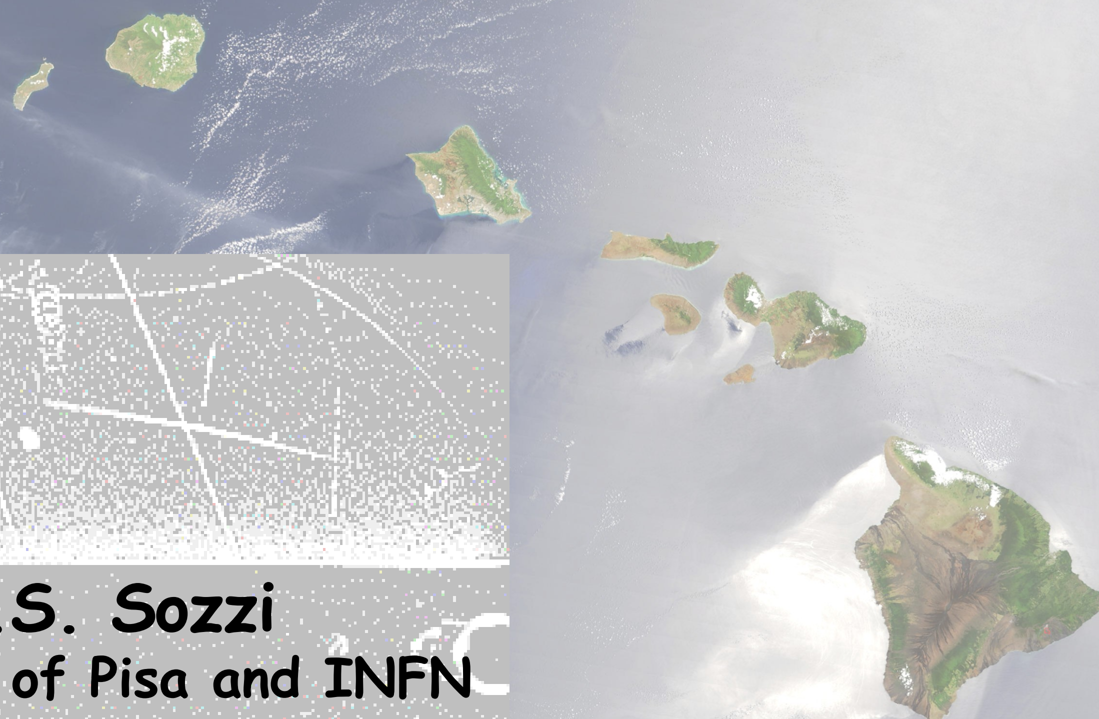
Kaons as high precision probes at CERN: From NA48 to P-326



M.S. Sozzi
University of Pisa and INFN

Joint meeting of Pacific Region Particle Physics Communities
October 30th 2006

MENU

- ***Appetizer***: fast forward from the past

  Direct CPV, η mass, K_S rare decays

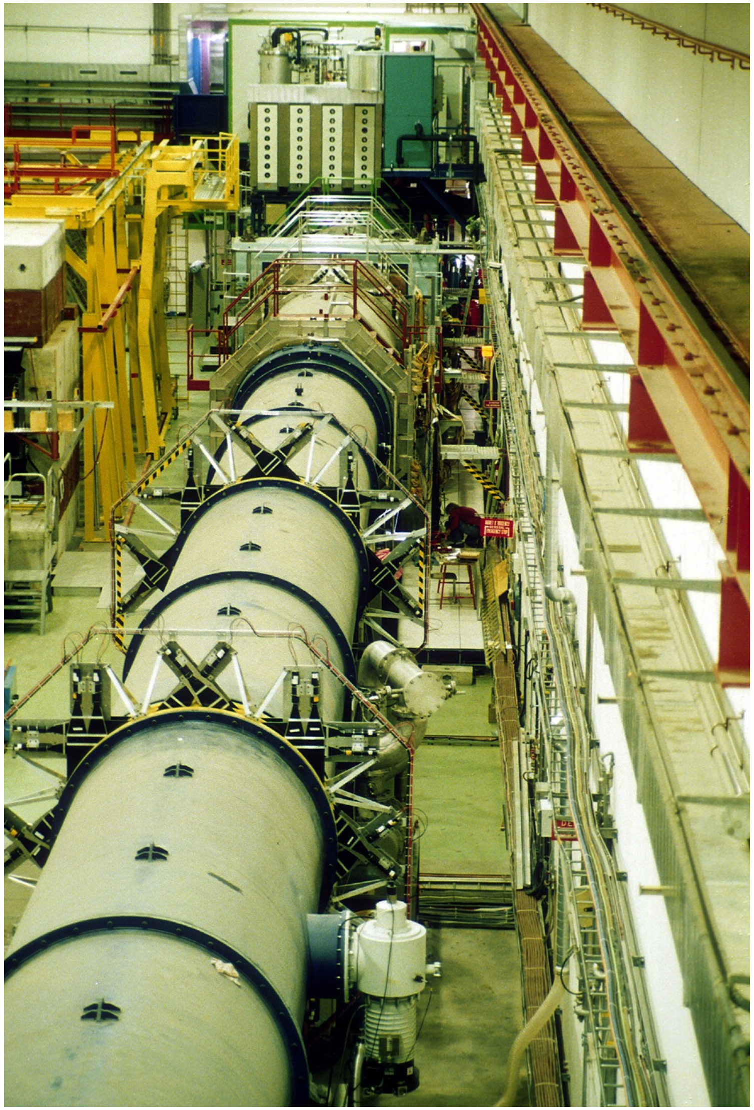
- ***Main course***: recent achievements

  CPV in K→3π decays
  Radiative decays
  Ke4 decays
  ππ scattering lengths
  Semileptonics
  Leptonics

- ***Dessert***: the future program

  Towards ultra-rare decays

- *Doggy bag*…



Once upon a time in Geneva…

NA48 [ɛn eı fôr'tē āt]: *n.,*
1. International collaboration (b. 1989) of 120–odd physicists formed by Cagliari, Cambridge, Edinburgh, Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Siegen, Torino, Warsaw universities, CERN, JINR Dubna, LAL Orsay, CEA Saclay and HEPHY Vienna to work on a particle physics experiment searching for direct CP violation in kaons at CERN

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

The NA48 detector

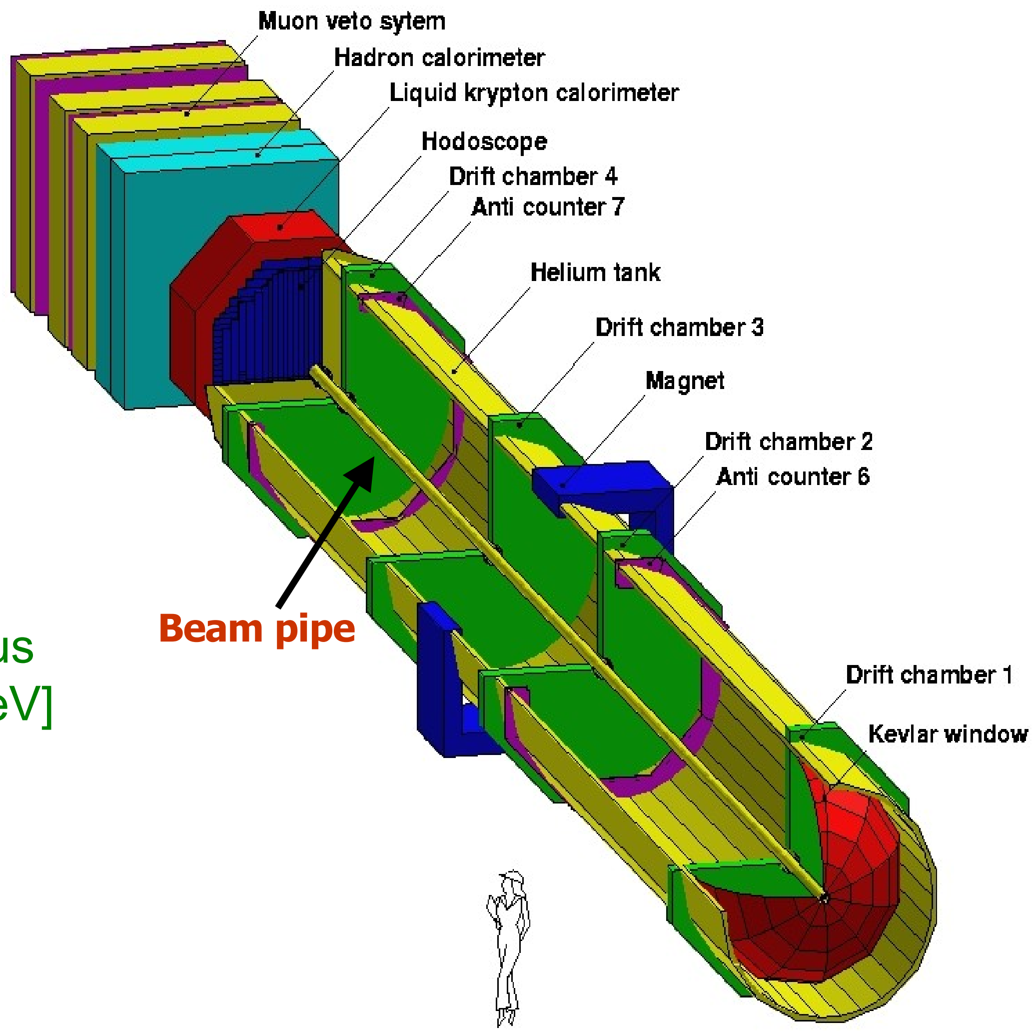
Main detector components:

- Magnetic spectrometer (4 DCHs):
  4 views: redundancy ⇒ efficiency
  $\sigma_p/p = 1.0\% + 0.044\%\ p\ [\mathrm{GeV}/c]$

- Hodoscope
  Fast trigger
  Precise time measurement (150ps)

- Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi−homogeneous
  $\sigma_E/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\%\ [\mathrm{GeV}]$
  e/π discrimination

- Hadron calorimeter, photon vetos,
  muon veto counters



The story so far…

NA48: ε'/ε		1997
ε'/ε		1998
ε'/ε	K_S	1999
K_L	no spectrometer K_S	2000
ε'/ε	K_S	2001
NA48/1: K_S		2002
NA48/2: $K^{\pm}$		2003
NA48/2: $K^{\pm}$		2004

- ***NA48:***
  - The quest for direct CP violation
  - Rare K_L decays
- ***NA48/1:***
  - Rare K_S decays
  - Hyperon decays
- ***NA48/2:***
  - Direct CP violation searches
  - Study of ππ interactions
  - Rare $K^{\pm}$ decays

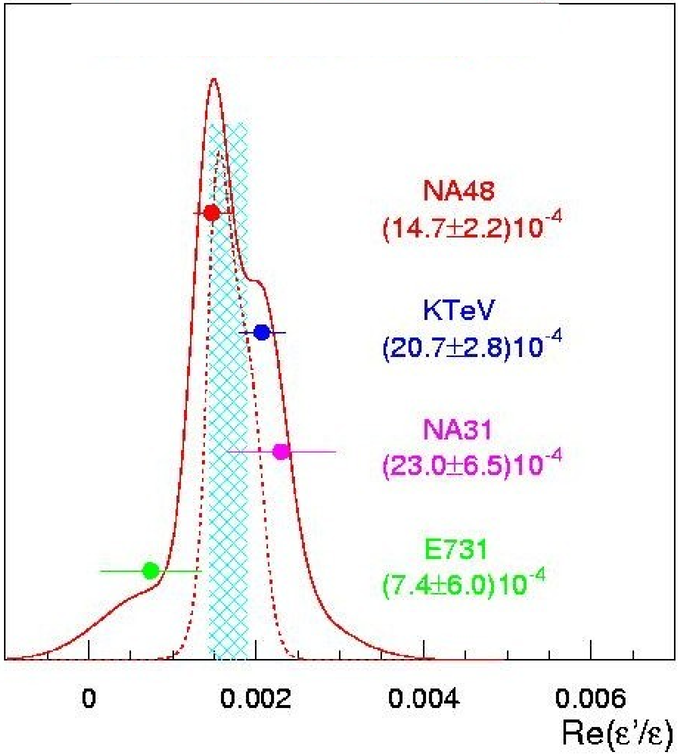
3 experiments in 1: a multi-purpose kaon laboratory

NA48: Direct CP violation: ε′/ε

1999: proof of direct CP violation (after 36 years!) at >7 σ

World average: $Re(\varepsilon'/\varepsilon) = (16.3 \pm 2.3) \cdot 10^{-4}$

$$\frac{\Gamma(K^0 \to \pi^+\pi^-) - \Gamma(\overline{K}^0 \to \pi^+\pi^-)}{\Gamma(K^0 \to \pi^+\pi^-) + \Gamma(\overline{K}^0 \to \pi^+\pi^-)} = (5.04 \pm 0.82) \times 10^{-6}$$



BREAKING NEWS !!!

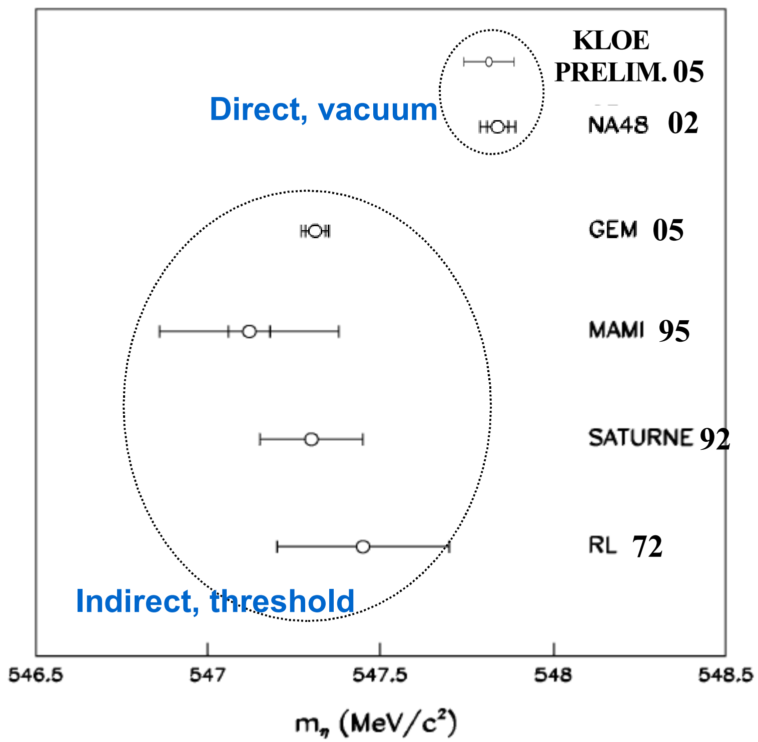
Italo Mannelli (Pisa), **Heinrich Wahl** (CERN) and **Bruce Winstein** (Chicago) receive the 2007 Panofsky Prize of the American Physical Society, for their leading role in a series of experiments on precision experiments with kaons

NA48: η mass

No sensitivity to absolute E scale (normalization to π^0 mass)

$M_\eta = (547.843 \pm 0.030 \pm 0.041)$ MeV/c^2

Phys. Lett. B 533 (2002) 196

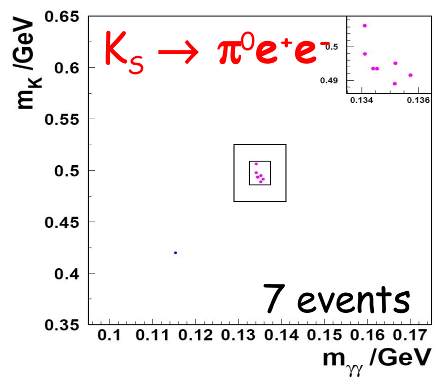


NA48/1: K_s decays

December 10, 1999

CERN/SPSC 2000-002
SPSC/P253 ADD.2

ADDENDUM 2 TO P253
A high sensitivity investigation of K_S and neutral hyperon decays using a modified K_S beam.

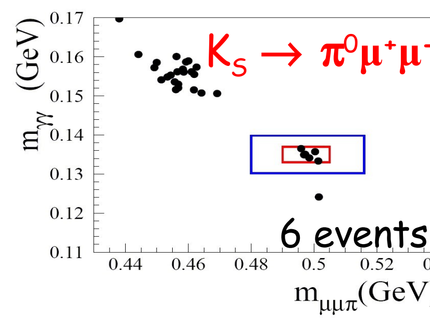


Highlight: first measurements of $K_S \to \pi^0 \ell^+ \ell^-$

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

Phys. Lett. B 599 (2004) 197

Outcome: indirect CPV dominates in $K_L \to \pi^0 \ell^+ \ell^-$



BR = $(2.8\ ^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9}$

Phys. Lett. B 576 (2003) 43

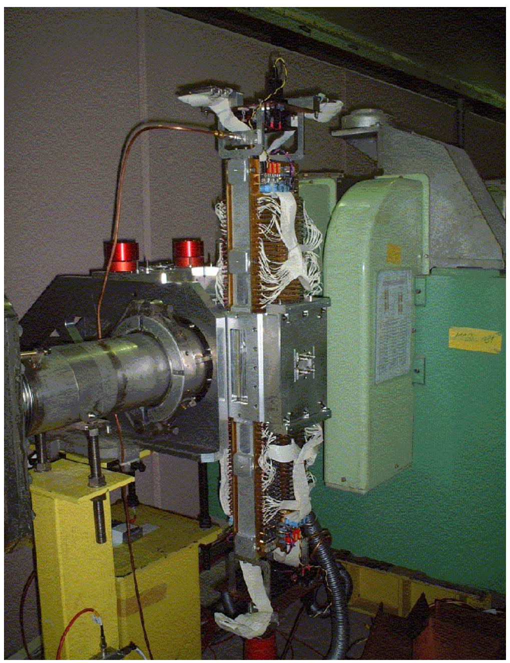
CERN/SPSC 2000-003
CERN/SPSC/P253 add.3
January 16, 2000

NA48/2: simultaneous K± decays

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

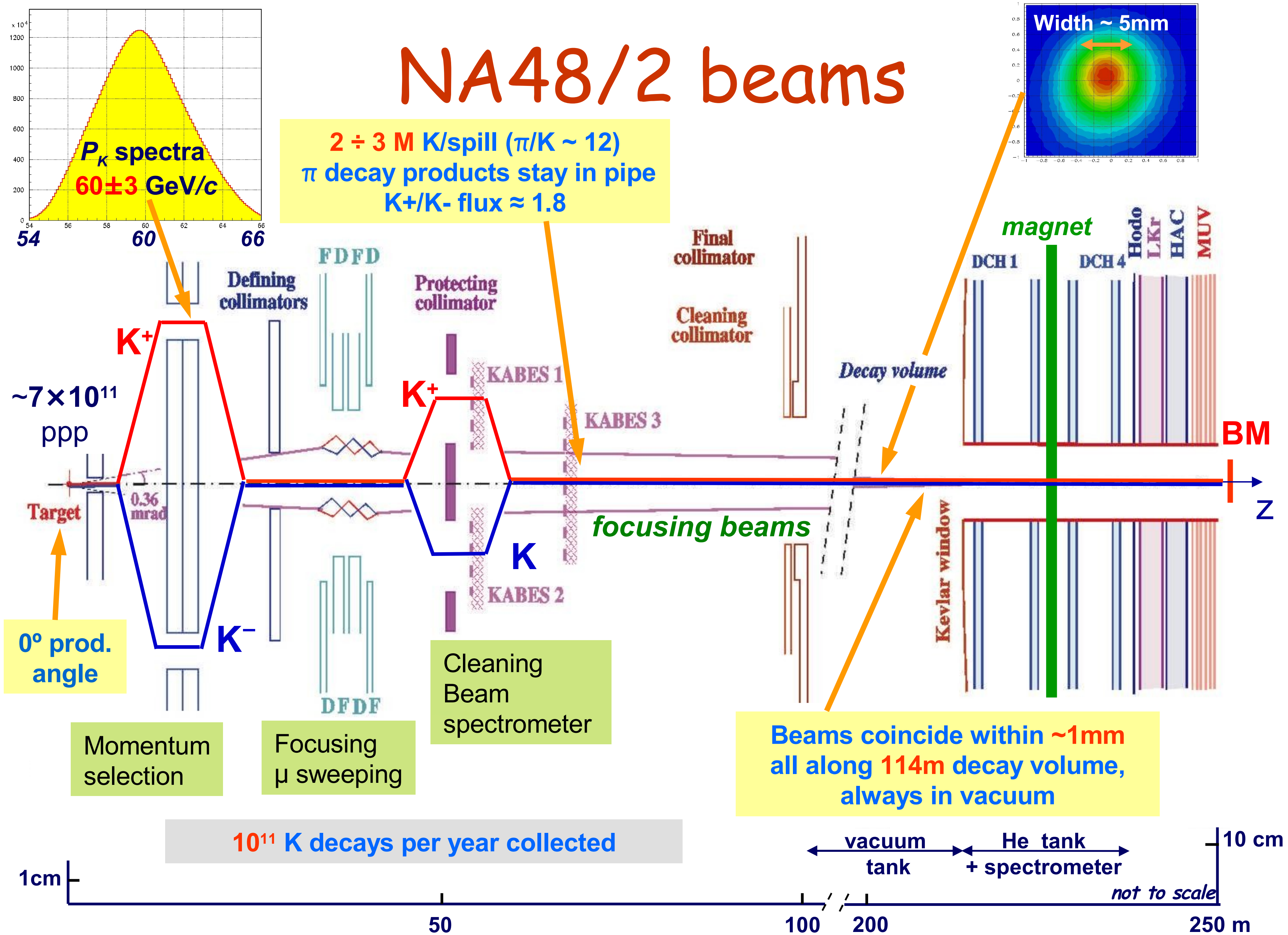
(1) Search for direct **CPV asymmetries** in K→3π decays
(2) Extraction of **ππ scattering lengths** from Ke4 decays
(3) High sensitivity study of **rare decays** (and TV, CPV)

Data taking completed (2003 and 2004, 110 days)
10^{11} K± through experiment, ~ 200 TB of data recorded



New beam line with two achromatic magnet quadruplets with K magnetic spectrometer: MICROMEGA TPC (0.7% resolution) at 2×10^7 particles/s <100 ps time resol.

NA48/2 beams


P_K spectra
60±3 GeV/c
54
60
66
Width ~ 5mm
2 ÷ 3 M K/spill (π/K ~ 12)
π decay products stay in pipe
K+/K- flux ≈ 1.8
~7×10^11
ppp
Target
0.36 mrad
0° prod. angle
K+
K−
Defining collimators
FDFD
DFDF
Protecting collimator
K+
K
KABES 1
KABES 2
KABES 3
Final collimator
Cleaning collimator
Decay volume
Kevlar window
magnet
DCH 1
DCH 4
Hodo
LKr
HAC
MUV
BM
Z
focusing beams
Momentum selection
Focusing μ sweeping
Cleaning Beam spectrometer
Beams coincide within ~1mm
all along 114m decay volume,
always in vacuum
10^11 K decays per year collected
vacuum tank
He tank + spectrometer
1cm
10 cm
not to scale
50
100
200
250 m

(Direct) CP violation in $K_{\pi 3}$

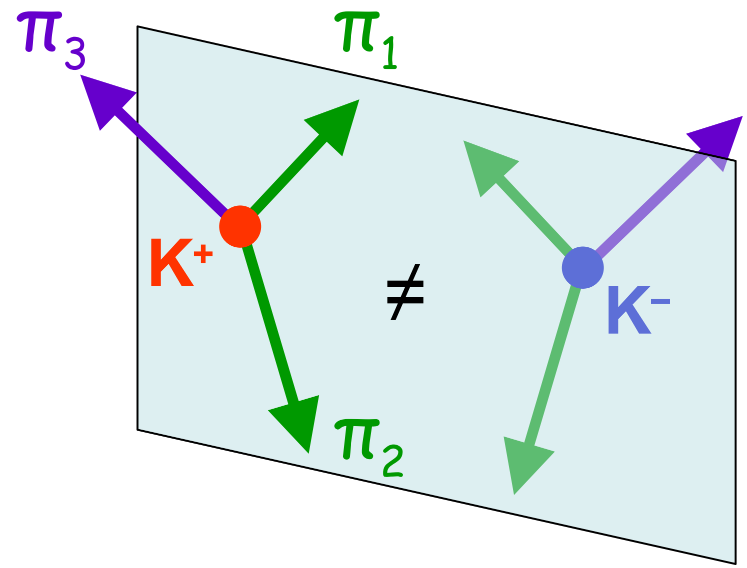
Kinematics:

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

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

$u = (s_3 - s_0)/m_\pi^2 = 2m_K\,(m_K/3 - E^*_{odd})/m_\pi^2$

$v = (s_2 - s_1)/m_\pi^2 = 2m_K(E^*_1 - E^*_2)/m_\pi^2$



Matrix element:

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

$A_g = (g_+ - g_-)/(g_+ + g_-) \neq 0\ ?$

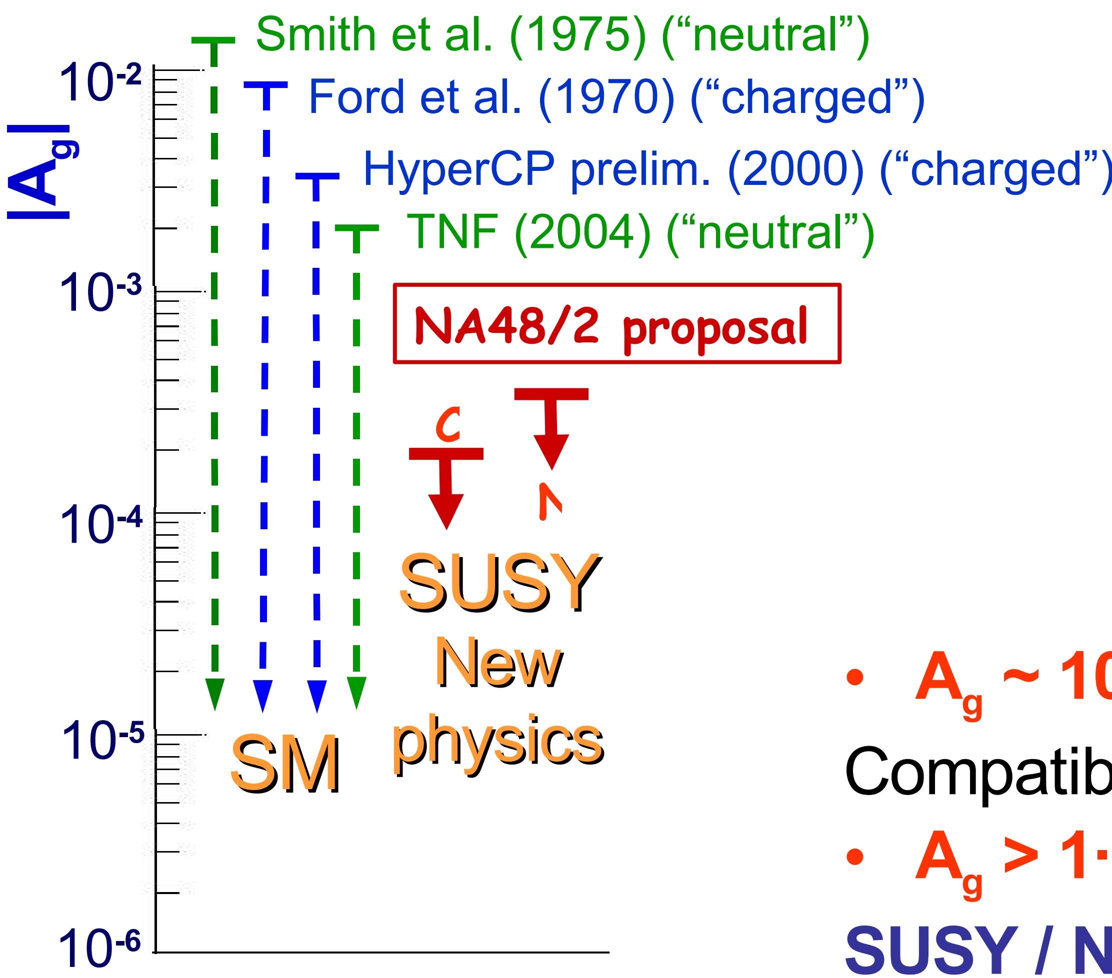
$K^\pm \to \pi^\pm \pi^+ \pi^-\ (\tau) \quad g = -0.2154 \pm 0.0035$

$K^\pm \to \pi^\pm \pi^0 \pi^0\ (\tau') \quad g = 0.652 \pm 0.031$

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

Potentially large effects (isospin)
Simple selection
Low backgrounds
No absolute K flux measurement:
compare only Dalitz plot **shapes**

$K^{\pm}$ asymmetries: status



THEORY:

SM contribution: many theoretical computations from several groups
Large uncertainties (~1 order of magnitude) esp. for "neutral"

Rate asymmetries further suppressed

Some enhancements possible beyond SM

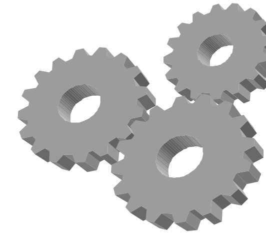
- $A_g \sim 10^{-5}$

Compatible with **SM**

- $A_g > 1 \cdot 10^{-4}$

SUSY / New Physics

The experimental method



Exploit maximal cancellations

- Simultaneous K^+ and K^- beams, superimposed in space, with narrow momentum spectra
- Detect asymmetry only from slopes of ratios of normalized u distributions
- Equalize averaged K^+ and K^- acceptances by frequently alternating polarities of relevant magnets

Project Dalitz plot onto u–axis
Neglect asymmetries in quadratic slopes

If acceptance is equal for K^+ and K^-

$$R(u) = N^+(u)/N^-(u) \approx n\cdot(1+g_+u)/(1+g_-u) \approx n\cdot(1+\Delta g\, u)$$

from which $Ag = \Delta g/2g$ is extracted

Any imperfection has to be charge-asymmetric AND non-flat in u to induce an effect

Acceptance cancellation

Detector left-right asymmetry cancels in 4 ratios of K^+ over K^- u distributions:

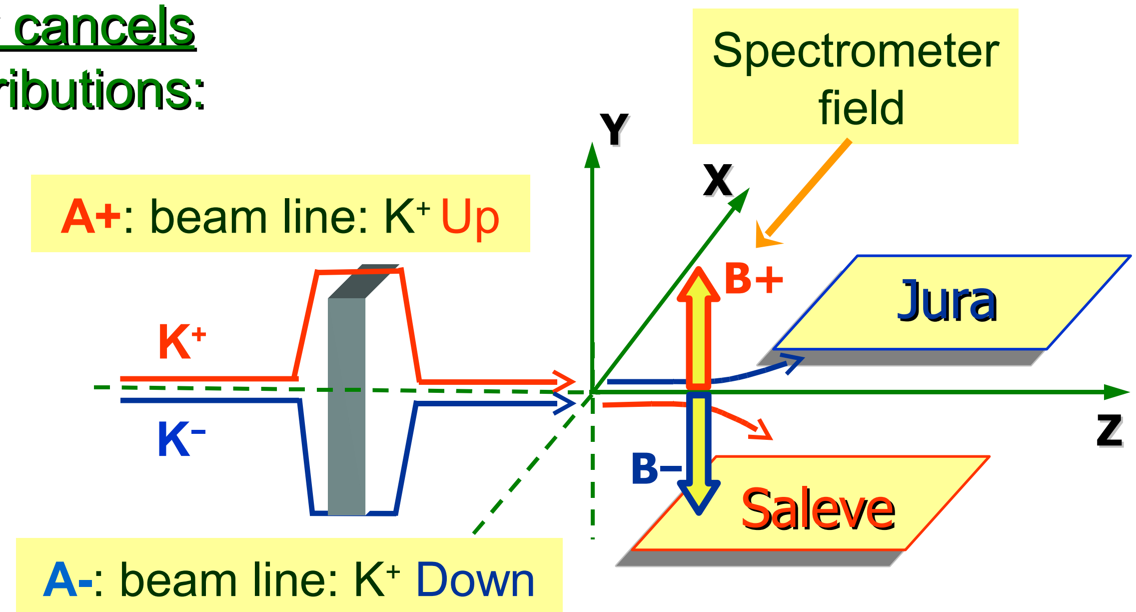
(same deviation by spectrometer in numerator and denominator)

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

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

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

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



- **Beam line** (achromat) polarity (A) reversed on weekly basis
- **Spectrometer magnet** polarity (B) reversed on daily or 3h basis

Analysis does not rely on Monte Carlo

More cancellations

Fit with **quadruple ratio**:

Cancel global time instabilities

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

Cancel beam differences

$$R = n \cdot (1 + 4\,\Delta g\, u)$$

Normalization (n)

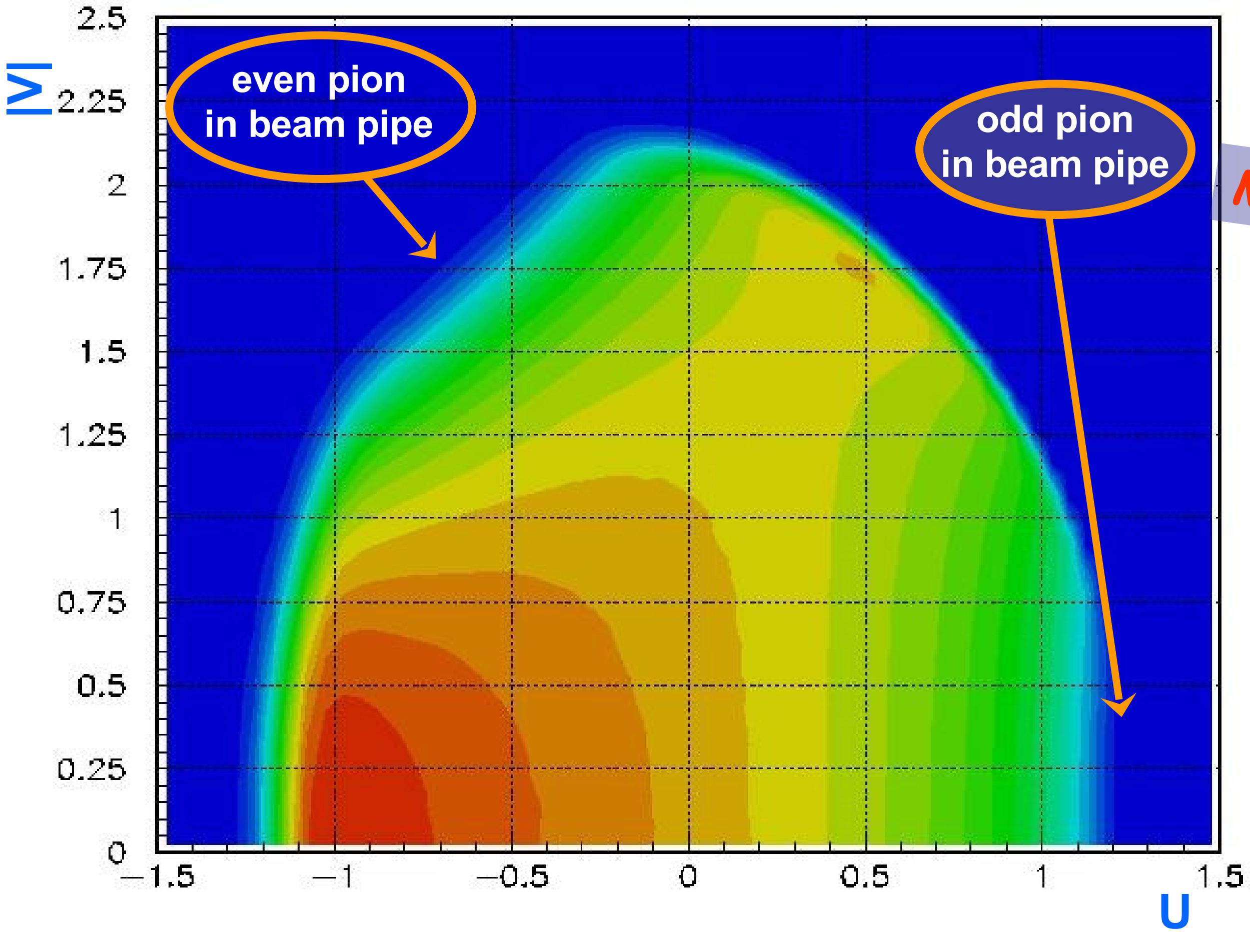
Slope difference (Δg)

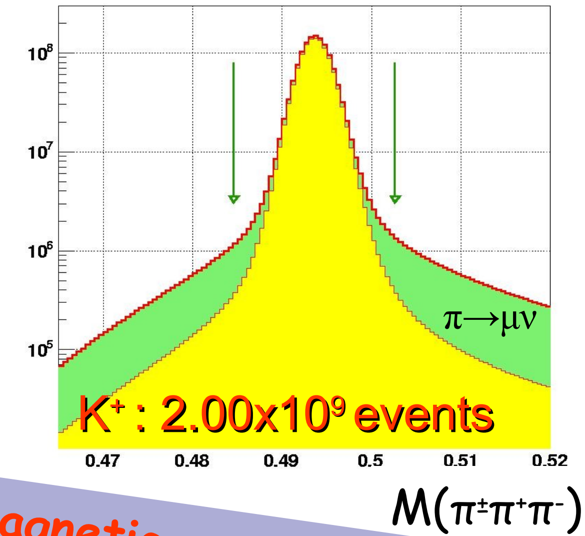
The fit result is sensitive only to time variation of left-right asymmetries of experimental conditions on a time-scale of ~1 subsample

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

Final sample 2003+2004:

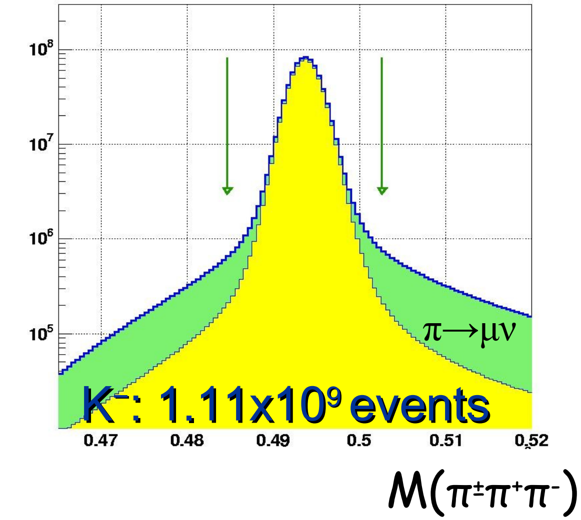
3.1x10⁹ *events selected* (K^{+} / K^{-} ≈ 1.8)





Magnetic spectrometer only

No significant background



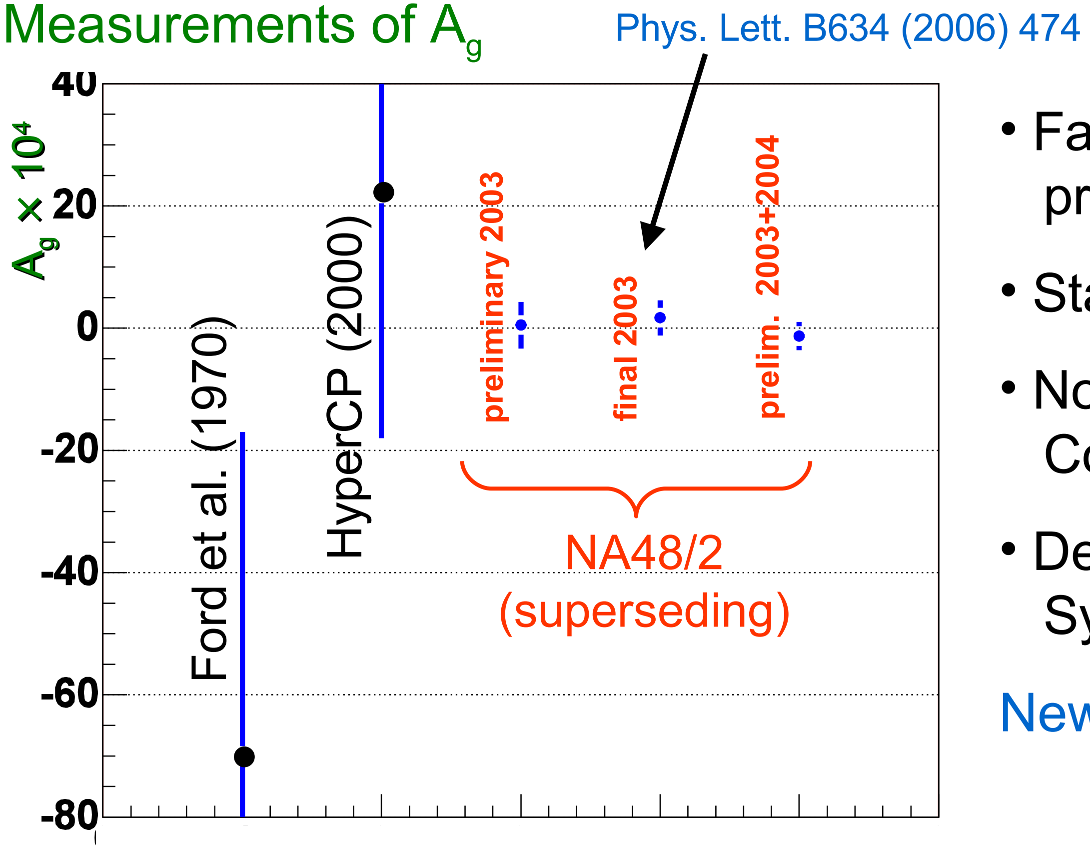
$K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ asymmetry results

PRELIMINARY
based on full statistics
accumulated in
the 2003 and 2004 runs

$$A_g = (1.3 \pm 1.5_{stat} \pm 0.9_{trig} \pm 1.4_{syst}) \times 10^{-4}$$

$$A_g = (1.3 \pm 2.3) \times 10^{-4}$$

Measurements of A_g



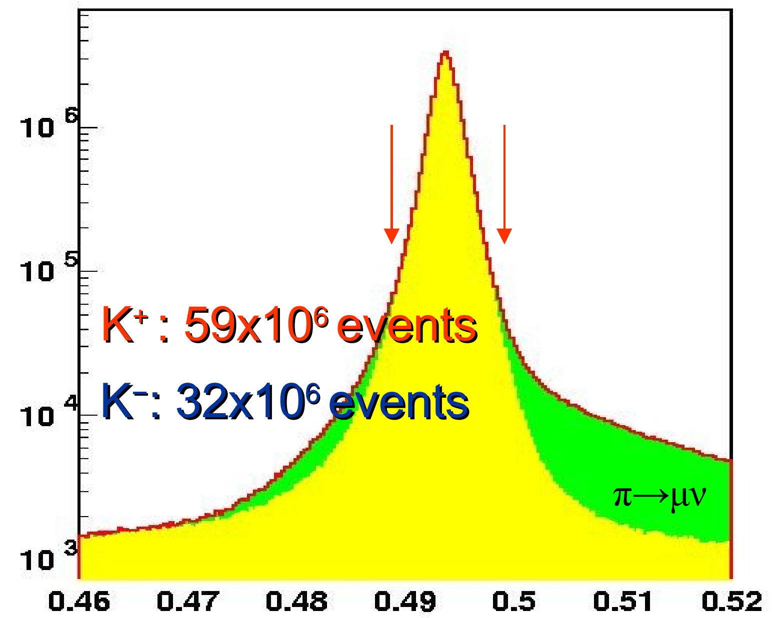
- Factor ~20 higher precision than previous measurements
- Statistical uncertainties dominate
- No CPV found
  Compatible with SM estimates
- Design goal reached
  Systematics finalized soon

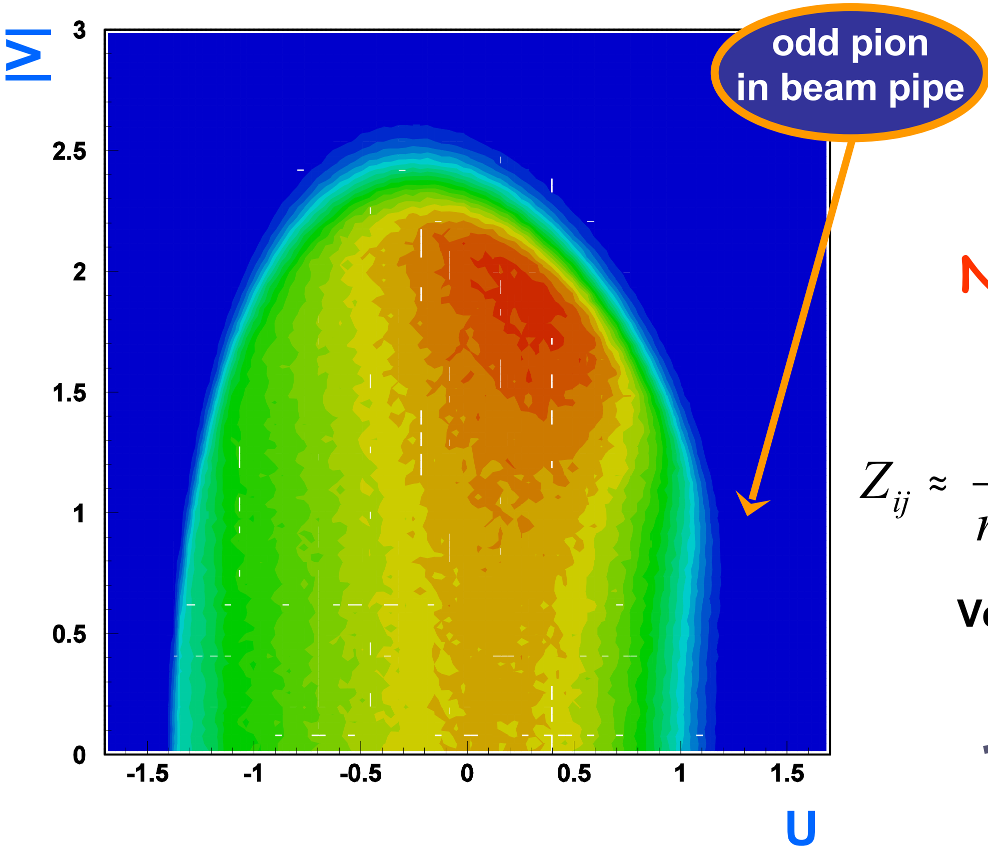
New physics window closed

$K^\pm \rightarrow \pi^\pm\pi^0\pi^0$

Final sample 2003+2004:

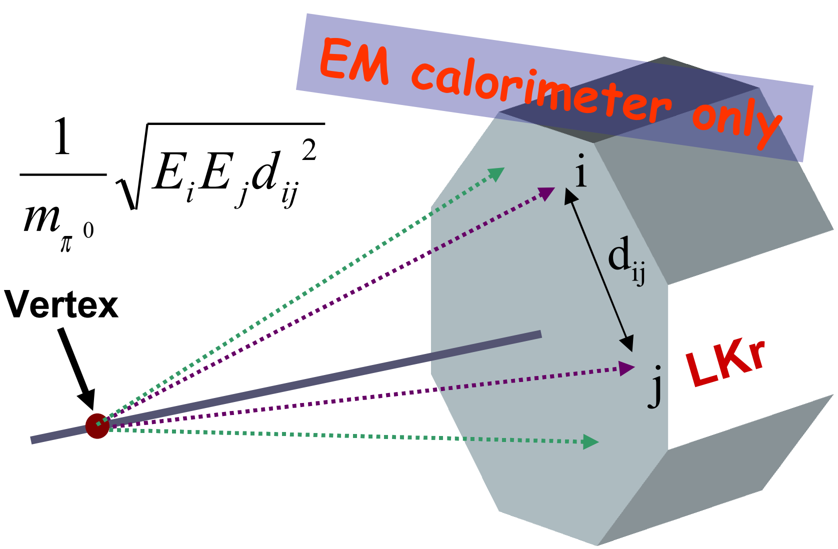
0.91×10^8 *events selected* ($K^+/K^- \approx 1.8$)





No significant background

$$Z_{ij} \approx \frac{1}{m_{\pi^0}}\sqrt{E_i E_j d_{ij}^2}$$



$K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ asymmetry results

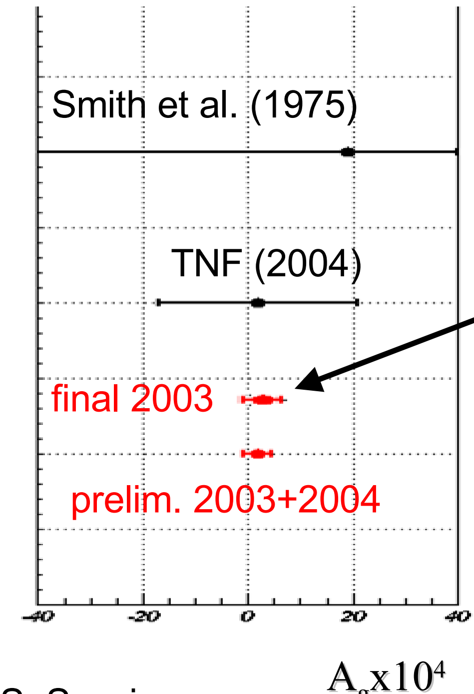
PRELIMINARY
based on full statistics
accumulated in
the 2003 and 2004 runs

$$A_g = (2.1 \pm 1.6_{stat} \pm 1.0_{syst} \pm 0.2_{ext}) \times 10^{-4}$$

$$A_g = (2.1 \pm 1.9) \times 10^{-4}$$

Statistics much lower than for "charged" mode
But more favourable Dalitz-plot distribution
Quadratic slope cannot be neglected

Measurements of A_g



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- Factor ~10 higher precision than previous measurements
- Statistical uncertainties dominate
- No CPV found
  Compatible with SM estimates
- Design goal reached
  Systematics finalized soon

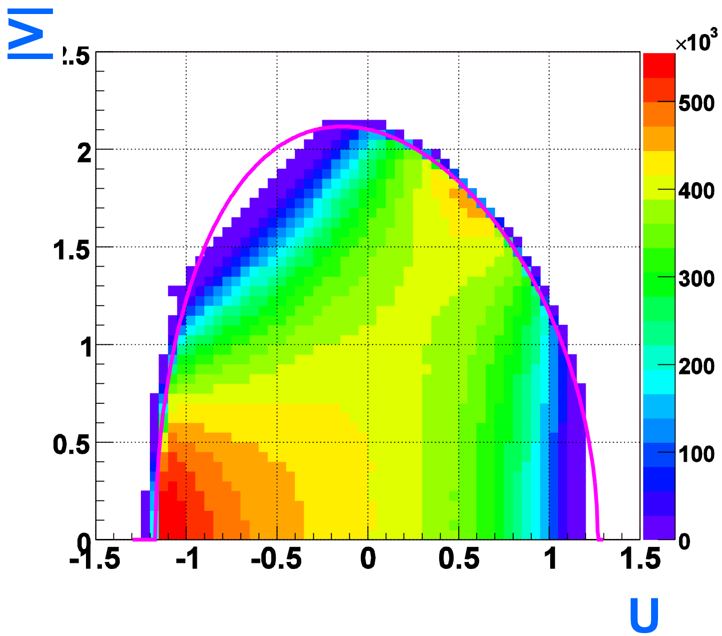
New physics window closed

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

Experiment designed for asymmetry measurements
Still, unprecedented statistics allows improvement in slope measurements
Deliberately ignore non-analytic (see later) and radiative effects
Full MC tuning, agreement to 10^{-3} level

$$d\Gamma/dudv \sim C(u,v)\times(1+gu+hu^2+kv^2)$$

Naïve Coulomb correction



Preliminary results
from partial 2003 statistics
(0.47×10^9 events)

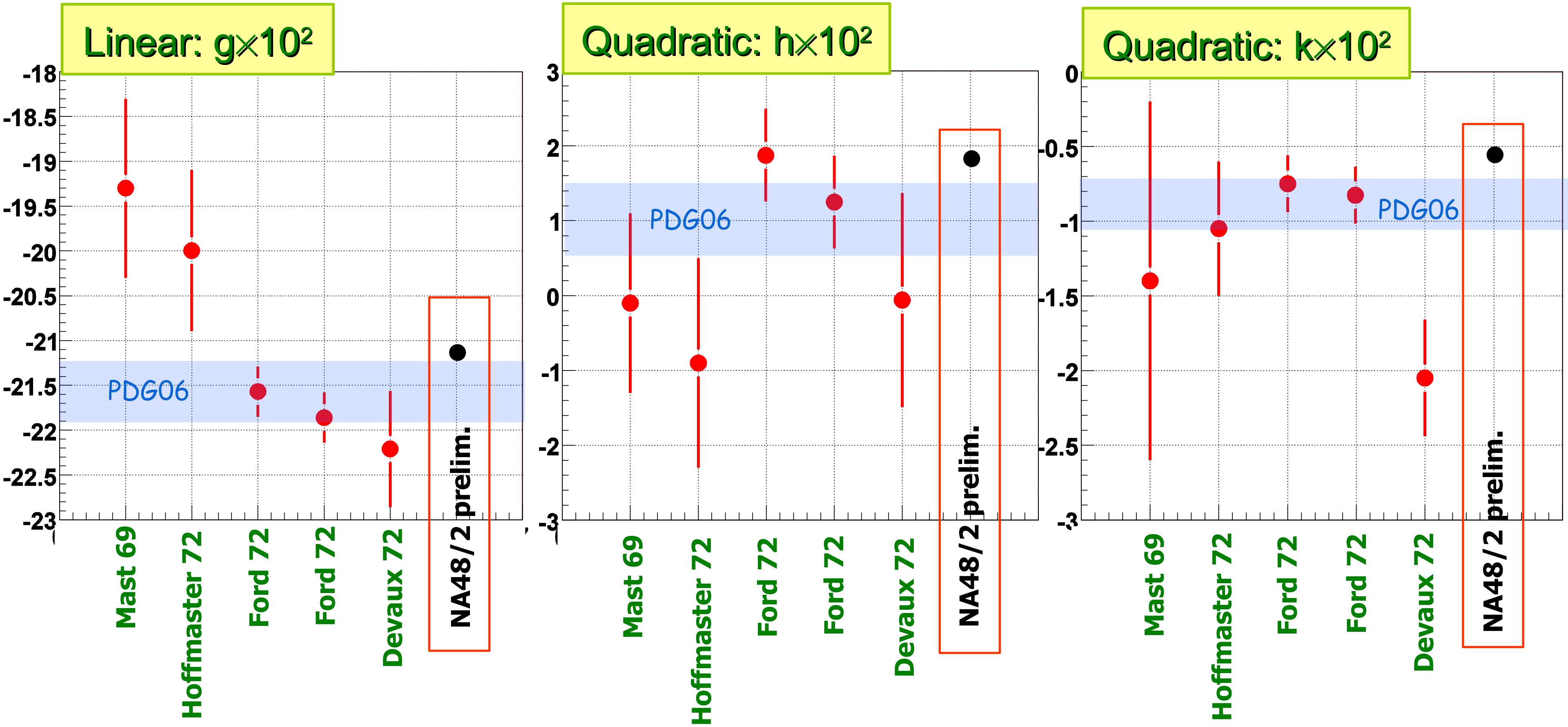
$g = -21.131 \pm 0.010 \pm 0.005$

$h = 1.829 \pm 0.017 \pm 0.031$

$k = -0.467 \pm 0.005 \pm 0.009$

"Naïve" slopes (comparable with PDG)
Systematics dominated by π mom. resolution

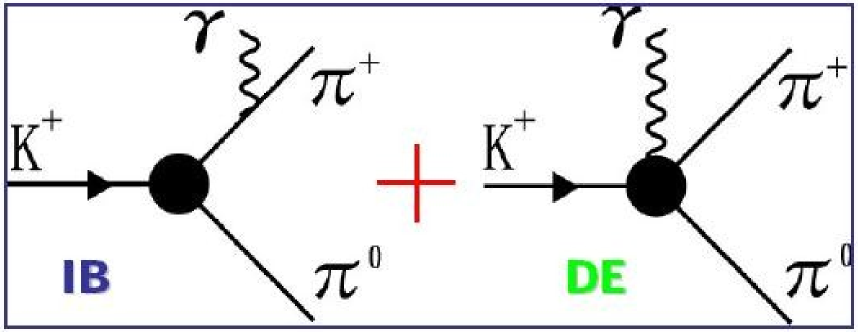
$K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-}$ Dalitz plot



One order of magnitude improvement in precision

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

BR ~ $3 \cdot 10^{-4}$ IB dominates, DE measured, interference term not yet



$$W^2 = \frac{(P_K^* \cdot P_\gamma^*)(P_\pi^* \cdot P_\gamma^*)}{(m_k m_\pi)^2}$$

$$\frac{d\Gamma^\pm}{dW} \simeq \underbrace{\left(\frac{d\Gamma^\pm}{dW}\right)_{IB}}_{IB} \left[1 + \underbrace{2\left(\frac{m_\pi}{m_K}\right)^2 W^2 |E| cos((\delta_1 - \delta_0) \pm \phi)}_{INT} + \underbrace{\left(\frac{m_\pi}{m_K}\right)^4 W^4 (|E|^2 + |M|^2)}_{DE}\right]$$

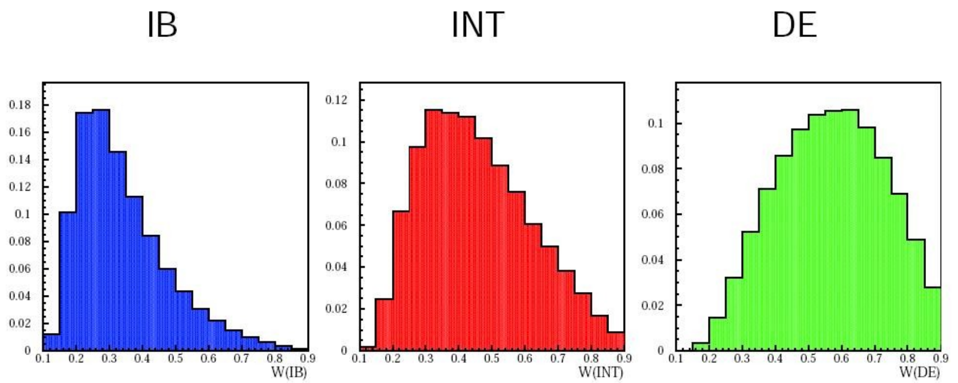
INT term could give CPV asymmetry

$|\varepsilon'_{+0\gamma}|$ <~ 10^{-4}

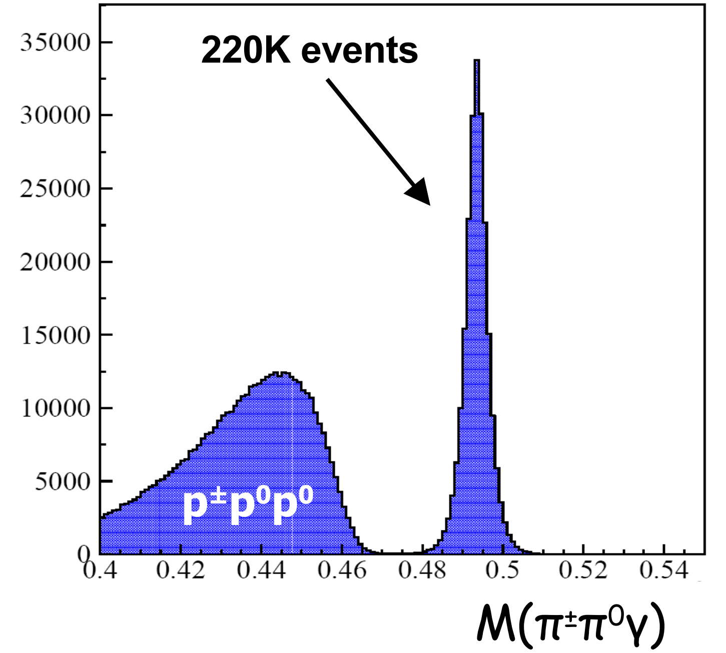
$$A_\Gamma = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ - \Gamma^-} \propto \varepsilon'_{+0\gamma} \tan(\Delta\delta) \qquad \Gamma^\pm = \int dE_\gamma \left[\frac{\partial\Gamma}{\partial E_\gamma} - \left.\frac{\partial\Gamma}{\partial E_\gamma}\right|_{IB}\right]$$

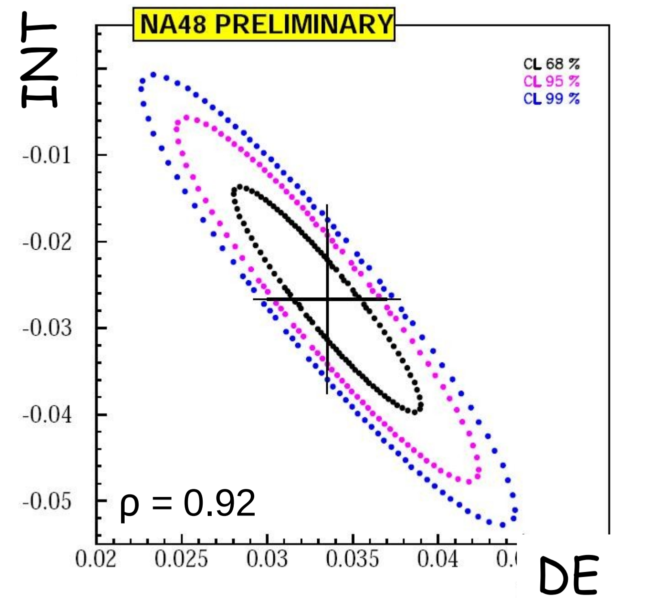
$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$

Background (3π) <1% of DE



Separation by photon spectrum (W)





NA48/2 (2006) preliminary: (30% sample)
First indication of INT
Systematics from trigger efficiency (improved in 2004)

$$Frac(DE)_{0<T_{\pi}^{*}<80MeV} = (3.35 \pm 0.35_{stat} \pm 0.25_{syst})\%$$

$$Frac(INT)_{0<T_{\pi}^{*}<80MeV} = (-2.67 \pm 0.81_{stat} \pm 0.73_{syst})\%$$

$K^\pm \to \pi^+\pi^-e^\pm\nu$ (Ke4) decays

"Classical" way to extract well-predicted difference of s-wave ππ scattering lengths (predicted by QCD at 2% – quark condensate)
Theoretical input required

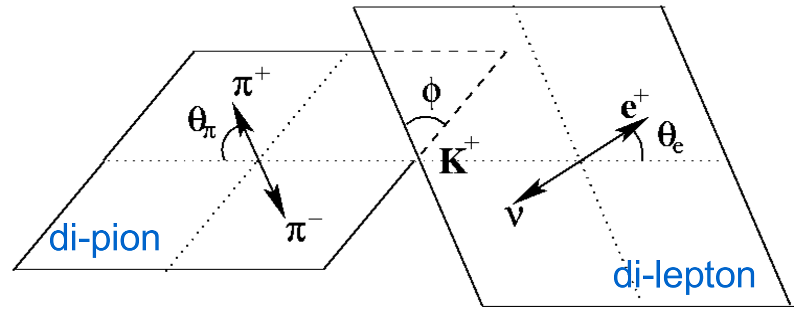
Form factors

$F = F_s e^{i\delta_0^0} + F_p e^{i\delta_1^1} \cos\theta$ + d–wave...

$G = G_p e^{i\delta_1^1}$ + d–wave...

$H = H_p e^{i\delta_1^1}$ + d–wave...

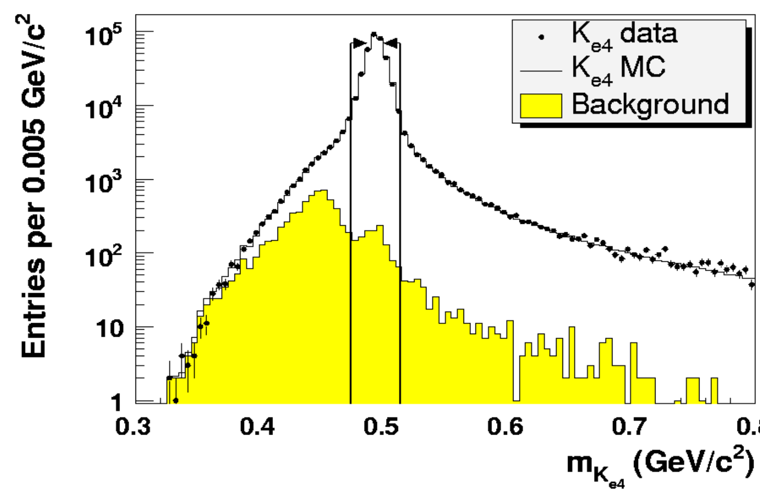
Keep only s– and p–waves (small q^2) and rotate by $\delta_1^1 \to$ 5 form factors



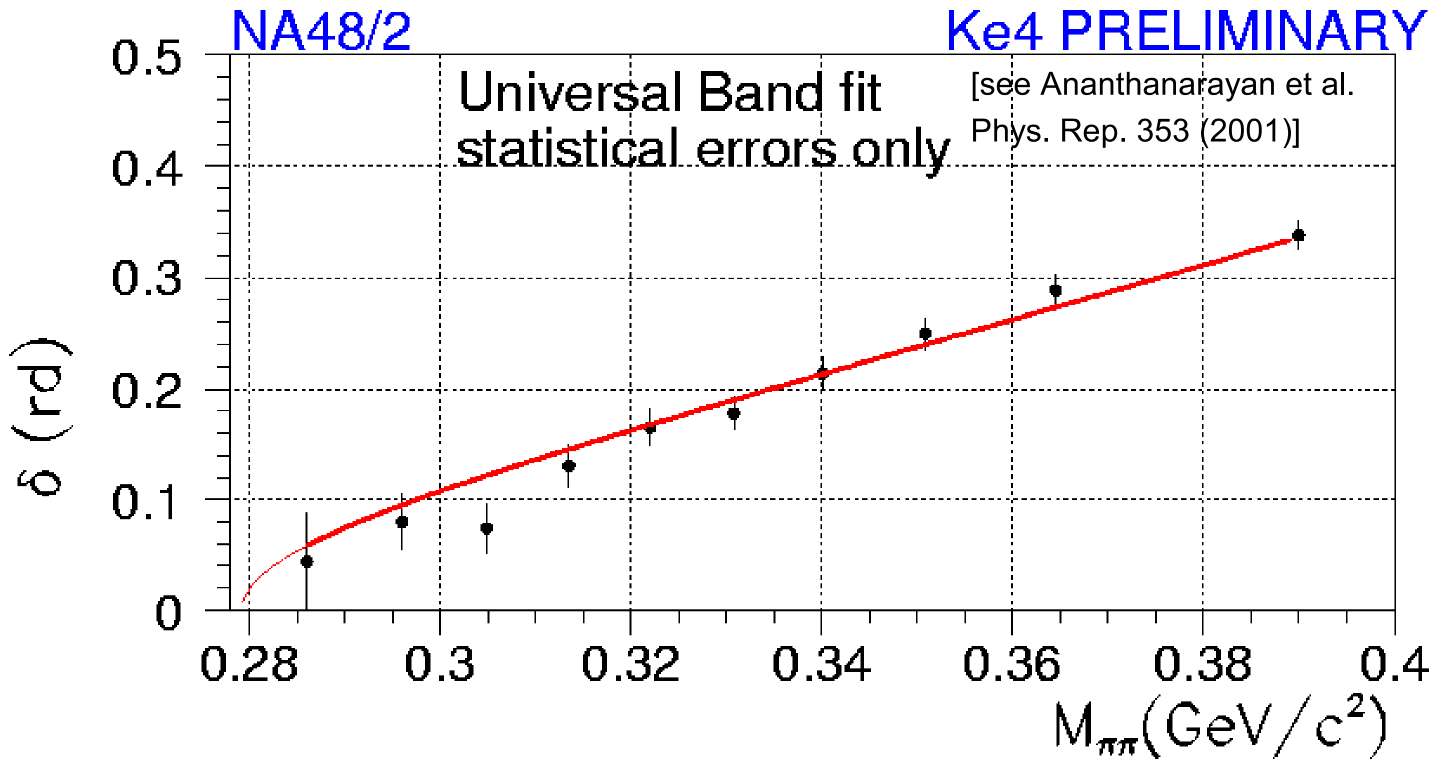
Cabibbo–Maksymovicz variables:
$M^2_{\pi\pi}$, $M^2_{e\nu}$, $\cos\theta_\pi$, $\cos\theta_e$, ϕ

(30% of sample) ~370000 events
with 0.5% background

10 independent fits on equal-population bins in 5–dim space (each $M_{\pi\pi}$ bin)



Ke4 results



$\delta = \delta_0^0 - \delta_1^1$ distribution fitted with 1 parameter a_0^0

New NA48/2 preliminary (350K events):

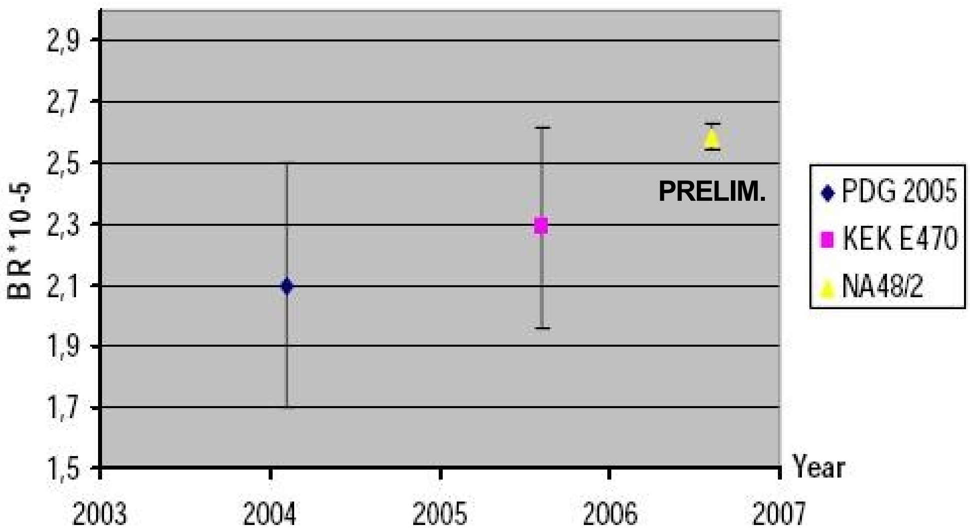
$a_0^0 = 0.256 \pm 0.008 \pm 0.007 \pm 0.018$

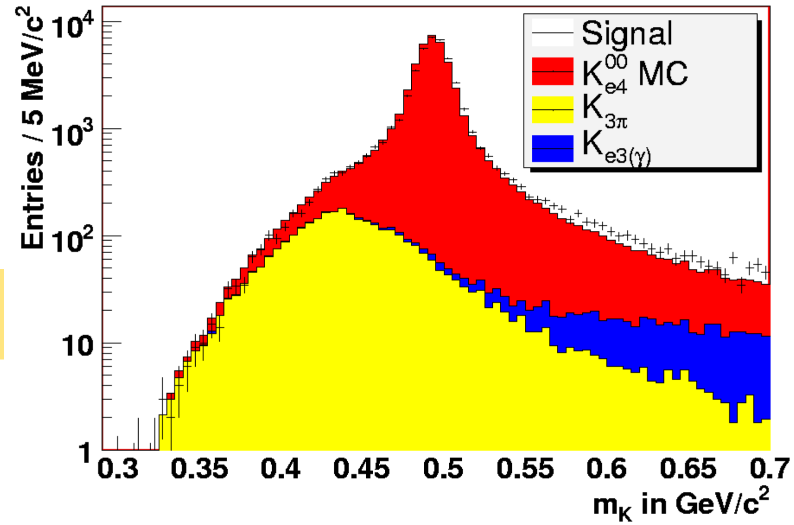
(and $a_0^2 = -0.031 \pm 0.015 \pm 0.015 \pm 0.009$ using U.B.)

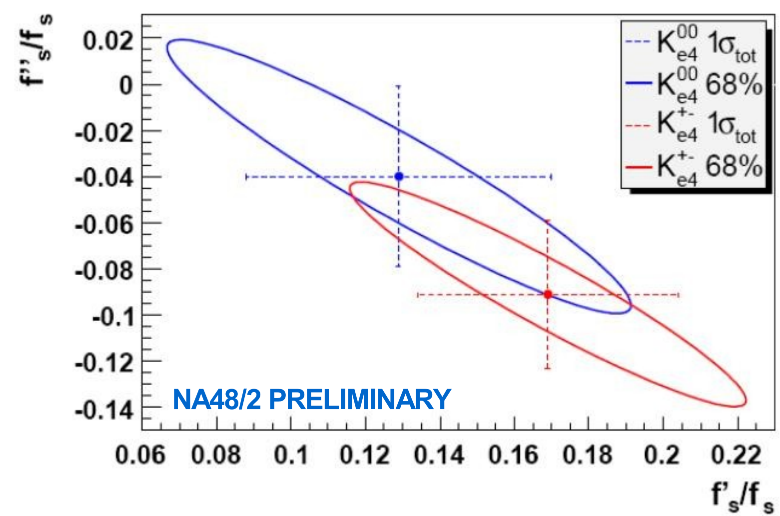
$K^{\pm} \rightarrow \pi^0\pi^0 e^{\pm}\nu$

Only 1 form factor in this case
2–3% background.
New NA48/2 preliminary measurement
(9600 events):

$$BR(K_{e4}^{00}) = (2.587 \pm 0.026_{stat} \pm 0.019_{syst} \pm 0.029_{ext}) \cdot 10^{-5}$$



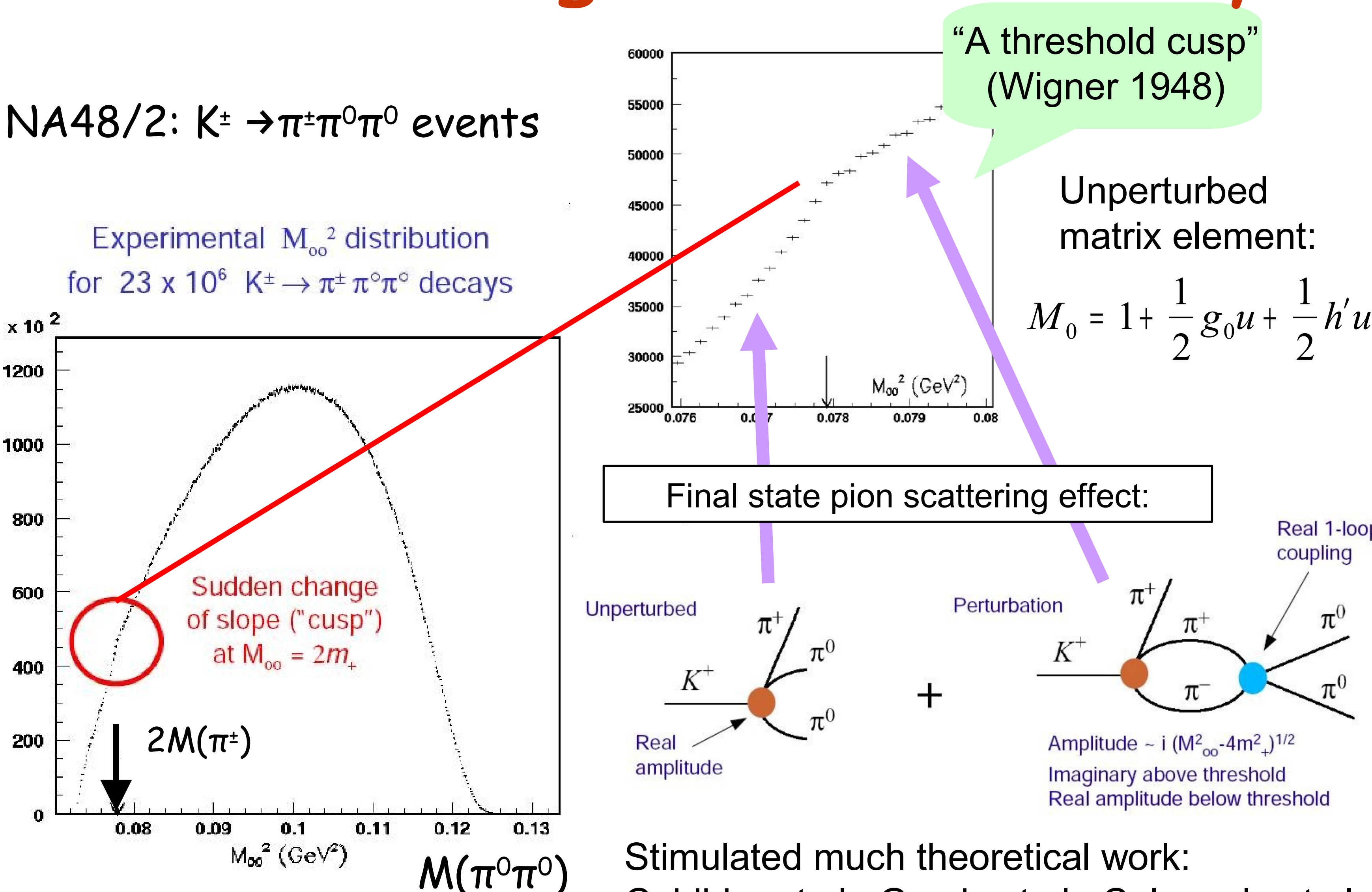




Form factors consistent with charged Ke4
(37K events)

ππ scattering in K→3π decays

NA48/2: $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ events



Unperturbed matrix element:

$$M_0 = 1 + \frac{1}{2} g_0 u + \frac{1}{2} h' u^2$$

Stimulated much theoretical work:
Cabibbo et al., Gamiz et al., Colangelo et al.

ππ scattering lengths

The magnitude of the discontinuity (cusp) is directly related to the $(a_0^0 - a_0^2)$ difference in ππ scattering lengths.

Using Cabibbo–Isidori 2nd order expansion (and assuming k=0), from the unconstrained fit:

$$(a_0 - a_2)\, m_\pi = 0.268 \pm 0.010_{stat} \pm 0.004_{syst} \pm 0.013_{ext}$$

$$a_2\, m_\pi = 0.041 \pm 0.022_{stat} \pm 0.014_{syst}$$

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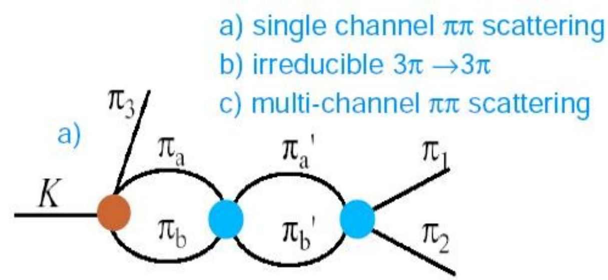
Radiative effects require improved theoretical framework

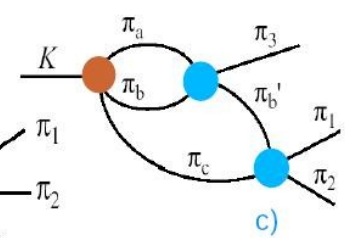
(20% of total statistics)

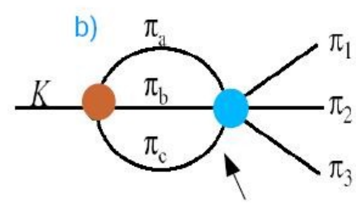
New approach, potentially very powerful, alternative to Ke4 and pionium (DIRAC expt)

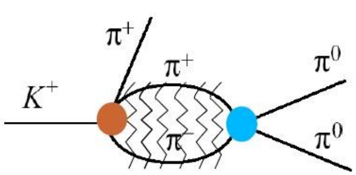
Evidence for pionium formation, sensitivity to higher–order effects…



[see Cabibbo, Isidori, JHEP 0503 (2005) 21]







ππ scattering lengths: improvements

Unperturbed matrix element:

$$M_0 = 1 + \frac{1}{2} g_0 u + \frac{1}{2} h' u^2 + \frac{1}{2} k' v^2 + \ldots$$

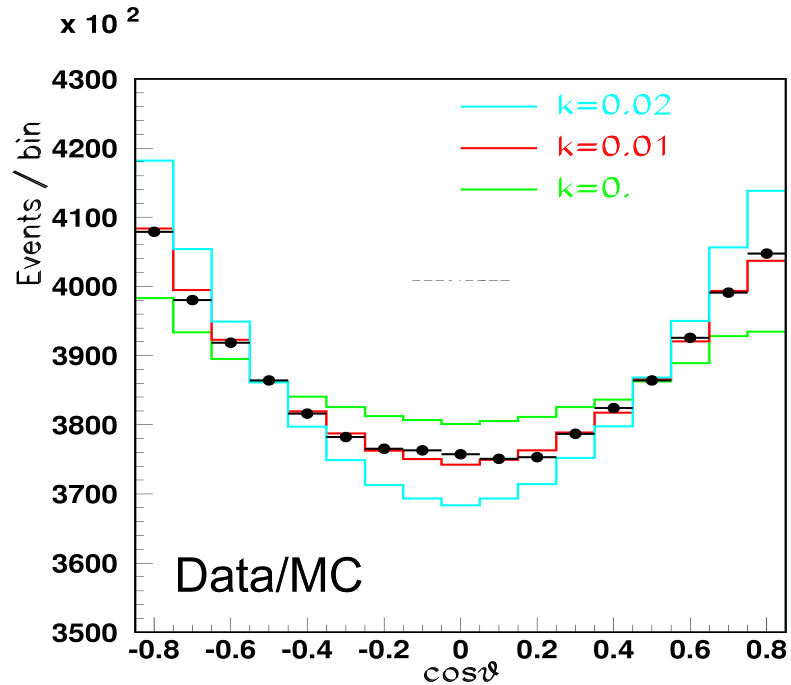
and k' ≈ 0 was assumed
(following PDG)

NA48/2 preliminary (2003 data):
Evidence for a non–zero k'

$k' = 0.0097 \pm 0.0003_{stat} \pm 0.0008_{syst}$

Significative changes in g_0 and h'

No change in $a_0^0 - a_0^2$ and a_0^2



Angle between $\pi^\pm$ and π^0 in $\pi^0\pi^0$ CM

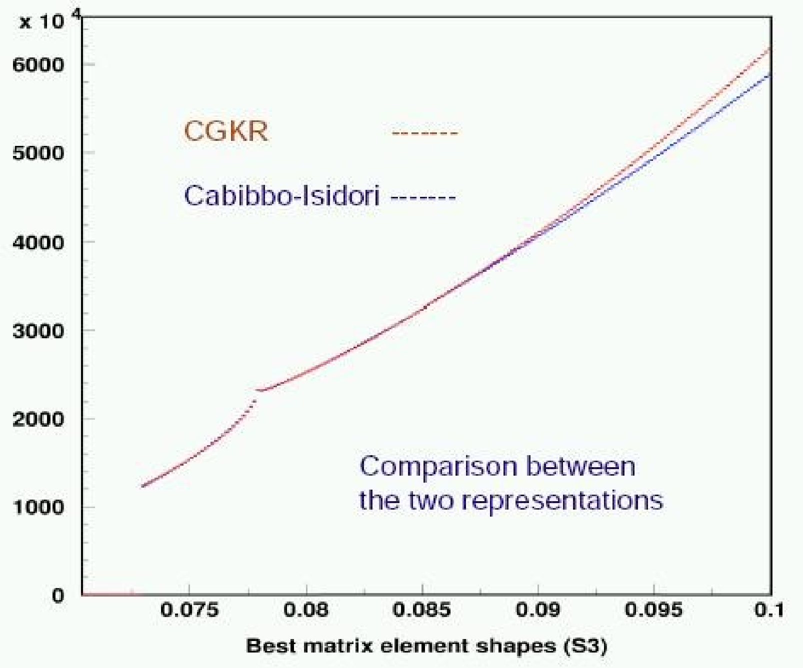
ππ scattering lengths: improvements

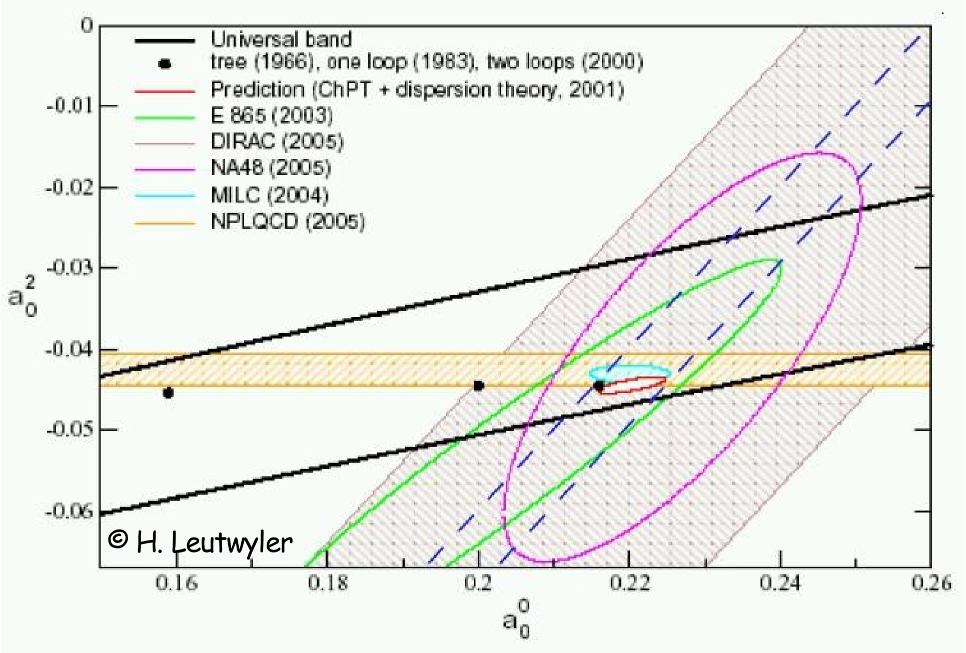
Non–relativistic lagrangian framework developed (Colangelo et al.)

Allows systematic improvement and inclusion of radiative effects

Allows fitting the whole Dalitz plot

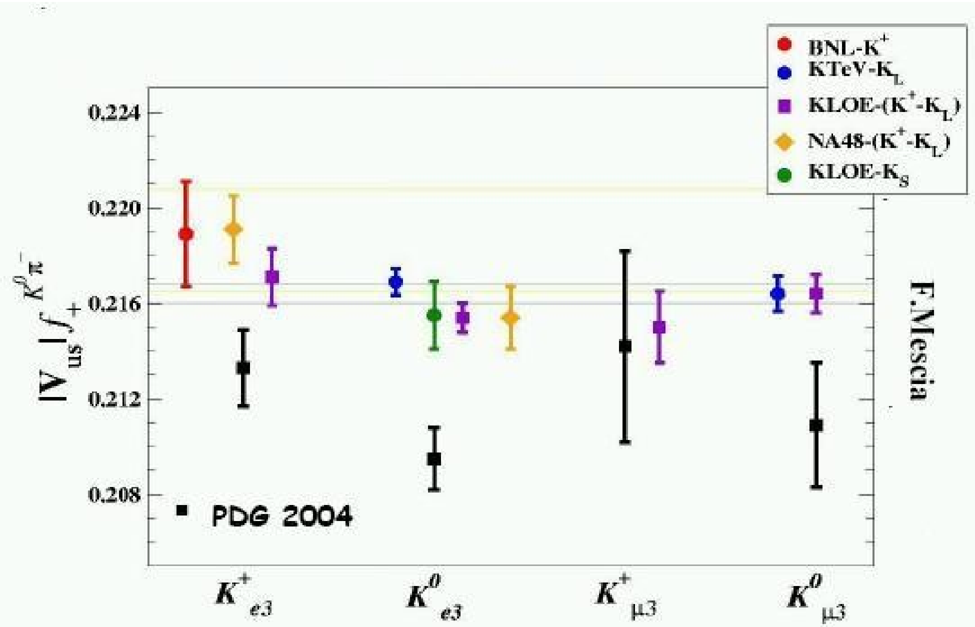
Includes quadratic terms at second order





WORK IN PROGRESS…

Kℓ3 decays: V_{us} and form factors



After the "semileptonic revolution" the Vus issue seems solved

More results expected

($K^{\pm}$, K_S, radiative)

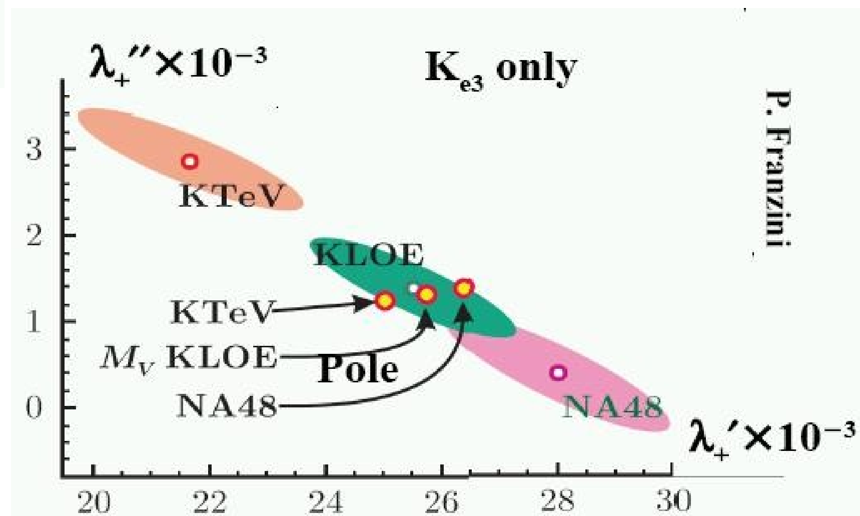
Kμ3 form factors:

2.6M $K_L \to \pi\mu\nu$ decays

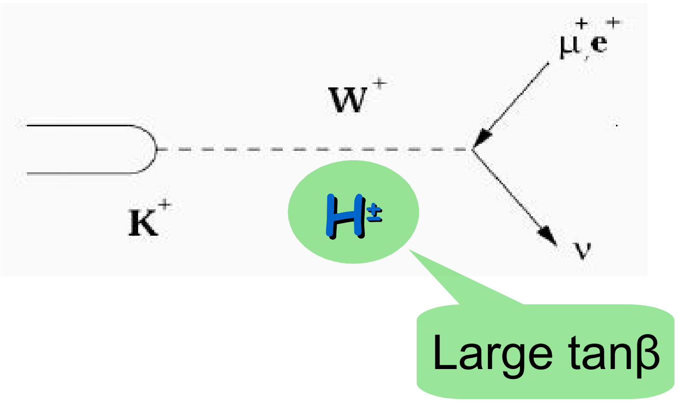
$$\lambda_+ = 0.0260 \pm 0.0007_{stat} \pm 0.0010_{syst}$$

$$\lambda_0 = 0.0120 \pm 0.0008_{stat} \pm 0.0015_{syst}$$

NA48 preliminary



Kℓ2 decays: unexpected fame



Masiero et al. (2006): $R_K = \Gamma(K^\pm \to e^\pm \nu) / \Gamma(K^\pm \to \mu^\pm \nu)$

as the most sensitive probe of SUSY LFV effects:

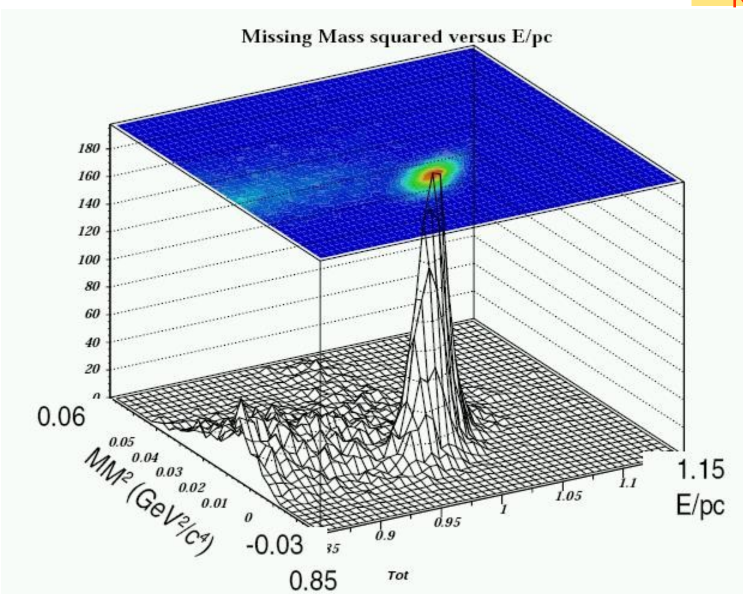
effects can reach 2–3% (!)

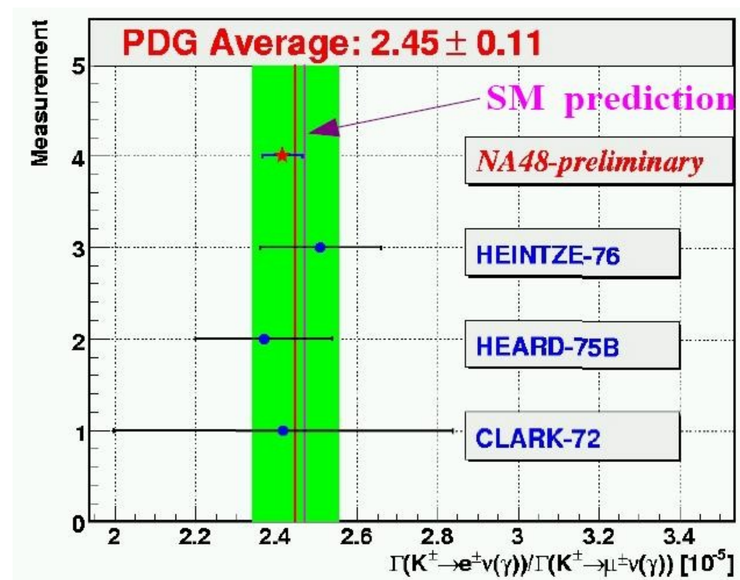
SM: $R_K = (2.472 \pm 0.001) \times 10^{-5}$

PDG: $R_K = (2.45 \pm 0.11) \times 10^{-5}$

NA48/2 preliminary (byproduct, 1 month run)

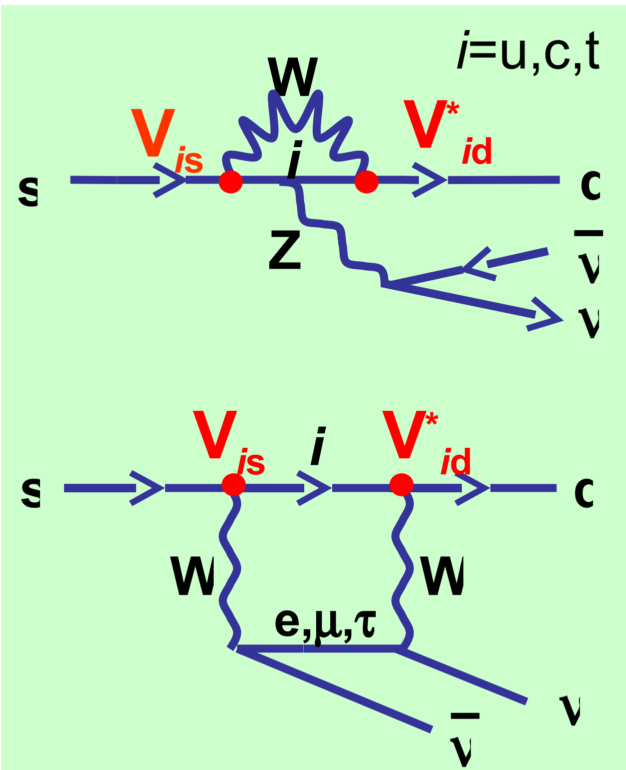
$R_K = (2.416 \pm 0.043 \pm 0.024) \times 10^{-5}$





A new run would have the potential to reach sub–percent accuracy.

K→πνν̄: the (new) "holy grail"



- Z(γ) penguin and box diagrams
- Top in loop, sensitivity to V_{td}
- Small theoretical uncertainty (also true BSM)

$$B(K^+ \to \pi^+ \nu \bar{\nu}) \approx 1.0 \times 10^{-10} A^4 \left(\eta^2 + (\rho_0 - \rho)^2\right)$$

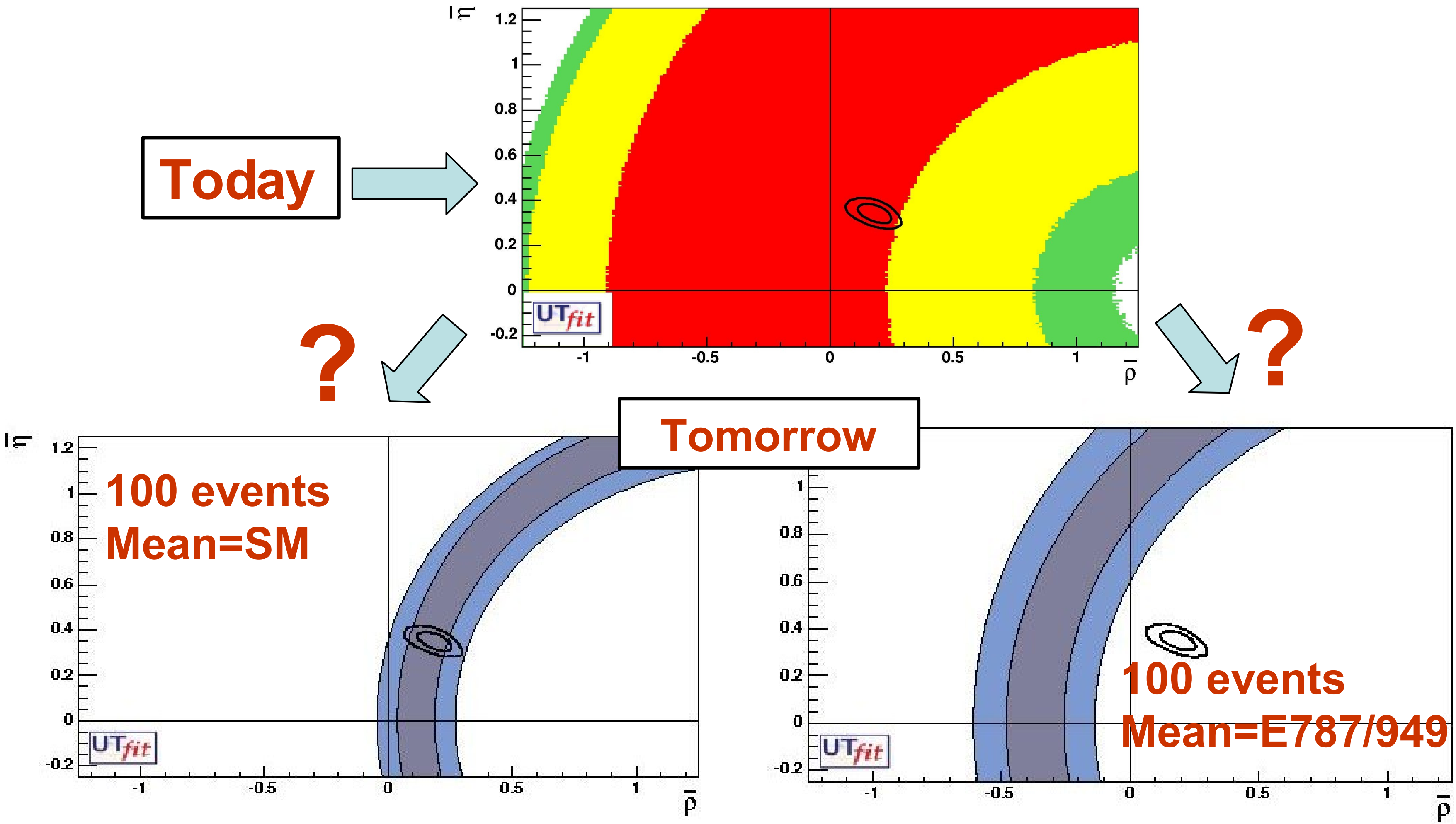
$$= (8.0 \pm 1.1) \times 10^{-11}$$

$$B(K_L \to \pi^0 \nu \bar{\nu}) = 2.2 \times 10^{-10} \left(\frac{\mathrm{Im}(V_{ts}^* V_{td})}{\lambda^5} X(x_t) \right)^2$$

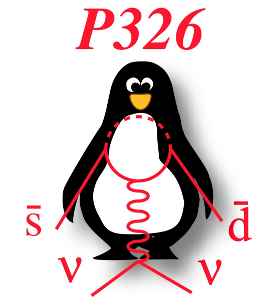
$$= (2.8 \pm 0.4) \times 10^{-11}$$

$K^+ \to \pi^+ \nu\bar{\nu}$ and the SM

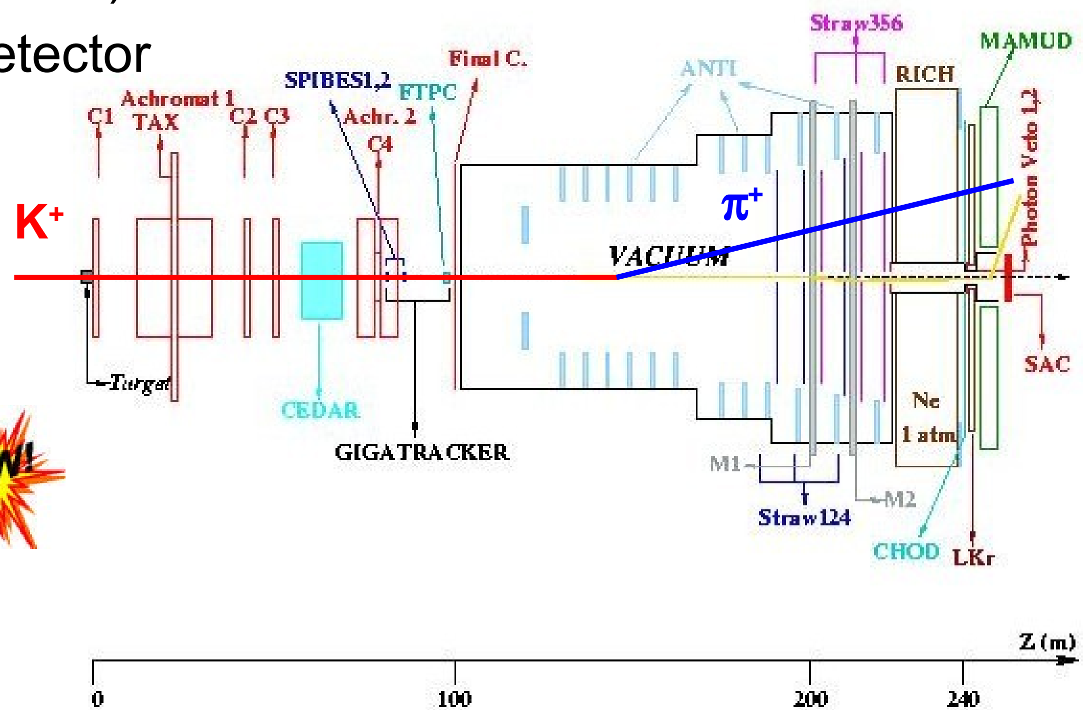
E787/E949: $BR(K^+ \to \pi^+ \nu\bar{\nu}) = 1.47^{+1.30}_{-0.89} \times 10^{-10}$



$K^+ \rightarrow \pi^+ \nu\bar{\nu}$: P-326 proposal

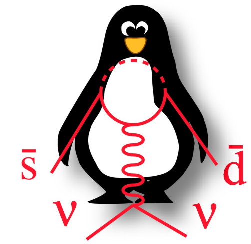


- At CERN SPS
- Decay *in flight*
  (75 GeV unseparated K^+ beam)
- Loosely based on NA48 detector (incl. LKr calorimeter)
- Background rejection:
  - PID(π/μ) by RICH
  - High E π^0, low ineff.
  - Missing mass cut
- K^+ tracking in 1 GHz
- Expect **80 SM events** in **2 years**



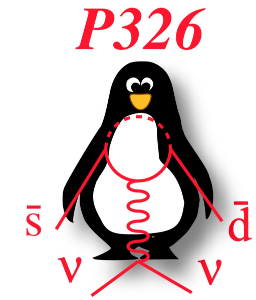
$K^+ \to \pi^+ \nu\bar{\nu}$: P-326 yield/yr

P326



	Total	Region I	Region II
Signal (SM)	**65**	**16**	**49**
$K^+ \to \pi^+\pi^0$	2.7 ± 0.2	1.7 ± 0.2	1.0 ± 0.1
$K_{\mu 2}$	1.2 ± 0.3	1.1 ± 0.3	< 0.1
K_{e4}	2 ± 2	Negligible	2±2
$K^+ \to \pi^+\pi^+\pi^-$ and other 3-tracks	1 ± 1	Negligible	1±1
$K_{\pi 2}\gamma$	1.3 ± 0.4	Negligible	1.3 ± 0.4
$K_{\mu 2}\gamma$	0.4 ± 0.1	0.2 ± 0.1	0.2 ± 0.1
K_{e3}, $K_{\mu 3}$,others	Negligible	-	-
Total bkg	**9 ± 3**	**3.0 ± 0.2**	**6 ± 3**

$K^+ \to \pi^+ \nu\bar{\nu}$: P-326 status



CERN-SPSC-2005-013
SPSC-P-326

CERN, Dubna, Ferrara, Firenze, Frascati, Mainz, Merced, Moscow, Napoli, Perugia, Protvino, Pisa, Roma, Saclay, San Luis Potosi, Sofia, Torino

and **looking for more collaborators…**

SPS used as LHC injector (it will run in the future)
No flagrant time overlap with CNGS
Fully compatible with rest of CERN fixed target program
Conservative beam request

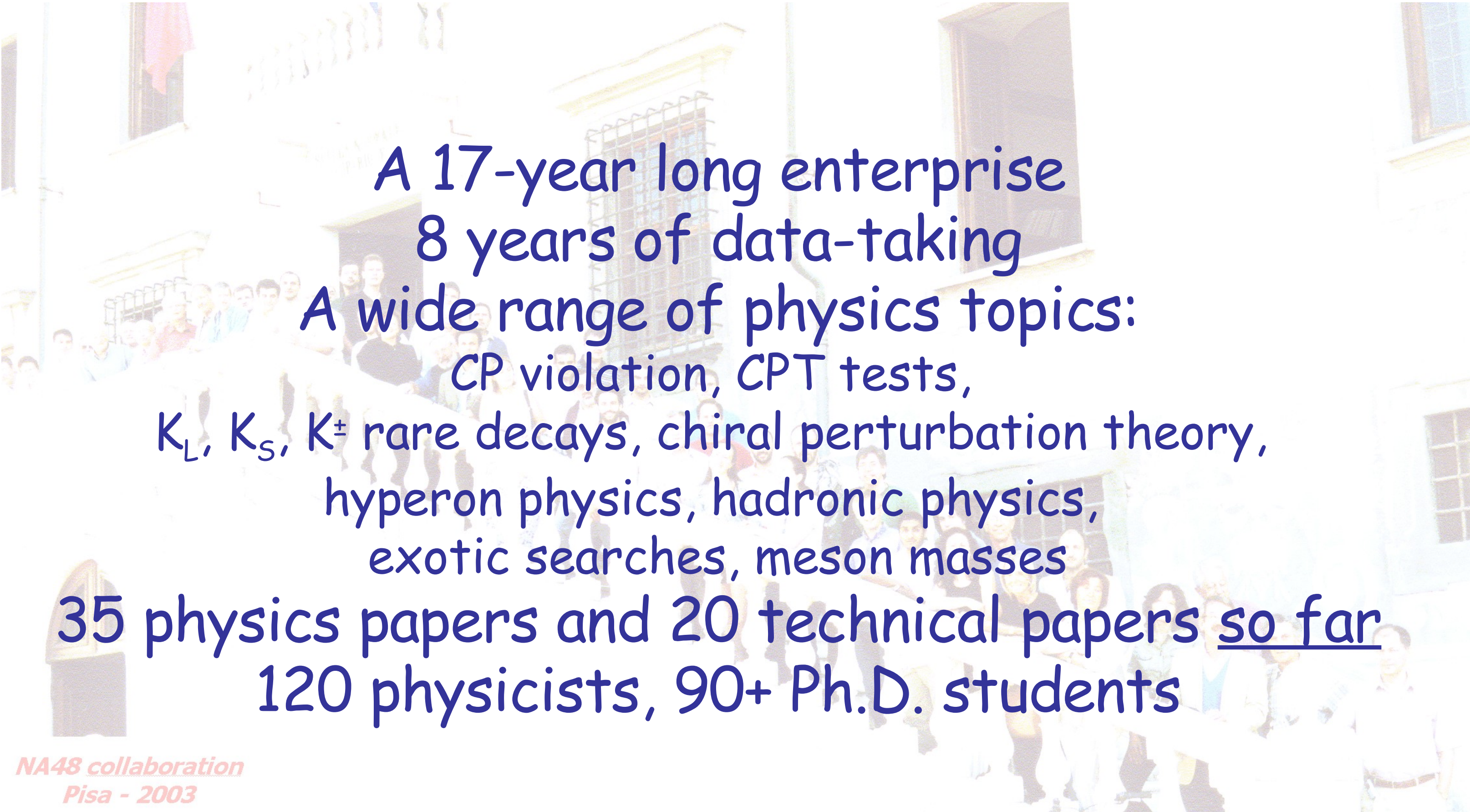
R&D endorsed by CERN Research Board on December 2005

Test beams Oct–Nov 2006

Aims to complete R&D by the end of 2007…

… to start data taking in 2011

Outlook



A 17-year long enterprise
8 years of data-taking
A wide range of physics topics:

CP violation, CPT tests,
K_L, K_S, $K^{\pm}$ rare decays, chiral perturbation theory,
hyperon physics, hadronic physics,
exotic searches, meson masses

35 physics papers and 20 technical papers <u>so far</u>
120 physicists, 90+ Ph.D. students

NA48 collaboration
Pisa - 2003

A new challenge ahead
for everybody who wants to join !

Spare slides

$K \to \pi \ell \bar{\ell}$

Experimental problems:

BR ≈ 10^{-11}, few (or no) kinematic constraints, backgrounds with BR x 10^{7}

$K_L \to \pi^0 e^+ e^-$	10^{-11} (CPV_{dir} $3 \cdot 10^{-12}$)	< 2.8 $\cdot 10^{-10}$ (FNAL KTeV)	CPC+CPV, eeγγ bkg. 3 ev. (2.05 bkg)
$K_L \to \pi^0 \mu^+ \mu^-$	10^{-11} (CPV_{dir} $1 \cdot 10^{-12}$)	< 3.8 $\cdot 10^{-10}$ (FNAL KTeV)	CPC+CPV 2 ev. (0.87 bkg)
$K^+ \to \pi^+ \nu \bar{\nu}$	$8 \cdot 10^{-11}$ (at 7%)	$1.47^{+1.30}_{-0.89} \cdot 10^{-10}$ (BNL E787+E949)	Dedicated expt. 3 evt. (bkg. 0.45)
$K_L \to \pi^0 \nu \bar{\nu}$	$2.8 \cdot 10^{-11}$ (at 2%)	< 5.9 $\cdot 10^{-7}$ (KTeV, Dalitz decay)	CPV dir "*Nothing to nothing*"

Dedicated experiments required

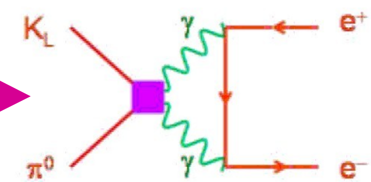
$K_L \to \pi^0 \ell^+ \ell^-$

KTeV limits (90% CL):

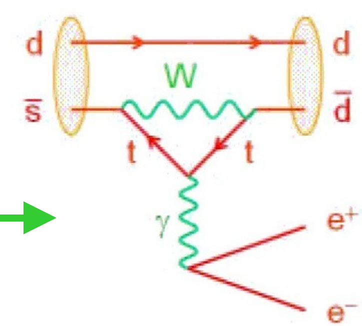
BR($K_L \to \pi^0 e^+ e^-$) < 2.8×10^{-10}
BR($K_L \to \pi^0 \mu^+ \mu^-$) < 3.8×10^{-10}

Complex situation: 3 contributions

- **CP-allowed**: not predicted, derived from $K_L \to \pi^0\gamma\gamma$ (NA48/KTeV)



- **Indirect CP violating**: not predicted, measured by $K_S \to \pi^0 \ell^+ \ell^-$ (NA48/1)
- **Direct CP violating**: predicted and proportional to CKM phase



$$BR(K_L \to \pi^0 e^+ e^-)_{CPV} \approx 10^{-12}\left[15.3 a_S^2 - 6.8 a_S \,\mathrm{Im}(\lambda_t)\times 10^{-4} + 2.8\,\mathrm{Im}(\lambda_t)^2 \times 10^{-8}\right]$$

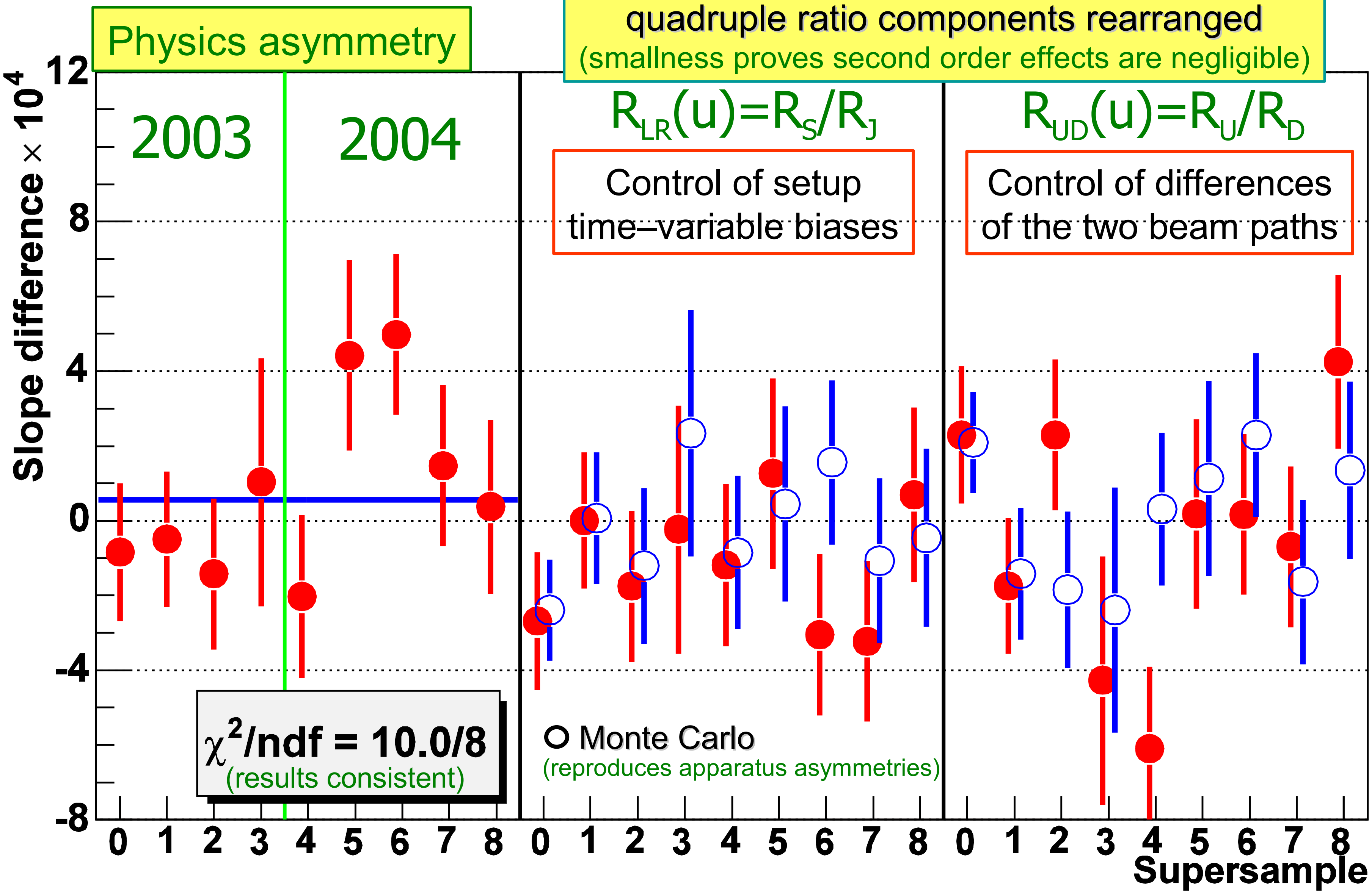
$\lambda_t = V_{ts}^* V_{td}$ $\quad |a_S| \approx 1 \div 1.5$ measured by K_S (sign ?)

$K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ CPV slope asymmetry

Theoretical predictions

Standard Model	L.Maiani, N.Paver (95)	$(2.3\pm0.6)\times10^{-6}$
	A. Bel'kov (95)	$< 4\times10^{-4}$
	G.D'Ambrosio, G.Isidori (98)	$<10^{-5}$
	E.Shabalin (01)	$< 3\times10^{-5}$
	E.Gamiz, J.Prades, I.Scimemi (03)	$(-2.4\pm1.2)\times10^{-5}$
	E.Shabalin (05)	$< 8\times10^{-5}$
New physics	G.D'Ambrosio, G.Isidori, G.Martinelli (00)	up to 10^{-4}
	E.Shabalin (98) [WHDM]	$\sim 4\times10^{-4}$
	I.Scimemi (04)	$> 3\times10^{-5}$

Time-stability & control



Ke4 form factor results

$K^{\pm} \rightarrow p^{+}p^{-}e^{\pm}n$

$f_s'/f_s = 0.169 \pm 0.009_{stat} \pm 0.034_{syst}$

$f_s''/f_s = -0.091 \pm 0.009_{stat} \pm 0.031_{syst}$

$f_p/f_s = -0.047 \pm 0.006_{stat} \pm 0.008_{syst}$

$g_p/f_s = 0.891 \pm 0.019_{stat} \pm 0.020_{syst}$

$g_p'/f_s = 0.111 \pm 0.031_{stat} \pm 0.032_{syst}$

$h_p/f_s = -0.411 \pm 0.027_{stat} \pm 0.038_{syst}$

$a_0^0 = 0.256 \pm 0.008_{stat} \pm 0.007_{syst} \pm 0.018_{theo}$

NA48/2 PRELIMINARY

$K^{\pm} \rightarrow p^{0}p^{0}e^{\pm}n$

$f_s'/f_s = 0.129 \pm 0.036_{stat} \pm 0.020_{syst}$

$f_s''/f_s = -0.040 \pm 0.034_{stat} \pm 0.020_{syst}$

Cusp in $K^\pm \rightarrow \pi^\pm\pi^0\pi^0$: results

The scattering length difference:

$$(a_0-a_2)m_+ = 0.268 \pm 0.010_{stat} \pm 0.004_{syst} \pm 0.013_{ext}$$

and

$$(a_2)m_+ = -0.041 \pm 0.022_{stat} \pm 0.014_{syst}$$

If correlation between a_0 and a_2 (universal band) is used:

$$(a_0-a_2)m_+ = 0.264 \pm 0.006_{stat} \pm 0.004_{syst} \pm 0.013_{ext}$$

From same fit slope parameters are obtained (assuming k=0!):

$$g_0 = 0.645 \pm 0.004_{stat} \pm 0.009_{syst}$$

$$h' = -0.047 \pm 0.012_{stat} \pm 0.011_{syst}$$

Main systematic uncertainties: acceptance, trigger efficiency, fit interval

NA48/2 measurements of $\pi\pi$ scattering lengths from Ke4 Charged decays:

- scattering lengths extracted in a model dependent way (input $\mathbf{a_0^2 = f(a_0^0)}$)
- use Universal Band function

NA48/2 Preliminary (370k decays) ➔ $\mathbf{a_0^0 = 0.256 \pm 0.008_{stat} \pm 0.007_{syst} \pm 0.018_{theo}}$

Previous published results:

CERN/PS Geneva-Saclay (30k decays) ➔ $\mathbf{a_0^0 = 0.253 \pm 0.037_{stat+sys} \pm 0.014_{theo}}$

BNL E865 (400k decays) ➔ $\mathbf{a_0^0 = 0.229 \pm 0.012_{stat} \pm 0.004_{sys} \pm 0.014_{theo}}$