NA48 highlights

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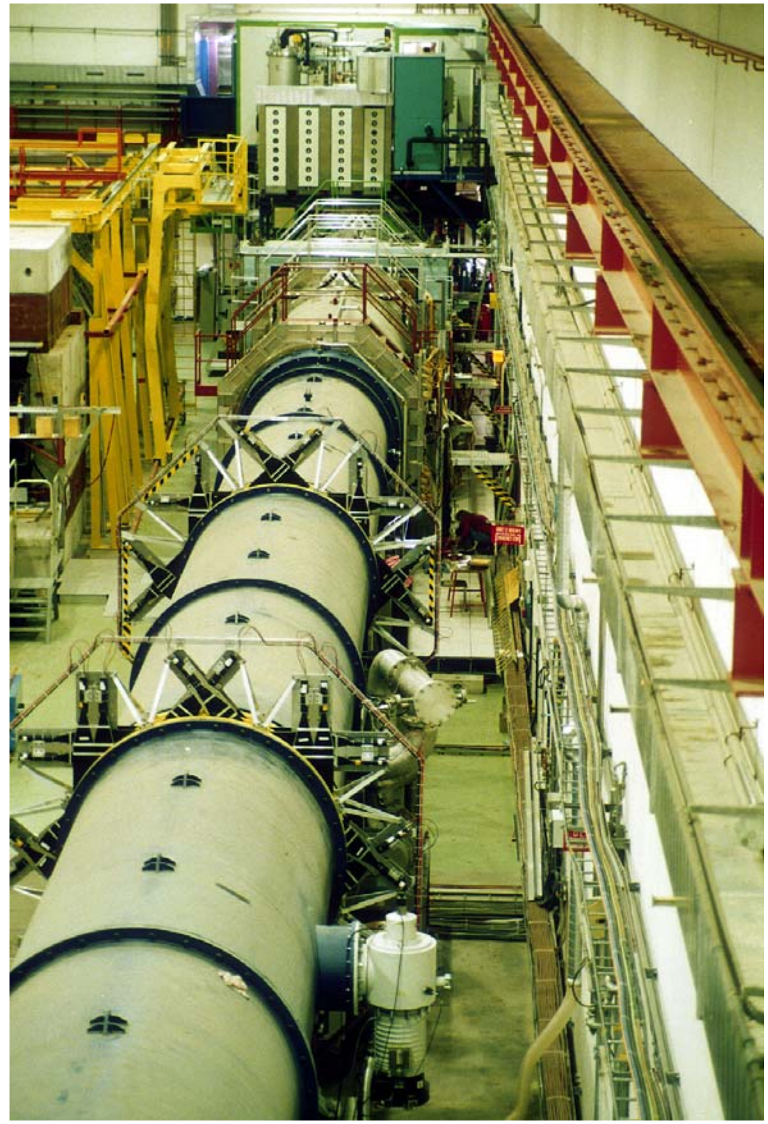
Scuola Normale Superiore
and INFN - Pisa

SPSC meeting
Villars
September 26th 2004



Outline

- ***NA48:***
  - The quest for direct CP violation
  - Rare K_L decays
- ***NA48/1:***
  - Rare K_S decays
  - Hyperon decays
- ***NA48/2:***
  - Direct CP violation searches
  - Study of $\pi\pi$ interactions
  - Rare $K^{\pm}$ decays
- ***Achievements, Key points, Surprises…***
- ***Outlook***

3 experiments in 1: a multi-purpose kaon laboratory

NA48 (1990-2001)

The quest for direct CP violation

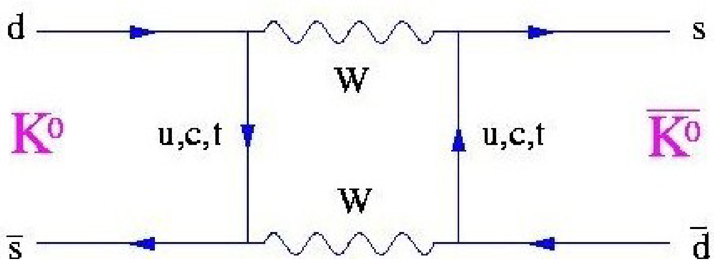
CERN/SPSC/90-22
SPSC/P253
20 July 1990

PROPOSAL FOR
A PRECISION MEASUREMENT OF ε'/ε IN CP VIOLATING $K^0 \to 2\pi$ DECAYS

It is the aim of the proposed experiment to measure Reε'/ε with an accuracy of 2×10^{-4}.

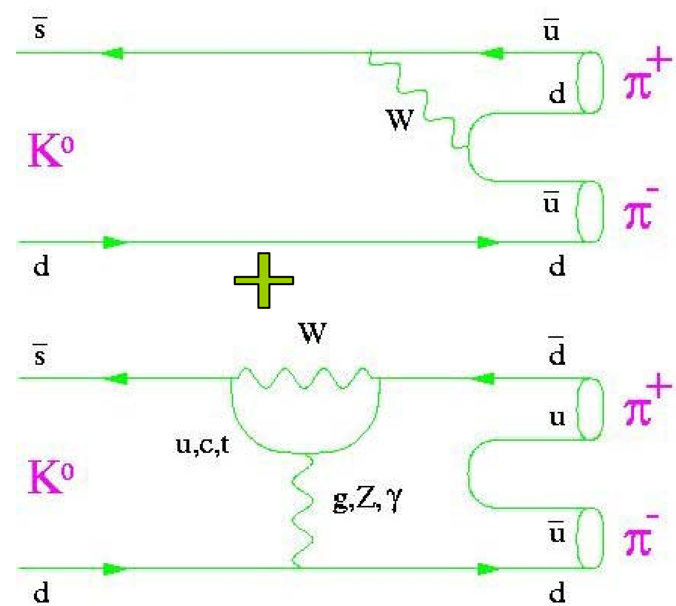
decays from
K^+ and K^- can be identified and accurately measured. Data could be taken with alternating polarity for the magnetic field of the spectrometer and the distributions in x obtained for both $\pi^-\pi^+\pi^+$, $\pi^+\pi^-\pi^-$ and $\pi^\pm\pi^0\pi^0$ from $K^\pm$ decays in a situation where to a very good accuracy the acceptance of the detection system, including the effect of accidentals, would be automatically the same for the $\pi^\pm$

The Quest for Direct CP Violation



Indirect CP violation in the mixing: ε

Direct CP violation in the decay: ε'



A fascinating 30-year long enterprise: "Is CP violation a peculiarity of kaons? Is it induced by a new superweak interaction?"

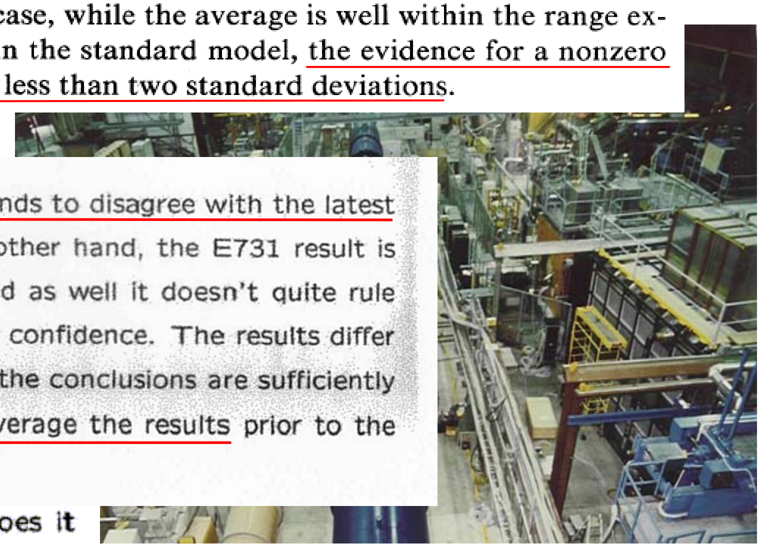
Direct CPV: 1996 a.D.

In any case, while the average is well within the range expected in the standard model, the evidence for a nonzero effect is less than two standard deviations.

Re(ε'/ε) = (7.4±6.0) · 10^{-4}

Not dispr

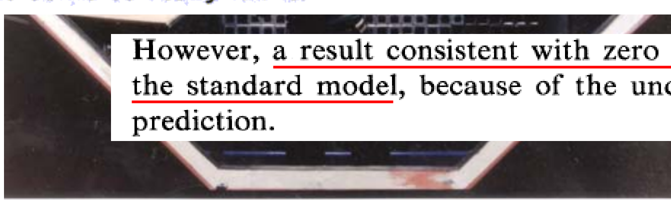
The NA31 result is more interesting in that it tends to disagree with the latest predictions from the Standard Model. On the other hand, the E731 result is in the range favored by the Standard Model and as well it doesn't quite rule out the Superweak Model ($\mathrm{Re}\,\varepsilon'/\varepsilon = 0$) with any confidence. The results differ by about two standard deviations; nevertheless, the conclusions are sufficiently different that it would not be appropriate to average the results prior to the establishment of a non-zero effect.



The E731 result does not confirm the non-zero result of NA31 nor does it significantly disagree with it.

so that we cannot as yet claim that direct CP violation is established.

What are we to conclude from these experiments? The most important conclusion is that they must be continued to still higher accuracy. The point is not to find the exact value of ε'; the point is to make absolutely sure that ε' is non-zero. The NA31 experiment has wounded the superweak theory. The time has come to really kill it.



However, a result consistent with zero will not rule out the standard model, because of the uncertainties in the prediction.

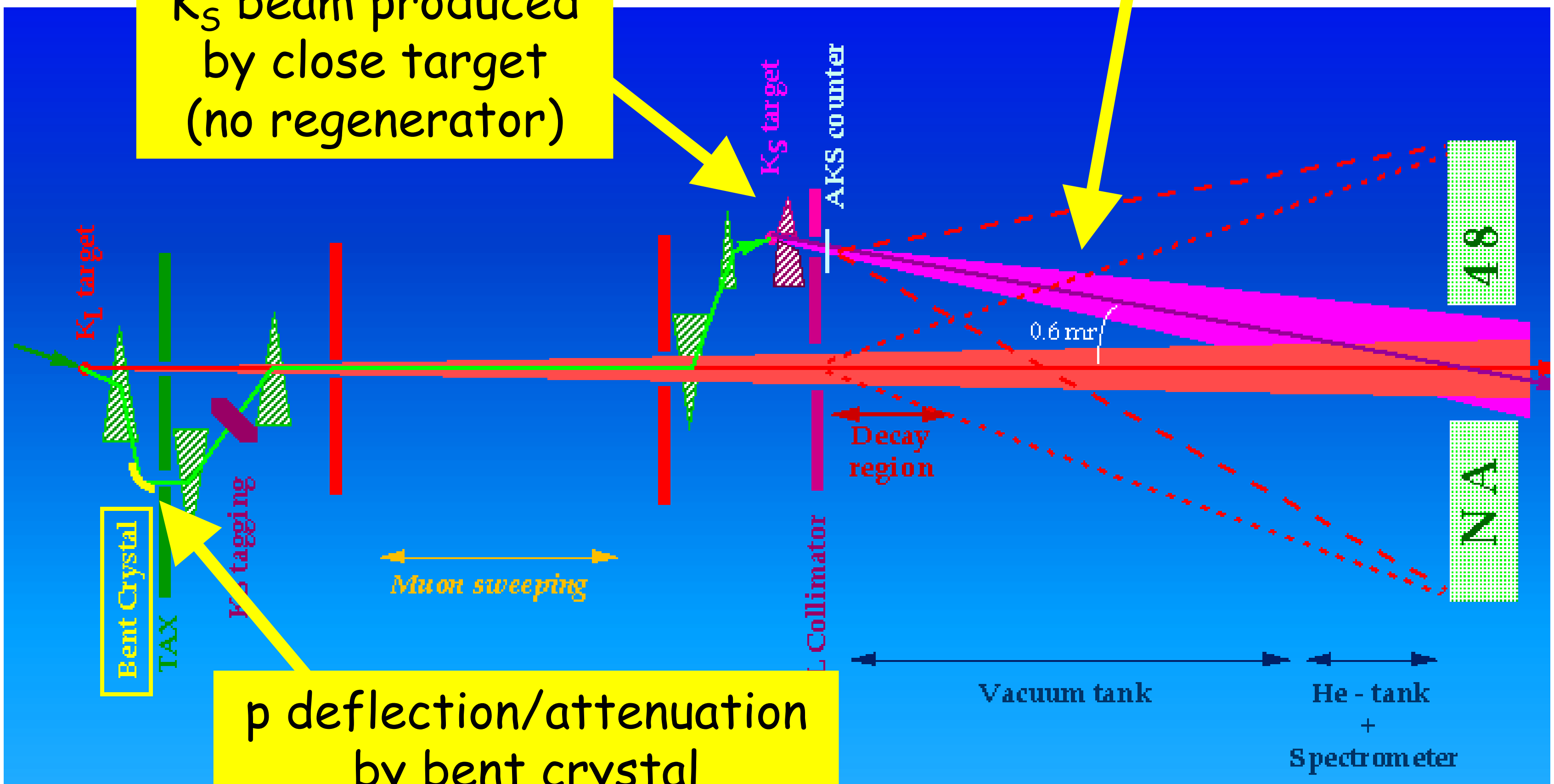
Re(ε'/ε) = (23.0±6.5) · 10^{-4}

Inconsistent with superweak

The NA48 concept: beam

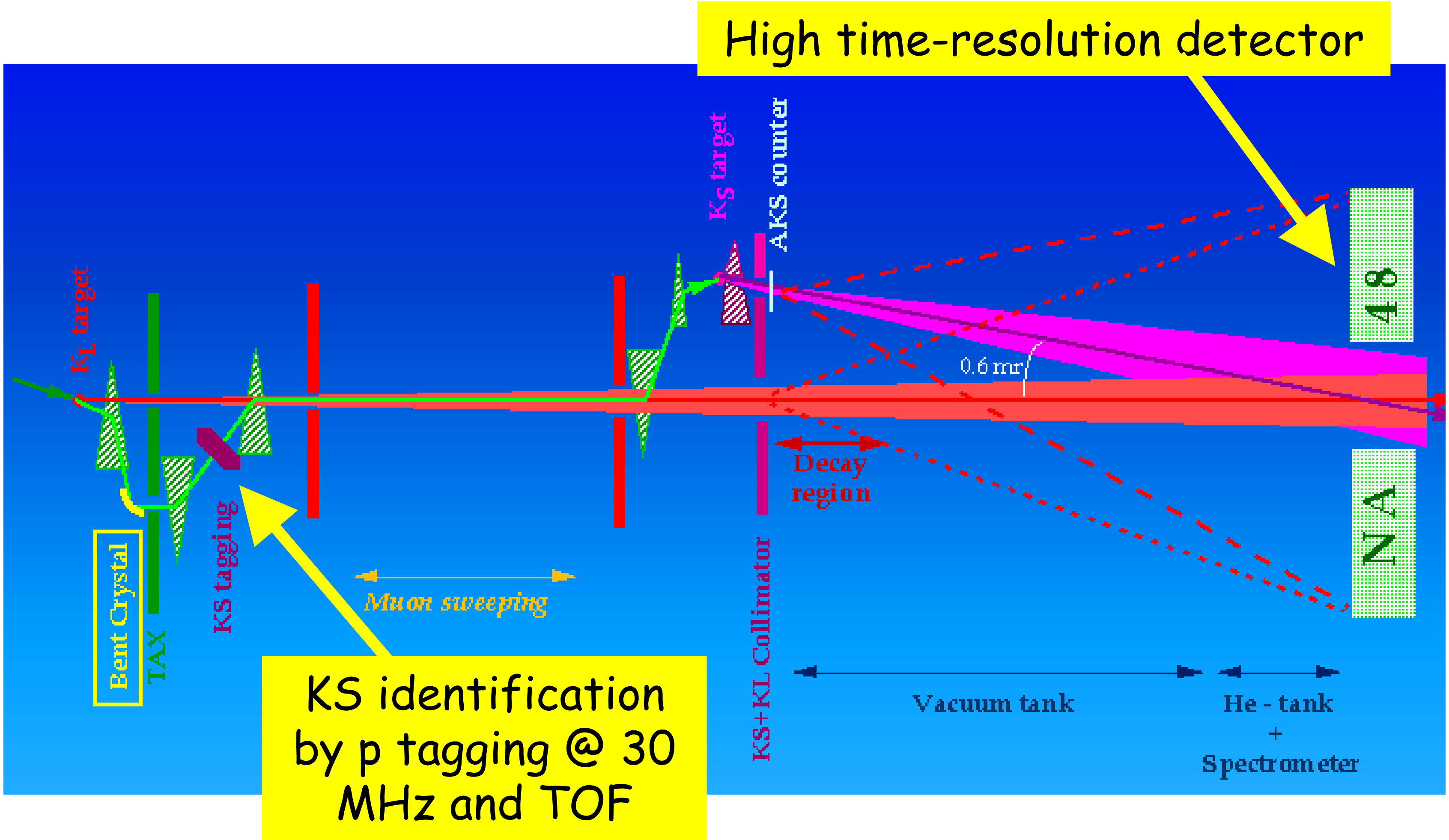
Simultaneous, converging K_S and K_L beams (<p>=100 GeV/*c*)

K_S beam produced by close target (no regenerator)

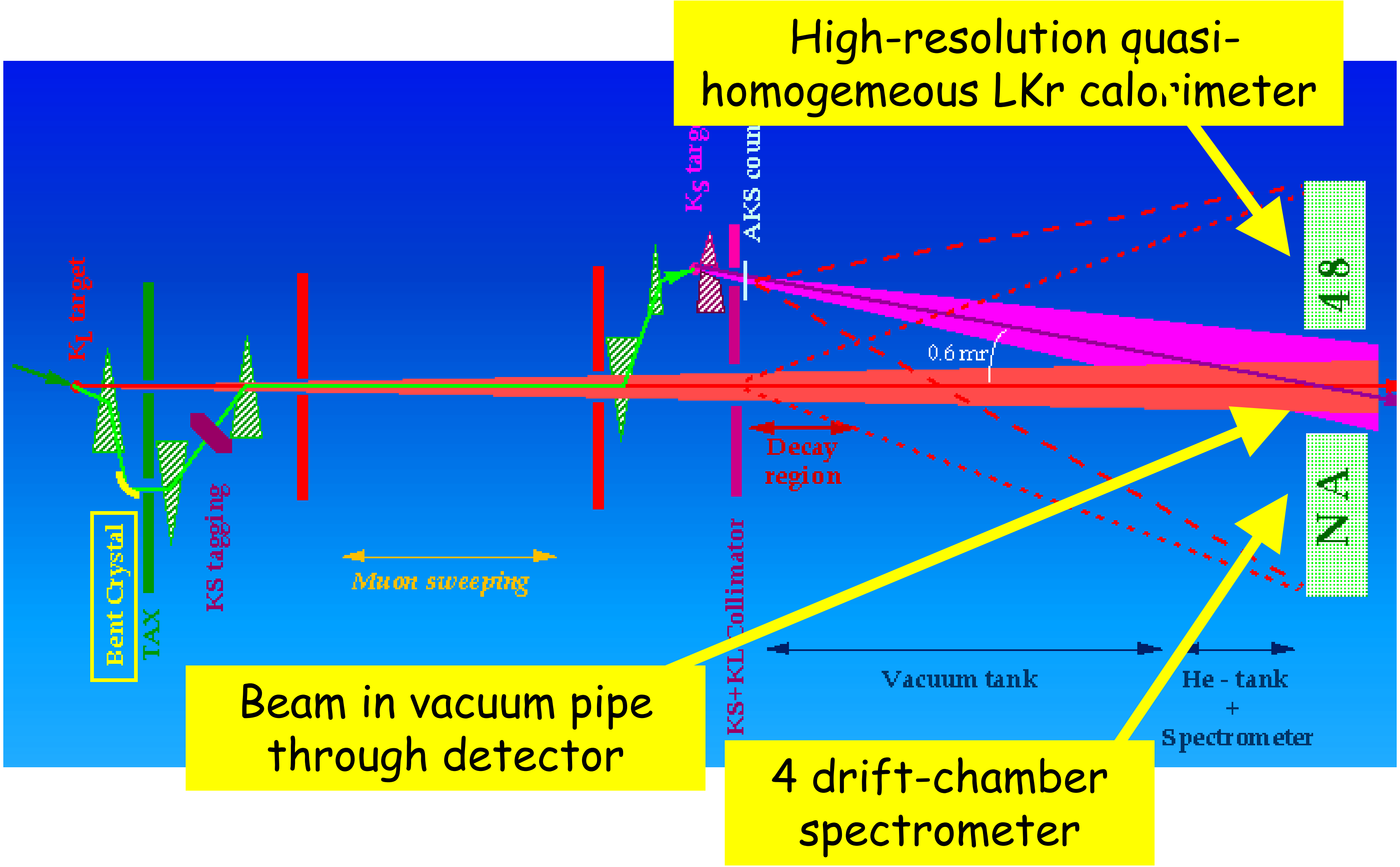


p deflection/attenuation by bent crystal channeling

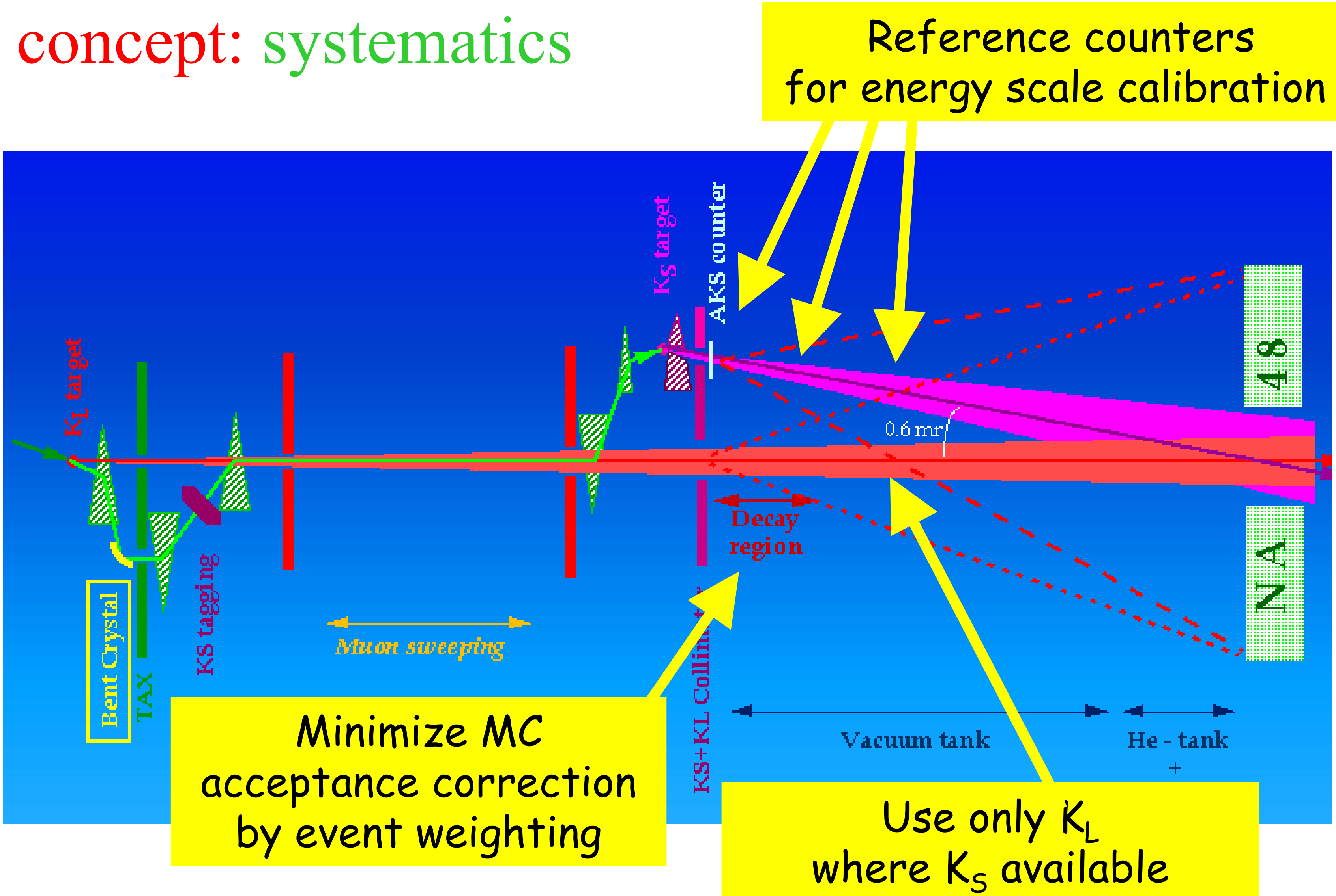
The NA48 concept: tagging



The NA48 concept: detectors



The NA48 concept: systematics

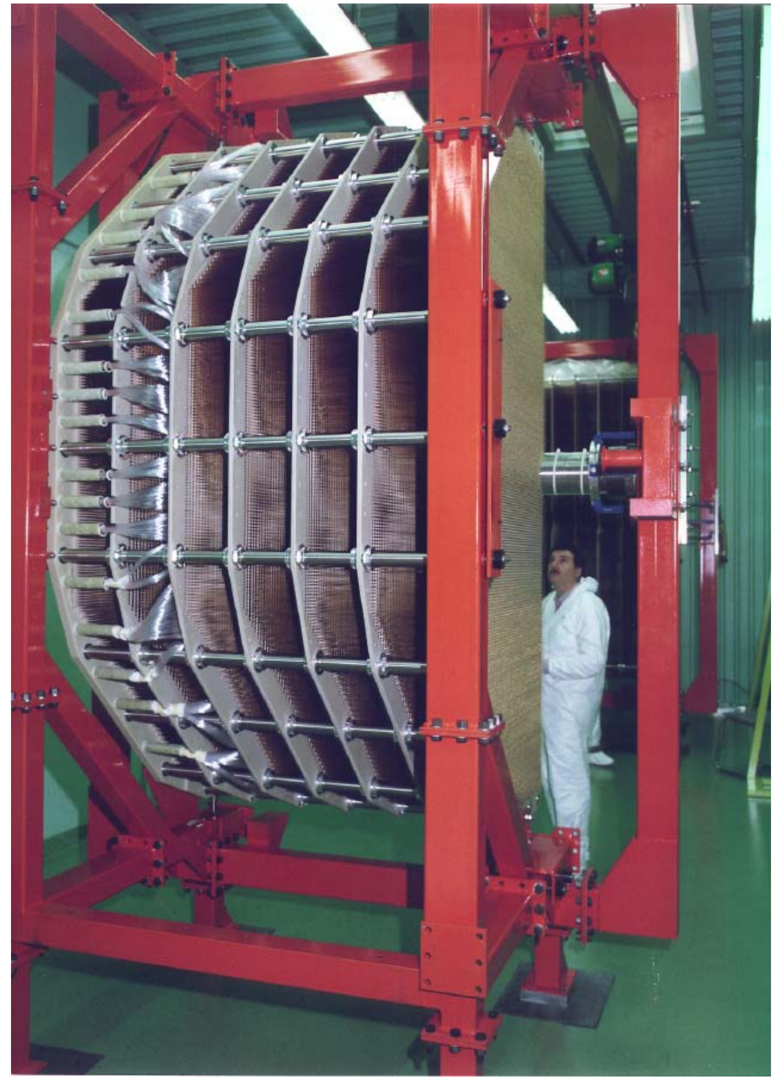


The Liquid Krypton calorimeter

4. **ELECTROMAGNETIC CALORIMETER**

For the detection of the K^0 neutral decays, an electromagnetic calorimeter is required, with the following design performance:

a) recording of multi-photon events occurring at a rate of -1 **Mhz;**
b) energy resolution -3% / $E^{1/2}$ and with a constant term < 0.5%;
c) space resolution ≤ 1 mm;
d) provision of K^0 neutral event trigger with a time resolution of < 1 ns, to cope with the rate of the tagging station.



13212 accordion towers 2x2cm^2 in projective geometry. 10m^3 liquid Kr.
Uniformity to 0.5% (0.2% after correction) over several years!

$$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{90 MeV}{E} \oplus 0.42\%$$

Better than 250ps time resolution

Better than 1mm space resolution

Direct CP violation: ε'/ε

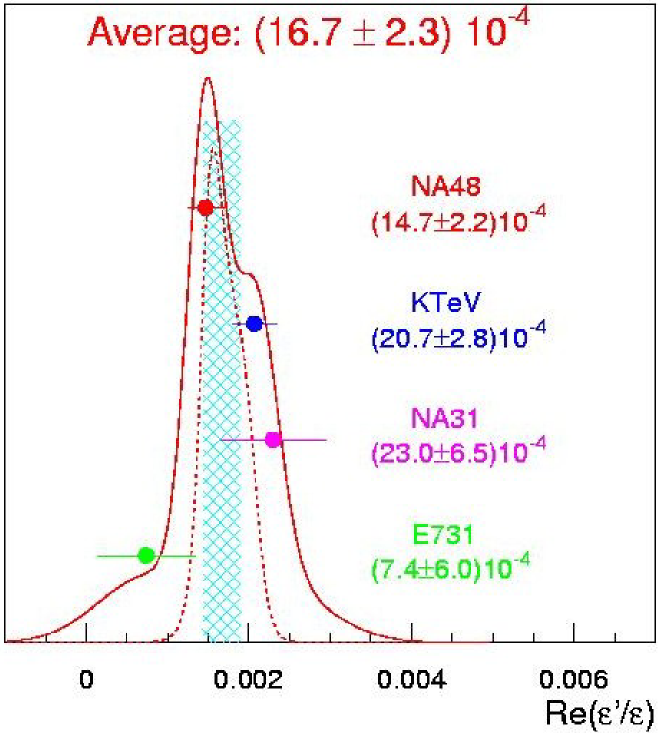
1999: proof of direct CP violation (after 36 years!) at >7 σ

NA48 final: $\mathrm{Re}(\varepsilon'/\varepsilon) = (14.7 \pm 2.2) \cdot 10^{-4}$

Nice confirmation of NA31 result

Experiments:
NA48 (1997-2001): final result
KTeV (1997-1999): ½ statistics (1997)
KLOE: working (interferometry?)
χ^2=6.2/3, consistency 10%
Room for improvement
(not for new experiments…)

$$\frac{\Gamma(K^0 \to \pi^+\pi^-) - \Gamma(\overline{K}^0 \to \pi^+\pi^-)}{\Gamma(K^0 \to \pi^+\pi^-) + \Gamma(\overline{K}^0 \to \pi^+\pi^-)} = (5.04 \pm 0.82) \times 10^{-6}$$



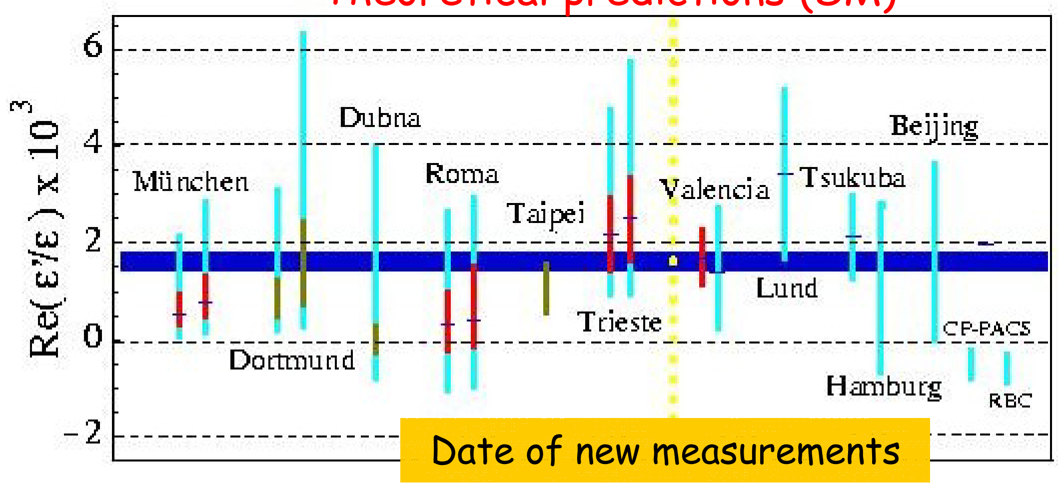
ε'/ε why ?

The *qualitative* importance of ε'/ε ≠ 0 *trascends* the theoretical difficulties of computing such parameter in the Standard Model:

- CP violation no longer described by a *single* number
- It is a property of *weak interactions* (no superweak)
- It is not a peculiarity of *neutral K mesons* (see B-factories)
- Qualitative confirmation of *CKM paradigm*

Theory:
Consistent with SM?
No! Yes! Maybe…
SM is *accidentally* a quasi-superweak model.
Waiting for lattice (?):
ε'/ε may become a quantitative test of SM.

Theoretical predictions (SM)



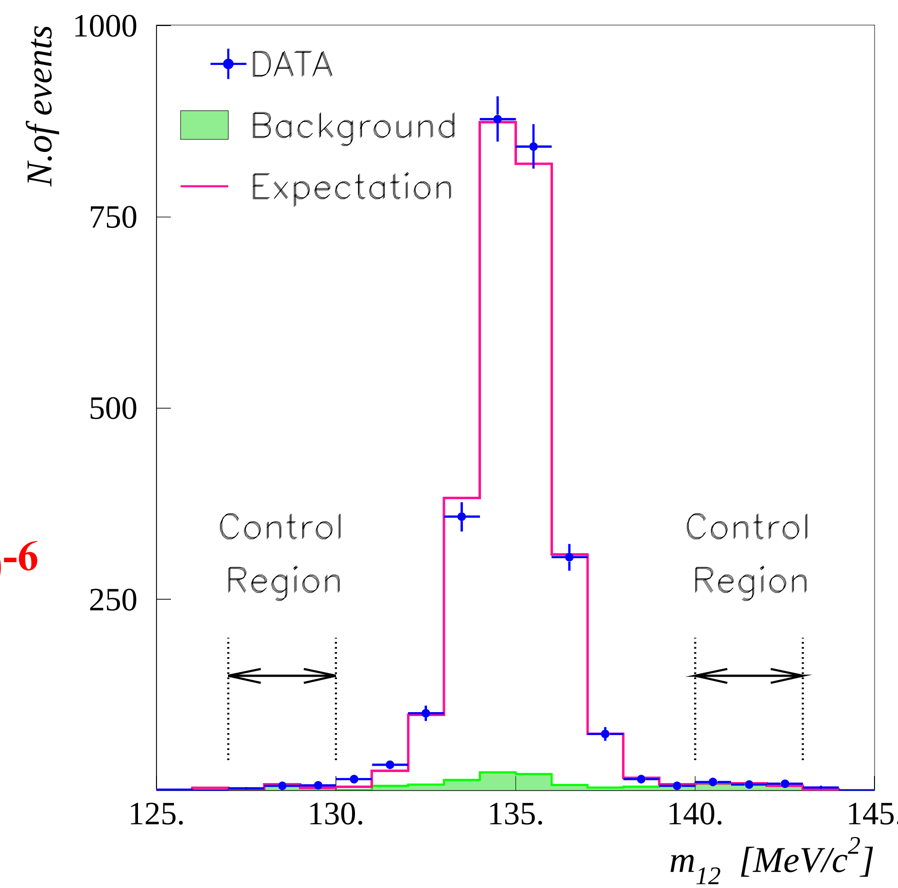
$K_L \to \pi^0\gamma\gamma$

First contribution at $O(p^4)$ in chiral perturbation theory, handle on $O(p^6)$ terms

1998-1999 data
2558 events
(3.2% background, mainly $3\pi^0$)

$BR(K_L \to \pi^0\gamma\gamma) =$
$(1.36 \pm 0.03 \pm 0.03 \pm 0.03) \cdot 10^{-6}$

Constrains the CP-conserving contribution to $K_L \to \pi^0 e^+e^-$:
→ relatively small



NA48/1 (2000-2002)

The search for rare K_S decays

December 10, 1999

CERN/SPSC 2000-002
SPSC/P253 ADD.2

ADDENDUM 2 TO P253

A high sensitivity investigation of K_S and neutral hyperon decays using a modified K_S beam.

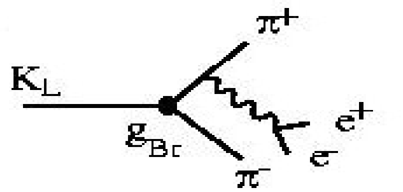
$K_S \rightarrow \pi^0 e^+ e^-$

The present proposal, with no upgrades to the detector read-out, would yield about 7 events at $a_s = 1$. The physics interest for the $K_S \rightarrow \pi^0 \mu^+ \mu^-$ is the same as for the electron channel. However, the backgrounds to this channel are quite different. The decay rate is suppressed by about a factor of 5 due to phase space.

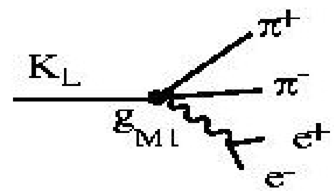
Sensitivity to the parameter η_{000}

Our sensitivity will allow to put bounds on η_{000} to ~1% with one year of data taking.

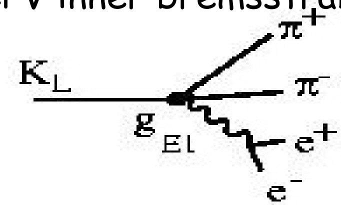
$K_{L,S} \rightarrow \pi^+\pi^-e^+e^-$



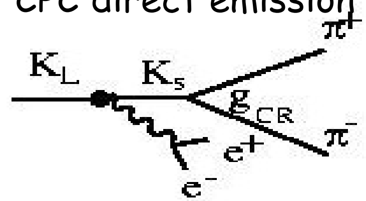
CPV inner bremsstrahlung



CPC direct emission



CPV direct emission

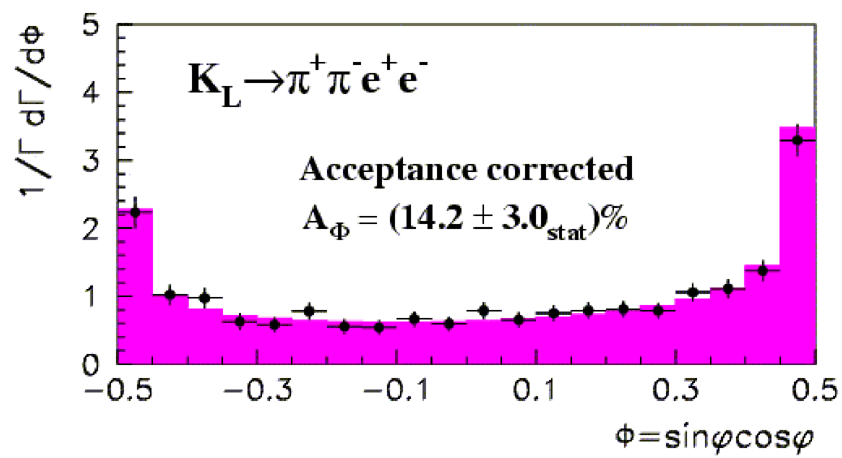


Charge radius

For K_L: interference gives *indirect CP-violating* asymmetry in the orientation of $\pi^+\pi^-$ and e^+e^- decay planes: large (≈ 14%) asymmetries predicted

1998-99 data
K_L: 1162 events
Background = 3.2%

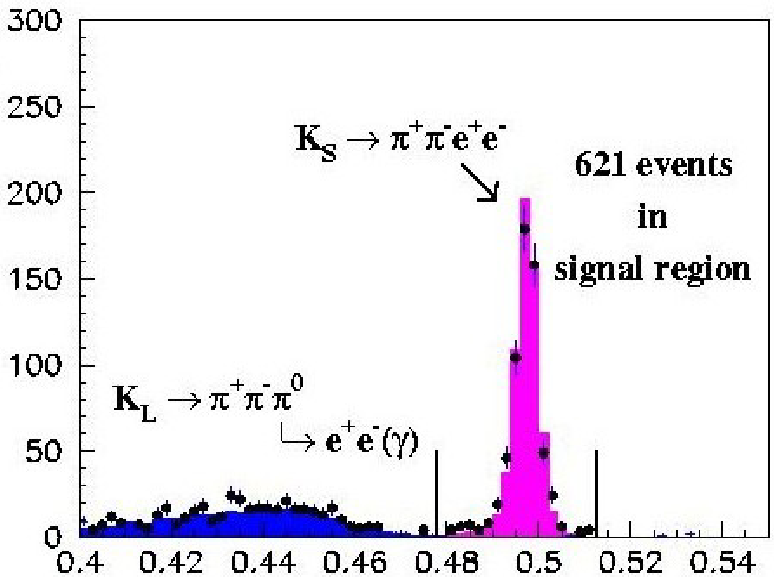
$BR = (3.08 \pm 0.20) \times 10^{-7}$



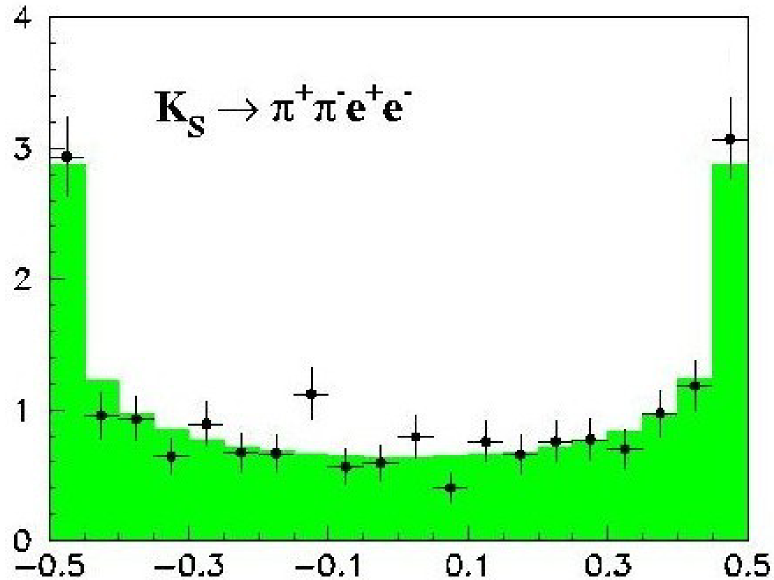
$A_\varphi = (14.2 \pm 3.6)$ %

$K_S \to \pi^+\pi^-e^+e^-$

K_S: first observation
621 events
Background = 0.1%



$BR = (4.71 \pm 0.32) \times 10^{-5}$



$A_\varphi = (0.5 \pm 4.3)$ %

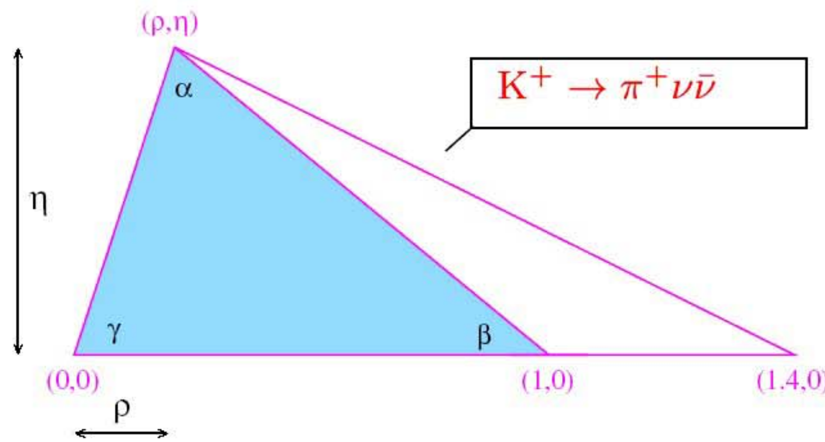
No asymmetry for K_S as expected

Unitarity triangle from K

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

$K_L \to \pi^0 e^+ e^- \quad \begin{cases} K_S \to \pi^0 e^+ e^- \\ K_L \to \pi^0 \gamma\gamma \end{cases}$

$\varepsilon, \varepsilon'$



Required ancillary measurements

$K_L \to e^+ e^- \quad \begin{cases} K_L \to \gamma\gamma,\ K_L \to e^+ e^- \gamma \\ K_L \to e^+ e^- e^+ e^-,\ e^+ e^- \mu^+ \mu^- \end{cases}$

$V^*_{us} V_{ud} + V^*_{cs} V_{cd} + V^*_{ts} V_{td} = \lambda_u + \lambda_c + \lambda_t = 0$

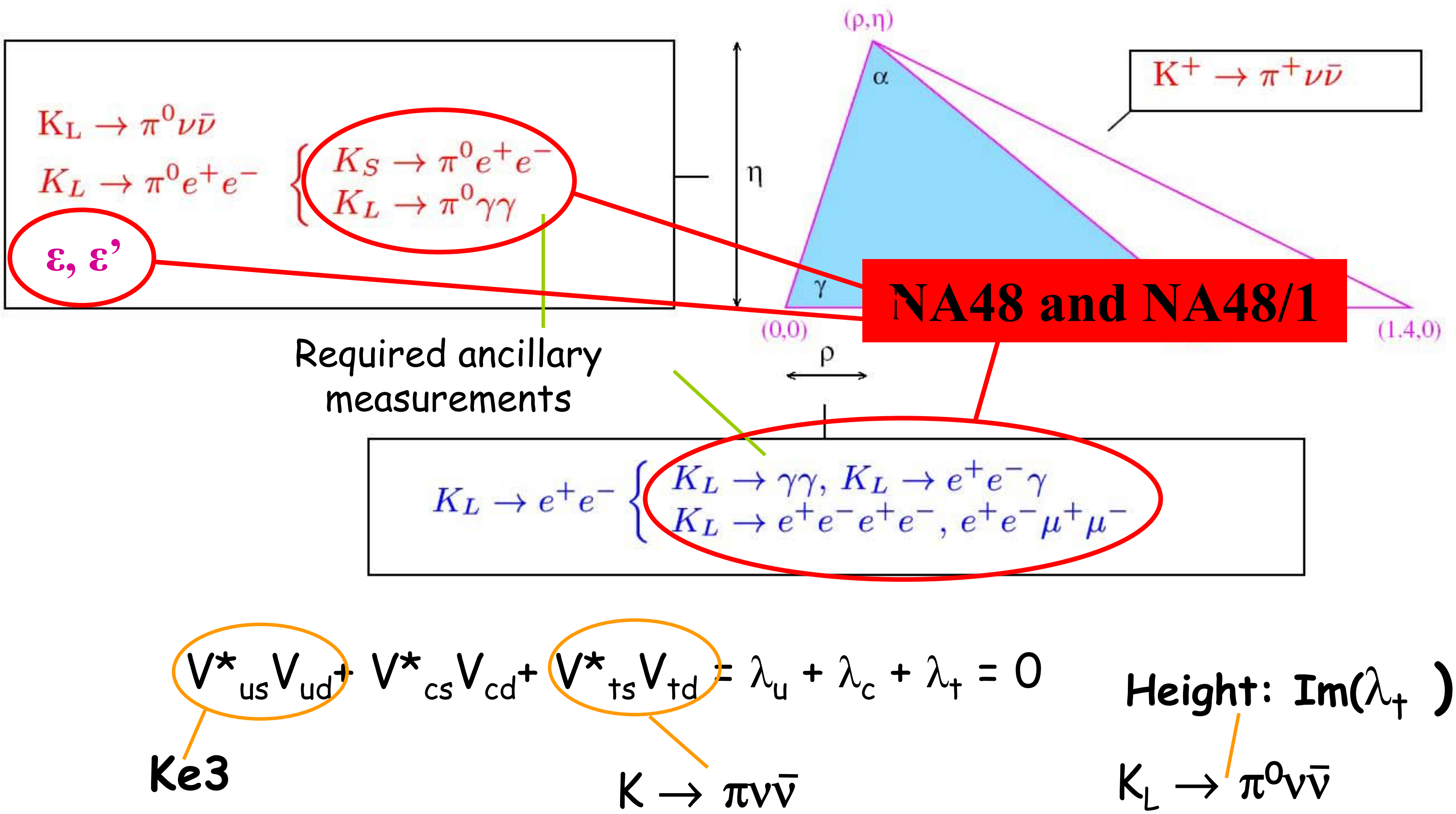
Ke3

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

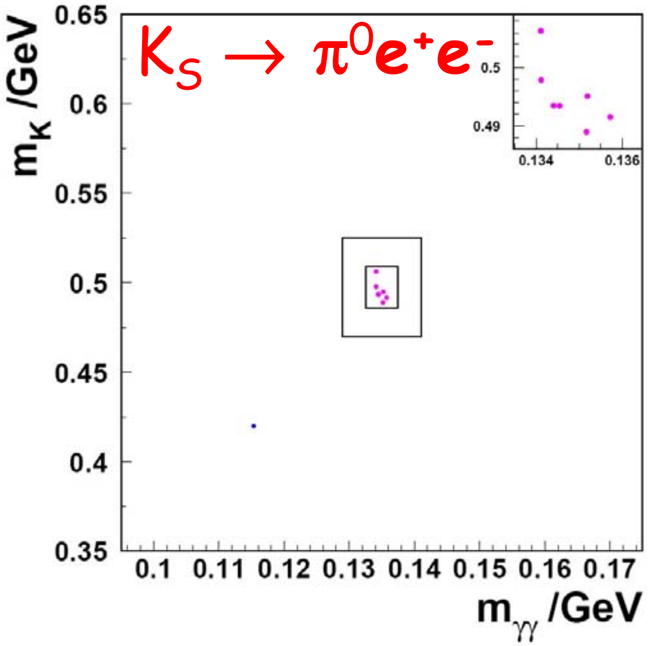
Height: Im(λ_t)

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

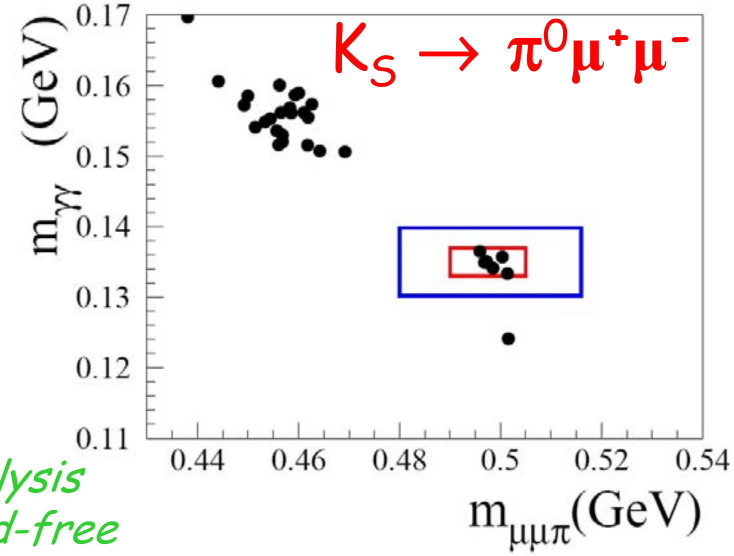
Unitarity triangle from K



NA48/1: $K_S \to \pi^0 \ell^+ \ell^-$



Blind analysis
Background-free



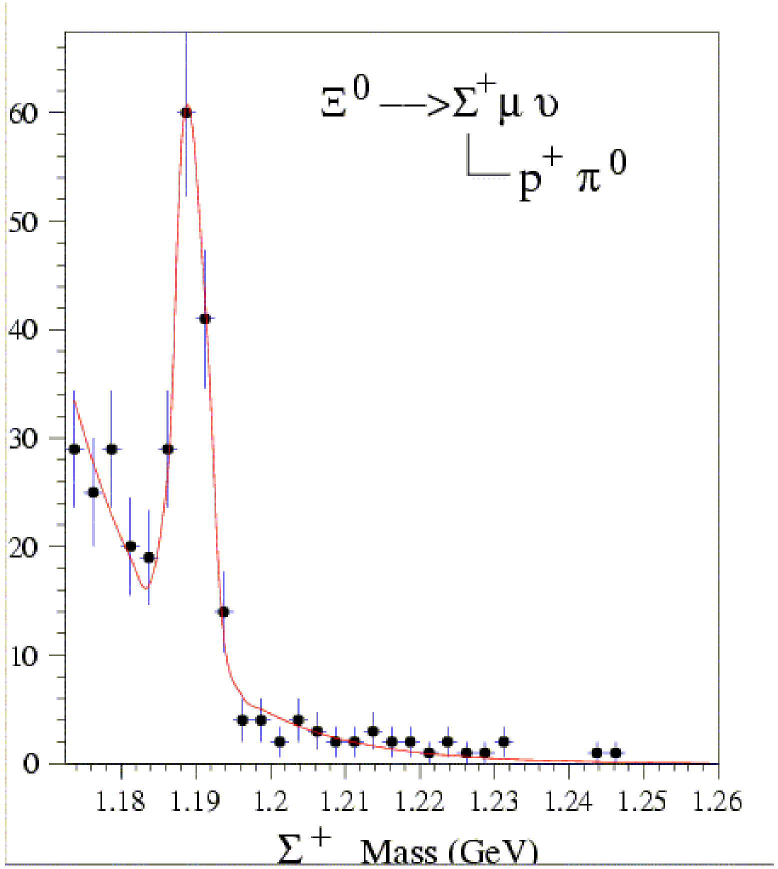
First measurement: 7 events
Bkg. 0.15 $^{+0.10}_{-0.04}$ ($K_L \to ee\gamma\gamma$ and accid.)
BR = $(5.8\ ^{+2.8}_{-2.3} \pm 0.8) \times 10^{-9}$

First measurement: 6 events
Bkg. 0.22 $^{+0.19}_{-0.12}$ (accid.)
BR = $(2.8\ ^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9}$

Important information for KL decays: indirect CPV dominates

Hyperons: Ξ^0 beta decay

More than $2 \cdot 10^9$ Ξ^0 decays in 2002
$\Xi^0 \to \Sigma^+ e^- \nu$ is only source of Σ^+
6238 signal events
(2.4% background)



$BR(\Xi^0 \to \Sigma^+ e^- \nu) = (2.51 \pm 0.03 \pm 0.11) \cdot 10^{-4}$

(preliminary)

NA48/2 (2003-2004)

CPV search in $K^{\pm}$ decays and more

CERN/SPSC 2000-003
CERN/SPSC/P253 add.3
January 16, 2000

ADDENDUM III
(to Proposal P253/CERN/SPSC)
for a Precision Measurement of Charged Kaon Decay Parameters with an Extended NA48 Setup

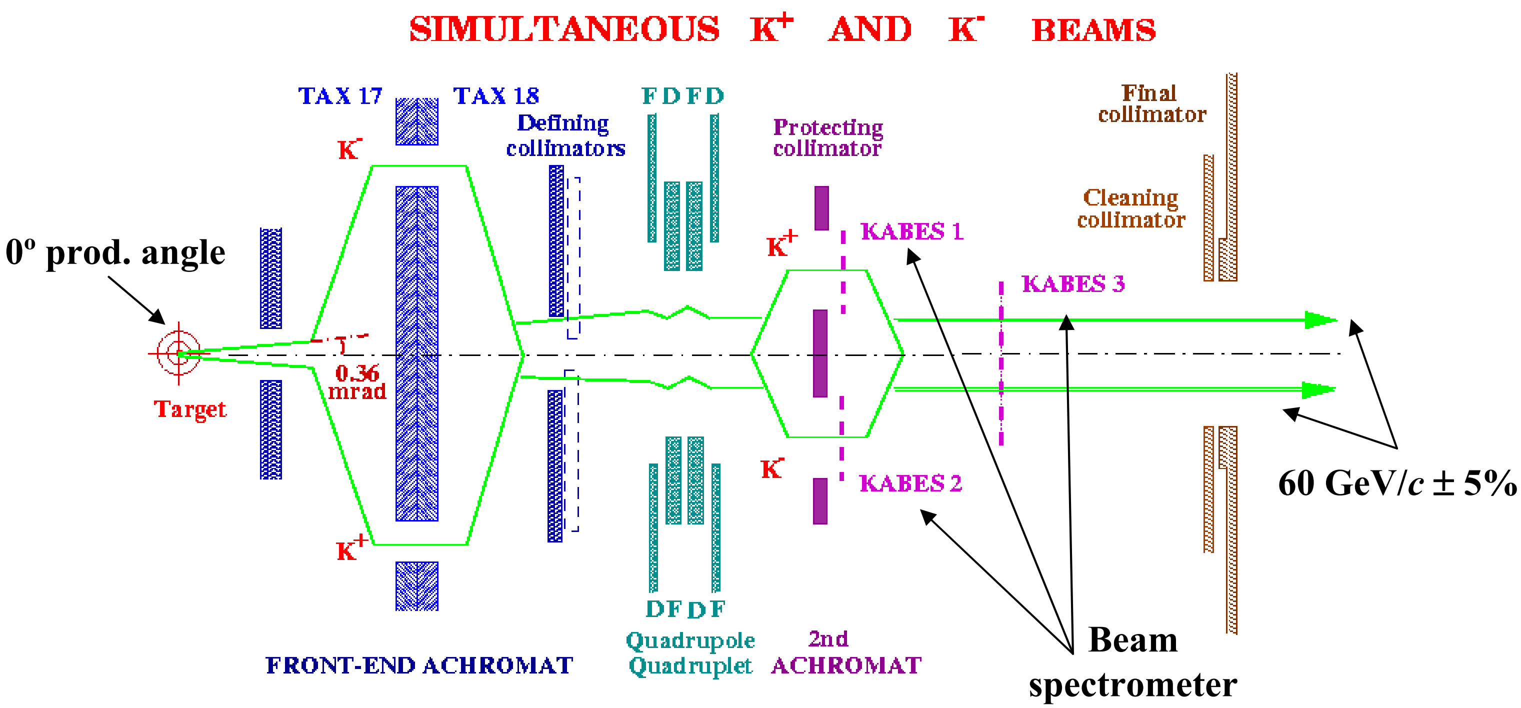
Direct CP-violation

More than 2×10^9 $K^{\pm} \to \pi^{\pm}\pi^{\pm}\pi^{\mp}$ and 1.2×10^8 $K^{\pm} \to \pi^0\pi^0\pi^{\pm}$ fully reconstructed decays are expected to be collected in one year of typical SPS and NA48 operation. Such statistics allows A_g to be measured with a precision better than 2.2×10^{-4}, and A_g^0 to better than 3.5×10^{-4}, including the estimated systematic uncertainties. An upper limit for the asymmetry in $K^{\pm} \to \pi^{\pm}\pi^0\gamma$ decays could be obtained at a level of 10^{-2}.

Charged K_{e4} decays ($K^{\pm} \to \pi^{\pm}\pi^{\mp}l^{\pm}\nu(\bar{\nu})$)

More than 10^6 K_{e4}^c charged kaon decays are expecting to be recorded in one year of running of the proposed NA48 setup. These should allow a_0^0 to be measured with an accuracy of 0.01 and the precision of the phase shift δ measurement to be improved.

NA48/2



Unique simultaneous K+ and K- narrow band beam

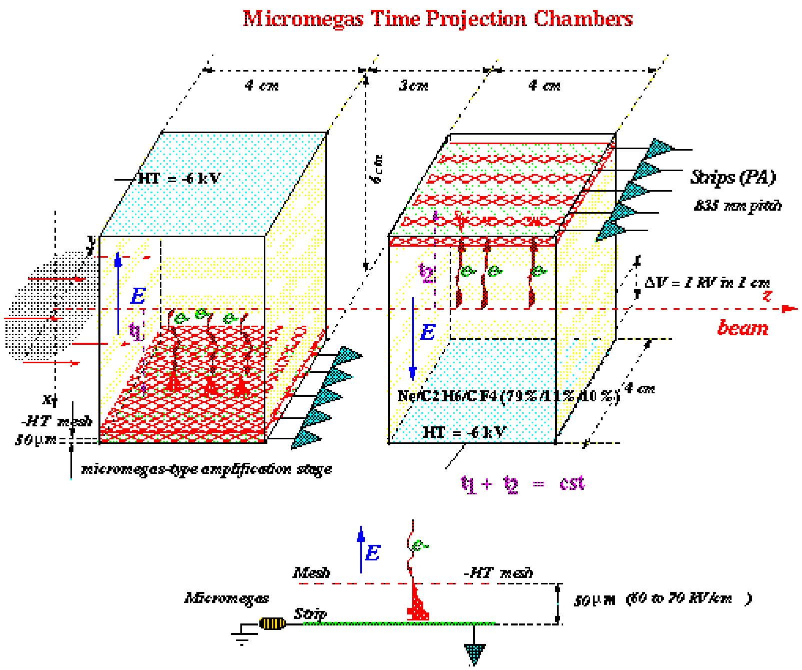
Kaon momentum spectrometer

10^{11} $K^{\pm}$ decays/year

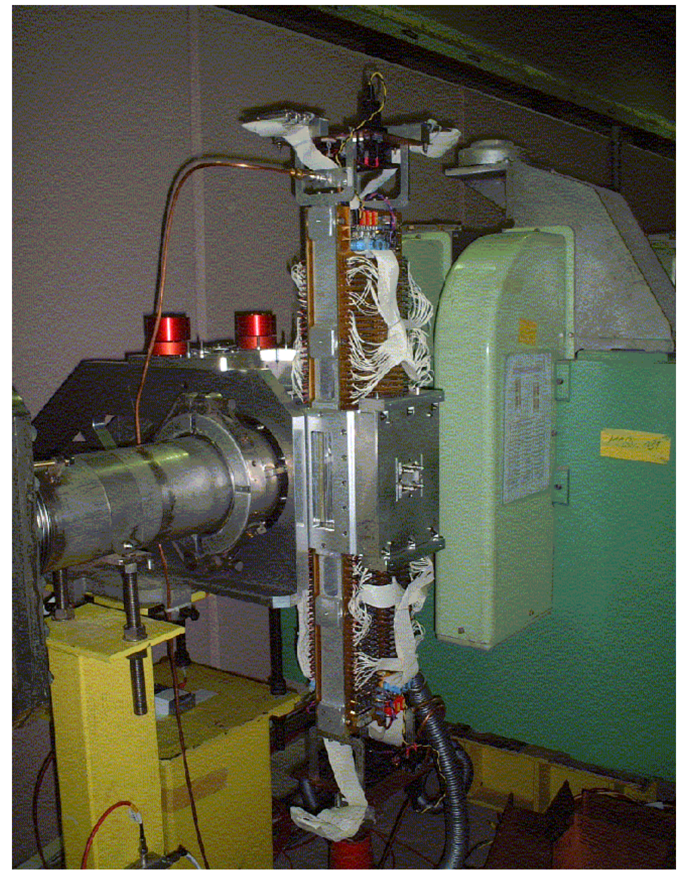
Systematics cancellations

KAon BEam Spectrometer

Close kinematics for Ke4 decays
Useful systematic check for asymmetry



1% momentum measurement at $2 \cdot 10^7$/s
Track angle measurement
Less than 100 ps time resolution



NA48/2: **CP violation**

Dalitz plot slope asymmetries in $K^{\pm} \rightarrow 3\pi$ decays:

$|M(u,v)|^2 \sim 1 + gu + f(u^2,v^2)$ u,v: Dalitz variables

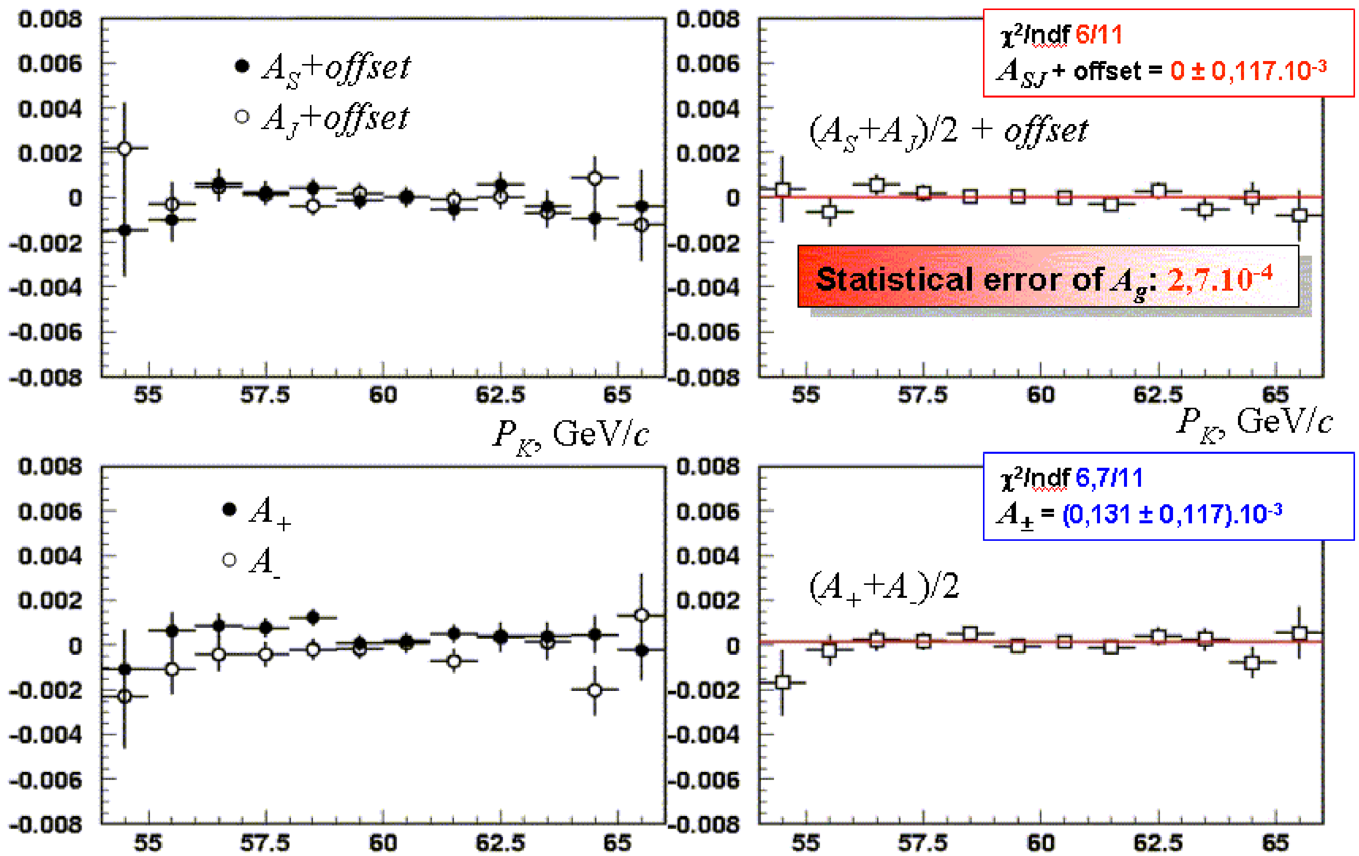
$\pi^{\pm}\pi^{+}\pi^{-}$ (BR = 5.6%): $g \approx -0.22$
$\pi^{\pm}\pi^{0}\pi^{0}$ (BR = 1.7%): $g \approx +0.65$

$Ag = (g_+ - g_-)/(g_+ + g_-) \neq 0$
would indicate direct CP violation

Previous experiments' precision: few 10^{-3}
SM predictions < $5{\times}10^{-5}$,
possible enhancements beyond SM

>$2{\cdot}10^9$ $\pi\pm\pi+\pi-$ decays on tape. Analysis in progress.

NA48/2: Asymmetry analysis



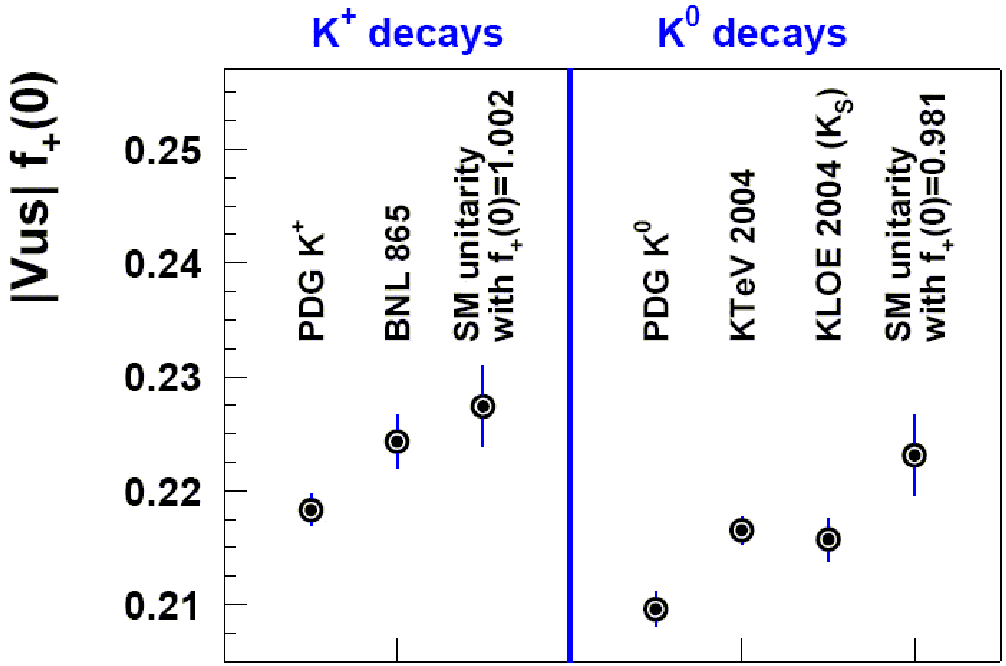
Part of 2003 data (not final cuts): no systematic limitation found

V_{us}: the Cabibbo angle

$|V_{us}| = 0.2196 \pm 0.0023$ (PDG2002)
$1-\Sigma_i |V_{ui}|^2 = 0.0032 \pm 0.0014$ (violating unitarity at 2.2σ)

Errors: 50% V_{ud} (will reach 10^{-4}) and 50% V_{us} → Measure V_{us} to 10^{-3}

BR of semileptonic K decays is best handle on V_{us}:
it measures $|V_{us}|$ f+(0): theory input required



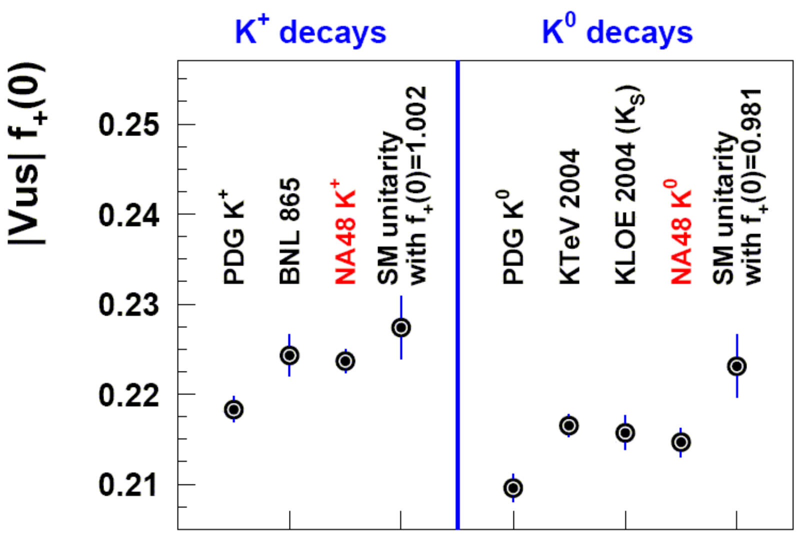
V_{us}: Cabibbo angle from NA48

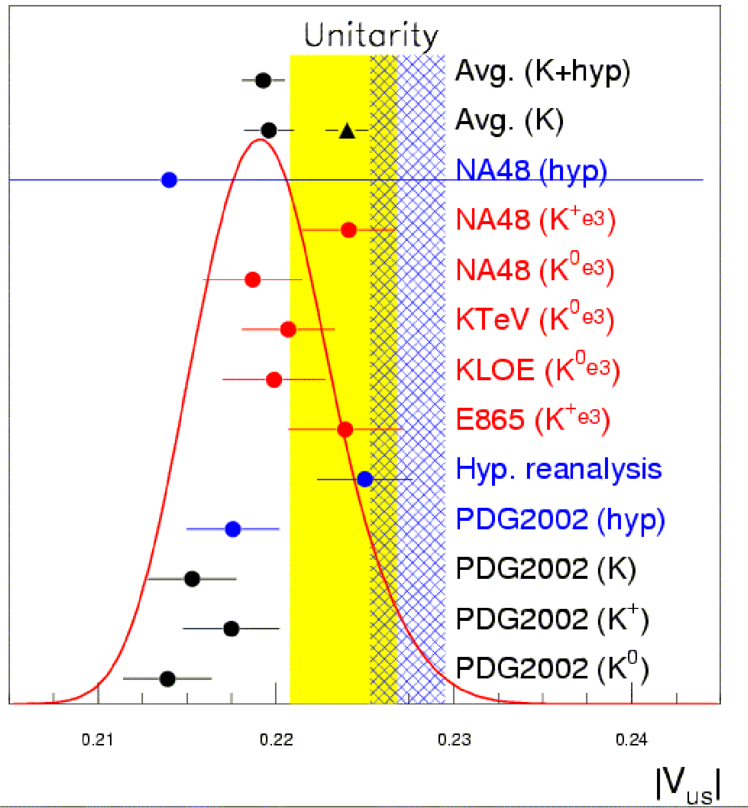
K^0_{e3}: special NA48 run 1999

$|V_{us}|= 0.2187 \pm 0.0028$

$K^{\pm}_{e3}$: special NA48/2 run 2003

$|V_{us}|= 0.2241 \pm 0.0026$





Using f+(0) from Cirigliano 2004

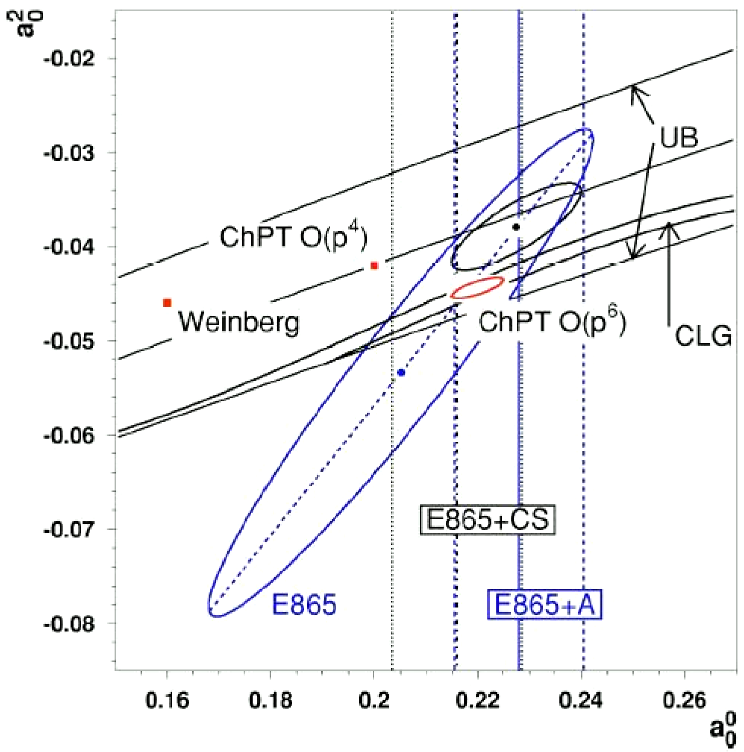
$\Xi^0 \rightarrow \Sigma^+ e^- \nu$: NA48/1 run 2002

$|V_{us}|= 0.214{+}0.030{-}0.025$

SM unitarity:

$|V_{us}|= 0.2274 \pm 0.0021$

ππ interactions and QCD

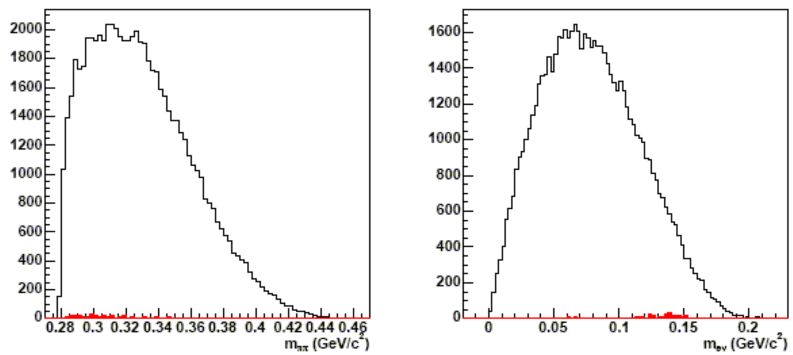


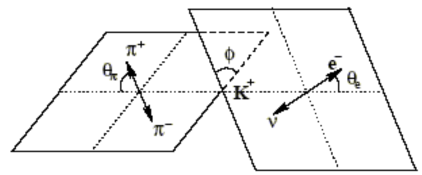
Theory precision still not reached!

- Ke4 decays allow study of low-energy ππ dynamics (asymmetry among di-pion and di-lepton planes sensitive to strong phase shifts).
- QCD quantity predicted with best precision: $a_0^0 = 0.220 \pm 0.005$
- BNL E865: 400K K^+e4 events $a_0^0 = 0.216 \pm 0.013 \pm 0.003$
- DIRAC goal: $|a_0 - a_2|$ at 6% (not using kaons)
- NA48/2 goal: >1M K^+e4 events and a_0^0 to 0.01

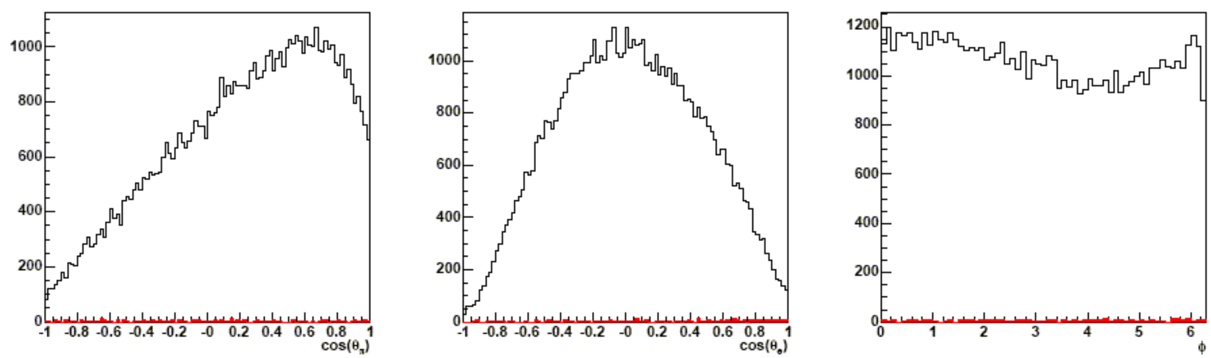
NA48/2: K^{+}_{e4} decays

2003-04 run: High statistics (>1M)
Tiny backgrounds (<1%)
Analysis in progress





Kinematic variables
(background in red)



Some pioneering concepts

- Bent crystal channeling
- Proton tagging at 30 MHz
- Overlapping simultaneous K_S and K_L beams
- LKr calorimeter with projective towers
- 40 MHz pipelined deadtimeless trigger
- Central Data Recording in Meyrin
- 100 TB/year of data
- Overlapping simultaneous $K^{\pm}$ beams
- Kaon beam spectrometer at 20 MHz

Key points

A succesful precision research project,
thanks to the presence of 3 important ingredients:

1. An accelerator capable of providing intense and high-quality beams
2. A stable, high-performance experimental apparatus with calibration linked to well-known physical quantities
3. A robust strategy of reducing the systematics to the accurate knowledge of detector geometry: relative positions and angles

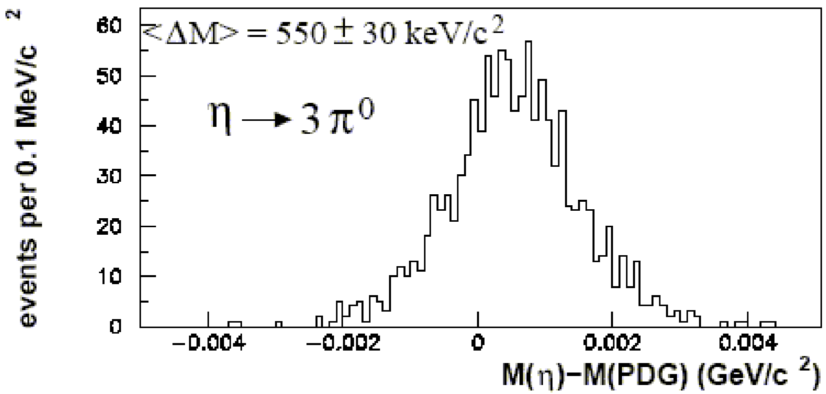
Unforeseen : eta mass

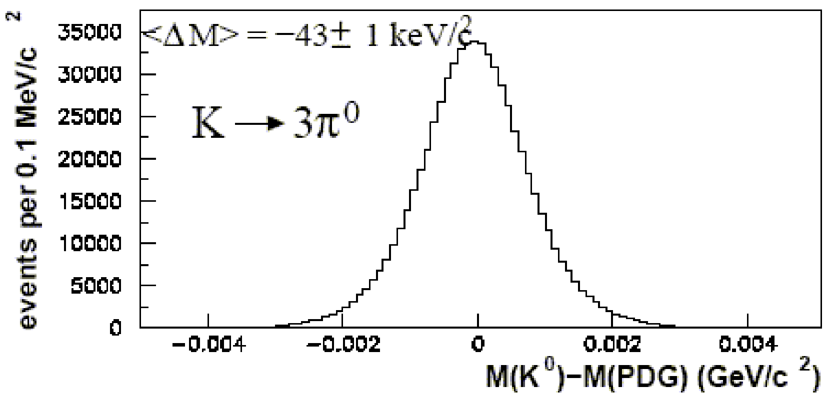
Byproduct of LKr calorimeter energy scale calibration in NA48

Use $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$ decays (background free, no K_S beam) from 2000 run

Decay vertex from π mass constraint: measure $M_{\eta(K)}/M_\pi$ independent from energy scale

4.2σ shift (0.1%) from PDG on M_η
Check with $K_L \rightarrow 3\pi^0$





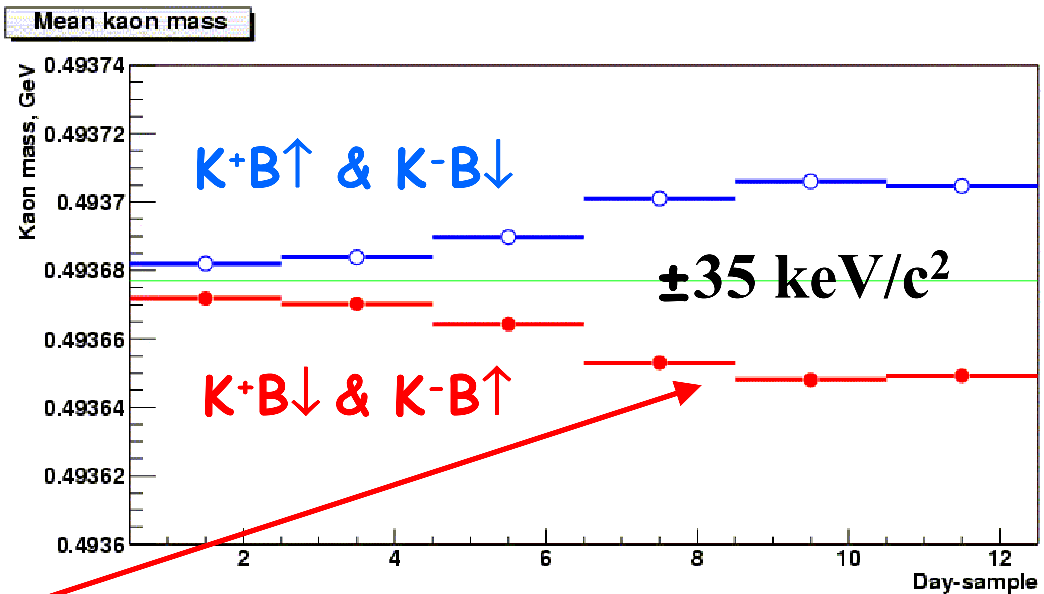
$M(\eta) = (547.843 \pm 0.051)$ MeV/c²
$M(K^0) = (497.625 \pm 0.031)$ MeV/c²

Unforeseen : DCH movements

NA48/2 2003:

Calibration of spectrometer field with K± mass difference

Calibration of spectrometer alignment with K± mass for right- vs. left- deflection



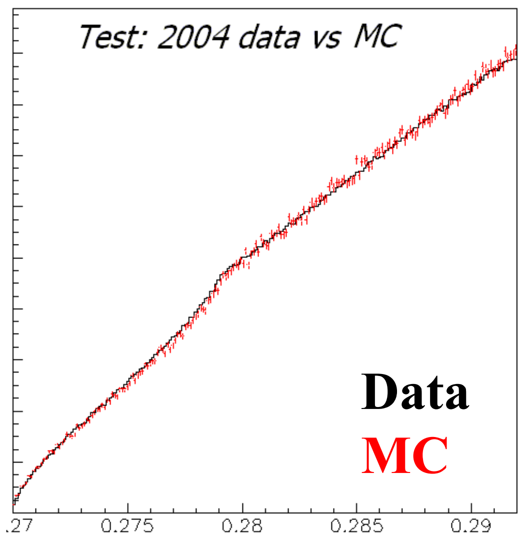
Detect and follow movement of DCH by 4μm/day in 2003 run

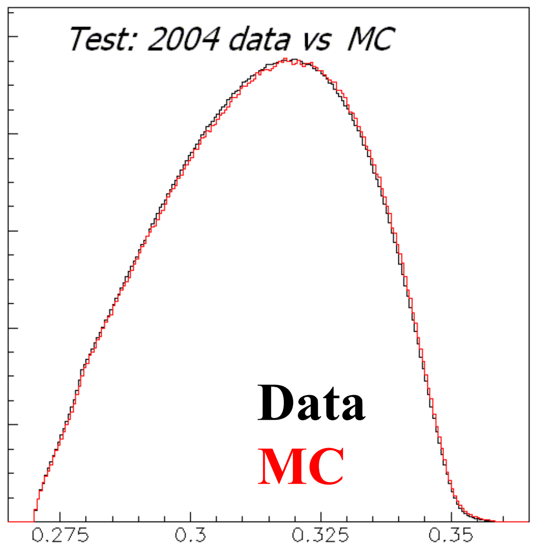
Very high quality control of the detector systematics

Unforeseen : a_0-a_2 from $K^+ \rightarrow \pi^+\pi^0\pi^0$

NA48/2: the process $\pi^+\pi^- \rightarrow \pi^0\pi^0$ can contribute to the $\pi^+\pi^-\pi^0$ Dalitz plot above its threshold

The distortion is linked to the $\pi^+\pi^-$ phase shifts a_2^0 - a_0^0 [N. Cabibbo – PRL 93 (2004) 121801] and allows a precise extraction of those



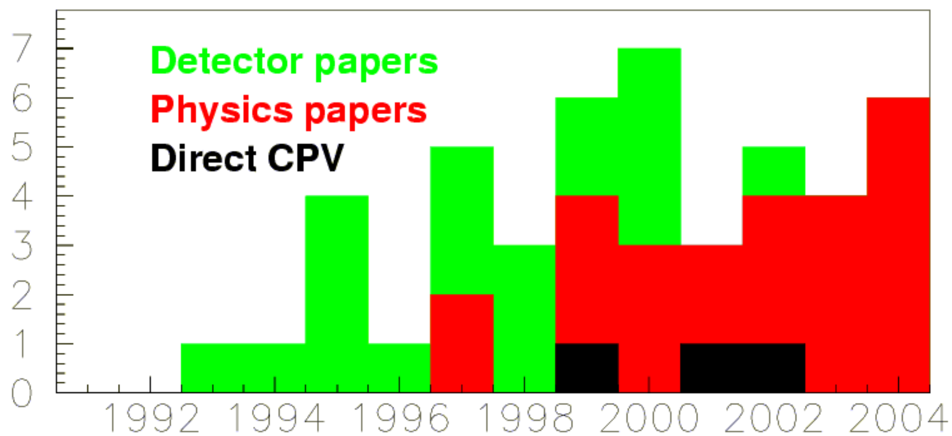


With NA48/2 unprecedented statistics the standard parameterization is no longer enough

More than 80 Ph.D. students

T. Anyev, R. Arcidiacono, H.G. Becker, M. Behler, M. Bender, M. Cirilli, M. Clemencic, J. Cogan, G. Collazuol, M. Contalbrigo, S. Crepe, T. Cuhadar-Donszelmann, A. Dabrowski, R.S. Dosanjh, D. Emelianov, M. Eppard, L. Fiorini, M. Fiorini, G. Fischer, A. Formica, T. Fonseca Martin, H. Fox, A. Gaponenko, T. Gershon, S. Giudici, B. Gorini, G. Govi, E. Goudzovski, G. Gouge, S. Goy Lopez, D. Guriev, R. Granier de Cassagnac, G. Graziani, B. Hay, A. Hirstius, K. Holtz, E. Imbergamo, A. Kalter, U. Koch, V. Kozhuharov, G. Lamanna, P. Lopes da Silva, A. Maier, E. Marinova, T. Fonesca Martin, P. Marouelli, V. Marzulli, L. Masetti, A. Michetti, I. Mikulec, N. Molokanova, U. Mossbrugger, C. Morales Morales, L. Musa, M. Needham, J. Ocariz, E. Olaiya, M. Patel, I. Pellmann, A. Peters, M.C. Petrucci, M. Piccini, M. Raggi, M. Ruggiero, R. Sacco, M. Scarpa, S. Schmidt, V. Schonharting, Y. Schue‘, M. Slater, S. Stoynev, A. Tkatchev, M. Wache, L. Widhalm, M. Wittgen, A. Winhart, S. Wronka, A. Zinchenko, M. Ziolkowski, S. Zhuchkova, …

A constant flow of publications



Definitely not a “single result” experiment!

Outlook

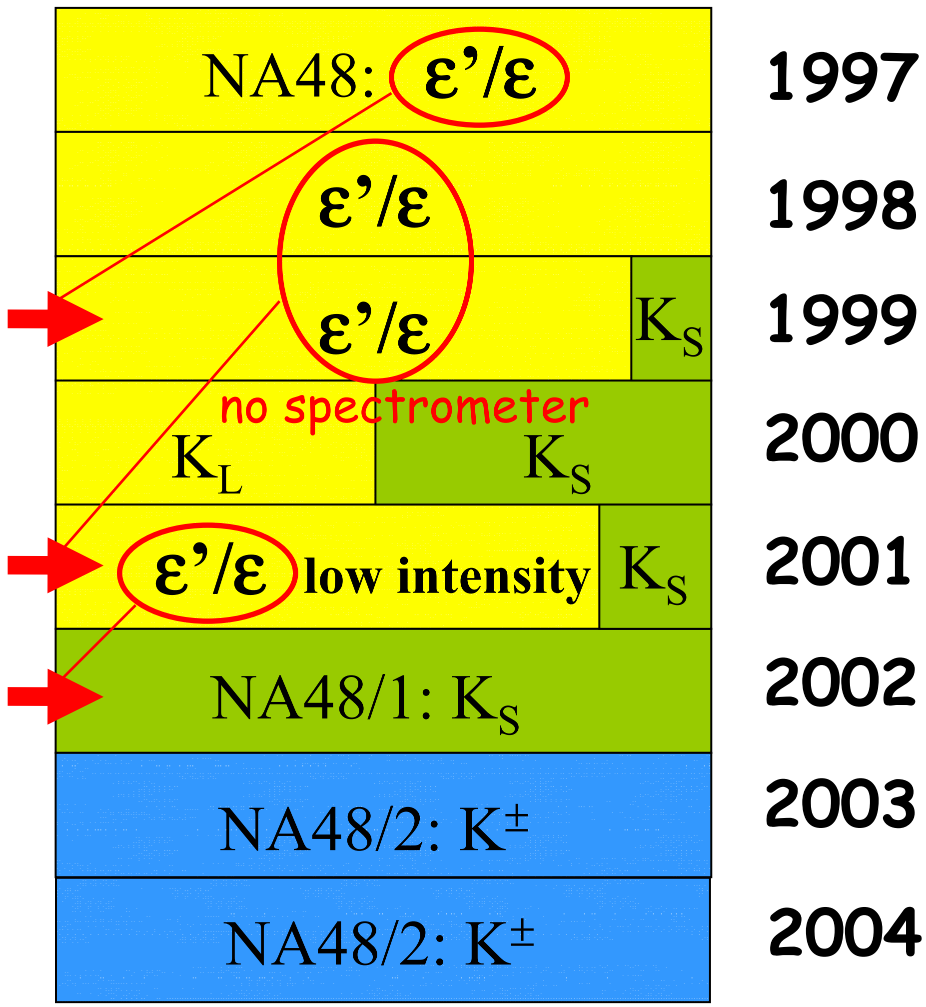
A 15-year long enterprise
8 years of data-taking
Some accidents, quickly overcome
A wide range of physics topics:
CP violation, CPT tests,
K_L, K_S, $K^{\pm}$ rare decays, chiral perturbation theory,
hyperon physics, hadronic physics,
exotic searches, meson masses
26 physics papers and 20 technical papers so far
Independent analysis, monthly analysis meetings
3 workshops at CERN with theorists

About 120 authors   16 ± 2 institutions
More than 80 Ph.D. students, many theses
A strong, dedicated and passionate collaboration

Looking forward towards a bright future

Spare slides

Data-taking periods



5.3M $K_L \to \pi^0\pi^0$
>2G $K^{\pm} \to 3\pi$
2.9G Ξ^0 decays

➡ = ε'/ε results