Review of New Strange Quark Results
XXVII Physics In Collision Conference

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June 27, 2008

Kloe
NA48
KTeV
ISRA+

64 years after first observation In 1944 of a charged kaon in a cloud chamber by Le Prince-Ringuet, strange quark physics is still vital and going strong

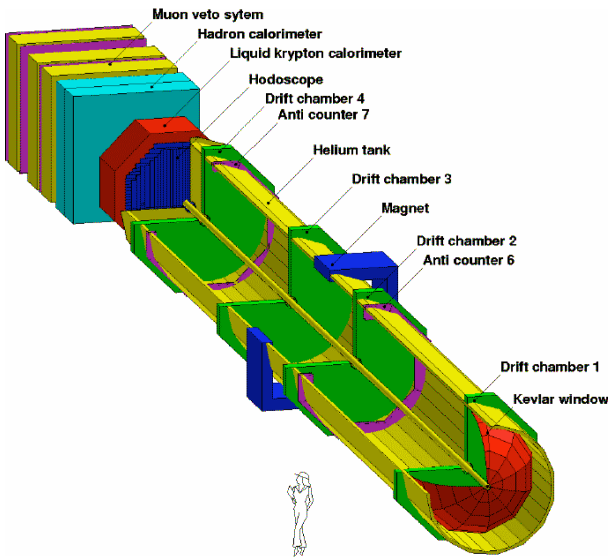
I. CP/CPT Violation
II. Lepton Flavor Violation/NP
III. e,μ universality in K_{l3}, K_{l2}
IV. V_{us}
V. ChPT
VI. Quantum Coherence
VII. Cusp Measurements

} Not covered for lack of time

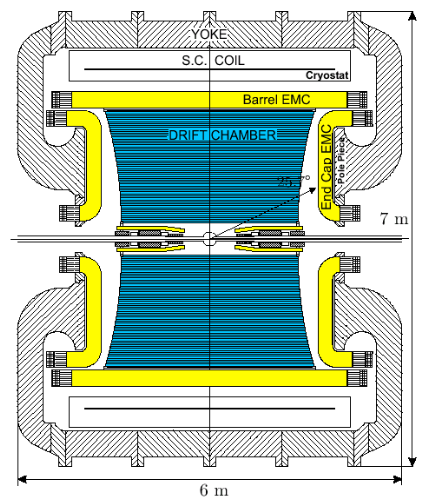
New Physics anywhere?

Four Active Kaon Collaborations

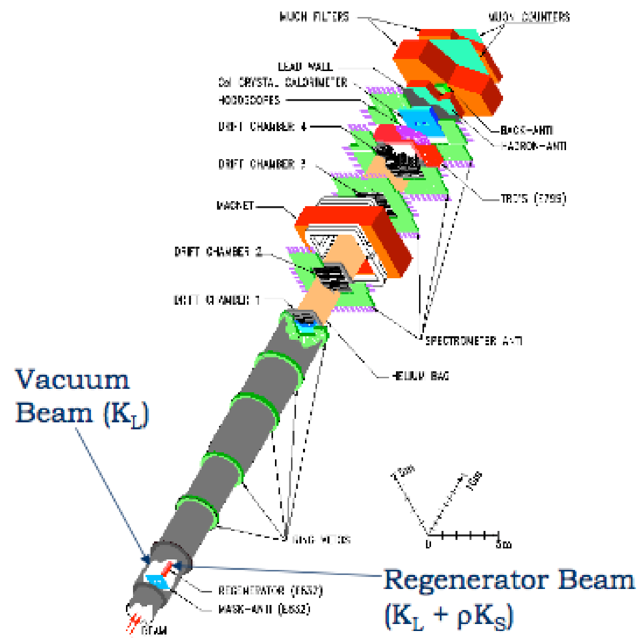
Charged and Neutral Kaon Decays*



NA48/2
Future NA62



KLOE
Future KLOE II

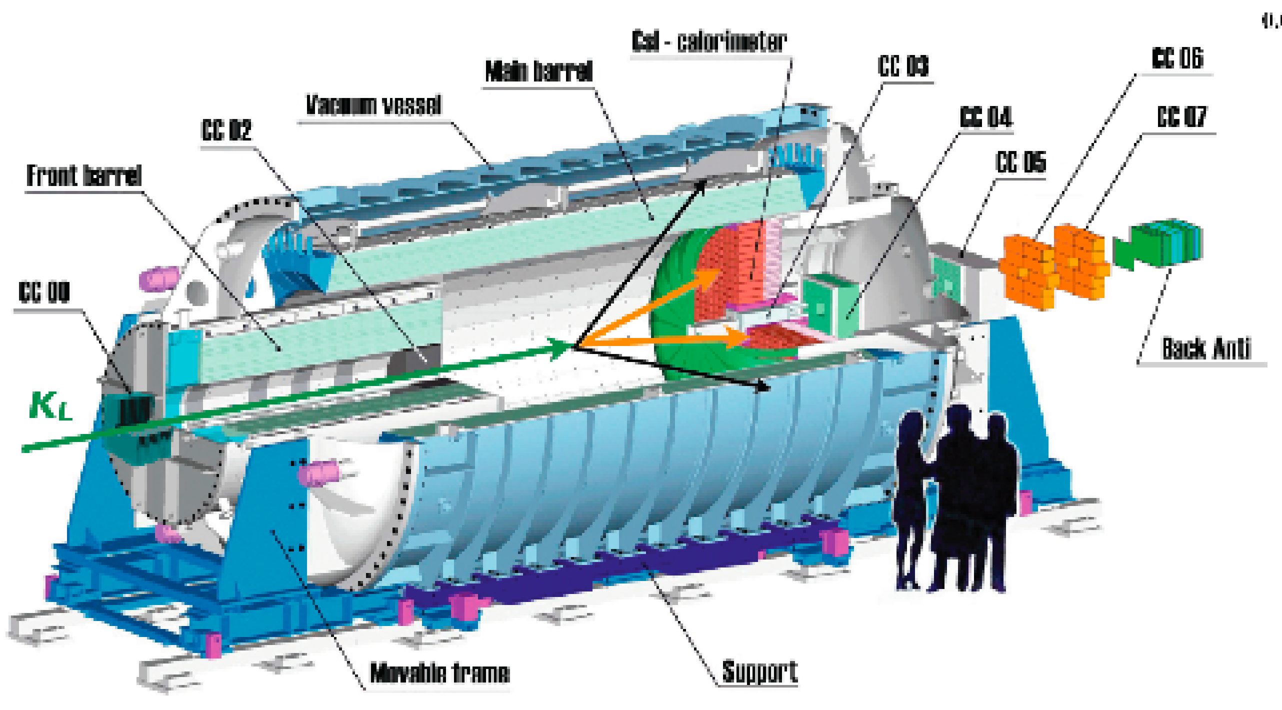


KTeV
Project x??

* Apologies to the Hyperon advocates

KEK E391a

First Dedicated $K_L \rightarrow \pi^0 \nu\nu$ Experiment



Future E14 at J-PARC

I. New Results on CP/CPT Violation (and associated parameters)

KTeV: Epsilon Prime

E391a: $K_L \rightarrow \pi^0 \nu\nu$

Final KTeV Measurement of ε′/ε
(1996, 1997 and 1999 Data Sets)

KTeV

$K_L \sim K_{odd} + \varepsilon K_{even}$

"Direct" in decay process ε'

"Indirect" from asymmetric $K^0 - \overline{K}^0$ mixing

$\pi\pi$

To distinguish between direct and indirect CP violation, compare $K_{L,S} \to \pi^+\pi^-, \pi^0\pi^0$:

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

$\varepsilon'/\varepsilon \neq 0$ ➡ **direct CP violation**

$$K^0 \to \pi^+\pi^- \neq \overline{K}^0 \to \pi^+\pi^-$$

Backgrounds and event yields

KTeV

Main classes of background:

- **Misidentified kaon decays**
- **For $K \to \pi^+\pi^-$: $K_L \to \pi e \nu$, $K_L \to \pi \mu \nu$**
- **For $K \to \pi^0\pi^0$: $K_L \to \pi^0\pi^0\pi^0$**
- **Scattered $K \to \pi\pi$ events**
- **From regenerator and final collimator**
- **Backgrounds are simulated with MC, normalized to data sidebands, and subtracted**
- **Background level is ~0.1% for charged mode and ~1% for neutral mode.**

After background subtraction:

	K_L Vacuum Beam	"K_S" Reg. Beam
$K \to \pi^+\pi^-$	25,107,242	43,674,208
$K \to \pi^0\pi^0$	5,968,198	10,180,175

Systematic Uncertainties in Re(ε′/ ε)

KTeV

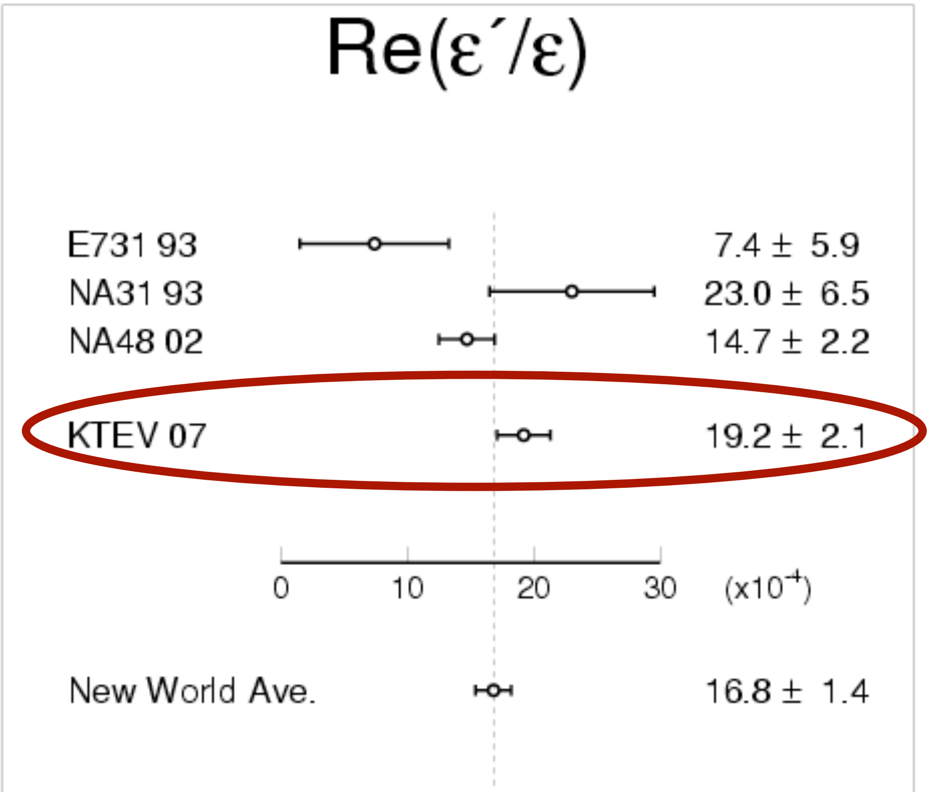
Source	Error on $Re(\epsilon'/\epsilon)$ $(\times 10^{-4})$ $K \to \pi^+\pi^-$	$K \to \pi^0\pi^0$
Trigger	0.23	0.20
CsI cluster reconstruction	—	0.75
Track reconstruction	0.22	—
Selection efficiency	0.23	0.34
Apertures	0.30	0.48
Acceptance	0.57	0.48
Backgrounds	0.20	1.07
MC statistics	0.20	0.25
Total	0.81	1.55
Fitting	0.31	
Total	1.78	

Reduced from 1.47

New KTeV Result:

KTeV

$$\text{Re}(\varepsilon'/\varepsilon) = [19.2 \pm 1.1(\text{stat}) \pm 1.8(\text{syst})] \times 10^{-4}$$
$$= (19.2 \pm 2.1) \times 10^{-4}$$



World average:

$$\text{Re}(\varepsilon'/\varepsilon) = (16.8 \pm 1.4) \times 10^{-4}$$

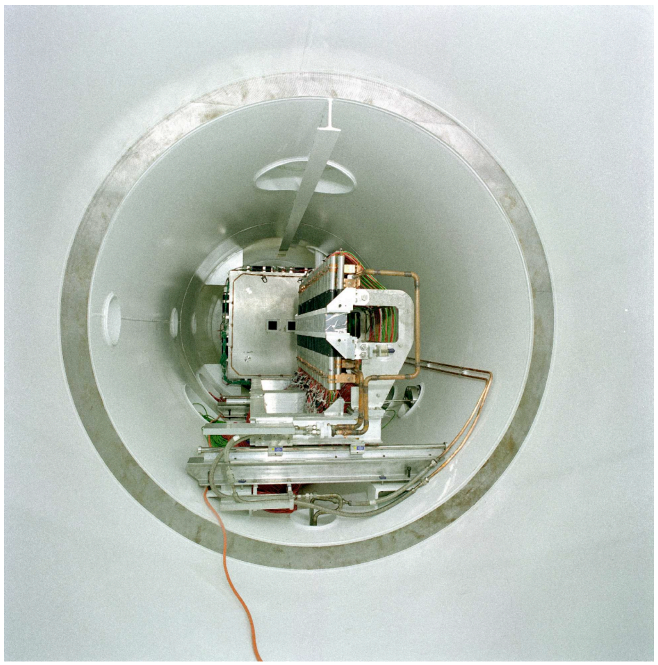
(confidence level = 13%)

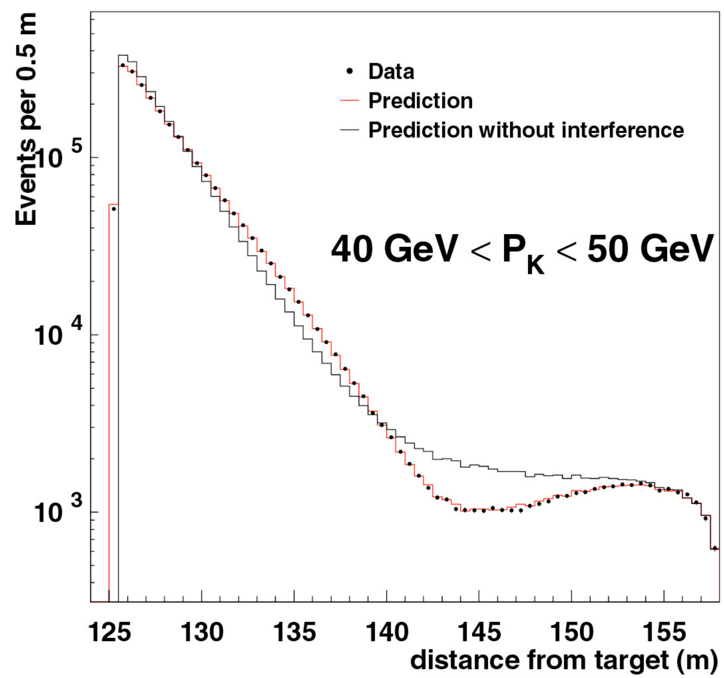
(KTeV 2003: $\text{Re}(\varepsilon'/\varepsilon) = [20.7 \pm 1.5(\text{stat}) \pm 2.4\ (\text{syst})] \times 10^{-4}$)

Other Neutral Kaon Decay Parameters

KTeV

K_L - K_S Interference Downstream of Regenerator





Regenerator Vertex Z distribution

$$R_{\pi\pi} \propto |\eta|^2 e^{-\Gamma_L t} + |\rho|^2 e^{-\Gamma_S t} + 2|\eta||\rho| e^{-(\Gamma_S + \Gamma_L)t/2} \cos(\Delta m t + \Phi_\rho - \Phi_\eta)$$

Fitting Strategy for z Decay Distribution

KTeV

- In contrast with Re(ε′/ε) fit, in which a single ~50 m z bin is considered, the regenerator beam data is fitter in 2 m z bins.
- Float $\Delta m = m_L - m_S$, τ_S, ϕ_ε, Re(ε′/ε), Im(ε′/ε) with no CPT assumption.
- CPT constraint ($\phi_\varepsilon = \phi_{SW}$ and Im(ε′/ε)=0) then applied *a posteriori* to find best values τ_s, Δm.

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

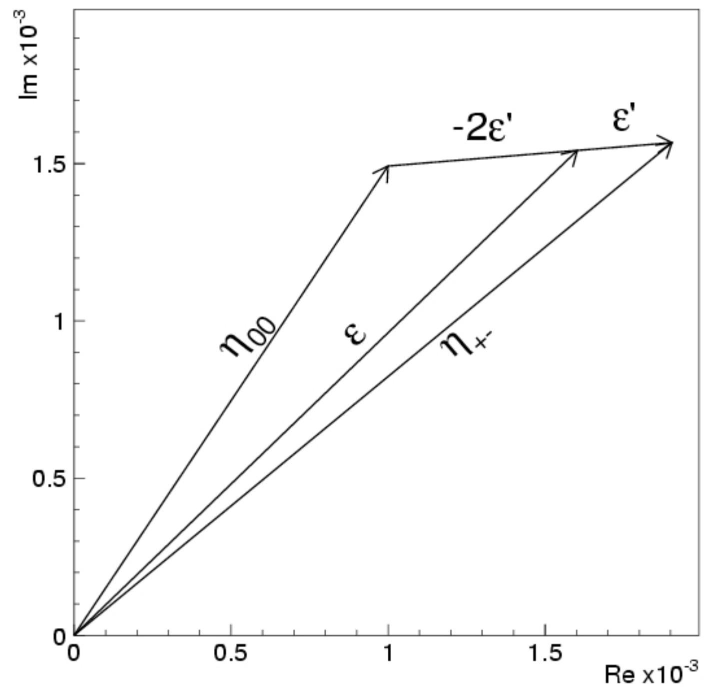
$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \varepsilon - 2\varepsilon'$$

$$\phi_{SW} = \tan^{-1}\left(\frac{2\Delta m}{\Delta\Gamma}\right)$$

$$\phi_{+-} \approx \phi_\varepsilon + \mathrm{Im}(\varepsilon'/\varepsilon)$$

$$\phi_{00} \approx \phi_\varepsilon - 2\,\mathrm{Im}(\varepsilon'/\varepsilon)$$

$$\Delta\phi \equiv \phi_{00} - \phi_{+-} \approx -3\,\mathrm{Im}(\varepsilon'/\varepsilon)$$



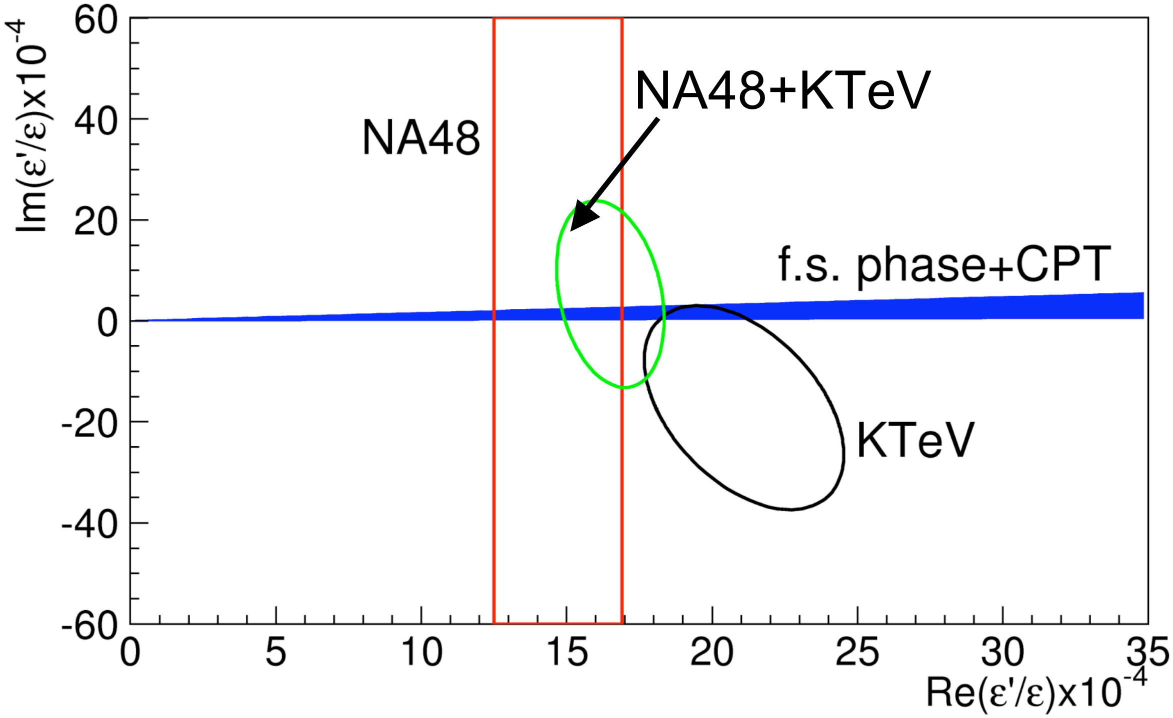
Z Distribution Fit Results

KTeV

$\phi_\varepsilon = (43.86 \pm 0.63)°$

$\phi_\varepsilon - \phi_{SW} = (0.40 \pm 0.56)°$

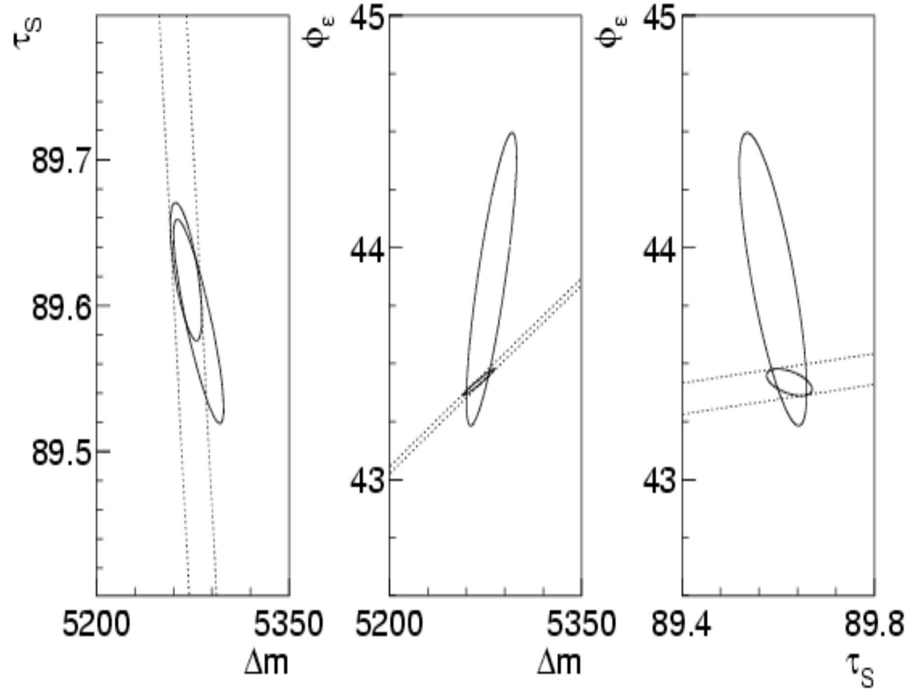
$\Delta\phi = (0.30 \pm 0.35)°$



All results consistent with CPT symmetry

Z Distribution Fit Results (cont)

KTeV



No CPT constraint:

$\Delta m = (5279.7 \pm 19.5) \times 10^{6}\ \hbar s^{-1}$

$\tau_S = (89.589 \pm 0.070) \times 10^{-12}$ s

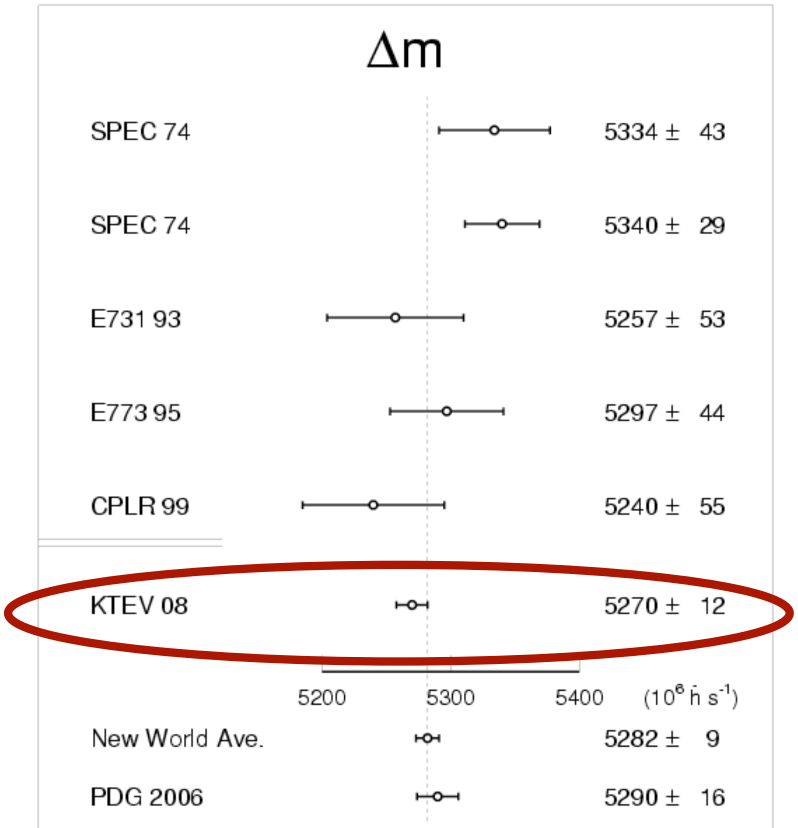
CPT constraint applied:

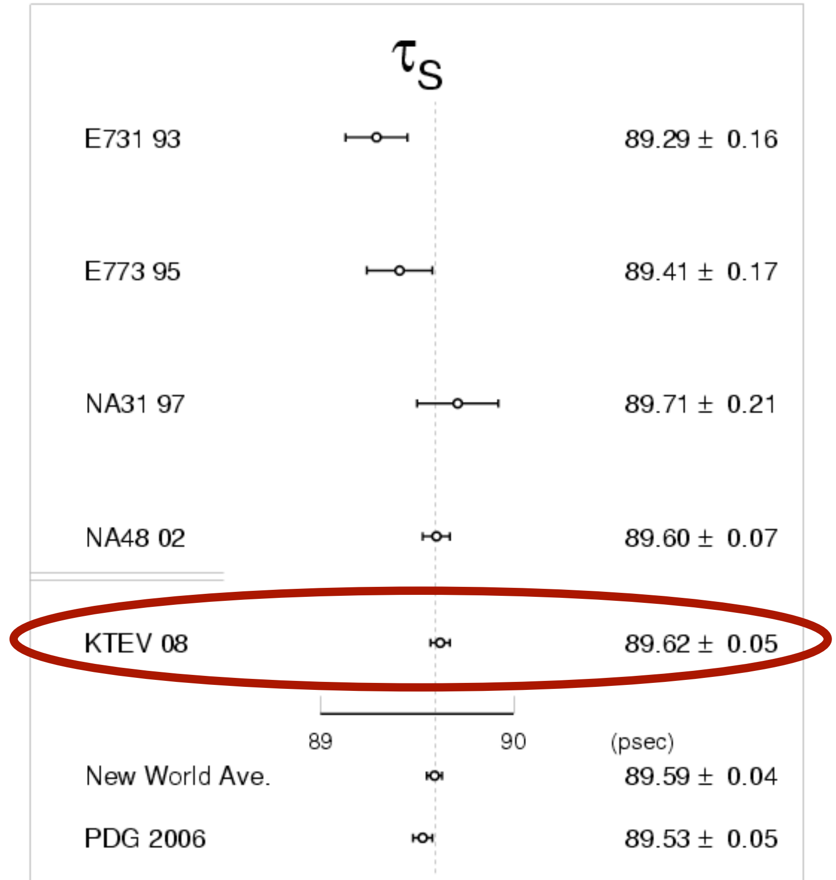
$\Delta m = (5269.9 \pm 12.3) \times 10^{6}\ \hbar s^{-1}$

$\tau_S = (89.623 \pm 0.047) \times 10^{-12}$ s

Δm and τ_S

KTeV





KTeV 2003: $\Delta m = (5261 \pm 13) \times 10^6\ \hbar s^{-1}$

KTeV 2003: $\tau_S = (89.65 \pm 0.07) \times 10^{-12}$ s

Summary of KTeV Results from Total Data (Preliminary)

KTeV

$$\frac{Rate(K^0 \to \pi^+\pi^-) - Rate(\bar{K}^0 \to \pi^+\pi^-)}{Rate(K^0 \to \pi^+\pi^-) + Rate(\bar{K}^0 \to \pi^+\pi^-)} = (5.5 \pm 0.5) \times 10^{-5}$$

Assuming CPT:

- $Re(\varepsilon'/\varepsilon) = (19.2 \pm 2.1) \times 10^{-4}$
- $\Delta m = (5269.9 \pm 12.3) \times 10^{6}\ \hbar s^{-1}$
- $\tau_S = (89.623 \pm 0.047) \times 10^{-12}$ s

No CPT assumption:

- $\phi_\varepsilon = (43.86 \pm 0.63)°$
- $\phi_\varepsilon - \phi_{SW} = (0.40 \pm 0.56)°$
- $\Delta\phi = (0.30 \pm 0.35)°$

Phases ϕ_{+-}, ϕ_{00} dominate uncertainty in unitarity fit in PDG

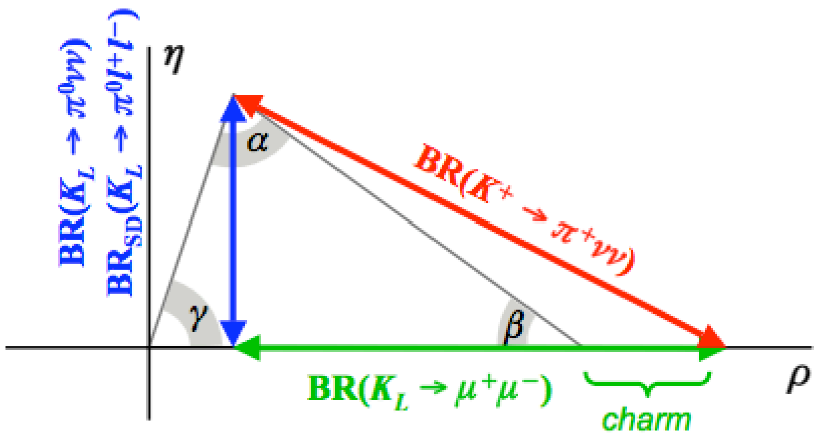
Future lattice calculations may allow precise tests of the S\MI.

All measurements consistent with CPT symmetry

Importance of $K_L \to \pi^0 \nu\nu$

E391a

One of a number of Golden Decays
Measures η (height of CKM Triangle) directly



	Γ_{SD}/Γ	Irreducible theory err. (amp)	SM BR
$K_L \to \pi^0 \nu\nu$	>99%	1%	3×10^{-11}
$K^+ \to \pi^+ \nu\nu$	88%	3%	8×10^{-11}
$K_L \to \pi^0 e^+ e^-$	38%	15%	3.5×10^{-11}
$K_L \to \pi^0 \mu^+ \mu^-$	28%	30%	1.5×10^{-11}

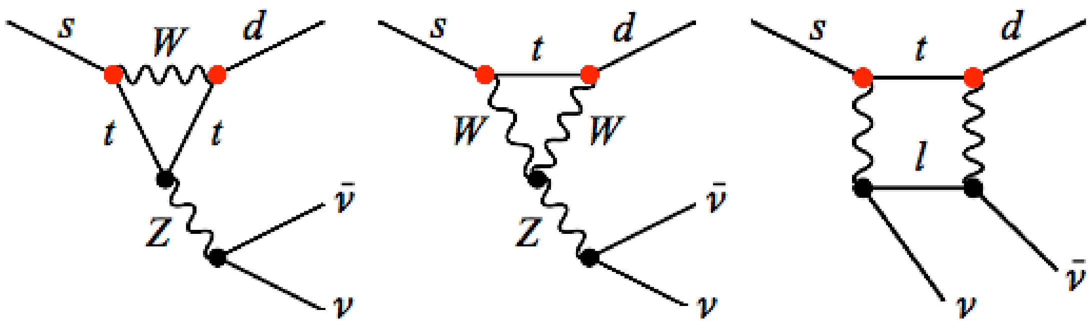
FCNC processes dominated by Z-penguin and box diagrams

Give direct information on CKM matrix elements:

- No LD contributions from processes with intermediate γs
- Hadronic matrix elements can be obtained from BRs for leading K decays
- $K_L \to \pi^0 \nu\nu$ is nearly pure direct CP violating

Theoretical Framework for $K_L \rightarrow \pi^0 \nu\nu$

E391a



$$\lambda = V_{us} \qquad \lambda_c = V_{cs}^* V_{cd} \qquad \lambda_t = V_{ts}^* V_{td}$$

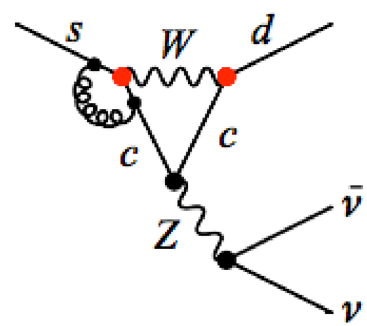
$$x_q = m_q^2 / m_W^2$$

Loop functions favor top contribution

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5} X(x_t) + \frac{\mathrm{Re}\,\lambda_c}{\lambda} P_c(X) \right)^2 \right]$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 \leftarrow \not{C}\!\!\not{P}$$

QCD corrections for charm diagrams contribute to uncertainty



Hadronic matrix element obtained from $\mathrm{BR}(K_{e3})$ via isospin rotation

$$\kappa_+ = r_{K^+} \frac{3\alpha^2\, \mathrm{BR}(K^- \to \pi^0 e^+ \nu)}{2\pi^2 \sin^4\theta_W} \lambda^8$$

E391a
KTEV

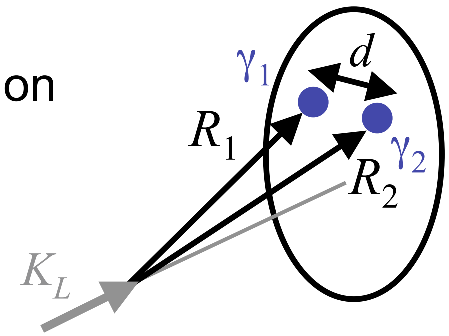
$K_L \to \pi^0\nu\nu$ searches

Essential signature: "2γ + nothing"

All other decays have 2 extra γ or 2 tracks except $K_L \to \gamma\gamma$
(not a big problem since $p_\perp = 0$, $\phi_{12} = 180°$)

Main backgrounds:

- $K_L \to \pi^0\pi^0$ **with 2 lost γ** ➡ Hermetic veto, including beam exit
- n **+ gas** $\to X\pi^0, X\eta$ ➡ High vacuum decay region



$$m_{\pi^0}^2 = 2E_1E_2\,(1-\cos\theta)$$

$$R_1 \approx R_2 \equiv R = \frac{d\sqrt{E_1E_2}}{m_{\pi^0}}$$

$M(\gamma\gamma) = m_{\pi 0}$ **is the only sharp kinematic constraint**

Generally used to reconstruct vertex position

Additional topological constraints advantageous:

- Small beam cross section
- Measurement of photon directions
- Microbunched beam for TOF constraints

Veto system performance & experiment design are paramount

KEK 391a New Result for BR($K_L \to \pi^0 \nu\nu$)

E391a

Neutral secondary beam from KEK PS

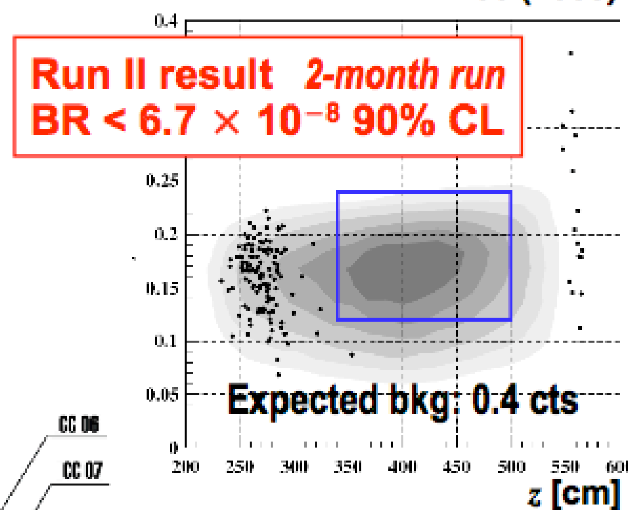
Pb and Be filters to screen γ, n

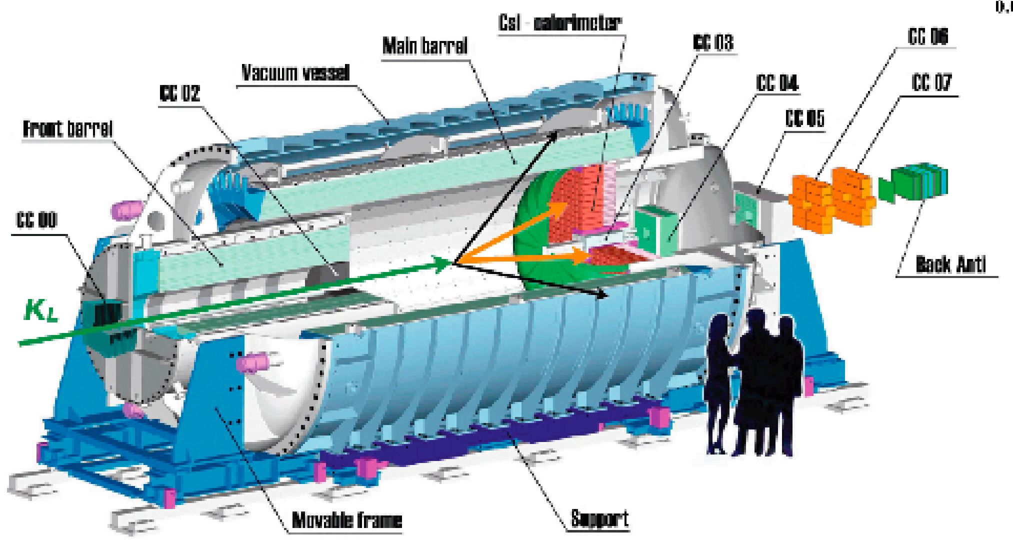
Peak K_L momentum 2 GeV at detector

Collimated to "pencil beam"

- Geometric constraint for π^0 vertexing
- Halo suppressed to 10^{-4} at r = 4 cm

PRL100 (2008)





Forward photon veto
- Pure CsI crystals
- $7 \times 7 \times 30\ cm^3$

Vacuum decay volume
- 10^{-7} mbar

Summary of All Results for upper limits for BR($K_L \rightarrow \pi^0 \nu\nu$)

E391a

E391* < $6.7\mathrm{x}10^{-8}$
KTeV < $5.9\mathrm{x}10^{-7}$**
KTeV < $1.6\mathrm{x}10^{-6}$

SM Prediction

Mescia, Smith '07
Update at http://www.lnf.infn.it/wg/vus

$$BR(K_L \to \pi^0 \nu\nu) = 2.76 \pm 0.40 \times 10^{-11}$$

* Will be upgraded by addition of CsI from KTeV and moved to J-Parc as E-14
** Required a Dalitz pair from one of the π^0 photons

II. Lepton Flavor Violation/NP

KTeV: $K_L \rightarrow \pi^0 \mu e$

$K_L \rightarrow \pi^0 \pi^0 \mu e$

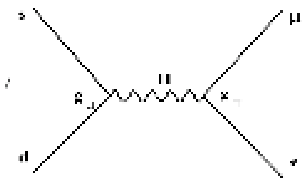
$\pi^0 \rightarrow \mu e$

Lepton Flavor Violation in K Decays In KTeV

KTeV

Searches motivation: tests for tree-level LFV amplitudes possible in Technicolor, SUSY, …

E.g., horizontal bosons in extended TC: $M_H \approx 85 \text{ TeV} \left[\frac{10^{-11}}{B(K^+ \to \pi^+ \mu^+ e)}\right]^{1/4}$



- **Look for two charged tracks in detector:**
  - **One muon**
    - **Track must match hits in the muon hodoscopes**
  - **One electron**
    - **Track momentum = cluster energy in CsI**
    - **TRD info is consistent with an electron**
- **Allows searches for:**
  - $K_L \to \pi^0 \mu e$
  - $K_L \to \pi^0 \pi^0 \mu e$
  - $\pi^0 \to \mu e$

LFV: $K_L \rightarrow \pi^0 \mu e$

KTeV

- **Highest background out of our trio of LFV decays**
  - **Ke3/Ke4 + π decay or π punch through to muon hodoscopes = fake signal**
    - **Make tight cut on accidental activity in detector**
    - **Apply cut on calculated $|p_\nu|$ assuming Ke4 decay**
      - **Real Ke4 events produce positive values**
      - **Other events produce negative (non-physical) values**

- **Sum of MC background estimates:**

  4.21 +/- 0.53 in control region

  –contains 99% of signal

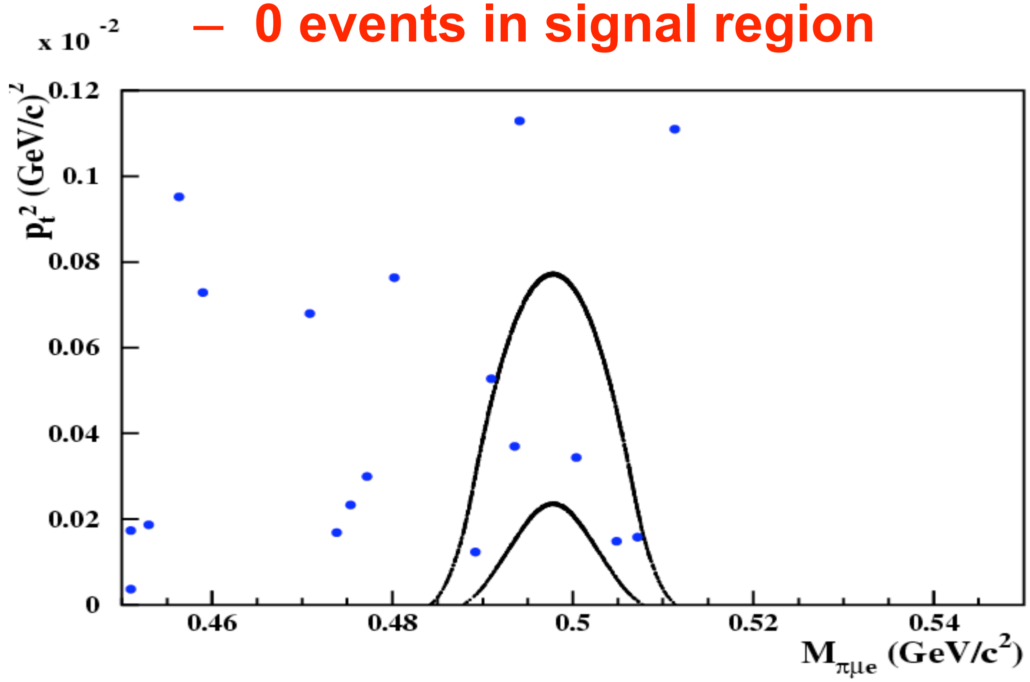
  0.66 +/- 0.23 in signal region

  –contains 95% of signal

LFV: $K_L \rightarrow \pi^0 \mu e$

KTeV

- **1997 plus 1999 Data after all cuts:**
  - **5 events in control region**
  - **0 events in signal region**



Resulting limit: $Br(K_L \rightarrow \pi^0 \mu e) < 7.56 \times 10^{-11}$ (90% C.L.)

Factor of 83 lower than previous limit

LFV: $K_L \to \pi^0\pi^0\mu e$

KTeV

- Extend $K_L \to \pi^0\mu e$ search
- Attempt to reconstruct 2^{nd} π^0
  - Slashes backgrounds
  - Offset by relaxing cuts to improve sensitivity
    - Remove tight cuts on accidental activity
    - Remove cuts on TRD information for electron track
- Largest background from $K_L \to \pi^0\pi^0\pi^0_D$
  - Need a bad electron cluster in CsI combined with an accidental muon in the muon hodoscope
  - Apply VERY loose TRD cut on muon track

LFV: $K_L \to \pi^0 \pi^0 \mu e$

KTeV

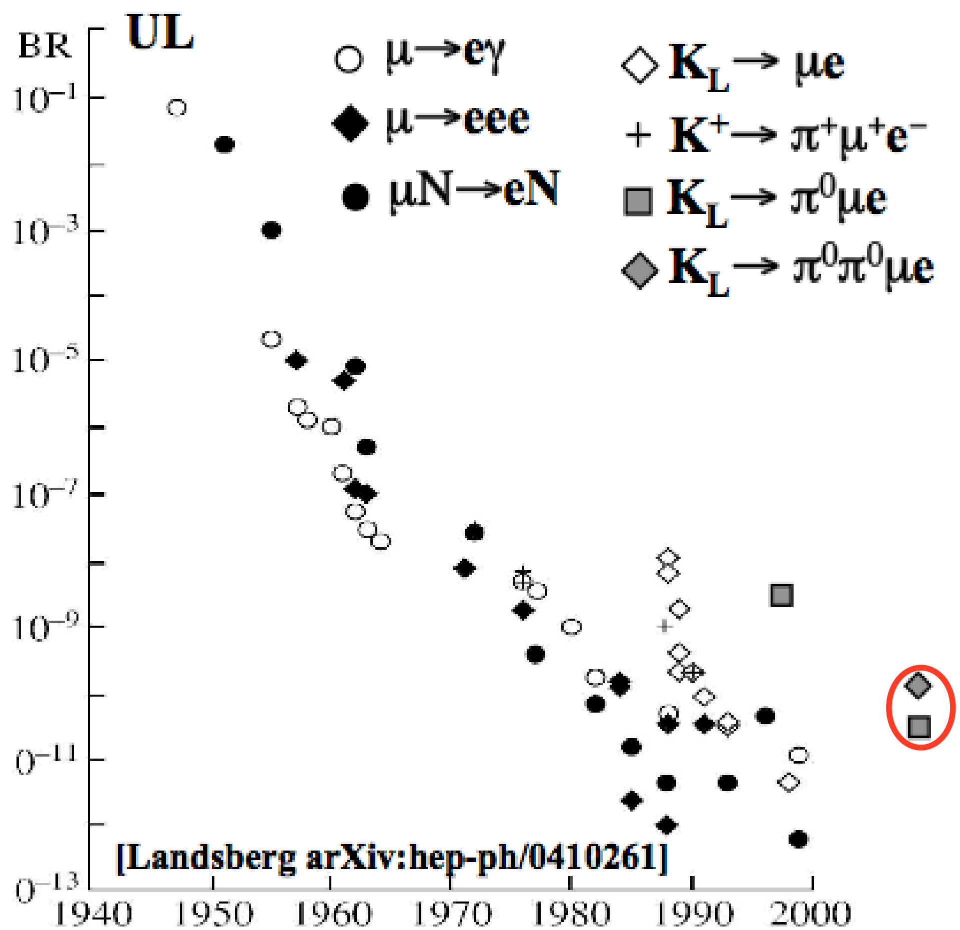
- Expect 0.44 +/- 0.23 events in signal region
- Observe no events in signal region
- Resulting limit: $Br(K_L \to \pi^0 \pi^0 \mu e) < 1.7 \times 10^{-10}$ (90% CL)
  - First reported limit on this decay mode

LFV: $\pi^0 \to \mu e$

- Analysis can be extended by placing an extra constraint:
  - $M_{\mu e}$ reconstructs near $M_{\pi 0}$
- Resulting limit: $Br(\pi^0 \to \mu e) < 3.59 \times 10^{-10}$ (90% CL)
- Limit 10x(2x) lower than previous best limit on $\pi^0 \to \mu^- e^+ (\mu^+ e^-)$)
- Equally sensitive to both charge modes

Lepton Flavor Violation Summary

KTeV



III. NP and Lepton Flavor Universality

KLOE
NA48
KTeV
ISRA+

NP and Lepton Universality in K Decays

KLOE
NA48
KTeV
ISRA+

In SM, electron and muon differs only by mass and coupling to Higgs

Can measure ratio of coupling constants, seeking deviations from prediction in processes well determined in SM, like:

$R_{e\mu} = \Gamma(K_{e3})/\Gamma(K_{\mu 3}) \rightarrow G_F^{\,e}/G_F^{\,\mu}$,

Test of lepton universality for weak vector currents

$R_{K\pi} = \Gamma(K \rightarrow \mu\nu)/\Gamma(\pi \rightarrow \mu\nu)$,

Test for H^+ exchange (scalar) or presence of right-handed currents

$R_K = \Gamma(K \rightarrow e\nu)/\Gamma(K \rightarrow \mu\nu)$

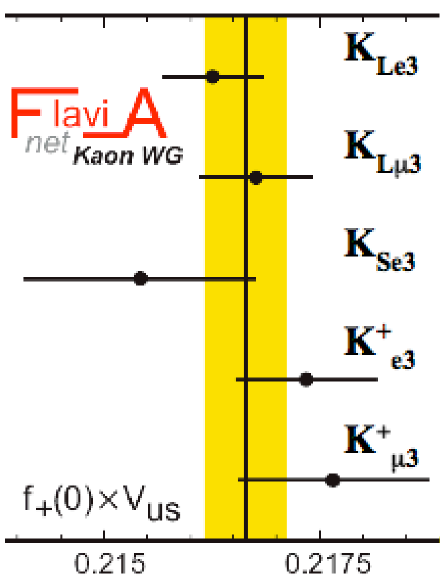
Test for LFV due to effective pseudoscalar weak currents

NP from K_{l3} Branching Ratios

KLOE
NA48
KTeV
ISRA+

World data for K_{l3} BR are in good shape due to Kloe, NA48, KTeV and ISTRA+

From: $$\Gamma(K_{\ell 3(\gamma)}) = \frac{G_F^2 m_K^5}{192\pi^3} C_K S_{\rm ew} |V_{us}|^2 f_+(0)^2 I_K^\ell(\lambda_{+,0}) \left(1 + \delta^K_{SU(2)} + \delta^{K\ell}_{\rm em}\right)^2$$



	$f_+(0) \times \|V_{us}\|$	Error,%	Contributions to % error BR	τ	Δ	I^l_K
K_{Le3}	0.2163(6)	0.28	0.09	0.19	0.15	0.09
$K_{L\mu3}$	0.2168(7)	0.31	0.10	0.18	0.15	0.15
K_{Se3}	0.2154(13)	0.67	0.65	0.03	0.15	0.09
K^+_{e3}	0.2173(8)	0.39	0.26	0.09	0.26	0.09
$K^+_{\mu3}$	0.2176(11)	0.51	0.40	0.09	0.26	0.15
	0.2166(5)	0.22	$P(\chi^2/ndf) = 58\%$			

NP Results in $R_{e\mu}$ from K_{l3}

KLOE
NA48
KTeV
ISRA+

$$\frac{\Gamma_{\mu 3}}{\Gamma_{e3}} \cdot \frac{I_{e3}\,(1+\delta_{e3})}{I_{\mu 3}\,(1+\delta_{\mu 3})} = \frac{[|V_{us}|\, f_+(0)]^2_{\mu 3,\,\mathrm{obs}}}{[|V_{us}|\, f_+(0)]^2_{e3,\,\mathrm{obs}}} = \frac{g_\mu^2}{g_e^2}$$

Result: e/μ universality satisfied:

K_L	$g_\mu^2/g_e^2 = 1.0049(61)$	cfr with	$g_\mu^2/g_e^2 = 1.054(15)$ [PDG04]
K^+	$g_\mu^2/g_e^2 = 1.0029(86)$	cfr with	$g_\mu^2/g_e^2 = 1.019(13)$ [PDG04]
Avg	$g_\mu^2/g_e^2 = 1.0043(52)$		

Compare with test sharing the same theoretical scenario, $\tau \to l\nu\nu$ decays:

$\tau \to l\nu\nu$ $\quad g_\mu^2/g_e^2 = 0.9998(40)$ [PDG07]

Precision from K's comparable with that from τ's

NP effects in K_{l2} vs π_{l2} Decays

KLOE

In two Higgs doublet models (MSSM, too), exchange of H^+ provides an additional scalar current, which might contribute sizeably wrt to SM:

$$\frac{\Gamma(\boldsymbol{K}\to\ell\nu)}{\Gamma_{SM}(\boldsymbol{K}\to\ell\nu)} \simeq \left|1-\frac{m_{K^+}^2}{M_{H^+}^2}\left(1-\frac{m_d}{m_s}\right)\frac{\tan^2\beta}{1+\epsilon_0\tan\beta}\right|$$

[Hou PRD48 (1992) 2342, Isidori-Paradisi]

NP effect is suppressed for π_{l2} wrt K_{l2}, so NP might appear in $Kl2$ / $\pi l2$, predicted in the SM to be:

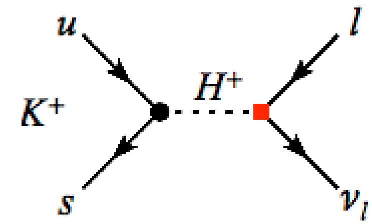
$$\frac{\Gamma(K^{\pm}_{\ell 2(\gamma)})}{\Gamma(\pi^{\pm}_{\ell 2(\gamma)})} = \left|\frac{V_{us}}{V_{ud}}\right|^2 \frac{f_K^2 m_K}{f_\pi^2 m_\pi}\left(\frac{1-m_\ell^2/m_K^2}{1-m_\ell^2/m_\pi^2}\right)^2 \times (1+\delta_{\rm em})$$

NP test from comparing V_{us}/V_{ud} from $M\to l\nu$ with $V_{us}(K_{l3})/V_{ud}(0^+\to 0^+)$:

$$\left|\frac{V_{us}(K_{\ell 2})}{V_{us}(K_{\ell 3})}\times\frac{V_{ud}(0^+\to 0^+)}{V_{ud}(\pi_{\ell 2})}\right| \stackrel{?}{=} \left|1-\frac{m_{K^+}^2}{M_{H^+}^2}\left(1-\frac{m_d}{m_s}\right)\frac{\tan^2\beta}{1+\epsilon_0\tan\beta}\right|$$

NP Results for R $_{K\pi} = \Gamma(K \to \mu\nu)/\Gamma(\pi \to \mu\nu)$

KLOE

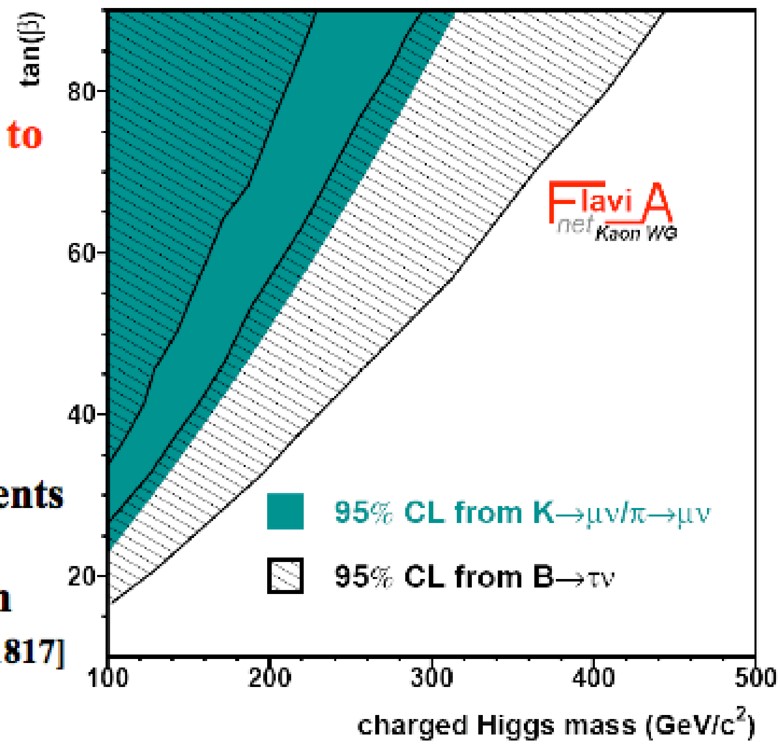


Result is: $\left| \frac{V_{us}(K_{\ell 2})}{V_{us}(K_{\ell 3})} \times \frac{V_{ud}(0^+ \to 0^+)}{V_{ud}(\pi_{\ell 2})} \right| = 1.0018(57)$

NP sensitivity from K→ μν comparable to that from BR(B → τν) = 1.42(44)×10^{-4}
[Babar-Belle average]

Error dominated by theoretical uncertainties in form factors

NP induced by weak right-handed currents can be also tested (there, complement lattice information with Callan-Treiman scalar ff constraint) [FlaviaNet arXiv:0801.1817]



NP in $R_K = \Gamma(Ke2)/\Gamma(K\mu 2)$

KLOE
NA48
NA62

SM prediction w 0.04% precision, benefits of cancellation of hadronic uncertainties (no f_K): $R_K = 2.477(1) \times 10^{-5}$ [Cirigliano Rosell arXiv:0707:4464]

Helicity suppression can boost NP [Masiero-Paradisi-Petronzio PRD74 (2006) 011701]

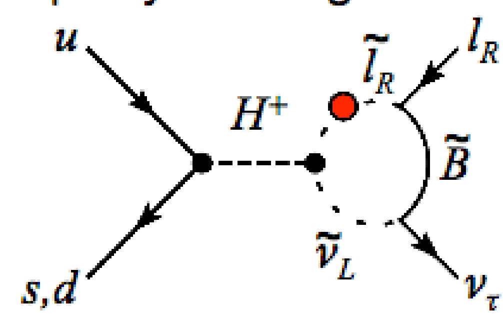
In R-parity MSSM, LFV can give 1% deviations from SM:

$$R_K^{LFV} \simeq R_K^{SM}\left[1 + \left(\frac{m_K^4}{M_H^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right)|\Delta_R^{31}|^2 \tan^6\beta\right]$$

NP dominated by contribution of $e\nu_\tau$ final state, with effective coupling

$$l H^\pm \nu_\tau \rightarrow \frac{g_2}{\sqrt{2}}\frac{m_\tau}{M_W}\Delta_{13}$$ **, from loop**

R-parity violating MSSM



Present exp. accuracy on R_K @ 6%

New measurement of R_K can be very interesting, if error is pushed @1% or better

NP Results for $R_K = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$

Kloe
NA48
NA62

KLOE

- preliminary result with 2001—5 data: $R_K = 2.55\ (5)_{stat}\ (5)_{syst}\ 10^{-5}$, from ~ 8000 Ke2 candidates (3% accuracy), perspectives to reach 1% error after analysis completion

NA48/2

- preliminary result with 2003 data: $R_K = 2.416\ (43)_{stat}\ (24)_{syst}\ 10^{-5}$, from ~ 4000 Ke2 candidates, statistical error dominating (2% accuracy)
- preliminary result with 2004 data: $R_K = 2.455\ (45)_{stat}\ (41)_{syst}\ 10^{-5}$, from ~ 4000 Ke2 candidates from special minimum bias run (3% accuracy)

NA62 (ex NA48)

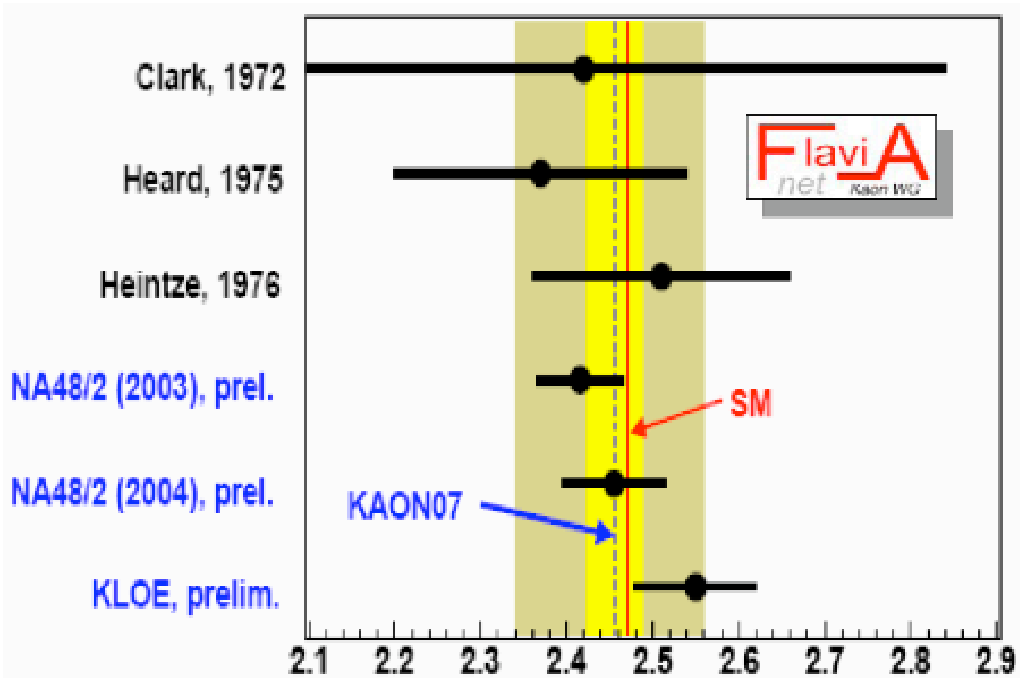
- collected ~ 100,000 Ke2 events in dedicated 2007 run, aims at breaking the 1% precision wall, possibly reaching $< \sim 0.5\%$

Summary of R_K measurements

KLOE
NA48
NA62

Recent (preliminary) results improved greatly with respect to 2006 PDG

World average, $R_K = 2.457(32)\times10^{-5}$, agrees with SM



R_K (10^{-5})

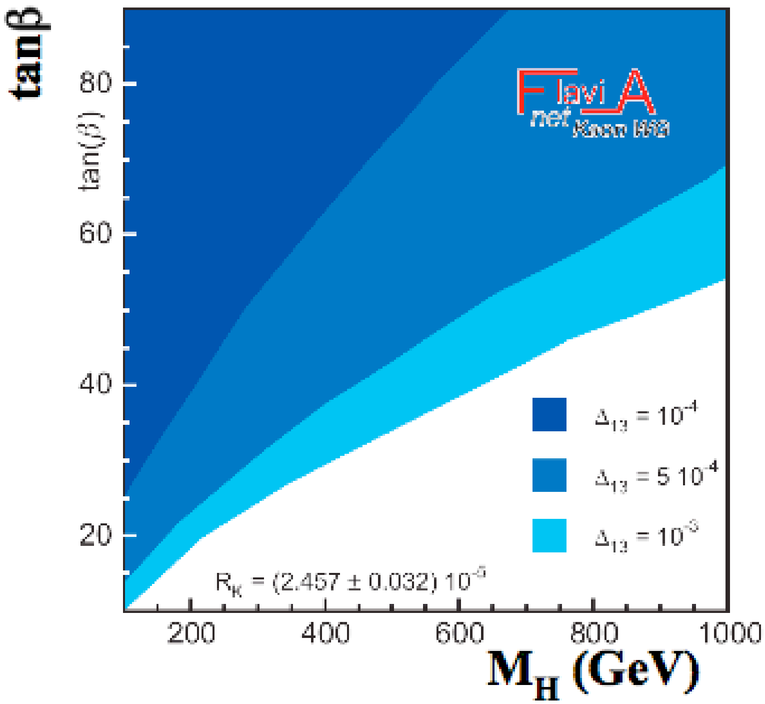
R_K Exclusion Regions for Higgs

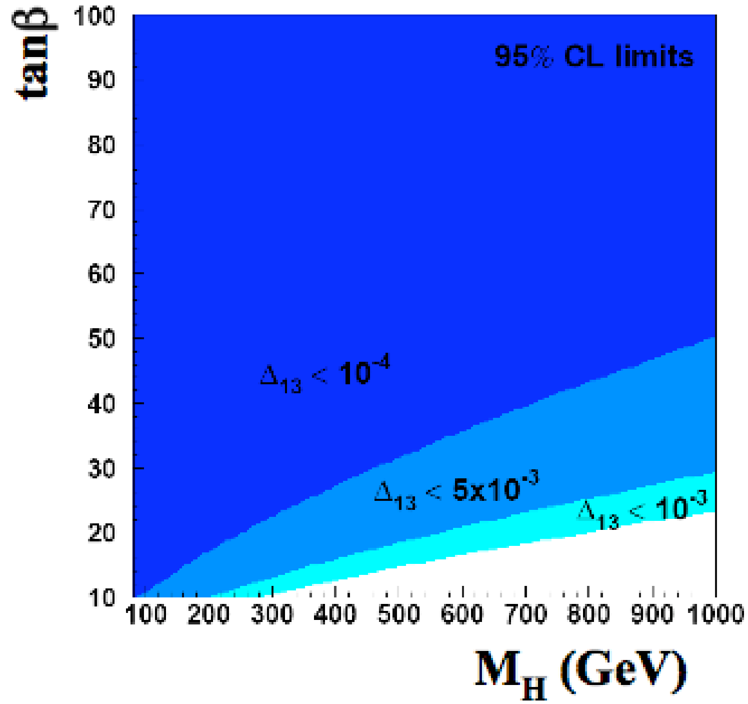
Kloe
NA48
NA62

Sensitivity shown as 95%-CL excluded regions in the tanβ - M_H plane, for fixed values of the 1-3 slepton-mass matrix element, $\Delta_{13} = 10^{-3}, 0.5\times10^{-3}, 10^{-4}$

Present world avg: $R_K = 2.457(32)\times10^{-5}$

Perspective: same R_K, $\delta R_K = 0.3\%$





IV. CKM Unitarity

KLOE
KTeV
NA48

In 2004 it was realized that the PDG branching ratios that had been used for decades to calculate V_{us} and the first row unitarity of the CKM matrix were flawed. A large effort by the these three experiments was mounted to remeasure the various K branching ratios and form factors and by the Flavia group to bring together the information to redo V_{us}.

The saga continues

Quantities for CKM Unitarity Check

KLOE
KTeV
NA48
ISTRA+

$|V_{us}| \times f_+(0)$

$$\Gamma(K_{\ell 3(\gamma)}) = \frac{G_F^2 m_K^5}{192\pi^3} C_K S_{ew} |V_{us}|^2 f_+(0)^2 I_K^\ell(\lambda_{+,0}) \left(1 + \delta_{SU(2)}^K + \delta_{em}^{K\ell}\right)^2$$

$|V_{us}|/|V_{ud}| \times f_K/f_\pi$.

$$\frac{\Gamma(K^\pm_{\ell 2(\gamma)})}{\Gamma(\pi^\pm_{\ell 2(\gamma)})} = \left|\frac{V_{us}}{V_{ud}}\right|^2 \frac{f_K^2 m_K}{f_\pi^2 m_\pi} \left(\frac{1 - m_\ell^2/m_K^2}{1 - m_\ell^2/m_\pi^2}\right)^2 \times (1 + \delta_{em})$$

Obtained from global fits and averages of dominant K_L, K_S, and $K^\pm$ BRs and lifetime and parameterization of the $K \rightarrow \pi$ interaction form factor

Determination of $|V_{us}| \times f_+(0)$

KLOE
KTeV
NA48
ISTRA+

$$\Gamma(K_{l3(\gamma)}) = \frac{C_K^2 G_F^2 M_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f_+^{K^0\pi^-}(0)|^2 I_{K\ell}(\lambda_{+,0}) (1+\delta^K_{SU(2)}+\delta^{K\ell}_{em})^2$$

with $K = K^+, K^0$; $\ell = e, \mu$ and $C_K^2 = 1/2$ for K^+, 1 for K^0

Inputs from theory:

S_{EW} Universal short distance EW correction (1.0232)

$\delta^K_{SU(2)}$ Form factor correction for strong SU(2) breaking

$\delta^{K\ell}_{em}$ Long distance EM effects

$f_+^{K^0\pi^-}(0)$ Form factor at zero momentum transfer (t=0)

Callan-Treiman

Inputs from experiment:

$\Gamma(K_{l3(\gamma)})$ **Branching ratios** properly inclusive of radiative effects; **lifetimes**

$I_{K\ell}(\lambda)$ Phase space integral: λ's parameterize form factor dependence on t :

K_{e3}: only λ_+

$K_{\mu 3}$: need λ_+ and λ_0

K_L leading branching ratios and τ_L

KLOE
KTeV
NA48

18 input measurements:

5 KTeV ratios
NA48 K_{e3}/2tr and $\Gamma(3\pi^0)$
4 KLOE BRs
KLOE, **NA48** $\pi^+\pi^-/K_{l3}$
KLOE, **NA48** $\gamma\gamma/3\pi^0$
PDG ETAFIT for $\pi^+\pi^-/\pi^0\pi^0$
KLOE τ_L from $3\pi^0$
Vosburgh '72 τ_L

Parameter	Value	S
$BR(K_{e3})$	0.4056(7)	1.1
$BR(K_{\mu3})$	0.2705(7)	1.1
$BR(3\pi^0)$	0.1951(9)	1.2
$BR(\pi^+\pi^-\pi^0)$	0.1254(6)	1.1
$BR(\pi^+\pi^-)$	$1.997(7) \times 10^{-3}$	1.1
$BR(2\pi^0)$	$8.64(4) \times 10^{-4}$	1.3
$BR(\gamma\gamma)$	$5.47(4) \times 10^{-4}$	1.1
τ_L	51.17(20) ns	1.1

8 free parameters, 1 constraint: ΣBR=1

Main differences wrt PDG06:

- For KLOE and KTeV, use values obtained before applying constraints.
- Make use of preliminary $BR(3\pi^0)$ and new $BR(\pi^+\pi^-)/BR(Ke3)$ from NA48
- Fit parameter $BR(\pi^+\pi^-)$ is understood to be inclusive of the DE component.

K_S leading branching ratios and τ_S

KLOE
KTeV
NA48

4 input measurements:

KLOE BR(Ke3)/BR($\pi^+\pi^-$)
KLOE BR($\pi^+\pi^-$)/BR($\pi^0\pi^0$)
Universal lepton coupling
NA48 BR(Ke3)
τ_S: non CPT-constrained fit value, dominated by 2002 NA48 and 2003 KTeV measurements

4 free parameters: $K_S\pi\pi$, $K_S\pi^0\pi^0$, K_Se3, $K_S\mu3$, 1 constraint: ΣBR=1

- **KLOE meas. completely determine the leading BR values**.
- NA48 Ke3 input improve the BR(Ke3) accuracy of about 10%.
- BR(K_Se3)/BR(K_Le3) from NA48 not included (need of a K_L and $K_S$combined fit)
- Combined fit would be useful in properly account for preliminary NA48 $\Gamma(K_L \rightarrow 3\pi^0)$ and PDG ETAFIT, used in the K_L fit.

$K^{\pm}$ leading branching ratios and $\tau^{\pm}$

KLOE
NA48
ISTRA+

26 input measurements:

5 older τ values in PDG

2 KLOE τ

KLOE BR(μν)

KLOE *Ke3*, *Kμ3*, and *Kπ2* BRs

ISTRA+ $K_{e3}/\pi\pi^0$

NA48/2 $K_{e3}/\pi\pi^0$, $K_{\mu3}/\pi\pi^0$

E865 K_{e3}/Kdal

3 old $\pi\pi^0/\mu\nu$

2 old *Ke3*/2 body

3 *Kμ3/Ke3* (2 old)

2 old + 1 KLOE results on 3π

7 free parameters,
1 constraint: ΣBR=1

Parameter	Value	S
$\mathrm{BR}(K_{\mu 2})$	63.57(11)%	1.1
$\mathrm{BR}(\pi\pi^0)$	20.64(8)%	1.1
$\mathrm{BR}(\pi\pi\pi)$	5.595(31)%	1.0
$\mathrm{BR}(K_{e3})$	5.078(26)%	1.2
$\mathrm{BR}(K_{\mu 3})$	3.365(27)%	1.7
$\mathrm{BR}(\pi\pi^0\pi^0)$	1.750(26)%	1.1
$\tau_{\pm}$	12.384(19) ns	1.7

Don't use the 6 BR meas. from Chiang;
- no implementation of radiative corrections
- 6 BR constrained to sum to unit.
- the correlation matrix not available.

What about discarding many other old meas.?
- no recent meas. involving BR(**πππ**)
- fit instable if only recent are used.

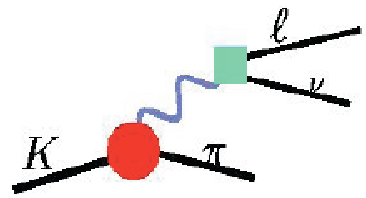
Parameterization of $K_{\ell 3}$ form factors

KLOE
KTeV
NA48
ISTRA+

• Hadronic K→**π** matrix element is described by two form factors $f_+(t)$ and $f_0(t)$ defined by:

$$\langle \pi^-(k)|\bar{s}\gamma^\mu u|K^0(p)\rangle = (p+k)^\mu f_+(t) + (p-k)^\mu f_-(t)$$

$$f_-(t) = \frac{m_K^2 - m_\pi^2}{t}\left(f_0(t) - f_+(t)\right)$$



•Experimental or theoretical inputs to define ***t***-dependence of $f_{+,0}(t)$.

• $f_-(t)$ term negligible for K_{e3}.

•**Taylor expansion**:

$$\tilde{f}_{+,0}(t) \equiv \frac{f_{+,0}(t)}{f_+(0)} = 1 + \lambda'_{+,0}\,\frac{t}{m_\pi^2} + \frac{1}{2}\,\lambda''_{+,0}\left(\frac{t}{m_\pi^2}\right)^2 + \ \ldots .$$

λ′ and **λ′′** are **strongly correlated: –95% for $f_+(t)$, and –99.96% for $f_0(t)$**

•**Pole parameterization**:

$$\tilde{f}_{+,0}(t) = \frac{M_{V,S}^2}{M_{V,S}^2 - t}$$

• **Dispersive approach plus Kπ scattering data for both $f_+(t)$ and $f_0(t)$**

Vector form factor from K_{e3}

KLOE
KTeV
NA48
ISTRA+

Quadratic expansion

- Measurements from ISTRA+, KLOE, KTeV, NA48 with $K_L e3$ and $K^- e3$ decays.
- **Good fit quality: χ^2/ndf=5.3/6(51%) for all data**; χ^2/ndf=4.7/4(32%) for K_L only
- The significance of the quadratic term is 4.2σ from all data and 3.5σ from K_L only.
- Using all data or K_L only changes the space phase integrals I^0_{e3} and $I^{\pm}_{e3}$ by 0.07% .
- Errors on I_{e3} are significantly smaller when K^- data are included.

Pole parameterization is in good agreement with present data:

$$\tilde{f}_+(t) = M_V^2/(M_V^2 - t), \text{ with } M_V \sim 892 \text{ MeV} \quad \lambda' = (m_{\pi+}/M_V)^2;\ \lambda'' = 2\lambda'^2$$

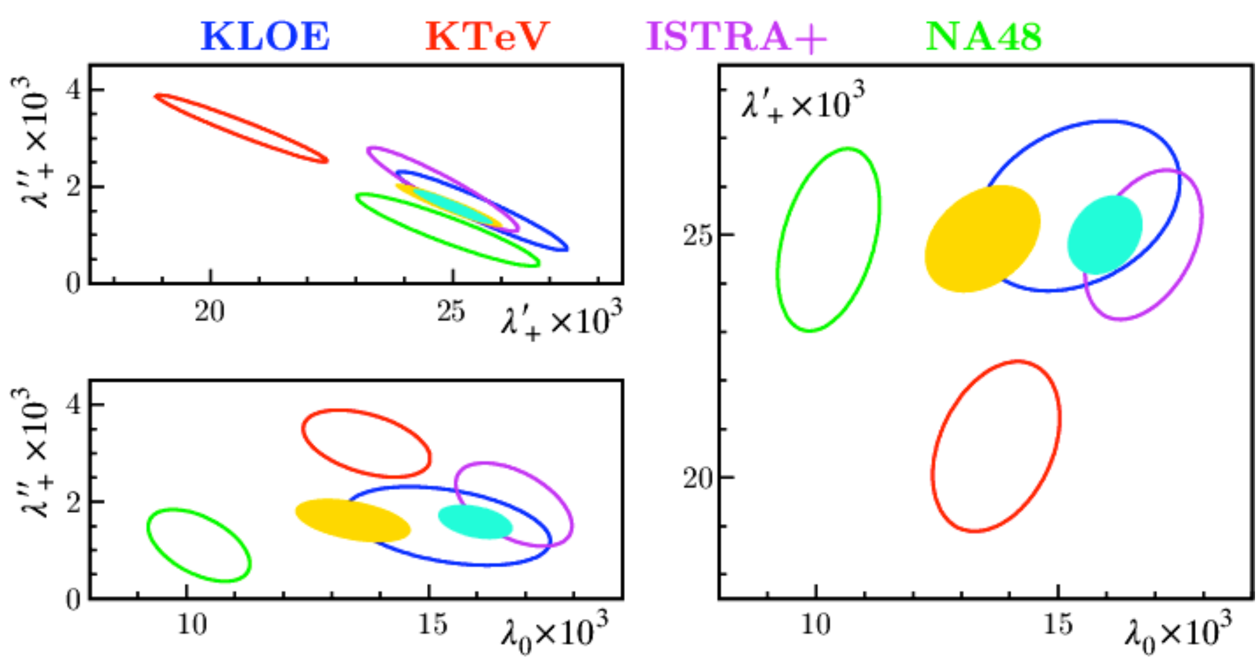
- KLOE, KTeV, NA48 quote value for M_V for pole fit to $K_L e3$ data (χ^2/ndf=1.8/2)
- The values for λ_+' and λ_+'' from pole expansion are in agreement with quadratic fit results.
- Using quadratic averages or pole fit results changes I^0_{e3} by 0.03% .

Dispersive parameterization show improvements for $f_+(t)$, with good analytical and unitarity properties and a correct threshold behavior, (e.g.Passemar arXiv:0709.1235[hep-ph])
Dispersive results for λ_+ and λ_0 are in agreement with pole parameterization.

KLOE
KTeV
NA4
ISTRA+

Vector and scalar form factor from $K_{\mu 3}$

- λ_+', λ_+'' and λ_0 measured for $K\mu 3$ from ISTRA+, KLOE, KTeV, and NA48.
- **new NA48 results are difficult to accommodate in the $[\lambda_+', \lambda_+'', \lambda_0]$ space**.
- Fit probability varies from 1×10^{-6} (with NA48) to 22.3% (without NA48).



1σ contour for all the experimental results.

Fit with NA48

Fit without NA48

- Because of correlation, is not possible measure λ_0'' at any plausible level of stat.
- Neglecting a quadratic term in the param. of scalar FF implies: $\lambda_0' \rightarrow \lambda_0' + 3.5\lambda_0''$

Vector and scalar form factor from $K_{\ell 3}$

KLOE
KTeV
NA48
ISTRA+

• Slope parameters λ_+' , λ_+'' and λ_0 from ISTRA+, KLOE, KTeV, and NA48.

	K_L and K^-	K_L only
Measurements	16	11
χ^2/ndf	54/13 (7×10^{-7})	33/8 (8×10^{-5})
$\lambda_+' \times 10^3$	24.9 ± 1.1 $(S = 1.4)$	24.0 ± 1.5 $(S = 1.5)$
$\lambda_+'' \times 10^3$	1.6 ± 0.5 $(S = 1.3)$	2.0 ± 0.6 $(S = 1.6)$
$\lambda_0 \times 10^3$	13.4 ± 1.2 $(S = 1.9)$	11.7 ± 1.2 $(S = 1.7)$
$\rho(\lambda_+', \lambda_+'')$	-0.94	-0.97
$\rho(\lambda_+', \lambda_0)$	$+0.33$	$+0.72$
$\rho(\lambda_+'', \lambda_0)$	-0.44	-0.70
$I(K^0_{e3})$	0.15457(29)	0.1544(4)
$I(K^\pm_{e3})$	0.15892(30)	0.1587(4)
$I(K^0_{\mu 3})$	0.10212(31)	0.1016(4)
$I(K^\pm_{\mu 3})$	0.10507(32)	0.1046(4)
$\rho(I_{e3}, I_{\mu 3})$	$+0.63$	$+0.89$

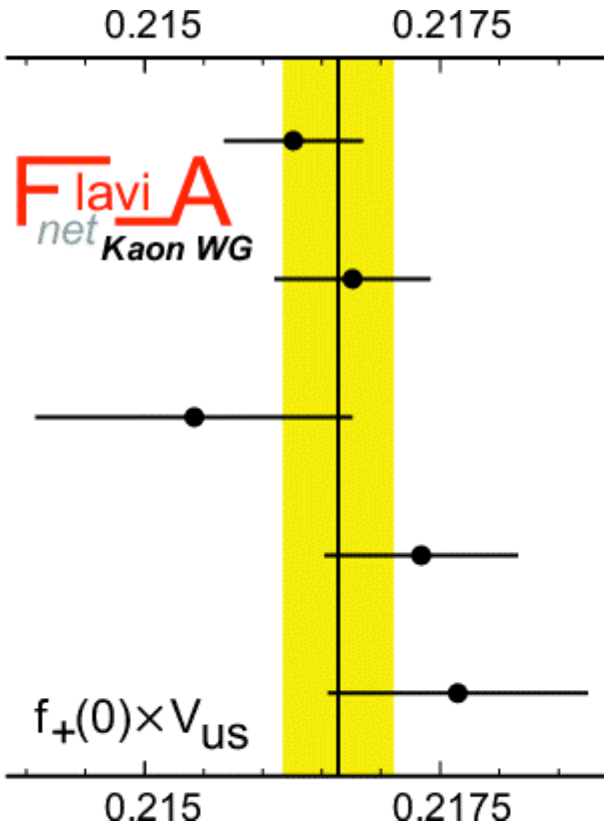
Space integral used for the $|V_{us}|f_+(0)$ determination

Averages of quadratic fit results for Ke3 and Kμ3 slopes.

• Adding Kμ3 data to the fit doesn't cause significant changes to I^0_{e3} and $I^\pm_{e3}$.

• **NA48: Δ[I(Kμ3)] = 0.6%, but Ke3+Kμ3 average gives $\Delta[V_{us}f_+(0)] = -0.08\%$.**

Determination of $|V_{us}|\times f_+(0)$



		% err	Approx. contribution to % err from: BR	τ	δ	$I_{K\ell}$
K_Le3	0.2163(6)	0.28	0.09	**0.19**	0.15	0.09
$K_L\mu3$	0.2168(7)	0.31	0.10	**0.18**	0.15	0.15
K_Se3	0.2154(13)	0.67	**0.65**	0.03	0.15	0.09
$K^{\pm}e3$	0.2173(8)	0.39	**0.26**	0.09	**0.26**	0.09
$K^{\pm}\mu3$	0.2176(11)	0.51	**0.40**	0.09	**0.26**	0.15

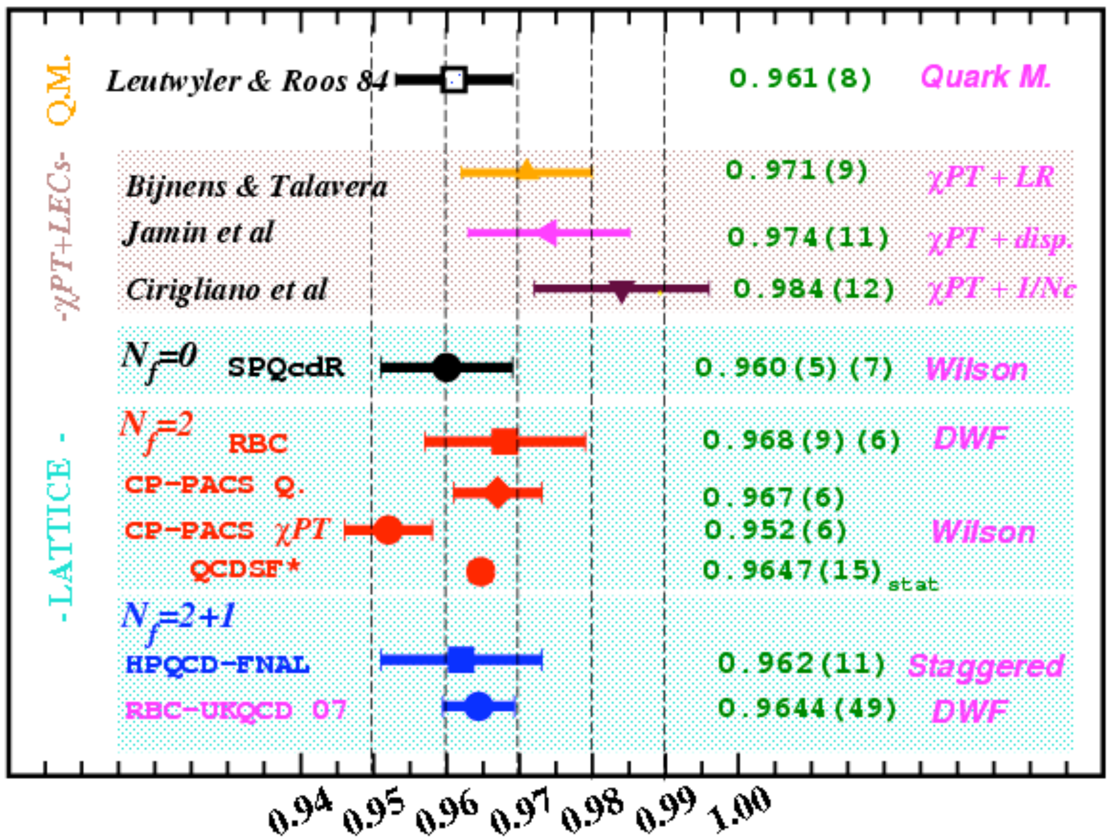
Average: $|V_{us}|\,f_+(0) = 0.2166(5)$ $\chi^2/\text{ndf} = 2.74/4\ (60\%)$

Theoretical estimate of $f_+(0)$

KLOE
KTeV
NA48
ISTRA+

Leutwyler & Roos estimate still widely used: **$f_+(0) = 0.961(8)$**.

Lattice evaluations generally agree well with this value; use RBC-UKQCD07 value: $f_+(0) = 0.9644(49)$ (0.5% accuracy, total err.).



Kl3: $|V_{us}| f_+(0) = 0.2166(5)$ and $f_+(0) = 0.964(5)$, obtain $|V_{us}| = 0.2246(12)$

KLOE
NA48
ISTRA+

V_{us}/V_{ud} determination from BR($K_{\mu 2}$)

$$\frac{\Gamma(K_{\mu 2(\gamma)})}{\Gamma(\pi_{\mu 2(\gamma)})} = \frac{|V_{us}|^2}{|V_{ud}|^2} \times \frac{f_K}{f_\pi} \times \frac{M_K(1-m_\mu^2/M_K^2)^2}{m_\pi(1-m_\mu^2/m_\pi^2)^2} \times (1+\alpha(C_K-C_\pi))$$

Inputs from experiment

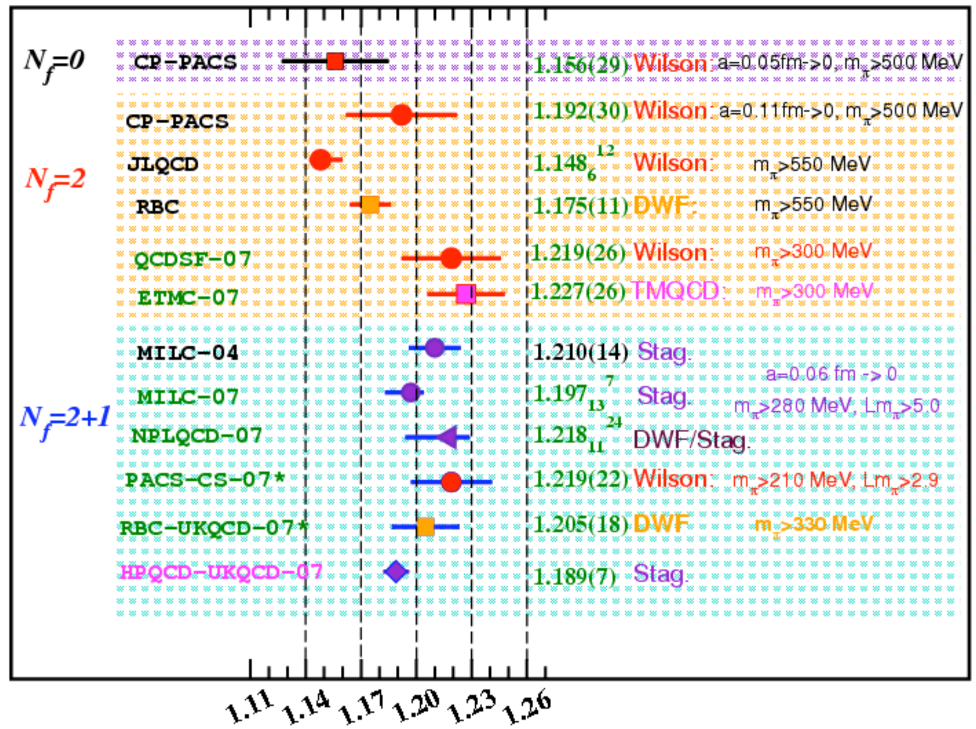
$\Gamma(\pi, K_{l2(\gamma)})$ BR properly includes **radiative effects**; **lifetimes**

Inputs from theory

$C_{K,\pi}$ Rad. includes EW corr.

f_K/f_π Not protected by the Ademollo-Gatto theorem: Lattice calculation of f_K/f_p and radiative corrections benefit of cancellations.

- Use HPQCD-UKQCD07 value: **f_K/f_p = 1.189(7)**.

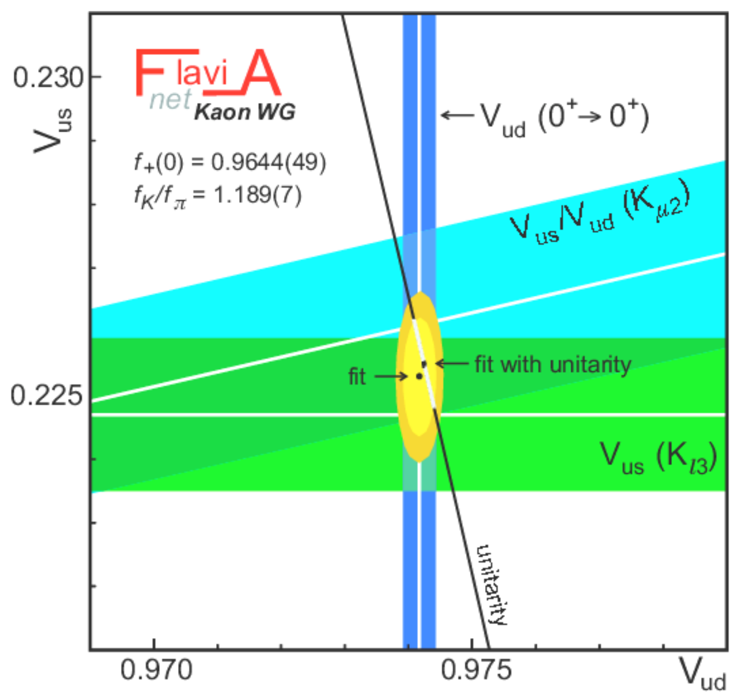


Kl2: $|V_{us}|/|V_{ud}|\, f_K/f_\pi$ = 0.2760(6) and f_K/f_π = 1.189(7), obtain $|V_{us}|/|V_{ud}|$=0.2321(15)

V_{ud}, V_{us} and V_{us}/V_{ud}

KLOE
KTeV
NA48
ISTRA+

|Vus| = 0.2246(12), |Vus|/|Vud|=0.2321(15)
Vud = 0.97418(26) from nuc. β decay:
[Hardy-Towner, nucl-th 0710.3181]



Fit (no CKM unitarity constraint)

V_{ud} = 0.97417(26); V_{us} = 0.2253(9)
χ^2/ndf = 0.65/1 (41%)
Unitarity: $1-V_{ud}^2-V_{us}^2$ = 0.0002(6)

- The test on the unitarity of CKM can be also interpreted as a **test of the universality of lepton and quark gauge coupling**:

$$G_{\rm CKM} \equiv G_\mu \left[|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2\right]^{1/2}$$

$$= (1.1662 \pm 0.0004) \times 10^{-5}\ \text{GeV}^{-2}$$

$$G_\mu = (1.166371 \pm 0.000007) \times 10^{-5}\ \text{GeV}^{-2}$$

Fit (with CKM unitarity constraint)

V_{us} = 0.2255(7) χ^2/ndf = 0.8/2 (67%)

V_{us} Summary

KLOE
KTeV
NA48
ISTRA+

- Dominant K_S, K_L, and $K^{\pm}$ BRs, and lifetime known with very good accuracy.
- Dispersive approach for form factors.
- Constant improvements from lattice calculations of $f_+(0)$ and f_K/f_π:
  Callan-Treiman relation allows checks from measurements;
  syst errors often not quoted, problem when averaging different evaluations.

- $|V_{us}|\, f_+(0)$ at 0.2% level.
- $|V_{us}|$ measured with 0.4% accuracy (with $f_+(0)$= 0.9644(49))
  Dominant contribution to uncertainty on $|V_{us}|$ still from $f_+(0)$.
  CKM unitarity test satisfied at 0.3σ level
  test of lepton-quark universality

- Comparing $|V_{us}|$ values from $K\mu2$ and Kl3, exclude large region in the (m_{H+-},tanβ) plane, complementary to results from $B\rightarrow\tau\nu$ decays.
- Test of Lepton Universality with Kl3 decays with 0.5% accuracy.

V. New Results contributing to ChPT

KLOE
KTeV
NA48

V. New Kaon Results on ChPT

Kloe
KTeV
NA48/2

NA48/2 recent results in charged Kaon decays

- $K^{\pm} \rightarrow \pi^{\pm} e^{+} e^{-}$ BR and Form Factors (preliminary)
- $K^{\pm} \rightarrow \pi^{\pm} \gamma\gamma$ BR and kinematics (preliminary)
- $K^{\pm} \rightarrow \pi^{\pm} e^{+} e^{-} \gamma$ Branching Ratio (final)

KTeV "recent" results in neutral Kaon decays

- $K_L \rightarrow \pi^0 e^+ e^-$ BR (99 data to be added)
- $K_L \rightarrow \pi^0 \gamma\gamma$ BR and kinematics (final)
- $K_L \rightarrow \pi^0 e^+ e^- \gamma$ Branching Ratio (final)

KLOE recent results in neutral Kaon decays

- $K_S \rightarrow \gamma\gamma$ Branching Ratio (final)
- $K_S \rightarrow e^+ e^-$ Direct Search, Upper Limit (final)
- $K_L \rightarrow \pi e \nu \gamma$ Branching Ratio (final)

KTeV
NA48

NA48/2: $K^{\pm} \rightarrow \pi^{\pm} e^{+} e^{-}$

KTeV: $K_L \rightarrow \pi^0 e^+ e^-$

$K^{\pm} \rightarrow \pi^{\pm}\gamma^{*} \rightarrow \pi^{\pm}e^{+}e^{-}$
Theoretical Framework

NA48/2

- ✓ **suppressed FCNC processes**
- ✓ **one-photon exchange**
- ✓ **useful test for ChPT**

$d\Gamma_{\pi ee}/dz \sim P(z)\cdot|W(z)|^2$

$z=(M_{ee}/M_K)^2$, P(z) phase space factor

Form-factor models:

(1) polynomial: $W(z) = G_F M_K^2 \cdot f_0 \cdot (1+\delta z)$

(2) ChPT $O(p^6)$: $W(z) = G_F M_K^2 \cdot (a_+ + b_+ z) + W^{\pi\pi}(z)$

(3) Dubna ChPT: $W(z) = W(M_a, M_\rho, z)$

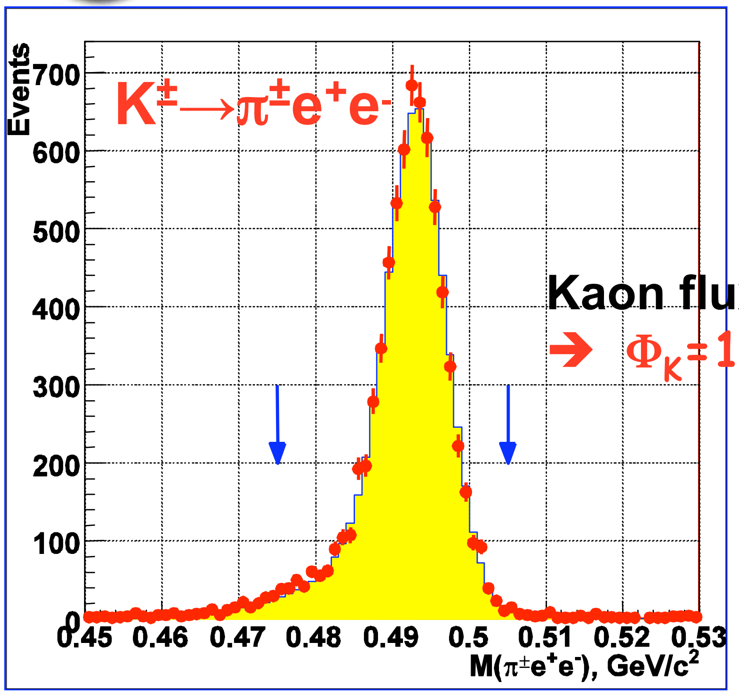
(2) D'Ambrosio et al. JHEP 8 (1998) 4 **(3) Dubnickova et al. hep-ph/0611175**

(f_0,δ) or (a_+,b_+) **or (M_a,M_ρ) determine a model-dependent BR**

- **Parameters of models and BR in full kinematical range**
- **Model-independent BR (z > 0.08) in visible kinematical range**

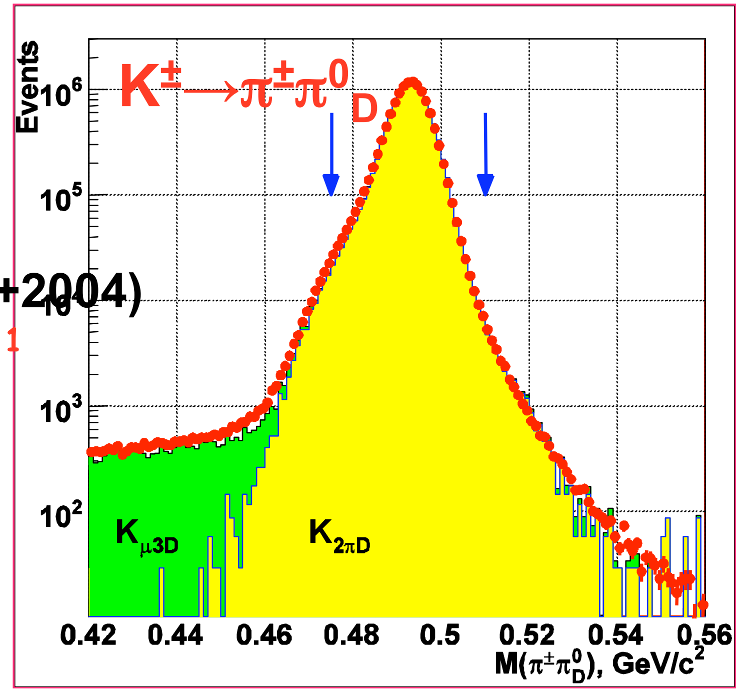
Data $K^{\pm} \to \pi^{\pm}\gamma^{*} \to \pi^{\pm}e^{+}e^{-}$

NA48/2



Kaon flux (2003+2004)

➔ $\Phi_K = 1.70 \cdot 10^{11}$



7146 events (M_{ee}>140 MeV) (BG 0.6%)

12.23 x 10^6 events (BG 0.15%)

- The BR is measured normalizing to $K^{\pm}\to\pi^{\pm}\pi^{0}_{D}\to\pi^{\pm}e^{+}e^{-}\gamma$
  - → particle ID efficiencies cancel at first order
- common selection criteria for signal and normalization channel
  - → 3 track vertex, electron (pion) ID with E/p > 0.95 (< 0.85)
- $K^{\pm}\to\pi^{\pm}\pi^{0}_{D}$ BG suppressed using a kinematical cut M_{ee}>140 MeV

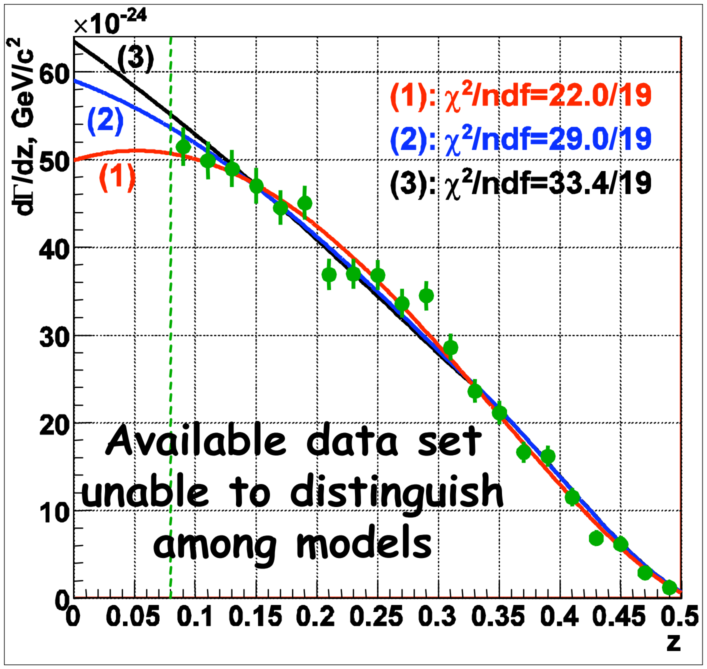
Fit results (preliminary)

NA48/2

polynomial: $W(z) = G_F M_K^2 \cdot f_0 \cdot (1+\delta z)$

ChPT $O(p^6)$: $W(z) = G_F M_K^2 \cdot (a_+ + b_+ z) + W^{\pi\pi}(z)$

Dubna ChPT: $W(z) = W(M_a, M_\rho z)$



(1) $\delta = 2.35 \pm 0.18$
$f_0 = 0.532 \pm 0.016$
$\rho(\delta, f_0) = -0.963$

(2) $a_+ = -0.579 \pm 0.016$
$b_+ = -0.798 \pm 0.067$
$\rho(a_+, b_+) = -0.913$

(3) $M_a = (0.965 \pm 0.033)$ GeV
$M_\rho = (0.711 \pm 0.013)$ GeV
$\rho(M_a, M_\rho) = 0.998$

Model-Independent BR computed by integrating dG/dz

BR_{MI} (z>0.08) = (2.26±0.08)x10–7

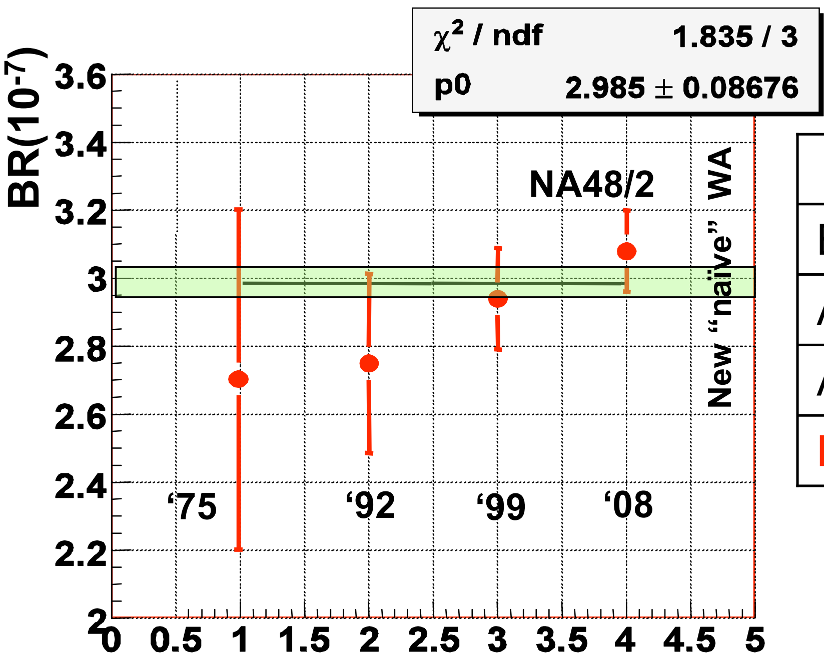
BR1 = (3.02 ± 0.04stat) ´ 10^{-7}
BR2 = (3.11 ± 0.04stat) ´ 10^{-7}
BR3 = (3.15 ± 0.04stat) ´ 10^{-7}

Results – BR in full kinematic range

NA48/2

$BR=(3.08\pm0.04stat\pm0.04syst\pm0.08ext\pm 0.07model)\times10^{-7}=(3.08\pm0.12)\times10^{-7}$

Including the uncertainty due to the model dependence (preliminary)



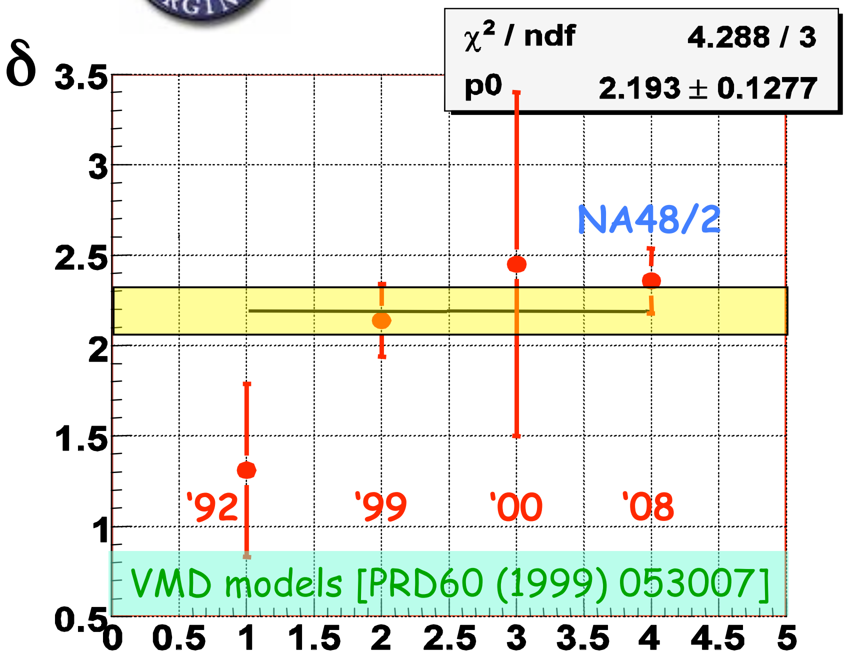
Measurement	$BR\times10^7$
Bloch et al., PL 56 (1975) B201	2.70±0.50
Alliegro et al., PRL 68 (1992) 278	2.75±0.26
Appel et al. [E865], PRL 83 (1999) 4482	2.94±0.15
NA48/2 preliminary (2008)	**3.08±0.12**

First measurement of CPV parameter (correlated K^+/K^- uncertainties excluded)

$$\Delta(K^{\pm}_{\pi ee}) = (BR^+ - BR^-)/(BR^+ + BR^-) = (-2.1 \pm 1.5stat \pm 0.3syst)\%$$

Results – FF slope δ

NA48/2

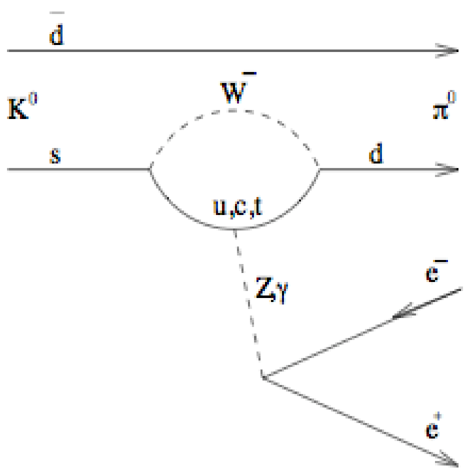


- **NA48/2 measurement of δ**
  good precision
  compatible with earlier results
- **Contradiction of the data to VMD**
  further confirmed
- **NA48/2 values of (f_0, a_+, b_+)**
  in agreement with BNL E865

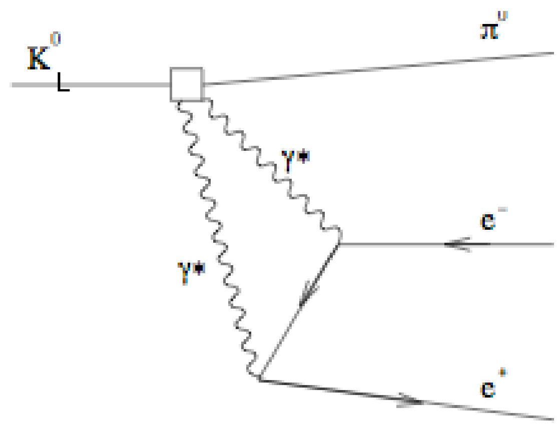
Measurement	Process	Result
Alliegro et al., PRL 68 (1992) 278	$K^+ \rightarrow \pi^+ e^+ e^-$	1.31±0.48
Appel et al. [E865], PRL 83 (1999) 4482	$K^+ \rightarrow \pi^+ e^+ e^-$	2.14±0.20
Ma et al. [E865], PRL 84 (2000) 2580	$K^+ \rightarrow \pi^+ \mu^+ \mu^-$	$2.45^{+1.30}_{-0.95}$
NA48/2 **preliminary** (2008)	$K^\pm \rightarrow \pi^\pm e^+ e^-$	2.35±0.18

KTeV

$K_L \rightarrow \pi^0\gamma^* \rightarrow \pi^0 e^+e^-$ Theoretical Framework



+



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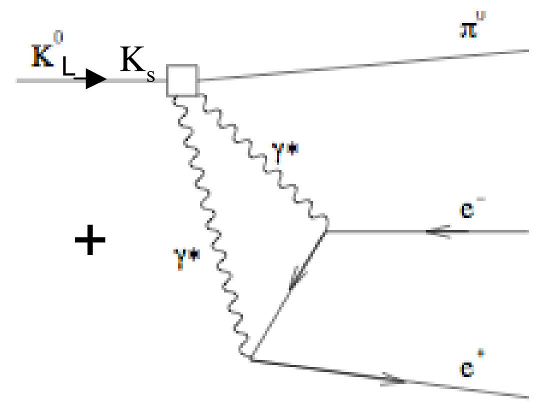


Direct CPV penguin

$2.8\text{-}6.5\times10^{-12}$

CP Conserving ~O(P^6)

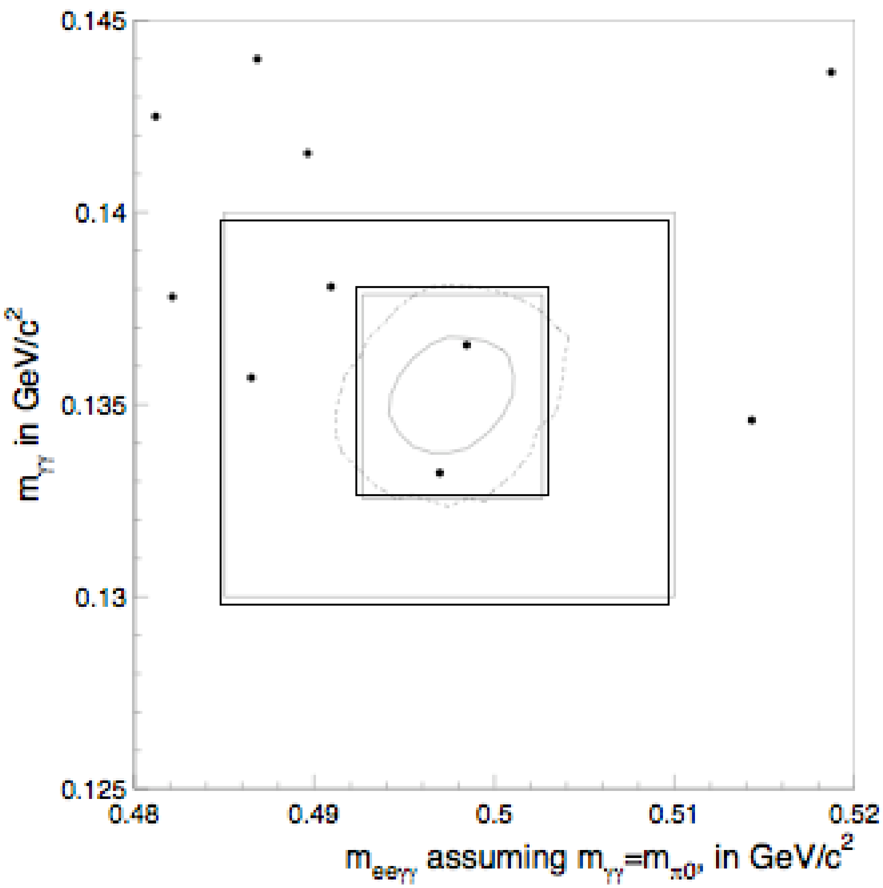
$1\text{-}3\times10^{-12}$

Indirect CPV

$\varepsilon\times(1\text{-}3)\times10^{-12}$

Results: $K_L \to \pi^0 e^+ e^-$ Search

KTeV



Two events observed in signal region

Total expected background from $K_L \to \pi^0 \pi^0_D$ 1.06±0.41 events

$BR(K_L \to \pi^0 e^+ e^-) < 5.1 \times 10^{-10}$

Only 1997 data
1999 data analysis in progress

KTeV
NA48

NA48/2 $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$

$K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma^{*} \rightarrow \pi^{\pm}\gamma e^{+}e^{-}$

KTeV: $K_L \rightarrow \pi^{0}\gamma\gamma$

$K_L \rightarrow \pi^{0}\gamma\gamma^{*} \rightarrow \pi^{0}\gamma e^{+}e^{-}$

$K^{\pm} \to \pi^{\pm}\gamma\gamma$ Theoretical Framework

NA48/2

$$\frac{\partial^2\Gamma}{\partial y \partial z} = \frac{m_{K+}}{(8\pi)^3}\left[z^2(|A+B|^2 + |C|^2) + \left(y^2 - \frac{1}{4}\lambda(1, r_\pi^2, z)\right)^2 (|B|^2 + |D|^2)\right]$$

relevant only at low $m_{\gamma\gamma}$

$$z = \frac{(q_1+q_2)^2}{m_{K+}^2} = \frac{m_{\gamma\gamma}^2}{m_{K+}^2} \qquad y = \frac{p\cdot(q_1-q_2)}{m_{K+}^2}$$

$O(p^4)$

A(z) → loop diagrams contribution
C(z) → Wess-Zumino-Witten functional (10%)
B=D=0

[G. Ecker, A. Pich and E. de Rafael, Nucl., Phys. B303 (1988), 665]

$O(p^6)$

unitarity corrections effects can increase the BR by 30-40 %

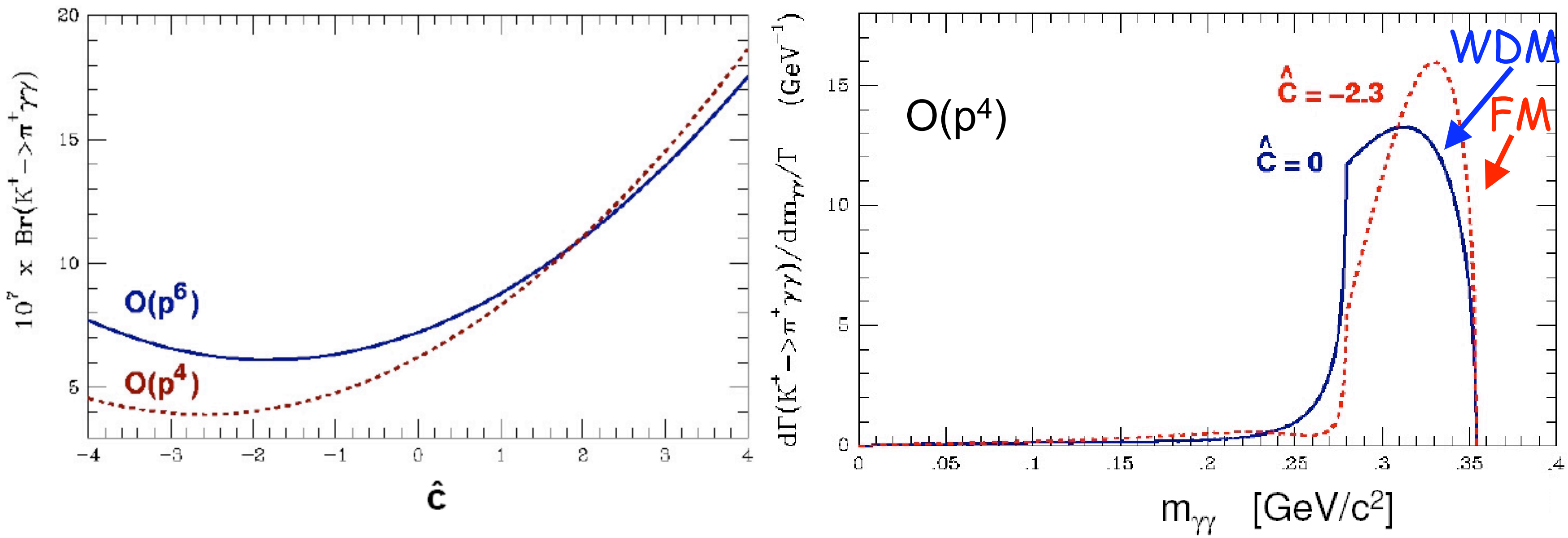
[G. D'Ambrosio and J. Portoles, Nucl., Phys. B386 (1996), 403]

$M_{\gamma\gamma}$ Spectrum from $K^{\pm}\to\pi^{\pm}\gamma\gamma)$ dependence on ĉ

NA48/2

- **Both decay spectrum and rate strongly depend on the single ĉ parameter**
- **The $M_{\gamma\gamma}$ spectrum has a pronounced cusp-like behaviour at 2π threshold.**

$$\Gamma(K^{\pm}\to\pi^{\pm}\gamma\gamma)=\Gamma_{loop}+\Gamma_{WZW}\begin{cases}\Gamma_{loop}=(2.80+0.87\cdot\hat{c}+0.17\cdot\hat{c}^2)\times10^{-23}\,GeV\\ \Gamma_{WZW}=0.26\times10^{-23}\,GeV\end{cases}$$

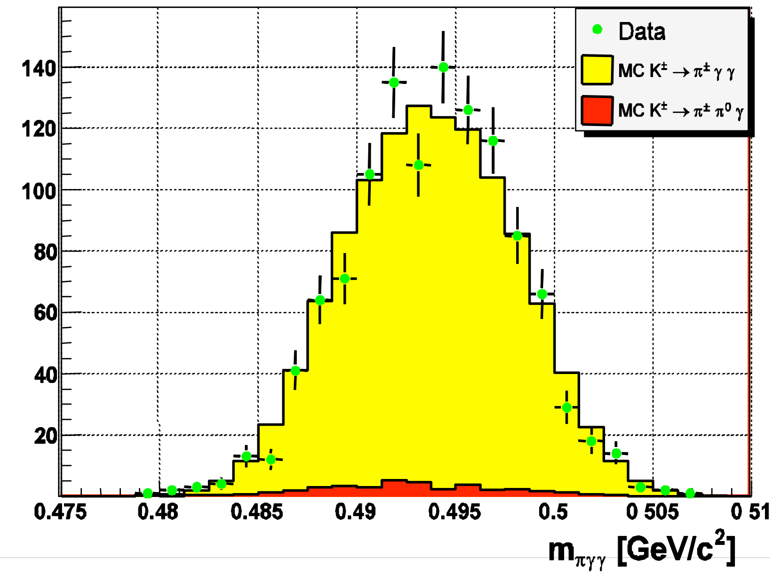


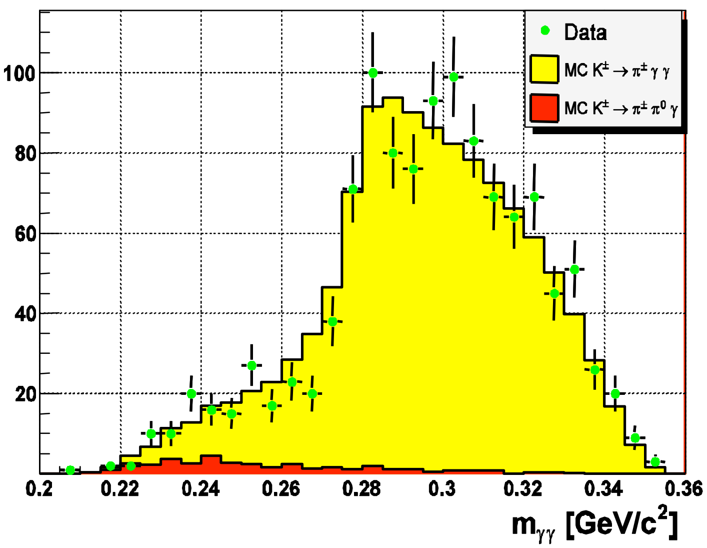
[G. D'Ambrosio and J. Portoles, Nucl., Phys. B386 (1996), 403]

$K^{\pm} \to \pi^{\pm}\gamma\gamma$ data

NA48/2

preliminary





1164 events in 40% of the full data
~40 times larger wrt to world sample
3.3% BG mainly from $\pi\pi\gamma$(IB)

The only previous measurement (E787), based on 31 events (5 BG events)

BR=(1.10±0.32)·10–6 ; ĉ=1.8±0.6

$BR_{(O(p6),\hat{c}=2)}=(1.07\pm0.04_{stat}\pm0.08_{sys})\cdot10^{-6}$

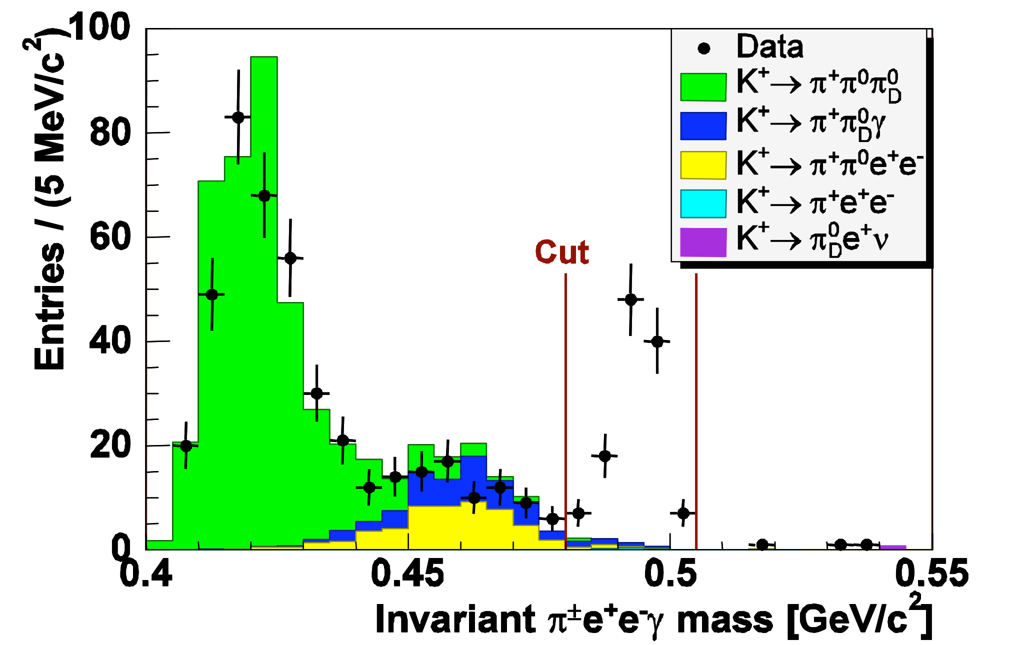
- MC O(p^6) and ĉ=2 comparison data shape follows ChPT prediction
- Model independent measurement and extraction of ĉ is ongoing

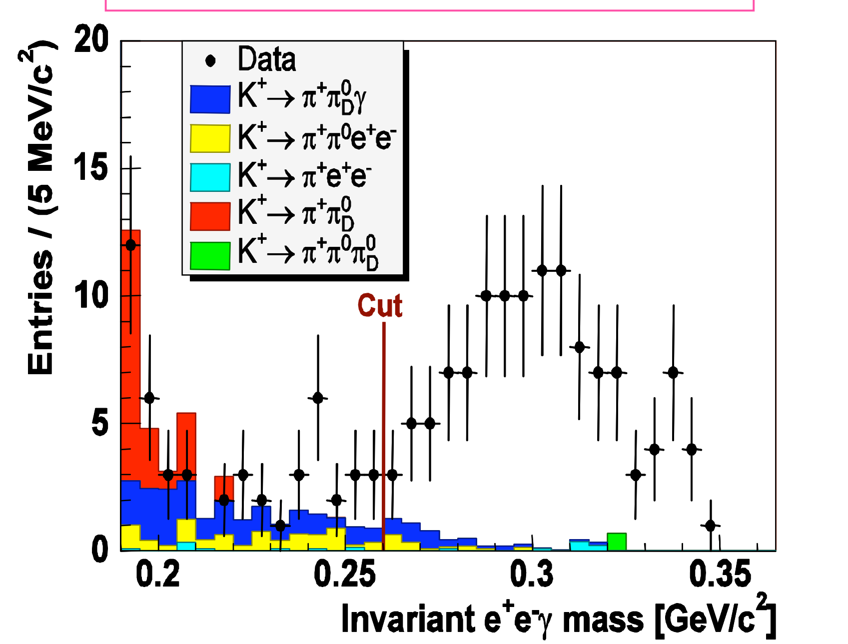
$K^{\pm} \to \pi^{\pm} e^+ e^- \gamma$ - first observation

NA48/2

120 candidate events (6.1% BG)

never observed before!!





Model-independent BR (M_{gee}> 260 MeV/c²)

$BR(\pi^{\pm} e^+ e^- \gamma) = (1.19 \pm 0.12_{stat} \pm 0.04_{sys}) \cdot 10^{-8}$

Shape analysis [ChPT $O(p^6)$ model, F. Gabbiani, PRD59 (1999) 094022]:

$\hat{c} = 0.90 \pm 0.45$

[final result published, PLB659 (2008) 493]

$K_L \to \pi^0\gamma\gamma$ + $K_L \to \pi^0 ee\gamma$ Theoretical Framework

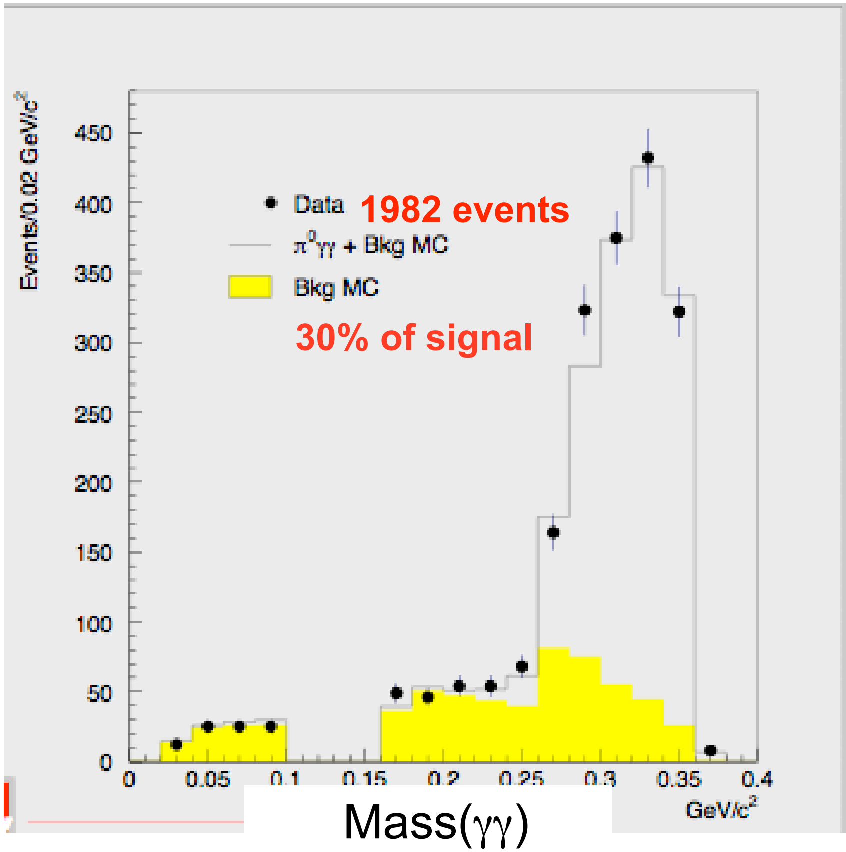
KTeV

- Tests of ChPT
  - No free parameters in branching ratio to $O(p^4)$
  - $O(p^6)$ terms include Vector Meson exchange terms (strength of which is described by A_V)
  - $O(p^6)$ terms increase branching ratios by factor of 2-3
- A_V determines CP conserving part of $K_L \to \pi^0 l^+ l^-$
  - CP conserving part is from $K_L \to \pi^0 \gamma^* \gamma^*$
- Indirect CP violating part of $K_L \to \pi^0 l^+ l^-$ determined by $Br(K_S \to \pi^0 l^+ l^-)$

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

KTeV

Physical Review D77, No.11(June1, 2008)



- Selection requirements:
  - Require 4 photon clusters in CsI, each with an energy > 2.0 GeV
  - Require energy center to be in vacuum beam hole in CsI
    - Rejects events from mixed K_L-K_S regenerator beam
  - Two photons must reconstruct to within 3 MeV/c^2 of the π^0 mass, while the other two must not.
- Normalize with $K_L \to \pi^0\pi^0$
  - Same final state

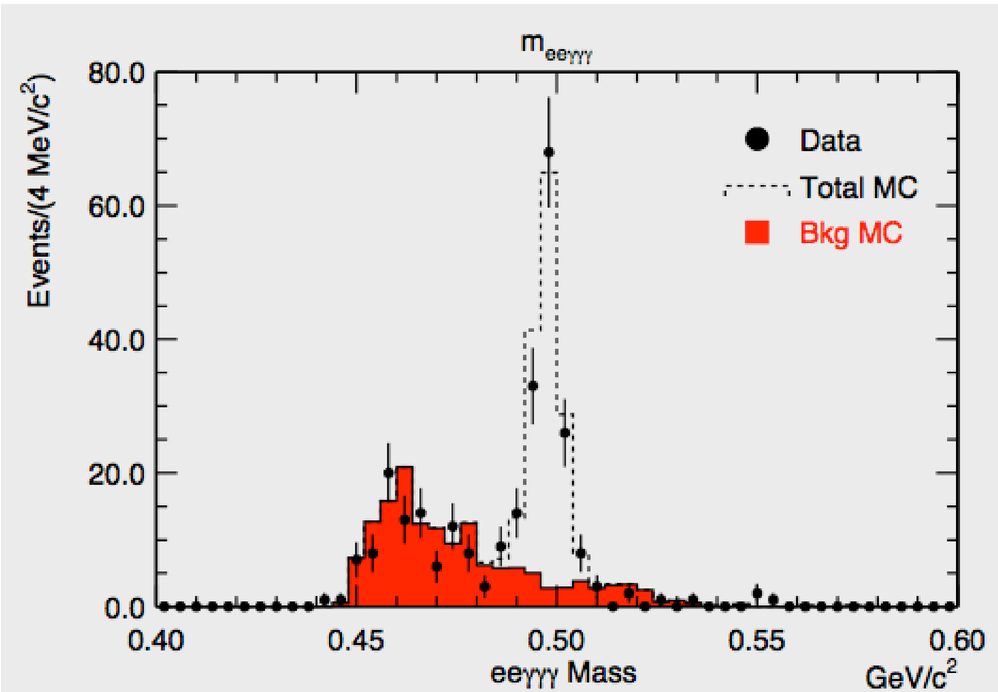
KTeV: $Br(K_L \to \pi^0\gamma\gamma) = (1.29 \pm 0.03_{stat} \pm 0.05_{syst})\times10^{-6}$

NA48: $Br(K_L \to \pi^0\gamma\gamma) = (1.36 \pm 0.03_{stat} \pm 0.03_{syst} \pm 0.03_{norm})\times10^{-6}$

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

KTeV

139 events
(Bkg:14.4 +/- 2.5 events)



Selection requirements...

- Require 2 tracks and 3 neutral CsI clusters
- Two neutral clusters must combine to an invariant mass near the π^0 mass
- Neutral decay vertex used to compute:
  - $M_{ee\gamma}$, $M_{ee\gamma\gamma\gamma}$
  - Mass resolution with neutral vertex is better than charged vertex since e^+ and e^- tracks are very close
  - None of the 3 possible $ee\gamma$ solutions reconstruct to a π^0.
  - Normalize using $K_L \to \pi^0 \pi^0_D$

$Br(K_L \to \pi^0 e^+ e^- \gamma) = (1.62 \pm 0.14_{stat} \pm 0.09_{syst}) \times 10^{-8}$

CHPT 0(p^6) predicts 1.51 X 10^{-8}

Extracting A_V

KTeV

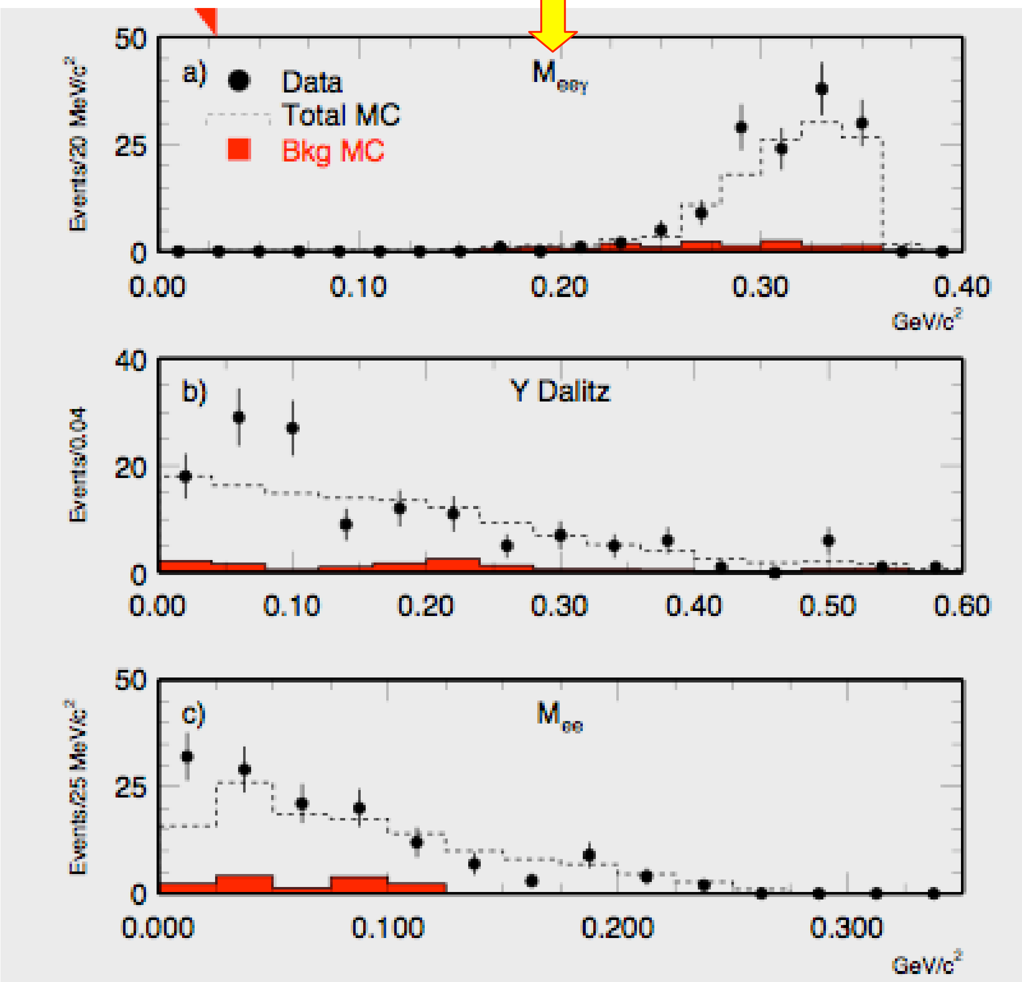
- $K_L \rightarrow \pi^0 \gamma\gamma$
- Maximum likelihood fit to the two Dalitz parameters:
  - $Z_{Dalitz} = m_{34}^2 / M_K^2$
  - $Y_{Dalitz} = (E_{\gamma 3} - E_{\gamma 4}) / M_K$

- $K_L \rightarrow \pi^0 ee\gamma$
- Maximum likelihood fit to the three Dalitz parameters:
  - $Z_{Dalitz} = M_{ee\gamma}^2 / M_K^2$
  - $Y_{Dalitz} = (E_\gamma - E_{ee}) / M_K$
  - $Q_{Dalitz} = M_{ee}^2 / M_K^2$

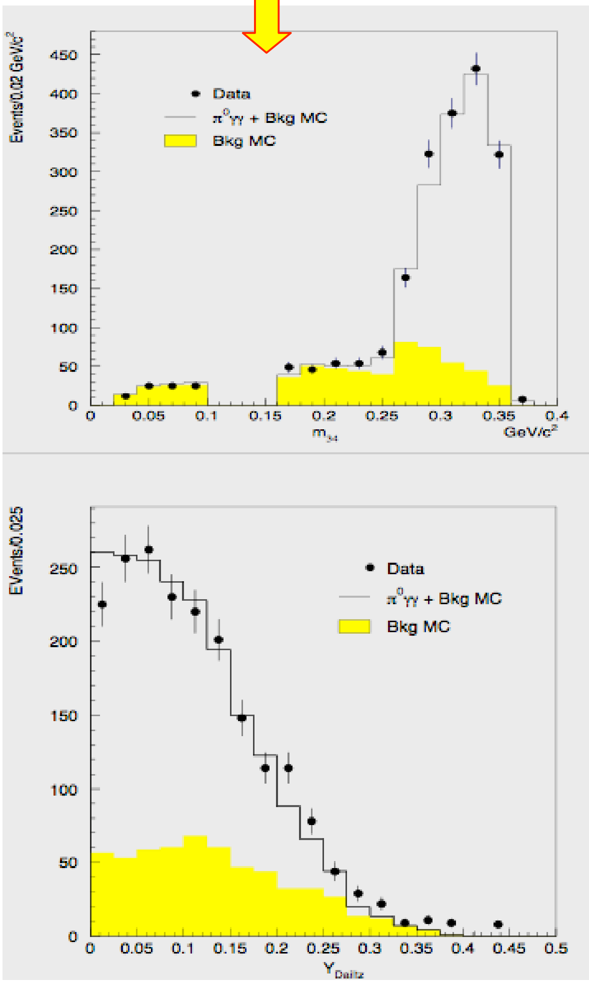
Data + Best Fit

KTeV

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

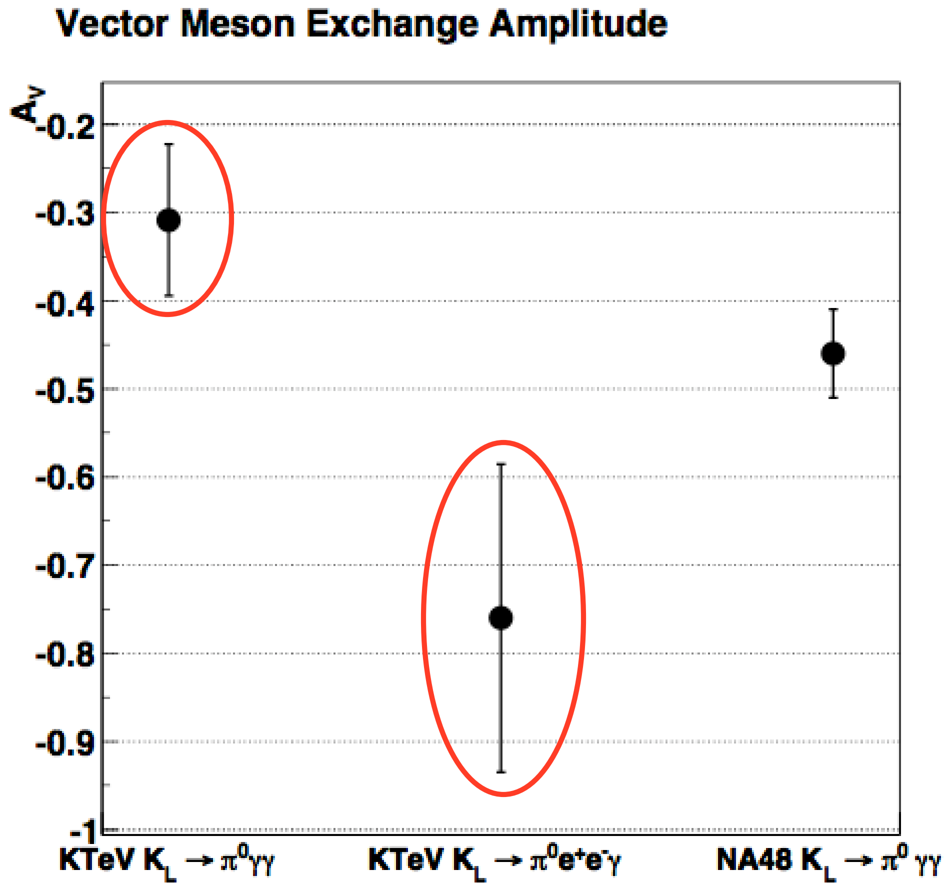


$K_L \rightarrow \pi^0 \gamma\gamma$



Results for A_V

KTeV



- **Values imply that $K_L \to \pi^0 l^+ l^-$ is indeed dominated by CPV terms**

KLOE

KLOE: Measurement of BR($K_S \rightarrow \gamma\gamma$)
Search for $K_S \rightarrow e^+e^-$
Measurement of BR($K_L \rightarrow \pi e \nu \gamma$)

Motivation to study $K_s \to \gamma\gamma$

KLOE

- Important probe of ChPT
- Decay amplitude evaluated at leading order, $O(p^4)$

  $BR(K_S \to \gamma\gamma) = 2.1 \times 10^{-6}$

  D'Ambrosio and Espriu, Phys.Lett.B 175(1986) 237
  Kambor and Holstein, Phys.Rew.D 49(1994) 2346
- No full $O(p^6)$ calculation exists
- Experimental value of the BR changed along the years,
- improving in precision
- Most recent measurement by NA48/1

  $BR(K_S \to \gamma\gamma) = (2.78 \pm 0.06 \pm 0.04) \times 10^{-6}$
- Differs from ChPT $O(p^4)$ by 30% possible large $O(p^6)$ contribution

In NA48, the $K_L \to \gamma\gamma$ background is a relevant component of the fit

In KLOE, the background from K_L is reduced to zero (tagging)

$K_s \to \gamma\gamma$ Analysis Strategy

KLOE

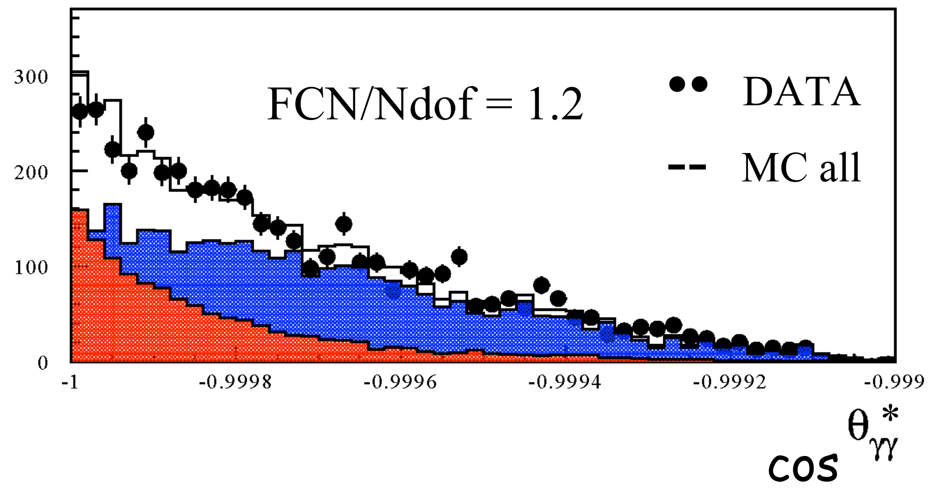
Main background $\to K_S \to 2\pi^0$ with 2 photons lost in the beam-pipe and/or colliding into QCAL

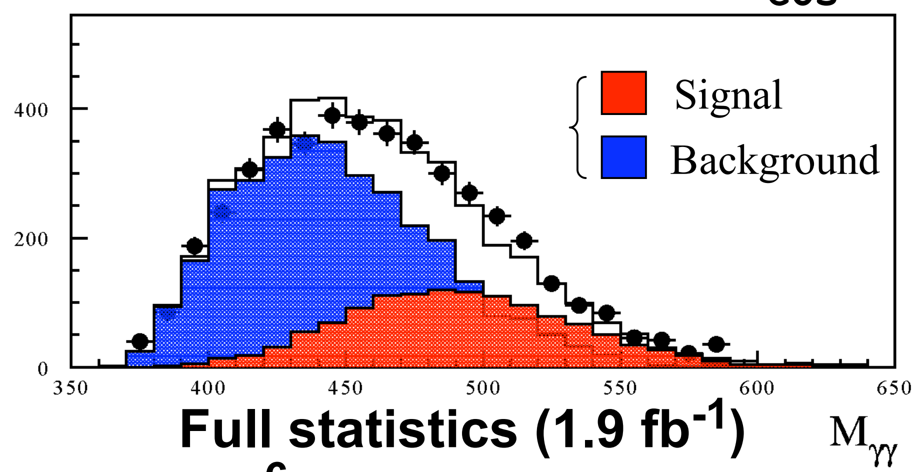
veto these photons using a cut on arrival time
$\Delta T = |T_{QCAL} - R_{QCAL}/c| < 5$ ns

Background reduction to 70 %

Determine signal events by fitting $M_{\gamma\gamma}$ and $\cos\theta^*_{\gamma\gamma}$ in the K_S cms

$N_{sig} = 711 \pm 35$
(4.9% stat. error)





Full statistics (1.9 fb^{-1})
700 x 10^6 K_S events after K_L tag

Result: BR($K_S \rightarrow \gamma\gamma$)

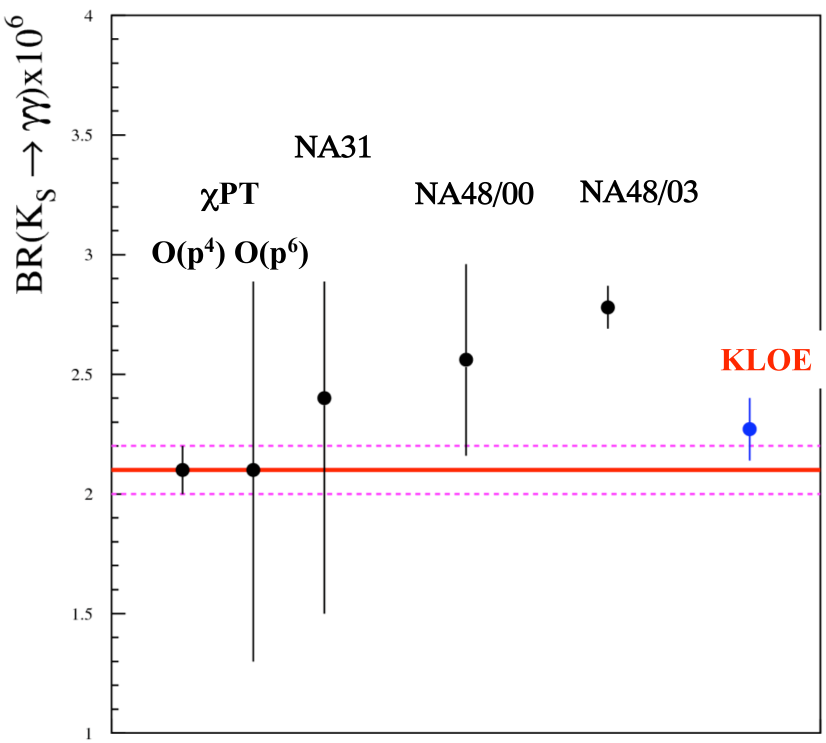
KLOE

now published: [JHEP05 (2008) 05]

NA48 Coll., Phys. Lett. B551 (2003) 7
NA48 Coll., Phys. Lett. B493 (2000) 29
NA31 Coll., Phys. Lett. B351 (1995) 579

There is a 3σ discrepancy between KLOE and NA48 results

- **The NA48 measurement implies the existence of a sizeable O(p^6) counterterm in ChPT**
- **The KLOE result makes this**
- **contribution practically negligible**



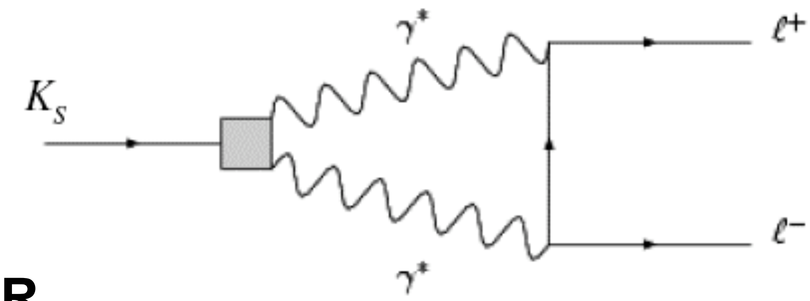
$$BR(K_S \rightarrow \gamma\gamma) = (2.26 \pm 0.12_{stat} \pm 0.06_{sys}) \cdot 10^{-6}$$

Search for FCNC in $K_S \rightarrow e^+e^-$

KLOE

Exotic mediators could produce tree level FCNC processes

- **Precise SM ChPT, O(p4) prediction:**
  $BR(K_S \rightarrow e^+e^-) = 1.6 \times 10^{-15}$
  [Ecker and Pich, Nucl. Phys. B366, 189, 1991]
- **Most precise measurement by CPLEAR**
  $BR(K_S \rightarrow e^+e^-) < 1.4 \times 10^{-7}$ (90% C.L.)

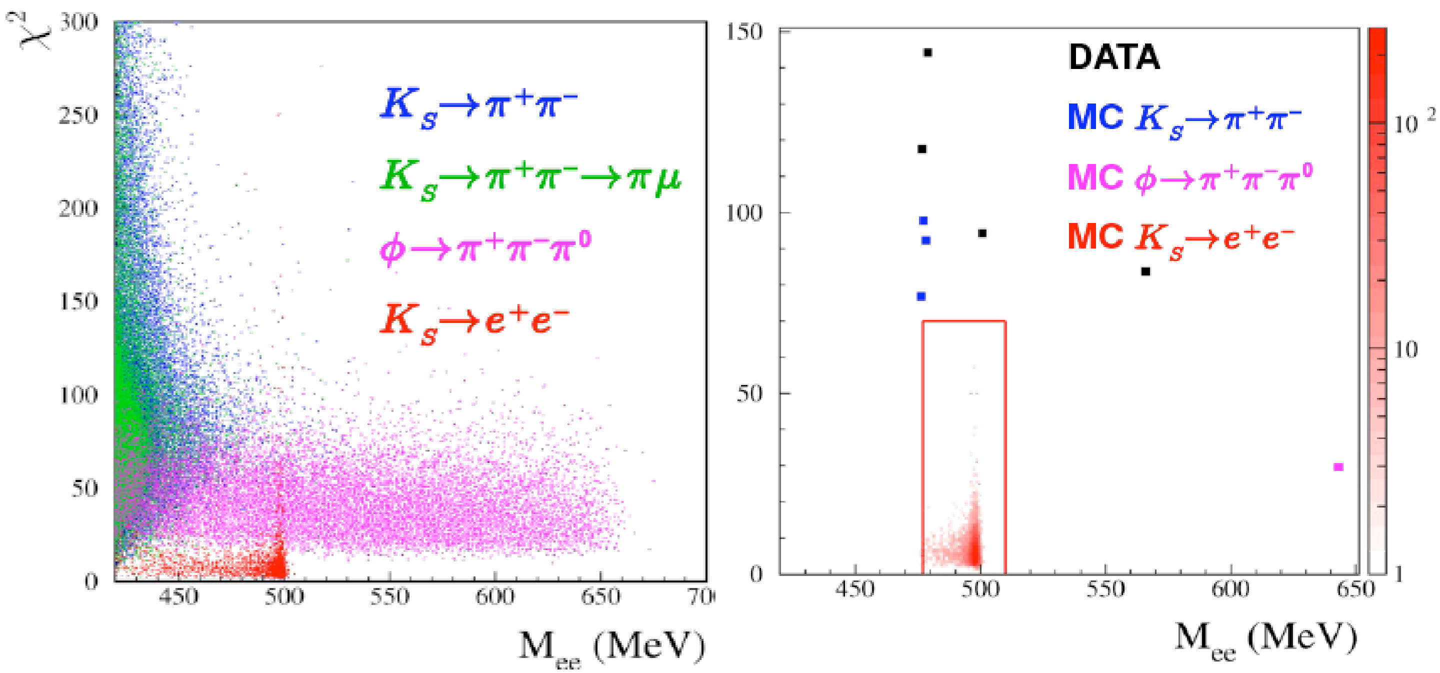


In KLOE è direct search of this decay using a pure K_S beam
After preselection: 1.1 M evts in Data sample

- **Signal identification using a χ^2 variable based on time of particles, E/p and cluster position**
- **Background rejection by kinematic cuts**
- **Signal box defined in the plane χ^2 vs M_{inv} (e^+e^- hypothesis))**

Result: Upper Limit for $K_S \rightarrow e^+e^-$

KLOE



NO events found in the signal box

Upper Limit evaluated normalizing to the number of $K_S \rightarrow \pi^+\pi^-$ events

$BR(K_S \rightarrow e^+e^-) < 9.3 \times 10^{-9}$ (90% C.L.)

Previous result improved by more than one order of magnitude

$K_L \to \pi e \nu \gamma$

KLOE

$$R \equiv \frac{\Gamma(K^0_{e3\gamma}; E^*_\gamma > 30\ \mathrm{MeV}, \theta^*_\gamma > 20°)}{\Gamma(K^0_{e3})}$$

$$\frac{d\Gamma}{dE^*_\gamma} \simeq \frac{d\Gamma_{\mathrm{IB}}}{dE^*_\gamma} + \langle X \rangle f(E^*_\gamma)$$

A 2-dimensional fit in (E_γ^*,θ_γ^*) allow to measure both R and <X>

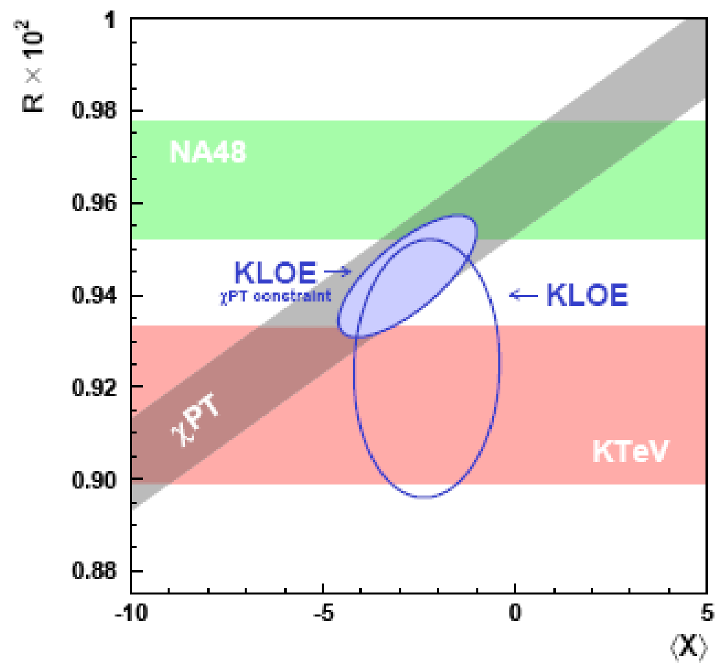
R = (924 ± 23 ± 16) × 10^{-5}
<X> = -2.3 ± 1.3 ± 1.4

R = (944 ± 14) × 10^{-5}
<X> = -2.8 ± 1.8

With ChPT constraint

arXiv:0710.3993

Largely dominated by IB, negligible DE
Interference IB-DE small (1%)
→ test of ChPT O(p^6)



NA48 Coll., Phys.Lett. B605 (2005) 247
KTeV Coll., Phys. Rew. D71 (2005) 012001

ChPT Summary

The NA48/2, KLOE and KTeV experiments have obtained important new experimental inputs to the Chiral Perturbation Theory, the effective theory of strong interaction at low energy

- **KTeV** neutral kaon sector
  - **Precise study of $K_L \rightarrow \pi^{\pm}\gamma\gamma$ decay (final)**
  - **Precise study of $K_L \rightarrow \pi^{\pm}\gamma e^+ e^-$ decay (final)**
- **NA48/2** charged kaon sector
  - **Precise study of the $K^{\pm} \rightarrow \pi^{\pm} e^+ e^-$ decay (preliminary)**
  - **Precise study of the $K^{\pm} \rightarrow \pi^{\pm}\gamma\gamma$ decay (preliminary)**
  - **First observation of the $K^{\pm} \rightarrow \pi^{\pm}\gamma e^+ e^-$ decay (final)**
- **KLOE** neutral kaon sector
  - **Measurement of $K_S \rightarrow \gamma\gamma$ decay (final)**
  - **Upper limit for $K_S \rightarrow e^+ e^-$ decay (final)**
  - **Measurement of decay (final)**

Conclusions

- **No new physics evidence**
- **Final ε'/ε prime result from KTeV:**
  (high precision; can someone calculate this?)
- **No breaks in e,μ universality**
- **First row CKM unitarity is better and better satisfied**
- **Many new results bearing on ChPT**
- **Many more new results to come**

Do we have a flavor problem? Where are all these new particles?

Many thanks to the following

Guiseppina Anzivino	-	Perugia University and INFN
Paolo Massarotti	-	Naples University and INFN
Matthew Moulson	-	INFN/LFN
Michael Ronquest	-	University of Virginia/North Carolina
Tommaso. Spadaro	-	INFN/LFN
Elizabeth Worcester	-	University of Chicago