

Recent Results

From the NA48 Experiment at CERN

29 January 2003

Phil Rubin

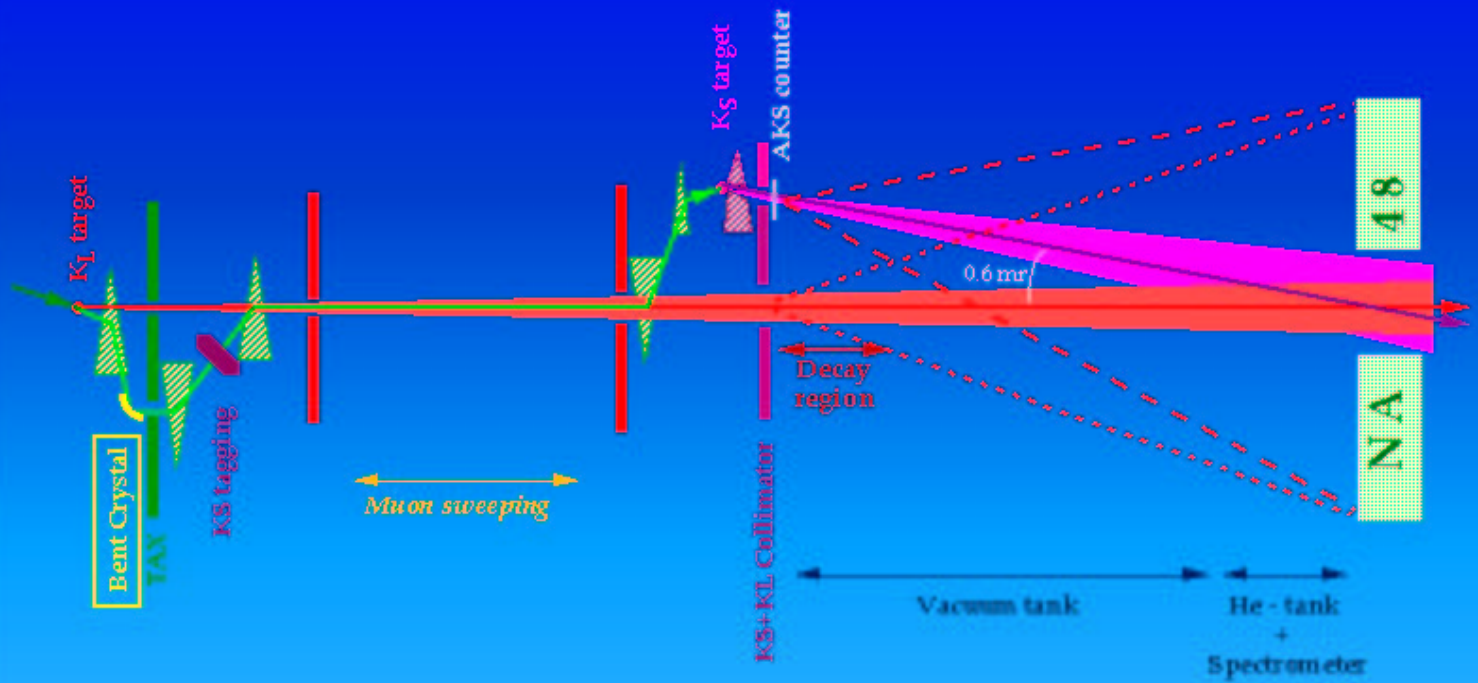
for the NA48 Collaboration

- DIRECT CP VIOLATION
- TESTS of χ_{PT} THEORY

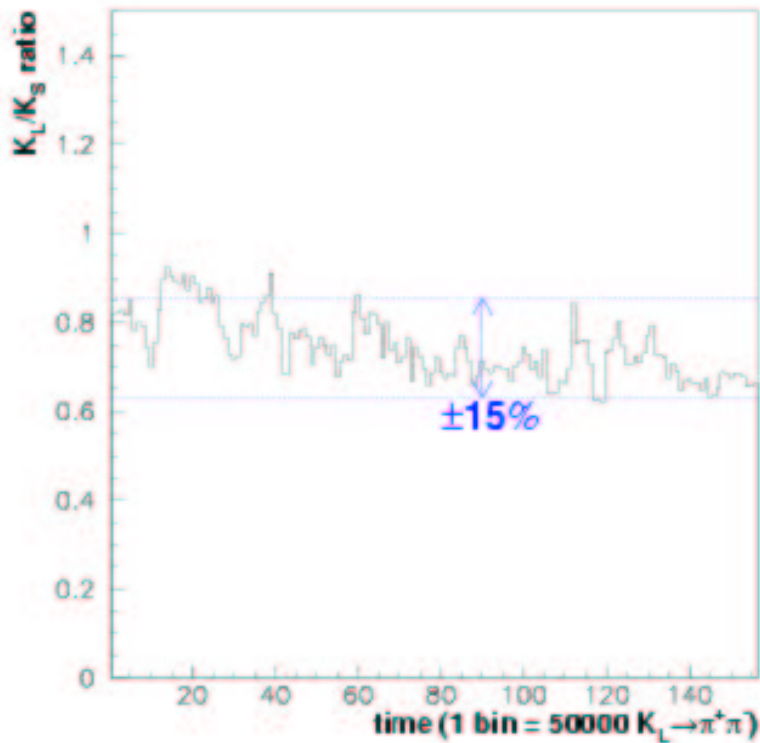
HISTORY

- **NA31** publish 3σ result $[Re(\epsilon'/\epsilon) = (23.0 \pm 6.5) \times 10^{-4}]$;
E731 publish null result $[Re(\epsilon'/\epsilon) = (7.4 \pm 5.9) \times 10^{-4}]$
- **1990**: NA48 proposal
- **1997**: ~ 0.5 million $K_L \rightarrow \pi^0\pi^0$
 $[Re(\epsilon'/\epsilon) = (18.5 \pm 7.3) \times 10^{-4}]$ (published 1999)
- **1998-1999**: Improved trigger and DAQ
 $\Rightarrow \sim 3$ million $K_L \rightarrow \pi^0\pi^0$
 $[Re(\epsilon'/\epsilon) = (15.0 \pm 2.6) \times 10^{-4}]$ (published 2001)
- **1999 (November)**: Beam tube implosion; drift chambers destroyed
- **2000**: Neutral data only (ϵ'/ϵ cross-checks and high intensity K_S beam)
- **2000-2001**: Drift chamber reconstruction
- **2001**: ~ 1.5 million $K_L \rightarrow \pi^0\pi^0$ (different beam conditions)
 $[Re(\epsilon'/\epsilon) = (13.7 \pm 3.1) \times 10^{-4}]$ (published 2002)
- **2002**: High intensity K_S beam (new drift chamber readout electronics)
- **2003**: Charged Kaon program

THE SIMULTANEOUS K_L AND K_S BEAMS



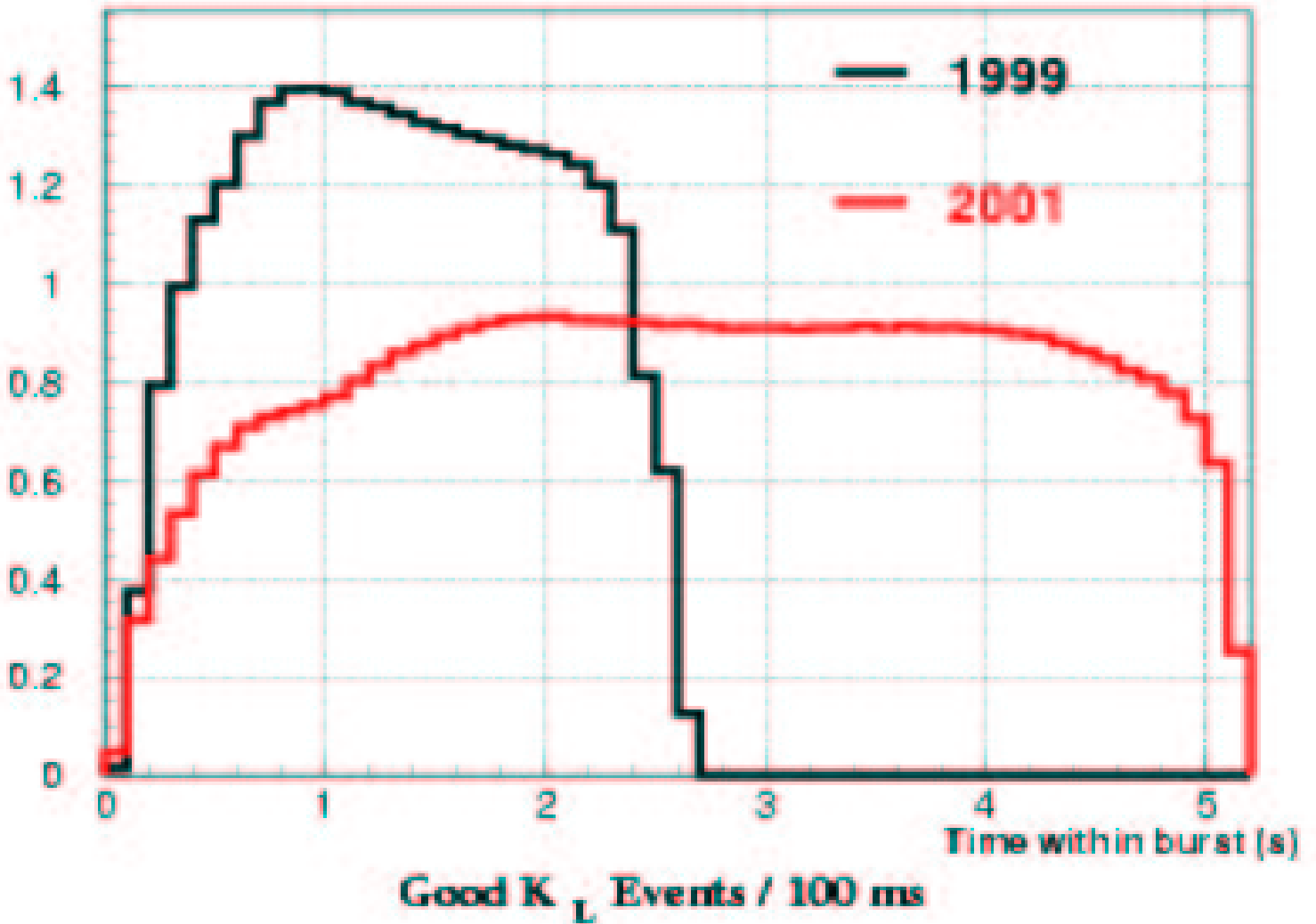
Not to scale!



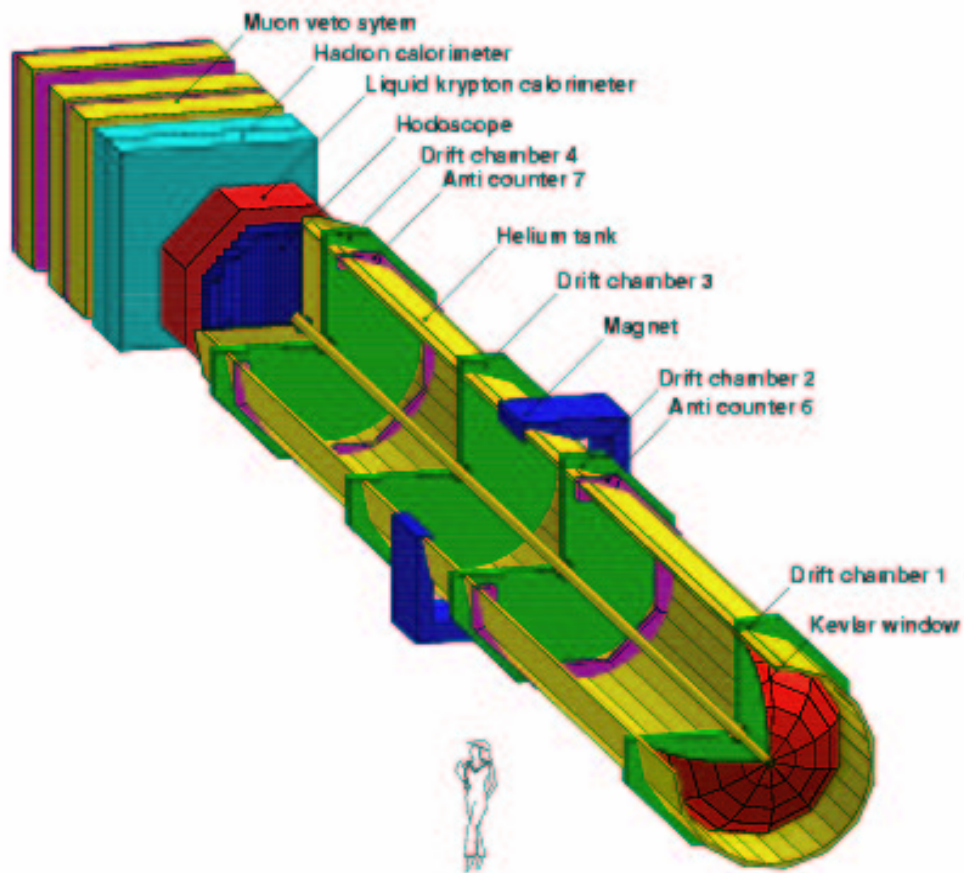
Running Conditions

	1998-1999	2000*	2001
Proton Momentum [GeV/c]	450	400	400
SPS Cycle Time [s]	14.4	14.4	16.8 s
Spill Length (Effective) [s]	2.4 (1.7)	3.2 (2.2)	5.2 (3.6)
Duty Cycle	0.17	0.22	0.31
K_L Beam Intensity [$(\times 10^{12})$ ppp]	1.5	1.0	2.4
K_S Beam Intensity [$(\times 10^7)$ ppp]	3.0	1.0×10^2	5.0

* No drift chambers

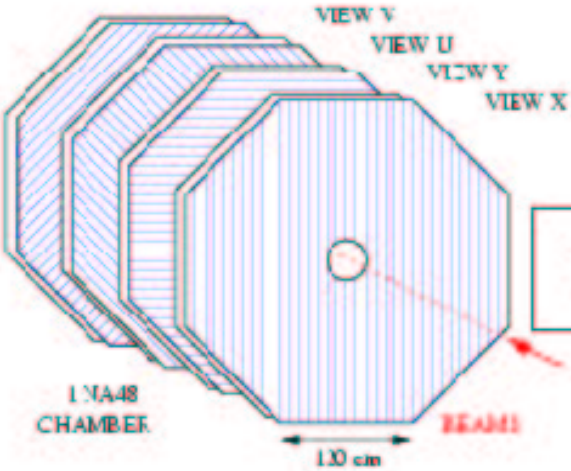


NA48 detectors



Magnetic Spectrometer

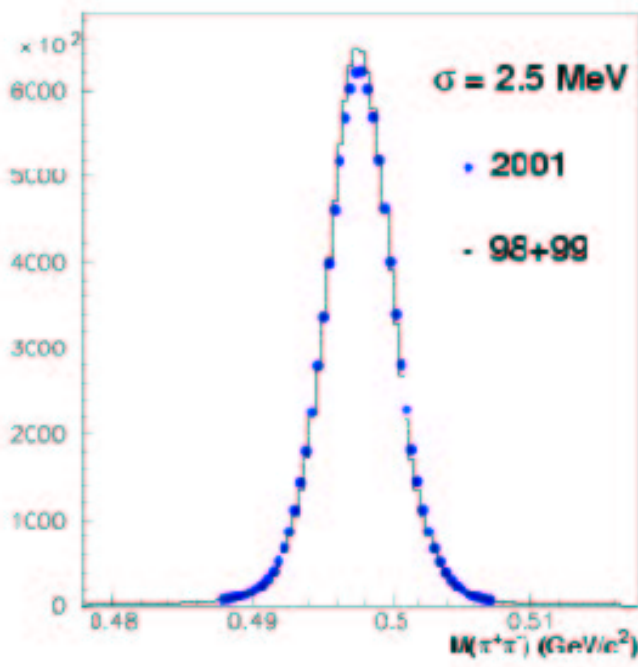
2 | 2 drift chambers | magnet > 265 MeV p_t kick



plane efficiency: 99.5%
space resolution: 95 μm

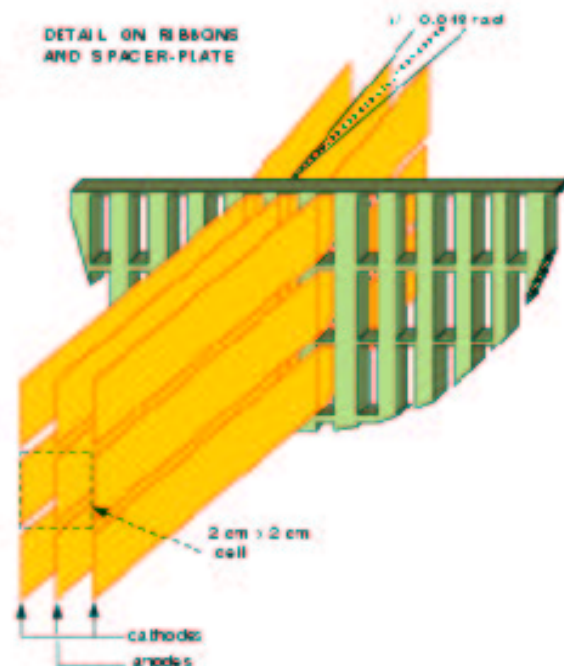
$$\frac{\sigma(p)}{p} \simeq 0.5\% \oplus 0.009 p\%$$

p in GeV/c



Liquid Krypton Calorimeter

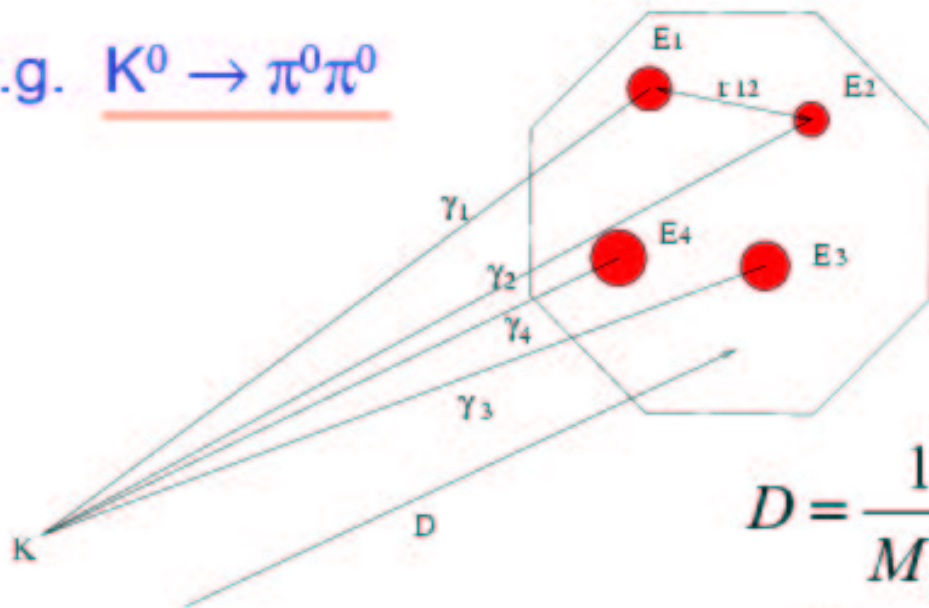
- Quasi-homogeneous detector: 10 m^3 lkr ($X_0 = 4.7 \text{ cm}$)
- 13212 cells
 - Granularity $2 \times 2 \text{ cm}^2$
 - Depth 1.25 m ($\approx 27 X_0$)
- Projective geometry pointing to decay region ($\approx 114 \text{ m}$ upstream)
- Accordion geometry



$$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{0.09}{E} \oplus 0.42\% \quad (E \text{ in GeV})$$

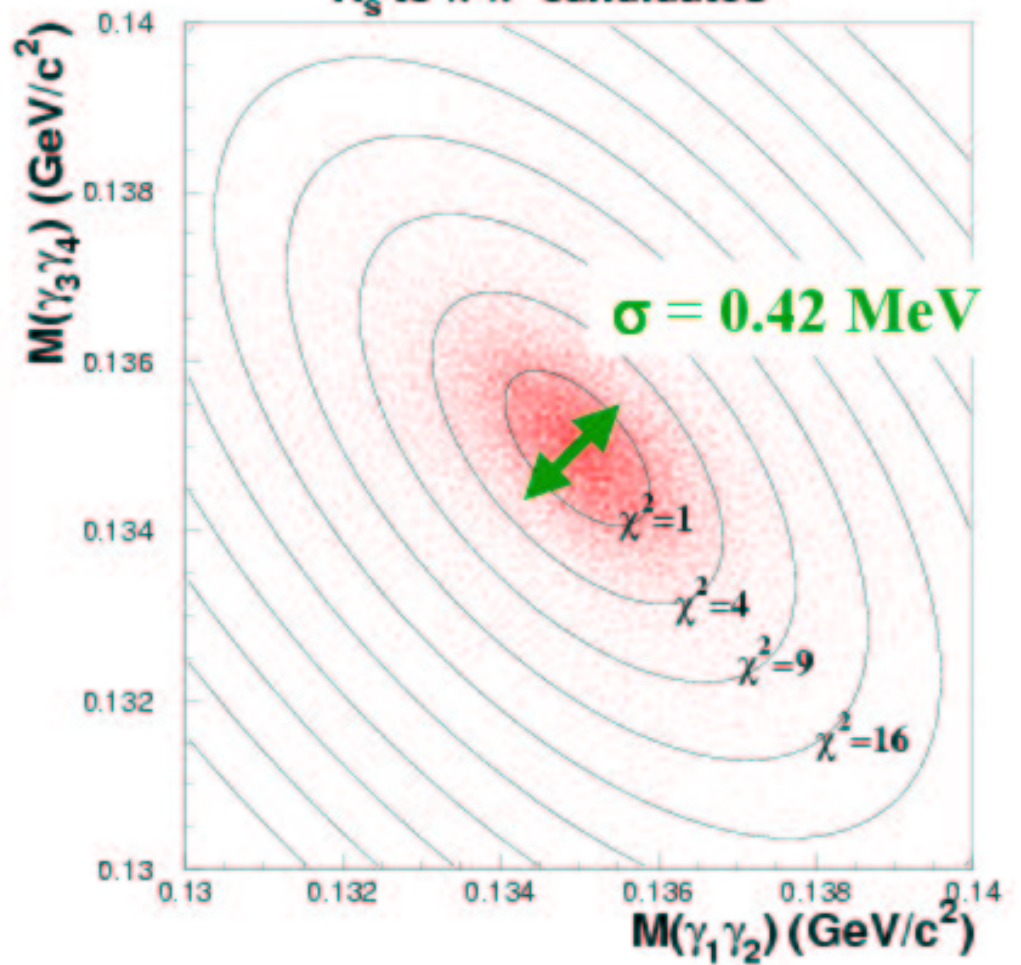
Neutral Reconstruction

e.g. $K^0 \rightarrow \pi^0\pi^0$



$$D = \frac{1}{M_K} \sqrt{\sum E_i E_j \times r_{ij}^2}$$

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



π^0 masses
in
 $K_S \rightarrow \pi^0\pi^0$

Neutral Kaons

- Production in Strangeness Eigenstates; Decay in CP Eigenstates

$$|K^0\rangle = \frac{1}{\sqrt{2}}(|K_1\rangle + |K_2\rangle), \quad (S = +1)$$

$$|\overline{K}^0\rangle = \frac{1}{\sqrt{2}}(|K_1\rangle - |K_2\rangle), \quad (S = -1)$$

$$CP|\pi\pi\rangle = +|\pi\pi\rangle \quad CP|\pi\pi\pi\rangle = -|\pi\pi\pi\rangle$$

- $K_1 \rightarrow \pi\pi$ and $K_2 \rightarrow \pi\pi\pi$ (allowed)
- $K_1 \not\rightarrow \pi\pi\pi$ and $K_2 \not\rightarrow \pi\pi$ (not allowed)

But CP NOT Conserved

- About 1% of the time, a “ K_2 ” $\rightarrow \pi\pi$
- Indirectly?

$$|K_S^0\rangle = \frac{1}{\sqrt{1+\epsilon^2}}(|K_1\rangle + \epsilon|K_2\rangle)$$

$$|K_L^0\rangle = \frac{1}{\sqrt{1+\epsilon^2}}(\epsilon|K_1\rangle + |K_2\rangle)$$

$$|\epsilon| = (2.28 \pm 0.02) \times 10^{-3}$$

- Directly?

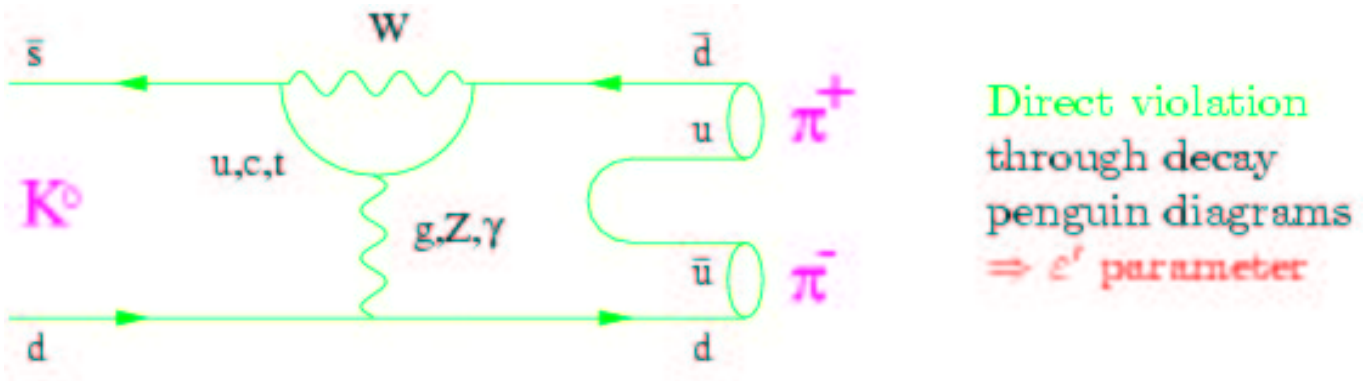
$$\Gamma(K^0 \rightarrow F) \neq \Gamma(\bar{K}^0 \rightarrow \bar{F})$$

$$\frac{\Gamma(K_L^0 \rightarrow \pi^0\pi^0)/\Gamma(K_S^0 \rightarrow \pi^0\pi^0)}{\Gamma(K_L^0 \rightarrow \pi^+\pi^-)/\Gamma(K_S^0 \rightarrow \pi^+\pi^-)} \neq 1$$

Direct CP Violation

- $\pi\pi$ from K^0 can have $I = 0$ or 2

Two Amplitudes: A_0 and A_2



- Define ratio of CP-violating / CP-conserving amplitudes:

$$\frac{A(K_L \rightarrow \pi^+\pi^-)}{A(K_S \rightarrow \pi^+\pi^-)} \equiv \eta_{+-} = \epsilon - \epsilon'$$

$$\frac{A(K_L \rightarrow \pi^0\pi^0)}{A(K_S \rightarrow \pi^0\pi^0)} \equiv \eta_{00} = \epsilon - 2\epsilon'$$

$$\epsilon' \text{ (direct CP violation parameter)} \approx \frac{i}{\sqrt{2}} \text{Im} \left(\frac{A_2}{A_0} \right) e^{i(\delta_2 - \delta_0)}$$

- Theoretical predictions: few $10^{-4} \leq |\epsilon'/\epsilon| \leq 2 \times 10^{-3}$
- Experimental observable:

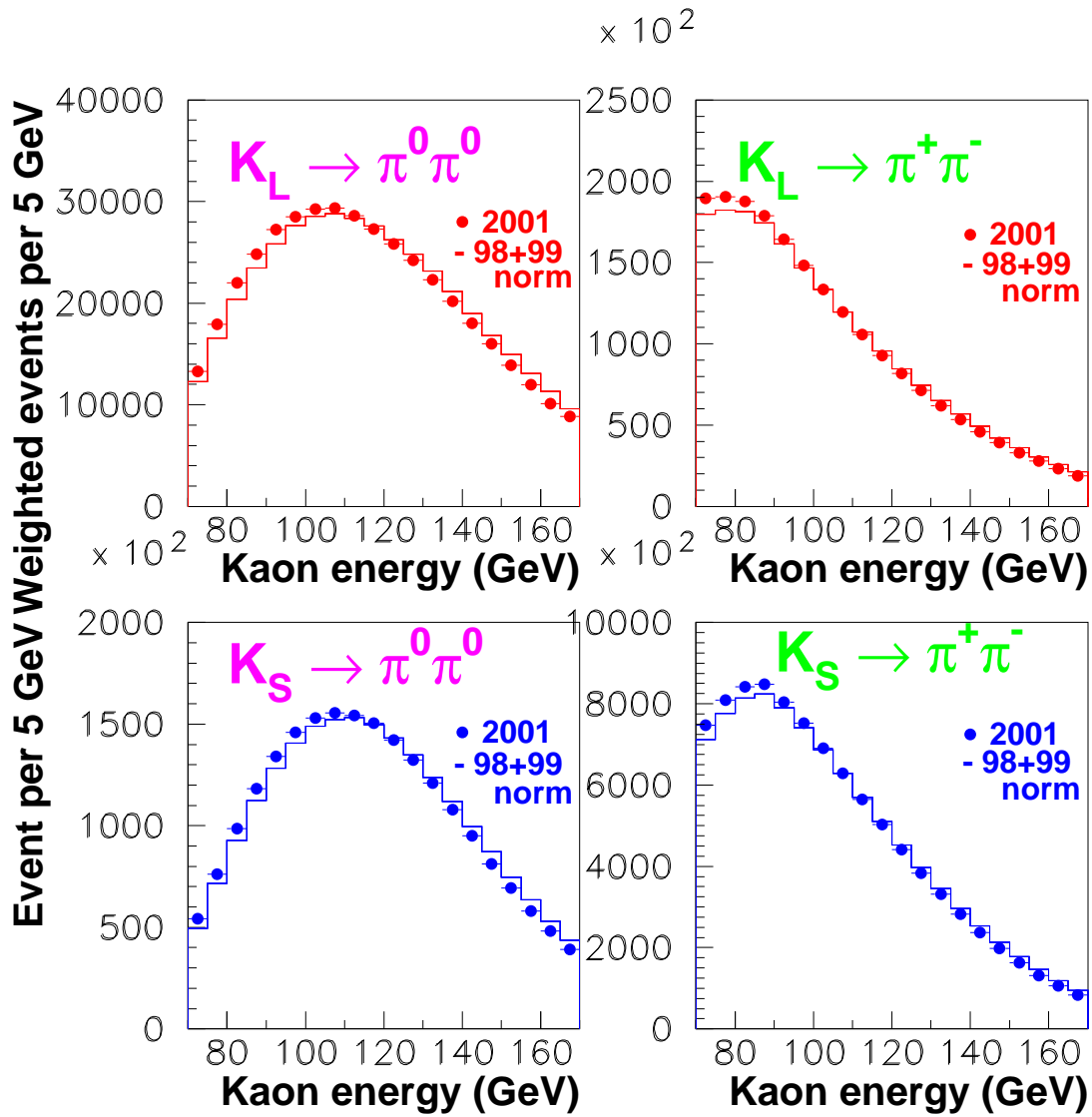
$$R \equiv \frac{\Gamma(K_L^0 \rightarrow \pi^0\pi^0)/\Gamma(K_S^0 \rightarrow \pi^0\pi^0)}{\Gamma(K_L^0 \rightarrow \pi^+\pi^-)/\Gamma(K_S^0 \rightarrow \pi^+\pi^-)} = 1 - 6\text{Re}(\epsilon'/\epsilon)$$

Analysis Philosophy and Approach

All effects cancel to first order

- Measure R in (5 GeV-wide) energy bins
- Weight K_L lifetime
- Apply charged deadtime fraction to all data
- Weight K_S flux
- Tag parent and correct for misidentification
- Identify decay channels and subtract backgrounds
- Correct for non-linearities and energy scale
- Compute residual acceptance differences
- Evaluate residual differences in accidental rates

Event statistics



2001 statistics:

$$K_L \rightarrow \pi^0\pi^0 : 1.55 \times 10^6$$

$$K_S \rightarrow \pi^0\pi^0 : 2.16 \times 10^6$$

$$K_L \rightarrow \pi^+\pi^- : 7.14 \times 10^6$$

$$K_S \rightarrow \pi^+\pi^- : 9.61 \times 10^6$$

Summary of corrections

Corrections on R and systematic uncertainties
(units 10^{-4})

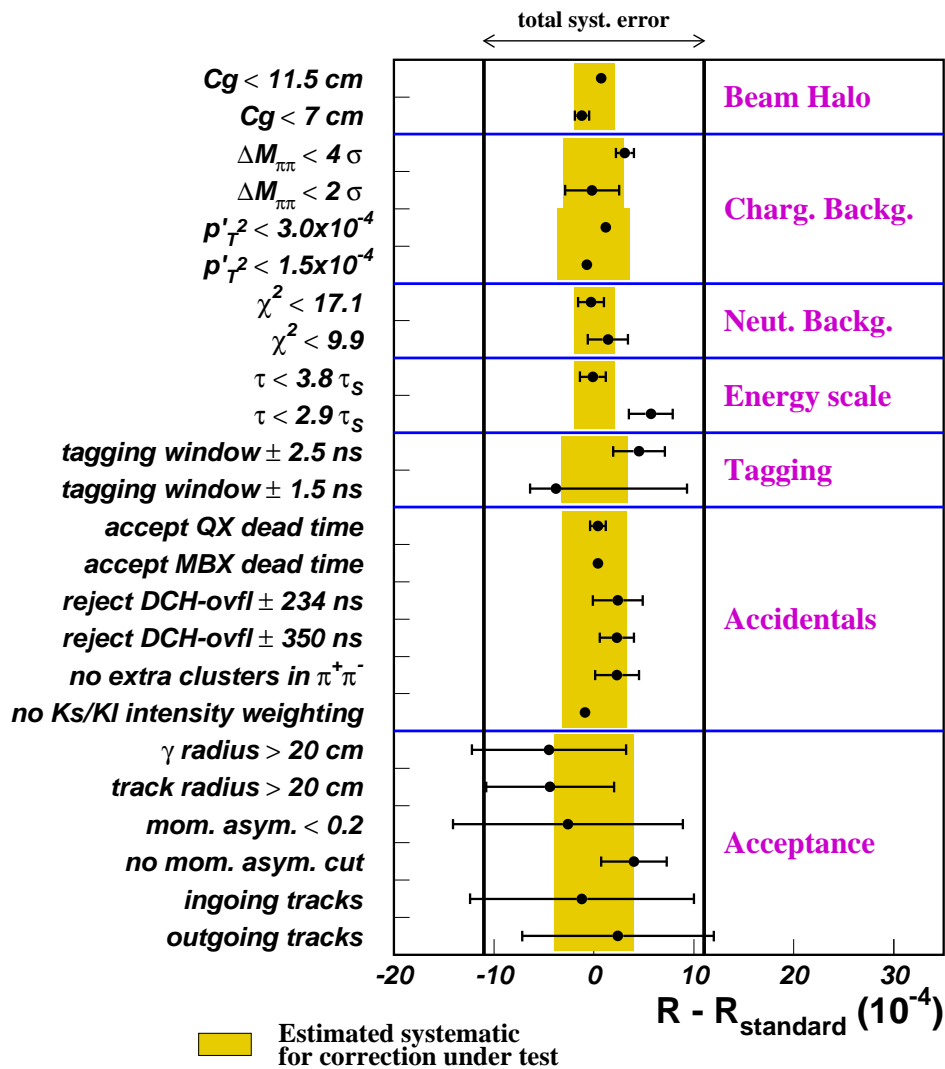
Source	2001	98-99
$\pi^+\pi^-$ background	14.2 ± 3.0	16.9 ± 3.0
$\pi^0\pi^0$ background	-5.6 ± 2.0	-5.9 ± 2.0
beam scatt. backgr.	-8.8 ± 2.0	-9.6 ± 2.0
Tagging ineffic.	± 3.0	± 3.0
Accidental tagging	6.9 ± 2.8	8.3 ± 3.4
$\pi^+\pi^-$ reconstruction	± 2.8	2.0 ± 2.8
$\pi^0\pi^0$ reconstruction	± 5.3	± 5.8
AKS inefficiency	1.2 ± 0.3	1.1 ± 0.4
Accept. corr.	21.9 ± 3.5	26.7 ± 4.1
	± 4.0	± 4.0
$\pi^+\pi^-$ trigger ineffic.	5.2 ± 3.6	-3.6 ± 5.2
Accidental event losses:		
intensity diff	± 1.1	± 3.0
illumination diff	± 3.0	± 3.0
K_S in-time activity	± 1.0	± 1.0
All	$+35.0 \pm 6.5$	$+35.9 \pm 8.1$
	± 9.0	± 9.6

Errors are pure stat or pure syst

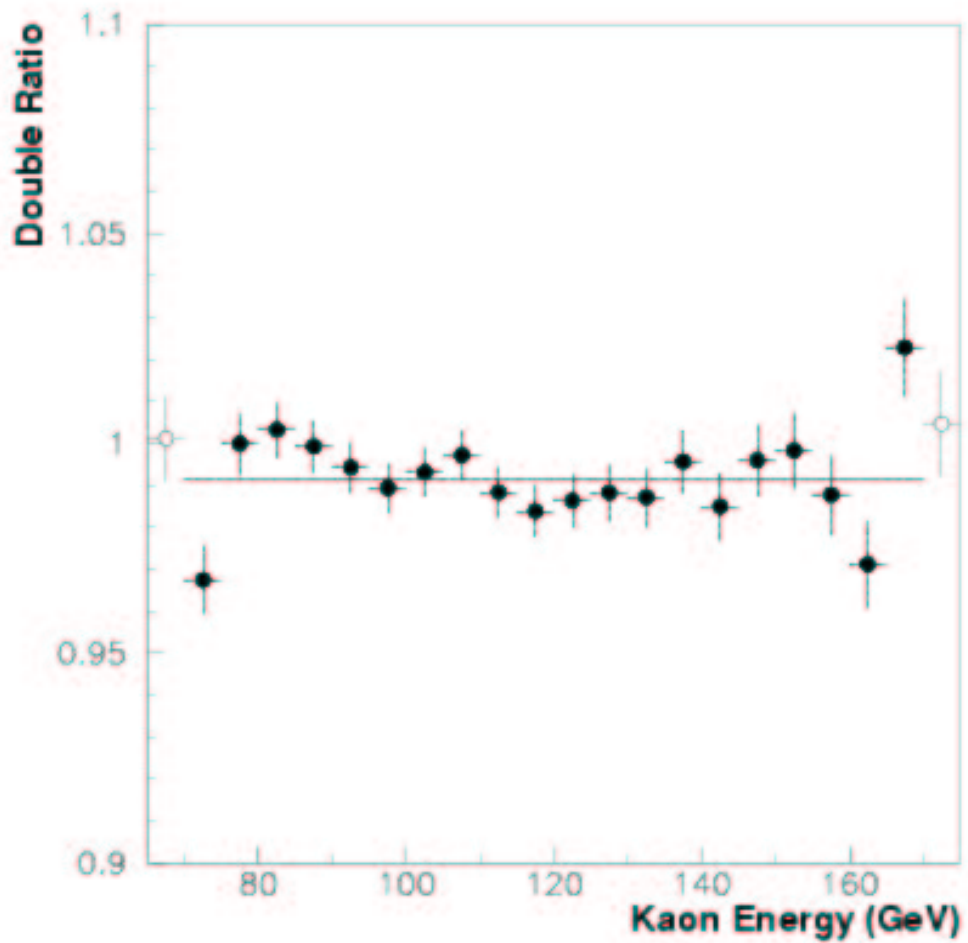
Systematic checks

Precise evaluation of systematics to 10^{-4} level is essential

R stability against cut variations



2001 Result (in Energy Bins)



$$R = 0.99181 \pm 0.00147(stat) \pm 0.00110(syst)$$

NA48 Results

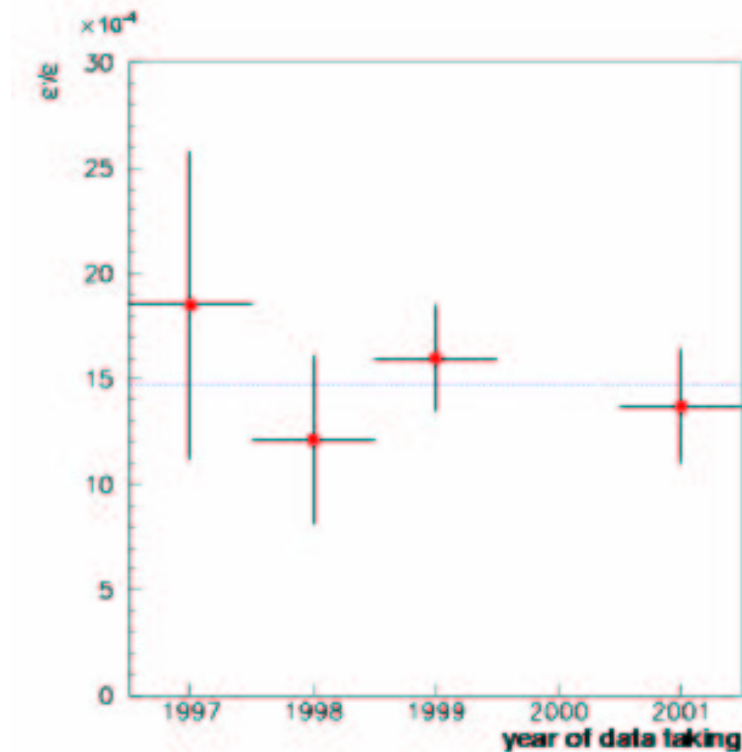
1997 $\text{Re}(\epsilon'/\epsilon) = [18.5 \pm 4.5(\text{stat}) \pm 5.8(\text{syst})] \times 10^{-4}$

98/99 $\text{Re}(\epsilon'/\epsilon) = [15.0 \pm 1.7(\text{stat}) \pm 2.1(\text{syst})] \times 10^{-4}$

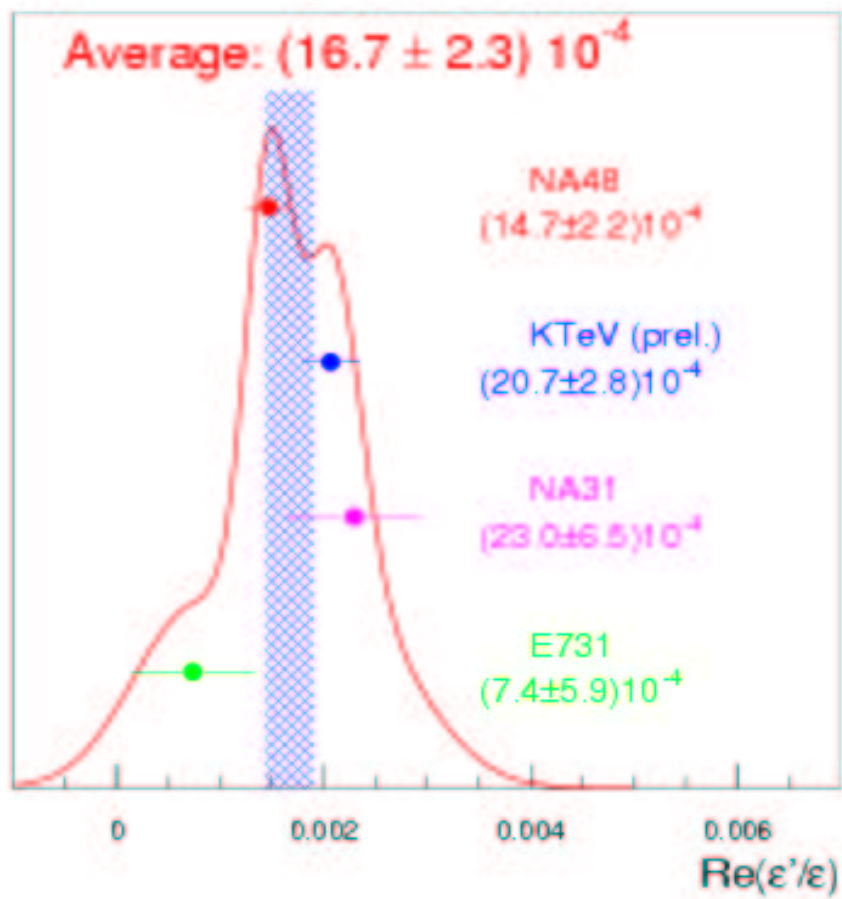
2001 $\text{Re}(\epsilon'/\epsilon) = [13.7 \pm 2.7(\text{stat}) \pm 1.5(\text{syst})] \times 10^{-4}$

AVERAGE $\text{Re}(\epsilon'/\epsilon) = [14.7 \pm 2.2] \times 10^{-4}$

Note: small correlation between systematic uncertainties accounted for in weighted average



Summary of Measurements



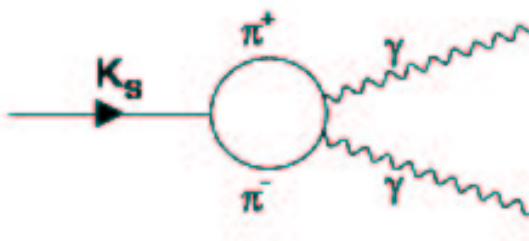
Chiral Perturbation Theory

- Low energy (scale $\leq 4\pi F_\pi \approx 1.2$ GeV) effective field theory:
Perturbative expansions in momentum and mass
- Chiral symmetry broken: $SU(3)_L \times SU(3)_R \rightarrow SU(3)_V$
 \Rightarrow Eight pseudoscalar Goldstone bosons (π, η, K)
- Boson mass $\neq 0$ [(soft) explicit breaking]
- Higher order bosonic loops diverge, but compensated by counter-terms with
(empirically determined) effective couplings
- Ought to describe kaon decays: eg., $K_{L,S} \rightarrow \pi^0 \gamma\gamma$, $K_{L,S} \rightarrow \gamma\gamma$

$$K_L^0 \rightarrow \pi^0 \gamma \gamma \text{ and } K_S^0 \rightarrow \gamma \gamma$$

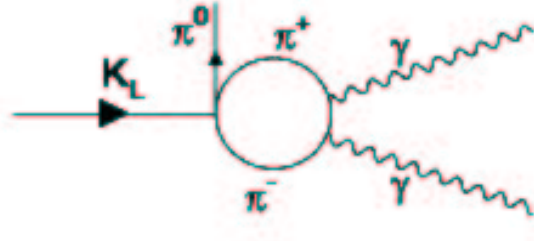
- $\mathcal{O}(p^2) = 0$ for both

- No counter-terms required for either: $\mathcal{O}(p^4)$ predictions unambiguous to better than 5%



$$2.1 \times 10^{-6}$$

D'Ambrosio, Espriu
Goity



$$0.6 \times 10^{-6}$$

Ecker, Pich, de Rafael
Capiello, D'Ambrosio

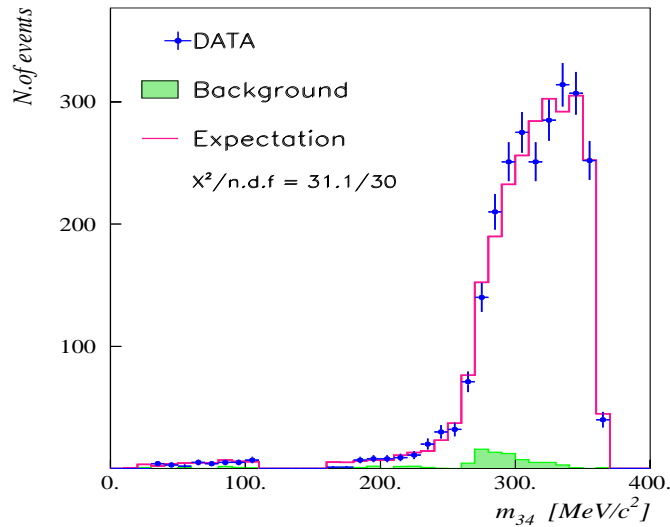
- PDG:

$$BR(K_S^0 \rightarrow \gamma \gamma) = (2.5 \pm 0.4) \times 10^{-6}$$

$$BR(K_L^0 \rightarrow \pi^0 \gamma \gamma) = (1.68 \pm 0.10) \times 10^{-6}$$

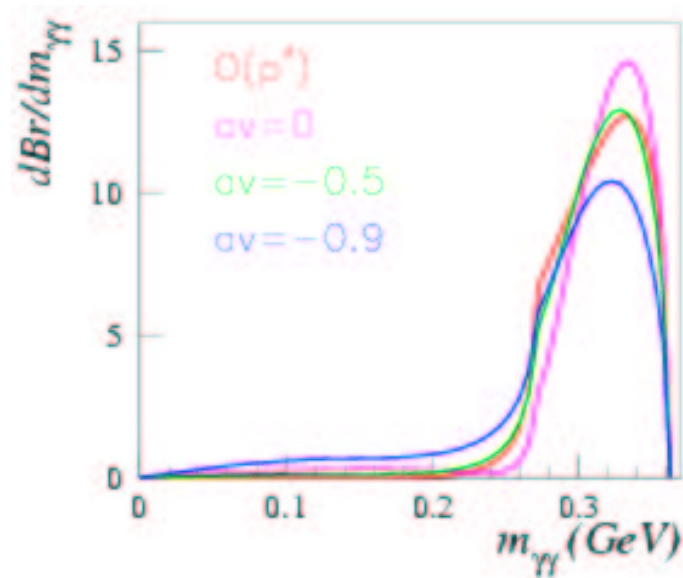
$$K_L^0 \rightarrow \pi^0 \gamma \gamma$$

- $\mathcal{O}(p^4)$ misses both the observed branching fraction, $(1.68 \pm 0.10) \times 10^{-6}$, and events with $m_{\gamma\gamma} < 0.2$ GeV



- $\mathcal{O}(p^6)$ terms (including vector meson exchange) **predict:**

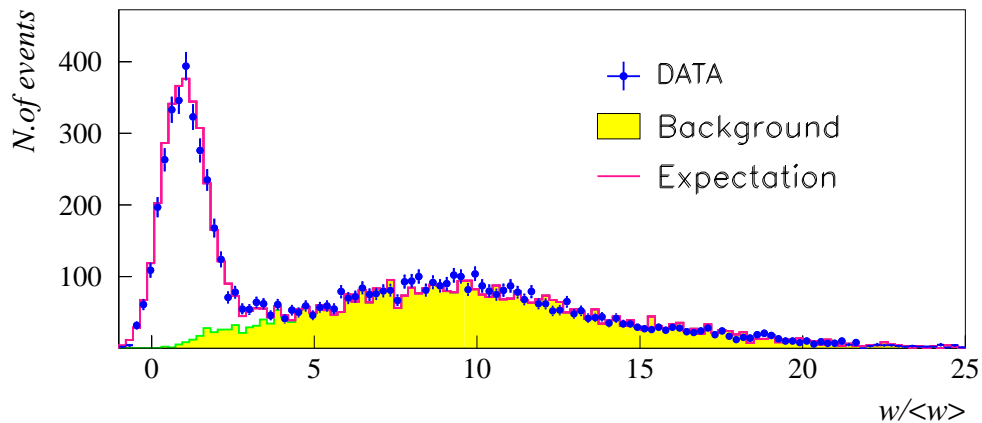
$$BR(K_L^0 \rightarrow \pi^0 \gamma \gamma) = 1.5 \times 10^{-6}, \quad a_v = -0.7$$



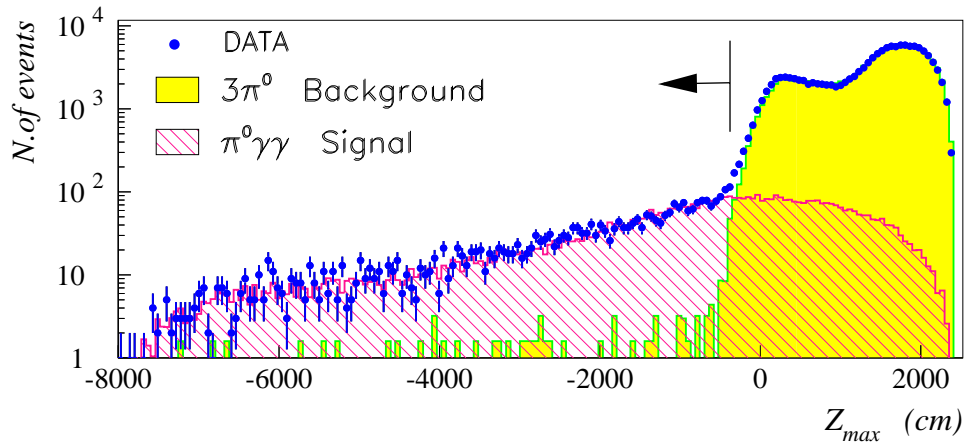
- a_v , extracted from $m_{\gamma\gamma}$ distribution, determines CP-conserving amplitude in $K_L \rightarrow \pi^0 e^+ e^-$

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

- Normalization channel $K_L^0 \rightarrow \pi^0 \pi^0$ collected with same trigger
- Reject $2\pi^0$ background:
 - $|m_{12} - m_{\pi^0}| < 3 \text{ MeV}$ and $|m_{34} - m_{\pi^0}| > 25 \text{ MeV}$
 - Transverse momentum of lowest energy unpaired photon $> 40 \text{ MeV}$
 - Subtract remnants with tails of $K_S^0 \rightarrow \pi^0 \pi^0$ distribution
- Reject $3\pi^0$ background (from missed or merged showers):
 - Shower width



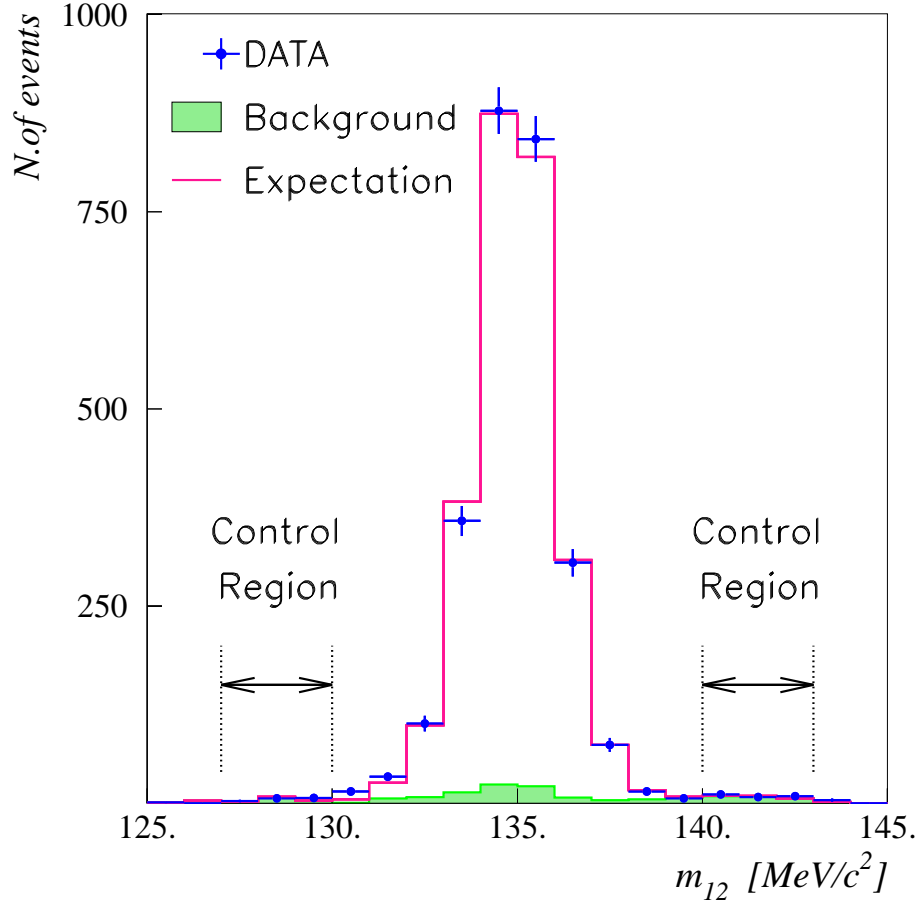
- Maximum vertex position from each possible combination



- Subtract pile-up using COG sidebands

$K_L^0 \rightarrow \pi^0 \gamma \gamma$ Results

- ~ 2500 candidates

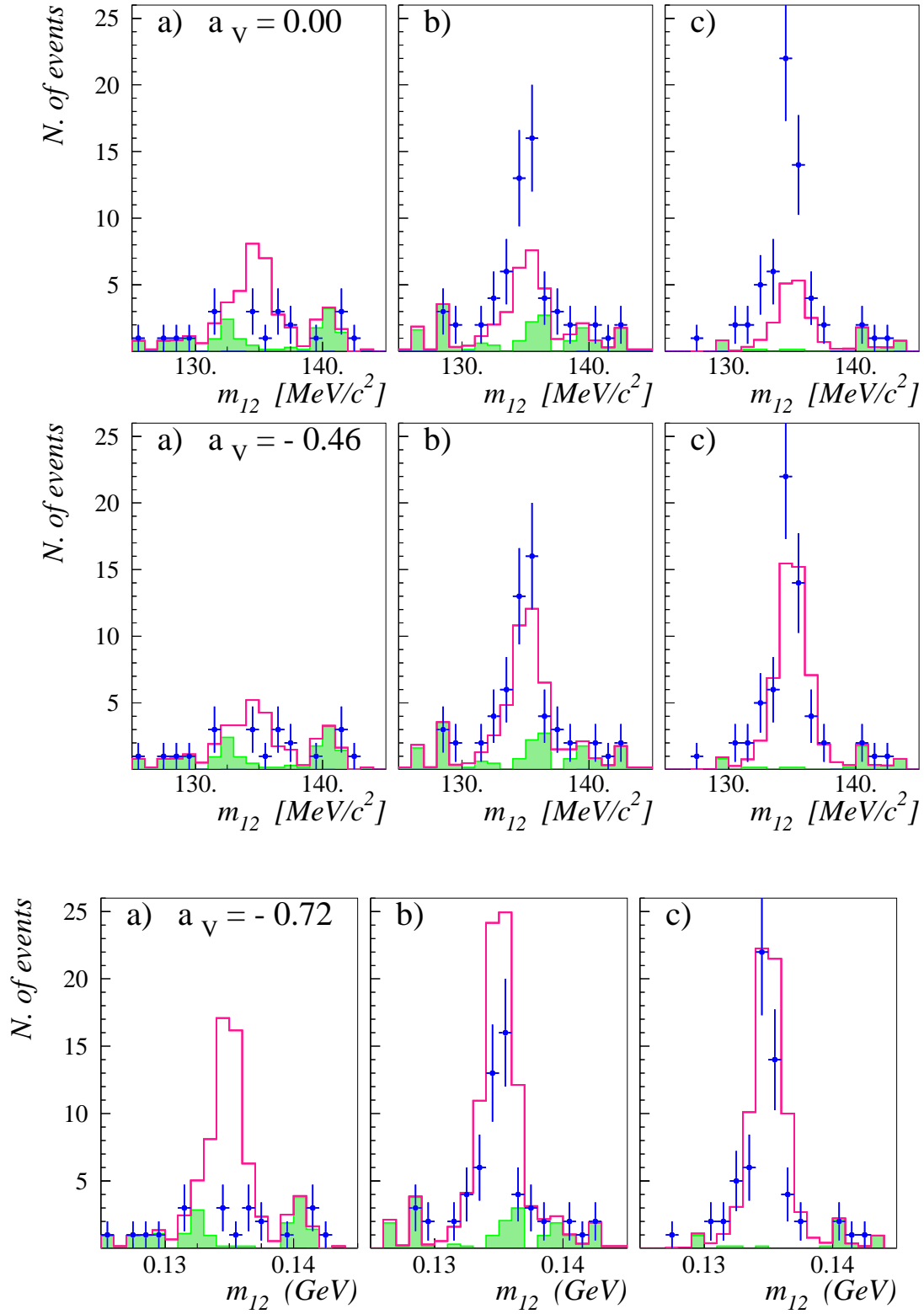


- $a_v = -0.46 \pm 0.03(\text{stat}) \pm 0.03(\text{syst}) \pm 0.02(\text{theo})$ (see plot)

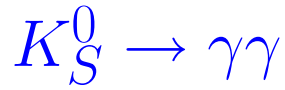
$$\Rightarrow BR(K_L \rightarrow \pi^0 e^+ e^-)_{CP-C} = (4.7 \pm 2.2) \times 10^{-13}$$

$$\Rightarrow BR(K_L \rightarrow \pi^0 \gamma \gamma) = [1.36 \pm 0.03(\text{stat}) \pm 0.03(\text{syst}) \pm 0.03(\text{norm})] \times 10^{-6}$$

[Note: KTeV finds $a_v = -0.72 \pm 0.08$, \Rightarrow non-negligible contribution to $BR(K_L \rightarrow \pi^0 e^+ e^-)_{CP-C}$, and $BR(K_L \rightarrow \pi^0 \gamma \gamma) = (1.68 \pm 0.10) \times 10^{-6}$]



In bins of m_{34} [MeV/c^2]: a) 30 - 110; b) 160 - 140; c) 240 - 260



- Year 2000 data: **single beams, no drift chambers**

- **Normalize to** $K_S^0 \rightarrow \pi^0\pi^0$

- **Irreducible background:** $K_L^0 \rightarrow \gamma\gamma$

$$\frac{N(K_L^0 \rightarrow \gamma\gamma)}{N(K_S^0 \rightarrow \gamma\gamma)} \approx 1.5 \text{ in decay volume}$$

Knowledge of this ratio limited by 3% K_L BR uncertainty:

$$(2.77 \pm 0.08) \times 10^{-3}$$

\Rightarrow **Improve K_L BR measurement relative to $K_L^0 \rightarrow \pi^0\pi^0\pi^0$**

$$[BR(K_S^0 \rightarrow \pi^0\pi^0\pi^0) \ll 1]$$

- Collect **five** data samples:

– **far target:** $\gamma\gamma, 3\pi^0$

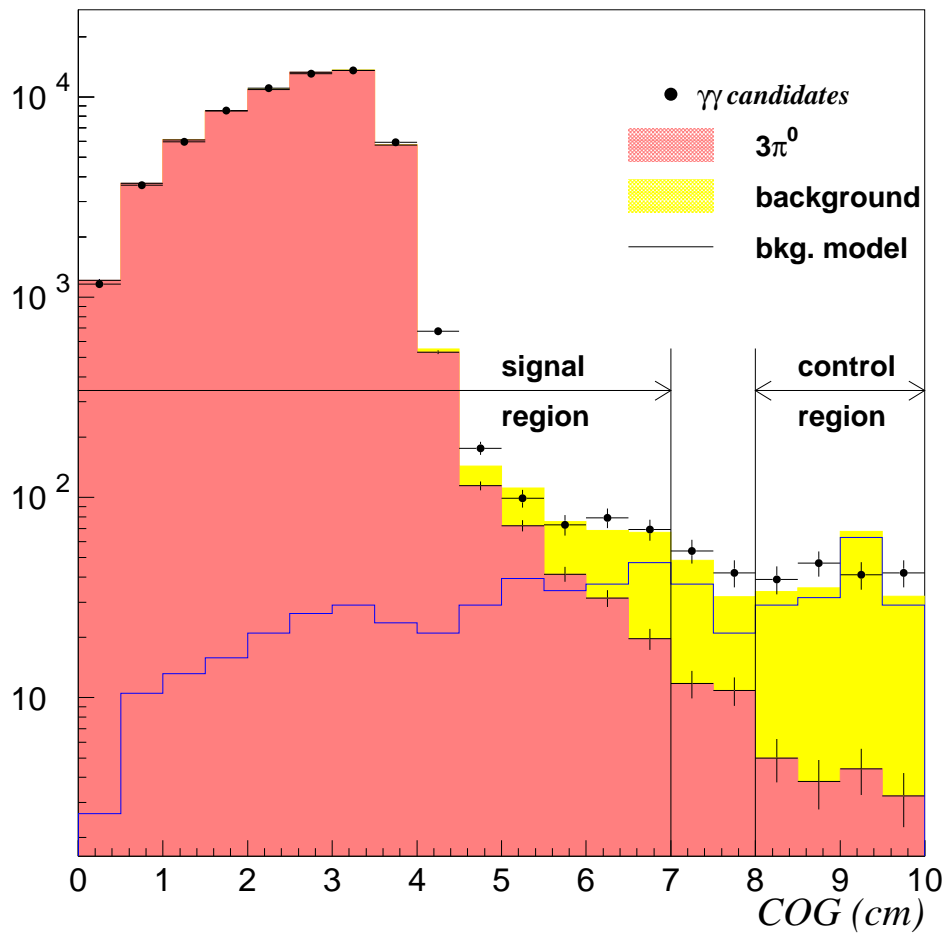
– **near target:** $\gamma\gamma, 2\pi^0, 3\pi^0$

- **Count $3\pi^0$ events** $\Rightarrow N(K_L^0 \rightarrow \gamma\gamma)$

$$\Rightarrow N(K_S^0 \rightarrow \gamma\gamma) = N(K^0 \rightarrow \gamma\gamma) - N(K_L^0 \rightarrow \gamma\gamma)$$

$$\frac{\Gamma(K_L^0 \rightarrow \gamma\gamma)}{\Gamma(K_L^0 \rightarrow 3\pi^0)}$$

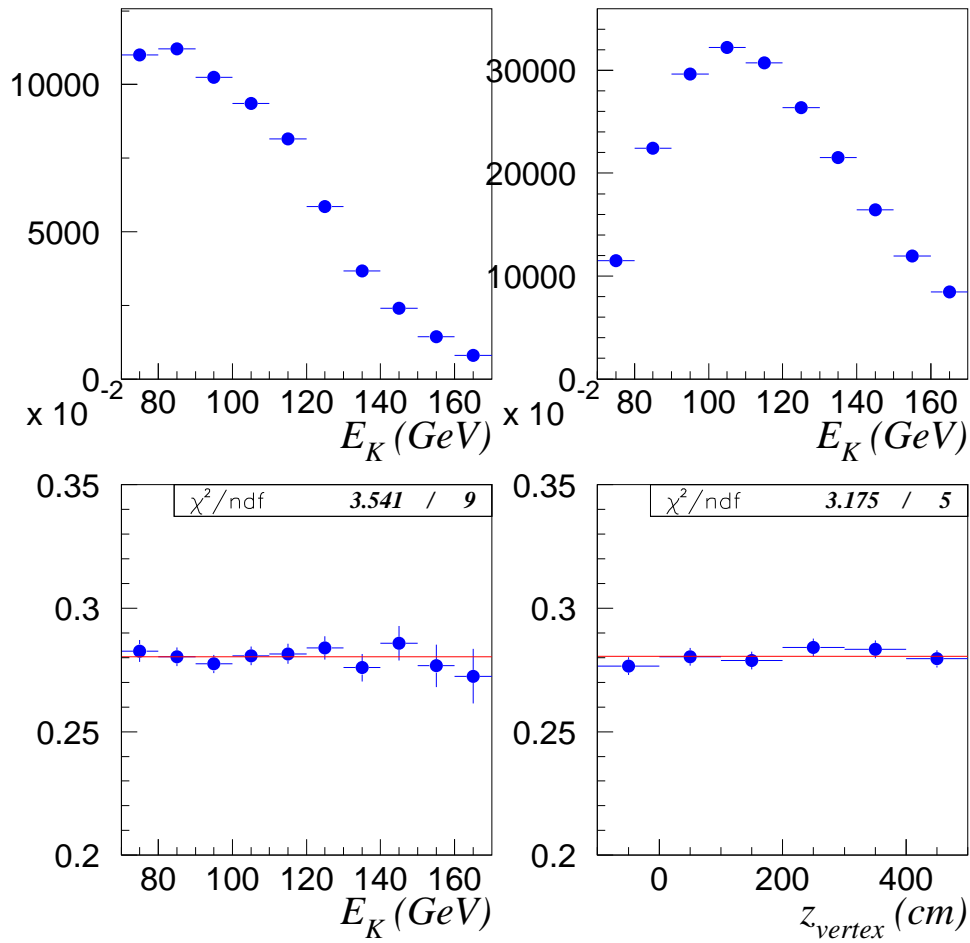
- Far-target data
- Restrict decay volume to that of $K_L^0 \rightarrow \gamma\gamma$
- Determine hadronic and other charged backgrounds from hadronic calorimeter and charged hodoscope hits as a function of COG distribution



$$\Rightarrow \text{Background} = (0.6 \pm 0.3)\%$$

$$\Delta[BR(K_S \rightarrow \gamma\gamma)] = (0.9 \pm 0.4)\%$$

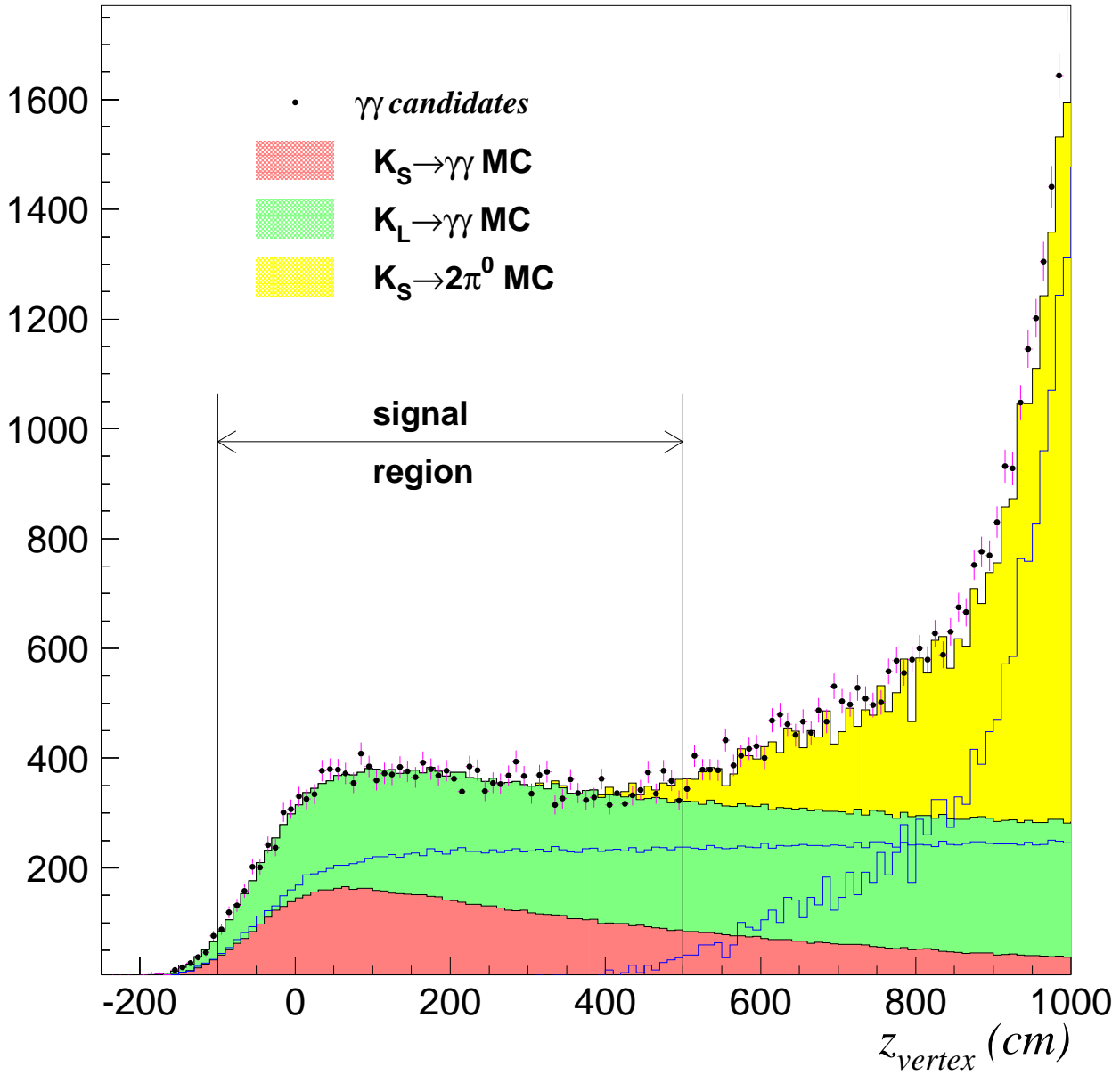
$$\frac{\Gamma(K_L^0 \rightarrow \gamma\gamma)}{\Gamma(K_L^0 \rightarrow 3\pi^0)} = [2.81 \pm 0.01(stat) \pm 0.02(syst)] \times 10^{-3}$$



Energy spectra and stability of result

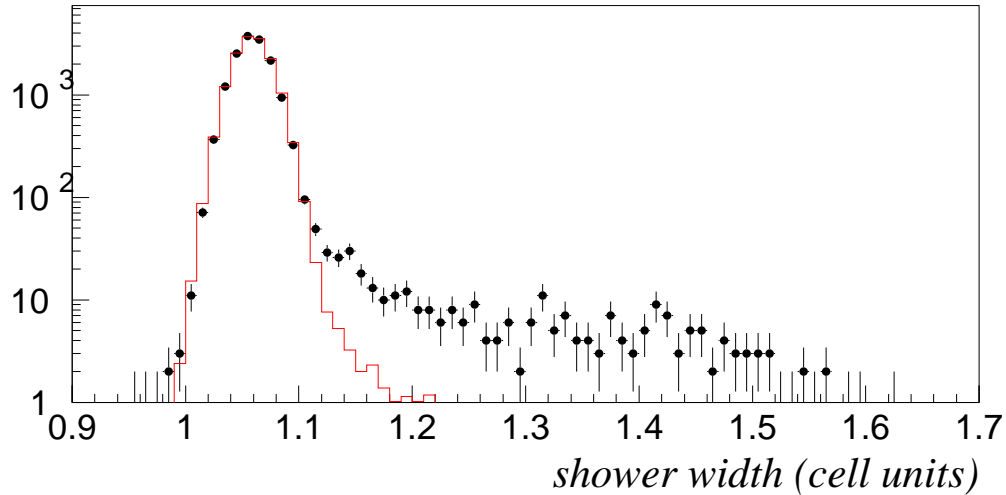
$K_S^0 \rightarrow \gamma\gamma$ Analysis

- Reject broken $K_S^0 \rightarrow \pi^0\pi^0$ events: $-1\text{m} < z_{\text{vertex}} < 5\text{m}$ wrt collimator exit

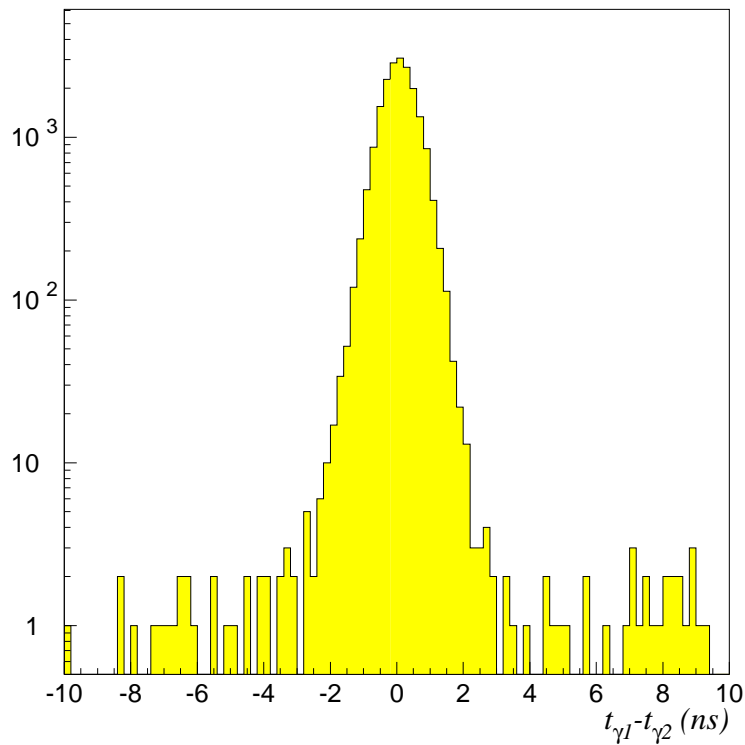


$2\pi^0$ background = $(0.8 \pm 0.2)\%$

- Reject hadronic background (no tracking): no in-time HAC cluster and cut on LKr cluster width

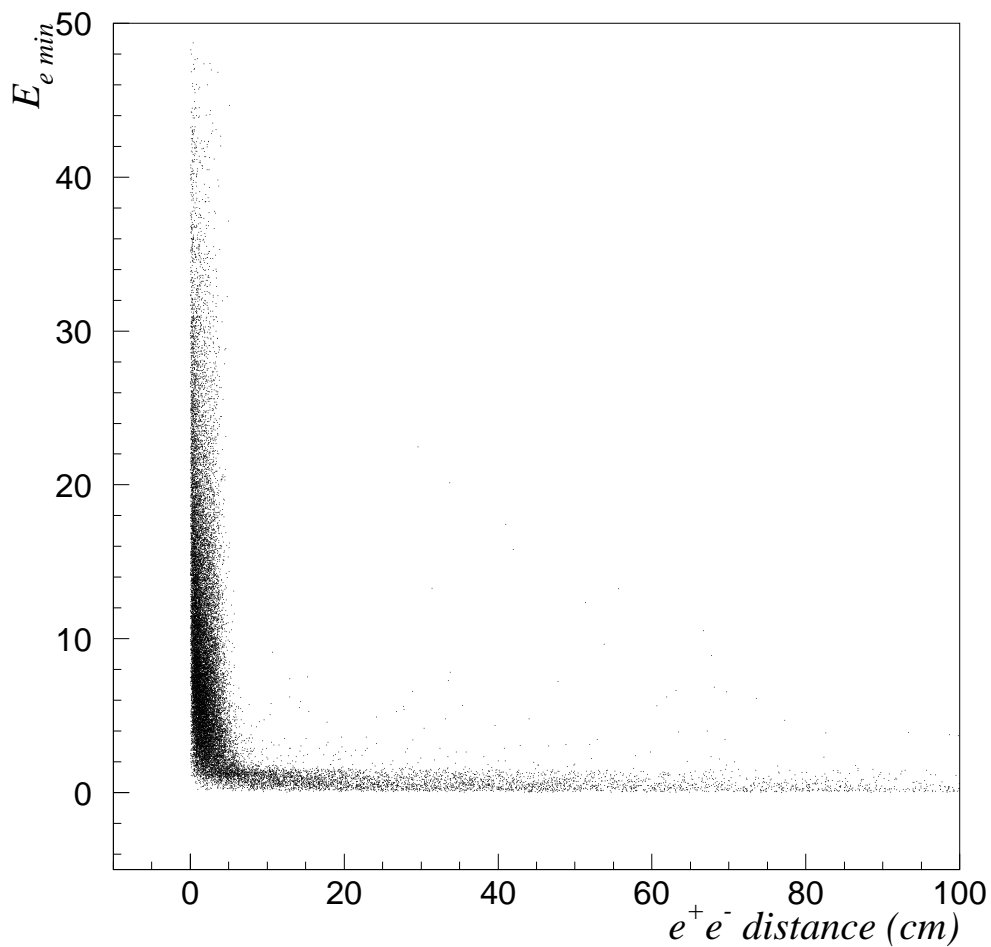


- Reject accidentals: $\Delta t_{\gamma\gamma} < 5$ ns and subtract extrapolated high P_t events



Hadronic and accidental background = $(0.8 \pm 0.3)\%$

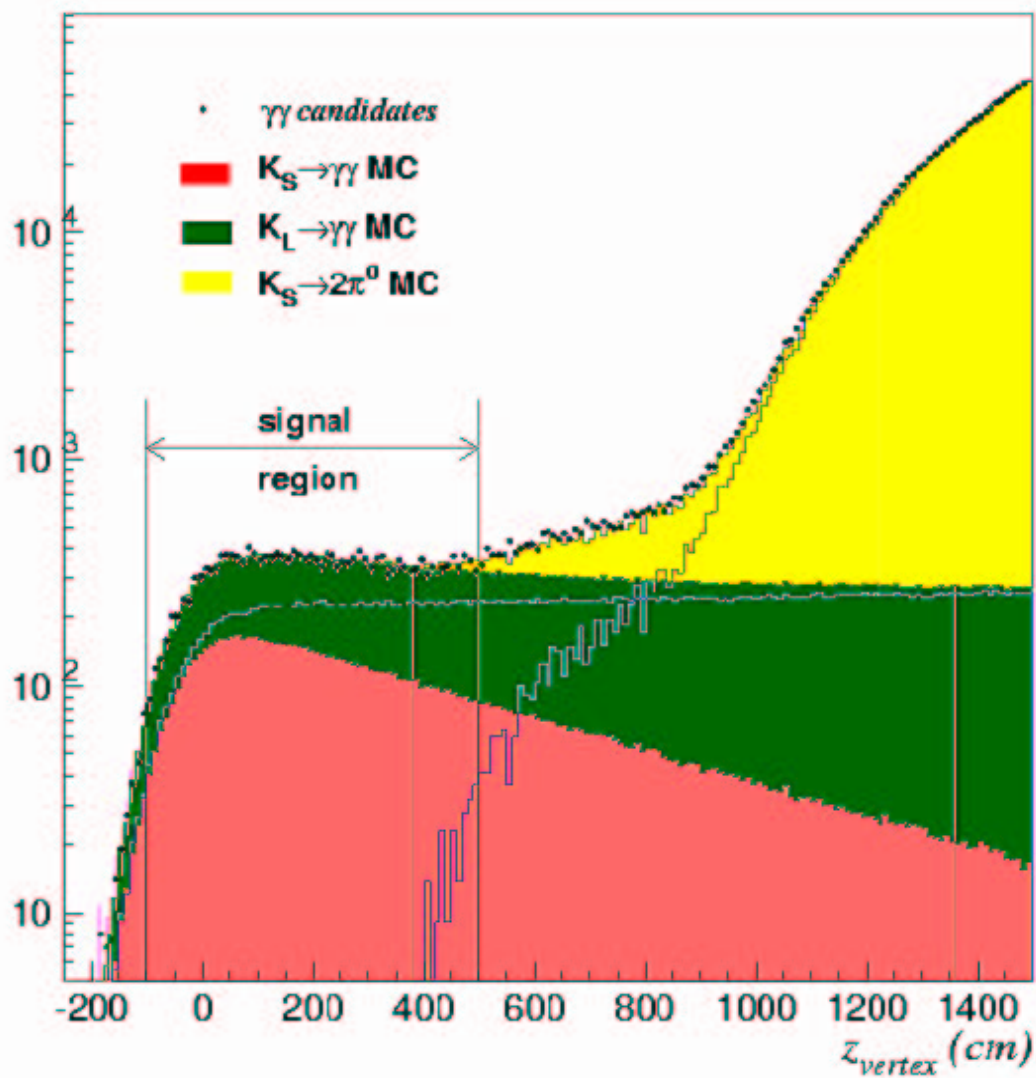
- Reject Dalitz decays (analyzing magnet off-on for far-target data), $\pi^0 \rightarrow e^+e^-\gamma$: pair fails to separate or one e too soft; correct via simulation (effect twice as large for normalization channel)



$$\frac{\Delta[BR(K_S^0 \rightarrow \gamma\gamma)]}{[BR(K_S^0 \rightarrow \gamma\gamma)]} = +(1.5 \pm 0.3)\%$$

$K_S^0 \rightarrow \gamma\gamma$ Result

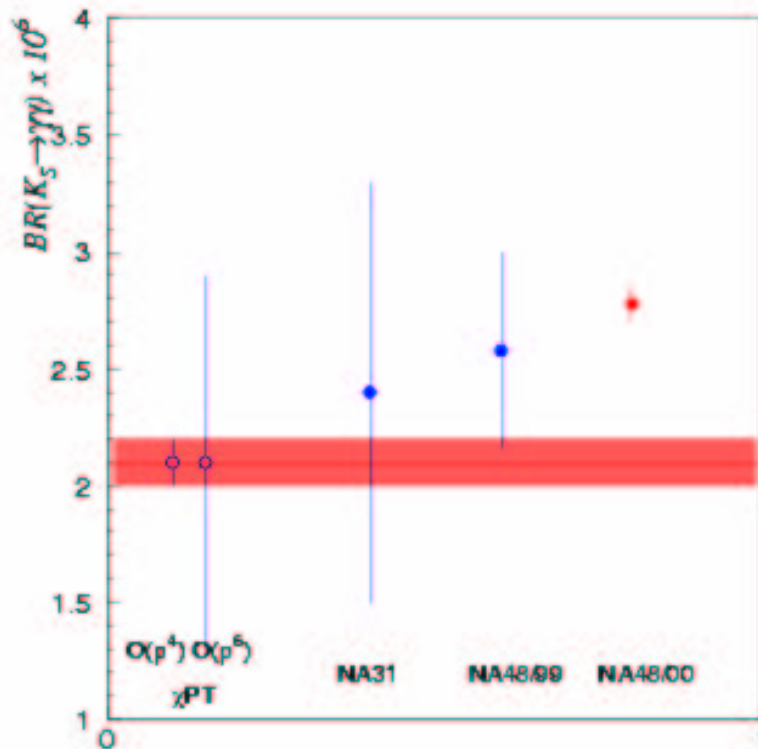
- Roughly 20,000 $K_{L,S}^0 \rightarrow \gamma\gamma$ events
- Non- $\gamma\gamma$ background $\sim 2.5\%$



$K_S^0 \rightarrow \gamma\gamma$ Corrections and Uncertainties

Hadronic backgrounds and accidentals	$-2.1 \pm 0.7\%$
Broken $K_S \rightarrow \pi^0\pi^0$	$-2.1 \pm 0.4\%$
Hadronic Background (far-target)	$0.9 \pm 0.4\%$
Dalitz Decay	$1.5 \pm 0.3\%$
χ^2 cut on π^0 masses	$\pm 0.3\%$
Trigger efficiency	$\pm 0.1\%$
$BR(K_S \rightarrow \pi^0\pi^0)$	$\pm 0.9\%$
TOTAL	$-1.8 \pm 1.4\%$
Statistical Uncertainty (data)	$\pm 2.0\%$
Statistical Uncertainty (MC)	$\pm 0.6\%$

$$BR(K_S^0 \rightarrow \gamma\gamma) = [2.78 \pm 0.06(stat) \pm 0.02(MC\ stat) \pm 0.04(syst)] \times 10^{-6}$$



- Compatible with previous results
- Differs by 30% from $\mathcal{O}(p^4)$ prediction \Rightarrow large $\mathcal{O}(p^6)$ contribution?

$$K_S^0 \rightarrow \pi^0 \gamma \gamma$$

- Dominated by pion pole of $K_S^0 \rightarrow \pi^0 \pi^0$: restrict to $z \equiv m_{\gamma\gamma}^2/m_K^2 \geq 0.2$
- Theoretical prediction: $BR(K_S^0 \rightarrow \pi^0 \gamma \gamma) = 3.8 \times 10^{-8}$ (Ecker, Pich, De Rafael, 1987)
- No PDG limit
- 1999 high intensity K_S run: 3×10^8 K_S decays

$K_S^0 \rightarrow \pi^0 \gamma \gamma$ Analysis

Backgrounds

- Broken $K_S \rightarrow \pi^0 \pi^0$ + accidental

2.1 ± 0.1 events (sideband extrapolation)

- Mismeasured π^0 mass from $K_S \rightarrow \pi^0 \pi^0$

0.1 ± 0.1 event (simulation)

- $K_S \rightarrow \pi^0 \pi_{dalitz}^0$ $K_S \rightarrow 3\pi^0$

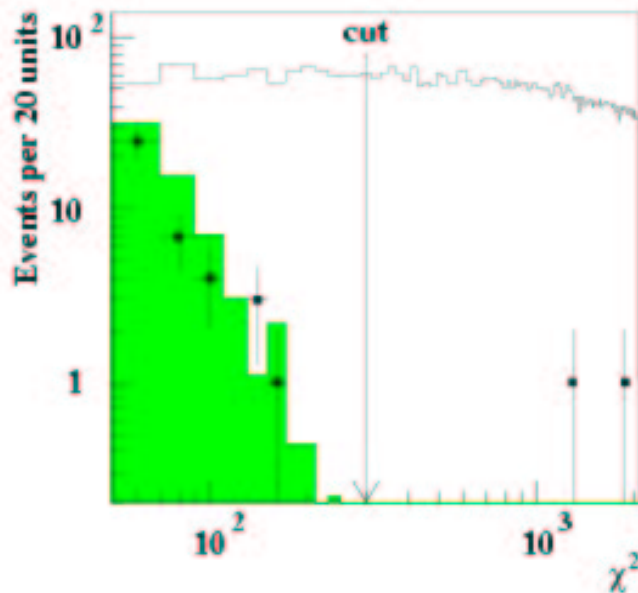
< 0.1 event (simulation)

- $K_L \rightarrow \pi^0 \gamma \gamma$

0.1 event (irreducible, but calculable)

TOTAL BACKGROUND: 2.1 ± 0.2 events

FOUND IN DATA: 2 events



PRELIMINARY LIMIT:

$BR(K_S \rightarrow \pi^0 \gamma \gamma) < 4.4 \times 10^{-7}$ at 90% CL

Summary and Conclusions

- Final measurement of direct CP violation: Physics Letters **B544** (2002) 97-112

$$2001: \text{Re}(\epsilon'/\epsilon) = [13.7 \pm 2.7(\text{stat}) \pm 1.5(\text{syst})] \times 10^{-4}$$

$$\text{Average: } \text{Re}(\epsilon'/\epsilon) = [14.7 \pm 2.2] \times 10^{-4}$$

$$\text{World Average: } \text{Re}(\epsilon'/\epsilon) = [16.7 \pm 2.3] \times 10^{-4}$$

- $K_L^0 \rightarrow \pi^0 \gamma \gamma$: Physics Letters **B536** (2002) 229-240

$$a_v = -0.46 \pm 0.03(\text{stat}) \pm 0.03(\text{syst}) \pm 0.02(\text{theo})$$

$$\Rightarrow BR(K_L \rightarrow \pi^0 \gamma \gamma) = [1.36 \pm 0.03(\text{stat}) \pm 0.03(\text{syst}) \pm 0.03(\text{norm})] \times 10^{-6}$$

$$\Rightarrow BR(K_L \rightarrow \pi^0 e^+ e^-)_{CP-C} = (4.7 \pm 2.2) \times 10^{-13}$$

- $K_L^0 \rightarrow \gamma \gamma$: Physics Letters **B551** (2003) 7

$$\frac{\Gamma(K_L^0 \rightarrow \gamma \gamma)}{\Gamma(K_L^0 \rightarrow 3\pi^0)} = [2.81 \pm 0.01(\text{stat}) \pm 0.02(\text{syst})] \times 10^{-3}$$

- $K_S^0 \rightarrow \gamma \gamma$: Physics Letters **B551** (2003) 7

$$BR(K_S^0 \rightarrow \gamma \gamma) = [2.78 \pm 0.06(\text{stat}) \pm 0.02(\text{MC stat}) \pm 0.04(\text{syst})] \times 10^{-6}$$

- $K_S \rightarrow \pi^0 \gamma \gamma$

$$BR(K_S \rightarrow \pi^0 \gamma \gamma) < 4.4 \times 10^{-7} \text{ at 90\% CL (preliminary)}$$

- 2002: High intensity K_S and neutral hyperon running; data being analyzed

- $K_S^0 \rightarrow \pi^0 e^+ e^-$

- $K_S^0 \rightarrow \pi^0 \mu^+ \mu^-$

- Hyperon semileptonic decays: $|V_{us}|$

- Radiative hyperon decays: asymmetries and new modes

- 2003: Charged Kaon program