The physics case for a DAΦNE upgrade

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- Introduction
  - General considerations about future low−energy experiments
  - Dreams & realistic possibilities for DAΦNE [*the Alghero heritage*]

- The unique features of a super Φ–factory for kaon physics
  - General considerations
  - A few selected examples:
    1. CPT tests
    2. Interferometry
    3. The V_{us} saga
    4. Rare (but not impossible...) decays
    5. Charge asymmetries, ππ phases *et al.*

- My conclusions

Introduction

General considerations about future low−energy experiments

Within a few years we shall enter in the LHC era

Possible scenarios ~ 2010:

- LHC has started and has clearly seen signals of NP
- LHC has started but has not seen any clear NP signal
- [*LHC has not started yet...*]

Within all these scenarios still important & interesting to perform high−precision low−energy experiments

Some of the main arguments why it is still important to perform high−precision low−energy experiments in the LHC era:

- No competition with LHC as far as the NP search is concerned [with some remarkable exception], but full complementarity for the identification of the symmetries of the NP model

  I. Study of rare & forbidden processes: $(g-2)_\mu$, $K \to \pi\nu\nu$, CPT, ...

- Several SM parameters[Yukawa sector], which are likely to play a fundamental role in the identification of the underlying theory, can only be measured at low energies

  II. Precision measurements of V_{CKM}, m_q, α_i

- There are still interesting aspects of non−perturbative QCD which are not fully understood and need to be investigated

  III. CHPT studies for K & π decays, exotic bound states [hadr. atoms, hypernuclei], e^+e^- & $\gamma\gamma \to$ hadr. form factors, ...

Dreams & realistic possibilities for DAΦNE

In principle an e^+e^- machine with flexible c.o.m. energy up to $\sqrt{s} \sim 2.5$ GeV and very high luminosity at the Φ peak would be an ideal machine for this type of physics:

$\sqrt{s} = M_\Phi$

- KAON PHYSICS
  - The golden rare modes $[\, K \to \pi\nu\nu, \quad K_L \to \pi^0 l^+ l^- \,]$
  - All the rest... [see 2nd DAΦNE handbook]
- Hypernuclei, Kaonic atoms
- $\sigma(\gamma\gamma \to \text{hadr.})$

$\sqrt{s} \neq M_\Phi$

- $\sigma(\gamma\gamma \to \text{hadr.})$
- $\sigma(e^+e^- \to \text{hadr.})$ vs. $\sqrt{s}$
- $e^+e^- \to N\bar{N}$ f.facotrs

↓

The Alghero Conference
[www.lnf.infn.it/conference/d2]

Highlights of the kaon–physics program @ Φ–factory vs. luminosity:

10^0 fb^{-1} [≈ 10^9 $K\bar{K}$]	≈ KLOE now	V_{us} from K_{l3} @ 10^{-3} (CKM); rare K_S decays down to BR~10^{-8} (CHPT/CPT); 10^{-2} bounds on $K_S \to \pi l \nu$ charge asym. (CPT) ⋮
10^1 fb^{-1} [≈ 10^{10} $K\bar{K}$]	original KLOE program	Re(ε'/ε) @ 10^{-4} (direct CPV); $K_{L,S}$ interf. ⇒ Im(ε'/ε) @10^{-2} (CPT); ππ phases from K_{l4} @ % level (QCD vacuum) ⋮
10^2 fb^{-1} [≈ 10^{11} $K\bar{K}$] [10^{34} cm^{-2}s^{-1}]		CPT tests @ uprecedented level of precision via rare K_S & $K_{L,S}$ interferences; search for exotic direct CPV in $K^{\pm}$ asym. and rare K_L decays ⋮
10^3 fb^{-1} [≈ 10^{12} $K\bar{K}$]	frontier of flavor physics	sensitivity to $K_L \to \pi^0 \nu\nu$ (& $K_L \to \pi^0 ee$) at the SM level: region of <u>high discovery potential</u> for non−standard sources of CPV via new tests of the CKM mech. in the kaon system
10^4 fb^{-1}	⋮ ⋮	⇒<u>very interesting also in a long−term perspective</u>⇐

$K_L \to \pi^0\nu\bar\nu$ cannot be measured

It has been said so often:

$$\Im V_{td}V_{ts}^* = A^2\lambda^5\eta = 25.6\sqrt{\mathrm{BR}(K_L \to \pi^0\nu\bar\nu)}$$

$$\mathrm{BR}(K_L \to \pi^0\nu\bar\nu) = 3\times 10^{-11}$$

10 eV/3×10^{-11}=3.3×10^{11} K's. @1% dec/ϕ, need 100×3.3×10^{11}=3.3×10^{13} ϕ's or 1.1×10^{13} μb^{-1}. In one year, need $\mathcal{L}$=10^6 μb^{-1}/s or $\mathcal{L}$=1×10^{36} cm^{-2} s^{-1}. For one hundred events, $\mathcal{L}$=1×10^{37} cm^{-2} s^{-1} or 10 year running.

$$J_{12}\ \frac{h = A^2\lambda^5\eta\ (\times 10)}{\lambda(1-\lambda^2/2)}$$

To get η need λ and A!

$\delta(A^2\lambda^5)/(A^2\lambda^5)\sim 5.6\%$, K. Schubert, LP03. Optimistic?

Dreams & realistic possibilities for DAΦNE

In principle...

$\sqrt{s} = M_\Phi$ →
- KAON PHYSICS →
  - ~~The golden rare modes [$K \to \pi\nu\nu$, $K_L \to \pi^0 l^+ l^-$]~~
  - All the rest...
- Hypernuclei, Kaonic atoms
- $\sigma(\gamma\gamma \to$ hadr.)

$\sqrt{s} \neq M_\Phi$ →
- $\sigma(\gamma\gamma \to$ hadr.)
- $\sigma(e^+e^- \to$ hadr.) vs. $\sqrt{s}$
- $e^+e^- \to$ NN f.facotrs [⇒ see next talk]

In practice we need to take into account that:

- If $L < 10^{35}$ cm^{-2}s^{-1} ⇒ No chance for the rare golden modes
  [even if enhanced over SM expectations]
- Strong external competition on almost all the remaining items from other machines/experiments
- Serious internal (time) competition between the Φ & non−Φ options
  [extrapolate from the present DAΦNE situation...]

• The unique features of a (super) Φ–factory for kaon physics

General considerations:

$$\Phi \rightarrow K^+K^- \ (50\%),\ K_L K_S \ (34\%), \ldots$$

- Pure K_S beam [K_L tag] ⇒ Rare K_S decays [so far, the most used feature by KLOE]
- $K_L K_S$ in a pure quatum state [L=1] ⇒ Neutral kaon interferometry
- Kaon beams of known momentum ⇒ Great advantage for any $K^\pm$ & K_L decay with missing energy
- K^+K^- & $K_L K_S$ in the same detector ⇒ Useful for CHPT & $K^\pm$ CPV studies

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N.B.: Kaon physics has also a unique *theoretical advantage* :

several systematic theoretical tools [CHPT, Lattice, OPE, ...] able to mach [not always, but in most cases...] the challenge of high−precision experiments

A few selected examples:

1. CPT tests

CPT symmetry is linked to the basic mathematical tools that we use in particle physics:

QFT + Lorentz invariance + Locality $\Rightarrow$ CPT

These tools have intrinsic limitations [we are not able to include gravity in consistent way] $\Rightarrow$ we should expect ~~CPT~~ at some level

But we do not have a consistent & predictive theory if we abandon these tools $\Rightarrow$ hard to define a reference scale/size for ~~CPT~~

$\downarrow$

$$\left| M_{\overline{K}} - M_K \right| < 10^{-18}\, M_K$$

suggestive...
but not to be over−emphasized

Main message: Kaon physics offer an ideal framework to test CPT
reference scale set by the most significant experimental bounds

1.1 The charge asymmetry in $K_S \to \pi^{\pm} l^{\mp} \nu$

$$\delta_{S,L} = \frac{\Gamma(K_{S,L} \to l^{+}\pi\nu) - \Gamma(K_{S,L} \to l^{-}\pi\nu)}{\Gamma(K_{S,L} \to l^{+}\pi\nu) + \Gamma(K_{S,L} \to l^{-}\pi\nu)} = 2\,\mathrm{Re}(\varepsilon) \pm \not{CPT}$$

Assuming ~~CPT~~ only in $\bar{K}-K$ mixing: $\frac{|M_{\bar{K}} - M_K|}{M_K} < 5\times10^{-15}\,|\delta_L - \delta_S|$

$\sim |M_L - M_S| / M_K$

$\delta_S = (-2\pm9\pm6)\times10^{-3}$ [KLOE '04]

$\delta_L = (3.322\pm0.058\pm0.047)\times10^{-3}$ [KTeV '02]

$\delta_L = (3.317\pm0.070\pm0.072)\times10^{-3}$ [NA48 '03]

Reference vale for the ulitmate measurement of δ_S → sensitivity on $\frac{|M_{\bar{K}} - M_K|}{M_K}$ in the 10^{-19} range !

1.2 Bell−Steinberger relation

Even if CPT is violated, we can assume that unitarity [=the conservation of prbability] holds:

$$\Gamma_K = \Sigma_f\, A(K\to f)\, A(K\to f)^*$$
$$\Gamma_{\bar{K}} = \Sigma_f\, A(\bar{K}\to f)\, A(\bar{K}\to f)^*$$

They should coincide in the limit of exact CPT

$$\left[\frac{\Gamma_L+\Gamma_S}{\Gamma_S-\Gamma_L} + i\tan(\phi_{SW})\right]\left[\frac{Re(\varepsilon_M)}{1+|\varepsilon_M|^2} + i\,\mathrm{Im}(\Delta)\right] = \frac{1}{\Gamma_S-\Gamma_L}\,\Sigma_f\, A_L(f)\, A_S(f)^*$$

A marvelous tool !

- Exact relation in the CPT limit
- Non−vanishing Im(D) could only be due to
  - violations of CPT
  - violations of unitarity
  - new exotic invisible final states

$$\Delta = \frac{M_{\bar{K}} - M_K}{M_L - M_S}\, e^{i\phi_{SW}} + \ldots$$

$$\phi_{SW} = \arctan[\, 2(M_L-M_S)/(\Gamma_S-\Gamma_L)\,]$$

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  - violations of CPT
  - violations of unitarity
  - new exotic invisible final states

no better place to measure this combination than a Φ factory !

$|\mathrm{Im}(\Delta)|_{000} < 6.4\times10^{-6}$ [KLOE '04]

...but still a lot of work to improve the bounds on the full contribution

2. Neutral kaon interferometry

Probably the most characteristic type of measurements for a Φ factory:

$$P[\,\Phi \to K_L K_S \to a(t_1)\, b(t_2)\,] = |A_{Sa}|^2 |A_{Lb}|^2 e^{-\Gamma_S t_1 - \Gamma_L t_2} + |A_{Sb}|^2 |A_{La}|^2 e^{-\Gamma_L t_1 - \Gamma_S t_2}$$

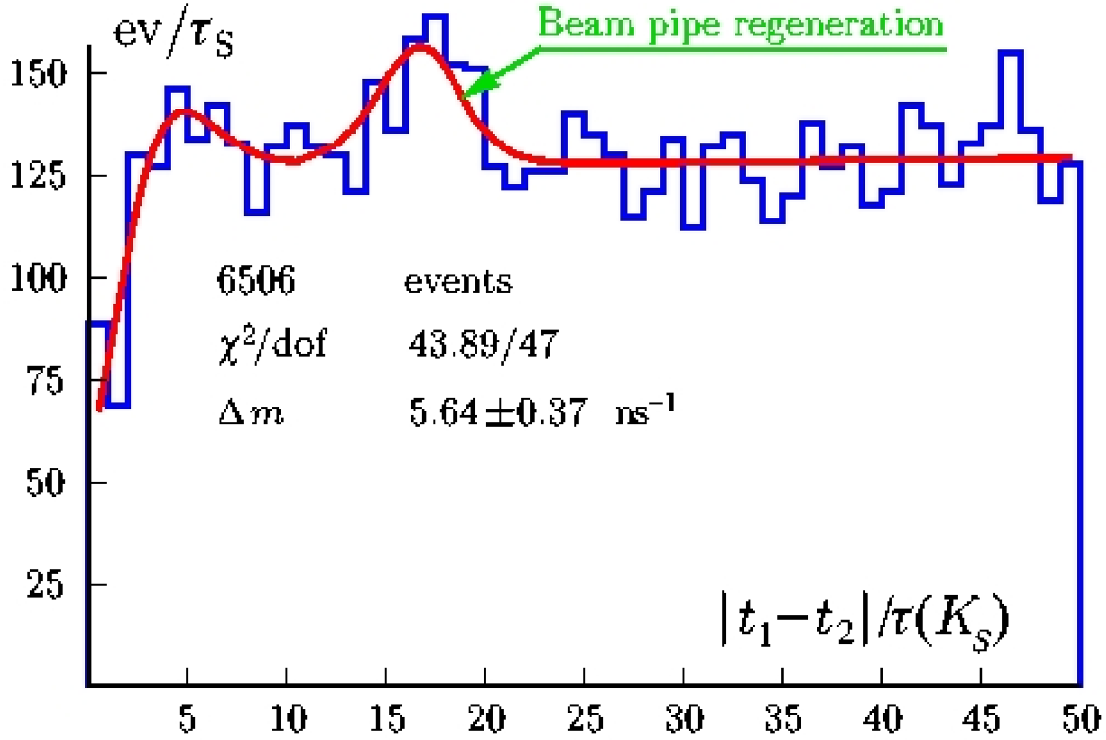
$$-2\,\mathrm{Re}[\, A_{Sa} A_{La}^* A_{Lb} A_{Sb}^*\, e^{+i\Delta m\,(t_1 - t_2)}\,]\, e^{-\Gamma\,(t_1+t_2)}$$

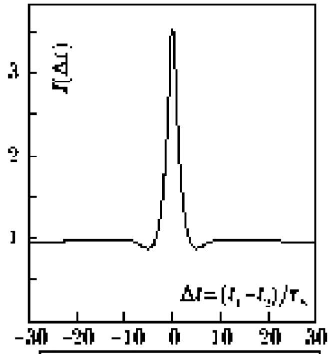
direct access to (strong & weak) phases

Examples of interesting & accessible final states [see 2nd DAΦNE handbook]:

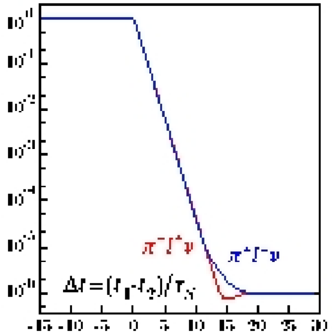
- $(\pi^+\pi^-)-(\pi^+\pi^-)$: Δm & $\Gamma_{L,S}$ + $\eta_{\pm}$ + tests of QM
- $(\pi^+\pi^-)-(\pi^0\pi^0)$: $\mathrm{Re}(\varepsilon'/\varepsilon)$ & $\mathrm{Im}(\varepsilon'/\varepsilon)$ + ππ phases + tests of CPT & QM
- $(\pi l \nu)-(\pi l \nu)$: tests of CPT
- $(\pi l \nu)-(3\pi)$: $\eta_{3\pi}$ + ππ phases
- $(3\pi)-(3\pi)$: $\eta_{3\pi}$ + ππ phases [different combinations]
- $(2\pi)-(\pi\pi\gamma)$: $\eta_{\pi\pi\gamma}$

⟶ Several interesting channels with $L \sim O(100\ \mathrm{fb}^{-1})$





$\phi \to K_S K_L$
$\to \pi e^+ \nu$
$+ \pi e^- \nu$



$\phi \to K_S K_L$
$\to \pi^+ \pi^-$
$+ \pi e \nu$

The first example of interference observed in KLOE.

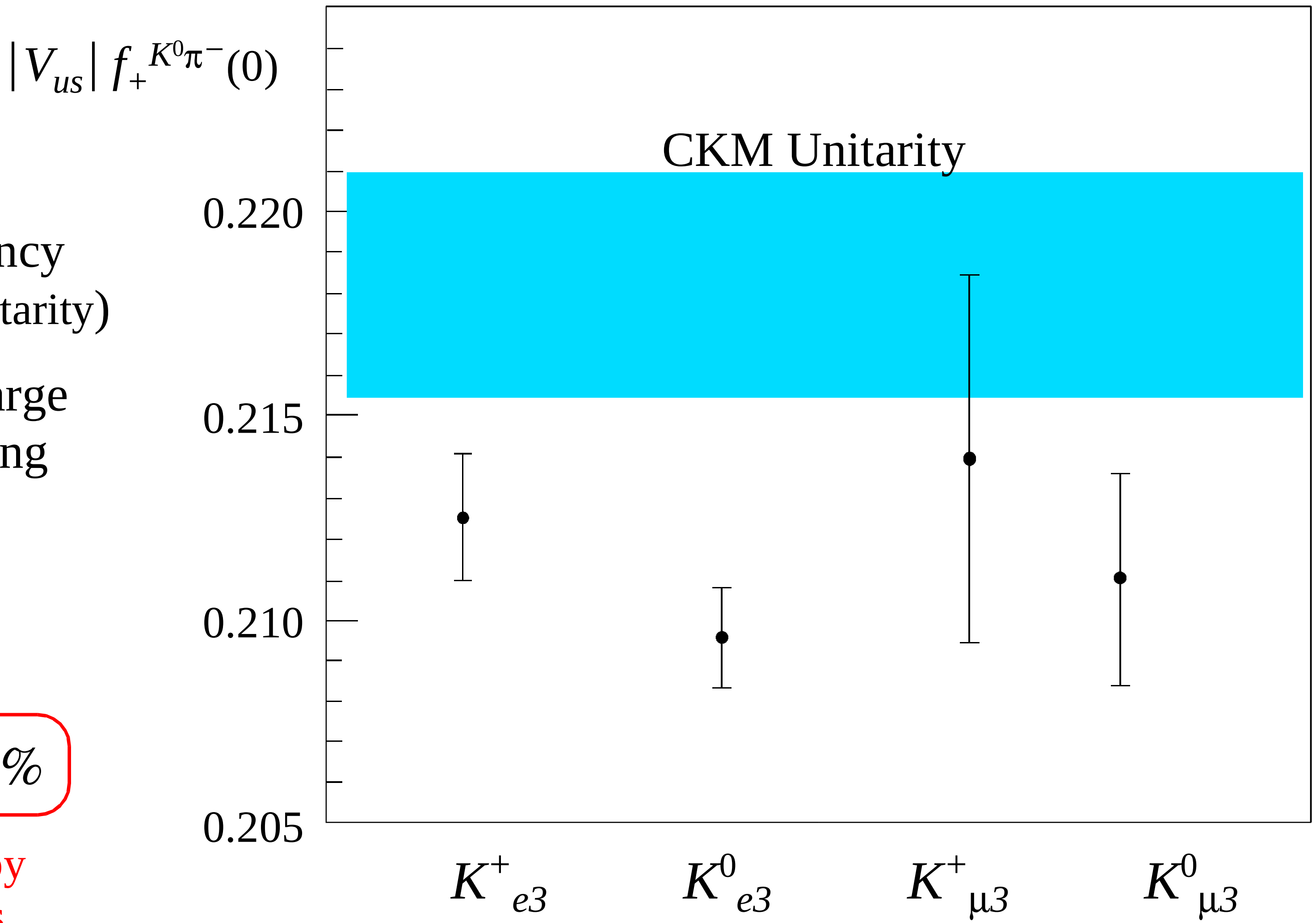
$$e^+e^- \to \phi \to K_S K_L \to \pi^+\pi^- + \pi^+\pi^-$$

$$\Rightarrow \Gamma_S,\ \Gamma_L,\ \Delta m,\ [\Re, \Im(\eta_i,\ \delta \ldots)]$$

$$I(f_1, f_2, \Delta t) = ..2|\eta_1||\eta_2|e^{-\Gamma \Delta t/2}\cos(\Delta m \Delta t + \phi_1 - \phi_2)$$

3. The V_{us} saga

Status in Feb. 2002 [1st CKM Workshop]

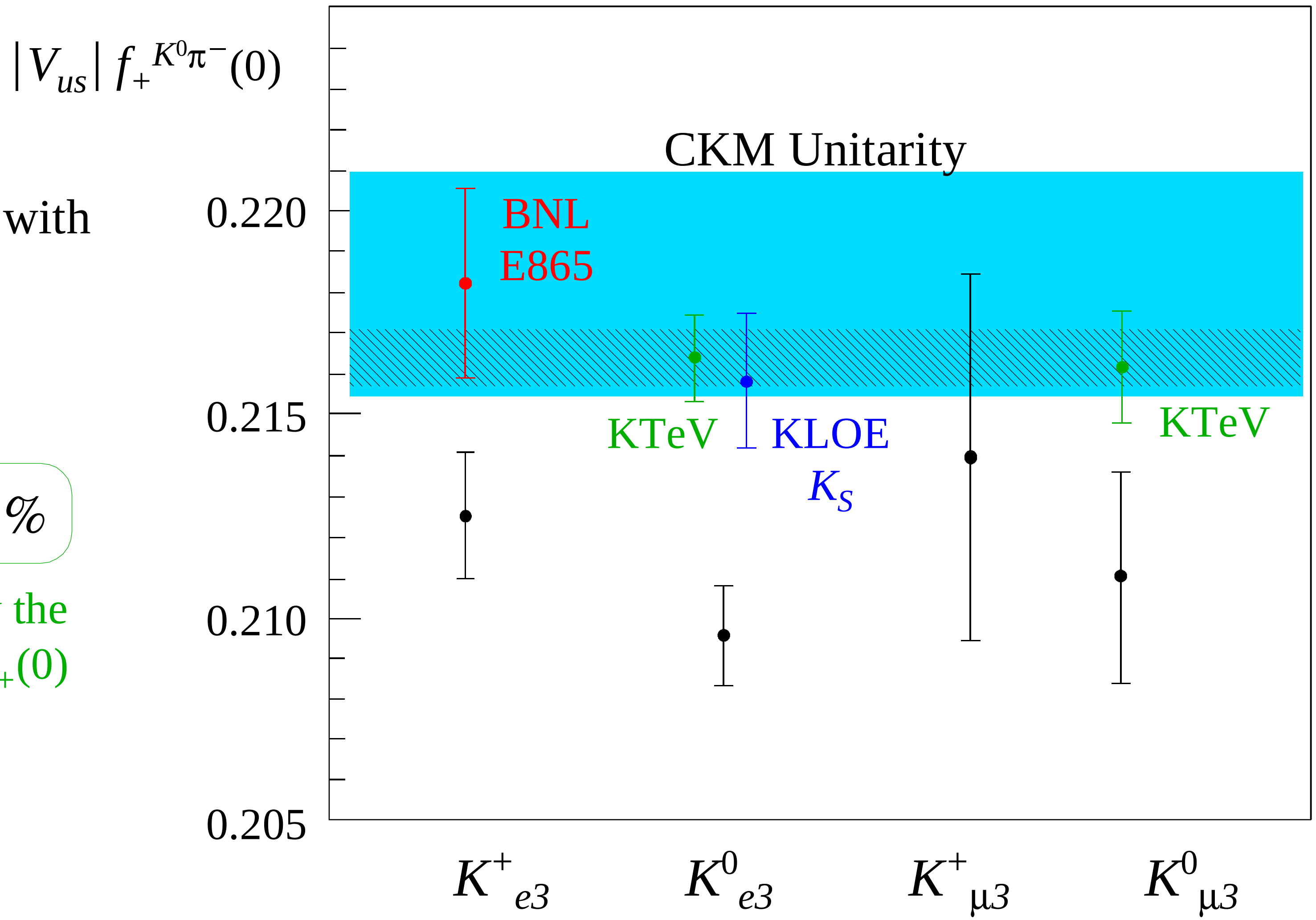


- Bad consistency with V_{ud} (unitarity)
- Potentially large SU(2) breaking effects

$$\delta|V_{us}| \approx 2\ \%$$

dominated by exp. errors

Status in June 2004:

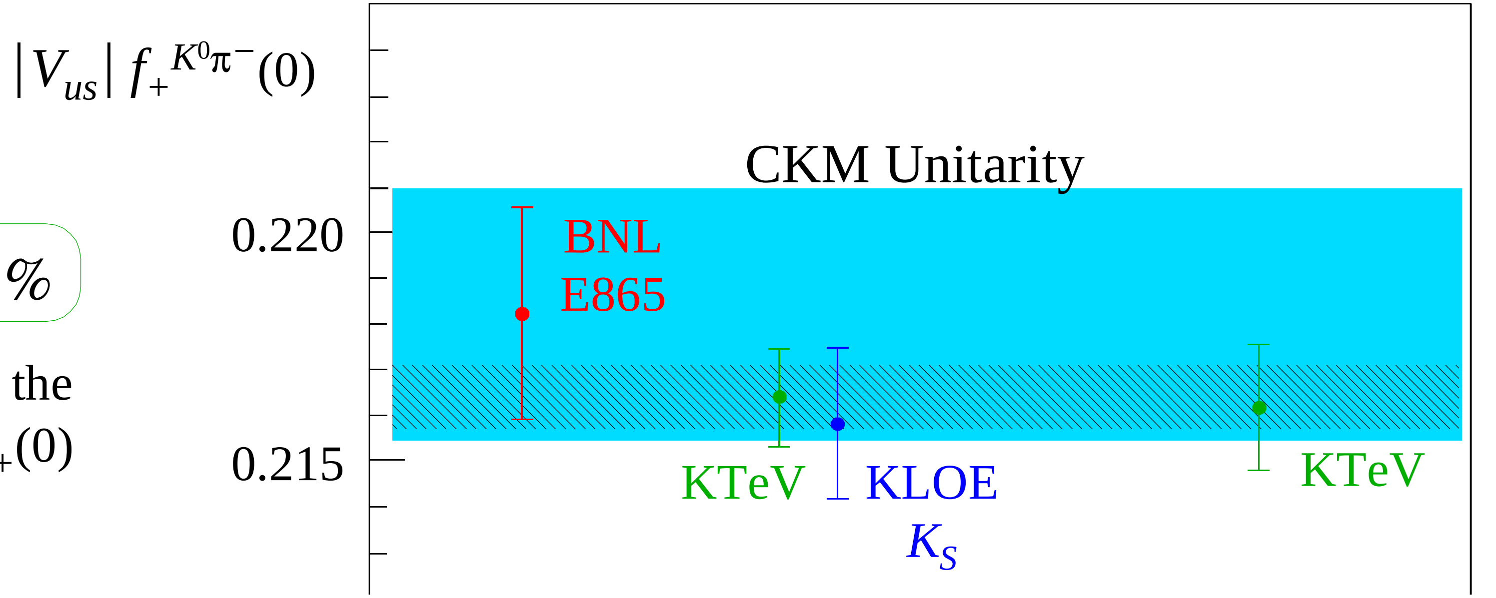


- Consistency with V_{ud} restored

$\delta|V_{us}| \approx 1\ \%$

dominated by the th. error on $f_+(0)$

But this is not the end of the story...



$\delta|V_{us}| \approx 1\ \%$

dominated by the th. error on $f_+(0)$

- SU(2) breaking not yet tested at the th. level (~ 0.3%)
- Exp. studies of the f.f. beyond the linear approximation are a key ingredient to reduce the th. error on $f_+(0)$ [similar to the hadronic moments in $B \to X l \nu$]

$$f_0(x, y) = 1 + \lambda_0 x + \delta\, y^2 + \lambda_2 x^2 + \ldots$$

$x = (p_K - p_\pi)^2 / m_\pi^2$

$y = (m_K^2 - m_\pi^2) / m_K^2$

$\Rightarrow$ V. Lubicz & M. Knecht

$F_K/F_\pi,\ \lambda_0, \ldots$ CHPT [Bijnens & Talavera, *et al.*]

The ambitious goal of $\delta|V_{us}| \sim 0.1\%$ is not impossible !

Natural goal for a high− or medium/high−L Φ factory

4. Rare (but not impossible...) decays

An interesting example:

The $K_L \to \pi^0 l^+ l^- \oplus K_S \to \pi^0 l^+ l^- \oplus K_L \to \pi^0 \gamma\gamma$ system

$\Rightarrow$ L. Sehgal & C. Smith

4. Rare (but not impossible...) decays

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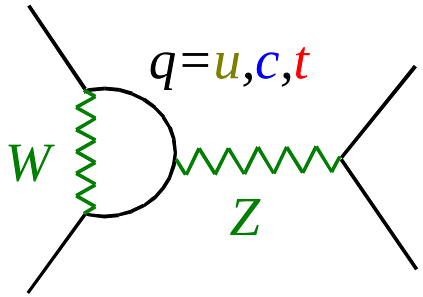
⇒ L. Sehgal & C. Smith

$$B_L(ee)_{SM} = 3.7 \pm 1.0 \times 10^{-11}$$
$$B_L(\mu\mu)_{SM} = 1.5 \pm 0.3 \times 10^{-11}$$

→ Very interesting goal for future fixed target experiements [NA48/4 ?]

with sizable (35%−45%) contr. from the th. clean & interesting

direct−CPV amplitude



+ *box*

similar to $K_L \to \pi^0 \nu\nu$, with different NP sensitivity

G.D'Ambrosio, G. Buchalla & G.I. '03
G.I., C. Smith & R. Unterdorfer, '04

4. Rare (but not impossible...) decays

An interesting example:

The $K_L \to \pi^0 l^+ l^- \oplus K_S \to \pi^0 l^+ l^- \oplus K_L \to \pi^0 \gamma\gamma$ system

control on the ind−CPV component

control on the CPC component

$B_L(ee)_{SM} = 3.7 \pm 1.0 \times 10^{-11}$

$B_L(\mu\mu)_{SM} = 1.5 \pm 0.3 \times 10^{-11}$

with sizable (35%−45%) contr. from the th. clean & interesting

direct−CPV amplitude

$B(K_S \to \pi^0 e^+ e^-) = (5.8\,^{+2.8}_{-2.3} \pm 0.3 \pm 0.8) \times 10^{-9}$

$B(K_S \to \pi^0 \mu^+ \mu^-) = (2.9\,^{+1.4}_{-1.2} \pm 0.2) \times 10^{-9}$

NA48/1 ’03−’04

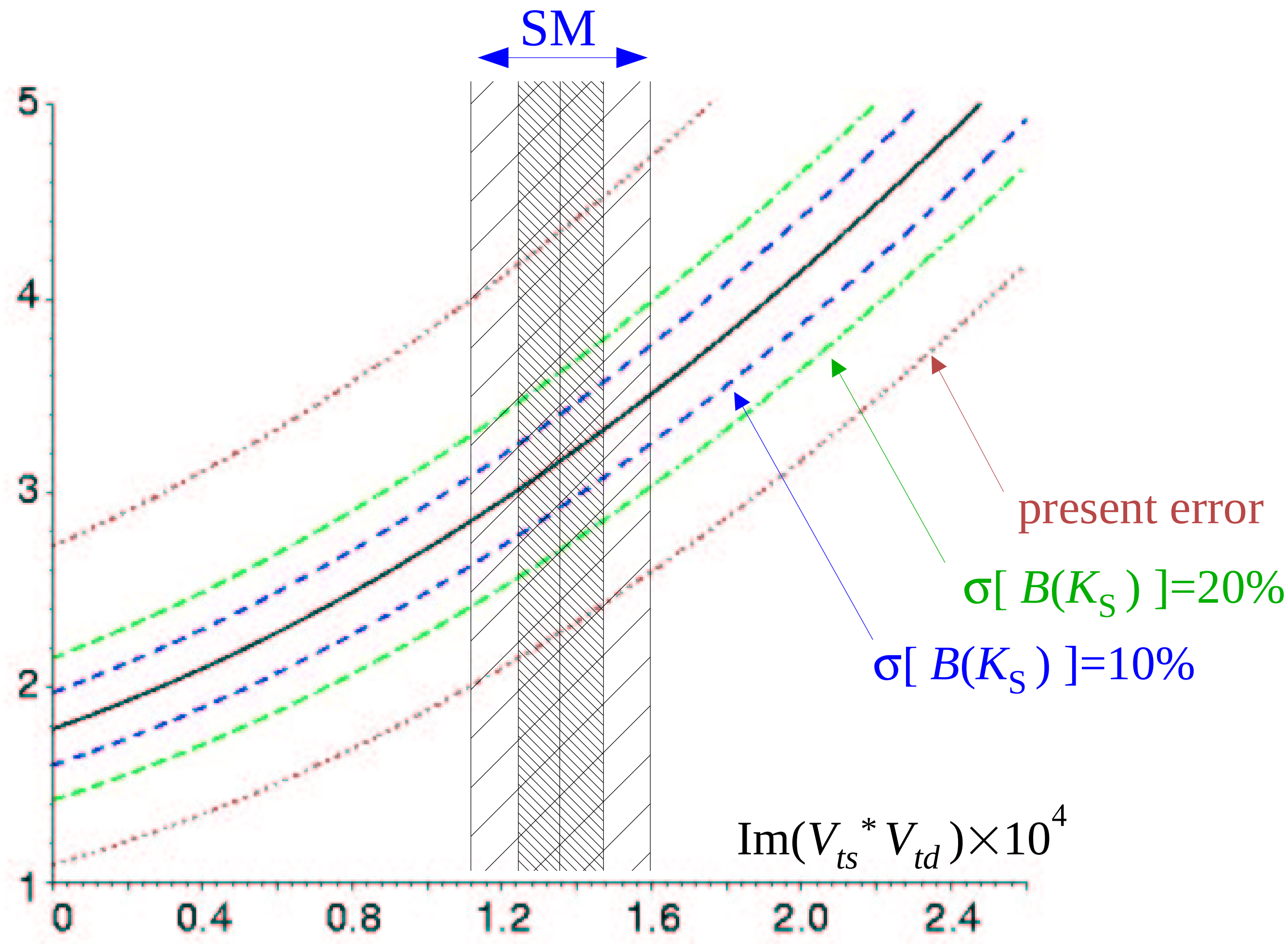
$B(K_L \to \pi^0 \gamma\gamma;\ M_{\gamma\gamma} < 110\ \text{MeV}) < 0.9 \times 10^{-8}$

$B_L(ee)_{CPC} < 3 \times 10^{-12}$

NA48/1 ’02

[not consistent with KTeV ’99]

These 2 key exp. inputs could improve with a high−L Φ factory



$K_L \to \pi^0 l^+ l^-$
represent a very
interesting opportunity
for precision tests of
$\Delta F=1$ s$\to$d FCNCs:

Irreducible error ~ 10%

[not as clean as $K_L \to \pi^0 \nu\nu$, but still extremely interesting + different NP sensitivity]

provided we can measure at a comparable level of accuracy
the corresponding K_S transitions $\Rightarrow$ possible at a super Φ factory with $O(100\ \mathrm{fb}^{-1})$

5.1 Charge asymmetries

$$\Delta_f = \frac{d\Gamma(K^+ \to f^+) - d\Gamma(K^- \to f^-)}{d\Gamma(K^+ \to f^+) + \delta\Gamma(K^- \to f^-)} \neq 0 \qquad \Leftrightarrow \qquad \text{direct } \not{CP}$$

Strong competition from NA48/2 and small chances to observe non−zero signals within the SM, but still worth to try...

A particularly interesting case: $K^\pm \to \pi^\pm \pi^0 \gamma$

[Th. cleaner + more sensitive to New Physics effects than $K \to 3\pi$]

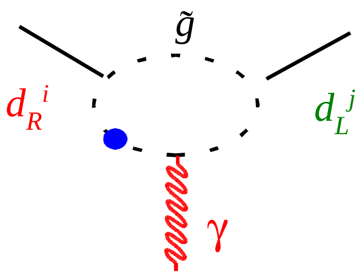
Dalitz−Plot variables:

T_c = charged kaon kin. energy

$$W^2 = \frac{q p_+ \, q \, p_K}{M_\pi^2 \, M_K^2}$$

$$\frac{\partial^2 \Gamma}{\partial T_C \partial W^2} = \frac{\partial^2 \Gamma_{IB}}{\partial T_C \partial W^2} \left[1 + \Re\left(\frac{E_{DE}}{A_{2\pi}} \right) W^2 + O(W^4) \right]$$

$$\not{CP} \Rightarrow \frac{\partial^2 \Gamma / \partial T_C \partial W^2 - \partial^2 \overline{\Gamma} / \partial T_C \partial W^2}{\partial^2 \Gamma / \partial T_C \partial W^2 + \partial^2 \overline{\Gamma} / \partial T_C \partial W^2} = \Omega W^2 + \ldots$$



$\Omega_{SM} \sim 10^{-5}$

$\Omega_{SUSY} \sim 10^{-4}$ [chromag. op. saturates ϵ'/ϵ $\Leftrightarrow$ realisitc models]

$\Omega_{SUSY} \sim 10^{-3}$ [large cancellations in ϵ'/ϵ $\Leftrightarrow$ possible, not natural]

5.2 ππ phases *et al.*

There are many interesting aspects of QCD at low energies which can still be studied in the kaon sector [most notable example: the precise determination of ππ phases from $K^{\pm}_{l4}$]

Many of them are described in the 2nd DAΦNE Handbook, others strategies have recently been inspired by the new precise NA48/2 data [e.g. the extraction of ππ phases from $K_{3\pi}$ ⇒ Cabibbo's talks], probably even more are still to come...

⬇

Not easy to anticipate the potential impact of a future DAΦNE upgrade in this context

but there are good chances for substantial contributions

My conclusions

The physics case of a high−intensity Φ factory with $10^{33} < L \, [\,\mathrm{cm}^{-2}\mathrm{s}^{-1}] < 10^{34}$ is certainly interesting and worth to be explored

Not a unique outstanding goal, but a series of interesting meas. in the K sector:

- clear targets [V_{us} & K_{l3} f.f., rare (K_S) decays, CPT tests]
- less clear targets [$K^{\pm}$−asym., interferometry, K_{l4} ,...]
  $\Rightarrow$ more work on real data needed to better quantify the potential impact

+ the usual non−K program at the Φ [worth to think about $\gamma\gamma \to \pi\pi$]

This of course does not mean that the high−energy option is not interesting

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However...

- The most clear goals in the high−L option will be less interesting if the time scale is too long [strong competition within the field of flavour physics]
- The high−L option is extremely challenging from the exp. point of view [huge statistics & high precision] $\Rightarrow$ a too long interruption of the kaon program could be dangerous

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⬇

In addition to the natural machine and experimental considerations

the time schedule of this program represents a key point

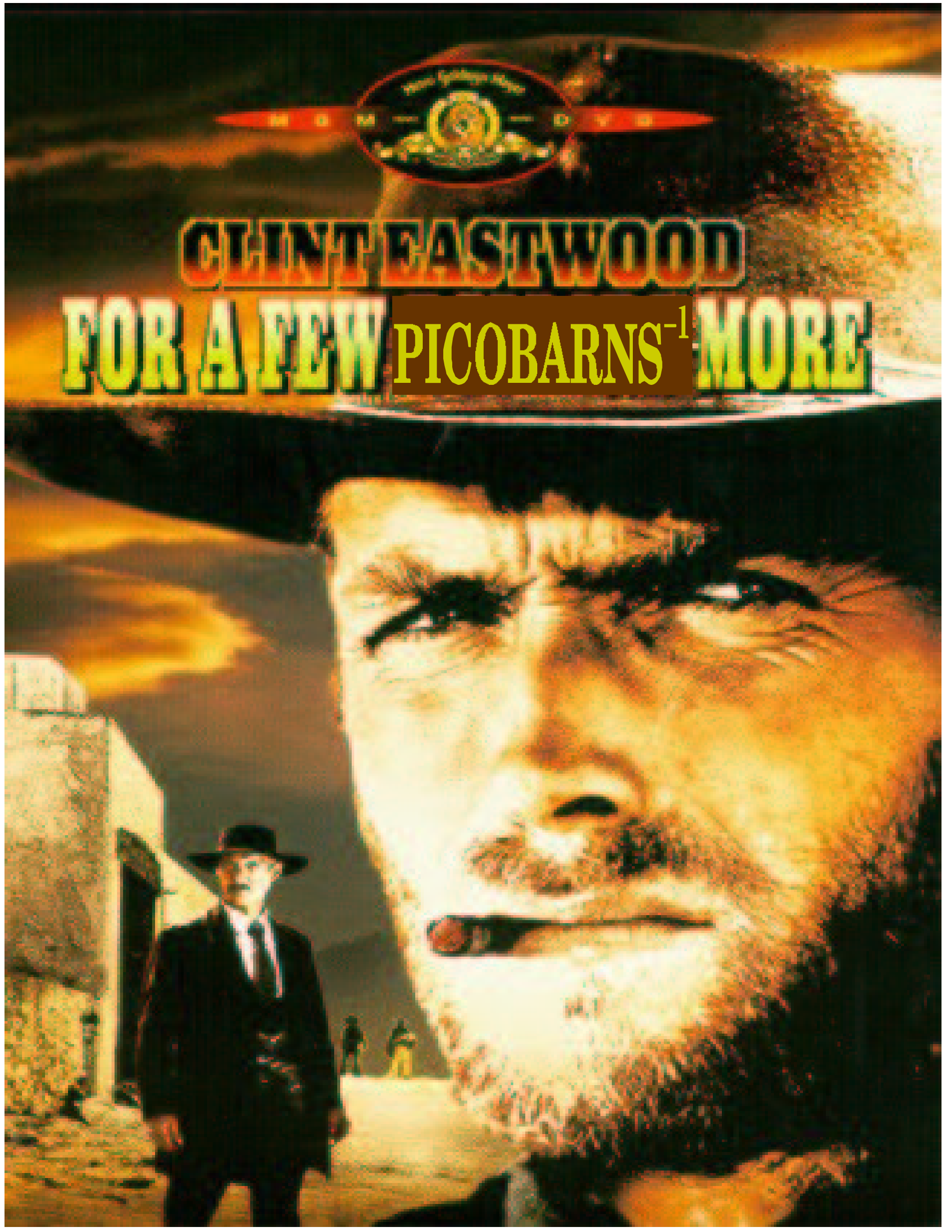
Rare Kaon decays

– The Good, The Bad, The Ugly –

George Redlinger

The physics case for DAΦNE upgrade

– For a few picobarns $^{-1}$ more –



Rare Kaon decays

– The Good, The Bad, The Ugly –