Bilan et perspectives du programme K chargés dans l'expérience NA48

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Outline

- L'expérience NA48/2: un peu d'histoire…
- Introduction aux faisceaux, détecteur et performances
- Les résultats de physique
  - Recherche de violation directe de CP
  - La matrice CKM
  - ★ Désintegrations rares (tests de ChPT)
  - Mesures precises de QCD basse energie: experiment vs theory
    - ★ **Ke4 decays ($K^{\pm} \rightarrow e^{\pm} \nu \pi^{+}\pi^{-}$) :**
      Form Factors, phase shifts and $\pi\pi$ scattering lengths
    - ★ **K3π decays ($K^{\pm} \rightarrow \pi^{\pm} \pi^{0}\pi^{0}$) :** the "cusp effect"
      Dalitz plot parameters and $\pi\pi$ scattering length
- Perspectives et futur du programme Kaon

Un peu d'histoire : les origines …

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

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noyau de Saclay
issu de E731

and more …

NA48

- 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 — K_S High Intensity — *NO Spectrometer*
- 2001 — ε'/ε run $K_L + K_S$ — K_S High Int.

Programme $K^\pm$ déjà anticipé en 1990

APPENDIX

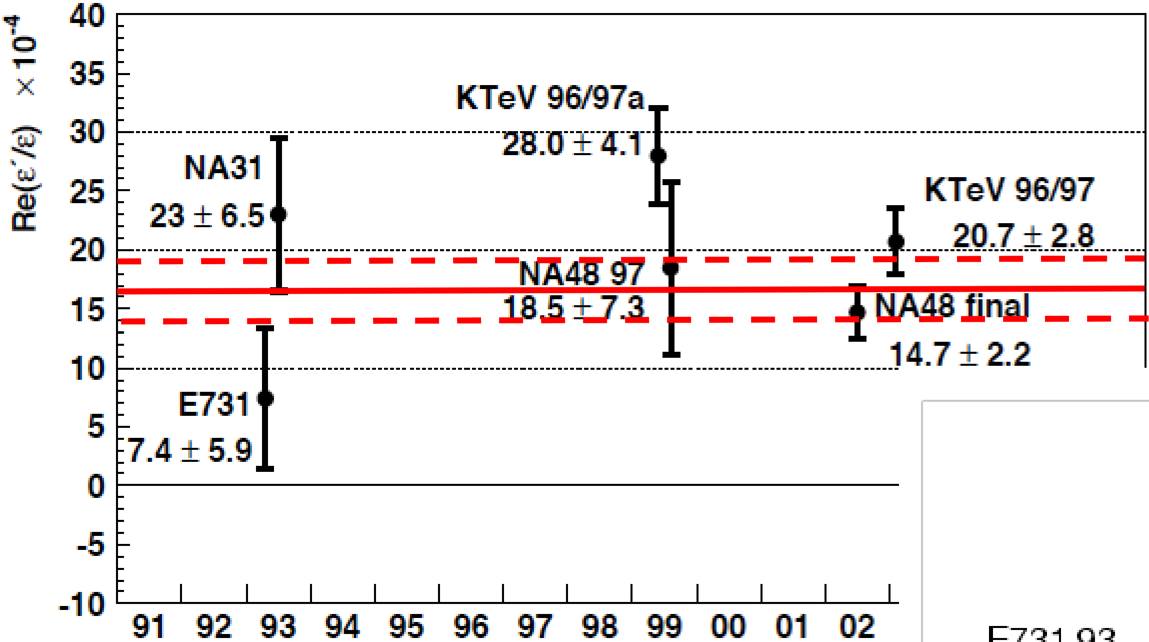
Study of CP violation asymmetries in $K^\pm \to 3\pi$ decays

In addition to causing a difference between $|\eta_{00}|^2$ and $|\eta_{+-}|^2$, direct CP violation is expected to produce an asymmetry in the C.M. energy distribution for pions of opposite charge from $K^\pm \to 3\pi$ decay.

For example, in a recent paper Bel'kov et al.[22] on the basis of the value of $\varepsilon'/\varepsilon = 3.3 \times 10^{-3}$ as measured by NA31, calculate:

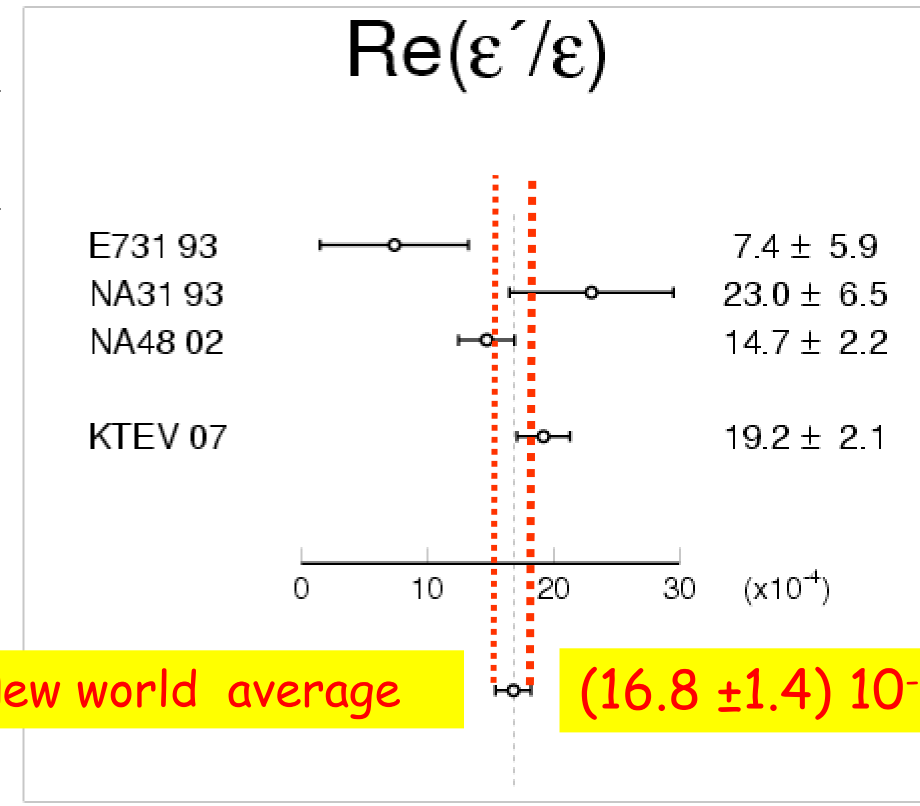
$$\Delta g = 1.4 \times 10^{-3}$$

NA48 : la fin de l'aventure CP avec les K^0



PDG 08 average :
$(16.5 \pm 2.6)\ 10^{-4}$

$$R = \frac{N(K_L \to \pi^0\pi^0) / N(K_S \to \pi^0\pi^0)}{N(K_L \to \pi^+\pi^-) / N(K_S \to \pi^+\pi^-)} = 1 - 6\, Re(\varepsilon'/\varepsilon)$$



Latest update by KTEV

New world average $(16.8 \pm 1.4)\ 10^{-4}$

Un peu d'histoire : la phase II   NA48/2

CERN/SPSC 2000-003
CERN/SPSC/P253 add.3
January 25, 2000

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

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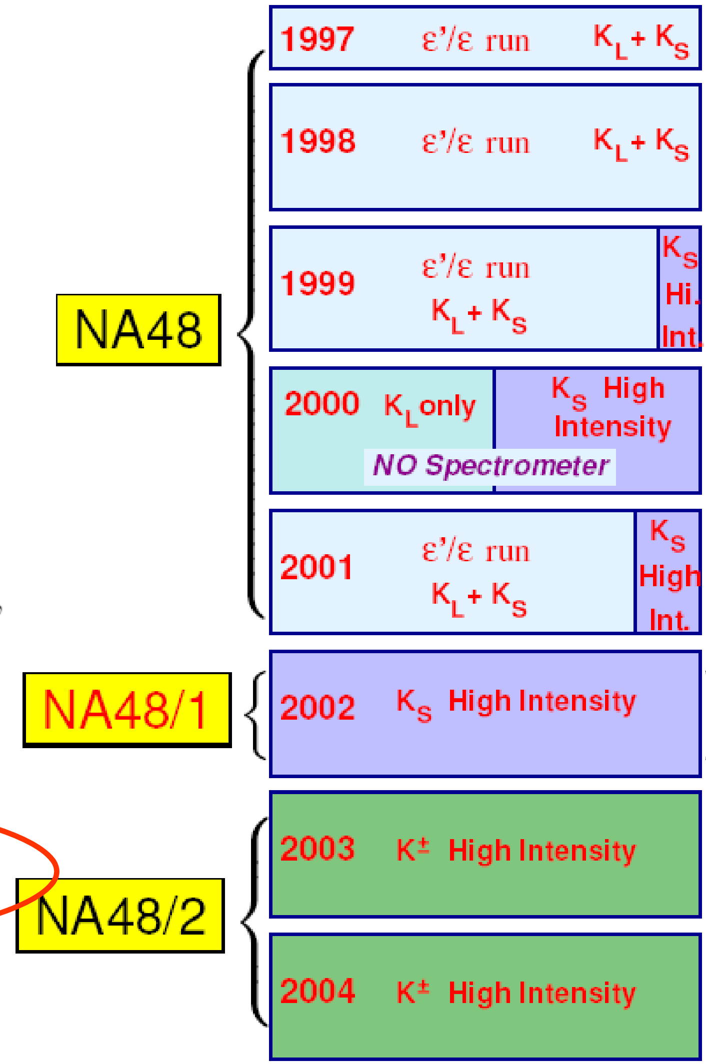
and many more people/institutes...



NA48/2 : les buts affichés du proposal

7.1 Expected results

The following main results are expected to be obtained in one year of running of the experiment with the simultaneous K^+/K^- beams:

1 – 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 will be be collected. 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. V

2 – More than 10^6 K_{e4}^c charged kaon decays will be reconstructed at the background level of $\sim 1\%$. 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 correspondingly improved. These data would allow the size of the QCD condensate to be established. V

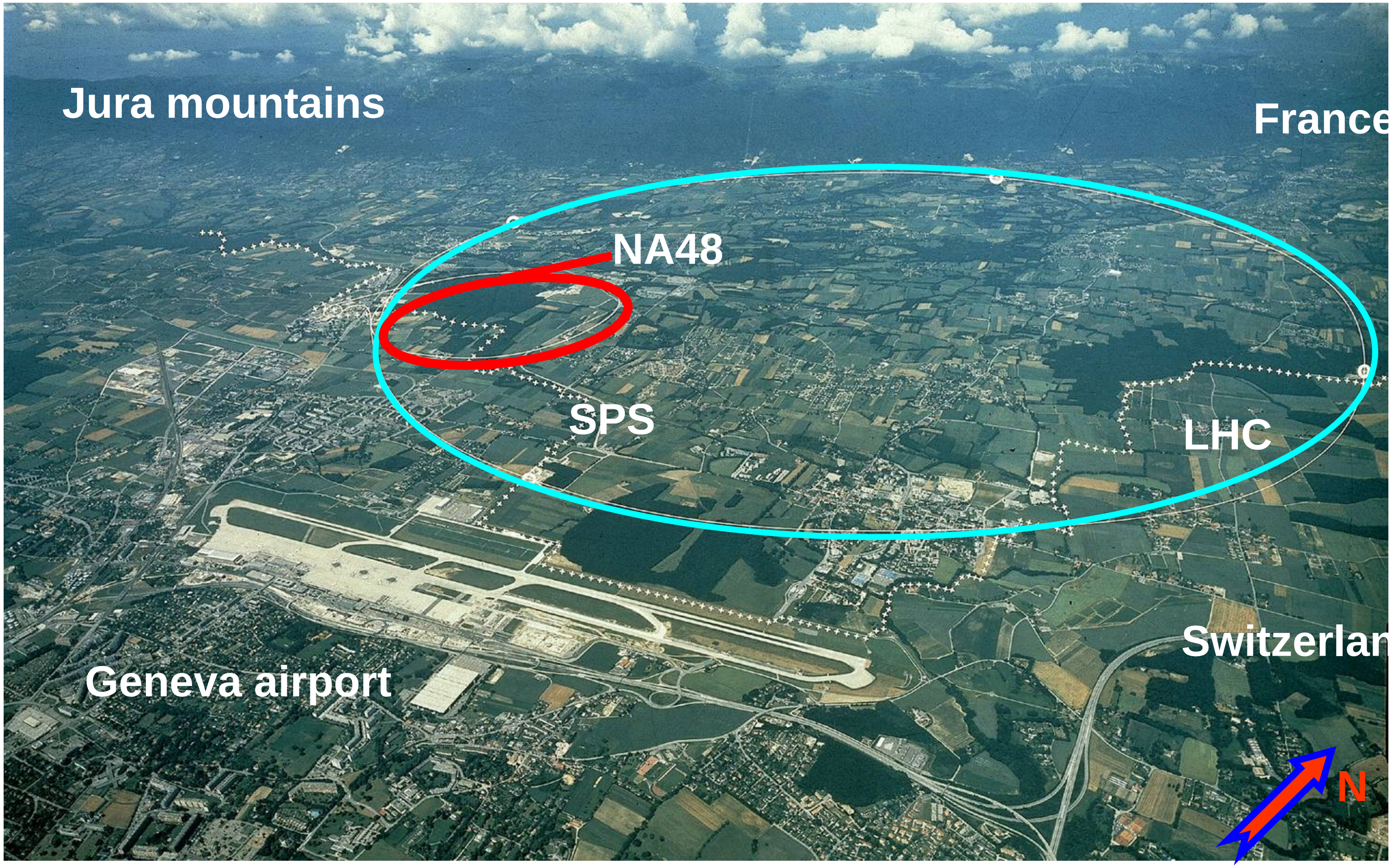
3 – Up to 10^5 and 10^4 of radiative decays $K^\pm \to \pi^\pm\pi^0\gamma$ and $K^\pm \to \pi^\pm\gamma\gamma$ will be collected, respectively. An upper limit on the $K^\pm \to \pi^\pm\gamma\gamma\gamma$ decay branching ratio of $\sim 10^{-6}$ could be established. These data would allow the ChPT parameters to be measured and an upper limit on the CP-violation asymmetry A_g' to be estimated. V

4 – More than 10^8 K_{e3}^c events to be recorded which would allow the scalar and tensor form-factors to be precisely measured.

+ more rare decays
+ unexpected effects …

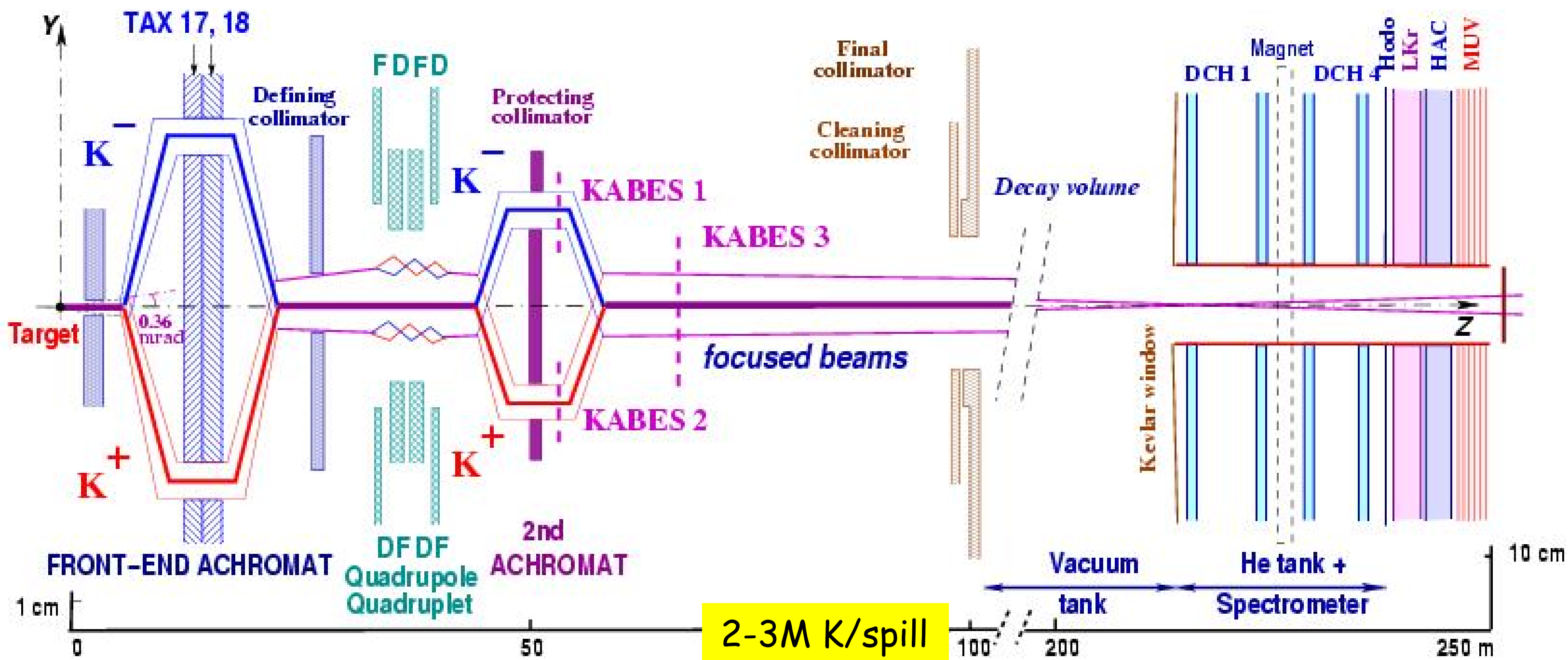
NA48/2 : a fixed target experiment at CERN dedicated to Kaon physics

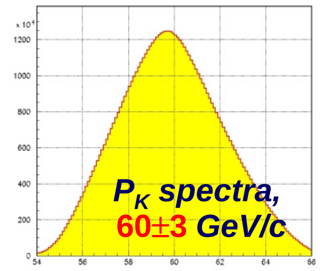
The NA48/2 collaboration: ~100 physicists from 15 Institutes in 8 countries
Cambridge, CERN, Chicago, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Saclay, Siegen, Torino, Wien



The NA48/2 experiment at the CERN-SPS :

2003 run: ~ 50 days + 2004 run: ~ 60 days and >200TB Data on tape

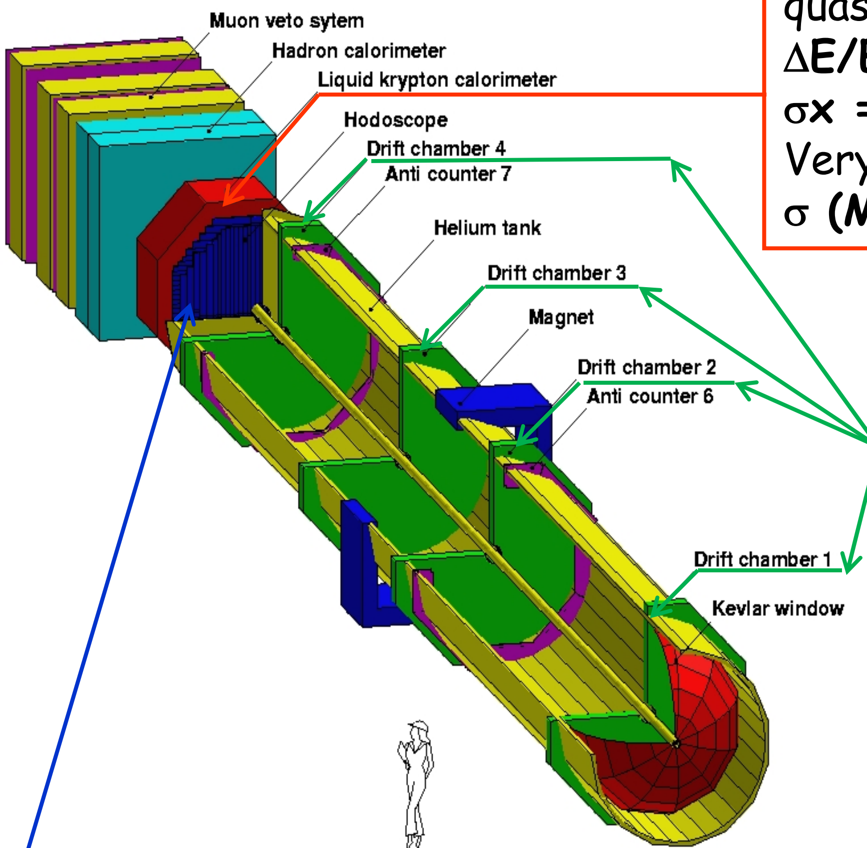




Simultaneous K^+ and K^- beams:
large charge symmetrization of experimental conditions

Beams coincide within ~1mm all along the 114m decay volume
flux ratio K^+/K^- ~1.8

The NA48/2 experiment: detector and performances



LKr electromagnetic calorimeter :
quasi-homogenous and high granularity
$\Delta E/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$ (E in GeV)
$\sigma x = \sigma y \sim 1.5$ mm for E=10 GeV
Very good resolution for neutrals ($\pi^0 \to \gamma\gamma$)
$\sigma(M\pi^0\pi^0) = 1.4$ MeV/c²

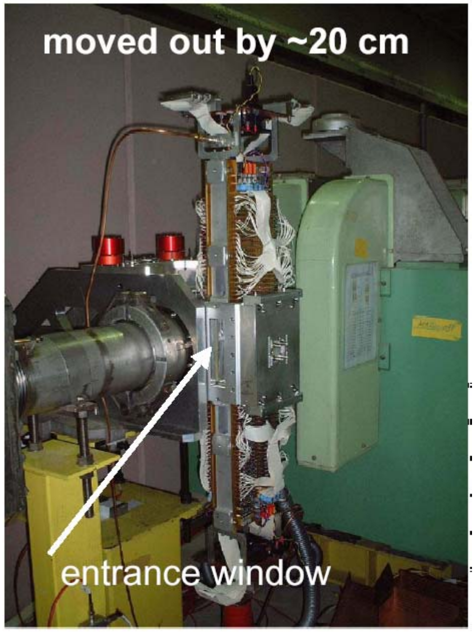
+

Magnetic spectrometer :
4 high-resolution DCH's + dipole magnet
$\Delta p/p = (1.0 \oplus 0.044\ p)\%$ (p in GeV/c)
Very good resolution for charged invariant masses: $\sigma(M3\pi^{\pm}) = 1.7$ MeV/c²

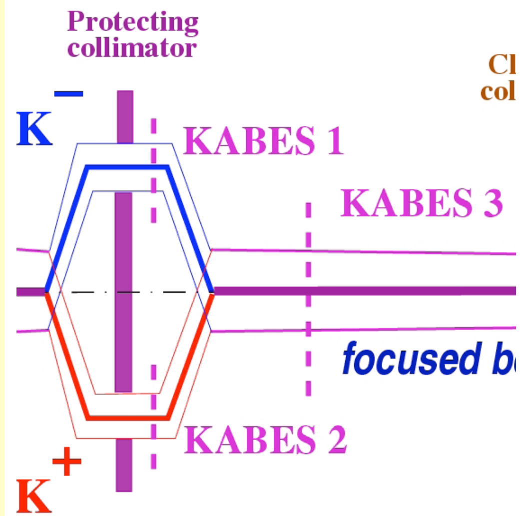
E/p ratio used for e/π discrimination

Hodoscope for charged fast trigger
$\sigma t = 150$ ps

The KABES beam spectrometer (contribution IRFU):

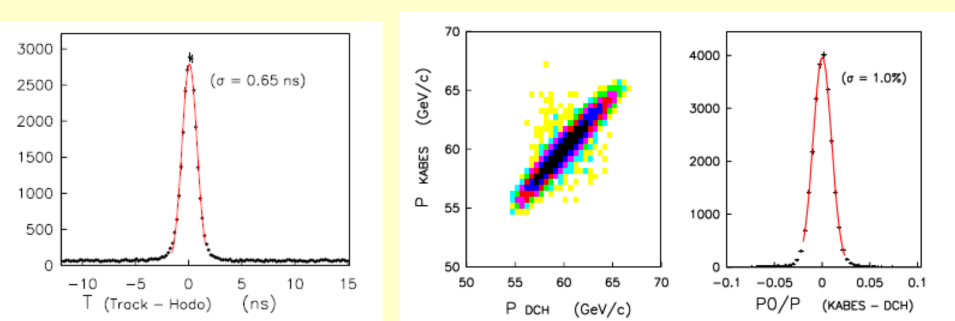


- 2 stations distant by 8 m along beam line
- Micromegas TPCs : transverse coordinates of charged tracks.
- upstream station: two doublets of detectors, KABES-1 (up) and KABES-2 (down), K+ /K- beams are separated in the achromat -> sign identification
- downstream station, KABES-3: one doublet of detectors, positive and negative particles are collinear + high rate environment
- rely on focusing properties of the beams to obtain the momentum of individual K^+ and K^- particles from the difference between the vertical coordinates recorded in KABES-1/2 and in KABES-3

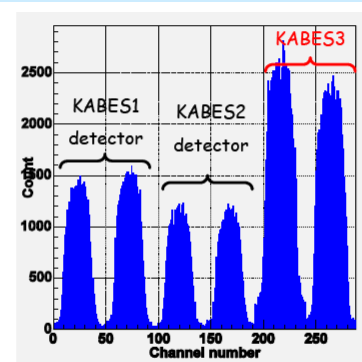


Rates in KABES-3:
38 10^6 positives
+26 10^6 negatives
= 64 10^6 per spill
and ~5% $K^\pm$

Performances : calibrate on fully reconstructed $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$



Time resolution
σt = 0.65 ns
momentum resolution
$\Delta p/p$ ~ 1% or better
Mistagging rate
~ 4%



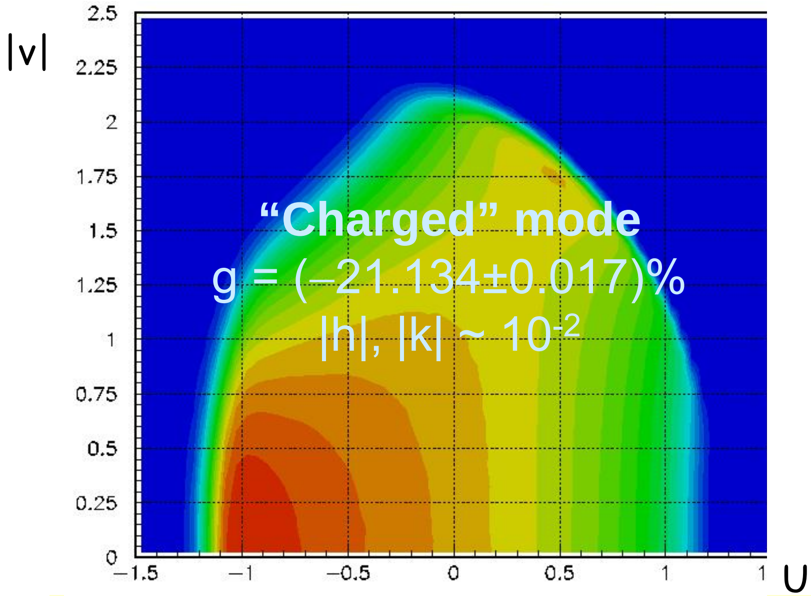
The CP Violating charge asymmetry in K3π decays

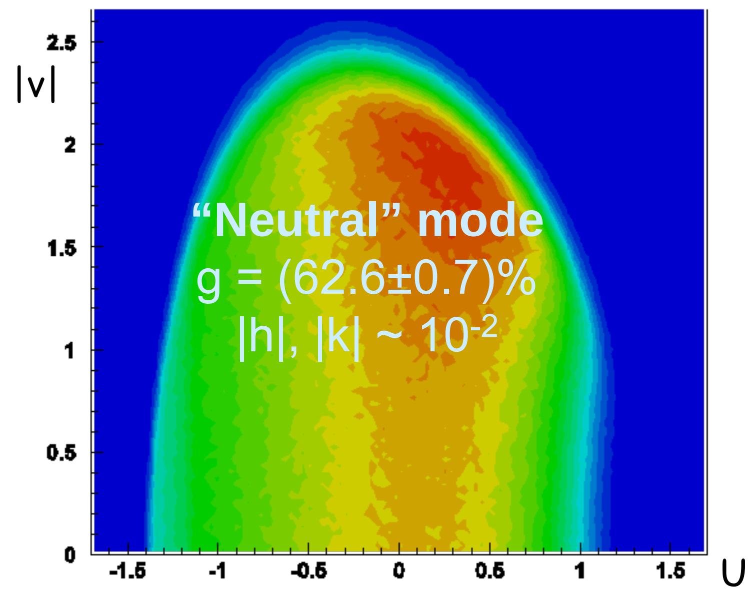
Only direct CPV in K± possible – mixing is not allowed

- Potentially large statistics: $BR(K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = 5.57\%$ $BR(K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}) = 1.73\%$
- Simple selection and low background
- Excellent mass resolution : 1.7 MeV/c2 for charged, 1.4 MeV/c2 for neutral mode

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

Neutral Matrix element:
$|M(u,v)|^2 \sim 1 + g_0u + h_0u^2 + k_0v^2$





Direct CP-violating quantity:
the slope asymmetry (K+ and K-)
$A_g = (g_+ - g_-)/(g_+ + g_-) = \Delta g/2g \neq 0$

Statistical precision in A_g^0 similar to "charged" mode:
Ratio of "neutral" to "charged" statistics: $N^0/N^{\pm} \sim 1/30$;
Ratio of slopes: $|g^0/g^{\pm}| \approx 3/1$;
Favorable Dalitz-plot distribution (gain factor $f \sim 1.5$).

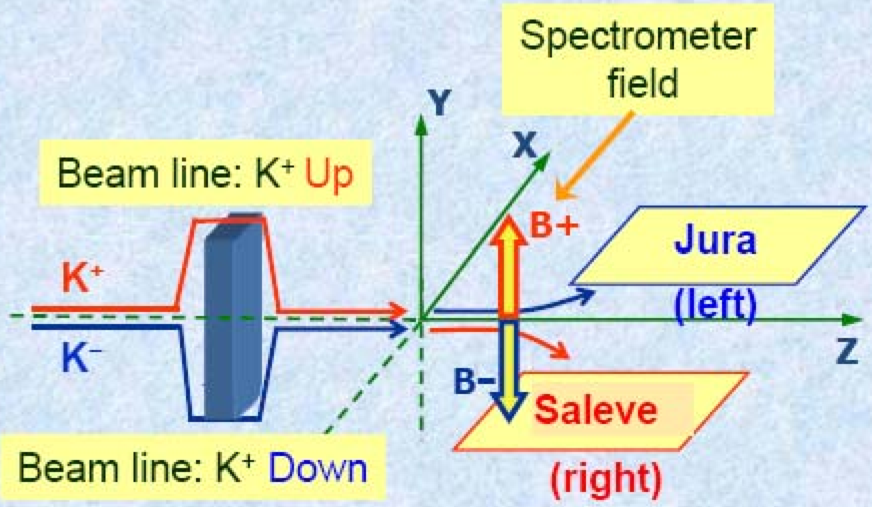
Method: the quadruple ratio product

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

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

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

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



$$R = R_{US} \cdot R_{UJ} \cdot R_{DS} \cdot R_{DJ} = f(u)$$

$$f(u) = n \cdot \left(1 + \frac{\Delta g u}{1 + gu + hu^2}\right)^4$$

- Cancellation of global time instabilities + local beam line biases (K+,K- simultaneously recorded)
- Cancellation of left-right detector asymmetries
- Cancellation of effect of permanent stray fields
- sensitive only to time variation in short time intervals
- independent of K+/K- flux ratio
- independent of relative sizes samples
- does not rely on a detailed MC acceptance calculation

CP Violating charge asymmetry in K3π decays: results

Charged mode: $3.11\ 10^9$ reconstructed evts

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

$A_g = (-1.5 \pm 1.5_{stat} \pm 0.9_{trig} \pm 1.1_{syst}) \times 10^{-4}$
$= (-1.5 \pm 2.2) \times 10^{-4}$

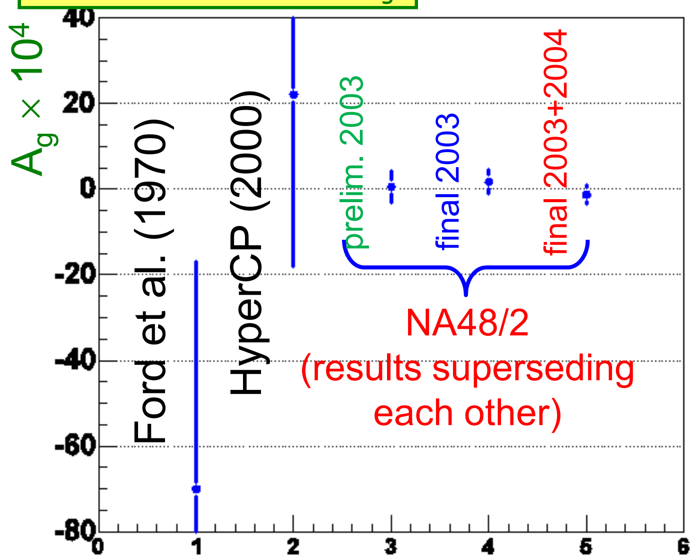
Neutral mode: $91.3\ 10^6$ reconstructed evts

$\Delta_{g0} = (2.2 \pm 2.1_{stat} \pm 0.7_{syst}) \times 10^{-4}$
$= (2.2 \pm 2.2) \times 10^{-4}$

$A_{g0} = (1.8 \pm 1.7_{stat} \pm 0.6_{syst})\ 10^{-4}$
$= (1.8 \pm 1.8)\ 10^{-4}$

- No evidence of direct CPV at the level of 2×10^{-4}
- order of magnitude improvement in precision
- results in agreement with the SM expectation (~1 ± 1) 10^{-5}
- precision limited mainly by statistics

Measurements of A_g

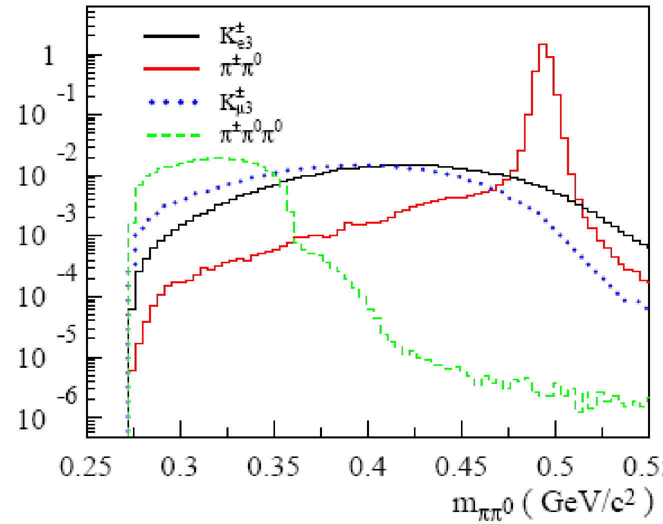


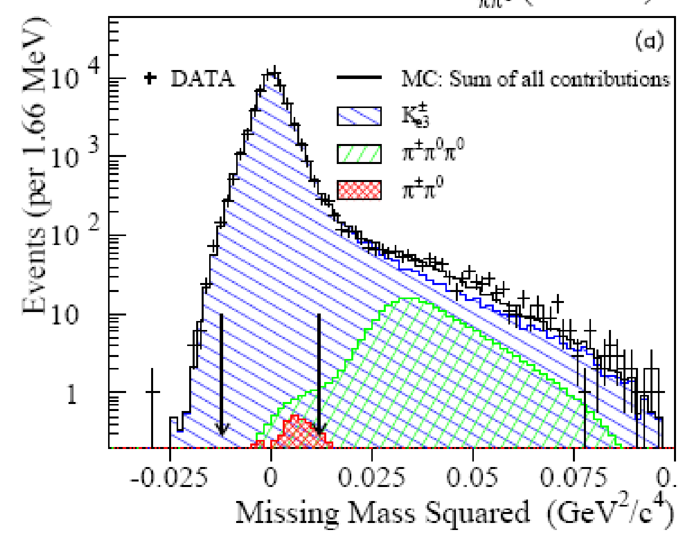
NA48/2 design goal reached
4 publications
PL B634 (2006), PL B638 (2006), PL B649 (2007), EPJ C52 (2007)
and several thesis

CKM matrix : semileptonic K decays (Ke3,Kμ3)

Minimum bias data taking in 2003:
•8 hours low intensity K+/K– with min. bias trigger.
•Measurement of hadronic and semileptonic decays.

Measurement method :
•Normalize Ke3 and Kμ3 to K2π
•very similar topologies and selection criteria.
•Select one track + two photons, consistent with a π0 from a common decay vertex.
•Distinction of Kl3 and K2π mainly through kinematics.





Decay channel	Acceptance × Part-ID	K^+	K^-	Backg level
$K^{\pm}\to\pi^0 e^{\pm}\nu$	~ 7.0%	56 195	30 898	<0.1%
$K^{\pm}\to\pi^0 \mu^{\pm}\nu$	~9.3%	49 364	27 525	~0.2%
$K^{\pm}\to\pi^{\pm}\pi^0$	~14.2%	461 837	256 619	~0.3%

CKM matrix : |Vus| from Kl3 decays

Flavianet : http://www.lnf.infn.it/wg/vus/

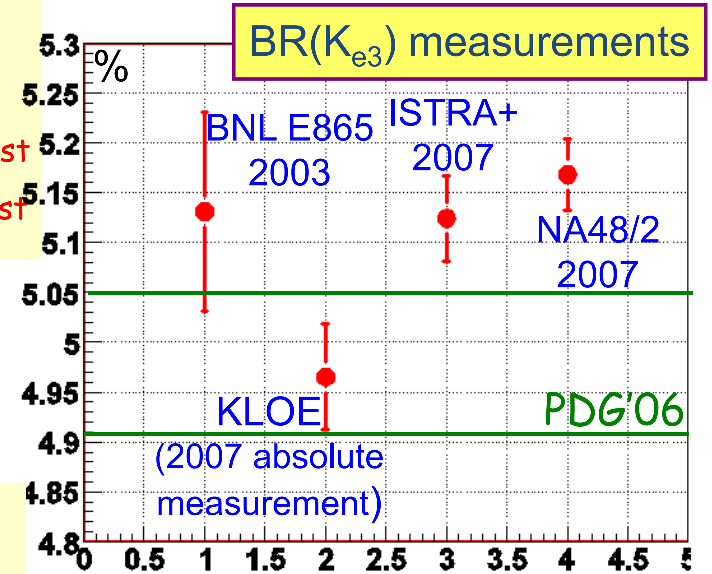
Results:

$BR(K_{e3})/BR(K^{\pm}\to\pi^{\pm}\pi^{0}) = 0.2470\pm0.0009_{stat}\pm0.0004_{syst}$

$BR(K\mu3)/BR(K^{\pm}\to\pi^{\pm}\pi^{0}) = 0.1637\pm0.0006_{stat}\pm0.0003_{syst}$

use PDG06 $BR(K^{\pm}\to\pi^{\pm}\pi^{0})$ to get absolute BR's

- agreement with other experiments normalizing to $\pi^{\pm}\pi^{0}$
- disagreement with absolute measurements (KLOE 07)
- slight disagreement with the PDG06



Use new KLOE measurement of Br(K2π) = 0.2065(5)(8), shifted (+0.06%)

$BR(K_{e3})$ = 0.05104 ± 0.00019stat ± 0.00008sys ± 0.00023norm

$BR(K\mu3)$ = 0.03380 ± 0.00013stat ± 0.00006sys ± 0.00015norm

Published EPJ C50(2007)
+ several thesis

Getting |Vus|:

$\Gamma(K_{l3}) = BR(K_{l3})/\tau_K \sim \delta_{em} |V_{us}|^2 |f_+(0)|^2 I_K (1+\delta_{SU2})$ with inputs from Flavianet

Ke3 : |Vus|f+(0) = 0.21794 (43)exp (52)norm (61)ext = 0.2179(9)

Kμ3 : |Vus|f+(0) = 0.21818 (46)exp (52)norm (66)ext = 0.2182(10)

Combined

|Vus| f+(0) = 0.2180 ± 0.0008

Using f+(0) = 0.964 ± 0.005 (RBC-UKQCD'07):

|Vus| = 0.2261 ± 0.0014

Rare Kaon Decays (non exhaustive list)

Interesting to test predictions from ChPT and possible insight into CP violation effects through K+/K- asymmetries

Mode	Status	BR	#evts	published? CPV?
Fully reconstructed modes				
• $K^\pm \to \pi^\pm\pi^0\gamma$	2 PhD (Silvia), (IB),DE,INT draft under review	$(10^{-4})10^{-6}$	600K	close √
• $K^\pm \to \pi^\pm \gamma\gamma$	2 PhD, draft being written	10^{-6}	6K	soon √
• $K^\pm \to \pi^\pm e^+ e^- \gamma$	1 diploma thesis, PLB 659 (2008)	10^{-8}	120	yes
• $K^\pm \to \pi^\pm e^+ e^-$	1 PhD, PLB 677 (2009)	10^{-7}	7.5K	yes √
• $K^\pm \to \pi^\pm \mu^+\mu^-$	1 PhD, analysis close to completion	10^{-7}	3K	soon
Missing neutrino modes				
• $K^\pm \to \pi^0 e^\pm \nu\gamma$	1 PhD, analysis close to completion (IB),DE	$(10^{-2})10^{-4}$	170K	close √
• $K^\pm \to \pi^+\pi^- e^\pm \nu$	1 PhD, EPJ C54 (2008) on 2003 stat.(670K)	10^{-5}	1130K	yes+soon√
• $K^\pm \to \pi^0\pi^0 e^\pm \nu$	1 diploma thesis, analysis to be completed	10^{-5}	40K	soon
• $K^\pm \to \pi^0\pi^0 \mu^\pm \nu$	1 diploma thesis, analysis to be completed	10^{-5}	5K	?

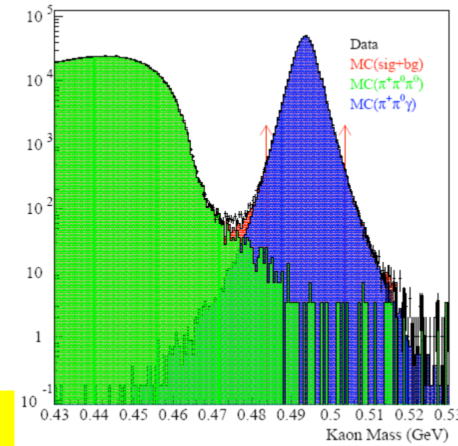
• and more …

Many first observations and improved measurements (better resolution and low background), two independent NA48 analyses required before blessing …

Study of $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ decays (Silvia's thesis, cotutelle Turin-Orsay)

Large statistics (600k), low background (<1%), extended kinematic range

NA48/2 Results: IB (dominant) + DE + INT
Frac(DE) $T^*\pi$(0-80)MeV= (3.32 ± 0.15stat ± 0.14sys)x10^{-2}
Frac(INT)$T^*\pi$(0-80)MeV= (-2.35 ± 0.35stat ± 0.39sys)x10^{-2}



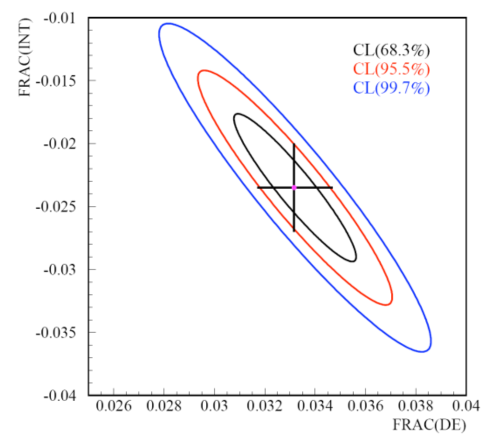
if INT =0 and $T^*\pi$(55-90) MeV
NA48/2 DE =(2.32±0.05stat±0.08sys)·10^{-6} 600K events
PDG 08 DE =(4.3±0.7) 10^{-6} ~30K events

First ≠ 0 observation/limit

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

$$\frac{\partial\Gamma^{\pm}}{\partial W} = \frac{\partial\Gamma^{\pm}_{IB}}{\partial W}\left[1 + \underbrace{2\cos(\pm\phi + \delta_1^1 - \delta_0^2) m_\pi^2 m_K^2 |X_E| W^2}_{\text{INT}} + m_\pi^4 m_K^4 (|X_E|^2 + |X_M|^2) W^4\right]$$

$$A_N = \frac{N_{\pi+\pi 0\gamma} - RN_{\pi-\pi 0\gamma}}{N_{\pi+\pi 0\gamma} + RN_{\pi-\pi 0\gamma}} \qquad R = \frac{N_{K+}}{N_{K-}}$$



A_N = (0.0 ± 1.0stat ± 0.6sys) 10^{-3} ⟹ $|A_N|$ < 1.5 10^{-3} @ 90% CL

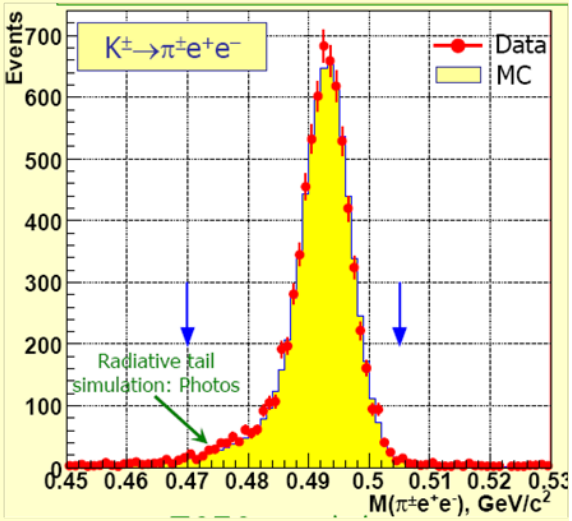
$\sin(\Phi)$ = (-0.01 ± 0.43) ⟹ $|\sin(\Phi)|$<0.56 @ 90% CL

Study of $K^{\pm} \to \pi^{\pm} e^{+}e^{-}$ decays (emotional attachment to my 1st experiment ..)

$K^{\pm} \to \pi^{\pm} \gamma^{*} \to \pi^{\pm} l^{+} l^{-}$: suppressed FCNC process proceeding through single virtual photon exchange.

$$d\Gamma_{\pi ee}/dz \sim P(z) \cdot |W(z)|^2$$

$z=(M_{ee}/M_K)^2$, $P(z)$ is a phase space factor

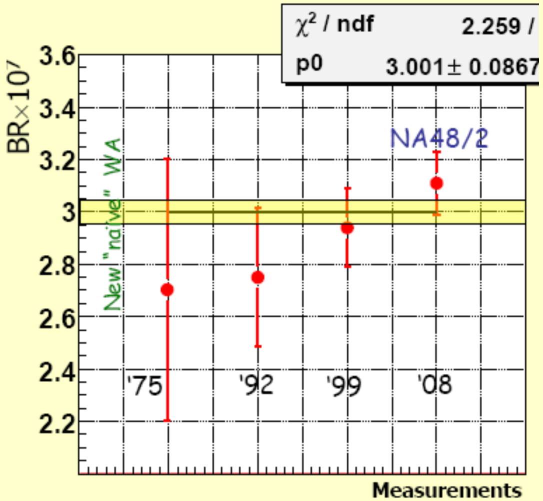


7253 events with ~1% background

BR = $(3.11 \pm 0.04_{stat} \pm 0.05_{syst} \pm 0.08_{ext} \pm 0.07_{model}) \times 10^{-7}$
= $(3.11 \pm 0.12) \times 10^{-7}$

CPV parameter (only uncorrelated K+/K– uncertainties):
$\Delta(K\pm\pi ee) = (BR+ - BR-) / (BR+ + BR-) = (-2.1 \pm 1.5_{stat} \pm 0.6_{syst}) \times 10^{-2}$

measurement	sample	BR x 10^7
Bloch et al. PL 56(1975) B	41 (K^+)	2.70 ± 0.5
Alliegro et al. PRL 68 (1992)	500 (K^+)	2.75 ± 0.26
Appel et al. [E865], PRL 83 (1999)	10300 (K^+)	2.94 ± 0.15
NA48/2 PL B677(2009) 246	7300 ($K^{\pm}$)	3.11 ± 0.12



Low energy QCD tests in the $\pi\pi$ system

Hadronic decay modes into 3 pions: (L.Di Lella seminar 12 Oct 2005)

- large Br's : $K^{\pm} \rightarrow \pi^0\pi^0\pi^{\pm}$ (1.7 %) and $K^{\pm} \rightarrow \pi^+\pi^-\pi^{\pm}$ (5.6 %),

60 Millions events now analyzed (PRL B633 (2006) partial sample)

- three pions : $\pi^0\pi^0$ system + nearby hadron (cusp effect)
- accessible $M_{\pi\pi}$ range from $\pi^0\pi^0$ threshold to (M_K-M_π)

Semileptonic decay mode Ke4: (big investment from SPP)

- small Br's : $K^{\pm} \rightarrow \pi^+\pi^- e^{\pm}\nu$ ($4.1\ 10^{-5}$),

1.1 Million events now analyzed (EPJC 54 (2008) partial sample)

- only two $\pi^+\pi^-$ pions, very clean environment
- accessible $M_{\pi\pi}$ range from $\pi^+\pi^-$ threshold to $(M_K-M_e) \cong M_K$

Two different but complementary approaches to $\pi\pi$ scattering near threshold to extract s-wave scattering lengths (a0, a2) for Isospin I = 0 and I = 2

Theoretical motivations

Standard Model

L weak

L QCD

L QED

L QCD = Lsym + Lnon-sym
(Chiral symmetry)

High energy

Perturbative QCD:
L QCD (q,g)
Expansion in coupling
Test of Lsym

Low energy

ChPT:
L eff (π,K,η)
Expansion in mass & momentum
Test of Lnon-sym and Lsym

Tree (p^2), 1-loop (p^4), 2-loop (p^6)

Spontaneous symmetry breaking

LEC l3bar,l4bar computed by lattice QCD

Quark condensate

$$M_\pi^2 = M^2\left(1 - \frac{M^2}{32\pi^2F^2}\bar{\ell}_3 + O(p^4)\right)$$

$$M^2 \equiv -\frac{m_u + m_d}{F^2}\langle 0|\bar{q}q|0\rangle$$

Gell-Mann, Oakes, Renner (68)

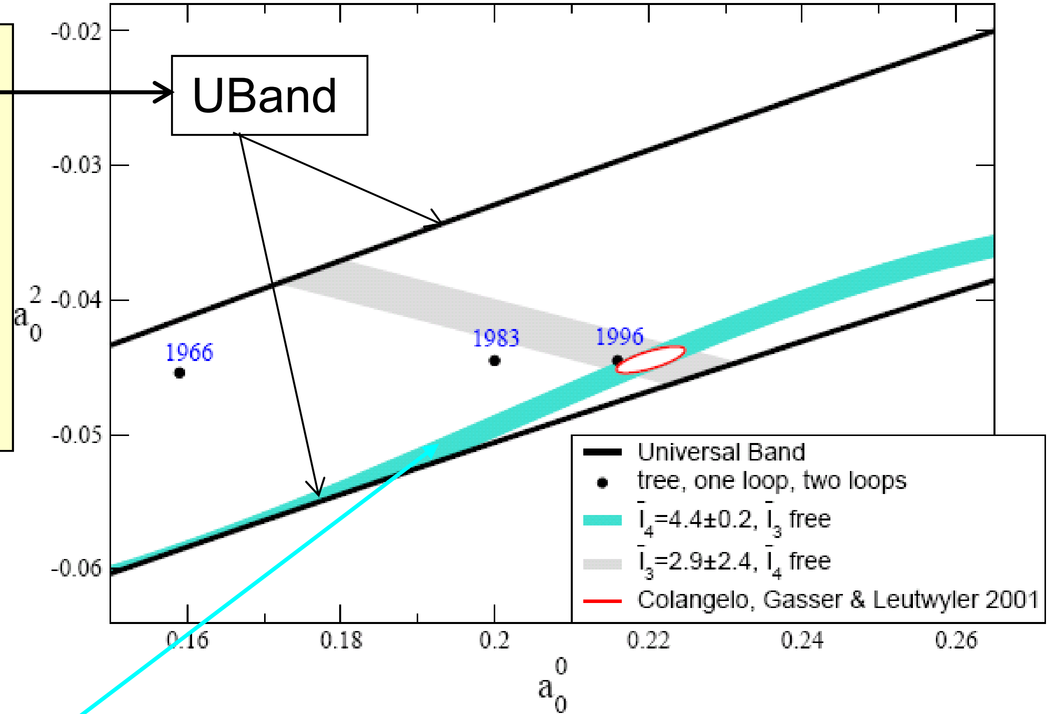
$$F_\pi = F\left(1 + \frac{M^2}{16\pi^2F^2}\bar{\ell}_4 + O(p^4)\right)$$

ππ scattering lengths

In the π π scattering process, it is possible to relate amplitudes with different Isospin using dispersion relations (Roy equations) which depend essentially on two subtraction constants, the s-wave scattering lengths a_0 and a_2 . Numerical solutions developed in Bern ACGL(2001) and Orsay DFGS (2002)

Universal Band :

$a_2 = (-0.0849 + 0.232\, a_0 - 0.0865\, a_0^2) \pm 0.0088$



ChPT predictions for low energy ππ interaction introduce further constrains between a_0 and a_2

ChPT band:

$a_2 = (-0.0444 + 0.236\,(a_0 - 0.22) - 0.61\,(a_0 - 0.22)^2 - 9.9\,(a_0 - 0.22)^3) \pm 0.0008$

Most precise predictions from ChPT (CGL 2001)

$a_0 = 0.220 \pm 0.005$

$a_2 = -0.0444 \pm 0.0008$

or in other words $(a_0 - a_2) = 0.264 \pm 0.004$

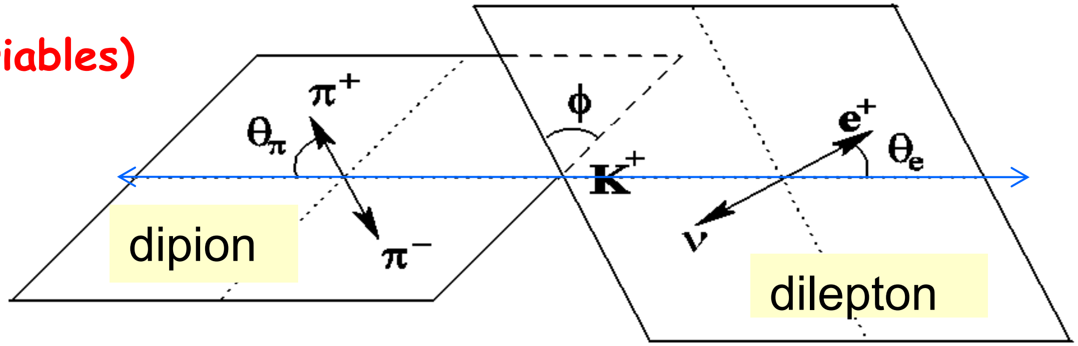
Ke4 decays : formalism

Five kinematic variables (Ca.Ma. variables)

(Cabibbo-Maksymowicz 1965)

S_π ($M^2_{\pi\pi}$), S_e ($M^2_{e\nu}$),

$\cos\theta_\pi$, $\cos\theta_e$ and ϕ.



Partial Wave expansion of the amplitude into s and p waves (Pais-Treiman 1968)
+ Watson theorem (T-invariance) for δ_ℓ^I

$$\delta_0^0 \equiv \delta_s \text{ and } \delta_1^1 \equiv \delta_p$$

F, G = 2 Axial Form Factors

$F = F_s\, e^{i\delta s} + F_p\, e^{i\delta p} \cos\theta_\pi$

$G = G_p\, e^{i\delta g}$

H = 1 Vector Form Factor

$H = H_p\, e^{i\delta h}$

F, G, H are complex

Map the distributions of the Ca.Ma. variables in the **five-dimensional space** with 4 Form factors and one phase shift , assuming identical phases for the p-wave Form Factors F_p, G_p, H_p:

The fit parameters are :

F_s F_p G_p H_p and $\delta = \delta_s - \delta_p$

(F_s , F_p , G_p, , H_p are real)

Ke4 decays: event selection and background rejection

Signal ($\pi^+\pi^- e^{\pm} \nu$) topology:
- 3 charged tracks and a good vertex
- two opposite sign pions,
- 1 electron (E(LKr) /p ~ 1),
- some missing energy and p_T (ν)
- reconstruct PK (missing ν hypothesis)

Background main sources :

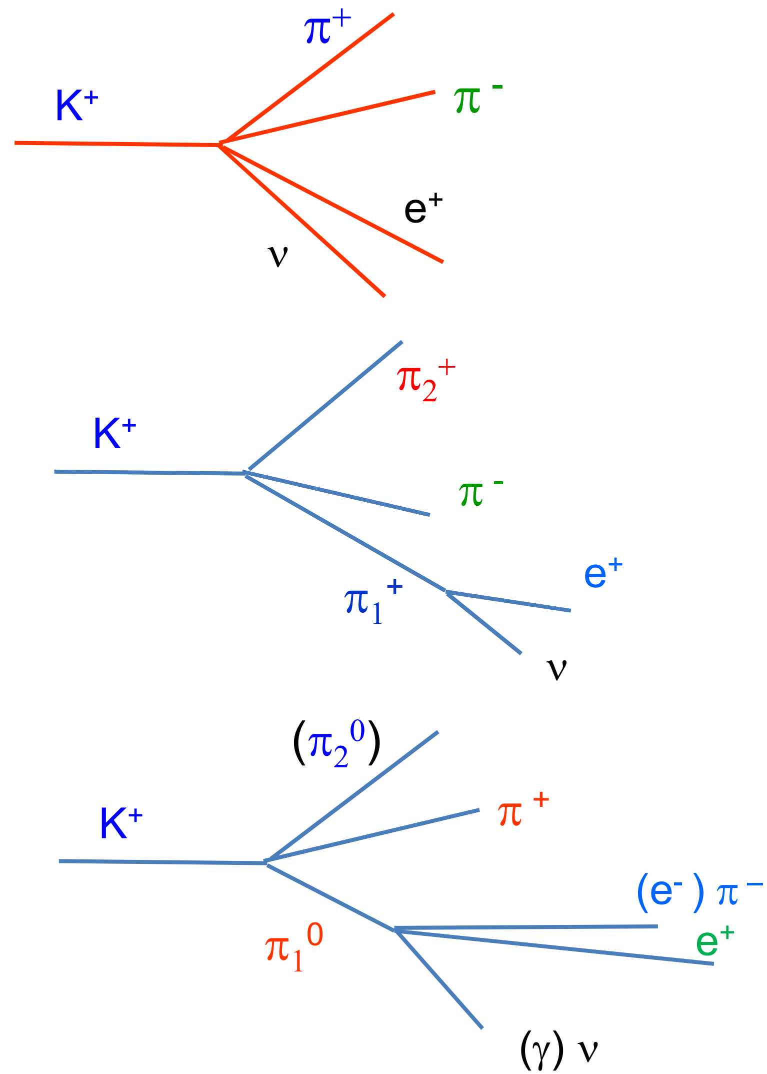
$K^+ \rightarrow \pi^- \quad \pi_2^+ \quad \pi_1^+$ (dominant)

↳ $e^- \nu$ or mis-ident e^-

$K^+ \rightarrow \pi^0 (\pi^0) \pi^+$

↳ ($e^+e^-\gamma$)

↳ mis-ident π^+ and γ (s) undetected



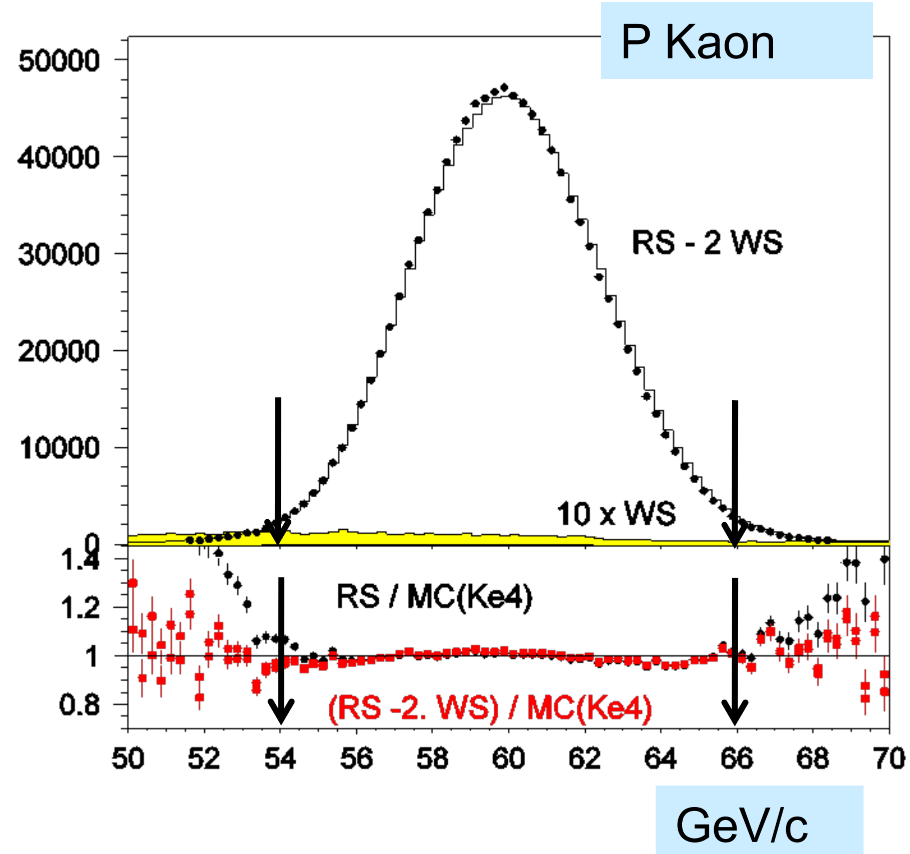
Ke4 decays: background rejection

Control sample from data
(assuming $\Delta S=\Delta Q$ valid)
$K^{\pm} \rightarrow \pi^{\pm}\pi^{\pm}e^{\mp}\nu$ "Wrong Sign" events
- total charge (±1) as "Right Sign" events
- electron charge opposite to total charge
- same sign pions

Ratio (RS/WS) events:

2/1 if coming from $K3\pi$ (dominant)

1/1 if coming from $K2\pi$ (π^0)



Total background level can be kept at ~ 2 x 0.3 % relative level
estimated from WS events rate and checked from MC simulation

Ke4 decays : fitting procedure

Total (2003+2004) 1.13 Million Ke4 decays

Using iso-populated boxes in the 5-dimension space of the Ca.Ma. variables, ($M_{\pi\pi}$, $M_{e\nu}$, $\cos\theta_\pi$, $\cos\theta_e$ and ϕ) one defines a grid of

10x5x5x5x12=15000 variable size boxes.

In each $M_{\pi\pi}$ "slice" (1500 boxes), a set of 4 fit parameters is found which minimizes the difference between the data and predicted populations

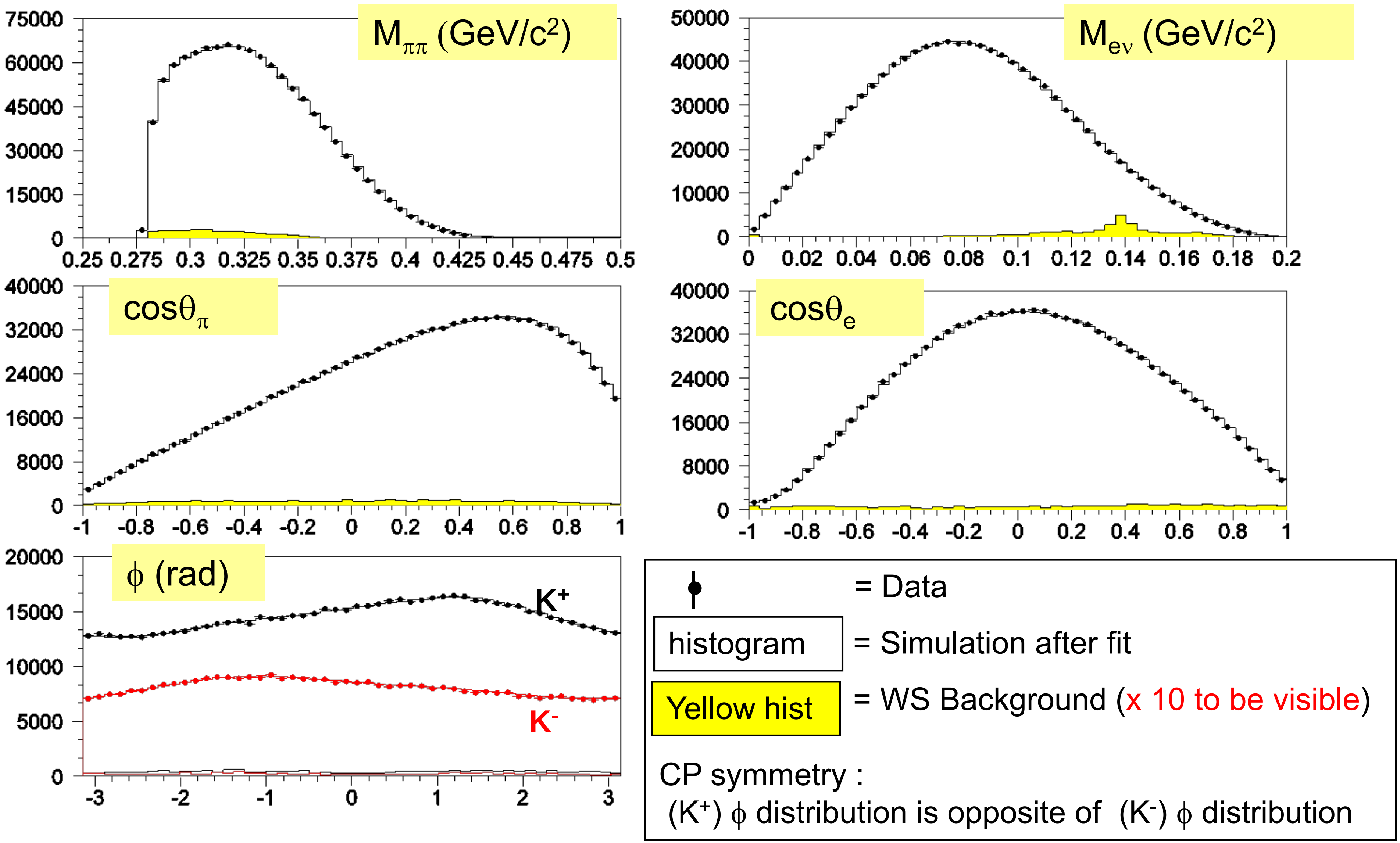
The normalisation F_s^2 is obtained in each bin/slice by the ratio $x_{slice} = \Sigma_{j \text{ in slice}} Nj/\Sigma_{j \text{ in slice}} MCj$

Data sample	MC sample
K^+ sample (726 400 events) 48 events/box	K^+ MC (17.4 Million events) 1160 events/box
K^- sample (404 400 events) 27 events/box	K^- MC (9.7 Million events) 650 events/box

K^+ and K^- samples fitted separately in 10 independent $M_{\pi\pi}$ bins/slices, then combined in each slice according to their statistical error.

No assumption is made on the shape of the variation of the phase δ (and FF) from one $M_{\pi\pi}$ slice to the next (i.e. "model independent" analysis)

Ke4 decays : Data/MC comparison after fit



Ke4 Form Factors : fit results

Series expansion with q^2 ($q^2 = S_\pi/4m_\pi^2 - 1$) and $S_e/4m_\pi^2$ used to describe the FF variations, in the isospin symmetry limit (Amoros Bijnens 1999)

$$F_s^2 = f_s^2(1 + f_s'/f_s\, q^2 + f_s''/f_s\, q^4 + f_e'/f_s\, S_e/4m_\pi^2)^2$$

Correlation	f_s''/f_s	f_e'/f_s
f_s'/f_s	-0.95	0.08
f_s''/f_s		0.02

$$G_p/f_s = g_p/f_s + g_p'/f_s\, q^2$$

Correlation -0.91

Preliminary (2003+2004)

	value	stat	syst
f_s'/f_s	0.152	± 0.007	± 0.005
f_s''/f_s	-0.073	± 0.007	± 0.006
f_e'/f_s	0.068	± 0.006	± 0.007
f_p/f_s constant	-0.048	± 0.003	± 0.004
g_p/f_s	0.868	± 0.010	± 0.010
g_p'/f_s	0.089	± 0.017	± 0.013
h_p/f_s constant	-0.398	±0.015	± 0.008

first evidence by NA48

systematics

- mostly from background + acceptance control
- ~ same size as statistical error or smaller

Ke4 decays: from phase shifts to scattering lengths (a_0,a_2)

$\pi\pi$ phases at threshold can be predicted from data above 0.8 GeV using **Roy equations** (unitarity, analyticity and crossing symmetries) and 2 subtraction constants **a_0 and a_2**

Numerical solutions have been developed (ACGL, DFGS) valid in the **Isospin symmetry limit (Universal Band in the [a_2,a_0] plane)**, but broken in the experimental world.

factorization of electromagnetic and mass effects :

Gamow factor x PHOTOS generator x Isospin corrections

Radiative effects (except mass effects) included in the simulation,

Gamow factor : "classical" Coulomb attraction between the 2 charged pions

PHOTOS generator: real photon(s) are emitted and tracked in the simulation

(-> effect on event selection + possible bias on reconstructed quantities)

Mass effects:

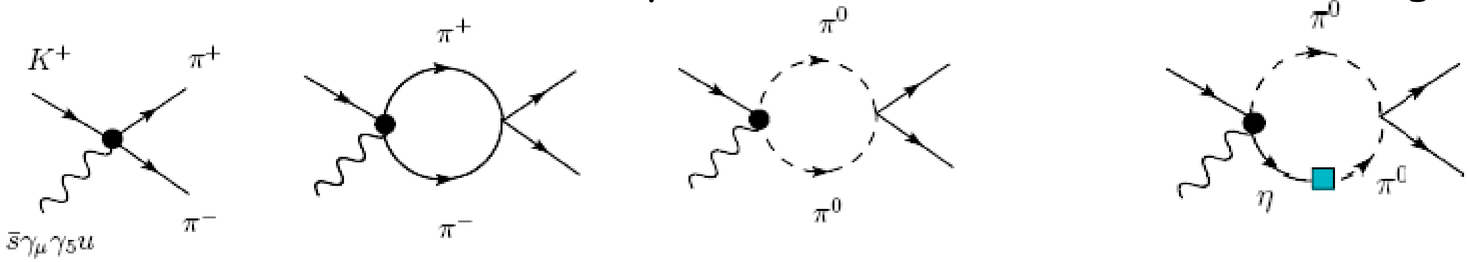
- recently computed as a correction to the measurements
- even larger than current experimental precision !

(CGR EPJ C59 (2009) 777,
DK preliminary June 2008 in progress)

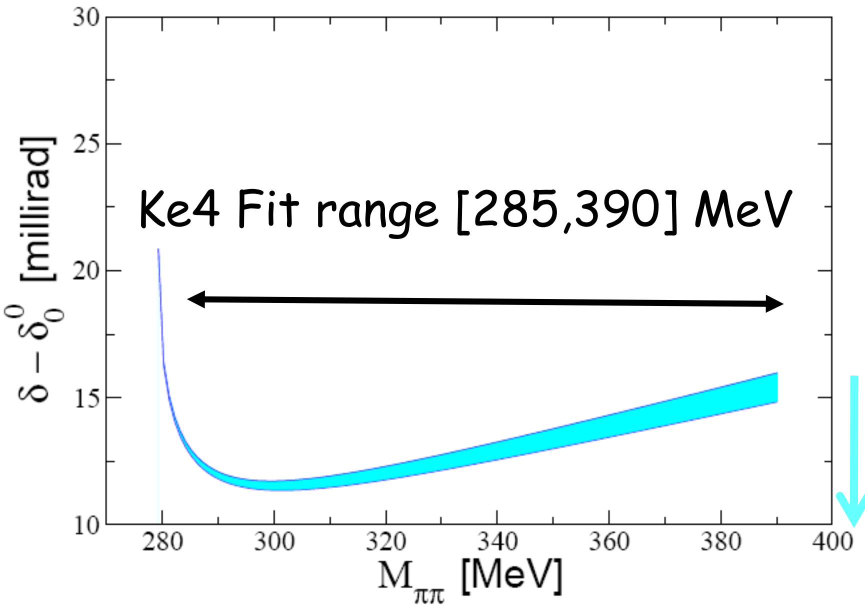
Ke4 charged decays : isospin corrections to δ

CGR EPJ C59 (2009) 777 formulation developed in close contact with NA48

tree | one loop | π^0–η mixing



$\delta_0^0 \rightarrow$ $$\delta = \frac{1}{32\pi F^2}\left\{(4\Delta_\pi + s)\sigma + (s - M_{\pi^0}^2)\left(1+\frac{3}{2R}\right)\sigma_0\right\}$$



$$\Delta_\pi = M_{\pi^+}^2 - M_{\pi^0}^2,$$

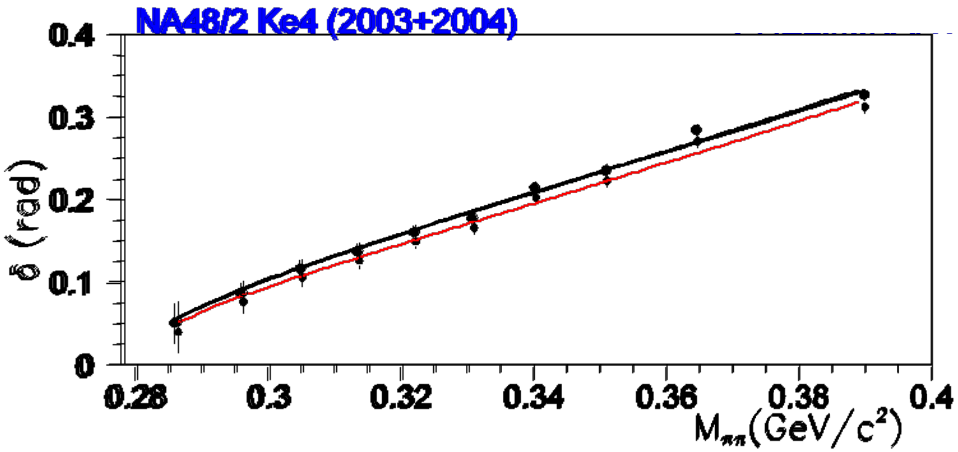
$$\sigma = \sqrt{1 - \frac{4M_\pi^2}{s}},$$

$$R = \frac{m_s - \hat{m}}{m_d - m_u}$$

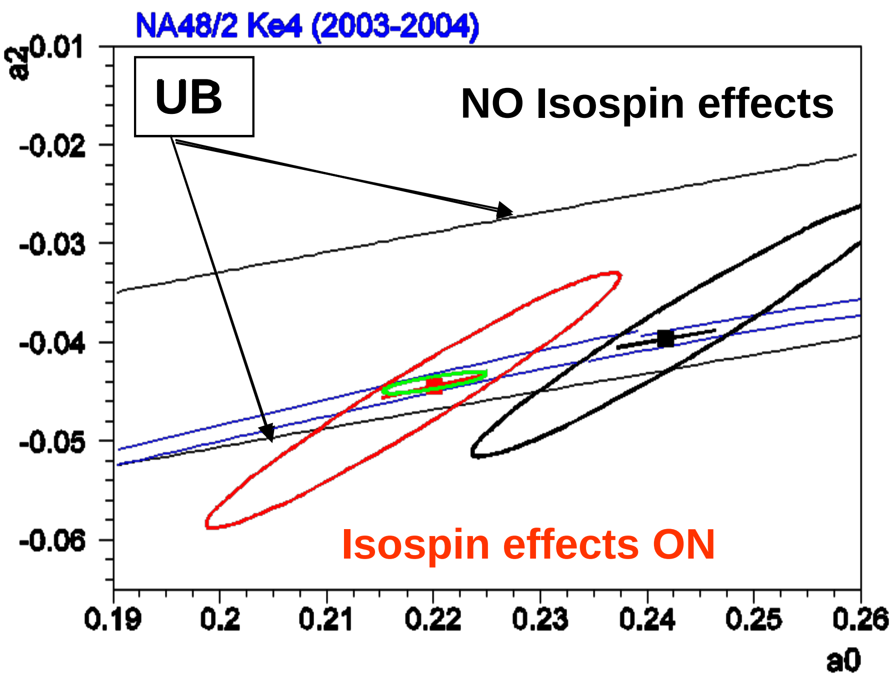
Correction is ~ 10-15 mrad

Exp. stat precision (δ) is ~ 7-8 mrad

Ke4 decays: from phase shifts to scattering lengths (a_0,a_2)



a tiny effect from theory…. a big change in now precise experimental measurement !



This induces a large **change** on (a_0,a_2) values

from a 2p fit			from a 1p fit	
Δa_0 = -0.025, Δa_2 = -0.007			Δa_0 = -0.022	
error	stat	syst	stat	syst
$\sigma(a_0)$:	± 0.0128	± 0.0050	± 0.005	± 0.002
$\sigma(a_2)$:	± 0.0084	± 0.0034		

Ellipses are 68% CL contours in 2p fits (statistical error only)

Ke4 decays: comparison with theoretical predictions

Preliminary (2003+2004)

THEORY prediction (green ellipse)

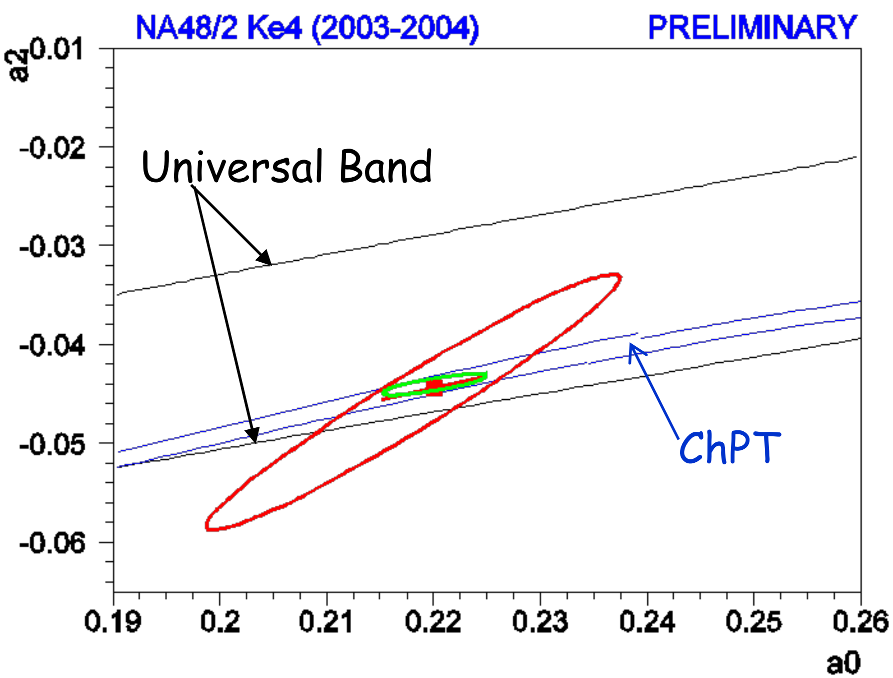
Using more inputs from ChPT and low energy constants, the prediction is better constrained (CGL NPB603(2001),PRL86(2001)):

$$a_0 = 0.220 \pm 0.005$$

$$a_2 = -0.0444 \pm 0.0008$$

Experimental measurement

a_0 ChPT 1p fit	0.2206 ± 0.0049 stat ± 0.0018 syst ± 0.0064 theo *
a_0 free	0.2220 ± 0.0128 stat ± 0.0050 syst ± 0.0037 theo*
a_2 free 2p fit	-0.0432 ± 0.0086 stat ± 0.0034 syst ± 0.0028 theo*
	Correlation 96.7%



*Theory error evaluated from control of the isospin corrections & inputs to Roy equation numerical solutions (CGR EPJ C59 (2009)777)

Comparison of Ke4 phase shift experimental measurements

Apply Isospin corrections (10-15 mrad) to all published points :

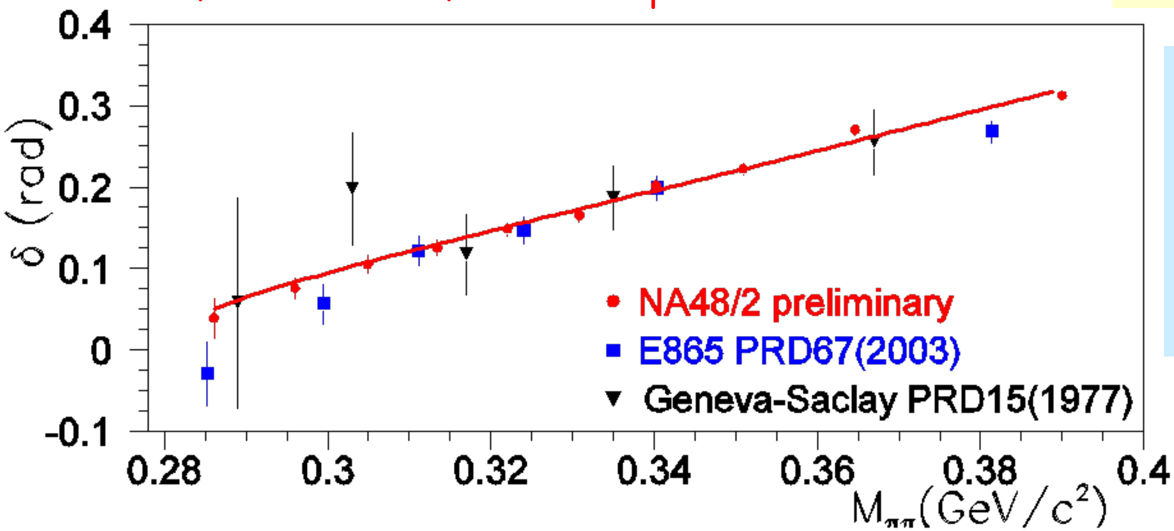
S118 (Geneva-Saclay): typical error 40-50 mrad

E865: typical error 15-20 mrad

Correction small wrt experimental error but coherent shift downwards for all data points

NA48/2 typical error 7-8 mrad

improved precision due to both
- -larger statistics ~3 x E865
- -larger acceptance at high $\pi\pi$ mass



- •All Phase points corrected for isospin mass effects
- •Independent experiments
- •Errors = stat + syst

Line from a 2p fit to NA48 data alone

Fit to all data points (21 points) : dominated by NA48/2 measurements

2p fit:

$a_0 = 0.2199 \pm 0.0125_{exp} \pm 0.0037_{theo}$

$a_2 = -0.0430 \pm 0.0083_{exp} \pm 0.0028_{theo}$

1p fit :

$a_0 = 0.2168 \pm 0.0048_{exp} \pm 0.0064_{theo}$

(theory error common to all expts)

Cusp effect in $K^{\pm} \rightarrow \pi^0 \pi^0 \pi^{\pm}$: first observation

In $K^{\pm} \rightarrow \pi^0 \pi^0 \pi^{\pm}$ decay, the matrix element is usually described as a polynomial expansion using the Dalitz Plot variables u and v

$u = (s_3 - s_0)/m_p^2$ $v = (s_2 - s_1)/m_p^2$

$s_0 = (s_1 + s_2 + s_3)/3$ $s_i = (P_K - P_{pi})^2 = M_{jk}^2$

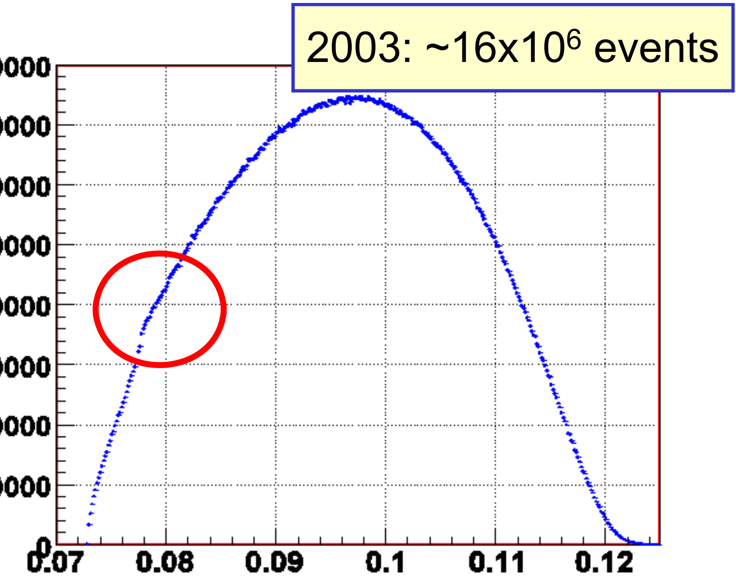
$|M_0|^2$ (PDG) ~ $1 + gu + hu^2 + kv^2$ (PDG) or

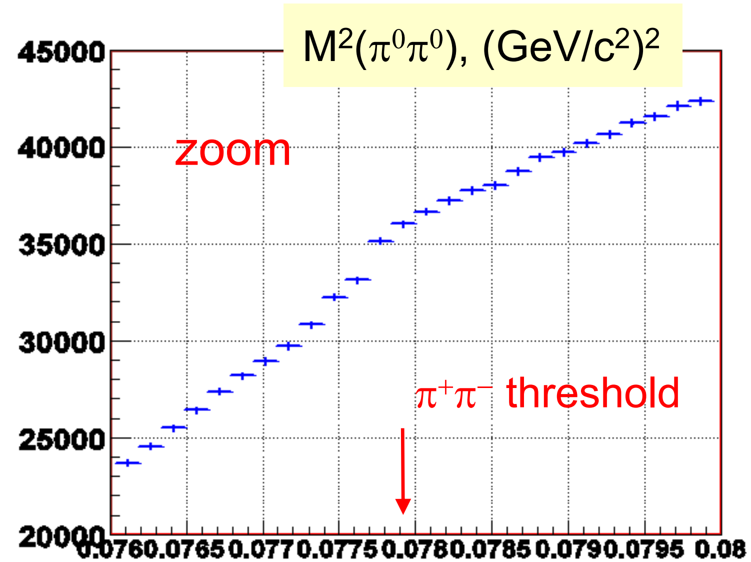
$M_0 = A_0(1 + g_0 u/2 + h'_0 u^2/2 + k'_0 v^2/2)$

So $g_0 \approx g$, $h'_0 \approx h - g^2/4$, $k'_0 \approx k$ and some confusion !

First observation of a cusp structure was made with 16 M events collected in 2003, PLB 633 (2006), thanks to the very good mass resolution.

increased statistics with 44 M more data from 2004 now analyzed



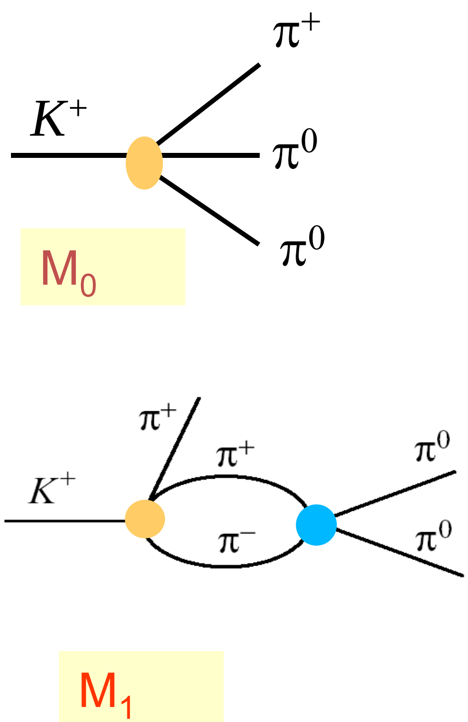


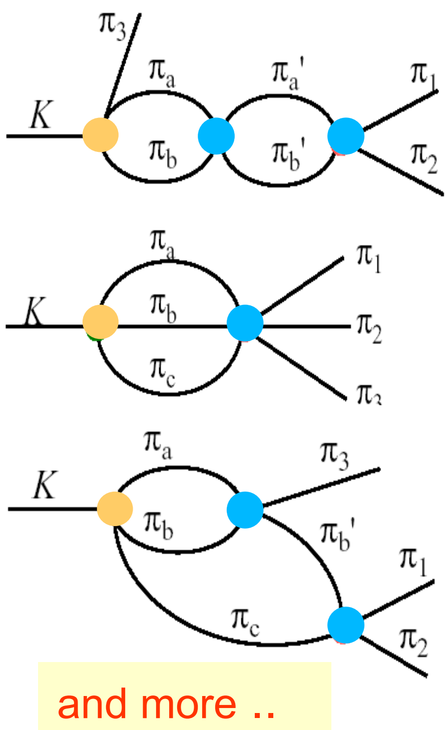
Cusp effect : "simple" interpretation from re-scattering effects

The structure at $\pi^+ \pi^-$ threshold was interpreted as due to the known pp re-scattering in the $K^\pm \rightarrow \pi^+ \pi^- \pi^\pm$ final state

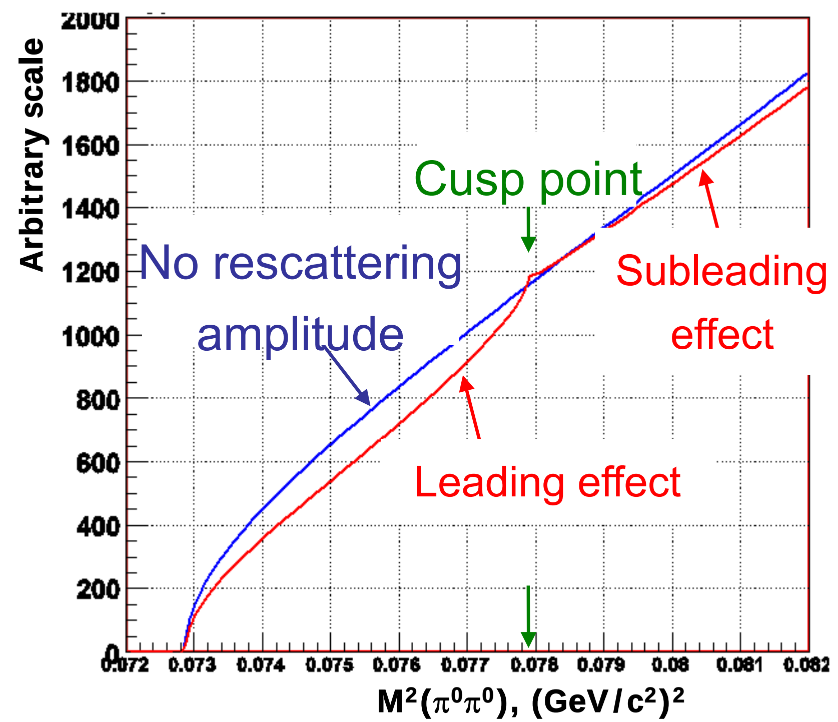
$$M_1 = -\frac{2}{3}(a_0 - a_2) m_{\pi^+} M_+ \sqrt{1 - \left(M_{\pi^0\pi^0}/2 m_{\pi^+}\right)^2}$$

M_1 real below threshold, imaginary above





Distortion due to loop effects



Cusp: Two different approaches to extract scattering lengths

Cabibbo-Isidori approach (CI)

Cabibbo PRL93(2004) , CI JHEP 0503(2005)

- $M = M_0 + M_1$

above threshold $|M|^2 = |M_0|^2 + |M_1|^2$

below threshold $|M|^2 = |M_0|^2 + |M_1|^2 + 2 M_0 M_1$

- Two-loop effects included
- Radiative corrections not included,

Bern-Bonn approach (BB)

CGKR PLB 638 (2006) , and recently BFGKR NPB 806(2009)

- effective field theory approach based on non-relativistic Lagrangian
- two-loop formulation, different from CI, introduces different (larger) correlations between scattering lengths and Dalitz plot parameters
- electromagnetic effects included in the amplitudes (can be switched off for comparisons

a_2 free	Both formulations (CI and BB) used to extract the physics parameters $(g_0, h'_0, a_0-a_2, a_2)$ correlations between a_2 and other parameters are larger in BB model ext is mainly due to $R=(A_+/A_0)^2 = 3.175\pm0.050$
CI model	$a_0-a_2 = 0.248 \pm 0.005_{stat} \pm 0.002_{syst} \pm 0.001_{ext} \pm 0.009_{th}$ $a_2 = -0.009 \pm 0.009_{stat} \pm 0.007_{syst} \pm 0.001_{ext} \pm 0.015_{th}$
BB model	$a_0-a_2 = 0.257 \pm 0.005_{stat} \pm 0.002_{syst} \pm 0.001_{ext} \pm 0.009_{th}$ $a_2 = -0.024 \pm 0.013_{stat} \pm 0.009_{syst} \pm 0.002_{ext} \pm 0.015_{th}$

Cusp: Final result   CERN-PH-EP/2009-010, submitted to EPJC

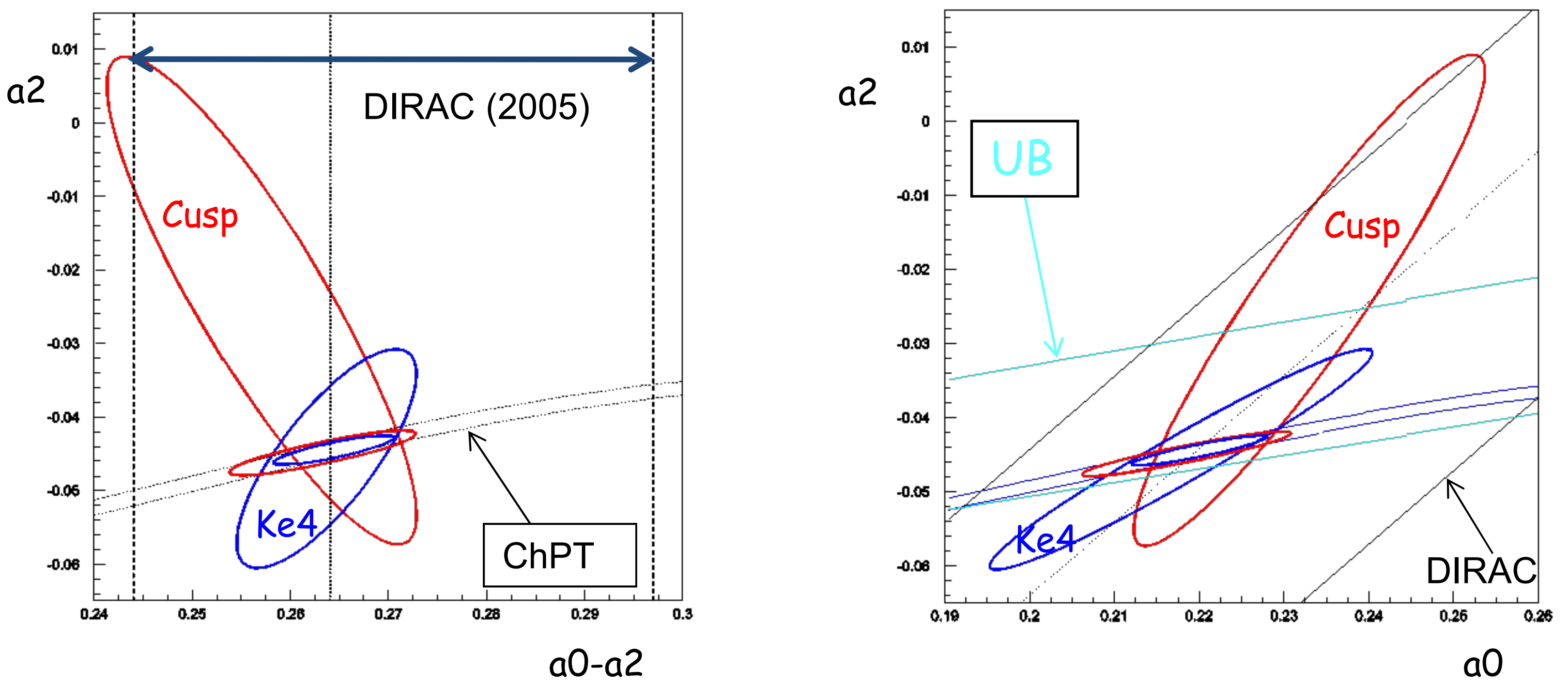
BB model chosen (most complete for rad.cor., |BB-CI| quoted as systematics

2 free parameter fit $(a_0-a_2) = 0.2571 \pm 0.0048\text{stat.} \pm 0.0025\text{syst} \pm 0.0014\text{ext} \pm 0.009_{th}$

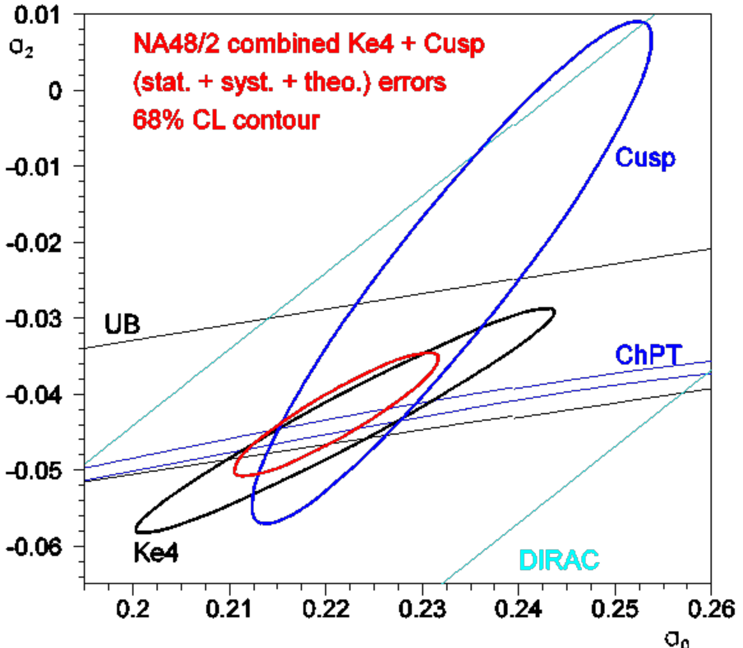
$a_2 = -0.024 \pm 0.013\text{stat.} \pm 0.009\text{syst} \pm 0.002\text{ext} \pm 0.015^{th}$

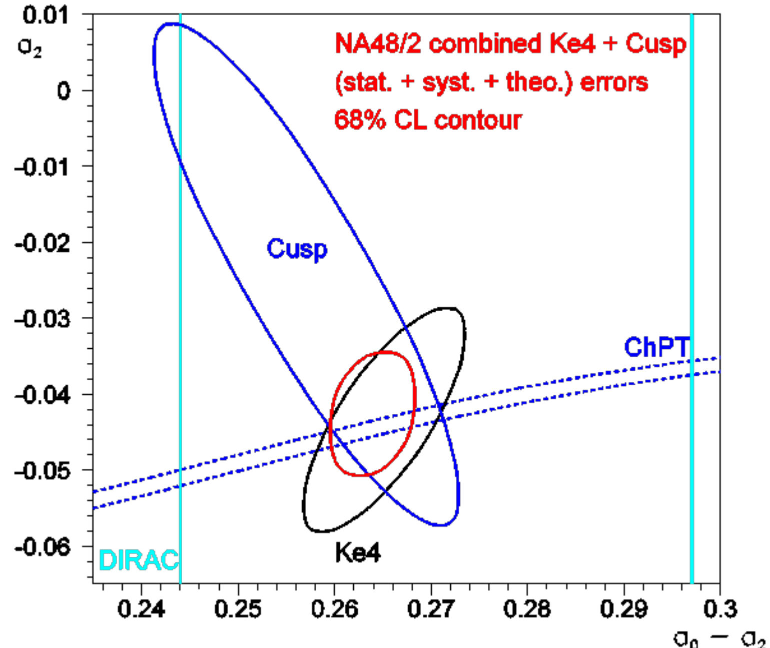
ChPT constrained fit: $(a_0-a_2) = 0.263 \pm 0.002_{stat} \pm 0.001_{syst} \pm 0.002_{ext} \pm 0.005_{th}$

and compare to Ke4 result in (a_0-a_2,a_2) and (a_0,a_2) planes



Combined results from cusp and Ke4





stat syst theo

a_0 = 0.2210 ± 0.0047 ± 0.0015 ± 0.0049
a_2 = - 0.0429 ± 0.0044 ± 0.0016 ± 0.0030
Correlation 0.912
Total errors Δa_0: ± 0.0070 (3% rel. precision)
Δa_2: ± 0.0055 (13% rel. precision)

stat syst theo

$a_0 - a_2$ = 0.2639 ± 0.0020 ± 0.0004 ± 0.0021
a_2 = - 0.0429 ± 0.0044 ± 0.0016 ± 0.0030
Correlation 0.277
Total errors $\Delta (a_0 - a_2)$: ± 0.0030 (1% rel. precision)
Δa_2: ± 0.0055 (13% rel. precision)

Including the ChPT constraint: stat syst theo

a_2 = -0.0444 ± 0.007 ± 0.005 ± 0.0012
a_0 = 0.2196 ± 0.0027 ± 0.0021 ± 0.0048 **or** $a_0 - a_2$ = 0.2640 ± 0.0020 ± 0.0017 ± 0.0035
Total error Δa_0 : ± 0.0059 Δa_2 : ± 0.0015 $\Delta (a_0 - a_2)$: ± 0.0044

Conclusions from KAON09 (June 09) by G. Colangelo :

Lattice QCD “brute force, first principles”

Dispersive relations “causality = analyticity, unitarity”

ChPT “symmetry”

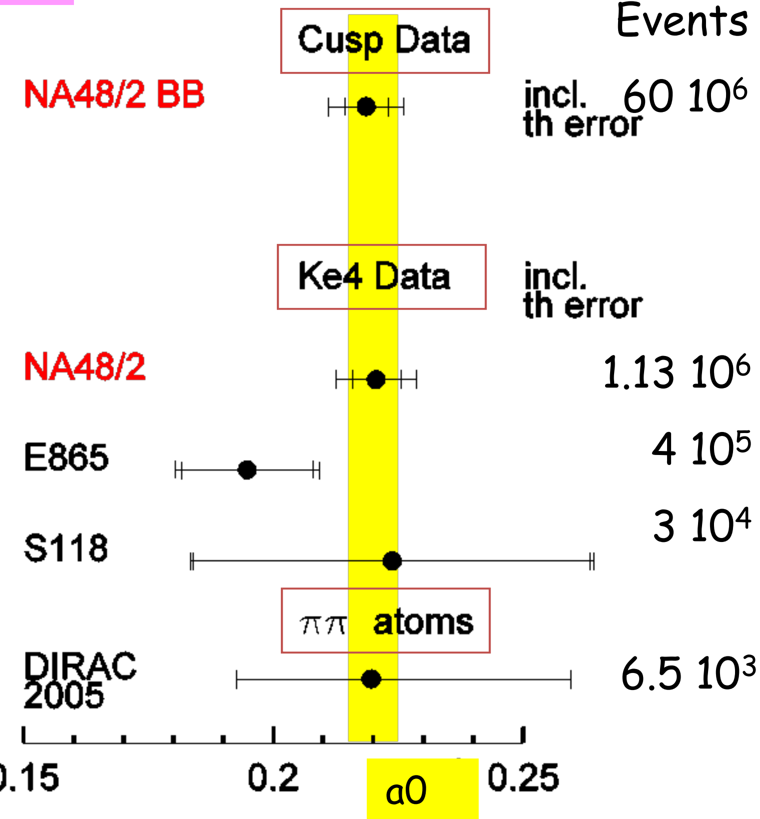
Best prediction with ChPT contraint

$a_0 - a_2 = 0.264 \pm 0.004$
$a_0 = 0.220 \pm 0.005$, $a_2 = -0.0444 \pm 0.0008$

$a_0 - a_2 = 0.264 \pm 0.002_{exp}$
$a_0 = 0.221 \pm 0.005_{exp}$, $a_2 = -0.0429 \pm 0.0047_{exp}$

NA48/2 (cusp+Ke4) 2p fit

a0 ChPT band prediction



Bilan et perspectives:

- Les buts principaux ont été atteints avec la précision requise dans la pluspart des domaines:
pas de violation de CP observée mais des limites améliorées et de nombreuses mesures nouvelles et/ou plus précises

- Une dizaine d'analyses publiées, une dizaine de publications en préparation avec une forte implication du SPP dans les analyses

- Quelques effets inattendus (cusp, Ke4)

- Collaboration avec les théoriciens fructueuse et indispensable !
en particulier avec l'Italie (Cabibbo, Isidori, ..), la Suisse (Gasser,Colangelo,..), la France (Descotes,Stern,Knecht) + …

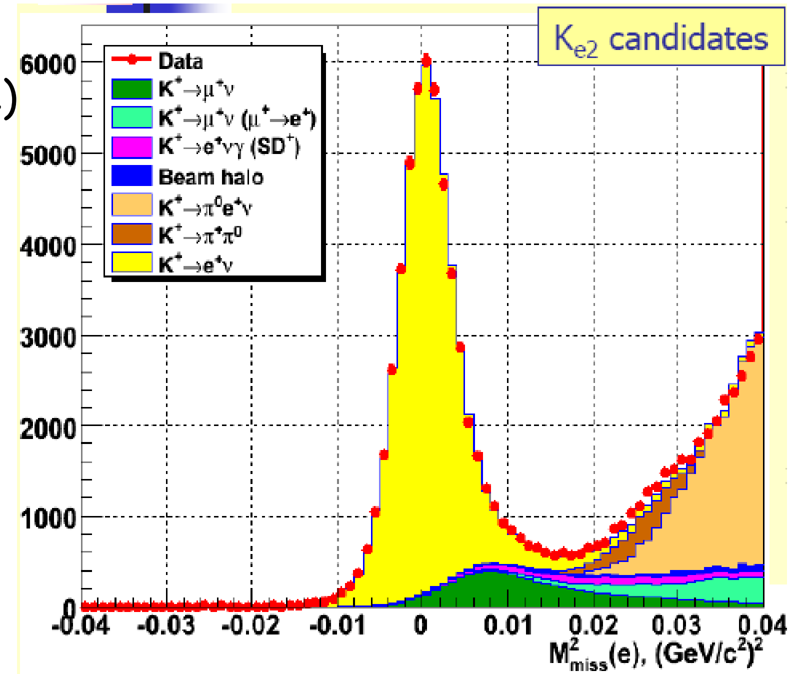
- Formation précieuse pour les étudiants : beaucoup de thèses en Italie et en Allemagne, trop peu d'etudiants en France malheureusement.

Bilan et perspectives:

Perpectives à court terme: 2007-2008 Data (participation perso de BP et BB)

Mesure du rapport **R_K= Ke2 /Kμ2**
NA62/1: 51 089 K+→e+ν candidats, (40% statistique)
99.2% electron ID efficiency, B/(S+B) = (8.0±0.2)%

$R_K = (2.500 \pm 0.012 \pm 0.011) \times 10^{-5}$



KLOE: 13.8K candidates (both K+ and K-)
~50% electron ID efficiency, 16% background

$R_K = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$

NA62 estimated total Ke2 sample:
~120K K+ & ~15K K- candidates.
Proposal (CERN-SPSC-2006-033):150K candidates
Precision relative 0.3% (stat), 0.4-0.5% (total)

SM prediction:

nouvelle physique (1+0.013) ?
à suivre..

$R_K(SM) = (2.477 \pm 0.001) \times 10^{-5}$

Bilan et perspectives:

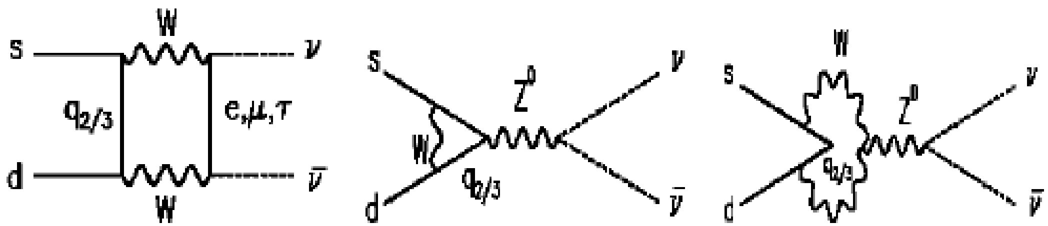
Perpectives à plus long terme: Nouvelle collaboration NA62 approuvée dec 2008

(pas de participation de Saclay)

2006–2010: design & construction (nouveau détecteur sauf calo LKr + aimant)

2011: start of $K^+ \to \pi^+ \nu\nu$ run

FCNC loop processes: sd coupling and highest CKM suppression



SM predictions (main uncertainties from CKM matrix elements):

BR ($K^+ \to \pi^+ \nu\nu$) = 8.5 ± 0.7×10^{-11} [mc = 1286±13 MeV / c2]

BR ($K_L \to \pi^0 \nu\nu$) = 2.76 ± 0.40×10^{-11}

Experimental results:

BR ($K^+ \to \pi^+ \nu\nu$) = $(1.73 +1.15 -1.05) \times 10^{-10}$ [E787 , E959 ' 08]

BR ($K_L \to \pi^0 \nu\nu$) ≤ 6.8×10^{-8} [E391a ' 08]

But

50 ($K^+ \to \pi^+ \nu\nu$) candidats/an avec 10% background