Kaon Physics Review

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Content of the Lectures

1. **Building the Standard Model (SM) with strange particles**
   - Introduction
   - CP-Violation
2. **Probing the SM and looking for New Physics**
   - Ultra Rare Decays
3. **Precision tests of Weak Interaction Universality**
   - Leptonic Decays
   - Semileptonic Decays
4. **Precision tests of the Strong Interaction**
   - pi –pi scattering
   - Radiative Decays

Tests of SM with Kaon leptonic and semileptonic decays

- **To perform:**
  - The most accurate determination of V_{us}
  - Stringent tests of universality of the weak interaction
- **Exploit:**
  - Precise experimental data
  - Good theoretical tools (CHPT, LQCD)

K_{l2} rates in SM

$$\frac{\Gamma^{\pm}_{Kl2}}{\Gamma^{\pm}_{\pi l2}} = \frac{|V_{us}|^2 f_K^2 m_K (1-m_l^2/m_K^2)^2}{|V_{ud}|^2 f_\pi^2 m_\pi (1-m_l^2/m_\pi^2)^2}(1+\delta_{EM})$$

- f_K and f_π are the kaon and pion «decay constants ». The computation of their ratio requires the use of Lattice QCD
- δ_{EM} denotes the the effect of long-distance electromagnetic corrections

Leptonic Decays

$$\Gamma(M \to l\nu) = \frac{G^2}{8\pi} f_M^2 \left|V_{ux}\right|^2 m_M m_l^2 \left(1 - \frac{m_l^2}{m_M^2}\right)^2$$

$$M = \pi \Rightarrow x = d$$

$$M = K \Rightarrow x = s$$

The experimental measurement is proportional to
The product of the coupling and the decay constant:

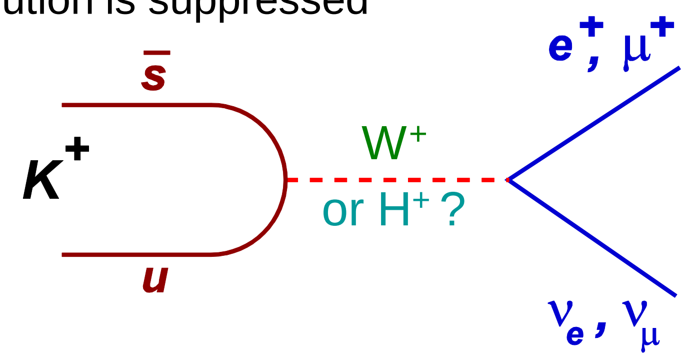
One must decide whether to make a test of the coupling
or a test of the calculation of the decay constants!

If we wish to test the universality, the decay constant are input
parameters to be computed by theory (lattice QCD)

Leptonic meson decays: $P^+ \to l^+ \nu$

Angular momentum and helicity conservation → SM contribution is suppressed

$$\Gamma(P^+ \to l^+\nu) = \frac{G_F^2 M_P M_l^2}{8\pi}\left(1 - \frac{M_l^2}{M_P^2}\right)^2 f_P^2 |V_{qq'}|^2$$



Models with 2 Higgs doublets (2HDM-II including SUSY): sizeable charged Higgs ($H^\pm$) exchange contributions

PRD48 (1993) 2342; Prog.Theor.Phys. 111 (2004) 295

(numerical examples for M_H=500GeV/c², tanβ = 40)

$\pi^+ \to l\nu$:	$\Delta\Gamma/\Gamma_{SM}$	$\approx -2(m_\pi/m_H)^2\, m_d/(m_u+m_d)\, \tan^2\beta$	$\approx -2\times10^{-4}$
$K^+ \to l\nu$:	$\Delta\Gamma/\Gamma_{SM}$	$\approx -2(m_K/m_H)^2 \tan^2\beta$	$\approx -0.3\%$
$D^+_s \to l\nu$:	$\Delta\Gamma/\Gamma_{SM}$	$\approx -2(m_D/m_H)^2\, (m_s/m_c) \tan^2\beta$	$\approx -0.4\%$
$B^+ \to l\nu$:	$\Delta\Gamma/\Gamma_{SM}$	$\approx -2(m_B/m_H)^2 \tan^2\beta$	$\approx -30\%$

(SM uncertainties: $\delta(f_B^2)/f_B^2$=10%, $\delta|V_{ub}|^2/|V_{ub}|^2$=13%)

Search for new physics is obstructed by hadronic uncertainties (f_P)

$R_K = K_{e2}/K_{\mu2}$ in the SM

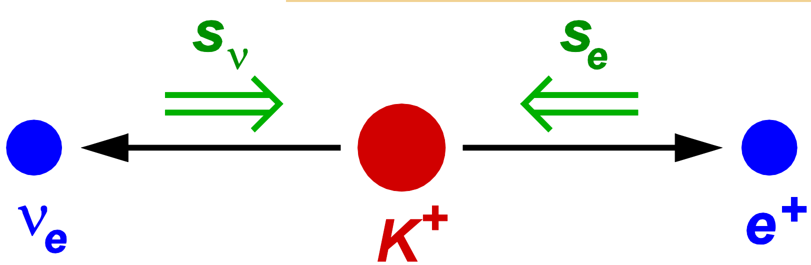
Observable sensitive to lepton flavour violation and its SM expectation:

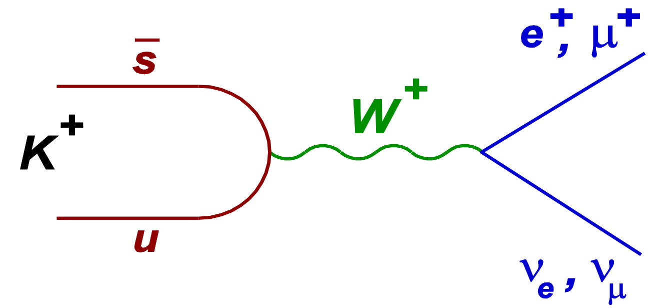
$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \frac{m_e^2}{m_\mu^2} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot \left(1 + \delta R_K^{rad.corr.}\right)$$

(similarly, R_π in the pion sector)

Radiative correction (few %) due to $K^+ \to e^+ \nu\gamma$ (IB) process, by definition included into R_K

Helicity suppression: $f \sim 10^{-5}$





- SM prediction: excellent sub-permille accuracy due to cancellation of hadronic uncertainties.
- Measurements of R_K and R_π have long been considered as tests of lepton universality.
- Recently understood: helicity suppression of R_K might enhance sensitivity to non-SM effects to an experimentally accessible level.

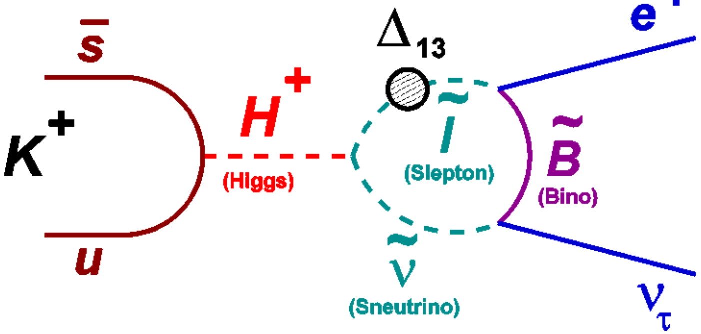
$R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$

$R_\pi^{SM} = (12.352 \pm 0.001) \times 10^{-5}$

V. Cirigliano and I. Rosell, Phys. Lett. 99 (2007) 231801

$R_K = K_{e2}/K_{\mu 2}$ beyond the SM

PRD 74 (2006) 011701,
JHEP 0811 (2008) 042



2HDM – tree level (including SUSY)

K_{l2} can proceed via exchange of charged Higgs $H^\pm$ instead of $W^\pm$

→ Does not affect the ratio R_K

2HDM – one-loop level

Dominant contribution to ΔR_K: $H^\pm$ mediated LFV (rather than LFC) with emission of ν_τ

→ R_K enhancement can be experimentally accessible

$$R_K^{LFV} \approx R_K^{SM}\left[1 + \left(\frac{m_K^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{M_e^2}\right)|\Delta_{13}|^2 \tan^6\beta\right]$$

Up to ~1% effect in large (but not extreme) $\tan\beta$ regime with a massive $H^\pm$

Example:
($\Delta_{13}=5\times10^{-4}$, $\tan\beta=40$, $M_H=500$ GeV/c^2)
lead to $R_K^{MSSM} = R_K^{SM}(1+0.013)$.

Analogous SUSY effect in pion decay is suppressed by a factor $(M_\pi/M_K)^4 \approx 6\times10^{-3}$

(see also PRD76 (007) 095017)

Large effects in B decays due to $(M_B/M_K)^4 \sim 10^4$:

$B_{\mu\nu}/B_{\tau\nu}$ → ~50% enhancement;

$B_{e\nu}/B_{\tau\nu}$ → enhanced by ~one order of magnitude.

Out of reach: $Br^{SM}(B_{e\nu}) \approx 10^{-11}$

R_K & R_π: experimental status

Kaon experiments:

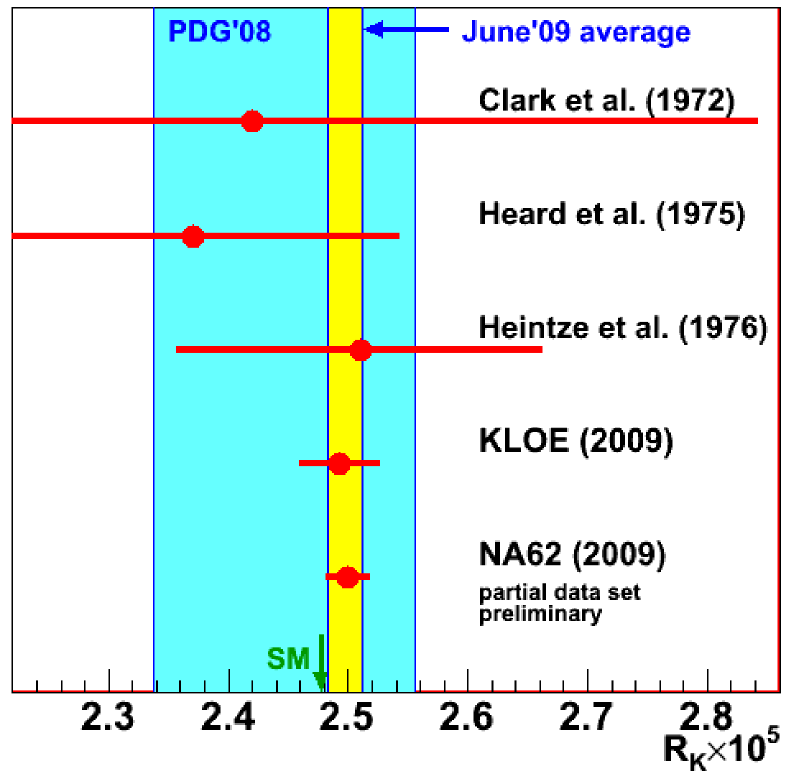
→ PDG'08 average (1970s measurements):
$R_K=(2.45\pm0.11)\times10^{-5}$ ($\delta R_K/R_K=4.5\%$).

→ 2009: KLOE (LNF), 2001–2005 data.
13.8K K_{e2} candidates, 16% background.
$R_K=(2.493\pm0.031)\times10^{-5}$ ($\delta R_K/R_K=1.3\%$).
(EPJ C64 (2009) 627)

→ 2009: NA62 (CERN), part of 2007 data.
preliminary result presented at Kaon'09:
51.1K K_{e2} candidates, $\delta R_K/R_K=0.7\%$.
(arXiv:0908.3858, 1005.1192)

→ Now: NA62 final result, same data set:
60.0K K_{e2} candidates, $\delta R_K/R_K=0.5\%$. (new!)

R_K world average (June 2009)



Pion experiments:

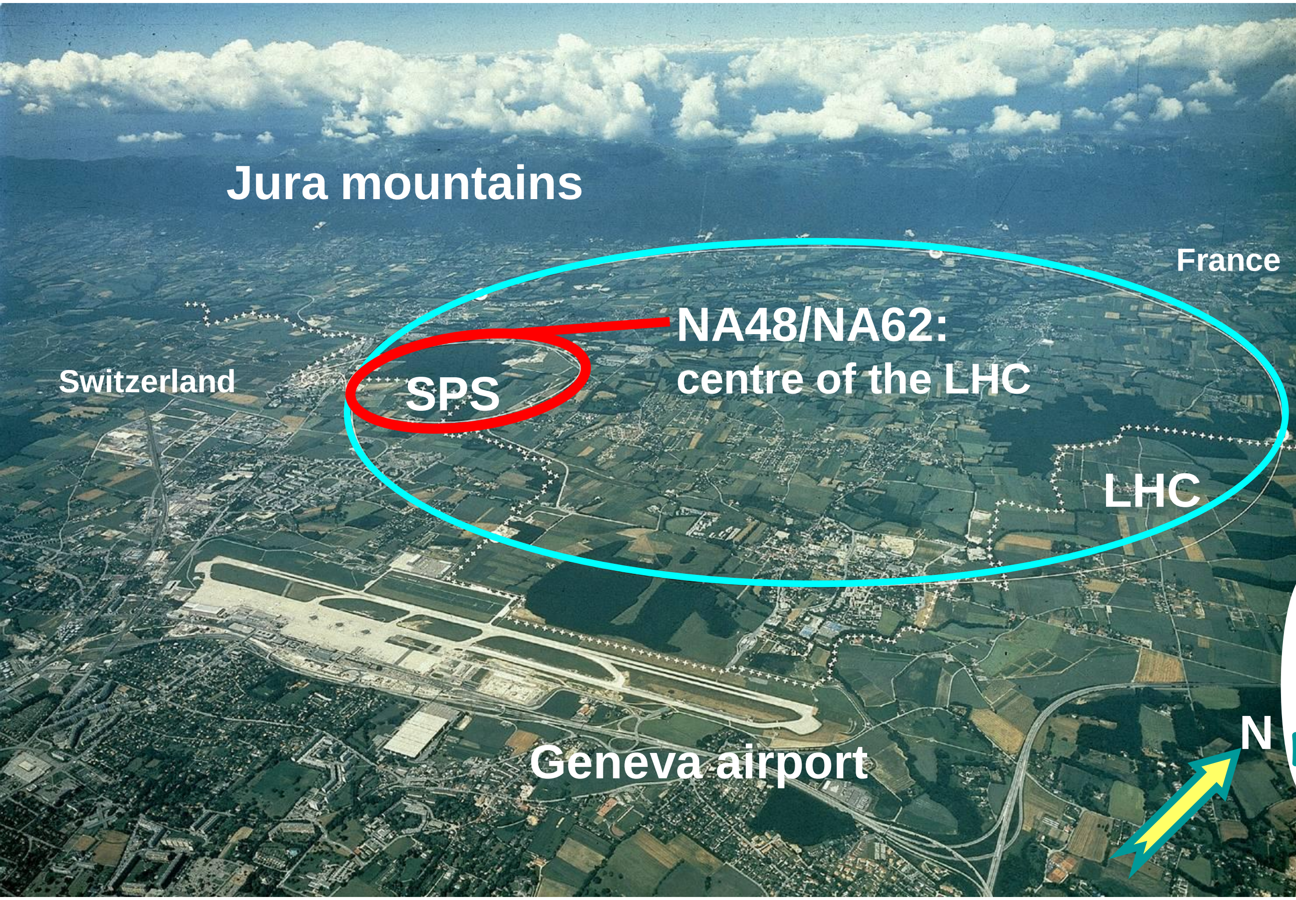
→ PDG'08 average (1980s, 90s measurements):
$R_\pi=(12.30\pm0.04)\times10^{-5}$ ($\delta R_\pi/R_\pi=0.3\%$)

→ Current projects: PEN@PSI (stopped π) running (CIPANP 2009; arXiv:0909.4358)
PIENU@TRIUMF (in-flight) proposed (T. Numao, PANIC'08 proceedings, p.874)
$\delta R_\pi/R_\pi$~0.05% foreseen (similar to SM precision)

The new R_K measurement by CERN NA62

New Result just presented by E. Gudzovski at BEACH 2010, Perugia, I

NA48/NA62 at CERN



NA62 phase I: Bern ITP, Birmingham, CERN, Dubna, Fairfax, Ferrara, Firenze, Frascati, Mainz, Merced, Moscow INR, Napoli, Perugia, Pisa, IHEP Protvino Rome I, Rome II, Saclay, San Luis Potosí, SLAC, Sofia, Torino, TRIUMF

NA48 discovery of direct CPV
- **1997:** ε'/ε: K_L+K_S
- **1998:** K_L+K_S
- **1999:** K_L+K_S | K_S HI
- **2000:** K_L only | K_S HI
- **2001:** K_L+K_S | K_S HI

NA48/1
- **2002:** K_S/hyperons

NA48/2
- **2003:** K^+/K^-
- **2004:** K^+/K^-

NA62 (phase I)
- **2007:** $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ | tests
- **2008:** $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ | tests

NA62 (phase II) G.Ruggiero's talk
- **2007–2012:** design & construction
- **2013–2015:** $K^+\to\pi^+\nu\bar{\nu}$ data taking

Data taking 2007

View of the NA48/NA62 beamline (2003-2008)

Data taking conditions optimized for a precision $K_{e2}/K_{\mu 2}$ measurement: a low intensity run with a minimum bias trigger

Primary SPS protons (400 GeV/c): 1.8×10^{12}/SPS spill

Unseparated secondary positive beam: p=(74.0±1.6) GeV/c. Entrance to the 114m long vacuum decay volume: 2.5×10^{7} particles/SPS spill

Composition: $K^+(\pi^+)$ = 5%(63%). K^+ decaying in vacuum tank: 18%.

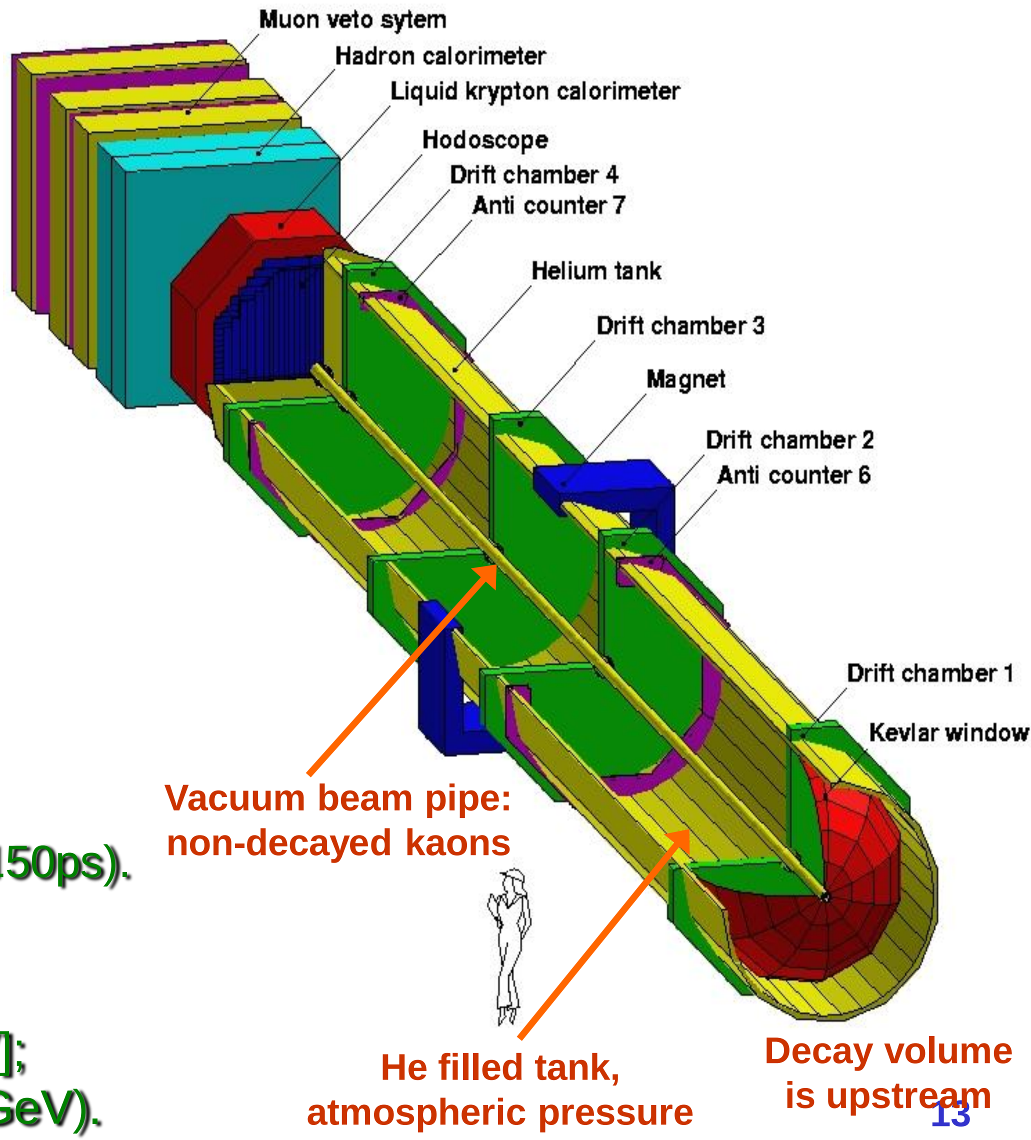
Detector

Data taking:

- Four months in 2007 (23/06–22/10):
  ~400K SPS spills, 300TB of raw data (90TB recorded); reprocessing & data preparation finished.
- Two weeks in 2008 (11/09–24/09):
  special data sets allowing reduction of the systematic uncertainties.

Principal subdetectors for R_K:

- Magnetic spectrometer (4 DCHs):
  4 views/DCH: redundancy ⇒ efficiency;
  $\Delta p/p = 0.47\% + 0.020\%*p$ [GeV/c]
- Hodoscope
  fast trigger, precise time measurement (150ps).
- Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi-homogeneous;
  $\sigma_E/E = 3.2\%/E^{1/2} + 9\%/E + 0.42\%$ [GeV];
  $\sigma_x=\sigma_y=0.42/E^{1/2} + 0.6$mm (1.5mm@10GeV).



Measurement strategy

(1) $K_{e2}/K_{\mu2}$ candidates are collected concurrently:

- analysis does not rely on kaon flux measurement;
- several systematic effects cancel at first order (e.g. reconstruction/trigger efficiencies, time-dependent effects).

(2) counting experiment, independently in 10 lepton momentum bins (owing to strong momentum dependence of backgrounds and event topology)

$$R_K = \frac{1}{D} \cdot \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu2}) - N_B(K_{\mu2})} \cdot \frac{A(K_{\mu2}) \times f_\mu \times \varepsilon(K_{\mu2})}{A(K_{e2}) \times f_e \times \varepsilon(K_{e2})} \cdot \frac{1}{f_{LKr}}$$

$N(K_{e2})$, $N(K_{\mu2})$:	numbers of selected K_{l2} candidates;
$N_B(K_{e2})$, $N_B(K_{\mu2})$:	numbers of background events;
$A(K_{e2})$, $A(K_{\mu2})$:	MC geometric acceptances (no ID);
f_e, f_μ:	directly measured particle ID efficiencies;
$\varepsilon(K_{e2})/\varepsilon(K_{\mu2})$>99.9%:	E_{LKr} trigger condition efficiency;
f_{LKr}=0.9980(3):	global LKr readout efficiency;
D=150:	downscaling factor of the $K_{\mu2}$ trigger.

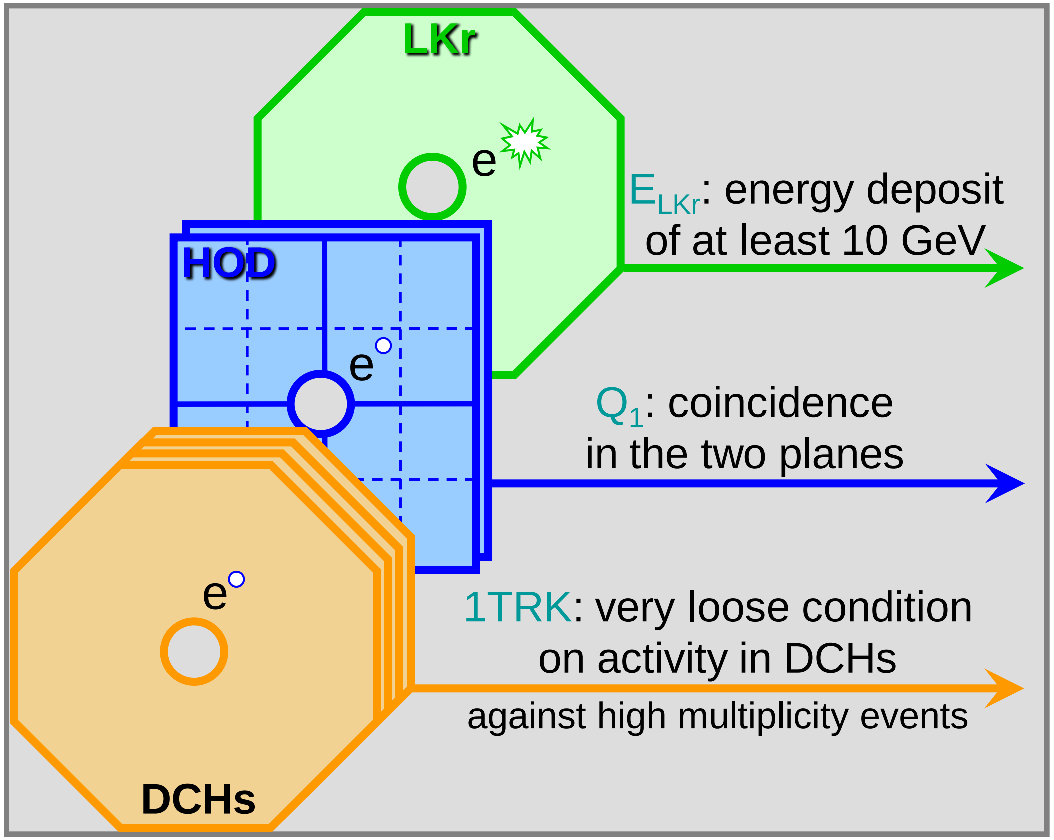
$N_B(K_{e2})$: main source of systematic errors

(3) MC simulations used to a limited extent:

- Geometrical part of the acceptance correction comes from simulation;
- PID, trigger, readout efficiencies are measured directly.

Trigger logic

NA62 trigger in 2007/08



Minimum bias
(high efficiency, but low purity)
trigger configuration used

K_{e2} condition: $Q_1 \times E_{LKr} \times 1TRK$.
Purity $\sim 10^{-5}$.

$K_{\mu 2}$ condition: $Q_1 \times 1TRK/D$,
downscaling (D) 50 to 150.
Purity ~2%.

- Efficiency of K_{e2} trigger: monitored with $K_{\mu 2}$ & other control triggers.
- Different trigger conditions for signal and normalization!

K_{e2} vs $K_{\mu 2}$ selection

Large common part (same topology)

- one reconstructed track (lepton candidate);
- geometrical acceptance;
- K decay vertex: closest approach of lepton track & nominal kaon axis;
- veto extra LKr energy deposition clusters;
- track momentum: 13GeV/c<p<65GeV/c.

Kinematic identification

missing mass $M^2_{miss} = (P_K - P_l)^2$

P_K : average measured with $K_{3\pi}$ decays

→ Sufficient $K_{e2}/K_{\mu 2}$ separation at p_{track}<25GeV/c

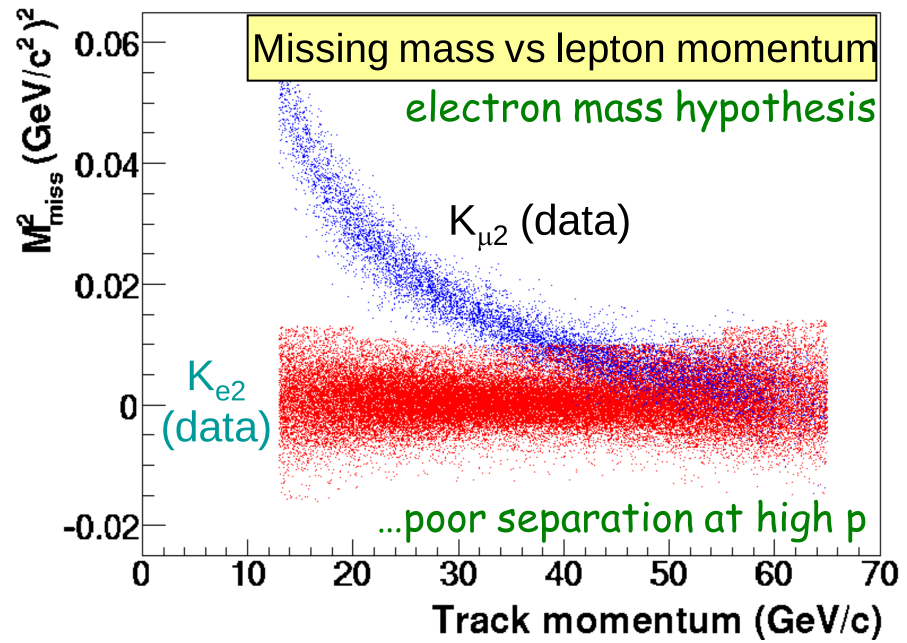
Lepton identification

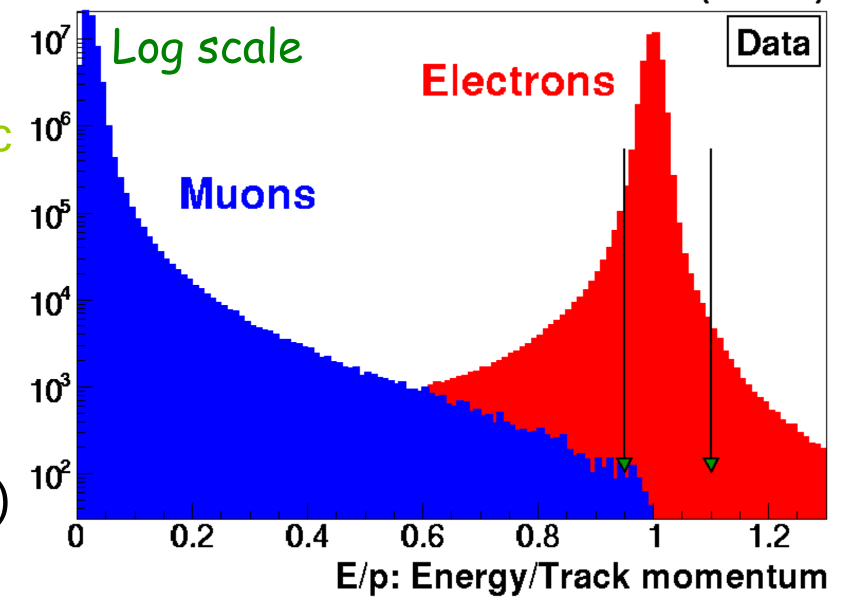
E/p = (LKr energy deposit/track momentum).

(0.90 to 0.95)<E/p<1.10 for electrons,

E/p<0.85 for muons.

→ Powerful $\mu^{\pm}$ suppression in $e^{\pm}$ sample (~10^6)





$K_{\mu 2}$ background in K_{e2} sample

Main background source

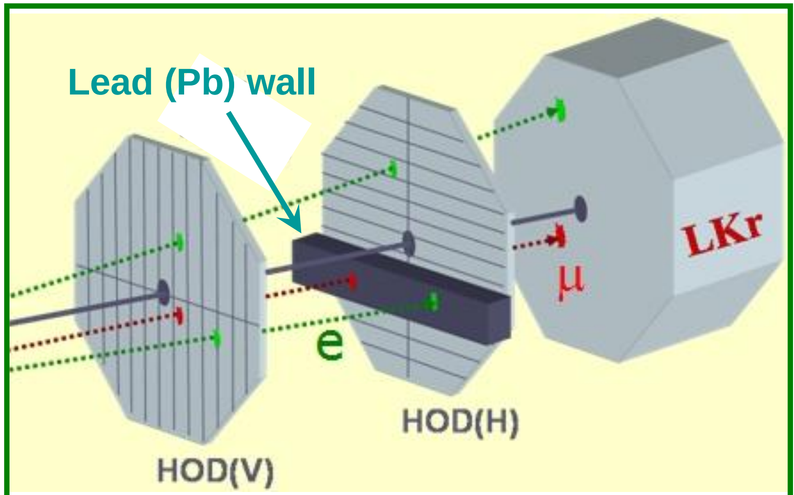
Muon “catastrophic” energy loss in LKr by emission of energetic bremsstrahlung photons. $P_{\mu e} \sim 3\times10^{-6}$ (and momentum-dependent).

> $P_{\mu e} / R_K \sim 10\%$:
> $K_{\mu 2}$ decays represent a major background

Direct measurement of $P_{\mu e}$

Pb wall ($9.2X_0$) in front of LKr: suppression of $\sim10^{-4}$ positron contamination due to $\mu\rightarrow e$ decay.

$K_{\mu 2}$ candidates, track traversing Pb, p>30GeV/c, E/p>0.95: positron contamination $<10^{-8}$.



Thickness:	$\sim10X_0$ (Pb+Fe)
Width:	240cm (=HOD size)
Height:	18cm (=3 counters)
Area:	~20% of HOD area
Duration:	~50% of R_K runs
	+ special muon runs

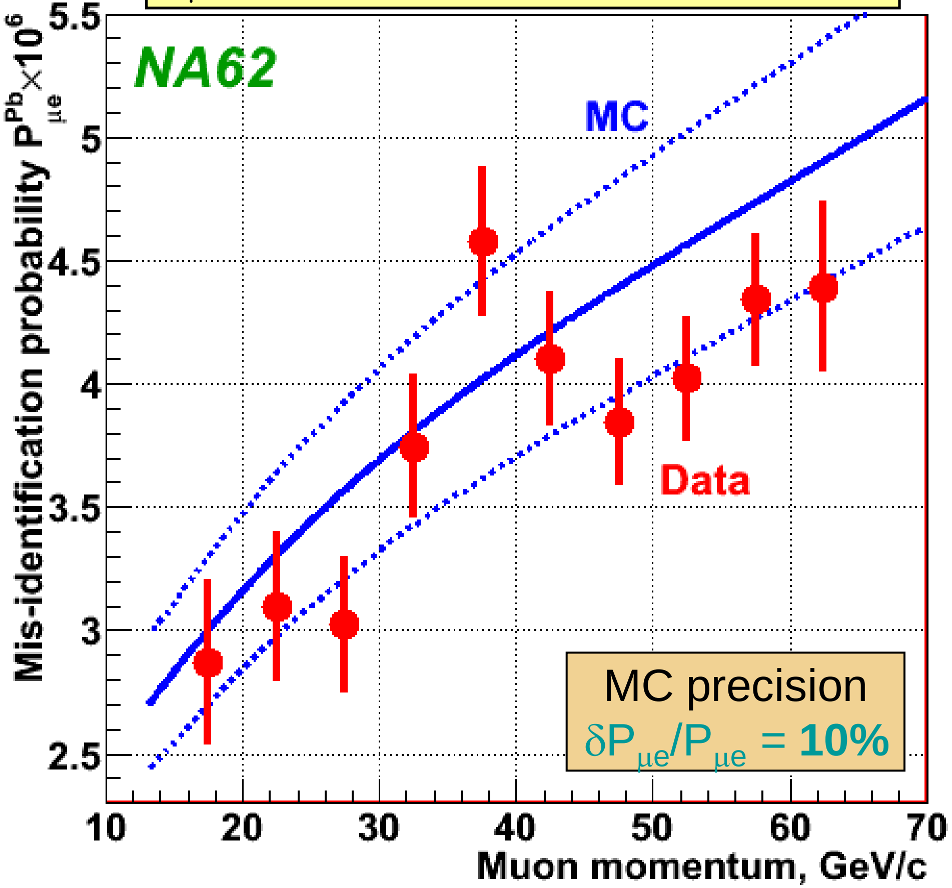
$P_{\mu e}$ is modified by the Pb wall:
→ ionization losses in Pb (low p);
→ bremsstrahlung in Pb (high p).

⇒ The correction $f_{Pb}=P_{\mu e}/P_{\mu e}^{Pb}$ is evaluated with a dedicated Geant4-based simulation

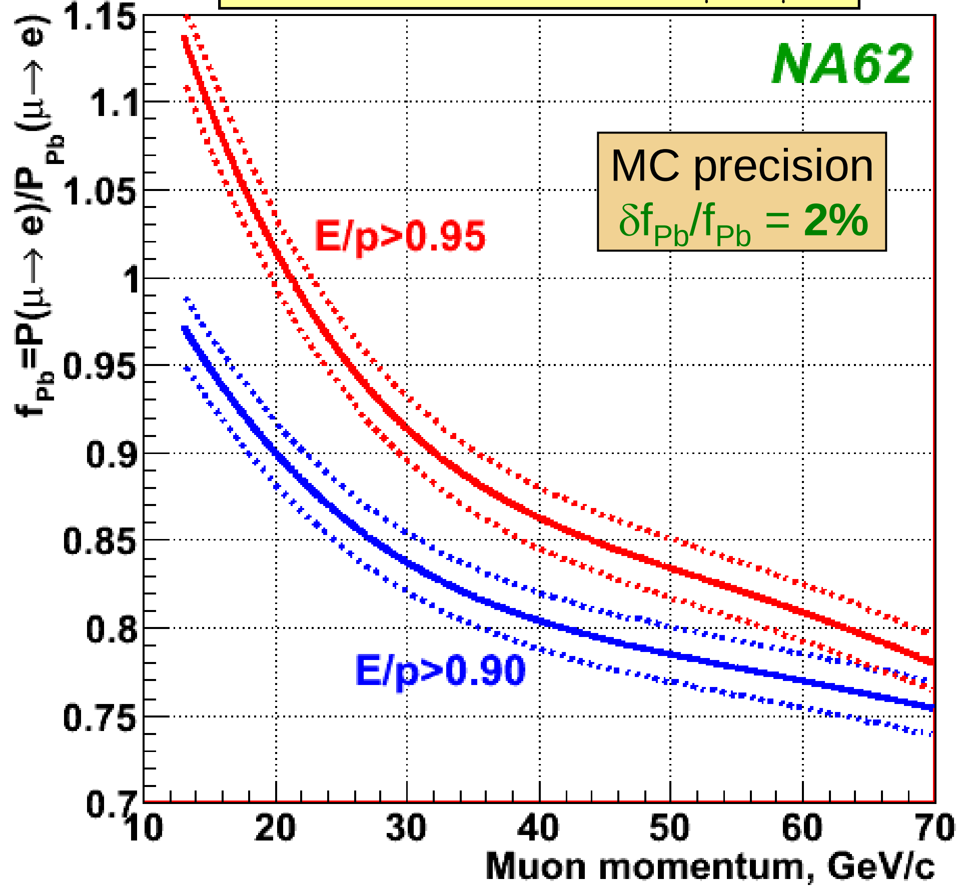
[Muon bremsttranlung: Phys. Atom. Nucl. 60 (1997) 576]

Muon mis-identification

$P_{\mu e}$ vs momentum (Pb wall installed)



Correction for Pb: $f_{Pb}=P_{\mu e}/P_{\mu e}^{Pb}$



Result: B/(S+B) = (6.10±0.22)%

Uncertainty is ~3 times smaller than the one obtained solely from simulation

Uncertainties

Limited data sample (0.16%);

MC correction (0.12%);

M^2_{miss} vs P_{track} correlation (0.08%).

$K_{\mu 2}$ with $\mu \to e$ decay in flight

For NA62 conditions
(74 GeV/c beam, ~100 m decay volume),

$N(K_{\mu 2}, \mu \to e \text{ decay})/N(K_{e2}) \sim 10$

$K_{\mu 2}$ ($\mu \to e$) naïvely seems a huge background

Muons from $K_{\mu 2}$ decay are fully polarized:
Michel electron distribution

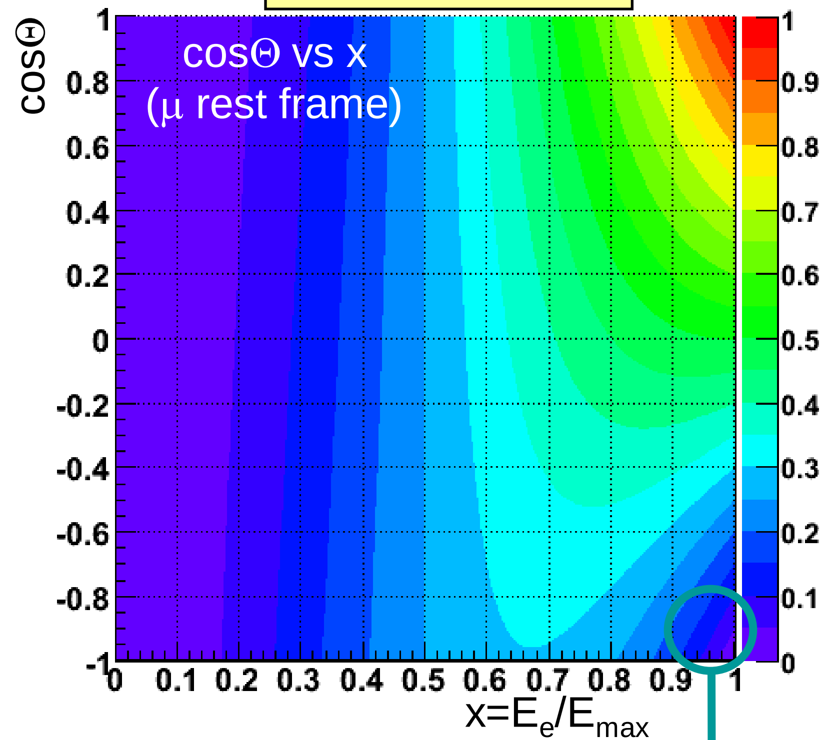
$$d^2\Gamma/dxd(\cos\Theta) \sim x^2[(3-2x) - \cos\Theta(1-2x)]$$

$x = E_e/E_{max} \approx 2E_e/M_\mu$,
Θ is the angle between p_e and the muon spin
(all quantities are defined in muon rest frame).

Result: $B/(S+B) = (0.27 \pm 0.04)\%$

Important but not dominant background

Michel distribution



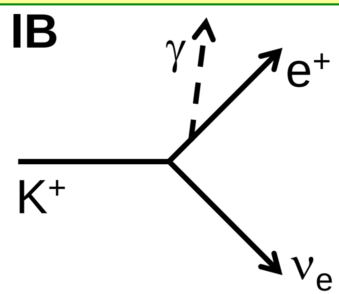
Only energetic forward positrons are selected as K_{e2} candidates

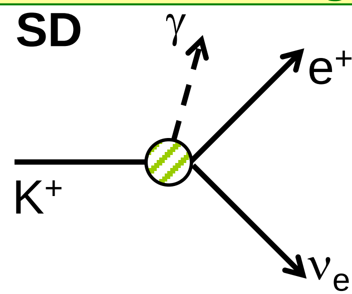
They are naturally suppressed by the muon polarisation

(radiative corrections provide another ~10% suppression)

Radiative $K^+ \to e^+\nu\gamma$ process

R_K is inclusive of IB radiation by definition.
SD radiation is a background. INT is negligible.





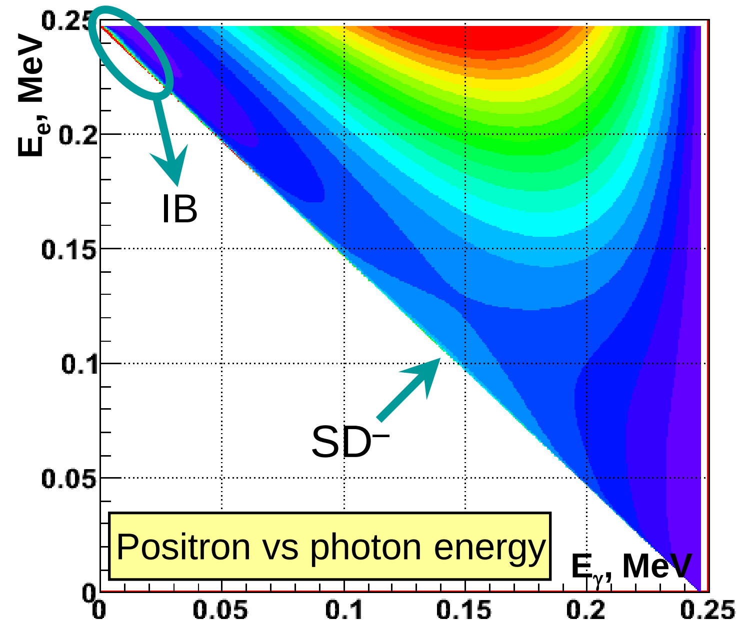
SD radiation is not helicity suppressed.
KLOE measurement of the form factor leads to
BR(SD^+, full phase space) = $(1.37\pm0.06)\times10^{-5}$.
(EPJC64 (2009) 627)

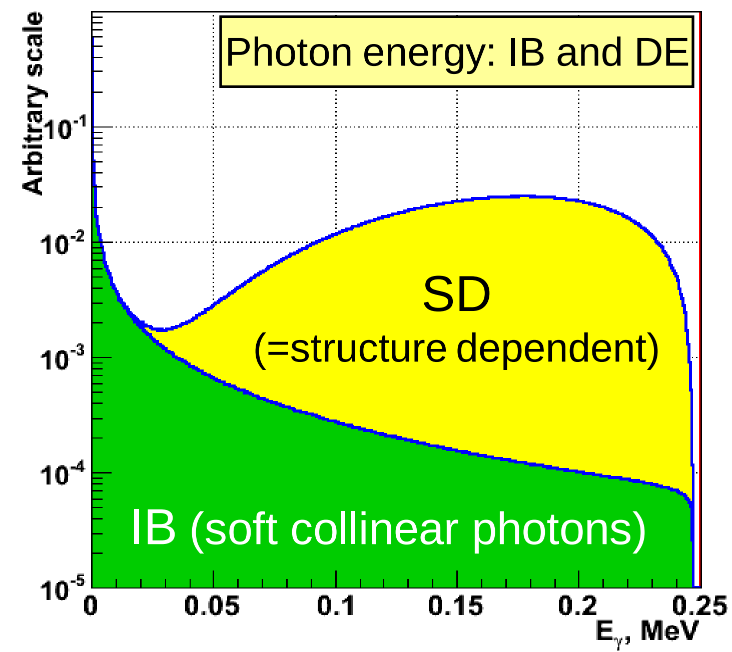
SD background contamination

$B/(S+B) = (1.15\pm0.17)\%$

Conservative uncertainty ($3\times\delta BR_{KLOE}$)
to accommodate the observed R_K variation
w.r.t the LKr veto selection condition.

A new $K_{e2\gamma}$ (SD^+) measurement
is being performed by NA62.





Beam halo background

Electrons produced by beam halo muons via $\mu \to e$ decay can be kinematically and geometrically compatible to genuine K_{e2} decays

Background measurement:

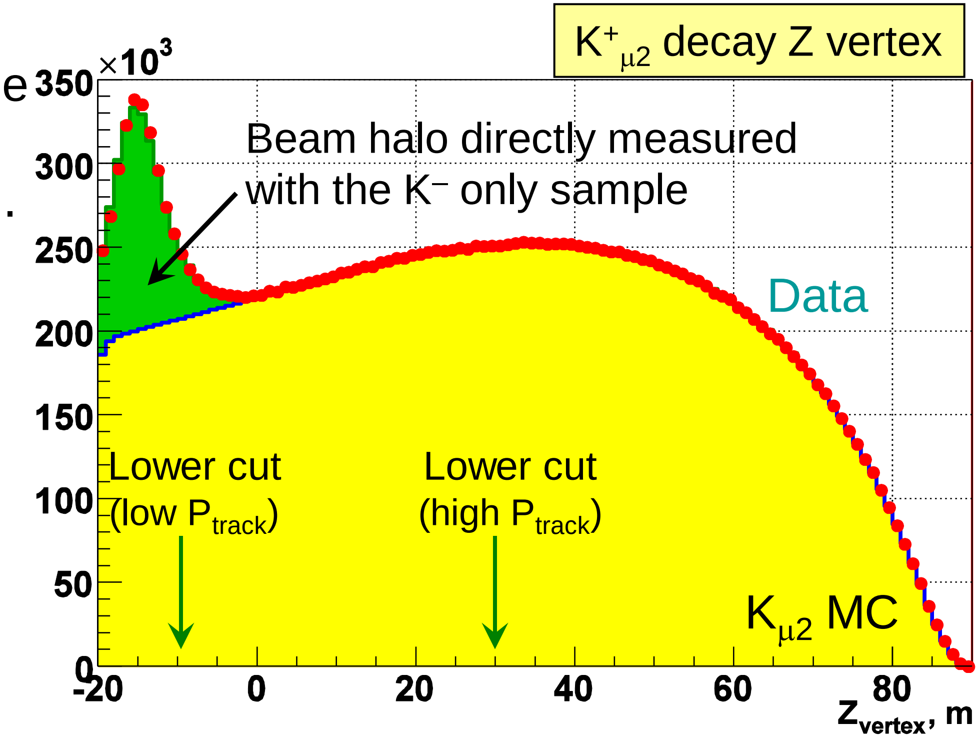
- Halo background much higher for K_{e2}^- (~20%) than for K_{e2}^+ (~1%).
- Halo background in the $K_{\mu 2}$ sample is considerably lower.
- ~90% of the data sample is K^+ only, ~10% is K^- only.
- K^+ halo component is measured directly with the K^- sample and vice versa.

The background is measured to sub-permille precision, and strongly depends on decay vertex position and track momentum.

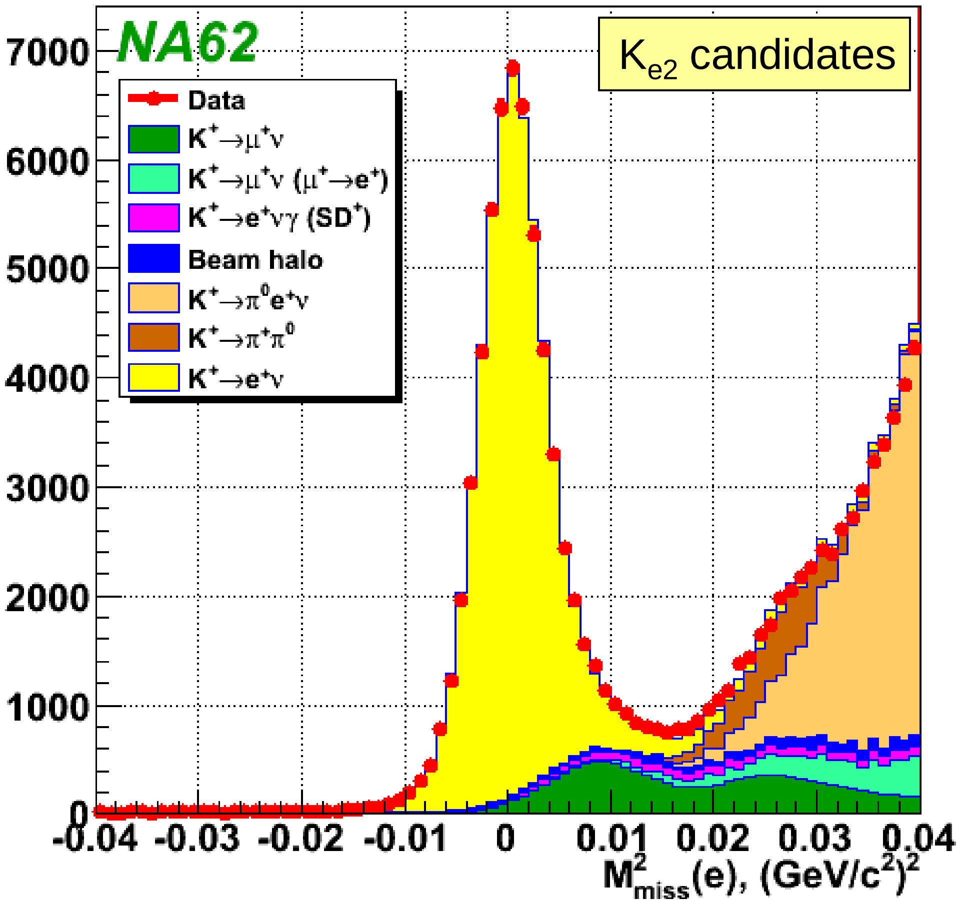
The selection criteria (esp. Z_{vertex}) are optimized to minimize the halo background.

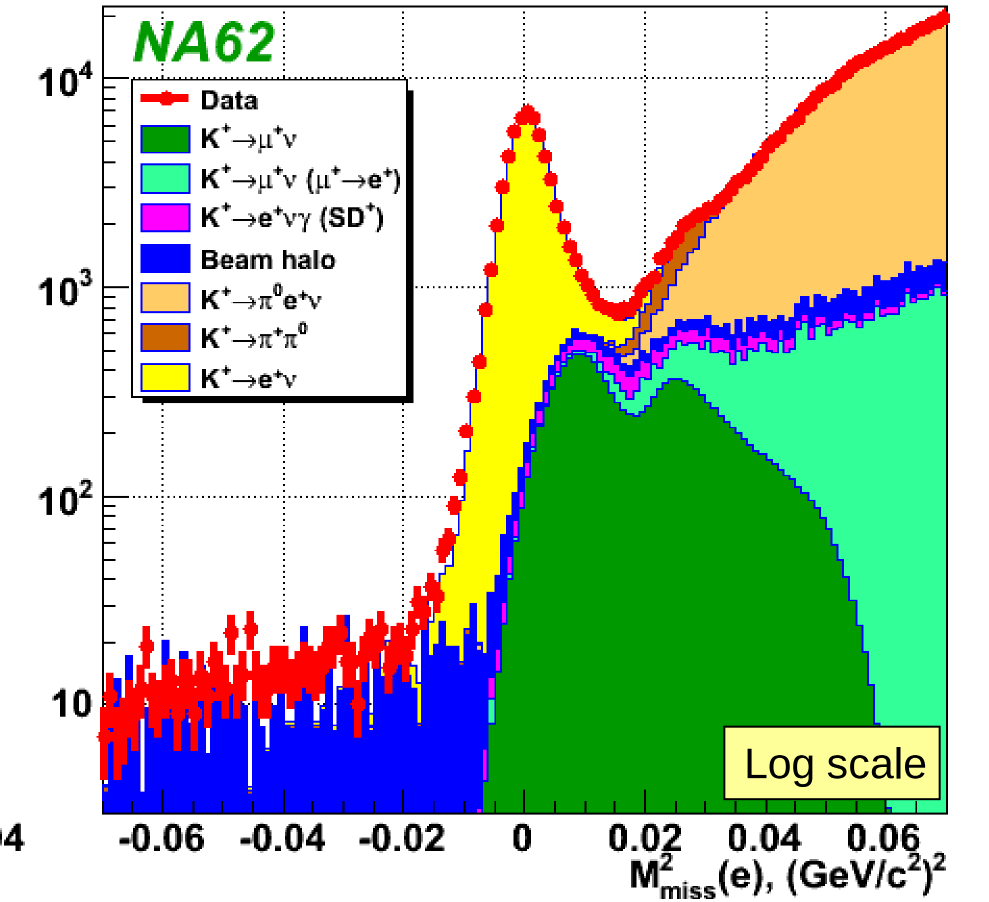
$B/(S+B) = (1.14 \pm 0.06)\%$

Uncertainty:
1) limited size of control sample;
2) π, K decays upstream vacuum tank.



K_{e2}: partial (40%) data set





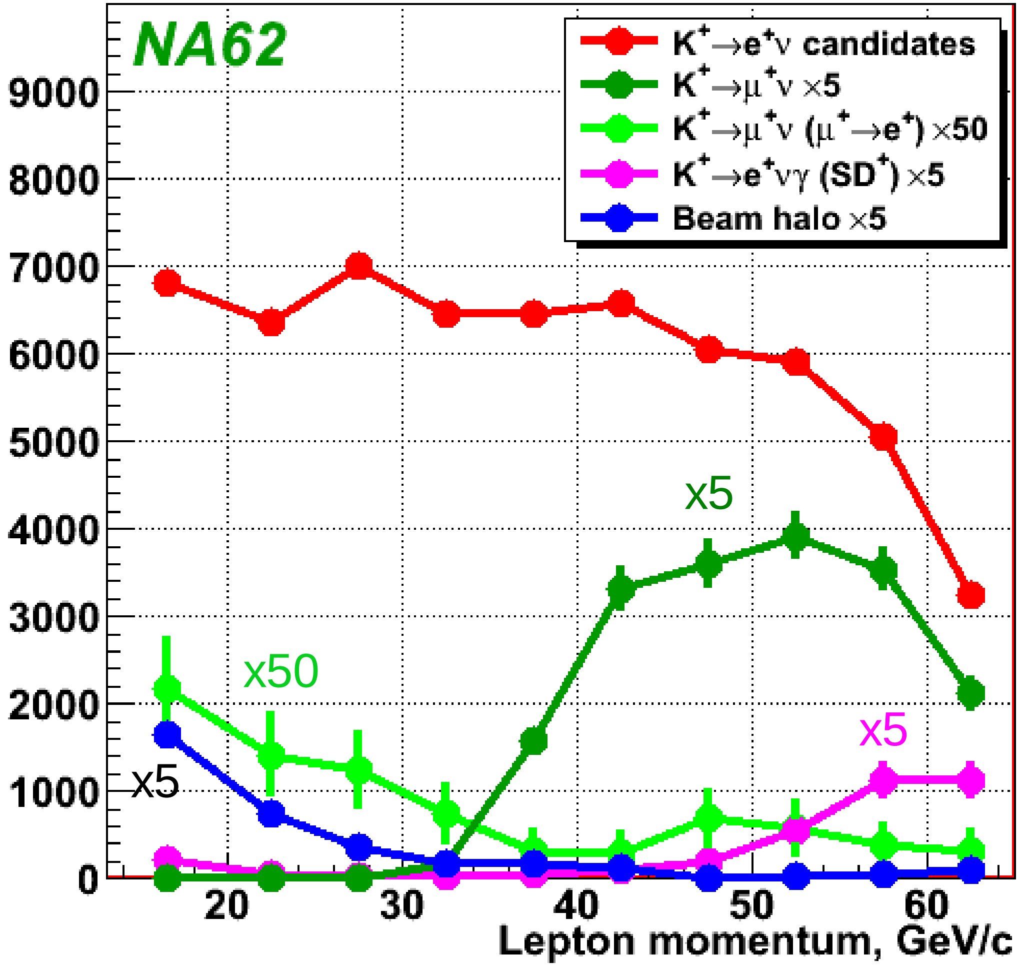
59,963 $K^+ \to e^+\nu$ candidates.
Positron ID efficiency: (99.27±0.05)%.
B/(S+B) = (8.8±0.3)%.

cf. KLOE: 13.8K candidates (K^+ and K^-),
~90% electron ID efficiency, 16% background

NA62 estimated total K_{e2} sample:
~130K K^+ & ~20K K^- candidates.
Proposal (CERN-SPSC-2006-033):
150K candidates

Backgrounds: summary

K_{e2} candidates and backgrounds in momentum bins



(selection criteria optimized individually in each P_{track} bin)

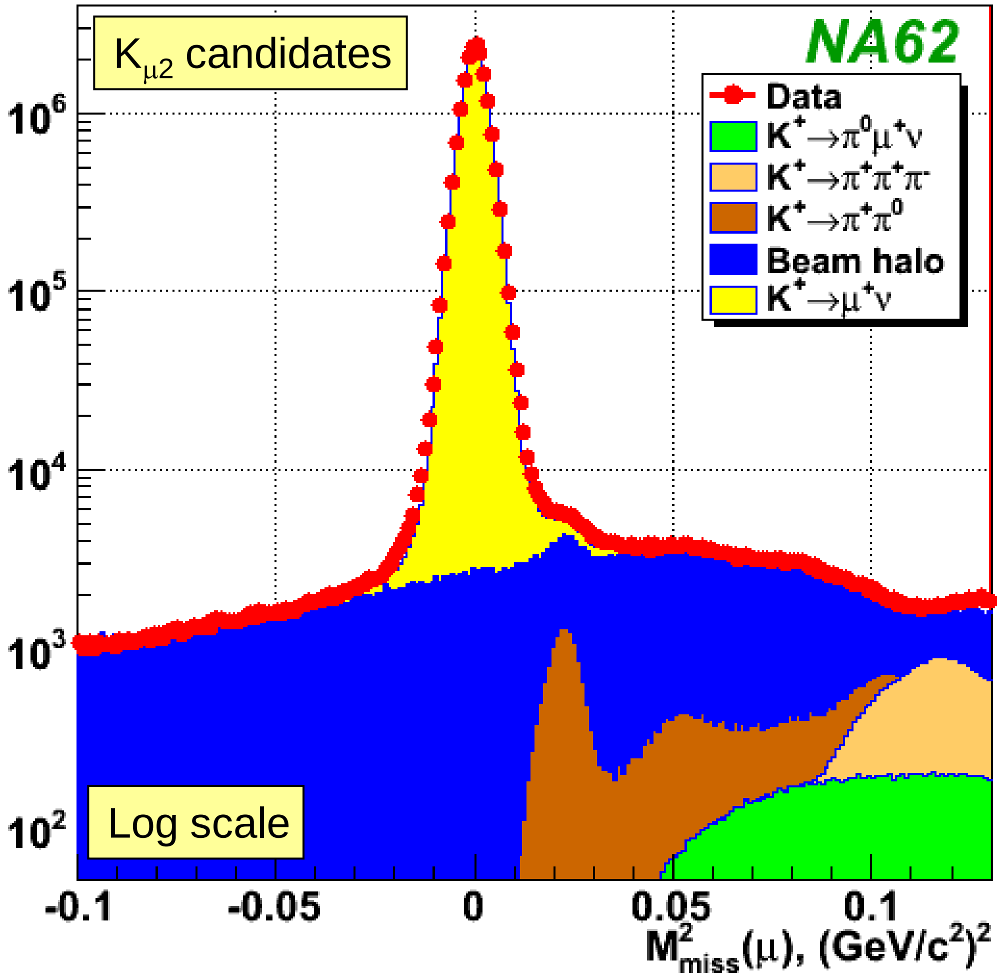
Backgrounds

Source	B/(S+B)
$K_{\mu 2}$	$(6.10\pm0.22)\%$
$K_{\mu 2}$ ($\mu \to e$)	$(0.27\pm0.04)\%$
$K_{e2\gamma}$ (SD^+)	$(1.15\pm0.17)\%$
Beam halo	$(1.14\pm0.06)\%$
$K_{e3(D)}$	$(0.06\pm0.01)\%$
$K_{2\pi(D)}$	$(0.06\pm0.01)\%$
Total	$(8.78\pm0.29)\%$

Record K_{e2} sample:
59,963 candidates
with low background
$B/(S+B) = (8.8\pm0.3)\%$

Lepton momentum bins are differently affected by backgrounds and thus the systematic uncertainties.

$K_{\mu 2}$: partial (40%) data set



Backgrounds

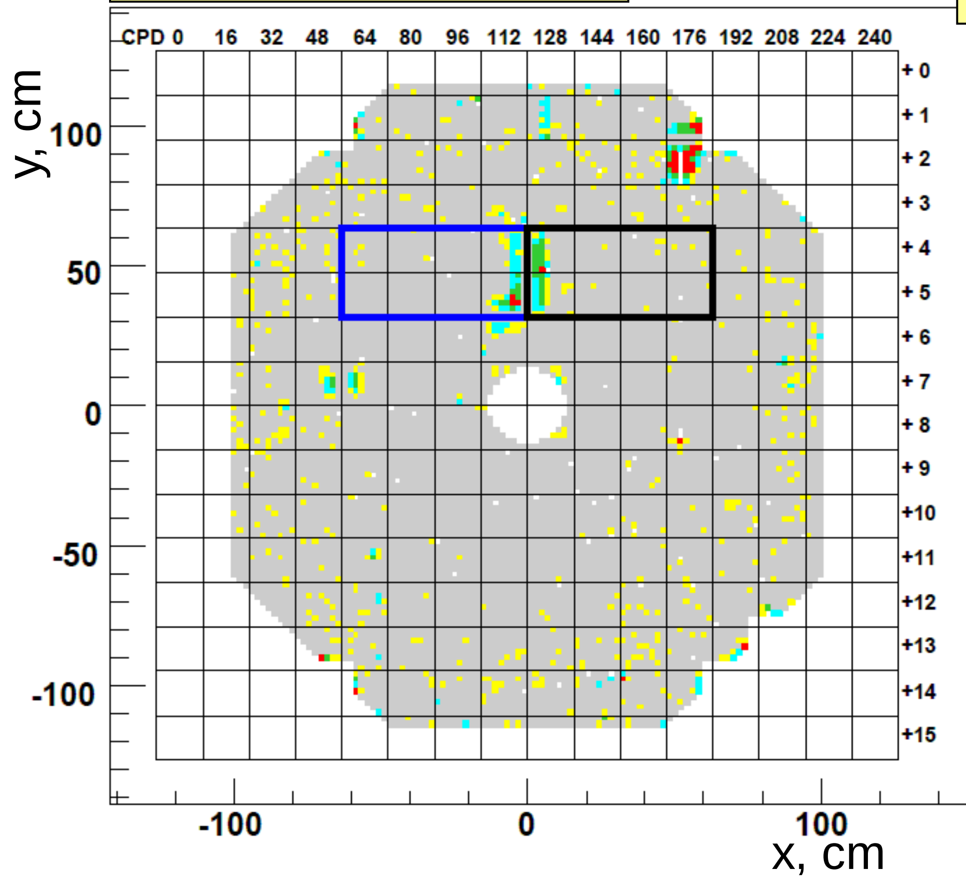
Source	B/(S+B)
Beam halo	(0.38±0.01)%
Total	(0.38±0.01)%

18.030 M candidates with low background B/(S+B) = 0.38%

(The $K_{\mu 2}$ trigger was pre-scaled by D=150)

Systematic effect: positron ID

A typical inefficiency map



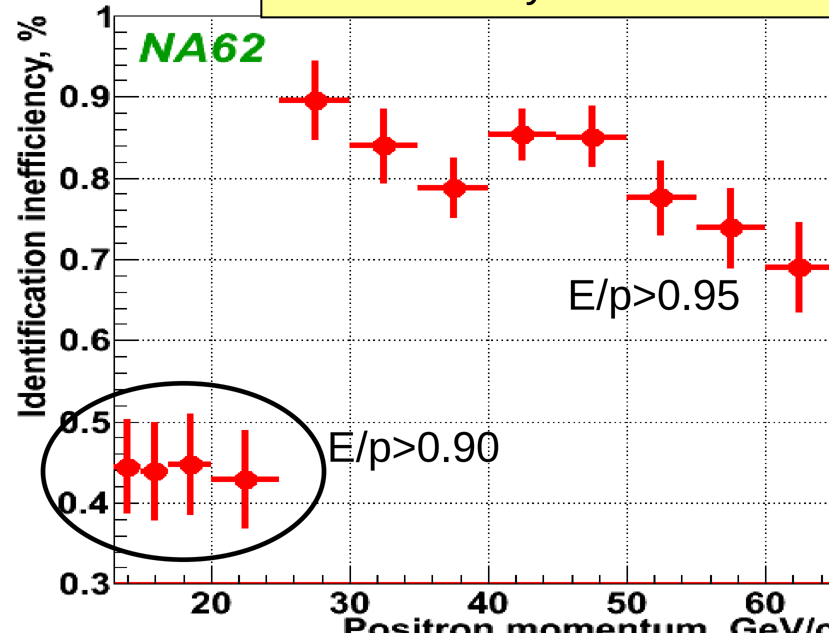
LKr energy response is calibrated for every $2\times2cm^2$ cell within acceptance

Colour code

- Ineff < 1.2%
- Ineff = (1.2 - 2)%
- Ineff = (2.0-4.0)%
- Ineff = (4.0-10)%
- Ineff > 10%

(an effect of a loose cable is visible in this map)

ID inefficiency vs momentum

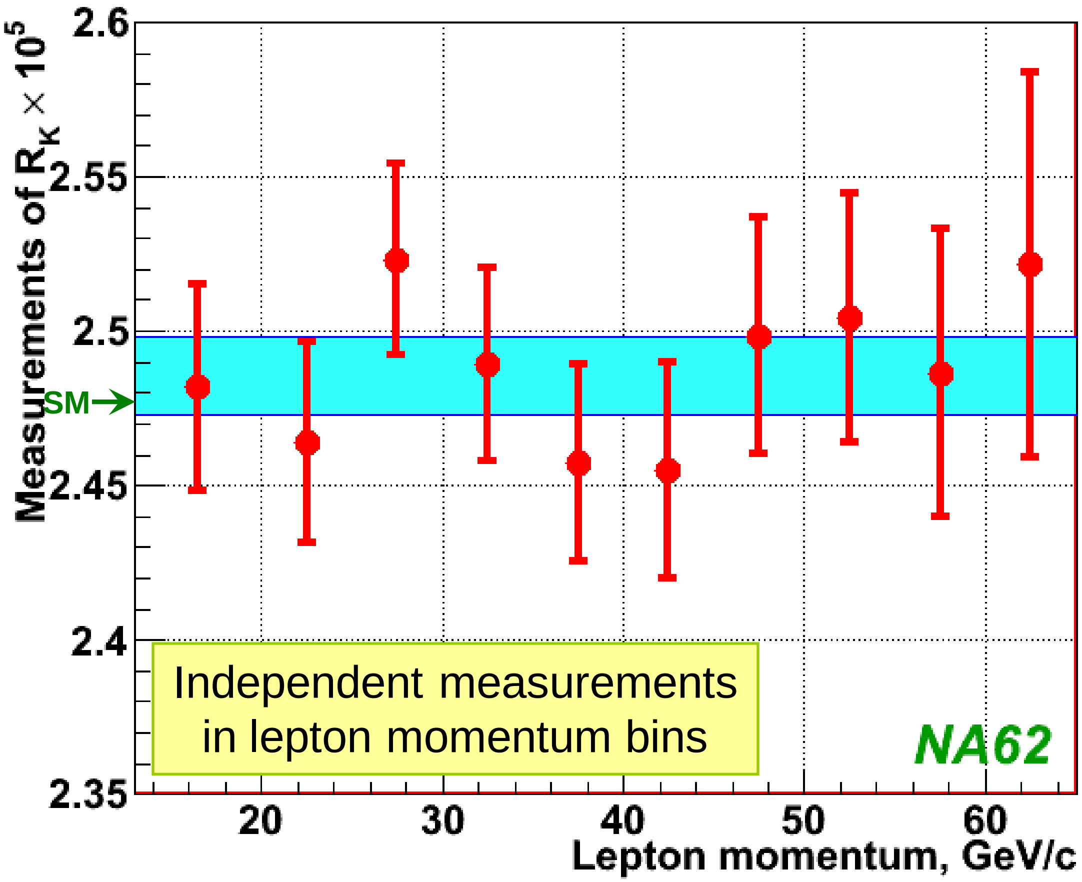


Positron ID efficiency is measured with $K^+\to\pi e\nu$ and special $K_L\to\pi e\nu$ samples: integral ε = (99.27±0.05)%

NA62 final result (40% data set)

$R_K = (2.486 \pm 0.011_{stat} \pm 0.007_{syst}) \times 10^{-5}$
$= (2.486 \pm 0.013) \times 10^{-5}$

(new: June 2010)



(systematic errors included, partially correlated)

Uncertainties

Source	$\delta R_K \times 10^5$
Statistical	0.011
$K_{\mu 2}$	0.005
$BR(K_{e2\gamma}\ SD^+)$	0.004
Beam halo	0.001
Acceptance corr.	0.002
DCH alignment	0.001
Positron ID	0.001
1-track trigger	0.002
Total	0.013

(0.52% precision)

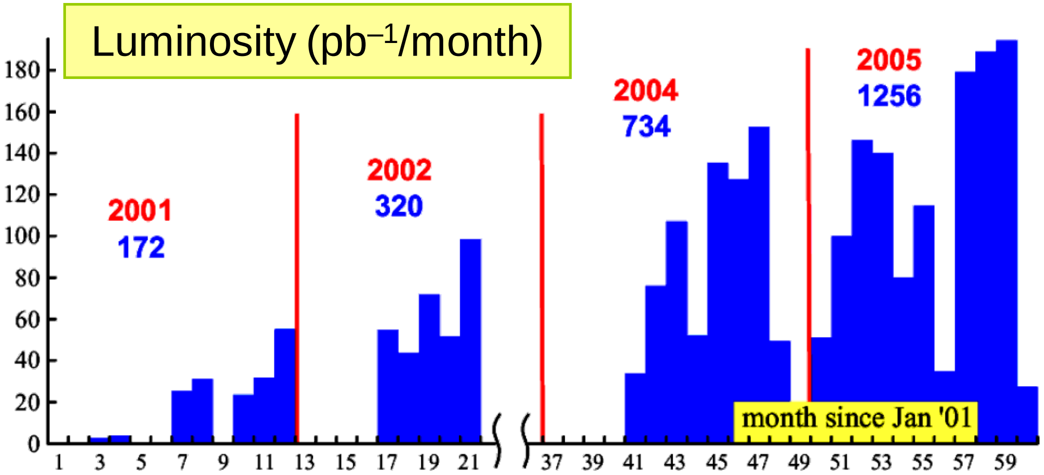
Preliminary result: $R_K = 2.500(16) \times 10^{-5}$.
Shift due to multi-photon corrections to the $K_{e2\gamma}$ (IB) decay.

The KLOE R_K measurement and the world average

KLOE: ~100 MeV kaons

DAΦNE: e^+e^- collider at LNF Frascati

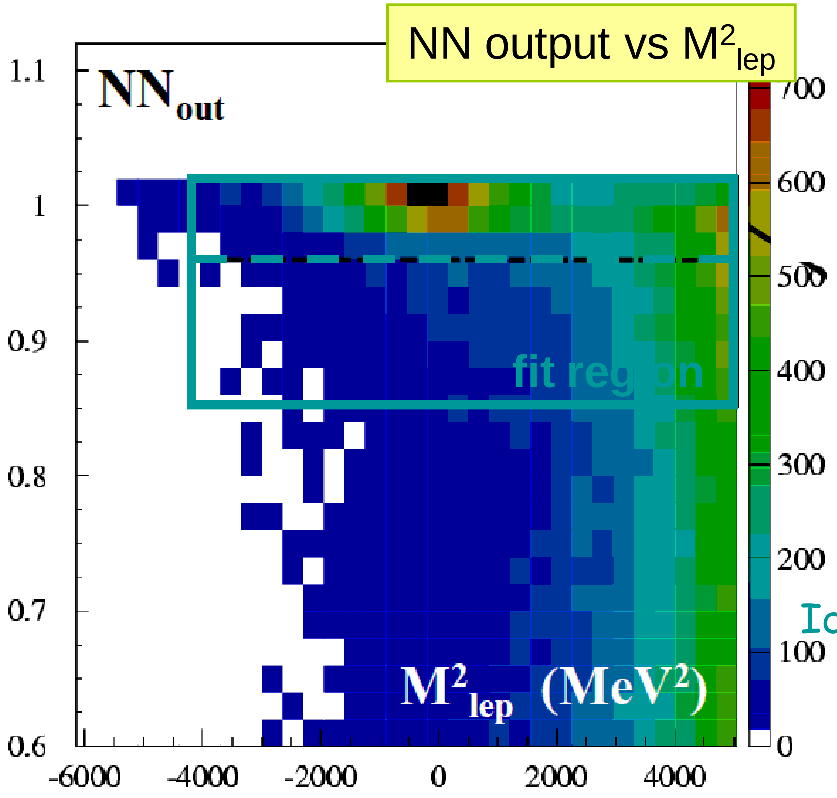
- CM energy ~ m_ϕ = 1.02 GeV;
- BR($\phi \to K^+K^-$) = 49.2%;
- ϕ production cross-section σ_ϕ=1.3μb;
- Data sample (2001–05): 2.5 fb^{-1}.

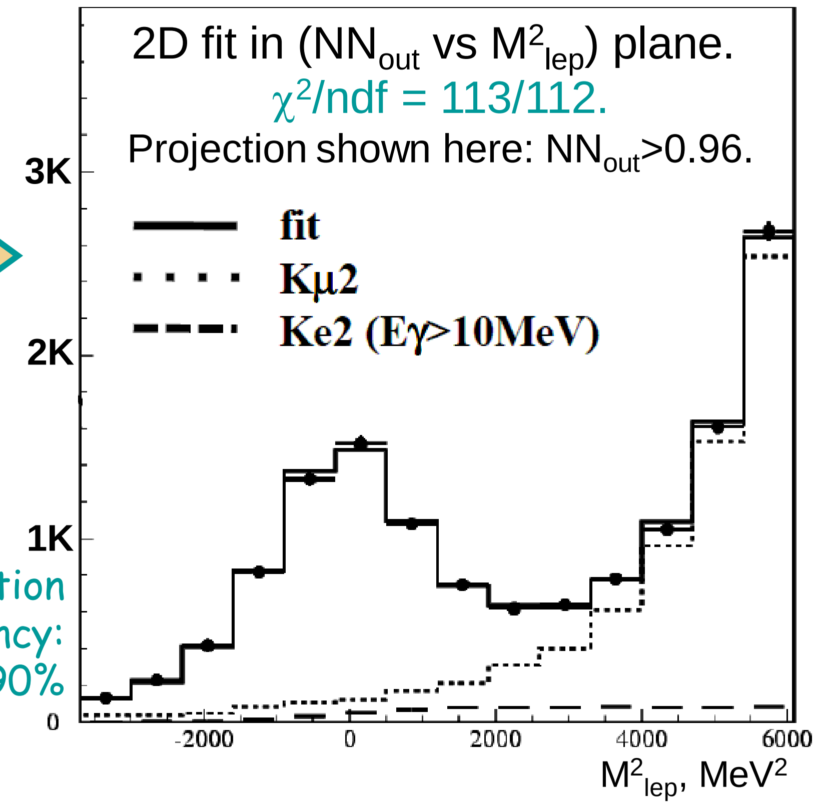


$K_{e2}/K_{\mu2}$ selection technique (vs NA62):

- Kinematics: by M^2_{lep} (equivalent to $M_{miss}{}^2$);
- PID: neural network with 12 input parameters (vs E/p for NA62).

KLOE K_{e2} analysis





Identification efficiency: ~90%

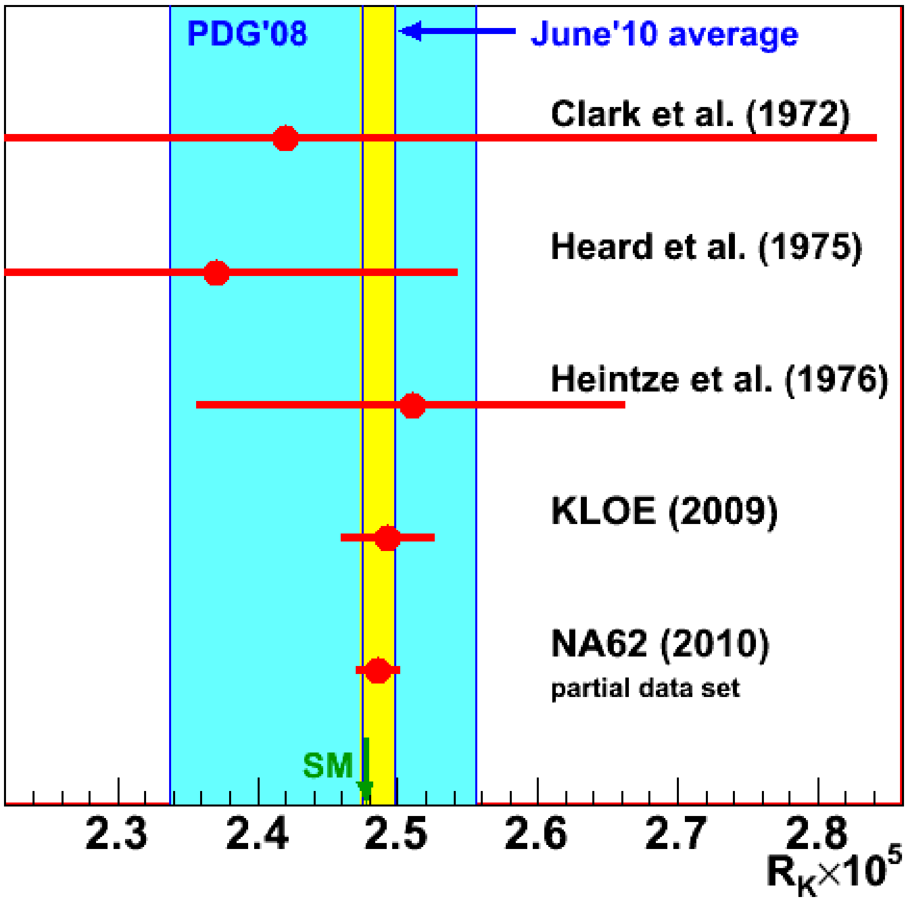
Uncertainties	$\delta R_K/R_K$ (%)
Statistical	1.0
$K_{\mu 2}$ subtraction	0.3
$K_{e2\gamma}$ (SD^+)	0.2
Reconstruction efficiency	0.6
Trigger efficiency	0.4
Total	1.3

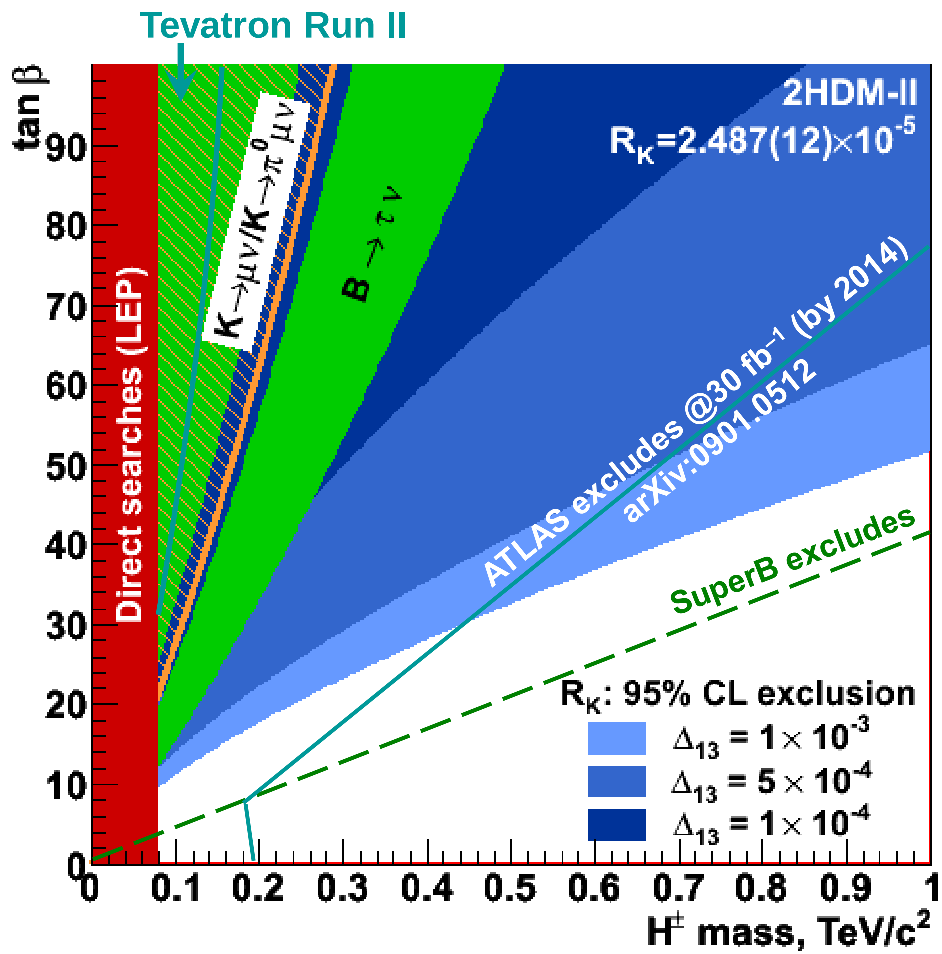
Full data sample analyzed
[EPJ C64 (2009) 627]

13.8K K_{e2} candidates, 16% background

KLOE-2: starting in 2010, expect $\delta R_K/R_K=0.4\%$.
[arXiv:1003.3862]

R_K: world average





World average	$\delta R_K \times 10^5$	Precision
March 2009	2.467±0.024	0.97%
June 2010	2.487±0.012	0.48%

For non-tiny values of the LFV slepton mixing Δ_{13}, sensitivity to $H^\pm$ in $R_K=K_{e2}/K_{\mu 2}$ is better than in $B\to\tau\nu$

Conclusions & prospects

- Leptonic meson decays and their ratios are well-suited for stringent tests of the Standard Model. In particular, $R_K=K_{e2}/K_{\mu2}$ is sensitive to lepton flavour violation in multi-Higgs models.
- NA62 data taking in 2007/08 was optimised for R_K measurement. NA62 K_{e2} sample is ~10 times the world sample, with excellent $K_{e2}/K_{\mu2}$ separation (99.3% electron ID efficiency, 6% $K_{\mu2}$ background).
- Final result based on ~40% of the NA62 K_{e2} sample $R_K = (2.486\pm0.013)\times10^{-5}$ reached a record 0.5% accuracy. A timely result, as searches for New Physics at the LHC are starting.
- Future experimental improvements on R_K:
  1) the full NA62 data sample of 2007/08: $\delta R_K/R_K<0.4\%$;
  2) NA62 phase II (2012–2015) and KLOE-2 (2010–) aim at ~0.2% and ~0.4% precision.

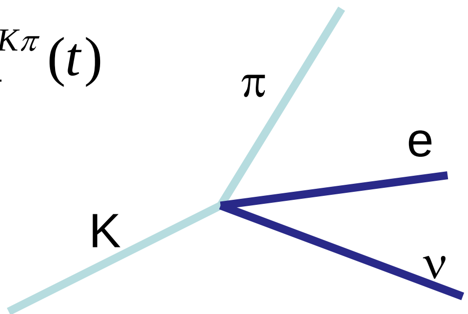
K Semi Leptonic Decays

- **K and π have spin 0**

$$L_\alpha = \bar{\nu}\gamma_\alpha(1+\gamma_5)e$$

$$V_\alpha = \langle \pi(p_\pi)|\bar{s}\gamma_\mu u|K(p_K)\rangle = p_\mu f_+^{K\pi}(t) + q_\alpha f_-^{K\pi}(t)$$

$$p = p_\pi + p_K \quad \mathrm{q} = p_K - p_\pi$$



$$\Gamma_{Kl3} = \frac{G_F^2 m_K^5}{192\pi^3} C_K^2 S_{EW} \left(|V_{us}|\, f^{K^0\pi^-}(0)\right)^2 I_{Kl}$$

$$\times(1+\delta_{EM}^{Kl}+\delta_{SU(2)}^{K\pi})$$

S_{EW}=1.0232(2) SD EW Corr. (Marciano, Sirlin)
C_K=1 for K^0; 1/√2 for K^+

$f_+^{K^0\pi^-}(0)$ is the $K^0 \to \pi^-$ vector form factor at zero momentum transfer
I_{Kl} is a phase-space integral sensitive to the momentum dependence of the form factor

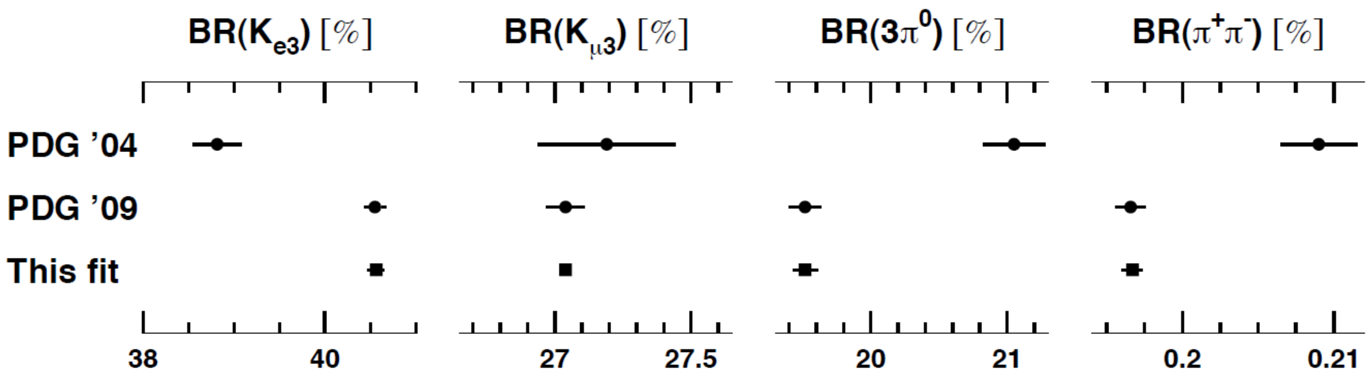
FLAVIANET KAON WG: K^0_L

P. Massarotti, FPCP 2010

- **21 input measurements**
- **10 free parameters**
- **1 constraint:** $\sum \mathrm{Br} = 1$

Parameter	Value	S
$\mathrm{BR}(K_{e3})$	0.4056(9)	1.3
$\mathrm{BR}(K_{\mu 3})$	0.2704(10)	1.5
$\mathrm{BR}(3\pi^0)$	0.1952(9)	1.2
$\mathrm{BR}(\pi^+\pi^-\pi^0)$	0.1254(6)	1.3
$\mathrm{BR}(\pi^+\pi^-)$	$1.967(7) \times 10^{-3}$	1.1
$\mathrm{BR}(\pi^+\pi^-\gamma)$	$4.15(9) \times 10^{-5}$	1.6
$\mathrm{BR}(\pi^+\pi^-\gamma_{\mathrm{DE}})$	$2.84(8) \times 10^{-5}$	1.3
$\mathrm{BR}(2\pi^0)$	$8.65(4) \times 10^{-4}$	1.4
$\mathrm{BR}(\gamma\gamma)$	$5.47(4) \times 10^{-4}$	1.1
τ_{K_L}	51.16(21) ns	1.1

Time evolution of selected K^0_L BR's



FLAVIANET KAON WG: K^0_S

- **6 input measurements**
- **5 free parameters**
- **1 constraint**

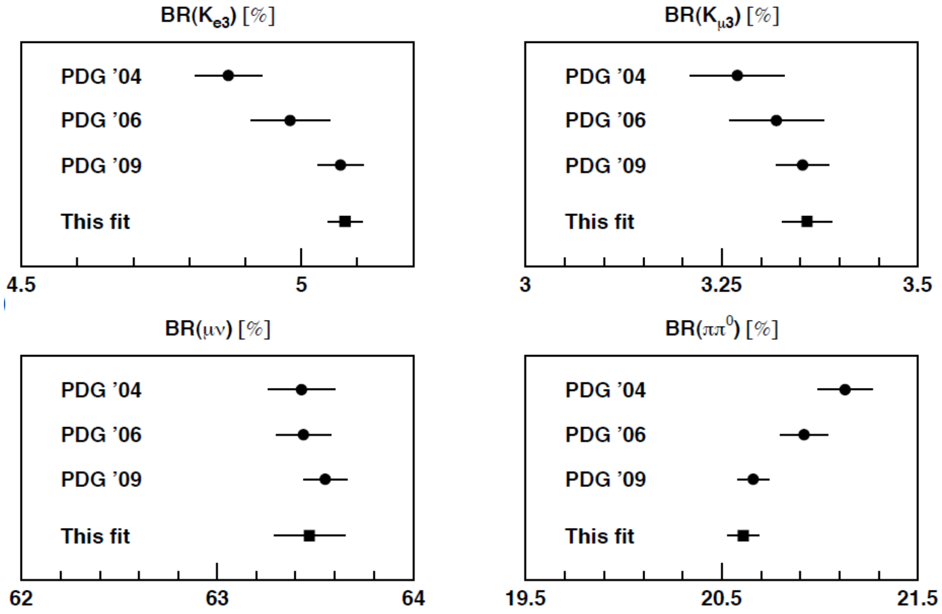
$$\sum \text{Br} = 1$$

Parameter	Value
$\text{BR}(\pi^+\pi^-)$	$0.6920(5)$
$\text{BR}(\pi^0\pi^0)$	$0.3069(5)$
$\text{BR}(K_{e3})$	$7.05(8) \times 10^{-4}$
$\text{BR}(K_{\mu 3})$	$4.69(6) \times 10^{-4}$
τ_{K_S}	$89.59(6)$ ps

FLAVIANET KAON WG: $K^{\pm}$

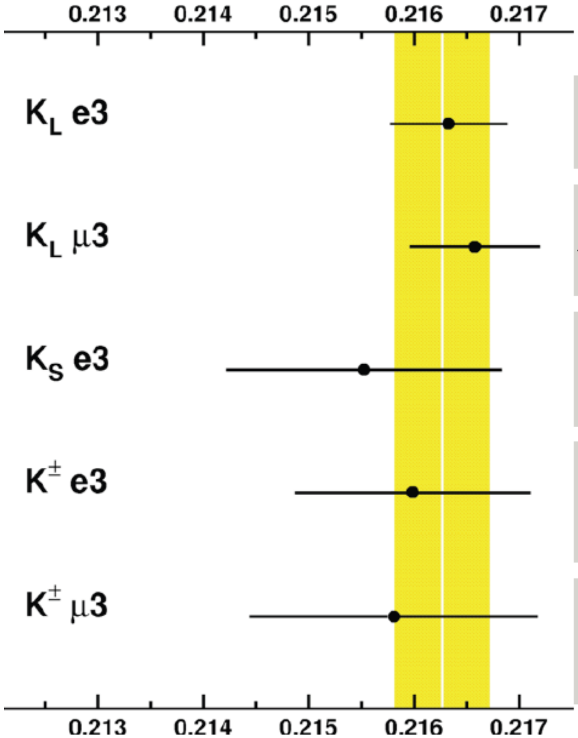
- 6 input measurements
- 5 free parameters
- 1 constraint $\sum Br = 1$

Parameter	Value	S
$\mathrm{BR}(K_{\mu 2})$	63.47(18)%	1.3
$\mathrm{BR}(\pi\pi^0)$	20.61(8)%	1.1
$\mathrm{BR}(\pi\pi\pi)$	5.73(16)%	1.2
$\mathrm{BR}(K_{e3})$	5.078(31)%	1.3
$\mathrm{BR}(K_{\mu 3})$	3.359(32)%	1.9
$\mathrm{BR}(\pi\pi^0\pi^0)$	1.757(24)%	1.0
$\tau_{K^{\pm}}$	12.384(15) ns	1.2



Time evolution of charged kaon selected Branching ratios

Determination of $|V_{us}| \times f_+(0)$



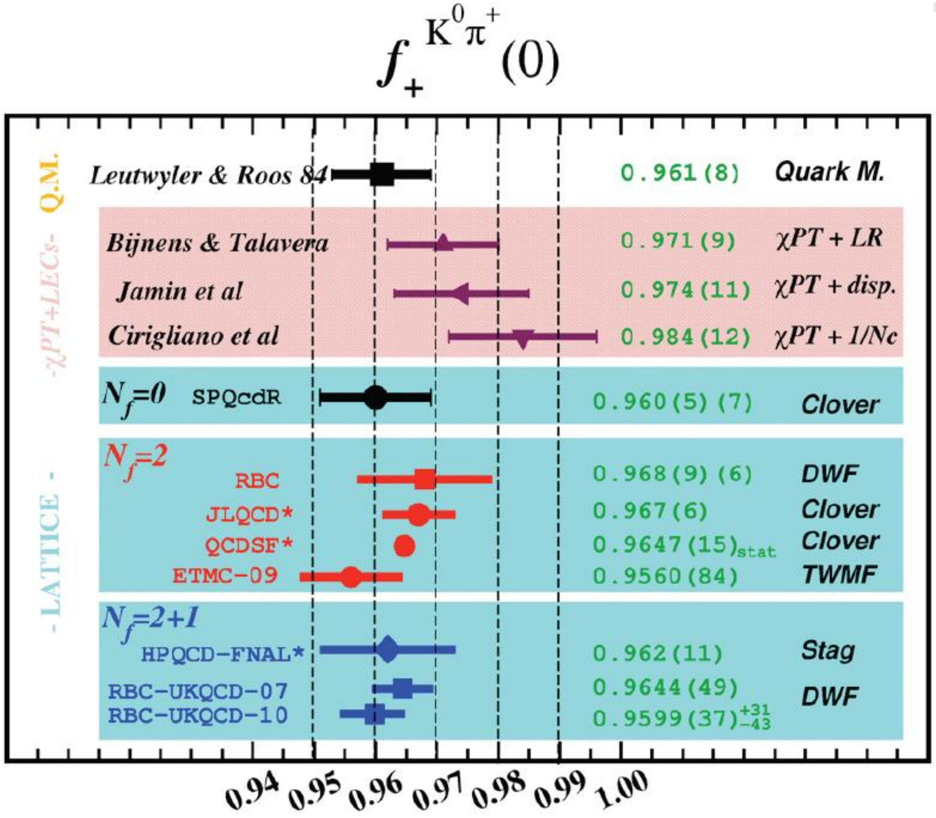
Mode	$\|V_{us}\| f_+(0)$	% err $\times 10^{-2}$	BR $\times 10^{-2}$	$\tau \times 10^{-2}$	$\Delta \times 10^{-2}$	$I_{K\ell} \times 10^{-2}$
$K_L e3$	0.2163(6)	26	9	20	11	6
$K_L \mu 3$	0.2166(6)	29	15	18	11	8
$K_S e3$	0.2155(13)	61	60	3	11	6
$K^\pm e3$	0.2160(11)	52	31	8	40	6
$K^\pm \mu 3$	0.2158(14)	63	47	8	39	8

Average: $|V_{us}| f_+(0) = 0.2163(5)$ $\chi^2/\text{ndf} = 0.77/4$ (94%)

Theoretical input of $f_+(0)$

- **Leutwyler & Roos estimate still widely used: f+(0)=0.961(8)**
- **Lattice QCD evaluations generally agree well with this value**
- **Using RBC-UKQCD10: $f_+(0)$=0.959(5) (0.5% accuracy)**

  → V_{us}=0.2254(13)



K_{l3}: lepton universality test

Comparison of $|V_{us}|$ determined from K_{e3} vs $K_{\mu3}$ decays

SM

$$r_{\mu e} = \frac{[|V_{us}|f_+(0)]^2_{\mu3,\,\mathrm{exp}}}{[|V_{us}|f_+(0)]^2_{e3,\,\mathrm{exp}}} = \frac{\Gamma_{K\mu3}}{\Gamma_{Ke3}} \frac{I_{e3}\,(1+2\delta^{Ke}_{\mathrm{EM}})}{I_{\mu3}\,(1+2\delta^{K\mu}_{\mathrm{EM}})} = (g_\mu/g_e)^2 = 1$$

lepton coupling at the $W \to l\nu$ vertex

Experimental results

$K^\pm$: $r_{\mu e} = 0.998(9)$

K^0: $r_{\mu e} = 1.003(5)$

→ $r_{\mu e} = 1.002(4)$

Non-kaon measurements:

$\pi \to l\nu$: $r_{\mu e} = 1.0042(33)$

$\tau \to l\nu\nu$: $r_{\mu e} = 1.000(4)$

(PRD 76 (2007) 095017)

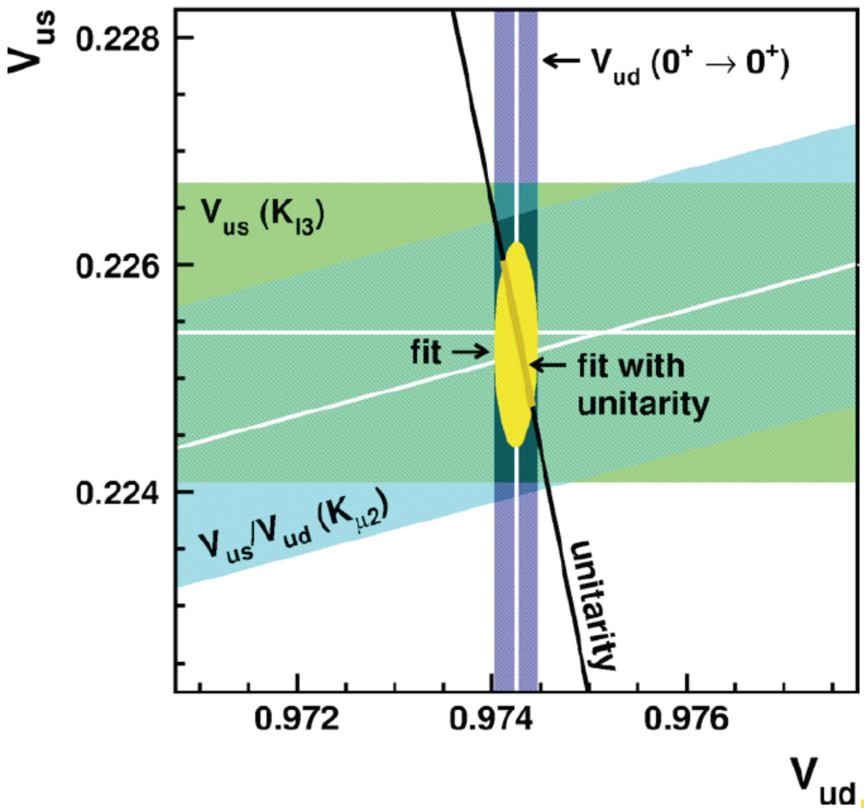
(Rev.Mod.Phys. 78 (2006) 1043)

The sensitivity in kaon sector approaches those obtained in the other fields.

Test of Unitarity

$|V_{us}| = 0.2254(13)$, $|V_{us}|/|V_{ud}| = 0.2312(13)$ $V_{ud} = 0.97425(22)$

Flavianet average



Fit (no CKM unitarity constraint):

$$V_{ud} = 0.97425(22); \; V_{us} = 0.2253(9)$$

$$\chi^2/\text{ndf} = 0.014/1 \; (91\%)$$

- $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.0001(6)$
- The test on the unitarity of CKM can be also interpreted as a **test of the universality of lepton and quark gauge coupling**:

$$G_{\text{CKM}} \equiv G_\mu \left[|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2\right]^{1/2} :$$
$$1.16633(35) \times 10^{-5} \text{ GeV}^{-2}$$

$$G_\mu = 1.166371(6) \times 10^{-5} \text{ GeV}^{-2}$$

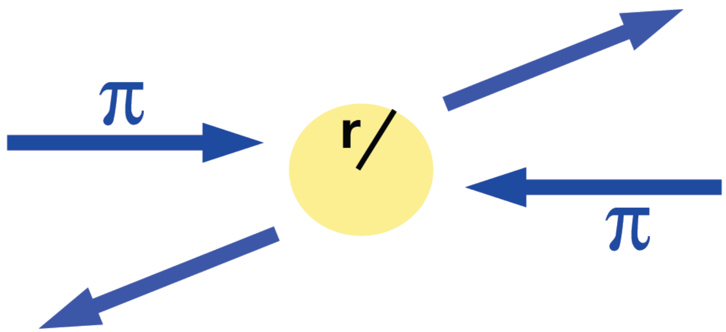
Fit (with CKM unitarity constraint):

$$V_{us} = 0.2254(6) \; \chi^2/\text{ndf} = 0.024/2 \; (99\%)$$

Pion Pion Scattering length from Kaon Decays

- **The Study of the strong interaction at low energy is a non-perturbative problem**
- **Chiral Perturbation Theory is a consistent framework of the strong interaction for low energy phenomena**
- **Effective theory in the expansion of masses and particle momenta**
- **Long-Standing issue is the measurement of the pion –pion scattering for which very precise theoretical predictions exists**
- **Pion Pion scattering is the simplest strong energy problem because it is not complicated by effects such the spin**
- **The overwhelming experimental problem is how to produce an initial pion pion state to study this process**
- **Kaons provide a well defined source of two pions:**
  in $K \rightarrow \pi\,\pi\,e\,\nu$ and $K \rightarrow \pi\,\pi\,\pi$ decays
- **Decisive progress has taken place over the past few years**

$\pi\pi$ Scattering Lengths



$$\mathbf{k} = \frac{\sqrt{2mE}}{\hbar}$$

<u>**At low energy *k r << 1*:**</u> **S-wave** dominates scattering amplitude.
Isospin *I = 0,2* because of Bose statistics.

- Scattering matrix $S|\pi\pi\rangle = e^{2i\delta}|\pi\pi\rangle$ parametrized by two phases:

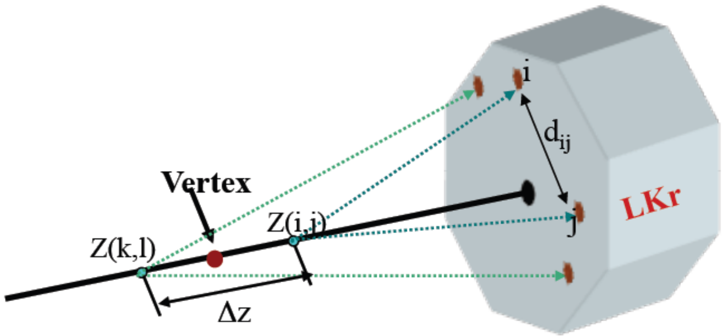
$$\delta_{0,2} = a_{0,2} \cdot k + \mathcal{O}(k^2)$$

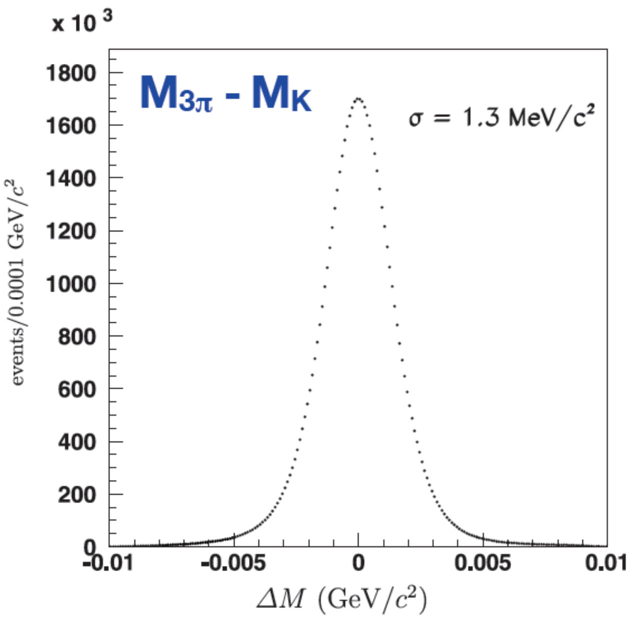
- At low energy **S-wave scattering lengths a_0, a_2** are essential parameters of **Chiral Perturbation Theory (ChPT).**

$K \to \pi\ \pi^0\pi^0$

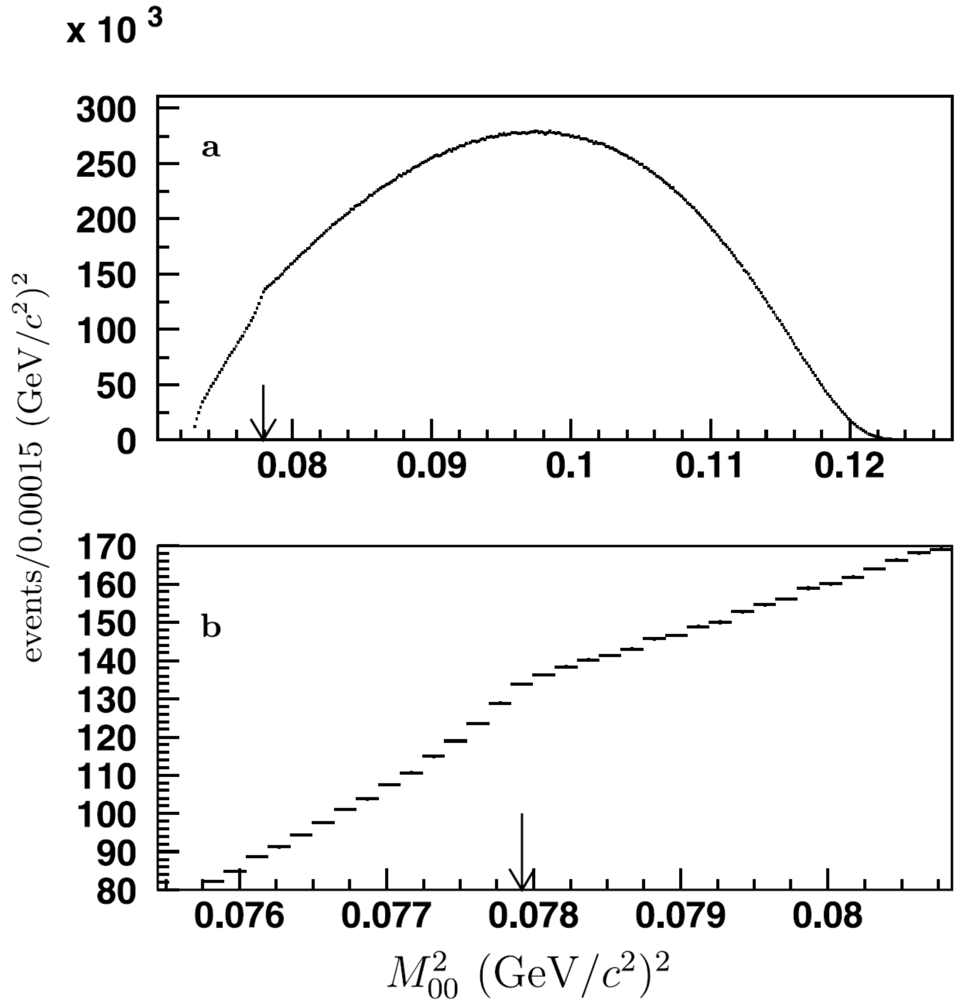
- 1 charged track + 4 e.m. clusters
- $\pi^0 \to \gamma\ \gamma$ selection:

  consider all 3 pairings and minimize vertex diference
- The computation of the invariant mass $M(\pi^0\pi^0)$ only involves calorimetric and vertex information
- About 100 M events with negligible background





Cusp in $K \rightarrow \pi\ \pi^0\pi^0$



M($\pi^0\pi^0$) distribution:

Clear cusp at

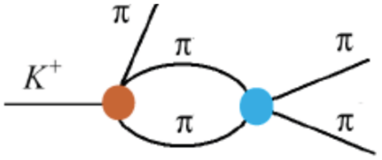
$M(\pi^0\pi^0) = 2\ m(\pi^\pm)$

(were expecting peak from pionium formation $K \rightarrow \pi^\pm\ (\pi\pi)_{atom} \rightarrow \pi^\pm\ \pi^0\ \pi^0$)

Theoretical Approach

Explanation: (Cabibbo, PRL 93 (2004) 121801)

- $\pi^+ \pi^- \rightarrow \pi^0 \pi^0$ rescattering amplitude
- depends on $a_0 - a_2$
- rescattering corrections from $\pi^+ \pi^- \rightarrow \pi^0 \pi^0$, $\pi^+ \pi^0 \rightarrow \pi^+ \pi^0$, ...



(Cabibbo, Isidori, JHEP03 (2005) 21)

Approach by the Bern-Bonn group:

(Colangelo, Gasser, Kubis, Rusetsky, PLB 638 (2006) 187;

Bissegger, Fuhrer, Gasser, Kubis, Rusetsky, PLB 659 (2008) 576; NPH B806 (2009) 178

- based on an effective non-relativistic lagrangian
- different structure of the expansion (w.r.t. CI)
- simultaneous fitting of neutral and charged amplitudes to extract Dalitz plot slope parameters (modified w.r.t. PDG parametrization)
- electromagnetic effects and radiative corrections outside the cusp point are included

➜ provides so far most complete description of rescattering effect

K_{e4} Decays

- very clean environment for the study of ππ system (no other hadron)
- Sensitivity to a_0 and a_2 from angular distributions
- Known for long but limited statistics

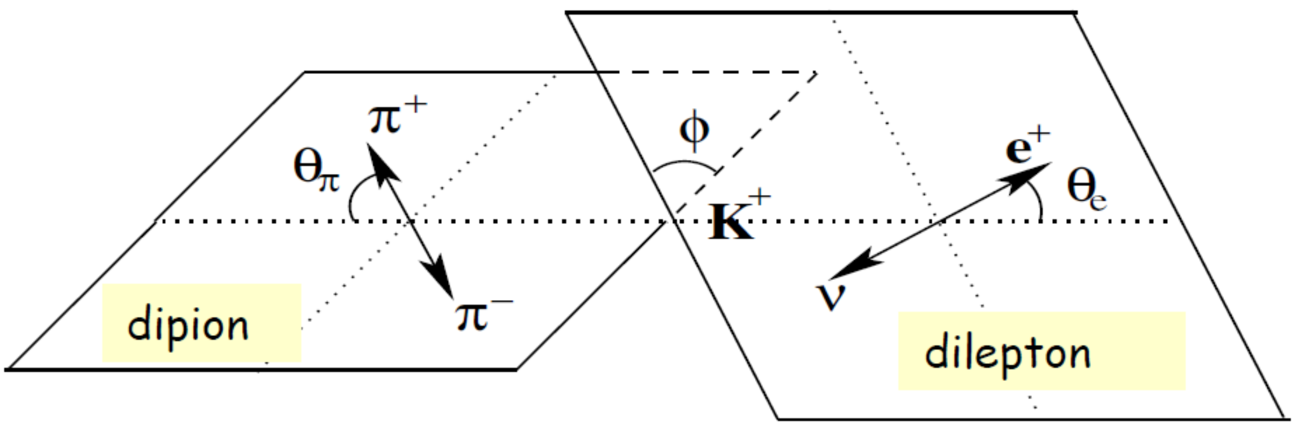
  BR = (4.09   0.09) x 10^{-5}

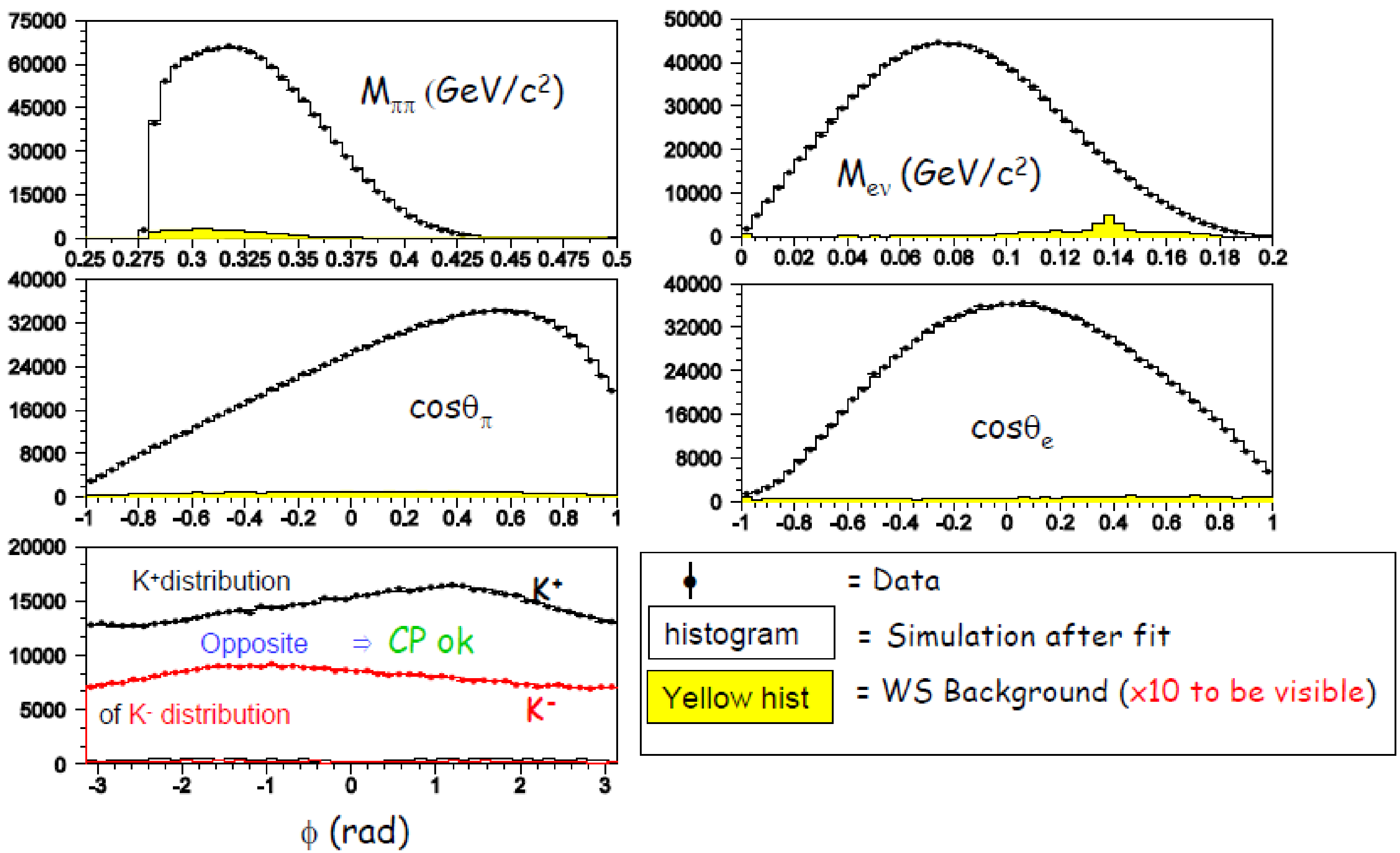
  – Geneva-Saclay CERN/PS S118 experiment: 30 000 K^+ (1977)
  – BNL E865 experiment: 400 000 K^+ (2003)
  – CERN/SPS NA48/2 : 1 130 000 K (2009)

- **5 kinematic variables**

(Cabibbo-Maksymowicz 1965)

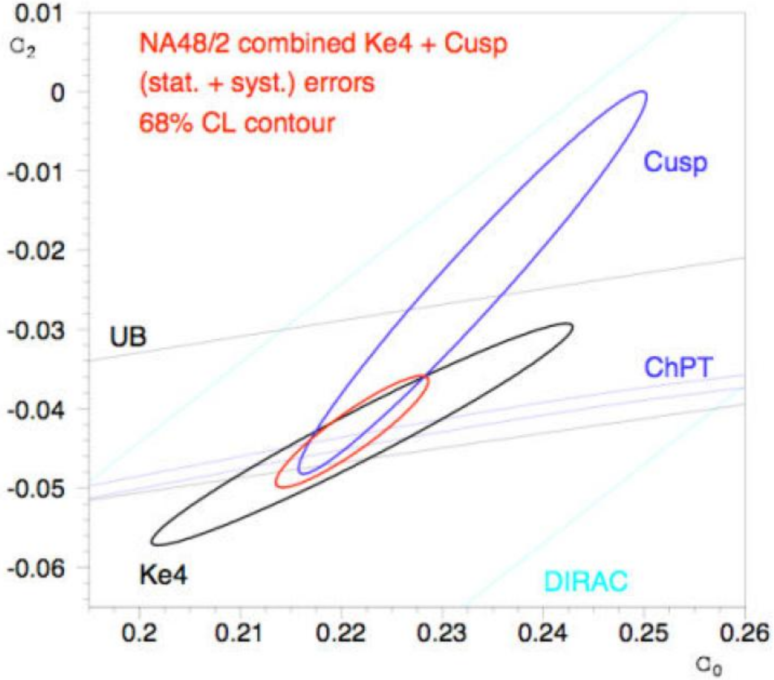
$S_\pi = M^2_{\pi\pi}$, $S_e = M^2_{e\nu}$, $\cos\theta_\pi$, $\cos\theta_e$ and φ.

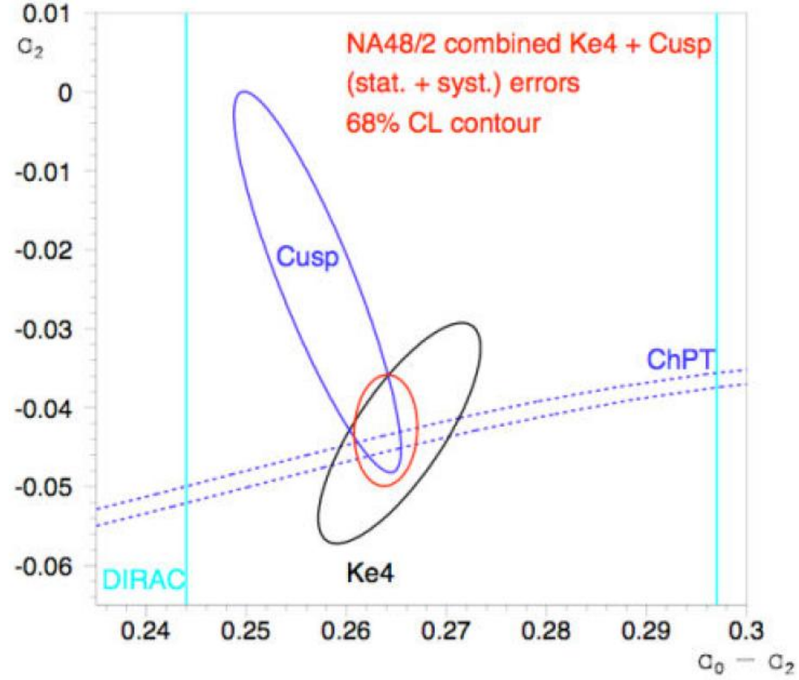




$M_{\pi\pi}$ (GeV/c^2)
$M_{e\nu}$ (GeV/c^2)
cosθ$_\pi$
cosθ$_e$
K+distribution
K+
Opposite ⇒ CP ok
of K- distribution
K-
φ (rad)
= Data
histogram = Simulation after fit
Yellow hist = WS Background (x10 to be visible)

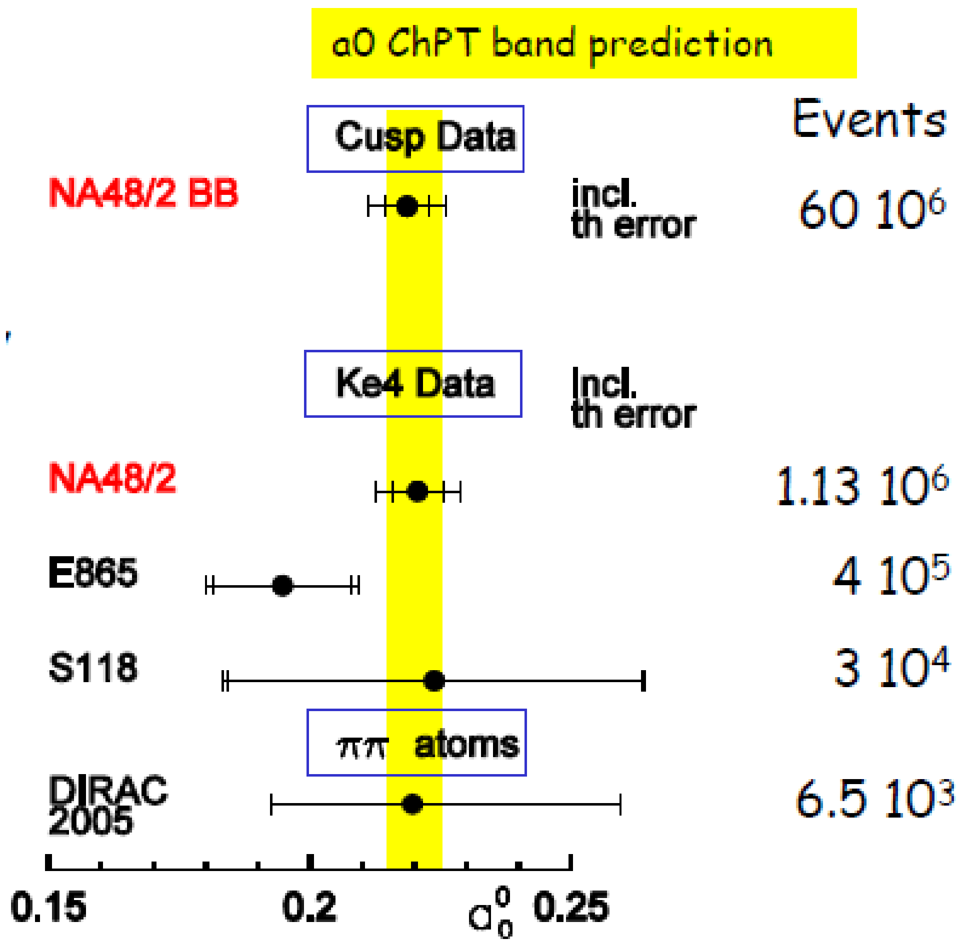
Cusp and Ke4: Scattering Lengths





Two Statistically independent measurements by NA48/2 in excellent agreement with precise Chiral Perturbation Predictions

Comparison Between Experiments



Radiative Decays (Example)

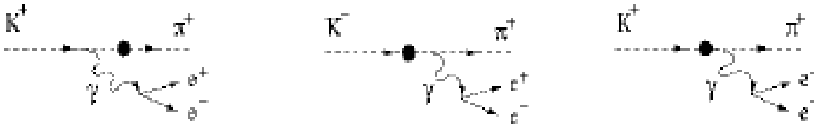
$$K^{\pm} \rightarrow \pi^{\pm}\gamma^{*} \rightarrow \pi^{\pm}l^{+}l^{-}$$

$K^\pm \rightarrow \pi^\pm l^+ l^-$ - motivation and theory

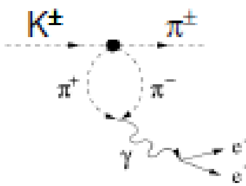
$$d\Gamma_{\pi ee}/dz \sim \rho(z)\cdot|W(z)|^2$$

$z=(M_{ee}/M_K)^2$, $\rho(z)$ phase space factor

- suppressed FCNC processes
- one-photon exchange
- useful test for ChPT



Form-factor models:



(1) polynomial: $W(z) = G_F M_K^2 \cdot f_0 \cdot (1+\delta z)$

(2) ChPT $O(p^6)$: $W(z) = G_F M_K^2 \cdot (a_+, b_+, z) + W^{\pi\pi}(z)$

(3) ChPT, large-Nc QCD: $W(z) = W(w, \beta, z)$

(4) Mesonic ChPT: $W(z) = W(M_a, M_\rho, z)$

(2) D'Ambrosio et al. JHEP 8 (1998) 4
(3) S. Friot et al. PLB 595 (2004) 301
(4) Dubnickova et al. hep-ph/0611175

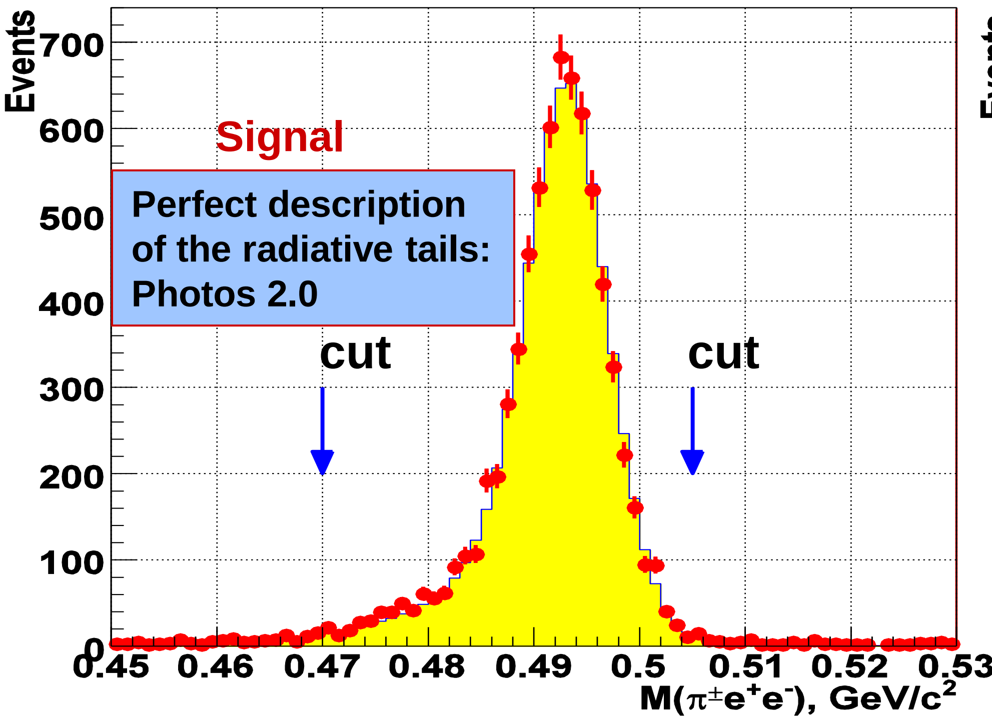
(f_0,δ) or (a_+,b_+) or (w, β) or (M_a,M_ρ) determine a model-dependent BR

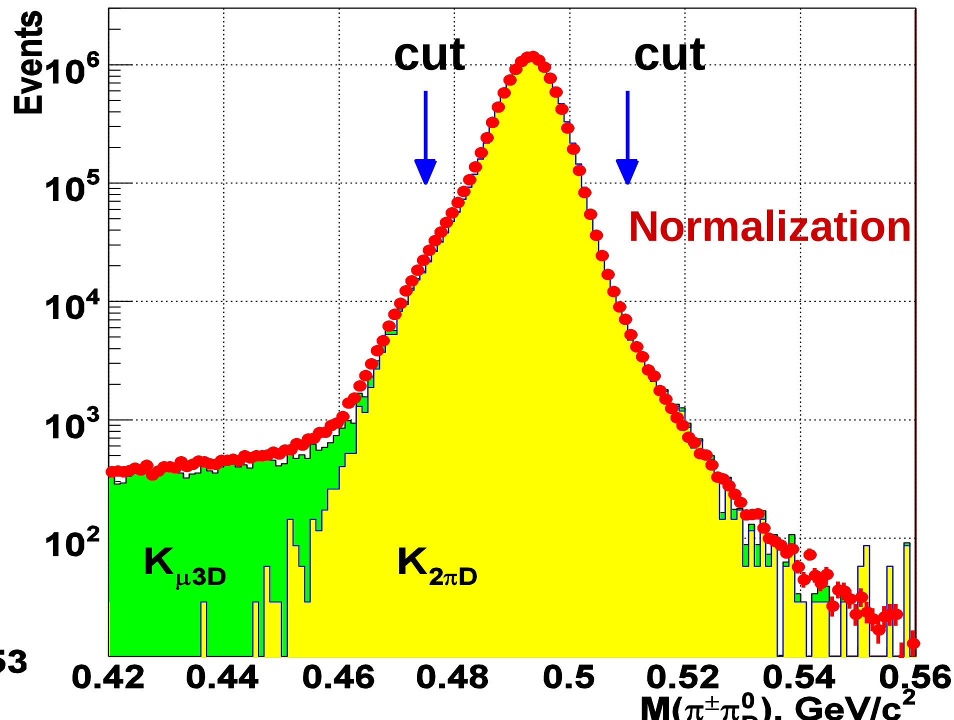
- Parameters of models and BR in full kinematical range
- Model-independent BR ($z > 0.08$) in visible kinematical range

$K^{\pm} \to \pi^{\pm}e^{+}e^{-}$ - signal and normalization samples

Selections of both channels based on very similar conditions: systematics (trigger, PID) in the BR ratio cancel particially

- Mee > 140 MeV – cut for bg suppression
- Aditional γ in the normalisation channel





7253 candidates
BG: 71 events estimated with data BG/SIG. ~ 1.0%

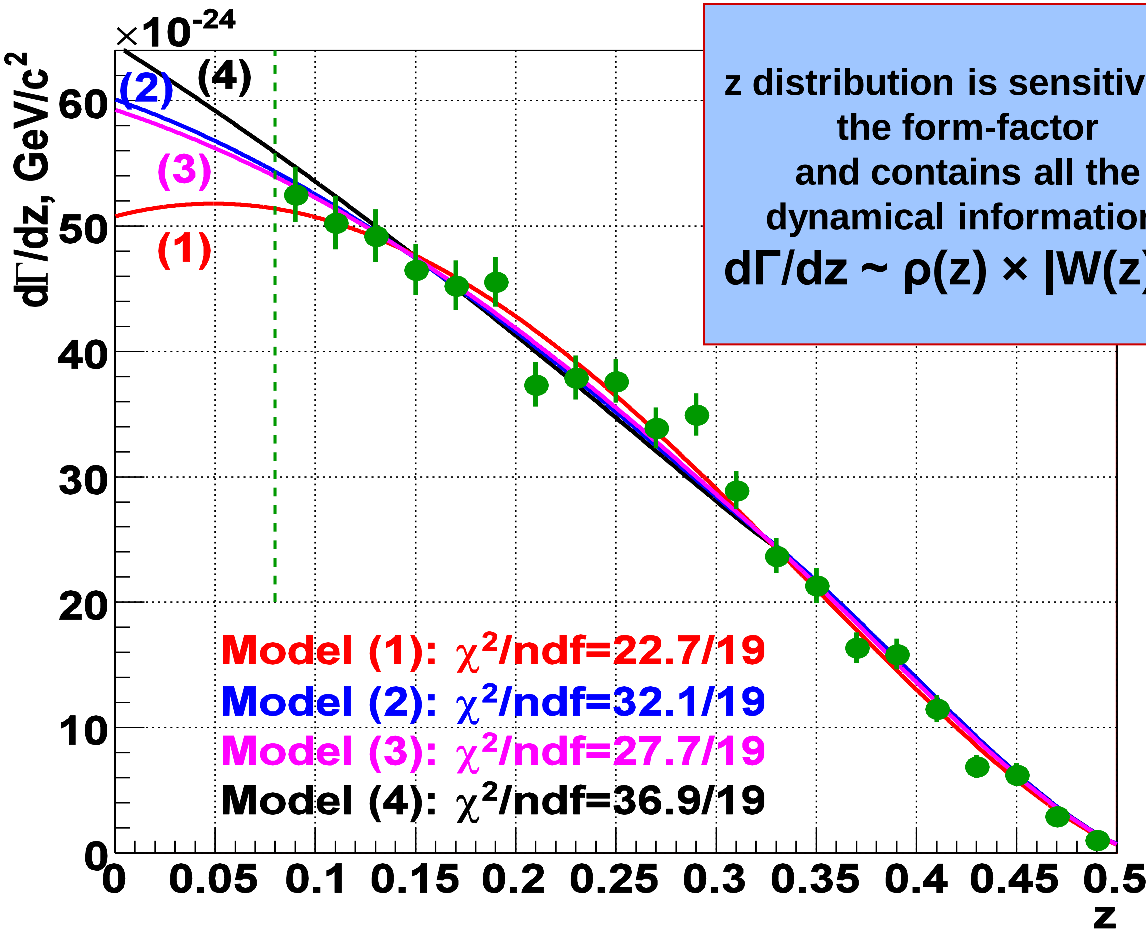
12.12 M candidates
BG/Signal ~ 0.15%
BG subtracted with MC

Kaon decay flux (2003+2004): $\Phi_K = 1.70\times10^{11}$ with Flavianet'08 $K^{\pm} \to \pi^{\pm}\pi^{0}$ BR

$K^{\pm} \rightarrow \pi^{\pm} e^{+} e^{-}$ - form factor measurement

GOALS

- Model-independent BR integrating $d\Gamma/dz$ in the observable z region
- Model dependent BRs using fit parameters.
- All models agree reasonably well with data



z distribution is sensitive to the form-factor and contains all the dynamical information:

$$d\Gamma/dz \sim \rho(z) \times |W(z)|^2$$

Fit results

$\delta = 2.32 \pm 0.18_{stat+syst}$

$|f_0| = 0.531 \pm 0.016_{stat+syst}$

$a_+ = -0.578 \pm 0.016_{stat+syst}$

$b_+ = -0.779 \pm 0.066_{stat+syst}$

$w = 0.057 \pm 0.007_{stat+syst}$

$\beta = 3.45 \pm 0.30_{stat+syst}$

$M_a = 0.974 \pm 0.035_{stat+syst}$ GeV

$M_\rho = 0.716 \pm 0.014_{stat+syst}$ GeV

Results – comparison with previous experiments

Model independent measurement

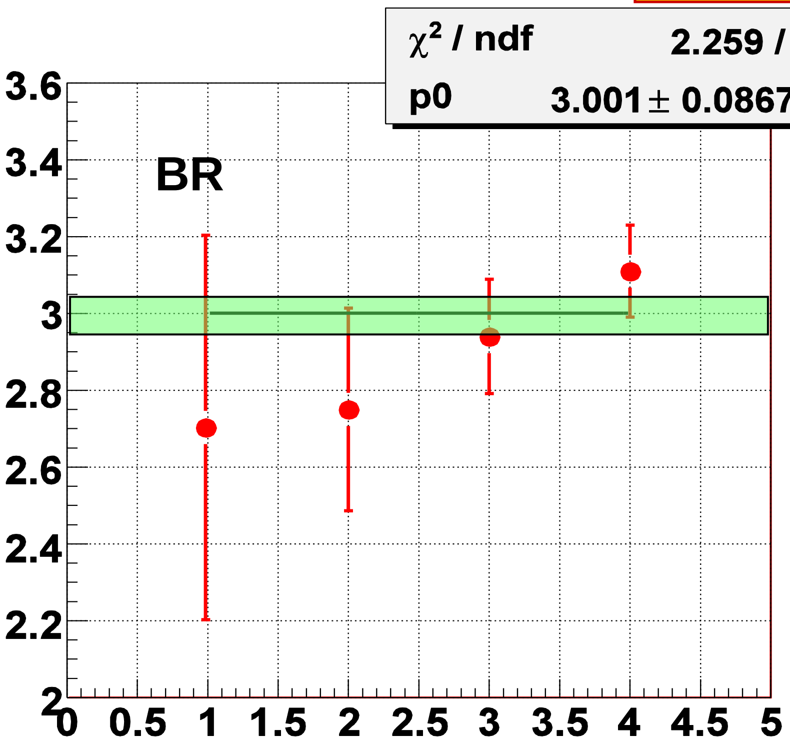
$BR_{mi}\times10^{7}$ $(M_{ee}>140MeV/c^2) = 2.28 \pm 0.03_{stat} \pm 0.04_{syst} \pm 0.06_{ext} = 2.28 \pm 0.08$

Combined result of the 4 models

$BR = (3.11\pm0.04_{stat}\pm0.05_{syst}\pm0.08_{ext}\pm 0.07_{model})\times10^{-7} = (3.11\pm0.12)\times10^{-7}$

CP violating asymmetry (first measurement! correlated K^+/K^- uncertainties excluded):

$\Delta(K^{\pm}_{\pi ee}) = (BR^+ - BR^-) / (BR^+ + BR^-) = (-2.2\pm1.5_{stat}\pm0.6_{syst})\%$



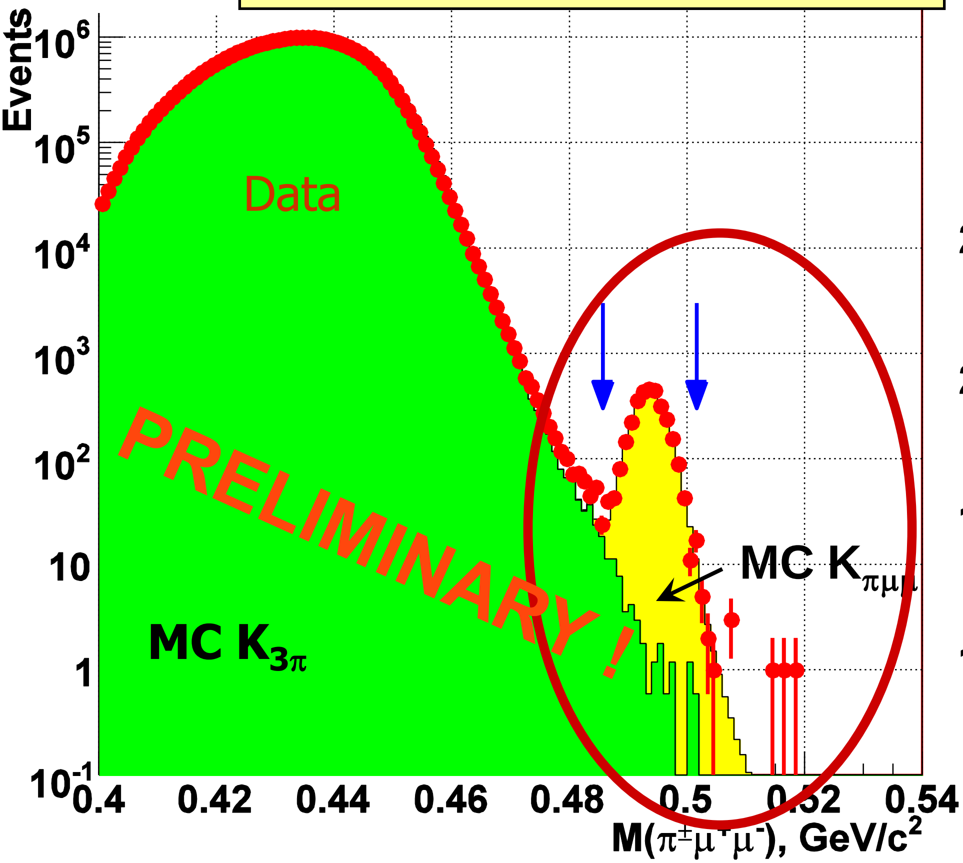
Measurement	events	$BR\times10^{7}$
Bloch et al., PL 56 (1975) B201	(41)	2.70±0.50
Alliegro et al.[E777], PRL 68 (1992) 278	(500)	2.75±0.26
Appel et al. [E865], PRL 83 (1999) 4482	(10000)	2.94±0.15
NA48/2 final (2009)	(7253)	3.11±0.12

- Form factor measurements for Model 1, 2 and 3* in agreement with previous measurements
- Model 4 – never tested before
- J.Prades, e-Print: arXiv:0707.1789 [hep-ph], predicts (up to its sign) $a_+ = -(0.6\ ^{+0.6}_{-0.23})$, in agreement with our result

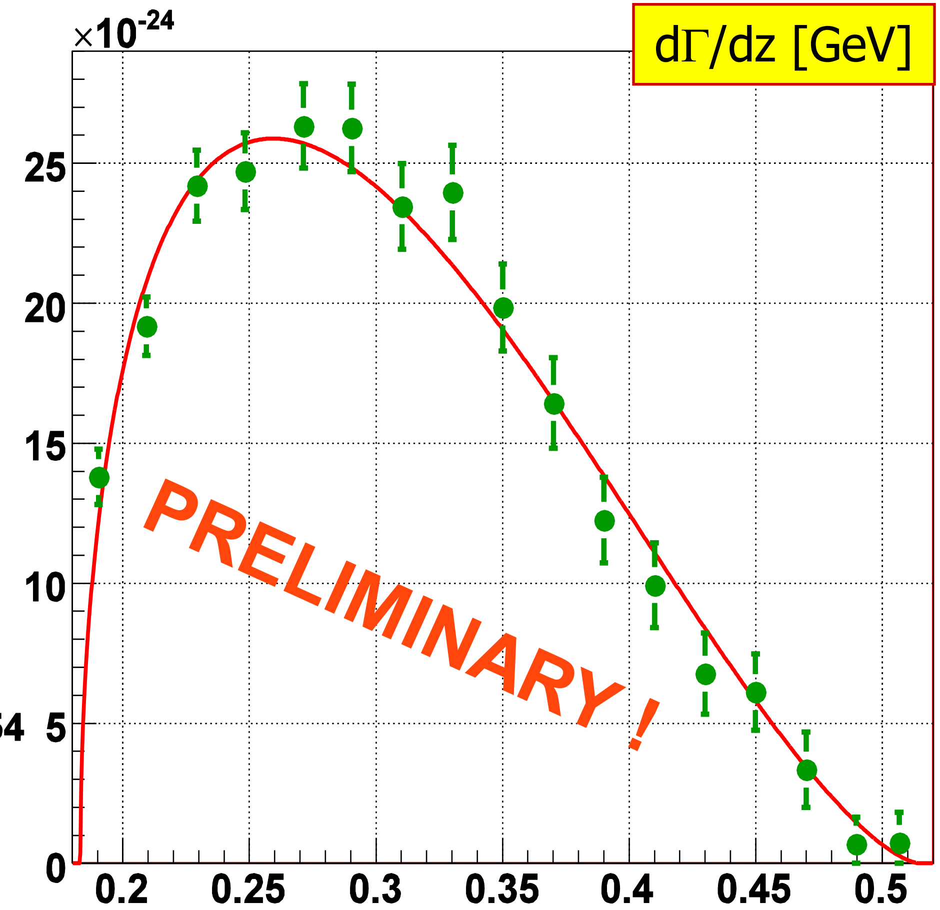
*fit done by the authors of Model 3 using BNL E865 data

$K^{\pm} \rightarrow \pi^{\pm}\mu^{+}\mu^{-}$ - signal region and fit

Data: Normal $\mu^{+}\mu^{-}$ candidates



Fit to the linear form-factor

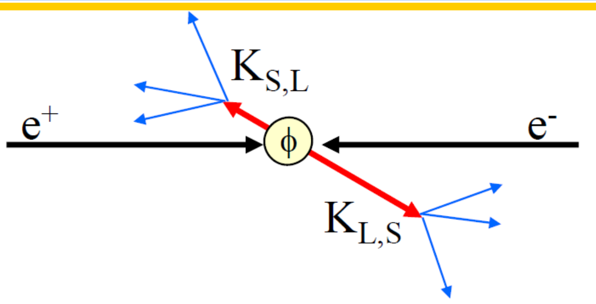


~3100 reconstructed events in the signal region: 4 times larger sample than the existing world statistics!

Kaon Interferometry

Neutral kaons at a ϕ-factory

Production of the vector meson ϕ in e^+e^- annihilations:



- $e^+e^- \to \phi \qquad \sigma_\phi \sim 3\ \mu b$
  $W = m_\phi = 1019.4$ MeV
- $BR(\phi \to K^0\bar{K}^0) \sim 34\%$
- $\sim 10^6$ neutral kaon pairs per pb^{-1} produced in an antisymmetric quantum state with $J^{PC} = 1^{--}$:

$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0(\vec{p})\rangle|\bar{K}^0(-\vec{p})\rangle - |\bar{K}^0(\vec{p})\rangle|K^0(-\vec{p})\rangle\right]$$

$$= \frac{N}{\sqrt{2}}\left[|K_S(\vec{p})\rangle|K_L(-\vec{p})\rangle - |K_L(\vec{p})\rangle|K_S(-\vec{p})\rangle\right]$$

$$N = \sqrt{\left(1+|\varepsilon_S|^2\right)\left(1+|\varepsilon_L|^2\right)}\Big/\left(1-\varepsilon_S\varepsilon_L\right) \cong 1$$

$p_K = 110$ MeV/c

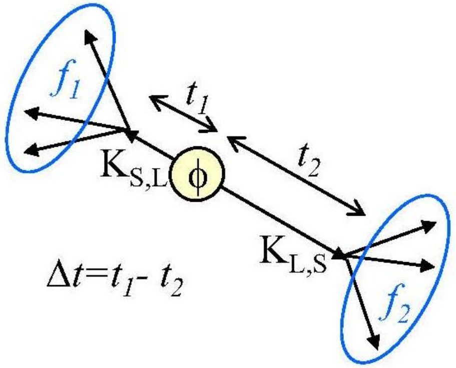
$\lambda_S = 6$ mm $\quad \lambda_L = 3.5$ m

The detection of a kaon at large (small) times tags a K_S (K_L)
$\Rightarrow$ possibility to select a pure K_S beam (**<u>unique</u>** at a ϕ-factory, not possible at fixed target experiments)

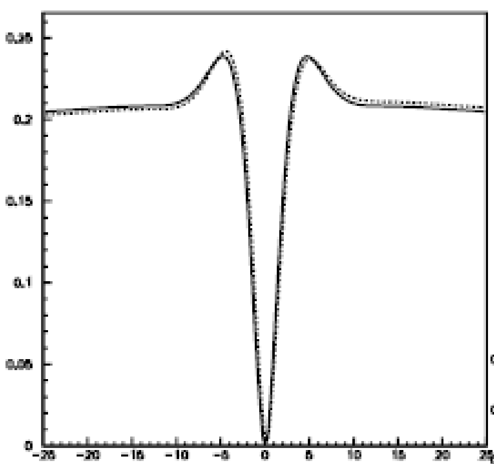
Quantum Interferometry

The most specific (and intriguing) feature of the neutral kaon system produced in Φ decays is that it is subject to quantum entanglement

This means that the decay probability of each one of the kaons depends also on what the other particles does



$$I(f_1,t_1;f_2,t_2) = C_{12}\left\{|\eta_1|^2 e^{-\Gamma_L t_1 - \Gamma_S t_2} + |\eta_2|^2 e^{-\Gamma_S t_1 - \Gamma_L t_2} - 2|\eta_1||\eta_2| e^{-(\Gamma_S+\Gamma_L)(t_1+t_2)/2}\cos[\Delta m(t_2 - t_1) + \phi_1 - \phi_2]\right\}$$



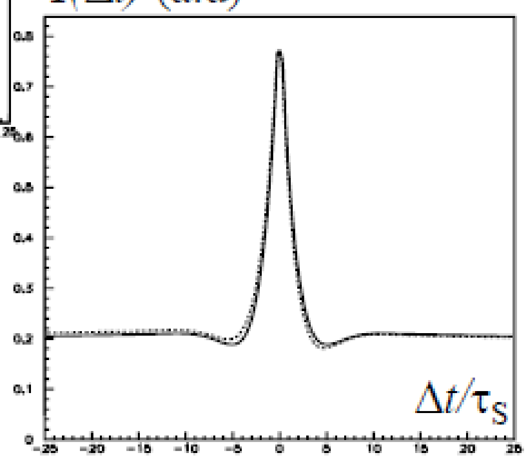
$\phi \to K_S K_L \to \pi^+\pi^- \ \pi^0\pi^0$

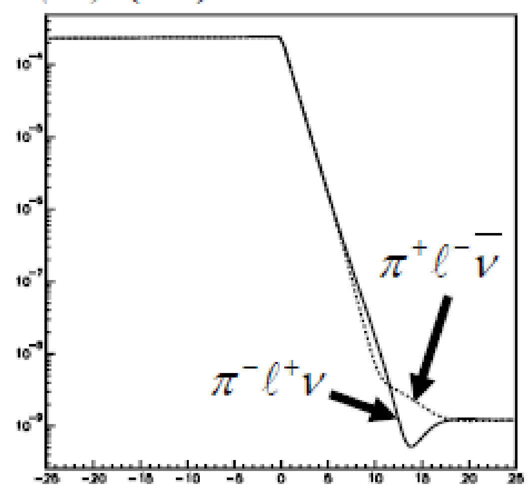
$\Re\left(\frac{\varepsilon'}{\varepsilon}\right) \quad \Im\left(\frac{\varepsilon'}{\varepsilon}\right)$

$\Re\delta + \Re x$

$\Im\delta + \Im x_+$

$\phi \to K_S K_L \to \pi^+\ell^-\bar{\nu} \ \ \pi^-\ell^+\nu$





$\phi \to K_S K_L \to \pi\pi \ \ \pi\ell\nu$

$A_L = 2\Re\varepsilon - \Re\delta - \Re y - \Re x_-$

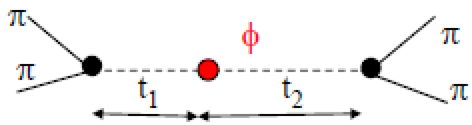
$\phi_{\pi\pi}$

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

$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle\right]$$

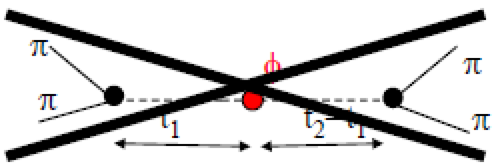
Same final state for both kaons: $f_1 = f_2 = \pi^+\pi^-$

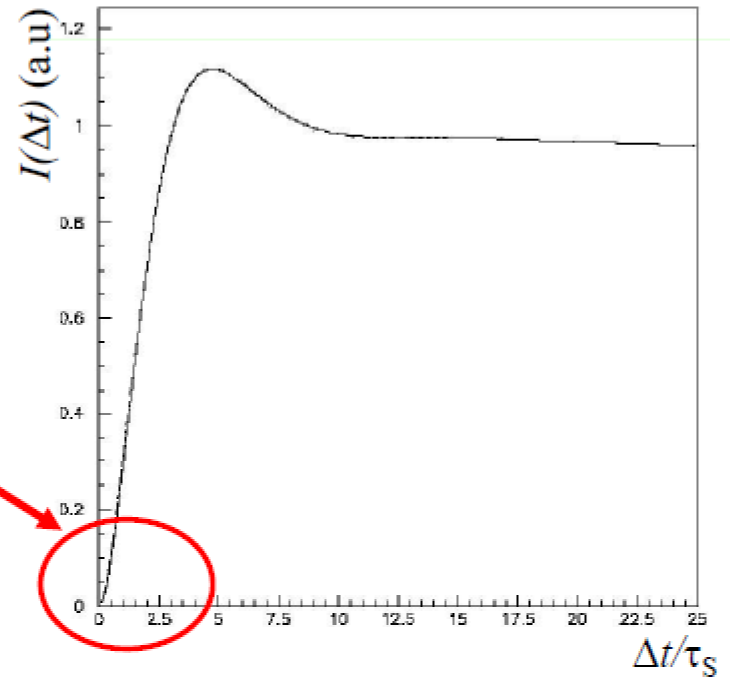
$$\Delta t = |t_1 - t_2|$$



EPR correlation:

no simultaneous decays (Δt=0) in the same final state due to the destructive quantum interference





The KLOE-2 strategy (Slides by F. Bossi)

We have proposed, and the Laboratory has accepted, an installation plan based on a two-step strategy

- *Step 0*: Preparation ongoing now. Start of data taking, spring 2010. Use of the present detector with the minimal upgrades required to run it safely and efficiently. Use also of newly built taggers for $\gamma\gamma$ physics.
- *Step 1*: Start of installation work, summer 2011. Insertion of the more demanding upgrades with the goal of a longer data taking campaign (2012-13)

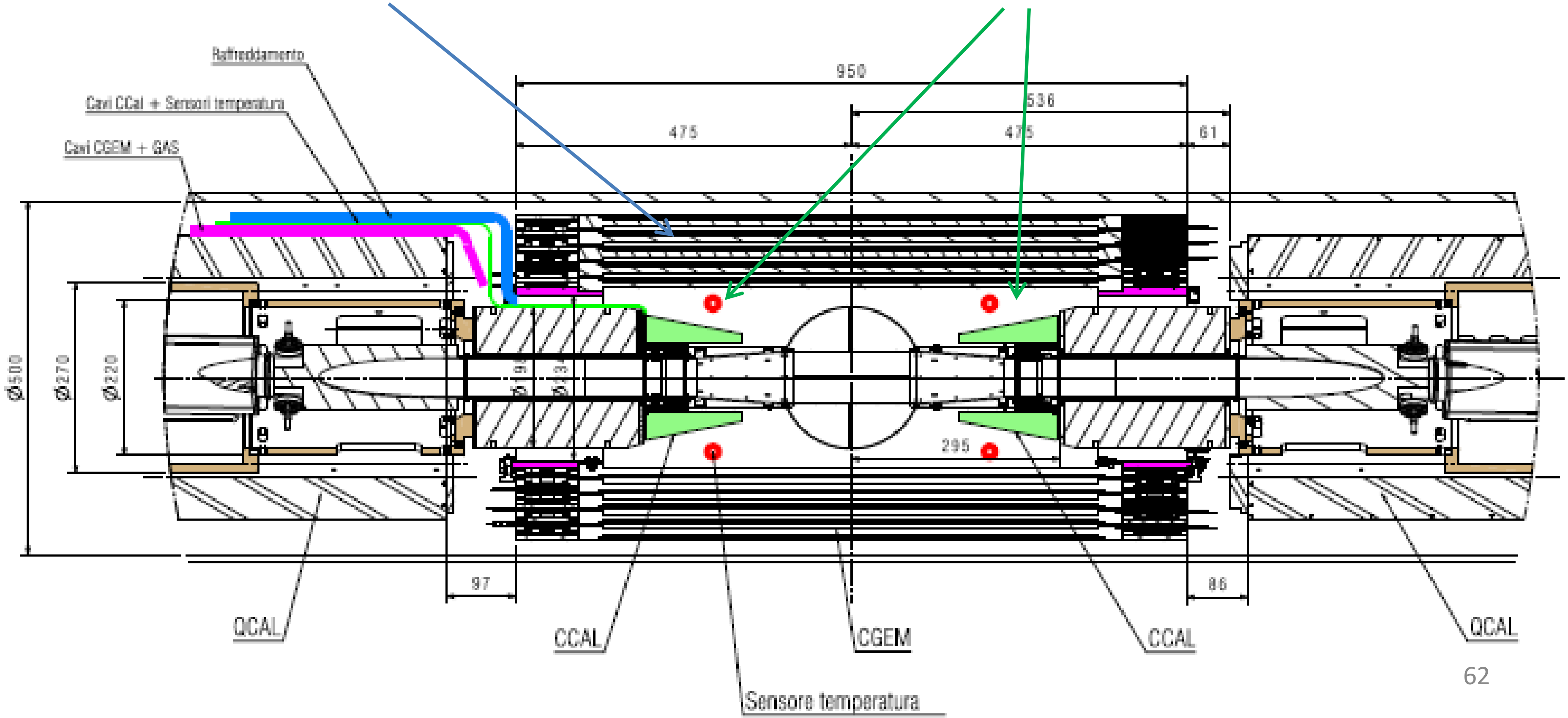
Thanks to crab waist upgrade, expect DAΦNE to deliver ≥ 300 pb^{-1}/month

The upgraded interaction region

New sub-detectors will be installed around the interaction region

An inner tracker to improve on tracking resolution and acceptance

Forward calorimeters to increase acceptance for photons



KLOE-2: physics motivations

There are several physics topics that can benefit of an acquired luminosity of order $10\ fb^{-1}$ with an upgraded detector

- Studies on CPT and QM violation with neutral kaons interferometry
- Tests of Lepton Flavor Violation with K_{e2} decays
- Studies on C, P, CP violation using rare η and K_S decays
- Tests of Chiral Perturbation Theory with η, η', and K_S decays
- Searches for signals of a Secluded Gauge Symmetry

Quantum Gravity and CPT violation

Hawking suggested that at the microscopic level, in a QG picture, non trivial space-time fluctuation could give rise to decoherence effects, which would necessarily entail CPT violation

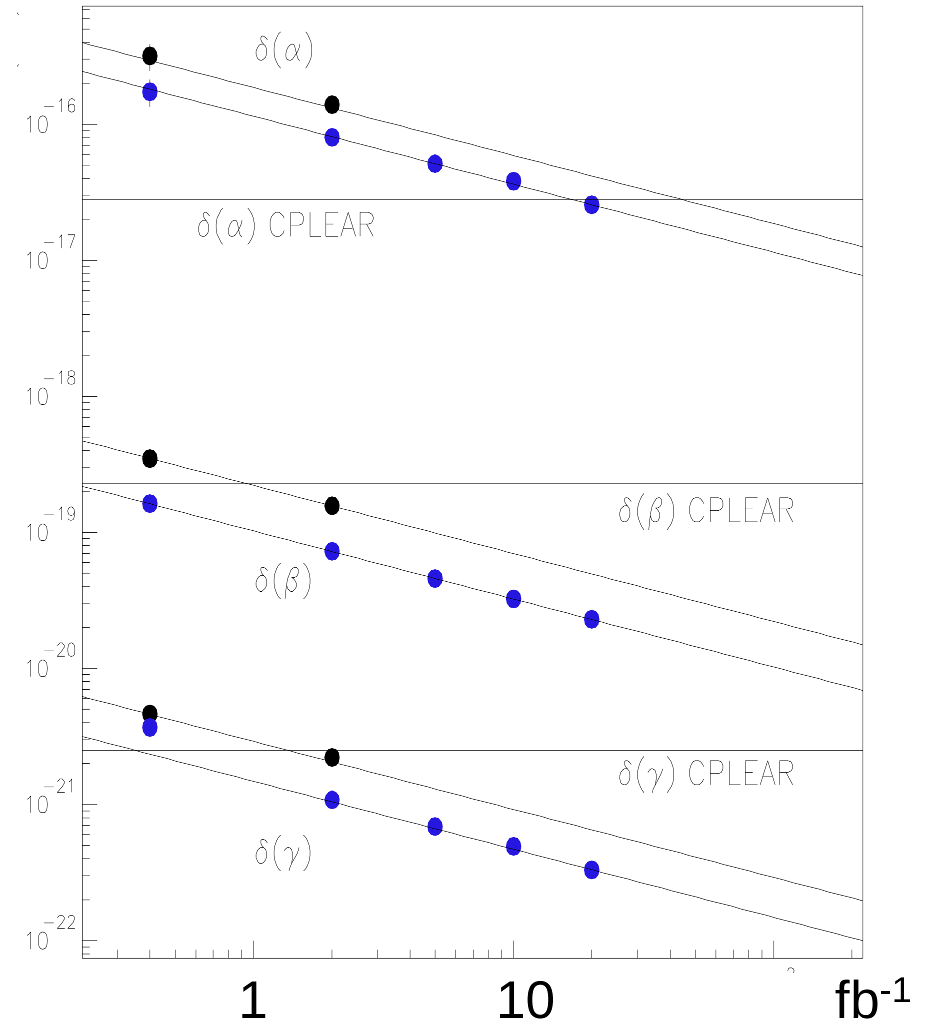
This idea has been applied, for instance, in a model by Ellis and collaborators, specifically for the neutral kaon system, introducing 3 CPTV parameters, α, β and γ, distorting the above mentioned decay intensity. Naively, one expects:

$$\alpha, \beta, \gamma = O\left(\frac{M_K^2}{M_{Plank}}\right) \approx 2 \times 10^{-20} GeV$$

KLOE-2 and QG

KLOE-2 becomes competive on γ and β with a few fb^{-1} collected, and also on α with $\geq 20\ fb^{-1}$

The use of a inner tracker (blue points in figure) improves on the reachable limits by a factor ~ 3 (note the logarithmic scale!)



CPT

Hadronic modes

Γ_1	$\pi^0\pi^0$	(30.69 ± 0.05) %
Γ_2	$\pi^+\pi^-$	(69.20 ± 0.05) %
Γ_3	$\pi^+\pi^-\pi^0$	$(3.5\ ^{+1.1}_{-0.9}) \times 10^{-7}$

K_S

Γ_4	π^+ ...	
Γ_5	π^+ ...	
Γ_6	$\pi^0\gamma$ ...	
Γ_{10}	$3\pi^0$	

Hadronic m...

K_L

Γ_6	$3\pi^0$	
Γ_7	π^+ ...	
Γ_8	π^+ ...	
Γ_9	$\pi^0\pi$ ...	
Γ_{12}	$\pi^0\pi$ ...	
Γ_{13}	π^+ ...	
Γ_{14}	π^+ ...	
Γ_{15}	$\pi^0 2\gamma$	
Γ_{16}	$\pi^0\gamma e^+ e^-$	$(1.62\ \pm0.17) \times 10^{-8}$

$|m_{K^0} - m_{\overline{K}^0}| \,/\, m_{average}$

A test of *CPT* invariance. "Our Evaluation" is described in the "Tests of Conservation Laws" section. It assumes *CPT* invariance in the decay and neglects some contributions from decay channels other than $\pi\pi$.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*
$<8 \times 10^{-19}$	90	PDG	08	

$(\Gamma_{K^0} - \Gamma_{\overline{K}^0})/m_{average}$

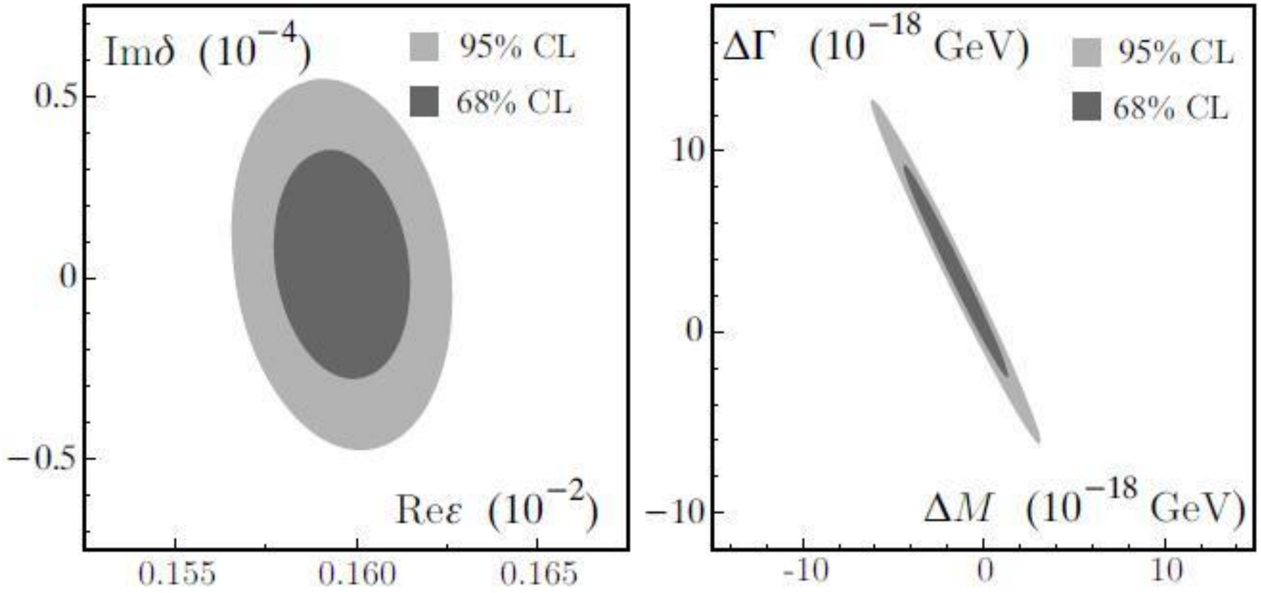
A test of *CPT* invariance.

VALUE	*DOCUMENT ID*		*TECN*
$(7.8\pm8.4) \times 10^{-18}$	[19] ANGELOPO...	99B	RVUE

[19] ANGELOPOULOS 99B assumes only unitarity and combines CPLEAR with other results. Correlated with $(m_{K^0} - m_{\overline{K}^0}) \,/\, m_{average}$ with a correlation coefficient of -0.95.

Bell-Steinberger

KLOE+ JHEP12(2006) 011



$$-5.3 \times 10^{-19}\ \mathrm{GeV} < m_{K^0} - m_{\overline{K^0}} < 6.3 \times 10^{-19}\ \mathrm{GeV} \quad \text{at } 95\ \%\ \mathrm{CL}\,.$$

No direct CPT assumption

$\pi^+\pi^-$ phase dominates

No significant contribution from 3π

CPT test from $\pi\pi$

$$\Delta = \frac{i(m_{K^0} - m_{\overline{K}^0}) + \frac{1}{2}(\Gamma_{K^0} - \Gamma_{\overline{K}^0})}{\Gamma_S - \Gamma_L} \cos\phi_{SW} e^{i\phi_{SW}}[1+\mathcal{O}(\epsilon)]$$

Á la CP/T (1999):

$$m_K - m_{\overline{K}} = 2\Delta m \frac{|\eta_{+-}|}{\sin\phi_{SW}} |\phi_{+-} - \phi_{\varepsilon}|$$

0.5% (KTeV, KLOE, NA48) BR

1.5% using ϕ00, no dir CPT and no CPV outside 2π, or use Im(x) and Im($\eta_{3\pi}$) (CPLEAR, NA48, KLOE)

0.3% (KTeV) reg. interference

1.5% (KTeV) reg. interference

Summary

- A World-Wide endeavor to corner the Standard Model in ultra-rare decays (CERN, J-PARC, possibly FNAL) is in place
- The Theory-Experiment interplay is pushing precision tests (e.g. V_{us}, Ke2) below 0.5% precision
- There is a stream of results coming from last round of experiments….
- ….and new data are expected from OKA (Protvino) and KLOE-2 (Frascati) very soon
- The experimental programme in Kaon Physics “in the time of the LHC” is alive and kicking