KTEV RESULTS

R. Kessler
University of Chicago

Aug 14, 1998

Slac Summer Institute

KTeV institutions:

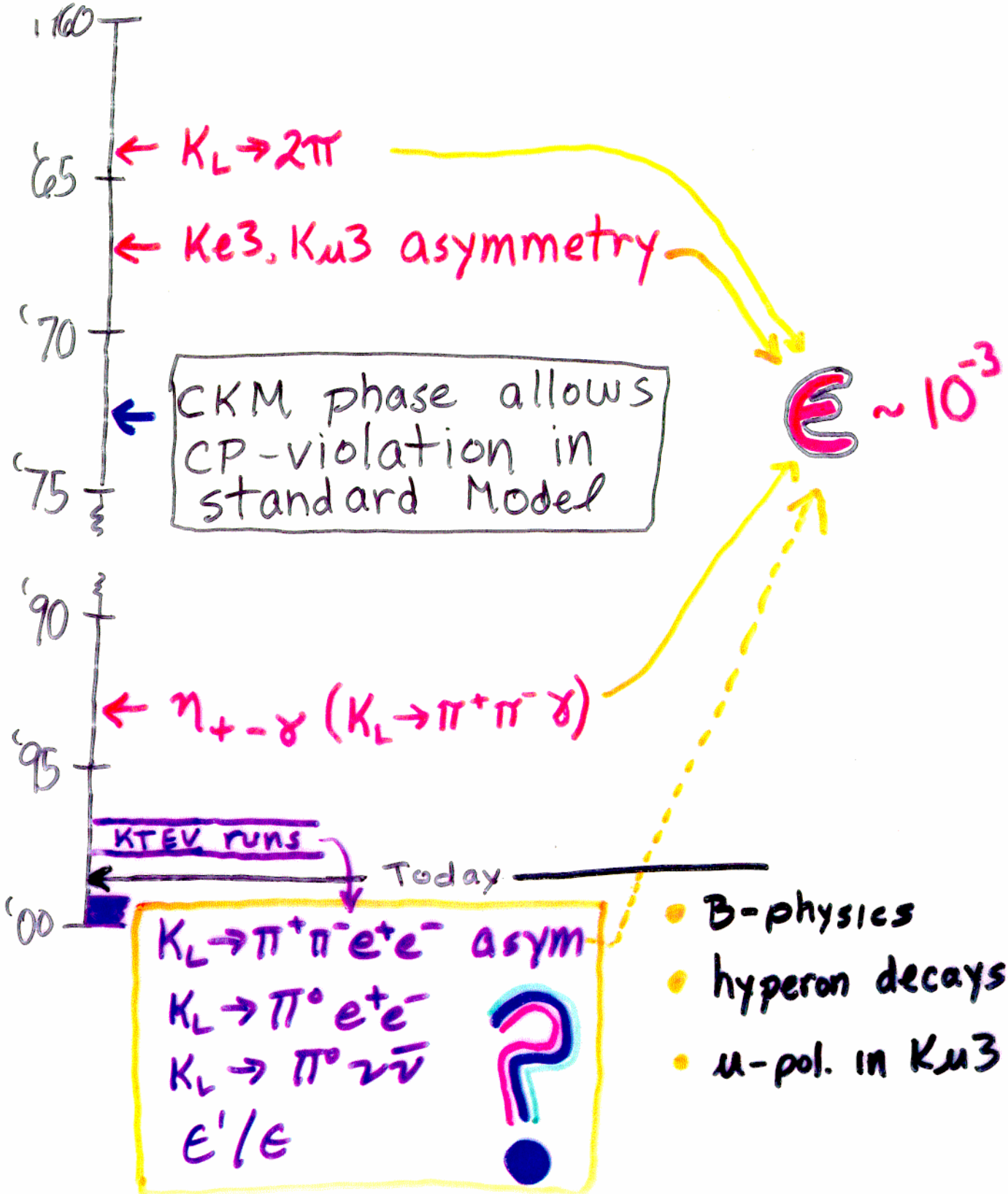
- Arizona
- Chicago
- Colorado
- Elmhurst
- Fermilab
- Osaka
- Rice
- Rutgers
- UCLA
- UCSD
- Virginia
- Wisconsin

OUTLINE:

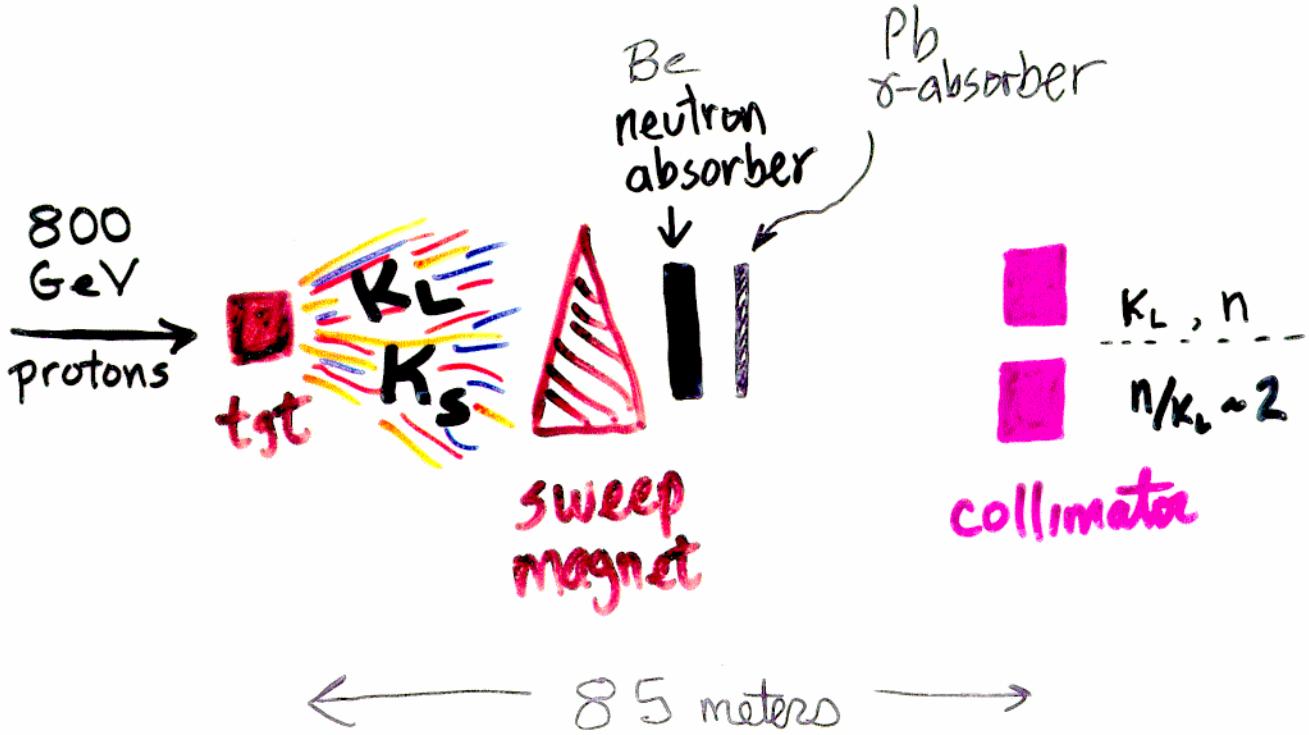
- CP-violating physics

- CP-conserving physics

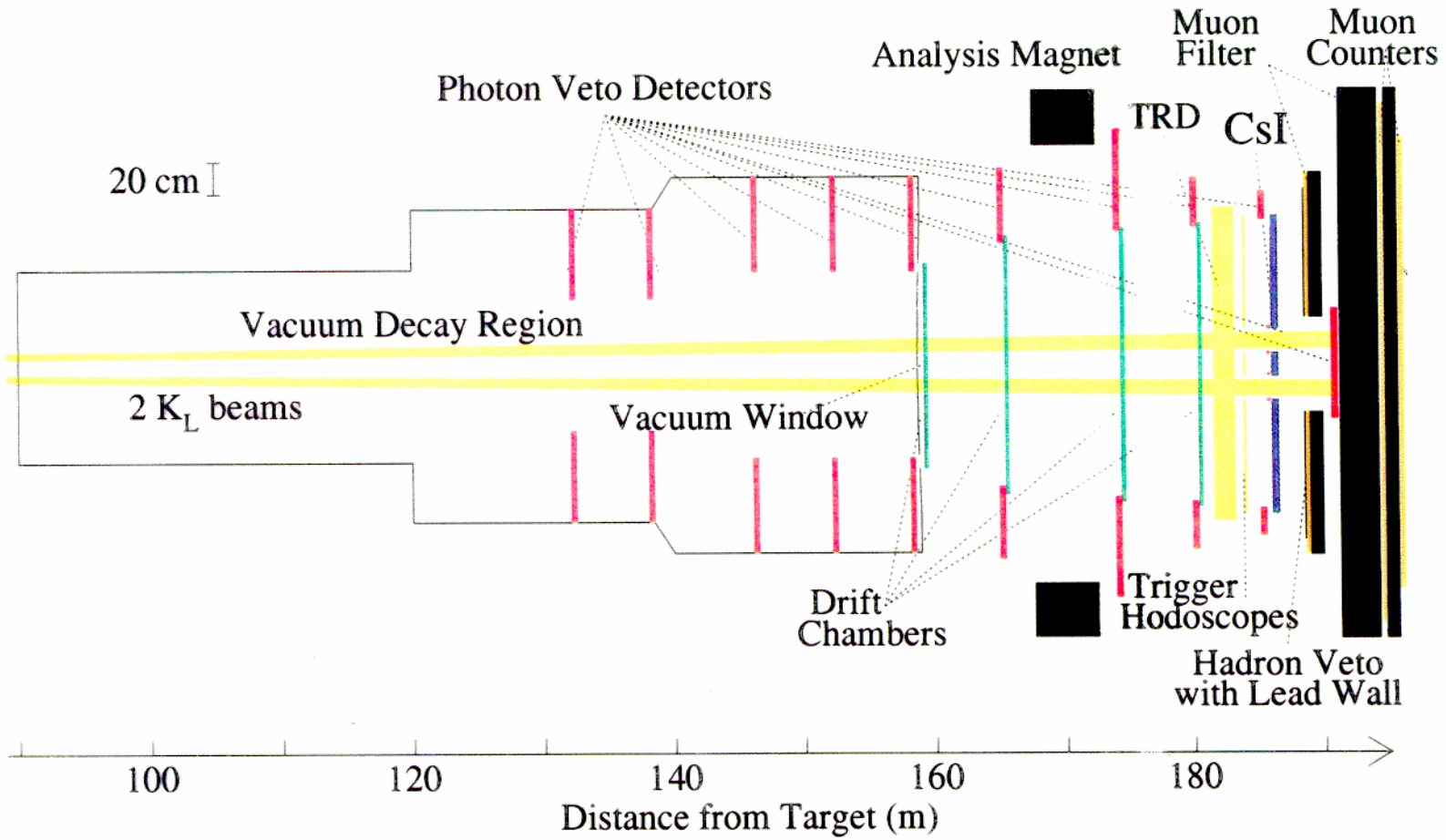
History of CP-violation

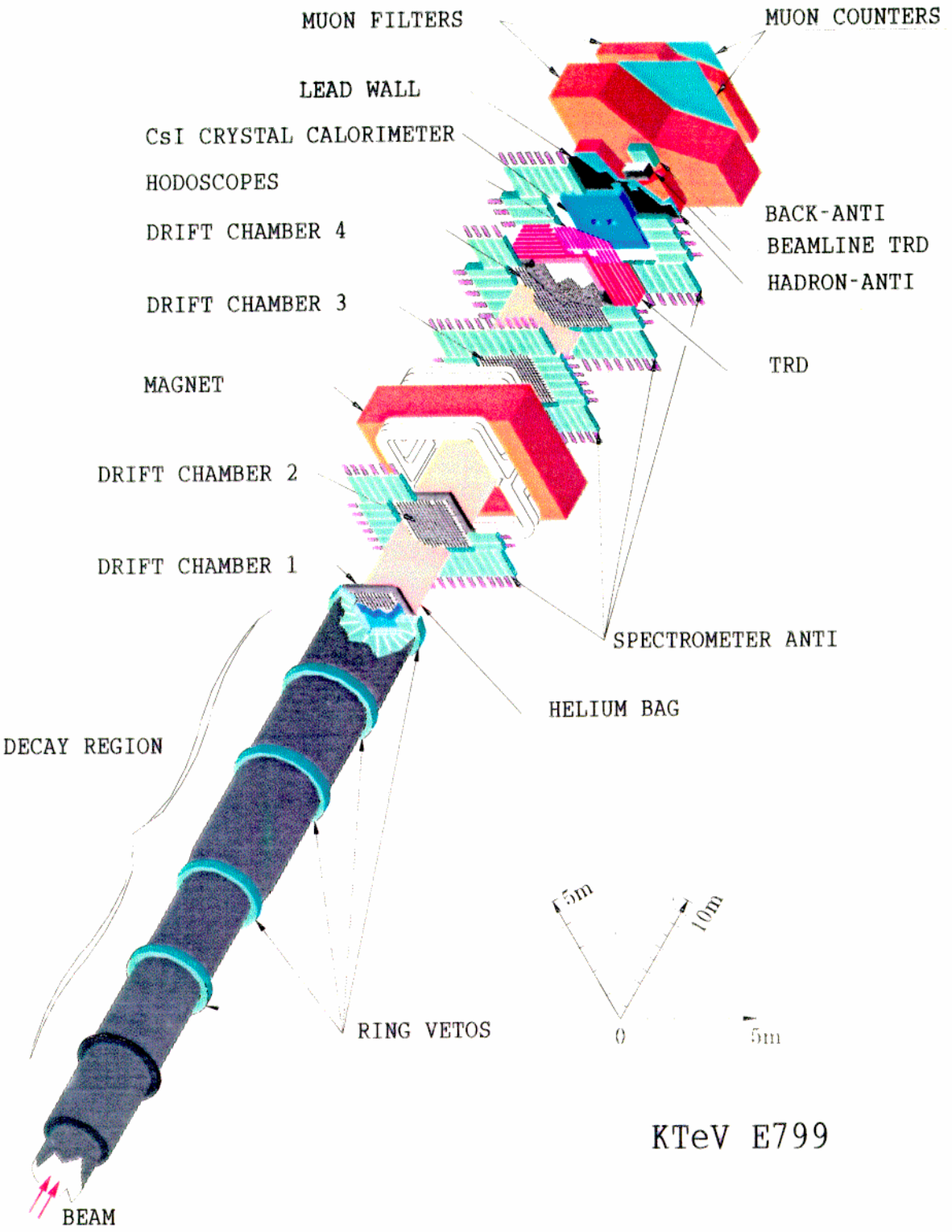


K_L beam @ FNAL

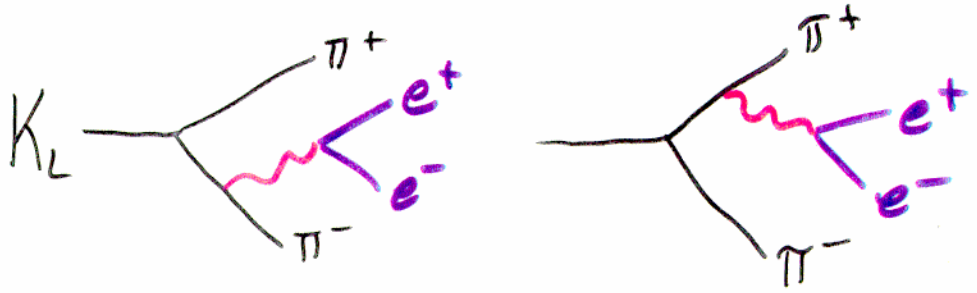


(not to scale)

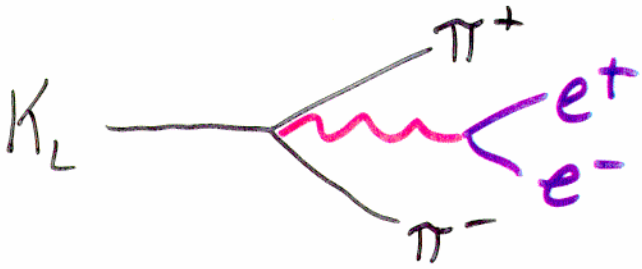




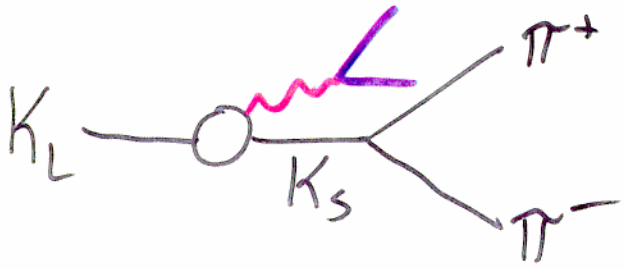
$K_L \to \pi^+ \pi^- e^+ e^-$



"Inner Brem" (CP-even)

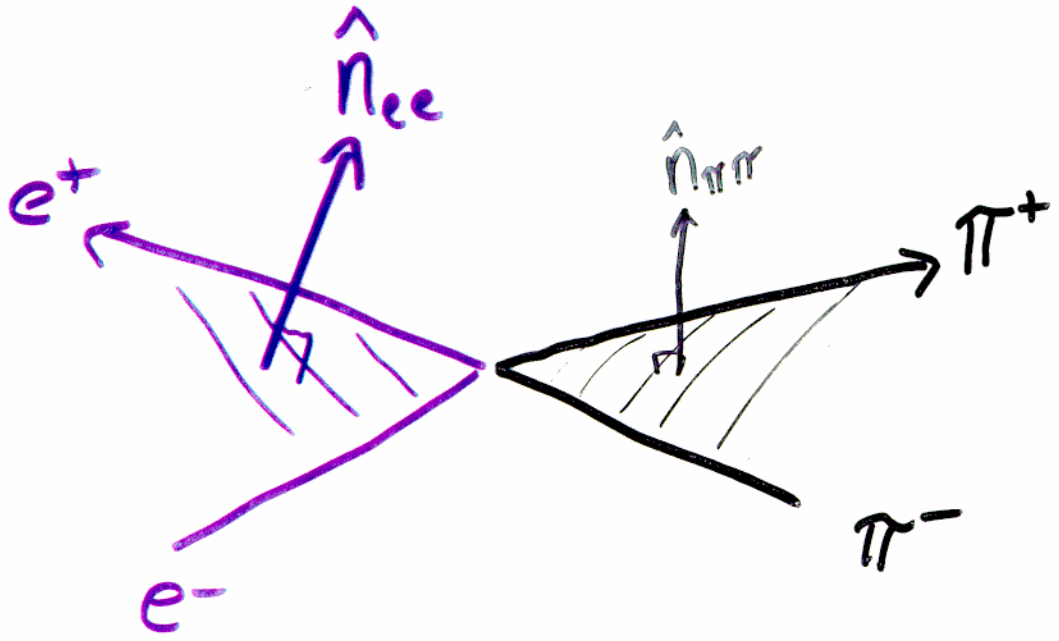


"M1" (CP-odd)



K°-charge radius

Interference between CP-odd and even amplitudes results in a CP-violating polarization.

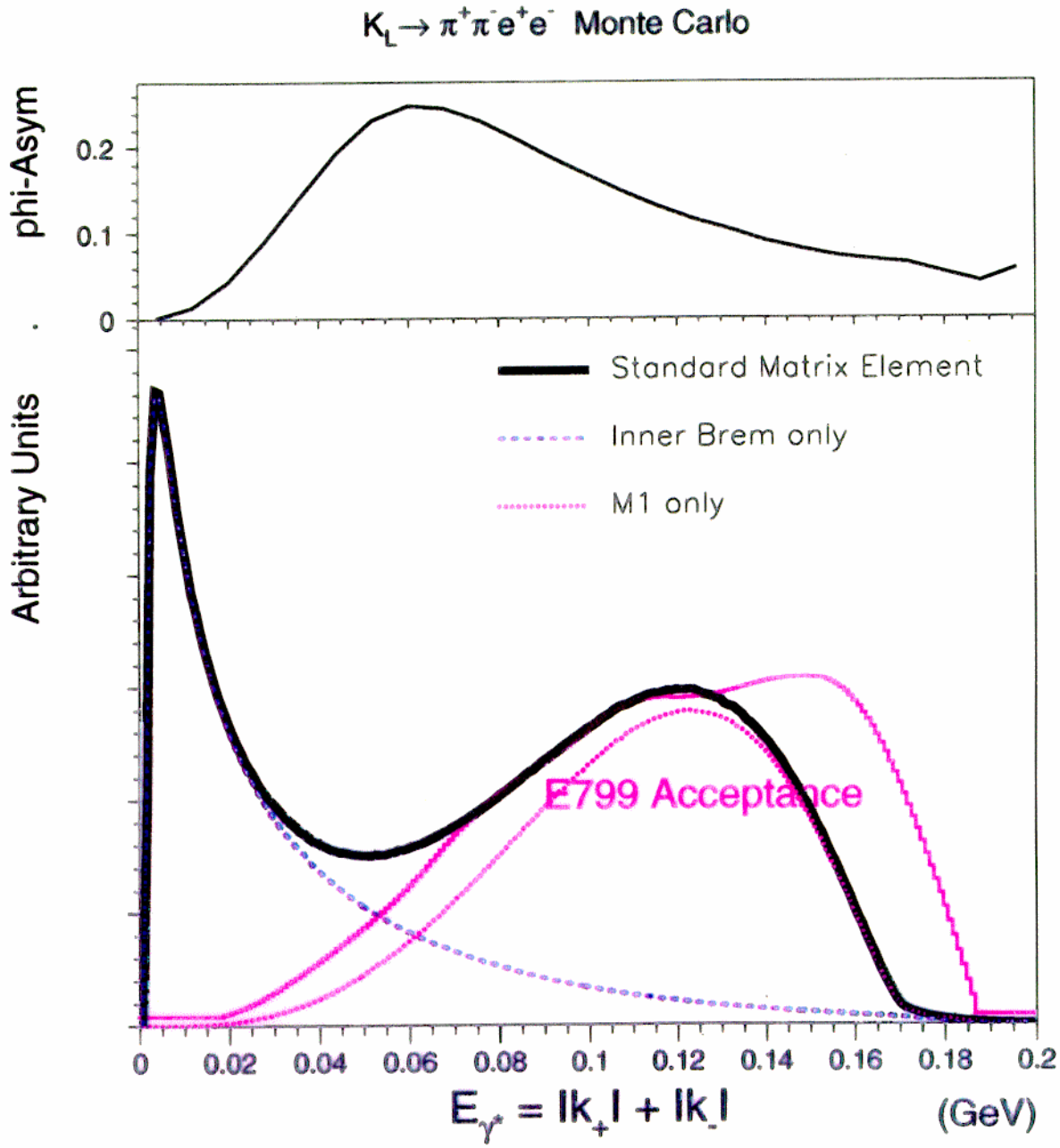


define $\hat{n}_{\pi\pi} \cdot \hat{n}_{ee} \equiv \cos\phi$,

CP-violating polarization results in an asymmetric ϕ-distribution.

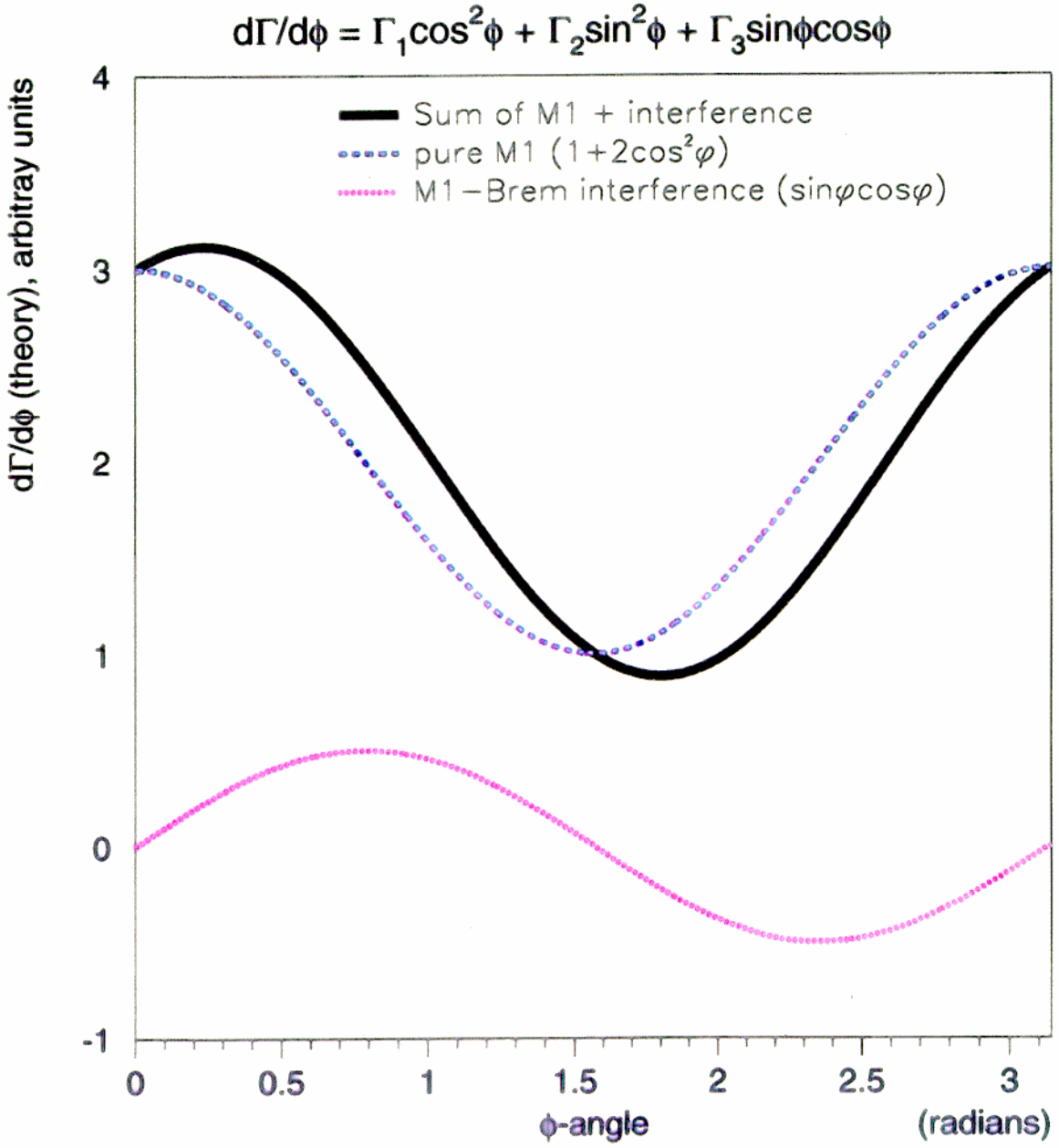
Note $\phi \xrightarrow{CP} -\phi$

Sehgal and Wanninger
PRD 46, 1035 Aug 1992



ϵ [$K_L \to \pi^+ \pi^- e^+ e^-$] + [$K_L \to \pi^+ \pi^- e^+ e^-$]

QUALITATIVE Expectation of ϕ-asymmetry in E799

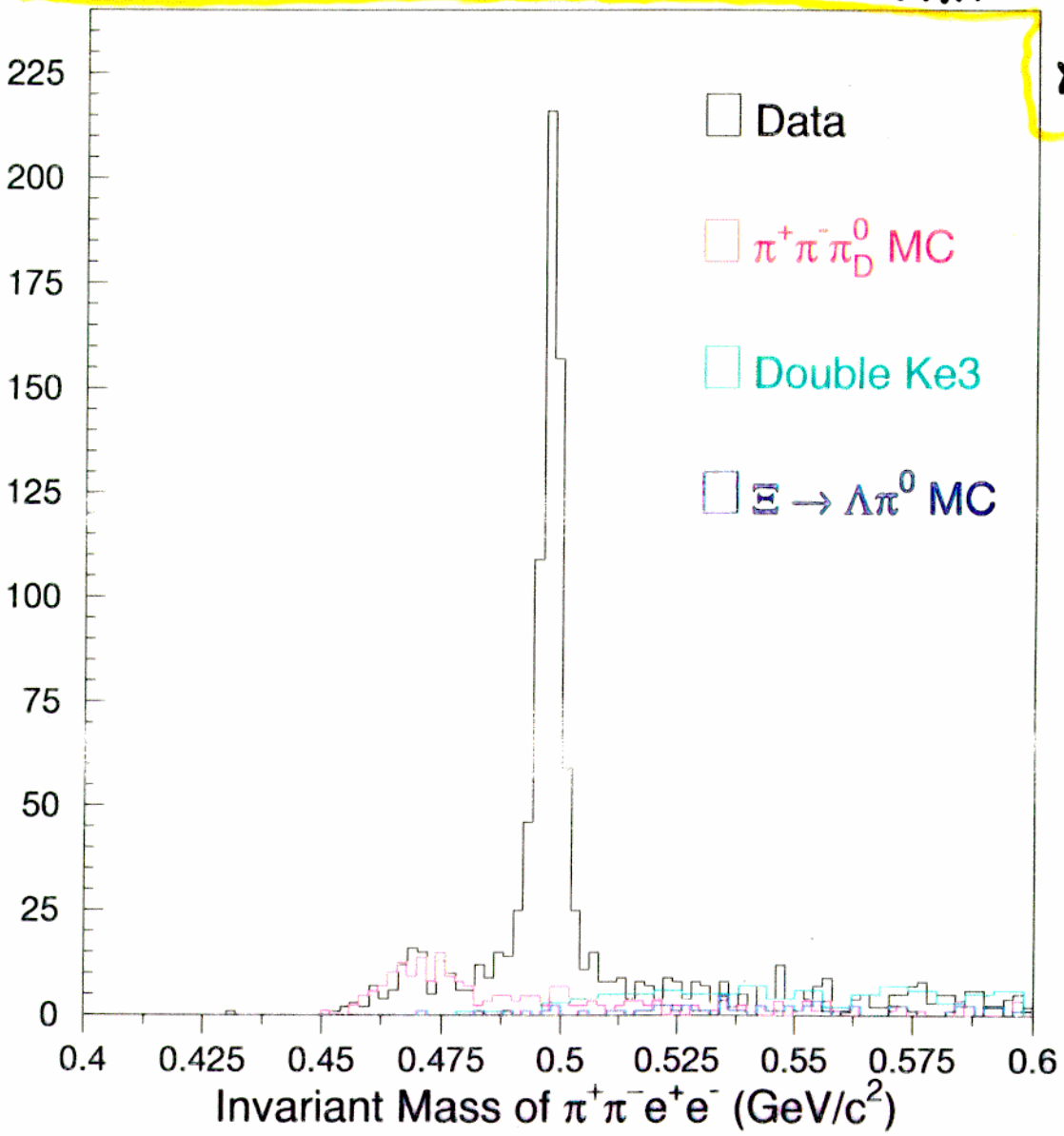


Note: pure BREM term is not shown because it has very small acceptance in E799 detector

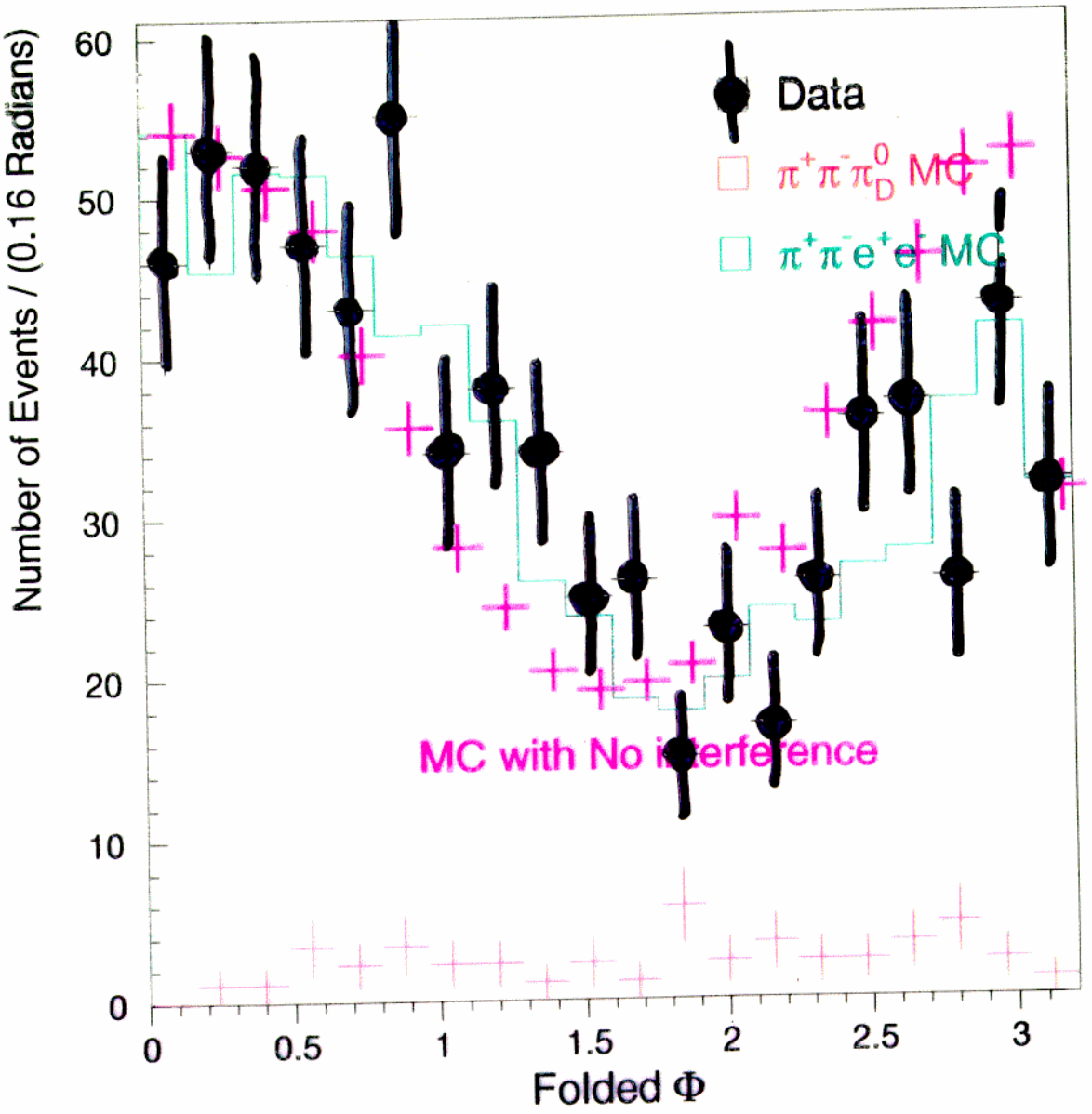
645 Signal

65 background

$BR(K_L \to \pi^+\pi^- e^+ e^-) = 3.32 \pm .14_{STAT} \pm .28_{syst} \times 10^{-7}$



$\sim \frac{1}{2}$ of E799 data set



- ~1/2 of E799 data set
- No acceptance corrections

$K_L \to \pi^0 \nu \bar{\nu}$

$BR \sim \eta^2 \sim 2 - 4 \times 10^{-11}$

⇓

pure CP-violation

Theoretically: very clean

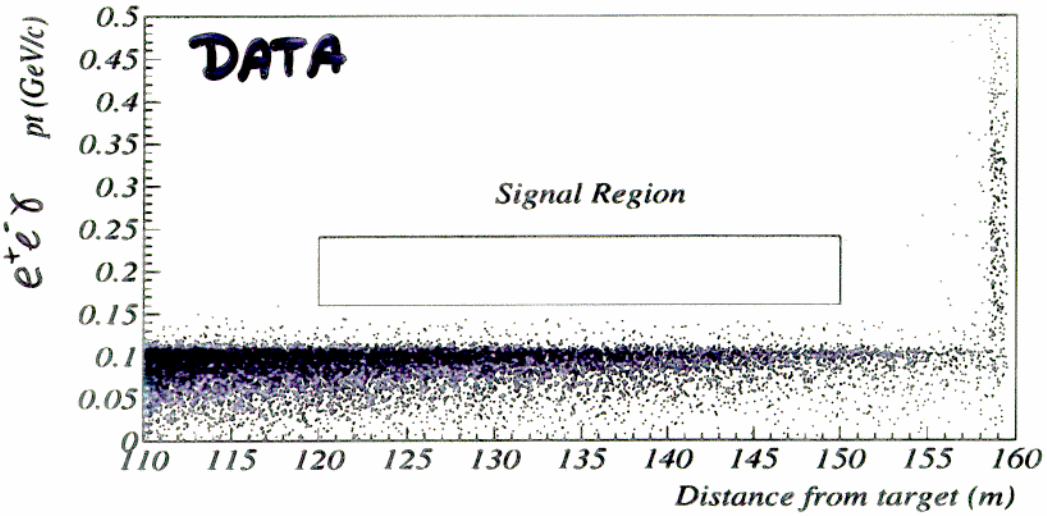
Experiment: very hard

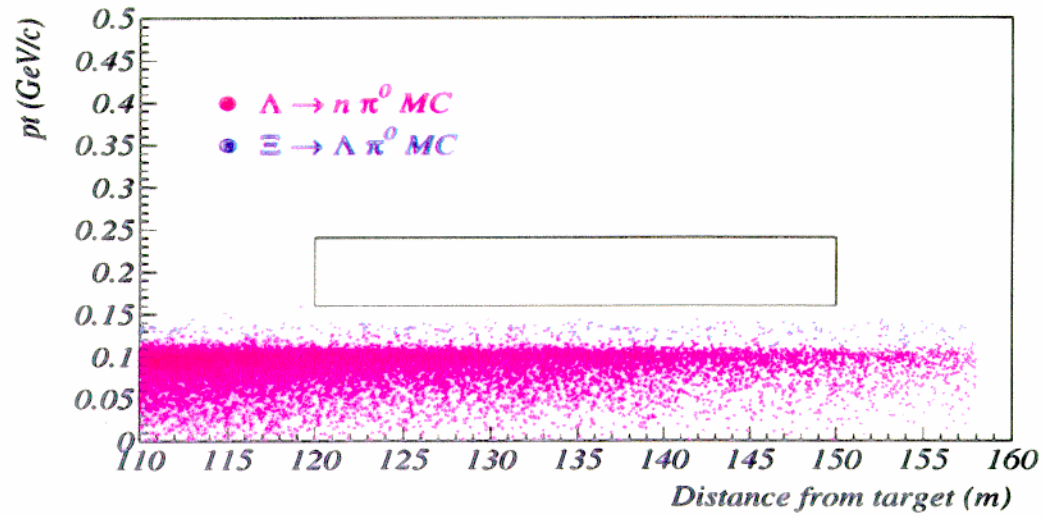
Two methods:

- $\pi^0 \to \gamma\gamma$: big BR, unconstrained vertex
- NEW $\pi^0 \to e^+e^-\gamma$: small BR, good vertex

→ submitted to PRL

KTEV





Search for $K_L \to \pi^0 \nu\bar{\nu}$

$\hookrightarrow e^+e^-\gamma$

BR < 6×10^{-7} (90% conf.)

$K_L \to \pi^0 \nu \bar{\nu}$

$BR \sim \eta^2 \sim 2-4 \times 10^{-11}$

⇓

pure CP-violation

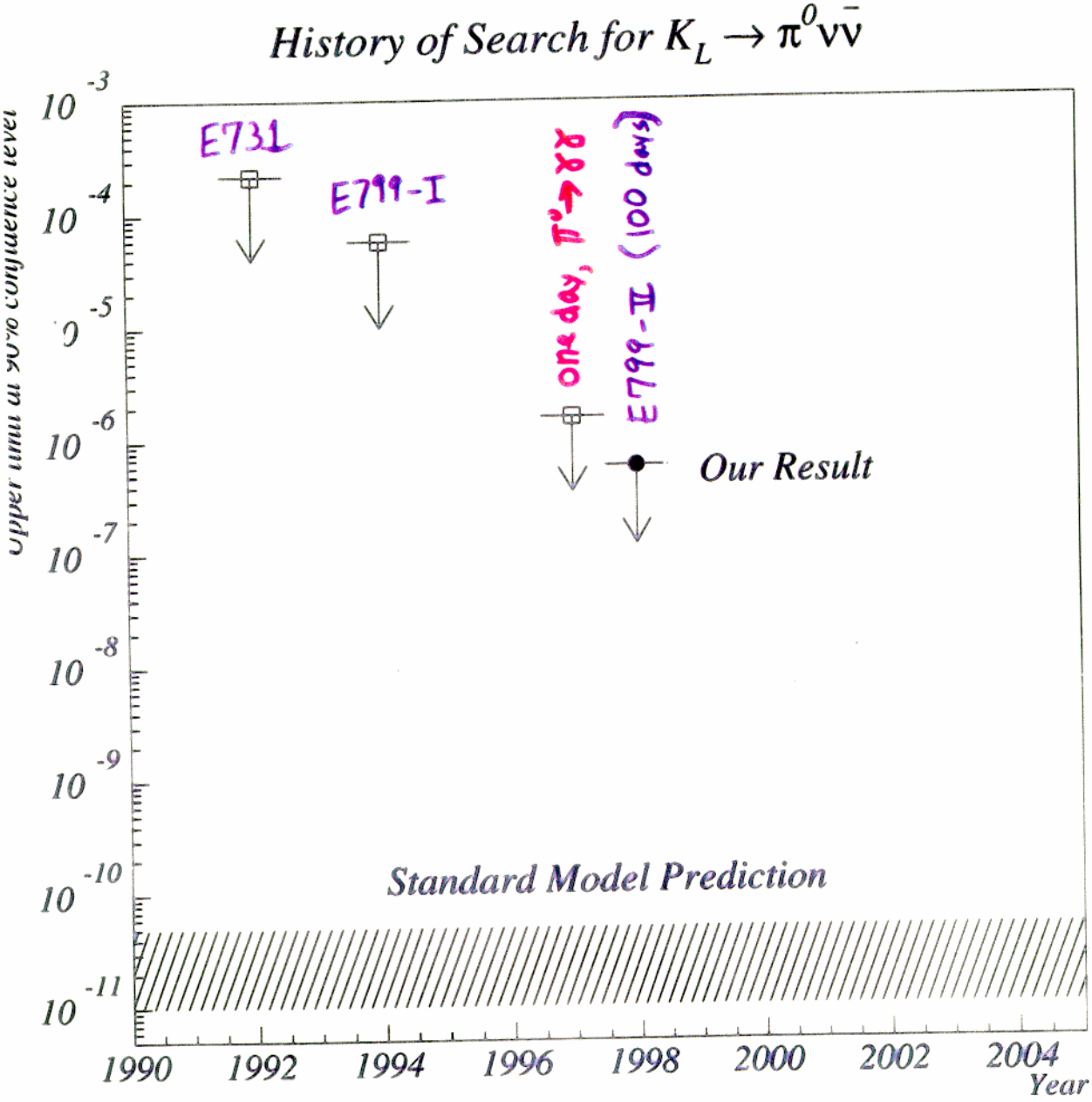
Theoretically: very clean

Experiment: very hard

Two methods:

- $\pi^0 \to \gamma\gamma$: big BR, unconstrained vertex
- NEW $\pi^0 \to e^+e^-\gamma$: small BR, good vertex

→ submitted to PRL


History of Search for $K_L \to \pi^0 \nu\bar{\nu}$
Upper limit at 90% confidence level
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
E731
E799-I
one day, $\pi^0 \to \gamma\gamma$
E799-II (100 days)
Our Result
Standard Model Prediction
1990
1992
1994
1996
1998
2000
2002
2004
Year

Direct CP-Violation: Measurement of ϵ'/ϵ in E832

$$\frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)} \approx 1 + 6\mathrm{Re}\,(\epsilon'/\epsilon)$$

Focus is on 20% of data:

- 7 weeks of 1996 $\pi^0\pi^0$ data (20% of total)
- 3 weeks of 1997 $\pi^+\pi^-$ data (17% of total)

The 1996 $\pi^+\pi^-$ data are *not* used for ϵ'/ϵ because a drift chamber pathology combined with the Level 3 software trigger rejected 20% of the events. Level 3 was modified in 1997 to recover this loss.

Statistics

ϵ'/ϵ mode	events	bkg/signal
Vac $(K_L \to)$ $\pi^0\pi^0$	1.0×10^6	0.8%
Reg $(K_S \to)$ $\pi^0\pi^0$	1.6×10^6	1.5%
Vac $(K_L \to)$ $\pi^+\pi^-$	1.9×10^6	0.1%
Reg $(K_S \to)$ $\pi^+\pi^-$	3.9×10^6	0.1%

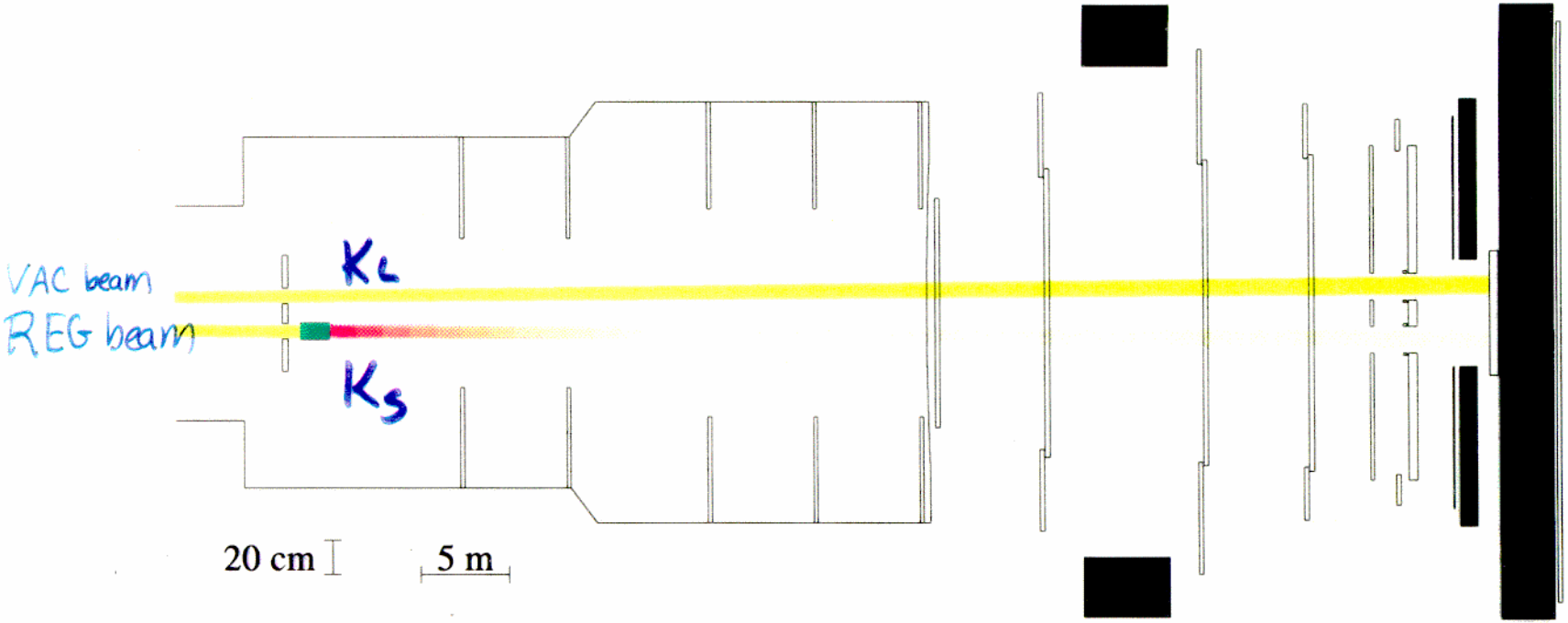
$\Longrightarrow \delta(\epsilon'/\epsilon)_{\mathrm{stat}} \sim 3 \times 10^{-4}$

BLIND ANALYSIS

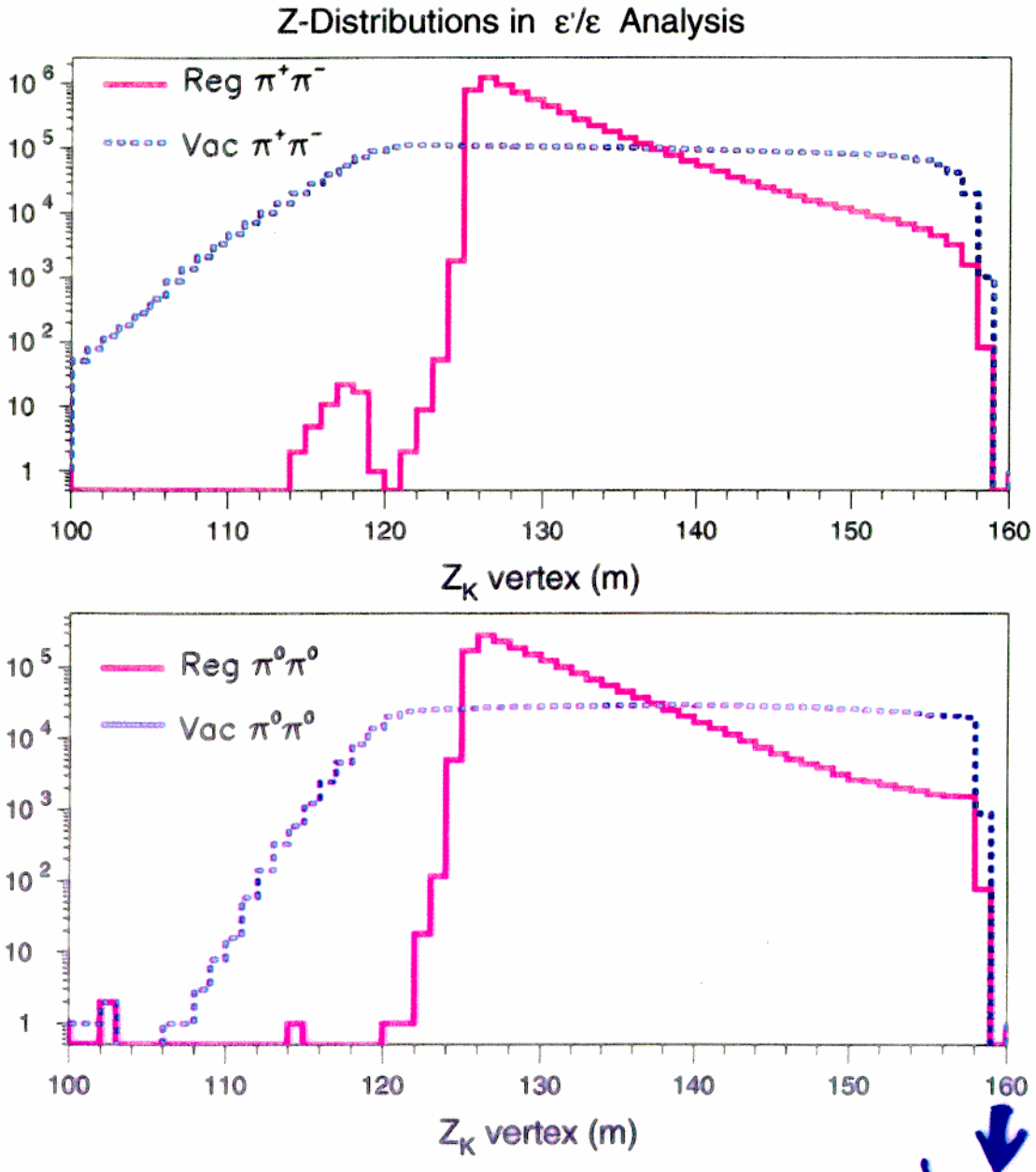
Other modes with large statistics (1996 data):

- 200 million $K \to \pi e \nu$ events for CsI calibration.
- 20 million $K \to 3\pi^0$ for "neutral" systematic studies.

Kaon Beams

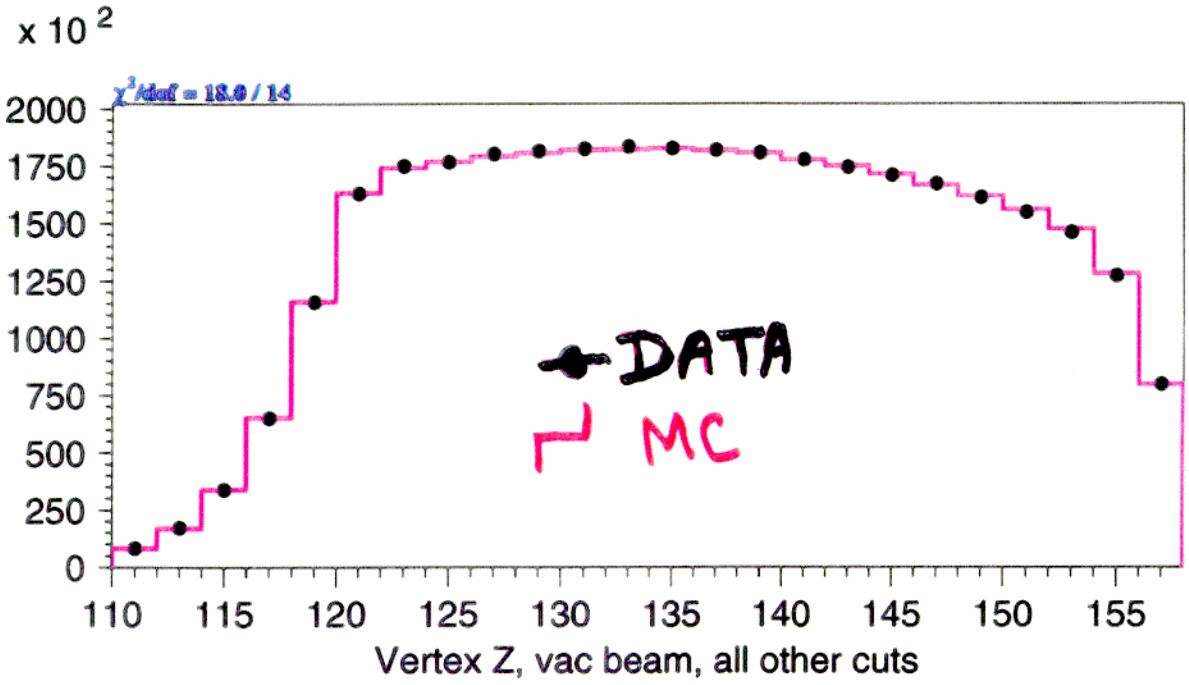


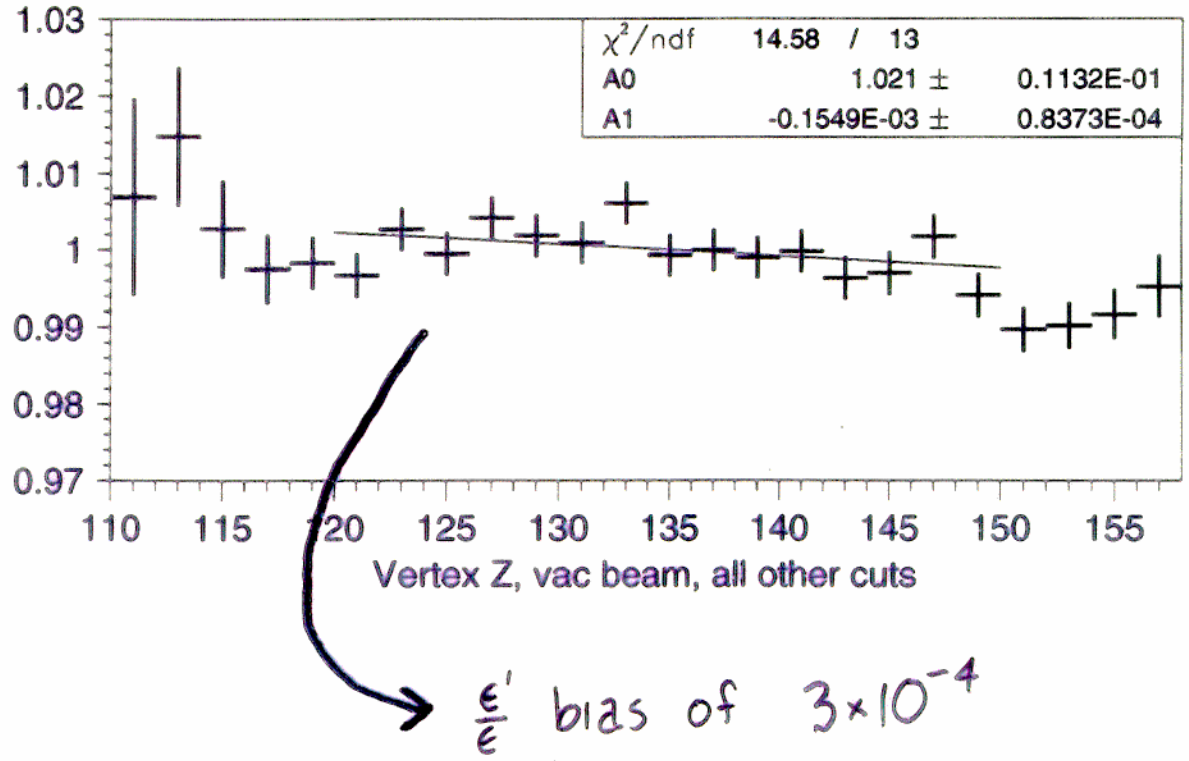
800 GeV protons on BeO target
Charged particles are swept away
Hyperons decay, leaving K_L and neutrons
Regenerator makes K_S by coherent regeneration
Regenerator alternates beams once per minute



$\delta Z_{syst} \sim 3$ cm $\Longleftrightarrow$ $\delta\left(\frac{\epsilon'}{\epsilon}\right) \sim 1 \times 10^{-4}$

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





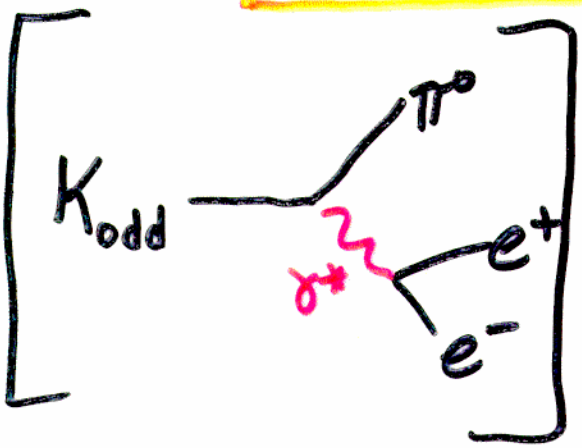
$\frac{\epsilon'}{\epsilon}$ bias of 3×10^{-4}

PART II:

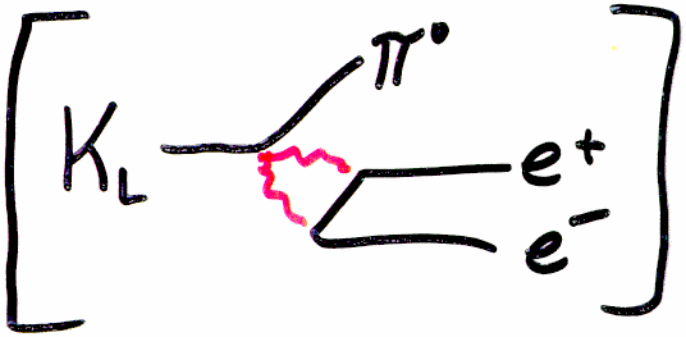
CP-conserving physics

- $K_L \to \pi^0 \gamma\gamma$
- $K_L \to \pi^0 e^+e^- \gamma$
- $K_L \to e^+e^- e^+e^-$
- $\pi^0 \to e^+e^- e^+e^-$
- $\pi^0 \to e^+e^-$
- $K_L \to \mu^+\mu^-\gamma$

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



CP-violating



CP-conserving

Expect: $BR_{CPV} \sim BR_{CPC} \sim$ few $\times 10^{-12}$

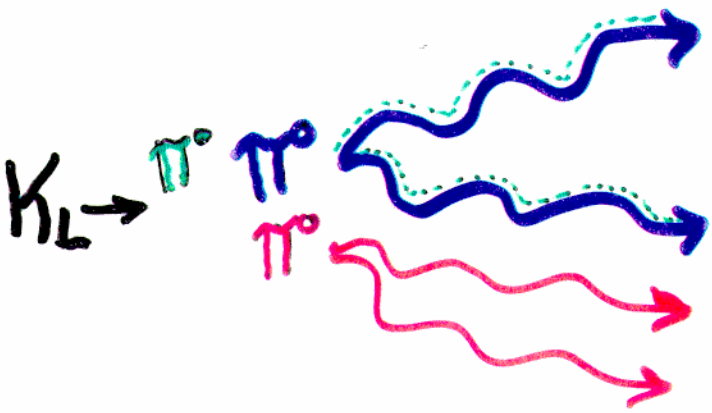
E799 SES $\lesssim 10^{-10}$

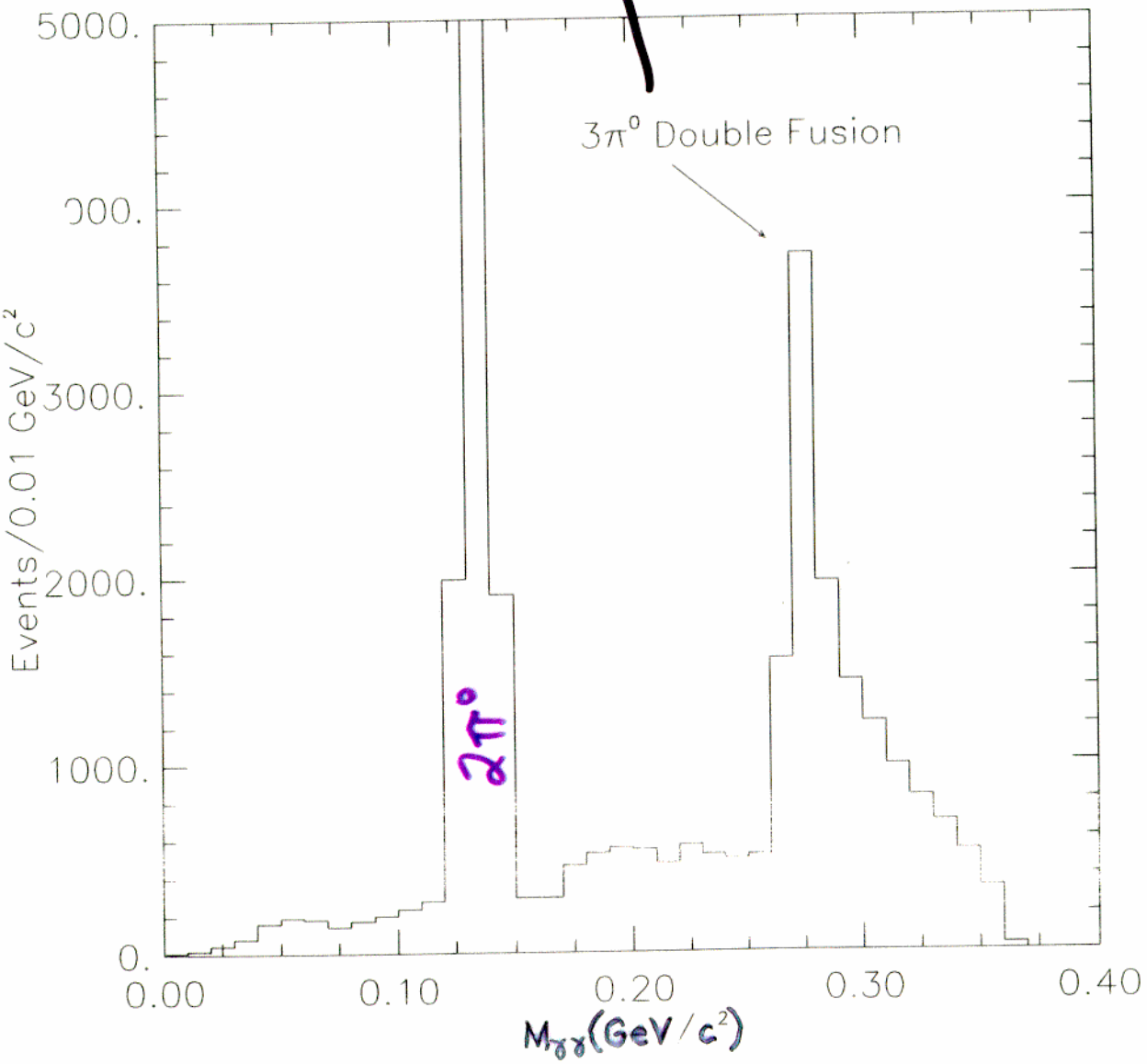
Current Limit: 4.3×10^{-9}

We used our $2\pi^0$ data (4 clusters) in E832 (ϵ'/ϵ) to search for

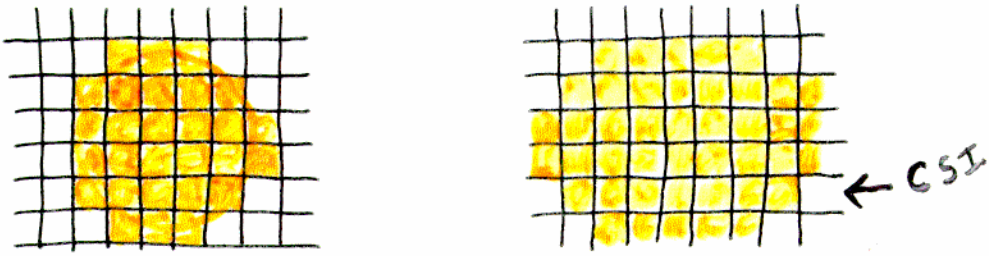
$K_L \to \pi^0 \gamma\gamma$

$K_L \to \pi^0 \gamma\gamma$ Analyis



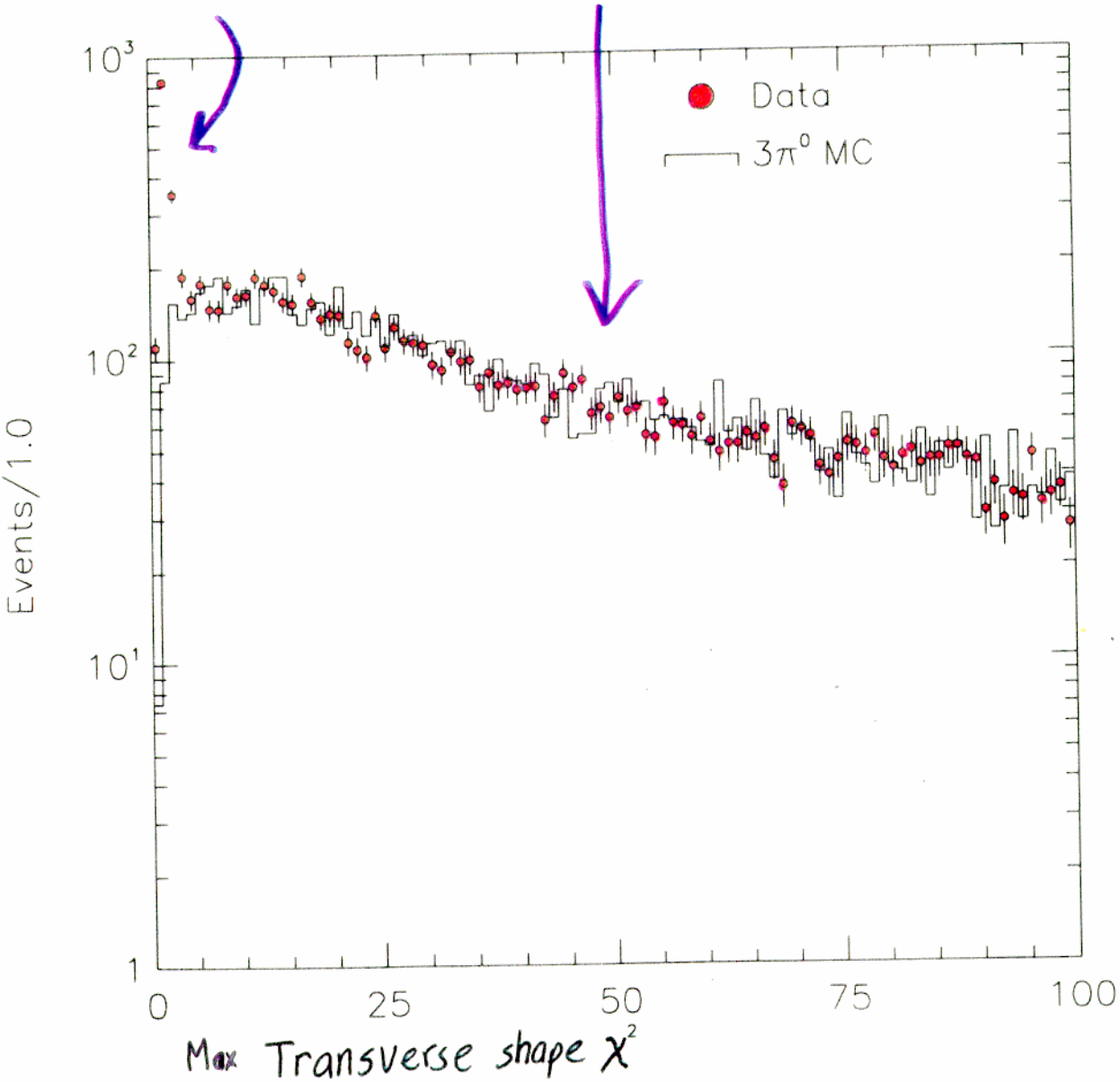


$K_L \to \pi^0 \gamma\gamma$ Analysis



Single cluster

fused clusters

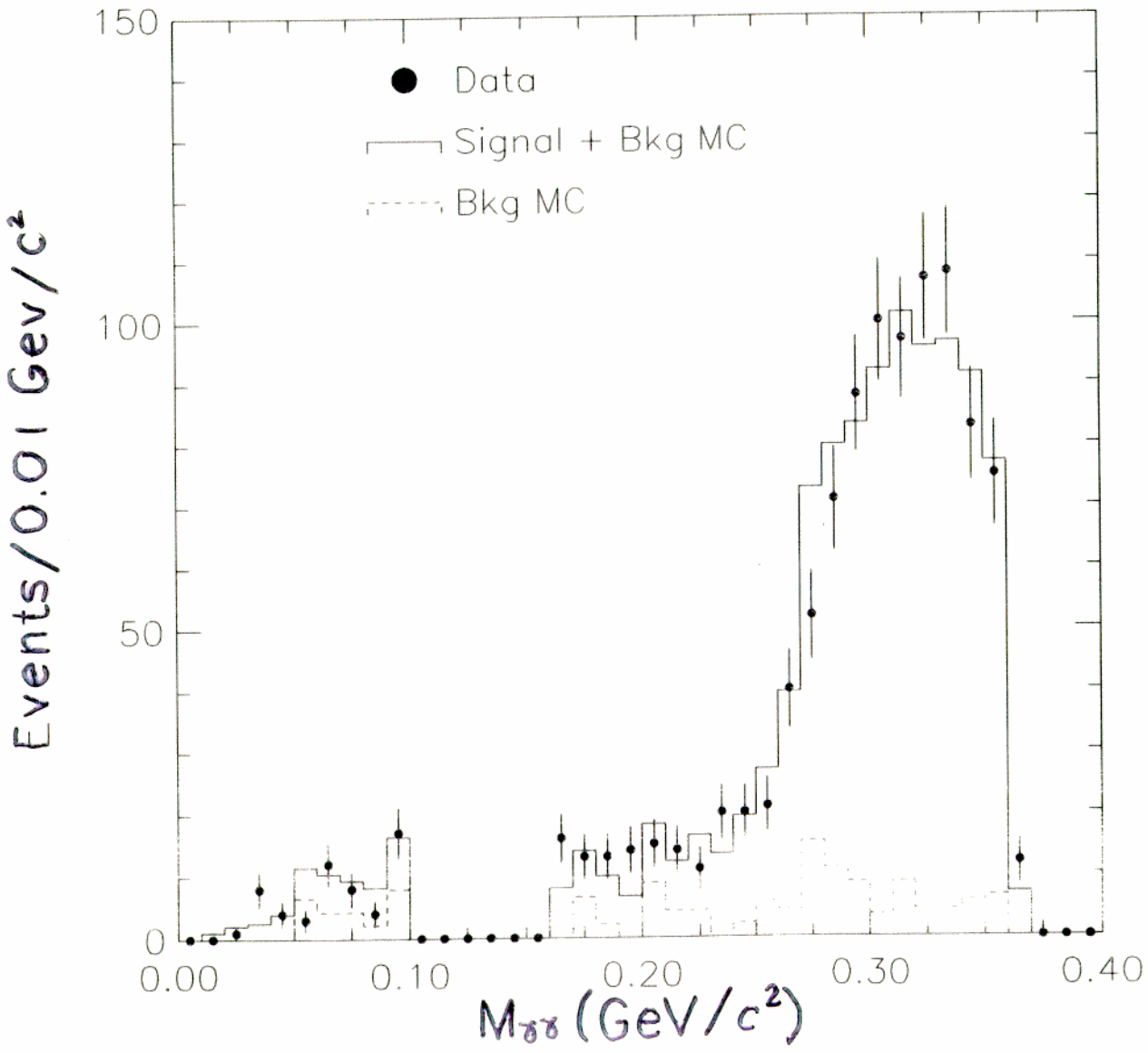


No. events : 814 signal

No. bkg : 138 (B/S = 17%)

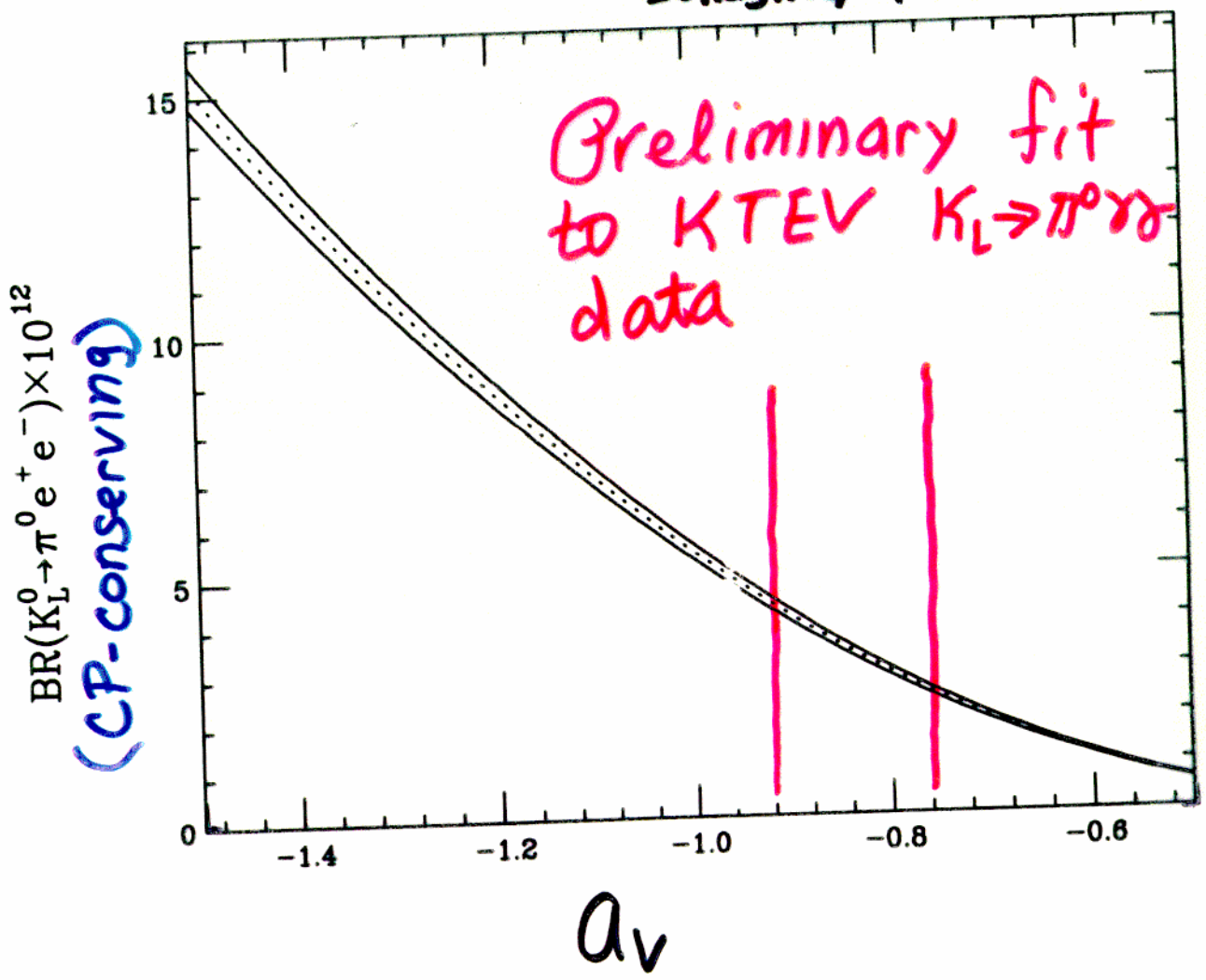
$BR(K_L \to \pi^0 \gamma\gamma) = [1.47 \pm 0.06\,(stat) \pm 0.11\,(syst)] \times 10^{-6}$

Preliminary!!



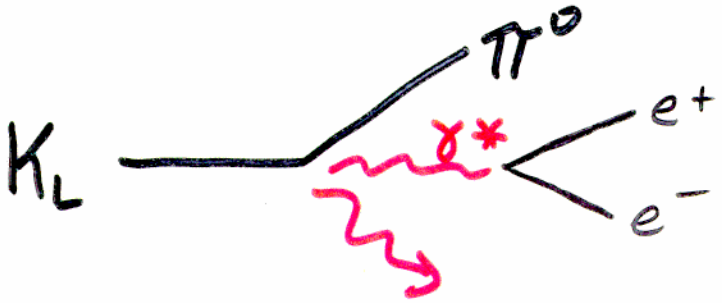
Previous result from CERN:
BR = $1.7 \pm 0.3 \times 10^{-6}$ with 60 events

Donaghue PRD51 (1995)



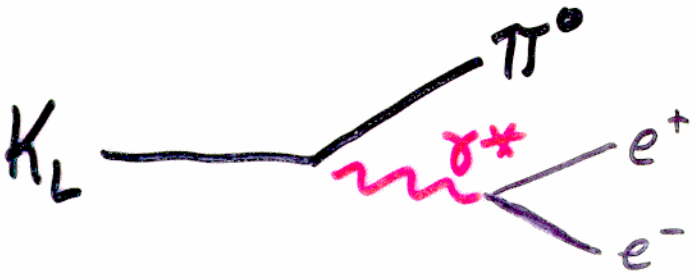
a_V Parametrizes the vector meson content in $K_L \to \pi^0 \gamma\gamma$

$K_L \to \pi^0 e^+ e^- \gamma$



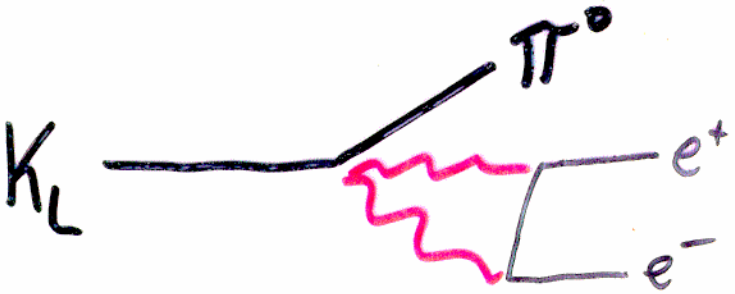
$\Gamma \sim \alpha_{em}^3$

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



$\Gamma \sim \alpha_{em}^2$

+ CP-violation



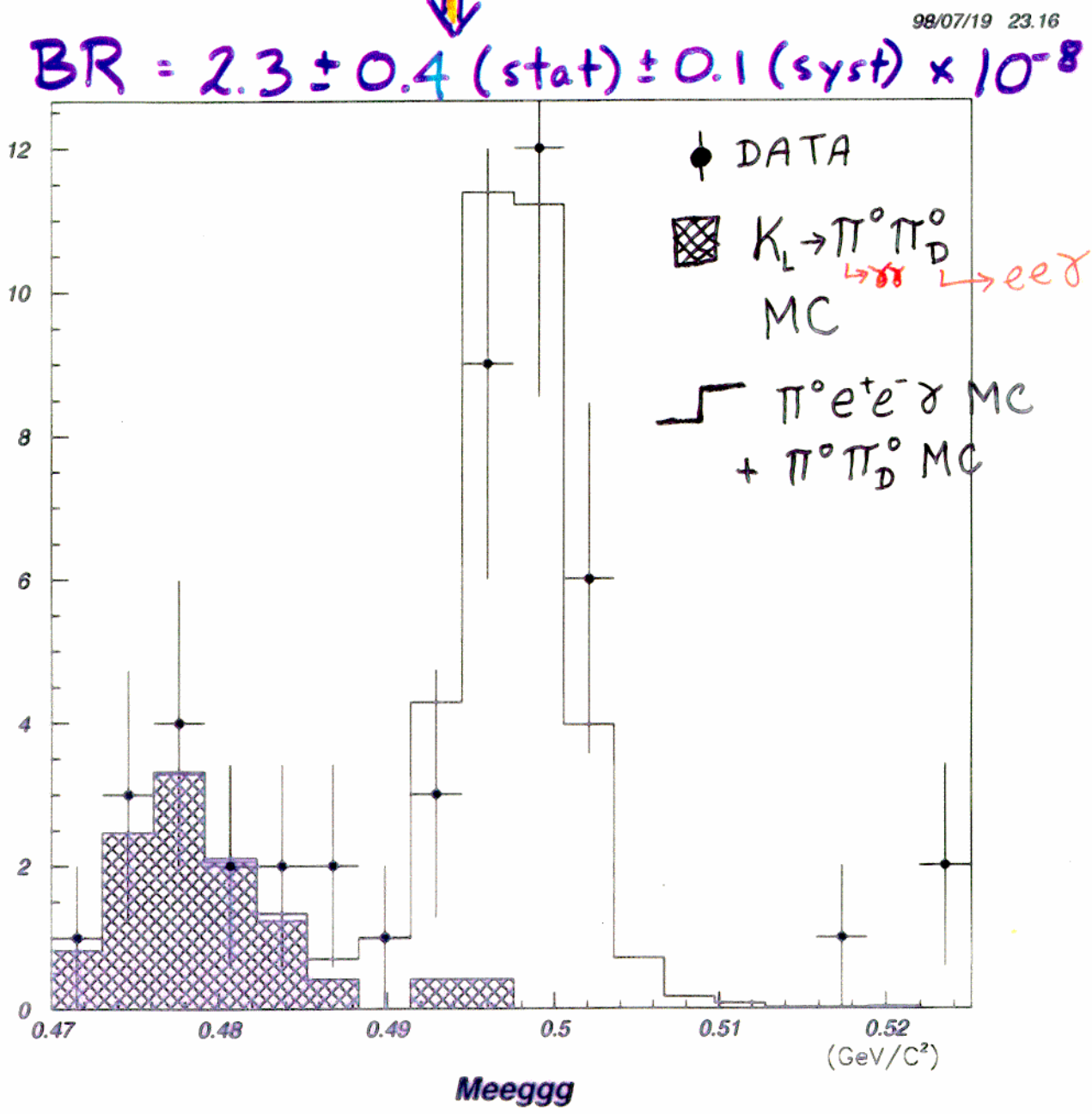
$\Gamma \sim \alpha_{em}^4$

$K_L \to \pi^0 e^+ e^- \gamma$

31 signal events on 1.1 bkg

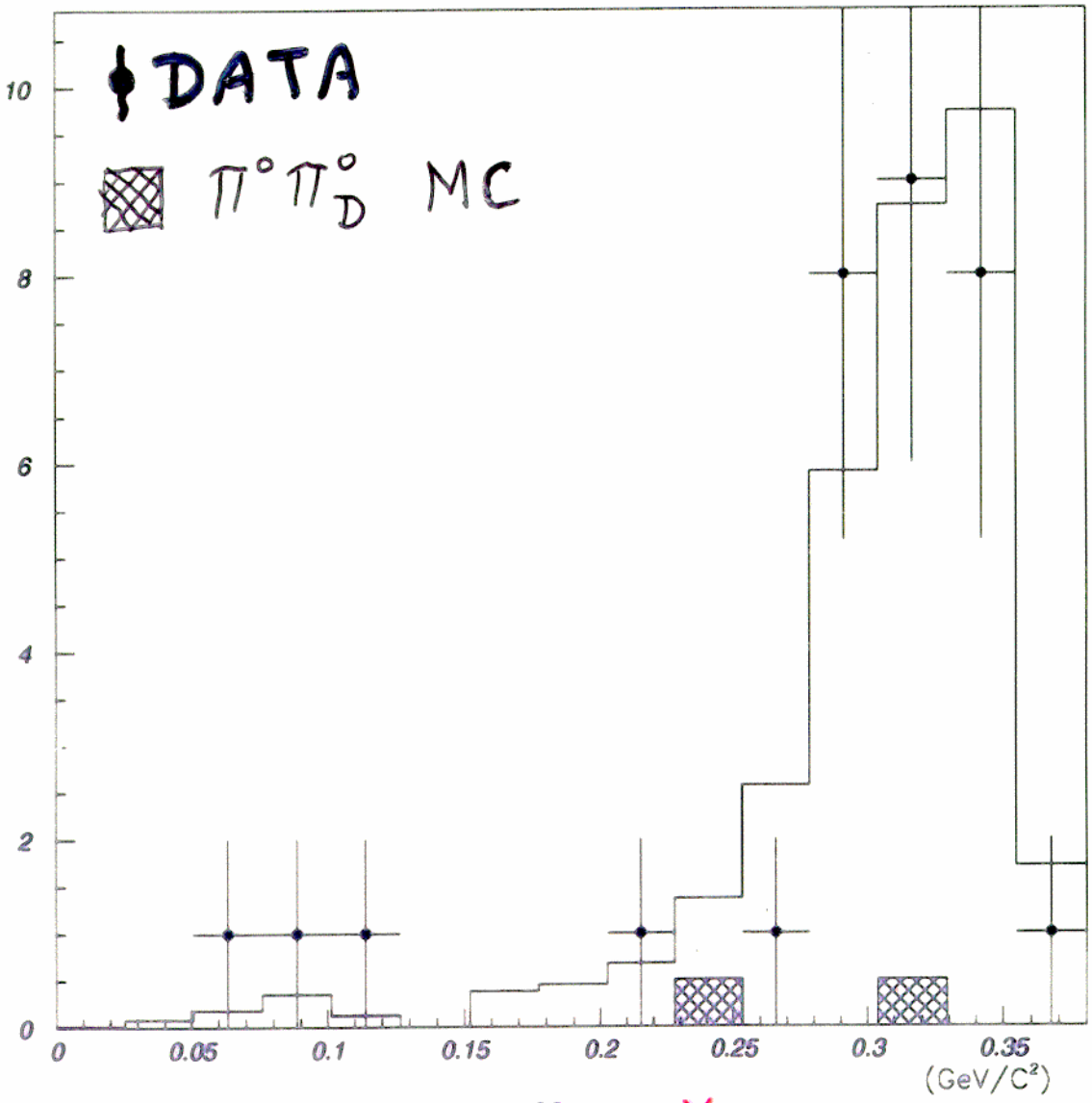
$\Downarrow$

$BR = 2.3 \pm 0.4\,(stat) \pm 0.1\,(syst) \times 10^{-8}$

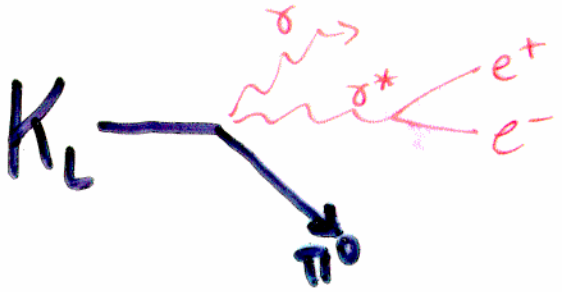


$K_L \to \pi^0 e^+ e^- \gamma$

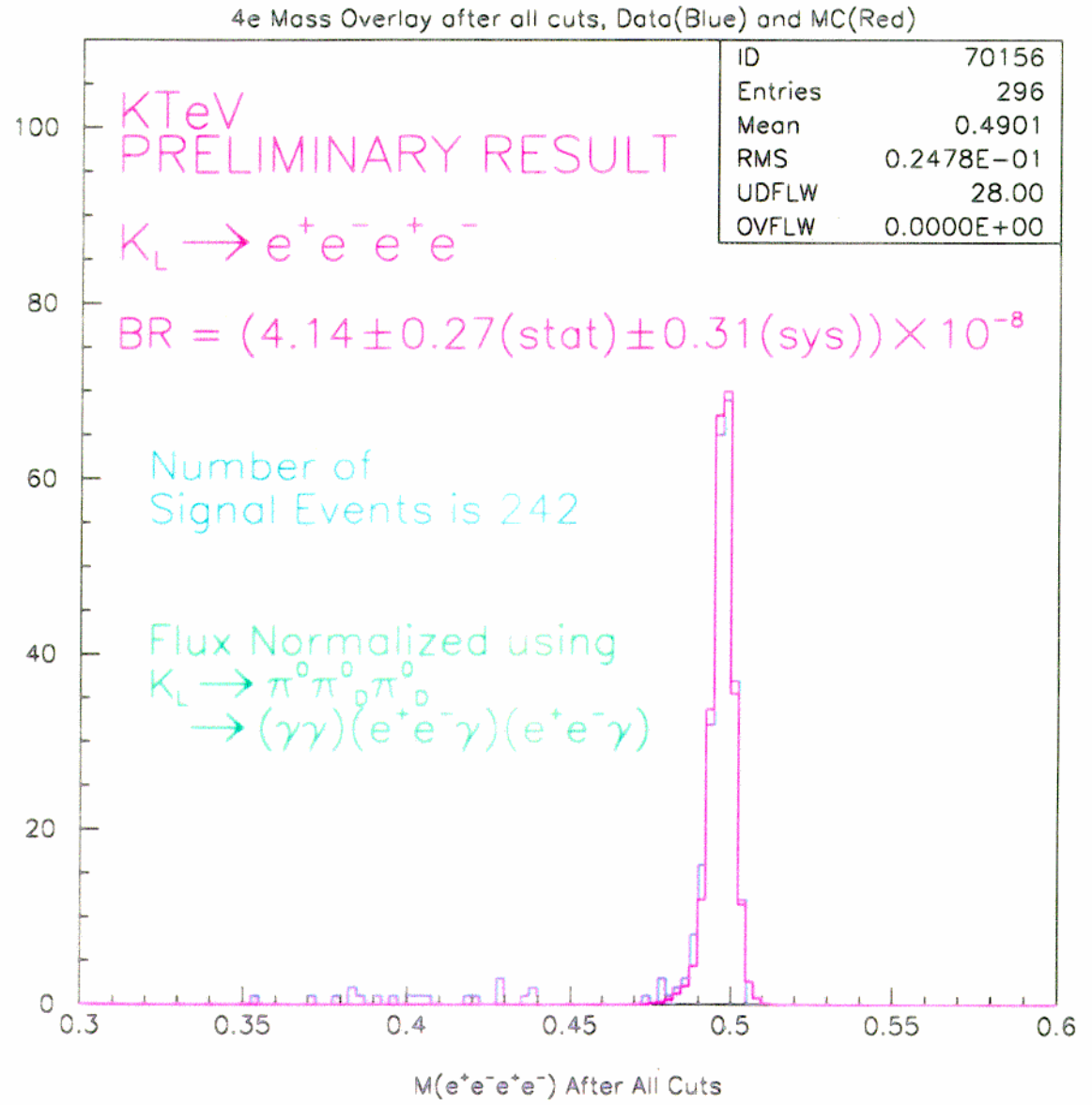
98/07/19 23.23



Meeg = $M_{\gamma\gamma^*}$



KTeV at FNAL: New E799 Results



Total Statistical Error 6.4%
Total Estimated Systematic Error 7.6%

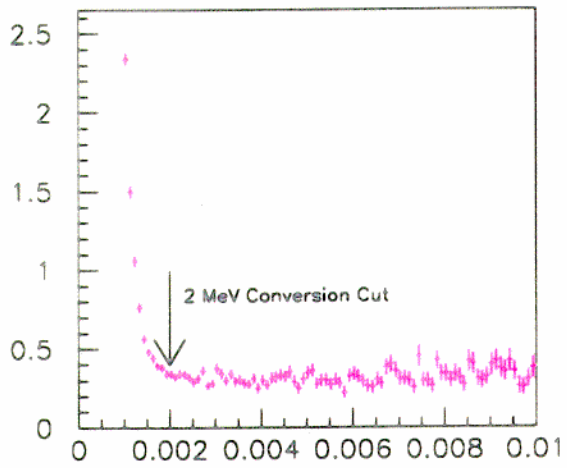
Includes Uncertainties in Flux Calculation 5.5%
Acceptance 5.1%

Best Previous Result: $[3.96 \pm 0.78(stat) \pm 0.32(sys)] \times 10^{-8}$

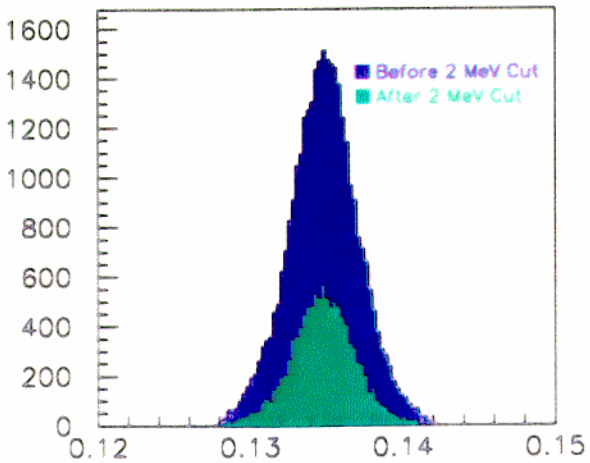
(P.Gu *et al.*, *Phys. Rev. Lett.*, **72**, 3000 (1994).)

KTeV at FNAL: New E799 Results

$K_L \rightarrow \pi^0\pi^0\pi^0_{DD}$



Lowest M(e^+e^-) Data/MC Ratio



$e^+e^-e^+e^-$ Mass

Ratio of $M(e^+e^-)$ Spectrum for $\pi^0 \Rightarrow e^+e^-e^+e^-$ candidate events in the data to the corresponding Monte Carlo Spectrum.

The excess in the data below 2 MeV is due to photon conversions in the material of the vacuum window and first chamber.

Blue histogram shows the $M(e^+e^-e^+e^-)$ spectrum for all $\pi^0 \Rightarrow e^+e^-e^+e^-$ candidate events in the data.

Green histogram shows the $M(e^+e^-e^+e^-)$ spectrum for those events with all $M(e^+e^-)$ values above 2 MeV, which are used to for all subsequent analysis.

Total $K_L \Rightarrow \pi^0\pi^0\pi^0_{DD}$ candidate events: 10715.
[Estimated residual background: 209.]

Total $K_L \Rightarrow \pi^0\pi^0_D\pi^0_D$ candidate events: 55006.
[Estimated residual background: 2560.]

KTeV PRELIMINARY Result

$$\frac{\Gamma(\pi^0 \Rightarrow e^+e^-e^+e^-)}{\Gamma(\pi^0 \Rightarrow \gamma\gamma)} = (3.31 \pm 0.04(stat) \pm 0.22(sys)) \times 10^{-5}$$

KTEV Event Display

/garage/leibig/4trk/dd.dat

Run Number: 8387
Spill Number: 89
Event Number: 10122255
Trigger Mask: 9
All Slices

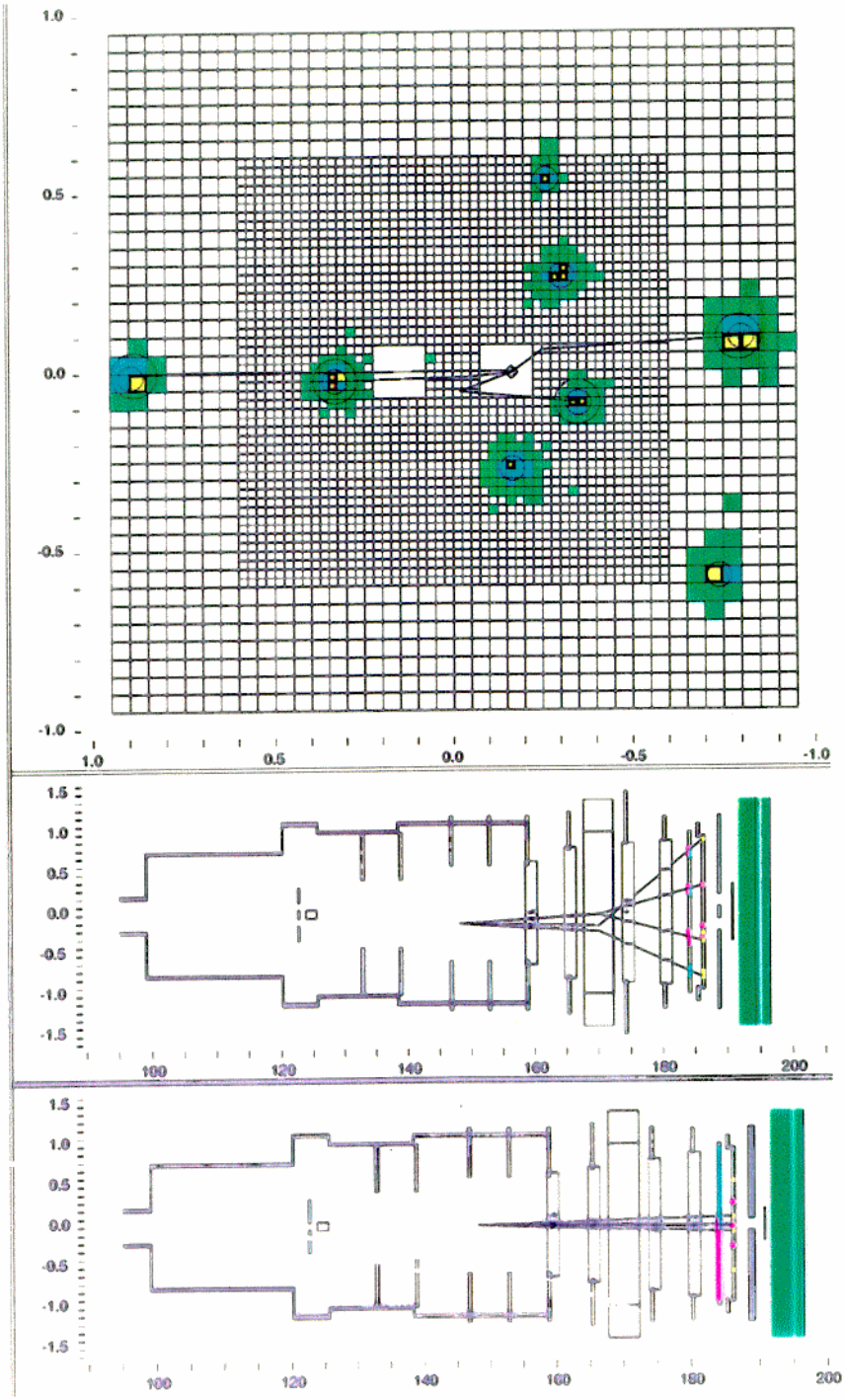
Track and Cluster Info
HCC cluster count: 8

ID	Xcsi	Ycsi	P or E
T 1:	-0.7928	0.0923	-6.71
C 5:	-0.8007	0.0937	6.69
T 2:	-0.3489	-0.0864	-7.98
C 7:	-0.3517	-0.0880	8.05
T 3:	0.3308	-0.0252	+12.03
C 2:	0.3312	-0.0257	12.05
T 4:	0.8858	-0.0040	+3.08
C 1:	0.8939	-0.0118	3.10
C 3:	-0.3069	0.2664	12.68
C 4:	-0.2637	0.5365	2.98
C 6:	-0.1676	-0.2724	13.13
C 8:	-0.7397	-0.5751	2.30

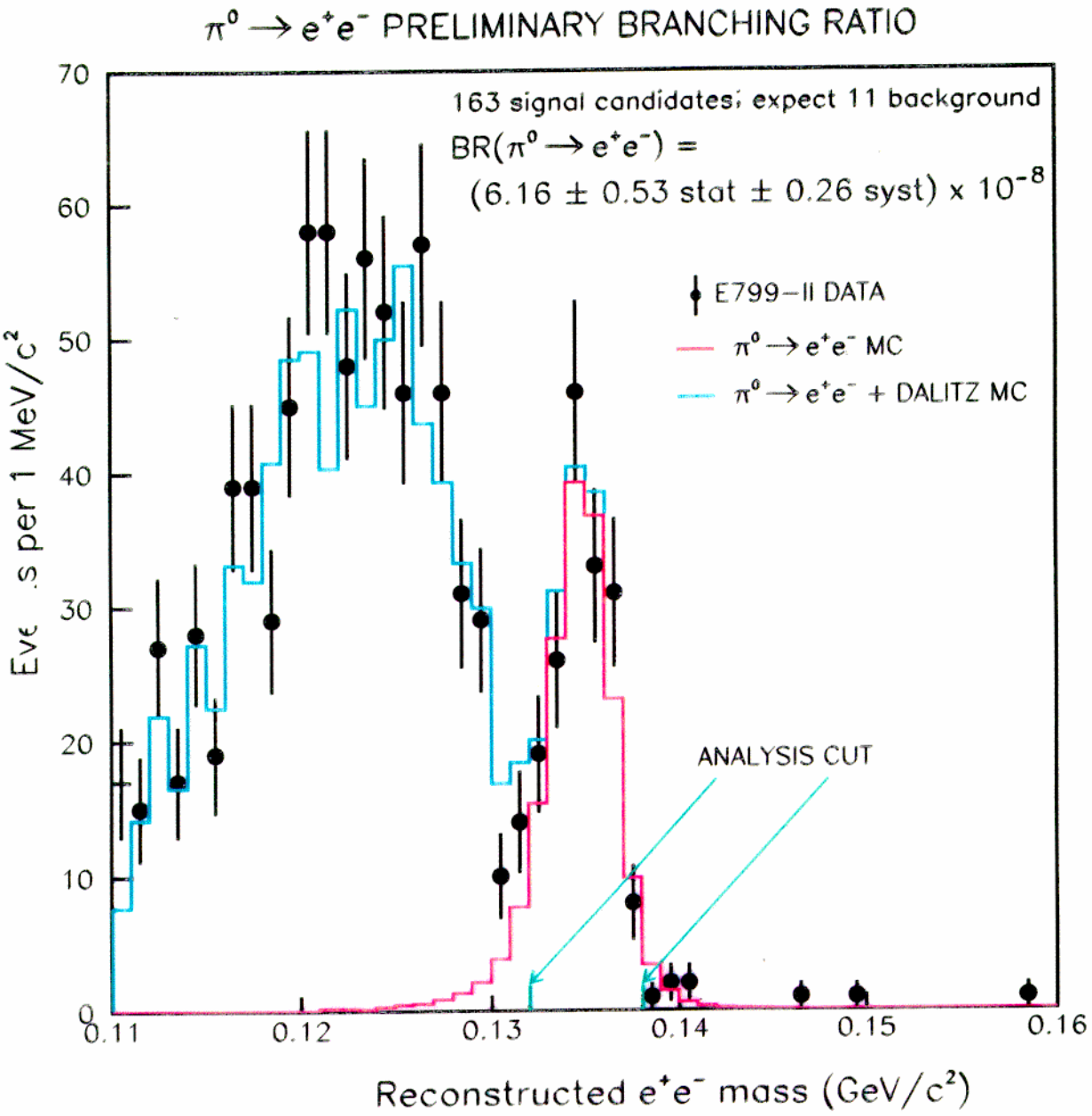
Vertex: 4 tracks

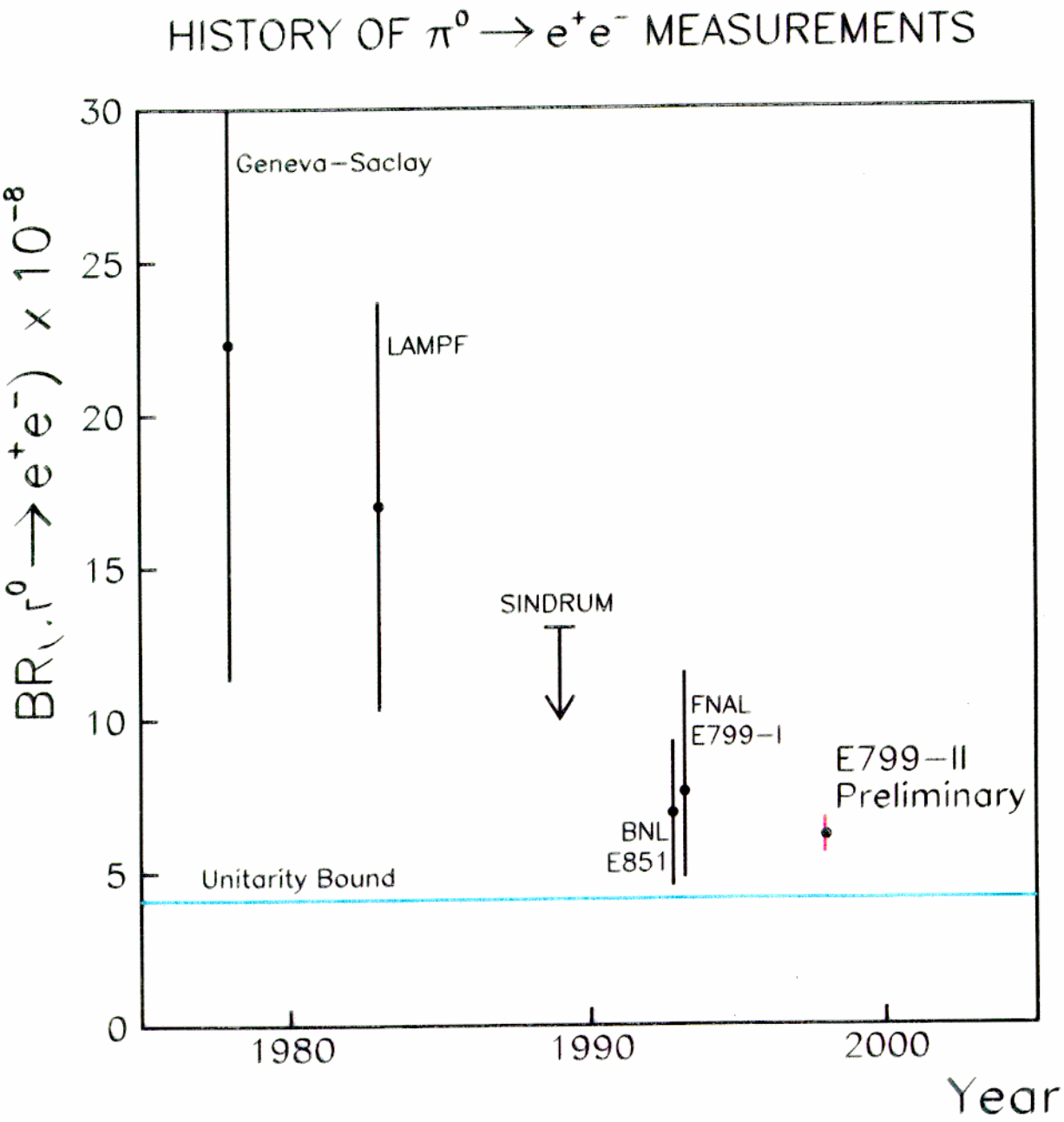
X	Y	Z
-0.1310	-0.0027	148.083

Chisq=3.74 Pt2v=0.008618



- Cluster
- Track
- 10.00 GeV
- 1.00 GeV
- 0.10 GeV
- 0.01 GeV


$\pi^0 \rightarrow e^+e^-$ PRELIMINARY BRANCHING RATIO
163 signal candidates; expect 11 background
BR($\pi^0 \rightarrow e^+e^-$) =
(6.16 ± 0.53 stat ± 0.26 syst) x 10^{-8}
E799–II DATA
$\pi^0 \rightarrow e^+e^-$ MC
$\pi^0 \rightarrow e^+e^-$ + DALITZ MC
ANALYSIS CUT
Events per 1 MeV/c^2
Reconstructed e^+e^- mass (GeV/c^2)
0
10
20
30
40
50
60
70
0.11
0.12
0.13
0.14
0.15
0.16



Summary of CP-Conserving Physics in KTEV

We have six new branching fraction measurements, including two "first observations" :

mode	stat. increase	physics/comment
$K_L \to \pi^+\pi^-e^+e^-$	–	first observation
$K_L \to \pi^0\gamma\gamma$	$\times 14$	CP-conserving part of $K_L \to \pi^0e^+e^-$. First observation of $\gamma\gamma$-mass events *below* 240 MeV/c^2.
$K_L \to \pi^0e^+e^-\gamma$	–	first observation, CP-conserving part of $K_L \to \pi^0e^+e^-$.
$K_L \to e^+e^-e^+e^-$	$\times 8$	$K\gamma^\star\gamma^\star$ vertex
$\pi^0 \to e^+e^-e^+e^-$	$\times 60$	$\pi^0\gamma^\star\gamma^\star$ vertex
$\pi^0 \to e^+e^-$	$\times 20$	ChPT models

KTEV99 plans to triple statistics.

Summary of CP-Violation Physics in KTEV

physics		*PRELIM.* KTeV result	additional sensitivity to reach SM
CP-violating asymmetry in $K_L \to \pi^+\pi^-e^+e^-$	I_{CPV}	"evidence"	none
	D_{CPV}	none	10^3
$K_L \to \pi^0\nu\bar{\nu}$	D_{CPV}	$< 6 \times 10^{-7}$	10^5
$K_L \to \pi^0e^+e^-$	$D_{CPV} + I_{CPV}$	not yet	10^2
ϵ'/ϵ	D_{CPV}	not yet	< 10

I_{CPV} = Indirect CP-violation.
D_{CPV} = Direct CP-violation.

First search for $K_L \to \pi^0\nu\bar{\nu}$ using $\pi^0 \to \gamma\gamma$.
(limited by background from vacuum window interactions)

KTEV99 plans to double the ϵ'/ϵ statistics and:

- Improve drift chamber performance.
- Upgrade/replace CsI readout electronics (the QIE's) to have better reliability.