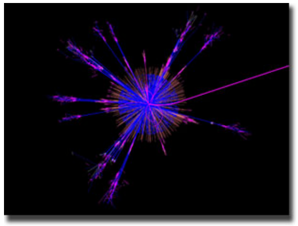

CP Violation Results From the NA48 Experiments

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on Behalf of the NA48/2 Collaboration

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

PASCOS-07

Imperial College, London, 2-7 July 2007

Outline

- NA48: the CP violation experiment
- Brief history
- The NA48 detector
- NA48 - The CP violation parameter η_{+-}
- NA48/2 - Direct CP violation in $K^{\pm} \rightarrow 3\pi$ decays
- NA48/3 (P326/NA62)
  - Measure the BR of the rare decay $K^{+} \rightarrow \pi^{+}\nu\bar{\nu}$
  - Testing μ-e universality with $K^{\pm}\rightarrow\ell^{\pm}\,\nu$ decays
- Conclusions

Data taking periods

NA48 (1997-2001)

- Direct CP violation in neutral kaon decays
  $Re(\varepsilon'/\varepsilon) = (14.7 \pm 2.2) \times 10^{-4}$
- Measurement of CP violation parameter $|\eta_{+-}|$
  New result

NA48/1 (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 $K^\pm \to 3\pi$ dacays
  Final result

and many other rare decay results!

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.
2002	K_S High Intensity	
2003	$K^\pm$ High Intensity	
2004	$K^\pm$ High Intensity	

The NA48 detector

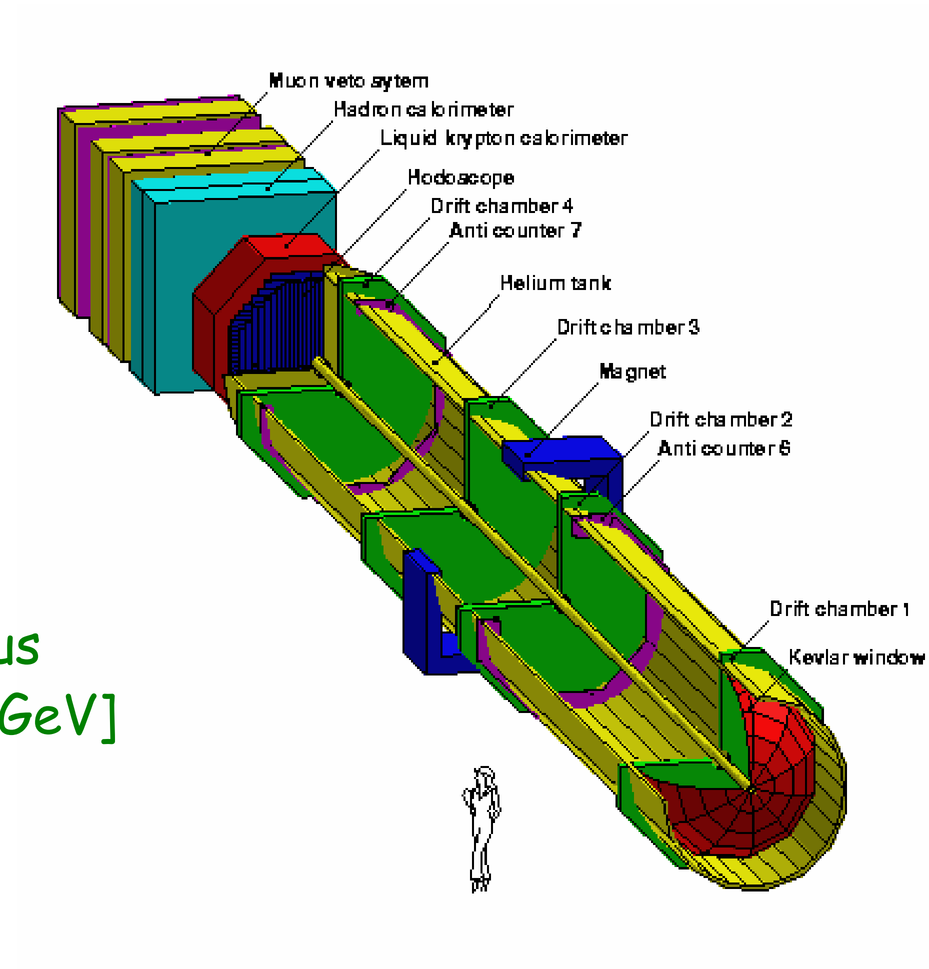
Main detector components:

- Magnetic spectrometer (4 DCHs):
  4 views: redundancy $\Rightarrow$ efficiency
  $\sigma(p)/p$ 1.0% + 0.044% p [GeV/c]

- Hodoscope: fast trigger and
  precise time measurement (150ps)

- Liquid Krypton e.m. calorimeter:
  High granularity, quasi-homogeneous
  $\sigma(E)/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\%$ [GeV]

- Hadron calorimeter, photon vetos,
  muon veto counters



CP violation parameter $|\eta_{+-}|$ NA48

CP violation parameter η+-

The parameter η+- → fundamental observable of CP violation defined as the ratio of K_L to K_S CPV decay amplitudes

related to indirect and direct CPV parameters

$$\eta_{+-} = \varepsilon + \varepsilon'$$

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)}$$

How we determine |η+-|

✓Measure the ratio of the decay rates →
$$\frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^\pm e^\mp \nu)}$$

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

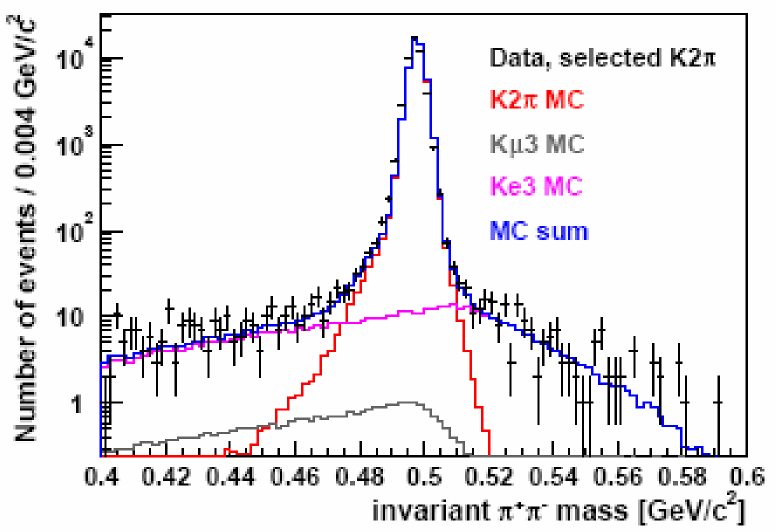
✓Extract |η+-| →
$$|\eta_{+-}| = \sqrt{\frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)}} = \sqrt{\frac{BR(K_L \to \pi^+\pi^-)}{BR(K_S \to \pi^+\pi^-)} \cdot \frac{\tau_{KS}}{\tau_{KL}}}$$

$\Gamma(K2\pi)/\Gamma(Ke3)$: event selection

Data sample: special run with pure K_L beam, low intensity
two days in 1999, ~ 80 million events collected

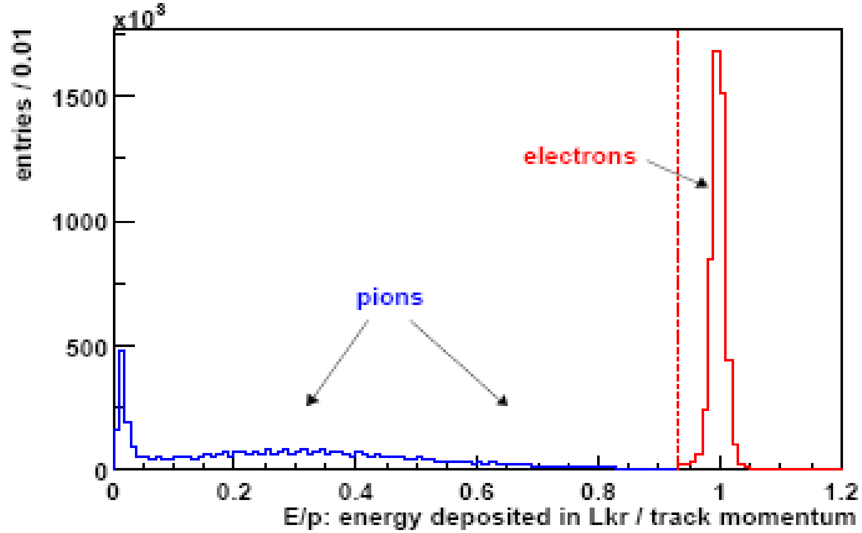
$K_L \to \pi^+ \pi^-$

- dominant background (K_{e3}, $K_{\mu3}$, $K_L \to \pi^+\pi^-\pi^0$) need to be suppressed by 4-5 order of magnitude
- data well described by MC
- about 47000 $\pi^+ \pi^-$ events selected



$K_L \to \pi^\pm e^\mp \nu$

- select K_{e3} decays via the ratio E/p (energy in electromagnetic calorimeter over track momentum)
- about 5 million K_{e3} events selected with small background



Results

$$\frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^\pm e^\mp \nu\ )} = (4.835 \pm 0.022_{stat} \pm 0.016_{syst}) \times 10^{-3}$$
$$= (4.835 \pm 0.027) \times 10^{-3}$$

$$BR(K_L \to \pi^+\pi^-) = \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_L \to \pi\ e\nu)} \cdot BR(K_L \to \pi\ e\nu)$$
$$= (1.941 \pm 0.019) \times 10^{-3}$$

$\pi^+\pi^-\gamma$ in data sample

- ✓ (IB) included
- ✓ (DE) subtracted (mostly CPC)
- ✓ used NA48 updated result for $BR(K_L \to \pi e \nu)$

Phys.Lett.B 602:41-51,2004

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

INPUT:

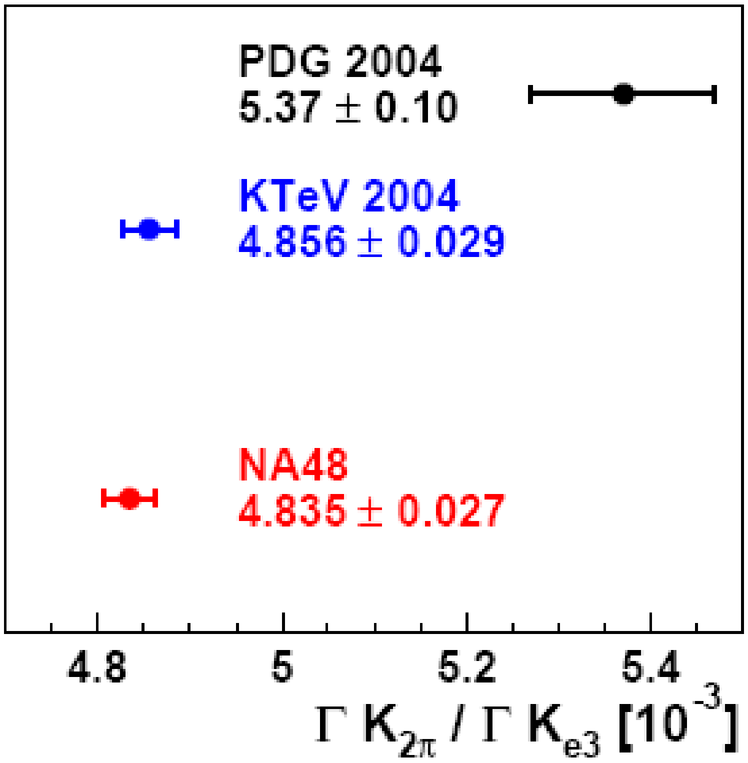
most precise mesurements

- ✓ $\tau_{KS} \to$ NA48
- ✓ $\tau_{KL} \to$ KLOE
- ✓ $BR(K_S \to \pi^+ \pi^-) \to$ KLOE

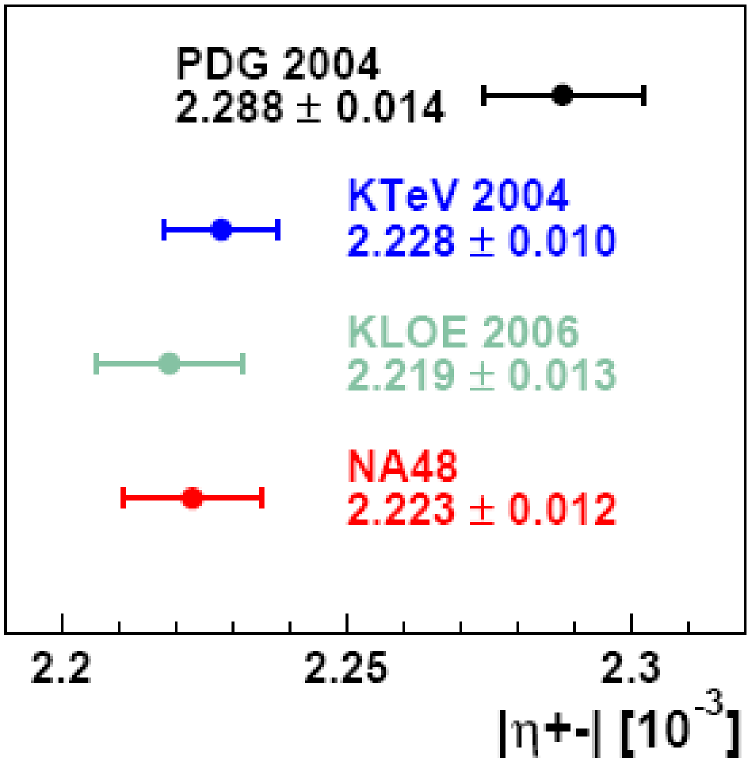
published in Phys.Lett.B 645:26-35,2007

Comparison of results

$\Gamma(K_{2\pi})/\Gamma(K_{e3})$



$|\eta_{+-}|$

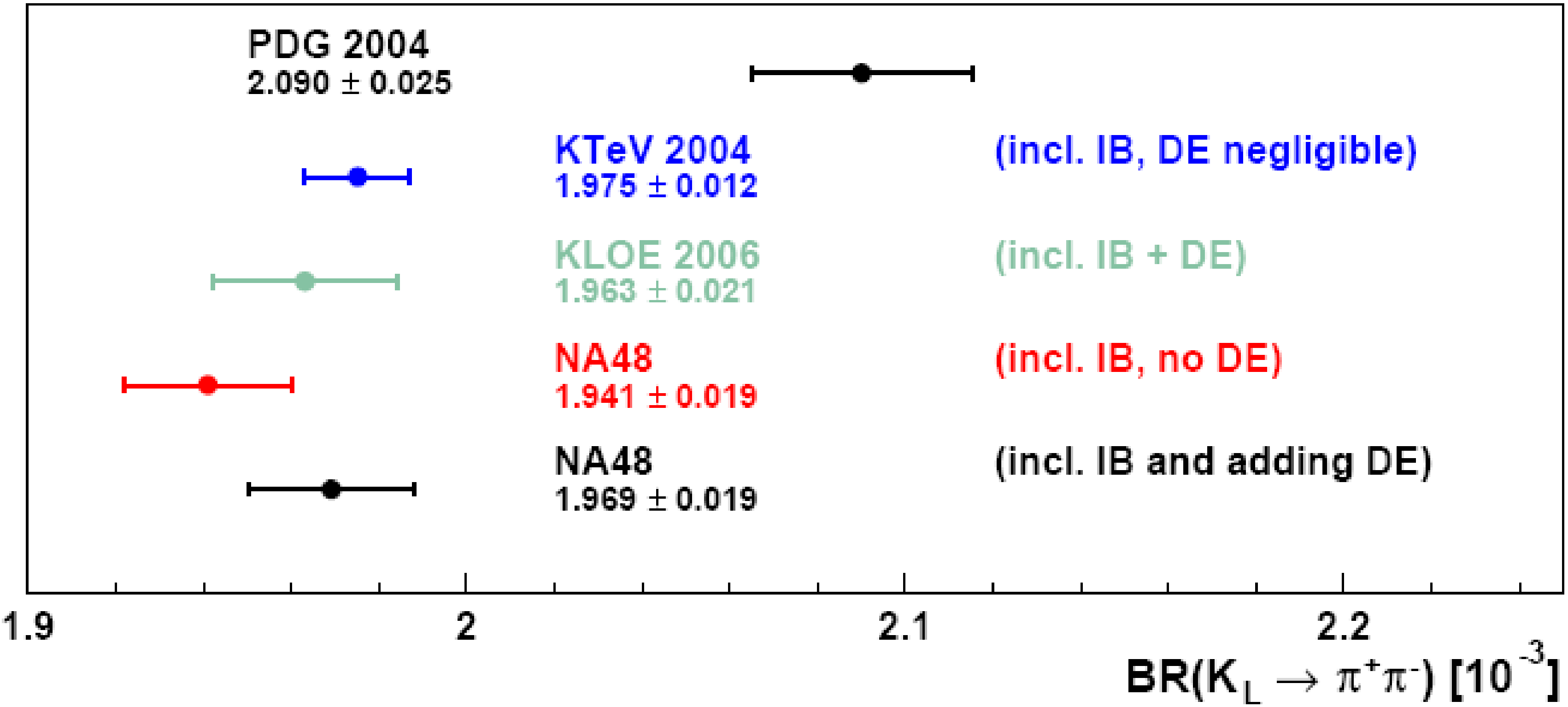


Good agreement with results from KTeV and KLOE

Experiments contradict PDG 2004

Comparison of results

$$BR(K_L \to \pi^+\pi^-)$$



For comparison it is important to point out the treatment of radiative decays (IB and DE)

CP violation in $K^{\pm}\rightarrow 3\pi$ decays
NA48/2

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

Look for direct CP violation in $K^\pm$ decays

(only direct CPV in $K^\pm$ possible – no mixing)

Complementary CP observables in Kaons:

neutral → ε' and ε ↔ charged → slope asymmetries

Large statistics

BR ($K^\pm \to \pi^\pm\pi^+\pi^-$) = 5.57%	BR ($K^\pm \to \pi^\pm\pi^0\pi^0$) = 1.73%

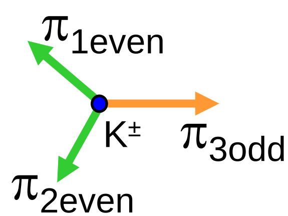
Kinematics:

$u = (s_3 - s_0)/m_\pi^2$

$v = (s_2 - s_1)/m_\pi^2$

$s_i = (P_K - P_{\pi i})^2$, i=1,2,3 (3=odd π)

$s_0 = (s_1 + s_2 + s_3)/3$



Matrix element as a function of the Dalitz variables u, v

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

Linear slope g dominates over quadratic terms h and k

$|h|, |k| \sim 10^{-2} \ll |g|$

Direct CP violation observable A_g

$$A_g \equiv \frac{g_+ - g_-}{g_+ + g_-} = \frac{\Delta g}{2g}$$

$g_+ \rightarrow K^+$ decays
$g_- \rightarrow K^-$ decays

1. Measure Δg
2. Use known value of g
3. Extract A_g

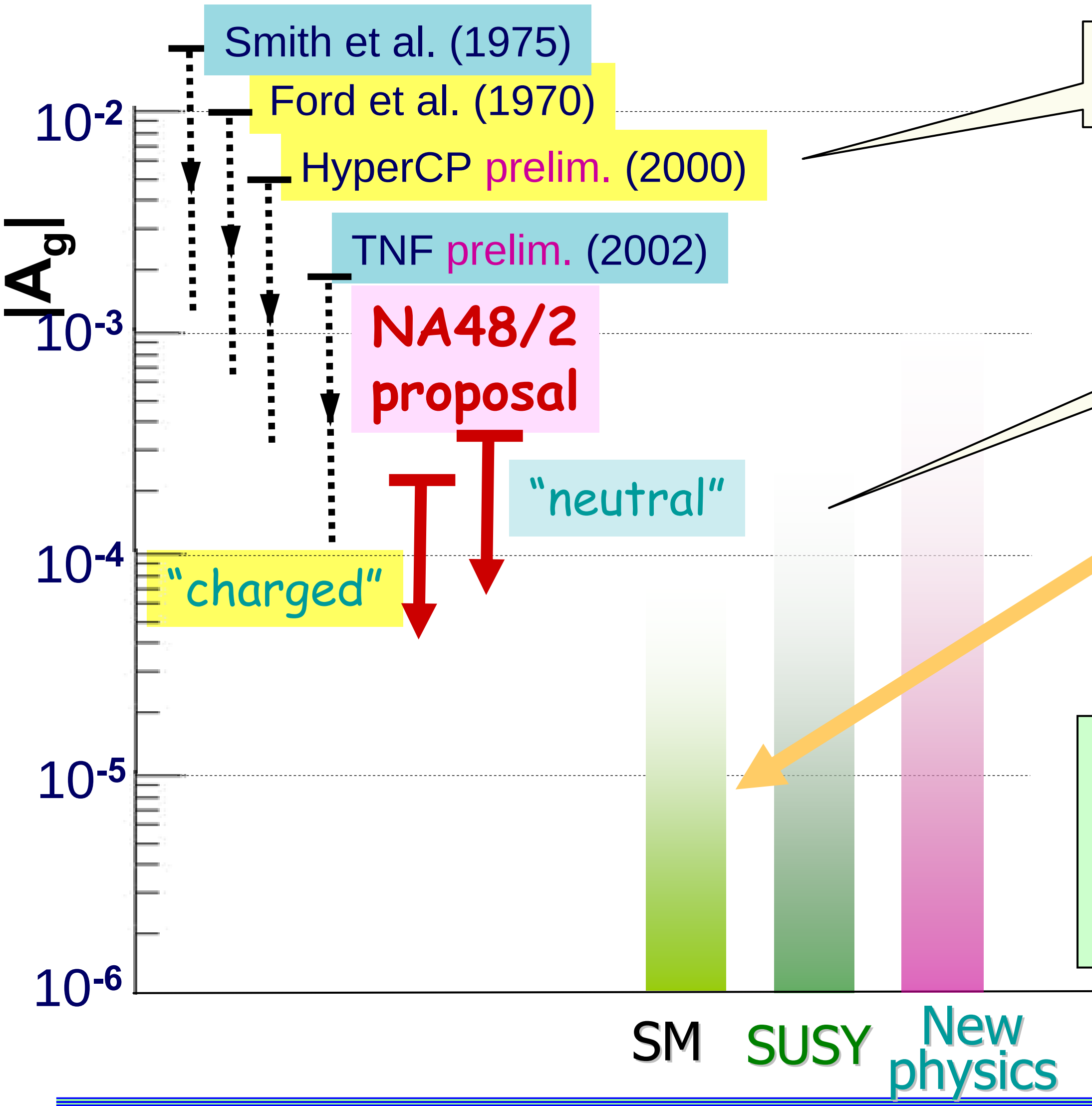
$K^\pm \rightarrow \pi^\pm\pi^+\pi^-$ $g = (-21.134 \pm 0.017)\%$
$h = (1.848 \pm 0.040)\%$
$k = (-0.463 \pm 0.014)\%$
hep-ex/0702045, accepted by PLB

NA48/2 final results for slopes
- Agreement with PDG
- Factor 10 smaller uncertainties
- First evidence of $h \neq 0$

$K^\pm \rightarrow \pi^\pm\pi^0\pi^0$ $g = (62.6 \pm 0.7)\%$ PDG value

$A_g \neq 0$ → Direct CP violation

Status before NA48/2



Experimental results

Theory

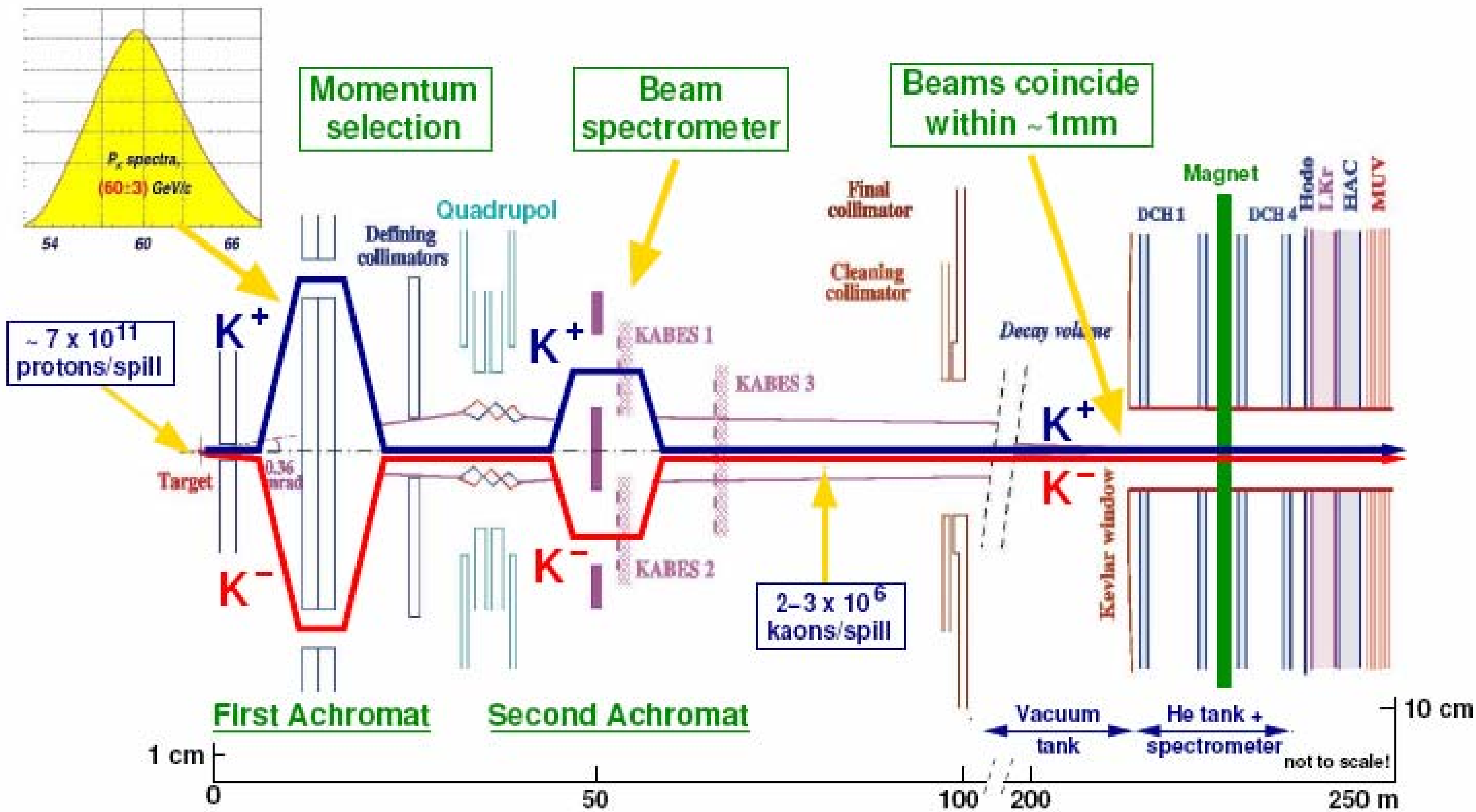
SM estimates of A_g vary within an order of magnitude (**few 10^{-6}.....few 10^{-5}**).

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

Goal and method

- **Primary NA48/2 goal:**
  - Measure slope asymmetries in "charged" and "neutral" modes with high accuracy (few 10^{-4}).
- **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 averaged K^{+} and K^{-} acceptances by frequently alternating the polarities of the relevant magnets.

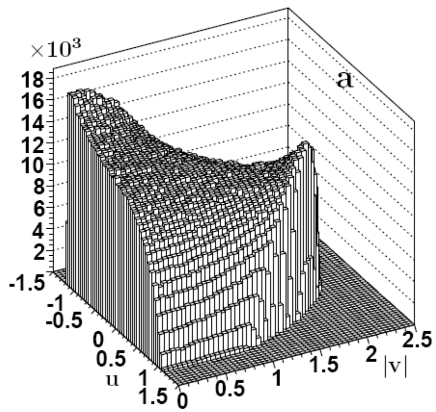
The K⁺/K⁻ simultaneous beam setup

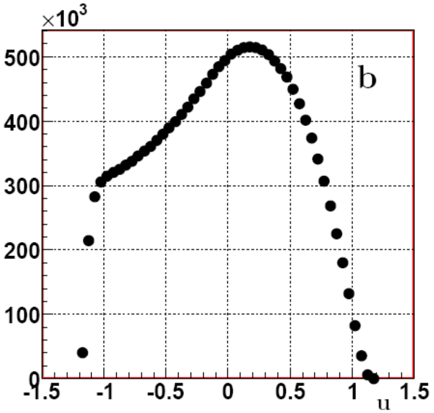


Method to extract A_g

- Build u projections of the Dalitz plot for K^+ and K^-: $N^+(u)$,$N^-(u)$
- Make the ratio of these two distributions: R(u)
- Fit a function to this ratio to extract Δg
  (This holds only if the acceptance for K+ and K- is the same)

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





BUT! There are experimental asymmetries that do not cancel in the simple ratio R(u)

To cancel the charge asymmetry in the detector and beam optics

➔Beam line (achromat) polarity (A) is reversed on weekly basis

➔Spectrometer magnet polarity (B) is reversed on few hours basis

Acceptance cancellation

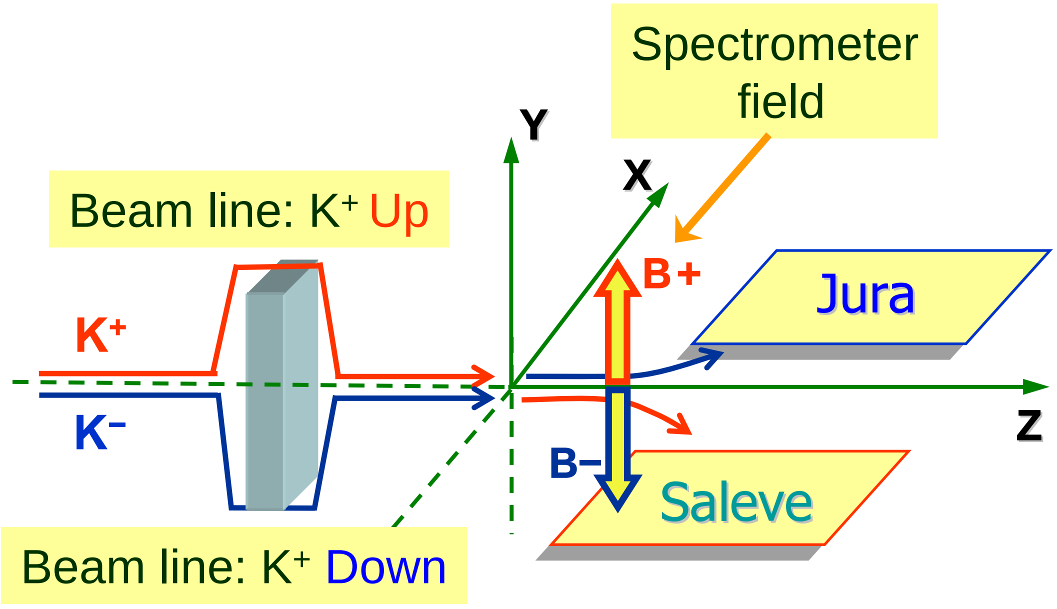
Detector left/right asymmetry cancels in 4 ratios of K^+/K^- distributions defined for the four possible combinations of the magnetic fields:

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

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

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

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



Indexes correspond to: beamline polarity (U/D)
left/right direction of kaon deviation in spectrometer (S/J)

K samples in numerator and denominator illuminate the same parts of the detector

Quadruple ratio

Use a quadruple ratio for cancellation of systematic biases

$$R_4 = R_{US} R_{UJ} R_{DS} R_{DJ} \sim 1 + 4 \cdot \Delta g \cdot u$$

Extract Δg by fitting the quadrupole ratio

1) Global time-variable biases (K^+,K^- simultaneously recorded)
2) Beam line biases (K^+ beam up / K^- beam up etc.)
3) Detector asymmetries (K^+ toward Saleve / K^- toward Saleve etc.)
4) Effects of permanent stray fields (earth, vacuum tank magnetisation) cancel

The result is sensitive only to time variation of asymmetries in the experimental conditions with a characteristic time smaller than the corresponding field alternation period (beam-week, detector-day)

Final results 2003+2004

Data samples →

Data taking:	2003	+	2004
Effective days:	~ 50	+	~ 60
Amount of data recorded:	$\sim 16 \cdot 10^9$ triggers		~200 TB

Charged mode (3.11×10^9 selected $K^\pm \to \pi^\pm \pi^+ \pi^-$)

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

Neutral mode (9.13×10^7 selected $K^\pm \to \pi^\pm \pi^0 \pi^0$)

$$A_g = (1.8 \pm 1.7_{stat} \pm 0.9_{syst}) \times 10^{-4} = (1.8 \pm 1.8) \times 10^{-4}$$

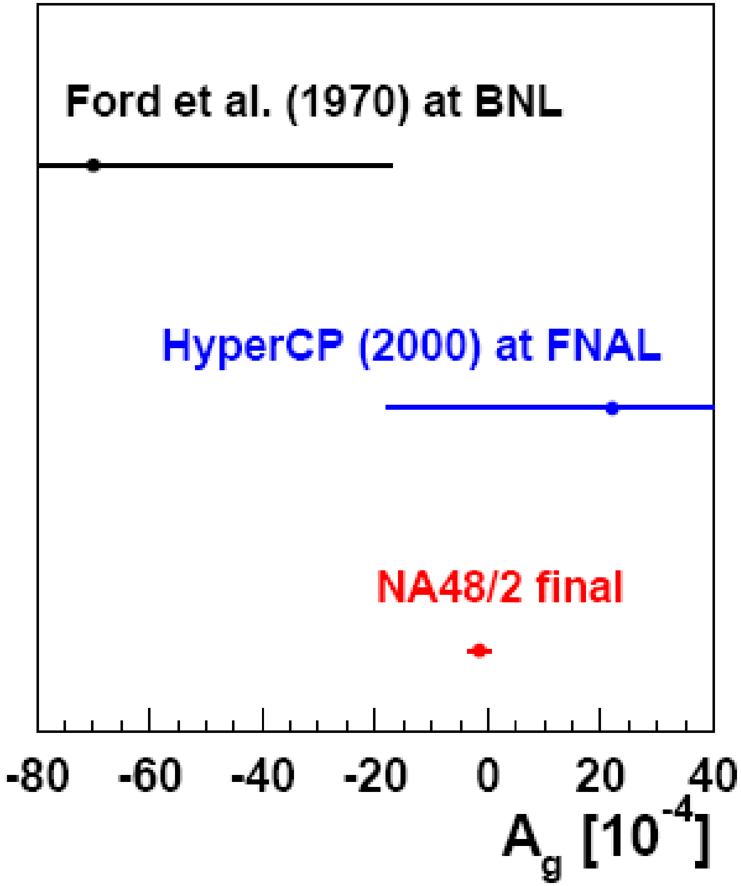
- ✓Charged and neutral results are consistent
- ✓Statistical error dominates in both cases
- ✓10 times more precise than previous experiments
- ✓Design goal reached
- ✓Results compatible with SM predictions

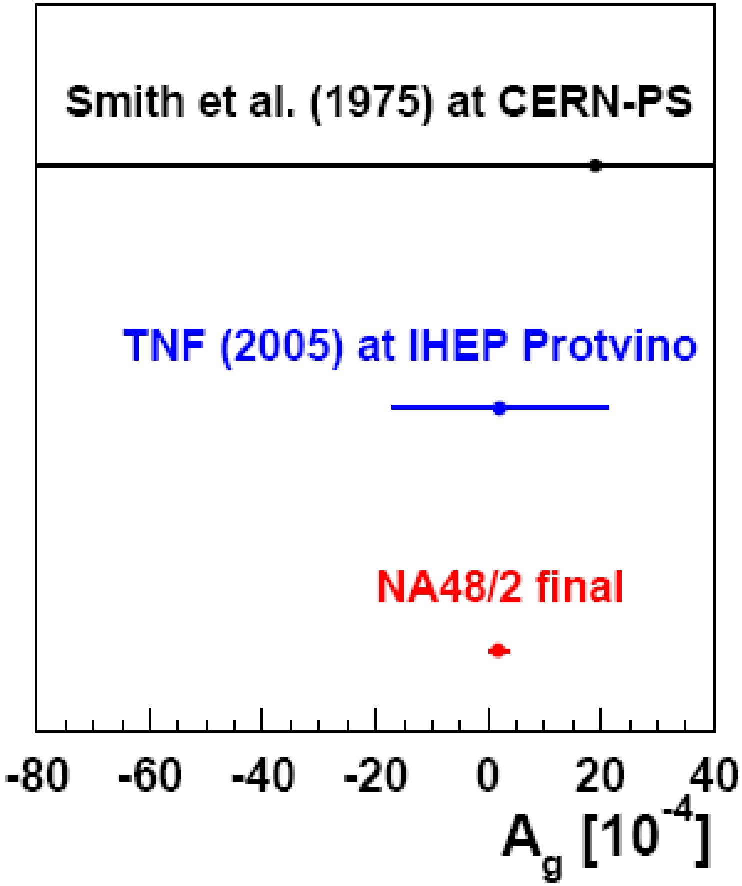
No evidence for direct CP violation at the order of 10^{-4}

Comparison of results

Charged mode
$K^{\pm} \rightarrow \pi^{\pm} \pi^{+} \pi^{-}$

Neutral mode
$K^{\pm} \rightarrow \pi^{\pm} \pi^{0} \pi^{0}$





Future and present

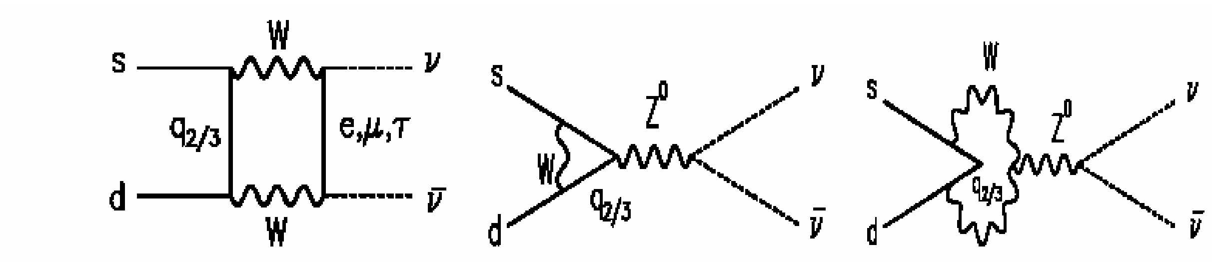
- Measure the BR of the rare decay $K^+ \rightarrow \pi^+ \nu\bar{\nu}$
- Testing μ-e universality with $K^\pm \rightarrow \ell^\pm \nu$ decays

NA48/3

P326/NA62 - Physics motivations

$K \rightarrow \pi\nu\bar{\nu}$ decays → golden modes to test SM and the mixing of quarks (CKM unitarity)

- FCNC loop processes, sensitive to V_{td}



- Very clean theoretically: short distance contributions dominate, hadronic matrix element can be related to measured quantities.
- **SM predictions (uncertainties from CKM elements):**
  - $BR(K^+ \rightarrow \pi^+\nu\nu) \approx (1.6\times10^{-5})|Vcb|^4[\sigma\eta^2+(\rho_c-\rho)^2] \rightarrow (8.0 \pm 1.1)\times10^{-11}$
  - $BR(K_L \rightarrow \pi^0\nu\nu) \approx (7.6\times10^{-5})|Vcb|^4\eta^2 \rightarrow (3.0 \pm 0.6)\times10^{-11}$
- Exsisting measurement $BR(K^+ \rightarrow \pi^+\nu\nu)$

  (BNL E787/949) $(1.47^{+1.30}_{-0.89})\times10^{-10}$ (3 events)
- **Sensitive to New Physics: clean probe up to Λ~100 TeV scale**

P326/NA62 - proposed experiment

P326/NA62 experiment

Measurement of the $Br(K^+ \to \pi^+ \nu\nu)$ with ~10% accuracy

+ other physics opportunities

Expected events:

- Signal events per year@BR=8 $\cdot 10^{-11}$ ~ 65
- Background events ~ 9
- Signal/Background ~ 8

~ 10^{-12} sensitivity per event

General design:

Mostly defined. Overall simulation and performances under review.

R&D program:

Well advanced. Construction of detector prototypes and test in progress. Important results by the end of 2007.

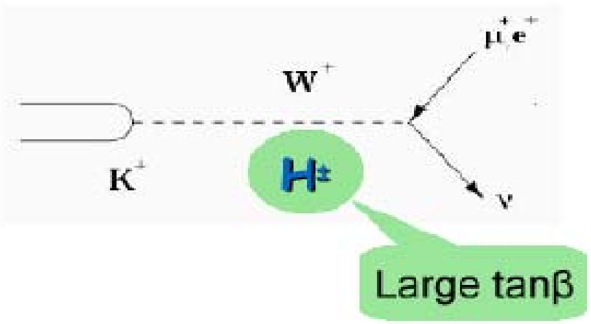
[CERN-SPSC-P-326, 11/06/2005]

Schedule:

2005: proposal presented at CERN SPSC
2005: R&D endorsed by CERN RB
2006: Start of test beams
2007: prototypes construction test
2008 – 2010: Technical design and construction
2011: Start of data taking

Ke2/Kμ2 - Physics motivations

Original motivation:
The measurement of $R_K=\Gamma(Ke2)/\Gamma(K\mu2)$ ratio is a test of SM Lepton Universality and V-A coupling



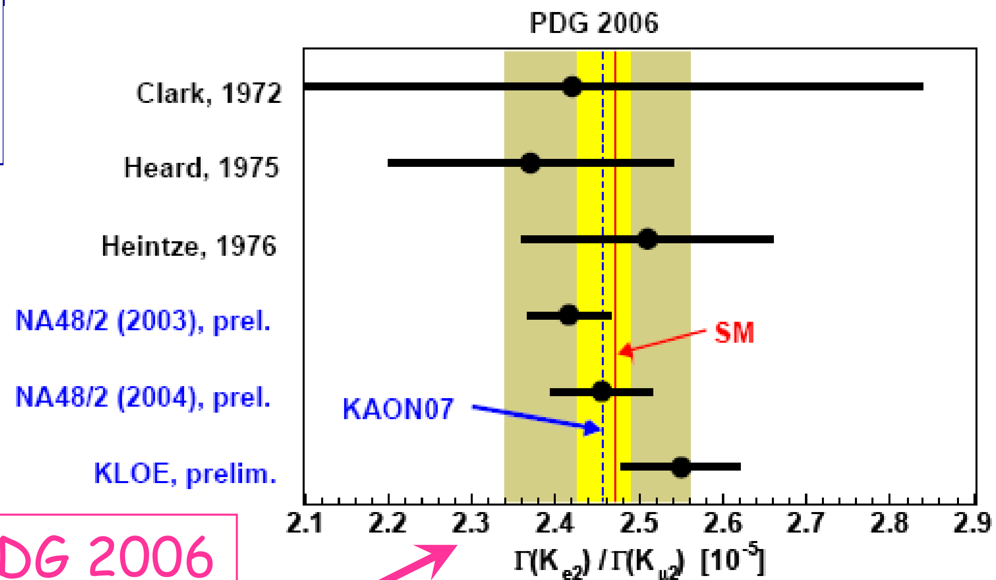
NA48/2 preliminary results

2003 data, presented in 2005

$R_k = (2.416 \pm 0.043 \pm 0.024) \times 10^{-5}$

2004 data presented at KAON07

$R_k = (2.455 \pm 0.045 \pm 0.041) \times 10^{-5}$



New motivation:
SUSY LFV could shift R_K by a relative amount of 2-3% with parameters $\tan\beta \sim 50$ e $M_{H+} \sim 500$ GeV/c^2

A. Masiero et.al.,Phys.Rev.D74:011701,2006

Combine all preliminary results + PDG 2006

$R_k = (2.457 \pm 0.032) \times 10^{-5}$

R. Wanke for the Flavianet WG @KAON07

Huge improvement!

Ke2/Kμ2 - present experiment

P326/NA62 is performing a dedicated run to measure R_K

4 months of data taking (June-October)
Collect 100K-150K Ke2 decays

- same set-up as for NA48/2
- beam parameters optimized wrt 2004
  - improved kinematic separation of Ke2
- simple minimum bias trigger
- systematics under control
- background to Ke2
  - p_{track} < 35 GeV kinamatic separation
  - p_{track} > 35 Gev electron identification

Overall expected precision ~ ± 0.3% ⟹ Sensitivity to LFV in SUSY

Conclusions

The NA48 experiments have produced important results providing fundamental contributions in the field of CP Violation both in neutral and in charged kaon systems

Presented at this conference:

- The measurement of the CP parameter $|\eta_{+-}|$
- A much improved limit on direct CP violation in $K^{\pm} \to 3\pi$ decays

A very rich program in the near future

- Testing μ-e universality with $K^{\pm} \to \ell^{\pm} \nu$ decays
- Measure BR of the rare decay $K^{+} \to \pi^{+}\nu\bar{\nu}$

Stay tuned!!