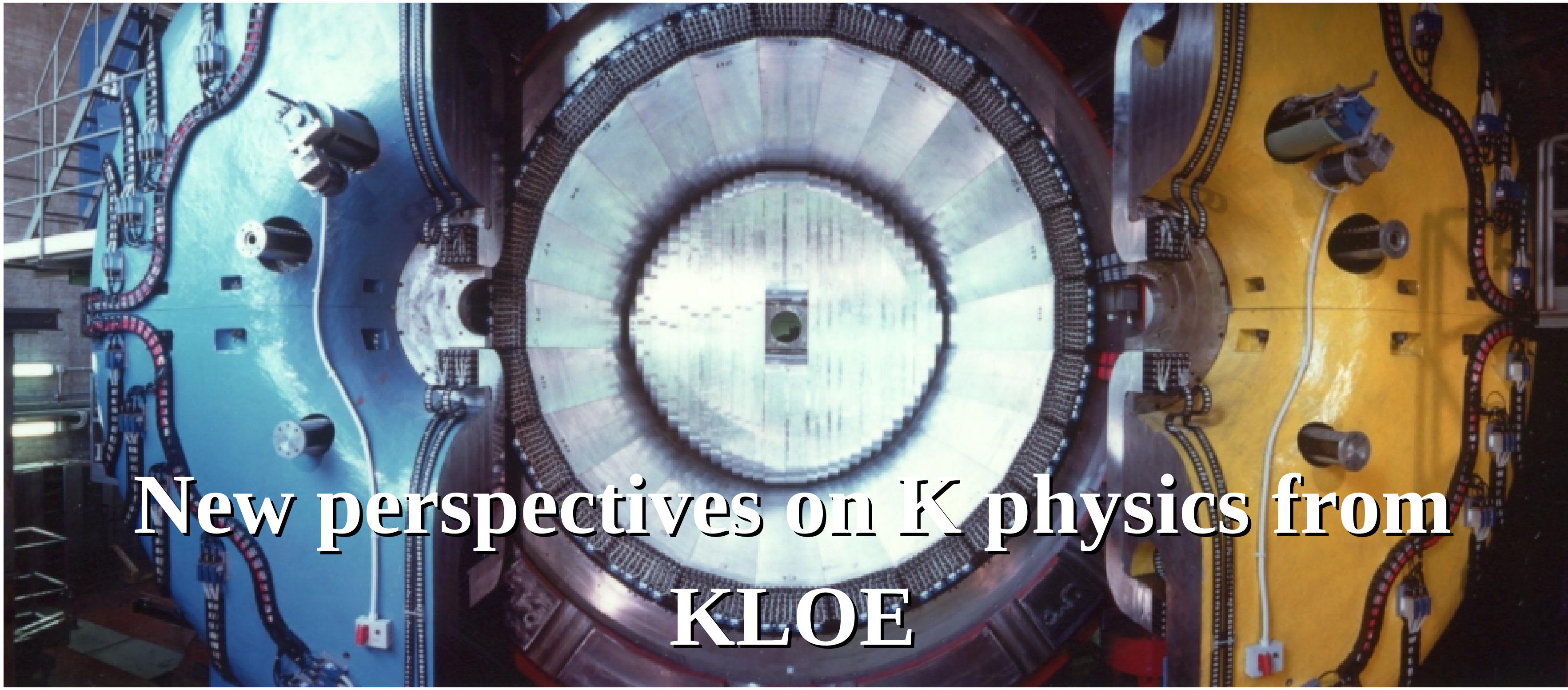

New perspectives on K physics from KLOE

T. Spadaro, LNF INFN
for the KLOE collaboration

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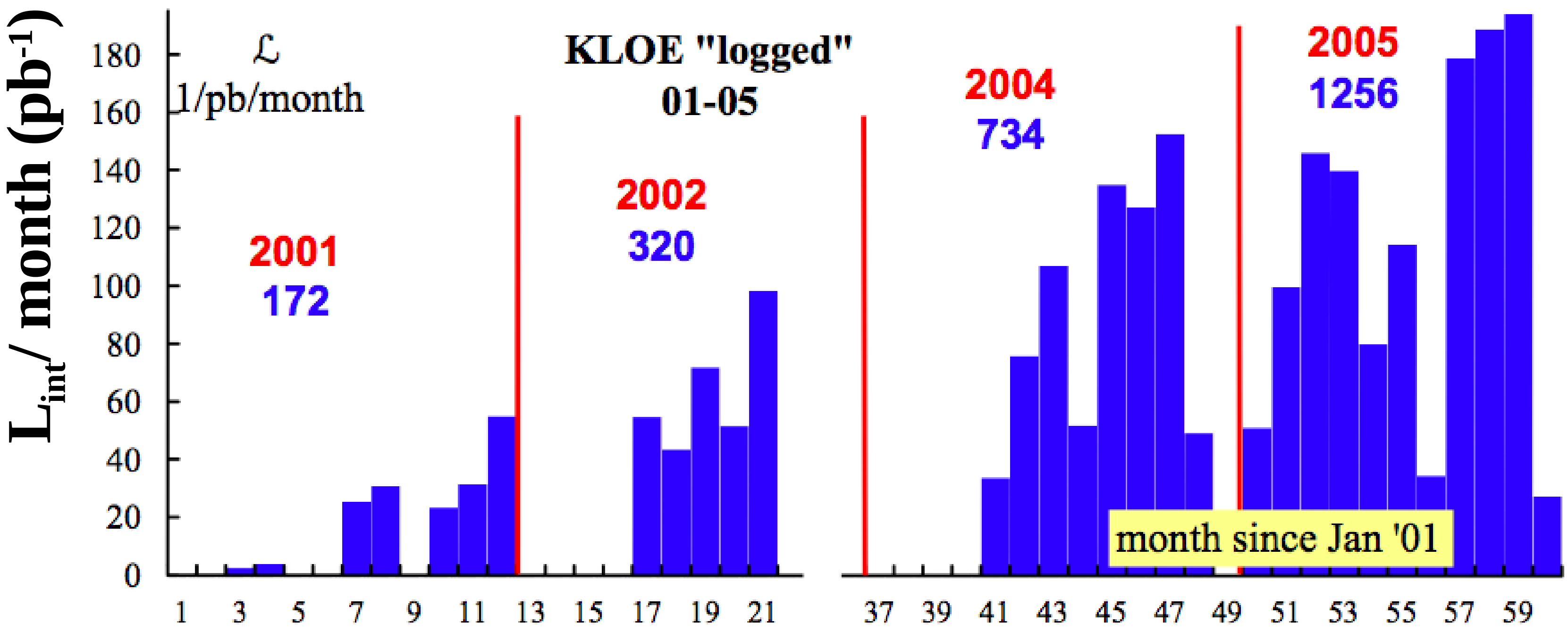
Overview of KLOE data

Data taking for KLOE experiment, years 2001-2005, now run completed

~2.5 fb^{-1} integrated @ $\sqrt{s}=M(\phi)$, corresponding to 2.5 10^9 K_SK_L pairs



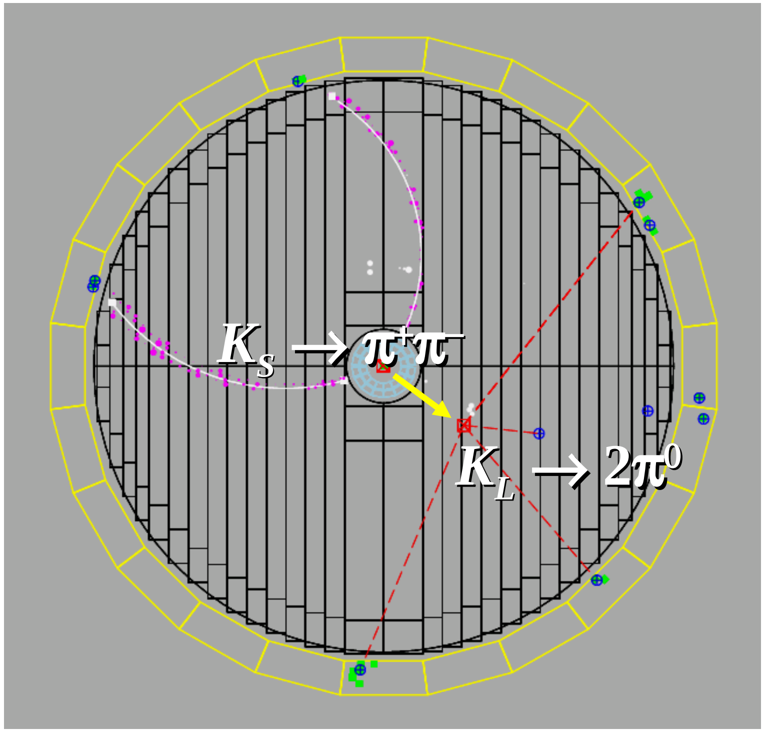
Kaon physics at KLOE

$K_S K_L$ pairs emitted ~back to back, p ~ 110 MeV

Identification of $K_S(K_L)$ decay (interaction) tags presence of $K_L(K_S)$

Almost pure $K_{L,S}$ beams of known momentum + PID (kinematics & TOF):

- **Access to absolute BR's**
- **Precise measurements of K_{Le3} ff's and K_L, K^+ lifetimes (accept ~0.5 τ_L, τ_+)**
- **Above points crucial for Vus determination: see M. Antonelli's talk**



K's are in a coherent state: access to quantum-interference t distributions

Kaon physics at KLOE: QM coherence

Test QM coherence: $I(\Delta t) \propto e^{-\Gamma_L|\Delta t|} + e^{-\Gamma_S|\Delta t|} - 2(1 - \zeta_{S,L})\, e^{-(\Gamma_S + \Gamma_L)|\Delta\tau|/2} \cos(\Delta m \Delta t)$

$K_{S(L)} \to \pi^+\pi^-$ at t_1 ⟵ ϕ ⟶ $K_{L(S)} \to \pi^+\pi^-$ at t_2

KLOE 380 pb^{-1} '01 + '02 data

Fit with PDG values for Γ_S, Γ_L:

$\Delta m = (5.61 \pm 0.33)10^9\ s^{-1}$

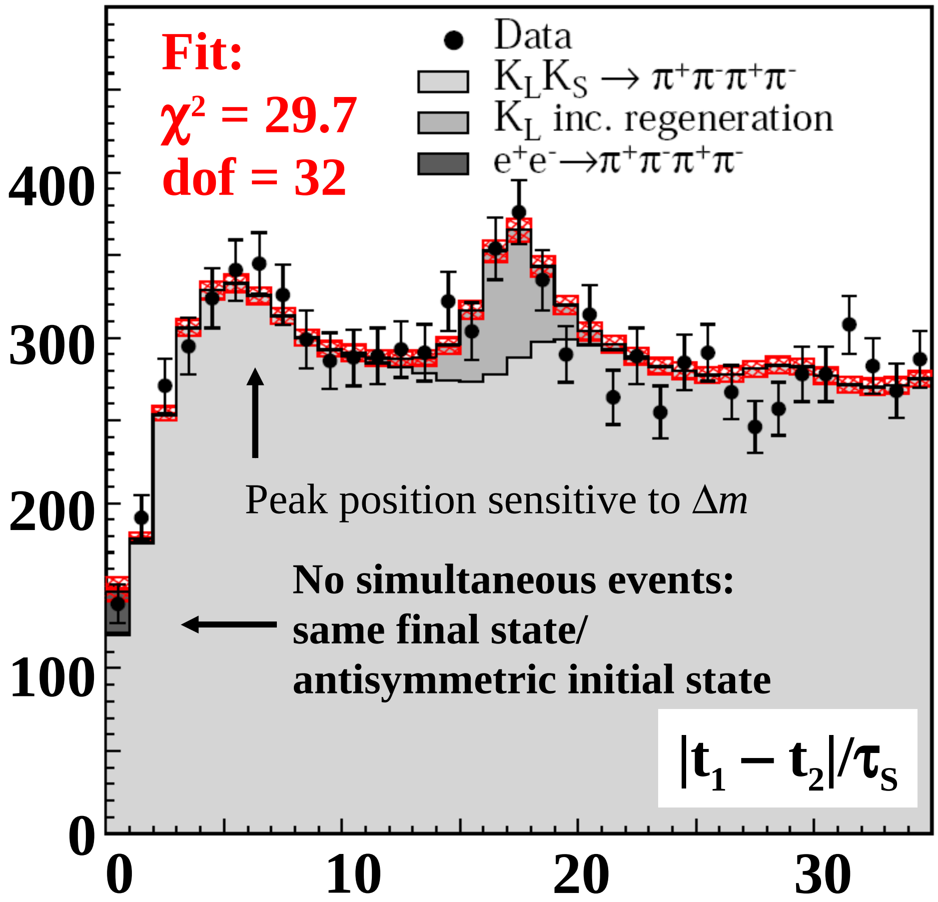
PDG04: $(5.301 \pm 0.016)10^9\ s^{-1}$

Fix Δm to PDG '04 value, obtain:

$\zeta_{S,L} = 0.018 \pm 0.040_{stat} \pm 0.007_{syst}$

$\zeta_{S,L} = 0.13^{+0.16}_{-0.15}$ Bertlmann 99 (CPLEAR data)

No QM violation observed with ×4 sensitivity improvement



The picture from K^0 decays and CPT

C, P, and T symmetries are violated, separately and in bilinear combinations

CPT conservation relies on Lorentz invariance, locality, unitarity

But: violations of CPT symmetry are expected, due to QG

At present no consistent and predictive theory of QG, energy scale for CPT violations unknown

Search for CPT violations is driven by phenomenology

The most precise test of CPT violation comes from K^0 decay amplitudes:

$$\left|\frac{m_{K^0} - m_{\bar{K}^0}}{m_{K^0}}\right| \approx 3 \times 10^{-18}$$

From time evolution to unitarity relation

The relation in the kaon system between total transition rates and decay widths gives the most precise test of CPT violation at present

Time evolution (Weisskopf-Wigner), $i\,\frac{d}{dt}\begin{bmatrix} K^0 \\ \overline{K}^0 \end{bmatrix} = [\,M - i\,\Gamma/2\,]\begin{bmatrix} K^0 \\ \overline{K}^0 \end{bmatrix}$

with diagonal states:

$$|K_S\rangle = N_S\,[\,|K_+\rangle + \varepsilon_S|K_-\rangle\,]$$
$$|K_L\rangle = N_L\,[\,|K_-\rangle + \varepsilon_L|K_+\rangle\,]$$

$,\ \varepsilon_{L,S} = \varepsilon \pm \delta$

The parameter $\delta = \frac{i(m_{K^0} - m_{\bar{K}^0}) + \frac{1}{2}(\Gamma_{K^0} - \Gamma_{\bar{K}^0})}{\Gamma_S - \Gamma_L}\cos\phi_{SW}e^{i\phi_{SW}}$

describes ~~CPT~~ **in mass or decay matrices: e.g., assuming** $\Gamma_{K^0} - \Gamma_{\bar{K}^0}$ **= 0,**

$$\left|\frac{m_{K^0} - m_{\bar{K}^0}}{m_{K^0}}\right| \approx 3\times10^{-14}\,|\,\mathrm{Im}(\delta)\,|$$

The unitarity relation

Only assumption is conservation of probability (unitarity),

$$\Gamma_{ij} = \sum_f A_i(f) A_j(f)^*$$ **, valid if summing over all possible final states *f***

One obtains (Bell-Steinberger relation):

$$\left[\frac{\Gamma_S + \Gamma_L}{\Gamma_S - \Gamma_L} + i \tan\phi_{SW}\right]\left[\frac{\mathrm{Re}(\epsilon)}{1+|\epsilon|^2} - i\mathrm{Im}(\delta)\right] = \frac{1}{\Gamma_S - \Gamma_L}\sum_f \underbrace{A_L(f) A_S^*(f)}_{\alpha_f}$$

Experimental inputs: $K_{S,L}$ lifetimes and masses + $K_{S,L}$ decay amplitudes

Outputs of the relation: Re(ε) and Im(δ)

Advantage of the K^0 system: few final states contribute significantly

The unitarity relation: size of the α's

Expression of α_f's in terms of measurable quantities (for Re ε = 1.6 10^{-3}):

Channel	Espression	$10^5 \times$ SM value of α_f
$\pi\pi$ decays:	$\alpha_{+-} = \eta_{+-}\ BR(K_S \to \pi^+\pi^-(\gamma))$	$111 + i\ 105$
	$\alpha_{00} = \eta_{00}\ BR(K_S \to \pi^0\pi^0)$	$49 + i\ 47$
$\pi\pi\pi$ decays:	$\alpha_{+-0} = \tau_S / \tau_L\ \eta_{+-0}^*\ BR(K_L \to \pi^+\pi^-\pi^0)$	$0.04 + i\ 0.04$
	$\alpha_{000} = \tau_S / \tau_L\ \eta_{000}^*\ BR(K_L \to \pi^0\pi^0\pi^0)$	$0.00 + i\ 0.00$
$\pi l \nu$ decays:	$\alpha_{kl3} = 2\ \tau_S / \tau_L\ \eta_{000}^*\ BR(K_L \to \pi l \nu) \times$ $\times [\mathrm{Re}(\varepsilon) - \mathrm{Re}(y) - i\ \mathrm{Im}(\delta) + i\ \mathrm{Im}(x_+)]$	$0.4 + i\ 0.0$

CP and CPT violation parameters are at both sides of B-S relation...

Test via unitarity: state of the art in 2001

Before last generation of K experiments, precision ~~CPT~~ tests by CPLEAR

- **Measurements @ CPLEAR of time distributions of S-tagged K_{l3} decays,**

$$R_\pm(\tau) = R\left[K^0 \to e^\pm \pi^\mp \nu(\overline{\nu})_{t=\tau}\right], \quad \overline{R}_\mp(\tau) = R\left[\overline{K}^0 \to e^\mp \pi^\pm \overline{\nu}(\nu)_{t=\tau}\right]$$

- **combined as** $\left\{\overline{R}_\pm - R_\mp\left[1 + 4\,\mathrm{Re}(\varepsilon_L)\right]\right\} \Big/ \left\{\overline{R}_\pm + R_\mp\left[1 + 4\,\mathrm{Re}(\varepsilon_L)\right]\right\}$,

- **and fit with the constraint of the unitarity relation, yield:**

$$\mathrm{Im}(x_+) = (-2.0 \pm 2.6) \times 10^{-3}$$
$$\mathrm{Re}(y) = (\ \ 0.3 \pm 3.0) \times 10^{-3}$$
$$\mathrm{Re}(\delta) = (\ \ 2.4 \pm 2.7) \times 10^{-4}$$
$$\mathrm{Re}(x_-) = (-0.5 \pm 3.0) \times 10^{-3}$$

and

$$\mathrm{Re}(\epsilon) = (164.9 \pm 2.5) \times 10^{-5}$$
$$\mathrm{Im}(\delta) = (\ 2.4 \pm 5.0) \times 10^{-5}$$

Limiting factors for the errors: the knowledge of πeν (perform a 6-parameter fit) and of πππ amplitudes

Impact of KLOE: K_S semileptonic decays

Sensitivity to CPT violating effects through charge asymmetry:

$$A_{S,L} = \frac{\Gamma(K_{S,L} \to \pi^- e^+ \nu) - \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}{\Gamma(K_{S,L} \to \pi^- e^+ \nu) + \Gamma(K_{S,L} \to \pi^+ e^- \bar{\nu})}$$

$$\begin{cases} A_S - A_L = 4\,[\mathrm{Re}\,(\delta) + \mathrm{Re}\,(x\_)] \\ A_S + A_L = 4\,[\mathrm{Re}\,(\varepsilon) - \mathrm{Re}\,(y)] \end{cases}$$

If CPT holds, $A_S=A_L$

$A_S \neq A_L$ signals CPT violation in mixing and/or decay with $\Delta S \neq \Delta Q$

Γ and A_S never measured before:

- Can extract $|V_{us}|$ by measuring $BR(K_S \to \pi e \nu) \to$ See Antonelli's talk
- **Completes set of measurements of Ke3 inputs to B-S relation: now,**

$$\alpha_{\pi l \nu} = 2\frac{\tau_{K_S}}{\tau_{K_L}} BR(K_L \to \pi l \nu)\left[(A_S + A_L)/4 - i\,\mathrm{Im}(x_+)\right]$$

Impact of KLOE: K_S semileptonic decays

- Precise identification of charge state, discriminating e from π using TOF
- Count number of $K_S \to \pi e \nu$ events fitting multiple kinematical variables
- Correct for selection efficiency by charge and measure **(450 pb^{-1} of data)**

$$A_S = (1.5 \pm 9.6_{\rm stat} \pm 2.9_{\rm syst}) \times 10^{-3}$$

Using A_L = (3.34 ± 0.07) 10^{-3} from KTeV,

From $A_S - A_L$, evaluate

$$\mathrm{Re}\, x_- + \mathrm{Re}\, \delta = (-0.5 \pm 2.5) \times 10^{-3}$$

use Re (δ) from CPLEAR, ×5 improvement for error on Re (x_)

From $A_S + A_L$:

$$\mathrm{Re}\, \epsilon - \mathrm{Re}\, y = (1.2 \pm 2.5) \times 10^{-3}$$

determine for the first time Re (y) independently of B-S relation

Other exp'tl improvements from KLOE

ππ decays:

$B(K_S \to \pi^+\pi^-)/B(K_S \to \pi^0\pi^0) = 2.2549 \pm 0.0059$

$B(K_L \to \pi^+\pi^-) = (1.930 \pm 0.017)\,10^{-3}$

$B(K_L \to \pi^0\pi^0) = (9.32 \pm 0.12)\,10^{-4}$

$\phi^{+-} = 0.757 \pm 0.012$

$\phi^{00} = 0.762 \pm 0.014$

K lifetimes:

$\tau_S = 0.08958 \pm 0.00006$ ns

$\tau_L = 50.84 \pm 0.23$ns

πππ decays:

$B(K_S \to \pi^+\pi^-\pi^0) = (3.2 \pm 1.2)\,10^{-7}$

$B(K_L \to \pi^+\pi^-\pi^0) = 0.1263 \pm 0.0012$

$B(K_S \to \pi^0\pi^0\pi^0) < 1.2\ 10^{-7}$

$B(K_L \to \pi^0\pi^0\pi^0) = 0.1997 \pm 0.0020$

πlν decays:

$B(K_L \to \pi l \nu) = 0.6705 \pm 0.0022$

$B(K_S \to \pi l \nu) = (11.77 \pm 0.15)\,10^{-4}$

$A_L = (3.32 \pm 0.06)\,10^{-3}$

$A_S = (1.5 \pm 10.0)\,10^{-3}$

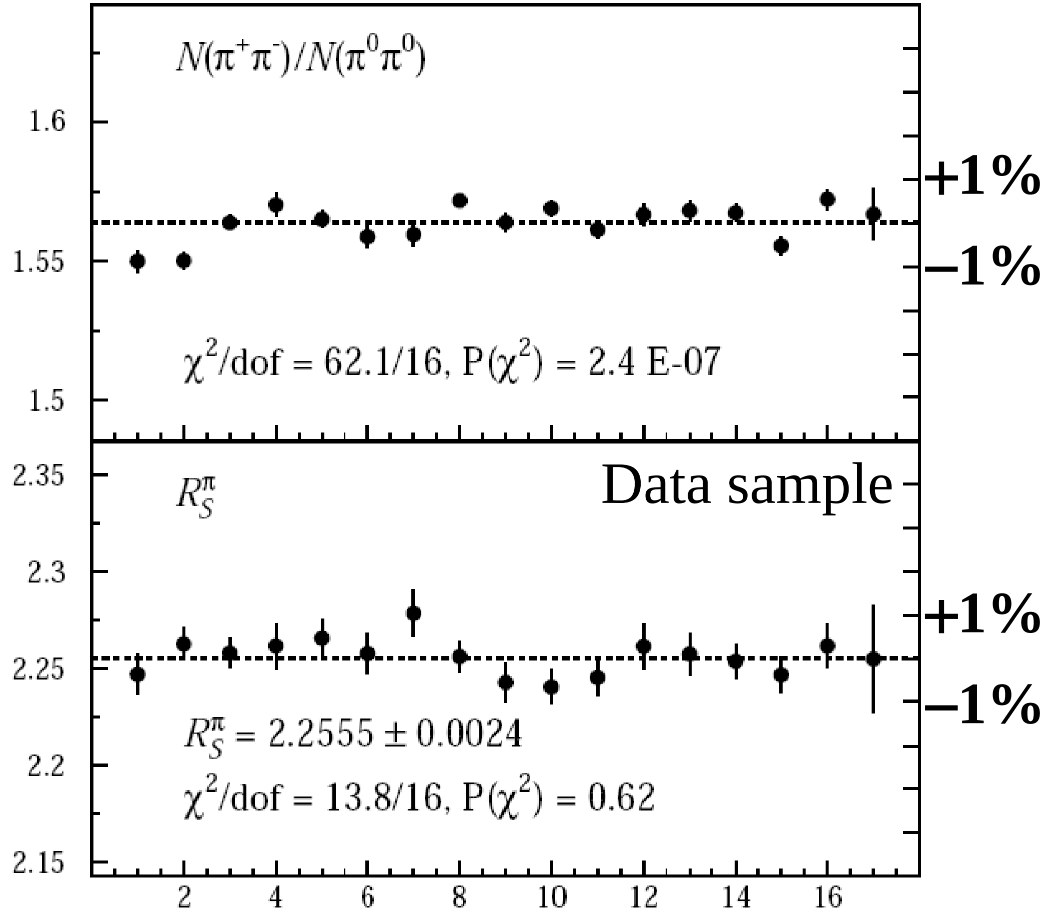
Impact of KLOE: K_S BR's

Precise measurement of $R = \frac{\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^0\pi^0)} = 2.2549 \pm 0.0054$

Measurement inclusive with respect to photon radiation

Careful check of systematic uncertainties:

- Ratio of selection efficiencies for $\pi^+\pi^-(\gamma)$ and $\pi^0\pi^0$
- Dependence of tagging efficiency on decay mode
- Dependence of R on level of machine background, stability studies



Impact of KLOE: K_S BR's

Combine R with ratio of Ke3 BR's measured at ~1%:

$$R_{e+} \equiv \frac{\Gamma(K_S \to \pi^- e^+ \nu)}{\Gamma(K_S \to \pi^+ \pi^-)} = (5.099 \pm 0.082_{\rm stat} \pm 0.039_{\rm syst}) \times 10^{-4}$$

$$R_{e-} \equiv \frac{\Gamma(K_S \to \pi^+ e^- \bar{\nu})}{\Gamma(K_S \to \pi^+ \pi^-)} = (5.083 \pm 0.073_{\rm stat} \pm 0.042_{\rm syst}) \times 10^{-4}$$

Obtain:

$$\mathrm{BR}(K_S \to \pi^+\pi^-) = (69.196 \pm 0.051) \times 10^{-2}$$
$$\mathrm{BR}(K_S \to \pi^0\pi^0) = (30.687 \pm 0.051) \times 10^{-2}$$
$$\mathrm{BR}(K_S \to \pi^- e^+ \nu) = (3.528 \pm 0.062) \times 10^{-4}$$
$$\mathrm{BR}(K_S \to \pi^+ e^- \bar{\nu}) = (3.517 \pm 0.058) \times 10^{-4}$$

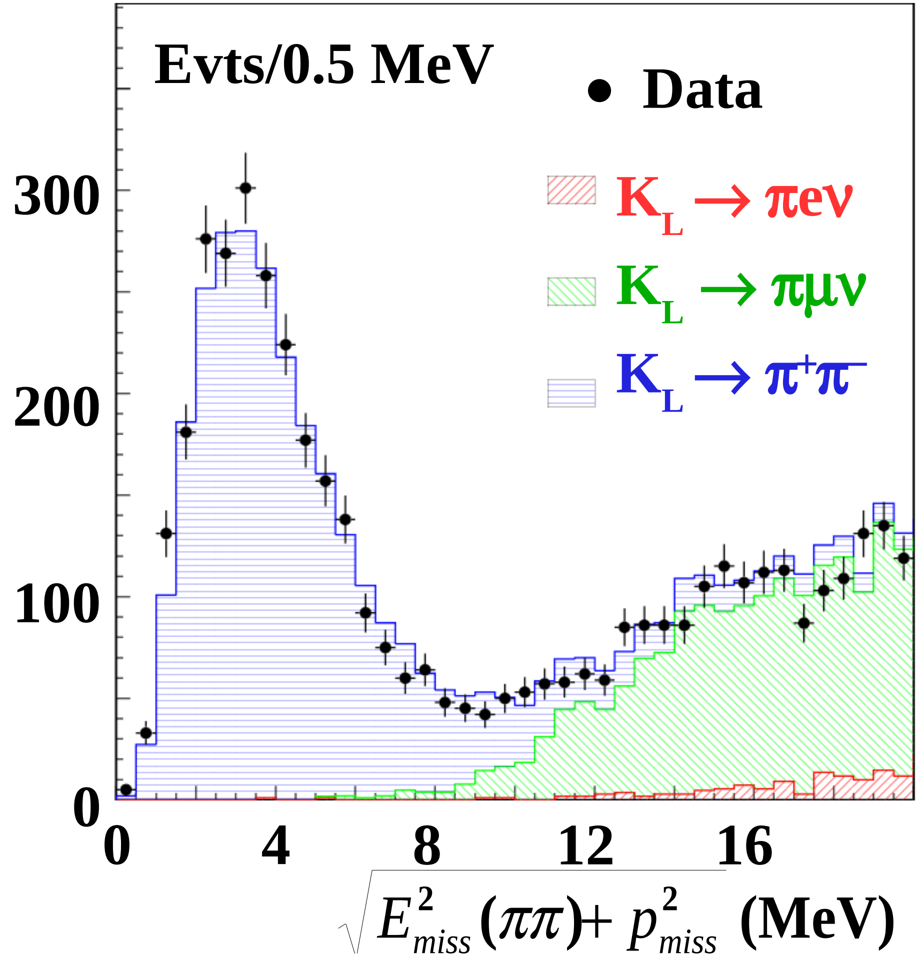
Comparing $\Gamma(K_S \to \pi e \nu)$ to $\Gamma(K_L \to \pi e \nu)$, test $\Delta S = \Delta Q$:

×2 improvement in precision on $\mathrm{Re}\, x_+ = (-0.5 \pm 3.6) \times 10^{-3}$

Impact of KLOE: $\pi\pi(\gamma)$ amplitudes

$BR(K_L \to \pi\pi(\gamma))$ measured @ 1%: $(1.963 \pm 0.012_{stat} \pm 0.017_{syst}) \times 10^{-3}$

- PID using decay kinematics, count ~ 45,000 signal events in ~ 328 pb^{-1}
- Normalize to $K_L \to \pi\mu\nu$ counts
- Measurement inclusive of all γ's



Consistency of K_S, K_L $\pi\pi$ amplitudes:

- Use $BR(K_S \to \pi\pi(\gamma))$, τ_L from KLOE
- Use ε'/ε and τ_S from world averages
- Subtract DE (from E731) and obtain:

KLOE: $|\varepsilon| = (2.216 \pm 0.013) \times 10^{-3}$

KTeV: $|\varepsilon| = (2.239 \pm 0.012) \times 10^{-3}$

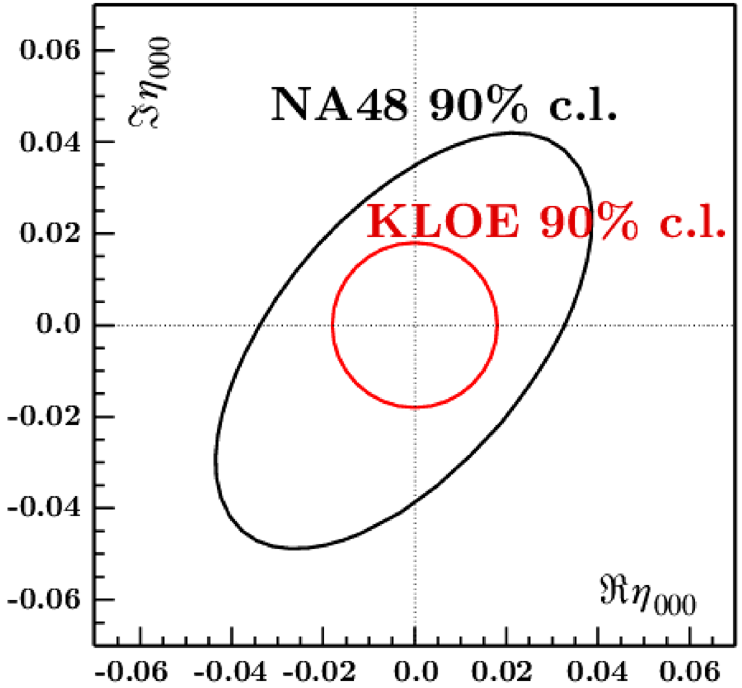
PDG 04: $|\varepsilon| = (2.284 \pm 0.014) \times 10^{-3}$

Impact of KLOE: πππ amplitudes

Direct search for $K_S \to 3\pi^0$ decays: BR($K_S \to 3\pi^0$) ≤ 1.2×10^{-7} @ 90% CL

$K_S \to 3\pi^0$ is CP violating: in SM, $\Gamma_S = \Gamma_L|\eta|^2$, BR($K_S \to 3\pi^0$) = 1.9×10^{-9}

- **2 events selected, 2.5 bkg expected in 450 pb^{-1}**
- **Bkg: $2\pi^0$ + 2 split/accidental clusters**
- Normalize to $K_S \to 2\pi^0$ counts



Contribution of $3\pi^0$ to B-S relation:

- **Use τ_L, BR($K_L \to 3\pi^0$) from KLOE**
- **Use τ_S from PDG 2004**
- **Obtain: η_{000} ≤ 0.018 @ 90% CL**
  $|\alpha_{000}| \le 10^{-5}$ @ 95% CL

Improvement with whole data:

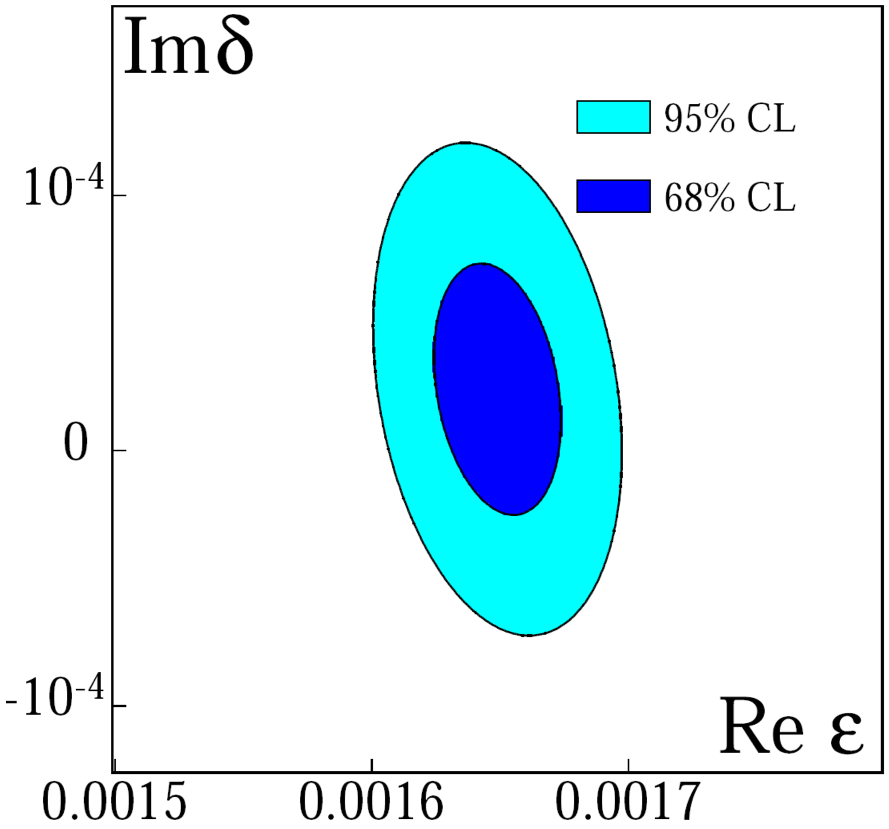
× 5 in statistics, × 10 in rejection, expect to reach 10^{-8} sensitivity on BR

Impact of KLOE: results (1)

After CPLEAR measurements (2001)

$$\mathrm{Re}(\epsilon) = (164.9 \pm 2.5) \times 10^{-5}$$

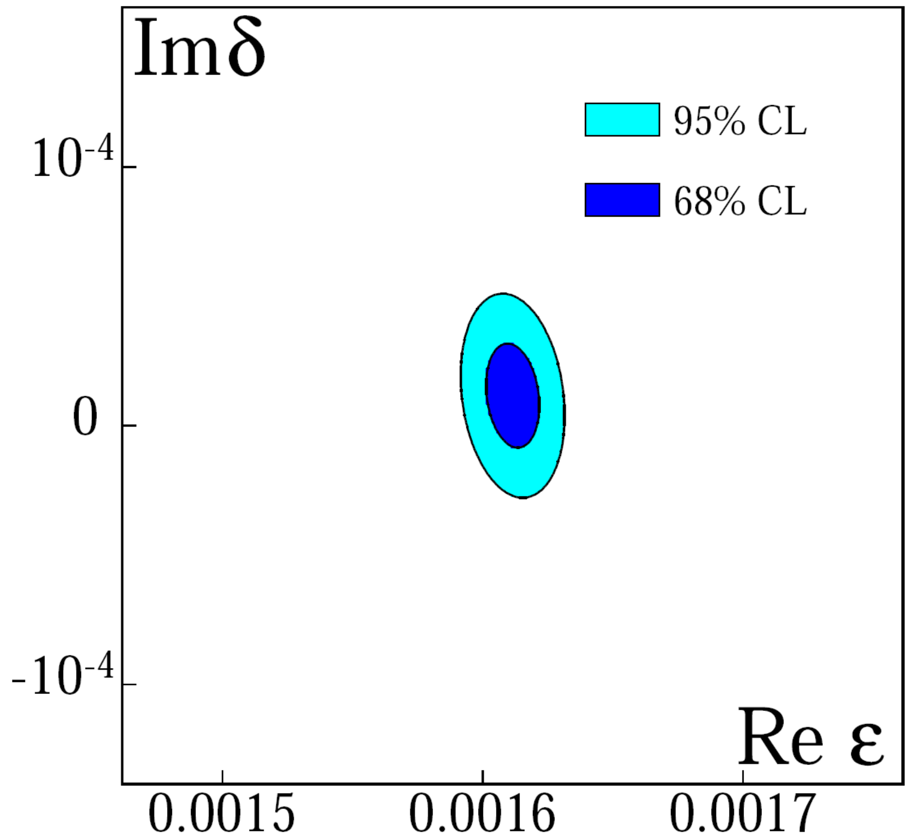
$$\mathrm{Im}(\delta) = (\ 2.4 \pm 5.0) \times 10^{-5}$$



After KLOE measurements (2006)

$$\mathrm{Re}(\epsilon) = (160.2 \pm 1.3) \times 10^{-5}$$

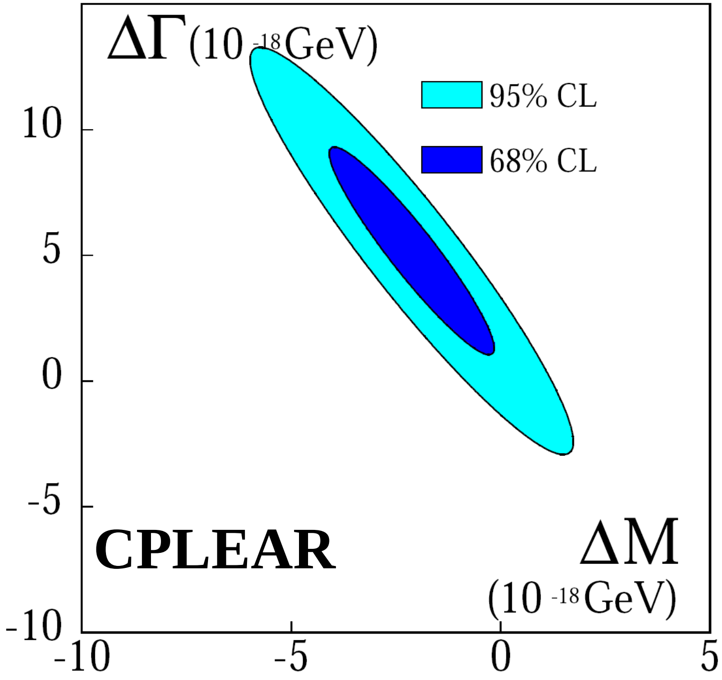
$$\mathrm{Im}(\delta) = (\ 1.2 \pm 1.9) \times 10^{-5}$$

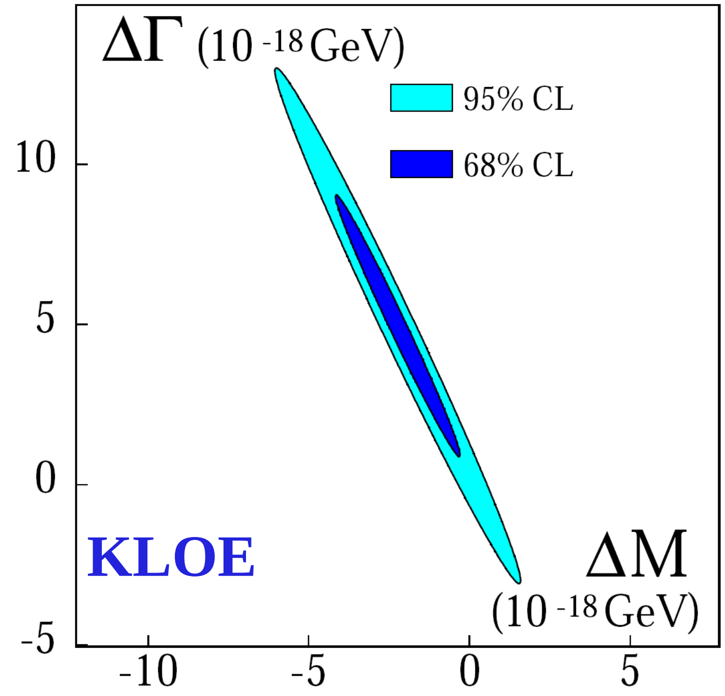


Impact of KLOE: results (2)

Translate to limits on ΔM vs ΔΓ:

for ΔΓ= 0, $-4 \times 10^{-19} < m_{K_0} - m_{\overline{K}_0} < 7 \times 10^{-19}$ GeV





Limiting quantities for the error:

Im (x_+) and ϕ_{+-} for Im (δ), η_{+-} and η_{00} for Re (ε)

What's next: analysis of $K_S \to \gamma\gamma$

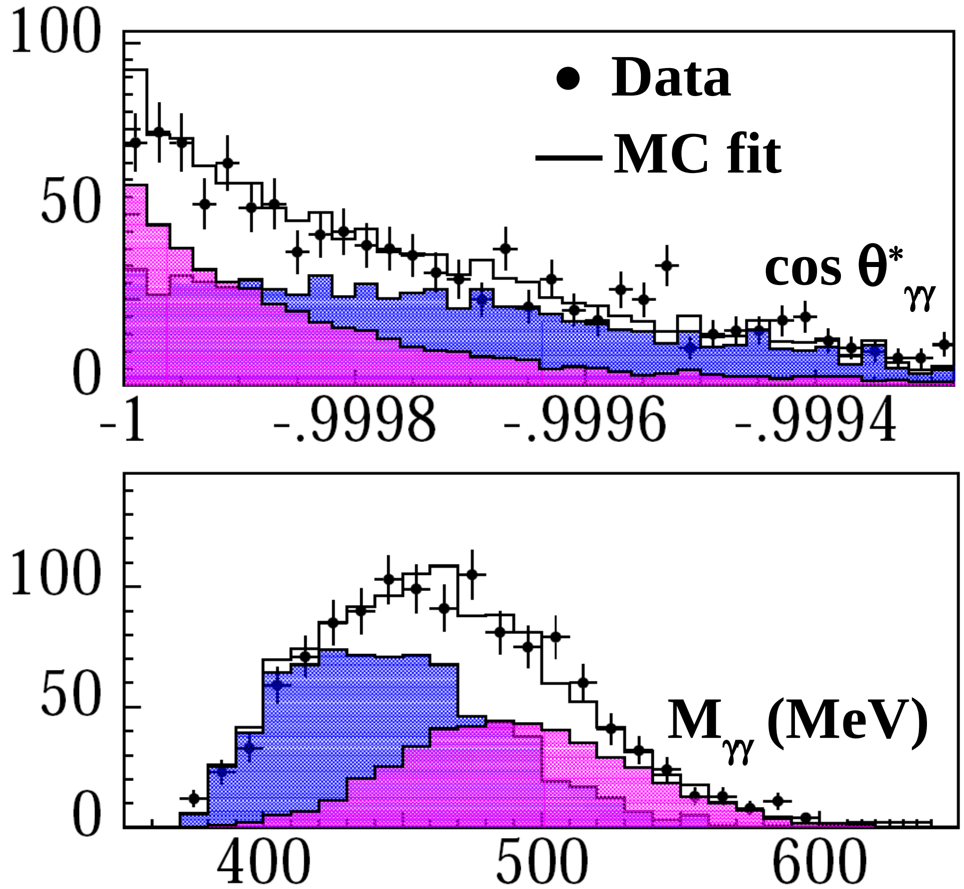
Test of χPt: BR($K_S \to \gamma\gamma$) predicted at O(p^4) as 2.1 10^{-6} within few percent

Disagrees with most precise measurement: (2.78 ± 0.07) 10^{-6} [NA48]

Data fit to $K_S \to \gamma\gamma$ + $K_S \to \pi^0\pi^0$ background from MC, identify 612 ± 40 signal events in 1.7 fb^{-1}

Statistical error dominated by MC,
error @ analysis end will be 5%

Can confirm or disprove discrepancy of NA48 with respect to O(p^4)



What's next: analysis of $K_L \to \pi e \nu \gamma$

Test of χPt: $R = BR(K_L \to \pi e \nu \gamma, E_\gamma > 30 \text{ MeV}, \theta_{\gamma e} > 20^\circ)/BR(K_L \to \pi e \nu(\gamma))$

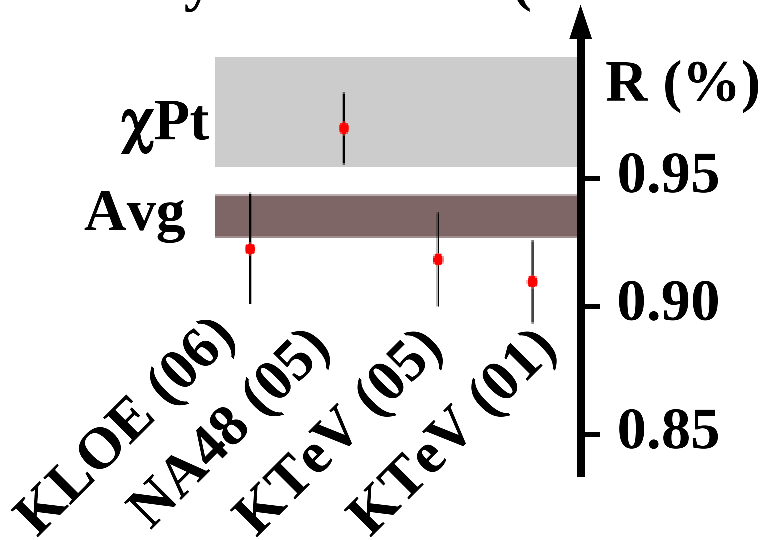
Test for presence of DE terms via fit of γ spectrum:

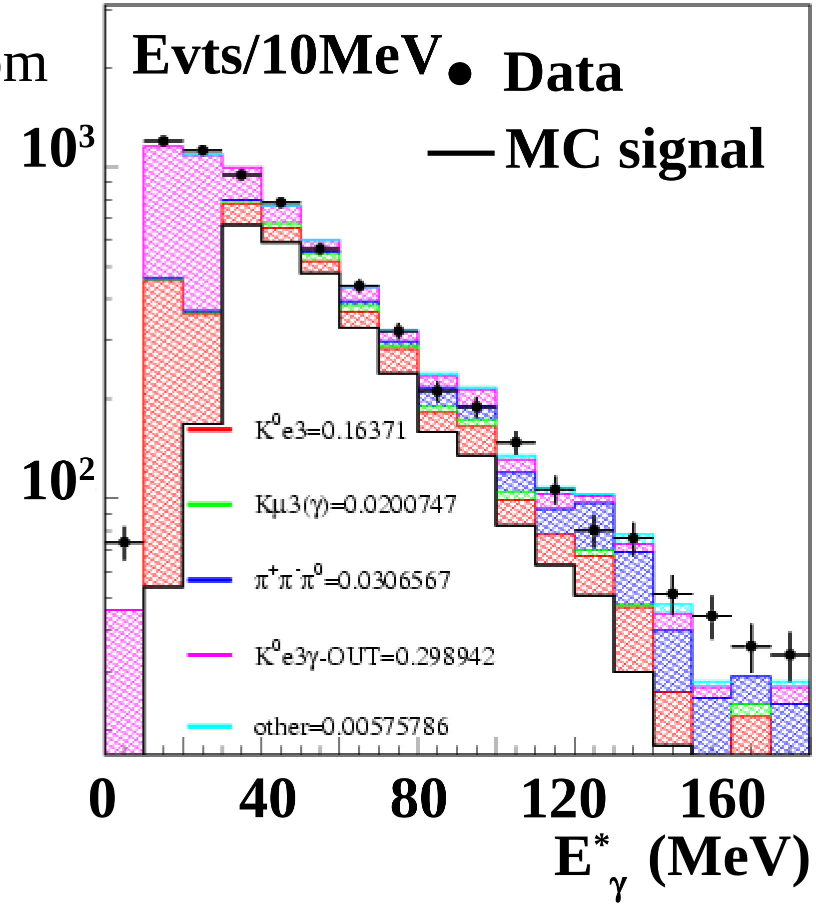
Fit data to signal (~ 48%) + background from

$K_L \to \pi e \nu(\gamma)$ (~ 46%),

$K_L \to \pi^+\pi^-\pi^0$, $K_L \to \pi\mu\nu(\gamma)$, other (~ 6%)

Preliminary result: R = (0.92 ± 0.02)%





What's next: analysis of $K_S \to \pi\mu\nu$

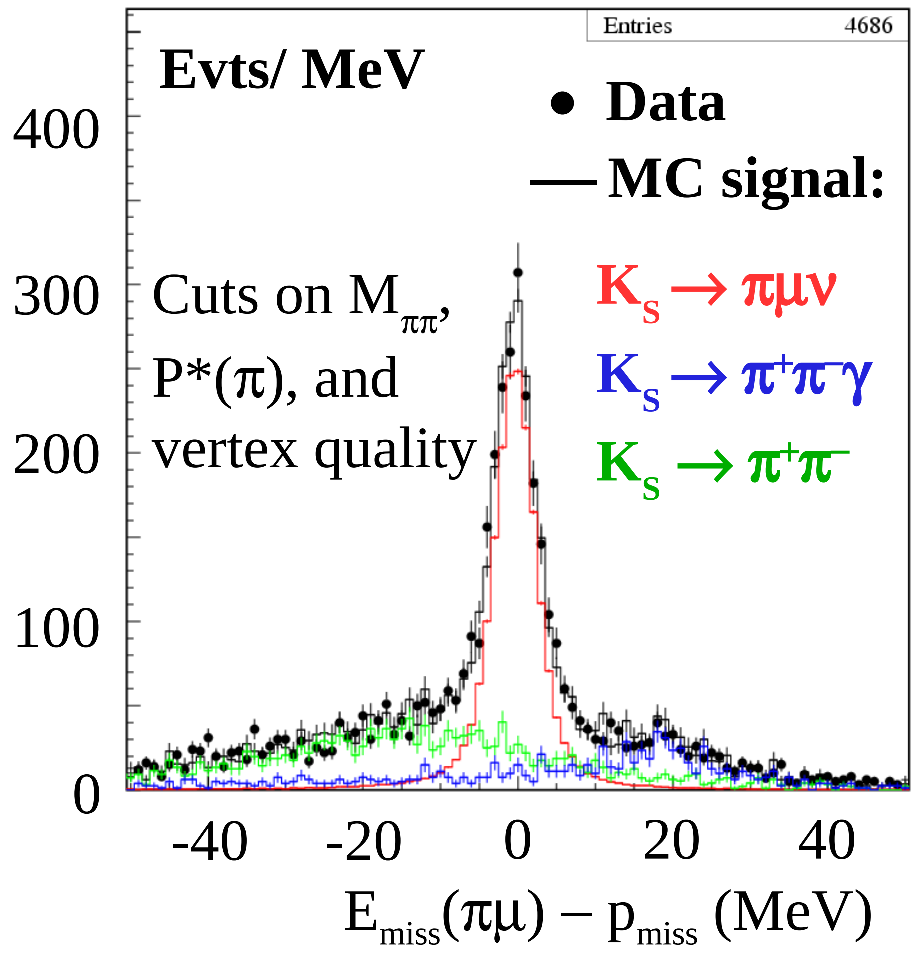
Decay mode has never been observed

Measure charge asymmetry: test of CPT, CP violation

Compare width with $K_L \to \pi\mu\nu$: test of validity of $\Delta S = \Delta Q$ rule

Compare with $K_S \to \pi e\nu$: test universality of lepton couplings

Total error dominated by statistics, expect 3% @ the end of analysis



Conclusions

New KLOE measurements greatly improve knowledge of $K_S K_L$ system:

Measurements of K_S decays unique to KLOE

From these results:

Test of 1st row CKM matrix unitarity, see M. Antonelli's talk

Consistent picture from unitarity relation

Improved precision of test of CPT violation

accuracy on Re (ε) and Im (δ) improved by a factor ~2.5

Future developments:

Analyses of whole data set for $K_L \to \pi e \nu \gamma$, $K_S \to \gamma\gamma$, $K_S \to \pi \mu \nu$