

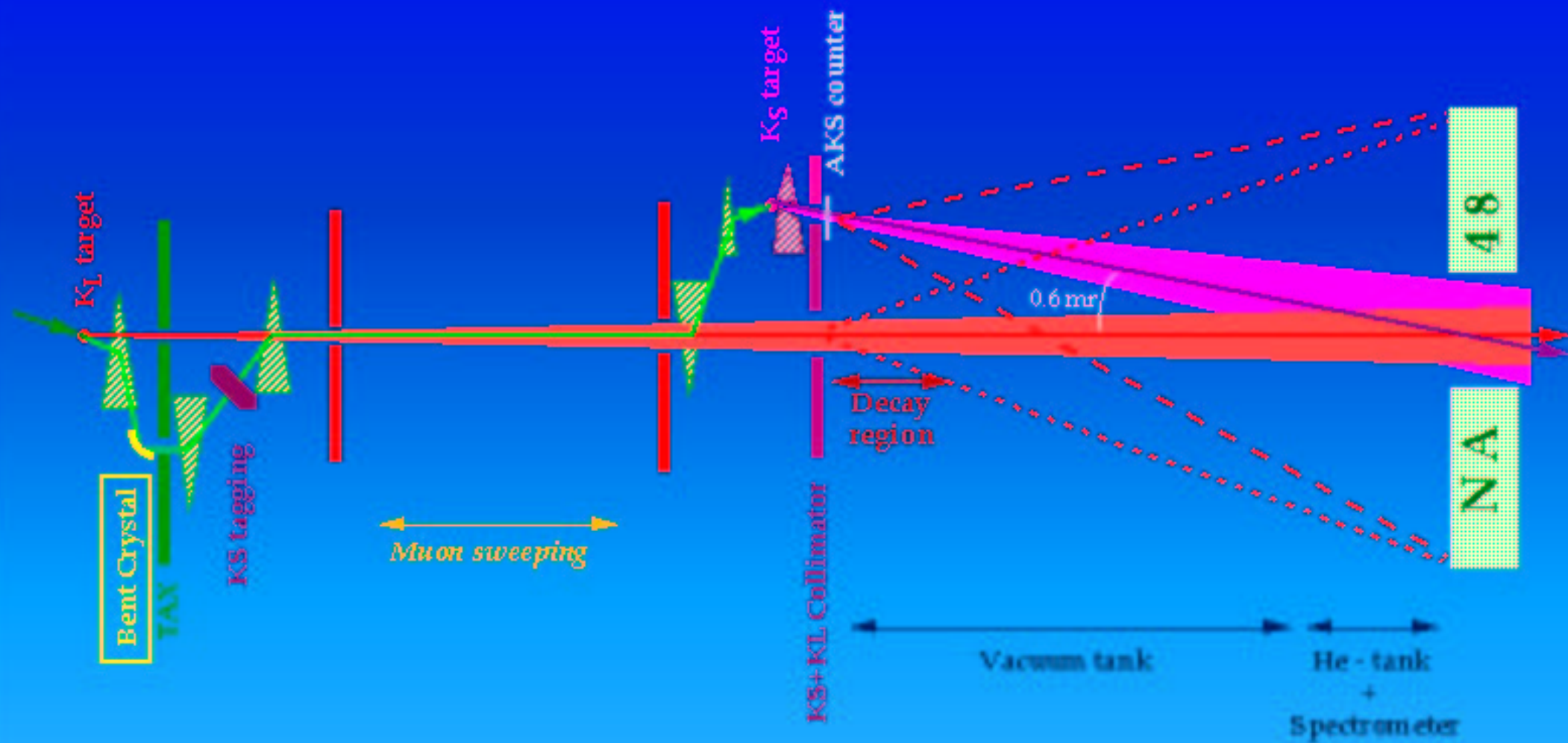
Phil Rubin
For the NA48 Collaboration

CIPANP 2003

22 May 2003

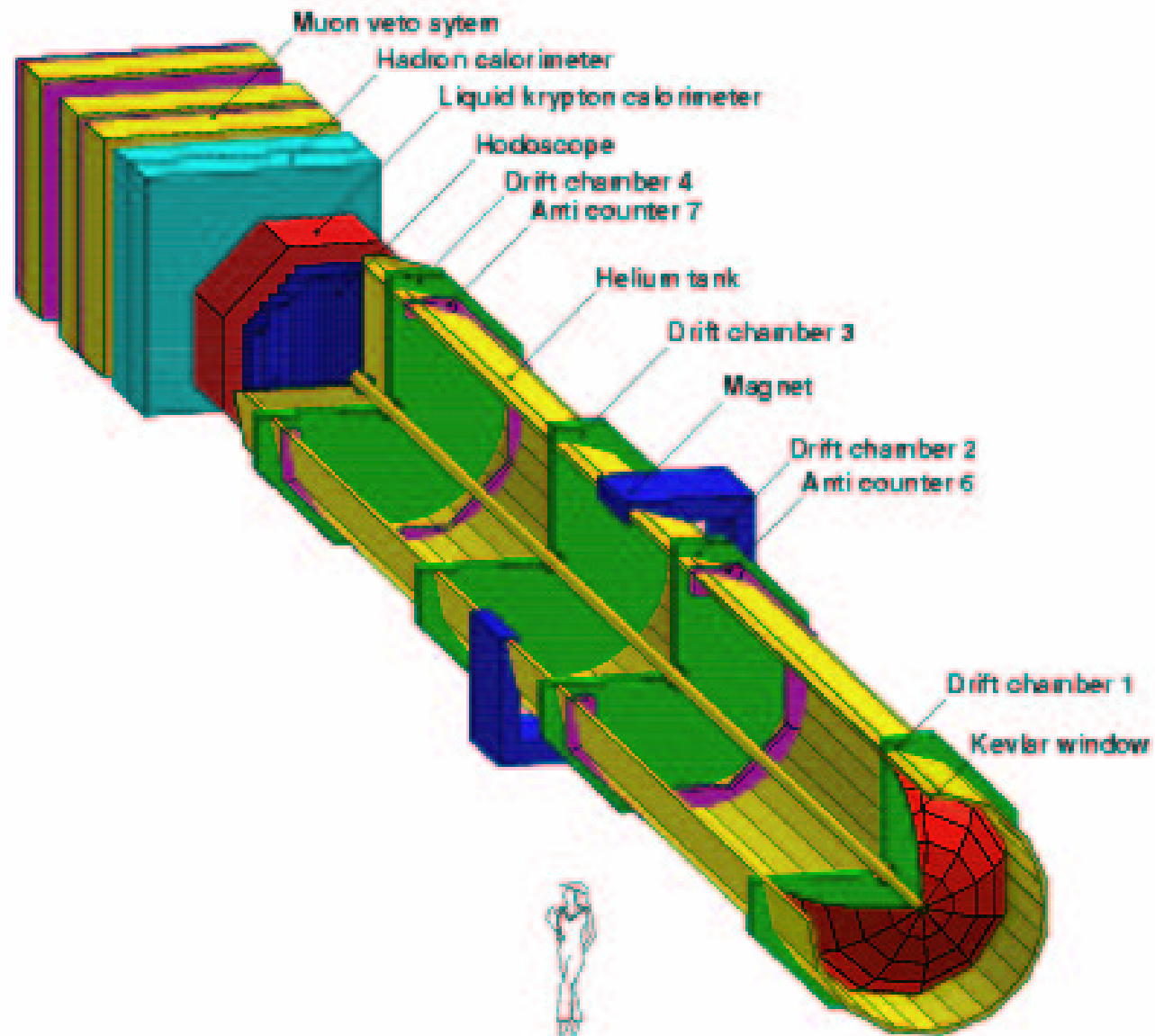
Recent Results from NA48, CERN's North Area Experiment 48

THE SIMULTANEOUS K_L AND K_S BEAMS



Not to scale!

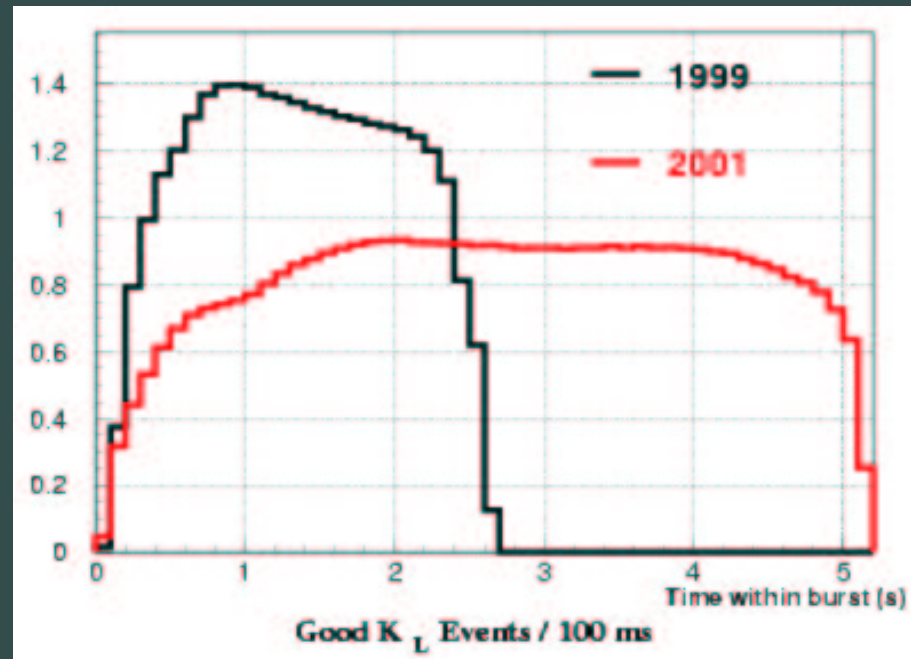
NA48 detectors



Running Conditions

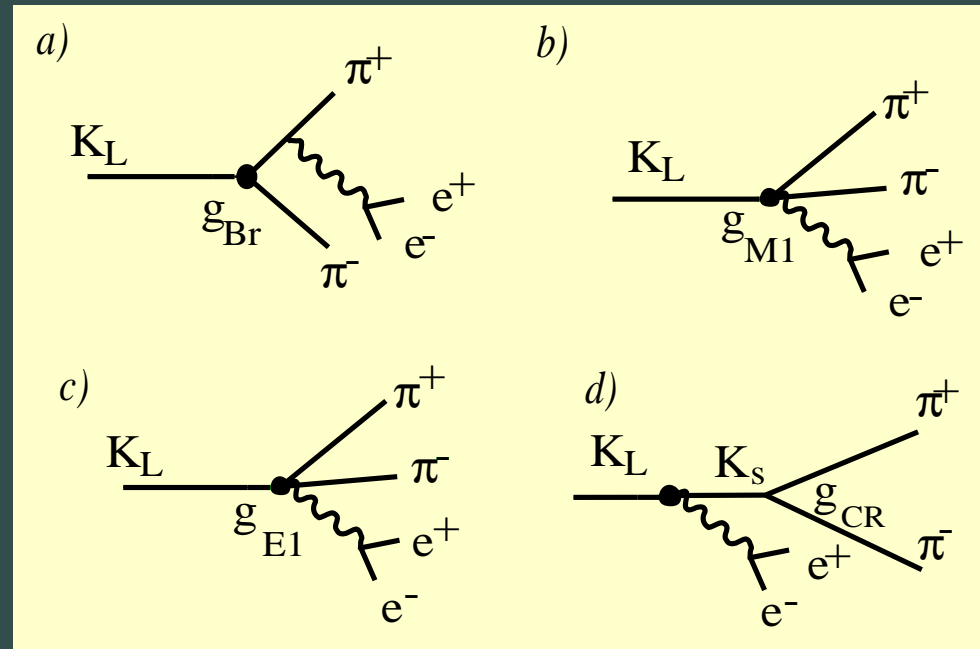
	1998-1999	2000*	2001
Proton Momentum [GeV/c]	450	400	400
SPS Cycle Time [s]	14.4	14.4	16.8 s
Spill Length (Effective) [s]	2.4 (1.7)	3.2 (2.2)	5.2 (3.6)
Duty Cycle	0.17	0.22	0.31
K_L Beam Intensity [$(\times 10^{12})$ ppp]	1.5	1.0	2.4
K_S Beam Intensity [$(\times 10^7)$ ppp]	3.0	1.0×10^2	5.0

* No drift chambers



$$K_{L,S} \rightarrow \pi^+ \pi^- e^+ e^-$$

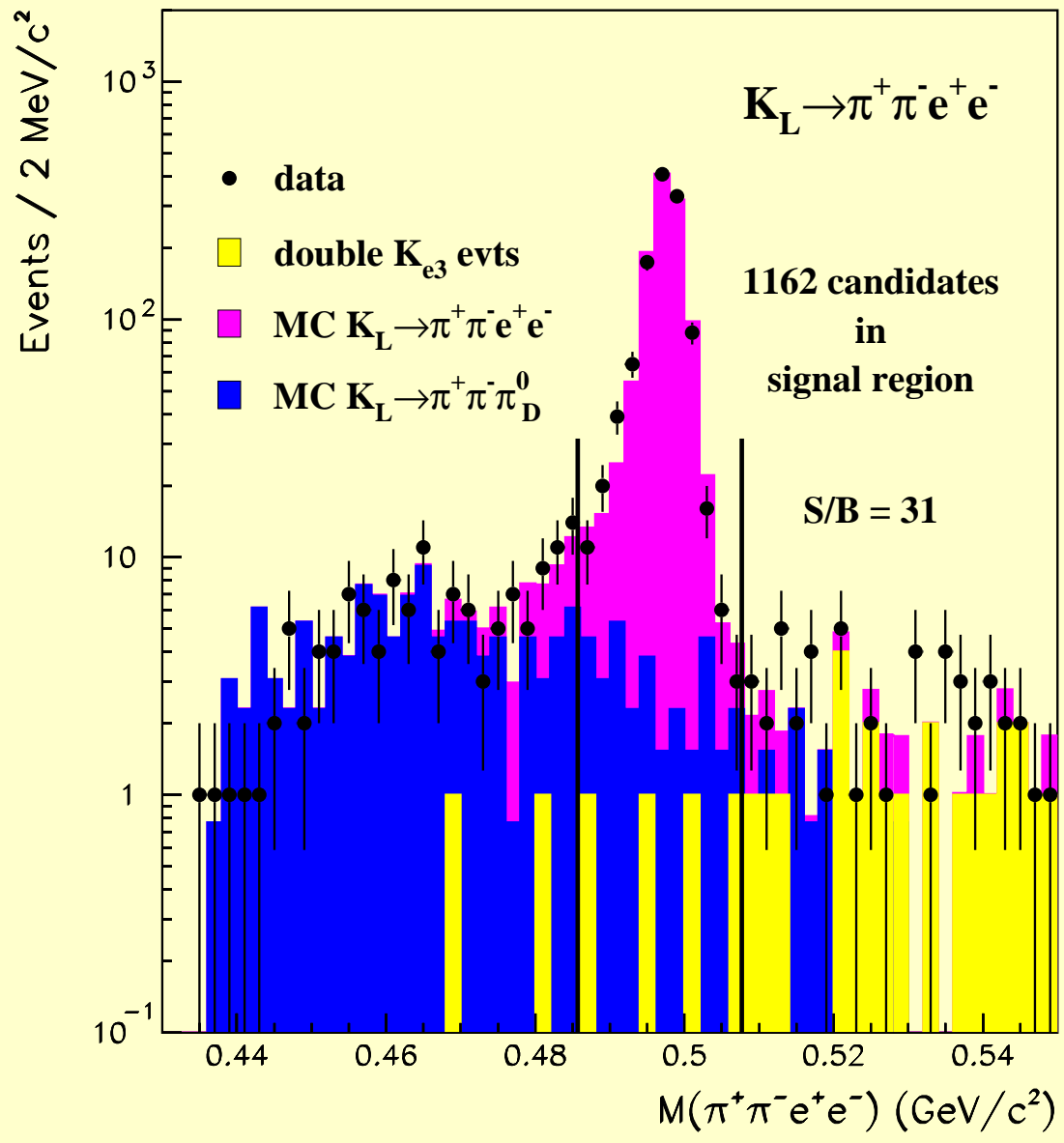
- 4 processes—inner bremsstrahlung, $M1$ and $E1$ direct emission, and direct CP violation—contribute to $K_L \rightarrow \pi^+ \pi^- e^+ e^-$ decay amplitude



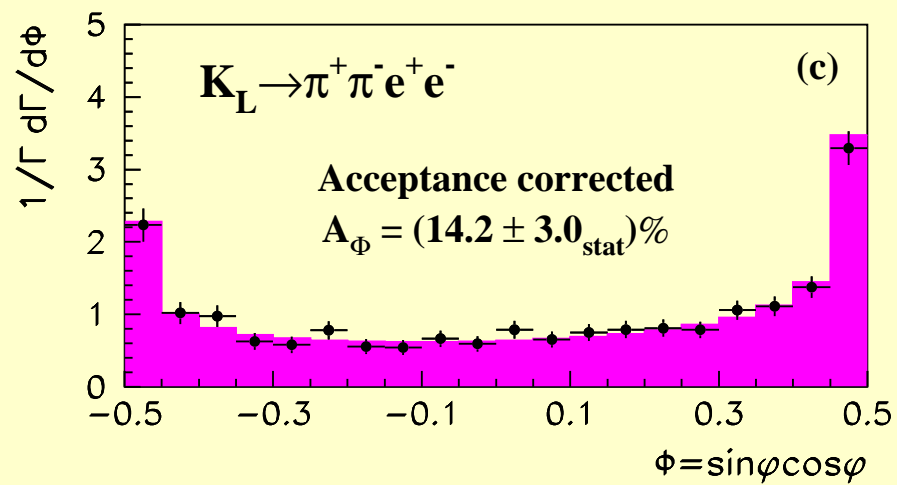
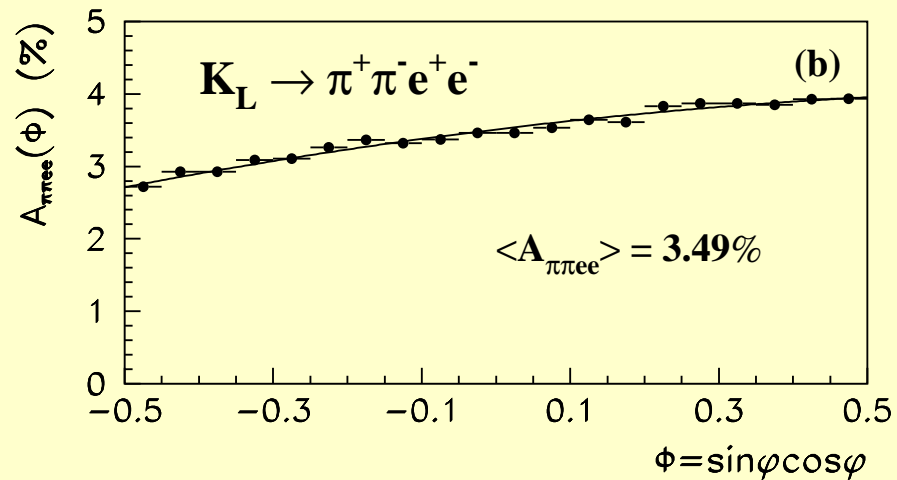
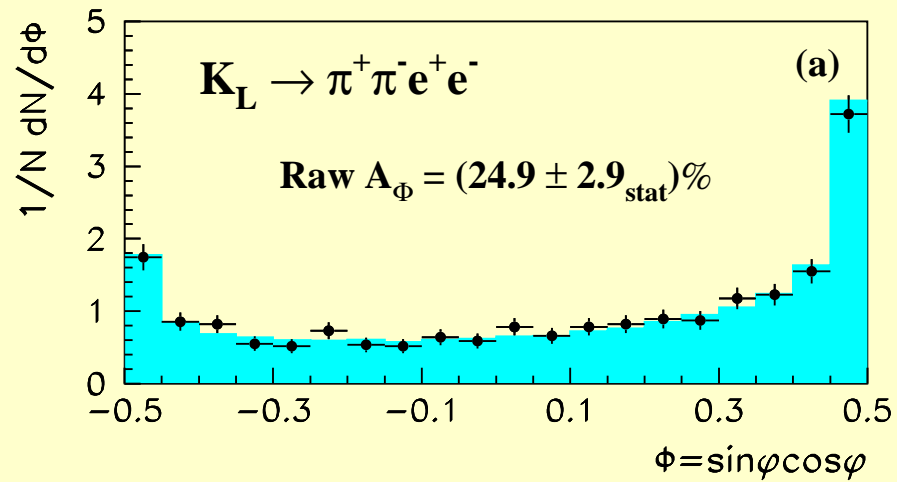
- Interference between first two \Rightarrow CP-violating circular polarized $\gamma^* \Rightarrow$ asymmetry in angle between $\pi^+ \pi^-$ and $e^+ e^-$ planes (14% predicted)
- No such effect expected from $K_S \rightarrow \pi^+ \pi^- e^+ e^-$

- Data from 1998 and 1999 (ϵ'/ϵ) and 1999 40-hour high-intensity K_S^0 runs
- Normalize to $K_L^0 \rightarrow \pi^+\pi^-\pi^0_{Dalitz}$
- $\frac{d\Gamma}{d\phi} = \Gamma_1 \cos^2 \phi + \Gamma_2 \sin^2 \phi + \Gamma_3 \sin \phi \cos \phi$
 $\Rightarrow \mathcal{A}_\phi = \frac{N_{\pi\pi ee}(\sin \phi \cos \phi > 0) - N_{\pi\pi ee}(\sin \phi \cos \phi < 0)}{N_{\pi\pi ee}(\sin \phi \cos \phi > 0) + N_{\pi\pi ee}(\sin \phi \cos \phi < 0)}$

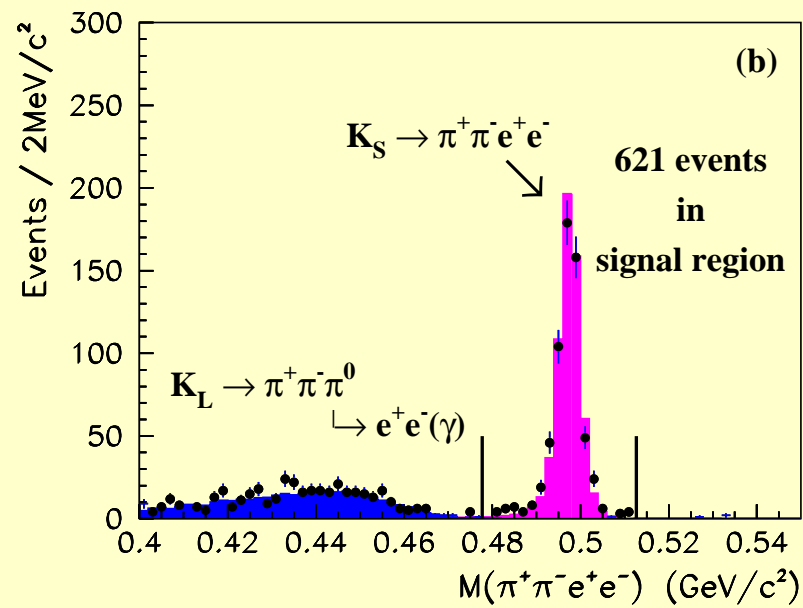
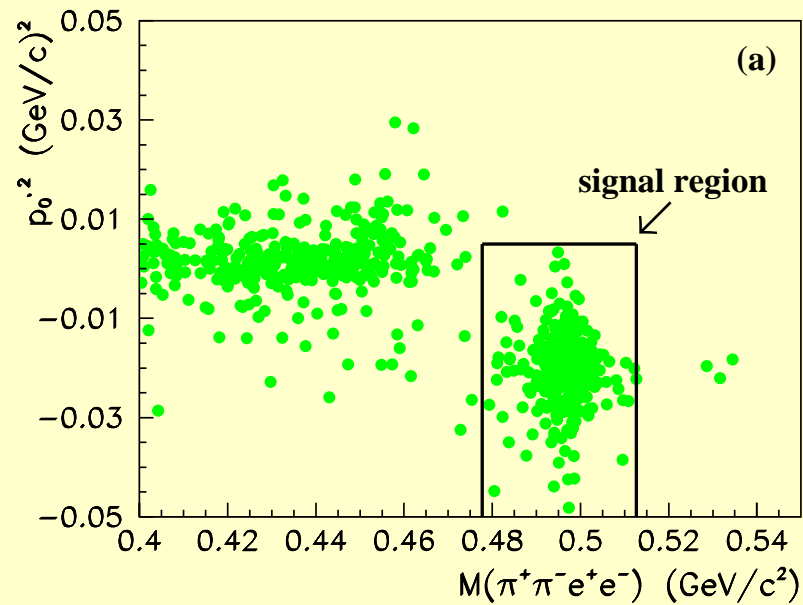
Submitted to European Physics Journal



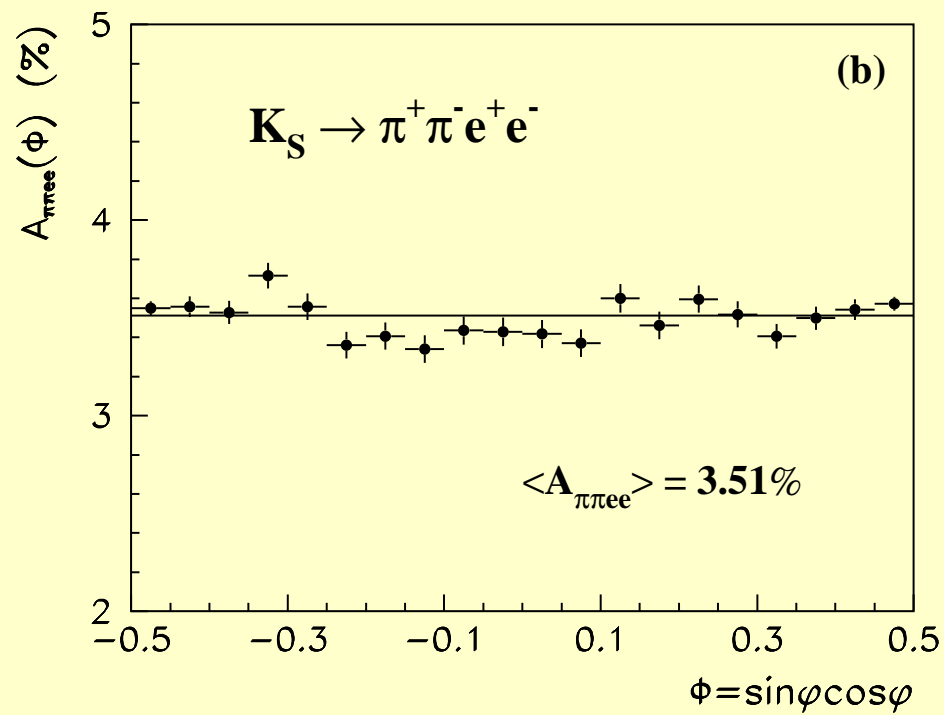
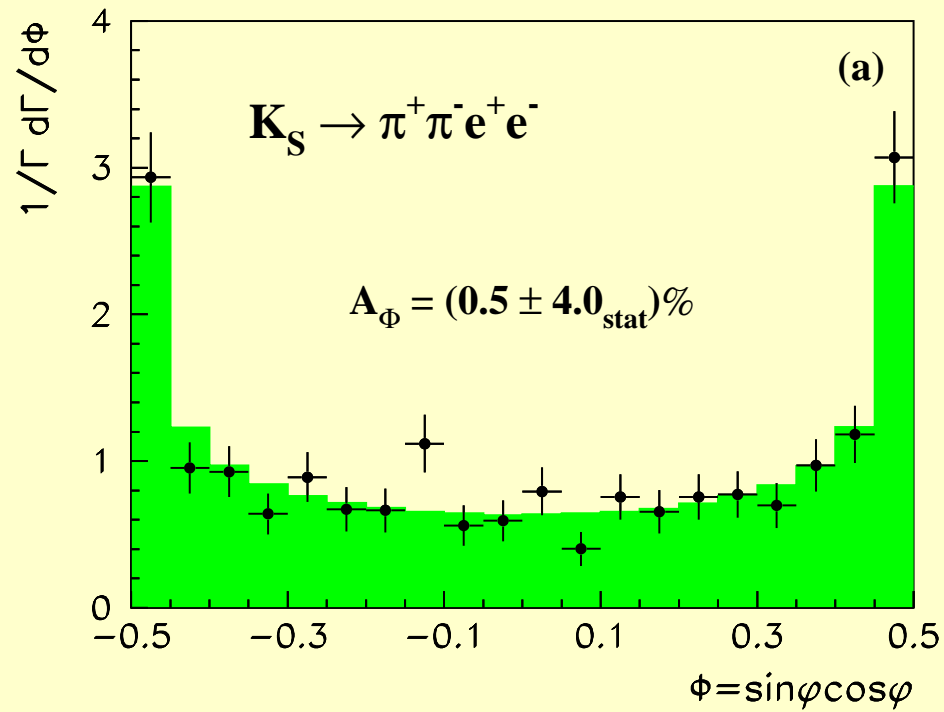
$$BR(K_L \rightarrow \pi^+ \pi^- e^+ e^-) = (3.08 \pm .20) \times 10^{-7}$$



Asymmetry $\Rightarrow CP$ violation



$$BR(K_S \rightarrow \pi^+\pi^-e^+e^-) = (4.69 \pm .30) \times 10^{-5}$$



No asymmetry in K_S^0 decay

Chiral Perturbation Theory

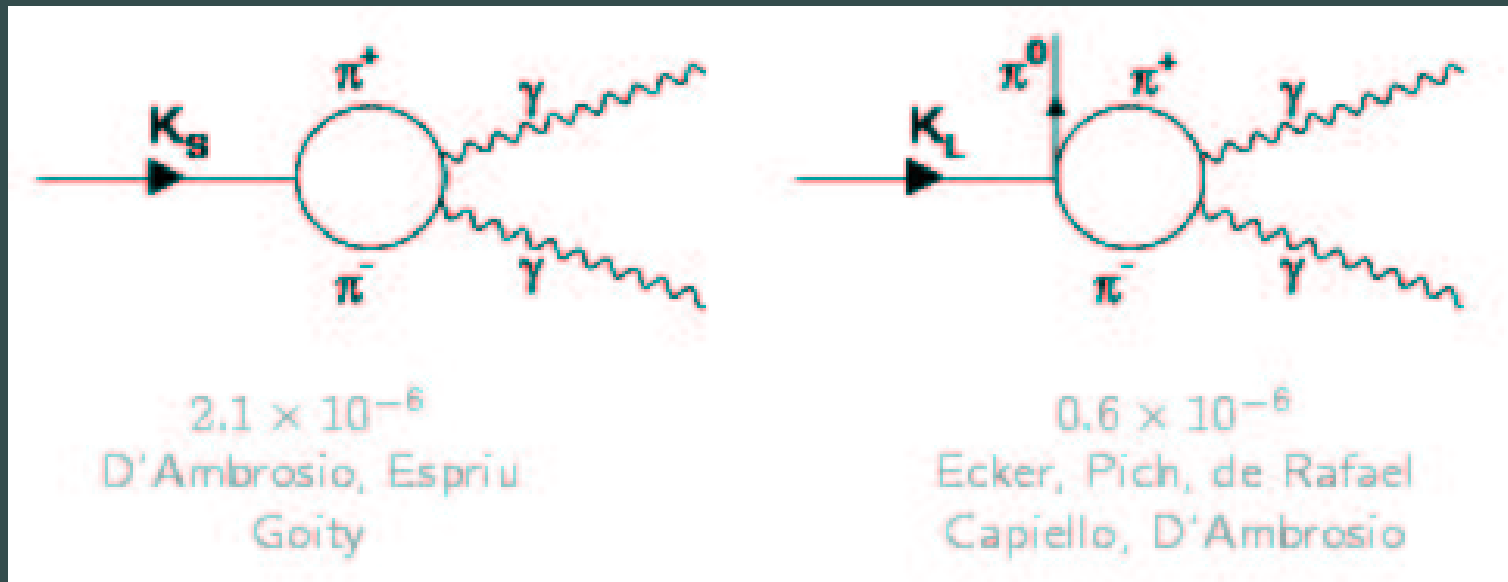
- Low energy (scale $\leq 4\pi F_\pi \approx 1.2$ GeV) effective field theory
- Ought to describe kaon decays: eg.,

$$K_{L,S} \rightarrow \pi^0 \gamma \gamma$$

$$K_{L,S} \rightarrow \gamma \gamma$$

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

- $\mathcal{O}(p^2) = 0$ for both
- No counter-terms required for either: $\mathcal{O}(p^4)$ predictions unambiguous to better than 5%



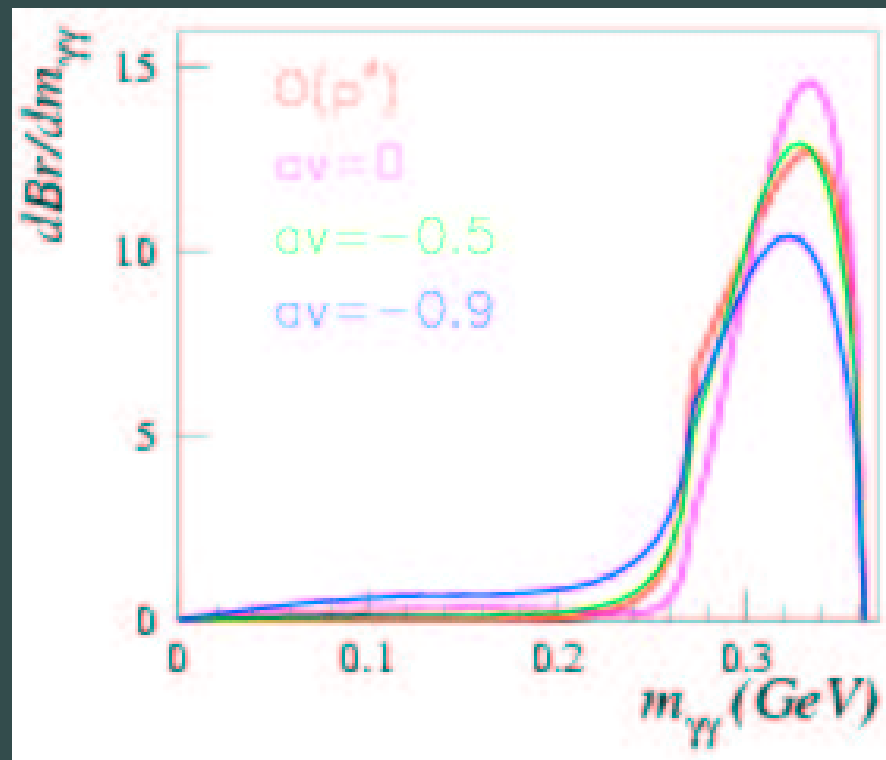
- PDG:

$$BR(K_S^0 \rightarrow \gamma\gamma) = (2.5 \pm 0.4) \times 10^{-6}$$
$$BR(K_L^0 \rightarrow \pi^0 \gamma\gamma) = (1.68 \pm 0.10) \times 10^{-6}$$

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

- $\mathcal{O}(p^4)$ 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:

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

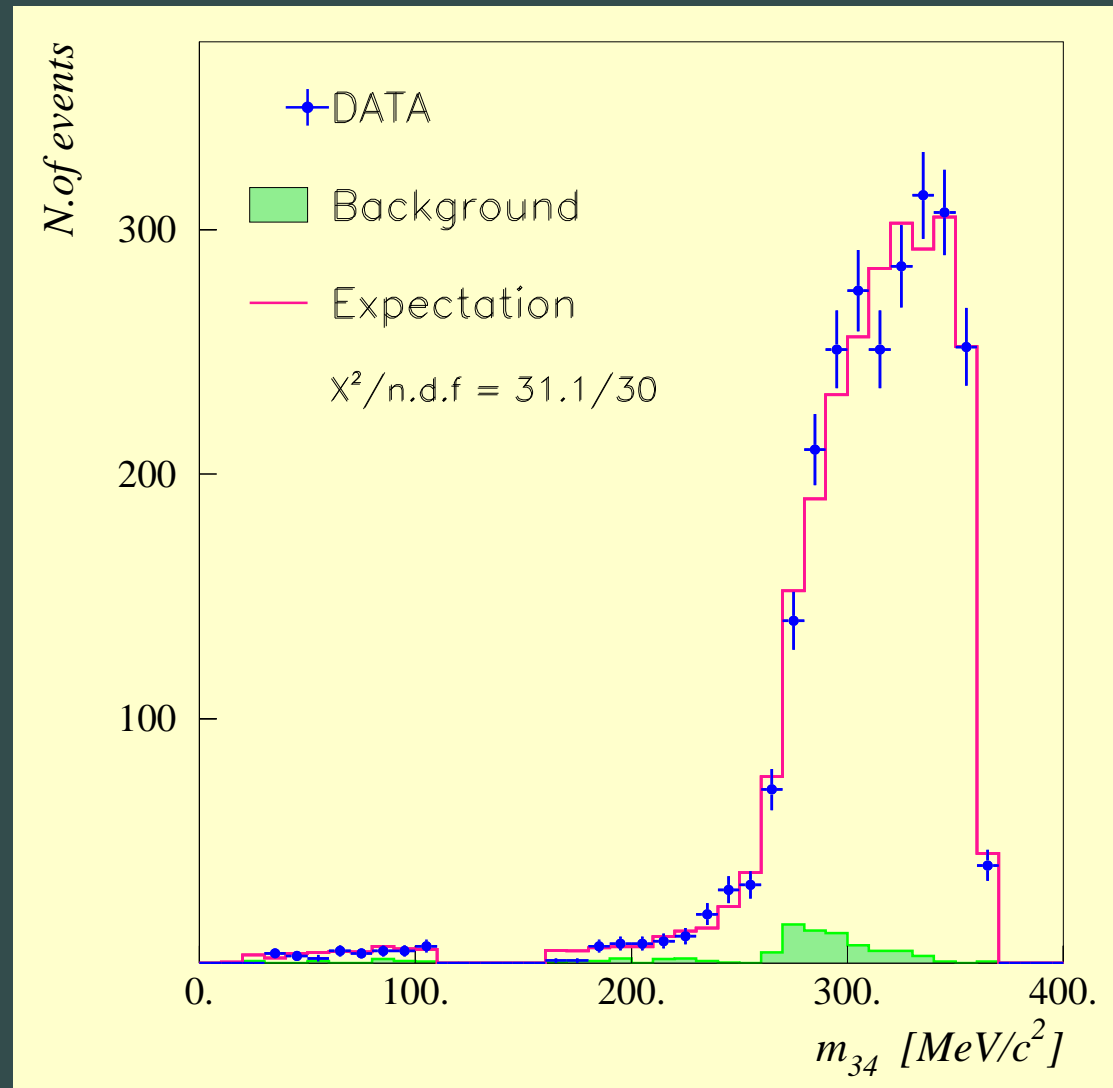


- a_ν
 - effective coupling of counter-term that compensates higher-order loop divergences
 - extracted from $m_{\gamma\gamma}$ distribution, determines CP-conserving amplitude in $K_L \rightarrow \pi^0 e^+ e^-$

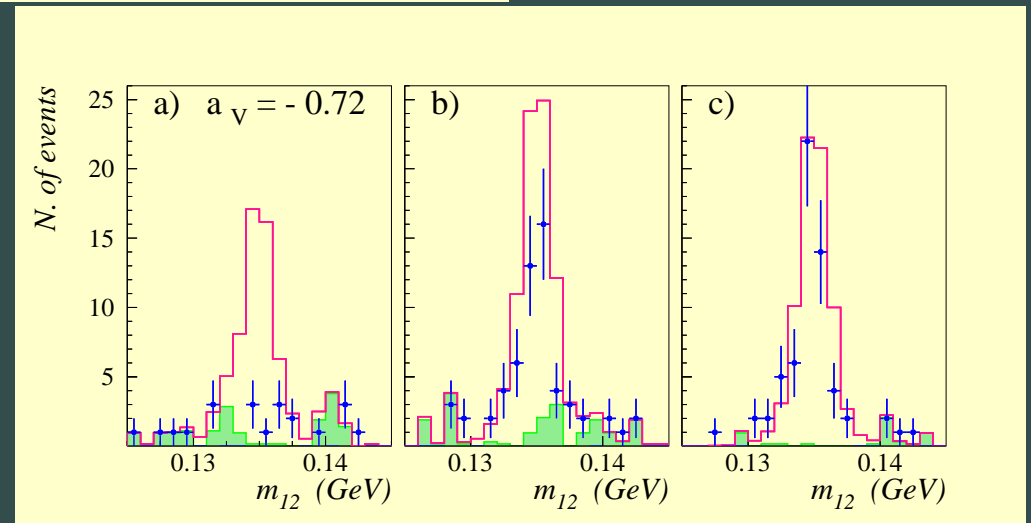
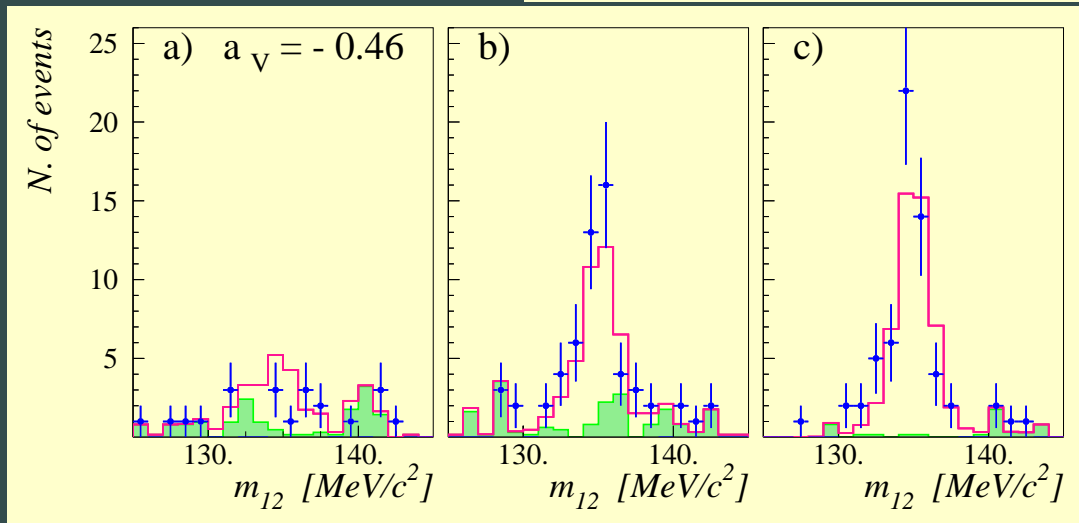
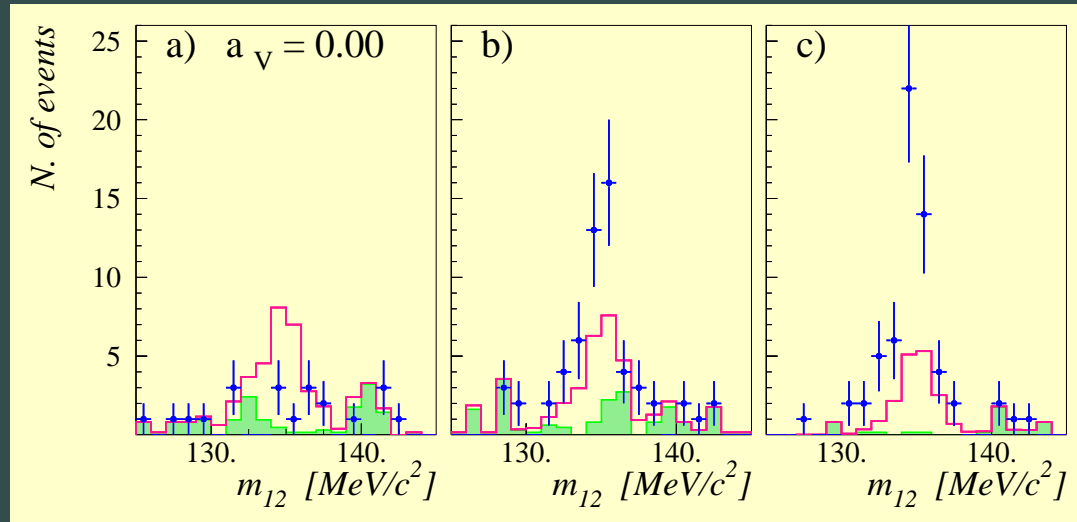
$K_L^0 \rightarrow \pi^0 \gamma \gamma$ Analysis

- Normalization channel $K_L^0 \rightarrow \pi^0 \pi^0$ collected with same trigger
- Reject $2\pi^0$ background
- Reject $3\pi^0$ background (from missed or merged showers)
- Subtract pile-up

$\Rightarrow \sim 2500$ candidates



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



In bins of m_{34} [MeV/c²]: a) 30 - 110; b) 160 - 240; c) 240 - 260

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

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

Phys.Lett. B536 (2002) 229-240

[Note: KTeV finds

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

$$a_\nu = -0.72 \pm 0.08 \Rightarrow$$

non-negligible contribution to $BR(K_L \rightarrow \pi^0 e^+ e^-)_{CP-C}$]

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

- 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

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

- 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: $(0.6 \pm 0.3)\%$

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

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

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

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

- **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

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

- **Reject Dalitz decays (analyzing magnet off–on for far-target data);** correct via simulation (effect twice as large for normalization channel)

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

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

$$\begin{aligned} BR(K_S^0 \rightarrow \gamma\gamma) &= [2.78 \pm 0.06(\text{stat}) \pm 0.03(\text{syst}) \pm 0.02(\text{ext})] \times 10^{-6} \\ &= (2.78 \pm 0.07) \times 10^{-6} \end{aligned}$$

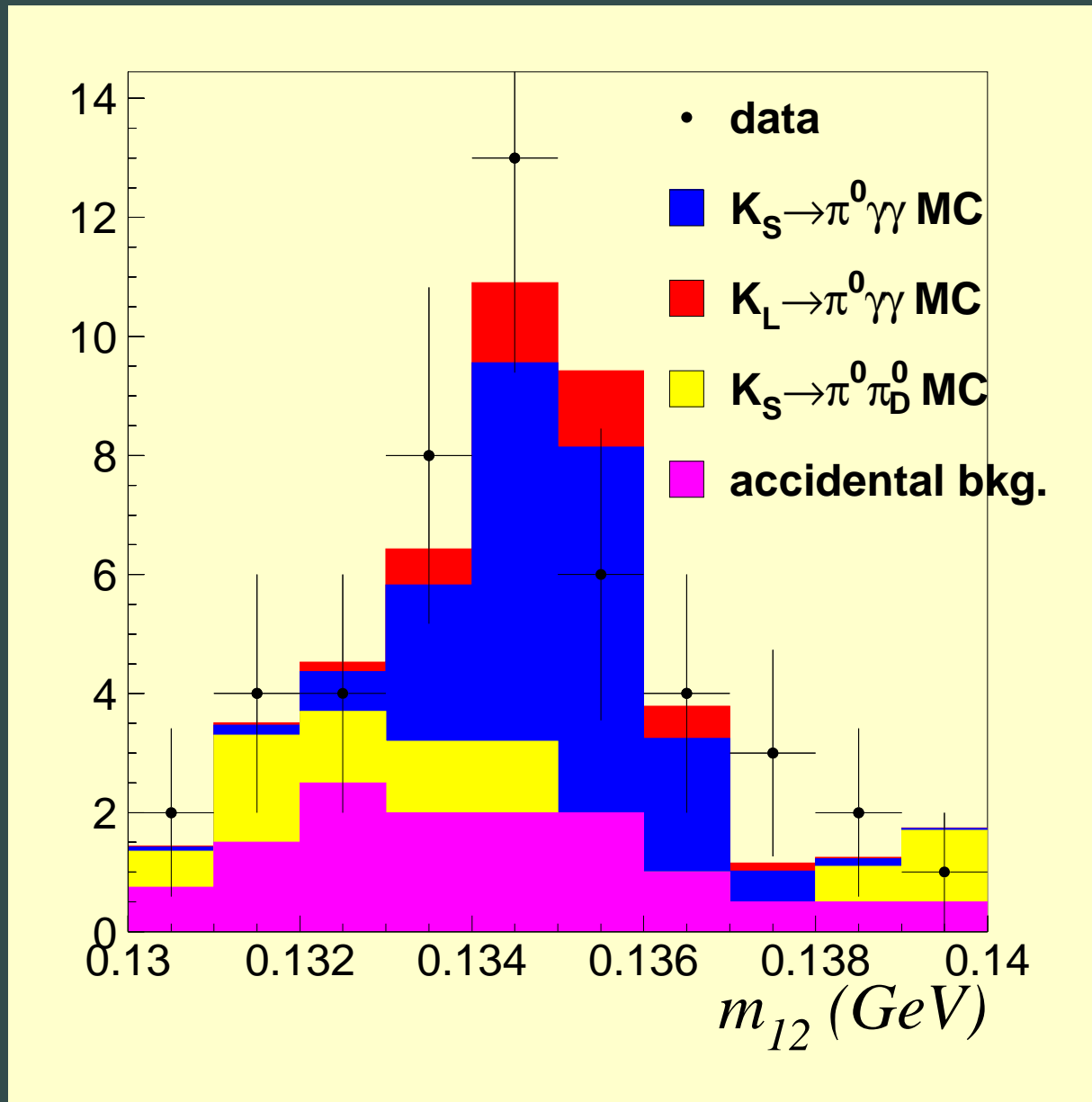
- Compatible with previous results
- Differs by 30% from $\mathcal{O}(p^4)$ prediction \Rightarrow large $\mathcal{O}(p^6)$ contribution?

Phys.Lett. B551 (2003) 7-15

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

- Dominated by π pole of $K_S^0 \rightarrow \pi^0 \pi^0$
 \Rightarrow restrict to $z_q \equiv m_{\gamma\gamma}^2/m_K^2 \geq 0.2$
- Theoretical prediction: $BR(K_S^0 \rightarrow \pi^0 \gamma \gamma, z_q \geq 0.2) = 3.8 \times 10^{-8}$
(Ecker, Pich, De Rafael, 1987)
- z_q -distribution shape tests chiral structure of weak vertex
- Limit: $BR(K_S \rightarrow \pi^0 \gamma \gamma, z_q \geq 0.2) < 3.3 \times 10^{-7}$ at 90% CL

Phys.Lett. B556 (2003) 105-113

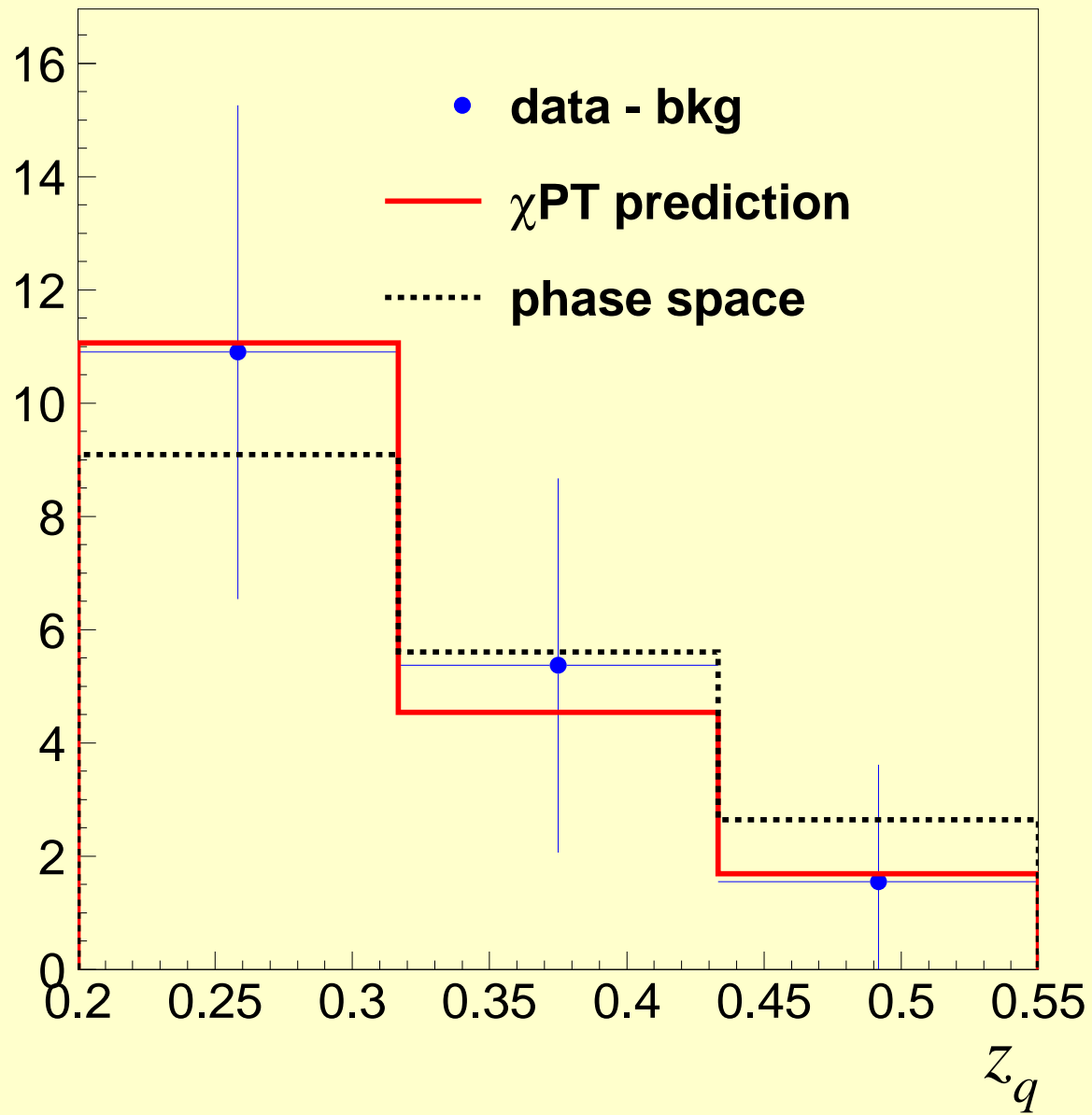


9×10^{-4} probability bump is consistent with background

Source	Events
Signal Region	31.0 ± 5.6
Beam-related bkgd	7.4 ± 2.4
$K_S^0 \rightarrow \pi^0 \pi^0_{Dalitz}$	2.4 ± 1.2
$K_L \rightarrow \pi^0 \gamma \gamma$	3.8 ± 0.0
Acceptance	± 0.7
NET	17.4 ± 6.2

PRELIMINARY

$$\begin{aligned}
 BR(K_S \rightarrow \pi^0 \gamma \gamma, z_q \geq 0.2) &= [4.9 \pm 1.6(\text{stat}) \pm 0.8(\text{syst})] \times 10^{-8} \\
 &= (4.9 \pm 1.7) \times 10^{-8}
 \end{aligned}$$

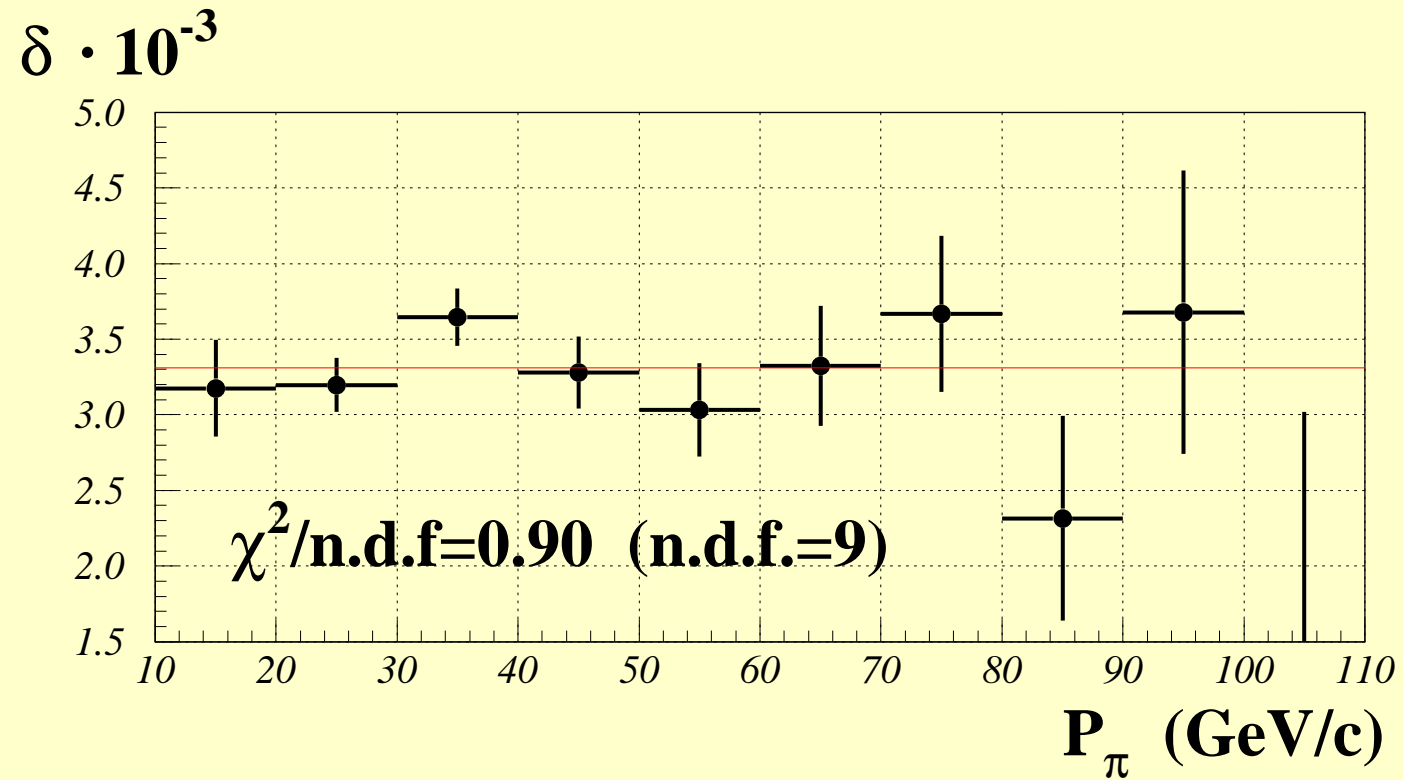


Can't test χ structure

K_{e3} Charge Asymmetry

$$\begin{aligned}\delta_{\ell}(e) &= \frac{BR(K_L^0 \rightarrow \pi^- e^+ \nu_e) - BR(K_L^0 \rightarrow \pi^+ e^- \bar{\nu}_e)}{BR(K_L^0 \rightarrow \pi^- e^+ \nu_e) + BR(K_L^0 \rightarrow \pi^+ e^- \bar{\nu}_e)} \\ &= 2\Re(\epsilon)\end{aligned}$$

- In 2001 data set, 2×10^8 K_{e3} events
- Background fraction $< 10^{-5}$
- Correct for trigger efficiency, pion ID, punch-through
- Measure asymmetry in pion momentum bins



$$\Rightarrow \delta_\ell(e) = [3.317 \pm 0.070(\text{stat}) \pm 0.072(\text{syst})] \times 10^{-3}$$

PRELIMINARY

η_{000}

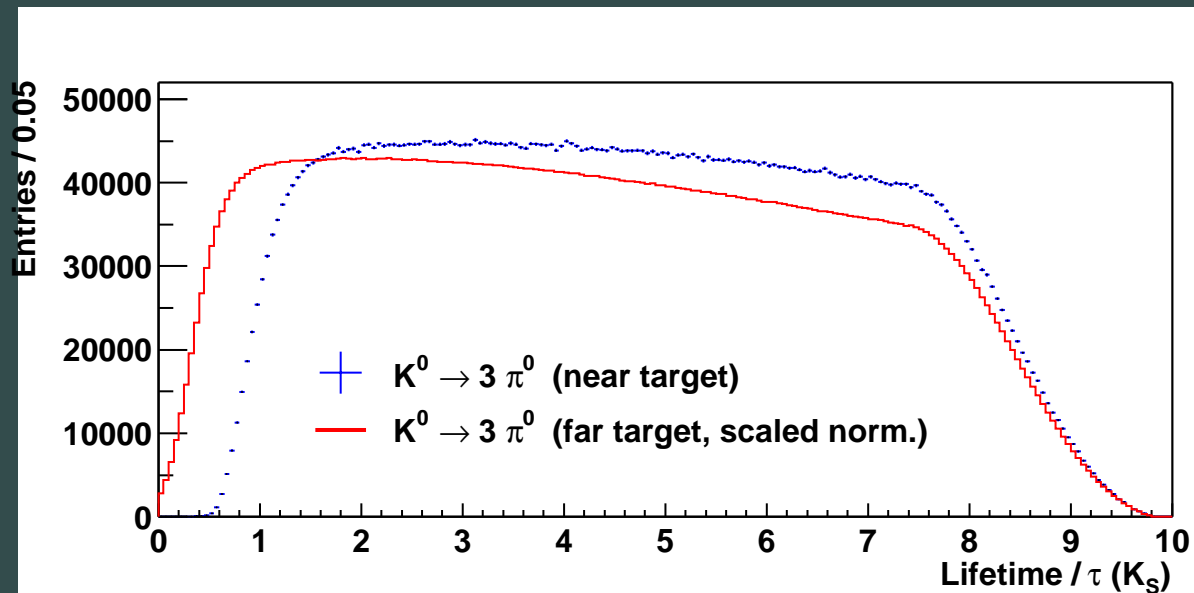
$$\eta_{000} = \frac{A(K_S^0 \rightarrow \pi^0 \pi^0 \pi^0)}{A(K_L^0 \rightarrow \pi^0 \pi^0 \pi^0)}$$

- From 2000, high-intensity K_S^0 run, 5.9×10^6 $\pi^0 \pi^0 \pi^0$ events
- Acceptance corrected with K_L^0 (dilution) run data

$$f(E, t) = \frac{I_{\pi^0\pi^0\pi^0}^{\text{near}}}{I_{\pi^0\pi^0\pi^0}^{\text{far}}} =$$

$$A(E) \left[1 + |\eta_{000}|^2 e^{t(\frac{1}{\tau_L} - \frac{1}{\tau_S})} + 2D(E) e^{\frac{t}{2}(\frac{1}{\tau_L} - \frac{1}{\tau_S})} (\Re\eta_{000} \cos \Delta mt - \Im\eta_{000} \sin \Delta mt) \right]$$

Fit in energy bins (70 – 170 GeV) to $A(E)$, $\Re\eta_{000}$, and $\Im\eta_{000}$



PRELIMINARY

$$\Re\eta_{000} = [-2.6 \pm 1.0(\text{stat}) \pm 0.5(\text{syst})] \times 10^{-2}$$

$$\Im\eta_{000} = [-3.4 \pm 1.0(\text{stat}) \pm 1.1(\text{syst})] \times 10^{-2}$$

CPLEAR:

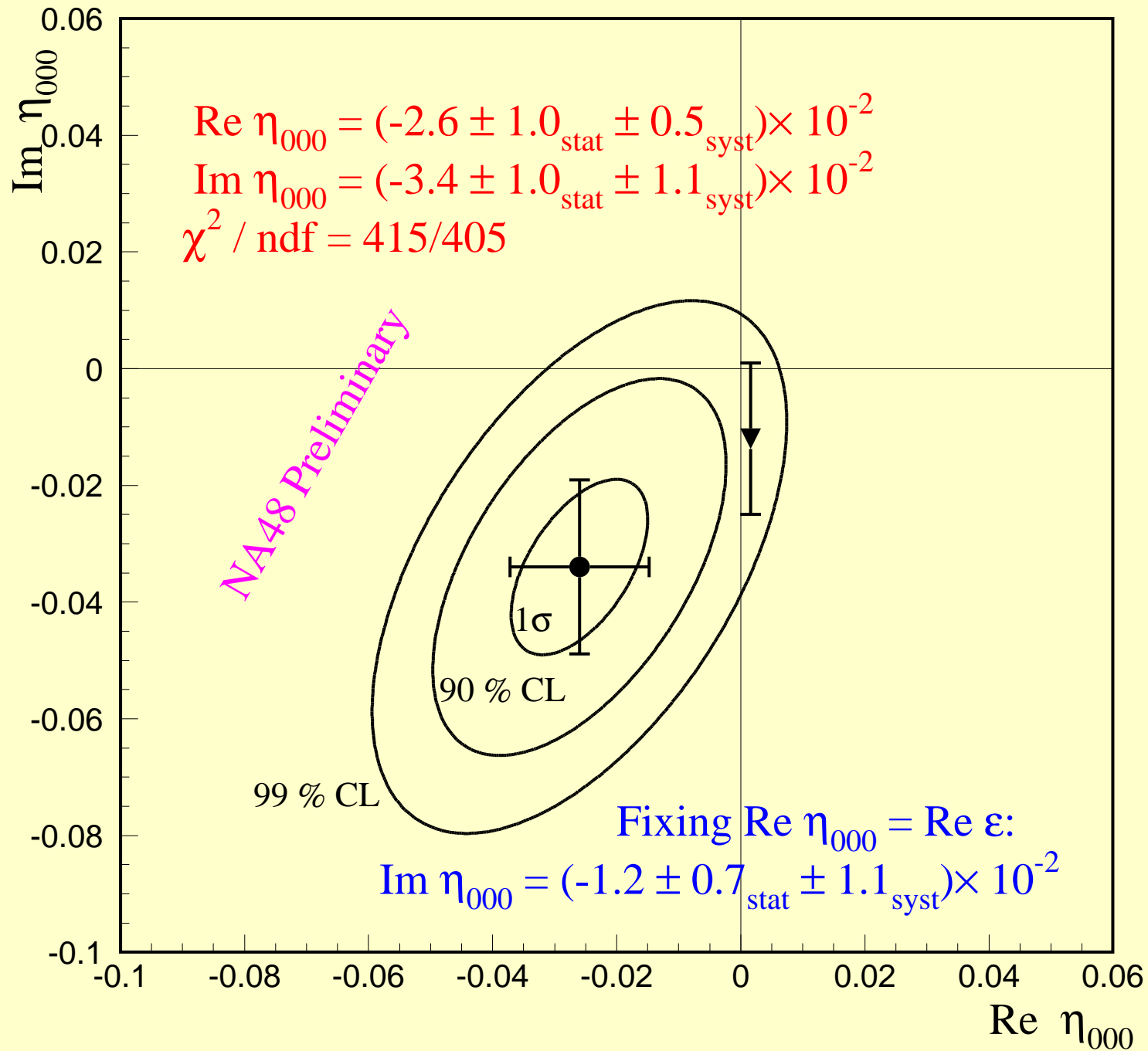
$$\Re\eta_{000} = [18 \pm 14(\text{stat}) \pm 6(\text{syst})] \times 10^{-2}$$

$$\Im\eta_{000} = [15 \pm 20(\text{stat}) \pm 2(\text{syst})] \times 10^{-2}$$

If CPT assumed good, $\Re\eta_{000} = \Re\epsilon$, and $\Im\eta_{000}$ sensitive to direct CP violation

$$\Im\eta_{000} = (-1.2 \pm 1.3) \times 10^{-2} \text{ (CPT)}$$

$$\Rightarrow BR(K_S^0 \rightarrow \pi^0\pi^0\pi^0) < 3.0 \times 10^{-7}$$



Outlook

- NA48/1: High intensity K_S^0 and neutral Hyperons (2002)
 - $K_S^0 \rightarrow \pi^0 e^+ e^-, \pi^0 \mu^+ \mu^-$
 - Ξ^0 semi-leptonic and weak radiative decays
- NA48/2: Charged Kaon beams (2003)
 - CP violation
 - Radiative and (semi-)leptonic decays