The physics program of a super Φ factory

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- Introduction
  - General considerations about future low-energy experiments
  - Realistic possibilities at e^+e^- colliders with $\sqrt{s} \lesssim 2$ GeV
- Highlights of the physics program of a Φ factory with $L \gtrsim 10^{33}$ cm^{-2}s^{-1}
  - General considerations about the kaon program
  - Main issues within kaon physics:
    - CPT tests & K_L-K_S interferometry
    - The rare $K_S \to \pi^0 l^+ l^-$ decays
    - The V_{us} saga
    - $\pi\pi$ phases *et al.*
  - Beyond kaon physics
- Conclusions

General considerations about future low-energy experiments

Within a few years we shall enter in the LHC era

Possible scenarios in 3-4 years from now:

- 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 it is still worth to perform high-precision low-energy experiments

Main arguments why it is still important to perform high-precision low-energy experiments in the LHC ⇔ main research directions :

- 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: $K \to \pi\nu\nu$, $\mu \to e\gamma$, ~~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, η decays, exotic bound states [hadr. atoms, hypernuclei], $e^+e^- \to$ hadr. form factors, ...

Realistic possibilities at e^+e^- colliders with $\sqrt{s} \lesssim 2$ GeV

In principle an e^+e^- machine with flexible c.o.m. energy up to 2 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: $K \to \pi\nu\nu$ & $K_L \to \pi^0 l^+ l^-$
  - All the rest...
    - CP, CPT & K_L-K_S interf.
    - V_{us} from K_{l2} & K_{l3}
    - Rare K_S decays
    - $\pi\pi$ phases (CHPT)
- ϕ, η, η' decays
- Hypernuclei, Kaonic atoms
- $\sigma(\gamma\gamma \to$ hadr.)

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

- $\sigma(\gamma\gamma \to$ hadr.)
- $\sigma(e^+e^- \to$ hadr.[NN])

↓

The Alghero Conference

[www.lnf.infn.it/conference/d2]

$K_L \to \pi^0 \nu\bar{\nu}$ 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$/3 \times 10^{-11}$=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.

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

To get η need λ and A!

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

Realistic possibilities at e^+e^- colliders with $\sqrt{s} \lesssim 2$ GeV

In principle ....

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..in practice we need to take into account that:

- If $L < 10^{35}$ cm $^{-2}$s $^{-1}$ $\Rightarrow$ no chances for the rare golden modes
- Severe external competition on most of the remaining items from other machines/experiments
- Serious internal (time) competition between Φ & non-Φ options
  [extrapolate from the present DAΦNE situation...]

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KAON PHYSICS → All the rest...

- CP, CPT & K_L-K_S interf.
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The Φ peak remains the most interesting option

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- Highlights of the physics program of a Φ factory with $L \gtrsim 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

General considerations about the kaon program

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

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

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...the only serious disadvantage is the *statistical limitation*

10 fb^{-1}@ Φ ⇒ ~ 10^{10} Kaon pairs ⇒ well below existing stat. on K_L & $K^{\pm}$

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➡ For a competitive program:

- *L* must definitely exceed 10^{33} cm^{-2}s^{-1}
- main focus on K_S & $K_L K_S$ interf.

Main issues within kaon physics:

1. CPT tests & neutral kaon interferometry

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

$$\text{QFT} + \text{Lorentz invariance} + \text{Locality} \;\Rightarrow\; \text{CPT}$$

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

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

↓

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

Very 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

E.g.: The charge asymmetry in $K_S \to \pi^{\pm} l^{\mp} \nu$

$$\delta_{S,L} = \frac{\Gamma(K_{S,L} \to l^+ \pi \nu) - \Gamma(K_{S,L} \to l^- \pi \nu)}{\Gamma(K_{S,L} \to l^+ \pi \nu) + \Gamma(K_{S,L} \to l^- \pi \nu)} = 2\,\mathrm{Re}(\varepsilon) \pm \text{CPT}$$

Assuming ~~CPT~~ only in $\bar{K}$-K mixing: $$\frac{|M_{\bar{K}} - M_K|}{M_K} < 5\times 10^{-15}\,|\delta_L - \delta_S|$$

$\sim |M_L - M_S| / M_K$

$\delta_S = -(2 \pm 9 \pm 6) \times 10^{-3}$ [KLOE '04]

$\delta_L = (3.322 \pm 0.058 \pm 0.047) \times 10^{-3}$ [KTeV '02]

$\delta_L = (3.317 \pm 0.070 \pm 0.072) \times 10^{-3}$ [NA48 '03]

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

E.g.: Bell-Steinberger relation

Even if CPT is violated, we can assume that unitarity [=probability is conserved] 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

$$\left[\frac{\Gamma_L+\Gamma_S}{\Gamma_S-\Gamma_L} + i\tan\phi_{SW}\right]\frac{\mathrm{Re}(\epsilon_M) - i\mathrm{Im}(\Delta)}{1+|\epsilon_M^2|} = \frac{1}{\Gamma_S-\Gamma_L}\sum_f \mathcal{A}_L(f)\mathcal{A}_S(f)^*$$

Exact relation (phase convention independent, no approximations) in the CPT limit

[only the CPT-violating parameter Δ has been treated as a small, and expanded to 1st non trivial order]

$$\left|\frac{m_{K^0}-m_{\bar{K}^0}}{m_{K^0}}\right| \approx 1.5\times 10^{-14}\left|\mathrm{Im}\left(\Delta\, e^{-i\Phi_{SW}}\right)\right|$$

$$\phi_{SW} = \arctan\left[\frac{2(m_L-m_S)}{\Gamma_S-\Gamma_L}\right] \approx 43.4^0$$

A marvelous tool:

$$\left[\frac{\Gamma_L + \Gamma_S}{\Gamma_S - \Gamma_L} + i \tan\phi_{SW}\right] \frac{\mathrm{Re}(\epsilon_M) - i\mathrm{Im}(\Delta)}{1 + |\epsilon_M^2|} = \frac{1}{\Gamma_S - \Gamma_L} \sum_f \mathcal{A}_L(f)\mathcal{A}_S(f)^*$$

Exp. Inputs
[$m_{L,S}$ & $\Gamma_{L,S}$]

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2 physical outputs

$\mathrm{Im}(\Delta) \neq 0$ could only be due to

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

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Exp. Inputs
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<u>2 physical outputs</u>

$\mathrm{Im}(\Delta) \neq 0$ could only be due to

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

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

E.g.:

$|\mathrm{Im}(\Delta)|_{000} < 6.4\times10^{-6}$

[KLOE '04]

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

→ Dominant error due to the dominant $\pi\pi$ and $\pi l\nu$ channels, where we need <u>interferometry</u>

Neutral kaon interferometry is the most characteristic type of measurements for a Φ factory:

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

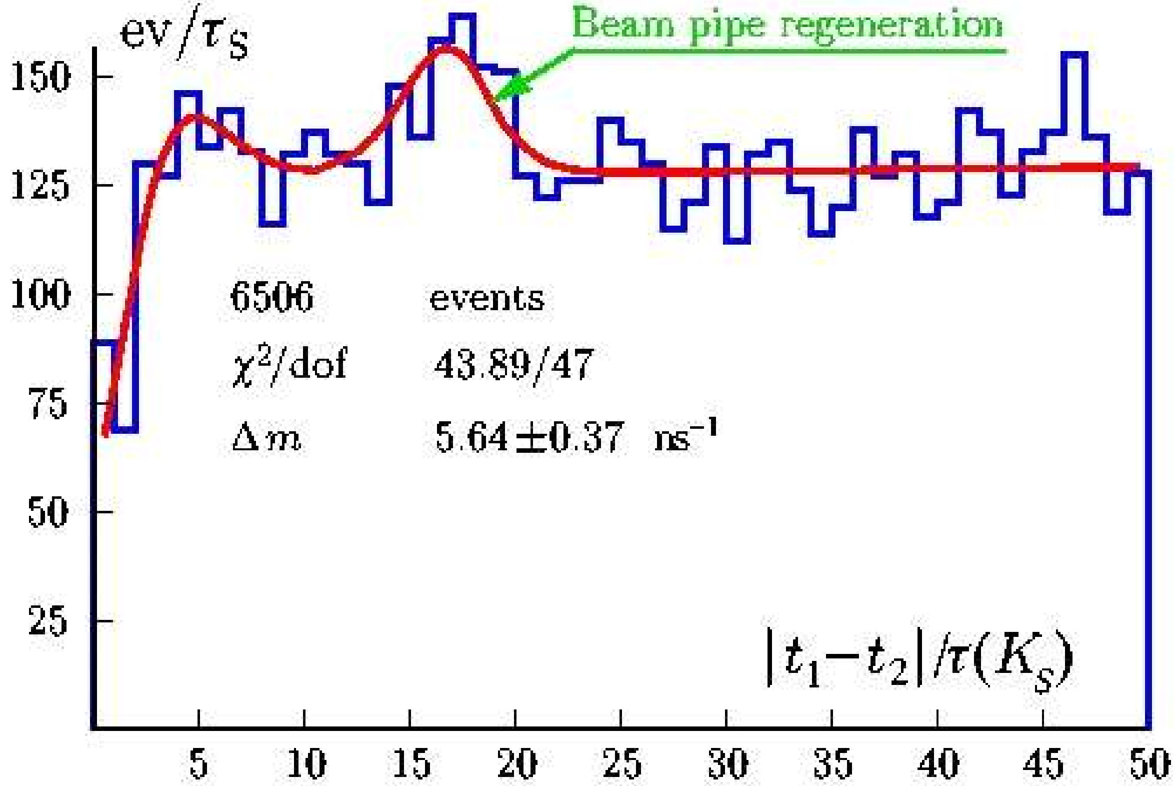
$$-2\,\mathrm{Re}\left[\, A_{Sa} A_{La}^{*} A_{Lb} A_{Sb}^{*}\, e^{+i\,\Delta m\,(t_1 - t_2)} \,\right] e^{-\Gamma\,(t_1+t_2)}$$

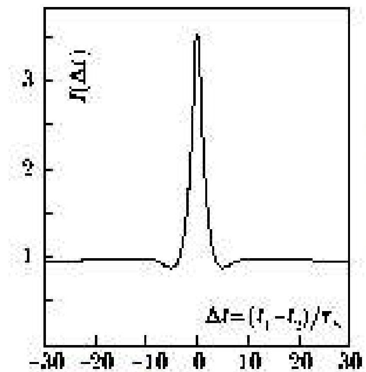
direct access to (strong & weak) phases

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

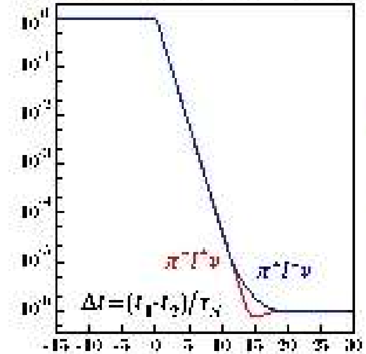
- $(\pi^+\pi^-)$-$(\pi^+\pi^-)$: Δm & $\Gamma_{L,S}$ + $\eta_{\pm}$ + tests of QM
- $(\pi^+\pi^-)$-$(\pi^0\pi^0)$: $\mathrm{Re}(\varepsilon'/\varepsilon)$ & $\mathrm{Im}(\varepsilon'/\varepsilon)$ + $\pi\pi$ phases + CPT & tests of QM
- $(\pi l \nu)$-$(\pi l \nu)$: CPT
- $(\pi l \nu)$-(3π) : $\eta_{3\pi}$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

→ Several interesting channels with L = few 10 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.

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

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

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

2. The rare $K_S \to \pi^0 l^+ l^-$ decays

Within kaon physics we can identify 4 golden modes [channels where it is possible to extract interesting & complementary short-distance info about flavour mixing]:

$K^+ \to \pi^+ \nu\nu$	$K_L \to \pi^0 e^+ e^-$
$K_L \to \pi^0 \nu\nu$	$K_L \to \pi^0 \mu^+ \mu^-$

In the case of the two $K_L \to \pi^0 l^+ l^-$ channels, it is necessary to measure also the corresponding $K_S \to \pi^0 l^+ l^-$ rates in order to extract the interesting s.d. info:

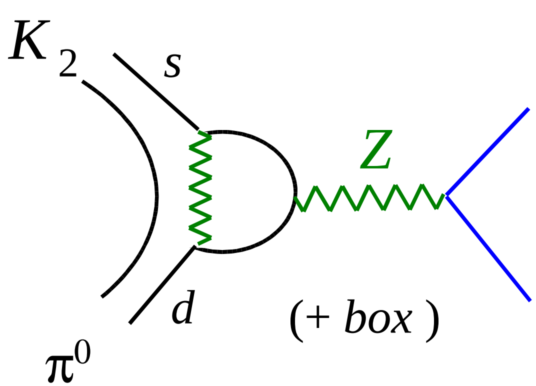
Direct CPV amplitude ⟷ *interference* ⟷ **Indirect CPV amplitude**

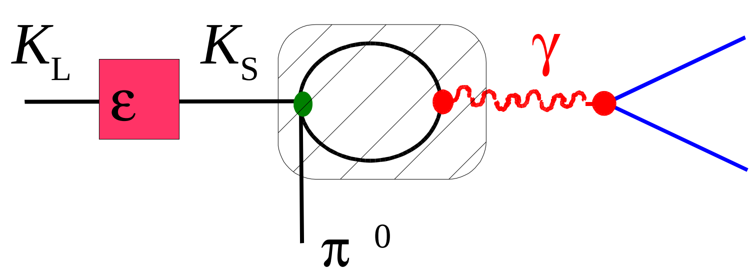
Direct CPV amplitude:

- short-distance dominated
- very similar to $K_L \to \pi^0 \nu\nu$

Indirect CPV amplitude:

- determined by $K_S \to \pi^0 l^+ l^-$ + theory to fix the sign





need exp. input

$B(K_L \to \pi^0 e^+e^-)^{[SM]} = (3.7 \pm 1.0) \times 10^{-11}$ [≈ 50% due to short dist.]

$B(K_L \to \pi^0 \mu^+\mu^-)^{[SM]} = (1.5 \pm 0.3) \times 10^{-11}$ [≈ 30% due to short dist.]

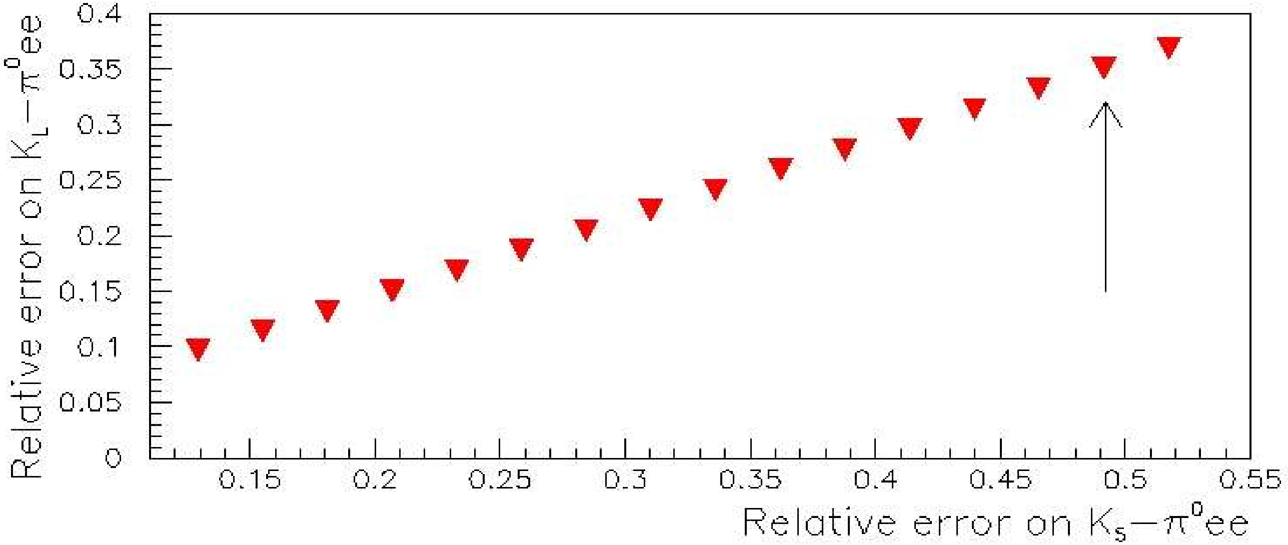
Irreducible theoretical error below 10%

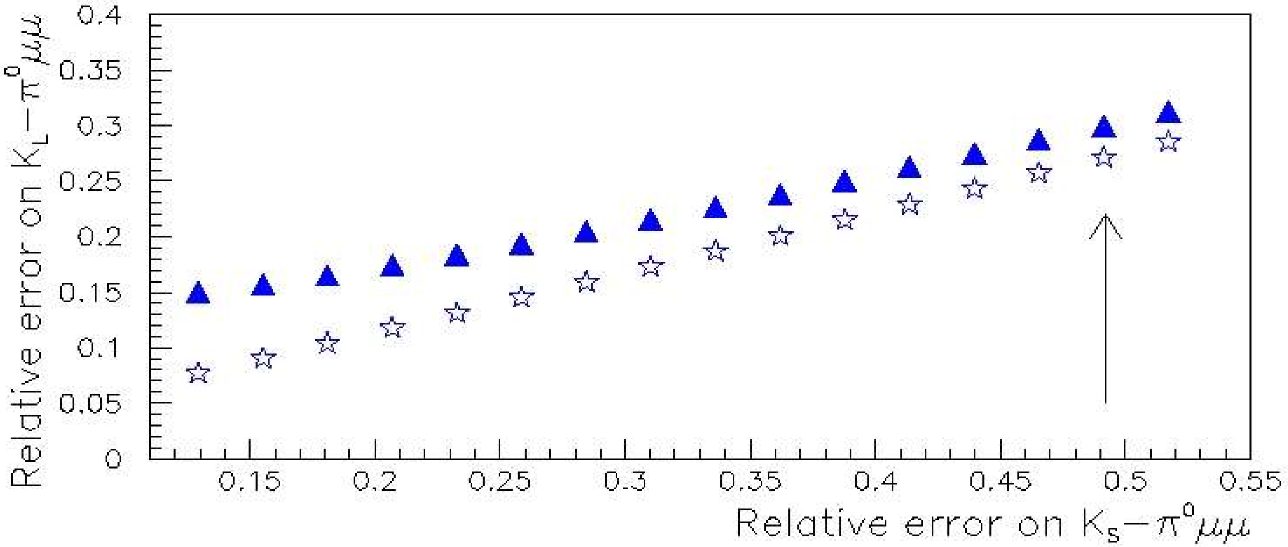
present large errors due to the large exp. uncertainty on $B(K_S \to \pi^0 l^+l^-)$:

$B_S(e^+e^-) \approx (6.0 \pm 2.9)\times 10^{-9}$

$B_S(\mu^+\mu^-) \approx (2.9 \pm 1.4)\times 10^{-9}$

NA48/1 '03-'04





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⇕

$B(K_L \to \pi^0 e^+e^-)^{exp} < 2.8\times10^{-10}$ [90% CL] KTeV '03

$B(K_L \to \pi^0 \mu^+\mu^-)^{exp} < 3.8\times10^{-10}$ [90% CL] KTeV '00

not too far...

⇓

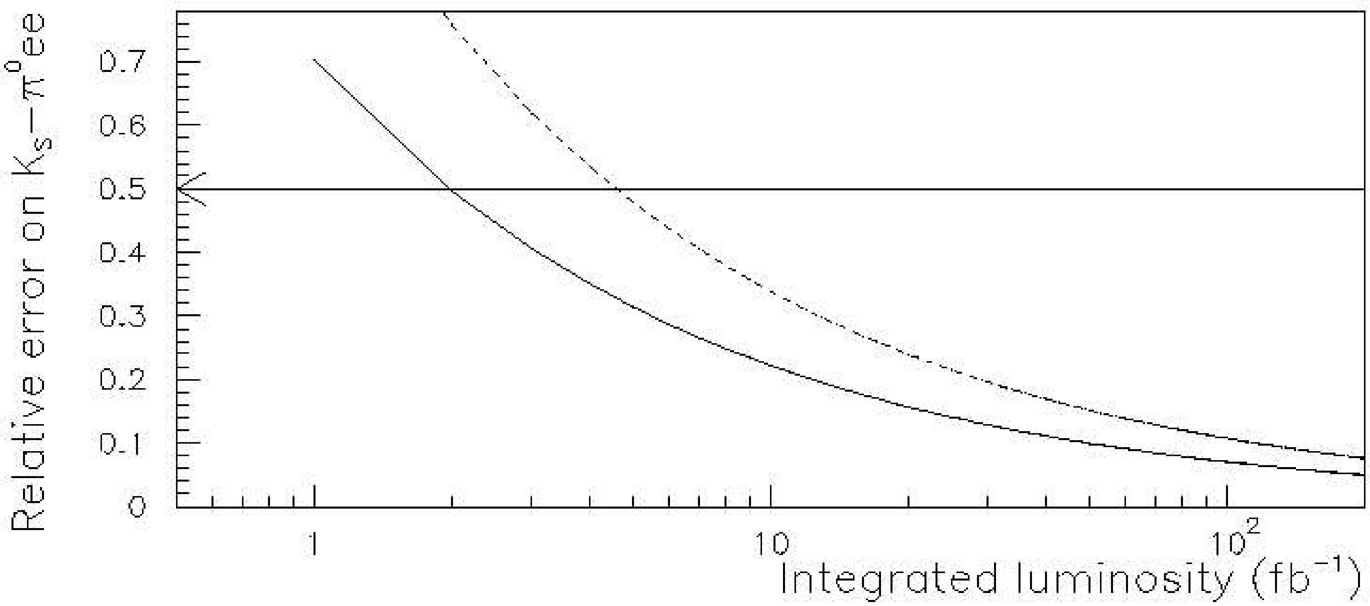
Very interesting candidates for future dedicated experiments @ fixed target...

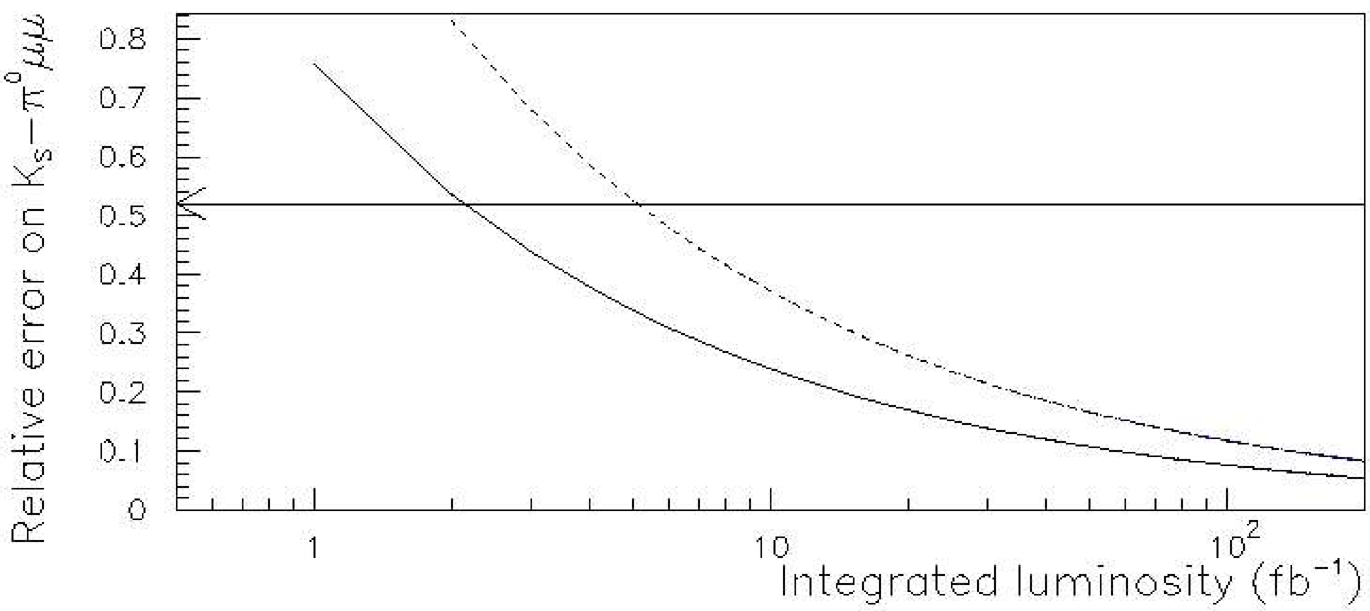
- More observables to be studied [Dalitz plot distribution]
- Different sensitivity to NP with respect to $K_L \to \pi^0 \nu\nu$

the 3 decay modes $K_L \to \pi^0 + e^+e^-, \mu^+\mu^-, \nu\nu$
are sensitive to different short-distance structures
⇒ 3 independent info on CPV beyond the SM

...provided it is possible to measure precisely also the K_S channels

⇒ @ super Φ factory ?





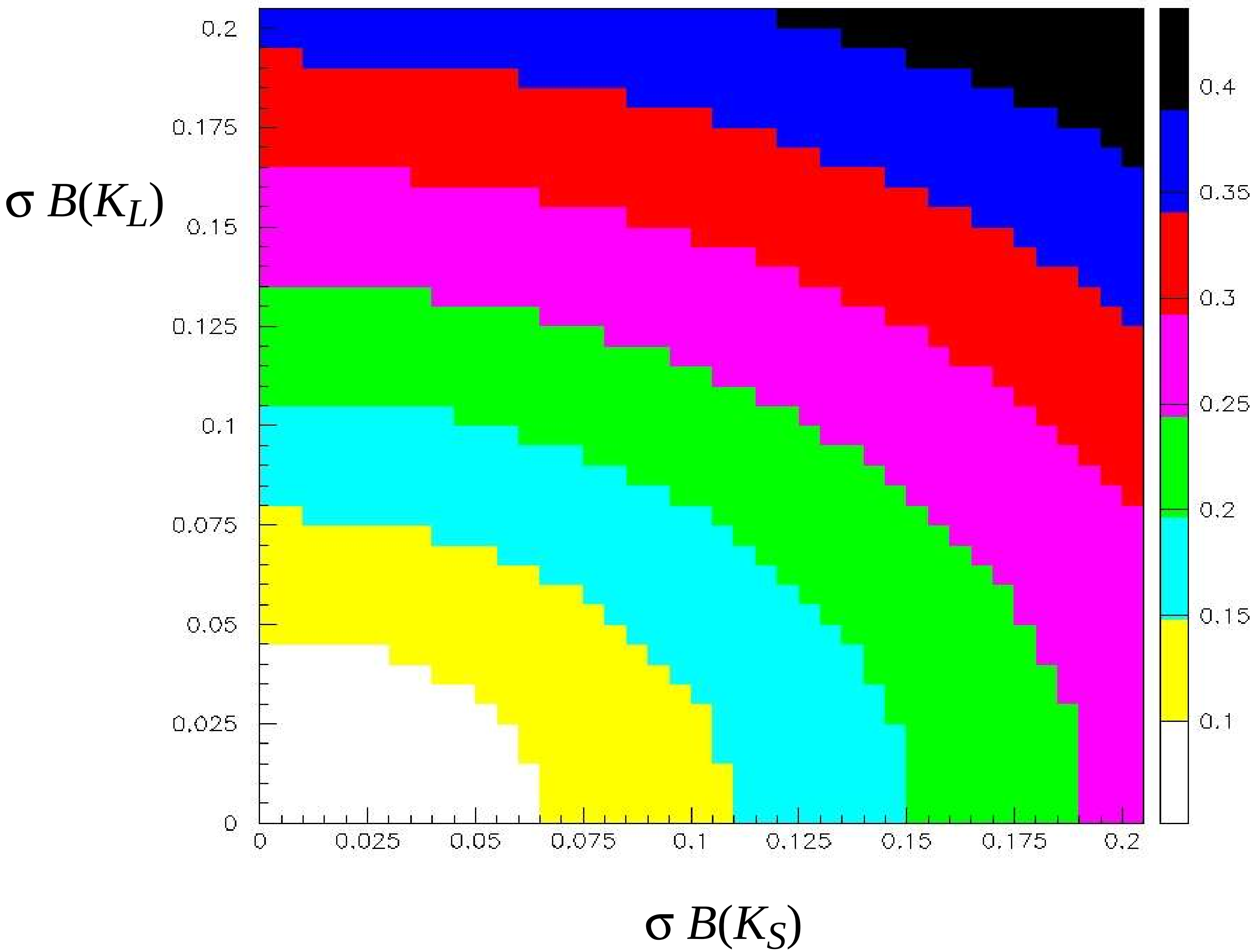
With ~ 30 fb^{-1} and a more optimized detector [vertex detect.] it would be possible to reach the 15% level on both $B(K_S \to \pi^0 l^+ l^-)$

F. Bossi, V. Patera & G.I., work in prog. '05

Relative error on $Im(V_{ts}^{*}V_{td})$

vs.

relative exp. errors on $B(K_S \to \pi^0 e^+e^-)$ & $B(K_L \to \pi^0 e^+e^-)$



3. The V_{us} saga

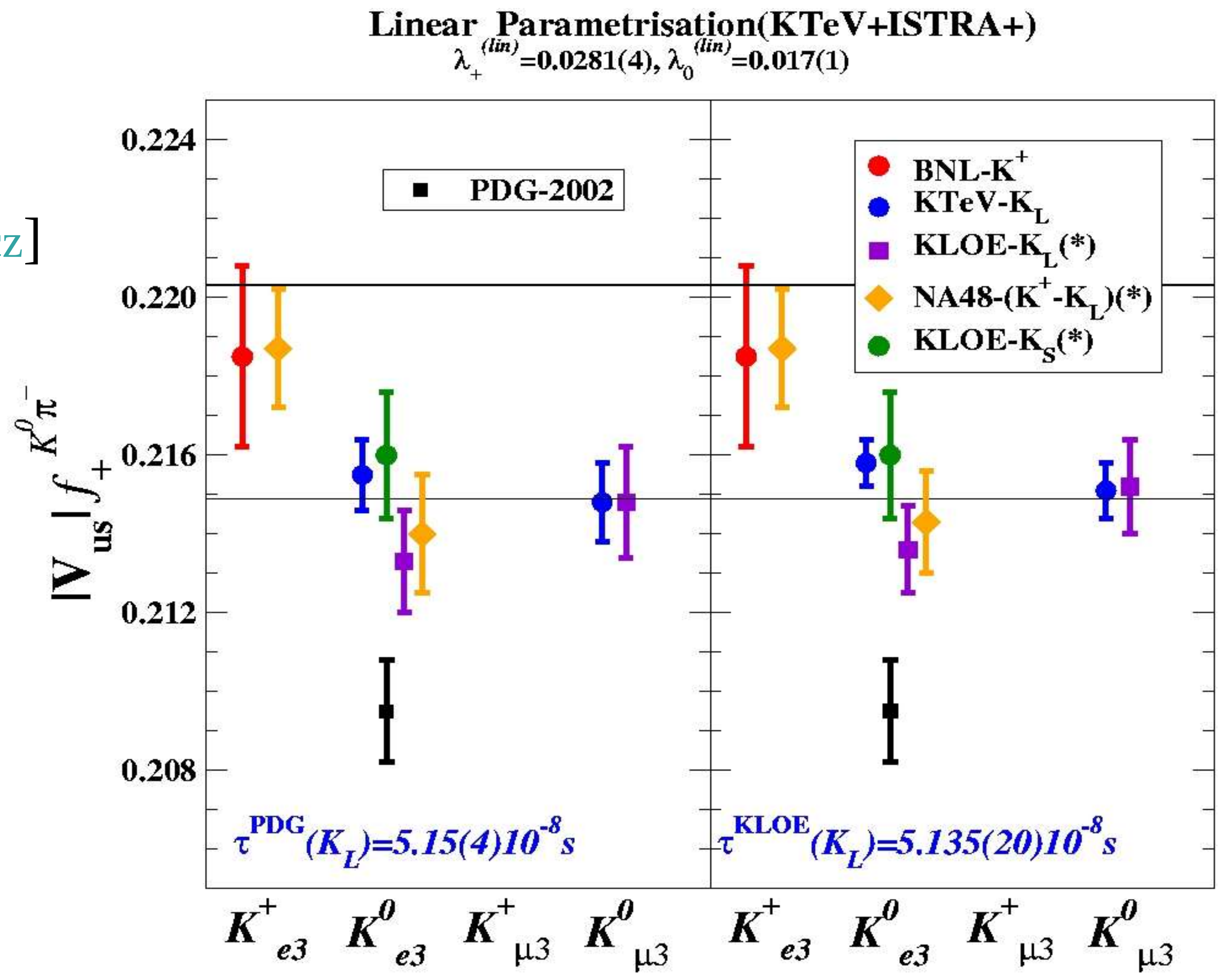
Present status:

[see M. Antonelli & V. Lubicz]

consistency with V_{ud}
(CKM unitarity)
restored

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

error dominated by
$f_+(0) \Leftrightarrow$ theory



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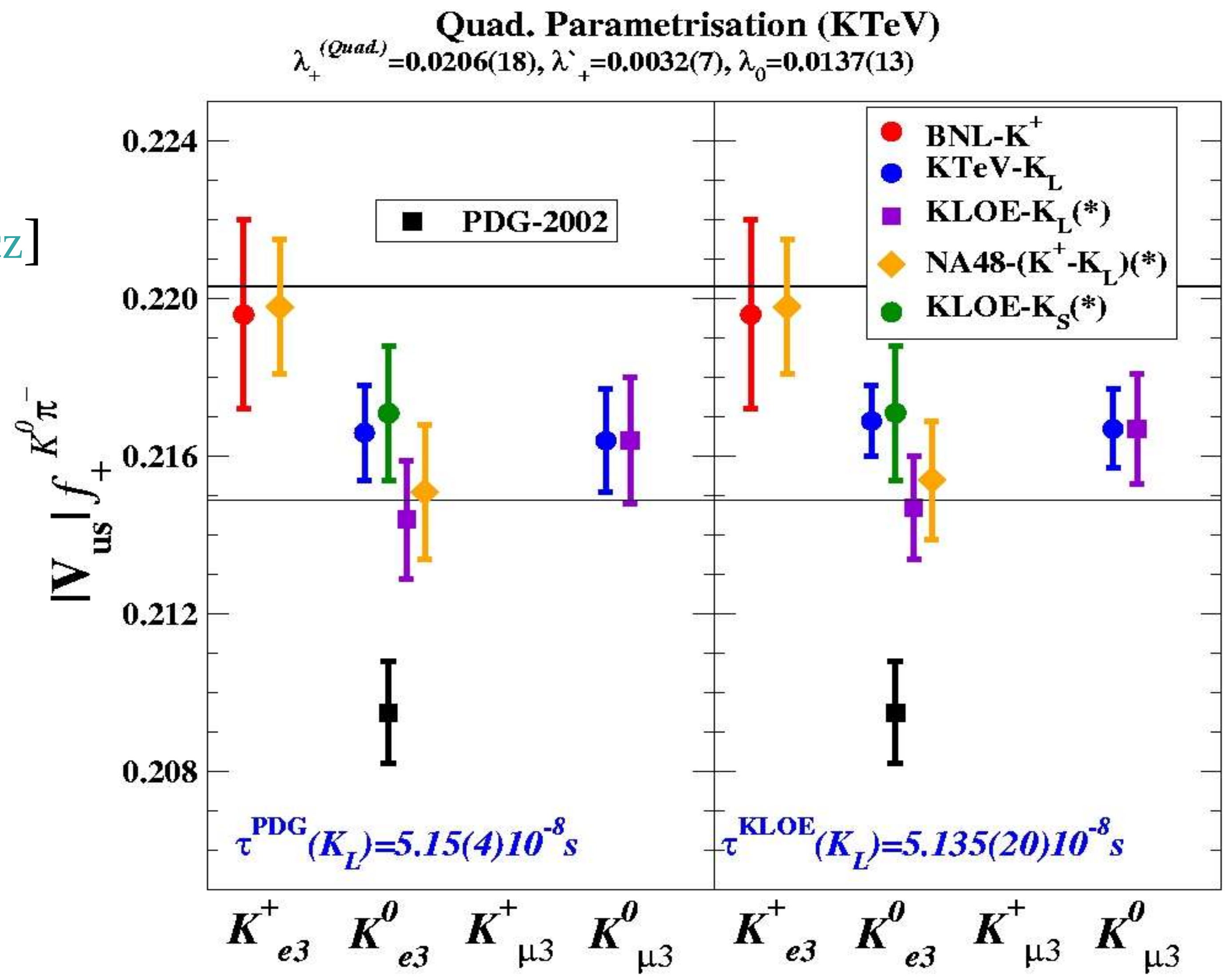

..but the situation is more complicated than it appears at first sight ...

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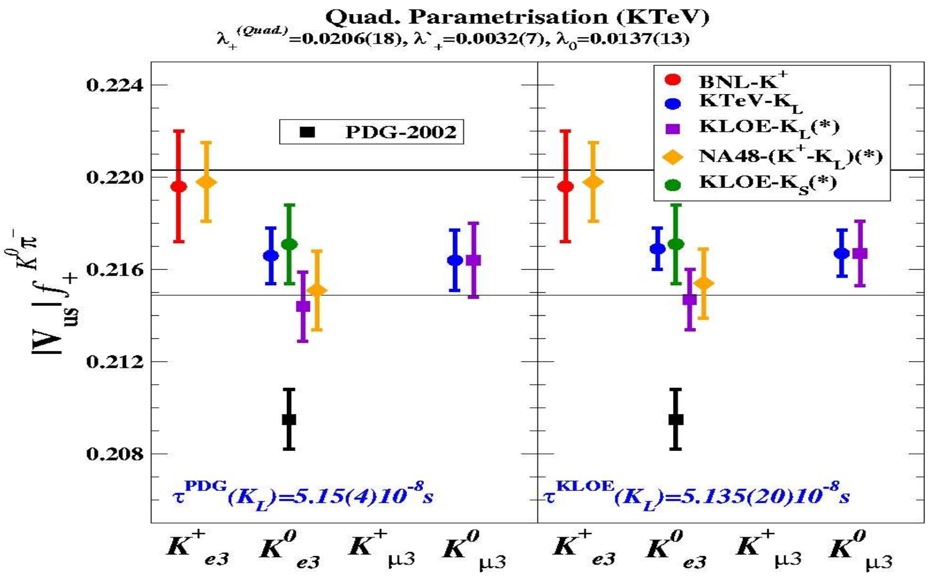

With higher stat. & better syst. there is certainly room for improvements:

- 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 error on V_{us} [similar to the hadronic moments in $B \to X l \nu$]

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

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

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

F_K/F_π, λ_0, ... CHPT [Bijnens & Talavera, *et al.*]

Natural goal for a high- or medium/high-*L* Φ factory

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

4. 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 $K^{\pm} \to \pi^+\pi^- l\nu$]

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 $K \to 3\pi$ [Cabibbo '04, Cabibbo & G.I. '05]

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

Beyond kaon physics

A Φ factory is not-only a kaon factory, but also

- an efficient η and η' factory
- an excellent laboratory for low-energy scalar mesons: f_0, a_0 , (σ ?)

[see F. Ambrosino]

Several measurements in this sector are still statistically limited
[E.g.: $d\Gamma(\eta\to\pi^0\gamma\gamma)$, $\Gamma(\eta\to\mu^+\mu^-)$, ... $d\Gamma(\Phi \to S_0\gamma \to KK\gamma)$]

⬇

Interesting opportunities to improve our knowledge about non-perturbative aspects of QCD [within some of the most simple & fundamental hadronic systems]

(my) conclusions

The physics case of a high-intensity Φ factory with L [$cm^{-2}s^{-1}$] $\gtrsim 10^{33}$ is 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} ,...]
  ⇒ more work on real data needed to better quantify the potential impact

\+ non-K program at the Φ [f_0, a_0 , η , η'] [clear]

\+ kaonic atoms / hypernuclei [compatibility with the K prog. to be explored]

⬇

Natural completion of the DAΦNE program

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A few important remarks:

- The most clear goals in this program will be less interesting if the time scale is too long [link/competition within the field of flavour physics]
- The program is challenging from the exp. point of view [huge statistics & high precision] & requires non-trivial hardware modifications [detector optimized for KS physics] ⇒ size of the exp. collaboration not to be underestimated

(my) conclusions

The physics case of a high-intensity Φ factory with L [$cm^{-2}s^{-1}$] $\gtrsim 10^{33}$ is 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

+ non-K program at the Φ [f_0, a_0 , η , η'] [clear]
+ kaonic atoms / hypernuclei [compatibility with the K prog. to be explored]

⬇

In addition to the natural machine and experimental considerations the time schedule of this program represents a key point