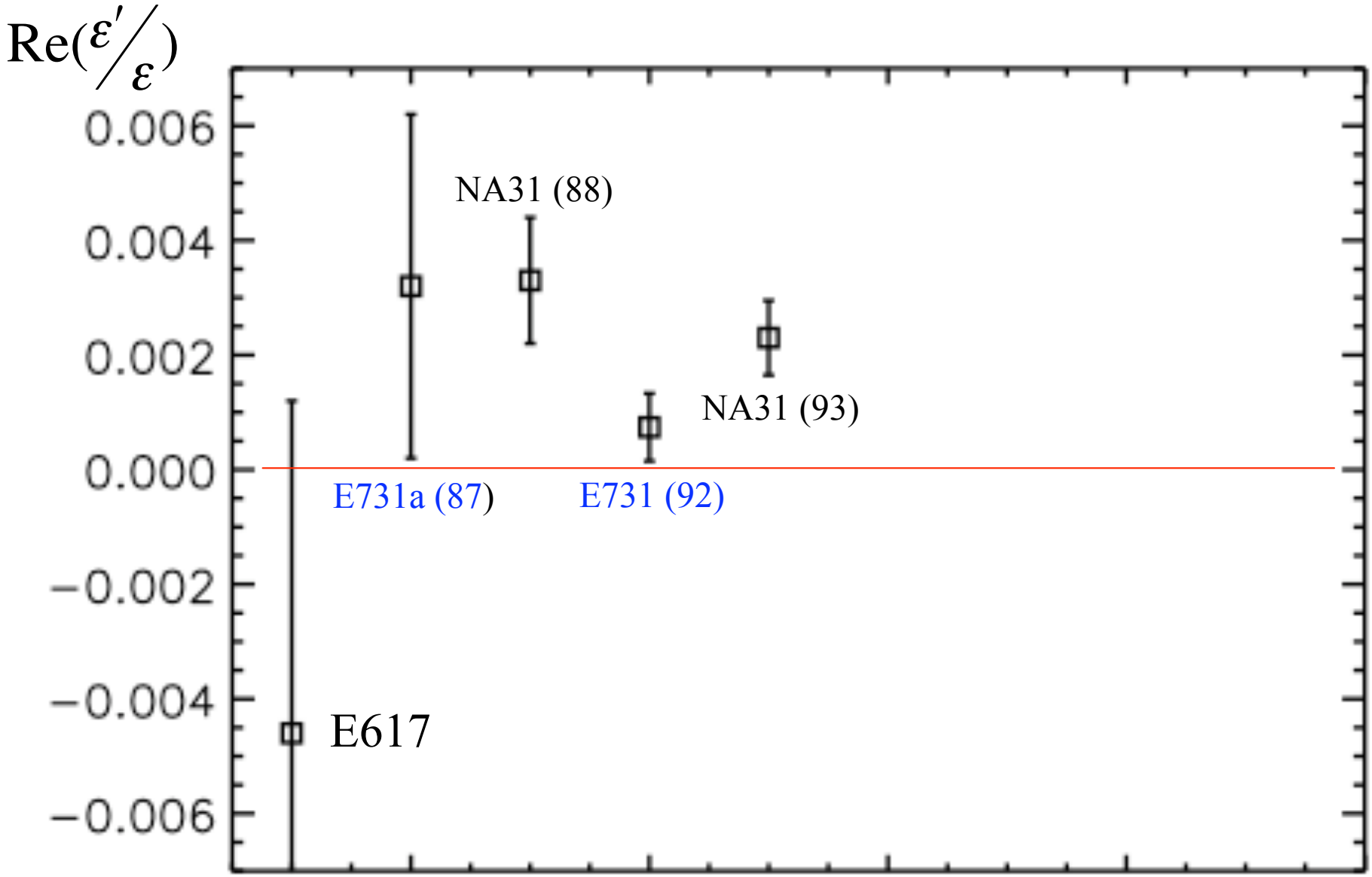
1) Bernard Peyaud, Rene Turlay

From the E731 Proposal 1983

We also note that we will remove the vacuum pipe which carried the neutron beam through the apparatus; now the beam will travel through Helium. The total neutron interaction rate will be only about 60 KHz assuming no improvement in the anomalous neutron flux. The removal of the pipe gives us another factor of 2 in acceptance.

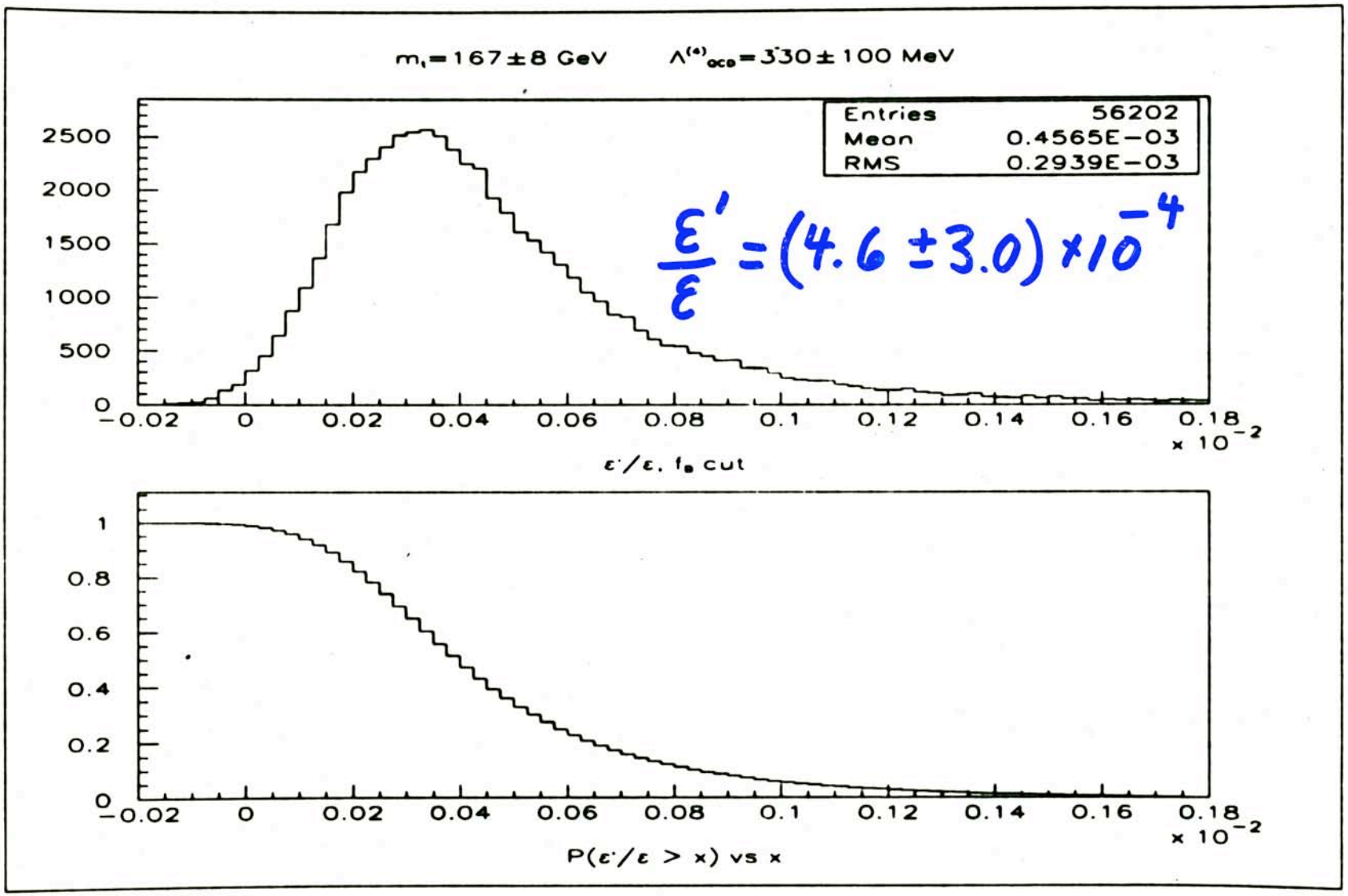

Re(ε′/ε)
"Evidence"
NA31 (88)
0.006
0.004
0.002
0.000
−0.002
−0.004
−0.006
E731a (87)
E617

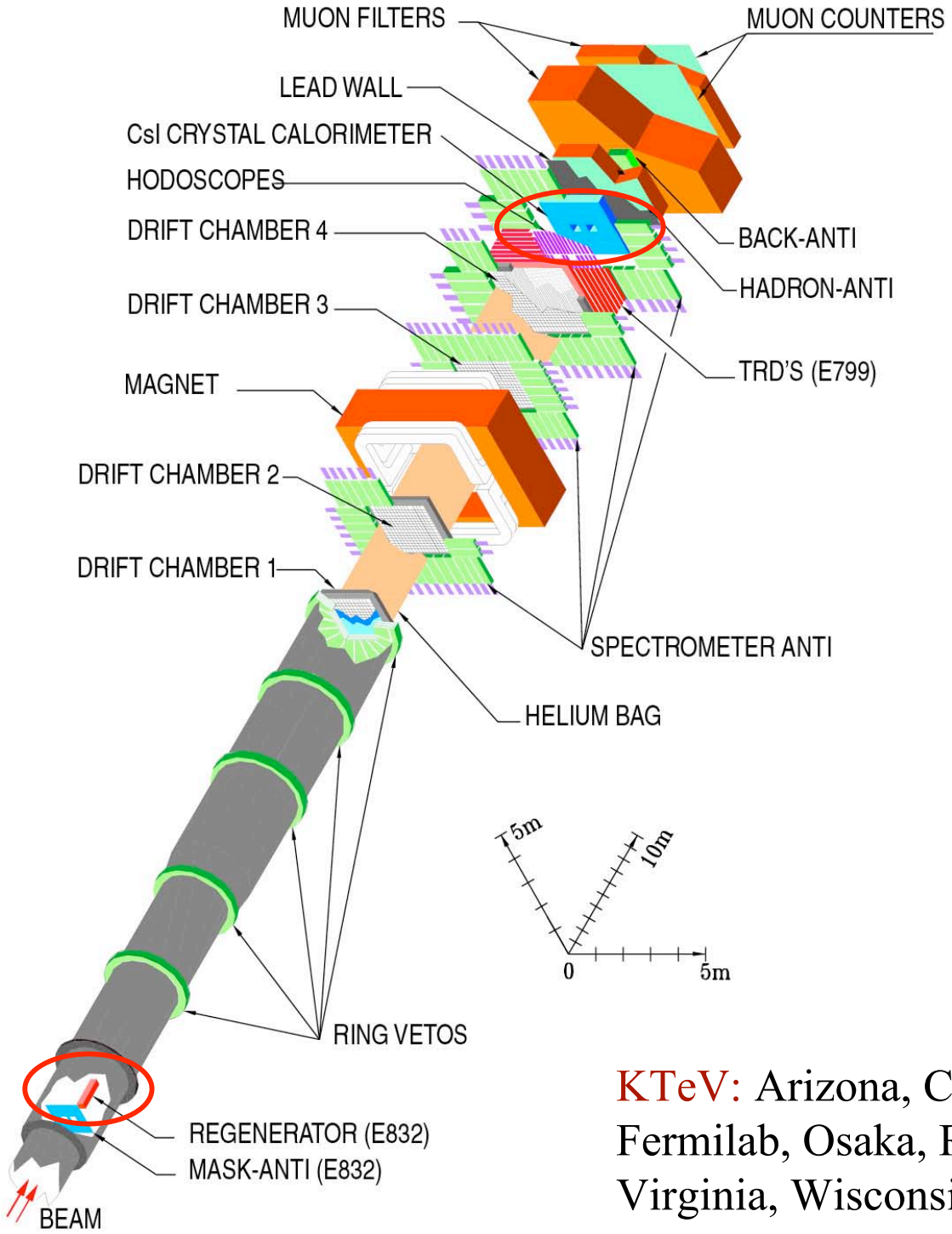

Re(ε′/ε)
"Evidence"
NA31 (88)
0.006
0.004
0.002
0.000
−0.002
−0.004
−0.006
E731a (87)
E731 (92)
E617


Re(ε′/ε)
0.006
0.004
0.002
0.000
−0.002
−0.004
−0.006
NA31 (88)
NA31 (93)
E731a (87)
E731 (92)
E617

Predictions at the time

Ciuchini et al.

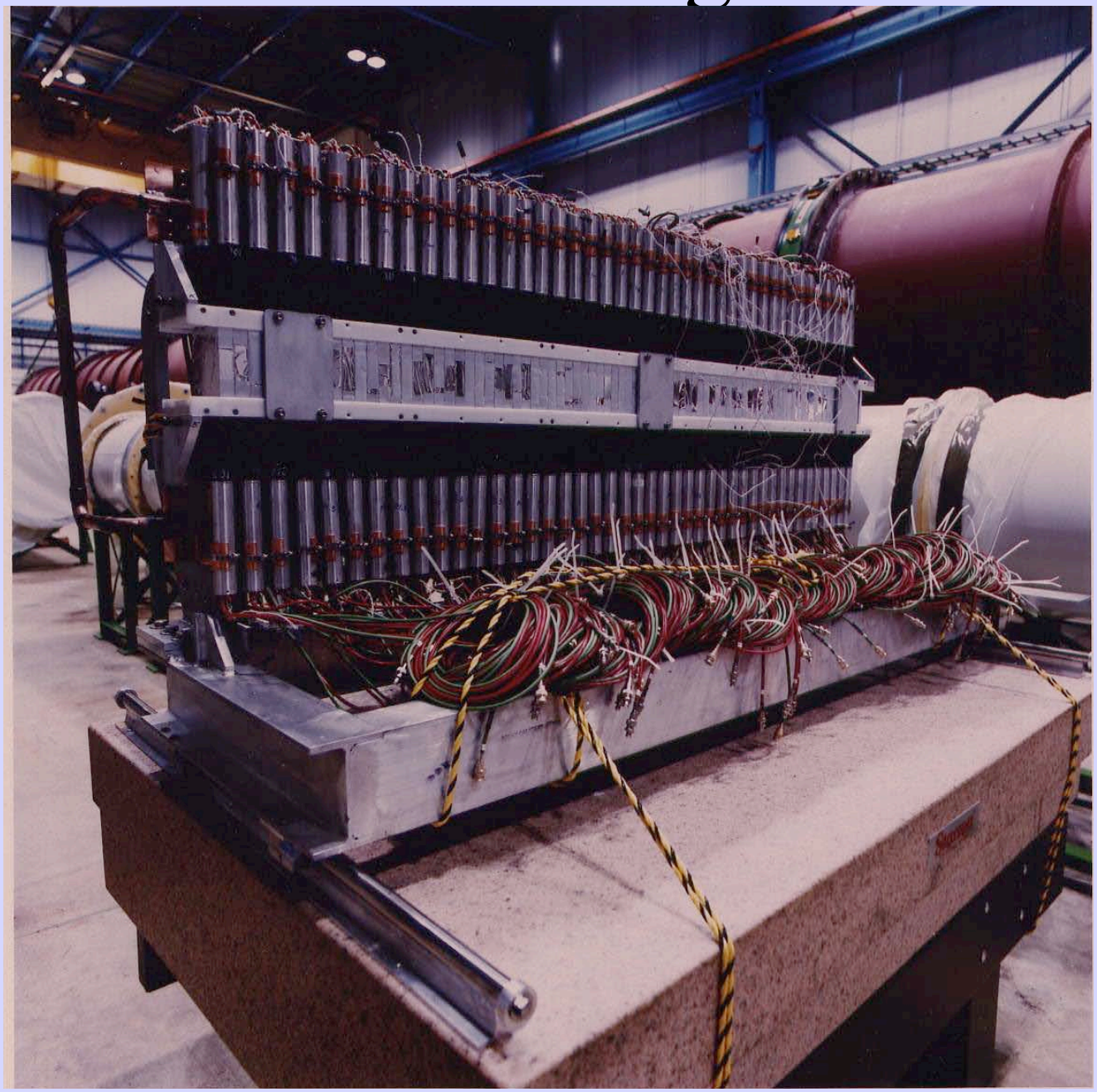




KTeV Detector

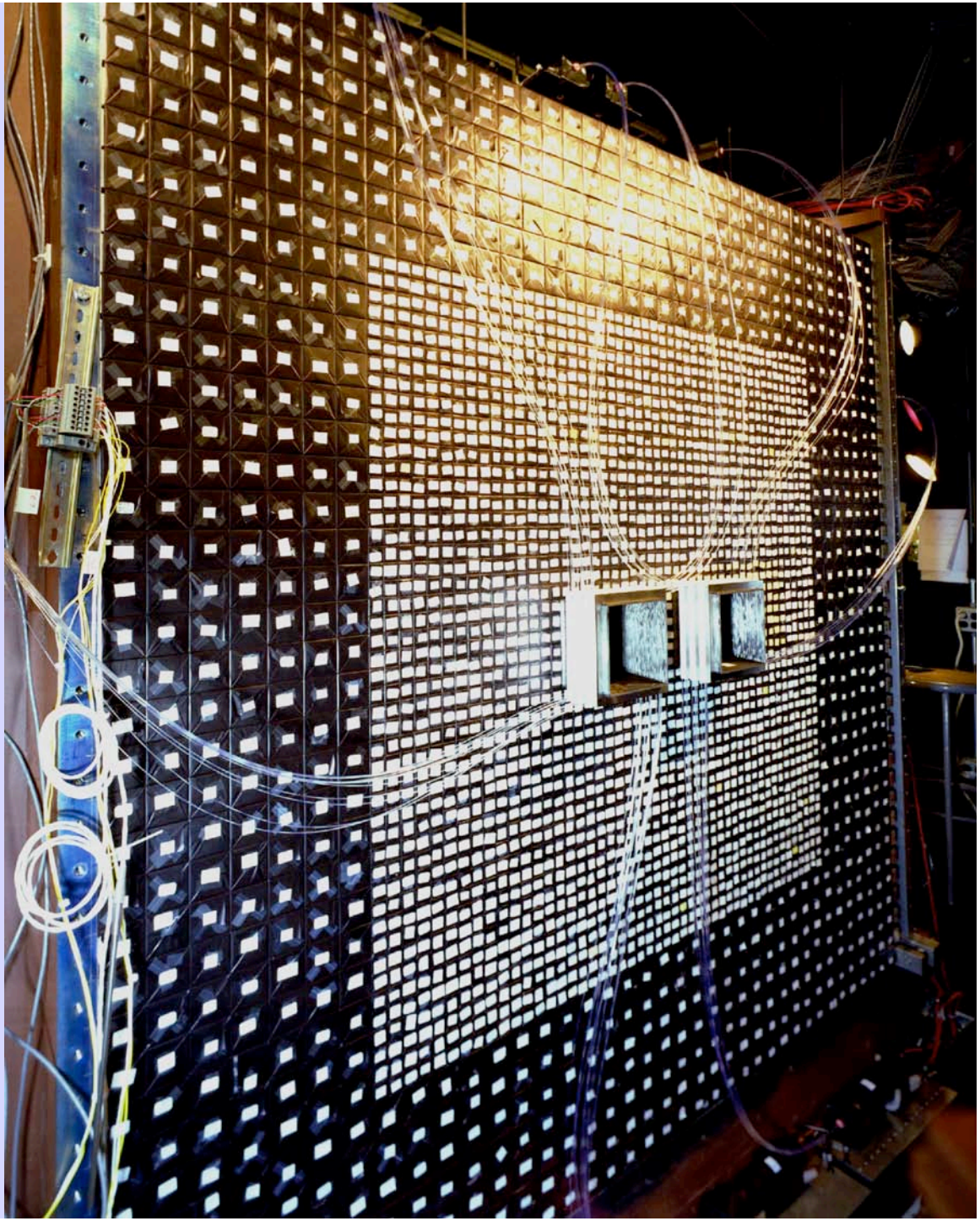
KTeV: Arizona, Chicago, Colorado, Elmhurst, Fermilab, Osaka, Rice, Rutgers, UCLA, UCSD, Virginia, Wisconsin

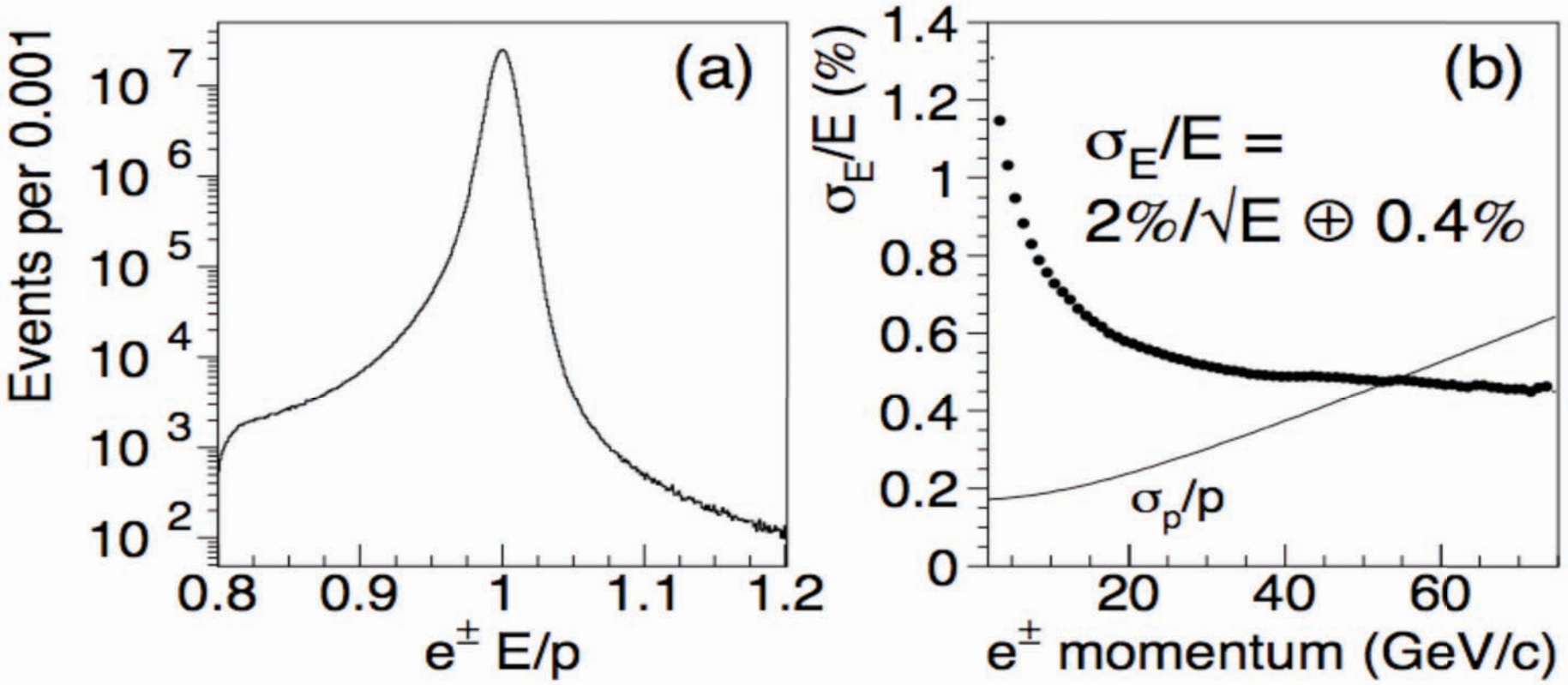
KTeV Active Regenerator



KTEV em Calorimeter for $K_L \rightarrow \pi^0\pi^0$

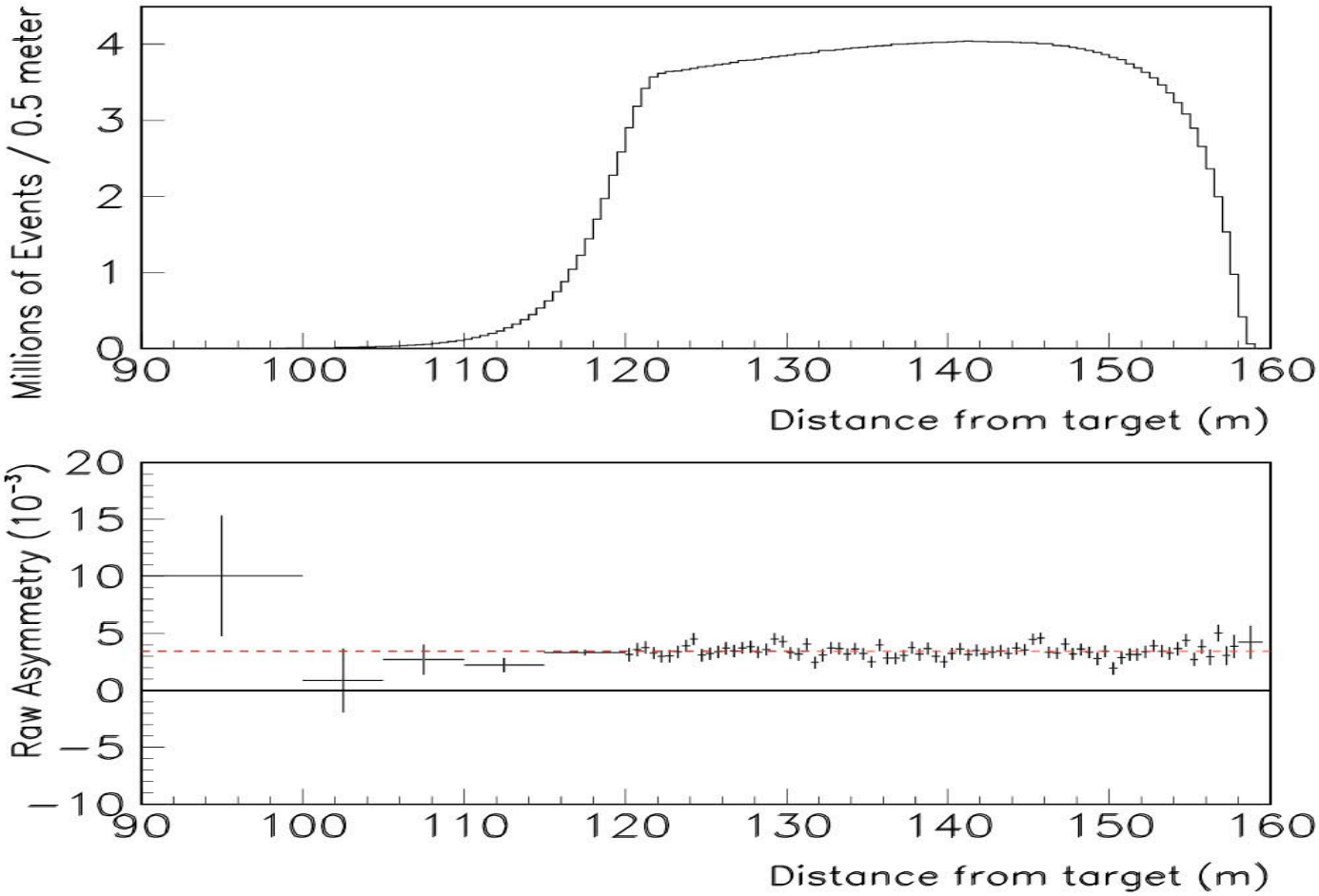
3100 Pure CsI crystals
27 rl





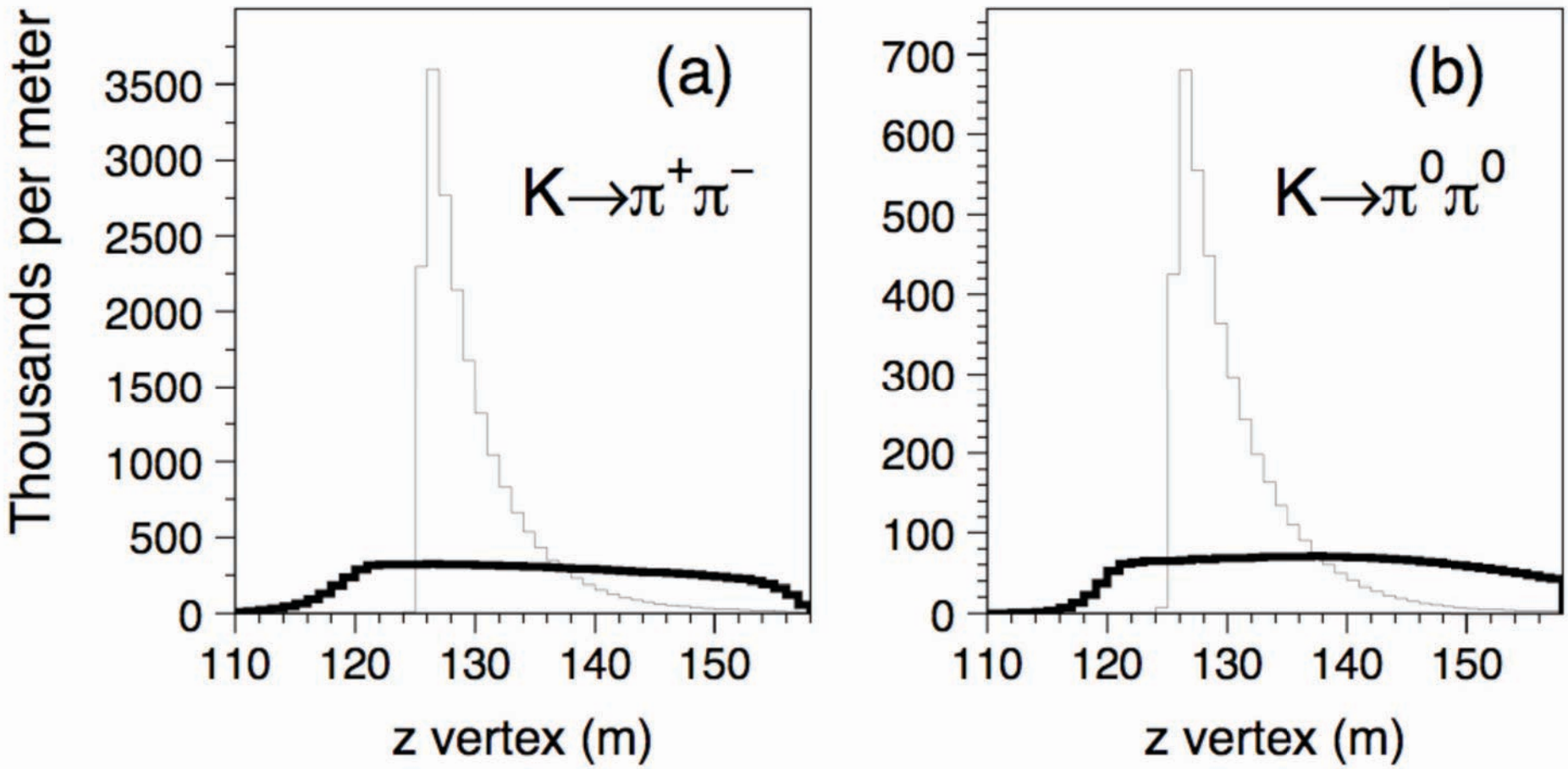
- ~2x10^9 Ke3 decays used for calibration
  - 0.03%/day/crystal

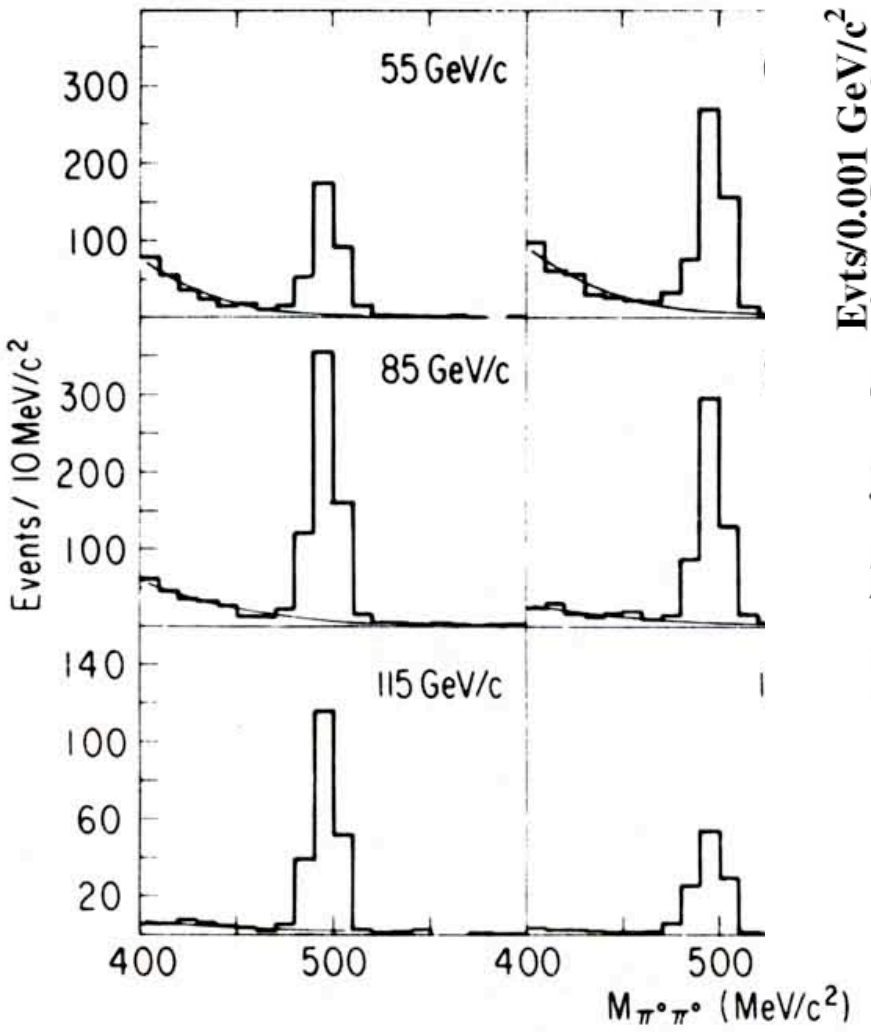
Semileptonic Charge Asymmetry from KTeV

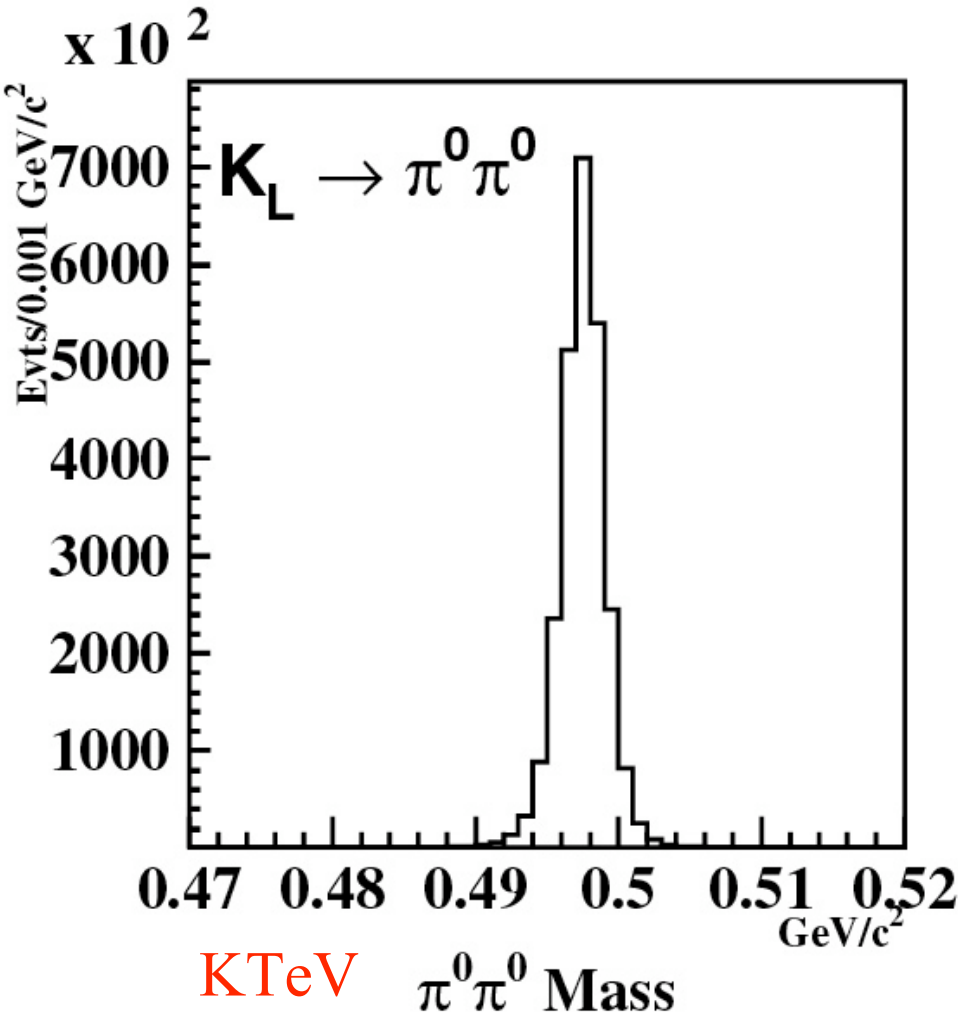


$\delta_L(\text{raw}) = (3.42 \pm 0.06) \times 10^{-3}$

$\delta_L = (3.32 \pm 0.06 \pm 0.05) \times 10^{-3}$


Thousands per meter
3500
3000
2500
2000
1500
1000
500
0
110
120
130
140
150
z vertex (m)
(a)
K→π+π−
700
600
500
400
300
200
100
0
110
120
130
140
150
z vertex (m)
(b)
K→π0π0





KTeV $\pi^0\pi^0$ Mass

FIG. 2. Invariant-mass distributions for $K_L \rightarrow 2\pi^0$ candidates with $P_t^2 < 2500$ (MeV/c)^2. A fit to the background is superimposed.

E617

Yield after Background Subtraction

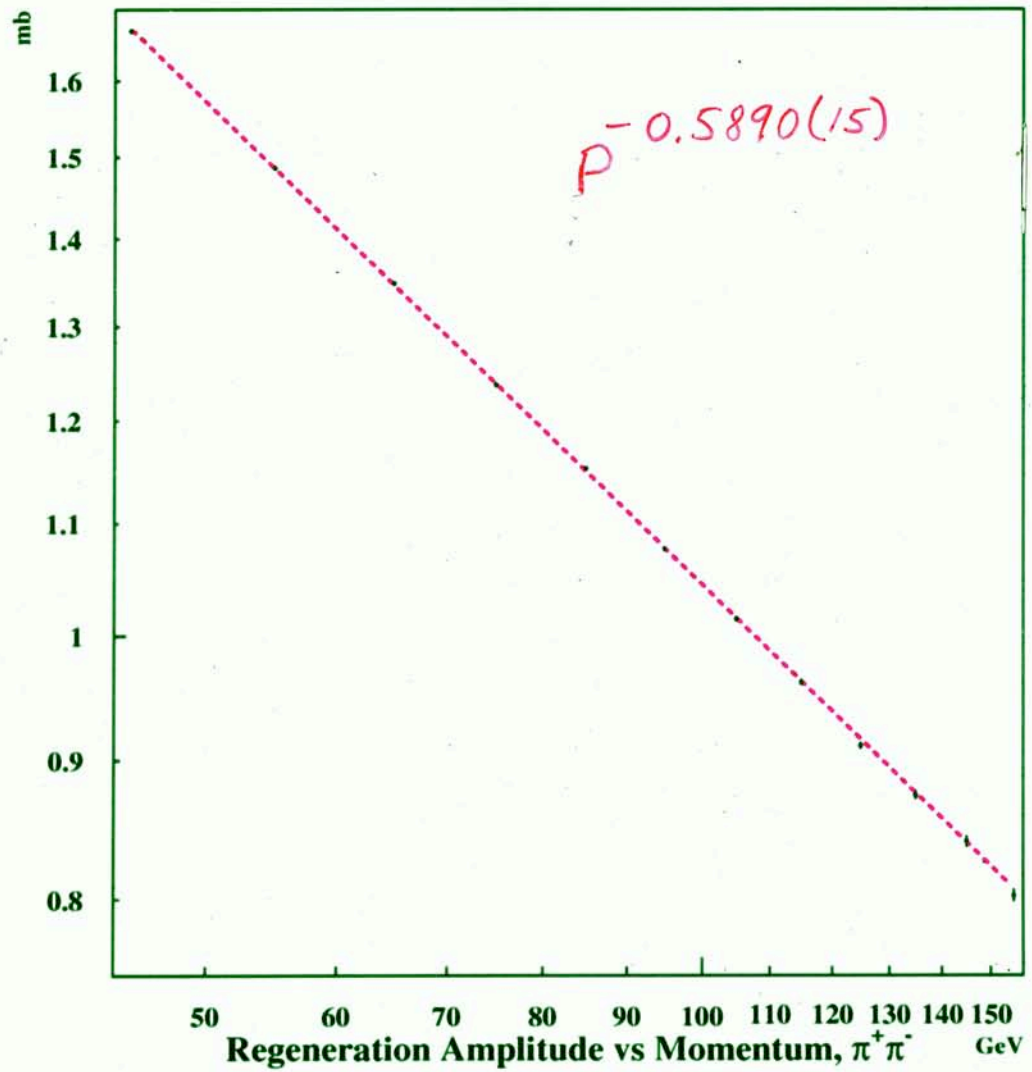
	K_L Vacuum Beam	"K_S" Reg. Beam
$K \to \pi^+\pi^-$	8,593,988	14,903,532
$K \to \pi^0\pi^0$	2,489,537	4,130,392

Raw double ratio:

$$R = \frac{8593988/14903532}{2489537/4130392} = 0.96$$

(no acceptance correction)

Regeneration Amplitudes Determined by Fitter

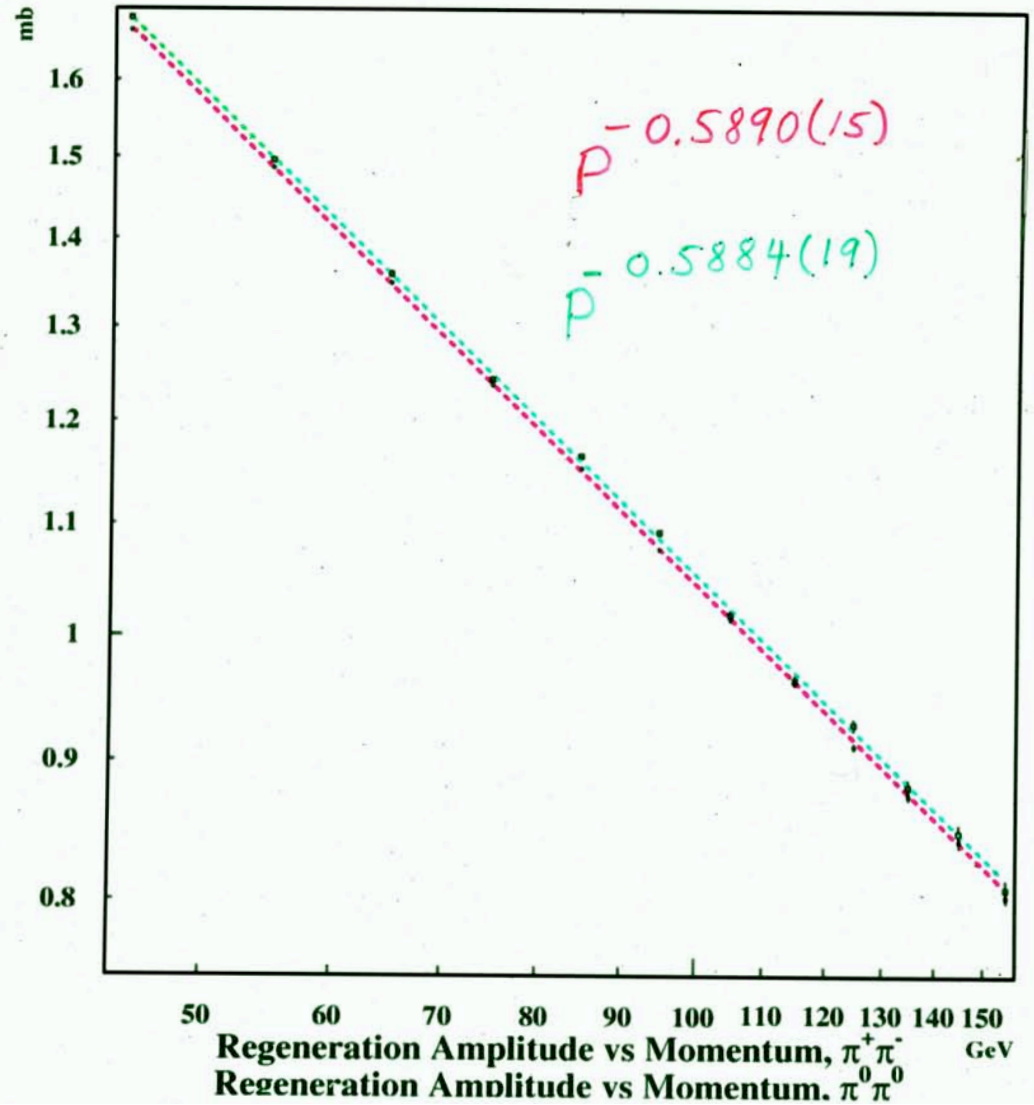


$P^{-0.5890(15)}$

$\chi^2 = 10.5/10$

$\frac{K_S \to \pi^+\pi^-}{K_L \to \pi^+\pi^-}$

Regeneration Amplitudes Determined by Fitter



$K_S \to \pi^+\pi^-$

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

$p^{-0.5890(15)}$

$\chi^2 = 10.5/10$

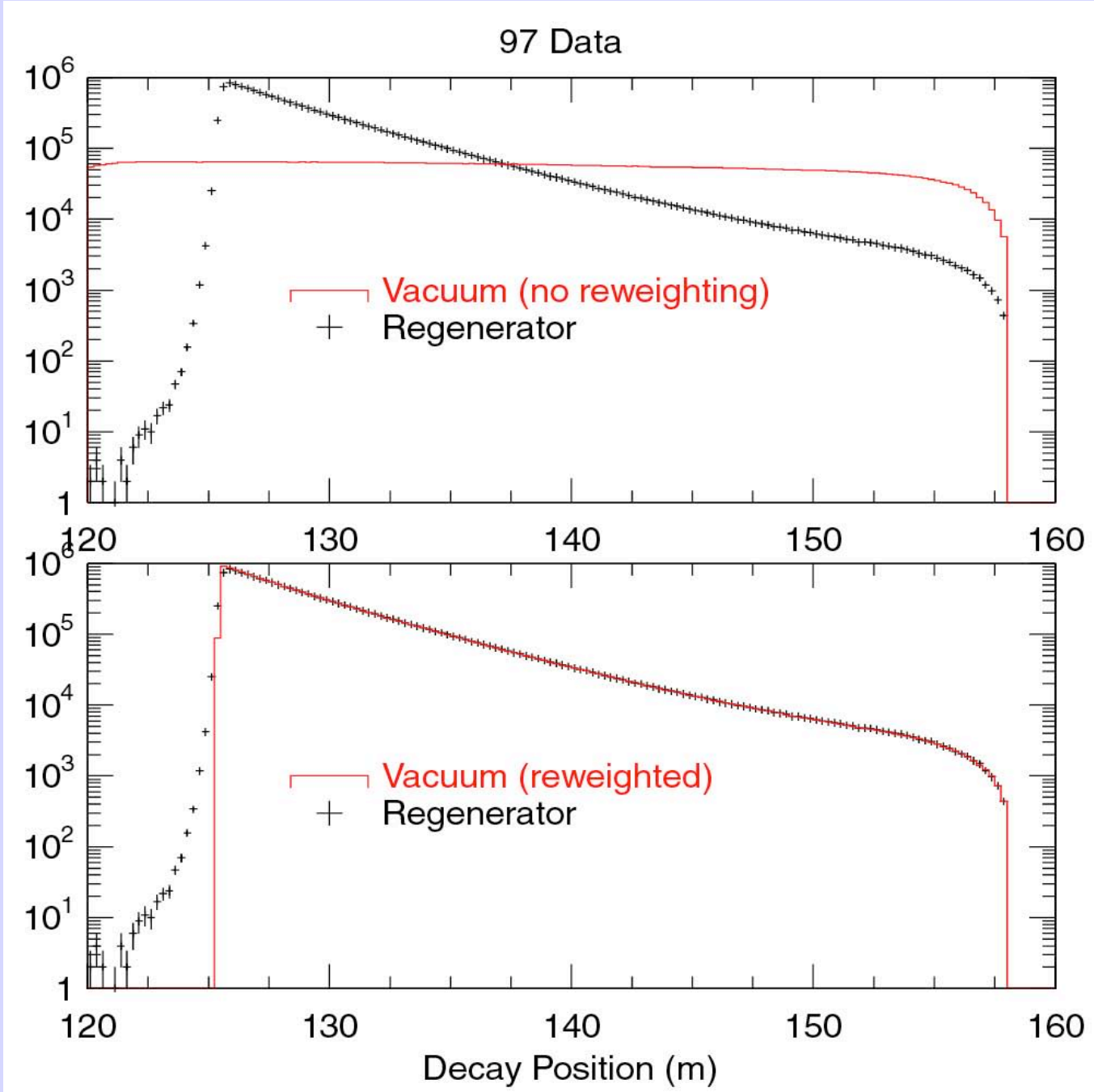
$K_S \to \pi^0\pi^0$

$K_L \to \pi^0\pi^0$

$p^{-0.5884(19)}$

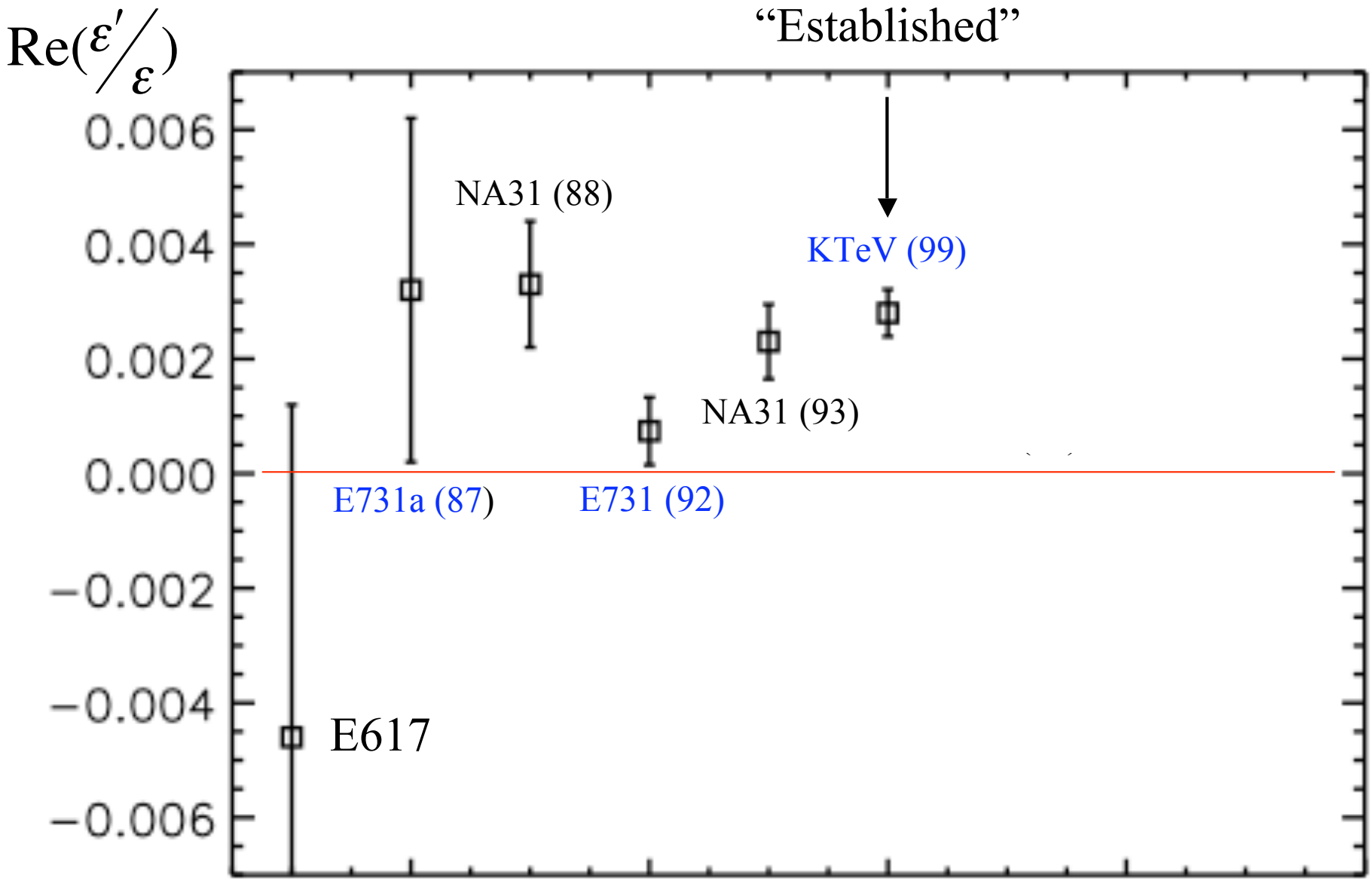
$\chi^2 = 16.2/10$

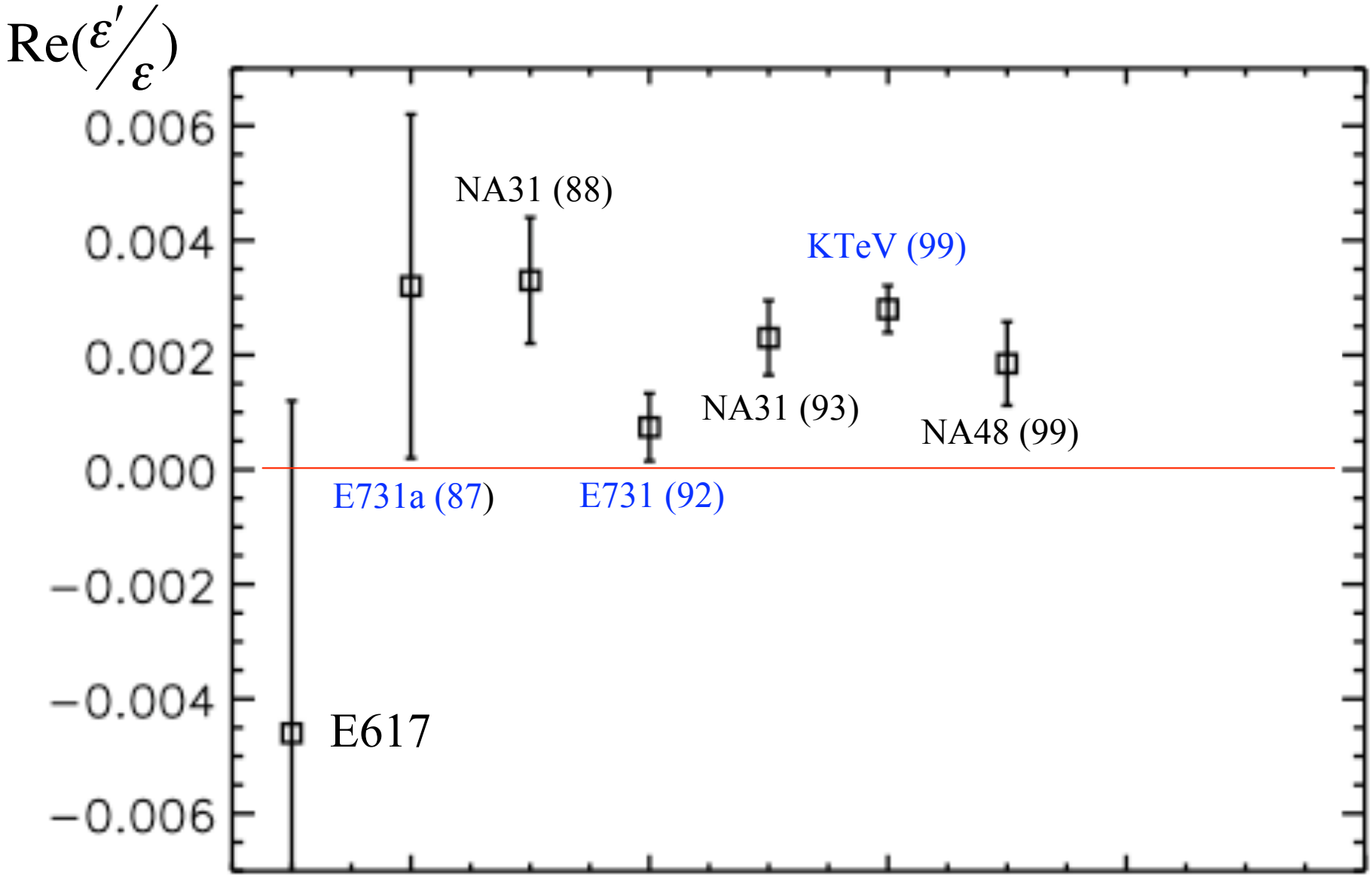
Reweight K_L decays to reg. beam distribution.

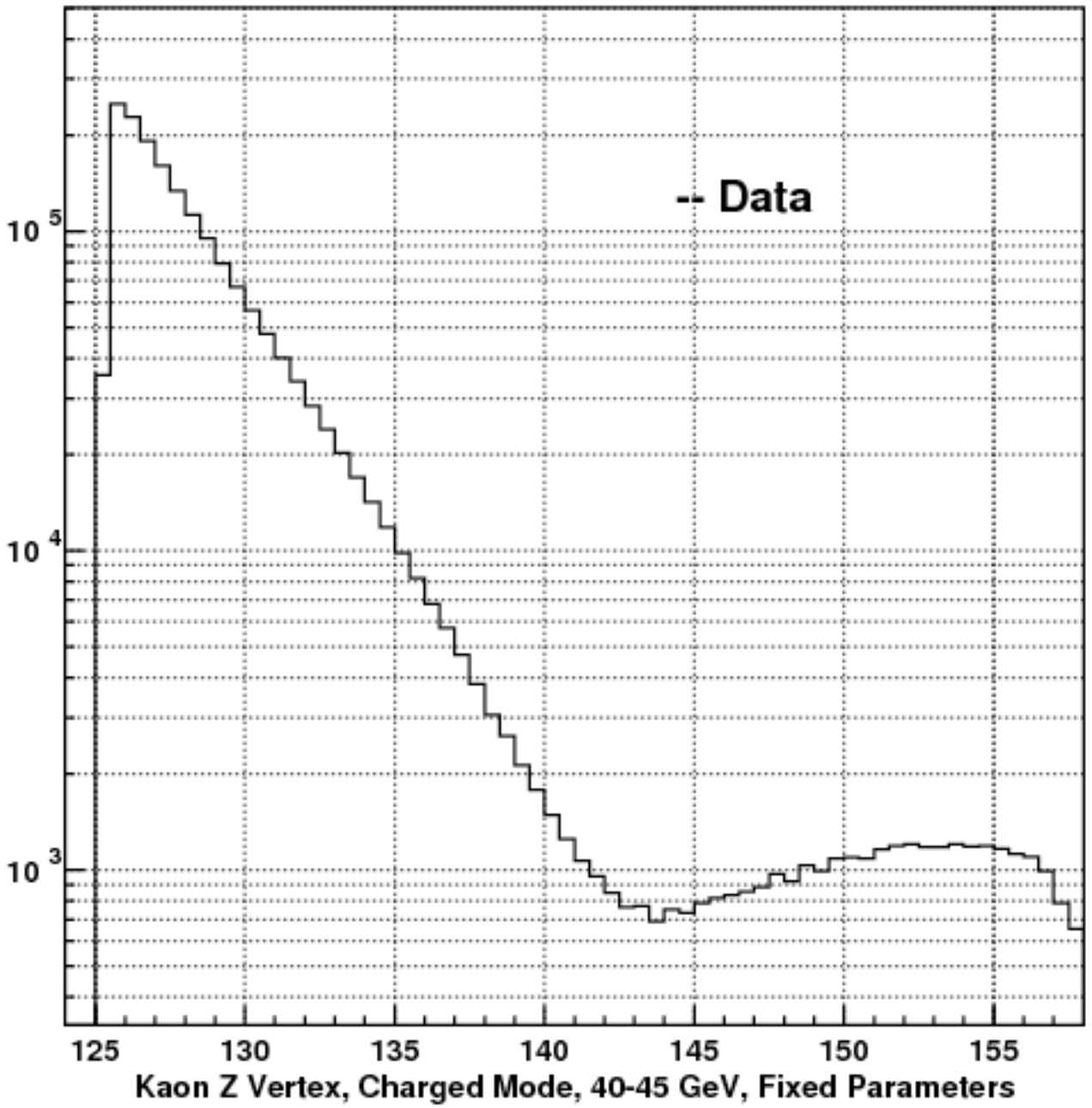


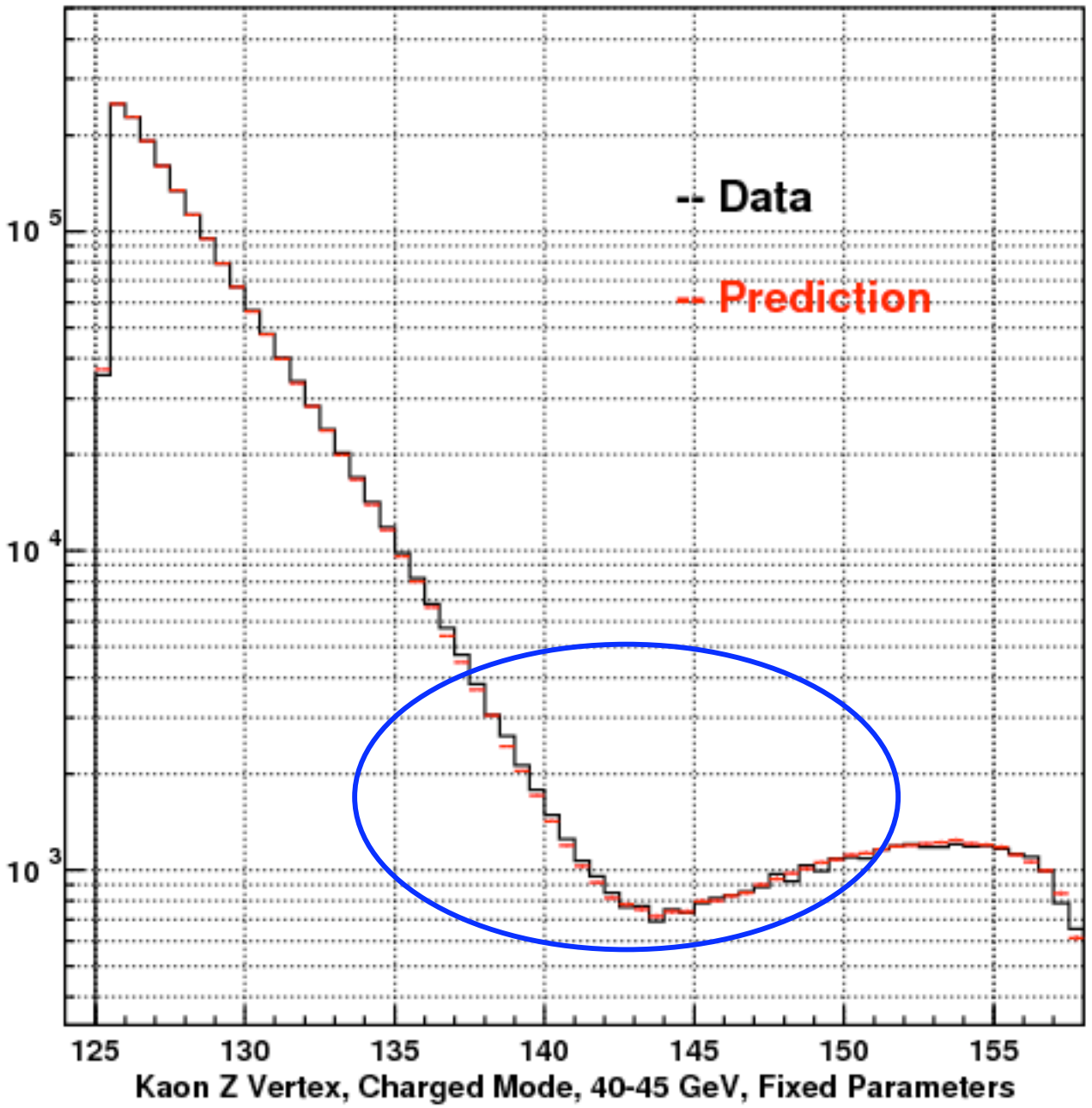
Needs no Monte Carlo

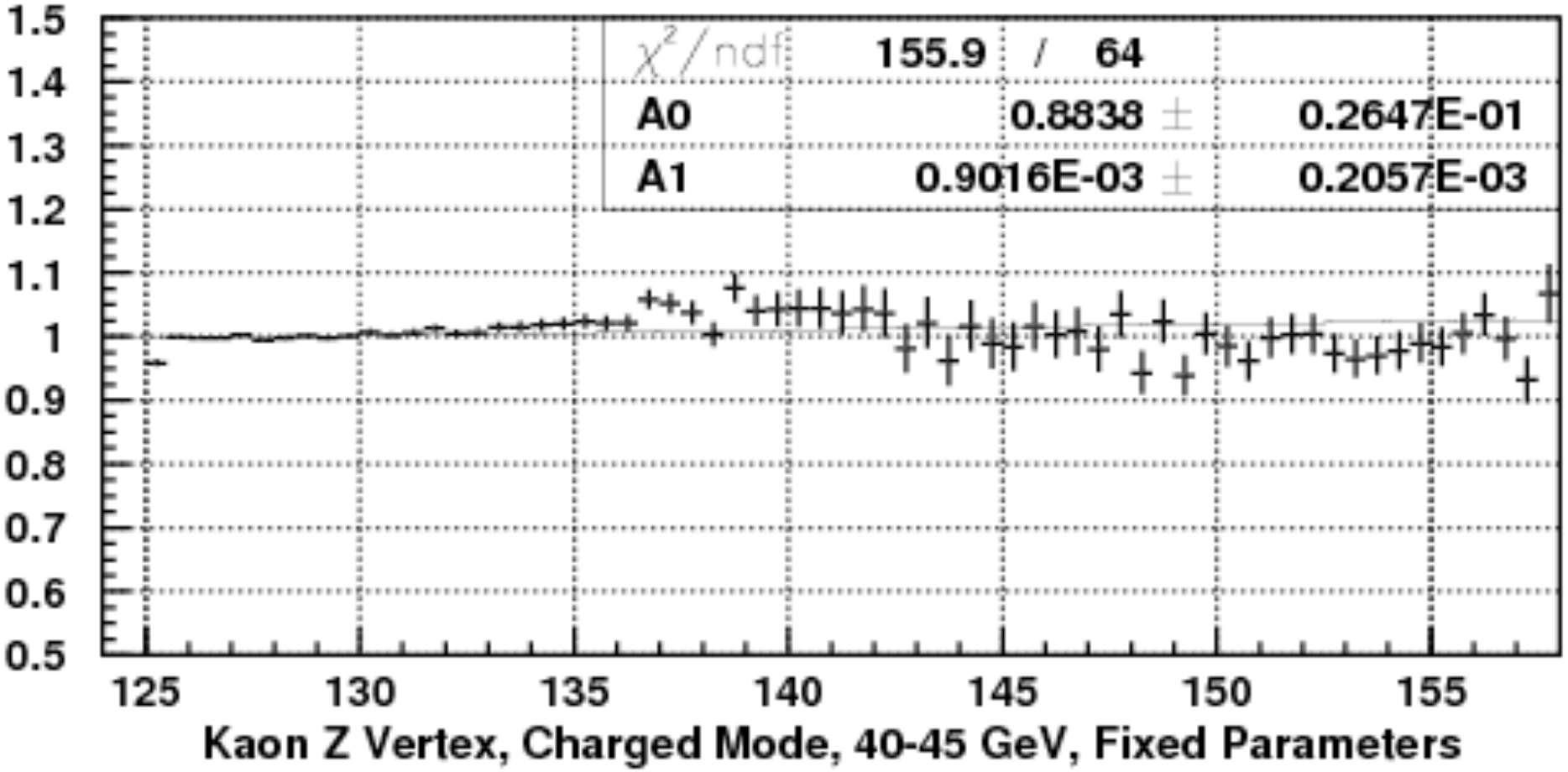
Used by NA48

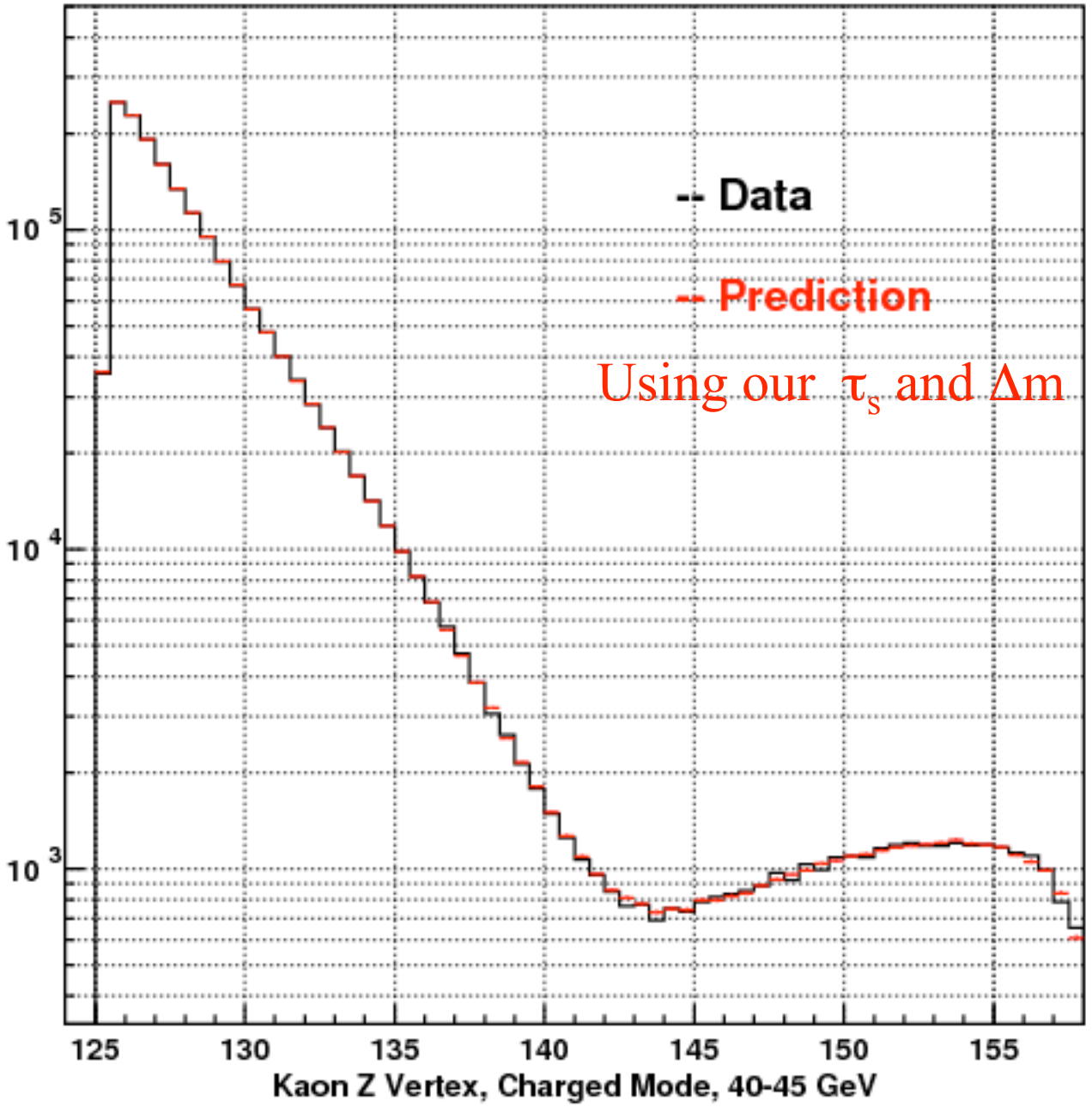

Re(ε′/ε)
"Established"
0.006
0.004
0.002
0.000
−0.002
−0.004
−0.006
NA31 (88)
KTeV (99)
NA31 (93)
E731a (87)
E731 (92)
E617


Re(ε′/ε)
0.006
0.004
0.002
0.000
−0.002
−0.004
−0.006
NA31 (88)
KTeV (99)
NA31 (93)
NA48 (99)
E731a (87)
E731 (92)
E617

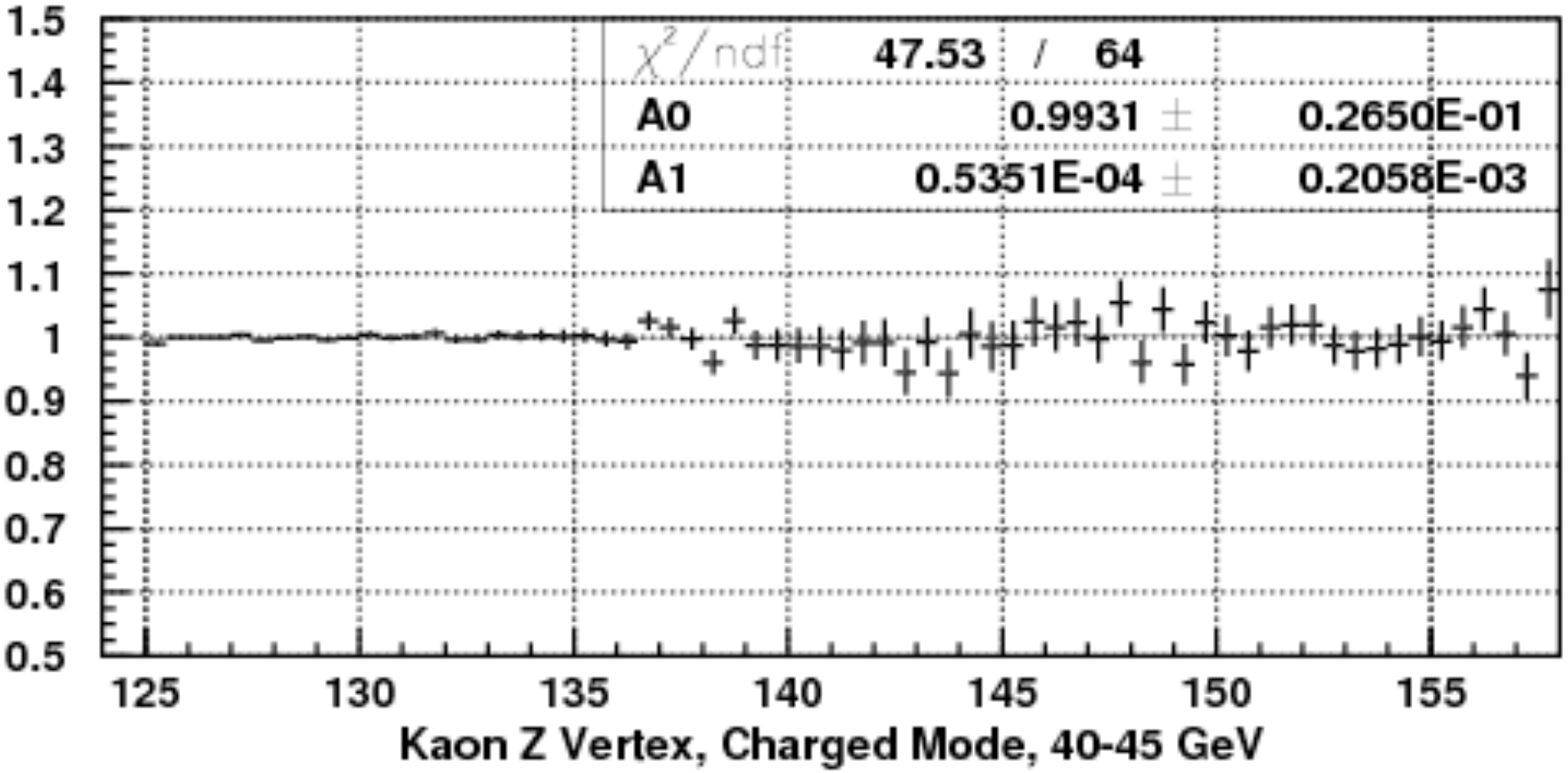

-- Data
10 5
10 4
10 3
125
130
135
140
145
150
155
Kaon Z Vertex, Charged Mode, 40-45 GeV, Fixed Parameters


-- Data
-- Prediction
10 5
10 4
10 3
125
130
135
140
145
150
155
Kaon Z Vertex, Charged Mode, 40-45 GeV, Fixed Parameters

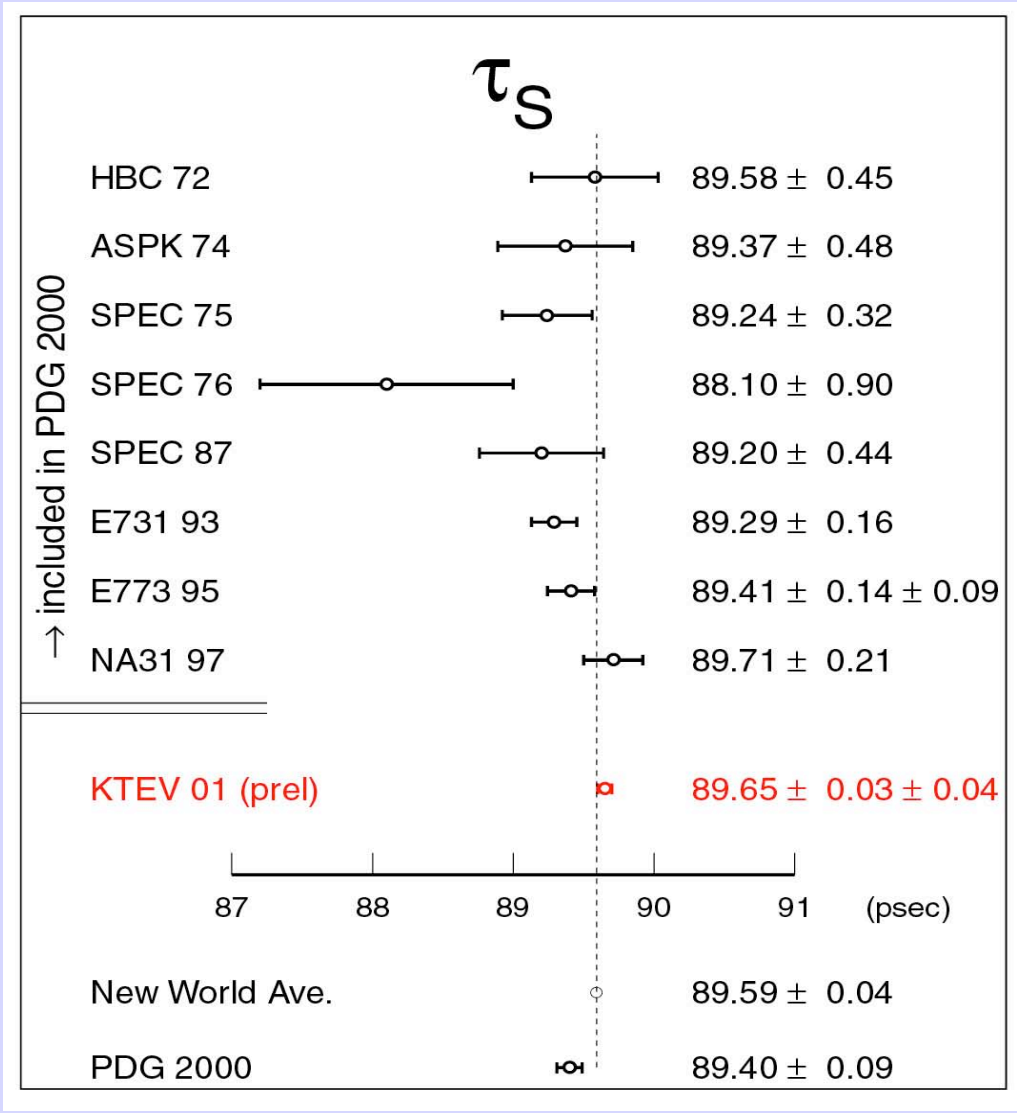

χ²/ndf 155.9 / 64
A0 0.8838 ± 0.2647E-01
A1 0.9016E-03 ± 0.2057E-03
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
125
130
135
140
145
150
155
Kaon Z Vertex, Charged Mode, 40-45 GeV, Fixed Parameters


-- Data
-- Prediction
Using our τ_s and Δm
10^5
10^4
10^3
125
130
135
140
145
150
155
Kaon Z Vertex, Charged Mode, 40-45 GeV

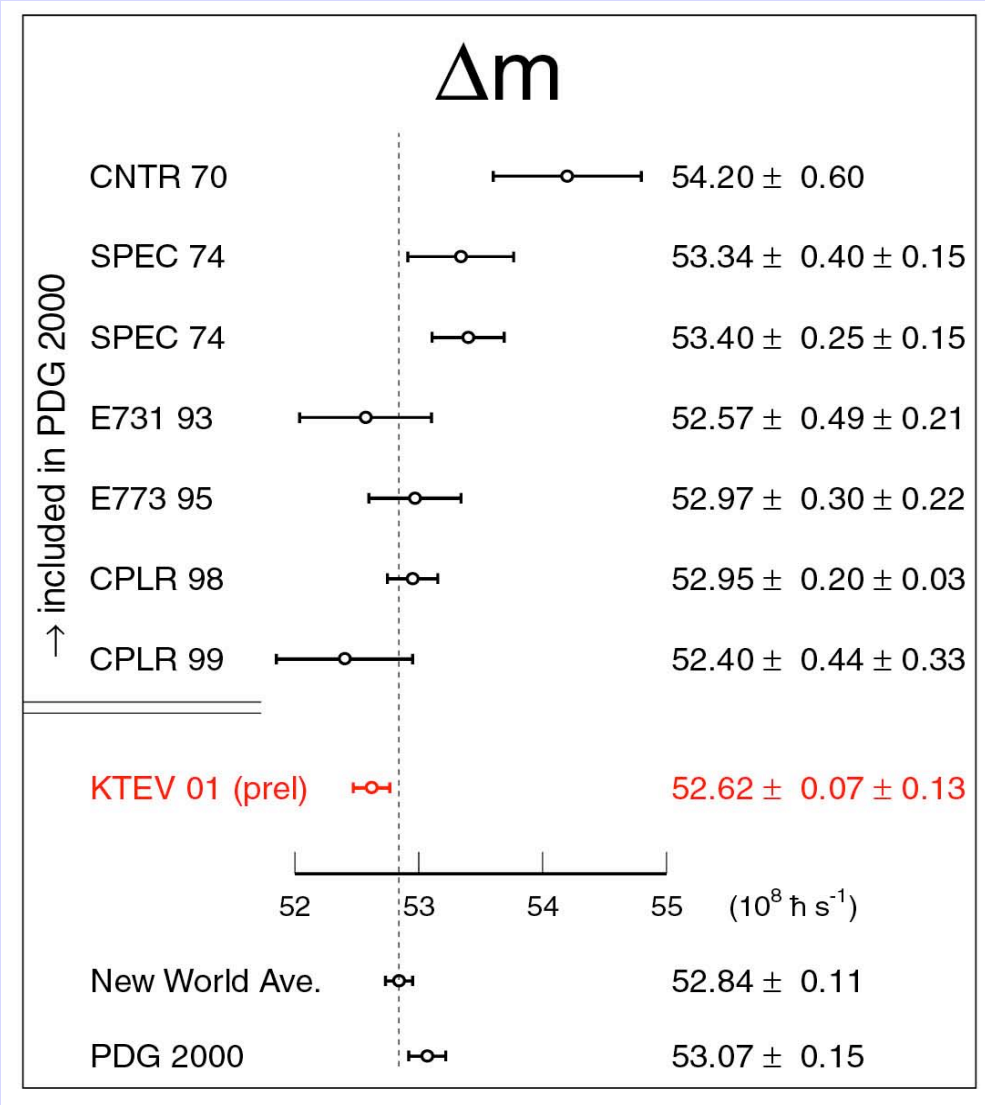
Using our τ_s and Δm



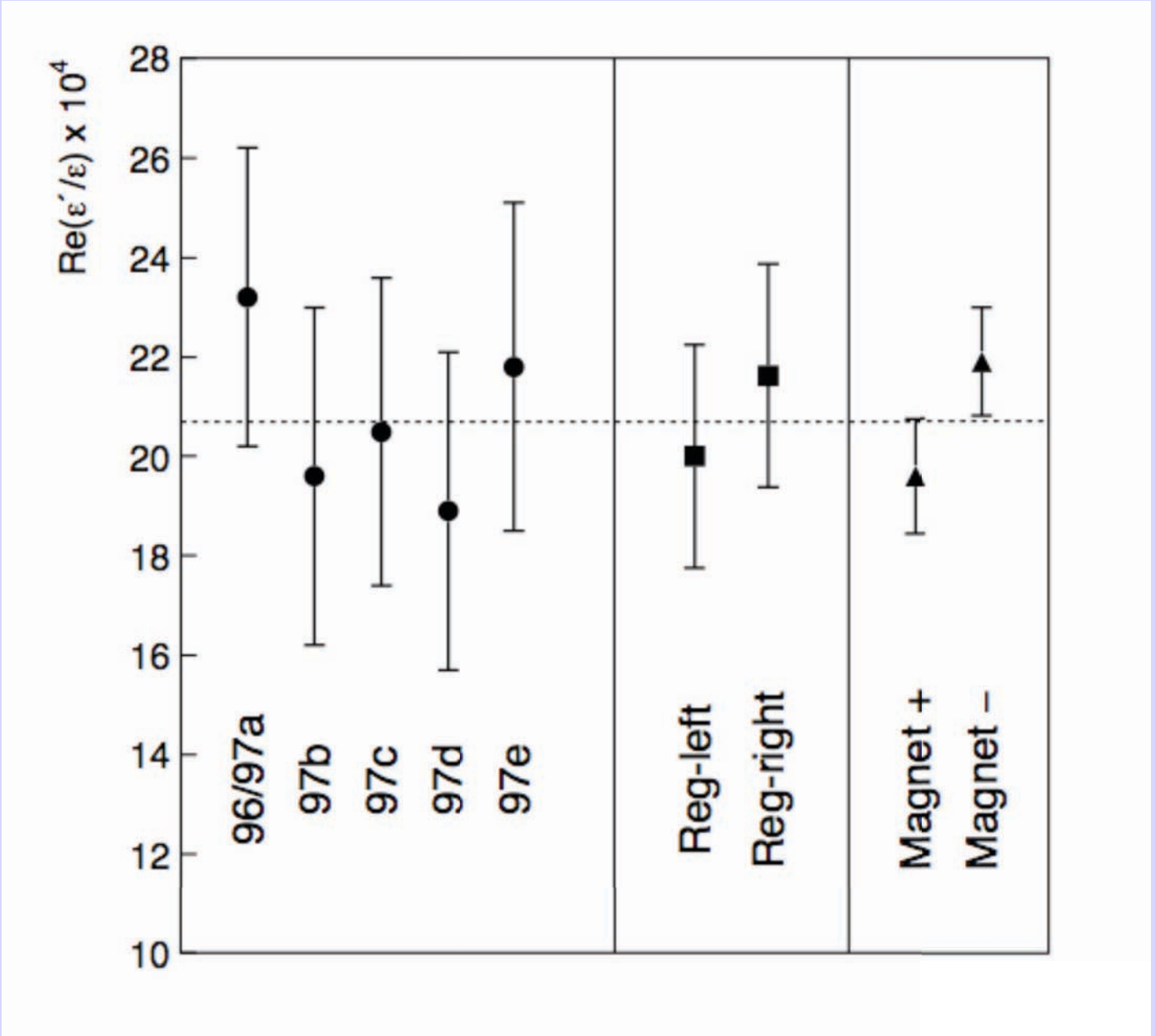
History of K_S Lifetime Measurements

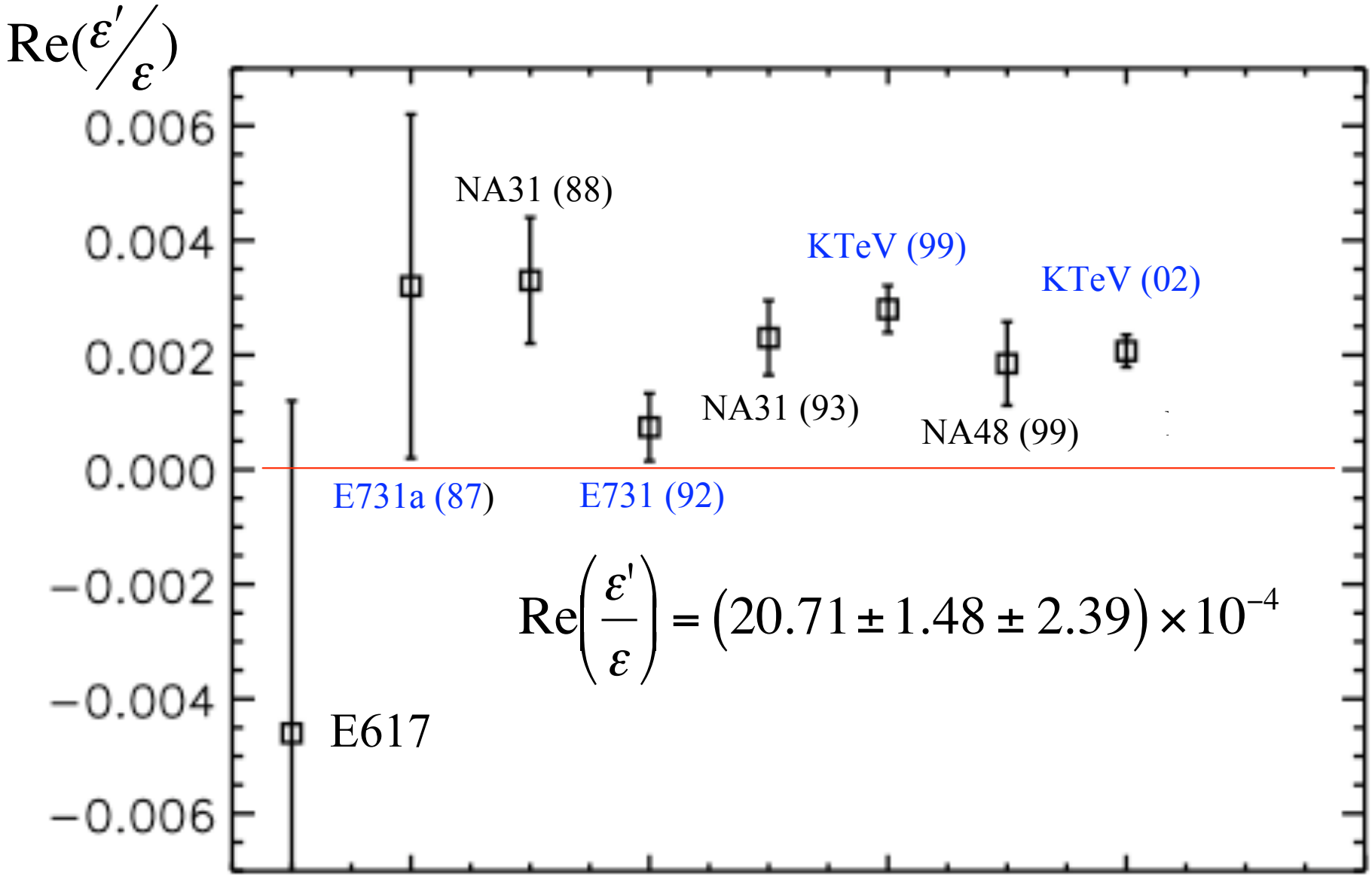


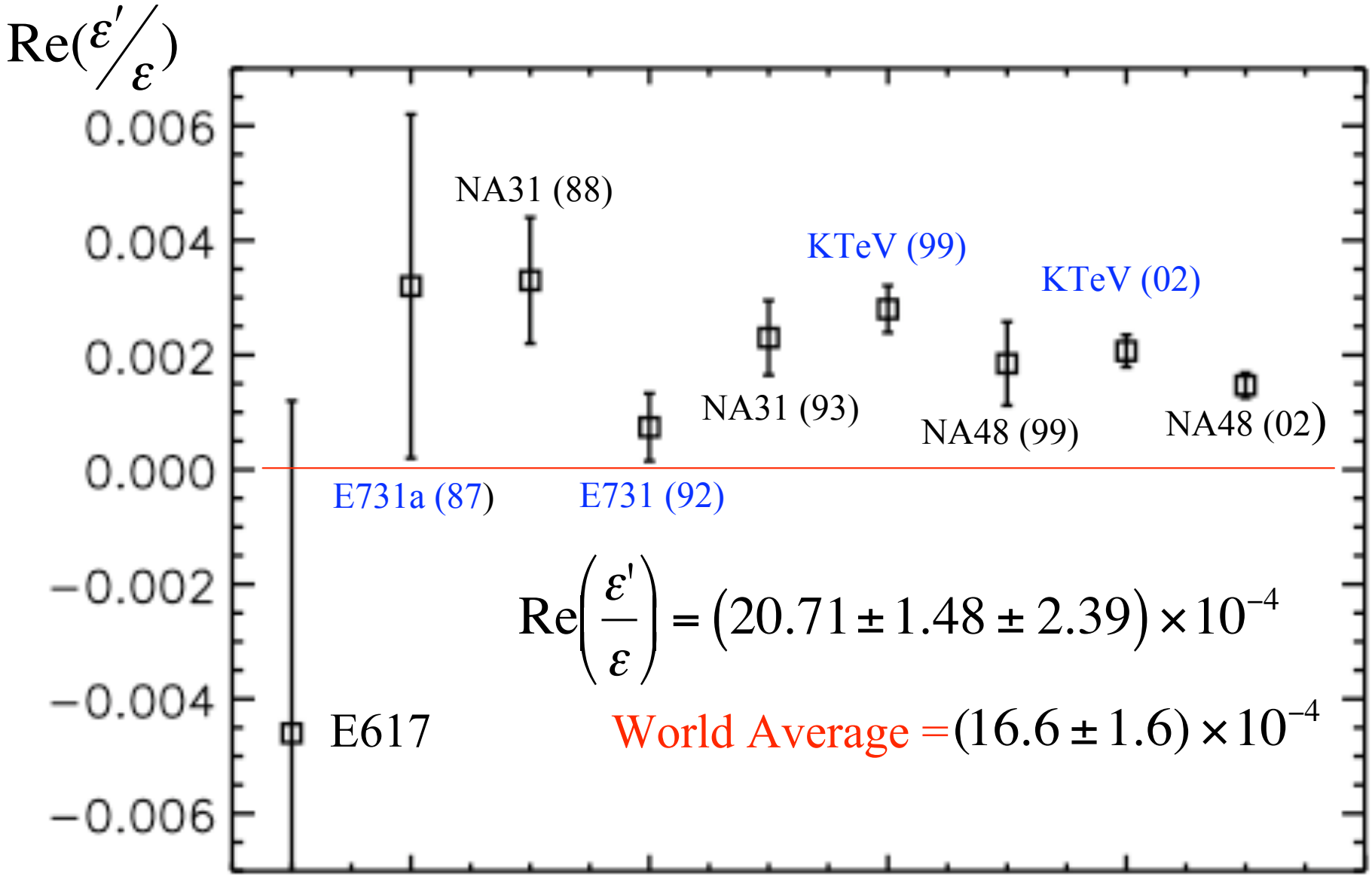
History of Δm Measurements



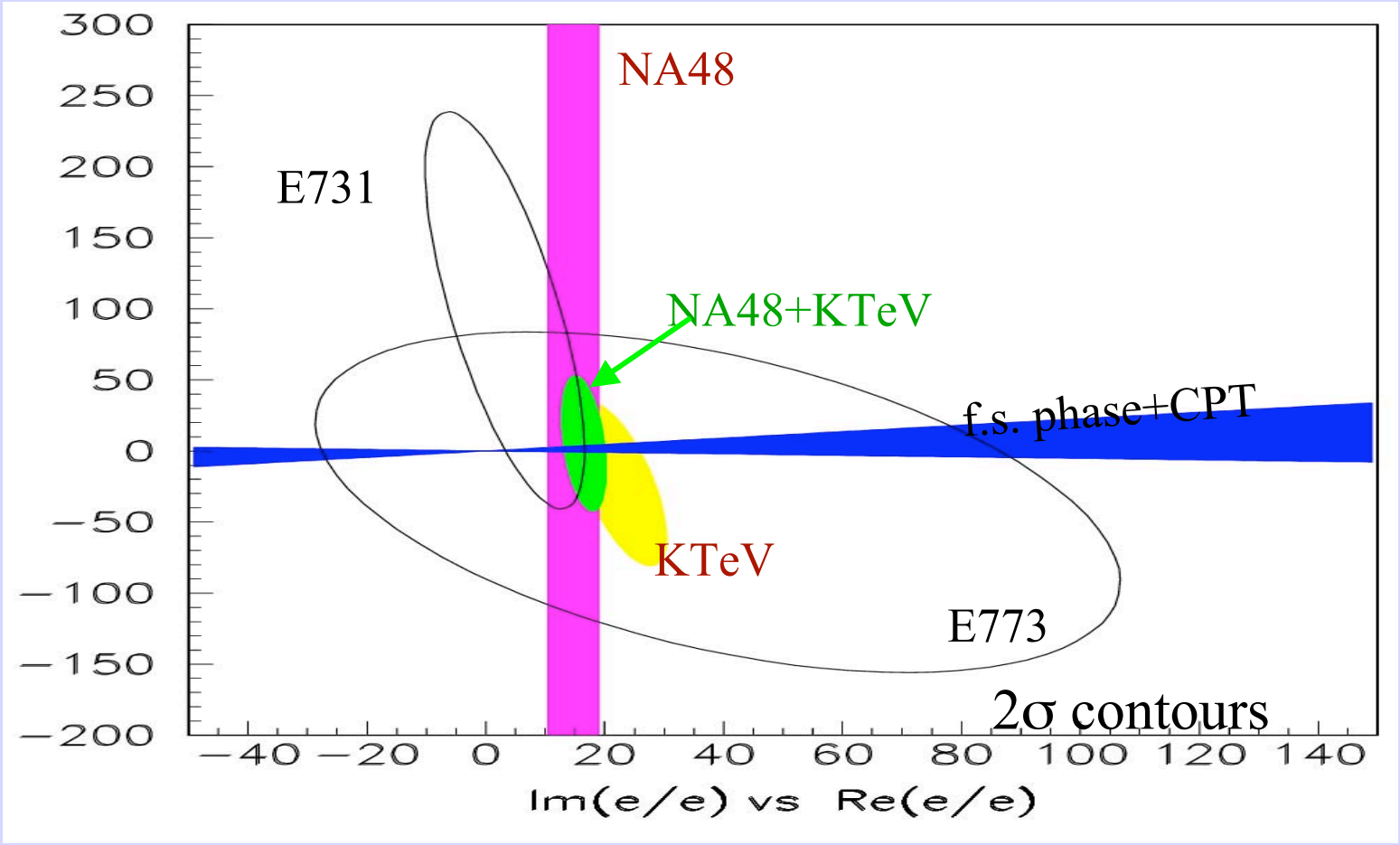
Systematic studies ε'/ε




Re(ε′/ε)
0.006
0.004
0.002
0.000
−0.002
−0.004
−0.006
NA31 (88)
KTeV (99)
KTeV (02)
NA31 (93)
NA48 (99)
E731a (87)
E731 (92)
E617
$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = \left(20.71 \pm 1.48 \pm 2.39\right) \times 10^{-4}$


$\mathrm{Re}(\varepsilon'/\varepsilon)$
0.006
0.004
0.002
0.000
−0.002
−0.004
−0.006
NA31 (88)
KTeV (99)
KTeV (02)
NA31 (93)
NA48 (99)
NA48 (02)
E731a (87)
E731 (92)
E617
$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = (20.71 \pm 1.48 \pm 2.39) \times 10^{-4}$
World Average $= (16.6 \pm 1.6) \times 10^{-4}$

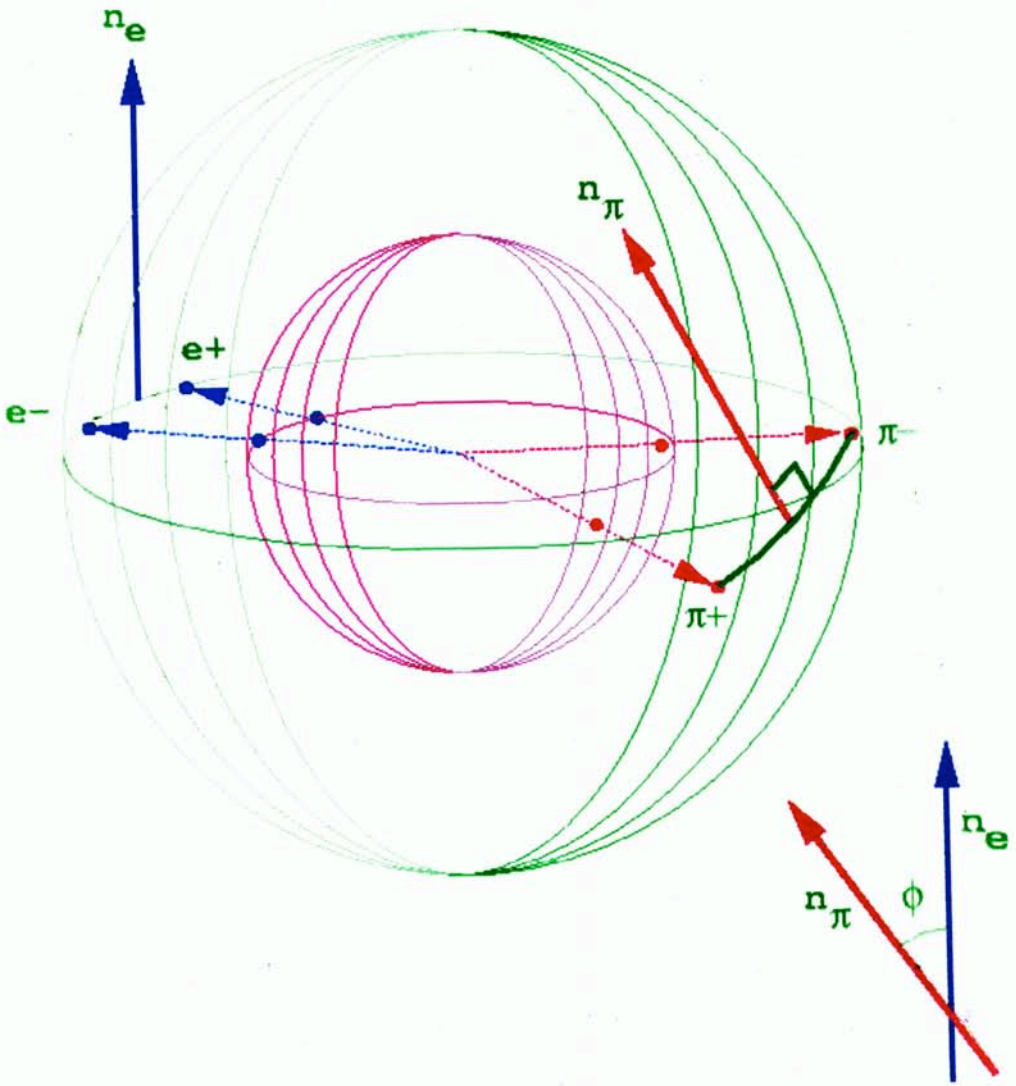
Re(ε′/ε) and Im(ε′/ε)



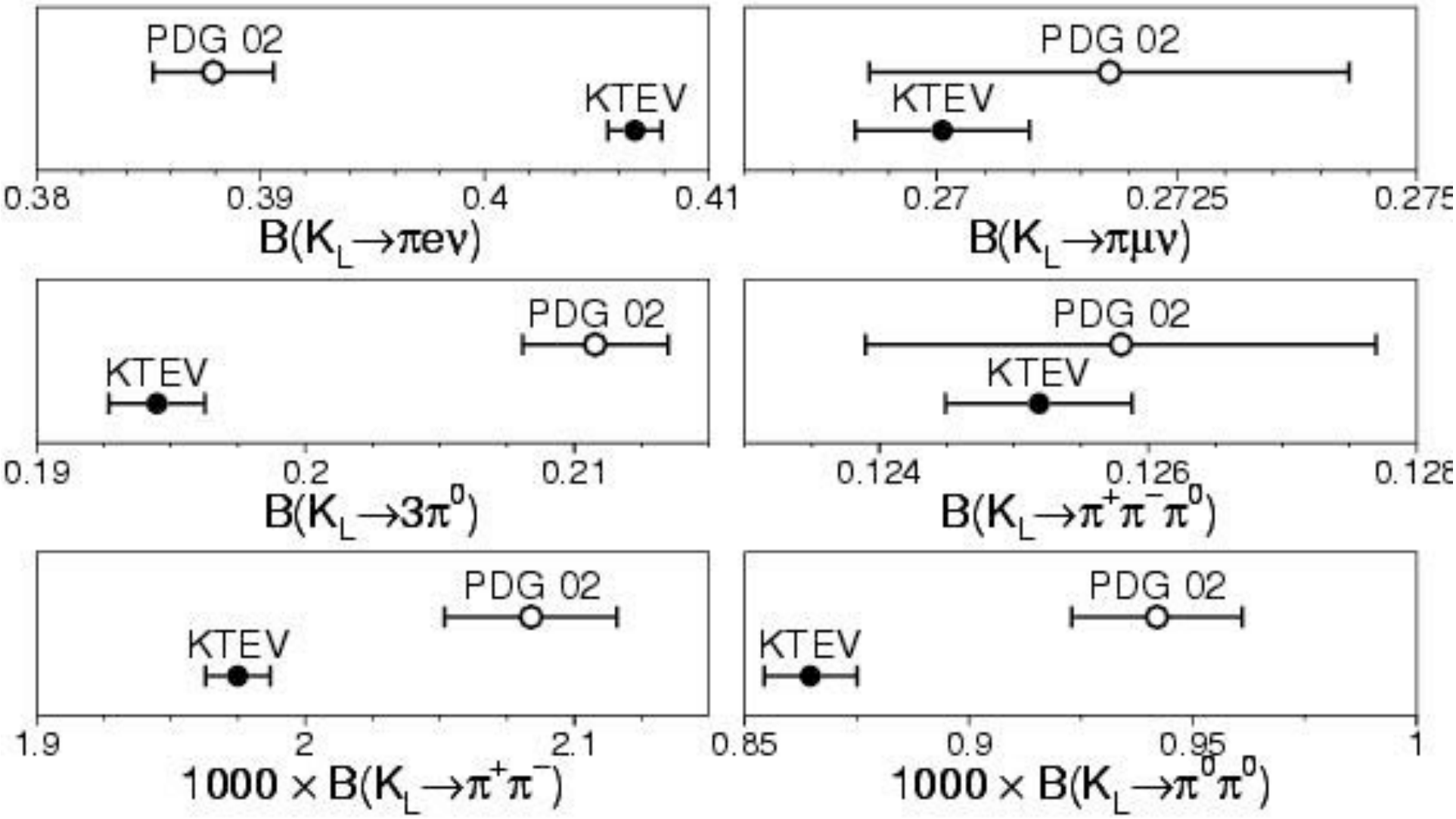
$(\Delta\Phi \cong -3Im(\varepsilon'/\varepsilon))$

$$K_L \rightarrow \pi^+\pi^-e^+e^-$$

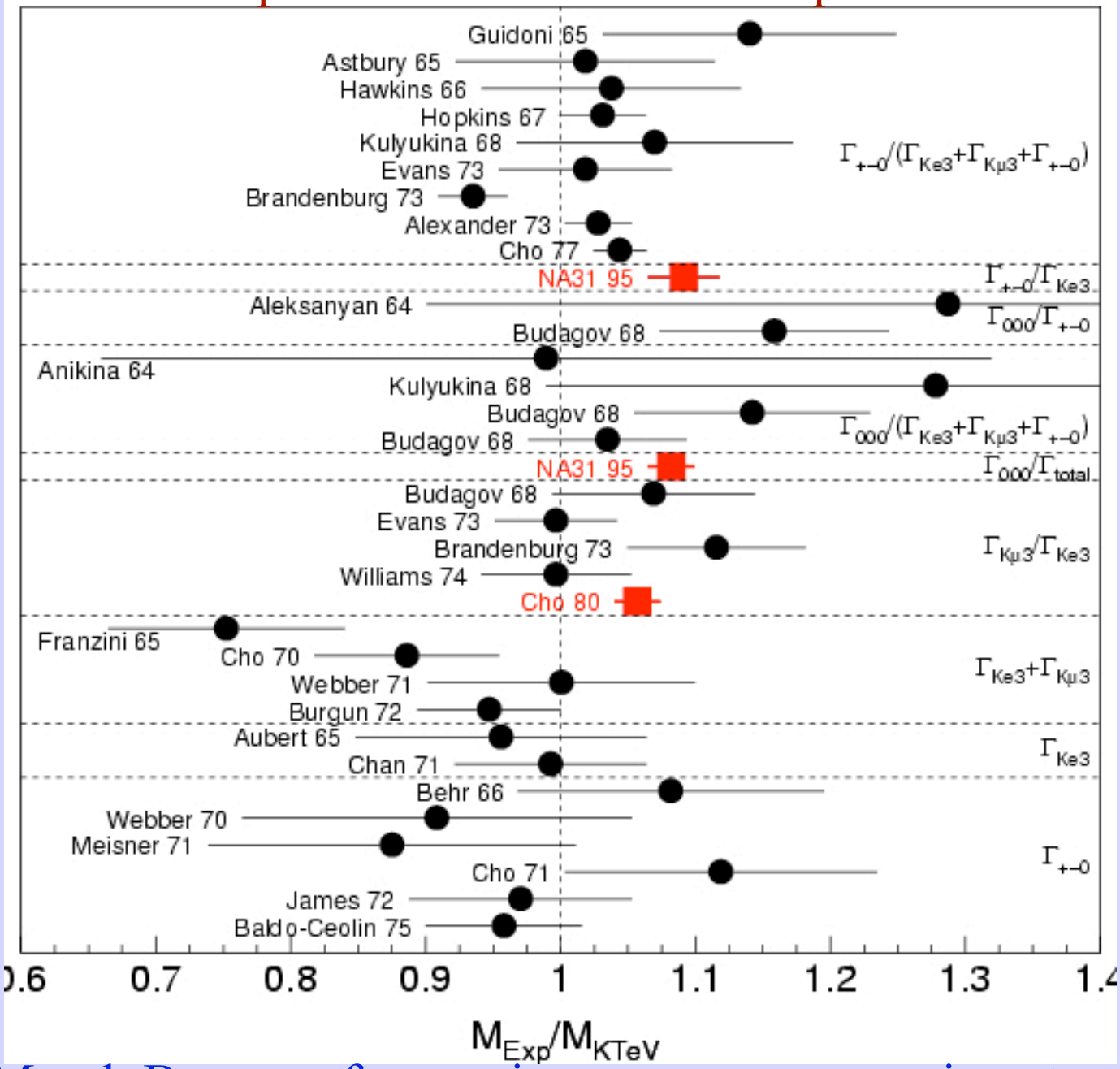
CP/T Violation



Comparison of KTeV and PDG Branching Fractions
(Blucher et al)

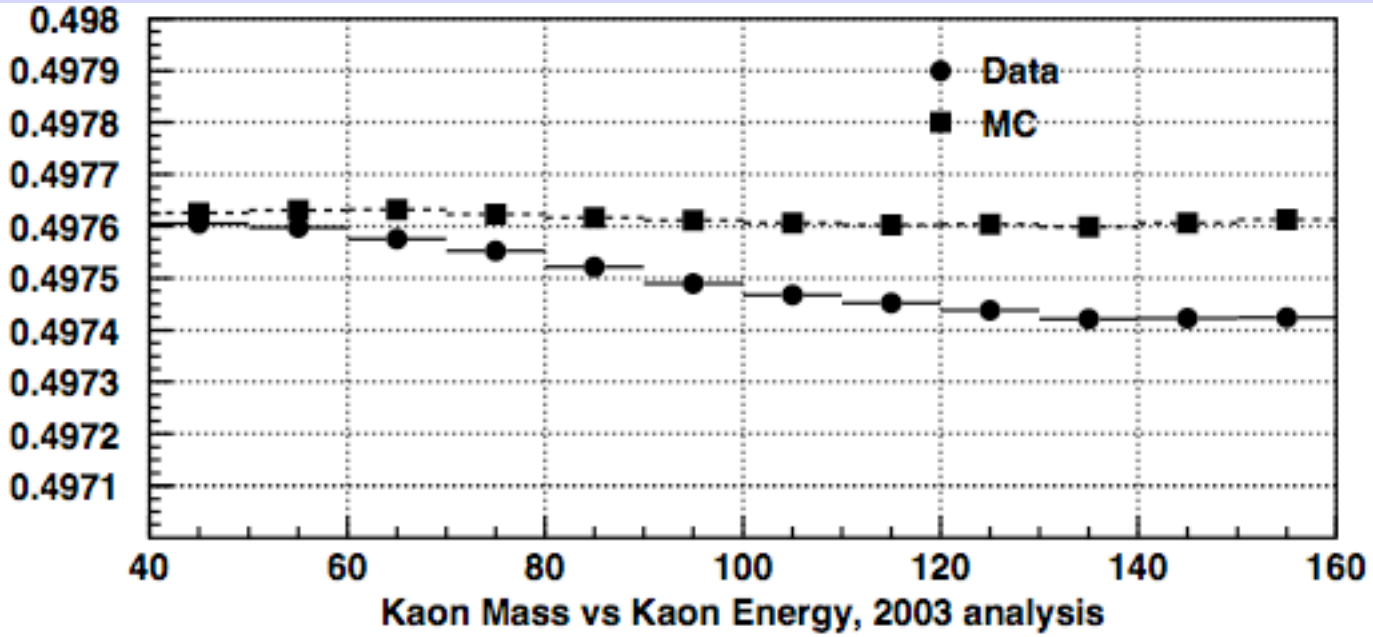


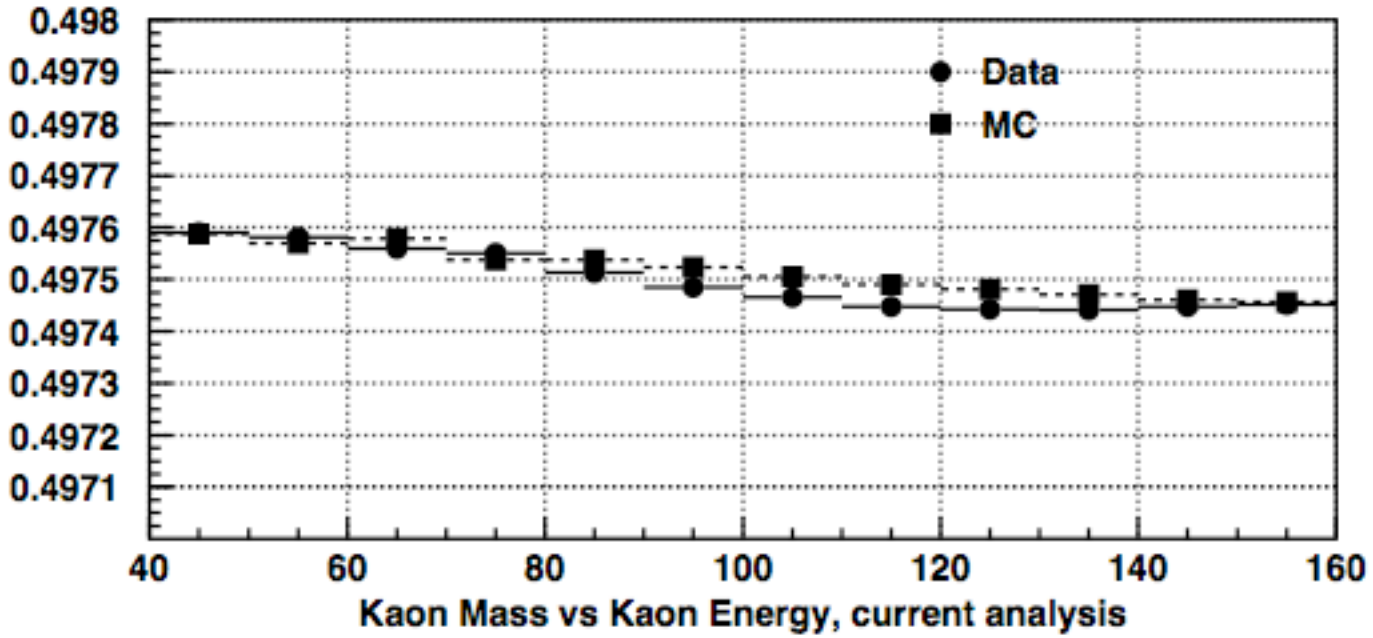
Comparison with Individual Experiments



Moral: Beware of averaging many poor experiments.

The vast majority of the measurements of neutral kaon branching ratios and limits come from this Fermilab program of experiments





Very Recent Work on by KTeV

Direct CPV Summary

$$\frac{\Gamma(K^0 \to \pi^+\pi^-) - \Gamma(\overline{K}^0 \to \pi^+\pi^-)}{\Gamma(K^0 \to \pi^+\pi^-) + \Gamma(\overline{K}^0 \to \pi^+\pi^-)} = (8.8 \pm 1.3) \times 10^{-6}$$

Subtle and perhaps important feature of Nature

Superweak is not the sole source of CPV

Satisfies one of the Sakharov Conditions

Concluding Thoughts

The Next Steps in K Physics

$$\left.\begin{aligned} K_L &\to \pi^0 \nu\bar{\nu} \\ K^+ &\to \pi^+ \nu\bar{\nu} \end{aligned}\right\} \rho, \eta$$

"Unfortunately , during the past couple of years, all the US-based Kaon projects have been stopped"

A. Ceccucci in "Kaons: Review and Outlook" 2006, hep-ex/0605120 v1

(Our CsI going to Japan ……)

How did the Universe become matter dominated???

"I remember in 1949, on a bulletin board at the Princeton IAS a photomicrograph of a nuclear emulsion event, showing what is now known as a K-meson decaying to three pions. We all saw it.

There could be no doubt that something interesting was going on, very different from what was then known."

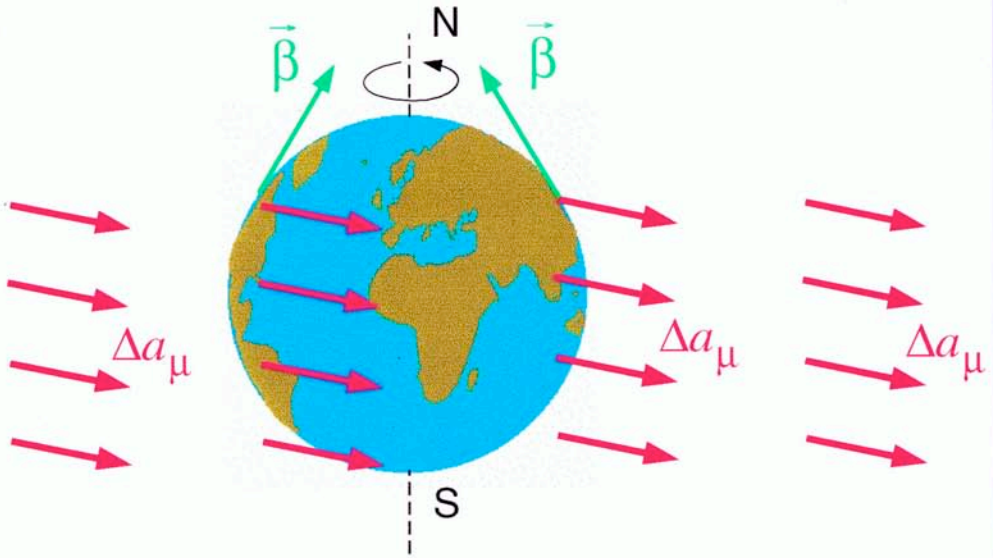
Jack Steinberger

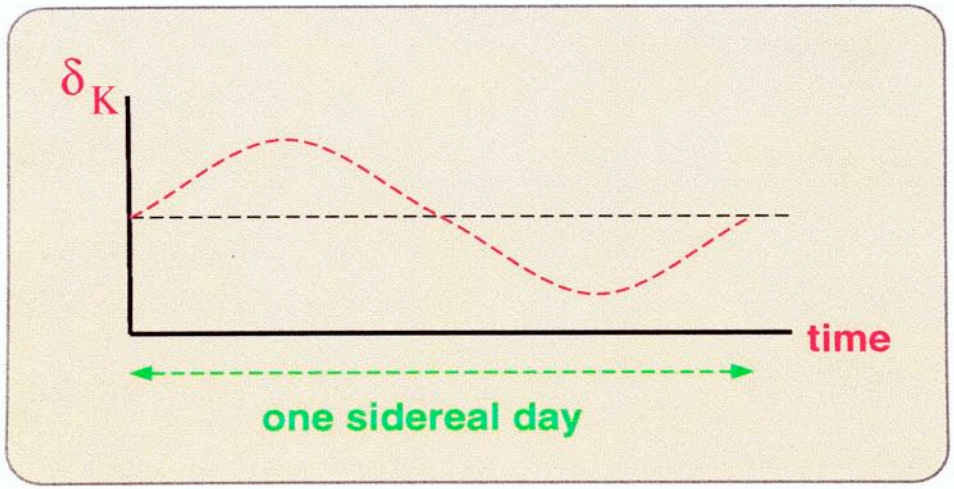
My new field (Observational Cosmology/CMB polarization)

- Exactly 15 years ago: first COBE results
- Anisotropies generated at 10^{-35} sec reconstructed from data at 10^{13} sec???
- Just can't increase energy by 7!

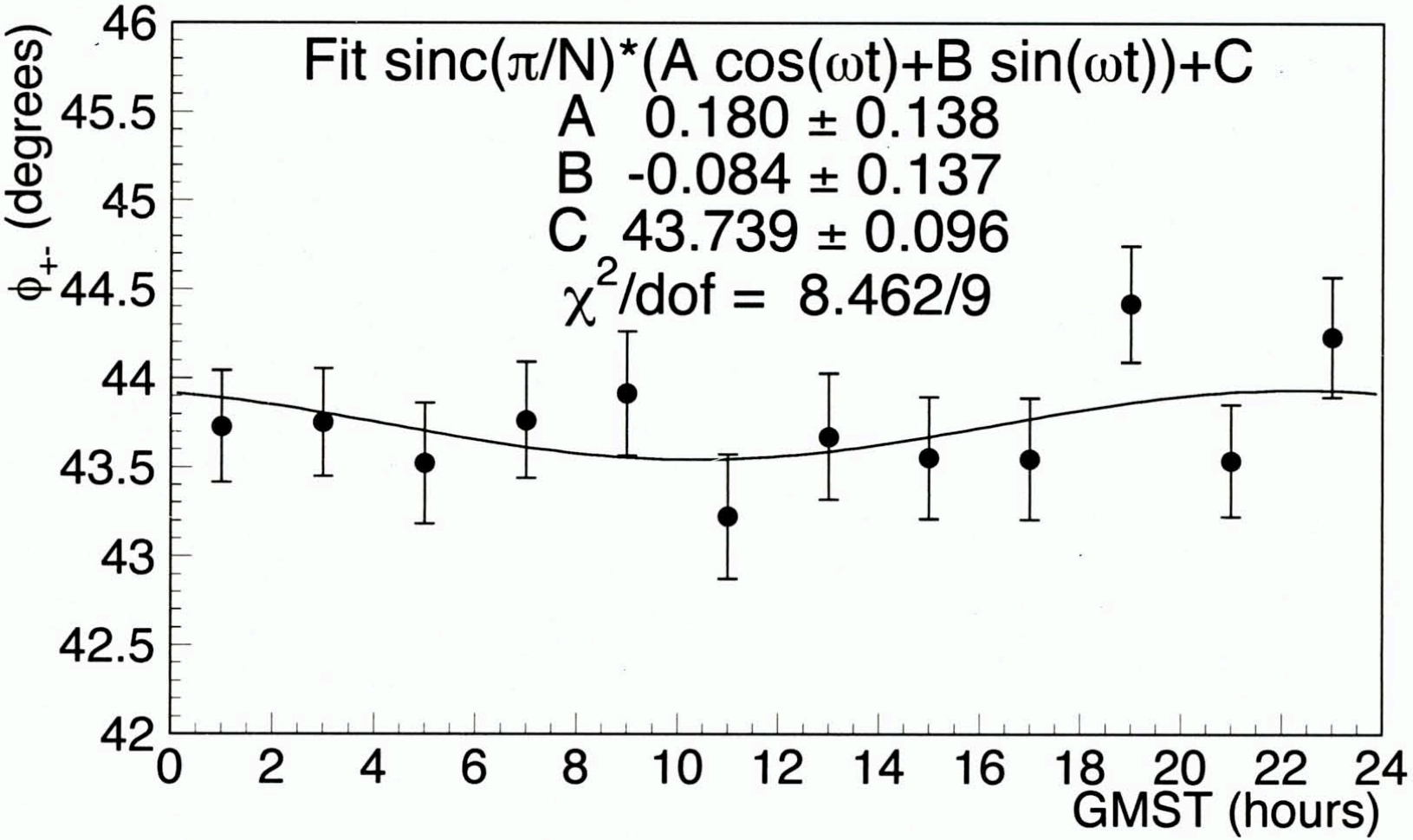
Diurnal variations

(A.K., PRL '98)





Test of **CPT/Lorentz** invariance:



Amplitude $< 0.37^o$ at 90% C.L.

My students in this venture

- Bob Bernstein
- Duncan Carlsmith
- Hamish Norton
- Mike Woods
- Ritchie Patterson
- Lawrence Gibbons
- Roy Briere
- Bernhard Schwingenheuer
- Peter Shawhan
- Colin Bown

Postdocs

- Greg Bock
- Ko Nishikawa
- George Gollin
- Yau Wah
- Taku Yamanaka
- Bob Hsiung
- Hitoshi Yamamoto
- Sunil Somalwar
- Tony Barker
- Hogan Nguyen
- Bob Tschirhart
- Aaron Roodman
- Elliott Cheu
- Rick Kessler
- Sasha Glazov

The Directors