Summary on CP Violation with Kaons

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On behalf of the NA48 Collaboration

Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Vienna

Overview

- Introduction
- CP Violation with Kaons
- Experiments: KLOE, KTeV, NA48
- Results:
  - Direct CP Violation with neutral Kaons
  - Charge Asymmetry in K^0_{e3}
  - $K_S \rightarrow 3\pi^0$
  - $K_{S,L} \rightarrow \pi^0 \, l^+ l^-$
  - Direct CP Violation in $K^{\pm}_{3\pi}$ decays
- Prospects and conclusions

Introduction

- **Why Kaons**
  - crucial for the present definition of Standard Model
  - search for explicit violation of SM: key element to understand flavour structure of physics beyond SM
- **Motivation for Kaons experiments**
  - Test of fundamental symmetries
    - *CP Violation: charge asymmetry, T violating observables*
    - *CPT test: tigher contraints from Bell-Steinberger rule, K_S/K_L semileptonic decays*
  - Sharpen theoretical tools
    - *Study low energy hadron dynamics: χPT tests and parameter determination, form factors*
  - Probe flavour structure of Standard Model and search for explicit violation (e.g. Lepton Flavour Violation)
    - *Rare decays suppressed (FCNC: 2nd order weak interactions) or not allowed by SM*
    - *Sensitivity to physics BSM*

CP Violation with Kaons

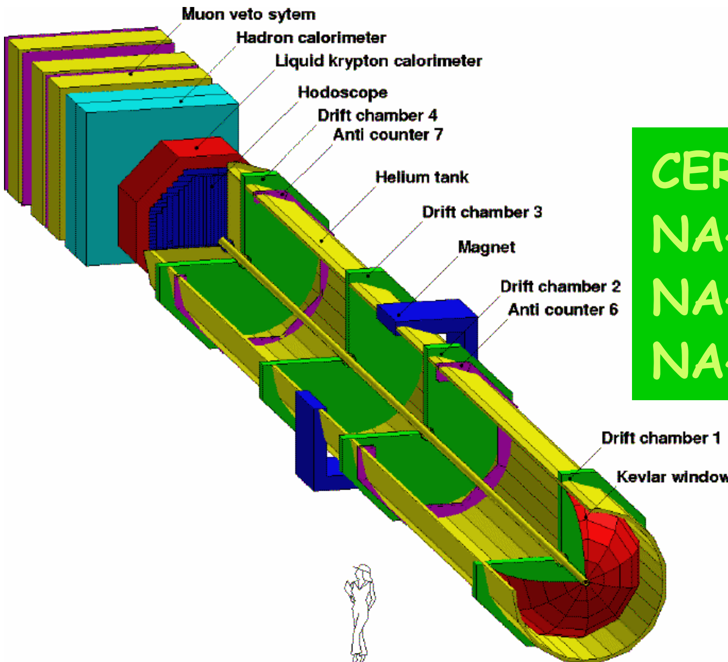
CP Violation: a window to physics beyond SM

Brief History of CP Violation

- **1964**: CP violation in K^0 *(Cronin, Christenson, Fitch, Turlay)*
- **1993-99**: Direct CP violation in K^0 *(NA31, NA48, KTeV)*
- **2001**: CP violation in B^0 decay with oscillation *(Babar, Belle)*
- **2004**: Direct CP violation in B^0 *(Belle, Babar)*

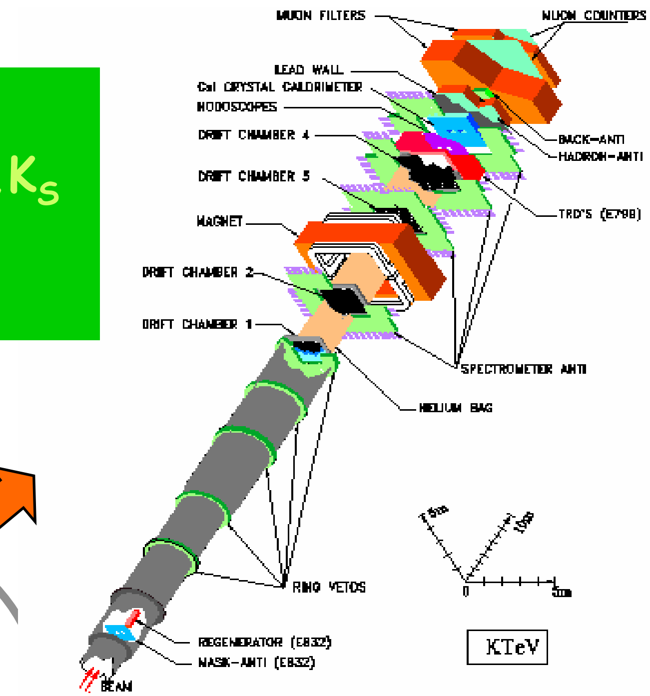
- CP Violation in Kaon decays can occur either in $\bar{K}^0$-K^0 mixing or in the decay amplitudes
- Only Direct CP Violation occurs in $K^\pm$ decays (no mixing)
- Complementary observables to measure Direct CP Violation in Kaons: ε'/ε, rare decays, A_g

Experiments with Kaons

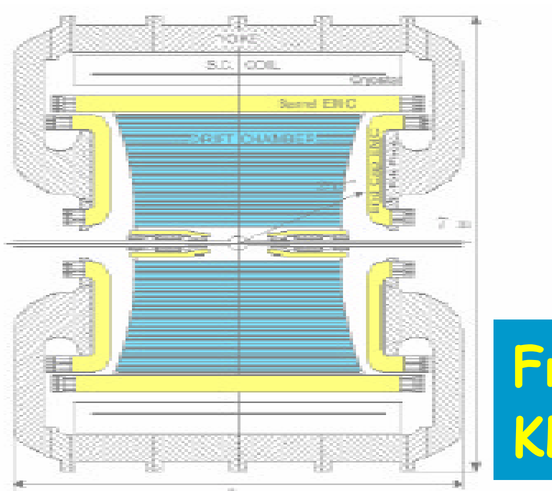


CERN
NA48 1997-2001 K_L, K_S
NA48/1 2000,2002 K_S
NA48/2 2003-2004 $K^{\pm}$

Active Experiments

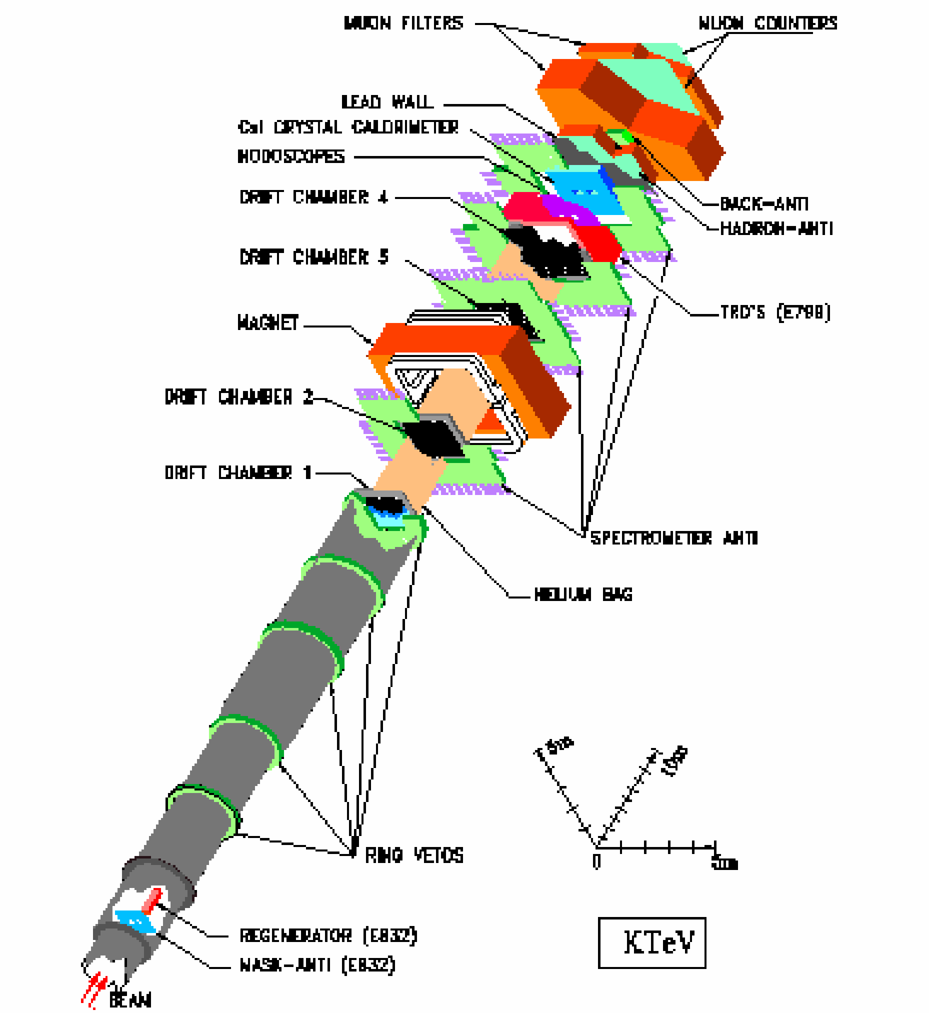


Fermilab
KTeV: 1997,1999 K_L, K_S



Frascati - DaΦne
KLOE > 2000 K_S ,K_L ,$K^{\pm}$

FNAL - KTeV Experiment



"Vacuum" beam $\rightarrow K_L$ beam

"Regenerator" beam $\rightarrow K_L + \rho K_S$ beam

- **Parallel K beams:**
  - 2 proton lines (~ 10^{12} ppp)
  - K_S from K_L on Regenerator (scintillator plates),
  - K_S identification via x-y position
  - switches beam line once per cycle
- $\pi^+\pi^-$: **Magnetic Spectrometer**

  $\sigma(p)/p \cong 0.17\% \oplus 0.007\ p[GeV/c]\%$
- $\pi^0\pi^0$: **CsI calorimeter**

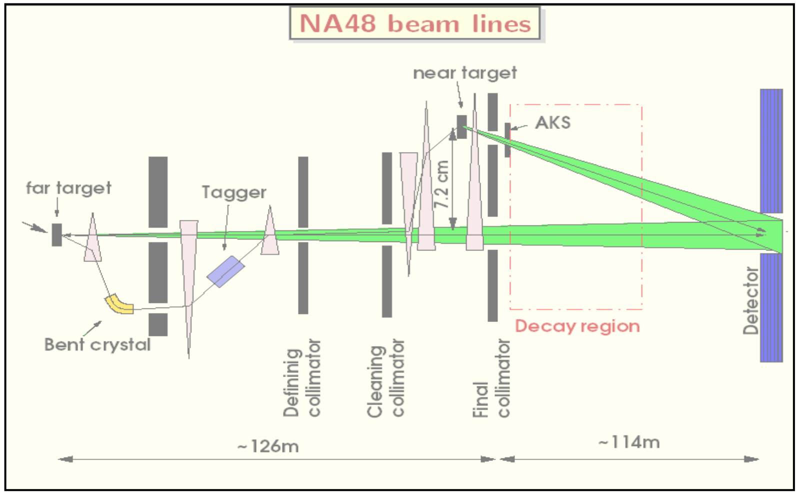
  $\sigma(E)/E \cong 2.0\%/\sqrt{E} \oplus 0.45\%$

$\sigma_M(\pi^0\pi^0) \sim \sigma_M(\pi^+\pi^-) \sim 1.5$ MeV

- **Photon veto and muon veto**

Experimental Program
KTeV: 1997,1999 K_L,K_S

CERN - NA48 Experiment



Beam pipe

- **Simultaneous K beams:**
  - split same proton beam (~10^{12} ppp)
  - convergent K_L-K_S beams
  - K_S from protons on near target
  - K_S identification via proton tagging
- **$\pi^+\pi^-$: Magnetic Spectrometer**

  $\Delta p/p = 1.0\% \oplus 0.044\% \times p$ [GeV/c]
- **$\pi^0\pi^0$: LKr Calorimeter**

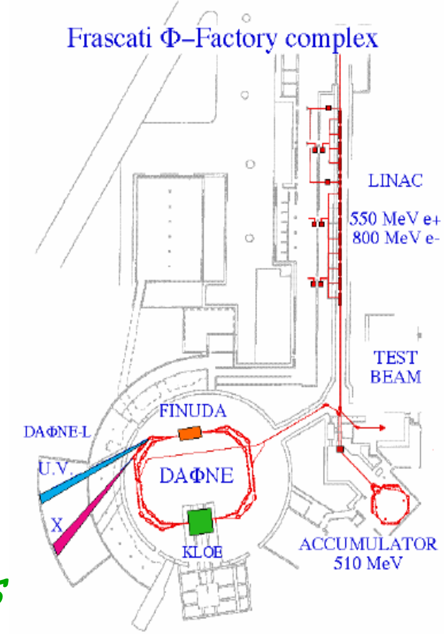
  $\Delta E/E = 3.2\%/\sqrt{E} \oplus 9\%/E \oplus 0.42\%$ [GeV]

$\sigma_M(\pi^0\pi^0) \sim \sigma_M(\pi+\pi-) \sim 2.5$ MeV

- **Photon and muon veto**

Experimental Program		
NA48	1997-2001	K_L,K_S
NA48/1	2000,2002	K_S
NA48/2	2003-2004	$K^{\pm}$

LNF DaΦne: the Φ Factory

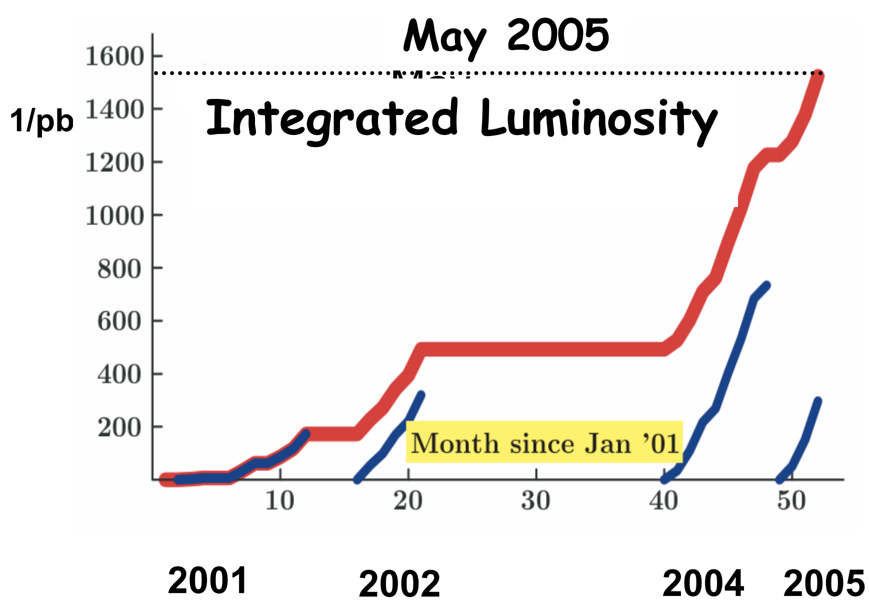


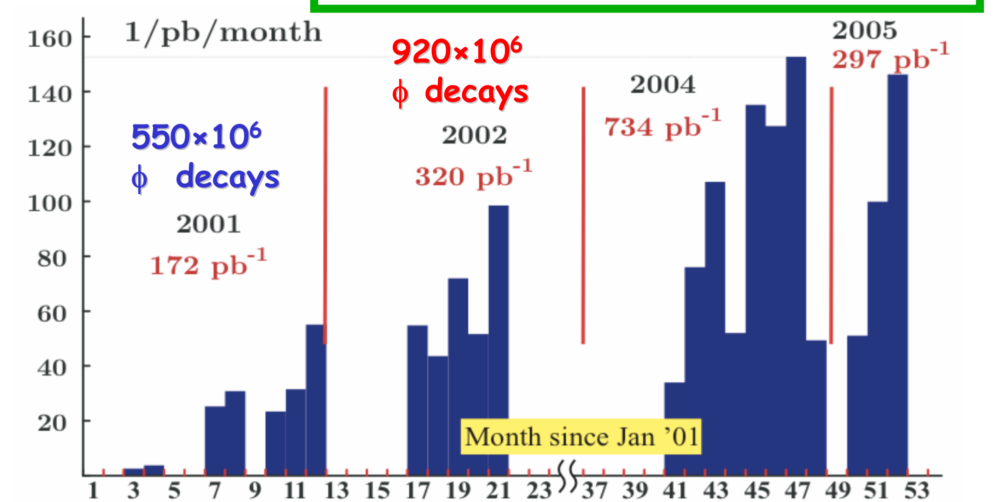
Φ Factory: e^+e^- collider@$\sqrt{s}$=1019.4 MeV = M_Φ

- Φ Decays: BR($\Phi \rightarrow K_L K_S$)=34.3%; BR($\Phi \rightarrow K^+K^-$)=49.31%
- tagged K decays from $\Phi \rightarrow \bar{K}K$ ⇒ pure K beams

  clean investigation of K decays and precision measurements
- KLOE data taking: 2000-01-02-04-05

New KLOE run in progress
- L_{peak}= 1.4 × 10^{32} $cm^{-2}s^{-1}$
- Goal: collect 2 fb^{-1} by end 2005





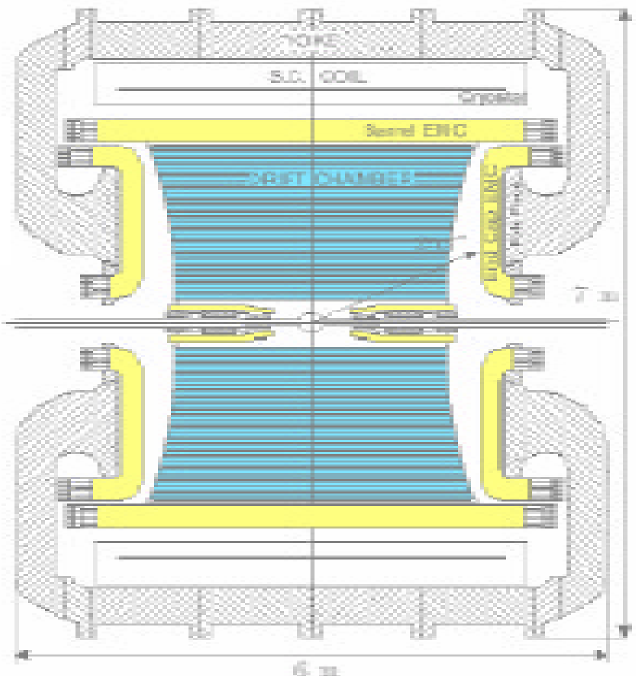
(Recent results from KLOE: S. Dell'Agnello – LNF SC Open Meeting, may '05 and M. Martini – Krare Workshop@LNF, may '05)

LNF: the KLOE detector

EM Calorimeter:
Lead and scintillating fibres

$$\frac{\sigma(E)}{E} = \frac{5.7\%}{\sqrt{E(GeV)}}$$

$$\sigma(t) = \frac{54\,ps}{\sqrt{E(GeV)}} \oplus 50\,ps$$



Drift Chamber:
Stereo geometry

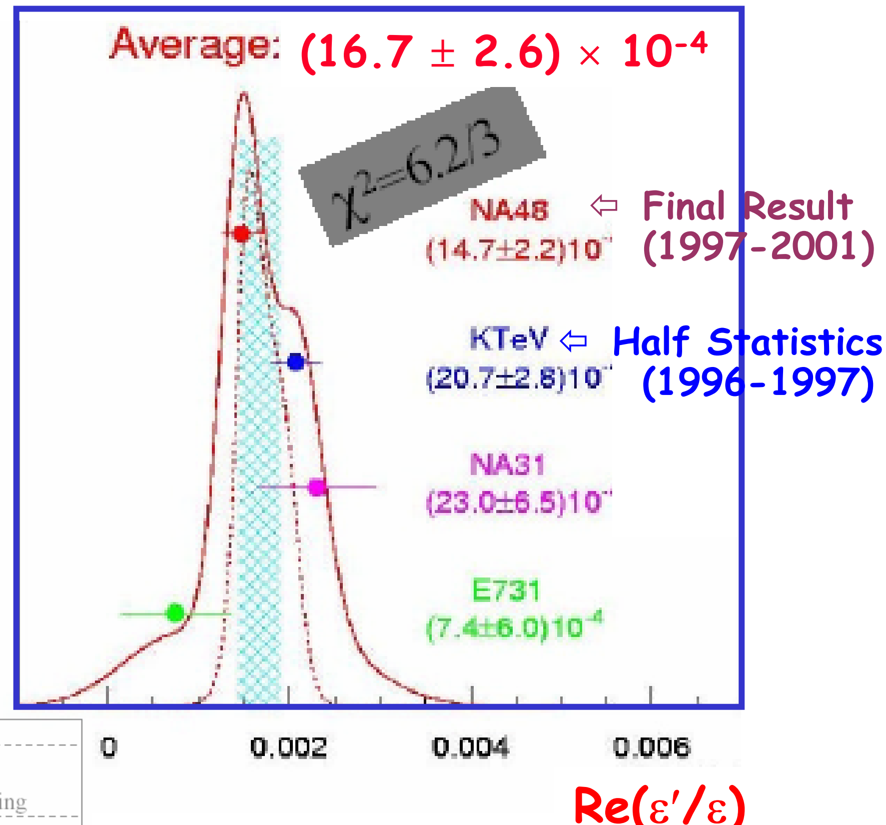
$$\delta p / p \approx 4 \times 10^{-3}$$

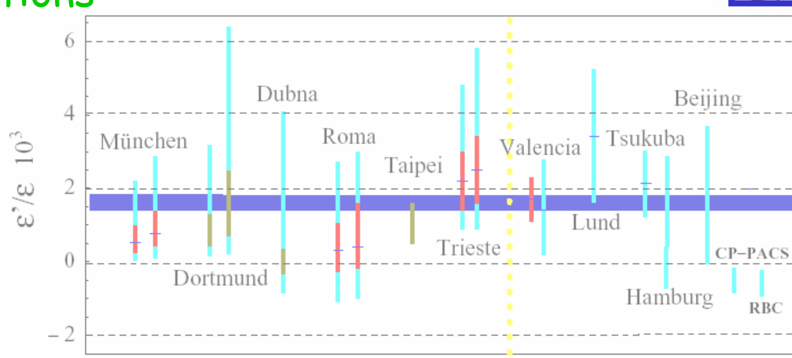
$$\sigma_{r\phi} = 150\,\mu m$$

$$\sigma_z = 2\,mm$$

Direct CP Violation: experimental results on ε'/ε

- Direct CPV established in $K^0 \to \pi\pi$ by NA48 and KTeV
  - more results expected (KTeV, KLOE)
  - no third generation experiments
- Result (roughly) compatible with SM
  - Exclude alternative to CKM mechanism (superweak models and approximate-CP)
  - Despite huge efforts, ε'/ε not yet computed reliably due to large hadronic uncertainties
  - Improvement of the calculation expected with lattice
- New physics may contribute as a correction to SM predictions





K^0_{e3} Charge Asymmetry

- Charge Asymmetry in K^0_{e3} is due to $\bar{K}^0$-K^0 mixing (Indirect CPV)
- Limits on CPT and $\Delta S=\Delta Q$
- Il CPT is conserved and $\Delta S=\Delta Q$:

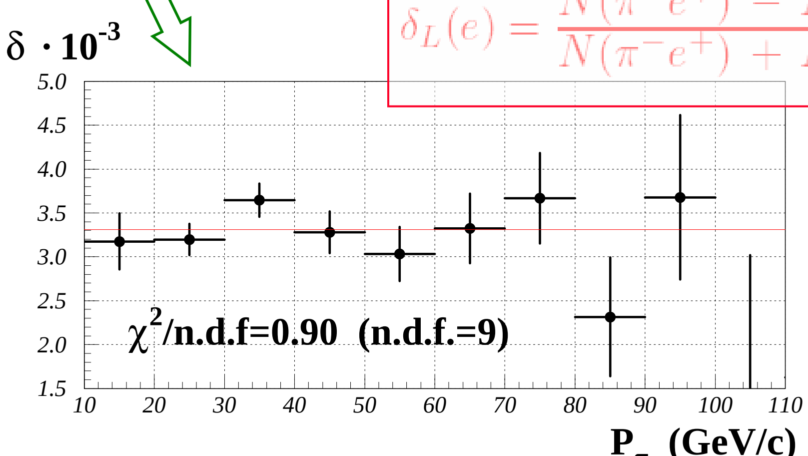
$$\delta_L(e) = \frac{\Gamma(K_L \to e^+\pi^-\nu) - \Gamma(K_L \to e^-\pi^+\bar{\nu})}{\Gamma(K_L \to e^+\pi^-\nu) + \Gamma(K_L \to e^-\pi^+\bar{\nu})} \simeq 2 \times Re(\varepsilon)$$

- Results in NA48 ($\sim 2\times10^8$ K_{e3}) and KTeV ($\sim 3\times10^8$ K_{e3})

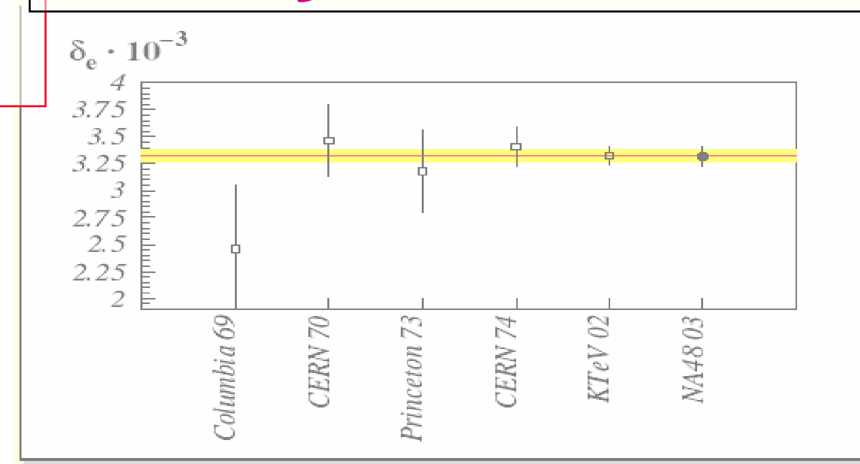
KTeV: $\delta_L(e) = (3.322 \pm 0.058_{stat} \pm 0.047_{syst}) \times 10^{-3}$

NA48: $\delta_L(e)=(3.317 \pm 0.070_{stat} \pm 0.072_{syst}) \times 10^{-3}$

$$\delta_L(e) = \frac{N(\pi^- e^+) - N(\pi^+ e^-)}{N(\pi^- e^+) + N(\pi^+ e^-)}$$



PDG2004: $\delta_L(e) = (3.27 \pm 0.12) \times 10^{-3}$



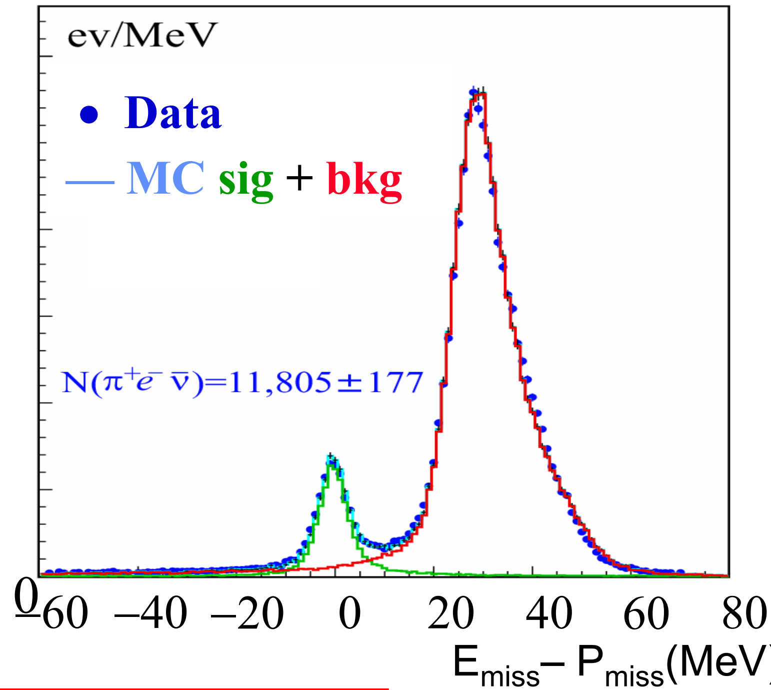
Semileptonic K_S decays

❖ **KLOE: first measurement (2002), update in progress**

➢ Method:

- K_S tagged by opposite K_L ($\Phi \rightarrow \bar{K}K$)
- Identify πe pairs using TOF
- Event counting by fitting the $[E(\pi e)-P]$ distribution (test for ν)
- Independent measurement of the two charge modes

➢ Selected ~10^4 signal events per charge in the 2001-02 data (0.5 fb^{-1})



❖ **New preliminary result:**

$$BR(K_S \rightarrow \pi e \nu) = (7.09 \pm 0.07_{stat} \pm 0.08_{syst})\ 10^{-4}$$

❖ **CPT Test:** new measurement of the charge asymmetry in K_S: $\delta_S(e) = (-2 \pm 9 \pm 6) \times 10^{-3}$ ($\delta_L(e) = 3.32 \pm 0.07) \times 10^{-3}$)

NA48

CP Violation in $K_S \to \pi^0\pi^0\pi^0$

- $K_S \to 3\pi^0$ is CP violating [$CP(K_S) = +1$, $CP(3\pi^0) = -1$]
- Allowed by SM, but never observed
- According to SM:

$$BR\left(K_S \to 3\pi^0\right) \approx |\varepsilon|^2 \frac{\tau_S}{\tau_L} BR\left(K_L \to 3\pi^0\right) = 1.9 \times 10^{-9}$$

- Last limit from direct search: $BR(K_S \to 3\pi^0) < 1.4\times10^{-5}$ (SND, 1999)
- Can be parametrized with the amplitude ratio η_{000}

$$|\eta_{000}| = \frac{A\left(K_S \to 3\pi^0\right)}{A\left(K_L \to 3\pi^0\right)} = \sqrt{\frac{\tau_L}{\tau_S}\frac{BR\left(K_S \to 3\pi^0\right)}{BR\left(K_L \to 3\pi^0\right)}} \Rightarrow |\eta_{000}| = \varepsilon + i\frac{\mathrm{Im}(A_1)}{\mathrm{Re}(A_1)}$$

If CPT is conserved:

- $\mathrm{Re}(\eta_{000})$: CPV in mixing
- $\mathrm{Im}(\eta_{000})$: direct CPV

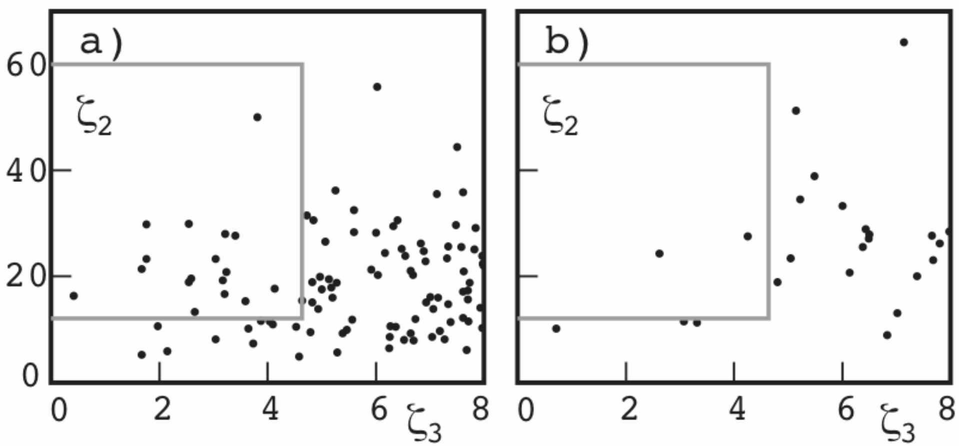
- The uncertainty on $K_S \to 3\pi^0$ amplitude limits the precision on CPT test (Bell-Steinberger relation)

$$\left(1+i\tan\phi_{SW}\right)\left(\Re e\varepsilon - i\Im m\delta\right) = \sum_f A^*\left(K_S \to f\right)A\left(K_L \to f\right)$$

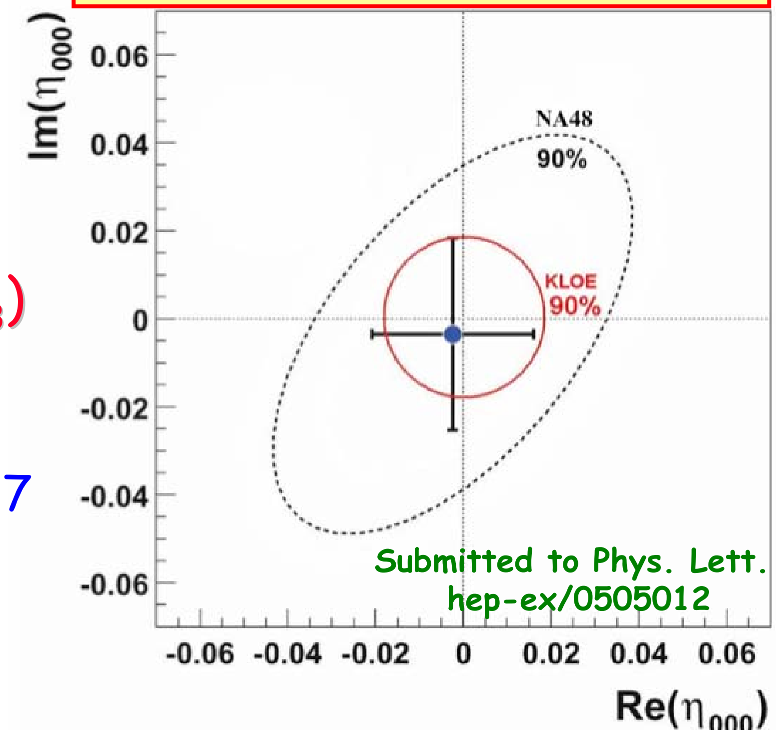
~~CP~~ ~~CPT~~

KLOE search for $K_S \to \pi^0\pi^0\pi^0$

- Direct search, new result
- Rarest decay studied by KLOE so far
- Data sample: 0.5 fb^{-1} (2001-2002 run)
  - 37.8×10^6 (K_L-crash tag + $K_S \to 2\pi^0$)
- Require 6 prompt photons
  - large background ~40K events
- Kinematic fit, $2\pi^0$,$3\pi^0$ estimators (ζ_2, ζ_3)
- After all analysis cuts ($\varepsilon_{3\pi}$ = 24.4%)
  - 2 candidate events found
  - expected background: 3.13 ± 0.82 ± 0.37



$BR(K_S \to 3\pi^0) \leq 1.2 \times 10^{-7}$ @90% CL ⇒ Best limit



Submitted to Phys. Lett.
hep-ex/0505012

Prospects with 2 fb^{-1}:
if background ~ negligible level
UL will improve by factor ~ 10
(down to few 10^{-8})

NA48/1: $K_S \to \pi^0\pi^0\pi^0$ and η_{000}

- Measurement in NA48
  - Sensitivity to η_{000} from K_S-K_L interference superimposed on a huge flat $K_L \to \pi^0\pi^0\pi^0$ component
  - Aim: O(1%) error on Re(η_{000}) and Im(η_{000})
  - Method: measure K_S-K_L interference near the production target
    - *use $3\pi^0$ events from near-target run for η_{000}*
    - *normalize to $K_L \to 3\pi^0$ from far-target run*
    - *use MC to correct for residuals acceptance difference and Dalitz decays*
- Time evolution of $K_{L,S} \to 3\pi^0$:

$$I_{3\pi^0}(t) \propto \underbrace{e^{-\Gamma_L t}}_{K_L \text{ decay}} + \underbrace{|\eta_{000}|^2 e^{-\Gamma_S t}}_{K_S \text{ decay}} \underbrace{+ 2\,D(p)\,(\mathrm{Re}(\eta_{000})\cos\Delta m\, t - \mathrm{Im}(\eta_{000})\sin\Delta m\, t)\; e^{-\frac{1}{2}(\Gamma_S+\Gamma_L)\,t}}_{K_L\text{-}K_S \text{ interference}}$$

Dilution $D(p) = \dfrac{N(K^0) - N(\overline{K^0})}{N(K^0) + N(\overline{K^0})} \approx 0.35$ momentum dependent.

NA48/1 results on $K_S \to \pi^0\pi^0\pi^0$

❖ Data samples (run 2000):

- Near-target run: 4.9×10^6 $K_{L,S} \to 3\pi^0$ data 90×10^6 $K_L \to 3\pi^0$ MC
- Far-target (K_L) run: 109×10^6 $K_L \to 3\pi^0$ data 90×10^6 $K_L \to 3\pi^0$ MC

❖ Fit method: fit double ratio

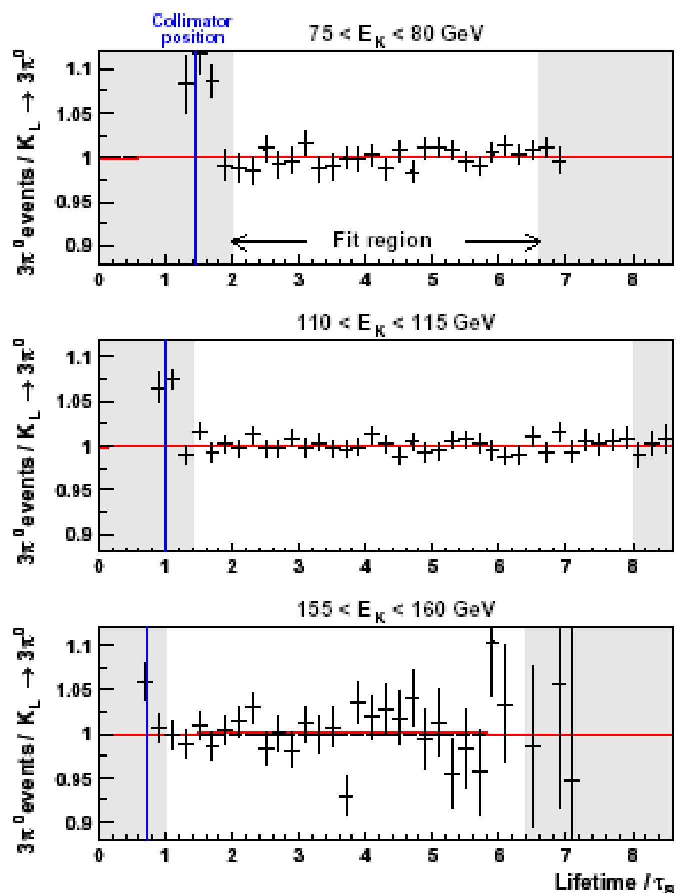
$$\frac{3\pi^0 \text{ (Data, } K_S \text{ run)}}{K_L \to 3\pi^0 \text{ (Data, } K_L \text{ run)}} \Big/ \frac{K_L \to 3\pi^0 \text{ (MC, } K_S \text{ run)}}{K_L \to 3\pi^0 \text{ (MC, } K_L \text{ run)}}$$

Final Results (2004) :

- $\text{Re}(\eta_{000}) = -0.002 \pm 0.011_{stat.} \pm 0.015_{syst}$
- $\text{Im}(\eta_{000}) = -0.003 \pm 0.013_{stat.} \pm 0.017_{syst}$
- $|\eta| < 0.045$ 90% CL
- $Br(K_S \to 3\pi^0) < 7.4 \times 10^{-7}$ 90% CL

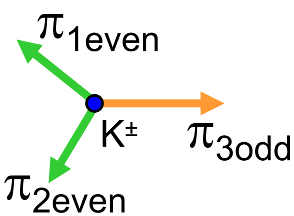
If $\text{Re}(\eta_{000}) = \text{Re}(\varepsilon) = 1.66 \times 10^{-3}$ (CPT):

- $\text{Im}(\eta_{000})_{CPT} = -0.000 \pm 0.009_{stat.} \pm 0.017_{syst}$
- $|\eta|_{CPT} < 0.045$ 90% CL
- $Br(K_S \to 3\pi^0)_{CPT} < 2.3 \times 10^{-7}$ 90% CL



Ratio of near-target and far-target data corrected for acceptance (3 Energy intervals)

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



$K^{\pm} \to 3\pi$ matrix element

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

$BR(K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = 5.57\%$

$BR(K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}) = 1.73\%$

Dalitz variables

$$u = \frac{s_3 - s_0}{m_\pi^2}$$

$$v = \frac{s_2 - s_1}{m_\pi^2}$$

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

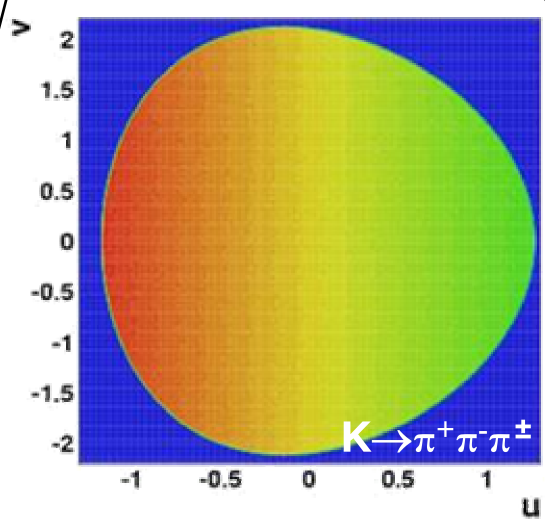
$$s_0 = \frac{1}{3}\sum s_i$$

i=3 is the odd pion

$K \to \pi^{+}\pi^{-}\pi^{\pm}$: g = -0.2154

$K \to \pi^{0}\pi^{0}\pi^{\pm}$: g = 0.652

|h|, |k| << |g|



K+-K- asymmetry in g

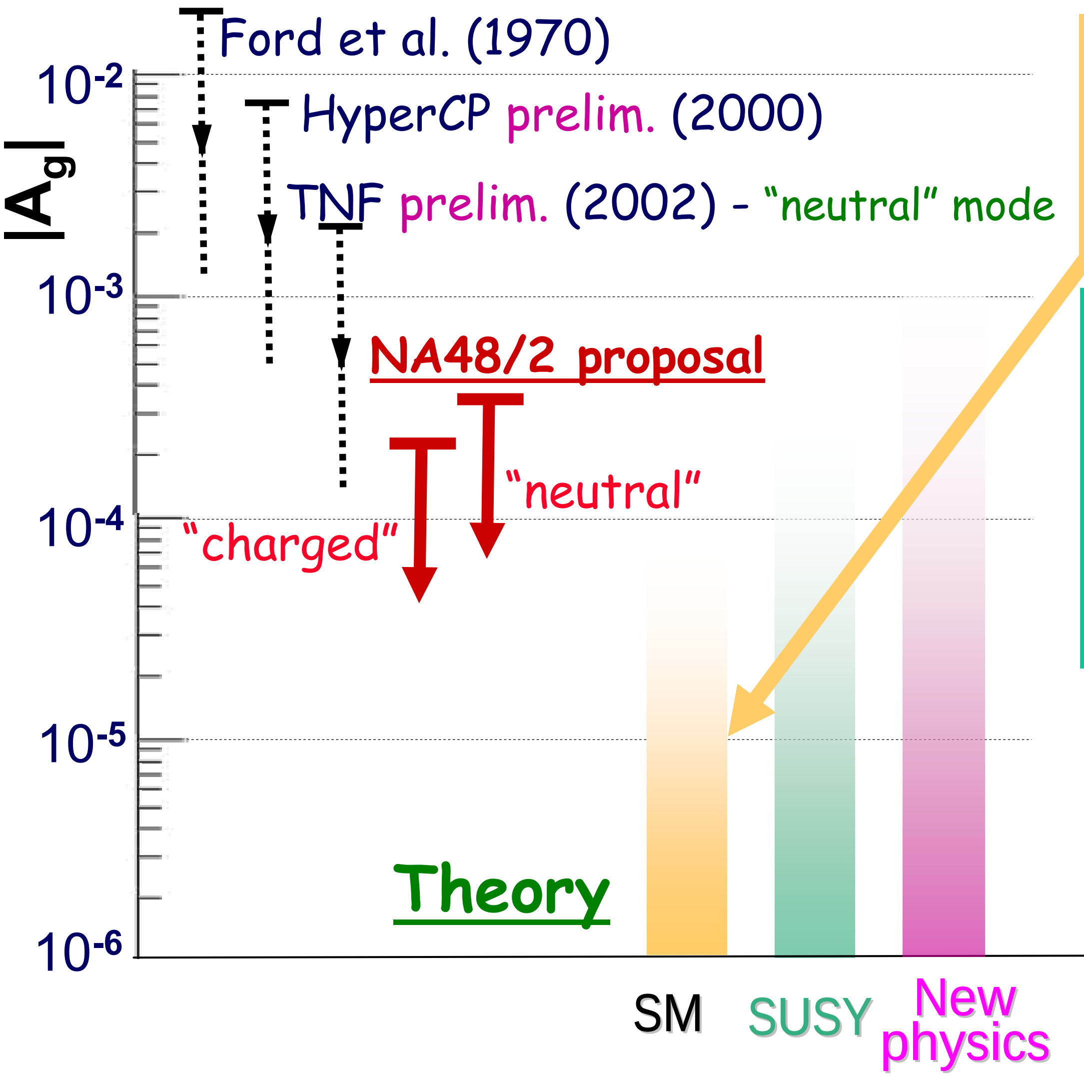
$$A_g = \frac{g_+ - g_-}{g_+ + g_-}$$

⇨ Direct CP violation if $A_g \neq 0$

NA48/2: search for Direct CPV by comparing the linear slopes $g_{\pm}$ for $K^{\pm}$

Experimental and theoretical status

Experimental results



SM estimates of A_g vary within an order of magnitude (few 10^{-6} to 8×10^{-5}).

Models beyond SM predict substantial enhancements partially within the reach of NA48/2.

(theoretical analyses are by far not exhaustive by now)

CPV asymmetry in decay width is much smaller than in Dalitz-plot slopes A_g (SM: $\sim10^{-7}...10^{-6}$)

NA48/2 goal and method

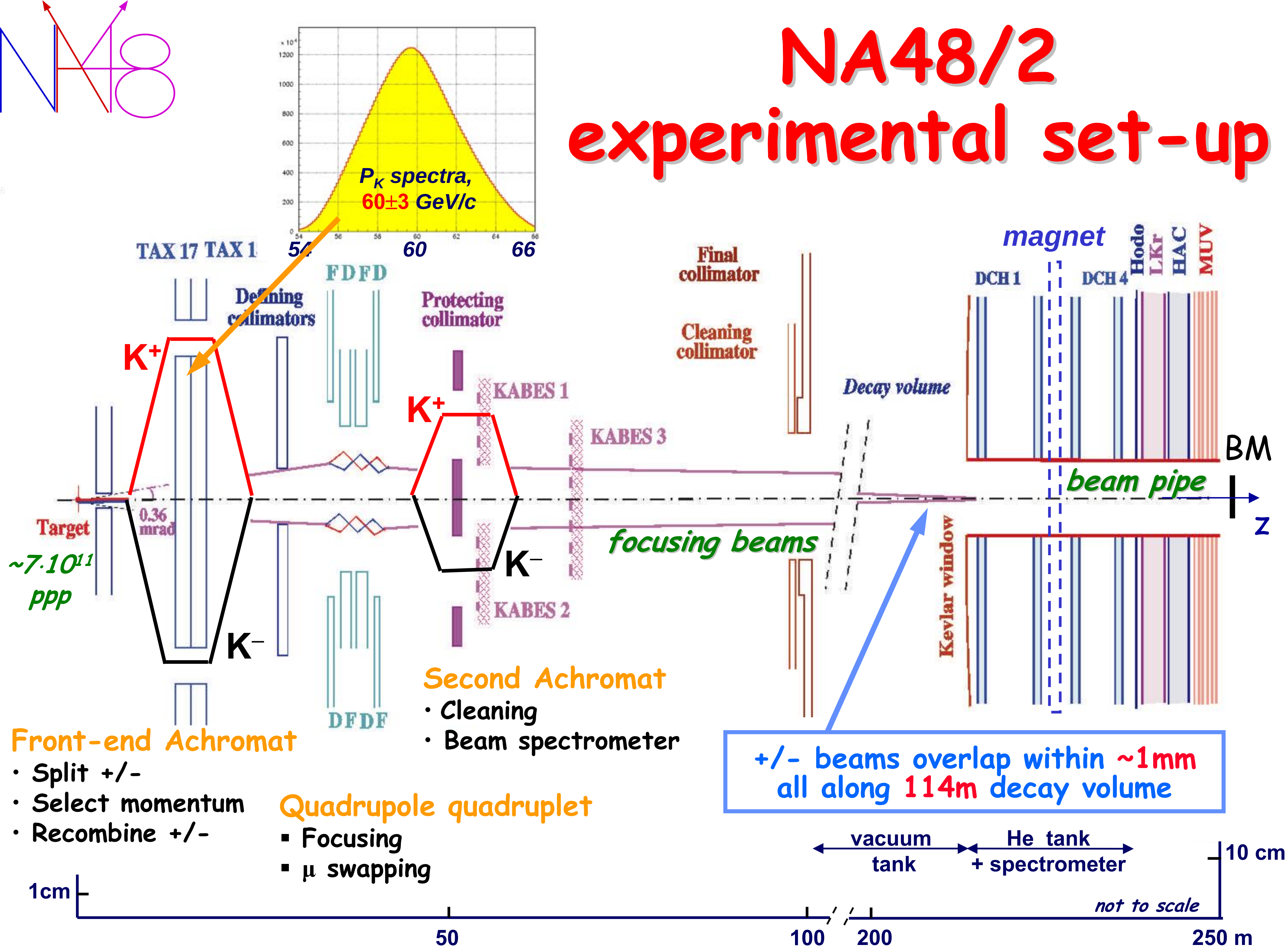
Primary NA48/2 goal:

- Measure slope asymmetries in "charged" and "neutral" modes with precisions $\delta A_g < 2.2\times10^{-4}$, and $\delta A_g^0 < 3.5\times10^{-4}$, respectively
- Statistics required for this measurement: $> 2\times10^9$ in "charged" mode and $> 10^8$ in "neutral" mode

NA48/2 method:

- Two simultaneous K^+ and K^- beams, superimposed in space, with narrow momentum spectra
- Detect asymmetry exclusively considering slopes of ratios of normalized u distributions
- Equalise K^+ and K^- acceptances by frequently alternating polarities of relevant magnets

NA48/2 experimental set-up



NA48/2 Data Taking

Data taking finished

2003 run: ~ 50 days

2004 run: ~ 60 days

Total statistics in 2 years:

$K^{\pm} \rightarrow \pi^{-}\pi^{+}\pi^{\pm}$: ~ 4×10^{9}

$K^{\pm} \rightarrow \pi^{0}\pi^{0}\pi^{\pm}$: ~ 2×10^{8}

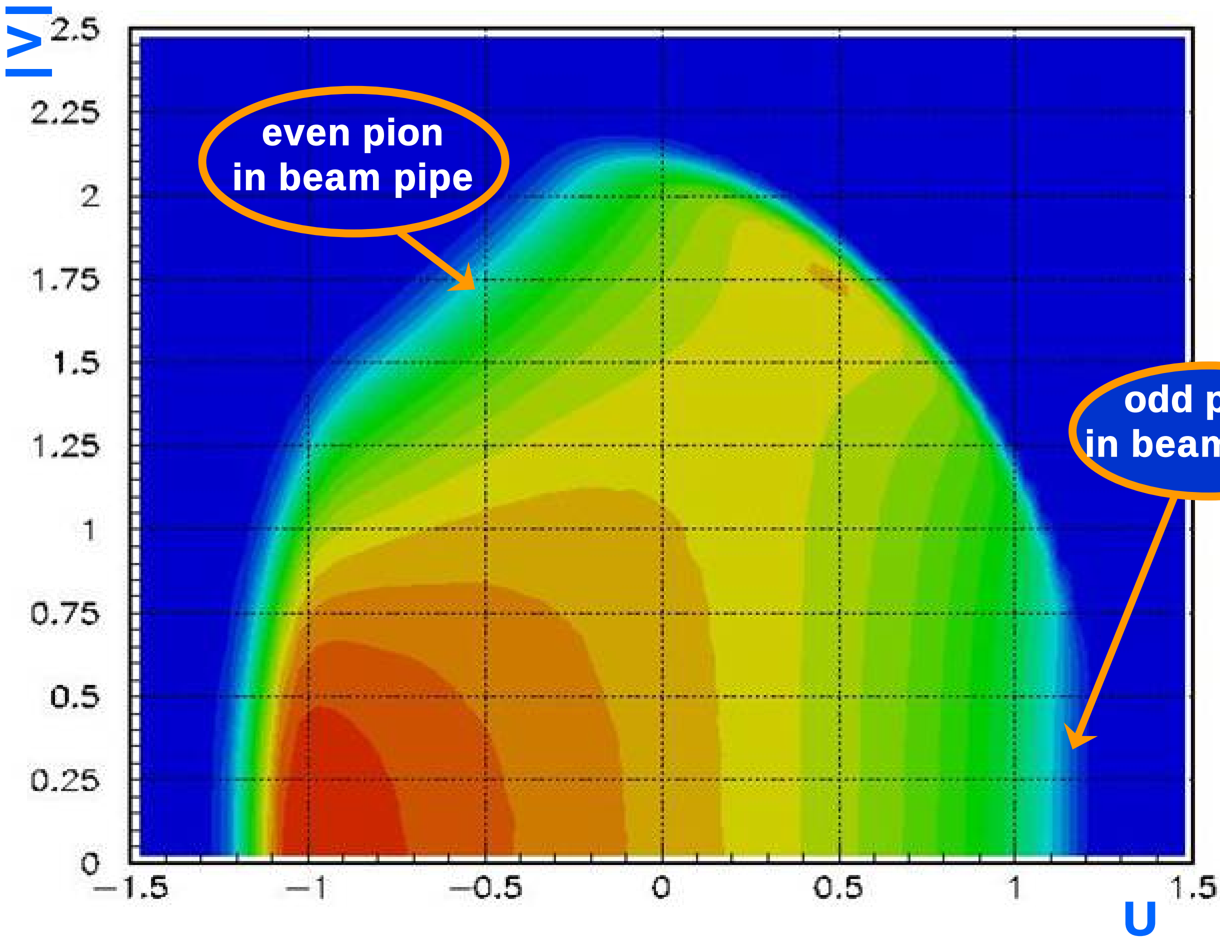
~ 200 TB of data recorded

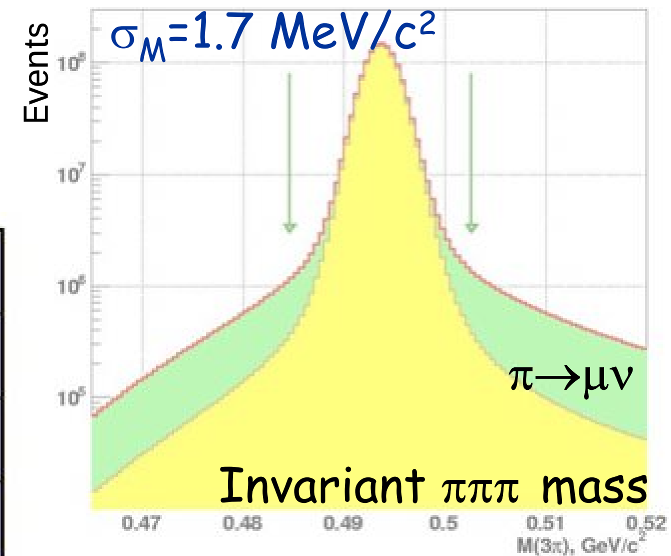
This presentation:
first result based on 2003 $K^{\pm} \rightarrow \pi^{\pm}\pi^{-}\pi^{+}$ sample

$K^{\pm}_{3\pi}$ statistics

Data taking 2003

1.61×10^{9} $K^{\pm} \rightarrow \pi^{\pm}\pi^{-}\pi^{+}$ events





Accepted statistics

K^{+} : 1.03×10^{9} events

K^{-} : 0.58×10^{9} events

$K^{+}/K^{-} \approx 1.8$

A_g measurement strategy - 1

- Use only the slopes of ratios of normalized u-distribution
  - Build u-distributions of K^+ and K^- events: $N^+(u)$, $N^-(u)$
  - Make a ratio of these distributions: $R(u)$
  - Fit a linear function to this ratio: normalised slope ≈ Δg

$$R(u) = \frac{N^+(u)}{N^-(u)} = \bar{R}\,\frac{1+g^+u}{1+g^-u} \approx \bar{R}(1+\Delta g u)$$

$$A_g = \frac{\Delta g}{2g}$$

⇒ e.g. uncertainty $\delta A_g < 2.2\cdot10^{-4}$ corresponds to $\delta\Delta g < 0.9\cdot10^{-4}$

- Compensate unavoidable detector asymmetry inverting periodically the polarity of the relevant magnets:
  - Every day: magnetic field B in the spectrometer (up/down: B+/B-)
  - Every week: magnetic field A of the achromat (up/down: A+/A-)

A_g measurement strategy - 2

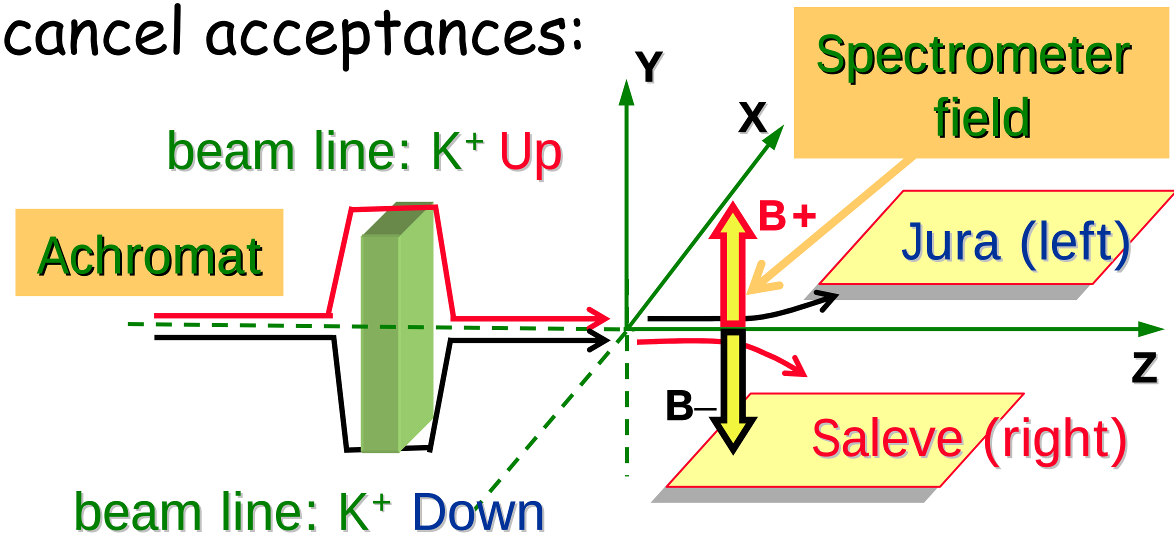
Four ratios are used to cancel acceptances:

$$R_{US} = \frac{N(A+B+K+)}{N(A+B-K-)}$$

$$R_{UJ} = \frac{N(A+B-K+)}{N(A+B+K-)}$$

$$R_{DS} = \frac{N(A-B+K+)}{N(A-B-K-)}$$

$$R_{DJ} = \frac{N(A-B-K+)}{N(A-B+K-)}$$



- beam line polarity (U/D)
- direction of kaon deviation in the spectrometer (S/J)

❖ "Supersample" data taking strategy:

- achromat polarity (A) was reversed on weekly basis
- spectrometer magnet polarity (B) was reversed on daily basis

⇨ 1 Supersample ~ 2 weeks ⇨ 2003 data: 4 Supersamples

A_g measurement strategy - 3

Quadruple ratio is used for further cancellation:

$$\mathbf{R} = R_{US} \times R_{UJ} \times R_{DS} \times R_{DJ} \sim 1 + 4 \times \Delta g \times u$$

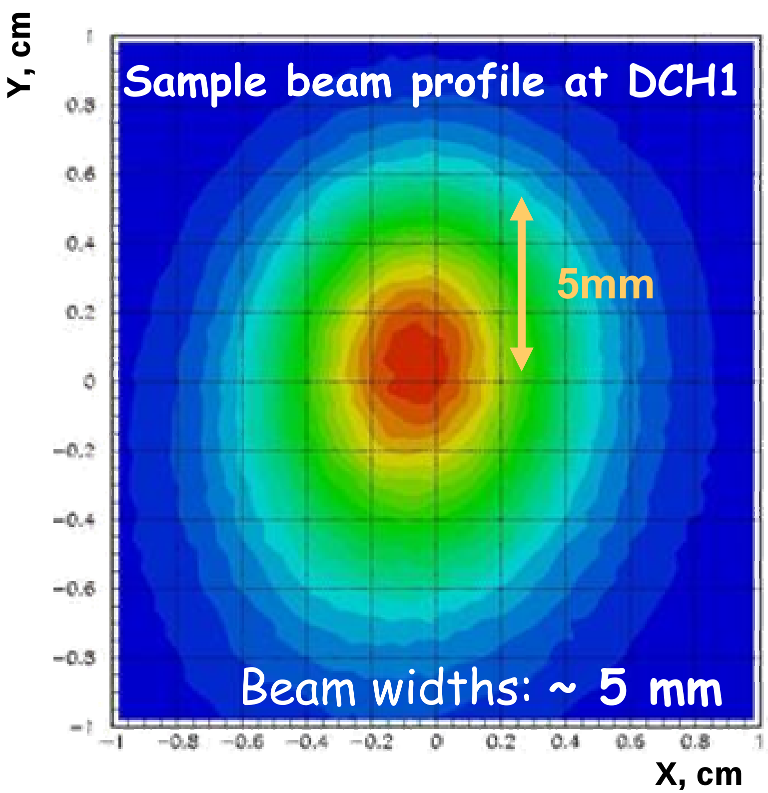
- Cancellation of systematic biases:
  1) Beam rate effects: global time-variable biases (K^+ and K^- simultaneously recorded)
  2) Beam geometry difference effects: beam line biases (K^+ beam up / K^- beam up etc)
  3) Detector asymmetries effects (K^+ and K^- illuminating the same detector region)

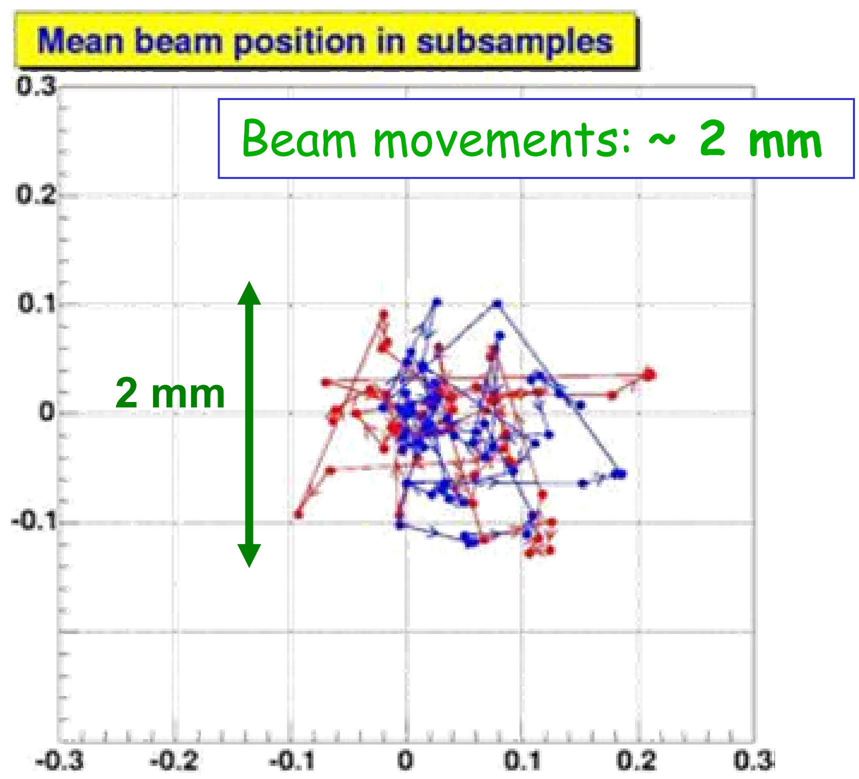
- Acceptance is defined respecting azimuthal symmetry:
  4) Effects of permanent stray fields (earth, vacuum tank magnetisation) cancels

The result is sensitive only to <u>time variation</u> of asymmetries in experimental conditions (beam+detector) with a characteristic time smaller than the corresponding field-alternation period (e.g. the supersample time scale: beam-week, detector-day)

Beam systematics

- **Time variations of beam geometry**
  - Acceptance largely defined by central beam hole edge (R~10 cm)
  - Acceptance cut defined by a (larger) **"virtual pipe"** - centered on averaged beam positions - as a function of charge, time and K momentum



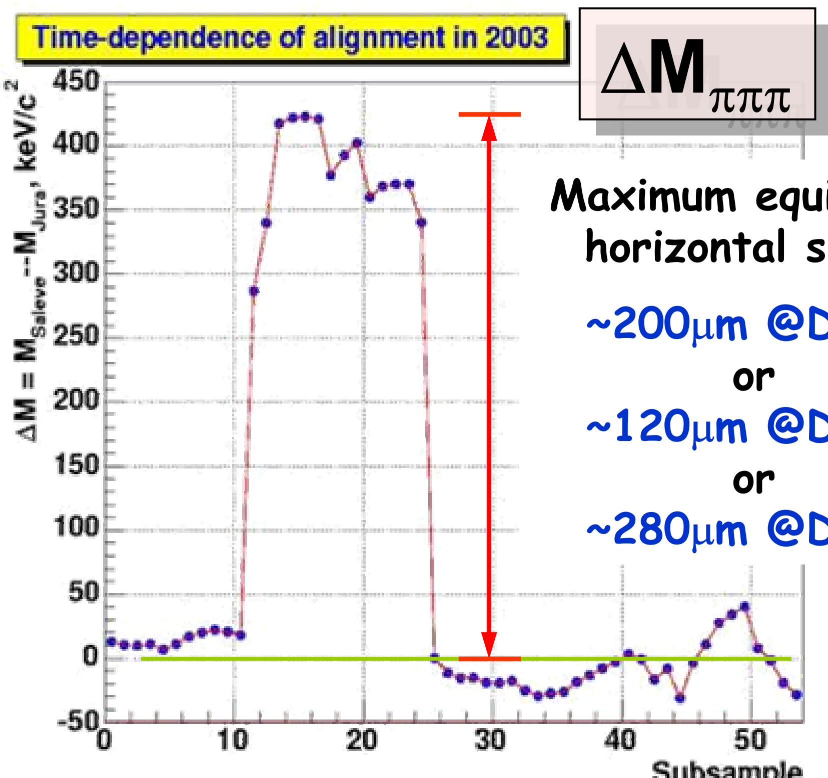


Spectrometer systematics

❖ Time variations of spectrometer geometry

➢ DCH drifts by O(100μm) in a 3 month run: asymmetry in p measurement

➢ alignment is fine tuned by forcing the average value of the reconstructed invariant 3π masses to be equal for K^+ and K^-



Maximum equivalent horizontal shift:

~200μm @DCH1
or
~120μm @DCH2
or
~280μm @DCH4

❖ Momentum scale

➢ due to variations of the magnet current (10^{-3})

➢ sensitivity to a 10^{-3} error on field integral: $\Delta M \approx 100$ keV

➢ mostly cancels due to simultaneous beams

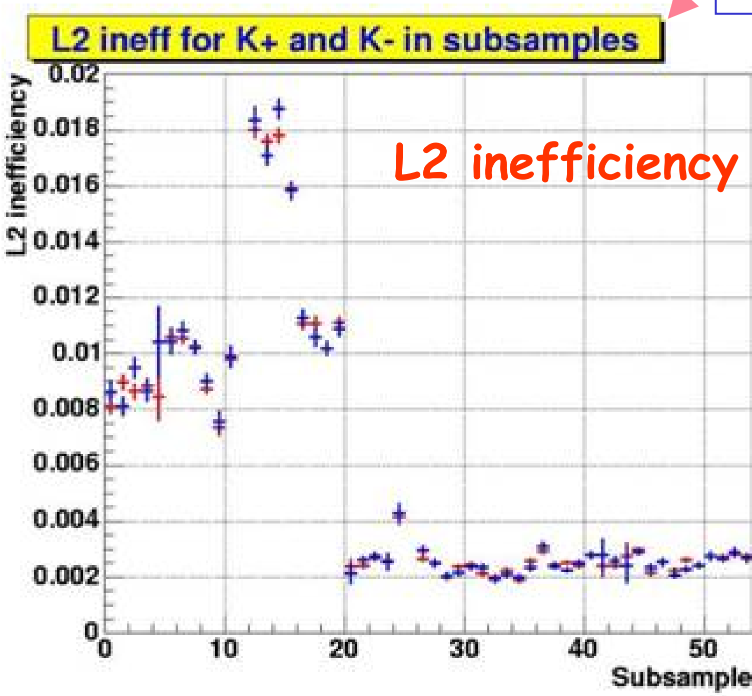
➢ in addition, it is adjusted by forcing the average value of reconstructed invariant 3π masses to the PDG value of M_{K+}

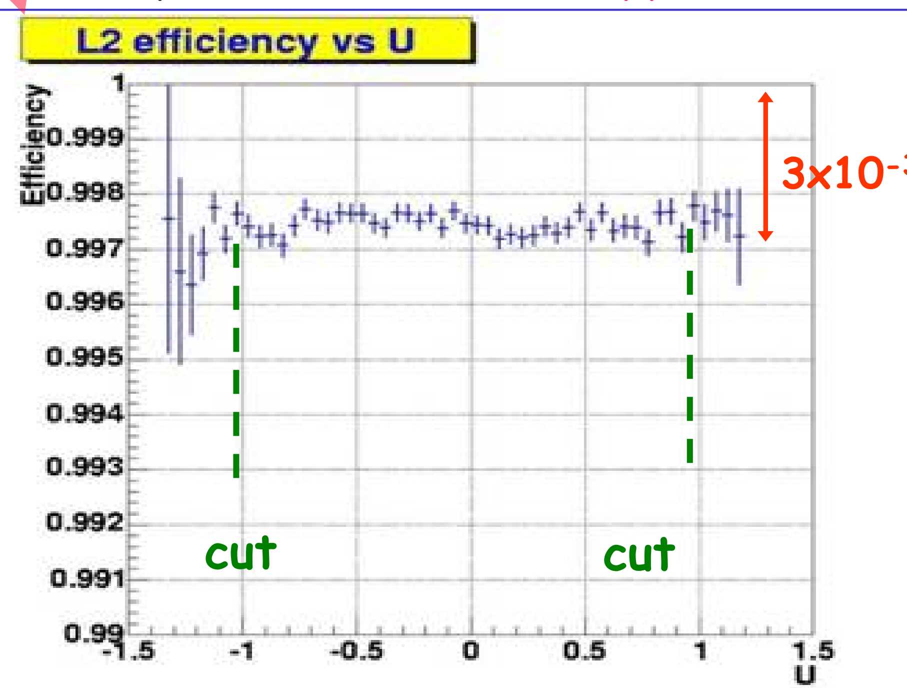
Trigger systematics

- **Measure inefficiencies using control data from low bias triggers**
- **Assume rate-dependent trigger inefficiencies symmetric**

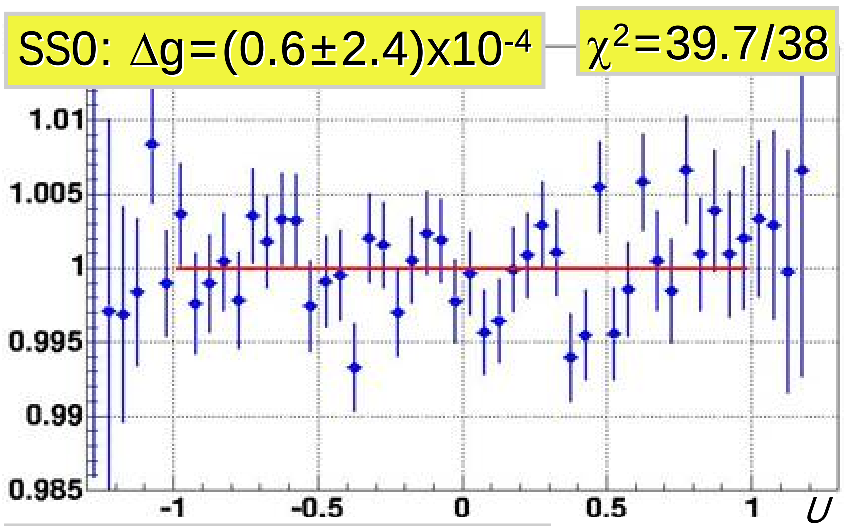
L1 trigger (2 hodoscope hits)
stable and small inefficiency
($\approx 0.7 \cdot 10^{-3}$): no correction

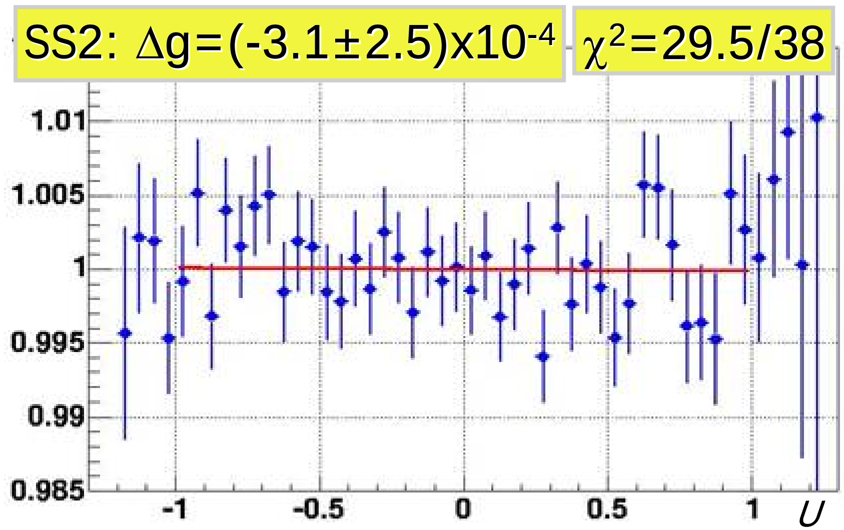
L2 trigger (online vertex reconstruction):
time-varying inefficienciy ($\approx$ 0.2% to 1.8%)
flat in u within measurement precision:
u-dependent correction applied

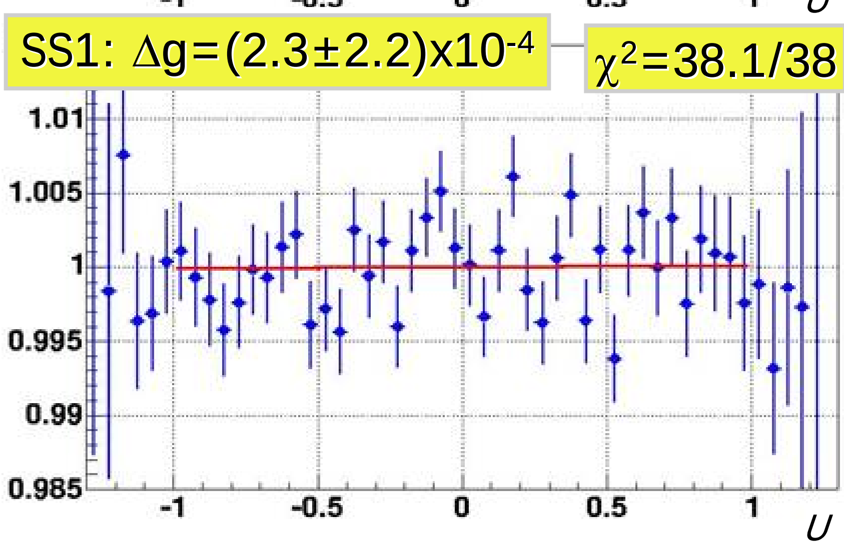


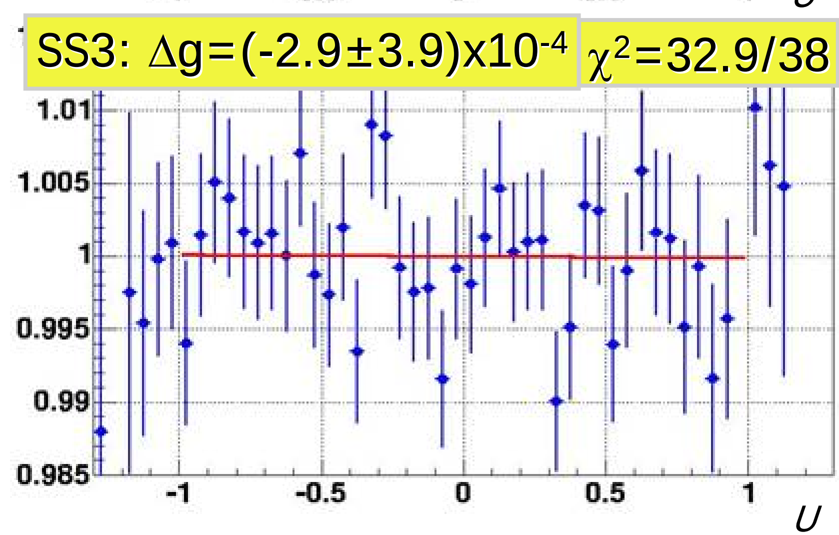


Fit linearity: 4 Supersamples









Systematics summary and results

Combined result
in $\Delta g \times 10^4$ units
(3 independent analyses)

	Raw	Corrected for L2 eff
SS0	0.0±1.5	0.5±2.4
SS1	0.9±2.0	2.2±2.2
SS2	-2.8±2.2	-3.0±2.5
SS3	2.0±3.4	-2.6±3.9
Total	**-0.2±1.0**	**-0.2±1.3**
χ^2	2.2/3	3.2/3

L2 trigger correction included

Conservative estimation of systematic uncertainties	Effect on $\Delta g \times 10^4$
Acceptance and beam geometry	0.5
Spectrometer alignment	0.1
Analyzing magnet field	0.1
$\pi^\pm \to \mu\nu$ decay	0.4
U calculation and fitting	0.5
Pile-up	0.3
Systematic errors of statistical nature	
Trigger efficiency: L2	0.8
Trigger efficiency: L1	0.4
Total systematic error	**1.3**

Stability of the result

$\Delta g = (-0.2 \pm 1.0_{stat.} \pm 0.9_{stat.(trig.)} \pm 0.9_{syst.}) \times 10^{-4}$

$\Delta g = (-0.2 \pm 1.7) \times 10^{-4}$

Quadruple ratio with

K(+)/K(-)

K(right)/K(left)

K(up)/K(down)

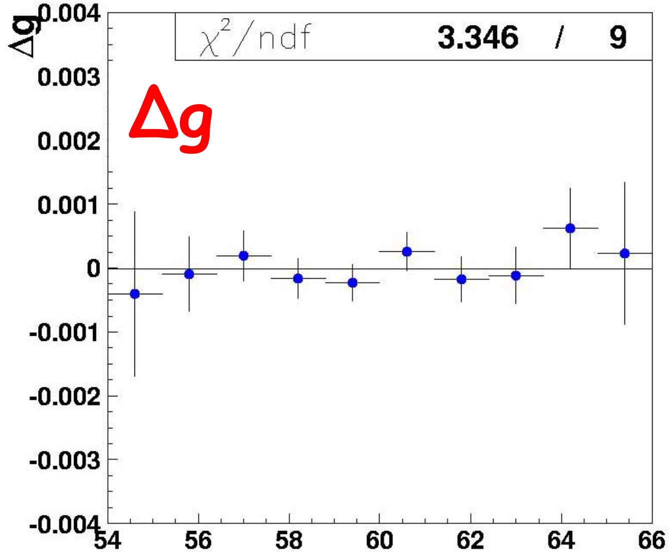
Δg

4 supersamples give consistent results

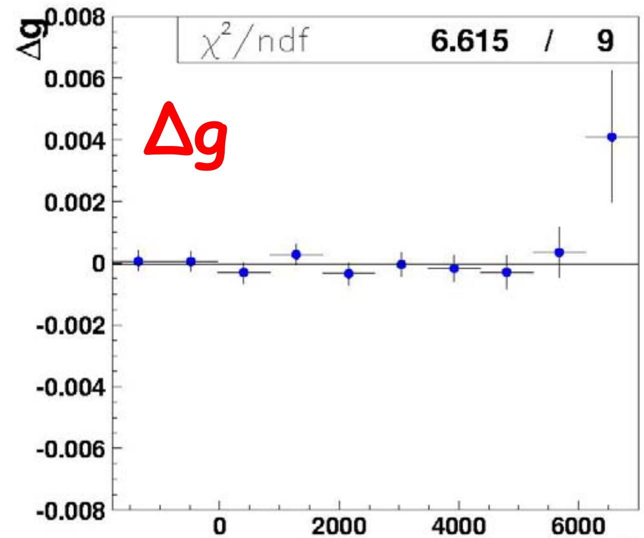
control of detector asymmetry

control of beam line asymmetry

MC reproduces these apparatus asymmetries



E_K (GeV)

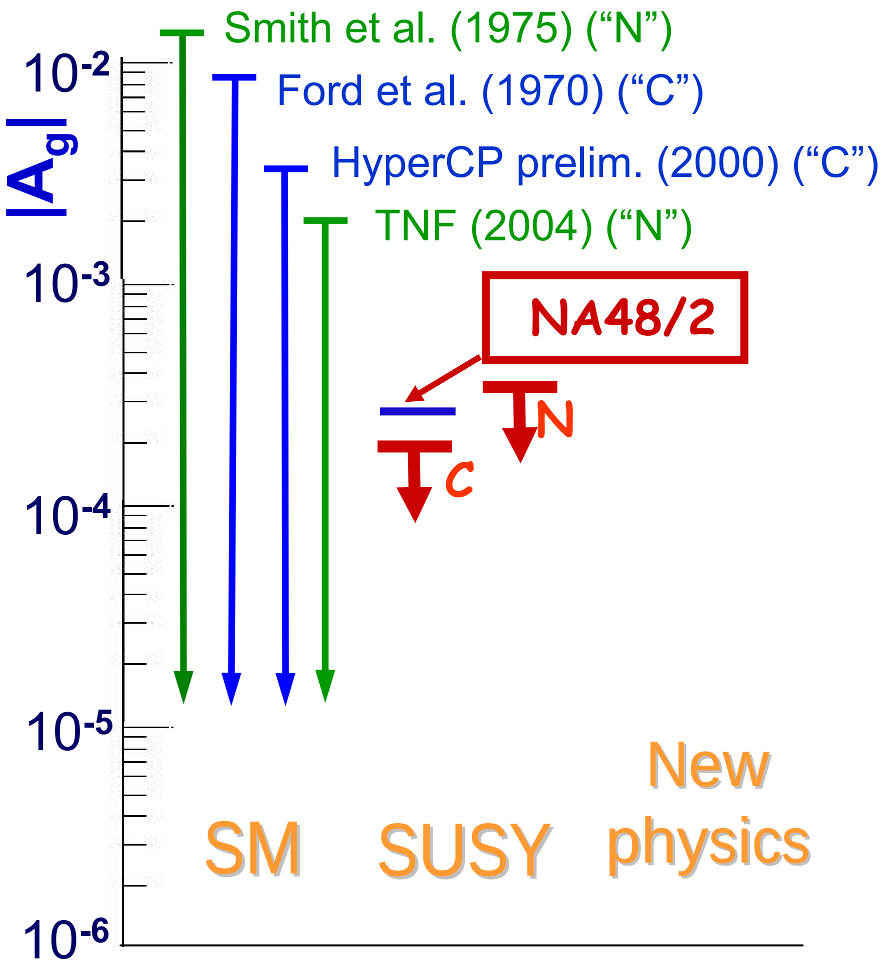


z_{vertex} (cm)

Preliminary result on A_g

$$A_g = (0.5 \pm 2.4_{stat.} \pm 2.1_{stat.(trig.)} \pm 2.1_{syst.}) \times 10^{-4}$$

$$A_g = (0.5 \pm 3.8) \times 10^{-4}$$ NA48/2 - 2003 data



- This is a preliminary result, with conservative estimate of the systematic errors
- The extrapolated statistical error 2003+04 is $\delta A_g = 1.6 \times 10^{-4}$
- 2004 data: expected smaller systematic effects (more frequent polarity inversion, better beam steering)

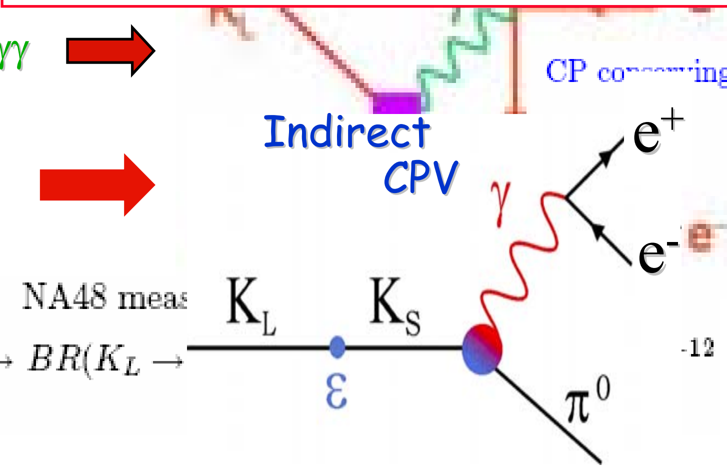
Search for $K_S \to \pi^0 e^+ e^-$

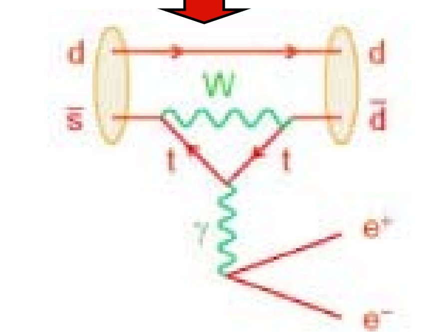
Motivation: determination of the indirect CP violating amplitude of the decay $K_L \to \pi^0 e^+ e^-$

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

$$|A_2 + A_3|^2 \to BR \cdot 10^{12} = 15.3 (a_s)^2 - 6.8\,(a_s)\{10^4\,\mathrm{Im}(\lambda_t)\} + 2.8\{10^4\,\mathrm{Im}(\lambda_t)\}^2$$

- $BR(SM) = 3\text{-}10 \times 10^{-12}$, $BR(\gamma\gamma e^+e^-) \approx 6 \times 10^{-7}$
- 3 contribution to this decay (χPT):
  - A_1(CPC): not predicted, derived from $K_L \to \pi^0 \gamma\gamma$ ($K_2 \to \pi^0 \gamma^* \gamma^* \to \pi^0 e^+ e^-$, NA48, KTeV)
  - A_2(CPV_{Ind}): not predicted, measured by $K_S \to \pi^0 e^+ e^-$ (NA48/1)
  - A_3(CPV_{Dir}): predicted in terms of CKM phase (electroweak penguins and W boxes with top





direct CP violating

Proportional to η or $\mathcal{I}m(\lambda_t)$

$$\mathcal{I}m(\lambda_t) = \eta A^2 \lambda^5 \qquad \lambda_t = V_{ts}^* V_{td}$$

$$\to BR(K_L \to \pi^0 e^+ e^-)_{dir} \sim few \times 10^{-12}$$

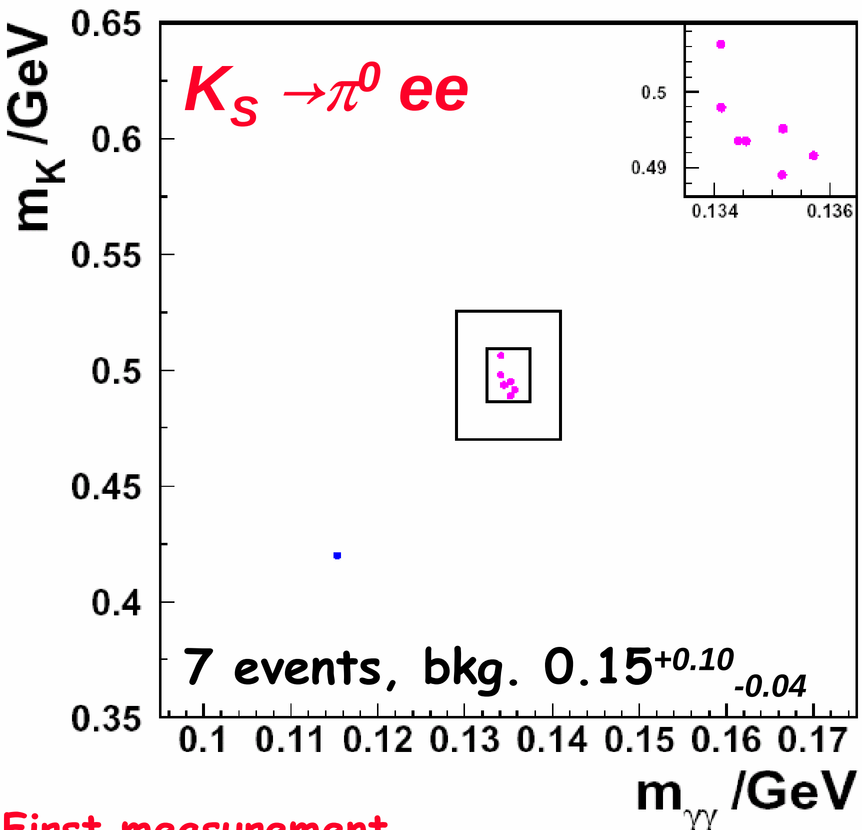
KTeV limits (90%CL)

$BR(\pi^0 ee)$ $< 2.8 \times 10^{-10}$

$BR(\pi^0 \mu\mu)$ $< 3.8 \times 10^{-10}$

NA48/1: $K^0_S \to \pi^0 l^+ l^-$

Main motivation for the NA48/1 proposal

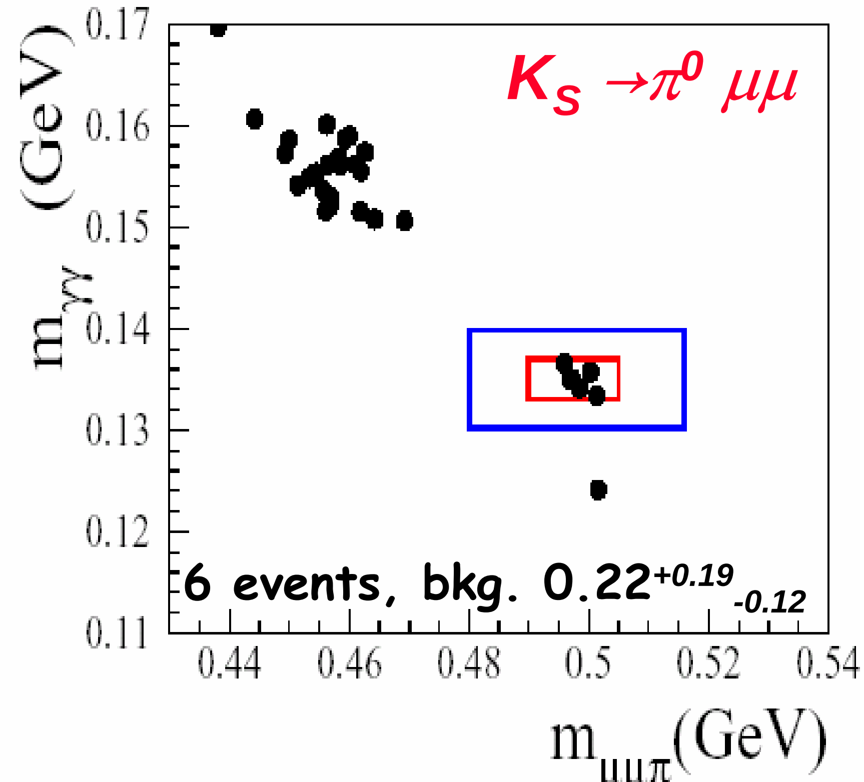


First measurement

$BR(\pi^0 ee) = 5.8\ ^{+2.8}_{-2.3}(stat) \pm 0.8(syst) \times 10^{-9}$

$|a_s|=1.06^{+0.26}_{-0.21}\ (stat) \pm 0.07\ (syst)$

PLB 576 (2003)



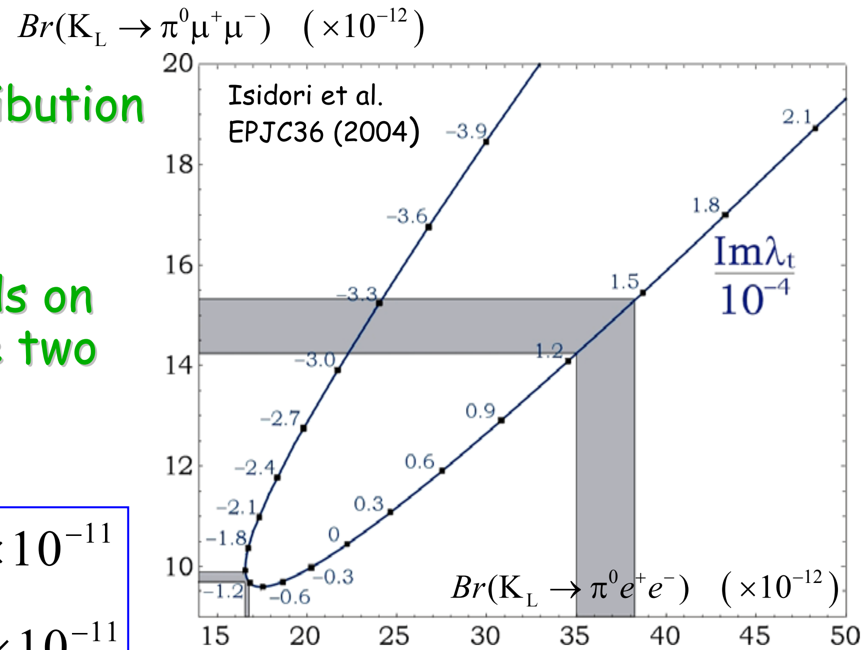
First measurement

$BR(\pi^0 \mu\mu) = 2.9\ ^{+1.4}_{-1.2}(stat) \pm 0.2(syst) \times 10^{-9}$

$|a_s|=1.55^{+0.38}_{-0.32}\ (stat) \pm 0.05\ (syst)$

PLB 599 (2004)

SM prediction for $K^0_L \to \pi^0 l^+ l^-$



- From K_L measurement: small CPC contribution
- From K_S measurement: indirect CPV contribution dominates
- Sensitivity of BR to CKM phase depends on the (unmeasurable) relative sign of the two CPV terms

Constructive	Destructive
$B_{K^0_L \to \pi^0 e^+ e^-} = 3.7^{+1.1}_{-0.9} \times 10^{-11}$	$B_{K^0_L \to \pi^0 e^+ e^-} = 1.7^{+0.7}_{-0.6} \times 10^{-11}$
$B_{K^0_L \to \pi^0 \mu^+ \mu^-} = 1.5^{+0.3}_{-0.3} \times 10^{-11}$	$B_{K^0_L \to \pi^0 \mu^+ \mu^-} = 1.0^{+0.2}_{-0.2} \times 10^{-11}$

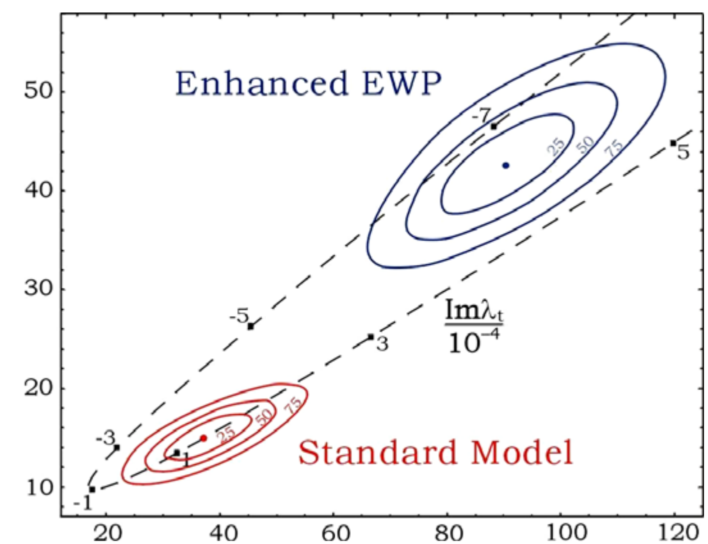
  - *Theory: constructive interference favored* *

- Sensitivity to new physics: enhanced electroweak penguins would enhance the BR

J. Buras et al.
hep-ph/0402112
NP B697 (2004)

$$B^{NP}_{K^0_L \to \pi^0 e^+ e^-} = 9.0^{+1.6}_{-1.6} \times 10^{-11}$$

$$B^{NP}_{K^0_L \to \pi^0 \mu^+ \mu^-} = 4.3^{+0.7}_{-0.7} \times 10^{-11}$$



* Two indeopendent analysis:
G. Buchalla, G. D'Ambrosio, G. Isidori, Nucl.Phys.B672,387 (2003) - S. Friot, D. Greynat, E. de Rafael, hep-ph/0404136, PL B 595

Prospects and conclusions

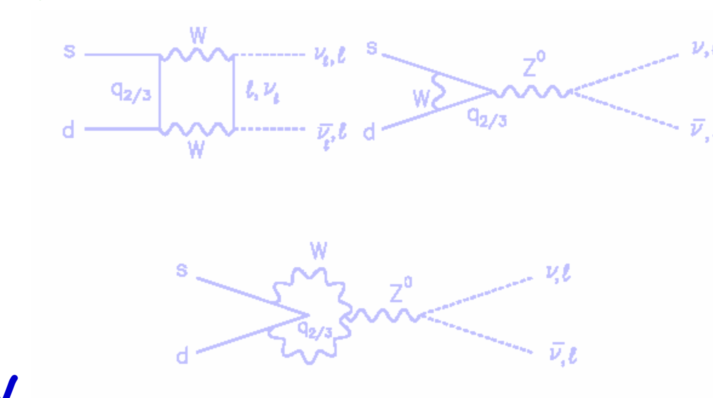
- Kaon was central in the definition of SM
- Quantitative tests of CKM mechanism and search for new physics beyond SM are possible with rare Kaon decay mesurements
- High level of precision is attainable
- Constraints to CKM variables and further test of CPV from FCNC processes ("golden decays"):
  - $K_L \to \pi^0 e^+ e^-$ decays
  - $K \to \pi \bar{\nu}\nu$ decays

SPARE

The “golden” $K \rightarrow \pi \bar{l} l$ decays

Motivation

- FCNC processes, no tree level, proceed via loop diagrams
- access to quark level physics with small theoretical uncertanties:
  - dominant short distance contributions
  - long distance only for charged lepton modes
  - matrix elements of quark operators related to K_{e3} decays
  - CPV K_L decays
- Charged leptons final states: easier lepton identification but high levels of radiative background
- Best change: $K \rightarrow \pi\nu\bar{\nu}$ decays:
  - no long distance contributions
  - clean theoretical predictions
  - no radiative background
  - K_L decay dominated by direct CPV



Why Kaon again?

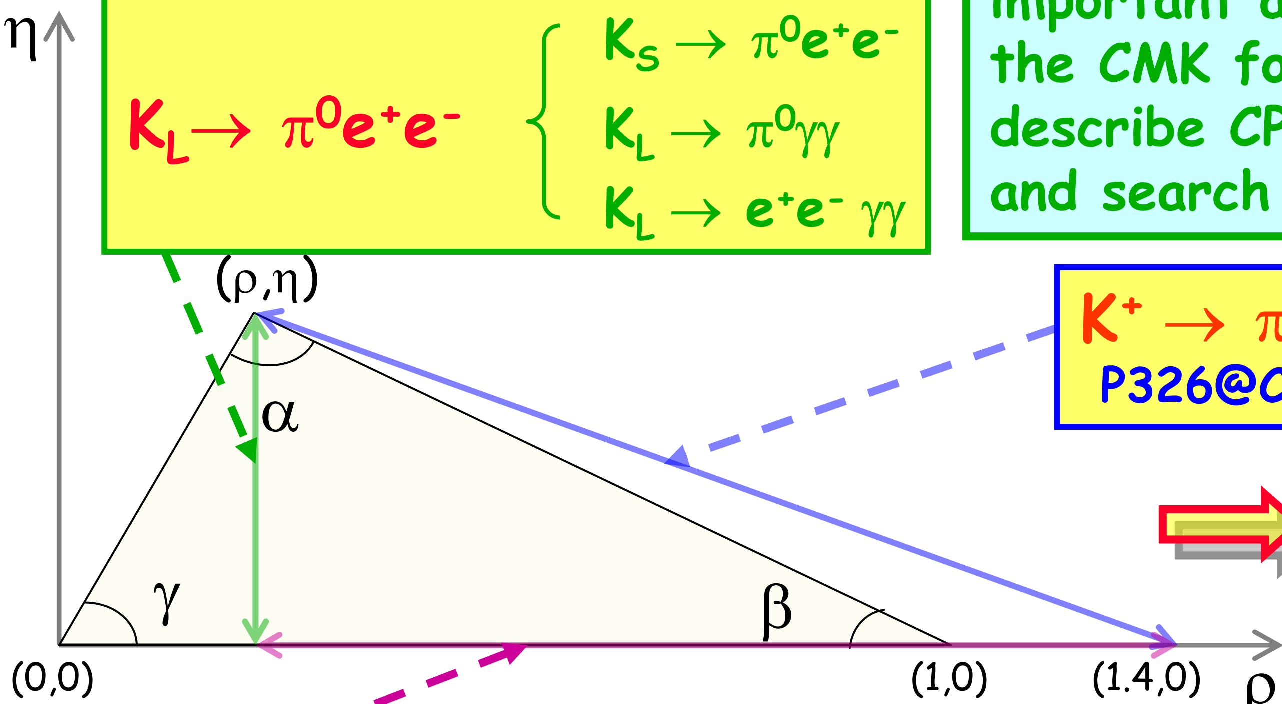
Unitarity Triangle: $V_{ud} V^*_{ub} + V_{cd} V^*_{cb} + V_{td} V^*_{tb} = 0$

$K_L \rightarrow \pi^0 \nu \bar{\nu}$ KOPIO@BNL

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

ρ and η precise measurements: important as precision test of the CMK formalism - used to describe CP and quark mixing - and search for new physics

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$
P326@CERN



$K_L \rightarrow \mu^+ \mu^-$
- $K_L \rightarrow \gamma\gamma$ $K_L \rightarrow e^+ e^- \gamma$
- $K_L \rightarrow e^+ e^- e^+ e^-$ $K_L \rightarrow e^+ e^- \mu^+ \mu^-$

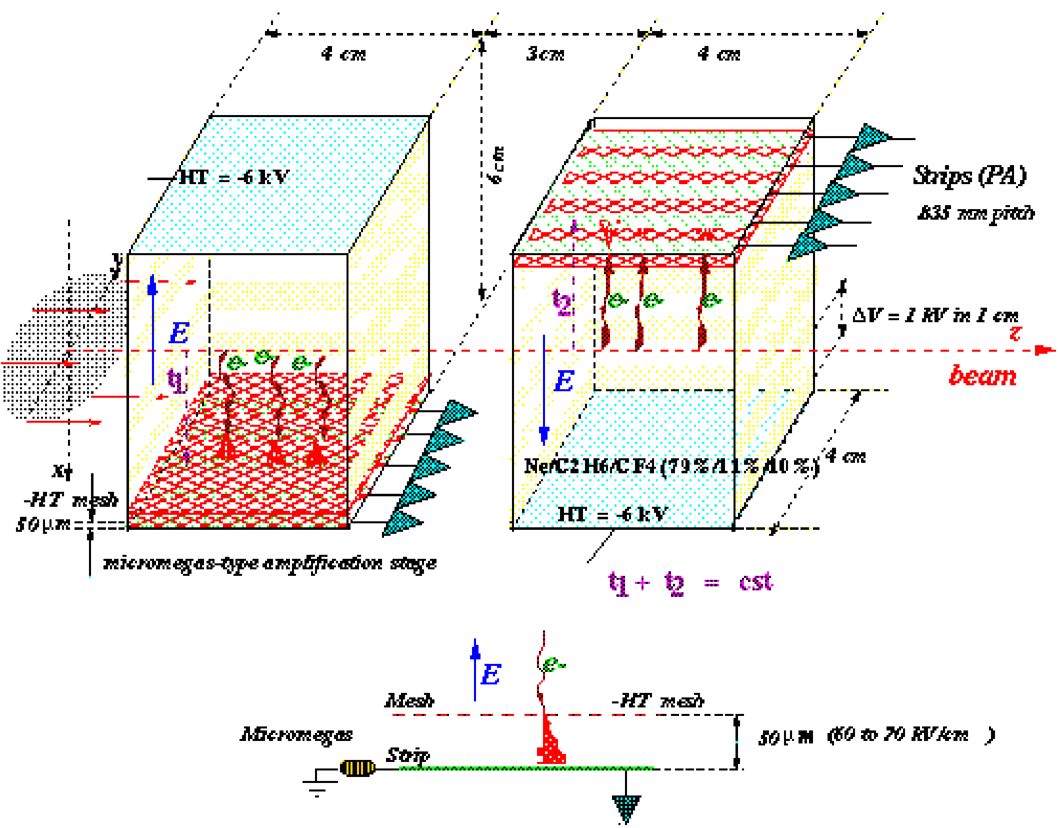
The study of K mesons allows quantitative tests of the SM independent and complementary to B physics

Experimental prospects

- $K^0_L \rightarrow \pi^0 \nu\nu$
  - Large window of opportunity exists.
  - Upper limit is 4 order of magnitude from the SM prediction
  - Expect results from data collected by E391a (proposed SES~3 10^{-10})
  - Next experiment KOPIO@BNL
  - Future: JPARC and KLOD@IHEP
- $K^0_L \rightarrow \pi^0 ee(\mu\mu)$
  - Long distance contributions under better control
  - Measurement of K_S modes has allowed SM prediction
  - K_S rates to be better measured (KLOE?)
  - Background limited (study time dep. Interference?)
  - 100-fold increase in kaon flux to be envisaged
- $K^+ \rightarrow \pi^+ \nu\nu$
  - The situation is different: 3 clean events are published
  - Experiment in agreement with SM
  - Next round of exp. need to collect O(100) events to be useful: P326 at CERN
  - Move from stopped to in flight experiments

KAon BEam Spectrometer (KABES)

Micromegas Time Projection Chambers



3 MICROMEGA gas chamber stations

measure beam particle

- charge (prob. mis-ID~10^{-2});
- momentum ($\delta p/p=0.7\%$);
- position in the 2nd achromat ($\delta x,y \approx 100\mu m$).

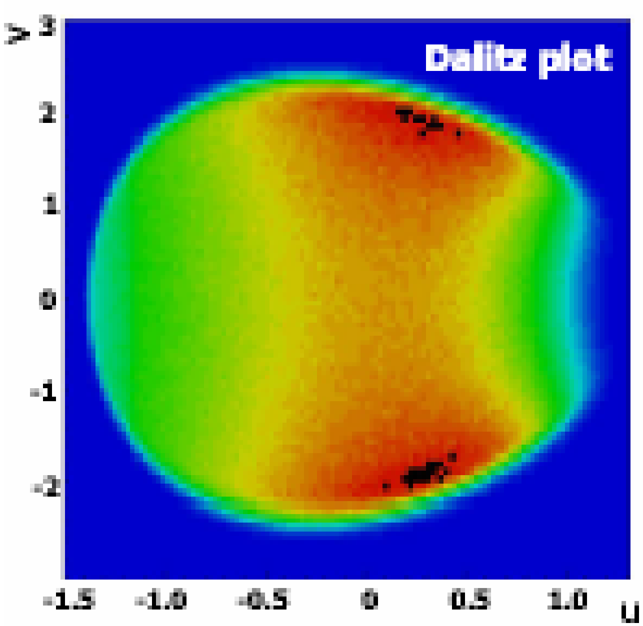
Measurement of kaon momentum:

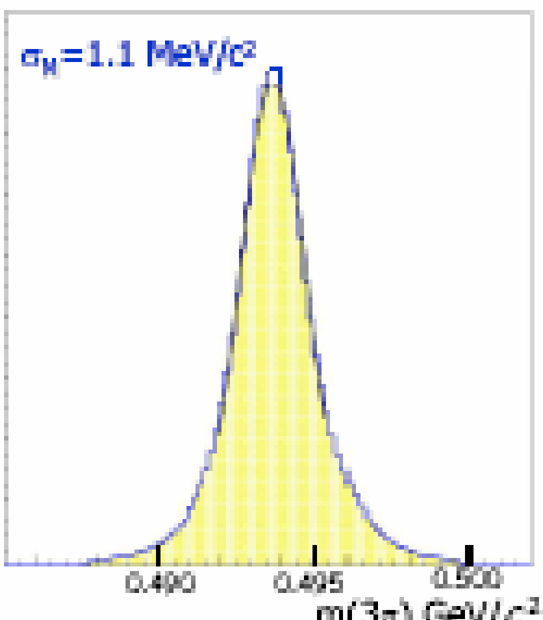
- Reconstruct $K_{3\pi}$ with a lost pion;
- Redundancy in $K_{3\pi}$ analysis;
- Resolve K_{e4} reconstruction ambiguity.

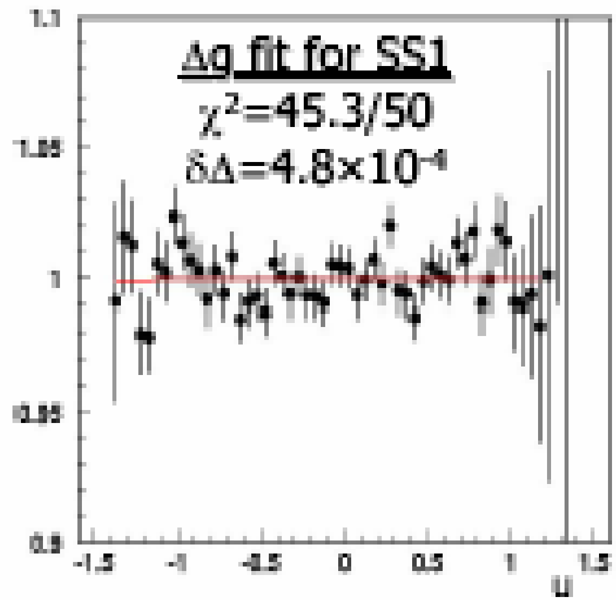
Not used yet for $K^\pm \to 3\pi^\pm$ analysis

Neutral mode asymmetry
$K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$

- Statistics analyzed: 28×10^{6} events (1 month of 2003)
- Statistical error with analyzed data: $\delta A_g = 2.2 \times 10^{-4}$
- Extrapolation to 2003 + 2004 data: $\delta A_g = 1.3 \times 10^{-4}$
- Similar statistical precision as in "charged" mode
- Possibly larger systematics errors







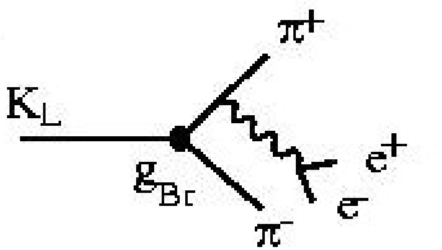
KLOE search for $K_S \to \pi^+\pi^-\pi^0$

- **Motivation:**
  - Present status:

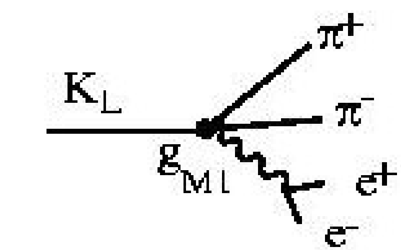
E621 (1996)	$4.8^{+2.2}_{-1.6}$(stat) ± 1.1(syst)	$\times 10^{-7}$
CPLEAR (1997)	$2.5^{+1.2}_{-1.0}$(stat)$^{+0.5}_{-0.6}$(syst)	$\times 10^{-7}$
PDG2004 (average)	$3.2^{+1.2}_{-1.0}$	$\times 10^{-7}$
χPT	2.4 ± 0.7	$\times 10^{-7}$

  - BR(CPC) ~ 3×10^{-7}, BR(CPV) ~ 1.2×10^{-9}
  - Direct measurement of CPC part possible with ultimate 2fb^{-1}
  - Measurement tests of prediction (untested) of χPT
- **Data sample: 740 pb-1**
  - 373 pb-1 (2001/2 data) + 367 (2004 data)
- **Assuming BR=3×10^{-7}:** ~230 signal events produced
- **Prospect with 2 fb^{-1}:**
  - **~16** events, of which **~9** background
  - **~60%** statistical accuracy on BR($K_S \to \pi^+\pi^-\pi^0$)
  - BR with accuracy below 50% : competitive with other measurements, and the only direct search

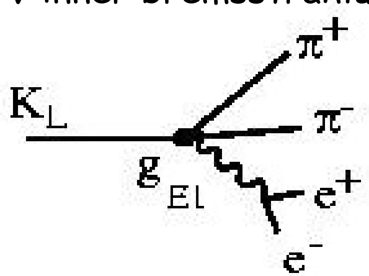
$K_{L,S} \to \pi^+\pi^-e^+e^-$: why?



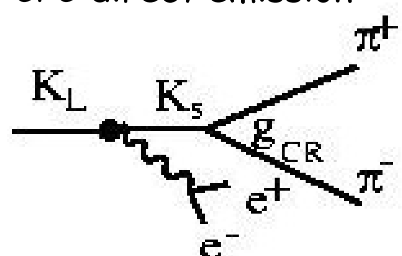
CPV inner bremsstrahlung



CPC direct emission



CPV direct emission



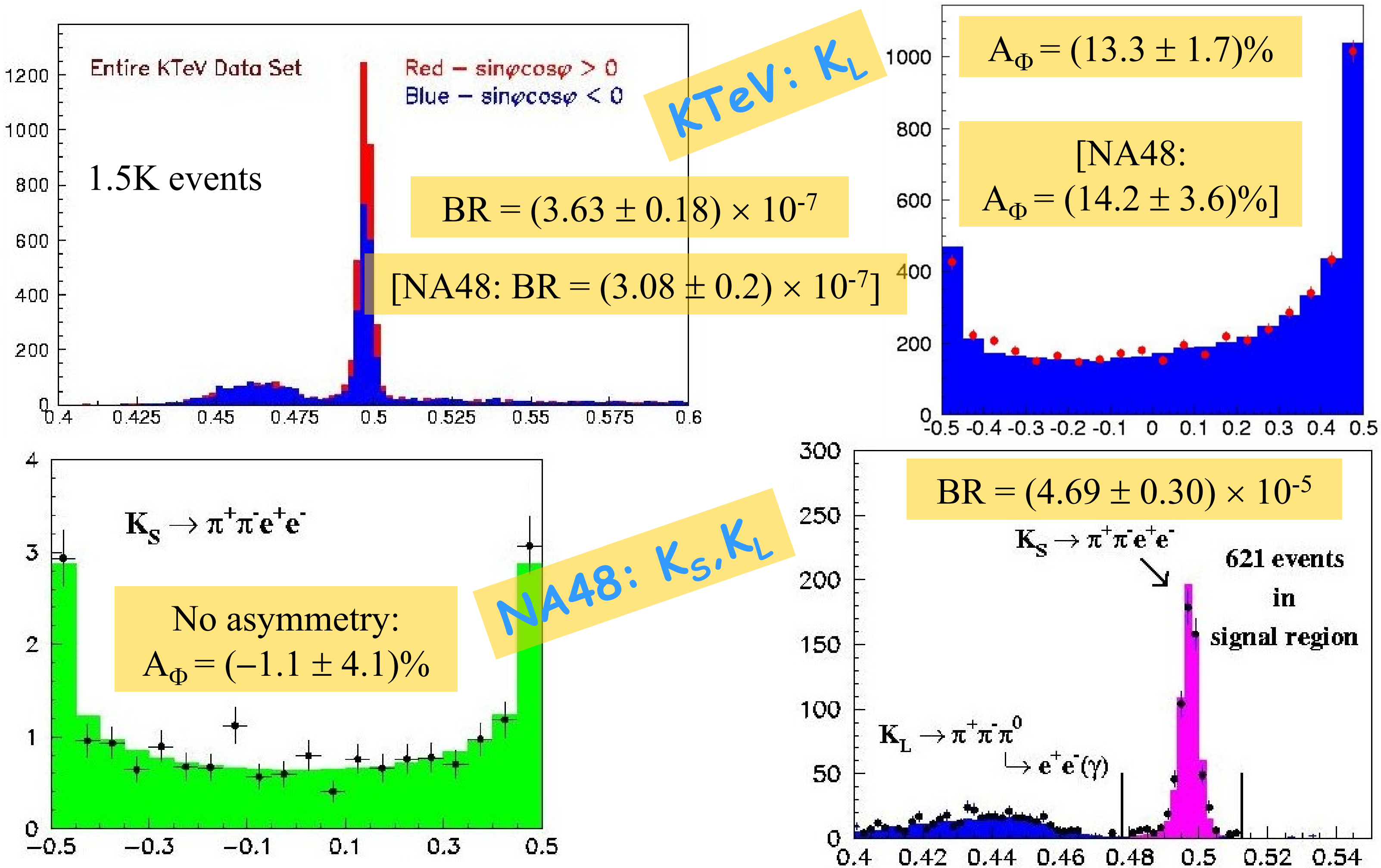
Charge radius

For K_L: interference gives indirect CP-violating asymmetry in the orientation of $\pi^+\pi^-$ and e^+e^- decay planes

Easier access to polarization asymmetry in $K \to \pi\pi\gamma$

Large ($\approx$ 14%) asymmetries predicted

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



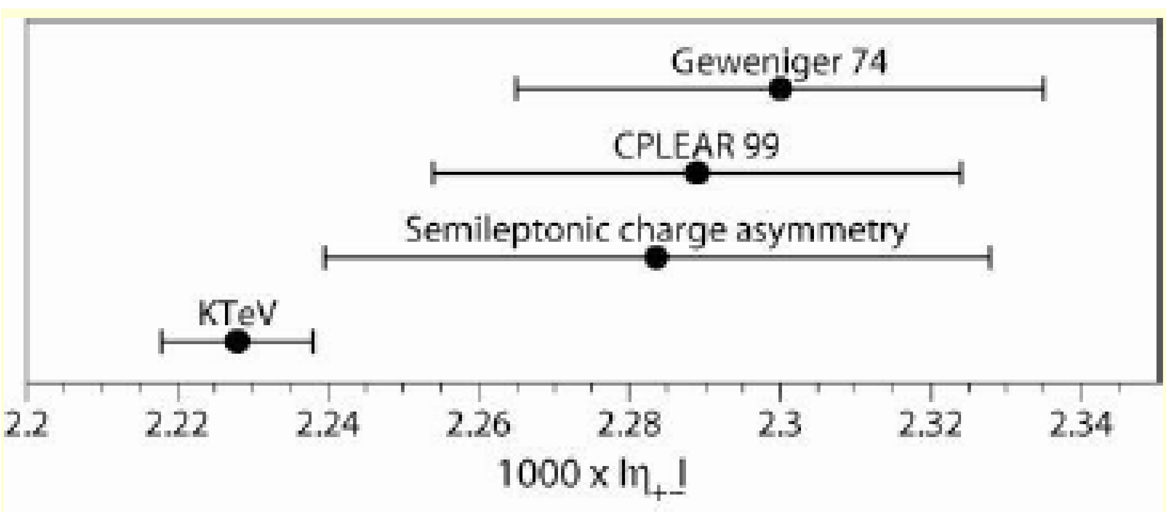
KTeV: $|\eta_{+-}|$ measurement

Direct CPV:

$$|\eta_{+-}|^2 = \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)} = \frac{\tau_S}{\tau_L} \frac{B^L_{\pi^+\pi^-} + B^L_{\pi^0\pi^0}\left[1 + 6\,\mathrm{Re}(\varepsilon'/\varepsilon)\right]}{1 - B^S_{\pi\ell\nu}}$$

Assuming $\Gamma(K_S \to \pi e \nu) = \Gamma(K_L \to \pi e \nu)$, the result is:

$$|\eta_{+-}| = (2.228 \pm 0.005_{KTeV} \pm 0.009_{\tau KL}) \times 10^{-3}$$



(hep-ex/0406002)

$\Rightarrow$ 2.7σ discrepancy with PDG average