Review of NA48 CP violation measurements with Neutral and Charged Kaons

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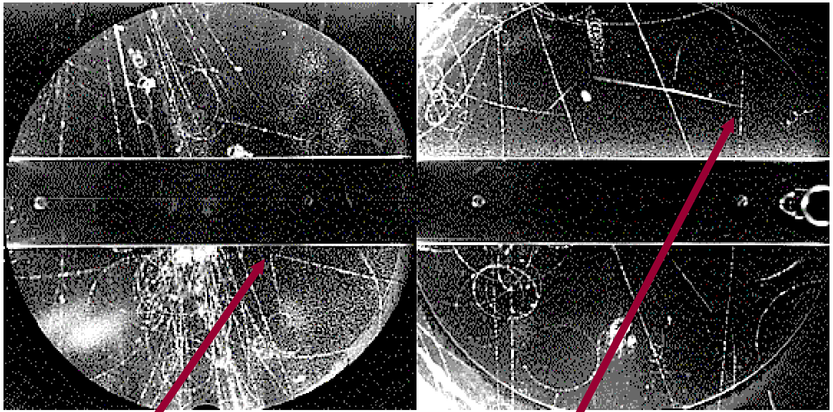


$K^0 \rightarrow \pi^+\pi^-$

$K^+ \rightarrow \mu^+\nu$

On behalf of the NA48, NA48/1 and NA48/2 Collaborations: *Cagliari, Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Northwestern, Orsay, Perugia, Pisa, Saclay, Siegen,Torino, Warsaw, Wien*

OUTLINE

- Kaons and CP Violation
- The NA48 experiment at CERN:
  - experimental program
- **NA48**: CP Violation in $K^0 \rightarrow 2\pi$ decays
- **NA48/1**: CP Violation in $K_S \rightarrow 3\pi$ decays
- **NA48/2**: CP Violation in $K^\pm \rightarrow 3\pi$ decays
- **NA48/2**: CP Violation in $K^\pm \rightarrow \pi^\pm\pi^0\gamma$ **NEW RESULTS**
- Conclusions

Kaons and CP Violation

- Motivation for Kaon experiments:
  - a powerful probe of the flavour structure of the Standard Model and an effective tool to investigate the nature of the physics beyond it
  - CP violation represents one of the sectors where a large sensitivity to possible New Physics (NP) effects can be expected.
- Kaon meson system is a privileged observatory for flavour physics:
  - Simple (minimal) flavour laboratory
  - Nicely accessible experimentally
  - CP violation of same size as in B
- All 3 types of CP Violation can be observed in K^0 decays
  - in K^0–$\bar{K}^0$ mixing ($\Delta S=2$, Indirect CPV: $Re(\varepsilon)$),
  - in the decay amplitudes ($\Delta S=1$, Direct CPV: $Re(\varepsilon')$)
  - in the Interference between decays with and without mixing ($Im(\varepsilon)$ and $Im(\varepsilon')$)
- Only Direct CP Violation occurs in $K^{\pm}$ decays (no mixing)
- Complementary observables to measure CP Violation in Kaons
  - ε'/ε, A_g , asymmetries and other parameters of rare decays, …

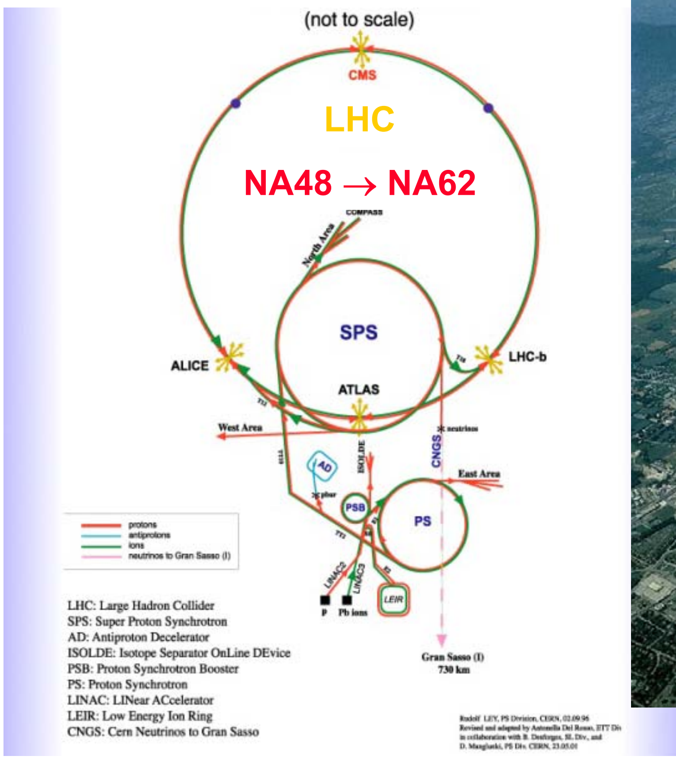
The NA48 Experiment at CERN

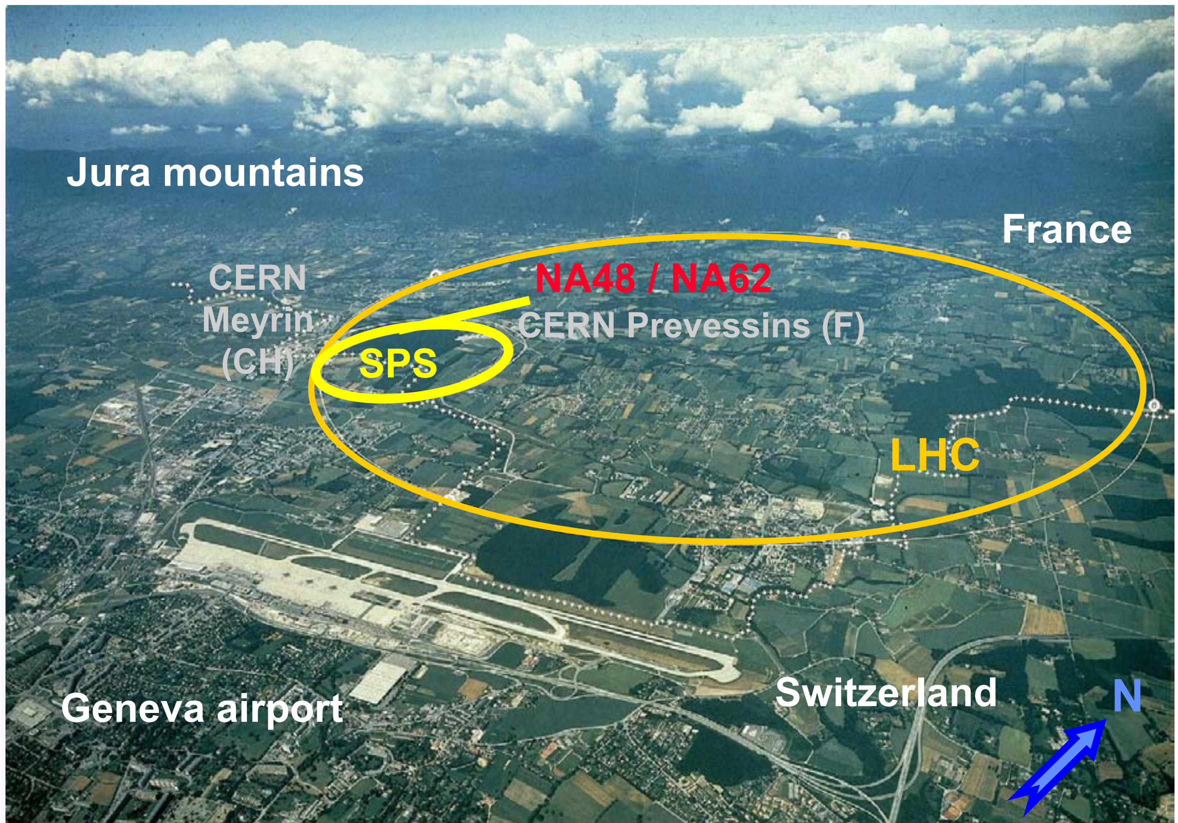
The CERN Accelerator Complex

The SPS at CERN provides protons at 400 GeV/c using a multi-turn, fast and slow, extraction system

The SPS is used as well as injector for the LHC accelerator

NA48 is a fixed target experiment at the CERN SPS aiming at studying CP violation and rare decays with Kaons





The NA48 experimental program

1997	ε'/ε run	$K_L + K_S$
1998	ε'/ε run	$K_L + K_S$
1999	ε'/ε run $K_L + K_S$	K_S Hi. Int.
2000	K_L only; *NO Spectrometer*	K_S High Intensity
2001	ε'/ε run $K_L + K_S$	K_S High Int.
2002	K_S High Intensity	
2003	$K^\pm$ High Intensity	
2004	$K^\pm$ High Intensity	

Data taking periods:

NA48 (1997-2001)

- Direct CP violation in neutral kaon decays:

  $\mathrm{Re}(\varepsilon'/\varepsilon) = (14.7 \pm 2.2) \times 10^{-4}$

NA48/1 (2000-2002)

- Rare K_S decays
  - **$BR(K_S \to \pi^0 e^+ e^-) = (5.8^{+2.8}_{-2.3} \pm 0.8) \times 10^{-9}$**
  - **$BR(K_S \to \pi^0 \mu^+ \mu^-) = (2.8^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9}$**

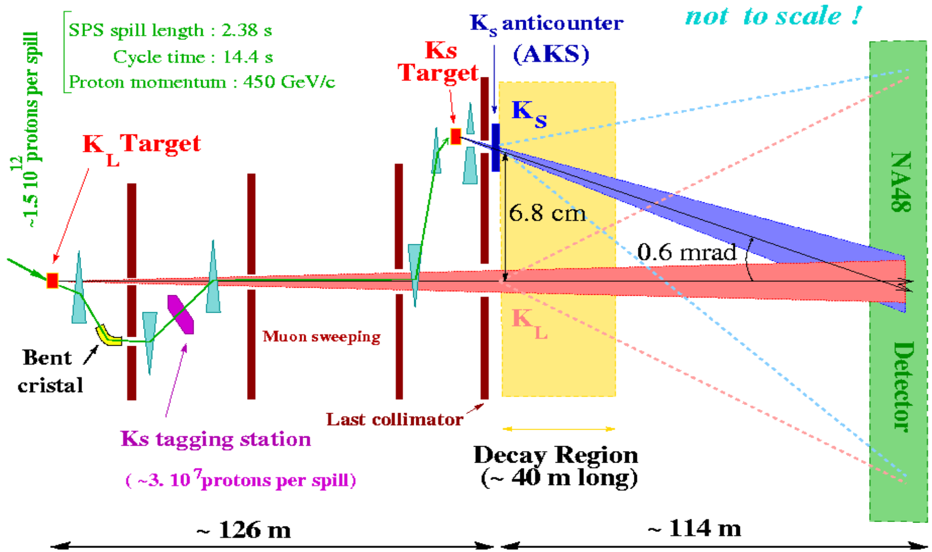
NA48/2 (2003-2004)

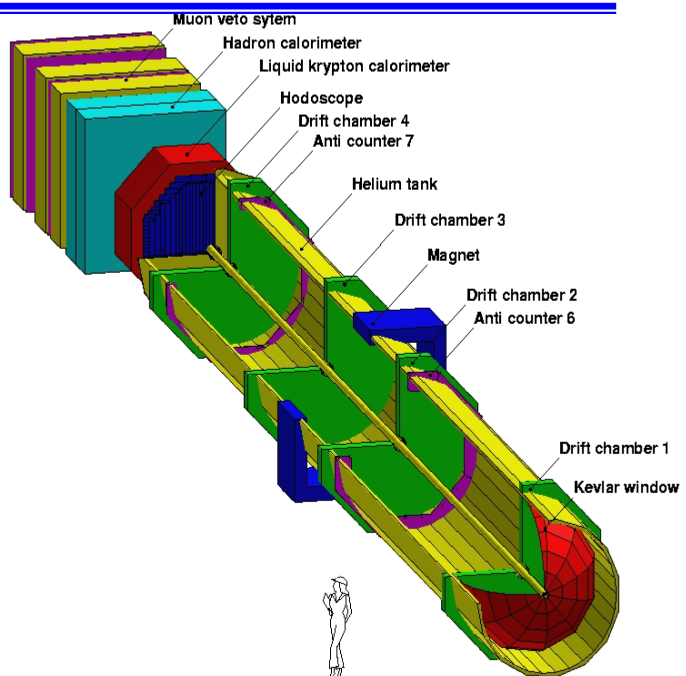
- Search for direct CP violation in **$K^\pm \to 3\pi$** decays
- Rare $K^\pm$ decays

Next: NA62 $\Rightarrow$ G. Collazuol, this conference

Results shown at this conference: E. Marinova, G. Lamanna

NA48: beam and detector





NA48 (1997-2001): simultaneous K_L-K_S 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*

NA48/1 (2000-02): high intensity K_S beam

- *new K_S target region*

more details in G. Lamanna talk

NA48/2 (2003-04): simultaneous K^+-K^- beam

- *non separated, high-intensity, narrow band $K^\pm$ beams*
- *upgraded detector: beam spectrometer, beam monitor*

Magnetic Spectrometer

$\Delta p/p = 1.02\% \oplus 0.044\% \times p$ [GeV/c]

LKr Calorimeter

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

$\Rightarrow$ NA48: $\sigma_M(\pi^0\pi^0) \approx \sigma_M(\pi^+\pi^-) \approx 2.5$ MeV

$\Rightarrow$ NA48/2: $\sigma_M(\pi^\pm\pi^0\pi^0) = 0.9$ MeV

+ trigger hodoscope, hadron calorimeter, photon and muon veto counters, …

Direct CP Violation in $K^0 \to 2\pi$

Direct CP Violation in neutral kaons: $\mathrm{Re}(\varepsilon'/\varepsilon) \neq 0$

$\Rightarrow$ measure the Double Ratio R of the 4 observable decay rates $K^0 \to 2\pi$ (counting experiments)

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

The last generation experiments for the $\mathrm{Re}(\varepsilon'/\varepsilon)$ measurement are designed to exploit cancellations of systematic effects at first order:

- High intensity simultaneous K_L and K_S beams
- Simultaneous collection of the 4 decay modes
  - *cancellation of detector inefficiencies*
- Precise magnetic spectrometer and EM calorimeter
  - *reduction of backgrounds due to other K decays*
  - *good control of the decay volume*

Experimental results on ε’/ε

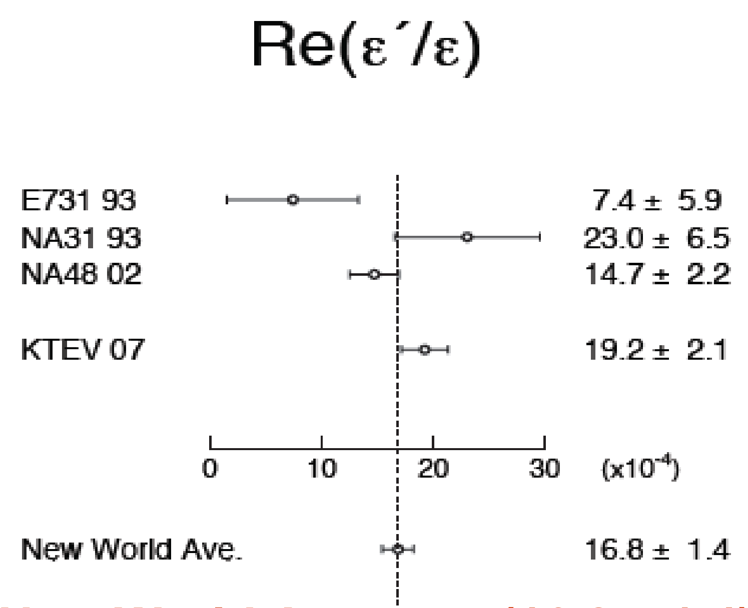
NA48 Final: $\mathrm{Re}(\varepsilon'/\varepsilon) = (14.7 \pm 2.2) \times 10^{-4}$

(PL B544, 2002)

PDG World Average: $(1.65 \pm 0.26)\times 10^{-3}$

PDG2008 and 2009 partial update for the 2010 edition

(KTeV final result not included)

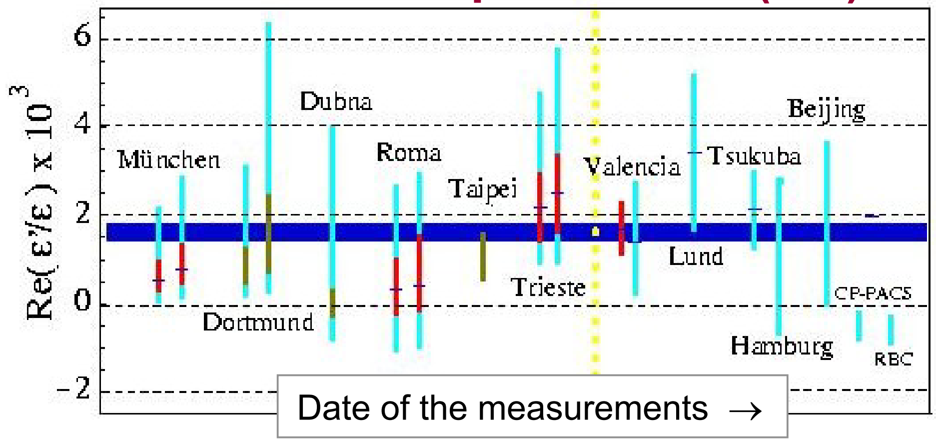


New World Average: $(16.8 \pm 1.4)\times 10^{-4}$

Confidence level: 13% *(E. Blucher, KAON2009)*

Waiting also for KLOE results: different method

Theoretical predictions (SM)

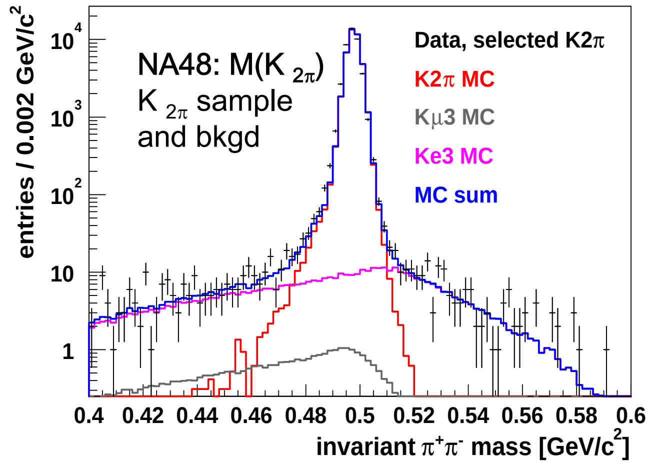


- Measurement compatible with SM
- Large hadronic uncertainty in the calculation
- Improvement expected with lattice QCD
  - *ε’/ε may become a quantitative test of SM*
  - *physics beyond SM may contribute*

The CP violation parameter $|\eta_{+-}|$

- The amplitude ratio η_{+-} is a fundamental observable of CP violation:

$$\eta_{+-} = \varepsilon + \varepsilon' = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \Leftarrow \textit{CPV decay}$$



- The NA48 measurement method:
  - Measure directly the ratio:

    BR($K_L \to \pi^+\pi^-$)/ BR($K_L \to \pi e \nu$) $\Rightarrow \dfrac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^\pm e^\mp \nu)}$

  - Compute $\Rightarrow BR(K_L \to \pi^+\pi^-) = \dfrac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^\pm e^\mp \nu)} BR(K_L \to \pi^\pm e^\mp \nu)$

  - Extract $\Rightarrow |\eta_\pm| = \sqrt{\dfrac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)}} = \sqrt{\dfrac{BR(K_L \to \pi^+\pi^-)}{BR(K_S \to \pi^+\pi^-)} \cdot \dfrac{\tau_{KS}}{\tau_{KL}}}$

- Use as external inputs the best single measurements of:
  - $BR(K_L \to \pi e \nu)$ (NA48'04 + KTeV'04, KLOE'06)
  - $BR(K_S \to \pi^+\pi^-)$ (KLOE'06)
  - K_S (NA48'02) and K_L (KLOE'06) *lifetime measurements*

NA48: the measurement of $|\eta_{+-}|$

- Dedicated K_L run in 1999 (2-days):
  - ~80 million 2-track events recorded
- Final data samples:
  - 47,142 $K_L \to \pi^+\pi^-$ (CP violating);
  - 4,999,126. $K_L \to \pi e \nu$
  - small residual background in both modes

Corrections and systematic uncertainties on R

Uncertainty source	Correction	Uncertainty
Particle ID (E/p)	+1.34%	0.05%
$K_{2\pi}$ background	–0.49%	0.03%
Muon ID	+0.48%	0.18%
Trigger efficiency	–1.29%	0.11%
K Energy spectrum		0.20%
Radiative corrections		0.10%
MC statistics		0.10%
Total	+0.04%	0.33%

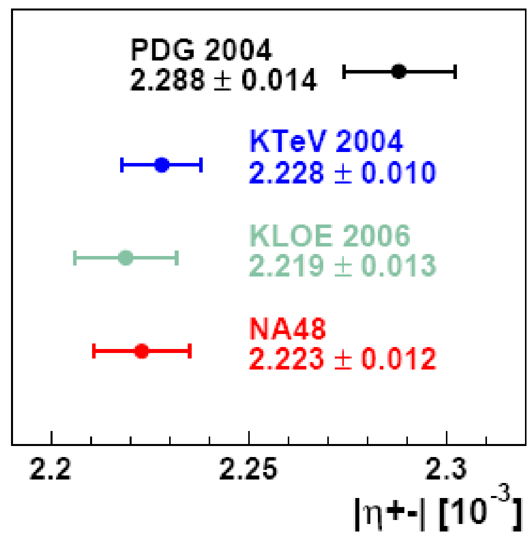
NA48 results (PL B645, 2007) :

- ratio R directly measured:

$$\frac{BR(K_L \to \pi^+\pi^-)}{BR(K_L \to \pi e \nu)} = (4.835 \pm 0.022_{stat} \pm 0.016_{syst.}) \times 10^{-3}$$

- branching fraction: $BR(K_L \to \pi^+\pi^-) = (1.941 \pm 0.019) \times 10^{-3}$
  - → Inner Bremsstrahlung $\pi^+\pi^-\gamma$ component included
  - → Direct Emission (CP conserving) component subtracted
- the CP violation parameter :

$$\boxed{|\eta_{+-}| = \sqrt{\frac{BR(K_L \to \pi^+\pi^-)}{BR(K_S \to \pi^+\pi^-)} \cdot \frac{\tau_{KS}}{\tau_{KL}}} = (2.223 \pm 0.012) \times 10^{-3}}$$



- *agreement among NA48, KTeV and KLOE results*
- *revision of previous PDG result* ⇒ $|\eta_{+-}| = 2.233 \pm 0.012$ (PDG 2008)

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

$K_S \to 3\pi^0$ is CP violating: $CP(K_S) \approx +1$, $CP(3\pi^0) = -1$

- In the SM: $BR(K_S \to 3\pi^0) = 1.9 \times 10^{-9}$
- Can be parametrized with the amplitude ratio η_{000}:

$$|\eta_{000}| = \frac{A(K_S \to 3\pi^0)}{A(K_L \to 3\pi^0)} = \sqrt{\frac{\tau_L}{\tau_S}\frac{BR(K_S \to 3\pi^0)}{BR(K_L \to 3\pi^0)}} \Rightarrow |\eta_{000}| = \varepsilon + \varepsilon'_{000}$$

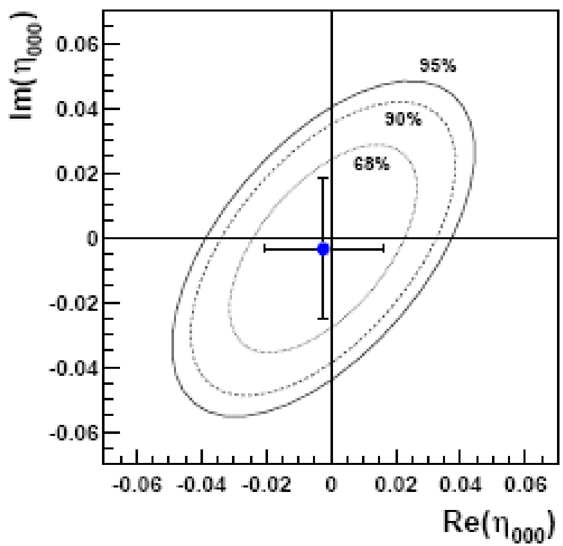
  - If CPT is conserved $\Rightarrow$ $Re(\eta_{000})$: CPV in mixing, $Im(\eta_{000})$: direct CPV
- Best experimental limit (direct search, KLOE 2005):
  - $BR(K_S \to 3\pi^0) < 1.2 \times 10^{-7}$
  - $|\eta_{000}| < 1.8 \cdot 10^{-2}$ at 90% CL
- NA48/1: no direct measurement
  - sensitivity to $|\eta_{000}|$ from $K_S/K_L \to 3\pi^0$ interference at small decay times near the target
  - aim: O(1%) error on $Re(\eta_{000})$ and $Im(\eta_{000})$
  - results based on ~4.9×10^6 reconstructed $K_S/K_L \to 3\pi^0$ (2000 run)

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

- Study the time evolution of $K_{L,S} \to 3\pi^0$ close to the production target
  - *measure the intensity of ($K \to 3\pi^0$) as a function of proper time*
  - *sensitivity to η_{000} from K_S-K_L interference superimposed on a huge flat $K_L \to 3\pi^0$ component*

- Method: measurement of K_S-K_L interference close to the production target
  - *use $3\pi^0$ events from near-target ("K_S") run $\Rightarrow K_S/K_L \to 3\pi^0$*
  - *normalize to $K_L \to 3\pi^0$ from far-target ("K_L") run*
  - *use MC to correct for residual acceptance difference and Dalitz decays*
  - *fit double ratio in E_K bins (free parameters: $Re(\eta_{000})$, $Im(\eta_{000})$):*

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



NA48/1 results:

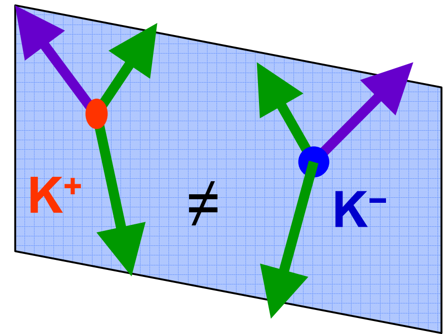
- $Re(\eta_{000}) = -0.002 \pm 0.011_{stat.} \pm 0.015_{syst}$
- $Im(\eta_{000}) = -0.003 \pm 0.013_{stat.} \pm 0.017_{syst}$
- $|\eta_{000}| < 0.045$ 90% CL
- $Br(K_S \to 3\pi^0) < 7.4 \times 10^{-7}$ at 90% CL

(PL B610, 2005)

NA48/2: Direct CP Violation in $K^{\pm}_{3\pi}$

CP Violation in charged K decays $\Rightarrow$ no mixing, any CPV is direct

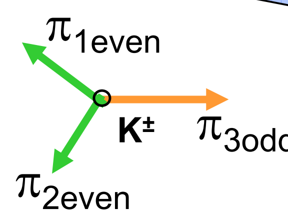
- Search for Direct CP Violation in $K^{\pm}_{3\pi}$
  - Two decay modes: $BR(K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-})=5.57\%$;
    $BR(K^{\pm}\to\pi^{\pm}\pi^{0}\pi^{0})=1.73\%$.
  - Rate asymmetry $\Gamma(K^{+})= \Gamma(K^{-})$ experimentally not simple:
    - CPV asymmetry of decay widths strongly suppressed
  - Better: measure difference in Dalitz plot slopes



- Method:
  - The $K^{\pm}_{3\pi}$ decay matrix: $\boxed{|M(u,v)|^2 \sim 1 + gu + hu^2 + kv^2}$

$u = (s_3-s_0)/m_{\pi}^2$ and $v = (s_2-s_1)/m_{\pi}^2$

$s_i = (P_K-P_{\pi i})^2$, i=1,2,3 (3=odd π); $s_0 = (s_1+s_2+s_3)/3$;



  - Direct CP violating asymmetry: $\boxed{A_g = \frac{g_+ - g_-}{g_+ + g_-} = \frac{\Delta g}{g}}$

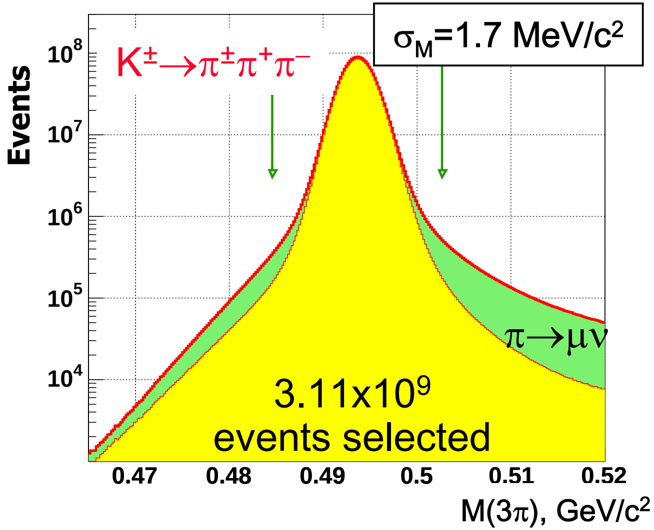
$g_+ = g(K^{+}\to\pi^{+}\pi\pi)$
$g_- = g(K^{-}\to\pi^{-}\pi\pi)$

  - SM~$O(10^{-5}-10^{-6})$ (Gamiz, Prades, Scimeni, JHEP 10 (2003))
  - New Physics (SUSY) could boost it up to $O(10^{-4})$ (G. D'Ambrosio et al., PLB480 (2000))
  - Experimental limit before NA48/2: $\gtrsim O(10^{-3})$
  - NA48/2 aim: precision $O(10^{-4})$ ➡ large statistics, simple selection, low background

$K^\pm \to \pi^\pm\pi\pi$ asymmetry: method

The method: exploit maximal cancellations

- *Simmetrization of running conditions:*
  - Simultaneous K^+ and K^- beams, superimposed in space, narrow momentum band with similar spectra
  - Equalize averaged K^+ and K^- acceptances and achieve cancellation of major systematic effects by combining data collected with opposite polarities in the relevant magnets (beam line and spectrometer);
  - Monitor residual fake instrumental asymmetries with control samples.

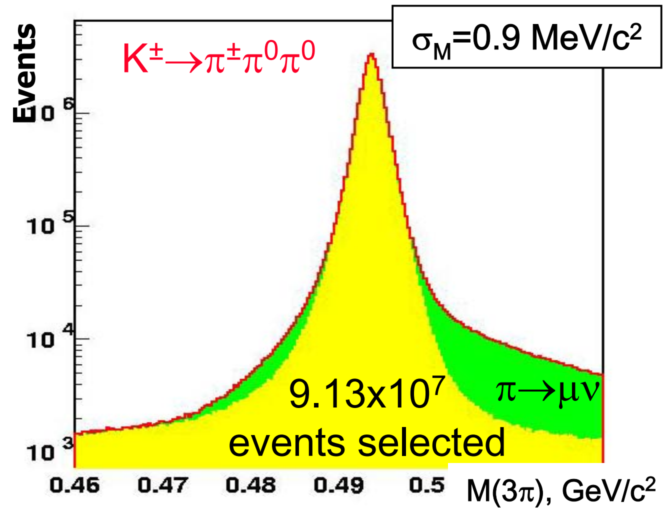


- *Measurement:*
  - measure the asymmetry exclusively from the slopes of the ratios of normalized u distributions for K^+ and K^-:

$$\boxed{R(u) = \frac{N^-(u)}{N^+(u)} \propto 1 + \frac{\Delta g\, u}{1 + gu + hu^2}}$$

  - fit a quadruple ratios of similar data samples taken at different beam line (up-down) and spectrometer (left-right) magnets polarities:

$$\boxed{R = R_{UR} \times R_{UL} \times R_{DR} \times R_{DL} \sim 1 + 4 \times \Delta g \times u}$$



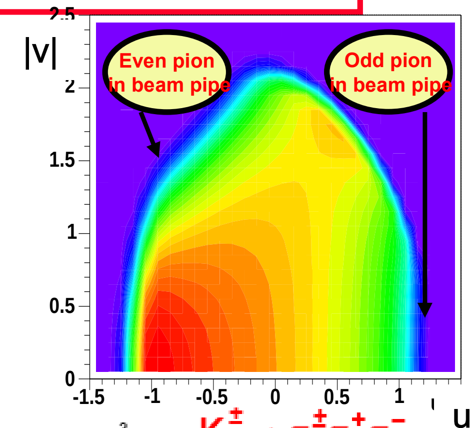
$K^{\pm}\rightarrow 3\pi^{\pm}$ asymmetry: result

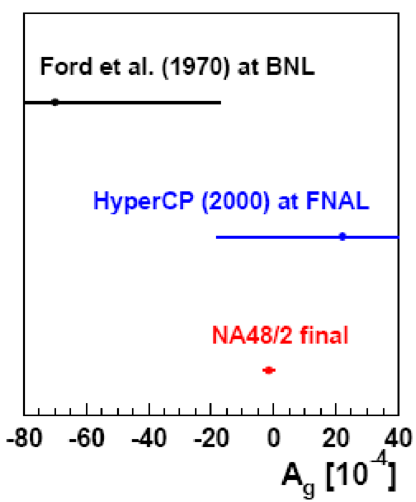
$$\Delta g = (0.6 \pm 0.7_{stat} \pm 0.4_{trig} \pm 0.5_{syst}) \times 10^{-4} = (0.6 \pm 0.9) \times 10^{-4}$$

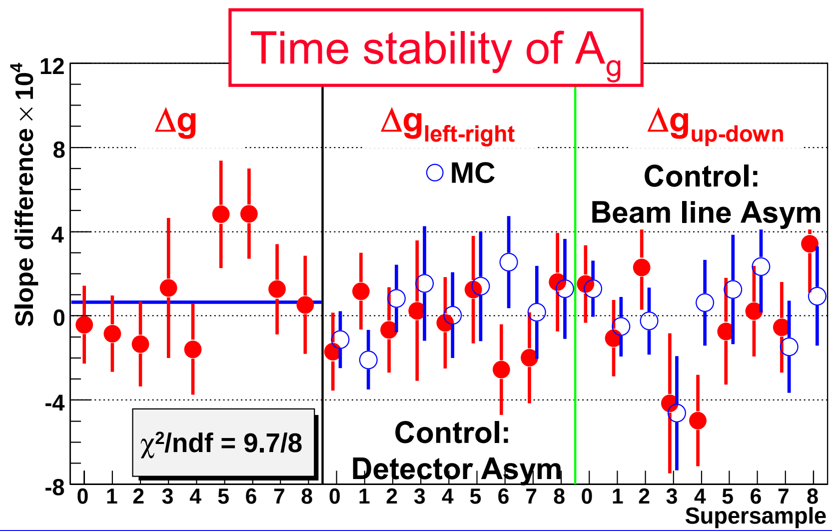
$$A_g = (-1.5 \pm 1.5_{stat} \pm 0.9_{trig} \pm 1.1_{syst}) \times 10^{-4} = (-1.5 \pm 2.1) \times 10^{-4}$$

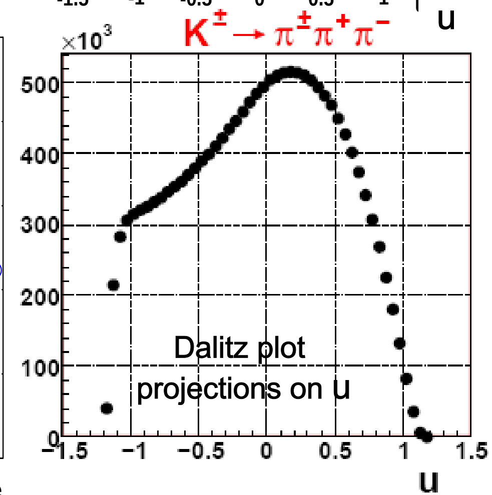
EPJ C52 (2007)

- Final result with the full NA48/2 data statistics (2003-04 run)
- A factor x20 better precision than the previous measurements
- Result compatible with SM, no evidence for CPV due to NP
- Statistical uncertainties dominate
- Limits improved to one order of magnitude to O(10^{-4})
  - NA48/2 design goal reached









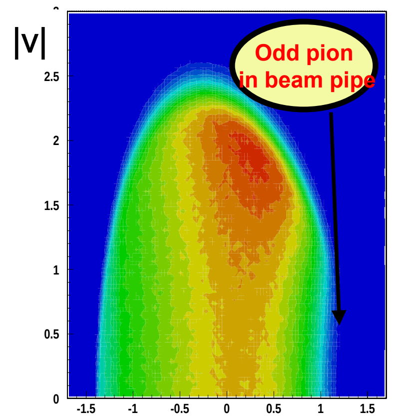
$K^{\pm}\to\pi^{\pm}\pi^{0}\pi^{0}$ asymmetry: result

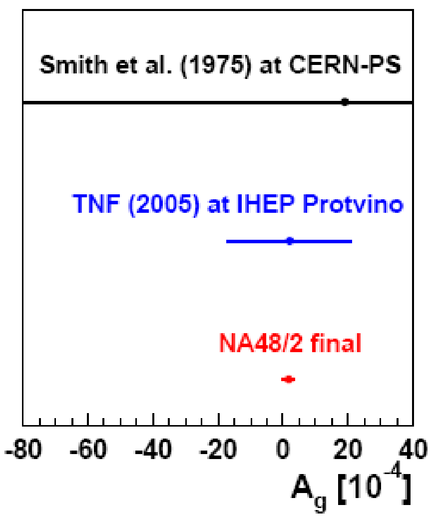
$$\Delta g^0 = (2.2 \pm 2.1_{stat} \pm 0.7_{syst}) \times 10^{-4} = (2.2 \pm 2.2) \times 10^{-4}$$

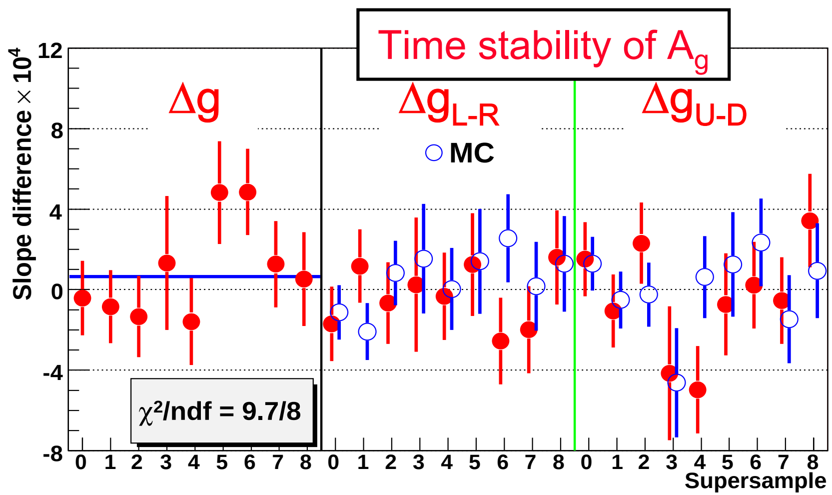
$$A_g^{\,0} = (1.8 \pm 1.7_{stat} \pm 0.6_{syst}) \times 10^{-4} = (1.8 \pm 1.8) \times 10^{-4}$$

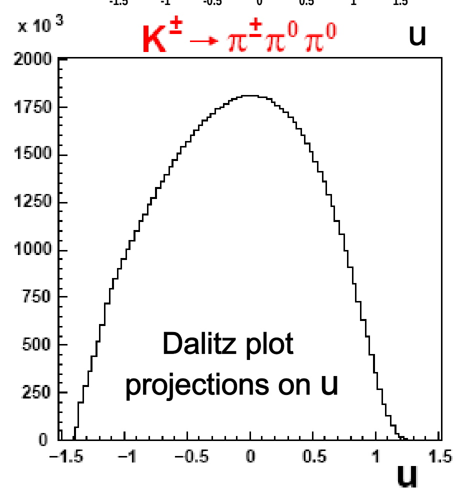
EPJ C52 (2007)

- Final result with the full NA48/2 data statistics (2003-04 run)
- Statistical precision in $A_g^{\,0}$ similar to $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ mode
- Results compatible with SM: no evidence for CPV due to NP
- Limits improved to one order of magnitude
    - NA48/2 design goal reached



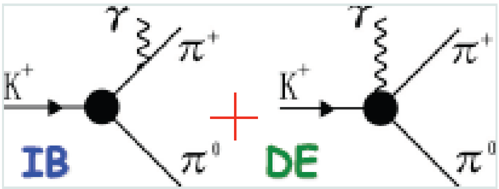






CP violation in $K^{\pm}\to\pi^{\pm}\pi^{0}\gamma$

- $K^{\pm}\to\pi^{\pm}\pi^{0}\gamma$: sources of γ radiation
  - Inner Bremmstrahlung and Direct Emission
  - Interference component: first evidence in NA48/2 $\Rightarrow$ E. Marinova, this conference



Kinematic Variable: $$W^2 = \frac{(P^*_\pi \cdot P^*_\gamma)(P^*_K \cdot P^*_\gamma)}{(m_K m_\pi)^2}$$

$$\frac{\partial \Gamma^{\pm}}{\partial W} = \frac{\partial \Gamma^{\pm}_{IB}}{\partial W}\Big[\underbrace{1}_{\text{IB}} + \underbrace{2\cos(\pm\phi + \delta^1_1 - \delta^2_0)\, m^2_\pi m^2_K\, |X_E|\, W^2}_{\text{INT}} + \underbrace{m^4_\pi m^4_K (|X_E|^2 + |X_M|^2)\, W^4}_{\text{DE}}\Big]$$

- A clean observable of direct CP violation is provided by the asymmetry between $K^{+}\to\pi^{+}\pi^{0}\gamma$ and $K^{-}\to\pi^{-}\pi^{0}\gamma$ decay widths (rates) and Dalits plots:
  - if $\phi \neq 0 \Rightarrow \Gamma(K^+) \neq \Gamma(K^-) \Rightarrow$ CP Violation

- SM prediction on asymmetry: 2×10^{-6}–10^{-5} for $50 < E^{\star}_{\gamma} < 170$ MeV.
- Possible SUSY contributions can push the asymmetry up to 10^{-4} in some W regions.

Search for CP violation in $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\gamma$

Summary of NA48/2 results on CP Violation in $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\gamma$

- Measurement of rate asymmetry (1.08 million events):

$$A_N = (\Gamma(K^+)-\Gamma(K^-))/(\Gamma(K^+)+\Gamma(K^-))$$
$$= (0.03 \pm 1_{stat} \pm 0.6_{sys})\cdot 10^{-3}$$
$$A_N < 1.5\cdot 10^{-3} \quad 90\%\ \text{C.L.}$$
PDG (2008): $(0.9\pm 3.3)\cdot 10^{-2}$

- First limit on $\sin\phi$:

$$\sin(\phi) = (-0.011\pm 0.43)$$
$$|\sin(\phi)| < 0.56 \quad 90\%\ \text{C.L.}$$

- Asymmetry in the W spectrum:

$$A_W = (-0.6 \pm 1_{stat})\cdot 10^{-3}$$

  - compatible with A_N
  - no evidence for CP asymmetry

Conclusions

Over 10 years, the NA48 experiment at CERN has carried out an extensive physics programme devoted to high precision study of CP violation (and rare decays) with both neutral and charged K

- Direct and Indirect CP Violation in neutral kaon decays (Direct CPV established)
- Precise $|\eta_{+-}|$ measurement (PDG revised)
- Search for direct CP violating charge asymmetry in $K^{\pm}\rightarrow 3\pi$ decays (order of magnitude improvement in precision)
- Search for CPV effects in radiative $K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\gamma$ decays
- All results all consistent with SM: no evidence for CPV effects due to NP
- However, matter-antimatter asymmetry of the universe requires additional sources of CP Violation generated by extensions to the Standard Model, to be measured as small deviations from it
- Quantitative tests of CKM mechanism and search for new physics beyond SM are needed and become possible with next generation K experiments:
    - Ultra-rare Kaon decay measurements ($K\rightarrow\pi\nu\nu$) $\Rightarrow$ G. Collazuol, this conference
    - J. Ocaritz, this conference (CKM): support kaon physics!