The Abdus Salam
International Centre for Theoretical Physics

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Workshop on the original of P, CP and T Violation

2 - 5 July 2008

The Kaon Variations Exploring CP and Flavour Physics with Kaons

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THE KAON VARIATIONS

Exploring CP and flavour physics with kaons

Prepared for connoisseurs,

for the refreshment of their spirits by

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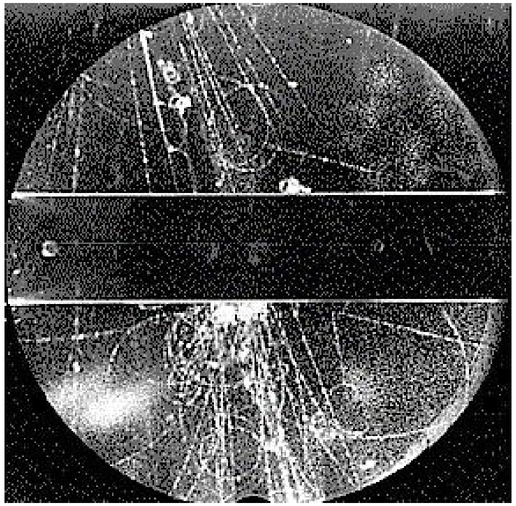
Trieste – July 2nd, 2008

PROGRAM

Aria	**Introduction**
Canone alla seconda	**ε'/ε**
Canone alla terza	**ε, semi-leptonics and CKM**
Canone all'unisono	**CPV in 3π decays**
Fughetta	**$\pi\pi$ scattering lengths and QCD**
Quodlibet	**Other decays and symmetries**
Alla marcia	**Future prospects**
Aria da capo	**Conclusions**

Introduction



Kaons: lightest kind of flavoured matter

- The birth of the flavour physics puzzle
- The first failure of a discrete symmetry
- The matter-antimatter asymmetry

A large and significant part of particle physics…






Is there still something to be learned by using kaons?

Kaons as the *minimal flavour laboratory*

Kaons remain a privileged observatory for flavour physics phenomena

- **All the features of flavour physics are present (i.e. all kinds of CP violation – "*same size*" as in B)**
- **Very simple (minimal) system**
- **Very nicely accessible experimentally (rates, branching ratios, backgrounds, …)**
- **Pretty *hard* for theorists…**

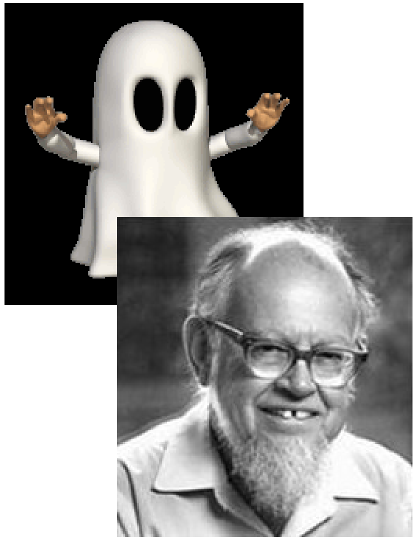
ARIA

Searches for CP/T violation with K

Transitions among CP eigenstates with opposite eigenvalues [direct CPV]	$K_2 \to \pi\pi$
Search for physical states not being CP eigenstates (non-exp. decay of CP eigenstates) [indirect CPV]	$K_L \to \pi\pi$ and $K_s \to \pi\pi\pi$
Differences in the partial decay widths or decay properties of particles and antiparticles [direct CPV]	$\Delta g(K \to 3\pi)$
Direct test of time-reversibility	$P(K^0 \to K^0) \neq P(K^0 \to K^0)$
Measure of non-zero T-odd quantities	$P_T(K_{\mu 3})$ Triple prod.
CPT tests	$M(K^0)\text{-}m(\overline{K}^0)$

CANONE ALLA SECONDA

Direct CPV



"At present our experimental understanding of CP violation can be summarized by the statement of a single number". (J. Cronin, 10.12.1980)

The search for (direct) CPV in the K→2π decay amplitude: a long series of precision counting experiments

$$\frac{|\eta_{00}|^2}{|\eta_{+-}|^2} = \frac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)}\frac{\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^+\pi^-)} = 1 - 6\,\mathrm{Re}(\varepsilon'/\varepsilon)$$

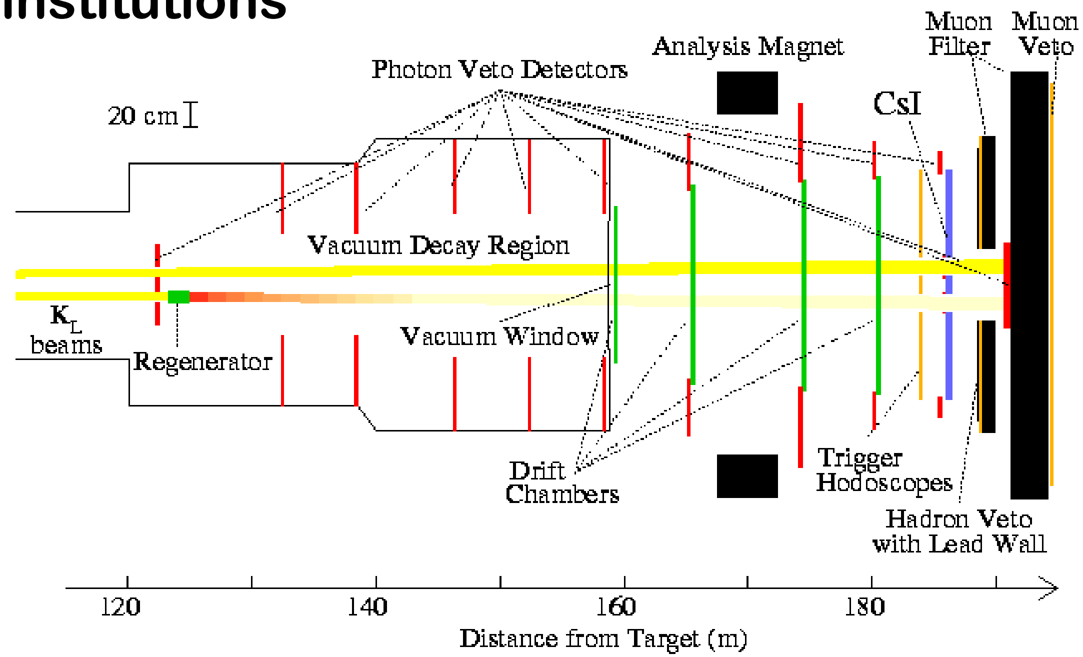
The (inconclusive) legacy of the NA31 (CERN) and E731 (FNAL) experiments

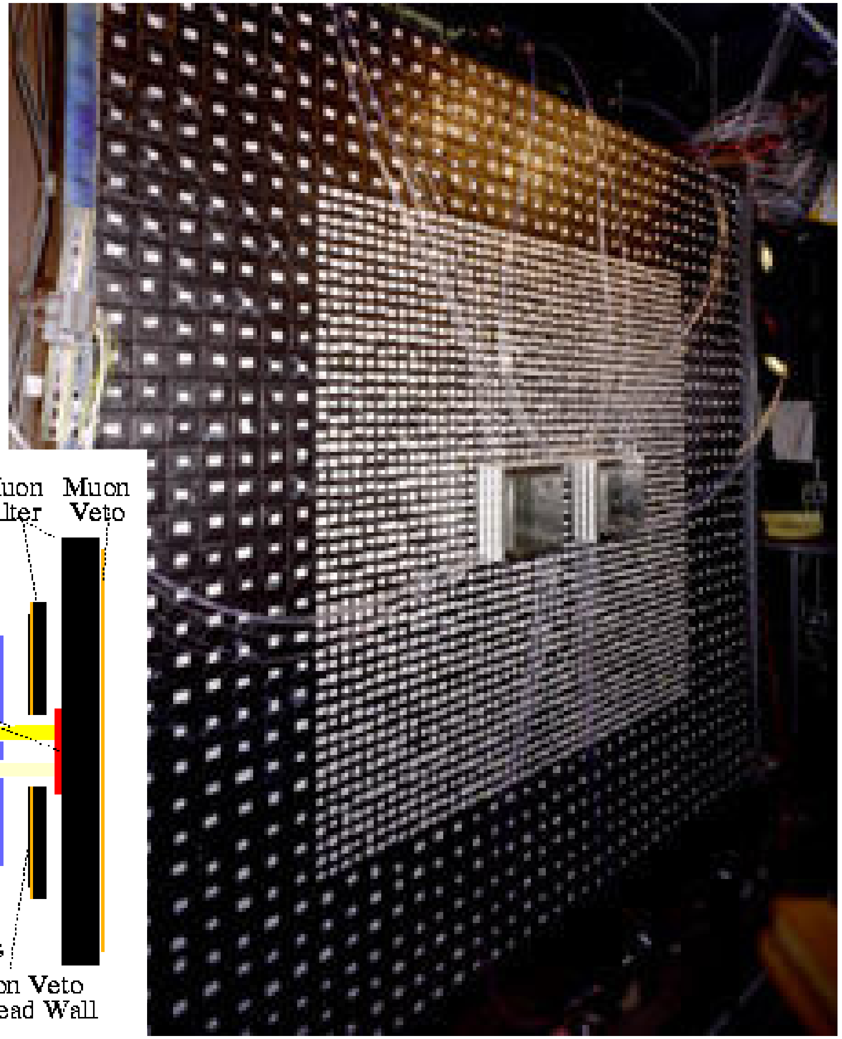
The whole of K physics in the last decade stems from this central experimental program

KTEV Kaons at the Tevatron

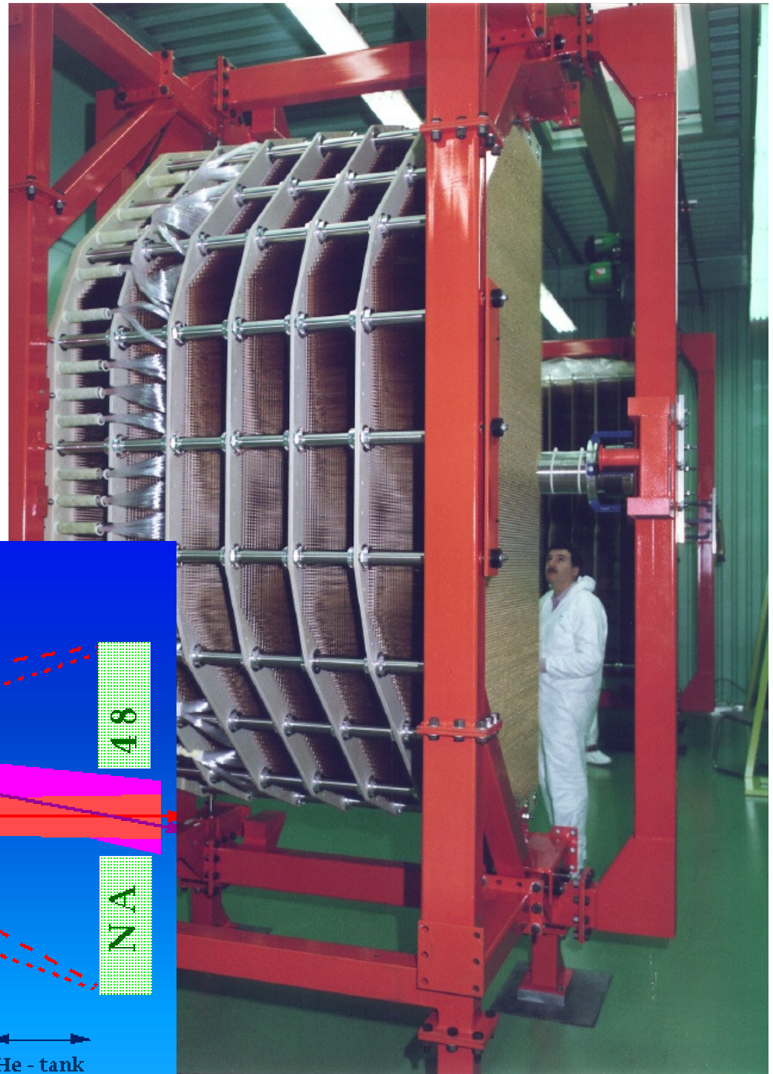
KTeV (1996-1999)

FNAL Main Injector (120 GeV) p
Double K_L beam (<p>=70 GeV/c)
Regenerated K_S
Pure CsI calorimeter
Data taking in 1997 and 1999
100 physicists, 12 USA/Japan institutions

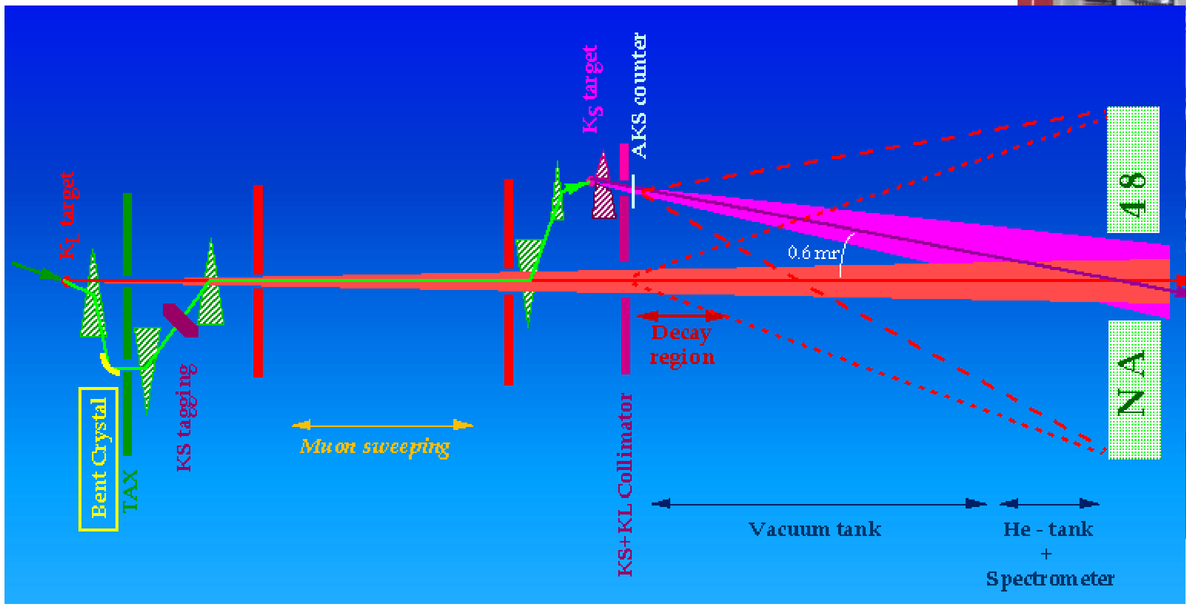




NA48 (1996-2001)



CERN SPS (450 GeV) p
K_S and K_L beams (<p>=100 GeV/*c*)
K_S tagging by time-of-flight
Liquid Krypton calorimeter
Data-taking 1998-1999-2001
130 physicists, 16 European institutions

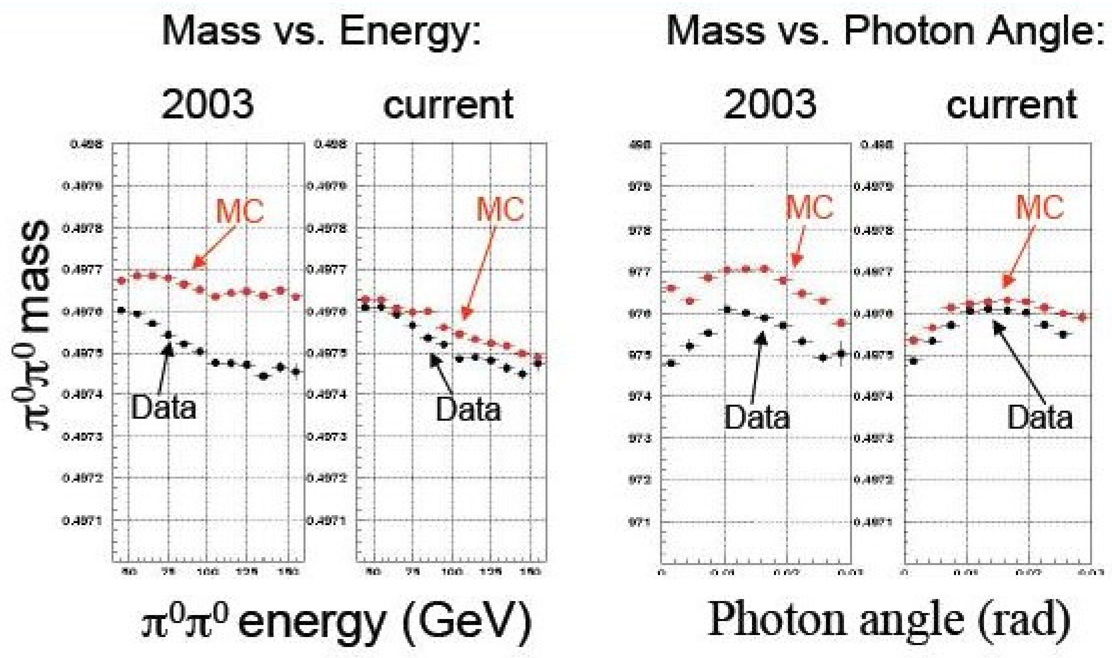


ε'/ε – New KTeV result

Preliminary result from 1999 data-taking

Doubling the statistics to full data set:
6M $K_L \to \pi^0\pi^0$, 10M $K_S \to \pi^0\pi^0$, 25M $K_L \to \pi^+\pi^-$, 43M $K_S \to \pi^+\pi^-$

Reduction of systematics through improvements in MC simulation, mostly for neutral mode



KTEV PRELIMINARY

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (19.2 \pm 1.1 \pm 1.8) \cdot 10^{-4}$$

KTeV (2003):
$(20.7 \pm 1.5 \pm 2.4) \cdot 10^{-4}$

ε'/ε

[PDG scaled error]

New world average:

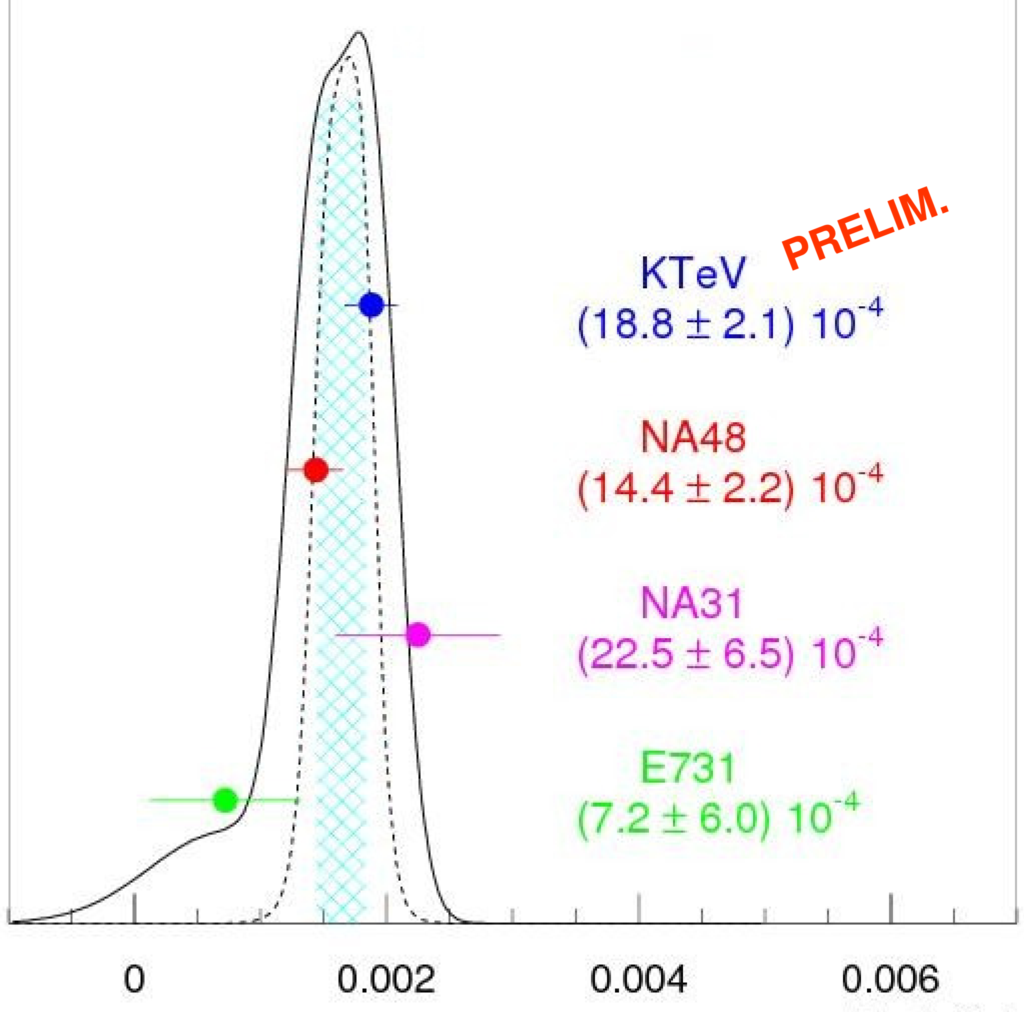
Including ΔI=3/2 correction
[EPJ C36 (2004) 37]

χ^2=5.3/3, consistency 14%

(was 6.2/3, consistency 10%)

Direct CPV in K decays at ≈ 9 standard deviations

$\mathrm{Re}(\varepsilon'/\varepsilon) = (16.4 \pm 1.9) \cdot 10^{-4}$



ε'/ε – its meaning

1999: proof of direct CP violation (after 36 years!)

The first test of the CKM paradigm for CP violation

CPV is a universal property of weak interactions

$$\frac{\Gamma(K^0 \to \pi^+\pi^-) - \Gamma(\overline{K}^0 \to \pi^+\pi^-)}{\Gamma(K^0 \to \pi^+\pi^-) + \Gamma(\overline{K}^0 \to \pi^+\pi^-)} = (5.18 \pm 0.61) \times 10^{-6}$$

(BR=$2.0 \cdot 10^{-3}$)
O(10^7) events

2005 EPS Prize to the NA31 collaboration

2007 APS Panofsky Prize to Italo Mannelli (Pisa), Heinrich Wahl (CERN) and Bruce Winstein (Chicago)

Compare e.g.

$$A_{CP}(B^0 \to \eta K^*(892)) = 0.21 \pm 0.06$$

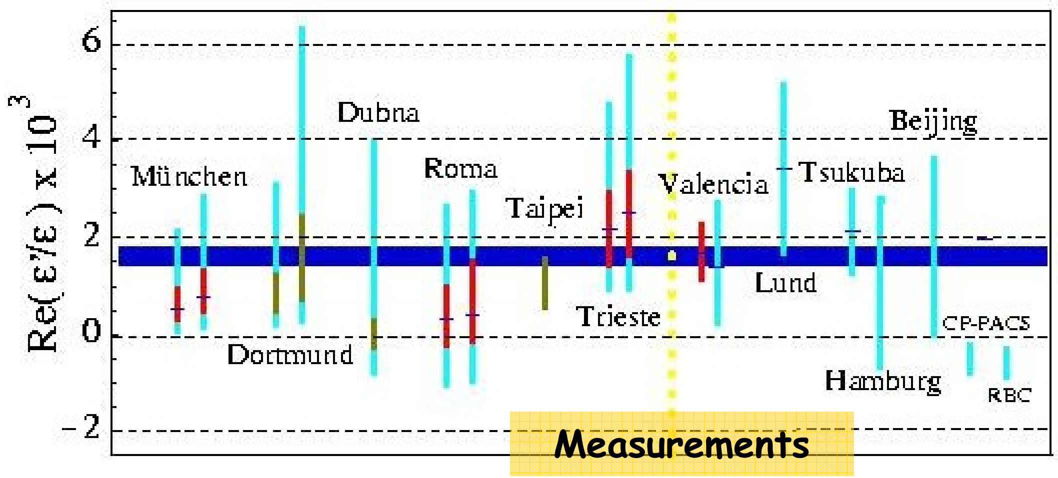
(BR=$1.6 \cdot 10^{-5}$) O(10^2) events

CANONE ALLA SECONDA

ε’ confronts the SM

While the significance of ε’ ≠ 0 clearly *trascends* its precise value… and (dire) theoretical difficulties make precise computation of such quantity within the Standard Model

ε’/ε theoretical pre/post-dictions (SM)



Experimental values are compatible with the SM
(accidentally quasi-superweak)
ε'/ε measured to 10%
(Impatiently) waiting for lattice QCD to become also
a *quantitative* test of SM.

New KTeV byproducts

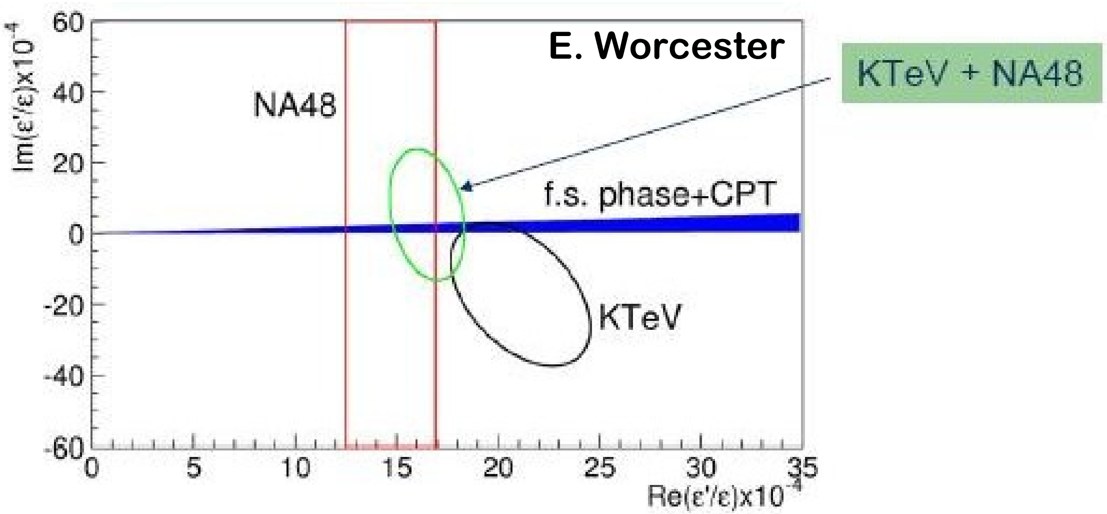
$\Delta m = (5269.9 \pm 12.3) \cdot 10^6 \hbar s^{-1}$ **[No CPT:** $\Delta m = (5279.7 \pm 19.5) \cdot 10^6 \hbar s^{-1}$ **]**

$\tau_S = (89.623 \pm 0.047) \cdot 10^{-12} s$ **[No CPT:** $\tau_S = (89.589 \pm 0.070) \cdot 10^{-12} s$ **]**

$\phi(\varepsilon) = (43.86 \pm 0.63)^\circ$

$\phi(\varepsilon) - \phi_{SW} = (0.40 \pm 0.56)^\circ$

$\phi_{00} - \phi_{+-} = (0.30 \pm 0.35)^\circ$



Full consistency with CPT symmetry

π **Using 30K double-Dalitz decays of π^0 ($\pi^0 \to e^+e^-e^+e^-$), the neutral pion is shown to be pseudoscalar to better than 89.2% (96.8% if CPT assumed) at 90% CL.**

CPV in charged $K_{\pi 3}$

- Any CPV in charged kaons is of the direct type

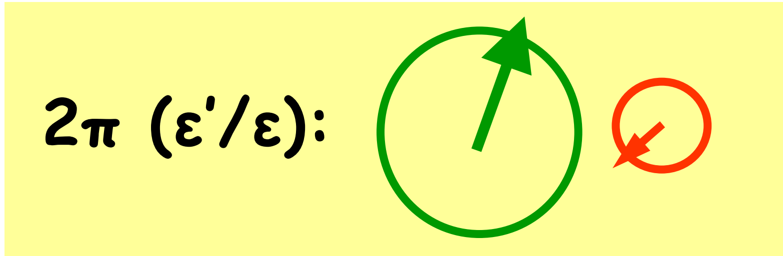
- Most copious decay modes possibly supporting CPV:

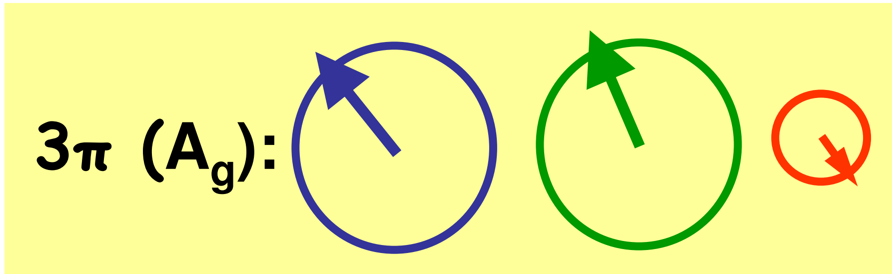
  BR($K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$) = 5.57% "charged"
  BR($K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$) = 1.73% "neutral"

Large statistics, simple selection, low backgrounds

- Hadronic uncertainties
Small rescattering phases
→ Small asymmetry in SM

No intrinsic ΔI=1/2 amplitude suppression (as for ε'/ε)





Width asymmetries suppressed: compare Dalitz plot *shapes* (no absolute K flux measurement)

NA48/2: search for CPV in $K_{\pi 3}$

Kinematics:

$s_i = (P_K - P_{\pi i})^2 \quad i=1,2,3\ (3=odd\ \pi)$

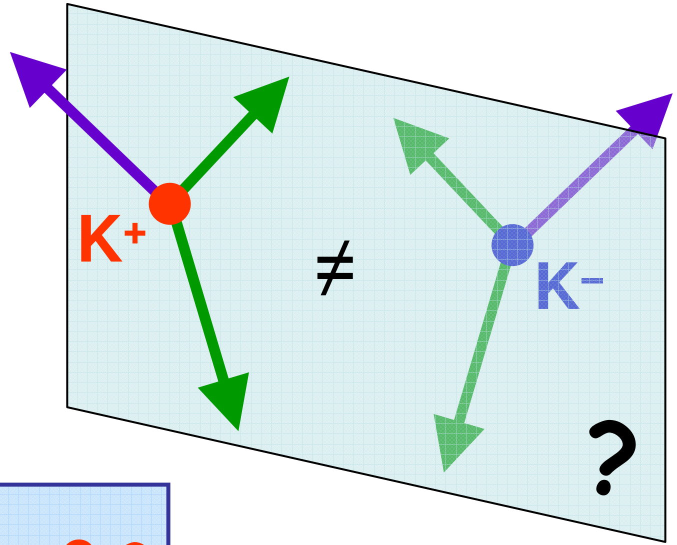
$s_0 = (s_1+s_2+s_3)/3$

$u = (s_3 - s_0)/m_\pi^2 = 2m_K\,(m_K/3 - E^*_{odd})/m_\pi^2$

$v = (s_2 - s_1)/m_\pi^2 = 2m_K(E^*_1 - E^*_2)/m_\pi^2$

Matrix element:

$|M(u,v)|^2 \sim 1 + gu + hu^2 + kv^2$

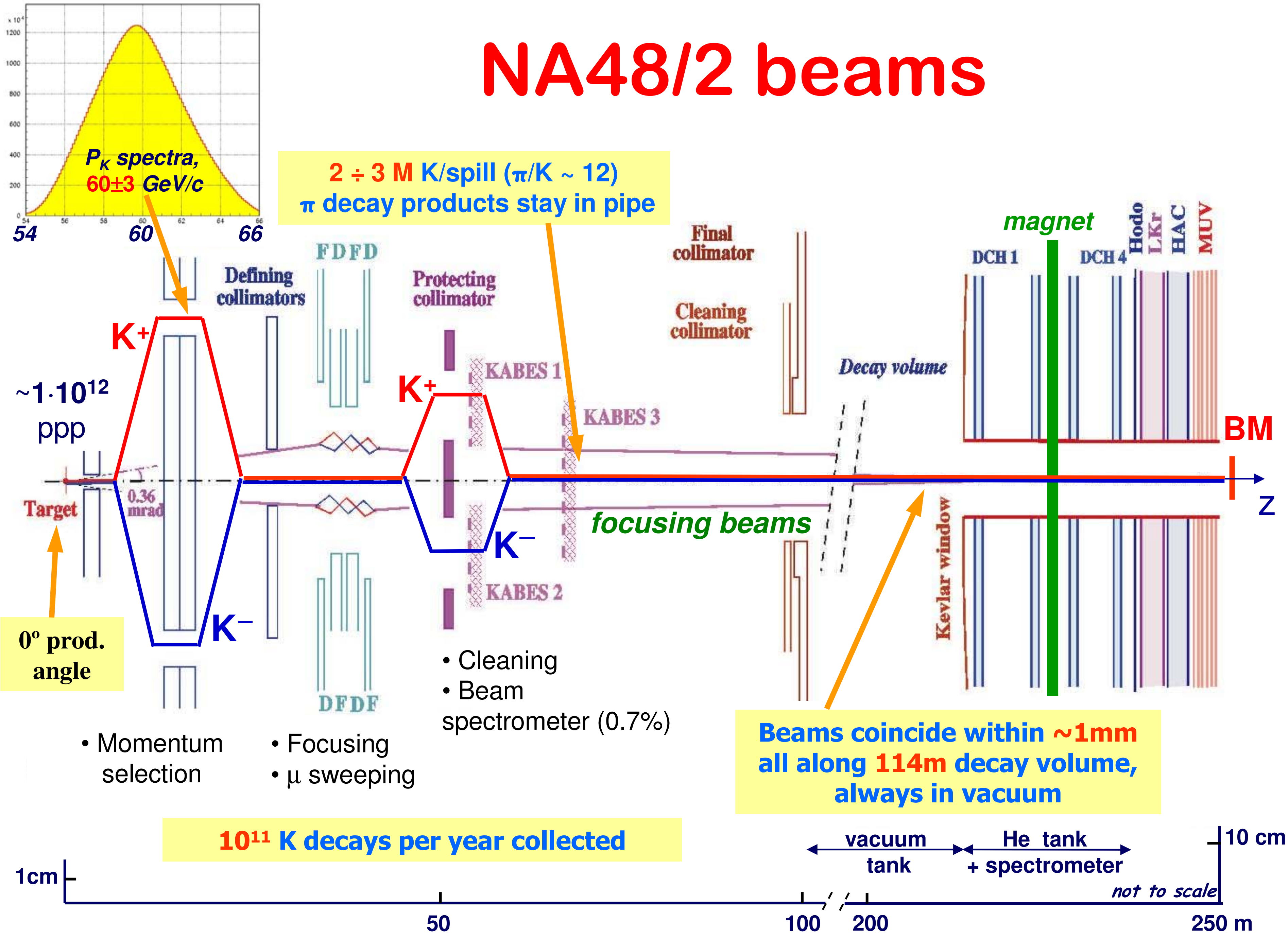


$$A_g = (g_+ - g_-)/(g_+ + g_-) \neq 0\ ?$$

NA48/2 exploited maximal cancellations (robustness)

- **Simultaneous K^+ and K^- beams, superimposed in space, with narrow momentum spectra**
- **Detect asymmetry only from slopes of ratios of normalized u distributions**
- **Equalize averaged K^+ and K^- acceptances by frequently alternating polarities of relevant magnets**

NA48/2 beams

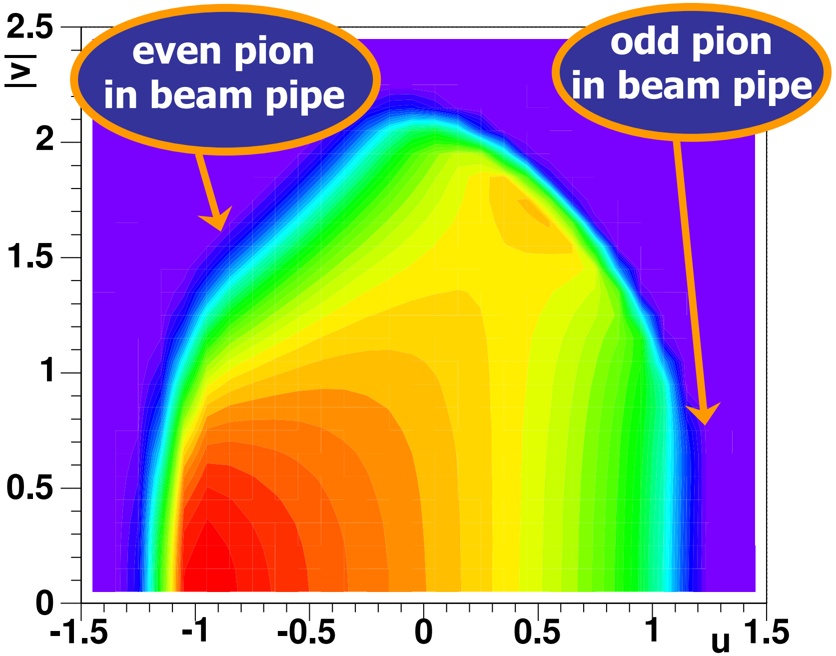


P_K spectra, 60±3 GeV/c
54
60
66
2 ÷ 3 M K/spill (π/K ~ 12)
π decay products stay in pipe
Defining collimators
FDFD
Protecting collimator
Final collimator
Cleaning collimator
magnet
DCH 1
DCH 4
Hodo
LKr
HAC
MUV
K^+
K^-
~$1 \cdot 10^{12}$ ppp
KABES 1
KABES 2
KABES 3
Decay volume
BM
Z
0.36 mrad
Target
focusing beams
Kevlar window
0° prod. angle
DFDF
• Cleaning
• Beam spectrometer (0.7%)
• Momentum selection
• Focusing
• μ sweeping
Beams coincide within ~1mm all along 114m decay volume, always in vacuum
10^{11} K decays per year collected
vacuum tank
He tank + spectrometer
not to scale
1cm
10 cm
50
100
200
250 m

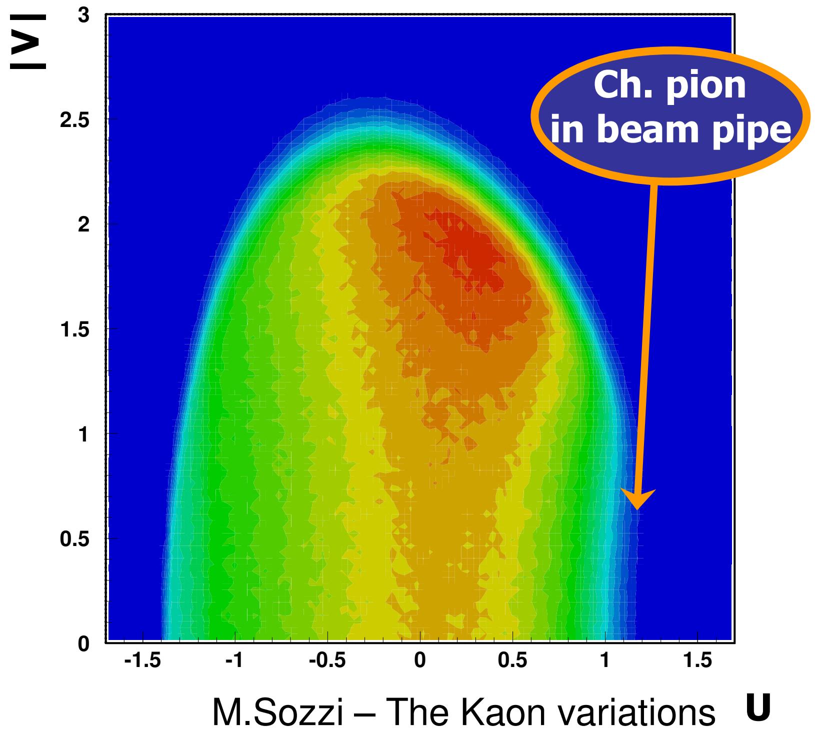
NA48/2: $K^{\pm} \rightarrow 3\pi$

Data-taking 2003-04: 3.1×10^9 + 9.1×10^7 events selected ($K^+/K^- \approx 1.8$)
No significant background, complementary analysis in the two modes
Exploit multiple cancellations of instrumental effects via inversion of magnetic fields and simultaneous beams

$3.1 \cdot 10^9$ $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$



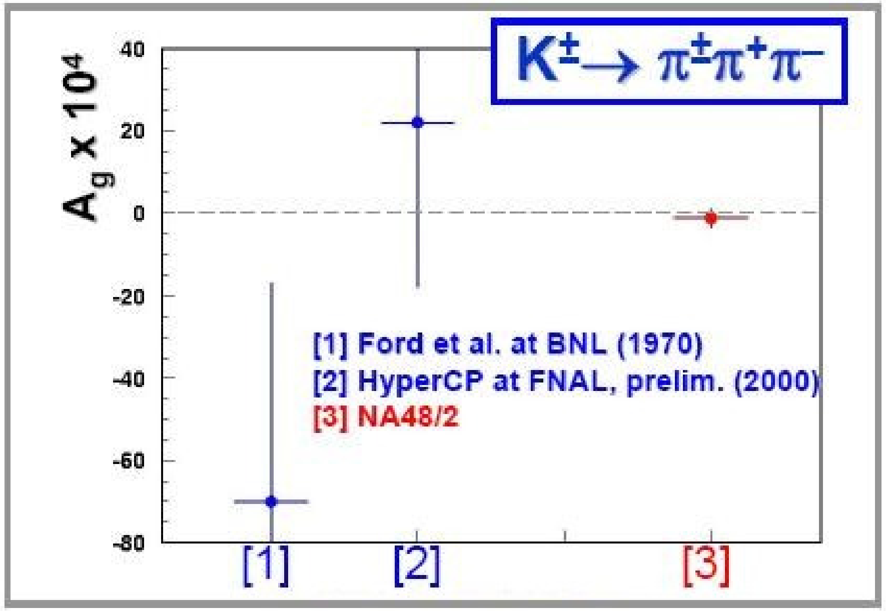
$9.1 \cdot 10^7$ $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$

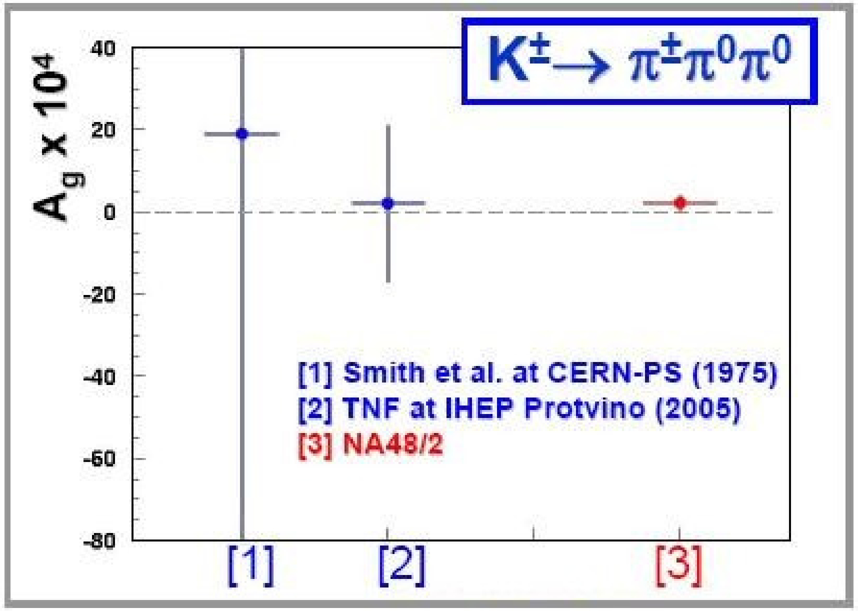


NA48/2: CPV in $K_{\pi3}$

Final results on full statistics (2003+2004)

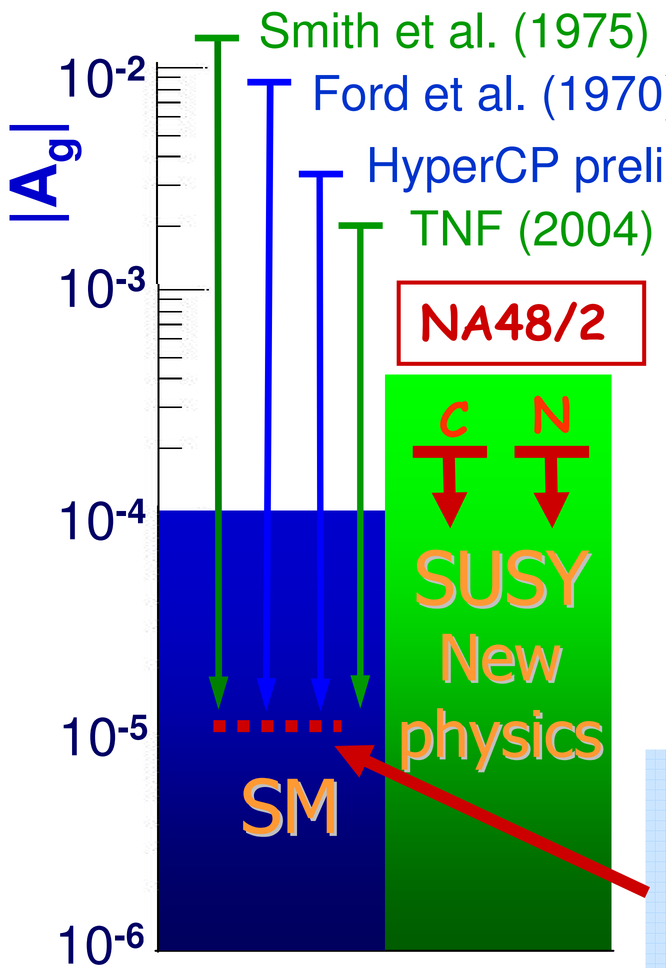
Ag(C)	Ag(N)
$= (-1.5 \pm 1.5_{stat} \pm 0.9_{trig} \pm 1.1_{syst})\cdot 10^{-4}$	$=(1.8 \pm 1.7_{stat} \pm 0.5_{syst})\cdot 10^{-4}$
$= (-1.5 \pm 2.1) \cdot 10^{-4}$	$= (1.8 \pm 1.8) \cdot 10^{-4}$
($3.1\cdot 10^9$ decays)	($9.1\cdot 10^7$ decays)





Statistics dominated. x10 improvement. No CPV found.

$K^\pm$ asymmetries vs. the SM



THEORY:

SM contribution: many theoretical computations
Large uncertainties
(~1 order of magnitude)
Enhancements possible beyond SM

- **$A_g \sim 10^{-5}$ compatible with SM**
- **$A_g > 1\cdot10^{-4}$ SUSY / New Physics**

NP window "closed", part of SUSY model parameter space excluded

E. Gámiz et al (2003)
SM estimate (NLO ChPT):
$A_g(C) = (-1.4\pm1.2\pm?)\cdot10^{-5}$
$A_g(N) = (1.1\pm0.7\pm?)\cdot10^{-5}$

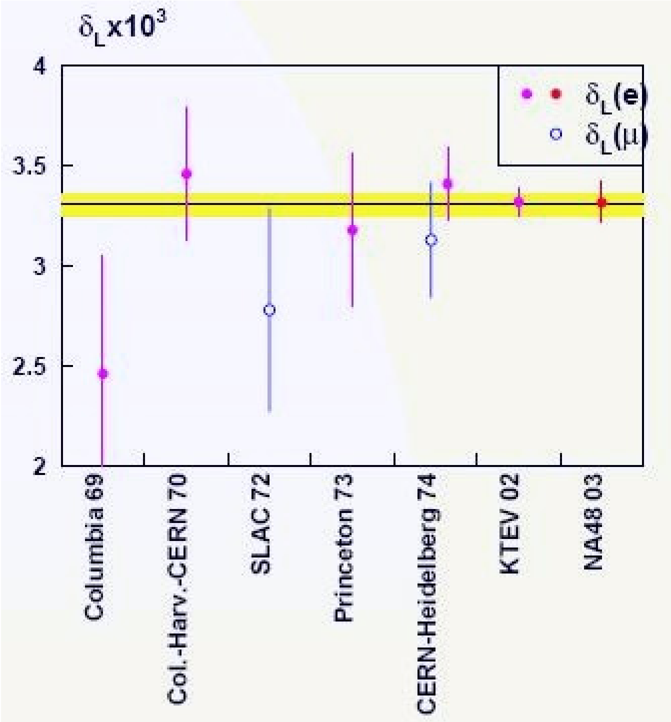
CANONE ALLA TERZA

KTeV, NA48: ε

Precise measurements obtained by K_L semi-leptonic charge asymmetry in KTeV and NA48 using a few 100M decays per experiment:

$$\delta_L(\ell) = \frac{\Gamma(K_L \to \pi^- \ell^+ \nu) - \Gamma(K_L \to \pi^+ \ell^- \overline{\nu})}{\Gamma(K_L \to \pi^- \ell^+ \nu) + \Gamma(K_L \to \pi^+ \ell^- \overline{\nu})} = \frac{2\,\mathrm{Re}(\varepsilon)}{1+|\varepsilon|^2}$$

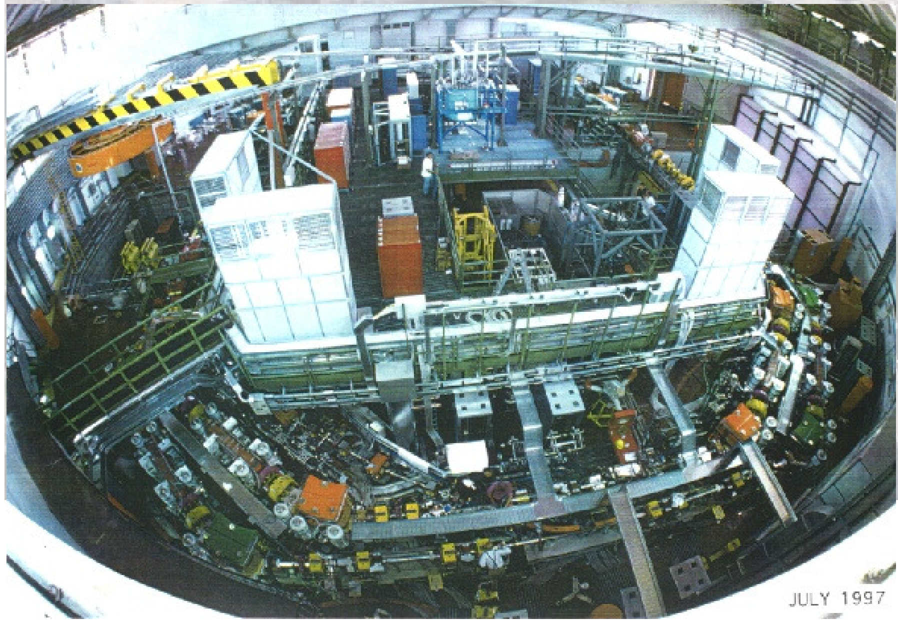
(assuming CPT)

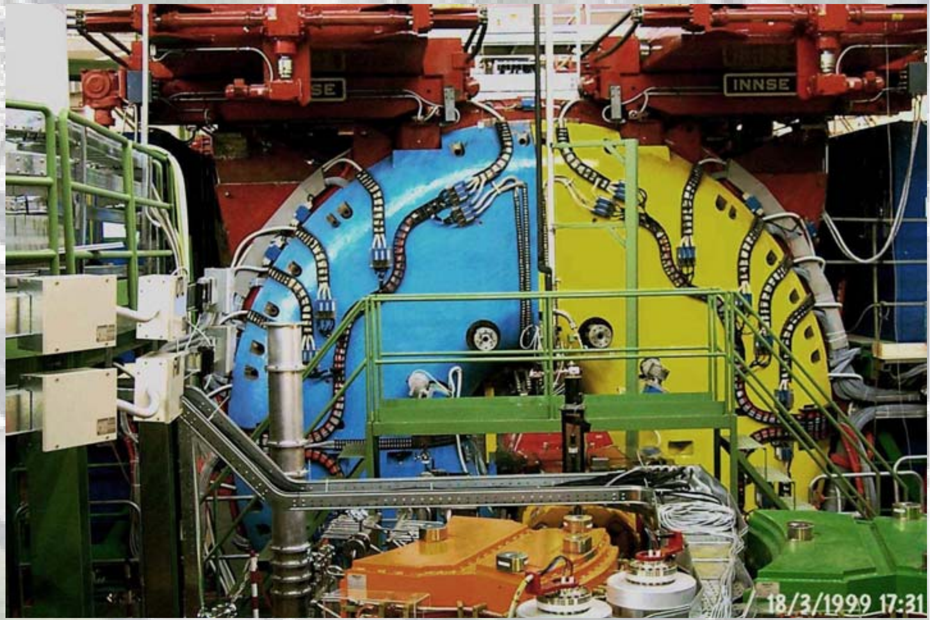


$$\delta_L(e) = (3.322 \pm 0.055)\cdot 10^{-3}$$ (world average)

KLOE (1999-2007)

At Frascati DAΦNE Φ-factory with separate e+e- rings and 12.5 mrad crossing angle working at $\sqrt{s} = m(\Phi) = 1019.4$ MeV



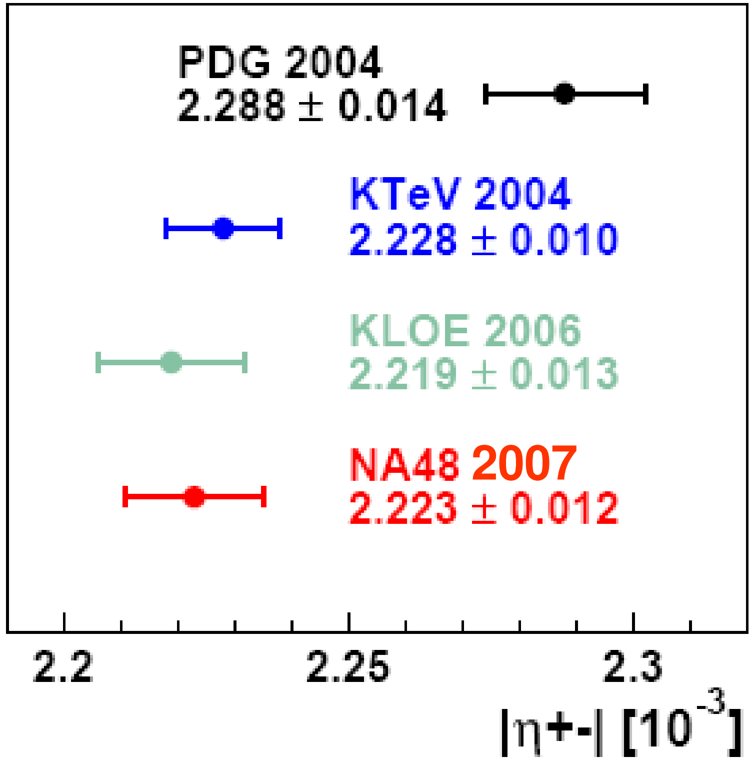


Integrated luminosity:
~ 2.5 fb^{-1} 1999-2006
(~ $2.5 \cdot 10^9$ $K_S K_L$ events)

KTeV, KLOE, NA48: ε

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

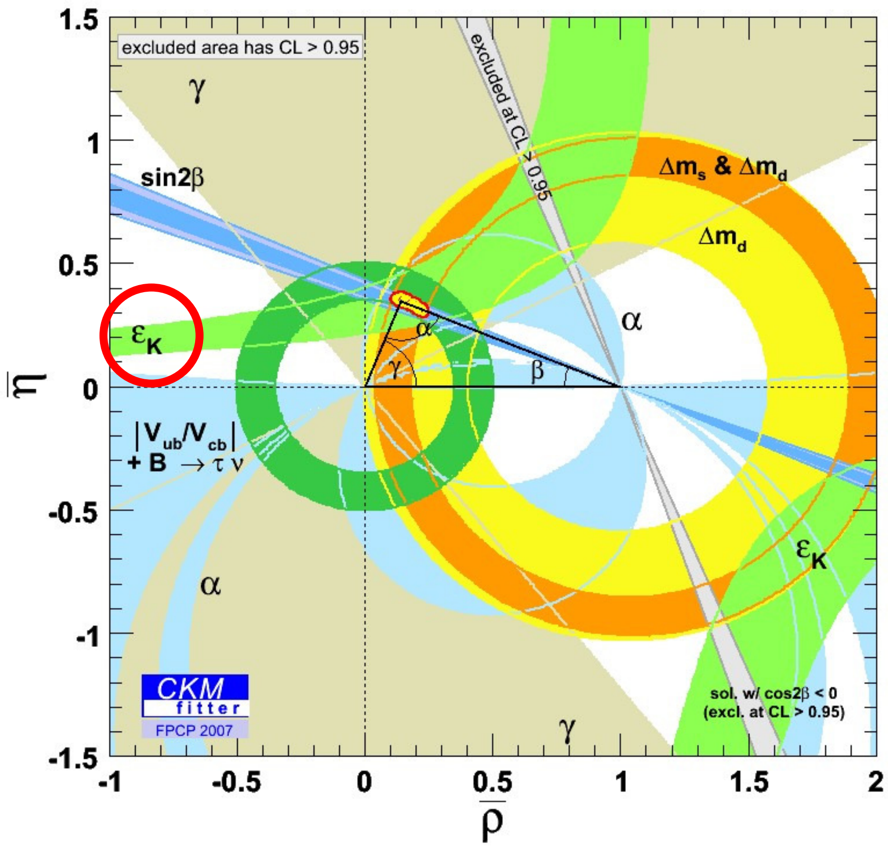
KTeV: direct measurement of
BR(KL→$\pi^+\pi^-$)/BR(KL→$\pi e\nu$)
84K events in 1997
KLOE: direct measurement of
BR($K_L \to \pi^+\pi^-$)/BR($K_L \to \pi\mu\nu$)
45K events from subsample of 2001-2002 data
NA48: direct measurement of
BR(KL→$\pi^+\pi^-$)/BR(KL→$\pi e\nu$)
47K events from 2-day run in 1999



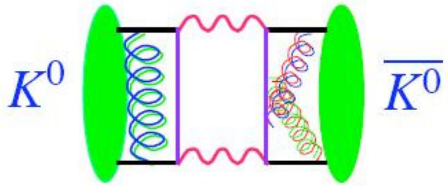
"The BR revolution"
- Proper treatment of radiative corrections
- Several correlations

ε confronts the SM

$\varepsilon \neq 0$ constrains (poorly) the apex of the Unitarity Triangle due to the theoretical difficulty in handling the hadronic uncertainties



ε measured to 0.5%
Waiting for lattice QCD for K to become also a *quantitative* test of SM.



CANONE ALLA TERZA

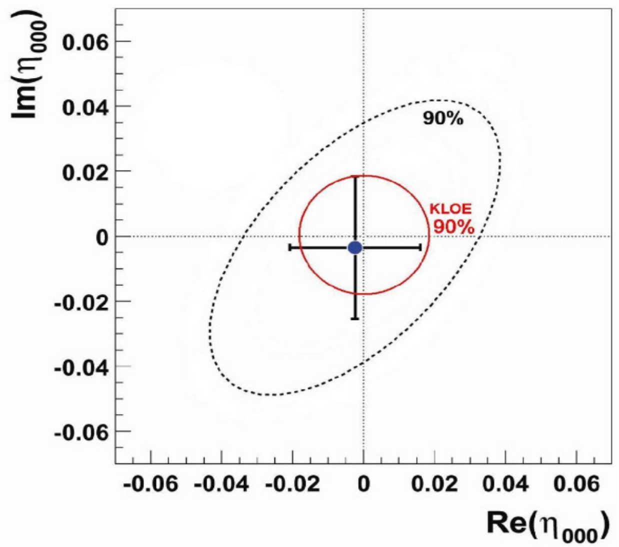
CPV in hadronic K_S decays

3π states are (predominantly) CP-odd

Estimate (indirect CPV): $\Gamma_S(3\pi) \approx \Gamma_L(3\pi)|\eta|^2$, or
$BR(K_S \to 3\pi^0) \approx BR(K_L \to 3\pi^0)\ |\varepsilon|^2\ (\tau_S/\tau_L) \approx 1.9 \cdot 10^{-9}$

Hadron machines: look for K_S-K_L interference.
NA48/1 (2005,assuming CPT): $BR(K_S \to 3\pi^0) < 2.3\times10^{-7}$ (90% CL)
with 5+100 million K decays.

Phi-factories: search for tagged $K_S \to 3\pi^0$ decays.
KLOE (2005): $BR(K_S \to 3\pi^0) < 1.2\times10^{-7}$ (90% CL)
with 2 signal events.
Improvements expected from here…



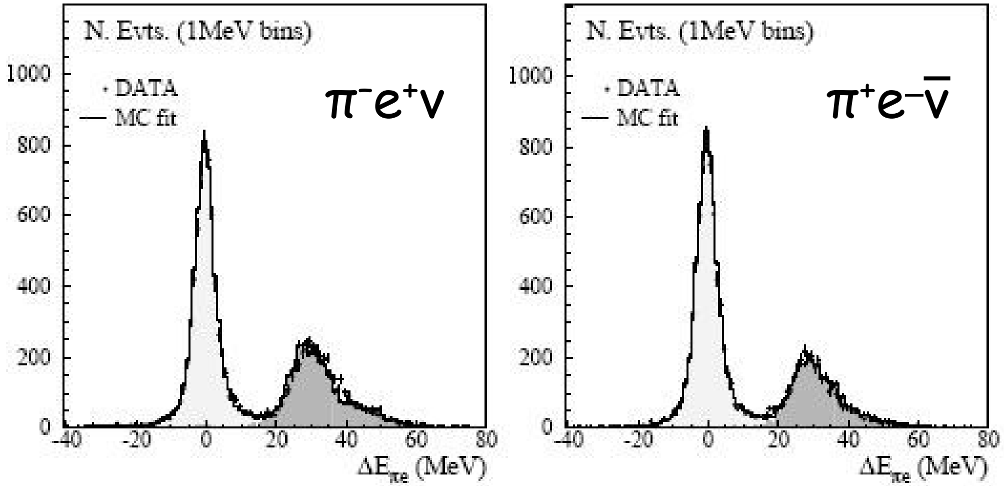
No CPV in sight yet

KLOE: $\delta_S(e)$

First measurement of K_S semi-leptonic decays ($K_S \to \pi\mu\nu$ also seen):

$BR(K_S \to \pi e \nu) = (7.028 \pm 0.092) \times 10^{-4}$

2001-2002 data (410 pb^{-1}): 13K events



(Indirect) CP-violating charge asymmetry:

$$\delta_S(e) = \frac{\Gamma(K_S \to \pi^- e^+ \nu) - \Gamma(K_S \to \pi^+ e^- \bar{\nu})}{\Gamma(K_S \to \pi^- e^+ \nu) + \Gamma(K_S \to \pi^+ e^- \bar{\nu})}$$

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

CPT test by comparison to $\delta_L(e)$ (still far from being significant)

Cabibbo angle 45 years later

UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)

In 2004 a slight violation of the unitarity appeared in the first (best) row of the CKM matrix:
$|V_{ud}|$ from β decays, $|V_{ub}| \approx 10^{-5}$ ignored

$$|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} = 1 ?$$

All experiments re-measured semi-leptonic decays of neutral and charged K with sub-percent precision.

iso-spin breaking

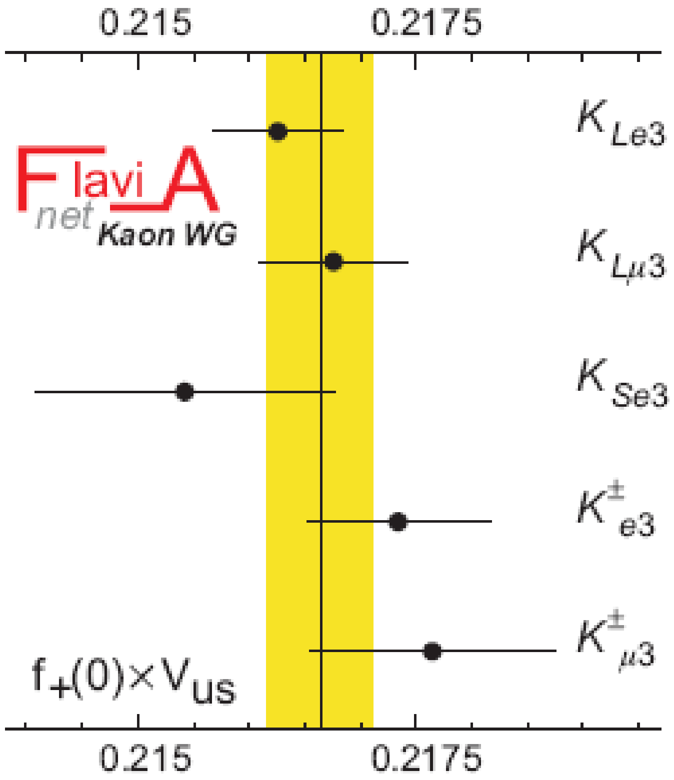
phase-space integral

FlaviA net Kaon WG

mode	$f_+(0)V_{us}$	% err	BR	τ	Δ	Int
$K_L \to \pi e \nu$	0.21625(60)	0.28	0.09	0.19	0.15	0.09
$K_L \to \pi \mu \nu$	0.21675(66)	0.31	0.10	0.18	0.15	0.15
$K_S \to \pi e \nu$	0.21542(134)	0.67	0.65	0.03	0.15	0.09
$K^\pm \to \pi e \nu$	0.21728(84)	0.39	0.26	0.09	0.26	0.09
$K^\pm \to \pi \mu \nu$	0.21758(111)	0.51	0.40	0.09	0.26	0.15
average	0.21661(47)					

error breakdown

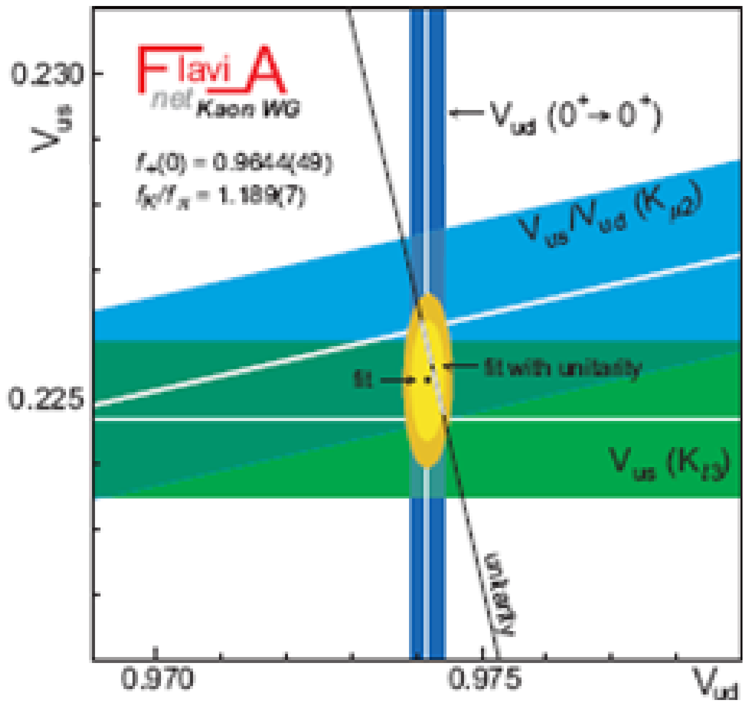
$|V_{us}|$: Cabibbo angle



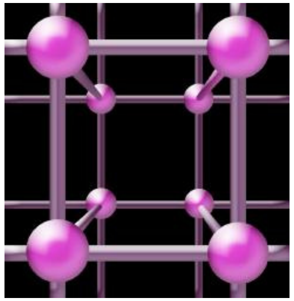
$f_+(0)$ needed from theory (lattice QCD): now around 0.5% error (?)

Using $f_+(0) = 0.9644(49)$ from RBC-UKQCD:

$|V_{us}|=0.22461\pm0.00124$

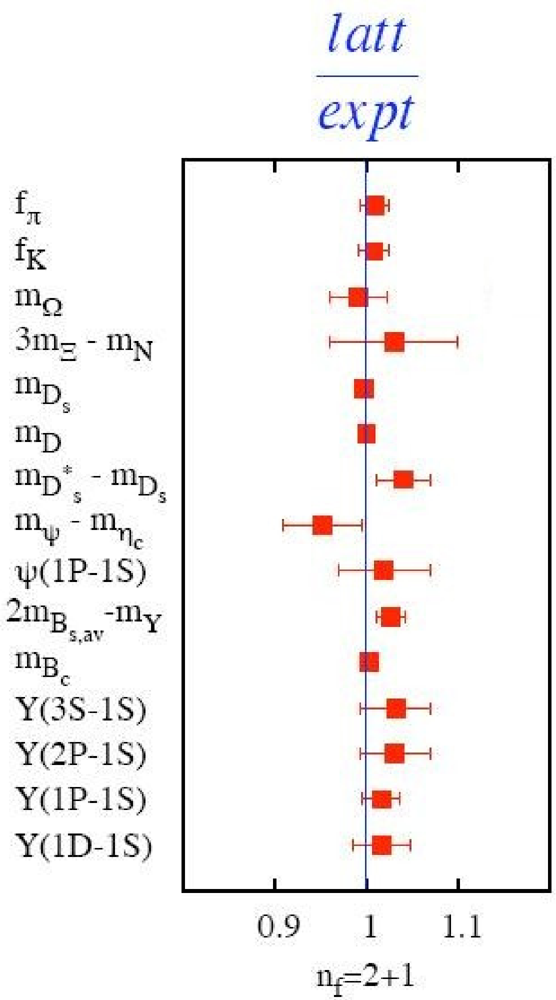


Unitarity is safe



Speaking of lattice QCD…

"Once upon a time, it is told, lattice QCD theorists used to work in the quenched approximation… That was a long time ago…"



It seems accuracy reached the few % figure

Issues for K physics:

- Percent control of $|V_{cb}|$ and m_c to exploit future $K^+ \to \pi^+ \nu\nu$

- B_K to exploit ε measurement (10% → 1%)

- ε'/ε (ΔI=1/2) (100% → anything)

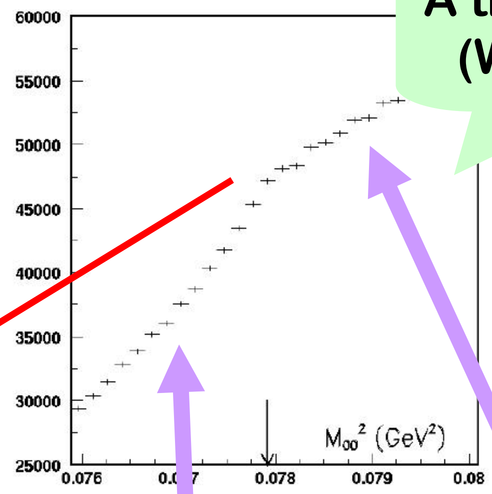
- f+(0) to extract $|V_{us}|$ (0.8% → 0.1%)

- Control of $K_L \to \gamma^* \gamma^*$ to possibly extract SD physics from $K_L \to \pi^0 \ell\ell$

FUGHETTA

NA48 byproducts: ππ scattering

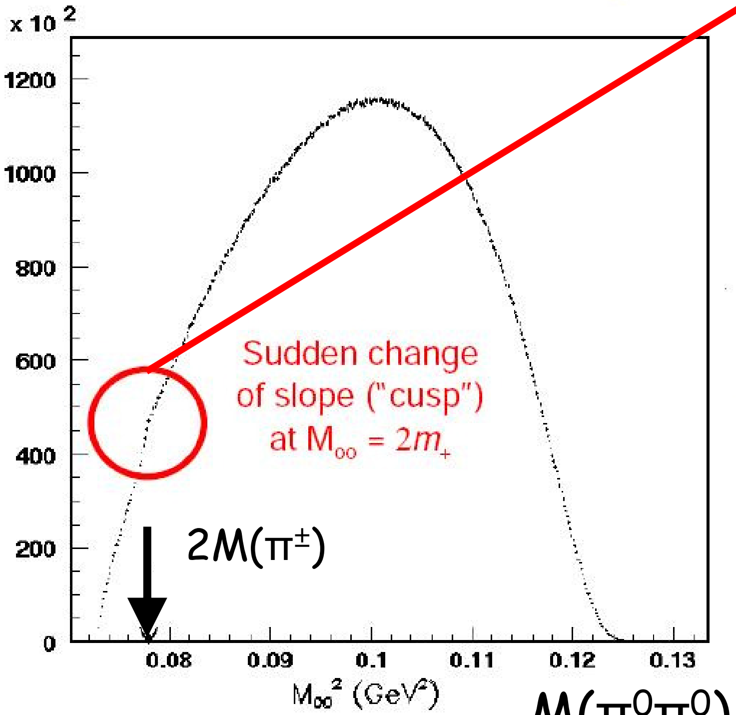
“A threshold cusp”
(Wigner 1948)



Unperturbed matrix element:

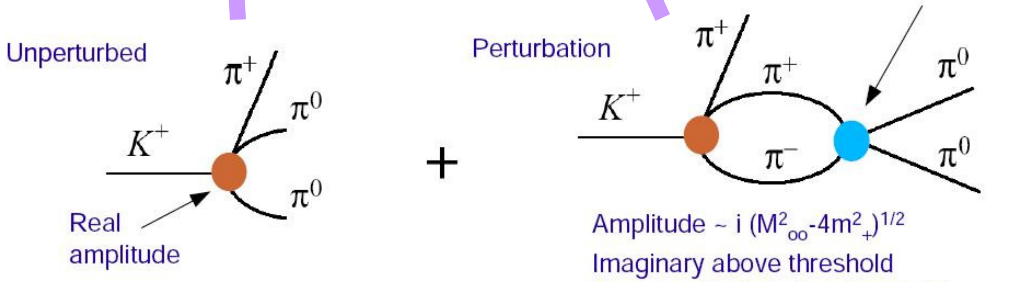
$$M_0 = 1 + \frac{1}{2} g_0 u + \frac{1}{2} h' u^2$$

Experimental M_{oo}^2 distribution
for 23 x 10^6 $K^\pm \to \pi^\pm \pi^\circ \pi^\circ$ decays



$M(\pi^0\pi^0)$

Final state pion scattering effect:



Amplitude ~ i $(M^2_{oo}-4m^2_+)^{1/2}$
Imaginary above threshold
Real amplitude below threshold

Stimulated much theoretical work:
Cabibbo et al., Gamiz et al., Colangelo et al.

NA48/2: $\pi\pi$ scattering

As remarked by N. Cabibbo (2004) this effect is potentially the best measurement of a fundamental observable of QCD (pion scattering lengths), also measured by other means (with and without Kaons)

60 M events (full statistics). Using a2(a0) constraint from ChPT:

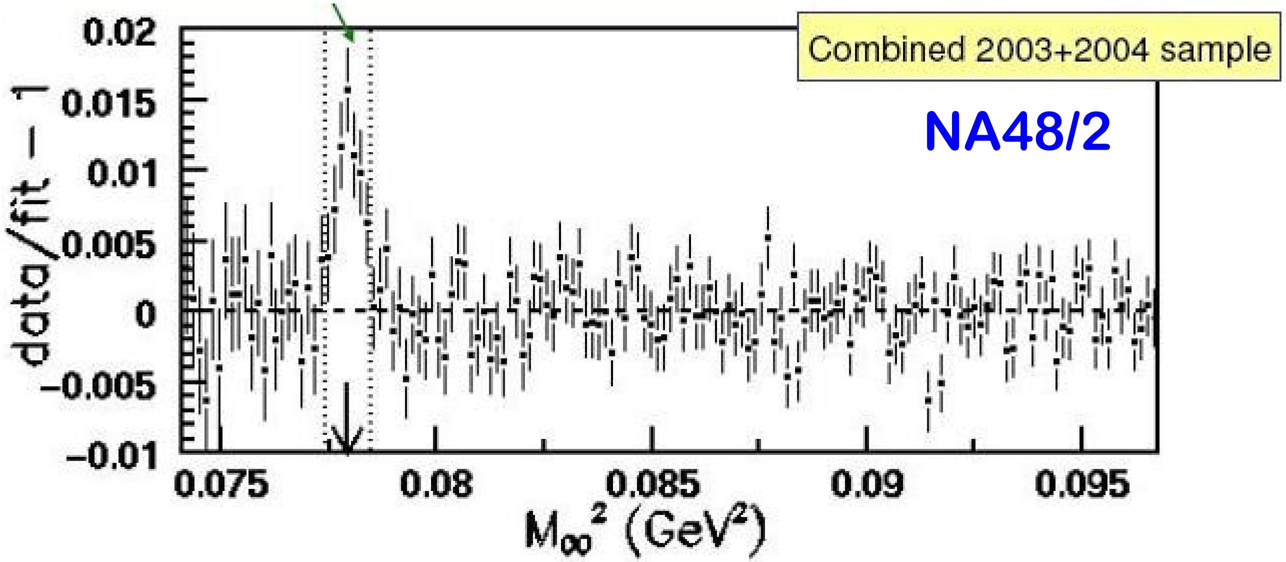
$(a_0 - a_2)m_+ = 0.268 \pm 0.003_{stat} \pm 0.002_{syst} \pm 0.001_{ext}$ **[Cabibbo et al.]**

$(a_0 - a_2)m_+ = 0.266 \pm 0.003_{stat} \pm 0.002_{syst} \pm 0.001_{ext}$ **[Colangelo et al.]**

PRELIMINARY

Theoretical work needed to fully exploit the precision of the experimental data (rad. corr., theory error)

Evidence for *pionium* bound state formation $O(10^{-5})$ of $K \rightarrow 3\pi$

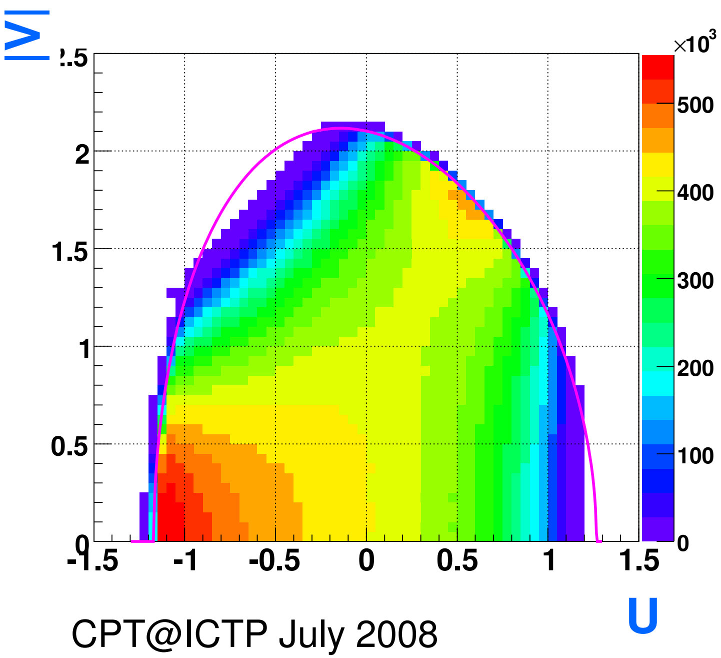


$K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ Dalitz plot

NA48/2 unprecedented statistics allows improvement in slope measurements.
Deliberately ignore **non-analytic (cusp) and radiative effects**
Full MC tuning, agreement to 10^{-3} level

$$d\Gamma/dudv \sim C(u,v)\times(1+gu+hu^2+kv^2)$$

Naïve Coulomb correction



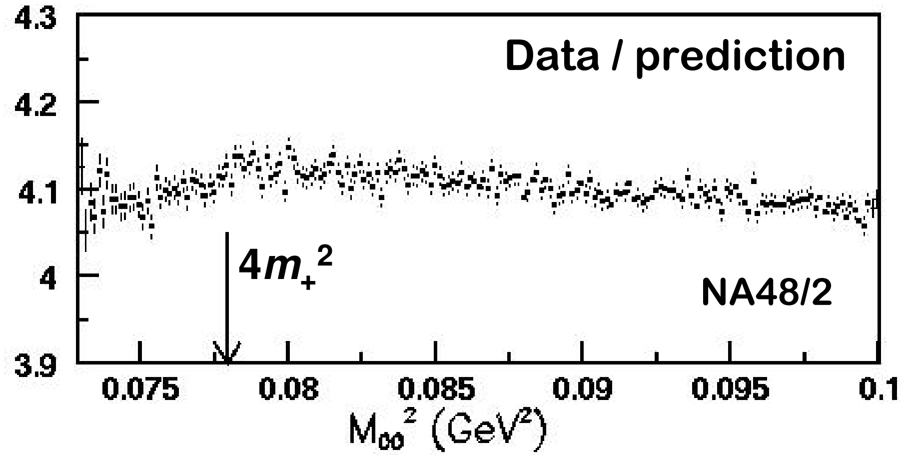
Final results from partial 2003 statistics
(0.47×10^{9} events)

$$g = (-21.134 \pm 0.014)\%$$
$$h = (1.848 \pm 0.039)\%$$
$$k = (-0.463 \pm 0.012)\%$$

"Naïve" slopes (comparable with PDG)
X10 PDG precision
Systematics dominated by π mom. resolution

FUGHETTA

Cusp in KL decays



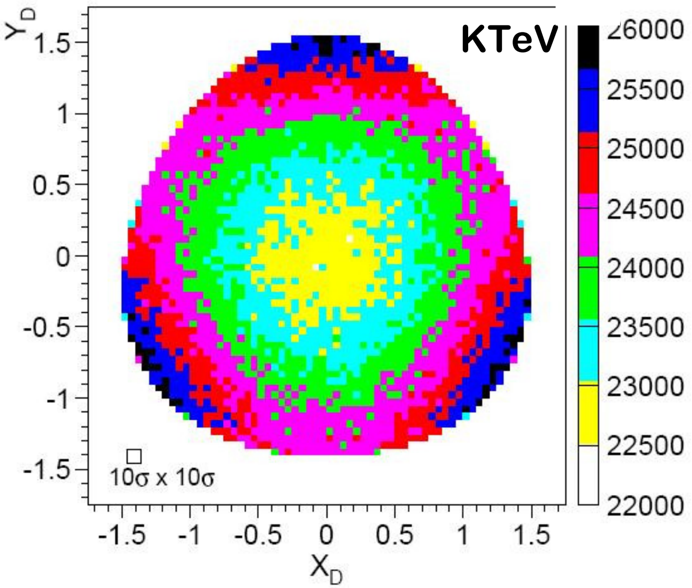
Same effect is present in KL→3π0 (visibility reduced by iso-spin).

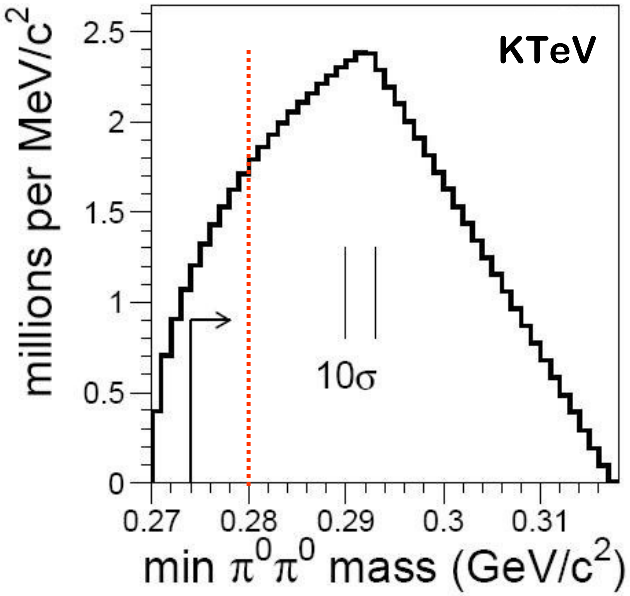
NA48/2: 100M events

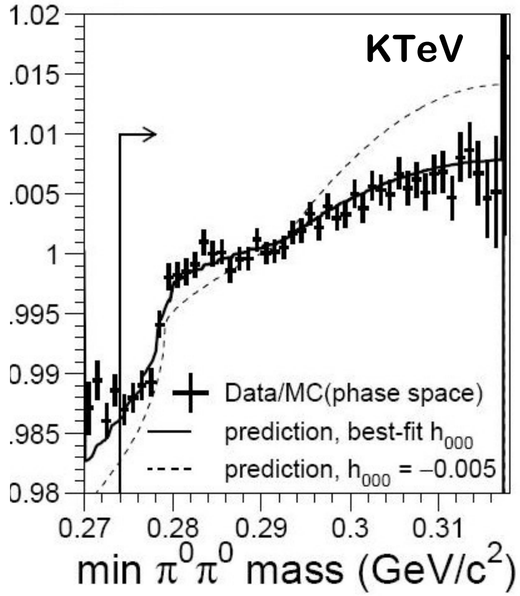
68.3M $K_L \to \pi^0\pi^0\pi^0$

KTeV

+125M MC events







FUGHETTA

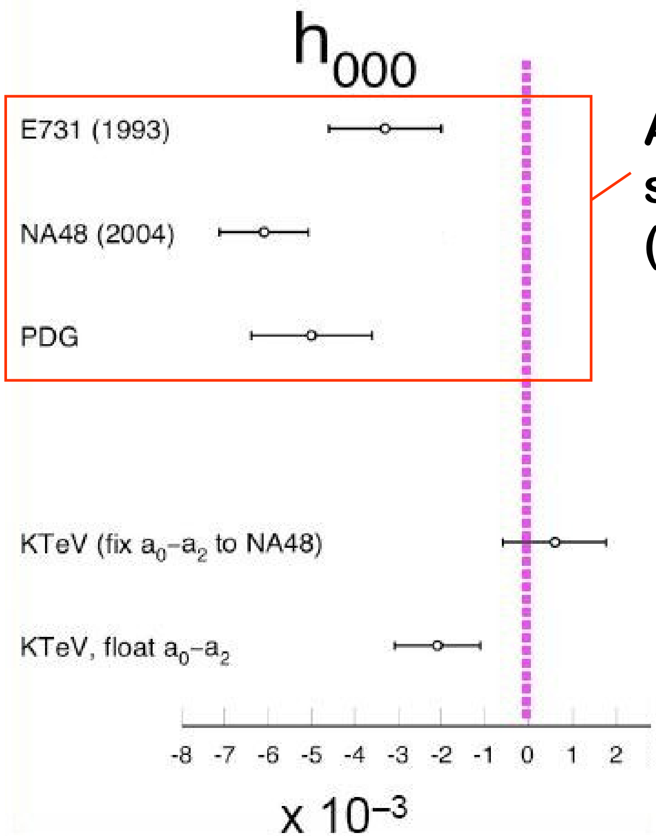
$K_L \to \pi^0\pi^0\pi^0$ Dalitz plot

KTeV

$$h_{000} = (0.59 \pm 0.20 \pm 0.48 \pm \underset{\text{ext}}{1.06}) \cdot 10^{-3}$$

fixing $m_+(a_0\text{-}a_2) = 0.268$

(χ^2/dof = 2805.3/2765)



Assuming circular symmetry of Dalitz plot (no rescattering)

However: fitting both the slope and the scattering length difference, the sensitivity is small and

$h_{000} = (-2.09 \pm 0.62 \pm 0.72 \pm 0.28)\cdot 10^{-3}$

$m_+(a0\text{-}a2) = 0.215 \pm 0.014 \pm 0.025 \pm 0.006$

(χ^2/dof = 2790.6/2764)

KTeV

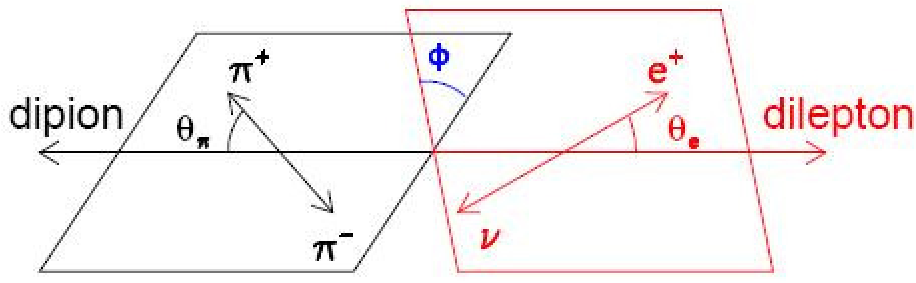
NA48/2: Ke4

$K^{\pm}e4$ ($K^{\pm} \to \pi^+\pi^- e^{\pm}\nu$) is the "classic" approach to low-energy $\pi\pi$ scattering.

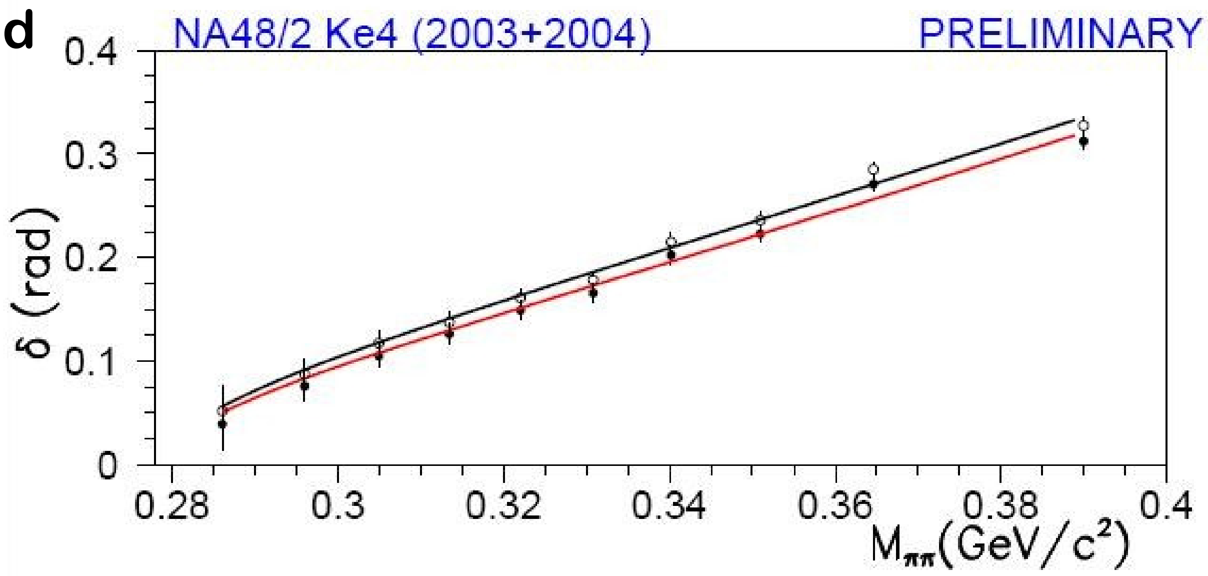
- **5 kinematic variables**
- **3 form factors**
- **Keep S- and P-waves**
- **Expand in powers of q^2 (dipion system)**

Extract $\delta = \delta_S - \delta_P$ phase difference between S- and P-waves in $F(q^2)$ axial form-factor

Isospin-breaking corrections

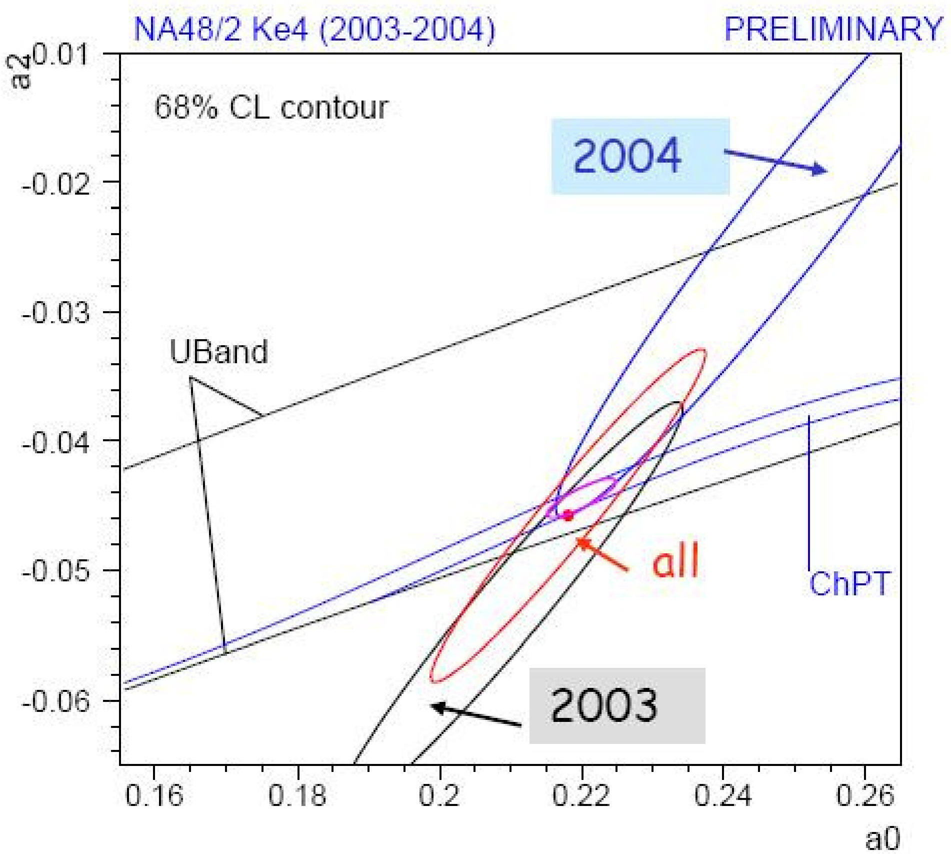


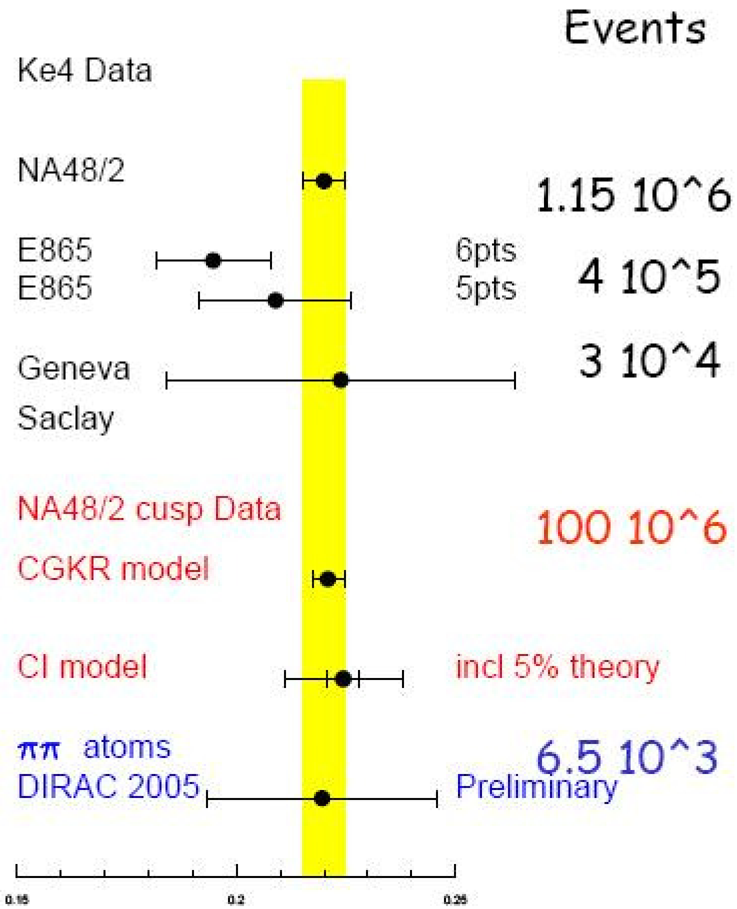
1.15 M events (2003+2004)
0.5% background
x24 MC statistics
Independent fits in bins of m($\pi\pi$)
Radiative corrections



NA48/2: scattering lengths

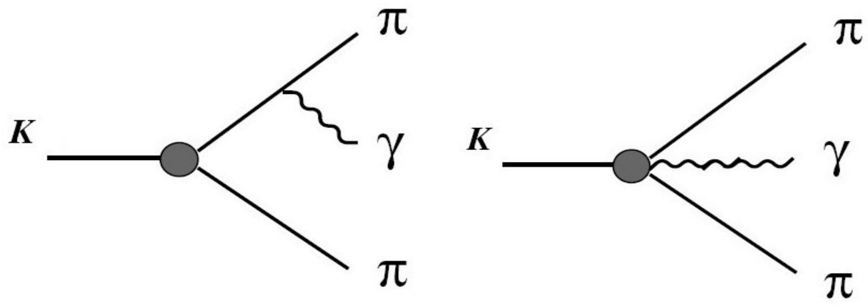
With theoretical input δ can be related to a_2 and a_0:





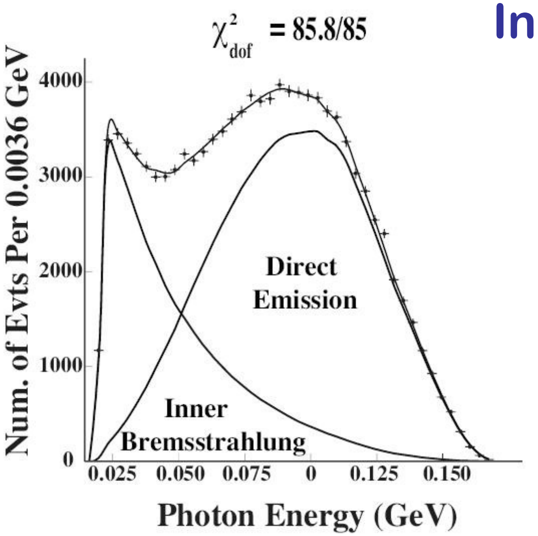
Reached ChPT error: good agreement

$K \to \pi\pi\gamma$

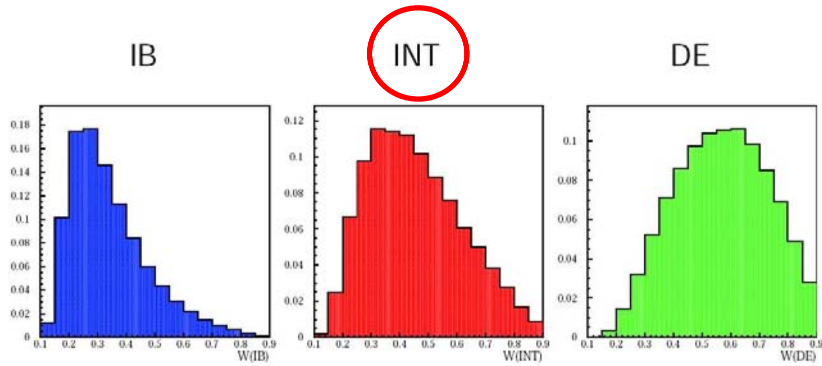


$K_L \to \pi^+\pi^-\gamma$

Inner *bremsstrahlung* (IB) Direct emission (DE)



$K^\pm \to \pi^+\pi^0\gamma$



Separation by photon spectrum

KTeV (2006): 112K events (40% of total)

DE/(IB+DE) = 0.689 ± 0.021

for Eγ > 20 MeV

NA48/2: 220K events (20% of total)

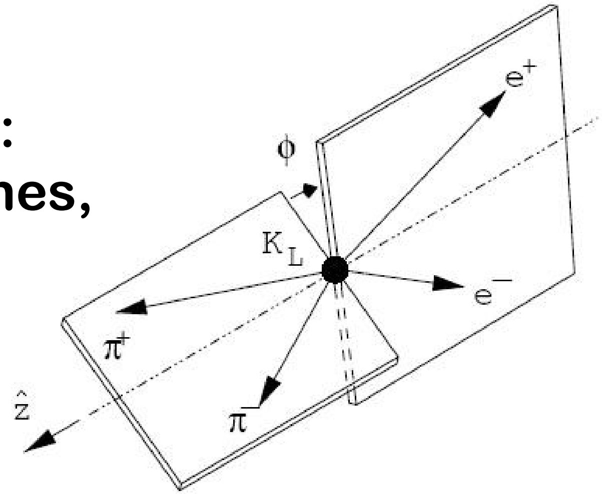
DE = (3.35 ± 0.43)% INT = (2.67± 1.09)%

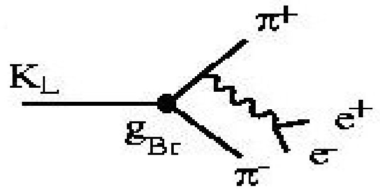
for $0 < T^*_\pi < 80$ MeV

INT could give (direct) CPV $O(10^{-4})$

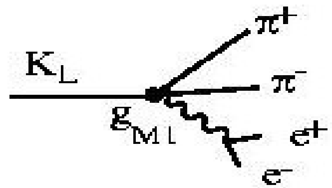
$K_{L,S} \rightarrow \pi^+\pi^-e^+e^-$ and CPV

Rare decay (BR ≈ $3\cdot10^{-7}$) first seen by KTeV
Internal γ conversion allows helicity analysis: asymmetry in angle φ between ππ and ee planes, in agreement with theory (indirect CPV)

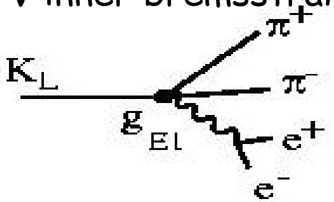




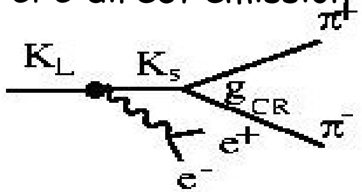
CPV inner bremsstrahlung



CPC direct emission



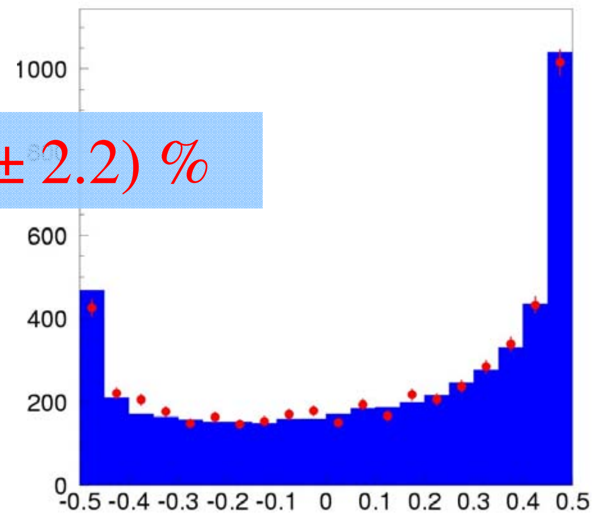
CPV direct emission



Charge radius

$A_\Phi = (13.8 \pm 2.2)$ %

(KTeV + NA48)



Also $K_L \rightarrow e^+e^-e^+e^-$ (KTeV, NA48) and related CPV parameters

T violation: Kabir's Test

Reminder: the only direct measurement of TV
Direct comparison of T-conjugate (virtual) transitions:

$$A_T = \frac{P(\overline{K}^0 \to K^0) - P(K^0 \to \overline{K}^0)}{P(\overline{K}^0 \to K^0) + P(K^0 \to \overline{K}^0)}$$

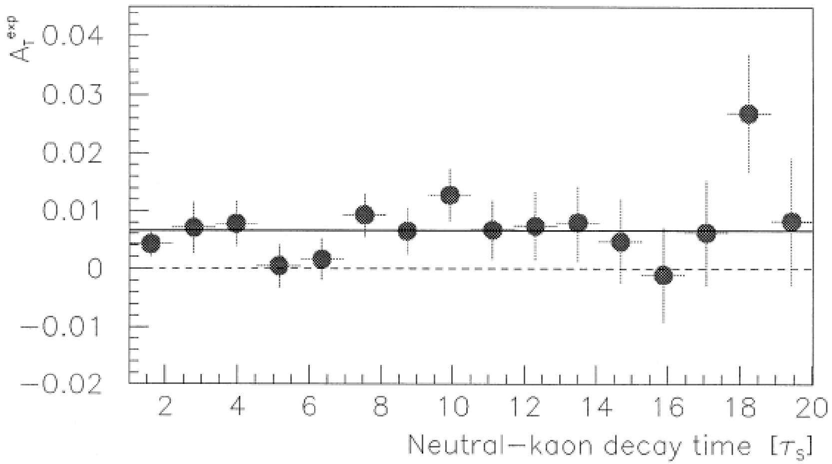
Using semi-leptonic decays and assuming CPT in decays

$$A_T(t) = 4\,\mathrm{Re}(\varepsilon) + 2\frac{\mathrm{Re}(x_-)\left[e^{-\Delta\Gamma t/2} - \cos(\Delta m t)\right] + \mathrm{Im}(x_+)\sin(\Delta m t)}{\cosh(\Delta\Gamma t/2) - \cos(\Delta m t)}$$

CPLEAR (1998):

$\langle A_T \rangle = (6.6 \pm 1.3) \cdot 10^{-3}$

Fully consistent with indirect CPV in K^0 mixing



QUODLIBET

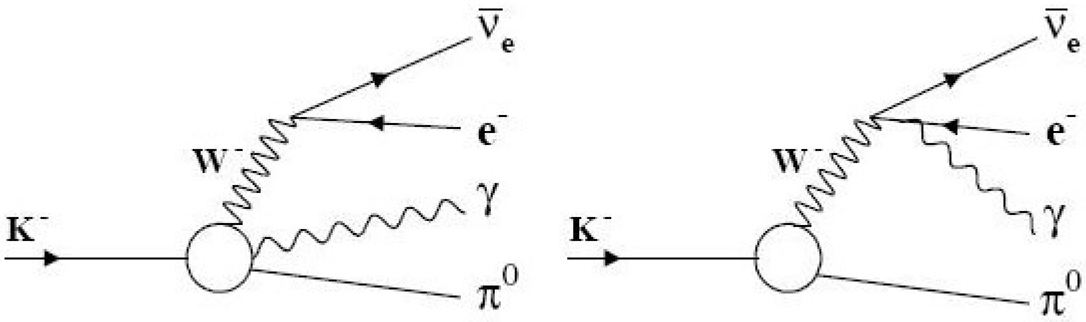
T-odd correlations

Looked for in 3-body decays (w. spin) or 4-body decays (momenta)

Beware of fake asymmetries by Final State Interactions

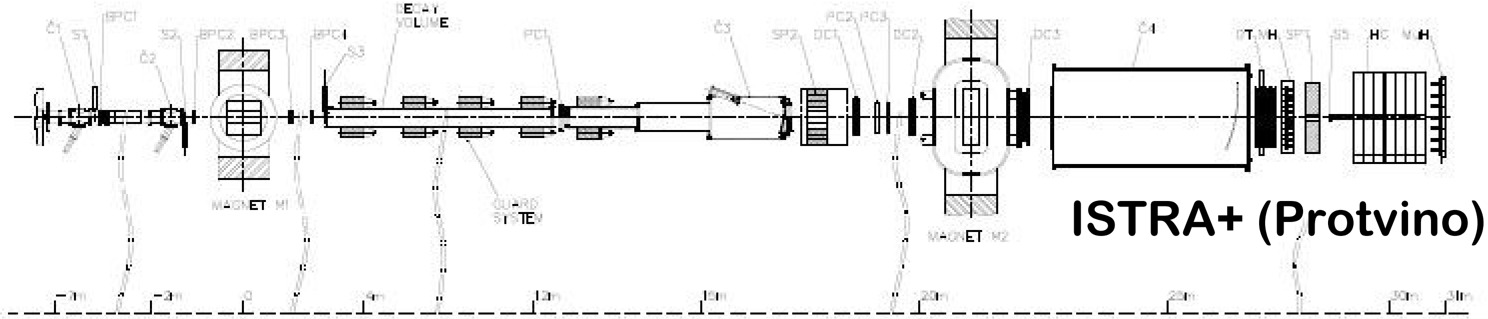
K_{e4} ($K \to \pi\pi e\nu$) BR $\approx 4.1 \cdot 10^{-5}$ or $K_{e3\gamma}$ ($K \to \pi e \nu \gamma$) BR $\approx 2.7 \cdot 10^{-4}$ or $K_{\mu 3\gamma}$ ($K \to \pi \mu \nu \gamma$) BR $\approx 2.4 \cdot 10^{-5}$

Ke3γ:



$$\xi = \frac{(\mathbf{p}_\pi \times \mathbf{p}_\mu) \cdot \mathbf{p}_\gamma}{|\mathbf{p}_\pi \times \mathbf{p}_\mu| |\mathbf{p}_\gamma|} \qquad A_\xi = \frac{N(\xi > 0) - N(\xi < 0)}{N(\xi > 0) + N(\xi < 0)}$$

$K\ell3\gamma$: ISTRA, NA48



$Ke3\gamma$: FSI: $A_\xi \approx (0.5\text{-}1)\cdot 10^{-4}$ in the SM - NP models: $A_\xi \approx$ few 10^{-4}

ISTRA+ (2005): $A_\xi = 0.015 \pm 0.021$ (1400 events)

NA48/2: few 10^5 events and cancellation of FSI effects by K+/K– comparison, in progress

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$K\mu3\gamma$: FSI: $A_\xi \approx 1.1\cdot 10^{-4}$ in the SM - NP models: $A_\xi \approx 2.5\cdot 10^{-4}$

ISTRA+ (2006): $BR(K^- \to \pi^0 \mu^- \nu\gamma) \approx 9\cdot 10^{-5}$

$A_\xi = -0.03 \pm 0.13$ (400 events)

QUODLIBET

More T-odd: PT(μ)

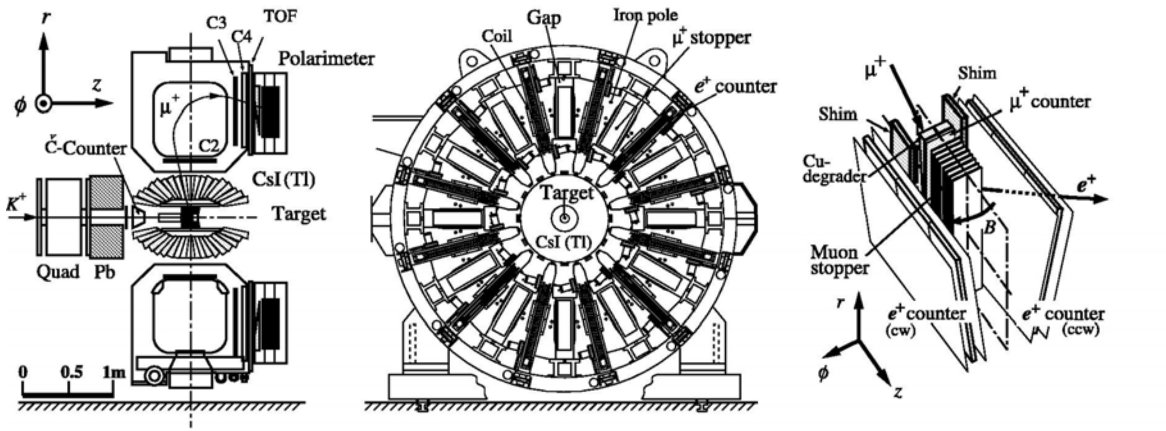
$P_T(\mu)$ in Kμ3 decays

$$P_T(\mu) = \frac{(\mathbf{p}_\pi \times \mathbf{p}_\mu)\cdot \mathbf{S}_\mu}{|\mathbf{p}_\pi \times \mathbf{p}_\mu||\mathbf{S}_\mu|}$$

Experiments in the '70s on $K_L \to \pi^- \mu^+ \nu$ reached the FSI limit:

Im $\xi = (-7 \pm 26) \times 10^{-3}$ (ξ = ratio of the two contributing FFs)

KEK E246:
660 MeV/*c* K^+ stopped in active target. Final result ($8.3M\ \pi^0\mu^+\nu$ decays, 1996-2000):



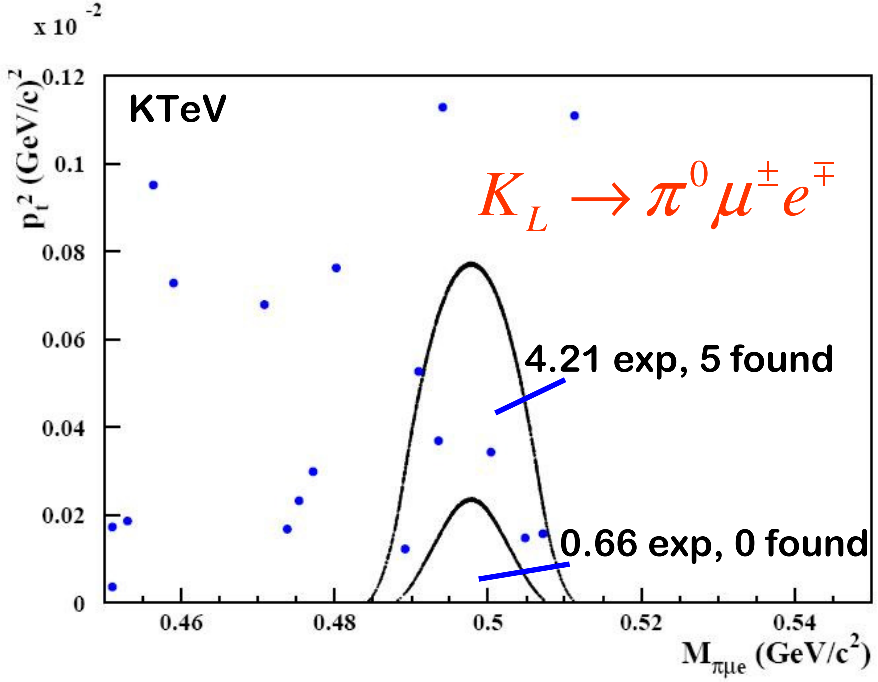
$P_T(\mu) = (-1.7 \pm 2.3 \pm 1.1) \times 10^{-3}$

Im $\xi = (-5.3 \pm 7.1 \pm 3.6) \times 10^{-3}$

x10 improvement expected at J-PARC

Lepton-flavour violation

KTeV exploited its large K_L sample and PID capability to search for LFV as a s→dμe transition:



[PRL 100 (2008) 131803]

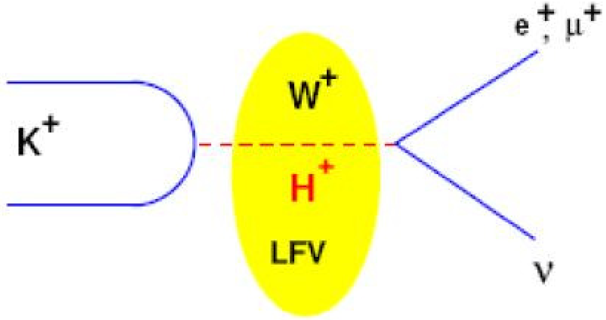
$$BR(K_L \to \pi^0 \mu^{\pm} e^{\mp}) < 7.56 \cdot 10^{-11} \qquad (90\%\ CL)$$

$$BR(K_L \to \pi^0 \pi^0 \mu^{\pm} e^{\mp}) < 1.64 \cdot 10^{-10} \qquad (90\%\ CL)$$

$$BR(\pi^0 \to \mu^{\pm} e^{\mp}) < 3.59 \cdot 10^{-10} \qquad (90\%\ CL)$$

Leptonic decays

$$R_K = \frac{\Gamma(K^{\pm} \to e^{\pm}\nu)}{\Gamma(K^{\pm} \to \mu^{\pm}\nu)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \left(1 + \delta R_{QED}\right) = (2.477 \pm 0.001)\cdot 10^{-5} \quad \textbf{[SM]}$$



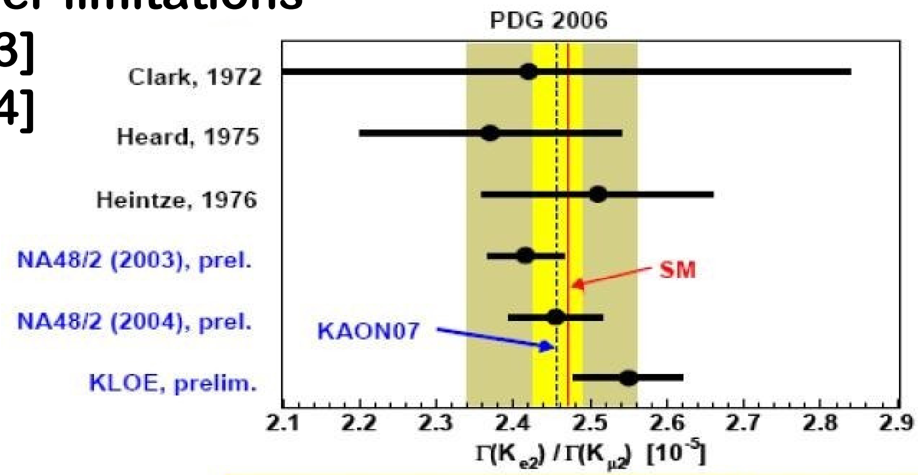
Strong helicity suppression: high sensitivity to NP

Was known to ≈ 5%
2005: 1-3% enhancements not unnatural in SUSY
[Masiero *et al.* PRD74 (2006) 011701]

NA48: 2 (non-dedicated) short runs in 2003,2004
8K evts., background (Kμ2) and trigger limitations
$R_K=(2.416\pm0.043\pm0.024)\cdot10^{-5}$ [prel. 03]
$R_K=(2.455\pm0.045\pm0.041)\cdot10^{-5}$ [prel. 04]

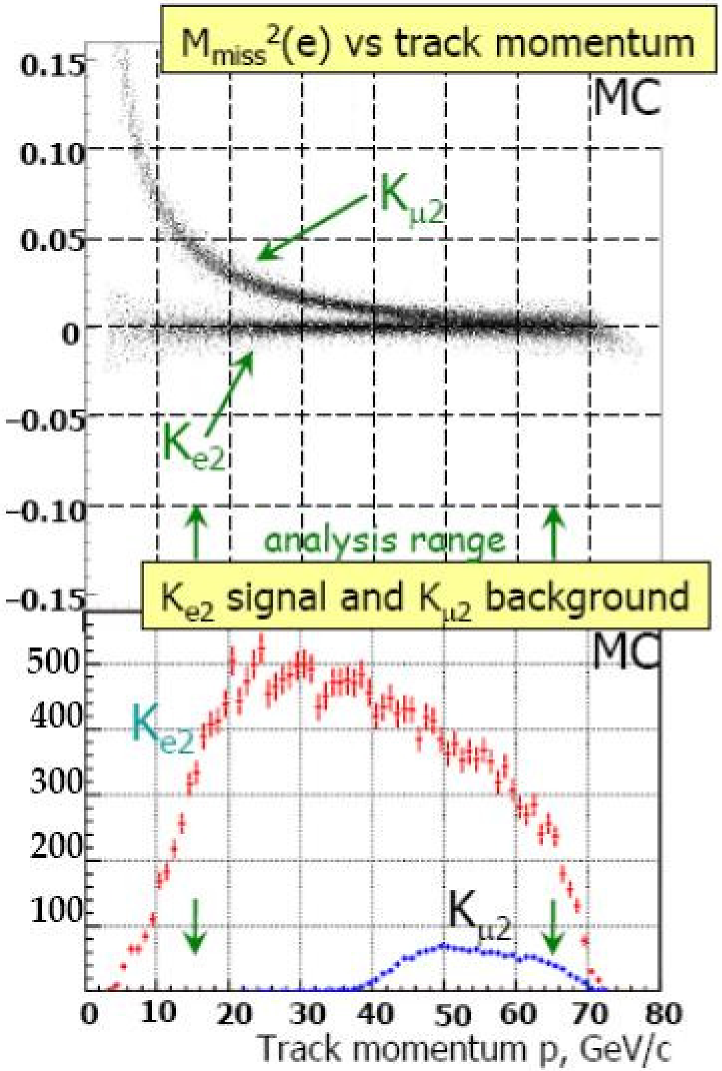
KLOE: 8K evts.
$R_K=(2.55\pm0.05\pm0.05)\cdot10^{-5}$ [prel.]

NA62: Dedicated 4-month run (2007)
Goal: 0.5% error



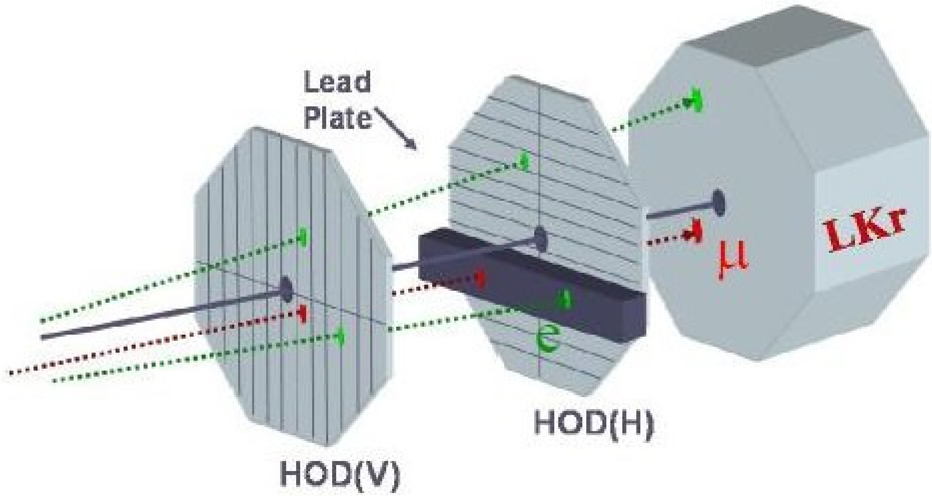
$$R_K = (2.457 \pm 0.032)\cdot 10^{-5} \qquad \left(\chi^2/ndf = 2.44/3\right)$$

NA62: Leptonic decays



2007 dedicated run:

- **Higher beam momentum (60 → 75 GeV/c)**
- **Higher momentum kick**
- **K^+ only**
- **Improved trigger**
- **Simultaneous sample of "pure" μ collected to check PID**



112K candidates (<10% background)
Analysis in progress

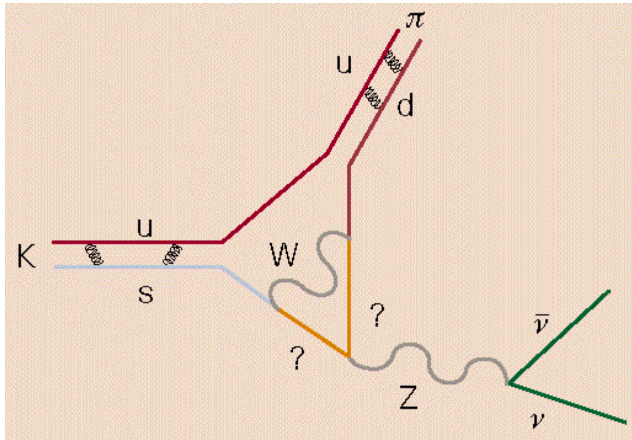
ALLA MARCIA

$K \to \pi \ell \bar{\ell}$ decays

Switch to *quantitative* test of the SM

Flavour sector, probing extremely high energy scales: precision frontier *complementary* to LHC energy frontier

Some (tiny!) BRs can be computed to *very high* (few percent) precision



$K_L \to \pi^0 e^+ e^-$	10^{-11} (CPV_{dir} $3 \cdot 10^{-12}$)	$< 2.8 \cdot 10^{-10}$ (FNAL KTeV)	CPC+CPV 3 ev. (2.05 bkg)
$K_L \to \pi^0 \mu^+ \mu^-$	10^{-11} (CPV_{dir} $1 \cdot 10^{-12}$)	$< 3.8 \cdot 10^{-10}$ (FNAL KTeV)	CPC+CPV 2 ev. (0.87 bkg)
$K^+ \to \pi^+ \nu\nu$	$8 \cdot 10^{-11}$ (at 7%)	$1.47^{+1.30}_{-0.89} \cdot 10^{-10}$ (BNL E787+E949)	Dedicated expt. 3 evt. (bkg. 0.45)
$K_L \to \pi^0 \nu\nu$	$2.8 \cdot 10^{-11}$ (at 2%)	$< 6.7 \cdot 10^{-8}$ (KEK E391a)	CPV dir "*Nothing to nothing*"

ALLA MARCIA

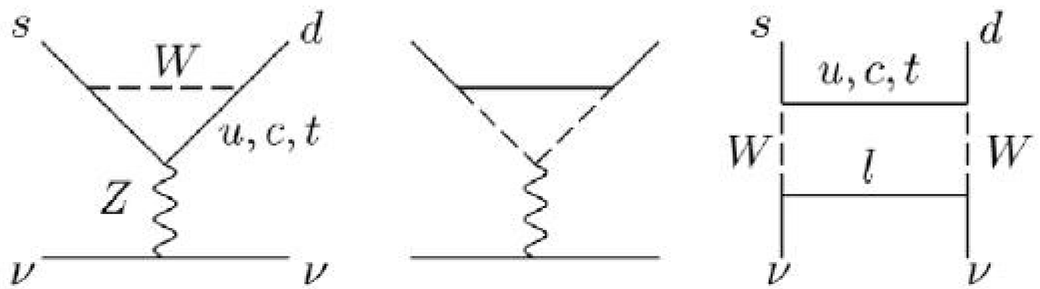
The (new) "holy grail"

$$BR_{SM}(K \to \pi\bar{\nu}\nu) \propto r_{IB}\, BR(K^+ \to \pi^0 e^+ \nu) \frac{\alpha^2}{\sin^4\theta_W}$$

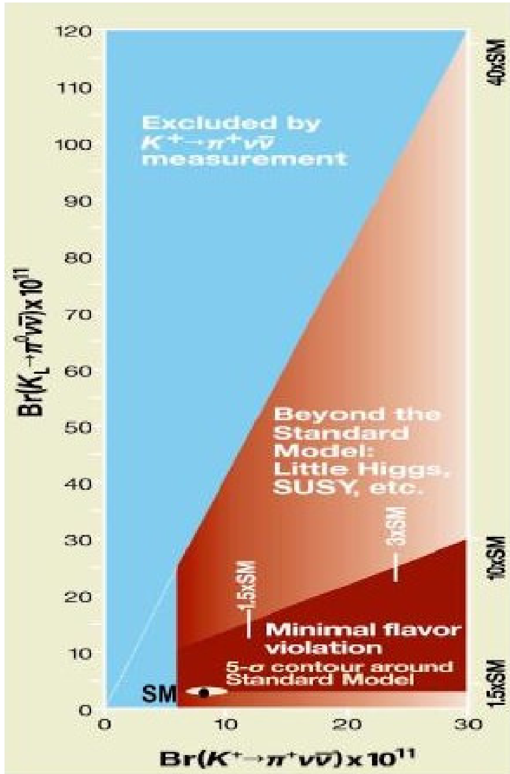
$$\sum_l \left[\frac{\mathrm{Im} V_{ts}^* V_{td}}{|V_{us}|} X(m_t, \alpha_S) + \frac{\mathrm{Im} V_{cs}^* V_{cd}}{|V_{us}|} X_{NL}(m_c, m_l, \alpha_S) \right]$$

Charged mode only

The best measurement of $|V_{td}|$?
Rather a highly-sensitive search for NP
Comparison of the two can discriminate by itself the flavour structure of NP



SM Leading diagrams to K → πνν decays



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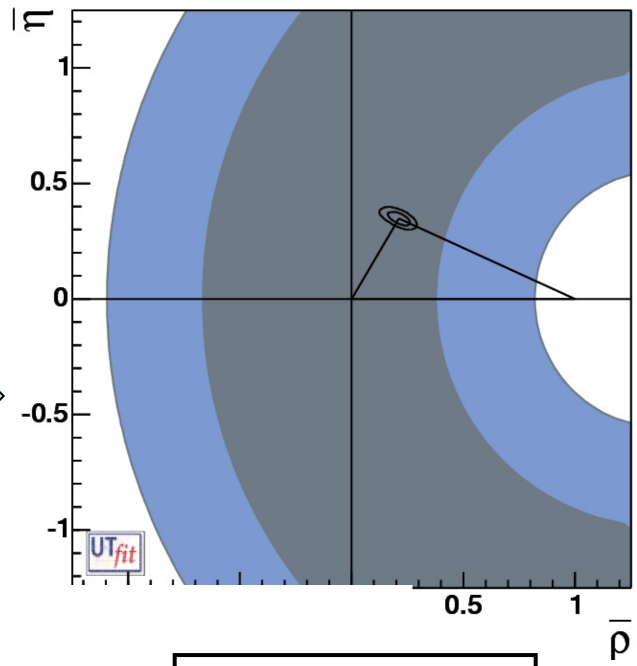
MARCIA

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$

E787/E949:
$1.47^{+1.30}_{-0.89} \times 10^{-10}$
(3 events)

Today

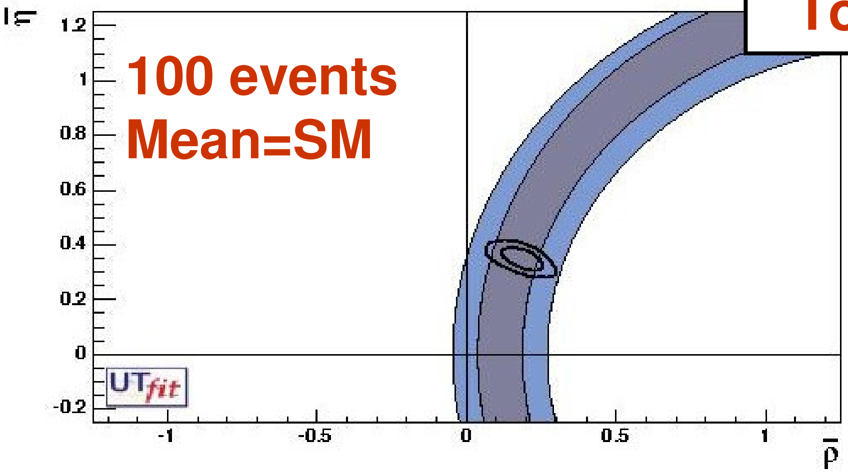


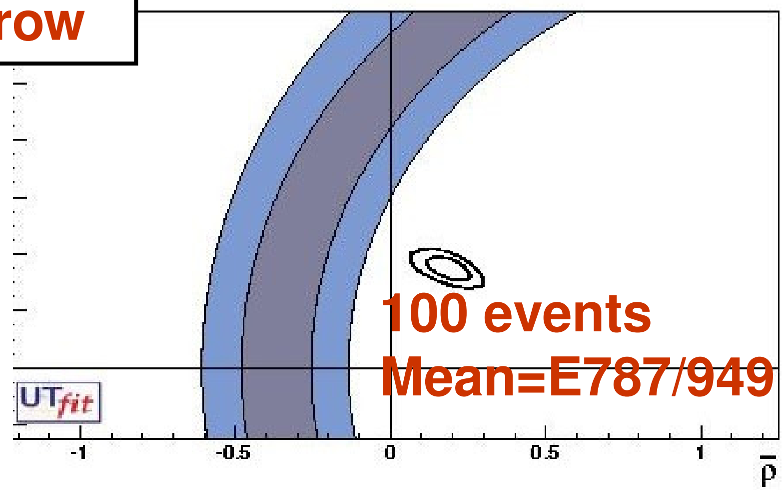
Process with very small parametric uncertainty

?

?

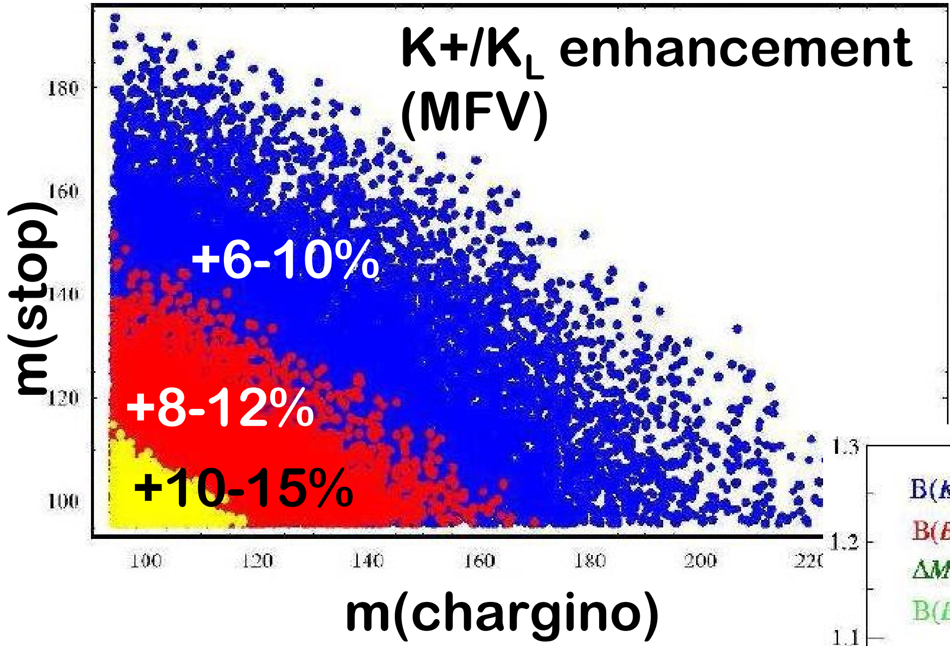
Tomorrow



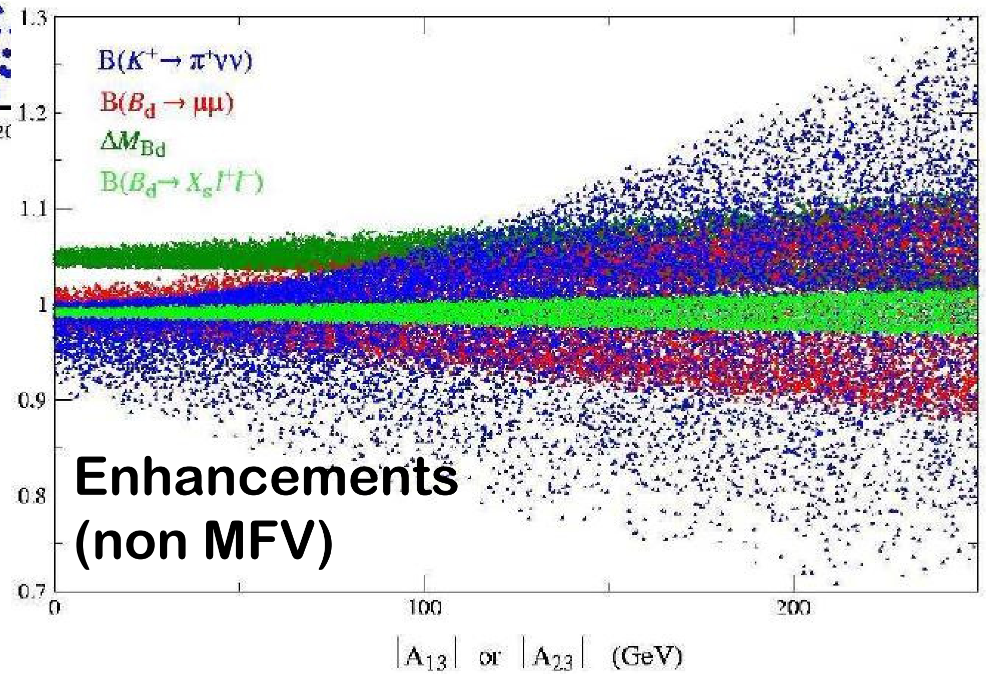


ALLA
MARCIA

Learning about new physics



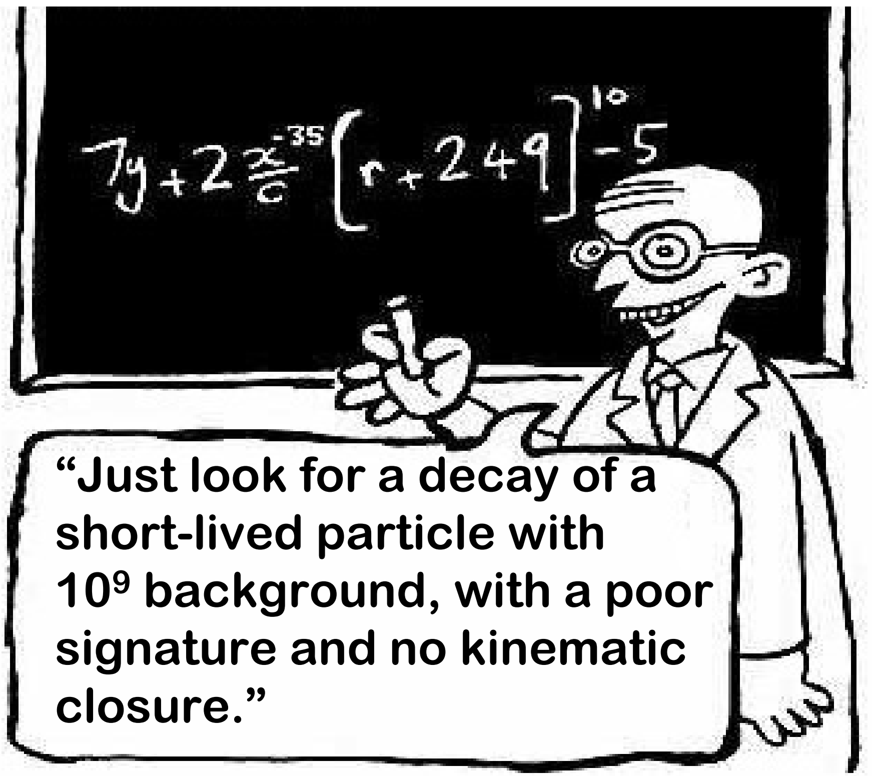
Isidori et al. JHEP 0608 (2006) 064

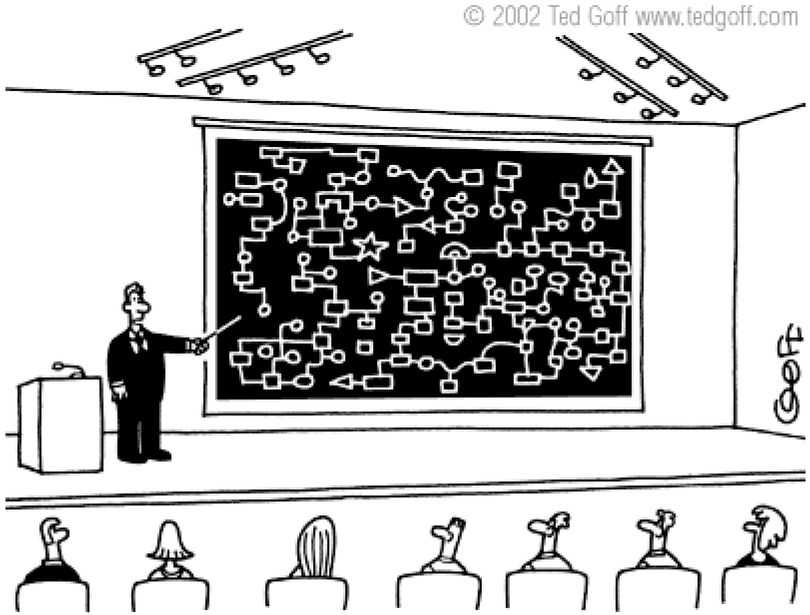


Astounding parametric precision:
≈ 5% for K⁺ and
≈1% for K$_L$.

Searching for the holy grail

"Normal science is when the theoretical processes which can be easily handled by theorists are experimental nightmares (and vice versa)".
(Apologies to T. Kuhn)





"This is our plan for the next 1,000 years."

**High fluxes, high vacuum, high ermeticity, excellent vetoing, excellent resolutions…
an interesting challenge**

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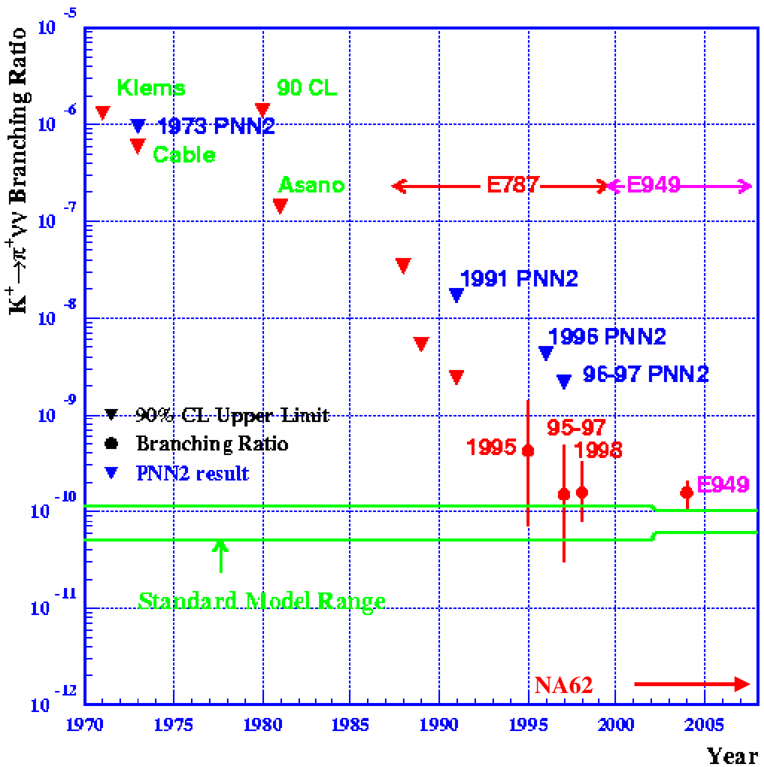
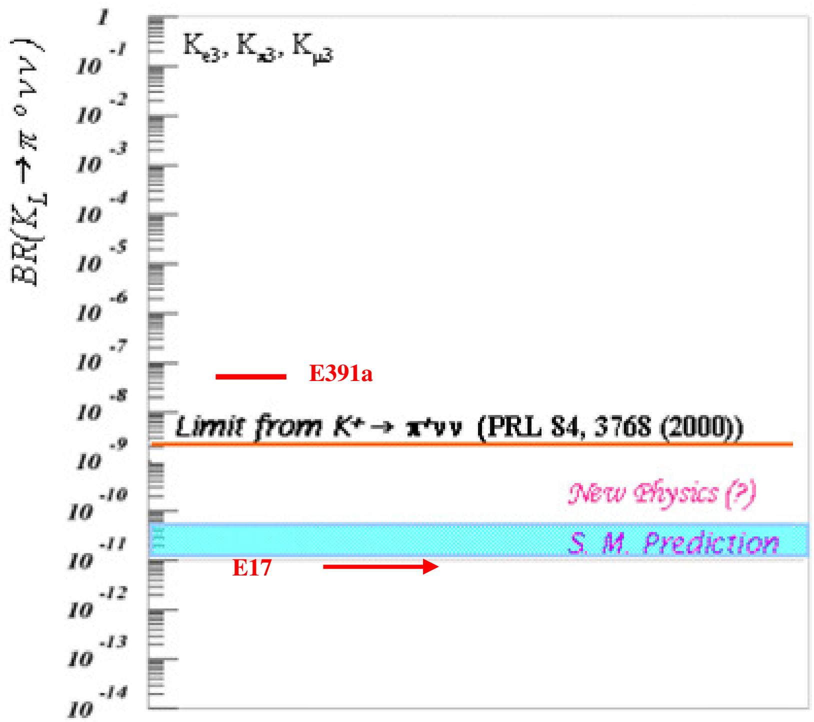
The long march





$K^+ \to \pi^+ \nu\bar{\nu}$

$K_L \to \pi^0 \nu\bar{\nu}$

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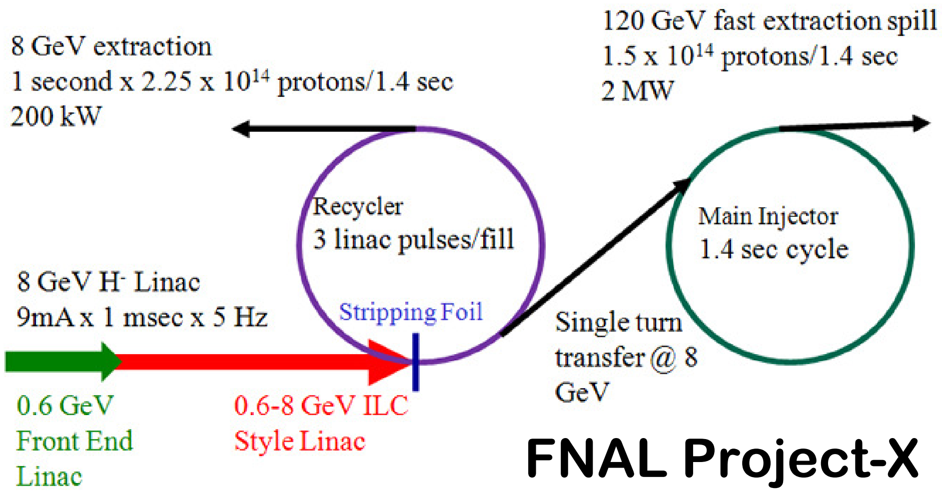
US: Project-X ?

The funding axe fell heavily on flavour physics in the US in recent times: KAMI ($K_L \to \pi^0 \ell\ell$ @ FNAL), E949 ($K^+ \to \pi^+ \nu\nu$ @ BNL), KOPIO ($K_L \to \pi^0 \nu\nu$ @ BNL), CKM ($K^+ \to \pi^+ \nu\nu$ @ FNAL).

The most recent proposals were for a $K_L \to \pi^0 \nu\nu$ and a stopped $K^+ \to \pi^+ \nu\nu$ experiment at the (improved) 8 GeV FNAL booster, in the perspective of a future MW proton driver (project-X):

$K_L \to \pi^0 \nu\nu$: 30 ev/year @ booster,
300-900 ev/year @ project-X
$K^+ \to \pi^+ \nu\nu$: 40 ev/year @ booster,
300-1500 ev/year @ project-X



FNAL Project-X

May 2008 - P5: only possible in a "HEP fund doubling" scenario

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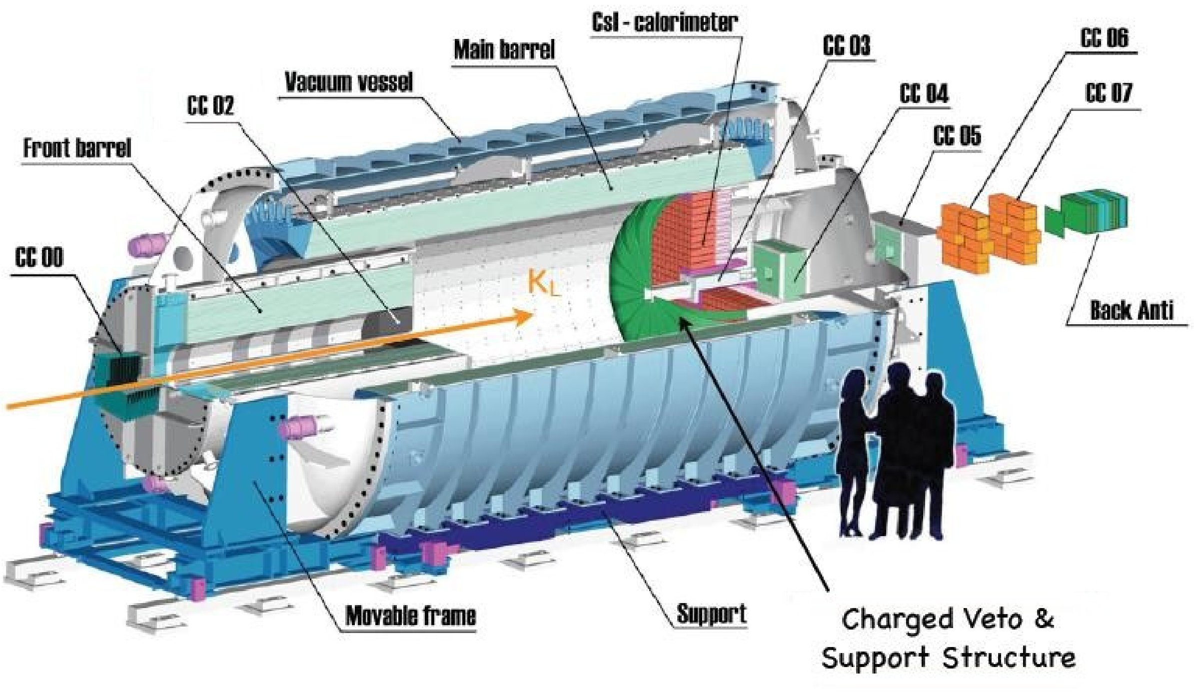
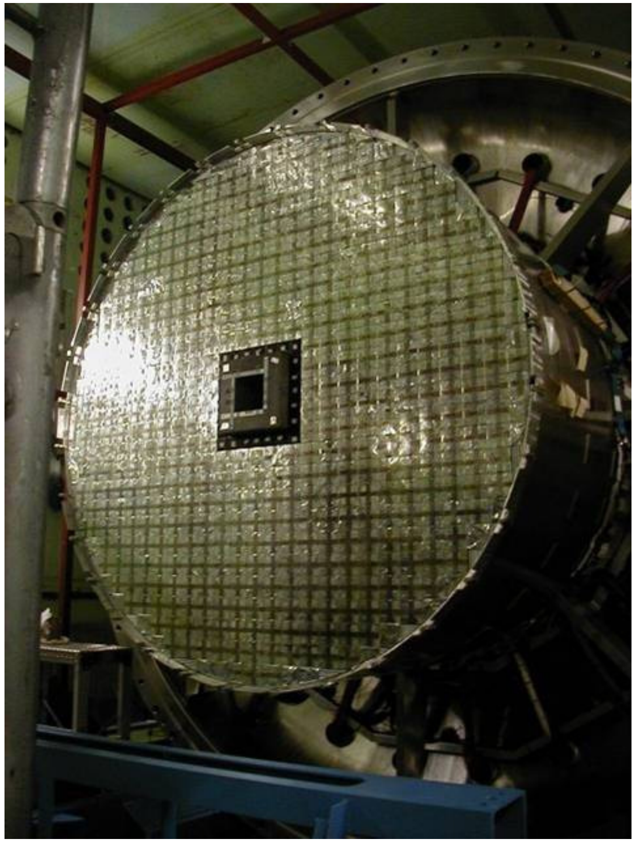
Japan: E391a (KEK)

Pilot project for J-PARC experiment
"Pencil" beam: ‹p› ≈ 3 GeV/c, n/K ≈ 60
Photon vetoes at 1 MeV level
Hadronic background MC
p_T and decay vertex cuts





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E391a new limit

Run I partial analysis (10% of data):

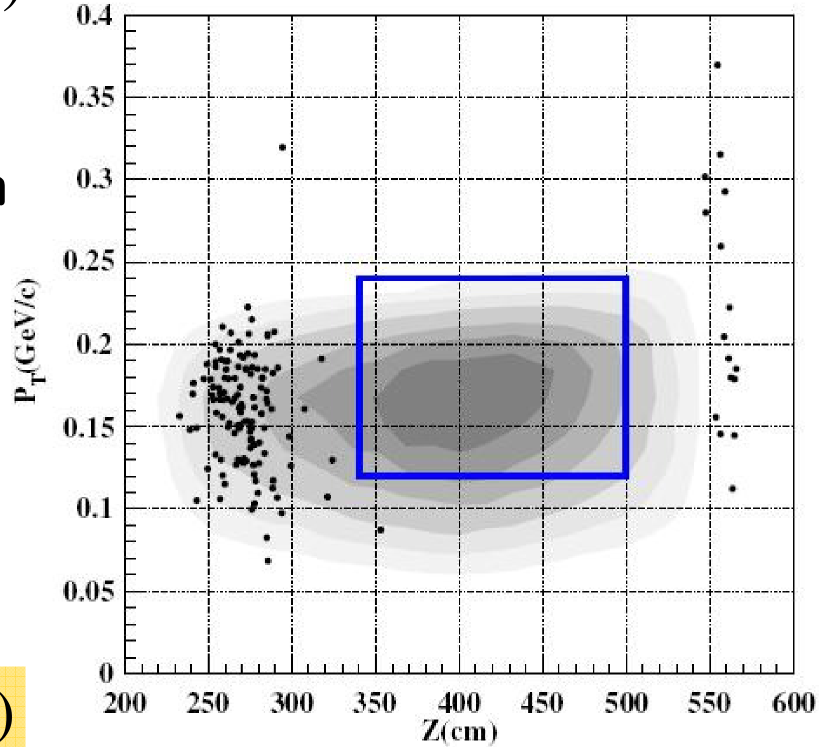
$$BR(K_L \to \pi^0 \nu \bar{\nu}) < 2.1 \cdot 10^{-7} \quad (90\%\ CL)$$

Run II:
Solved problems with material on beam and DAQ inefficiency, reduced n flux

Control bkg: 1.9±0.2, obs. 3,
0.39±0.08, obs. 2
Background: exp. 0.44±0.11, obs. 0

Acceptance 0.67%

$$BR(K_L \to \pi^0 \nu \bar{\nu}) < 6.7 \cdot 10^{-8} \quad (90\%\ CL)$$



Single-event sensitivity: 2.89·10^{-8}
Still below Grossman-Nir bound

Also: $BR(K_L \to \pi^0 \pi^0 \nu \bar{\nu}) < 4.7 \cdot 10^{-5}$ $(90\%\ CL)$

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Japan: J-PARC

Beam to experiments in second half of 2008

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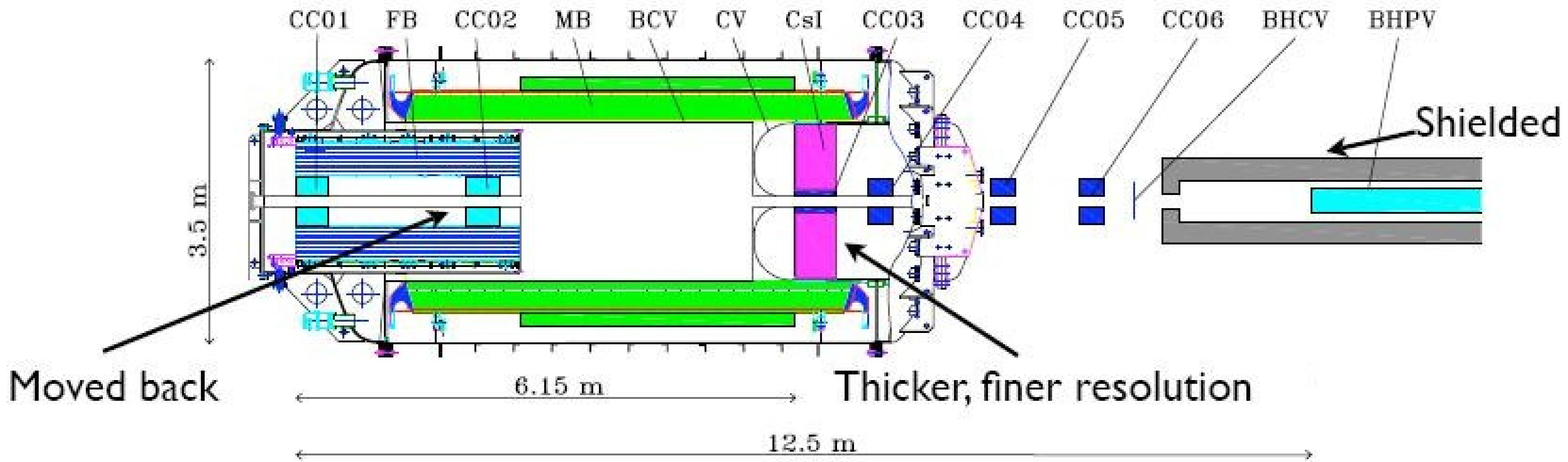
Japan: J-PARC E14

Improved beamline (reduced halo, n/K ≈ 7, lower background, veto)
Re-use E391a barrel
Thicker and more fine-grained CsI calorimeter (KTeV)
Waveform digitization
Upgraded vetos (KOPIO-like beam hole γ veto)



Flux x10, Time x10, Performance x10

Goal: 2.7 ev. (S/N ≈ 1.6) in 3 years
Construction 2009, first physics run 2011 ?
Step 2: 100 SM events (S/N ≈ 4.8)

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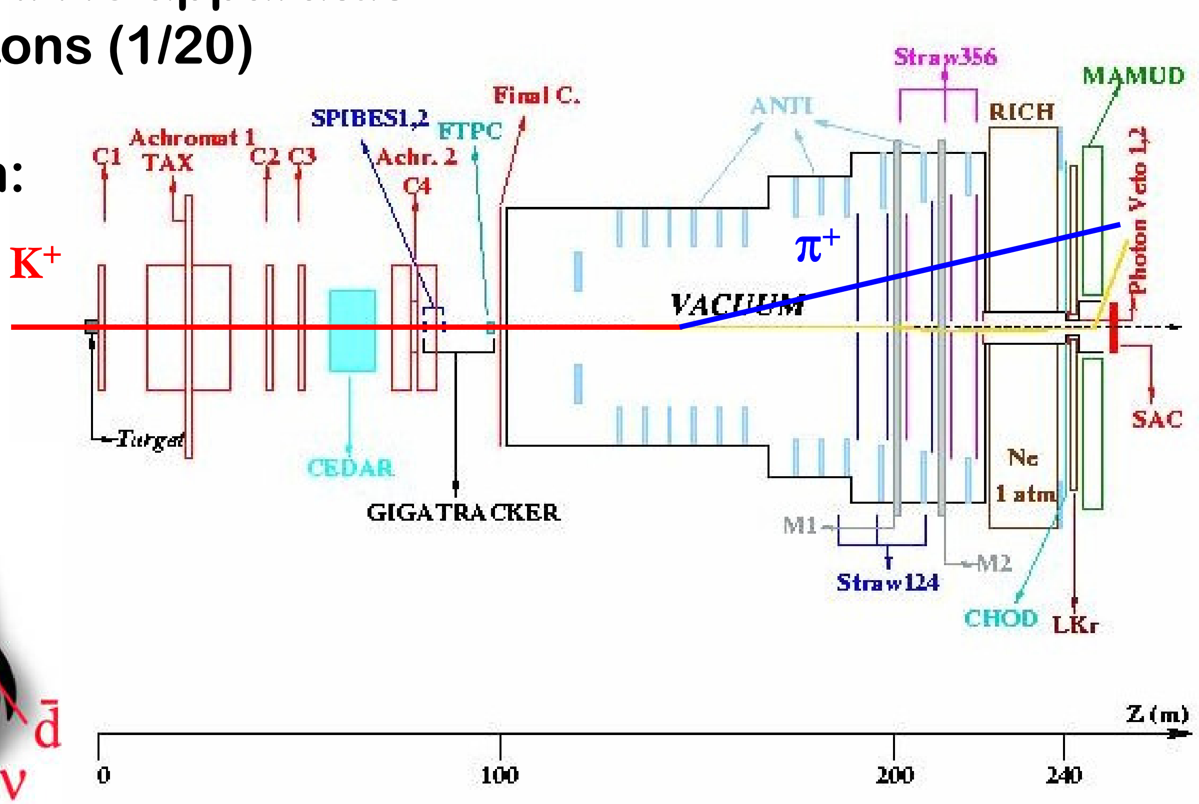
Europe: CERN NA62

New approach: decay in flight
(75 GeV/c unseparated K+ beam)

Reuse some parts of NA48 apparatus
and existing SPS protons (1/20)

Background rejection:
-K+ tracking in 1 GHz
- PID(π/μ) by RICH
- γ vetoing (low-E π, low ineff.)
- Kinematics



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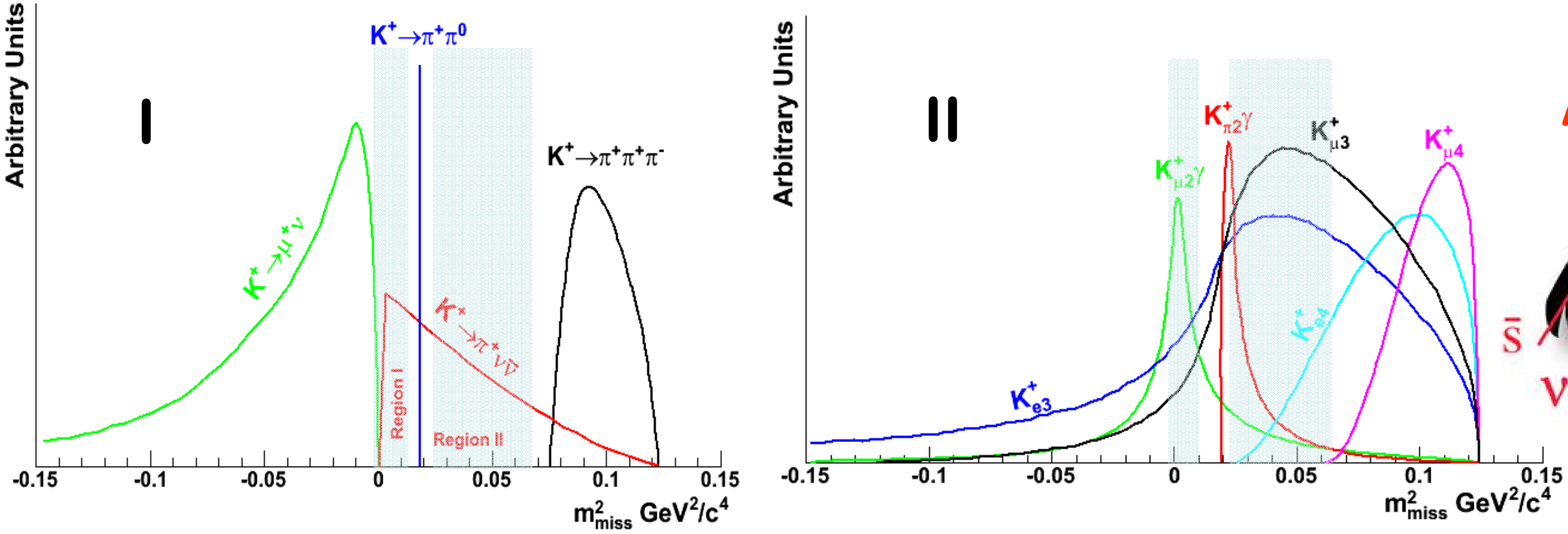
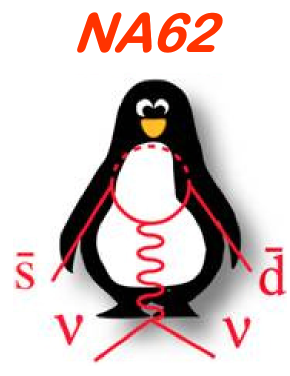
NA62





2 signal regions:
I (92% kinematically constrained bkg.)
II (8% not-constrained bkg.)

Expect ≈ 80 SM events
with S/N≈10 in 2 years (2012+)

Waiting for final approval
Strenghtening the collaboration

ARIA DA CAPO

Is there still something to be learned by using kaons?

I think so.

The program has been quite varied so far,

much more than could be expected at the start.

As the focus of HEP moves and shifts

in the era of the coming of LHC

there is reason to believe it will continue to be so.