Kaon physics

XXVI Physics in Collision
Buzios, Brasil
6-9 July 2006

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Outline

Plenty of new results on kaon physics since PIC05:

KLOE:
- **BR($K_L \to \pi^+\pi^-$)**
- **K_Le3 form factors**
- **BR($K_S \to \pi e \nu$) and A_S**
- **$\Gamma(K_S \to \pi^+\pi^-(\gamma))/\Gamma(K_S \to \pi^0\pi^0)$**
- **BR($K^+ \to \mu^+\nu$)**
- **$K^\pm$ semileptonic decays**
- **$K^\pm$ lifetime**

NA48:
- **CP violation in $K^\pm \to 3\pi$**
- **$\pi\pi$ scattering lengths from $K^\pm \to \pi^\pm\pi^0\pi^0$**
- **$K_S \to \pi^+\pi^-\pi^0$**
- **$\Gamma(K^\pm_{e2})/\Gamma(K^\pm_{\mu 2})$**

KTEV:
- **BR($K_L \to \pi^+\pi^-\gamma$)**
- **Hadronic radiative decays of K_L with virtual photons ($K_L \to \pi\pi\gamma^*$ and $K_L \to \pi\pi\pi\gamma^*$)**

In this talk focus on:
- **Direct CP violation in charged decays and (totally unexpected) $\pi\pi$ scattering lengths from $K^\pm \to \pi^\pm\pi^0\pi^0$ decays**
- **V_{us} measurement and unitarity test of CKM matrix.**
- **Determination of CP and CPT violation parameters using the Bell-Steinberger relation.**
- **μ/e universality in $K^\pm_{\ell 2}$ decays**
- **Status of rare K decays ($K \to \pi\nu\nu$) measurements.**

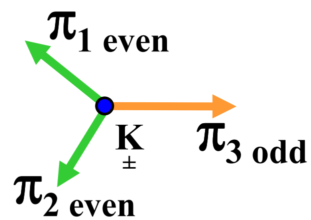
Direct CP violation in $K^{\pm}_{3\pi}$ decays

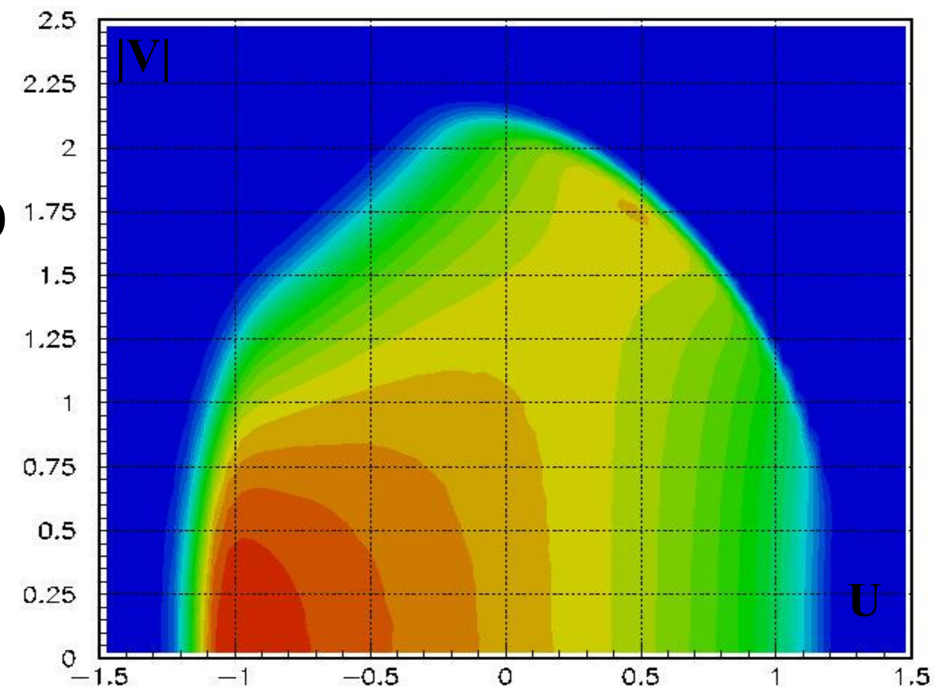
- Compare the Dalitz plot density for K^+ and K^-, in the $K^{\pm}3\pi$ decay modes:
  $BR(K^{\pm}\rightarrow\pi^{\pm}\pi^{+}\pi^{-})=5.57\%$ (charged)
  $BR(K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0})=1.73\%$. (neutral)

- Matrix element:
  $|M(u,v)|^2 \sim 1 + gu + hu^2 + kv^2$
  $g_{ch} = -0.2154\pm0.0035$
  $g_n=+0.638\pm0.020$.
  $|h|$ and $|k|$ ($\sim10^{-2}$) negligible wrt g
- The slope asymmetry is the direct CP–violation quantity: $A_g = (g_+-g_-)/(g_++g_-) \neq 0$
- SM estimates vary within an order of magnitude (few $10^{-6}\ldots8\times10^{-5}$). Models beyond SM predict substantial enhancement.

- Data-taking 2003:
  1.61×10^9 events selected.

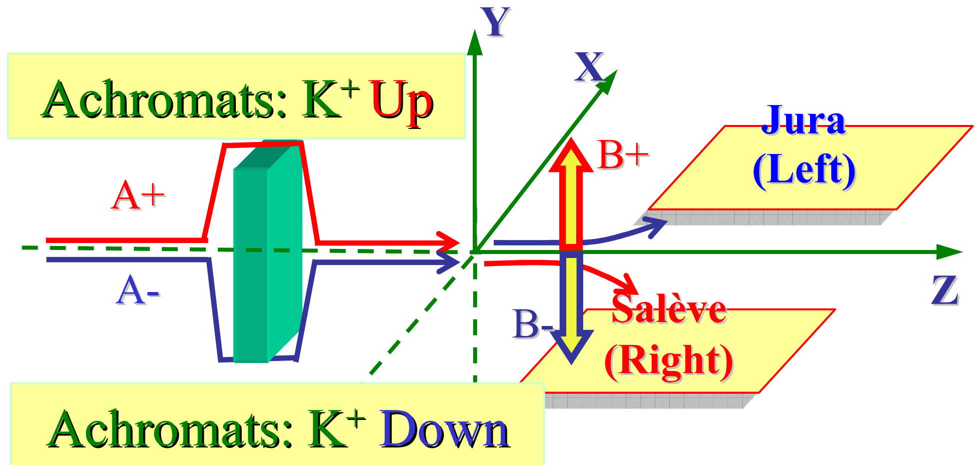
Lorentz-invariants:
$s_i = (P_K-P_{\pi i})^2$, i=1,2,3 (3=odd π);
$s_0 = (s_1+s_2+s_3)/3$;
$u = (s_3-s_0)/m_\pi^2$;
$v = (s_2-s_1)/m_\pi^2$.
Kaon rest frame:
$u = 2m_K\cdot(m_K/3-E_{odd})/m_\pi^2$;
$v = 2m_K\cdot(E_1-E_2)/m_\pi^2$.





Direct CP violation in $K^{\pm}_{3\pi}$ decays

•Careful control of detector (Δg_{LR}) and of beamline (Δg_{UD}) asymmetries.

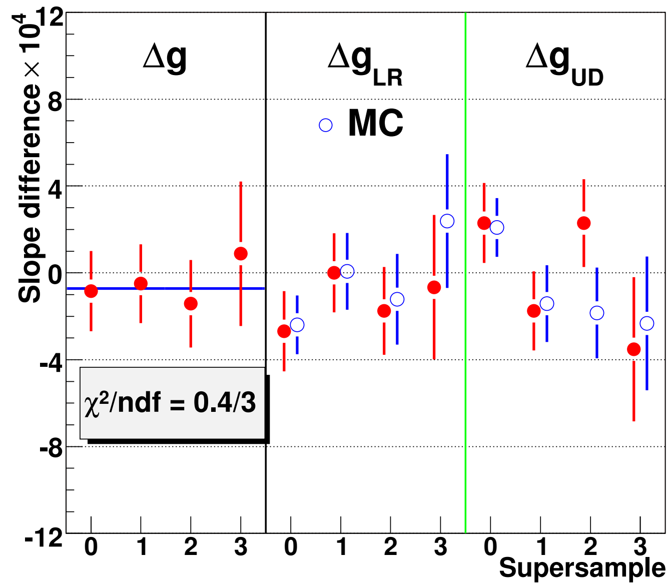


BR($K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-}$)

- Slope difference:
  $\Delta g = (-0.7\pm1.0)\times10^{-4}$
- Charge asymmetry:
  $A_g = (1.7\pm2.9)\times10^{-4}$

BR($K^{\pm}\to\pi^{\pm}\pi^{0}\pi^{0}$): small BR and acceptance, larger slope.

- Slope difference:
  $\Delta g = (2.2 \pm 3.1)\times10^{-4}$
- Charge asymmetry (using g_0=0.638):
  $A^0_g = (1.8 \pm 2.6)\times10^{-4}$

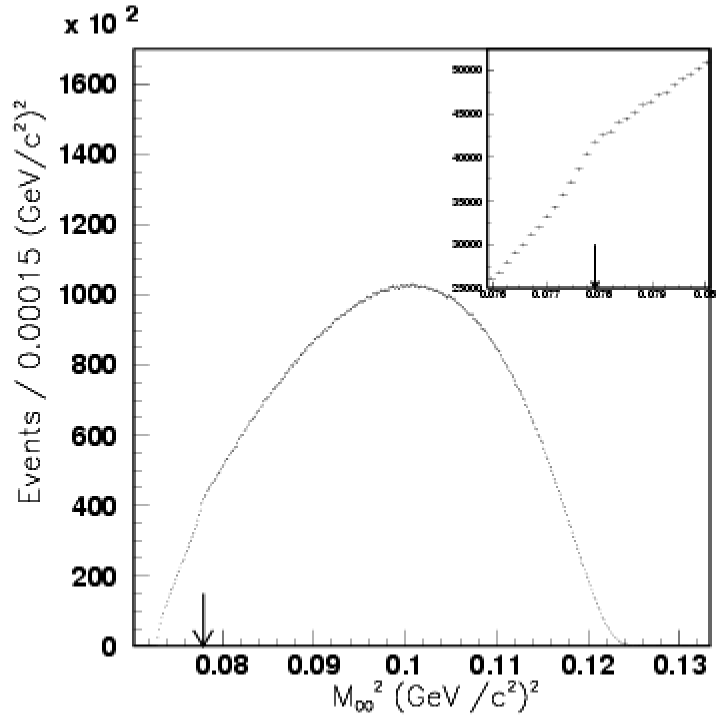


- Errors dominated by statistics
- Order of magnitude improvement

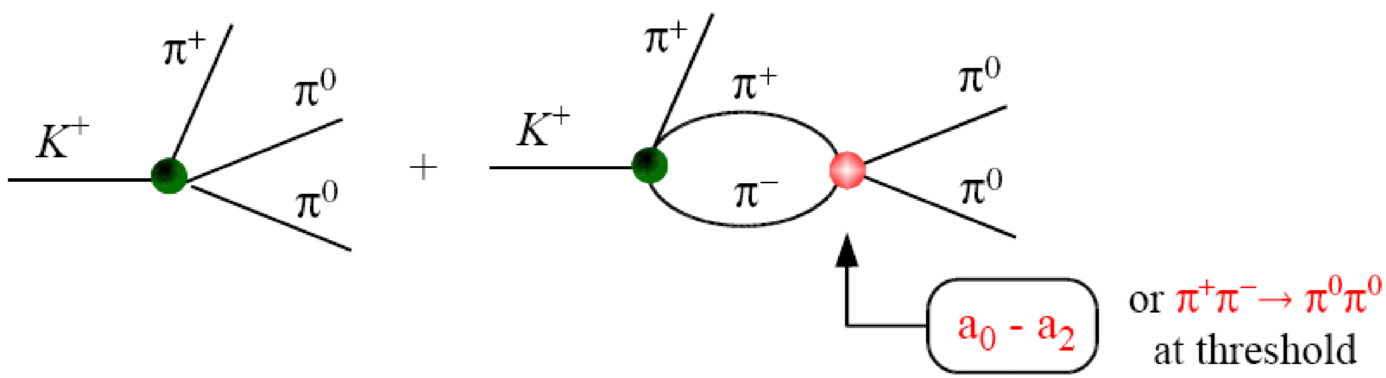
hep-ex/0602014; PLB 634 (2006)

Cusp-like effect in $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$ decays

The high resolution of the NA48/2 experiment has allowed to observe –for the first time– a subtle and interesting phenomenon in $K^{\pm} \rightarrow 3\pi$ decays: anomaly in the $\pi^0\pi^0$ (M^2_{00}) invariant mass distribution in the region $M_{00}=2m_{\pi\pm}$.



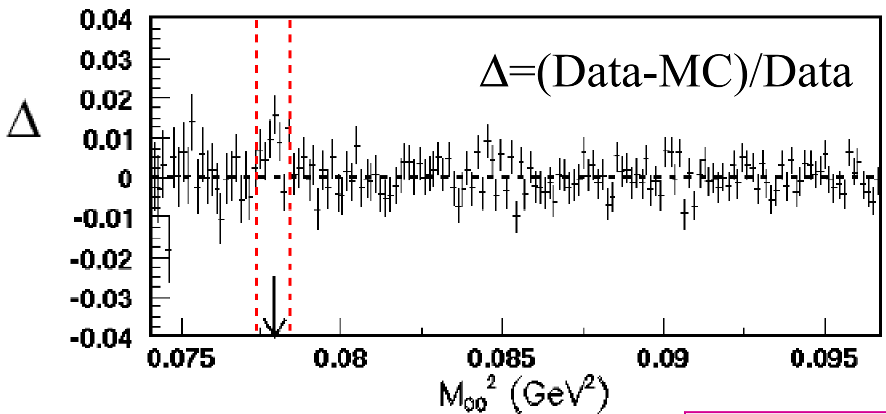
The origin of this discontinuity is due to the following interference/re-scattering effect:

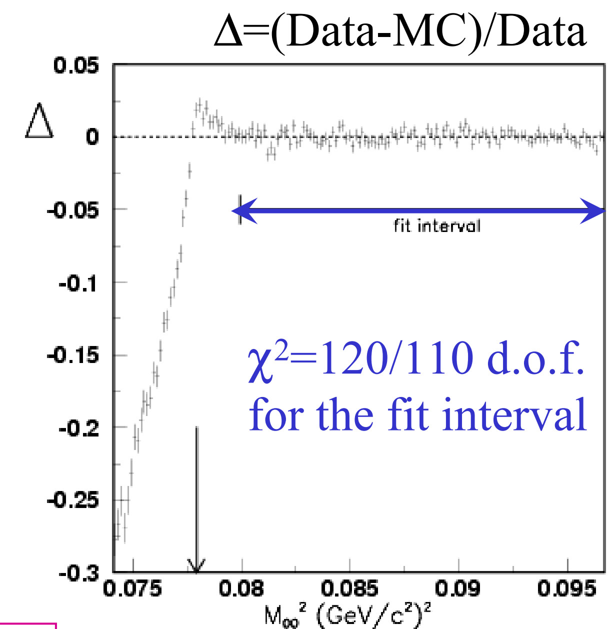


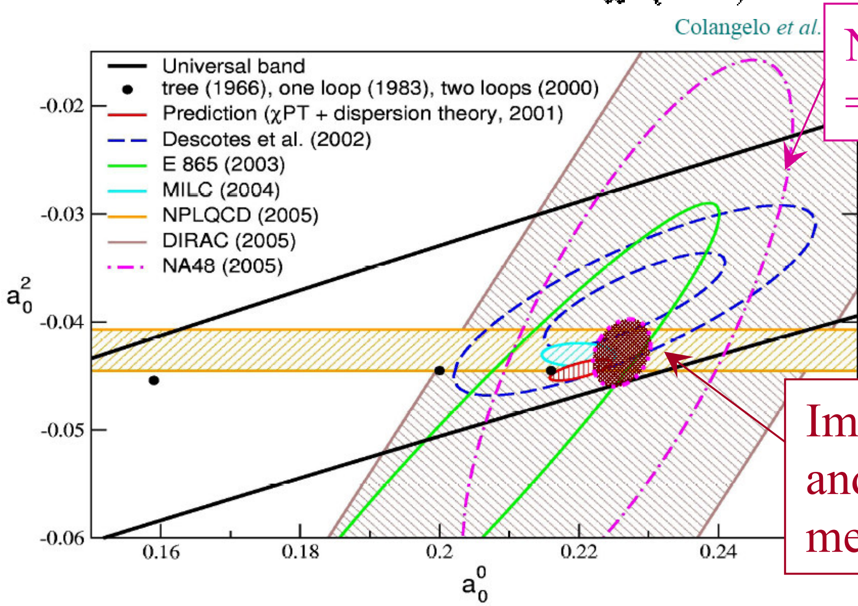
From this effect a new way to measure a_0-a_2, important parameters of the χ_{PT}.

Cusp-like effect in $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0}$ decays

- Without the re-scattering effect: χ^2=13 574/148 d.o.f
- With re-scattering plus pionium: χ^2=141/139 d.o.f







NA48 now: $(a_0\text{-}a_2)m_\pi$ = $0.268(10)_{Stat}(14)_{Th}$

Impact of a_0-a_2 (at 2%) and a_2 (at 5%) measurements.

In a few years this method could provide the most precise determination of S-wave ππ scattering lengths (better than from $K_{\ell 4}$ decays).

Unitarity test of CKM matrix – V_{us}

- Universality of weak interactions + 3 generations:

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

- Most precise **test of unitarity** possible at present comes from 1^{st} row:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \sim |V_{ud}|^2 + |V_{us}|^2 \equiv 1 - \Delta$$

Can test if $\Delta = 0$ at 10^{-3} level:

from super-allowed nuclear β-decays: $2|V_{ud}|\delta V_{ud} = 0.0005$

from semileptonic kaon decays: $2|V_{us}|\delta V_{us} = 0.0009$

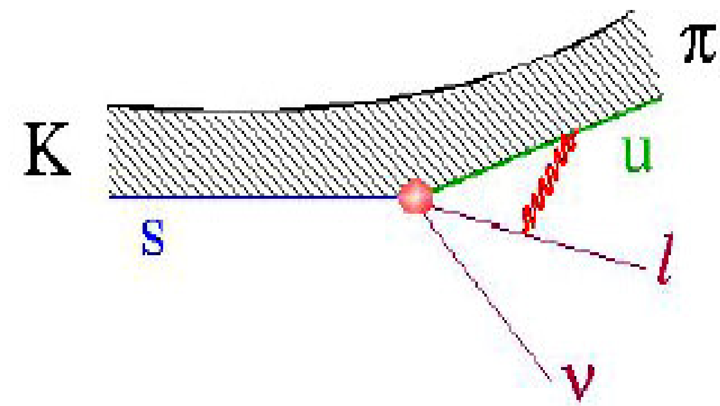
- **Extract $|V_{us}|$ from K_{l3} decays (e.m. effects must be included):**

$$\Gamma(K \to \pi \ell \nu(\gamma)) \propto |V_{us}\, f_+^{K0\pi-}(0)|^2 I(\lambda_t)\, S_{EW}(1 + \delta_{EM} + \delta_{SU(2)})$$

Relative uncertainty: $$\frac{\delta|V_{us}|}{|V_{us}|} = 0.5\,\frac{\delta\Gamma}{\Gamma} \oplus 0.5\,\frac{\delta I(\lambda_t)}{I(\lambda_t)} \oplus \frac{\delta f_+^{K0\pi-}(0)}{f_+^{K0\pi-}(0)}$$

Details on the V_{us} extraction

$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW} (1+\delta_K^\ell) C^2 |V_{us}|^2 f_+^2(0) I_K^\ell$$



Theoretical inputs

- $f_+(0)$ form factor at zero momentum transfer: pure theory calculation (χ_{PT}, lattice) presently known at 1% level.
- S_{EW} short distance corrections (1.0232)
- C = 1 ($2^{-½}$) for neutral (charged) kaon decays
- δ^ℓ_K electromagnetic and isospin breaking ($K^\pm$ only) effects presently known at the 0.1% level.

Experimental inputs

- $I^\ell_K = I(\lambda_+, \lambda_0, 0)$ phase space integral; depends on the decay mode $K^{\pm,0}(e3)$, $K^{\pm,0}(\mu 3)$
- λ_+, λ_0 slopes (momentum dependence of the vector and scalar form factors)
- $\Gamma_{K\ell 3}$ (BR and lifetime)
- **Measure all inputs: branching ratios, lifetimes, and form factors.**

Experimental inputs for V_{us}: 2003-2006

BR($K^{\pm} \to \pi^0 e\nu$)

K_L dominant BR's
K_L semileptonic form factor slopes

BR($K_L \to \pi e\nu$)
K_L semileptonic form factor slopes
BR($K^{\pm} \to \pi^0 e^{\pm}\nu$)

BR($K_S \to \pi e\nu$)
K_L dominant BR's
K_L lifetime
K_Le3 form factor slopes

$K^{\pm}$ semileptonic BR's
BR($K^+ \to \mu^+\nu(\gamma)$)
$K^{\pm}$ lifetime

BR($K^- \to \pi^0 e\nu$)
K^- semileptonic form factor slopes

K physics at KLOE - tagging

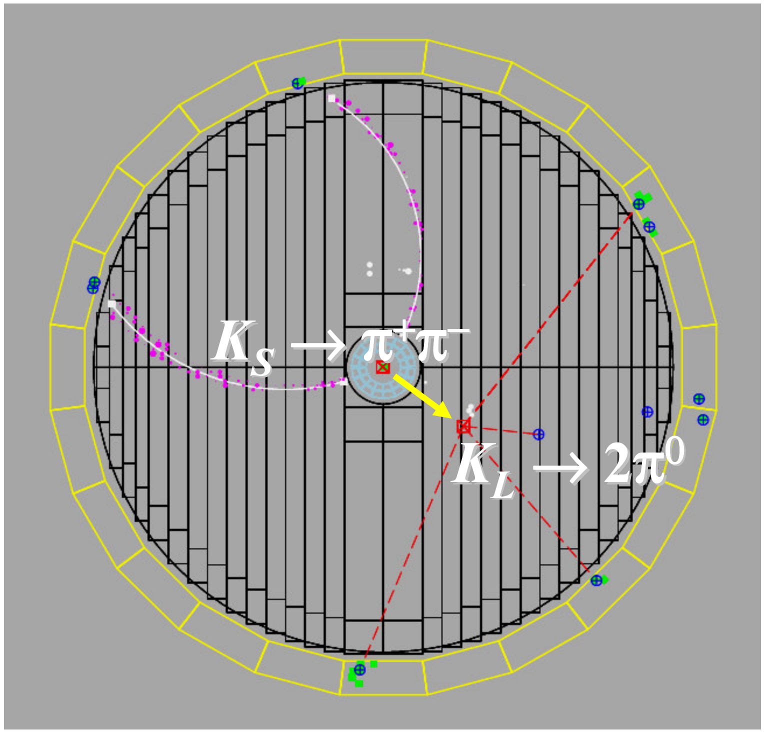
Kaon physics at a ϕ-factory has some peculiar characteristics:

ϕ decay mode	BR
K^+K^-	**49.1%**
K_SK_L	**34.1%**

• K_SK_L (K^+K^-) produced from ϕ are in a pure $J^{PC} = 1^{--}$ state:

$$K_S, K^+ \longleftarrow \phi \longrightarrow K_L, K^-$$

$$\frac{1}{\sqrt{2}}\left(|K_L,\mathbf{p}\rangle|K_S,-\mathbf{p}\rangle - |K_L,-\mathbf{p}\rangle|K_S,\mathbf{p}\rangle\right)$$



• Allows interference measurements of K_SK_L system

• Observation of $K_{S,L}$ signals presence of $K_{L,S}$; $K^{+,-}$ signals $K^{-,+}$

• Allow **absolute** branching ratio measurement, by means of a tag technique.

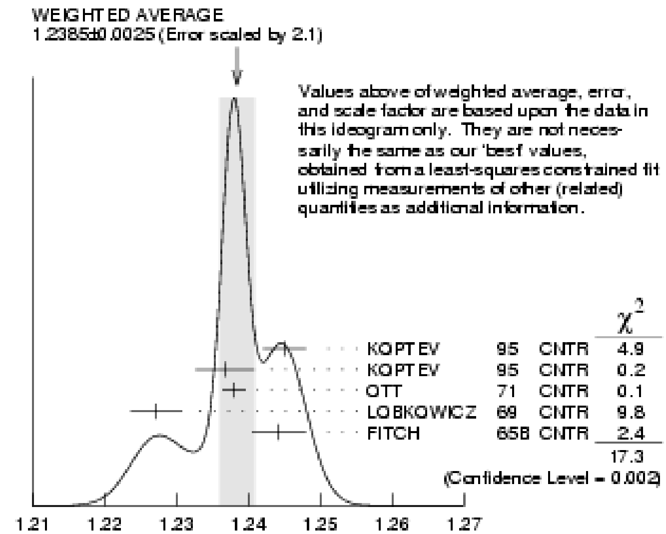
• Pure K_S beam

• $K_{S,L}$ momentum measured from tag kaon ($K_{L,S}$):

$K_{S,L}$ angular resolution: ~ 1°; $K_{S,L}$ momentum resolution: ~ 1 MeV

• Kaon momentum (p_L~110 MeV, $p_\pm$ ~127 MeV) is an excellent lever arm for lifetime measurements (acceptance about 0.5 λ).

$K^{\pm}$ *lifetime*



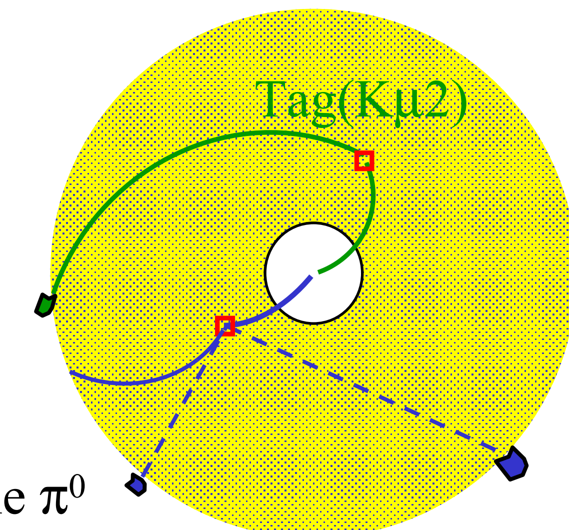
- $\tau_{\pm}$ PDG entries: discrepancies between in-flight and at-rest measurements; discrepancies between different stoppers in at-rest measurements.

Tag events with $K^{\pm} \rightarrow \mu^{\pm}\nu$ decay
Identify a kaon decay vertex on the opposite side

- **1st method: obtain $\tau_{\pm}$ from the K decay length**
  Measure the kaon decay length taking into account the energy loss: $\tau_K = \sum_i \Delta L_i/(\beta_i\gamma_i c)$

$$\boldsymbol{\tau_{\pm} = 12.367 \pm 0.044_{stat} \pm 0.065_{syst}\ \text{ns}}$$

(preliminary)



- **2nd method: obtain $\tau_{\pm}$ from the K decay time**
  Use only $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}$ decays
  Measure the kaon decay time: $\tau_K = (t_\gamma - R_\gamma/c)/\gamma_K$, using the π^0 ***(in progress)***.

Comparison of the two methods allows to keep systematics under control

Dominant K_L BR's and K_L lifetime

- Using also the constraint $\sum BR(K_L) = 1$:

$BR(K_L \to \pi e \nu(\gamma)) = 0.4007 \pm 0.0006_{stat} \pm 0.0014_{syst}$
$BR(K_L \to \pi \mu \nu(\gamma)) = 0.2698 \pm 0.0006_{stat} \pm 0.0014_{syst}$
$BR(K_L \to 3\pi^0) = 0.1997 \pm 0.0005_{stat} \pm 0.0019_{syst}$
$BR(K_L \to \pi^+\pi^-\pi^0(\gamma)) = 0.1263 \pm 0.0005_{stat} \pm 0.0011_{syst}$

Published PLB608(2005) 199 PLB626(2005)15

$\tau_L = 50.72 \pm 0.17 \pm 0.33$ ns

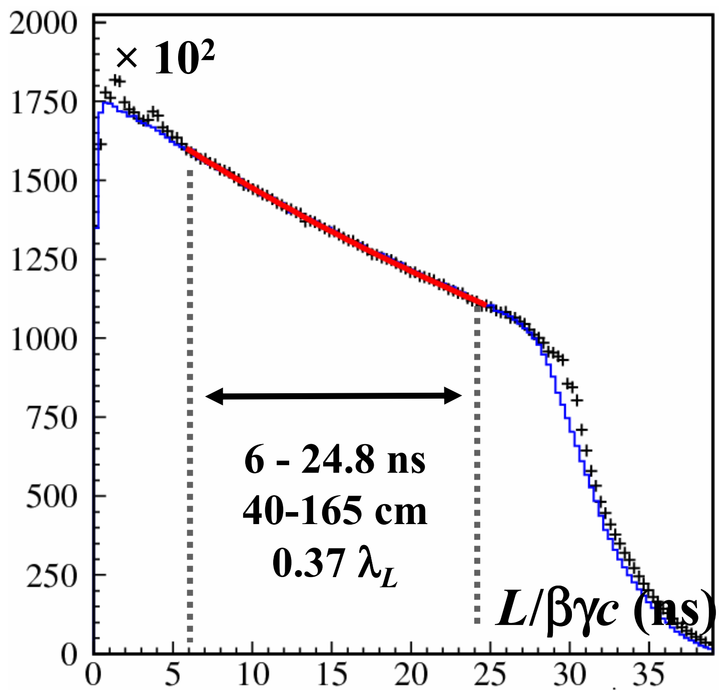
- Direct measurement of K_L lifetime using $K_L \to \pi^0\pi^0\pi^0$ decays:

$\tau_L = 50.92 \pm 0.17 \pm 0.25$ ns

- Average of KLOE results:

$\tau_L = 50.84 \pm 0.23$ ns

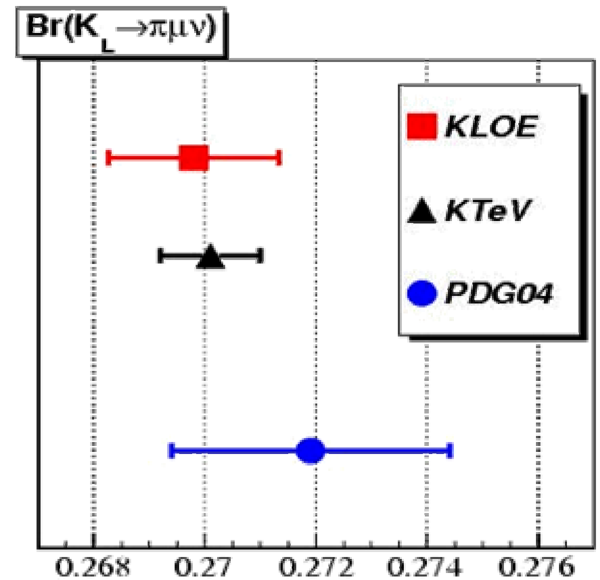
- cf .Vosburg'72: $\tau_L = 51.54 \pm 0.44$ ns, a factor ×2 better



K_L semileptonic branching ratios

KTEV
Kaons at the Tevatron

• KTeV measured 5 K_L decay ratios of 6 decay modes which account for 99.93% of K_L decays
• The ratios can be combined to extract BRs of the 6 main K_L decay modes. (PRD 70 (2004))



NA48

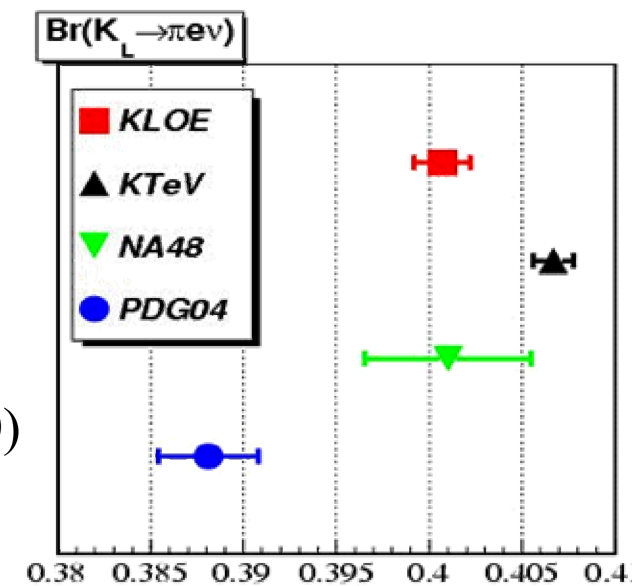
• Preliminary result (HEP2005) with 6×10^6 K_{e3} events.
• Measure ratio of BRs:

$BR(K_L\to\pi e\nu)/BR(2\ track) = 0.4978\pm0.0035$

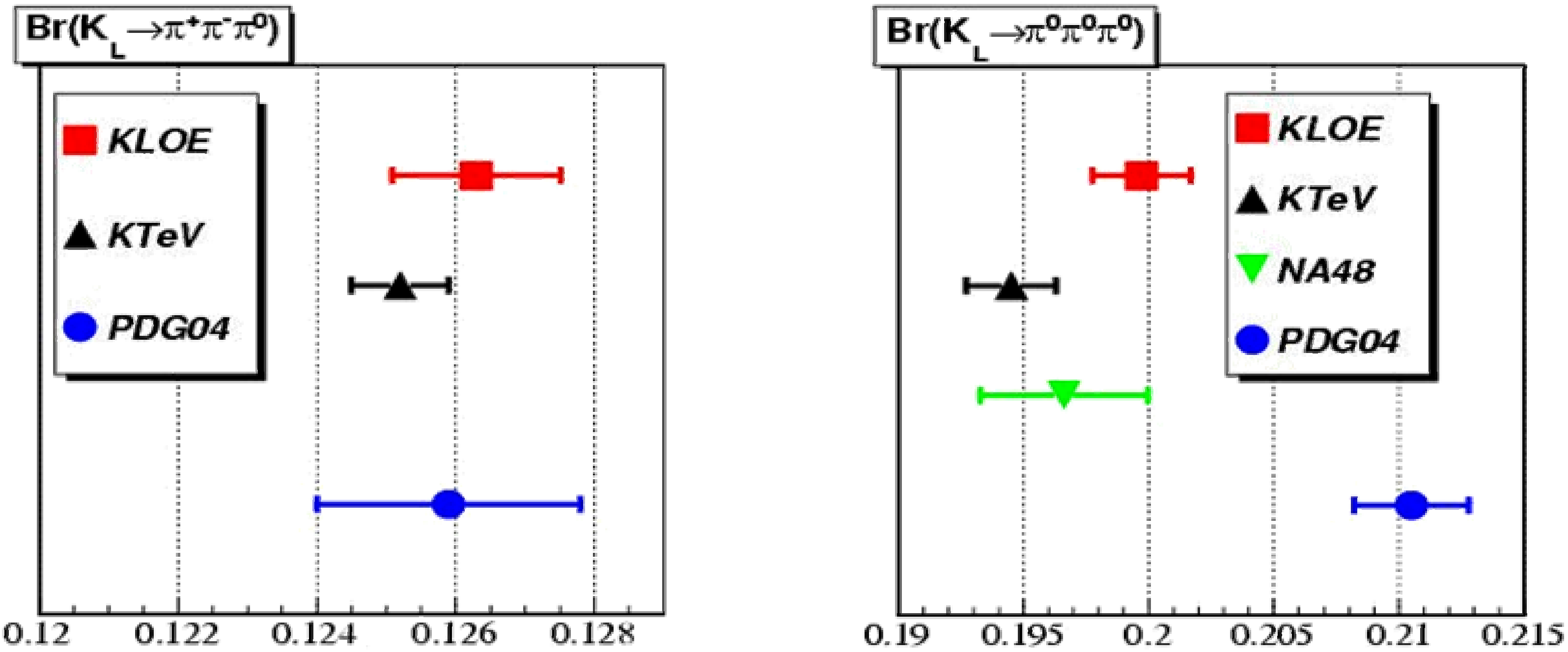
$BR(2\ track) \approx 1\text{-}BR(K_L\to3\pi^0)$

Using PDG-KTeV average for $BR(K_L 3\pi^0) = 0.1992(70)$

$\mathbf{BR(K_L\to \pi e\nu) = 0.4010 \pm 0.0028_{exp} \pm 0.0035_{norm}}$



$K_L \to \pi\pi\pi$ branching ratios



NA48 preliminary measurement of **$BR(K_L \to 3\pi^0)$**

Extracted from $BR(K_L \to 3\pi^0)/BR(K_S \to 2\pi^0)$

$BR(K_L \to 3\pi^0) = 0.1966 \pm 0.0006 \pm 0.0033$ (PDG value for $BR(K_S \to 2\pi^0)$)

$BR(K^{\pm} \rightarrow \pi^0 \ell^{\pm} \nu)$ preliminary results

PDG (pre E865)
$(4.87\pm0.06)\%$
E865(2003)
$(5.13\pm0.10)\%$

KLOE preliminary:

- **Absolute** BR measurement of both $K^{\pm}\rightarrow\pi^0 e^{\pm}\nu$ and $K^{\pm}\rightarrow \pi^0\mu^{\pm}\nu$ decay modes.
- $BR(K^{\pm}\rightarrow\pi^0 e^{\pm}\nu) = (5.047\pm0.019_{stat} \pm0.039_{syst})\%$
- $BR(K^{\pm}\rightarrow\pi^0\mu^{\pm}\nu) = (3.310\pm0.016_{stat} \pm0.045_{syst})\%$

NA48 preliminary:

- Measurement of $BR(K^{\pm} \rightarrow \pi^0 e\nu)/BR(K^{\pm} \rightarrow\pi^{\pm}\pi^0)$
- $BR(K^{\pm}\rightarrow\pi^0 e\nu) = (5.14\pm0.02_{stat}\pm0.06_{syst})\%$

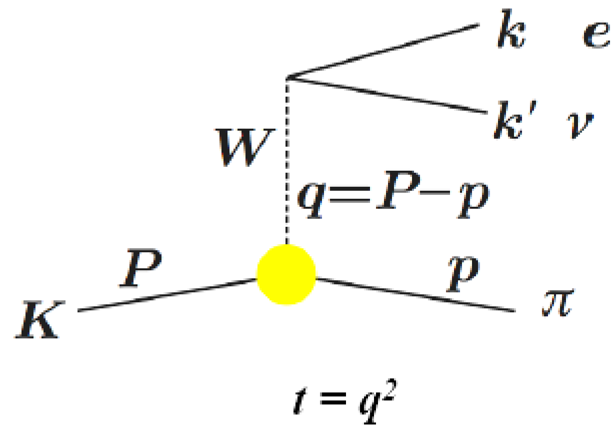
ISTRA+ preliminary:

- Measurement of $BR(K^{-}\rightarrow\pi^0 e^{-}\nu)/BR(K^{-} \rightarrow \pi^{-}\pi^0)$
- $BR(K^{-} \rightarrow \pi^0 e\nu) = (5.22\pm0.11)\%$

<u>Note</u>: **NA48/2** and **ISTRA+** values depend on $BR(K^{\pm} \rightarrow\pi^{\pm}\pi^0)$. Post-PDG'04 results for Ke3 (**E865**) and Kμ2 (**KLOE**) decrease $BR(K^{\pm}\rightarrow\pi^{\pm}\pi^0)$ by ~1% from global fit to $K^{\pm}$ BRs

$K_{\ell 3}$ *form factor slopes*

In the extraction of V_{us}: needed for evaluation of phase-space integrals I^{ℓ}_{K}
Fit of momentum transfer spectrum with different hypothesis on form factor $f_+(t)/f_+(0)$:



Linear: $1 + \lambda_+ t$

Quadratic: $1 + \lambda'_+ t/m^2_{\pi+} + 1/2\, \lambda''_+ (t/m^2_{\pi+})^2$

Pole model: $M_V^2/(M_V^2 - t)$,

Taylor exp. with $\lambda'_+ = (m_\pi/M_V)^2$, $\lambda''_+ = 2\lambda'^2_+$

KLOE Published PLB 636 (2006) 166

- **328 pb^{-1}, 2×10^{6} Ke3 decays**
- Momentum transfer **t measured** from π and K_L momenta: $\sigma_t/m_\pi^2 \sim 0.3$.
- Separate measurement for each charge state ($e^-\pi^+$, $e^+\pi^-$) to check systematics.

Quadratic:

$\lambda'_+ = (25.5 \pm 1.5 \pm 1.0) \times 10^{-3}$

$\lambda''_+ = (1.4 \pm 0.7 \pm 0.4) \times 10^{-3}$

$\rho(\lambda'_+, \lambda''_+) = -0.95$

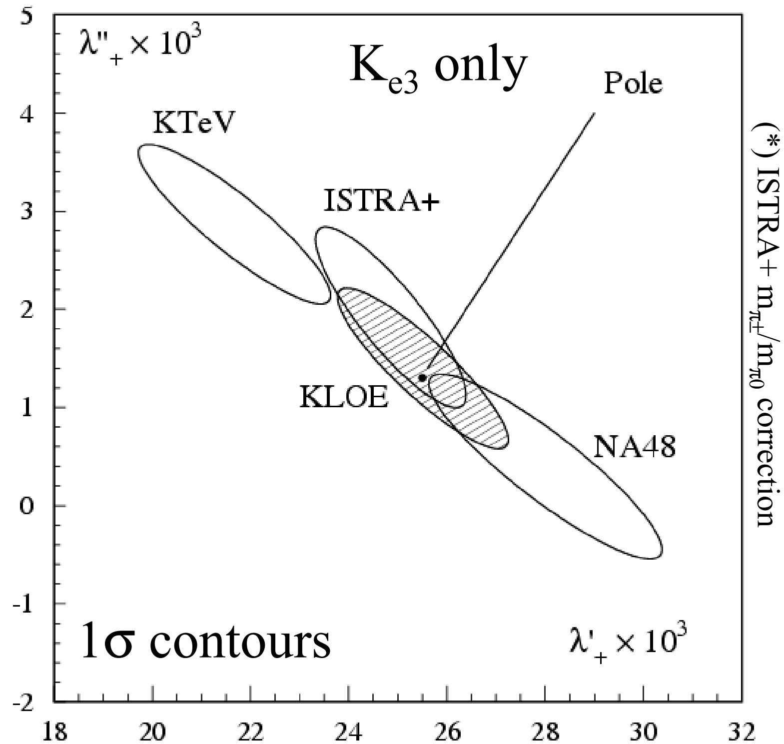
Pole model:

$m_V = (870 \pm 7)$ MeV

$K_{\ell 3}$ form factor slopes

KTeV (PRD 70 (2004))

Measured in K^0_{e3} and $K^0_{\mu 3}$ decays.
Uses quadratic parameterization
Slopes consistent for the two decay modes
$\lambda_0 = (13.72 \pm 1.31) \times 10^{-3}$



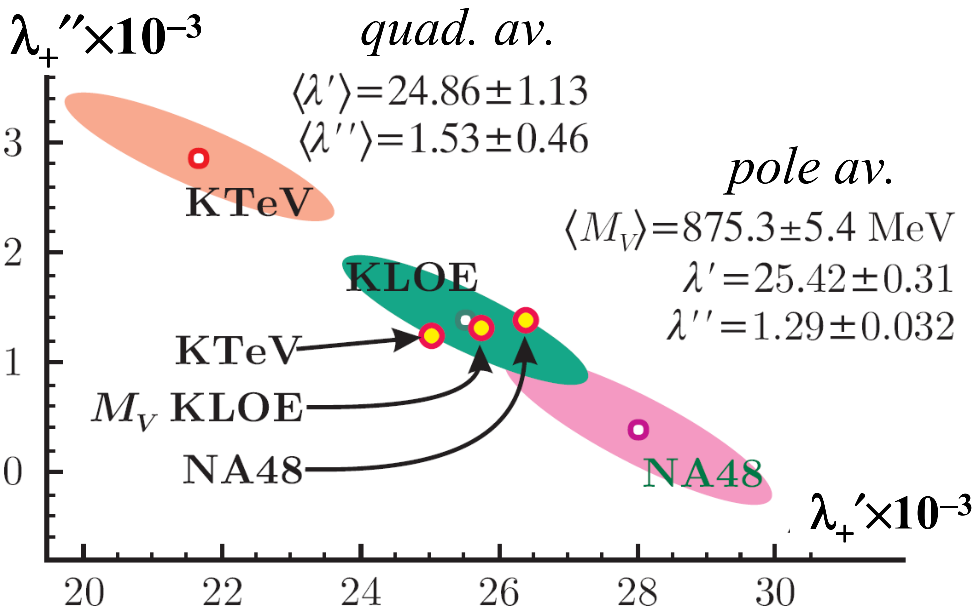
NA48 preliminary (HEP2005) 289

K^0_{e3} and $K^0_{\mu 3}$ Linear fit
no evidence for quadratic term
$\lambda_0 = (12.0 \pm 1.7) \times 10^{-3}$
compatible with KTeV

ISTRA+ (PLB 581 (2004), PLB 589 (2004))

$K^{\pm}_{e3}$ quadratic fit
2σ significance for the non linear term
$K^{\pm}_{\mu 3}$ quadratic fit $\lambda_0 = (17.11 \pm 2.31) \times 10^{-3}$

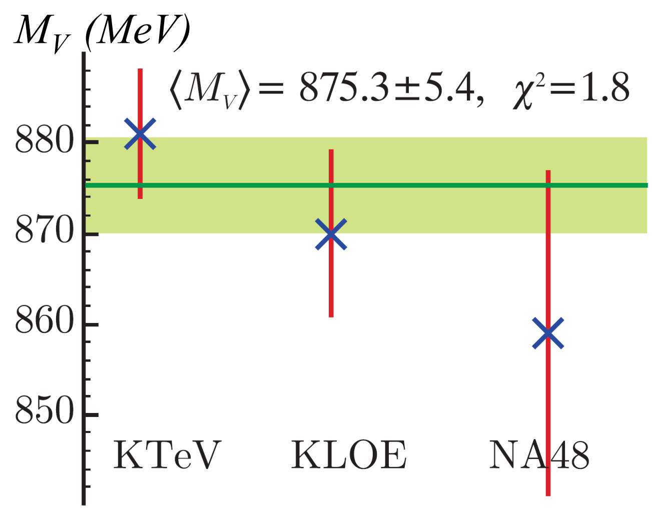
K_{Le3} form factor slopes



Good agreement between experiments, if correlation between λ' and λ'' is taken into account:

- quad $\chi^2/\text{dof} = 4.4/4$
- pole $\chi^2/\text{dof} = 1.8/2$

plots: P. Franzini courtesy

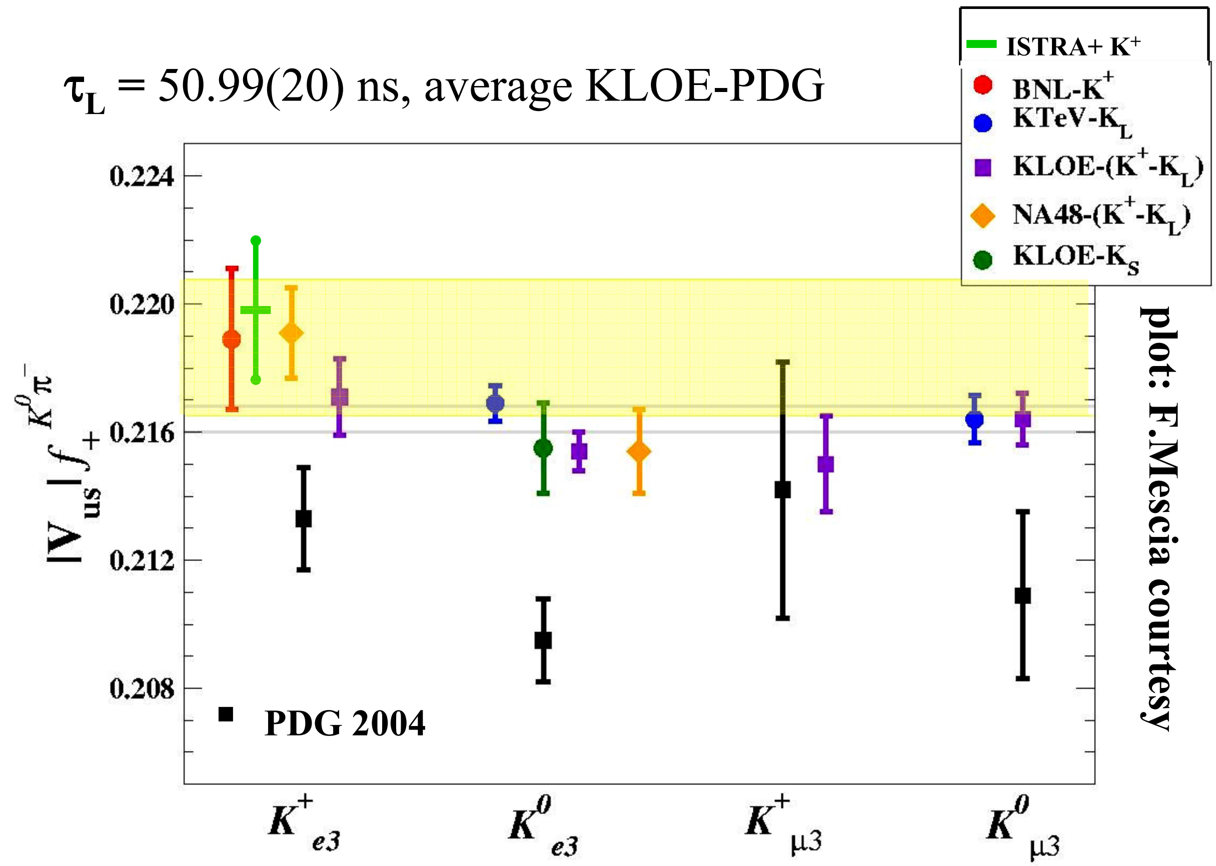


- Phase space integral $I(\lambda)$ depends on the parameterization:

	$(I_{Pole}-I_{Quad})/\ I_{Quad}$
KLOE	0.5×10^{-3}
KTeV	6.0×10^{-3}
World av.	0.3×10^{-3}

V_{us} from all results

τ_L = 50.99(20) ns, average KLOE-PDG



$<V_{us}\times f_+(0)>_{\text{WORD AV.}}$ **= 0.2164(4)**

- CKM unitarity within ~ 1σ

Slopes

$\lambda'_+ = 0.02542(31)$

$\lambda''_+ = 0.00129(3)$

(Pole model: KLOE, KTeV, and NA48 av.)

$\lambda_0 = 0.01587(95)$

(KTeV and ISTRA+ av.)

From unitarity

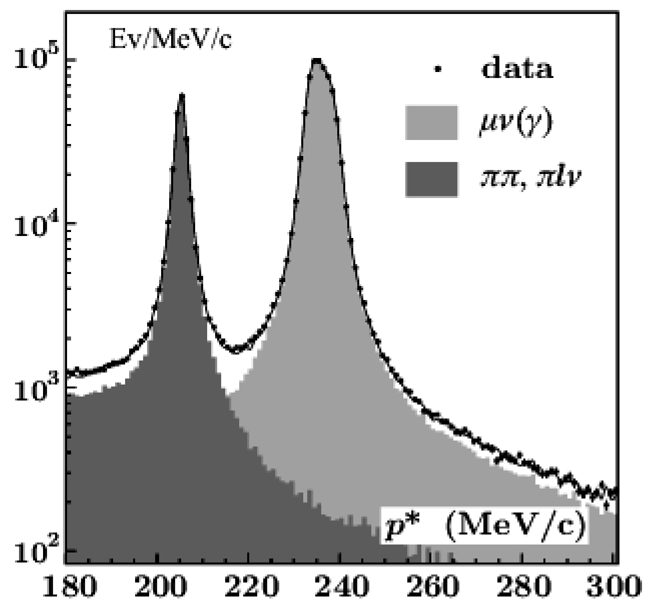
- $f_+(0)$=0.961(8)
  Leutwyler and Roos Z. [Phys. **C25**, 91, 1984]
- V_{ud}=0.97377(27)
  Marciano and Sirlin [Phys.Rev.Lett.96 032002,2006]

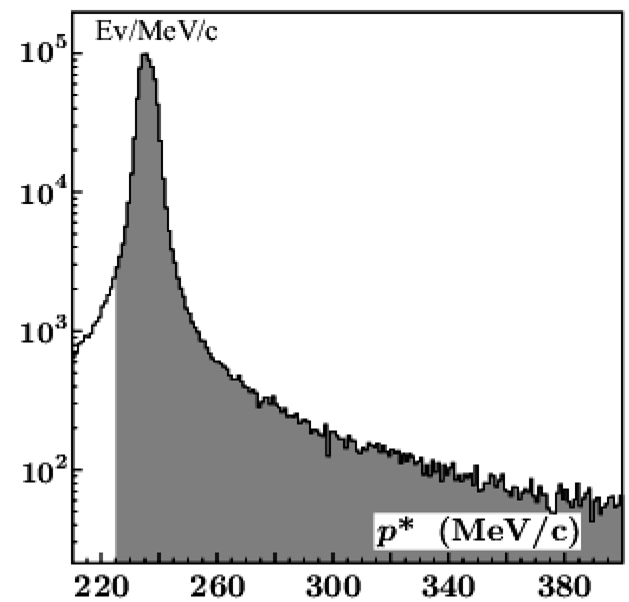
$V_{us}\times f_+(0)$ =0.2187(22)

Measurement of $BR(K^+ \to \mu^+ \nu(\gamma))$

- The ratio $|\mathbf{V}_{us}|/|\mathbf{V}_{ud}|$ can be extract from the ratio of μ2 decays of kaons and pions: $\boldsymbol{\Gamma(K \to \mu\nu(\gamma))/\Gamma(\pi \to \mu\nu(\gamma)) \propto |V_{us}|^2/|V_{ud}|^2 f_K^2/f_\pi^2}$
- From lattice calculations: $f_K/f_\pi = 1.198(3)(^{+16}{}_{-5})$ (MILC Coll. PoS (LAT2005) 025)
- Kℓ3−independent $\mathbf{V}_{us}$ determination

- Tag from $K^- \to \mu^- \nu$. Subtraction of $\pi^+\pi^0$, $\pi^0 l^+ \nu$ background.
- Count events in (225,400) MeV window of the momentum distribution in K rest frame.





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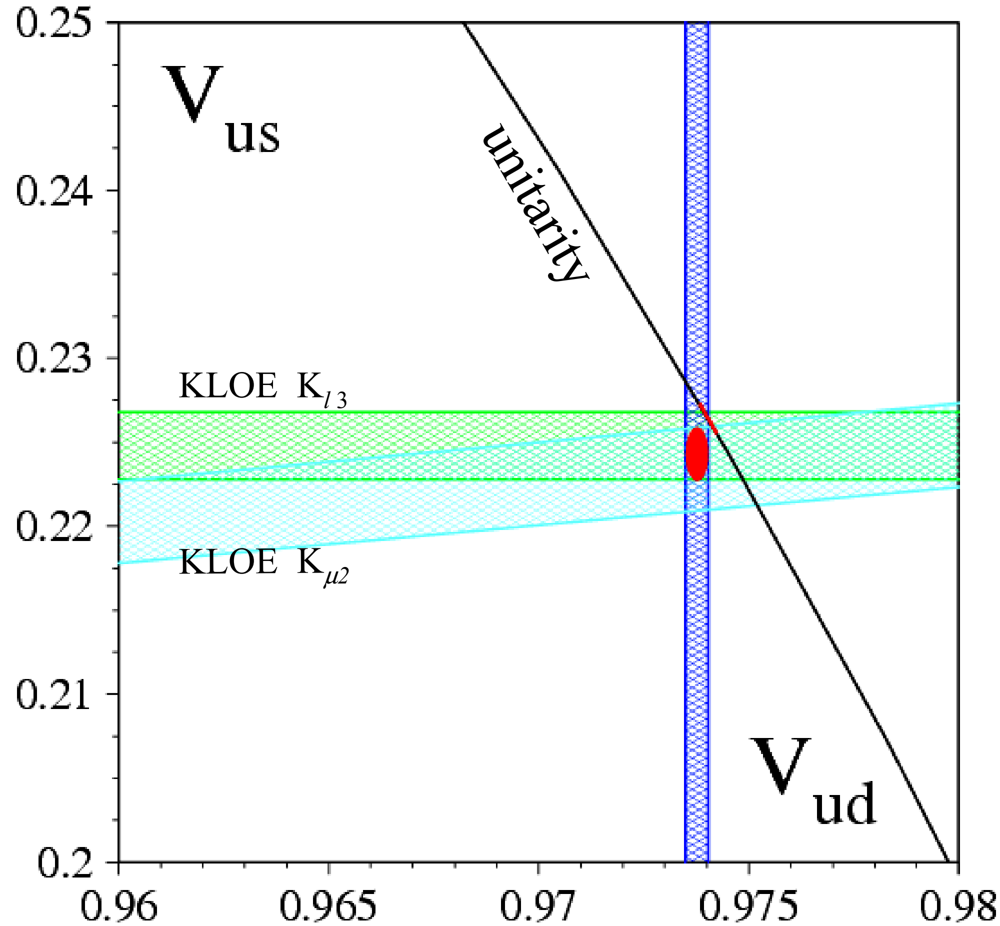
$$\mathbf{BR(K^+ \to \mu^+\nu(\gamma)) = 0.6366 \pm 0.0009_{stat.} \pm 0.0015_{syst.}}$$

The $V_{us} - V_{ud}$ plane

- Using f_K/f_π=1.198(3)($^{+16}_{-5}$) from MILC Coll. (2005) and KLOE BR($K^+ \to \mu^+\nu$) we get V_{us}/V_{ud} = 0.2294 ± 0.0026

- V_{us} = 0.2248 ± 0.0020
  K_{l3} KLOE, using $f_+(0)$=0.961(8)
- V_{ud} = 0.97377 ± 0.00027
  Marciano and Sirlin
  Phys.Rev.Lett.96 032002,2006



Fit of the above results:

V_{us} = 0.2242 ± 0.0016
V_{ud} = 0.97377 ± 0.00027
$P(\chi^2)$ = 0.8

Fit assuming unitarity:

V_{us} = 0.2264 ± 0.0009
$P(\chi^2)$ = 0.1

CPT symmetry

• CPT symmetry is linked to the basic mathematical tools that we use in particle physics: QFT + Lorentz invariance + Locality $\rightarrow$ CPT

• These tools have intrinsic limitations (we are not able to include gravity in a consistent way) and we should expect CPT violation at some level

• It's hard to define a reference scale/size for CPT violation (no consistent and predictive theory without these tools)

• Phenomenologically driven search i.e. reference scale set by the most significant experimental bounds

• The **neutral kaon system** is an ideal testing ground:

- Charge asymmetries of the semileptonic decays.
- The unitarity (Bell-Steinberger) relation.

The unitarity and the Bell-Steinberger relation

Even if CPT is violated, we can assume that unitarity (i.e. the conservation of the probability) is conserved.

$$\Gamma_{K^0} = \Gamma_{11} = \sum_f \mathcal{A}(K^0 \to f)\mathcal{A}(K^0 \to f)^*$$
$$\Gamma_{\bar{K}^0} = \Gamma_{22} = \sum_f \mathcal{A}(\bar{K}^0 \to f)\mathcal{A}(\bar{K}^0 \to f)^*$$
$$\Gamma_{12} = \sum_f \mathcal{A}(K^0 \to f)\mathcal{A}(\bar{K}^0 \to f)^*$$
$$\Gamma_{21} = \sum_f \mathcal{A}(\bar{K}^0 \to f)\mathcal{A}(\bar{K} \to f)^*$$

Expressing the neutral kaon decay amplitudes in the K_L-K_S basis: $\mathbf{K_S \propto K_+ + (\varepsilon-\delta)K_-}$; $\mathbf{K_L \propto K_- + (\varepsilon+\delta)K_+}$,
ε and δ: CP and CPT violation parameters

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

This is an exact relation: phase convention independent, no approximations in the CPT limit (δ treated as small parameter and expanded to 1st non trivial order).

- Experimental inputs: Γ_S, Γ_L, m_S, m_L, and α_f.

$$\phi_{SW} = \arctan\left[\frac{2(m_L - m_S)}{\Gamma_S - \Gamma_L}\right] \approx 43.4^0$$

- Two physical outputs: $\mathcal{Re}\,\varepsilon$ and $Im\,\delta$:

If $Im\,\delta \neq 0$: CPT violation, unitarity violation, new exotic invisible final sates.

$$\delta = \frac{i(m_{K_0} - m_{\overline{K}_0}) + \frac{1}{2}(\Gamma_{K_0} - \Gamma_{\overline{K}_0})}{\Gamma_S - \Gamma_L}\cos\phi_{SW} e^{i\phi_{SW}}[1 + O(\epsilon)]$$

- If $\Delta\Gamma$=0 (CPT conserved in the decay): $|\Delta m/m_{K0}| \approx 3\times 10^{-14}\,|Im\,\delta|$

Details on definition of decay amplitudes

$$\left[\frac{\Gamma_S+\Gamma_L}{\Gamma_S-\Gamma_L}+i\tan\phi_{SW}\right]\frac{Re(\epsilon)-iIm(\delta)}{1+|\epsilon^2|}=\sum_f \alpha_f$$

ππ decays: $\alpha_{+-}=\eta_{+-}\ \mathbf{Br(K_S\to\pi^+\pi^-)}$

$\alpha_{00}=\eta_{00}\ \mathbf{Br(K_S\to\pi^0\pi^0)}$

$\alpha_{+-\gamma}=\eta_{+-\gamma}\ Br(K_S\to\pi^+\pi^-\gamma)$

πππ decays: $\alpha_{+-0}=\tau_S/\tau_L\ \eta_{+-0}^*\ Br(K_L\to\pi^+\pi^-\pi^0)$

$\alpha_{000}=\tau_S/\tau_L\ \eta_{000}^*\ Br(K_L\to\pi^0\pi^0\pi^0)$

CPT-violation in decay

Semileptonic decays: $\alpha_{kl3}=2\tau_S/\tau_L\ Br(K_L l3)\ [\mathcal{Re}\,\varepsilon-\mathcal{Re}\,\boldsymbol{y}-i(\,Im\,\delta+Im\,x_+)]$

$=2\tau_S/\tau_L\ Br(K_L l3)\ [\,(\mathbf{A_S}+A_L)/4-i(\,Im\,\delta+Im\,\boldsymbol{x_+})]$

from "($\mathbf{A_S}-A_L$) and CPLEAR"

Other decays contribute less than 10^{-6}

Inputs to B-S relation

input	value	Used sources
τ_S	0.08958 ± 0.00006 ns	PDG (*) [3]
τ_L	50.84 ± 0.23 ns	KLOE [4,5]
$\Gamma(K_S \to \pi^+\pi^-)/\Gamma(K_S \to \pi^0\pi^0)$	2.2549 ± 0.0054	KLOE [6]
$BR(K_L \to \pi^+\pi^-)$	$(1.965 \pm 0.010) \times 10^{-3}$	KLOE [7], KTeV [8]
$BR(K_L \to \pi^0\pi^0)$	$(0.865 \pm 0.010) \times 10^{-3}$	KTeV [8]
$BR(K_S \to \pi^+\pi^-\gamma)_{DE}$	$< 1.8 \times 10^{-4}$ 95%CL	E731 [11]
$BR(K_L \to \pi^+\pi^-\gamma)_{DE}$	$(31 \pm 1) \times 10^{-6}$	KTeV [10]
$BR(K_L \to \pi l \nu)$	0.6705 ± 0.0022	KLOE [5]
η_{+-0}	$(-2 \pm 7)10^{-3} + i(-2 \pm 9)10^{-3}$	CPLEAR [13]
$BR(K_L \to \pi^+\pi^-\pi^0)$	0.1263 ± 0.0012	KLOE [5]
$BR(K_S \to 3\pi^0)$	$< 1.2\ 10^{-7}$ 90%CL	KLOE [12]
$BR(K_L \to 3\pi^0)$	0.1997 ± 0.0020	KLOE [5]
Φ_{+-}	$(43.4 \pm 0.7)^\circ$	PDG (*) [3]
Φ_{00}	$(43.7 \pm 0.8)^\circ$	PDG (*) [3]
Φ_{SW}	$(43.51 \pm 0.06)^\circ$	PDG [3]
$\Phi^{000}, \Phi^{+-\gamma}$	$[0, 2\pi]$	
A_L	$(3.32 \pm 0.06) \times 10^{-3}$	PDG [3]
A_S	$(1.5 \pm 10.0) \times 10^{-3}$	KLOE [14]
$Im(x_+)$	$(0.8 \pm 0.7) \times 10^{-3}$	CPLEAR [13], KLOE [14], PDG [3]

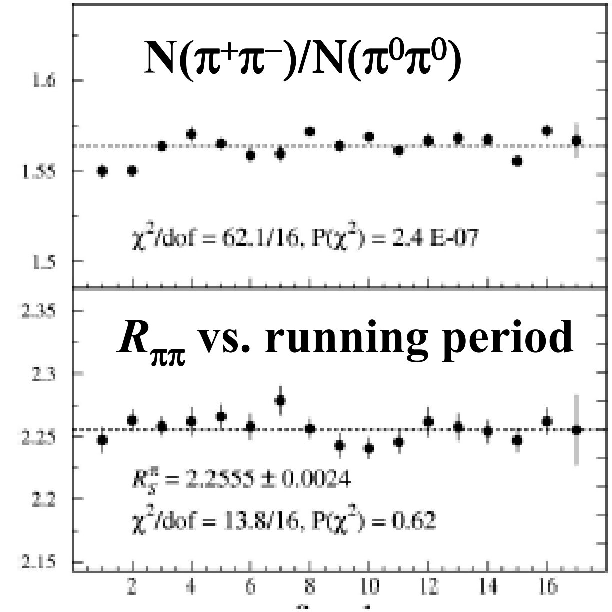
- 2006 results
- Quantities evaluated without assuming CPT invariance.
- $Im\, x_+ = (1.2 \pm 2.2) \times 10^{-2}$ by CPLEAR.
  A combined fit of CPLEAR data with KLOE-KTeV ($A_S - A_L$) gives a ×3 improvement
  $Im\, x_+ = (0.8 \pm 0.7) \times 10^{-2}$

K_S physics

$BR(K_S \to \pi^+\pi^-(\gamma))/BR(K_S \to \pi^0\pi^0)$

- Fixes $BR(K_S \to \pi^+\pi^-(\gamma))$, used to normalize $BR(K_S \to \pi e \nu)$

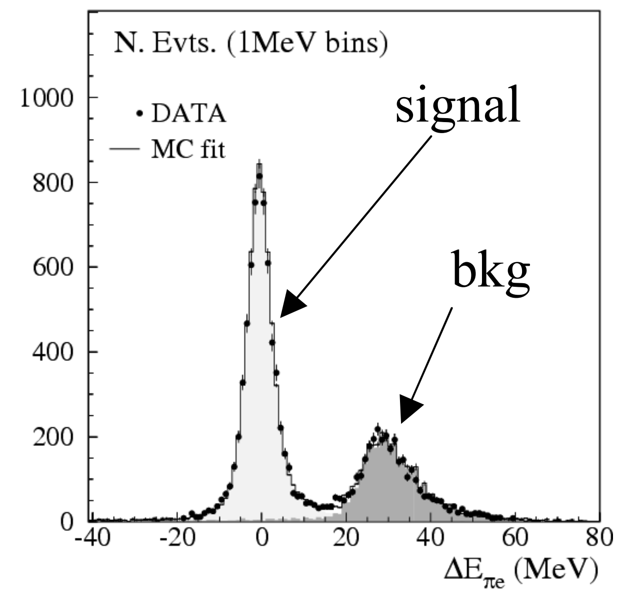
$R_{\pi\pi}$ = 2.2549±0.0054 (hep-ex/0601025, subm. EPJC)
Fractional error 0.24%



$BR(K_S \to \pi^\pm e^\pm \nu)/BR(K_S \to \pi^+\pi^-(\gamma))$

- TOF e/π identification, fit to E_{miss}-P_{miss} spectrum
- Normalize to $\pi^+\pi^-$ counts in the same dataset.
- Separate measurement for each charge state ($e^-\pi^+$,$e^+\pi^-$)

$BR(\pi e \nu) = (7.046 \pm 0.077 \pm 0.049) \times 10^{-4}$
Fractional error 1.3% = $1.1\%_{STAT} \oplus 0.7\%_{SYST}$
K_{Se3} form factor slope: $\lambda_+ = (33.9 \pm 4.1) \times 10^{-3}$
First measurement, compatible with K_L



CPT test from A_S and A_L

• Sensitivity to CPT violating effects through charge asymmetry of the semileptonic neutral kaon decays:

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

$$A_S = 2(\mathrm{Re}\,\varepsilon + \mathrm{Re}\,\delta - \mathrm{Re}\,y + \mathrm{Re}\,x_-)$$
$$A_L = 2(\mathrm{Re}\,\varepsilon - \mathrm{Re}\,\delta - \mathrm{Re}\,y - \mathrm{Re}\,x_-)$$

• A_L already measured by KTeV (2002): $A_L = (3.322 \pm 0.058 \pm 0.047)\ 10^{-3}$

• **A_S measured for the first time by KLOE (2006): $A_S = (1.5 \pm 9.6 \pm 2.9)\ 10^{-3}$**

• $A_S - A_L = 4(\mathrm{Re}\,\delta + \mathrm{Re}\,x_-) \neq 0$ implies CPT and $\Delta S = \Delta Q$ rule violation

Re δ: CPLEAR $\sigma = 3.4 \times 10^{-4}$

Re $x_- = (-0.8 \pm 2.5)\ 10^{-3}$

Factor 5 of improvement wrt current most precise measurement: CPLEAR, $\sigma = 1.3 \times 10^{-2}$

• $A_S + A_L = 4(\mathrm{Re}\,\varepsilon - \mathrm{Re}\,y) \neq 0$ implies CPT violation

Re ε from PDG not assuming CPT

Re $y = (0.4 \pm 2.5)\ 10^{-3}$

Comparable with best result: CPLEAR from unitarity, $\sigma = 3.1 \times 10^{-3}$.

$BR(K_L \rightarrow \pi^+\pi^-(\gamma_{IB+DE}))$

KLOE: PID using decay kinematics.

Normalize to $K_L\mu3$ events

$BR(K_L \rightarrow \pi^+\pi^-(\gamma_{IB+DE})) = (1.963 \pm 0.021) \times 10^{-3}$ PLB638

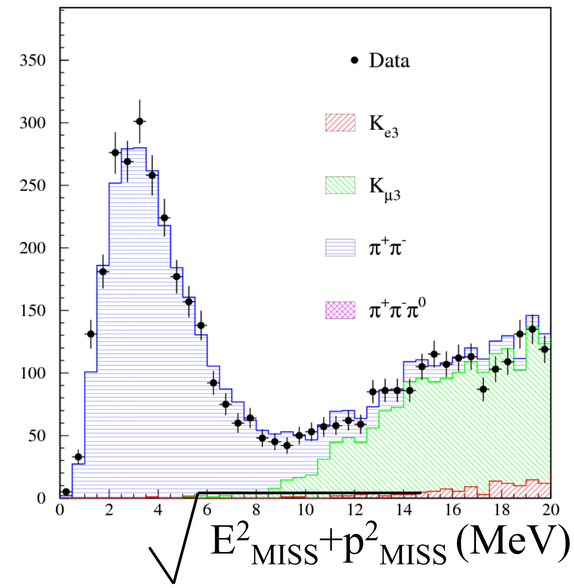
Fractional error 1.1% = $0.6\%_{STAT} \oplus 0.9\%_{SYST}$

In agreement with KTeV 2004 BR = $1.975(12) \times 10^{-3}$

It confirms the 4σ discrepancy with PDG04

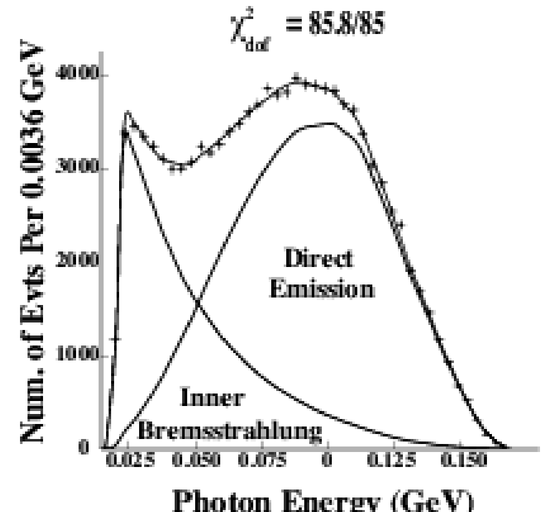
$|\eta_{+-}| = (2.216 \pm 0.013) \times 10^{-3}$

$BR(K_S \rightarrow \pi\pi)$ and τ_L from KLOE, τ_S from PDG04



$BR(K_L \rightarrow \pi^+\pi^-(\gamma_{DE}))$

- 1997 dataset of E832 (collected during ε'/ε data taking)
- After all analysis cuts 112.1×10^3 candidates with an estimated background of 671 events, mostly $K_L\mu3$ and K_Le3 decays.
- $BR(K^0_L \rightarrow \pi^+\pi^-(\gamma_{DE})) = (29 \pm 1) \times 10^{-6}$; hep-ex/0604035 (subm. PLB)



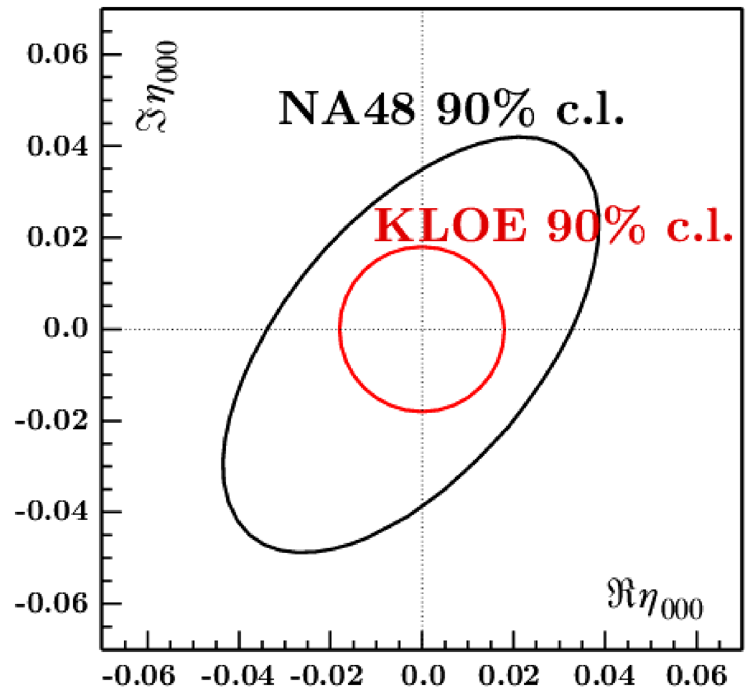
$K_S \to \pi^0\pi^0\pi^0$ decays

Observation of $K_S \to 3\pi^0$ signals CP violation in mixing and/or decay:

SM prediction: $\Gamma_S = \Gamma_L|\eta|^2$, giving $BR(K_S \to 3\pi^0) = 1.9\times10^{-9}$

NA48: Measures directly η_{000} through the $K\to3\pi^0$ rate as a function of the proper time.

- $\eta_{000} = (-0.002\pm0.019) + i\,(-0.003\pm0.021)$



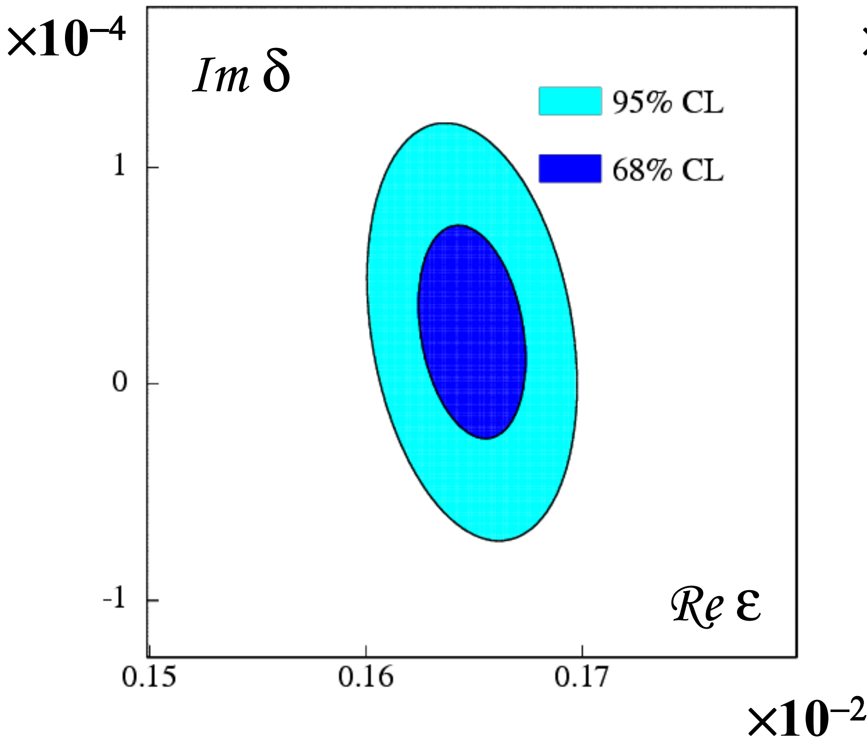
KLOE:

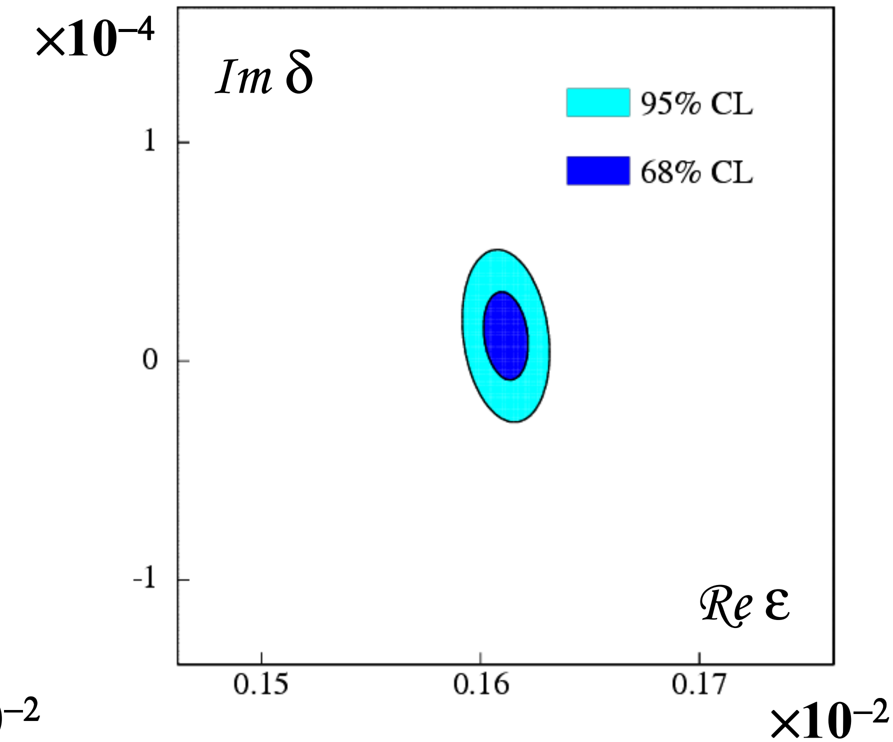
- Direct search for $K_S\to3\pi^0$ decays
- Normalize to the $K_S\to2\pi^0$ in the same data sample
- $BR(K_S\to3\pi^0) \le 1.2\times10^{-7}$, 90% C.L.
- $\eta_{000} \le 0.018$

$$\alpha_{000}= \tau_S/\tau_L\, \eta_{000}^{*}\, B(K_L\to\pi^0\pi^0\pi^0) \le 0.010,\ 95\%\ \text{C.L.}$$

CPT test from unitarity: result

$$\left[\frac{\Gamma_S+\Gamma_L}{\Gamma_S-\Gamma_L}+i\tan\phi_{SW}\right]\frac{Re(\epsilon)-iIm(\delta)}{1+|\epsilon^2|}=\sum_f \alpha_f$$





CPLEAR:

$Re\,\varepsilon = (164.9 \pm 2.5)\ 10^{-5}$

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

KLOE:

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

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

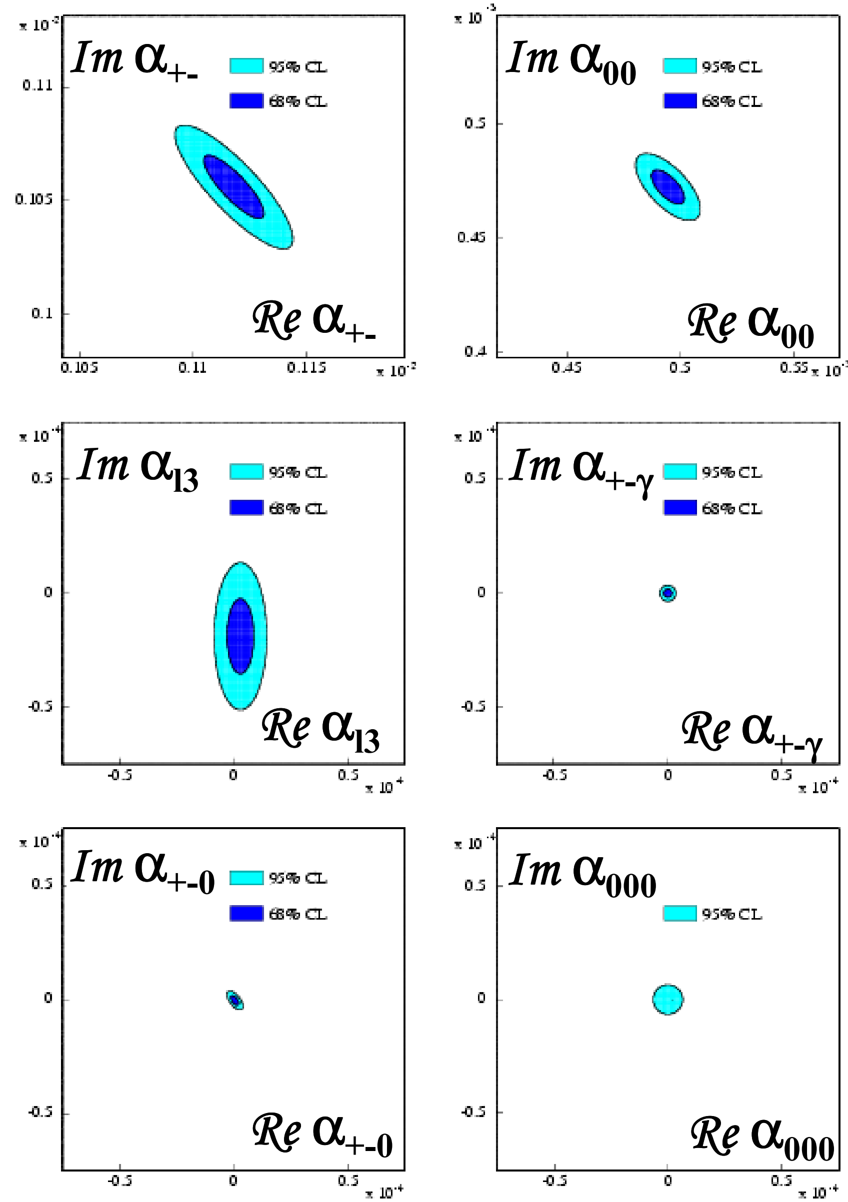
Inputs to B-S: summary

- Before, the accuracy on *Re* ε and *Im* δ was dominated by the poor knowledge of η_{000}

- Thanks to the KLOE measurements of η_{000} and A_S, the accuracy on *Re* ε and *Im*δ improved of a factor ~2.5.

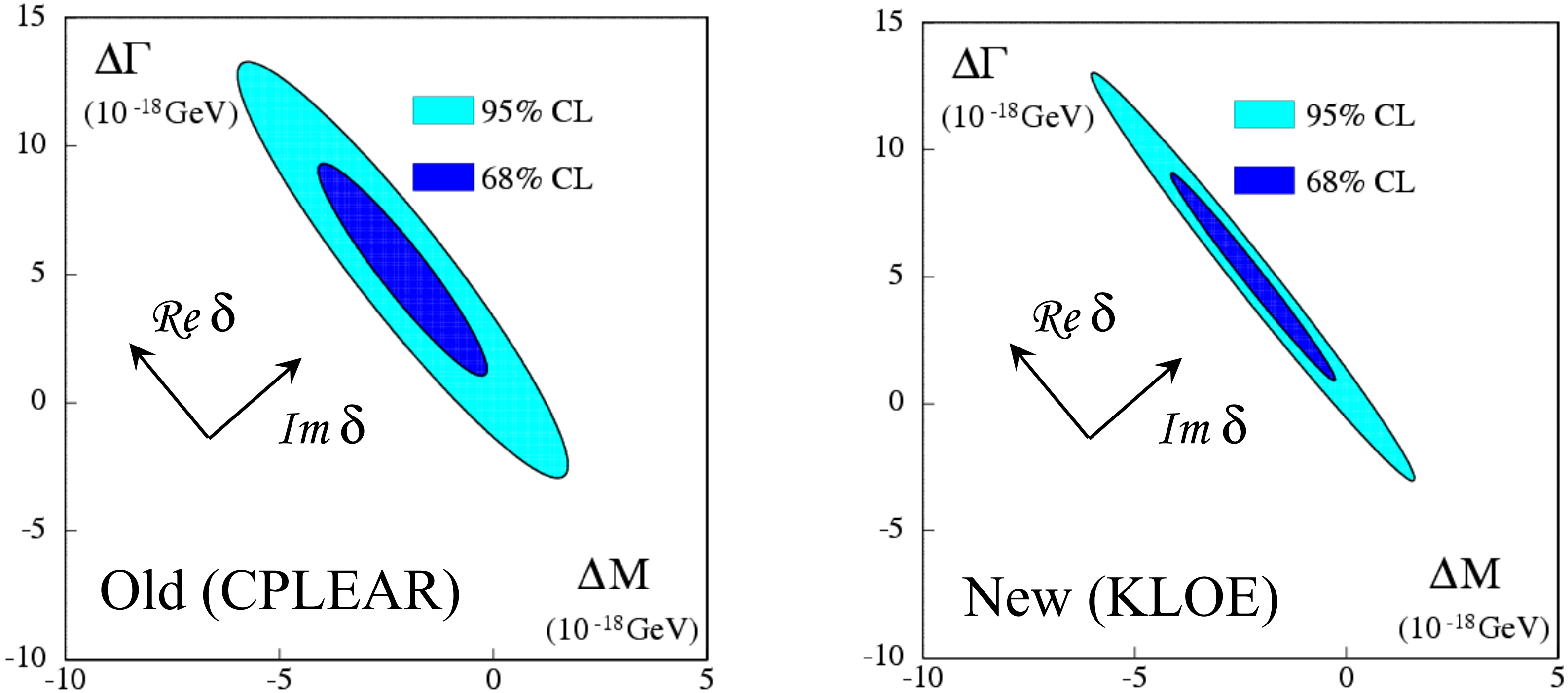
- The limiting quantities are
  Im x_+ and ϕ_{+-} for *Im* δ
  η_{+-} and η_{00} for *Re*ε.

- The semileptonic sector contributes by 15% and induces a small correlation between *Re* ε and *Im* δ.



CPT test: $\Delta\Gamma$ vs Δm

From *Im* δ and *Re* δ it is possible to extract limits on $\Delta m = (m_{K0} - m_{\overline{K0}})$ and $\Delta\Gamma = (\Gamma_{K0} - \Gamma_{\overline{K0}})$

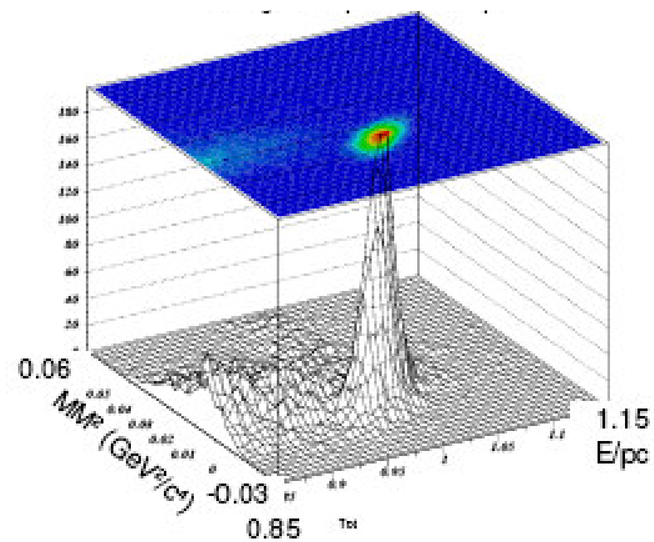


Assuming no CPT violation in the decay ($\Delta\Gamma = 0$) obtain the limit on the neutral kaon mass difference:

$$-4\times10^{-19}\ \text{GeV} < m_{K0} - m_{\overline{K0}} < 7\times10^{-19}\ \text{GeV}$$

$R_K = \Gamma(K^+ \to e^+\nu)/\Gamma(K^+ \to \mu^+\nu)$

- Present measurement come from 3 experiments of '70. Low energy K^+ beam stopped in a target, decay at rest.
- 2003 data set
  $K^{\pm}_{e2}$ signature: E/p=1 & $m_\nu^2=0$
  N_{TOT} = 5329 (73); Bkg = 659 (26)
  N_{SIG} = 4670 (77)$(^{+29}_{-8})_{SYST}$
- Preliminary (EPS05) NA48/2 measurement.



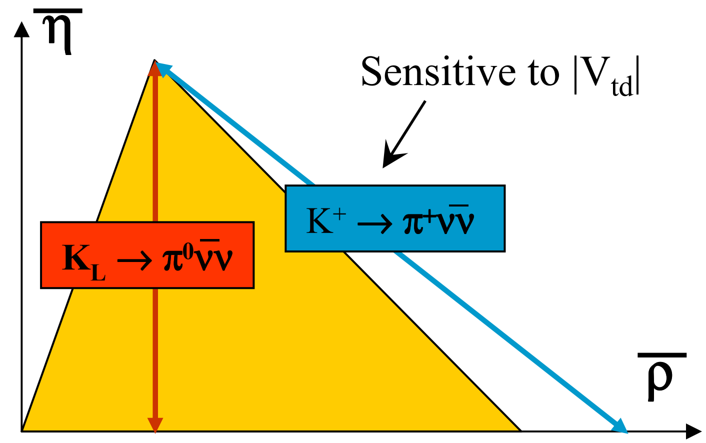
	$R_K \times 10^5$
PDG average	**2.45 (11)**
SM prediction	**2.472 (1)**
NA48/2 (2003)	**2.416 $(43)_{STAT}(24)_{SYST}$**

Future:
- **NA48/2** 2004 statistics: about ×2 of 2003
- **KLOE** complete data set (2.5 fb^{-1})

- Slight discrepancy between R_K measurement and the SM predcition
- 2−body K decays are suppressed (helicity) in SM but generally unsuppressed in SM−extensions (hep-ph/0511289):

$$R_K = (1+\Delta r^{e-\mu}_{NP}) \frac{\Gamma(K\to e\nu_e)_{SM}}{\Gamma(K\to \mu\nu_\mu)_{SM}}$$

CKM unitarity and $K\to\pi\nu\nu$ decays

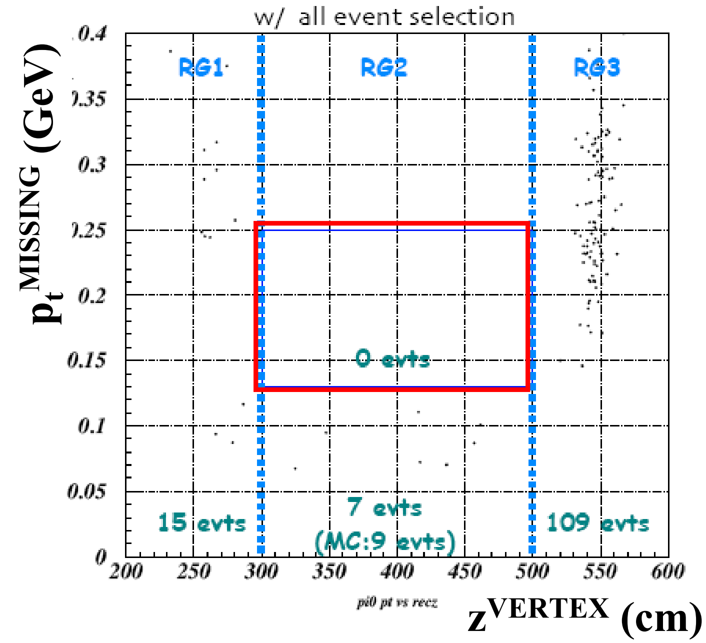


- "Golden-plated decays": BR($K\to\pi\nu\nu$) can be predicted in the SM framework with very high theoretical accuracy and may provide grounds for precision tests of the flavor structure of the SM
- $\mathbf{K^0_L} \to \pi^0\nu\nu$ and $\mathbf{K^+}\to\pi^+\nu\nu$ completely determine the Unitarity Triangle.
- Comparison with Unitarity Triangle from B sector could provides decisive tests in the flavor physics: new physics may differentiate between K and B measurement
- The *a priori* unknown hadronic matrix element obtained from $K\to\pi e\nu$ decays.
- **SM predictions:**

  $\mathbf{Br(K^+\to\pi^+\nu\nu)} \approx (1.6\times10^{-5})|V_{cb}|^4\ (\rho\eta^2+(\rho_c\text{-}\rho)^2) \to \mathbf{(8.0\pm1.1)\times10^{-11}}$

  $\mathbf{Br(K^0_L \to \pi^0\nu\nu)} \approx (7.6\times10^{-5})|V_{cb}|^4\ \eta^2 \to \mathbf{(3.0\pm0.6)\times10^{-11}}$
- Combined $\mathbf{K\to\pi\nu\nu}$ measurement determine $(\sin 2\beta)_K$ without being affected by the $|V_{cb}|$ uncertainty.

$K_L \to \pi^0 \nu\nu$: reminder and outlook



KEK-E391a Upper Limit

No events in the signal box; S.E.S.=1.17×10^{-7}

BR($K^0_L \to \pi^0\nu\nu$)<2.86×10^{-7} 90%CL

Preliminary (KAON2005) ×6 improvement over KTeV one day special run

×2 improvement over published limit (KTeV Dalitz technique)

KOPIO @ BNL stopped

In Japan a step by step approach is followed:

KEK:

E391a has completed data taking (three runs).

They aim to reach the Grossman-Nir bound from the accumulated data.

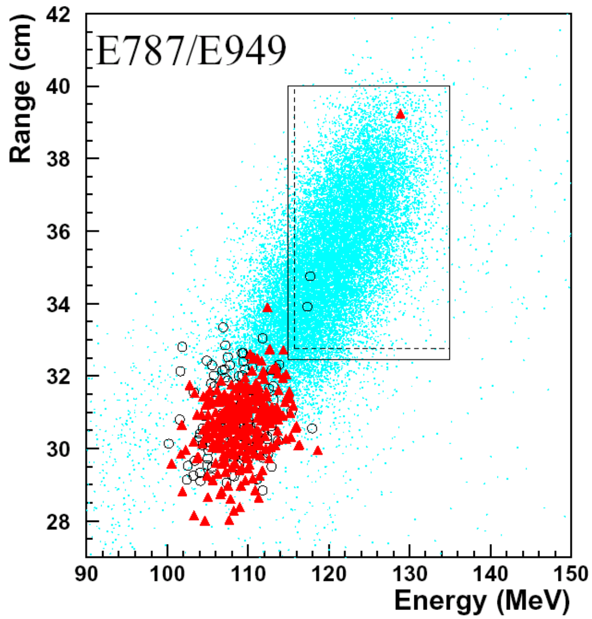
J-PARC:

A proposal is being prepared for the new J-PARC hadron facility:

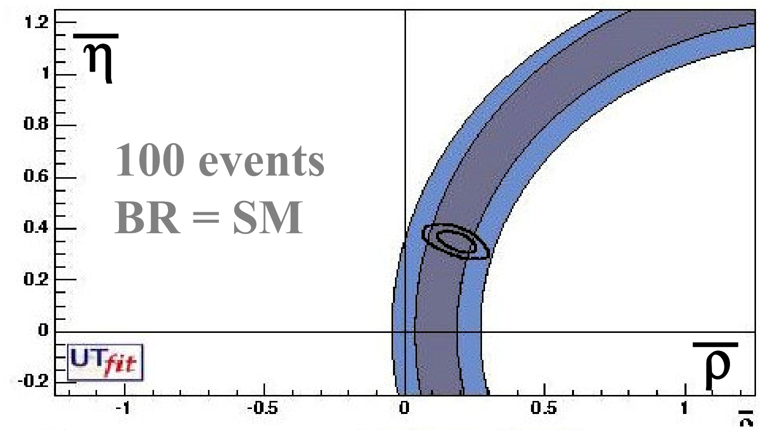
Step I: move the E391a detector at J-PARC

Step II: build a new detector and a dedicated beamline to be able reach about 100 SM events

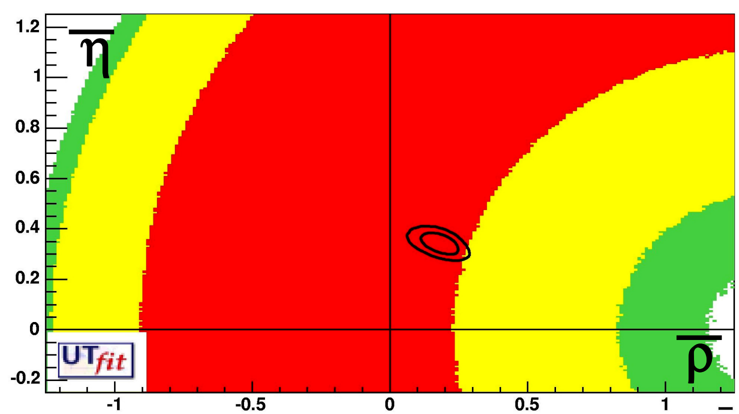
$K^+ \to \pi^+ \nu\nu$: reminder and outlook

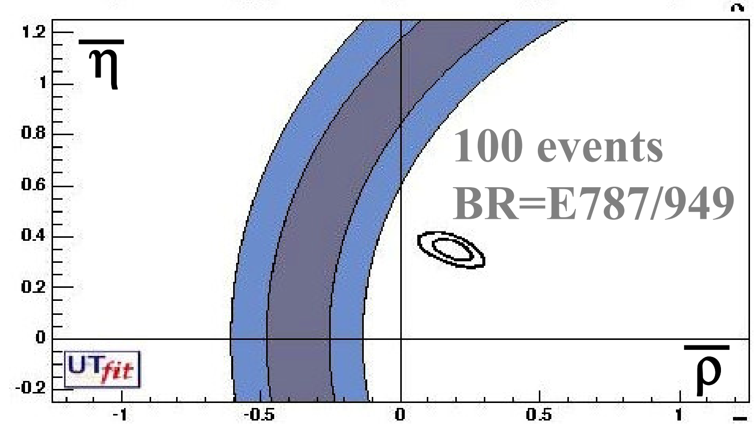


BNL-E787/E949:
Stopped K^+, ~0.1% acceptance
$BR(K^+ \to \pi^+ \nu\nu) = 1.47^{+1.30}_{-0.89}\ 10^{-10}$
hep-ex/0403036 PRL93 (2004)

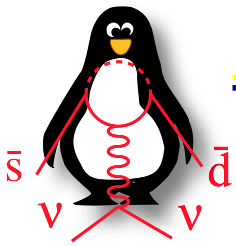


• Current constraint on (ρ,η) plane:



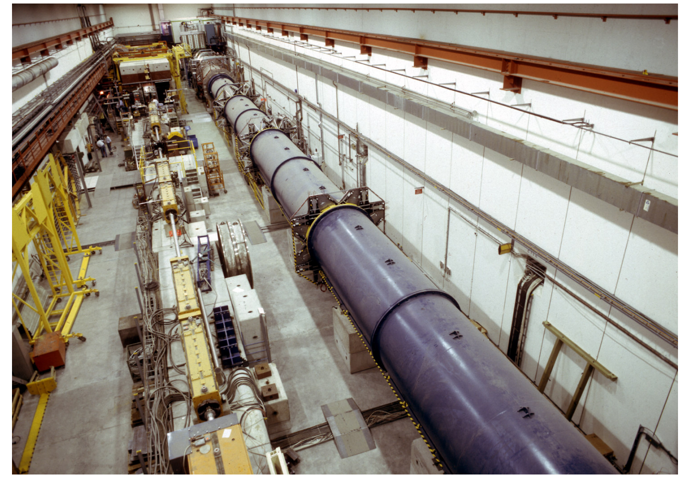


P326

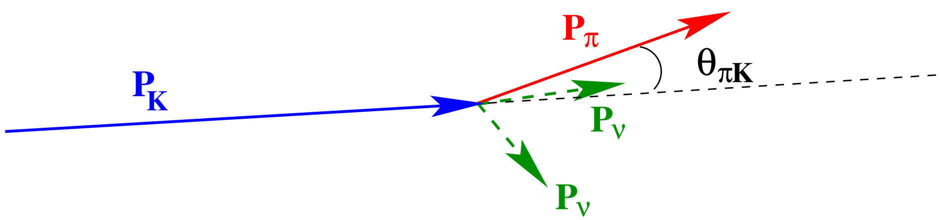


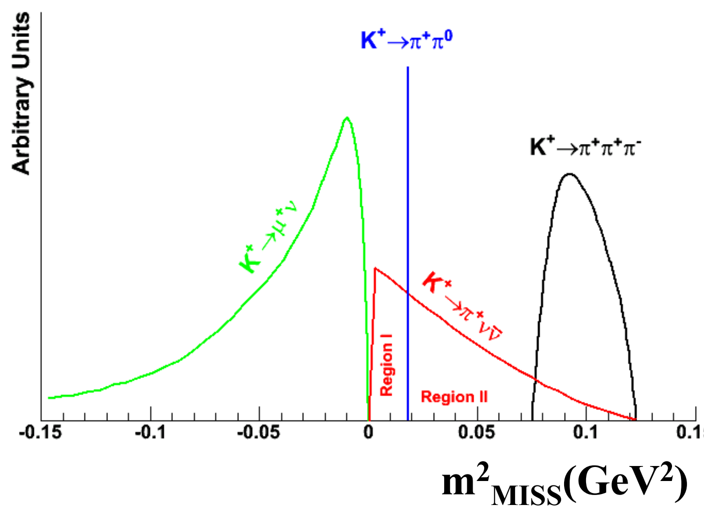
$K^+ \to \pi^+ \nu\nu$: outlook

P326 (a.k.a. NA48/3)



- Proposal to measure the rare decay **BR($K^+ \to \pi^+ \nu\nu$)** at the CERN SPS (CERN-SPS-2005-013, SPSC-P-326)
- Aims to receive full approval by end of 2006… to be able to start data taking some time in 2009-2010





- Kinematic rejection (m^2_{MISS})+photon veto+PID.
- To reject $K^+ \to \pi\pi^0$ events: 10^{-8} π^0 rejection. (require single photon rejection 10^{-5} for E_γ>1 GeV)
- GIGA-tracker.
- **Expect ~100 events in two year with ~10% of background.**

Region I: $0 < m^2_{miss} < 0.01$ GeV^2
Region II: $0.026 < m^2_{miss} < 0.068$ GeV^2

Conclusions

Plenty of new results in **kaon physics** since PIC05.

• Totally unexpected $\pi\pi$ scattering length measurement from $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ decays

• Precise bounds on direct CP-violation measured in $K \to 3\pi$ charged kaons decays.

• New V_{us} world average. Unitarity of CKM matrix tested at 1σ level.

• New determination of CP and CPT parameters: the accuracy on $\mathcal{R}e\,\varepsilon$ and $\mathit{Im}\,\delta$ improved of a factor ~2.5.

• Renewed interest in $K^{\pm} \to \ell^{\pm}\nu$ decays as new physics probe.

• Status and perspectives of the $K \to \pi\nu\nu$ measurements.

Kaons offer a unique playground to test SM and to shed light on physics beyond SM.

Thanks to G.Isidori and F.Mescia for illuminating discussions in preparing this talk.

Spare slides

Extraction of $\delta_0 - \delta_2$

Cirigliano et al. '04 (EPJC 33 369)

Using KLOE '02 result for $\Gamma(\pi^+\pi^-)/\Gamma(\pi^0\pi^0)$:

Isospin-conserving treatment:	**$\chi_0 - \chi_2$**
$\Gamma(K_S \to \pi\pi)$ fully inclusive of $\pi\pi\gamma$ channel	**$(48.6 \pm 2.6)°$**
Isospin breaking in amplitudes (mainly EM):	**$\chi_0 - \chi_2$**
$A_I \to A_I + \delta A_I$	**$(54.6 \pm 2.2_{exp} \pm 0.9_{th})°$**
A_0, A_2 amplitudes mixed	
$\Delta I = 5/2$ component introduced	
Small contribution from strong isospin breaking	
Isospin breaking in final state phase shifts:	**δ_0 - δ_2**
$\delta_I = \chi_I - \gamma_I$	**$(60.8 \pm 2.2_{exp} \pm 3.1_{th})°$**
$\delta_0 - \delta_2 = (-6 \pm 3)°$ [χPT $O(e^2p^2)$]	

For comparison:

		δ_0 - δ_2
χPT estimate	(Gasser & Meissner '91)	**$(45 \pm 6)°$**
$\pi\pi$ scattering	(Colangelo et al. '01 $a_0 - a_2 = 0.265 \pm 0.004$)	**$(47.7 \pm 1.5)°$**
	(Peláez & Ynduráin '04 $a_0 - a_2 = 0.277 \pm 0.014$)	**$(52.9 \pm 1.6)°$**

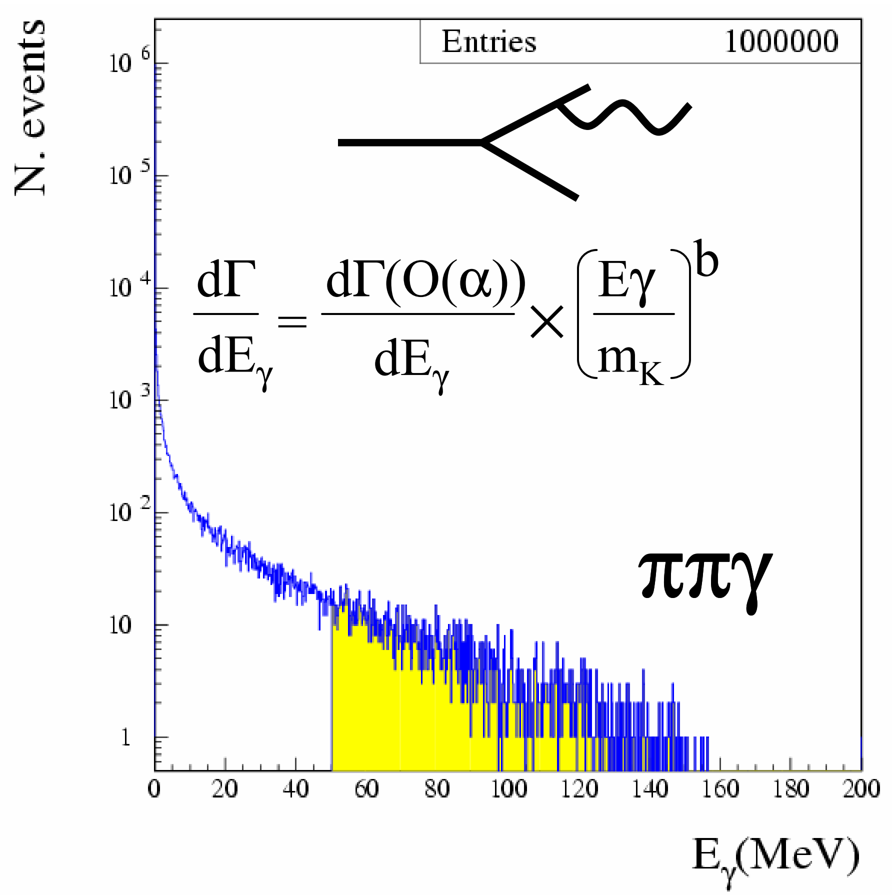
Generators for radiative K decays

Generators for neutral kaon decays include radiation, no cutoff energy

- Full O(α) amplitudes (real and virtual contributions) summed to all orders in α by exponentiation (soft-photon approximation)
- Carefully checked against all available data and calculations

$$\frac{BR(K_L \to \pi e \nu \gamma, E_\gamma > 30\,MeV\ \theta_{e\gamma} > 20°)}{BR(K_L \to \pi e \nu)} =$$

kTeV	$(0.908 \pm 0.015) \times 10^{-2}$
Bijnens et al	0.93×10^{-2}
MC	0.93×10^{-2}



$$\frac{BR(K_S \to \pi\pi\gamma, E_\gamma > 50\,MeV)}{BR(K_S \to \pi\pi)} =$$

E731	$(2.56 \pm 0.09) \times 10^{-3}$
MC	2.6×10^{-3}

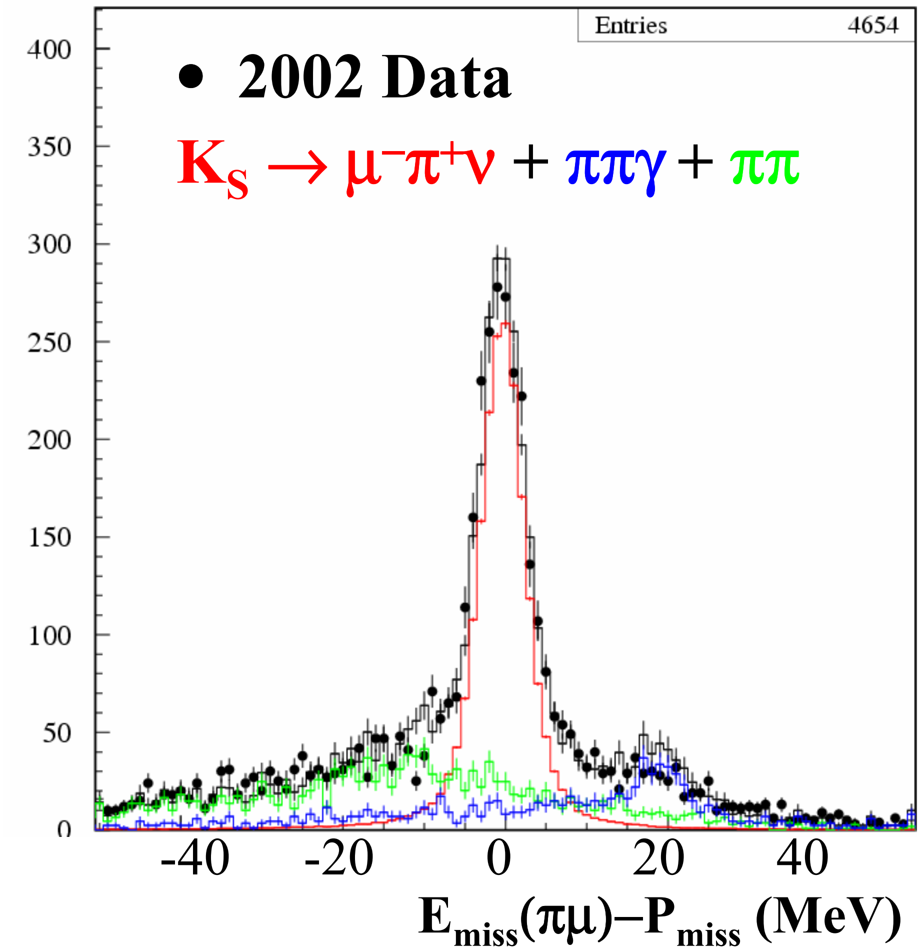
KLOE Note 194
(http://www.lnf.infn.it/kloe)

$K_S \to \pi\mu\nu$: *first observation*

- Measurement never done before

- More difficult than K_{Se3}:
  1) Lower BR: expect 4×10^{-4}
  2) Background events from $K_S \to \pi\pi$, $\pi \to \mu\nu$: same PIDs of the signal
- Event counting from the fit to $E_{miss}(\pi\mu) - P_{miss}$ distribution
- Efficiency estimate from $K_{L\mu3}$ early decays and from MC + data control samples.

- Selected about 4500 events per charge in ~400 pb^{-1}. (~ 3% stat error)



Situation before 2004

Apart from unitarity problem, V_{us} seemed to be well understood before the new data has arrived:

- Measured with $K_L e3$ ($0.2182 \pm 0.0012_{\rm exp}$), $K^{\pm}e3$ ($0.2208 \pm 0.0016_{\rm exp}$) and Hyperon decays ($0.2176 \pm 0.0026$). The most precise measurement came from $K_L e3$ decays.
- $K_L e3$ branching fraction is extracted from various measurements of 36 different experiments performed between 1967-1995, they show good internal agreement
- $f_+(t)$ form factor is measured by ~ 10 experiments, well described by linear λ^+ term. The value of λ^+ is consistent between $K^{\pm}$ (0.028 ± 0.003) and K_L (0.030 ± 0.002) as well as with theory (chiral QCD) expectations (~ 0.028).
- $f_+(0)$ is calculated by Leutweyler and Roos in 1984, their analysis shows that $K^{\pm}e3$ and $K_L e3$ data are consistent.

The only problem in this picture was BNL E865 determination of V_{us} based on $K^{\pm}e3$ data (PRL **91** 261802, published on 31 Dec 2003) which triggered a lot of new experimental activity.

Dominant K_L branching ratios

Absolute BR measurements to 0.5-1%
from '01-'02 data set (328 pb^{-1})

***K_L* tagged by *K_S* $\to \pi^+\pi^-$:**

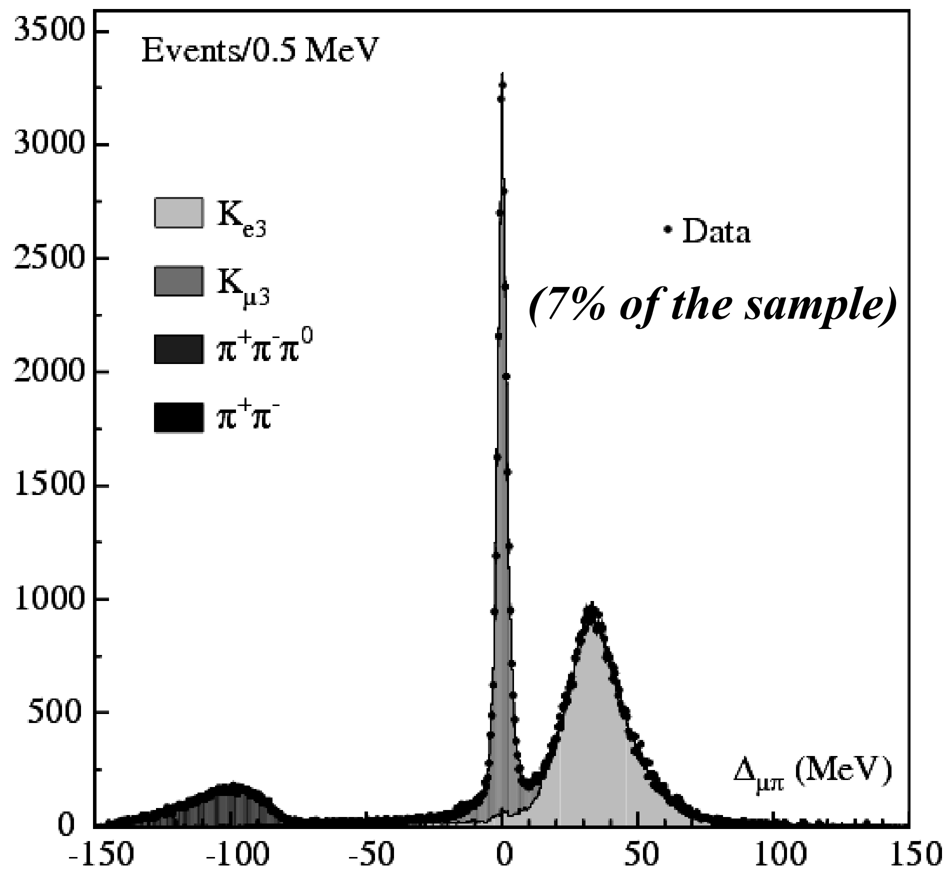
- 13×10^6 for the measurement
- 4×10^6 used to evaluate efficiencies

BR's to $\pi e\nu$, $\pi\mu\nu$, and $\pi^+\pi^-\pi^0$:

- K_L vertex reconstructed in DC
- PID using decay kinematics
- Fit with MC spectra including radiative processes and optimized EmC response to $\mu/\pi/K_L$

BR to $\pi^0\pi^0\pi^0$:

- Photon vertex reconstructed by TOF using EmC (3 clusters)
- E_{rec} = 99%, background < 1%



Lesser of $p_{miss}-E_{miss}$ in $\pi\mu$ or $\mu\pi$ hyp.

Direct measurement of K_L lifetime

Measure using $K_L \to \pi^0\pi^0\pi^0$
- Require ≥ 3 γ's
- $\varepsilon(L_K) \sim 99\%$, uniform in L
- $\sigma_L(\gamma\gamma) \sim 2.5$ cm
- Background ~ 1.3%

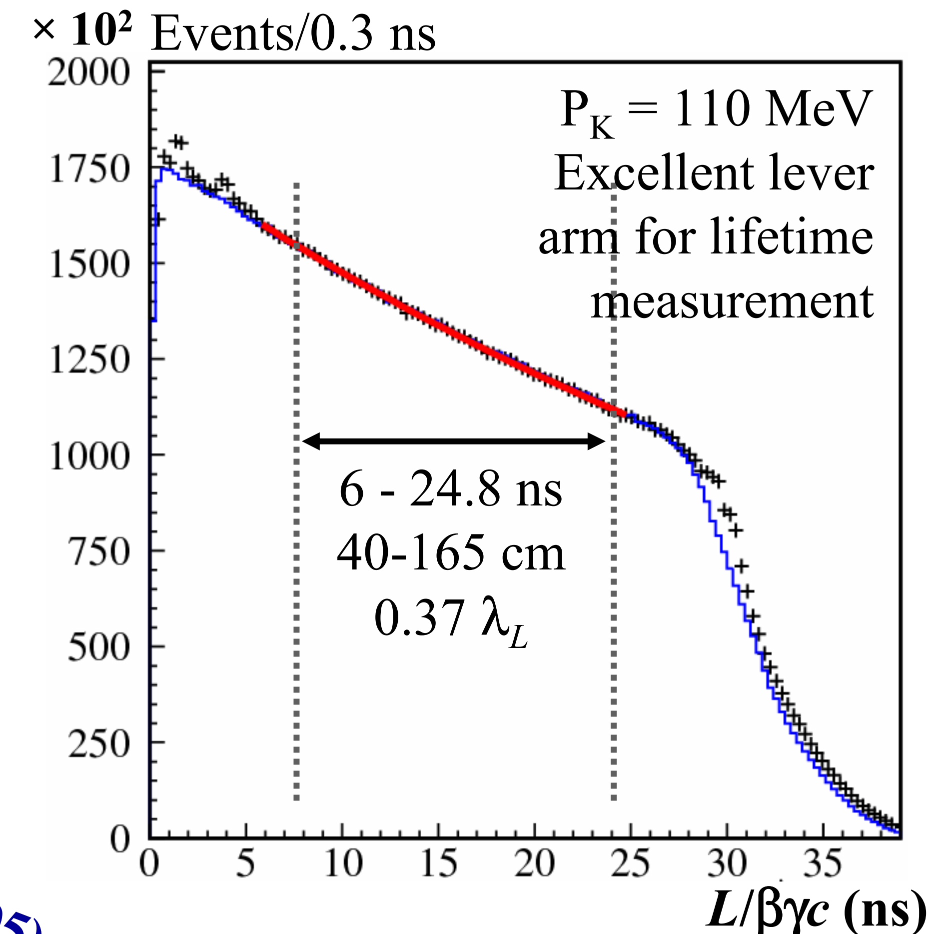
Use $K_L \to \pi^+\pi^-\pi^0$ to determine:
- EmC time scale
- Photon vertex efficiency

KLOE 400 pb^{-1}:

10^7 $K_L \to \pi^0\pi^0\pi^0$ evts

Published PLB626(2005) 15

$\tau_L = 50.92 \pm 0.17 \pm 0.25$ ns

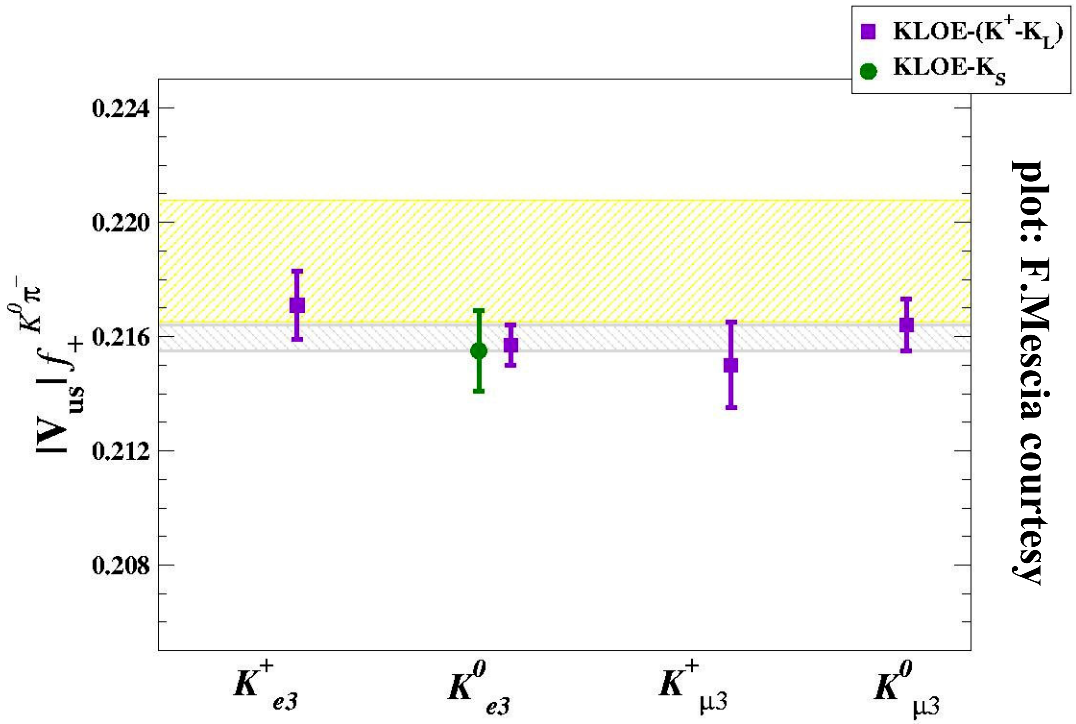


Average with result from K_L BR's:
$\tau_L = 50.84 \pm 0.23$ ns

Vosburg, '72:
$\tau_L = 51.54 \pm 0.44$ ns

V_{us} from KLOE results

	$K_L\,e3$	$K_L\,\mu3$	$K_S\,e3$	$K^{\pm}\,e3$	$K^{\pm}\,\mu3$
BR	0.4007(15)	0.2698(15)	$7.046(91)\times10^{-4}$	0.05047(46)	0.03310(40)
τ	50.84(23) ns		89.58(6) ps	12.384(24) ns	



plot: F.Mescia courtesy

$$\langle V_{us}\times f_+(0)\rangle_{\text{KLOE AV.}} = 0.2160(5)$$

CKM unitarity within ~ 1σ

Slopes

$\lambda'_+ = 0.02542(31)$

$\lambda''_+ = 0.00129(3)$

(Pole model: KLOE, KTeV, and NA48 ave.)

$\lambda_0 = 0.01587(95)$

(KTeV and Istra+ ave.)

From unitarity

- $f_+(0)=0.961(8)$
  Leutwyler and Roos Z. [Phys. **C25**, 91, 1984]
- $V_{ud}=0.97377(27)$
  Marciano and Sirlin [Phys.Rev.Lett.96 032002,2006]

$$V_{us}\times f_+(0) = 0.2187(22)$$

Dominant K_L branching ratios

• KTeV measures 5 K_L decay ratios of 6 decay modes:
$\Gamma(e3)/\Gamma(\mu 3)$, $\Gamma(\pi^+\pi^-\pi^0)/\Gamma(e3)$, $\Gamma(\pi^0\pi^0\pi^0)/\Gamma(e3)$, $\Gamma(\pi^+\pi^-)/\Gamma(e3)$, $\Gamma(\pi^0\pi^0)/\Gamma(\pi^0\pi^0\pi^0)$

• These 6 decay modes account for 99.93% of K_L decays and the ratio can be combined to extract BR, i.e.:

$$B_{Ke3} = \frac{0.9993}{1 + \frac{\Gamma_{K\mu3}}{\Gamma_{Ke3}} + \frac{\Gamma_{000}}{\Gamma_{Ke3}} + \frac{\Gamma_{+-0}}{\Gamma_{Ke3}} + \frac{\Gamma_{+-}}{\Gamma_{Ke3}} + \frac{\Gamma_{00}}{\Gamma_{Ke3}}}$$

[PRD 70 (2004)]

• Results are:

$BR(K_L \to \pi e \nu) = 0.4067 \pm 0.0011$

$BR(K_L \to \pi \mu \nu) = 0.2701 \pm 0.0009$

$BR(K_L \to \pi\pi\pi^0) = 0.1252 \pm 0.0007$

$BR(K_L \to \pi^0\pi^0\pi^0) = 0.1945 \pm 0.0018$

$BR(K_L \to \pi^+\pi^-) = (1.975 \pm 0.012)\times 10^{-3}$

$BR(K_L \to \pi^0\pi^0) = (0.865 \pm 0.010)\times 10^{-3}$

Kaon radiative decays: summary

• Hadronic radiative decays of neutral kaons with real and virtual photons give insight into structure of the kaon
• Summary status of the results presented in La Thuile 2006

Real γ	Virtual $\gamma^* \to e^+e^-$
$K_L \to \pi^0\pi^0\gamma$ Preliminary results	$K_L \to \pi^0\pi^0 e^+e^-$ Published
$K_L \to \pi^+\pi^-\gamma$ New Preliminary results	$K_L \to \pi^+\pi^- e^+e^-$ New results, accepted in PRL
$K_L \to \pi^+\pi^-\pi^0\gamma$ New Preliminary results	$K_L \to \pi^+\pi^-\pi^0 e^+e^-$ New Preliminary results
$K_L \to \pi^0\pi^0\pi^0\gamma$ Analysis in progress	$K_L \to \pi^0\pi^0\pi^0 e^+e^-$ Analysis in progress

Kaon radiative decays: summary

Hadronic radiative decays of neutral kaons with real and virtual photons give insight into structure of the kaon

$K^0_L \to \pi^+\pi^-\gamma$

g_{M1} = 1.198 ± 0.035 (stat)±0.086 (syst)

a_1/a_2 = -0.738 ± 0.007 (stat) ± 0.018 (syst)

g_{E1} < 0.21 (90% CL)

BR($K^0_L \to \pi^0\pi^0\gamma$) < 2.52 10^{-7} 90%CL

BR($K^0_L \to \pi e \nu e^+e^-$,$M_{ee}$>5 MeV) =1.606±0.012(stat)$^{+0.026}_{-0.016}$(syst)±0.045(ext.) 10^{-5}

BR(π^0□ e^+e^-,X>0.95) = 6.56 ± 0.26(stat) ± 0.23(syst) 10^{-8}

$K^0_L \to e^+e^-\gamma$

BR($K^0_L \to e^+e^-\gamma$) = 9.25 ± 0.03(stat) ± 0.07(syst) ± 0.26 (ext) 10^{-6}

$C\alpha K^*$ = -0.517 ± 0.030 (fit) ± 0.022 (syst)

α_{DIP}= -1.729 ± 0.043(fit) ± 0.028(syst)

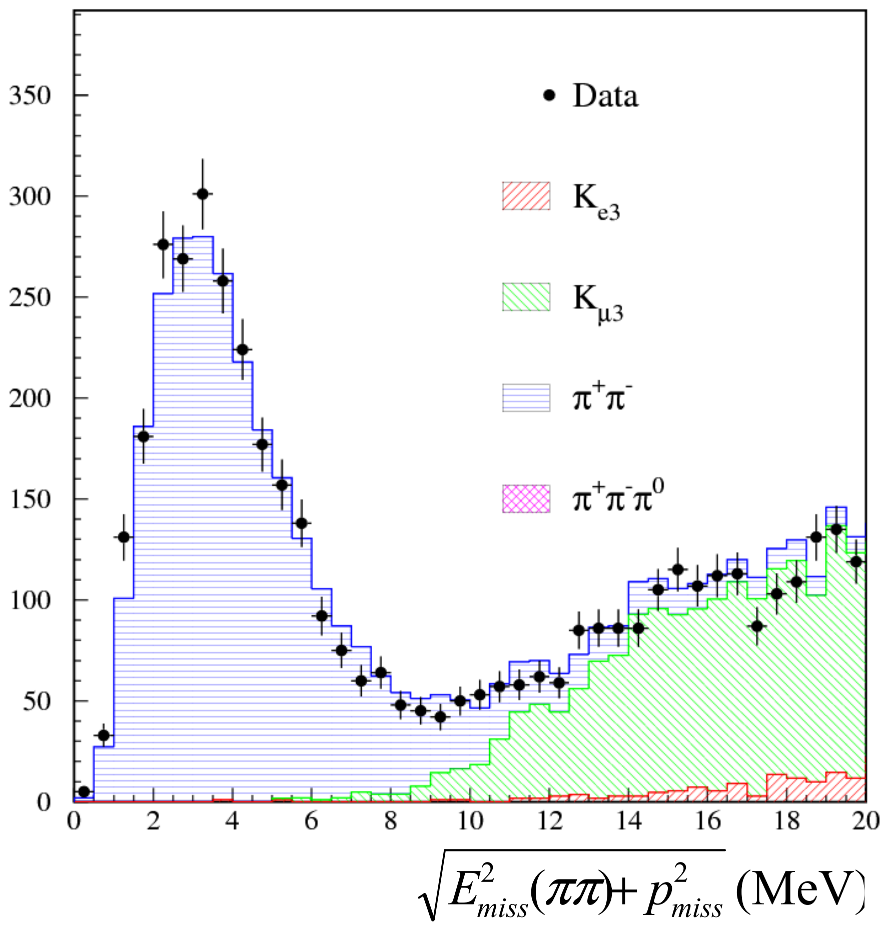
BR($K^0_L \to \pi^+\pi^-\pi^0\gamma$) = 1.70 ± 0.03(stat) ± 0.04(syst)) ± 0.03(norm) 10^{-4}

BR($K^0_L \to \pi^+\pi^-\pi^0 e^+e^-$,$E_{ee}$>20 MeV/$c^2$) = 1.60 ± 0.18(stat) 10^{-7}

$BR(K_L \to \pi^+\pi^-(\gamma_{IB}))$

BR = (1.963±0.012±0.017)×10^{-3}

PID using decay kinematics
Normalize to $K_L \to \pi\mu\nu$ events



σ_{rel}: 1.1% = 0.6%$_{stat}$ ⊕ 0.9%$_{syst}$

- in agreement with KTeV 2004
  BR = (1.975 ± 0.012) ×10^{-3}
- it confirms the 4–σ discrepancy with PDG04 = (2.080 ± 0.025) ×10^{-3}
- we get:

$|\eta_{+-}|$ = (2.216 ± 0.013) ×10^{-3}

[BR($K_S \to \pi\pi$) and τ_L from KLOE, τ_S from PDG04]

PDG04: |ε| = (2.280 ±0.013)×10^{-3}

PLB638 (hep-ex/0603041)

Lepton Universality from KTeV

Consistency of BRs and Form Factors results with lepton universality.
Compare Γ's for K_{e3} and $K_{\mu3}$:

$$\Gamma_{Kl3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW} \left(1+\delta_K^l\right) \left|V_{us}\right|^2 \left|f_+^2(0)\right| I_K^l$$

$$\left[\frac{\Gamma_{K\mu3}}{\Gamma_{Ke3}}\right]_{PRED} = \left(\frac{1+\delta_K^\mu}{1+\delta_K^e}\right)\left(\frac{I_K^\mu}{I_K^e}\right)$$

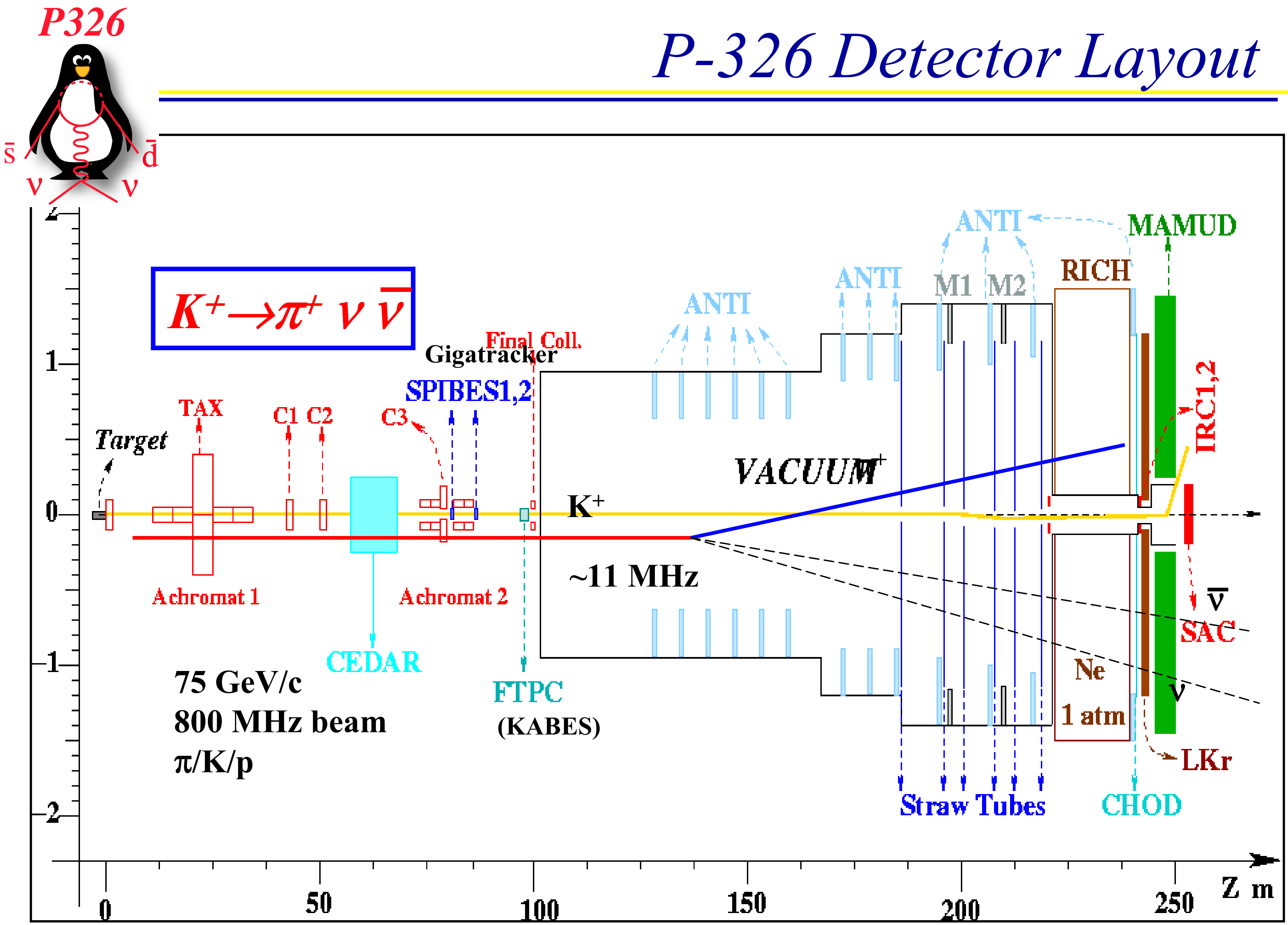
1.0058(10)
from T. Andre

0.6622(18)
from KTeV

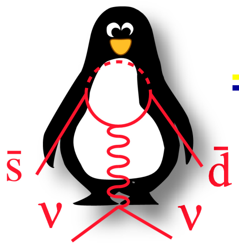
$$\left[\frac{\Gamma_{K\mu3}}{\Gamma_{Ke3}}\right]_{MEAS} \Bigg/ \left[\frac{\Gamma_{K\mu3}}{\Gamma_{Ke3}}\right]_{PRED} = 0.9969 \pm 0.0048 = \left(\frac{G_F^\mu}{G_F^e}\right)$$

Same test with PDG values gives 1.0270 ± 0.0182

P-326 Detector Layout



P326



*Signal & bkg from K decays/year**

	Total	Region I	Region II
Signal (SM)	**65**	**16**	**49**
$K^+ \to \pi^+ \pi^0$	2.7±0.2	1.7±0.2	1.0±0.1
$K_{\mu 2}$	1.2±0.3	1.1±0.3	<0.1
K_{e4}	2±2	negligible	2±2
$K^+ \to \pi^+ \pi^+ \pi^-$ and other 3-tracks bckg.	1±1	negligible	1±1
$K_{\pi 2}\gamma$	1.3±0.4	negligible	1.3±0.4
$K_{\mu 2}\gamma$	0.4±0.1	0.2±0.1	0.2±0.1
K_{e3}, $K_{\mu 3}$,others	negligible	–	–
Total bkg	**9±3**	**3.0±0.2**	**6±3**

***Before taxes. Proposal quotes 40 evt/year @BR=10^{-10}**

- **SPS used as LHC injector (so it will run in the future)**
- **No flagrant time overlap with CNGS**
- **P-326 fully compatible with the rest of CERN fixed target because P-326 needs only ~1/20 of the SPS protons**
- **Beam time estimates based on decennial NA48 experience at SPS**