Highlights of the physics program of DAΦNE – 33

Gino Isidori [*INFN-Frascati*]

- Introduction
  - Main directions for 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 $L > 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - 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

Main research directions for low-energy experiments in the LHC era:

I. Study of rare processes potentially sensitive to physics beyond the SM

[$\tau \to \mu\gamma$, $0\nu\beta\beta$, edm's , $K \to \pi\nu\nu$, ...]

full complementarity with LHC for the study of New Physics

[identification of the *symmetries* of the NP model]

II. Precision measurements of fundamental SM couplings: $V_{\rm CKM}$, m_q , α_i

some complementarity with LHC for a better study of the underlying theory

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

III. Hadronic measurements:

A. better understanding of QCD [research direction orthogonal to LHC]

B. reduction of theory errors for I. & II.

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
    - ππ 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 [Sept. '03]
[www.lnf.infn.it/conference/d2]

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↓

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→ unfortunately, limited progress since then...

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<u>In principle</u> ....

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<u>..in practice</u> we need to take into account that:

- L cannot exceed ~ 10^{34} cm $^{-2}$s $^{-1}$ $\Rightarrow$ no chances for the rare golden modes
- Serious <u>internal</u> (time) competition between Φ & non-Φ options
  [extrapolate from the present DAΦNE situation...]

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

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if this is not a too serious problem...

⬇

see next talk

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

General considerations about the kaon program

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

- 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 quantum state [L=1] ⇒ Neutral kaon interferometry
- Kaon beams of known momentum ⇒ Great advantage for any decay with missing energy
- K^+K^- & $K_L K_S$ in the same detector ⇒ Useful for QCD & CPV studies

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➡ For a competitive program:

- *L* must definitely <u>exceed</u> $10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- 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:

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~~

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

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 $K_S \to \pi^{\pm} l^{\mp} \nu$

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

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

$\sim |M_L - M_S| / M_K$

$\delta_S = -(2 \pm 9 \pm 6)\times10^{-3}$ [KLOE '04]

$\delta_L = (3.322 \pm 0.058 \pm 0.047)\times10^{-3}$ [KTeV '02]

$\delta_L = (3.317 \pm 0.070 \pm 0.072)\times10^{-3}$ [NA48 '03]

Reference vale for the ultimate measurement of δ_S → sensitivity on $\dfrac{|M_{\bar{K}} - M_K|}{M_K}$ 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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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 interferometry

Relevant final states in the unitarity sum:

$$\alpha_f = \frac{1}{\Gamma_S} A_L(f) A_S(f)^* = \eta_f \mathcal{B}(K_S \to f)$$

contributions expected within the SM [for $\mathrm{Re}(\varepsilon_M) = 2.28 \cdot 10^{-3}$]

Channel	$B(K_S)$	$B(K_L)$	$10^5 \cdot \alpha_f^{SM}$
$\pi^+\pi^-(\gamma)$	0.69	$2.1 \cdot 10^{-3}$	114.3 + 108.1 i
$\pi^0\pi^0$	0.31	$9.3 \cdot 10^{-3}$	51.3 + 48.5 i
$\pi^\pm e^\mp \nu$	$6.7 \cdot 10^{-4}$	0.39	0.22 + 0.00 i
$\pi^\pm \mu^\mp \nu$	$4.7 \cdot 10^{-4}$	0.27	0.17 + 0.00 i
$\pi^0\pi^0\pi^0$	$1.9 \cdot 10^{-9}$	0.21	0.06 + 0.06 i
$\pi^+\pi^-\pi^0$	$2.7 \cdot 10^{-7}$	0.12	0.04 + 0.04 i
$\pi^+\pi^-\gamma_{DE}$	$\sim 10^{-5}$	$\sim 10^{-5}$	< 0.01

The only terms which needs a measurement (not only a bound) up to $\sigma \sim 10^{-6}$

others — bounds $\sim 10^{-6}$ already by rate measurements:

$$|\alpha_f| \leq \left[\frac{\Gamma_L}{\Gamma_S}\right]^{1/2} [\mathcal{B}(K_L \to f)\mathcal{B}(K_S \to f)]^{1/2}$$

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The only terms which needs a measurement (not only a bound) up to $\sigma < 10^{-5}$

bounded below 10^{-5} by means of interference meas.

others: bounds $\sim 10^{-6}$ already by rate measurements:

$$|\alpha_f| \le \left[\frac{\Gamma_L}{\Gamma_S}\right]^{1/2} [\mathcal{B}(K_L \to f)\mathcal{B}(K_S \to f)]^{1/2}$$

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

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

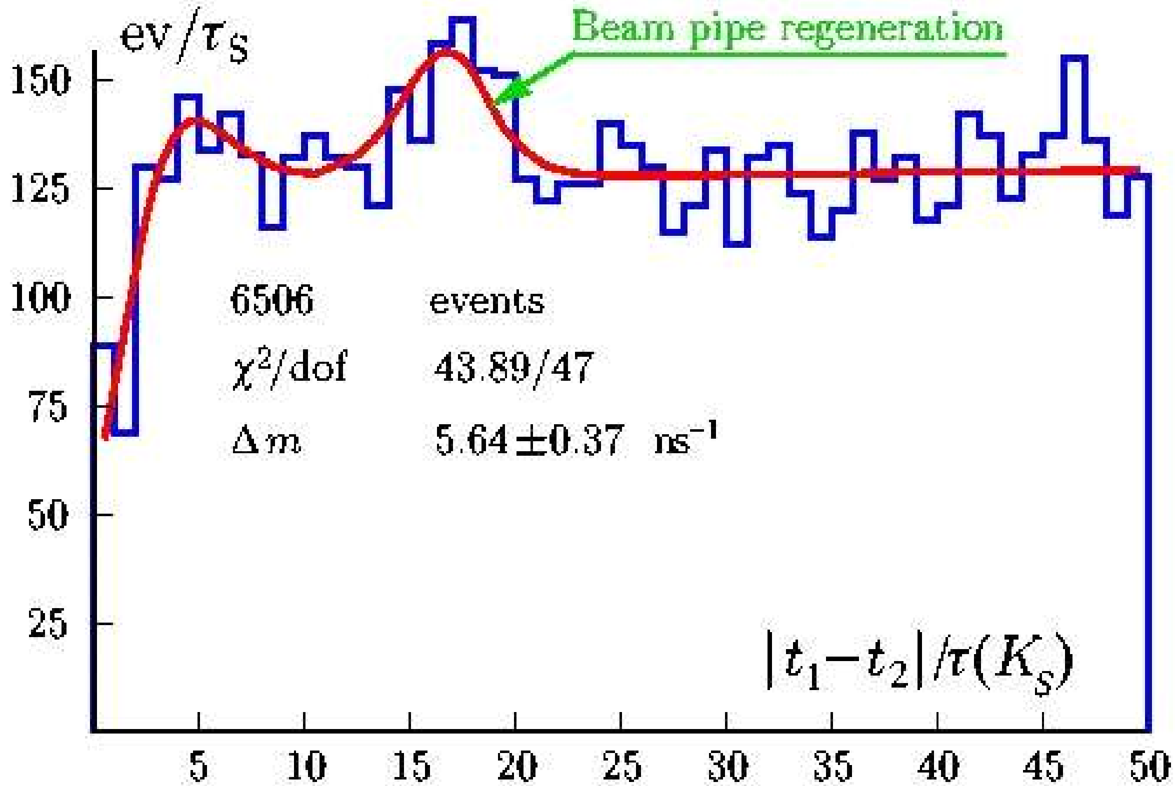
$$-2\,\mathrm{Re}\left[\, A_{Sa} A_{La}^* A_{Lb} A_{Sb}^*\, e^{+i\,\Delta m\,(t_1 - t_2)}\,\right] e^{-\Gamma\,(t_1+t_2)}$$

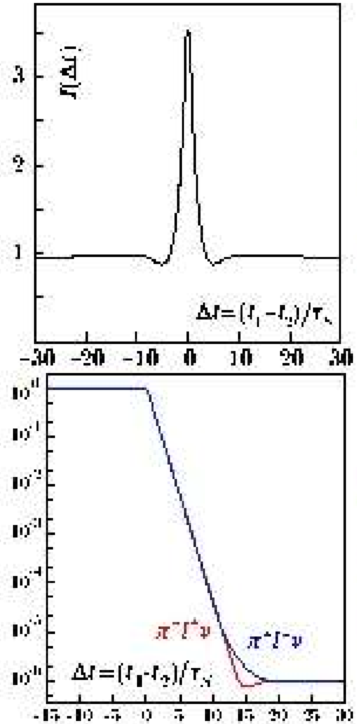
direct access to (strong & weak) phases

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

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

→ Several interesting channels with L = few $\times$ 10 fb^{-1}





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

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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]:

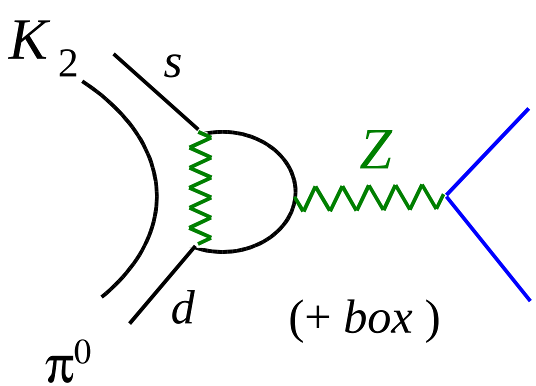
$K^+ \to \pi^+ \nu\nu$	$K_L \to \pi^0 e^+ e^-$
$K_L \to \pi^0 \nu\nu$	$K_L \to \pi^0 \mu^+ \mu^-$

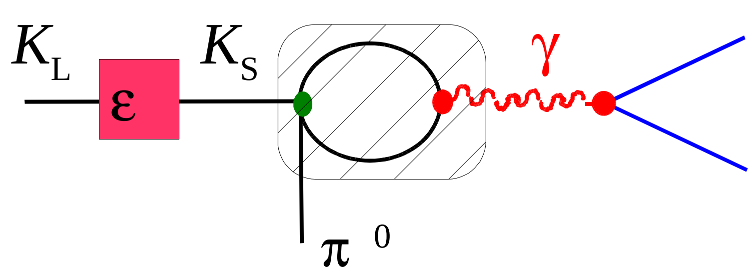
In the case of the two $K_L \to \pi^0 l^+ l^-$ channels, it is necessary to measure also the corresponding $K_S \to \pi^0 l^+ l^-$ rates in order to extract the interesting s.d. info:

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.]

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

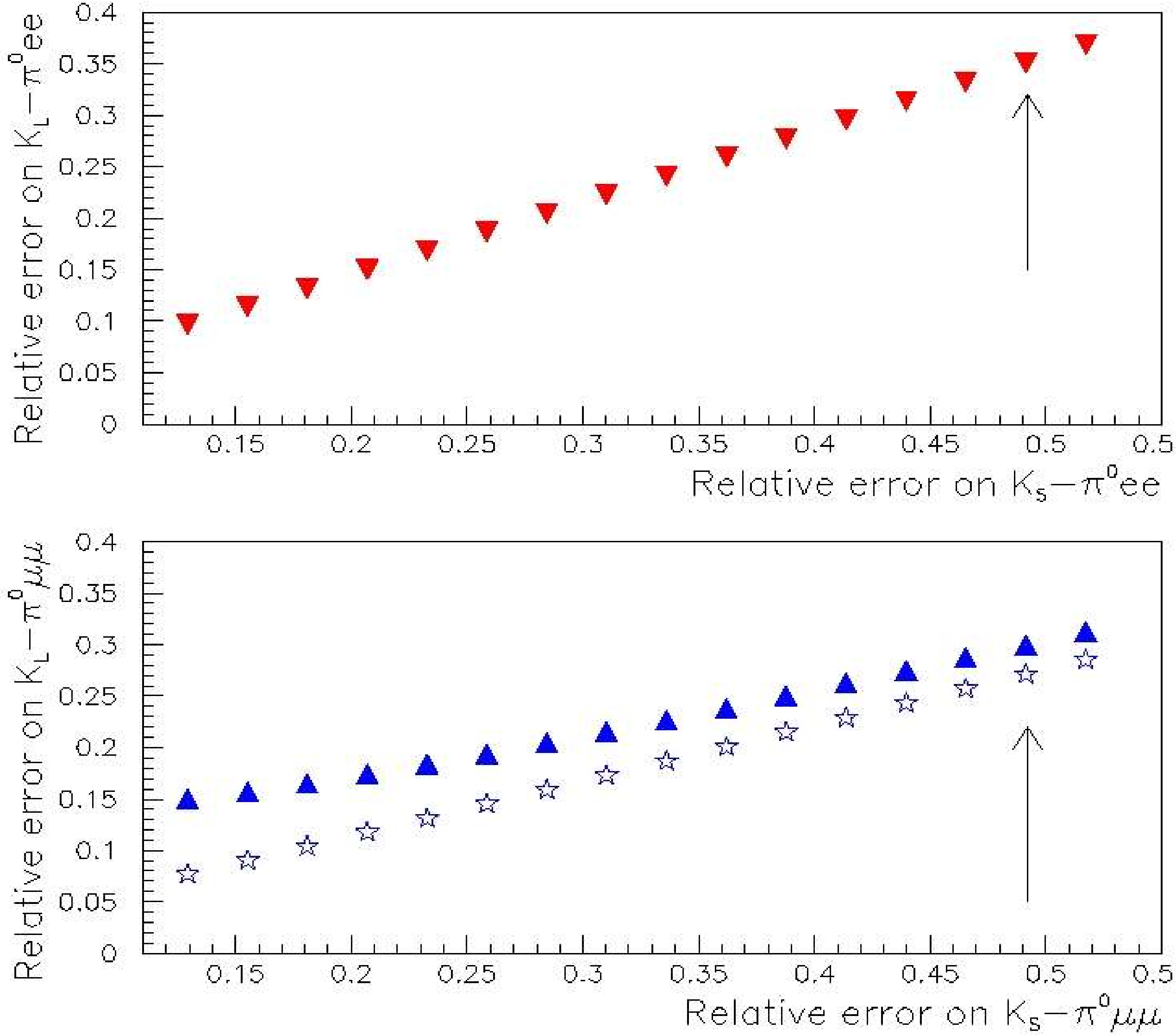
<u>Irreducible theoretical error below 10%</u>

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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⇕

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

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

not too far...

⇓

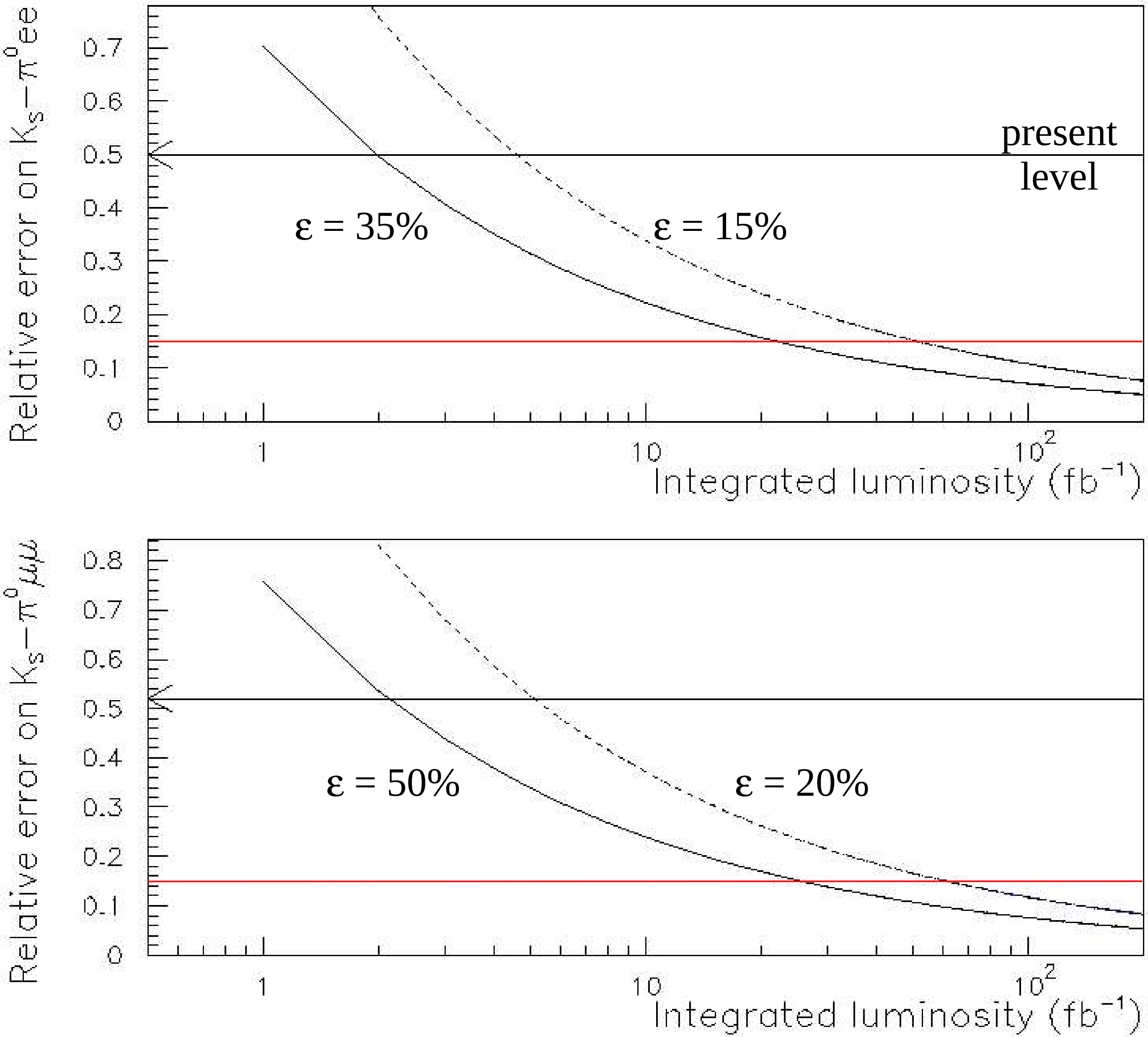
Very interesting candidates for future dedicated experiments @ fixed target...

- 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 $\geq 20\ fb^{-1}/yr$ and
a more optimized detect.
[vertex detector ?]
it could be possible to
reach the 15% level
on both $B(K_S \to \pi^0 l^+ l^-)$

Courtesy of F. Bossi & V. Patera

3. The V_{us} saga

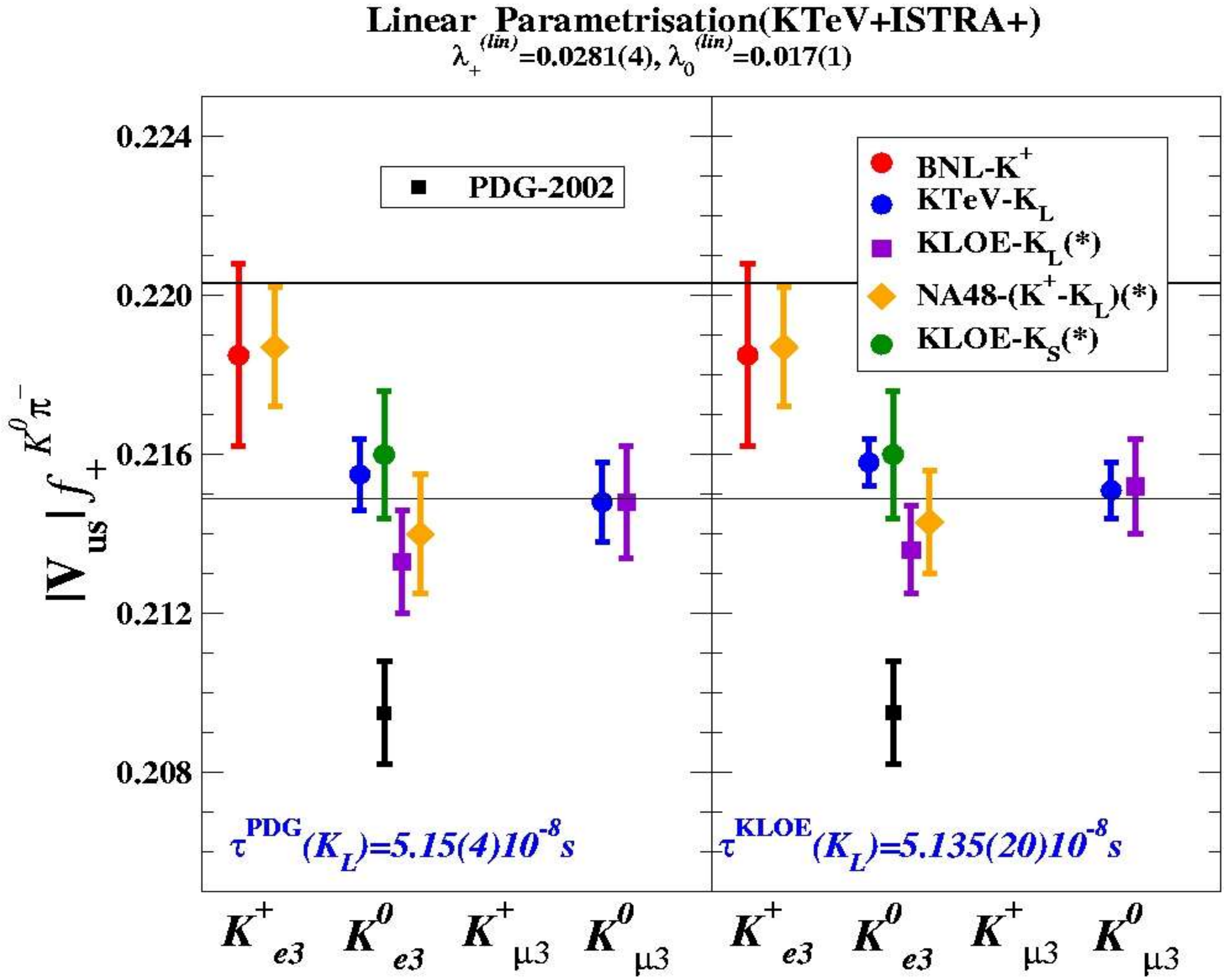
Present status:

consistency with V_{ud}
(CKM unitarity)
restored

↓

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

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



F. Mescia

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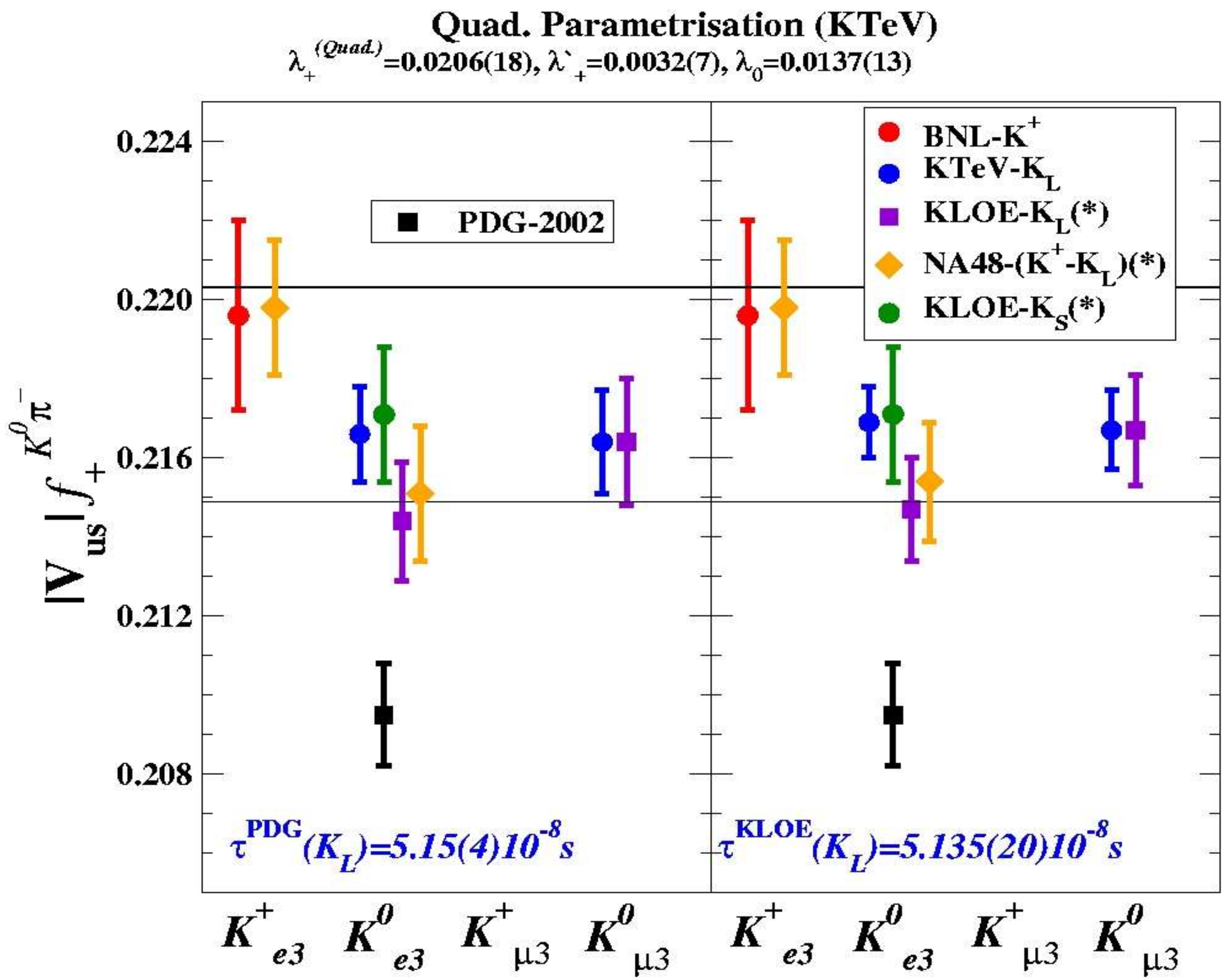


F. Mescia

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

3. The V_{us} saga

Present status: $\delta|V_{us}| \approx 1\%$

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

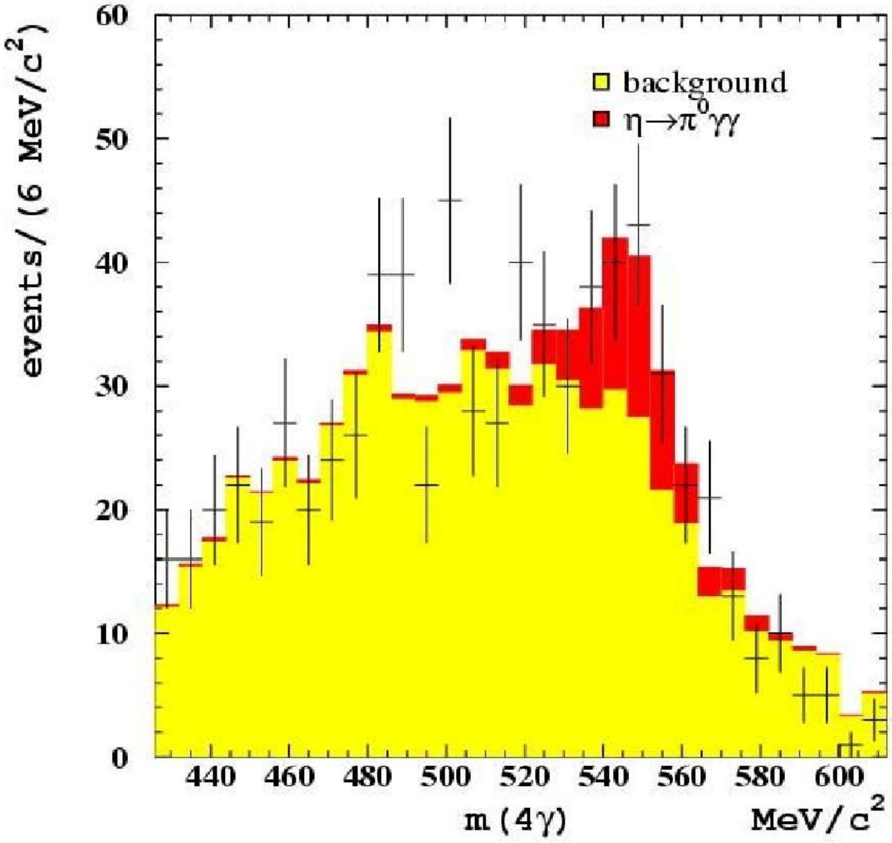
- an efficient η and η' factory
- an excellent laboratory for low-energy scalar mesons: f_0, a_0, (σ ?)

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]

Preliminary KLOE results on $\eta\to\pi^0\gamma\gamma$:



The shape of background + signal after fit well reproduce the DATA.

$P_{bkg} = 0.907 \pm 0.049$

$P_{sig} = 0.093 \pm 0.031$

$N_{DATA} = 735$

$N_{bkg} = 667 \pm 36$ $N_{sig} = 68 \pm 23$

$\varepsilon(\eta\to\pi^0\gamma\gamma) = 4.63 \pm 0.09$ (only stat)

$N(\eta\to 3\pi^0) = 2288882$

$\varepsilon(\eta\to\pi^0\pi^0\pi^0) = 0.378 \pm 0.08_{syst} \pm 0.01_{stat}$

$$\frac{Br(\eta\to\pi^0\gamma\gamma)}{Br(\eta\to 3\pi^0)} = \frac{N(\eta\to\pi^0\gamma\gamma)\cdot\epsilon(\eta\to 3\pi^0)}{N(\eta\to 3\pi^0)\cdot\epsilon(\eta\to\pi^0\gamma\gamma)} = (2.43 \pm 0.82)\times 10^{-4}$$

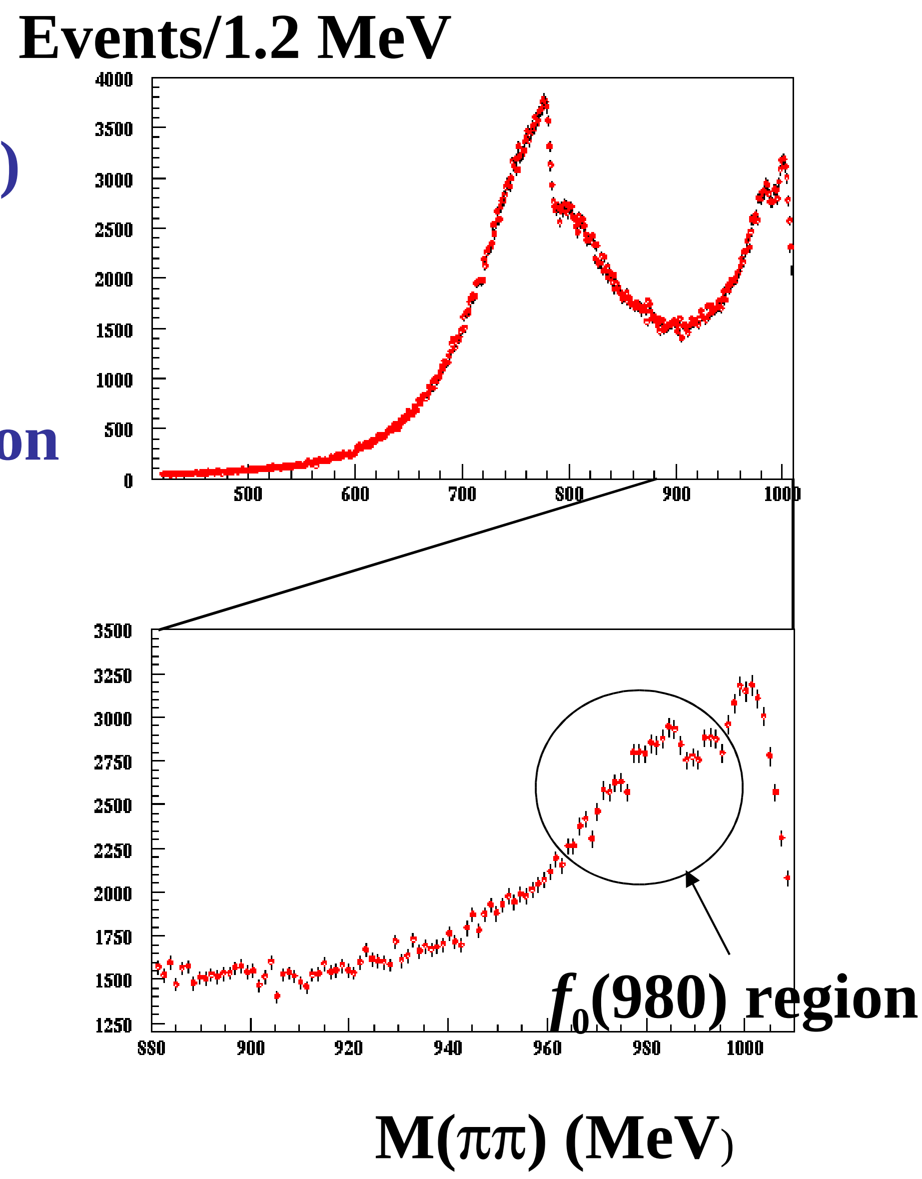
$$Br(\eta\to\pi^0\gamma\gamma) = (8.0 \pm 2.7)\times 10^{-5}$$

$f_0(980) \to \pi^+\pi^-$

- $e^+e^- \to \pi^+\pi^-\gamma$ **events with the photon at large angle** ($45° < \vartheta_\gamma < 135°$)
- **Main contributions:**
  ISR (radiative return to ρ, ω)
  FSR
- **Search for the** f_0 **signal as a deviation on** $M(\pi^+\pi^-)$ **spectrum from the expected ISR + FSR shape**

- **Data sample: 350** pb^{-1}
  from 2001 – 2002 data
  at ϕ peak

676000 events selected



$(a_0,f_0) \rightarrow KK$

- **A very interesting process for studying the scalars would be $\phi \rightarrow (a_0,f_0)\gamma \rightarrow KK\gamma$**

$\Rightarrow$ **$N(\phi\rightarrow(a_0,f_0)\gamma \rightarrow K^+K^-\gamma)$ $\rightarrow$ 6000-12000 evts**

$\Rightarrow$ **$N(\phi\rightarrow(a_0,f_0)\gamma \rightarrow K^0K^0\gamma)$ $\rightarrow$ 70-300 evts**

$\Rightarrow$ **golden channel: $K_SK_S\gamma$ $\rightarrow$ 10 – 100 evts**

Last but not least...

The Φ factory is a ideal machine also to study nuclear physics

- Hypernuclei
- Hadronic atoms

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The Φ factory is a ideal machine also to study nuclear physics

- Hypernuclei
- Hadronic atoms
  Kaonic

$\bar{K}X$

$X = \pi, K$; p; d; ^{3}He; ^{4}He .

Basic idea:

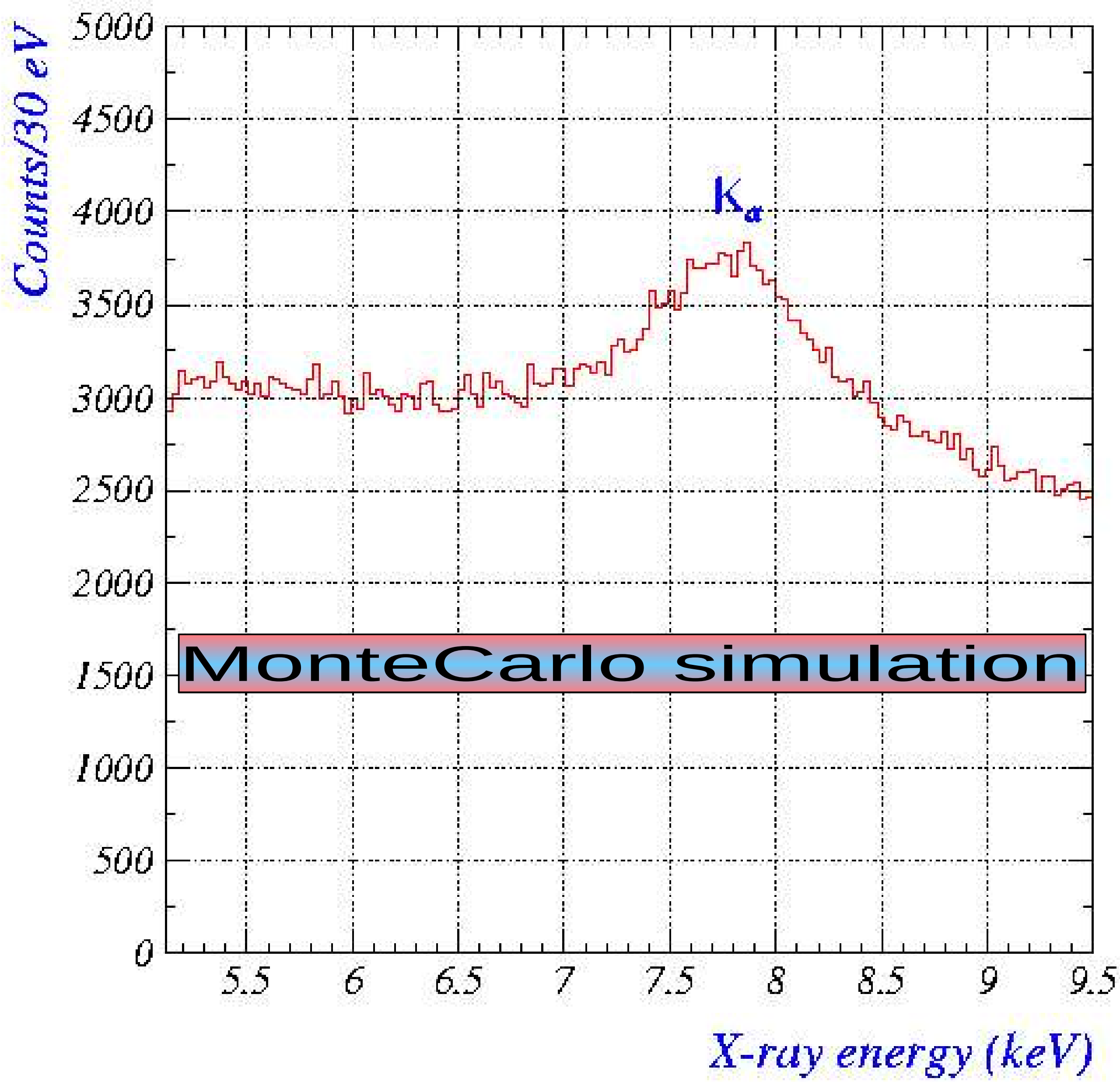
- System bound by electromagnetic interactions
- Hadronic interactions
  - change spectrum
  - let atoms decay

Energy shift, lifetime

$\Updownarrow$ [1]

→ $T-$ matrix at threshold

SIDDHARTA Kaonic deuterium simulated spectrum



Precision on shift < 10 eV

S/B = 1/4

integrated luminosity
100 pb^{-1}

M. Iliescu, Dafne '04

Last but not least...

The Φ factory is a ideal machine also to study nuclear physics

- Hypernuclei
- Hadronic atoms

↓

The compatibility with the Kaon program in a high-intensity

(one interaction region) machine need to to be explored

(my) conclusions

The physics case of a high-intensity Φ factory with L [$cm^{-2}s^{-1}$] = (2-4) × 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, interferometry]
- less clear targets [$K^{\pm}$-asym., K_{l4} ,...]
  ⇒ more work on existing 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 / extension of the DAΦNE program

(my) conclusions

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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/enthussiam of the collaboration not to be underestimated !

(my) conclusions

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⬇

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