Direct CP Violation measurements with the NA48 experiment: status and perspectives

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on behalf of the NA48 Collaboration

CAGLIARI, CAMBRIDGE, CERN, DUBNA, EDINBURGH, FERRARA, FIRENZE, MAINZ, ORSAY, PERUGIA, PISA, SACLAY, SIEGEN, TORINO, VIENNA, WARSAW

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CP Violation in K^0 system

Strangeness eigenstates

$K^0(\bar{s}d)$ S=+1 CP $(K^0) = \overline{K^0}$

$\overline{K^0}(s\bar{d})$ S=-1 CP $(\overline{K^0}) = K^0$

CP eigenstates

K_1 CP = +1 $\Rightarrow \pi\pi$

K_2 CP = -1 $\Rightarrow \pi\pi\pi$

$K_{1,2} = (K^0 \pm \overline{K^0}) / \sqrt{2}$

Mass eigenstates $\mathbf{K_S}$, $\mathbf{K_L}$

CP conserved: $\mathbf{K_S \equiv K_1}$ **&** $\mathbf{K_L \equiv K_2}$

$$\mathbf{K_S \div K_1 + \varepsilon K_2}$$

$$\mathbf{K_L \div K_2 + \varepsilon K_1}$$

$\pi\pi$ ← (K_2)

Direct CPV , ε'

$|A(K^0 \rightarrow F)| \neq |A(\overline{K^0} \rightarrow \bar{F})|$

(εK_1) →

1964: $K_L \rightarrow \pi\pi$

Christenson, Cronin, Fitch, Turlay

$\varepsilon = 2.3\text{x}10^{-3}$, indirect CPV

Observe direct CPV through the interference of final states $\pi\pi$ I=0,2

$$\epsilon' = \frac{i}{\sqrt{2}} \Im\left(\frac{A_2}{A_0}\right) \exp\left(i\left(\delta_2 - \delta_0\right)\right)$$

CP viol / CP cons

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

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

The double ratio R:

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

Direct CPV if $\varepsilon' \neq 0 \Rightarrow R \neq 1$

K_L

$\pi e \nu$ (K_{e3})	38.78 %	CPcons	Bkg
$3\pi^0$	21.13 %	CPcons	Bkg
$\pi \mu \nu$ ($K_{\mu 3}$)	17.18 %	CPcons	Bkg
$\pi^+\pi^-\pi^0$	12.55 %	CPcons	Bkg
$\pi^+\pi^-$	**0.206%**	**CPviol**	Signal 0.3% !!
$\pi^0\pi^0$	**0.09 %**	**CPviol**	Signal 0.3% !!

τ_L=5.2x10^{-8} s

K_S

$\pi^+\pi^-$	**68.61%**	**CPcons**
$\pi^0\pi^0$	**31.39%**	**CPcons**
$\pi^+\pi^-\gamma$	0.18%	CPcons
$3\pi^0$	<1.4x10^{-5} %	CPV

τ_S=0.9x10^{-10} s

$\tau_L \simeq 600 \times \tau_S$

@ 110GeV (NA48 energy range 70-170GeV)

$\lambda_L \simeq$ 3.4Km e $\lambda_S \simeq$ 6m

$$\mathbf{R} = \frac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)} \times \frac{\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^+\pi^-)} \simeq \mathbf{1 - 6Re(\varepsilon'/\varepsilon)}$$

- Concurrent $\pi^0\pi^0$ and $\pi^+\pi^-$ detection ⇒ fluxes cancel
- Concurrent K_L and K_S ⇒ detection and reconstruction inefficiency cancel

⇒ **Best cancelation if all 4 modes recorded simultaneously:**
fluxes, inefficiencies, dead times, accidental losses

- From the same fiducial region (lifetime ≤ 3.5 τ_S)
- Quasi-collinear beams (K_L , K_S)
- K_L , K_S similar energy spectra (energy range 70-170GeV) , analysis in energy bins to minimize remaining differencies
- Offline lifetime weighting applied to K_L events ⇒ equilize and K_L and K_S decay position distributions

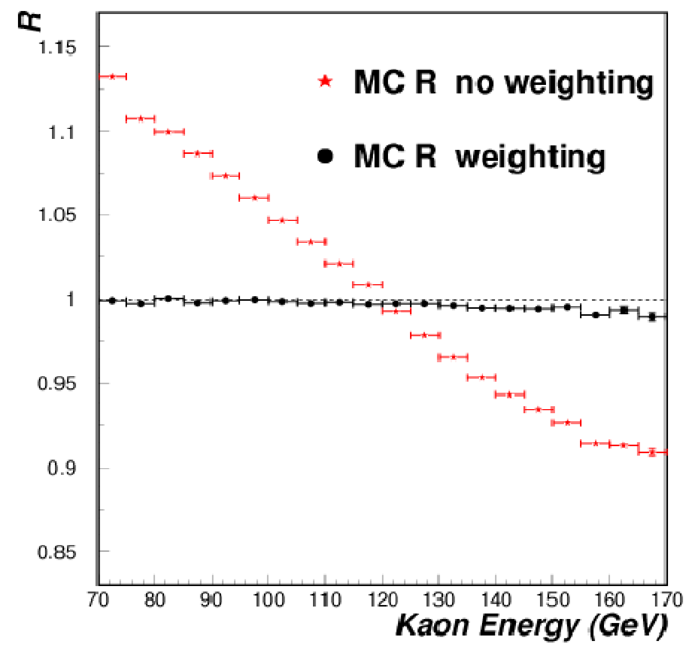
⇒ **Minimize acceptance correction**

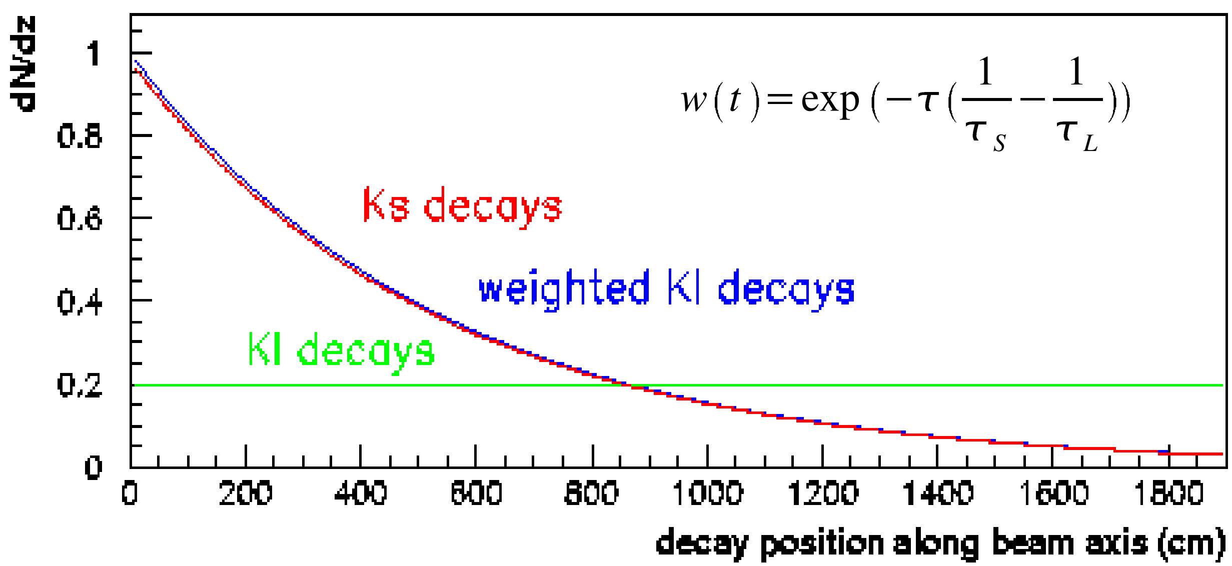
High resolution detectors ⇒ small background level

Bkg subtracted ⇒

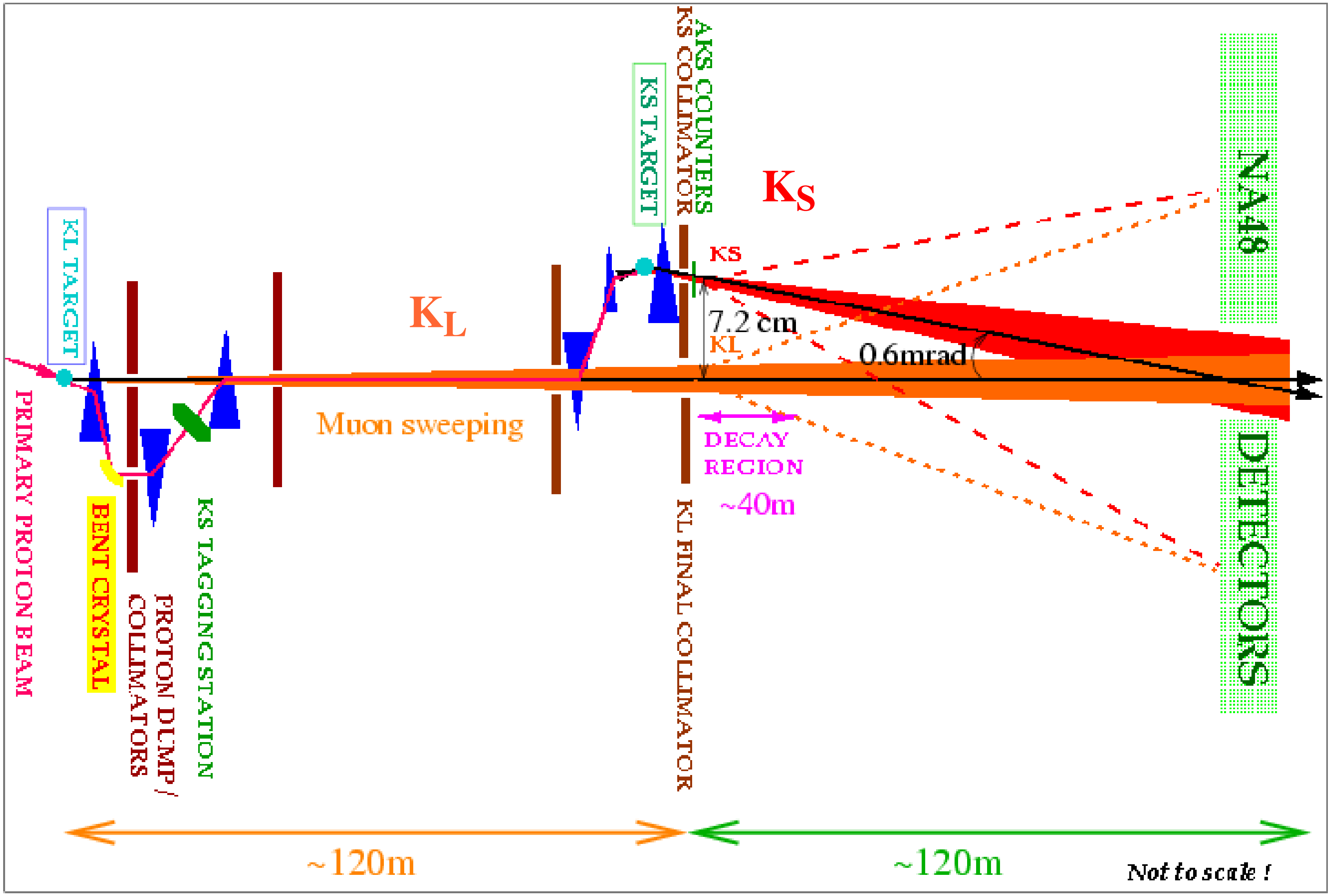
$$\frac{\mathbf{N(K_L \to \pi^0\pi^0)}}{\mathbf{N(K_S \to \pi^0\pi^0)}} \times \frac{\mathbf{N(K_S \to \pi^+\pi^-)}}{\mathbf{N(K_L \to \pi^+\pi^-)}}$$

K_L lifetime weighting





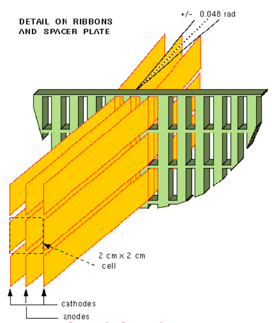
NA48 beams: far (K_L) and near (K_S)



NA48 Detector

Lkr e.m. Calorimeter

- Projective geom. toward decay region
- $\approx 10 m^3$ liquid Krypton, 125cm (27 X_0)
- high granularity (~13260 cells, 2x2cm^2)
- $\sigma_t \simeq 220$ps



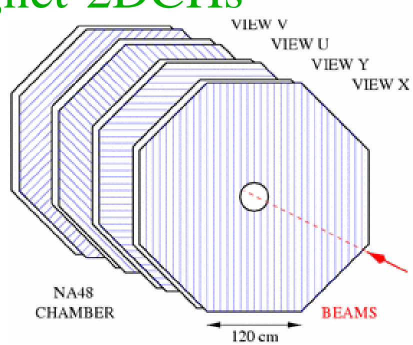
$\sigma(E)/E = 3.2\%/\sqrt{E} \oplus 0.09/E \oplus 0.42\%$ (E GeV)

<1% for E_γ> 25GeV

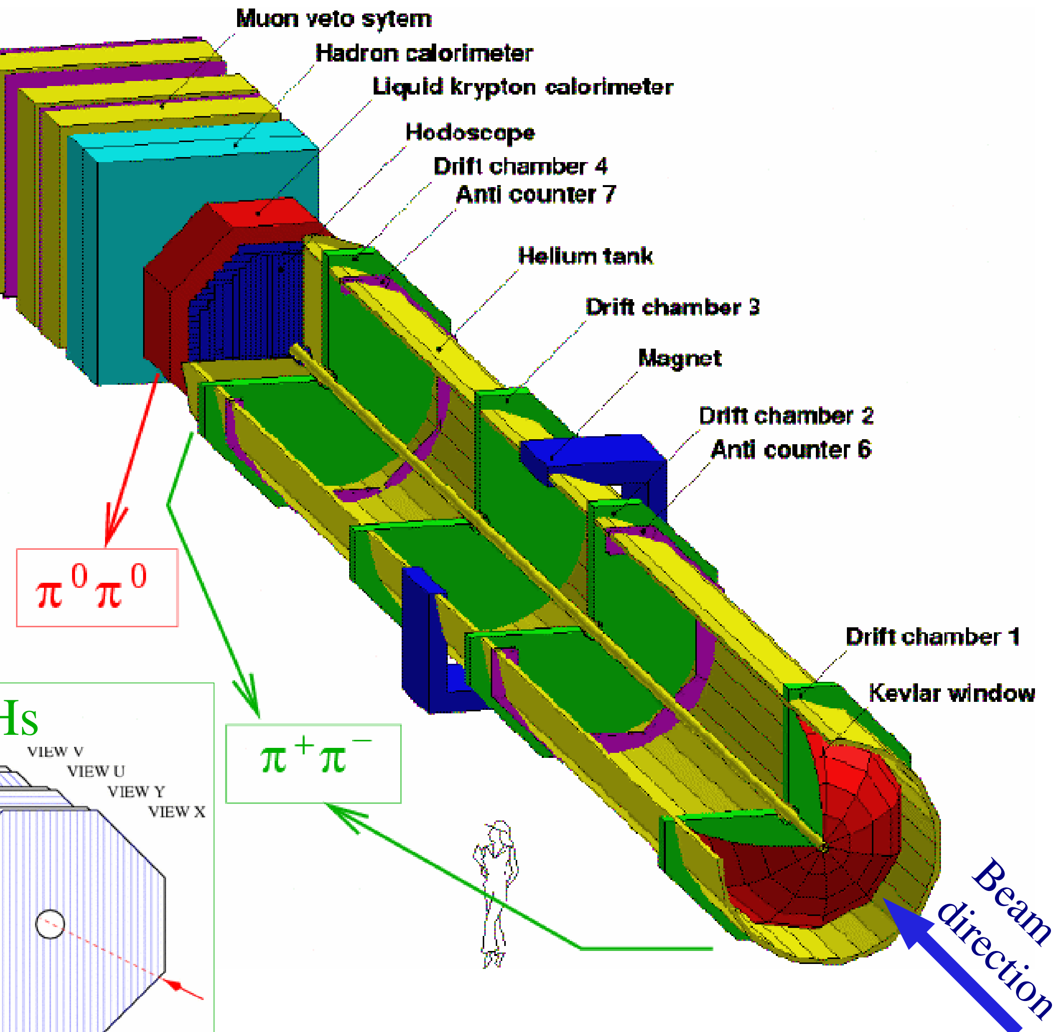
Spectrometer : 2DCHs-magnet-2DCHs

265MeV p_t kick

- Plane efficiency: 99.5%
- $\sigma_{X,Y} \simeq 100$ µm



$\sigma(p)/p \simeq 0.5\% \oplus 0.009p\%$ (p in GeV/c)



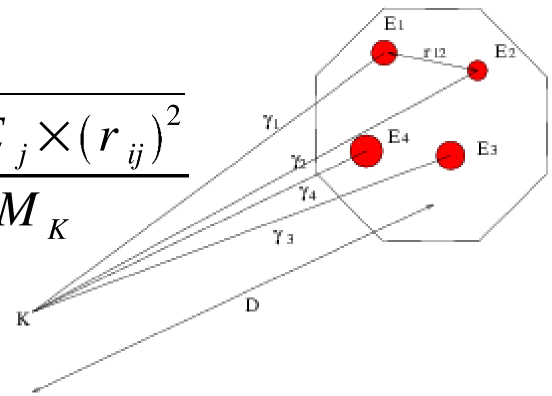
Lkr e.m. Calorimeter

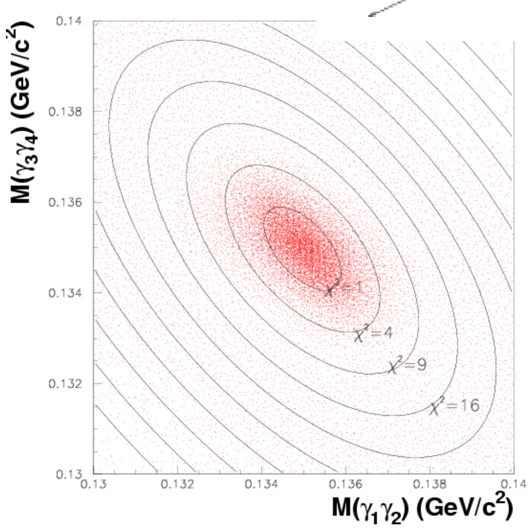
$\sigma(\pi^0 \text{ mass}) \simeq 1.1 \text{MeV}/c^2$

$\pi^0\pi^0 \rightarrow 4\gamma$

$$m_{ij} = \frac{\sqrt{E_i E_j}\, r_{ij}}{D}$$

$$D_{vtx,\,Lkr} = \frac{\sqrt{E_i E_j \times (r_{ij})^2}}{M_K}$$





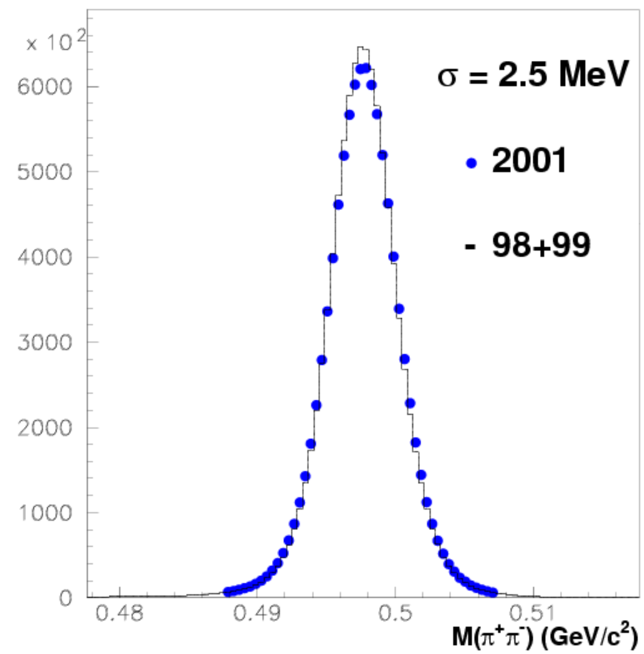
Two photon pairs invariant mass in $K_S \rightarrow \pi^0\pi^0$ candidates

χ^2-like varible: compatibility with $\pi^0\pi^0$ final state

Spectrometer

$\sigma(K \text{ mass}) \simeq 2.5 \text{MeV}/c^2$

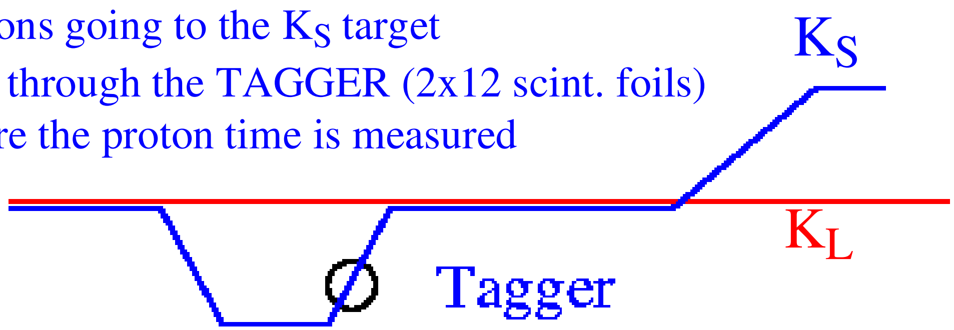
$\pi^+\pi^-$

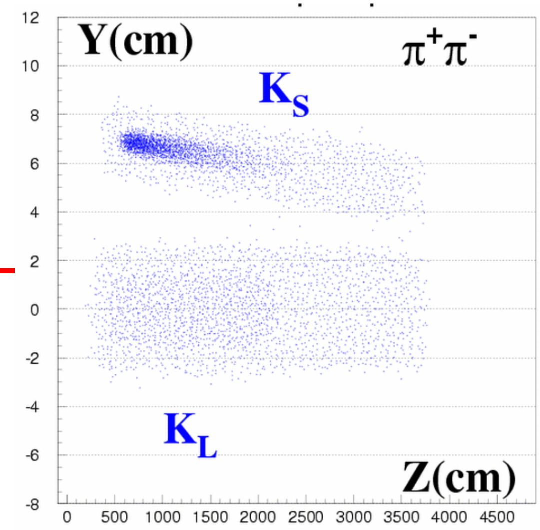


kaon invariant mass in $K_S \rightarrow \pi^+\pi^-$ candidates

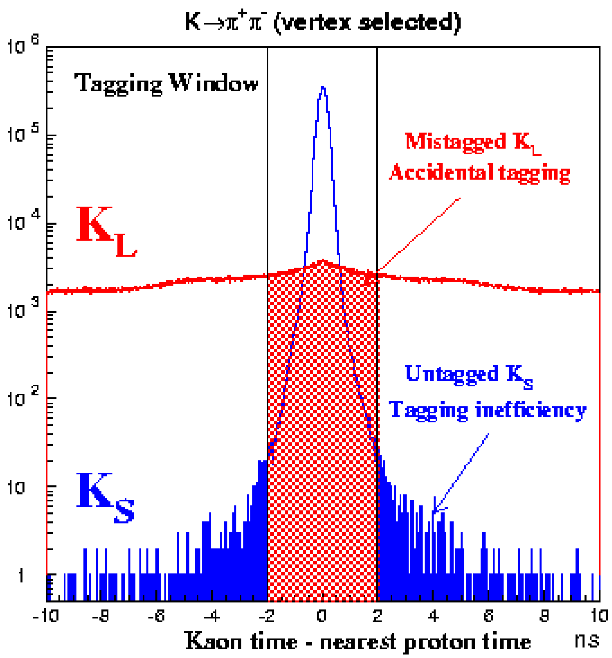
TAGGING: K_L or K_S decay?

Protons going to the K_S target pass through the TAGGER (2x12 scint. foils) where the proton time is measured





Charged decays: spectrometer vtx resolution and small divergence btw beams



K_S event are identified by tagging the parent proton

$T_{event} - T_{parent\ proton}$ coincidence (±2ns)

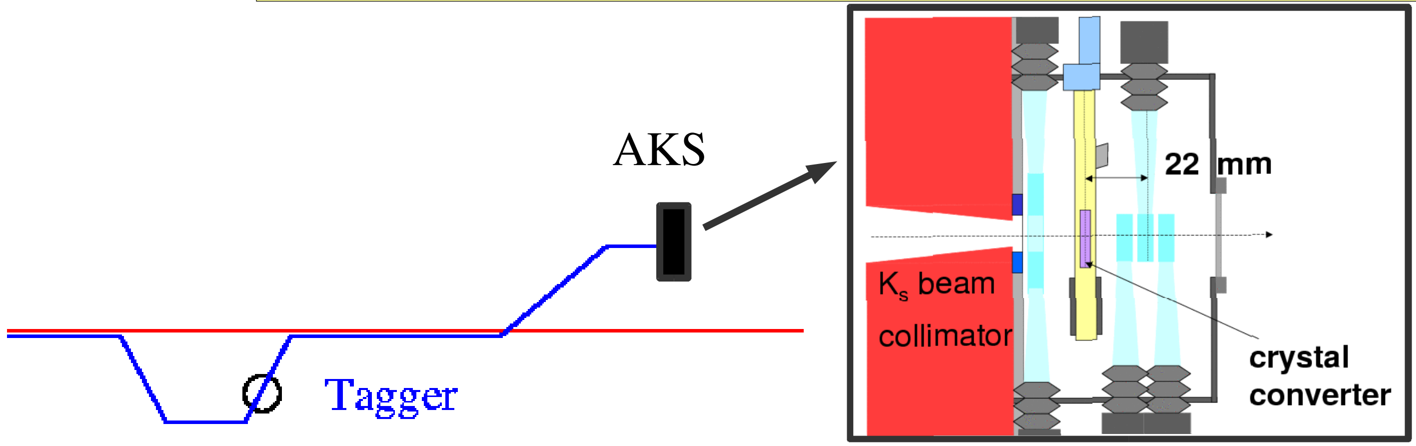
used for both Ch and N decays to avoid asymm. in R

Accidental tagging: $P(K_L \to K_S) = \alpha_{LS} \simeq 8\%$ in 2001

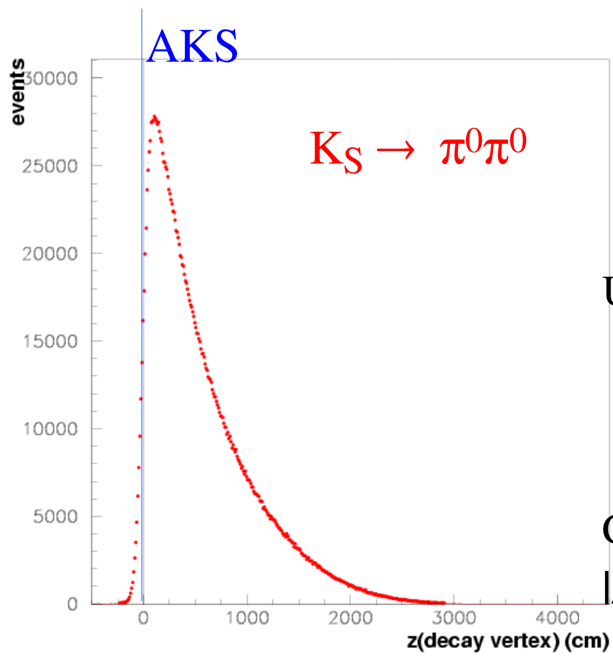
($\simeq$11% < 2001)

Tagger inefficiency: $P(K_S \to K_L) = \alpha_{SL} \simeq 1\text{x}10^{-4}$

Beginning of the decay region: AKS



Converter (γ e^+e^-)
followed by
3 scintillators



Defines the beginning of the decay region vetoing the upstream decays

Use K_S events to adjust energy scale (neutral) matching AKS position

↪ fit R in energy bins:

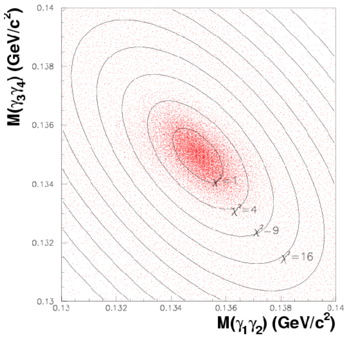
0.1% energy-scale ⇒ 10^{-4} on $Re(\varepsilon'/\varepsilon)$

Check geometry of DCHs (charged)

$|\Delta Z|<1$cm on AKS reconstructed position ⇒ error ~10^{-4} on $Re(\varepsilon'/\varepsilon)$

Background rejection

Neutral

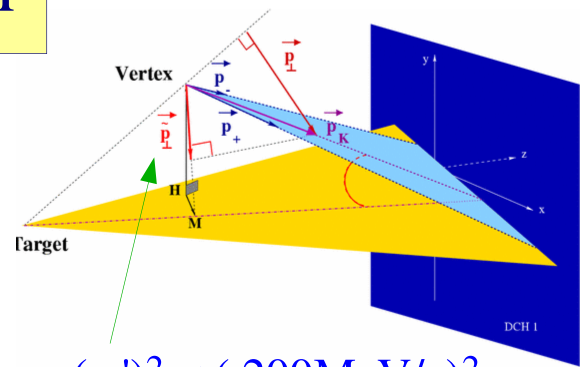


cut on Rellipse (χ^2-like varible)
veto events with 5th cluster in time

Charged

- $K_{\mu3}$: MuonVeto
- K_{e3}: $E/p < 0.8$
- 3 bodies and scattering: $(p_t')^2 < (200 MeV/c)^2$

  p_t' 'symmetric' tranverse momentum:
  P_K component ⊥ line "Target- K Xpoint at DCH1"



Analysis

- Reconstruct and count $\pi^0\pi^0$ and $\pi^+\pi^-$
- Apply dead times offline to all events
- Disentangle K_L and K_S
- Subtract remaining background
- Evaluate R and systematics
- Checks and stability of the result

Corrections to be applied

- Charged background
- Neutral background
- Beam scattering background
- Tagging (Neutral – Charged difference)
- Triggers inefficiency
- AKS veto inefficiency
- Energy scale uncertainty
- Acceptance
- Accidental activity induced losses

NA48 Runs

1997

K_L+K_S

ε'/ε run

0.5M $K_L \to \pi^0\pi^0$

1998

K_L+K_S

ε'/ε run

1M $K_L \to \pi^0\pi^0$

(K_L rare decays, ..)

1999

K_L+K_S

ε'/ε run

2M $K_L \to \pi^0\pi^0$

(K_L rare decays, ..)

K_L

K_{e3}

$K_{\mu3}$

K_S

HI

test

2000

NO DCH (implosion nov. 99)

ε'/ε checks

K_L

η

K_SHI

NA48/1

phase I

2001

K_L+K_S

ε'/ε run

1.5M $K_L \to \pi^0\pi^0$

(K_{e3}, $K_{\mu3}$,..)

2002

K_S HI

NA48/1

phase II

new DCH r/o

2003

$K^+ + K^-$

NA48/2

new beam line,

kabes, beam mon.

NA48 changed condition in 2001

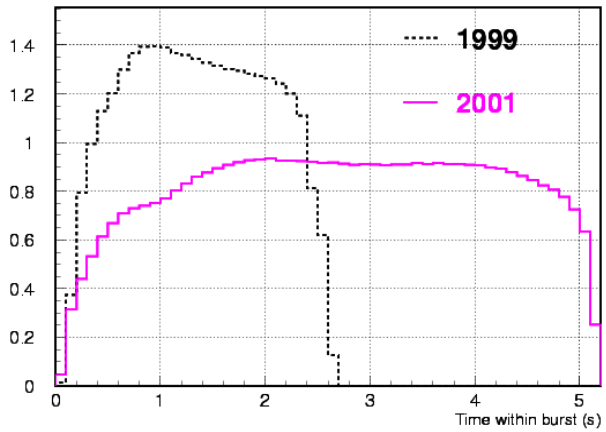
Last ε'/ε data taking

Additional statistics + test intensity related systematics

New DCHs and beam pipe(after 1999 implosion)

New beam monitors (4 intgration times: 200ns,1μ, 3μ,15μs)

	1998-99	2001
Proton momentum	450 GeV/c	400 GeV/c
SPS spill lenght/cycle time	2.4s/14.4 s	5.2s/16.8 s
duty cycle	0.17	0.31
K_L beam intensity	$\approx 1.5 \times 10^{12}$ ppp	$\approx 2.4 \times 10^{12}$ ppp
K_S beam intensity	$\approx 3 \times 10^{7}$ ppp	$\approx 5 \times 10^{7}$ ppp



Good K_L Events / 100 ms

instantaneous intensity 30% lower

↪ lower dead time on charged events

trigger: 1.5% ('99) → 0.3% (2001)

DCH mult. 20% ('99) → 11% (2001)

Cut on first 200ms due to very strong beam structure

Accidental activity

Accidental activity from beam ⇒ event losses

Intensity of K_L beam >> K_S ⇒ K_L beam responsible for event losses and **losses ∝ Intensity of K_L beam**

Difference in losses btw C-N and L-S minimized by:

- C-N: simultaneous data taking, dead time applied offline to all modes
- L-S: simultaneous beams: same Intensity (K_L beam) seen by K_S and K_L events

  quasi collinear beams, K_S and K_L^w events same detector ilumination

Residual effects ⇒ $\Delta R_{accidental}$

Difference btw C -N losses
Difference in accidental activity seen by K_L and K_S events

$\Delta R_{Int} = \Delta(\text{C-N})*\Delta(\text{L-S})$
$= (1.0\pm0.5)\% * (0\pm1)\%$ (2001)

K_S - K_L deterctor illumination difference, different detector parts ⇒different losses e.g. At the spectrometer

$\Delta R_{Illum} = \pm3.0\text{x}10^{-4}$ (2001)

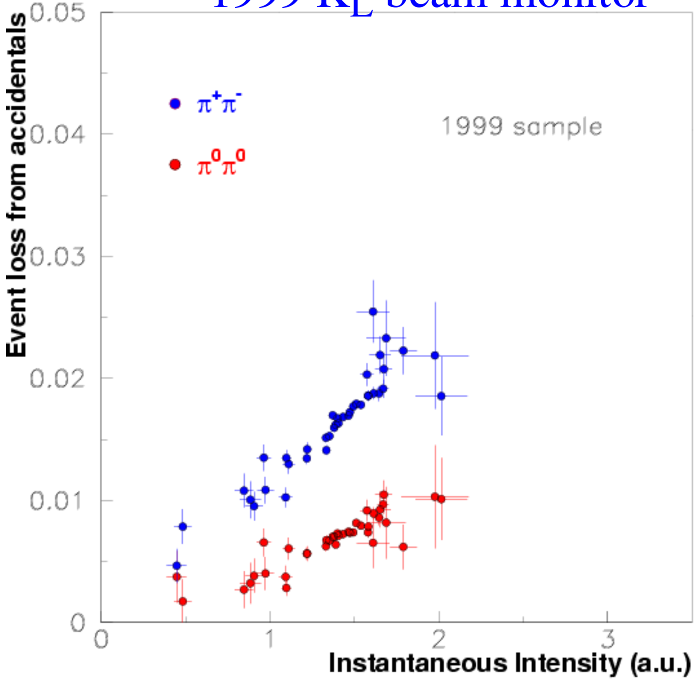
Beam monitors and losses vs K_L beam intensity

Beam monitors (K_L and K_S) to trigger "random" events (~10+10 per burst) dowscaled and delayed (3 SPS cycles, same intensity conditions) : record accidental activity proportionally to K_L and K_S beam intensity

2001: Integrators (K_L and K_S) to measure beam intensity, 4 integration times each

200ns, 1µs, 3µs, 15µs

1999 K_L beam monitor



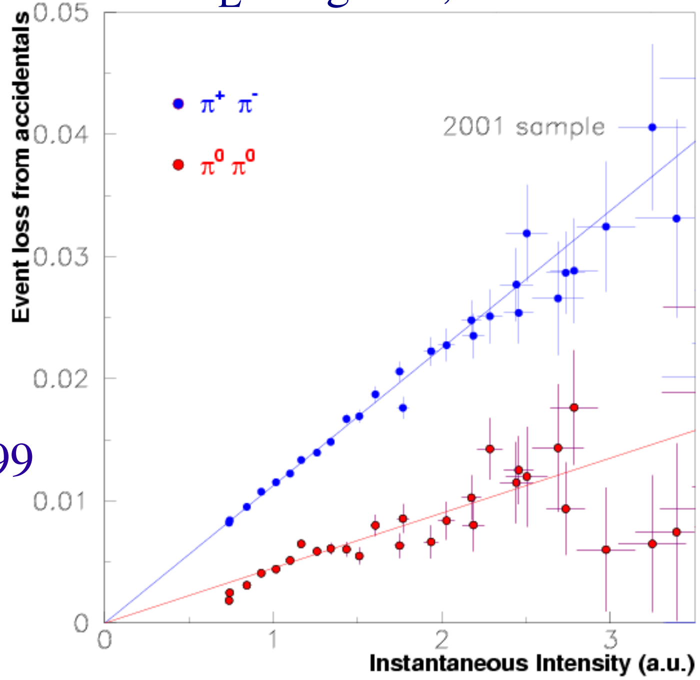
Losses in OMC events: MC+"random" vs K_L Intensity

Δ(C-N) =

(1.4±0.7)% 1998-99

(1.0±0.5)% 2001

2001: K_L Integrator, 200ns channel



$$\Delta R_{accidental} = \Delta R_{Int} + \Delta R_{Illum}$$

$\Delta R_{Int} = \Delta(C\text{-}N) * \Delta I(K_L\text{-}K_S)/I = (0 \pm 1.1)\text{x}10^{-4}$

98-99: was $(0 \pm 3)\text{x}10^{-4}$

$\Delta(C\text{-}N)$

- DO: data events overlayed with "random"
- OMC: MC events overlayed with "random"
- N/C in K_L+K_S wrt pure K_S runs
- N/C variation vs KL beam intensity

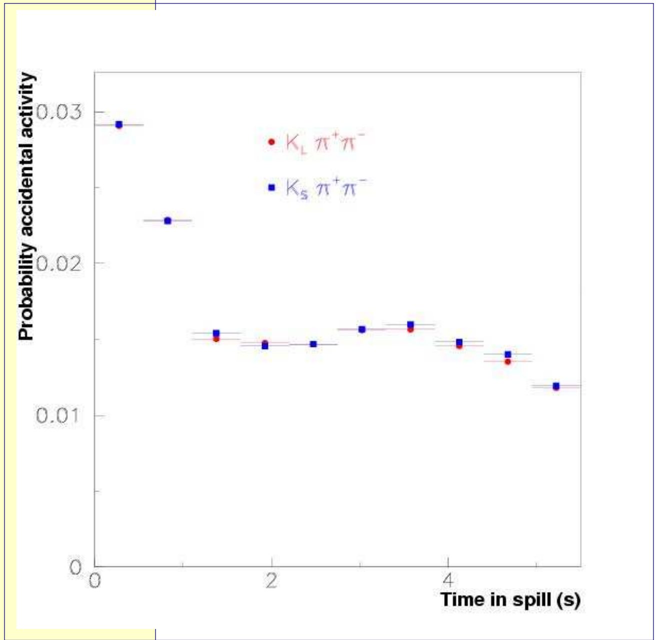
$\Delta I(K_L\text{-}K_S)/I$

- Lkr extra clustes in good C events
- DCH extra tracks in good C events
- Beam monitor rates in C events
- Integrator rates correlation in flat triggers

$\Delta R_{Illum} = (0 \pm 3)\text{x}10^{-4}$

as in 98-99. Stat. Limited

- DO
- OMC
- DMC: OMC + "random"

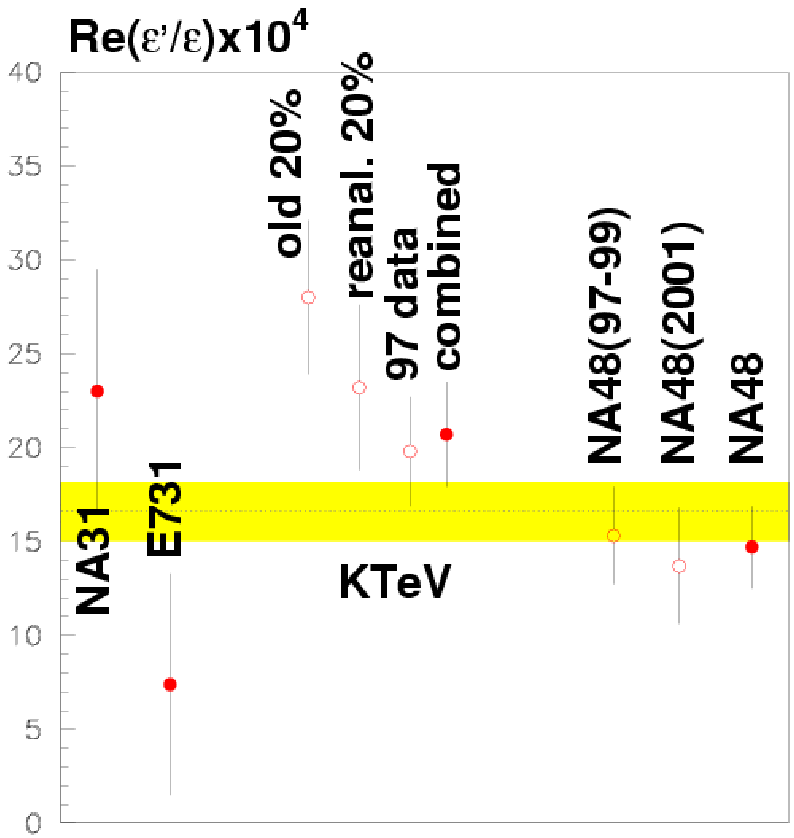


Correction to R

$Re(\varepsilon'/\varepsilon)=(1-R)/6$

	1998-99	2001	
Tagging ineff. α_{SL}	±3.0	±3.0	
Accidental tagging α_{LS}	8.3±3.4	6.9±2.8 ↓	
$\pi^+\pi^-$ trigger ineff.	-3.6±5.2	5.2±3.6 ↓	Intensity related
Accidental activity			
ΔR_{Int}	±3.0	±1.1 ↓	
ΔR_{Geom}	±3.0	±3.0	
$\pi^+\pi^-$ background	16.9±3.0	14.2±3.0	
$\pi^0\pi^0$ background	-5.9±2.0	-5.6±2.0	
beam scattering	-9.6±2.0	-8.8±2.0	
$\pi^+\pi^-$ scale	2.0±2.8	±2.8	
$\pi^0\pi^0$ scale	±5.8	±5.3	
AKS ineff.	1.1±0.4	1.2±0.3	
Acceptance	26.7±4.1±4.0	21.9±3.5±4.0	
KS in time activity	±1.0	±1.0	
TOTAL	+35.9±8.1±9.6	+35.0±6.5±9.0 ↓	stat, syst

Re(ε'/ε) experimental results



NA31 = $(23.0 \pm 6.5)\times10^{-4}$
E731 = $(7.4 \pm 5.9)\times10^{-4}$
KteV = $(20.7 \pm 2.8)\times10^{-4}$

$Re(\varepsilon'/\varepsilon)_{(97-99)} = (15.3 \pm 2.6)\times10^{-4}$

$Re(\varepsilon'/\varepsilon)_{(2001)} = (13.7 \pm 3.1)\times10^{-4}$

$Re(\varepsilon'/\varepsilon)_{(97-01)} = (14.7 \pm 2.2)\times10^{-4}$

⇒ proposal goal reached

V.Fanti et al, Phys. Lett. B 465, 335 (1999)
A.Lai et al. Eur. Phys. J. C 22, 231 (2001)
J.R.Batley et al. Physics Letters B 544, 92 (2002)

⇒ world average $Re(\varepsilon'/\varepsilon) = (16.6 \pm 1.6)\times10^{-4}$

χ^2/ndf =6.3/3 10% probability

NA48/2 simultaneous K^+ and K^- beams

CERN, Chicago, Dubna, Ferrara, Firenze, Mainz,

Northwestern, Perugia, Pisa, Saclay, Siegen, Torino,

Vienna

Main Goal:

Direct CP violation: A_g **slope asymmetry** measurement in

$K^\pm \to \pi^\pm \pi^+ \pi^-$

~2×10^9 events $\Rightarrow$ $\delta(A_g) \leqslant 2.2 \times 10^{-4}$ (*limited by* statistics)

Theory: A_g from 10^{-6} to 10^{-4}

and A^0_g **slope asymmetry** measurement in

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

~1×10^8 events $\Rightarrow$ $\delta(A^0_g) \leqslant$ few $\times 10^{-4}$ (*statistics)*

Direct CP violation $\Rightarrow$ difference btw K^+ and K^- decay matrix elements

Compare $K^+ \to \pi^+ \pi^+ \pi^-$ relative to $K^- \to \pi^- \pi^+ \pi^-$

Compare $K^+ \to \pi^+ \pi^0 \pi^0$ relative to $K^- \to \pi^- \pi^0 \pi^0$

Matrix element $K^\pm \to (3\pi)^\pm$ can be parametrized as

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

$u=(s_3 - s_0)/m_\pi^2$, $v=(s_1 - s_2)/m_\pi^2$, $s_0 = (s_1 + s_2 + s_3)/3$, $s_i=(P_K - P_i)^2$ i=1,2,3 (odd π)

CP conservation: same g,h,k for $K^+ \to (3\pi)^+$ and $K^- \to (3\pi)^-$

$$\text{CP violation:} \quad A_g = (g^+ - g^-)/(g^+ + g^-) \neq 0$$

Measure: $$R(u) = \frac{\int dv |M^+(u,v)|^2}{\int dv |M^-(u,v)|^2} \approx 1 + u * (g^+ - g^-)$$

Up to now... and more..

A_g $K^\pm \to (3\pi)^\pm$ B.r. (5.576 ±0.031)%

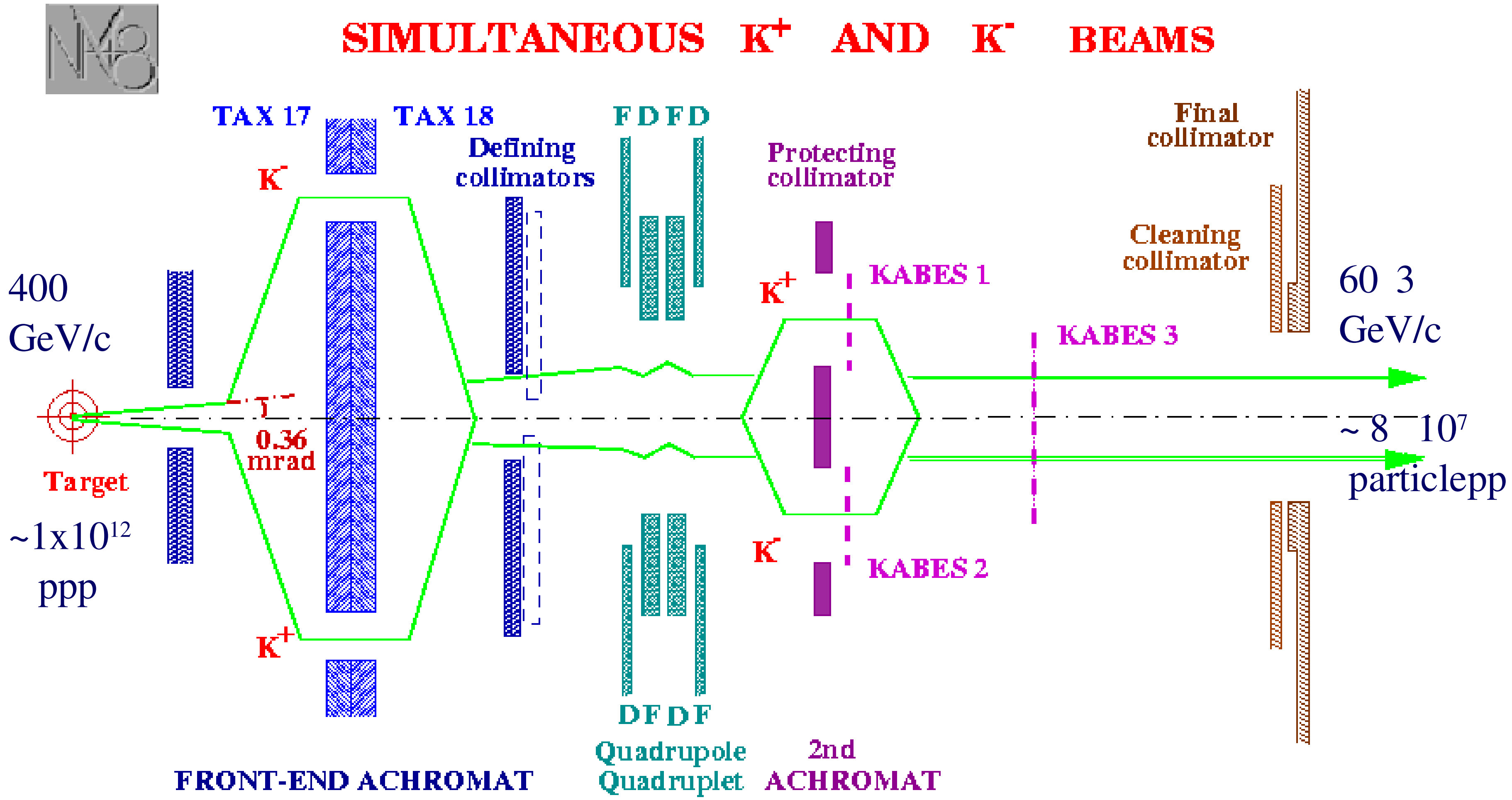
- Ford (1970) -0.0070 ± 0.0053 (80% statistical, 3M events)
- FNAL E871 (2000, unpublished, 54M events) $(2.2\pm1.5\pm3.7)\times10^{-3}$
- KLOE 2000-2002: 400pb^{-1} available with 10^6 K^+K^- per pb^{-1}
- NA48 first experiment with simultaneous $K^\pm$ beams.

  Goal ~2×10^9 events $\Rightarrow$ $\delta(A_g) \leqslant 2.2\times10^{-4}$

A_g^0 $K^\pm \to \pi^0\pi^0\pi^\pm$ B.r. (1.73 ±0.04)%

- PDG 0.03 ± 0.05
- Protvino prel. $(0.3\pm2.5\pm1.5)\times10^{-3}$ < 0.5M
- KLOE 2000-2002: 400pb^{-1} available with 10^6 K^+K^- per pb^{-1}
- NA48: goal ~1×10^8 events $\Rightarrow$ $\delta(A^0_g) \leqslant$ few $\times10^{-4}$

NA48/2: new beam lines



spill 4.8/16.8 s

General considerations

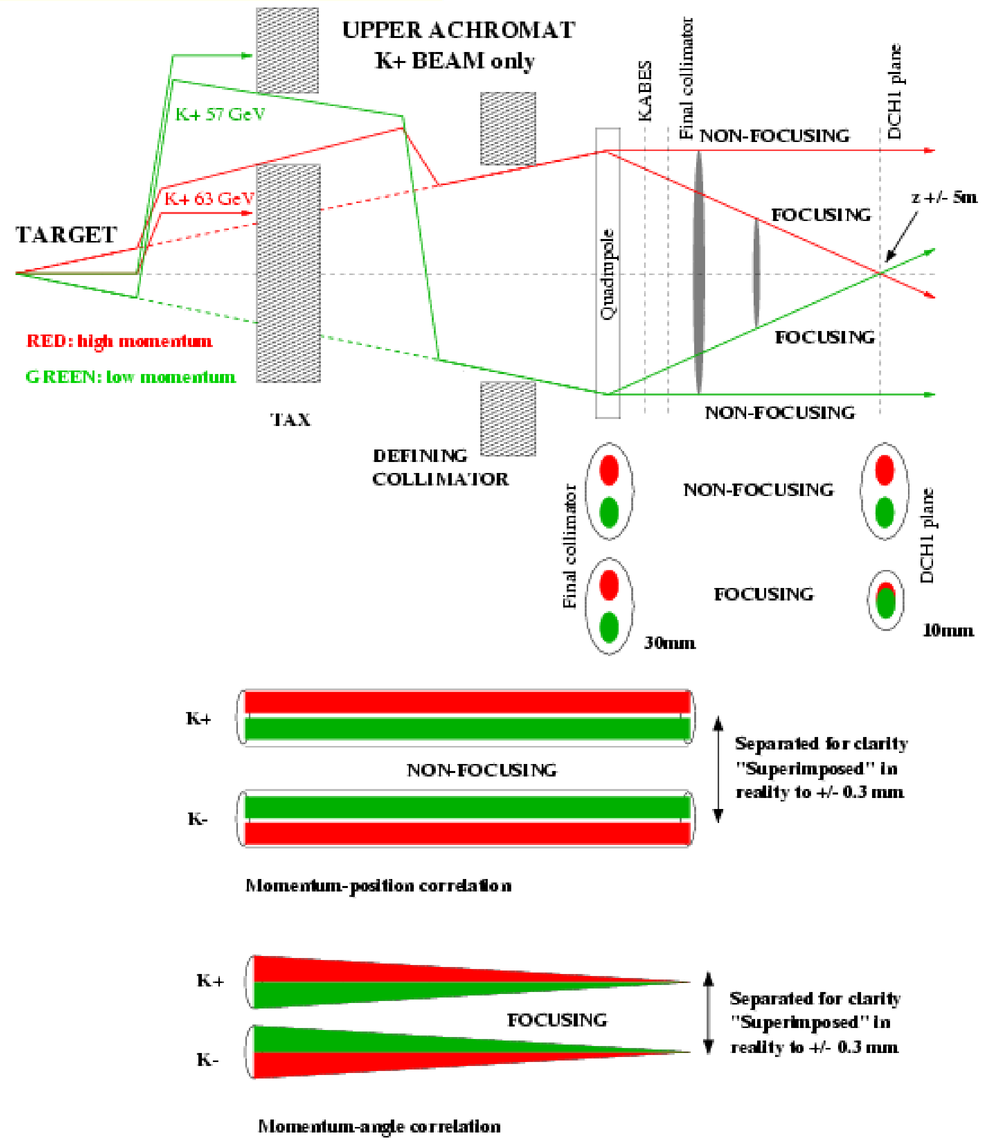
Symmetry between K^+, K^- $\Rightarrow$ cancellation of several systematic effects

- Simultaneous K^+, K^- beams (first experiment!)
- Simultaneous K^+, K^- decays data taken, same decay region
- Beam adjustment: steering and focusing
- Achromat symmetry: inverted every week
- Alignment beam-spectrometer
- High precision spectrometer (2dch-magnet-2dch, P_T kick = *120 MeV/c*)
- Magnet polarity inverted every day
- High precision e.m. Calorimetr (Lkr)
- K beam spectrometer (Kabes) allows reconstructions of events with missing particles
- Analysis in K momentum bins

$\Rightarrow$ accurate K^+ - K^- comparisons are possible

Focused beams

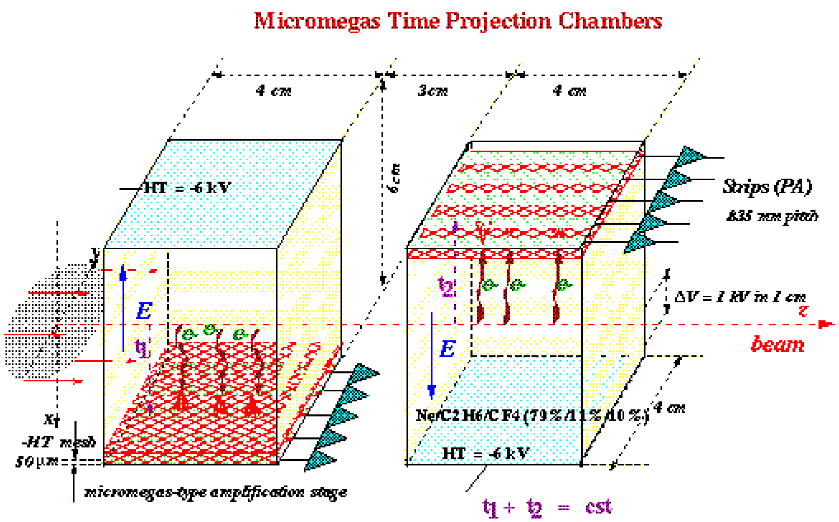
Effect on A_g coming from differences in K^+/K^- acceptance at the spectrometer (DCH1)

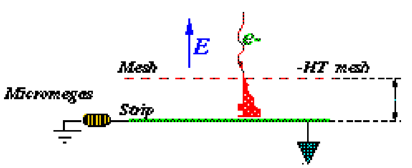


Steering: bring K^+ and K^- beams onto a common axis at final collimator and DCH1 (with a precision of ~ ±0.3mm)

AND

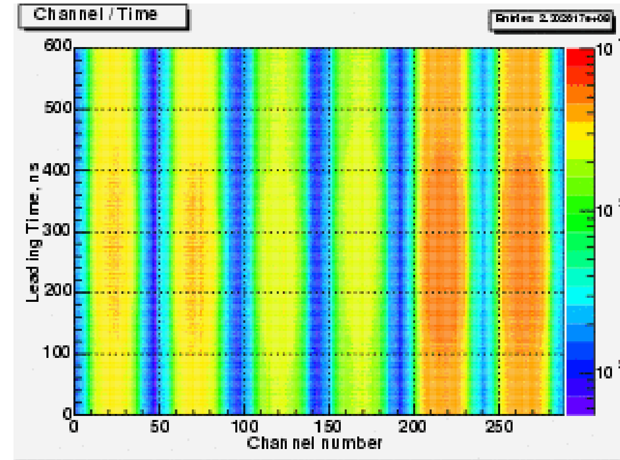
Focusing: similar and gentle convergence of each beam in both planes. Small angles of convergence: ~ 0.04mrad (<1mm displacement from Dch1 to Dch4) Avoid “production angle-momentum” correlation in the vertical plane



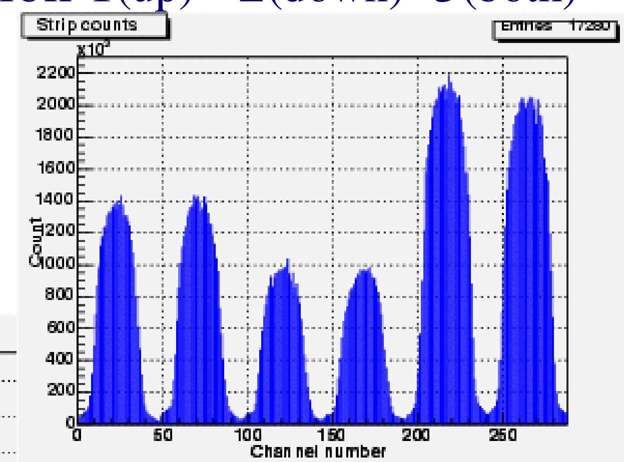


Kabes

e.g. Beam
K^+ UP
K^- DOWN

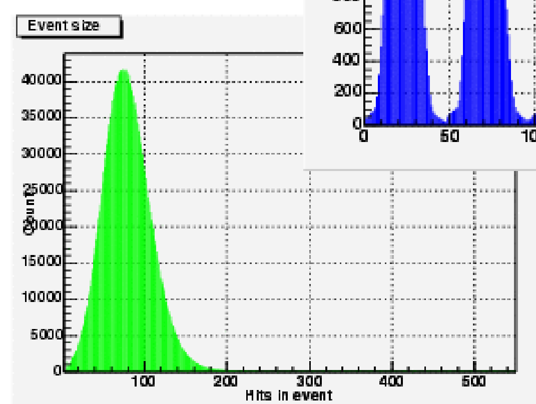


Station 1(up) 2(down) 3(both)



P_K measure to reconstruct 3π decays in which one π is not detected

(and resolve K_{e4} reconstruction ambiguity)



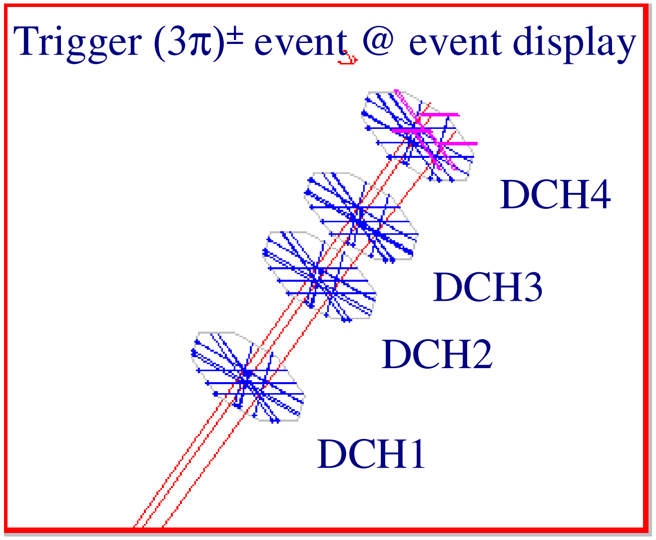
MSGC, 1mm strips max-rate: 2MHz/strip
highest flux: 30MHz
X(drift) , Y(strips) measure
$\sigma_X \sim 50\mu m$, $\sigma_Y \sim 80\mu m$, $\sigma_t \sim 0.7n$
$\Rightarrow \sigma(\Delta p)/p < 1\%$

Running...

$P_K = 60 \pm 3$ GeV/c

$K^+/K^- \sim 1.7$

> 1.5×10^9 3π @25th Aug



$\sigma(P_{K\to 3\pi}) \sim 0.5$ GeV/c

$\sigma(M_{K\to 3\pi}) \sim 1.6$ MeV/c^2

Proposal: 120 days
2003: ~ 80 days but .....

Acceptance for diffenet decay modes (5-50)%

~35% $\pi^{\pm}\,\pi^{+}\,\pi^{-}$; ~10% $\pi^{\pm}\,\pi^{0}\,\pi^{0}$

Conclusions

NA48 Direct CP violation

$Re(\varepsilon'/\varepsilon)_{(97\text{-}2001)} = (14.7 \pm 2.2)x10^{-4}$

NA48/2 Direct CP violation

running now.....

But not only Direct CPV!

See next NA48 talk (G.Collazuol)!