Kaon Physics
A Tribute to Nicola Cabibbo

Augusto Ceccucci/CERN

Cabibbo 60 Convegno
Accademia Nazionale dei Lincei

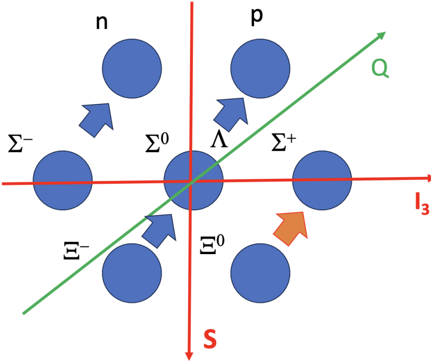
Roma, December 4, 2023

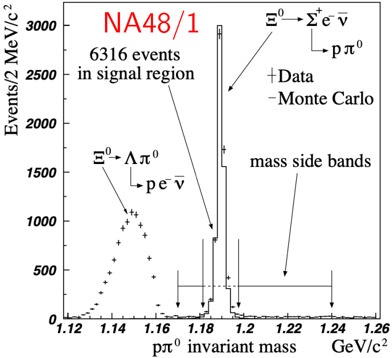
Cabibbo and the Kaons (and the Hyperons!)

I cannot do justice to Nicola Cabibbo's many contributions, so I will present just a few well known examples:

- The last Cabibbo decay:
  $\Xi^0 \rightarrow \Sigma^+ e^- \bar{\nu}_e$ and the full verification of the Cabibbo theory with hyperon decays
- CP-Violation:
  From a puzzling experimental observation to the success of the flavour mixing interpretation
- Strong Interactions at Low Energy:
  Determination of the $\pi\pi$ scattering length from a "cusp" in the $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ data
- Rare Kaon Decays:
  From qualitative to quantitative tests of the Cabibbo, Kobayashi, Maskawa (CKM) matrix with kaons

The Last Cabibbo Decay: $\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$





- Modern Appraisal: N. Cabibbo, E. Swallow, R.Winston, Annu. Rev. Nucl. Part. Sci. 2003. 53:39–75
- Intense high energy neutral beams are by-products of the ε'/ε experiments
- $\Xi^0 \to \Sigma^+ e^- \bar{\nu}$: same form factors of $n \to p e^- \bar{\nu}$, the Σ^+ can originate only from Ξ^0 decays and it is self-analysing

Cabibbo Theory and Hyperon Leptonic Decays

Cabibbo Theory [PRL10(1963)] vs. Experiment

$(\Delta S = \Delta Q = +1)$

Decay	BR(Cabibbo) $\times 10^4$	BR(PDG) $\times 10^4$
$\Lambda \to p e^- \bar{\nu}$	7.5	8.34 ± 0.14
$\Sigma^- \to n e^- \bar{\nu}$	19	10.2 ± 0.34
$\Xi^- \to \Lambda e^- \bar{\nu}$	3.5	5.63 ± 0.31
$\Xi^- \to \Sigma^0 e^- \bar{\nu}$	0.7	0.87 ± 0.17
$\Xi^0 \to \Sigma^+ e^- \bar{\nu}$	2.6	2.52 ± 0.08

It took time to complete the experimental verification, for instance:

- 1983 M. Bourquin et al.: $\Xi^- \to \Sigma^0 e^- \bar{\nu}$
- 1988 FNAL-E715: negative sign of g_1/f_1 in $\Sigma^- \to n e^- \bar{\nu}$
- KTeV (1999), NA48/1 (2007) $\Xi^0 \to \Sigma^+ e^- \bar{\nu}$
- KTeV (2005), NA48/1 (2013) $\Xi^0 \to \Sigma^+ \mu^- \bar{\nu}$

CP-Violation in Kaon Decays

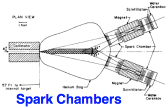
CP Conservation splits the neutral kaons in a short-lived state allowed to decay into $\pi^+\pi^-$ and a long-lived one forbidden to do so

$$\pi^+\pi^- \ (\text{CP}=+1) \quad K_1 = 1/\sqrt{2}(K_0 + \bar{K}_0) \qquad (\text{CP}=+1)$$

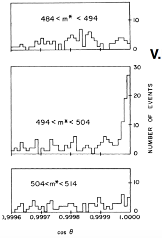
$$K_2 = 1/\sqrt{2}(K_0 - \bar{K}_0) \qquad (\text{CP}=-1)$$

The discovery that the long-lived neutral kaon decays also into two pions came as a big surprise

$K^0_L \to \pi^+\pi^- \quad \Rightarrow$



Spark Chambers



V.L.Fitch **R.Turlay** **J.W.Cronin** **J.H.Christensor**

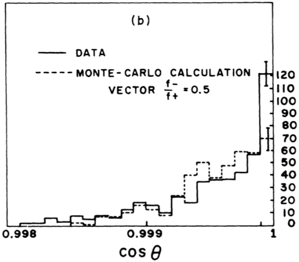
Phys. Rev. Lett. 13 (**1964**) 138.

$$|K_L^0\rangle = \frac{\varepsilon|K_1\rangle + |K_2\rangle}{\sqrt{1+\varepsilon^2}}$$

$$|K_S^0\rangle = \frac{|K_1\rangle + \varepsilon|K_2\rangle}{\sqrt{1+\varepsilon^2}}$$

$$|\varepsilon| = (2.229 \pm 0.010) \times 10^{-3}$$

13



- The sum of the momenta must line up with the beam direction
- The mass must match the K^0 one

ICHEP1966, Weak Interactions, Nicola Cabibbo, Rapporteur

"Figure 2-1 comments on the general good situation of the field. "

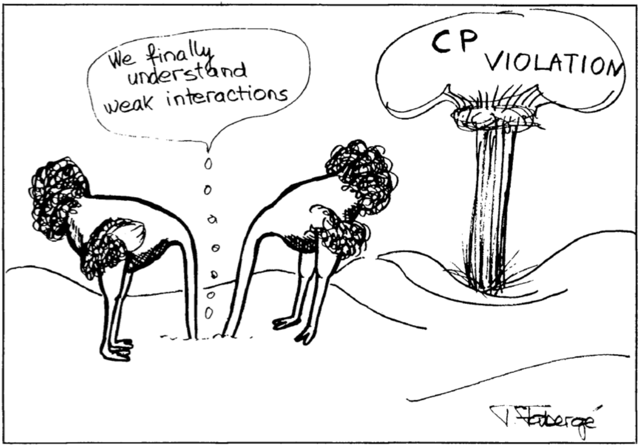


Fig. 2-1. Where we stand.

Mixing (ε) and Decay (ε') CP-Violation

Phenomenology: T.T. Wu and C.N. Yang, (1964)

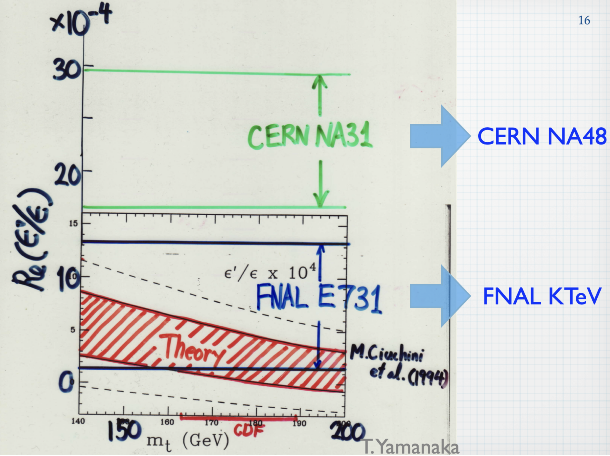
$$\varepsilon' = i/\sqrt{2} Im(A_2/A_0) \exp[i(\delta_2 - \delta_0)]$$

$$\eta_{\pm} = \varepsilon + \varepsilon' \qquad \eta_{00} = \varepsilon - 2\varepsilon'$$

$$\eta_{\pm} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \qquad \eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)}$$

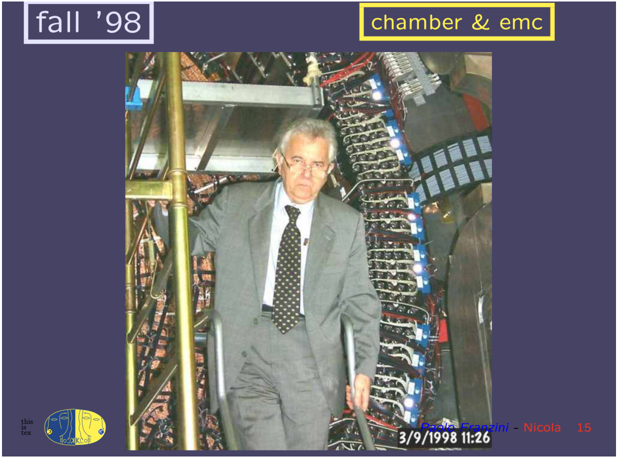
$$R = \left|\frac{\eta_{00}}{\eta_{\pm}}\right|^2 \frac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)} / \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)} \simeq 1 - 6 \; Re \; \varepsilon'/\varepsilon$$

Status Early 1990's



- Big puzzles, Kaons quite popular
- Five Φ and one K factories proposed
  → One realised in Frascati

Cabibbo and KLOE at DAΦNE



fall '98

chamber & emc

this is tex

3/9/1998 11:26

Paolo Franzini - Nicola 15

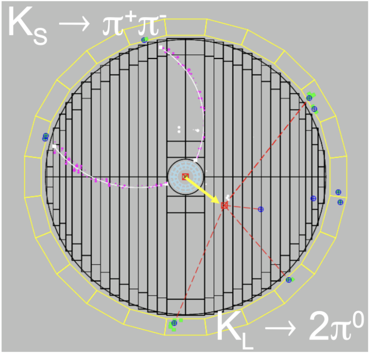
Paolo Franzini, Cabibbo Memorial Symposium, 2010

DAΦNE: tagged neutral kaon pairs

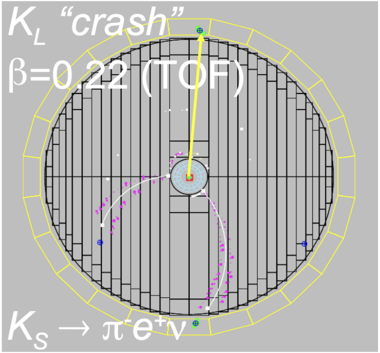
Example: $\mathrm{BR}\left(K_S \to 3\pi^0\right) \leqslant 2.6 \times 10^{-8}$ at 90% C.L.

$$|\eta_{000}| = \sqrt{\frac{\tau_L}{\tau_S}\frac{BR(K_S\to3\pi^0)}{BR(K_L\to3\pi^0)}} \leq 0.0088 \quad \text{at 90 \% CL}$$

Phys. Lett.B 723 (2013) 54-60 KLOE-2 Collab. UNIQUE



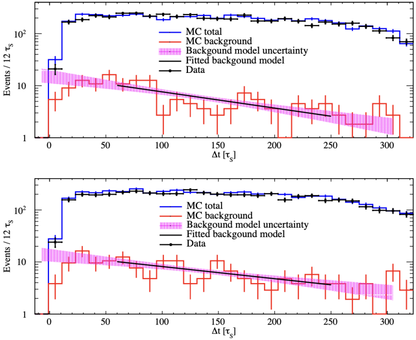
K_L tagged by
$K_S \to \pi^+\pi^-$ vertex at IP

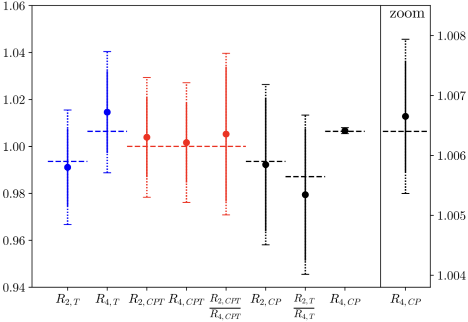


K_S tagged by
K_L interaction in EmC

Entanglement of $K^0\bar{K}^0$ pairs

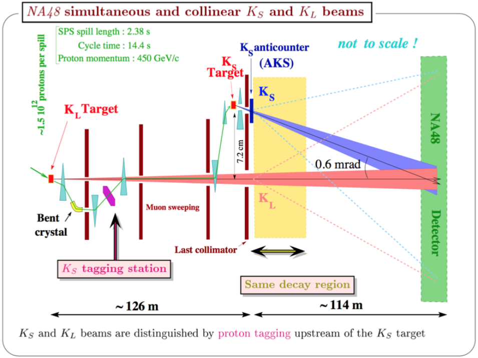
Direct tests of T, CP, CPT symmetries in transitions of neutral K mesons with the KLOE experiment, Phys.Lett.B 845 (2023) 138164





$$\phi \to K_S K_L \to (\pi^\pm e^\mp \nu)(3\pi^0)$$

Measuring ε'/ε: NA48@CERN



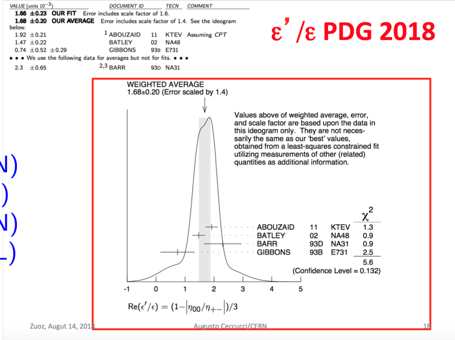
K_S and K_L beams are distinguished by proton tagging upstream of the K_S target

- Two beams and two target
- Simoultaneous detection of K_L, K_S into $\pi^+\pi^-$ and $\pi^0\pi^0$
- K_S decay distinguished by proton tagging (30 MHz)
- 0.1% background levels

Electrode structure (half) of the Liquid Krypton Calorimeter, **now used by NA62, cold (~120 K) since 1998**

ε'/ε

NA31 (CERN)
E731 (FNAL)
NA48 (CERN)
KTeV (FNAL)



VALUE (units 10^{-3})			DOCUMENT ID		TECN	COMMENT
1.66	**±0.23**		**OUR FIT** Error includes scale factor of 1.6.			
1.68	**±0.20**		**OUR AVERAGE** Error includes scale factor of 1.4. See the ideogram below.			
1.92	±0.21		[1] ABOUZAID	11	KTEV	Assuming *CPT*
1.47	±0.22		BATLEY	02	NA48	
0.74	±0.52	±0.29	GIBBONS	93B	E731	
• • • We use the following data for averages but not for fits. • • •						
2.3	±0.65		[2,3] BARR	93D	NA31	

ε' /ε PDG 2018

WEIGHTED AVERAGE
1.68±0.20 (Error scaled by 1.4)

Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our 'best' values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

			χ^2
ABOUZAID	11	KTEV	1.3
BATLEY	02	NA48	0.9
BARR	93D	NA31	0.9
GIBBONS	93B	E731	2.5
			5.6

(Confidence Level = 0.132)

The measurement of a non-zero ε'/ε:

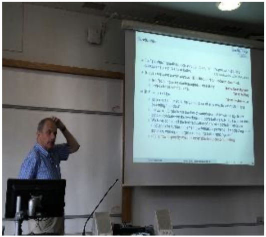
$$\varepsilon'/\varepsilon_{(\mathrm{PDG\ average})} = (1.68 \pm 0.20) \times 10^{-3}$$

ruled out super-weak models and gave strong support to the hypothesis that CP-Violation is naturally included into the Kobayashi and Maskawa extension to six quarks of Cabibbo flavour mixing (CKM). Decisive confirmation was provided by the discovery of CP-violation in the *B* system

ε'/ε Theory

A non-zero value of ε'/ε established direct CP-Violation. Theoretical "predictions" ranged from 10^{-4} to a few 10^{-3}.

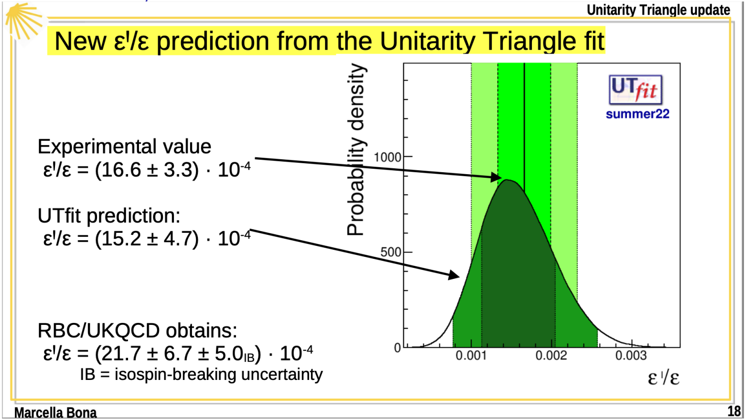
A. Buras and T. Pich, MITP Mainz,
"NA62 Physics Handbook" 2016



C. Sachraida, Kaon2016:
"ε'/ε is now a quantity which is amenable to lattice calculations"

The importance to arrive to a precise theoretical calculation stems from the high sensitivity of ε'/ε to physics beyond the SM

UTfit and ε'/ε



Unitarity Triangle update

New ε'/ε prediction from the Unitarity Triangle fit

Experimental value
$\varepsilon'/\varepsilon = (16.6 \pm 3.3) \cdot 10^{-4}$

UTfit prediction:
$\varepsilon'/\varepsilon = (15.2 \pm 4.7) \cdot 10^{-4}$

RBC/UKQCD obtains:
$\varepsilon'/\varepsilon = (21.7 \pm 6.7 \pm 5.0_{IB}) \cdot 10^{-4}$
IB = isospin-breaking uncertainty

Marcella Bona 18

Solid lattice QCD determinations allow one to include ε'/ε in the fit to the Unitarity Triangle

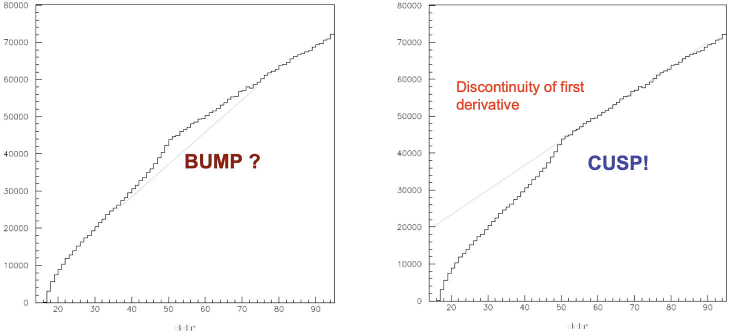
A lot of progress since the pioneering "Weak Interactions on the Lattice" paper by Cabibbo, Martinelli and Petronzio of 1984 [NPB 244 (1984) 381-399]

Strong Interactions at Low Energy: $\pi\pi$ Scattering Length

- At low energy the strong coupling becomes large and a perturbative approach is no longer possible
- Chiral Perturbation Theory predicts precisely the S-wave $\pi\pi$ scattering lengths in the isospin 0 and 2, denoted a_0^0 and s_0^2
- Cabibbo and Maksymowicz (1965) worked out the phenomenology to determines the scattering lengths from the $K^\pm \to \pi^+\pi^- e^\pm \nu$ (K_{e4}) decays
- Scattering lengths can also be extracted from the lifetime of pionium atoms. Searching for pionium in K decays.....Italo Mannelli observed a strange feature in the $\pi^0\pi^0$ invariant mass of $K^\pm \to \pi^\pm\pi^0\pi^0$ decays
- Nicola Cabibbo was at CERN as guest professor where he joined NA48/2: he saw the data, found the origin of the puzzle ($\pi\pi$ re-scattering) and a new way to measure $a_0^0 - a_0^2$ from the $K^\pm \to \pi^\pm\pi^0\pi^0$ decays

Cusp in the $\pi^0\pi^0$ mass distribution of $K^\pm \to \pi^\pm\pi^0\pi^0$ decays

Searching for direct CP-violation in charged kaon decays, NA48/2 accumulated approx. 100 millions $K^\pm \to \pi^\pm\pi^0\pi^0$ decays



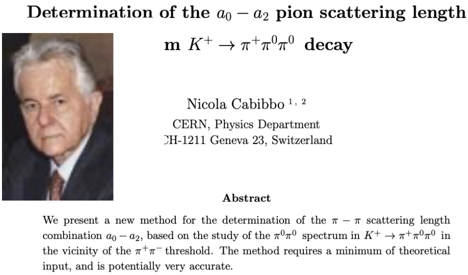
BUMP ?

Discontinuity of first derivative

CUSP!

Italo Mannelli, Cabibbo Memorial Symposium, 2010
cf. NA48/2 Collaboration, PLB 633 (2006)

Interplay Between Theory and Experiment



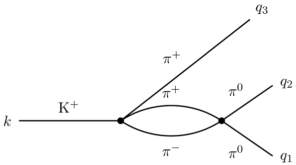
Determination of the $a_0 - a_2$ pion scattering length

m $K^+ \to \pi^+\pi^0\pi^0$ decay

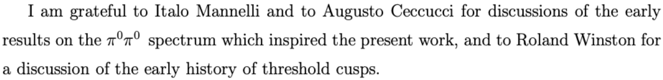
Nicola Cabibbo [1, 2]
CERN, Physics Department
CH-1211 Geneva 23, Switzerland

Abstract

We present a new method for the determination of the $\pi - \pi$ scattering length combination $a_0 - a_2$, based on the study of the $\pi^0\pi^0$ spectrum in $K^+ \to \pi^+\pi^0\pi^0$ in the vicinity of the $\pi^+\pi^-$ threshold. The method requires a minimum of theoretical input, and is potentially very accurate.



Contribution of $\pi^+\pi^- \to \pi^0\pi^0$ to $K^+ \to \pi^+\pi^0\pi^0$.

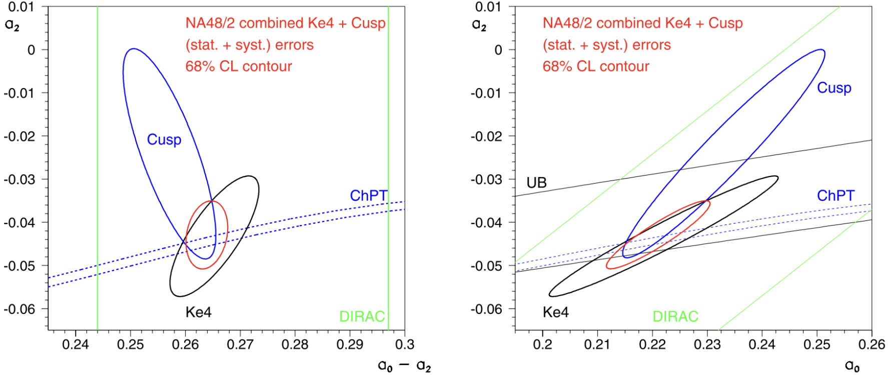


I am grateful to Italo Mannelli and to Augusto Ceccucci for discussions of the early results on the $\pi^0\pi^0$ spectrum which inspired the present work, and to Roland Winston for a discussion of the early history of threshold cusps.

See N. Cabibbo and G. Isidori JHEP 05 (2005) 021 for the complete theory and NA48/2 Collab. EPJC 64 (2009) 589 for the final data analysis

NA48/2: $\pi\pi$ Scattering Length

From $K^+ \to \pi^+\pi^0\pi^0$ and $K^+ \to \pi^+\pi^-e^+\nu$ decays



Eur. Phys. J. C. (2010) 70

$$a_0^0 = 0.2210 \pm 0.0047_{\text{stat}} \pm 0.0040_{\text{syst}},$$

$$a_0^2 = -0.0429 \pm 0.0044_{\text{stat}} \pm 0.0028_{\text{syst}},$$

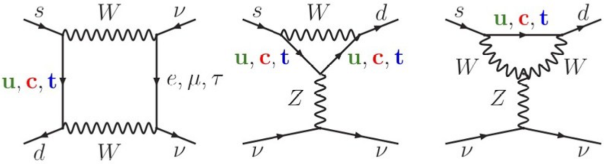
$$a_0^0 - a_0^2 = 0.2639 \pm 0.0020_{\text{stat}} \pm 0.0015_{\text{syst}}$$

Rare Kaon Decays

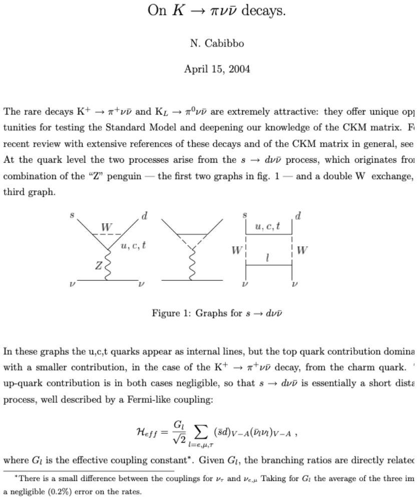
Earliest rare kaon decay results

Decay	UL (90% CL)	Year	Ref.
$K^+ \to \pi^+ e^+ e^-$	2.45×10^{-6}	1964	U. Camerini et al.
$K^+ \to \pi^+ \mu^+ \mu^-$	3×10^{-6}	1965	U. Camerini et al.
$K_L \to \mu^+ \mu^-$	1.6×10^{-6}	1967	M. Bott-Bodenhausen et al.
$K^+ \to \pi^+ \nu \bar{\nu}$	1×10^{-4}	1969	U. Camerini et al.

- Absence of Flavour Changing Neutral Currents (FCNC): → c-quark (Glashow, Iliopoulos, Maiani)
- Sensitivity to genuine higher order electro-weak contributions precisely predictable



Motivation to study $K \to \pi\nu\bar{\nu}$



On $K \to \pi\nu\bar{\nu}$ decays.

N. Cabibbo

April 15, 2004

The rare decays $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ are extremely attractive: they offer unique op
tunities for testing the Standard Model and deepening our knowledge of the CKM matrix. F
recent review with extensive references of these decays and of the CKM matrix in general, see
At the quark level the two processes arise from the $s \to d\nu\bar{\nu}$ process, which originates fro
combination of the "Z" penguin — the first two graphs in fig. 1 — and a double W exchange,
third graph.

Figure 1: Graphs for $s \to d\nu\bar{\nu}$

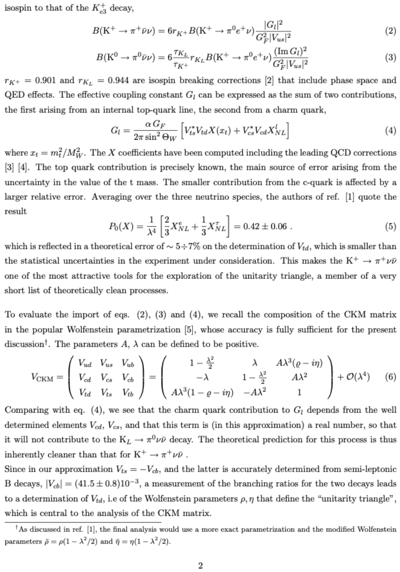
In these graphs the u,c,t quarks appear as internal lines, but the top quark contribution domina
with a smaller contribution, in the case of the $K^+ \to \pi^+\nu\bar{\nu}$ decay, from the charm quark.
up-quark contribution is in both cases negligible, so that $s \to d\nu\bar{\nu}$ is essentially a short dista
process, well described by a Fermi-like coupling:

$$\mathcal{H}_{eff} = \frac{G_l}{\sqrt{2}} \sum_{l=e,\mu,\tau} (\bar{s}d)_{V-A}(\bar{\nu}_l\nu_l)_{V-A} \ ,$$

where G_l is the effective coupling constant*. Given G_l, the branching ratios are directly relate

---

*There is a small difference between the couplings for ν_τ and $\nu_{e,\mu}$ Taking for G_l the average of the three im
a negligible (0.2%) error on the rates.



isospin to that of the K^+_{e3} decay,

$$B(K^+ \to \pi^+\bar{\nu}\nu) = 6 r_{K^+} B(K^+ \to \pi^0 e^+ \nu) \frac{|G_l|^2}{G_F^2 |V_{us}|^2} \tag{2}$$

$$B(K^0 \to \pi^0\bar{\nu}\nu) = 6 \frac{\tau_{K_L}}{\tau_{K^+}} r_{K_L} B(K^+ \to \pi^0 e^+ \nu) \frac{(\mathrm{Im}\, G_l)^2}{G_F^2 |V_{us}|^2} \tag{3}$$

$r_{K^+} = 0.901$ and $r_{K_L} = 0.944$ are isospin breaking corrections [2] that include phase space and QED effects. The effective coupling constant G_l can be expressed as the sum of two contributions, the first arising from an internal top-quark line, the second from a charm quark,

$$G_l = \frac{\alpha\, G_F}{2\pi \sin^2 \Theta_W} \left[V_{ts}^* V_{td} X(x_t) + V_{cs}^* V_{cd} X_{NL}^l \right] \tag{4}$$

where $x_t = m_t^2/M_W^2$. The X coefficients have been computed including the leading QCD corrections [3] [4]. The top quark contribution is precisely known, the main source of error arising from the uncertainty in the value of the t mass. The smaller contribution from the c-quark is affected by a larger relative error. Averaging over the three neutrino species, the authors of ref. [1] quote the result

$$P_0(X) = \frac{1}{\lambda^4} \left[\frac{2}{3} X_{NL}^e + \frac{1}{3} X_{NL}^\tau \right] = 0.42 \pm 0.06 \ . \tag{5}$$

which is reflected in a theoretical error of $\sim 5 \div 7\%$ on the determination of V_{td}, which is smaller than the statistical uncertainties in the experiment under consideration. This makes the $K^+ \to \pi^+\nu\bar{\nu}$ one of the most attractive tools for the exploration of the unitarity triangle, a member of a very short list of theoretically clean processes.

To evaluate the import of eqs. (2), (3) and (4), we recall the composition of the CKM matrix in the popular Wolfenstein parametrization [5], whose accuracy is fully sufficient for the present discussion†. The parameters A, λ can be defined to be positive.

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\varrho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \varrho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4) \tag{6}$$

Comparing with eq. (4), we see that the charm quark contribution to G_l depends from the well determined elements V_{cd}, V_{cs}, and that this term is (in this approximation) a real number, so that it will not contribute to the $K_L \to \pi^0\nu\bar{\nu}$ decay. The theoretical prediction for this process is thus inherently cleaner than that for $K^+ \to \pi^+\nu\bar{\nu}$.

Since in our approximation $V_{ts} = -V_{cb}$, and the latter is accurately determined from semi-leptonic B decays, $|V_{cb}| = (41.5 \pm 0.8)10^{-3}$, a measurement of the branching ratios for the two decays leads to a determination of V_{td}, i.e of the Wolfenstein parameters ρ, η that define the "unitarity triangle", which is central to the analysis of the CKM matrix.

---

†As discussed in ref. [1], the final analysis would use a more exact parametrization and the modified Wolfenstein parameters $\bar{\rho} = \rho(1 - \lambda^2/2)$ and $\bar{\eta} = \eta(1 - \lambda^2/2)$.

2

Motivation to study $K \to \pi\nu\bar{\nu}$

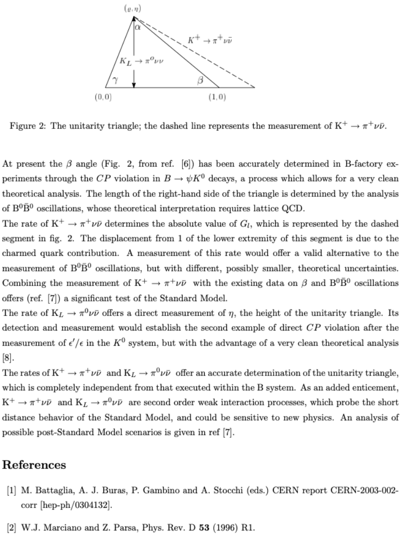


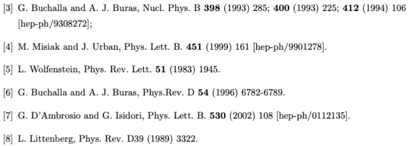
Figure 2: The unitarity triangle; the dashed line represents the measurement of $K^+ \to \pi^+\nu\bar{\nu}$.

At present the β angle (Fig. 2, from ref. [6]) has been accurately determined in B-factory experiments through the CP violation in $B \to \psi K^0$ decays, a process which allows for a very clean theoretical analysis. The length of the right-hand side of the triangle is determined by the analysis of $B^0\bar{B}^0$ oscillations, whose theoretical interpretation requires lattice QCD.
The rate of $K^+ \to \pi^+\nu\bar{\nu}$ determines the absolute value of G_l, which is represented by the dashed segment in fig. 2. The displacement from 1 of the lower extremity of this segment is due to the charmed quark contribution. A measurement of this rate would offer a valid alternative to the measurement of $B^0\bar{B}^0$ oscillations, but with different, possibly smaller, theoretical uncertainties. Combining the measurement of $K^+ \to \pi^+\nu\bar{\nu}$ with the existing data on β and $B^0\bar{B}^0$ oscillations offers (ref. [7]) a significant test of the Standard Model.
The rate of $K_L \to \pi^0\nu\bar{\nu}$ offers a direct measurement of η, the height of the unitarity triangle. Its detection and measurement would establish the second example of direct CP violation after the measurement of ϵ'/ϵ in the K^0 system, but with the advantage of a very clean theoretical analysis [8].
The rates of $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ offer an accurate determination of the unitarity triangle, which is completely independent from that executed within the B system. As an added enticement, $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ are second order weak interaction processes, which probe the short distance behavior of the Standard Model, and could be sensitive to new physics. An analysis of possible post-Standard Model scenarios is given in ref [7].

References

[1] M. Battaglia, A. J. Buras, P. Gambino and A. Stocchi (eds.) CERN report CERN-2003-002-corr [hep-ph/0304132].

[2] W.J. Marciano and Z. Parsa, Phys. Rev. D **53** (1996) R1.


[3] G. Buchalla and A. J. Buras, Nucl. Phys. B **398** (1993) 285; **400** (1993) 225; **412** (1994) 106 [hep-ph/9308272];

[4] M. Misiak and J. Urban, Phys. Lett. B. **451** (1999) 161 [hep-ph/9901278].

[5] L. Wolfenstein, Phys. Rev. Lett. **51** (1983) 1945.

[6] G. Buchalla and A. J. Buras, Phys.Rev. D **54** (1996) 6782-6789.

[7] G. D'Ambrosio and G. Isidori, Phys. Lett. B. **530** (2002) 108 [hep-ph/0112135].

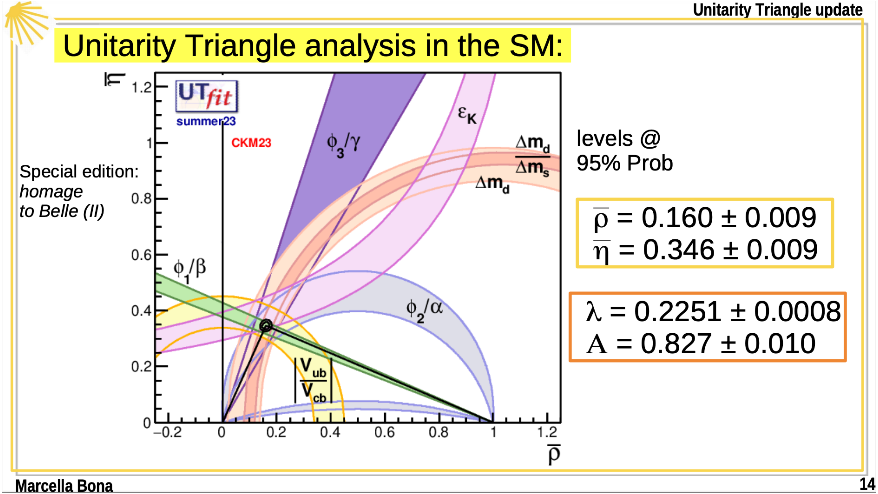
[8] L. Littenberg, Phys. Rev. D39 (1989) 3322.

$$B(\mathrm{K}^+ \to \pi^+\bar{\nu}\nu) = 6 r_{\mathrm{K}^+} B(\mathrm{K}^+ \to \pi^0 e^+\nu)\frac{|G_l^+|^2}{G_F^2|V_{us}|^2}$$

$$B(\mathrm{K}_L \to \pi^0\bar{\nu}\nu) = 6\frac{\tau_{K_L}}{\tau_{\mathrm{K}^+}} r_{K_L} B(\mathrm{K}^+ \to \pi^0 e^+\nu)\frac{(\mathrm{Im}\ G_l^L)^2}{G_F^2|V_{us}|^2}$$

This article formed the physics motivation of the NA62 proposal

CKM Triangle



Unitarity Triangle update

Unitarity Triangle analysis in the SM:

Special edition:
homage
to Belle (II)

levels @
95% Prob

$\bar{\rho}$ = 0.160 ± 0.009
$\bar{\eta}$ = 0.346 ± 0.009

λ = 0.2251 ± 0.0008
A = 0.827 ± 0.010

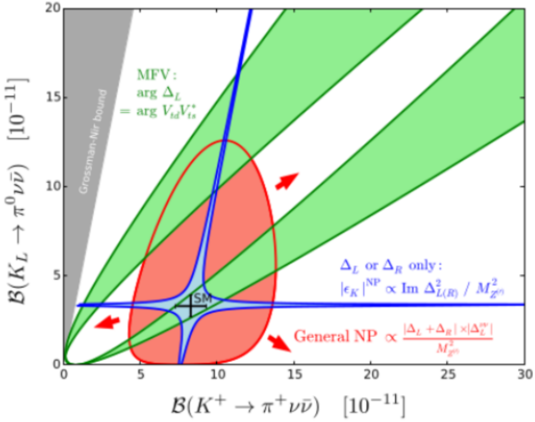
Marcella Bona

14

Important test of SM: use precise CKM inputs from B decays to predict BR of rare K decays and compare with experiments

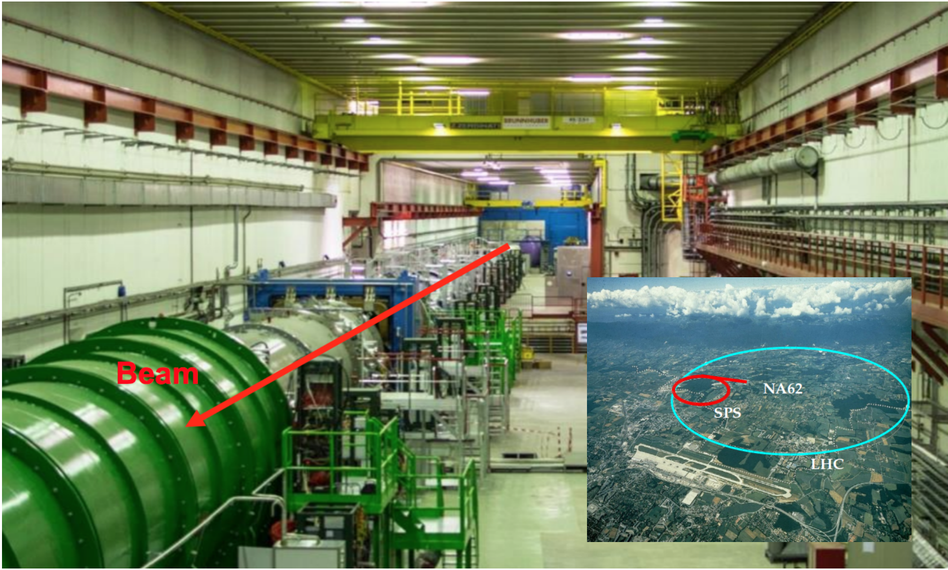
Beyond SM

Buras et al., JHEP11 (2015) 166

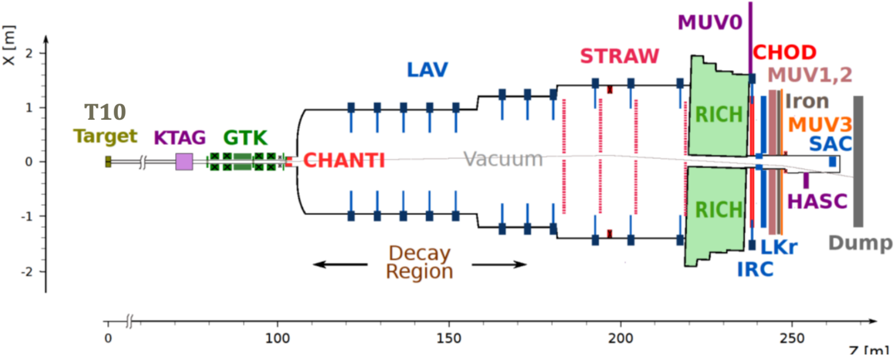


Most extensions of SM predict contributions to the branching ratio, e.g.: MFV; Simplified Z, Z'; LFU violation; Custodial Randall-Sundrum; MSSM; Littlest Higgs with T-parity; Leptoquarks,...

NA62@CERN: $K^+ \to \pi^+ \nu \bar{\nu}$ with Decays-in-flight



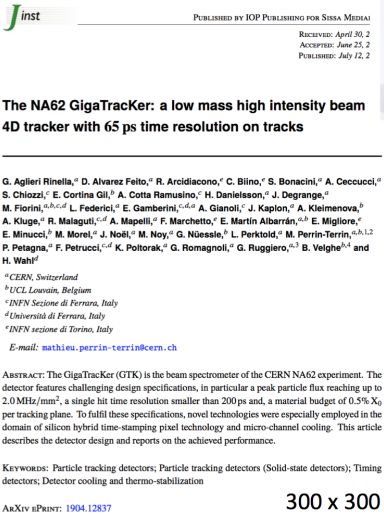
NA62 Beam and Layout



Nominal Intensity	33×10^{11} ppp SPS 400 GeV/c
Incoming K^+, 75 GeV/c, 1% rms	Timing by KTAG (σ_t~70 ps); measured by GTK; rate at GTK ~600 MHz
Outgoing π^+	Timing by RICH (σ_t~70 ps); measured by STRAW; rate at Straw ~5 MHz
γ/multitrack veto (LAV, LKr, IRC, SAC, HASC)	$\pi^0 \to \gamma\gamma$ suppression $\sim 10^{-8}$
Particle ID (RICH, LKr, MUV1,2,3)	μ^+ suppression $\sim 10^{-8}$

JINST 12 P05025 (2017)

NA62 Gigatracker: State-of-the-art 4D Tracking



Jinst Published by IOP Publishing for Sissa Mediai

Received: April 30, 2
Accepted: June 25, 2
Published: July 12, 2

The NA62 GigaTracKer: a low mass high intensity beam 4D tracker with 65 ps time resolution on tracks

G. Aglieri Rinella,[a] D. Alvarez Feito,[a] R. Arcidiacono,[e] C. Biino,[e] S. Bonacini,[a] A. Ceccucci,[a] S. Chiozzi,[c] E. Cortina Gil,[b] A. Cotta Ramusino,[c] H. Danielsson,[a] J. Degrange,[a] M. Fiorini,[a,b,c,d] L. Federici,[a] E. Gamberini,[c,d,a] A. Gianoli,[c] J. Kaplon,[a] A. Kleimenova,[b] A. Kluge,[a] R. Malaguti,[c,d] A. Mapelli,[a] F. Marchetto,[e] E. Martín Albarrán,[a,b] E. Migliore,[e] E. Minucci,[b] M. Morel,[a] J. Noël,[a] M. Noy,[a] G. Nüessle,[b] L. Perktold,[a] M. Perrin-Terrin,[a,b,1,2] P. Petagna,[a] F. Petrucci,[c,d] K. Poltorak,[a] G. Romagnoli,[a] G. Ruggiero,[a,3] B. Velghe[b,4] and H. Wahl[d]

[a] *CERN, Switzerland*
[b] *UCL Louvain, Belgium*
[c] *INFN Sezione di Ferrara, Italy*
[d] *Università di Ferrara, Italy*
[e] *INFN sezione di Torino, Italy*

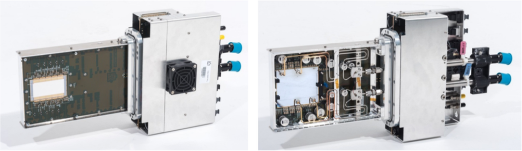
E-mail: mathieu.perrin-terrin@cern.ch

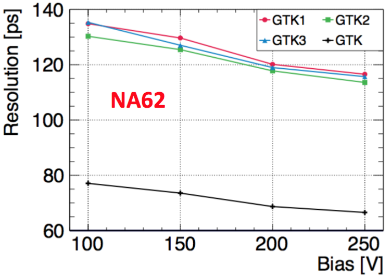
Abstract: The GigaTracKer (GTK) is the beam spectrometer of the CERN NA62 experiment. The detector features challenging design specifications, in particular a peak particle flux reaching up to 2.0 MHz/mm^2, a single hit time resolution smaller than 200 ps and, a material budget of 0.5% X_0 per tracking plane. To fulfil these specifications, novel technologies were especially employed in the domain of silicon hybrid time-stamping pixel technology and micro-channel cooling. This article describes the detector design and reports on the achieved performance.

Keywords: Particle tracking detectors; Particle tracking detectors (Solid-state detectors); Timing detectors; Detector cooling and thermo-stabilization

ArXiv ePrint: 1904.12837

2019 JINST 14 P07010





300 x 300 micron^2 time res ~ 65 ps, ~ 0.5% X_0/station

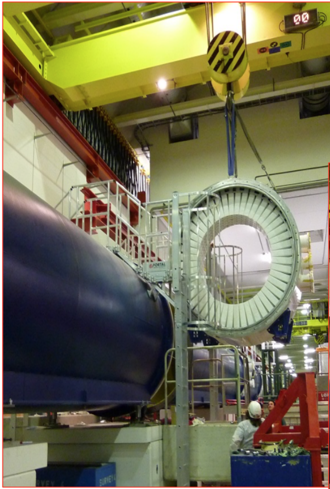
NA62 Straws Tracker

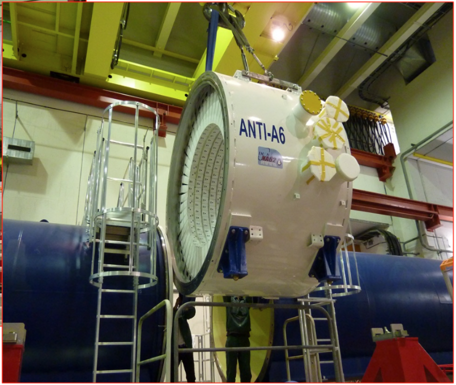
- Straw tubes (9.8 mm diameter)
- 36 μm thick mylar
- Ultrasonic welding

- Operated inside vacuum tank

NA62: Large Angle Vetos (LAV)

π^0 Rejection

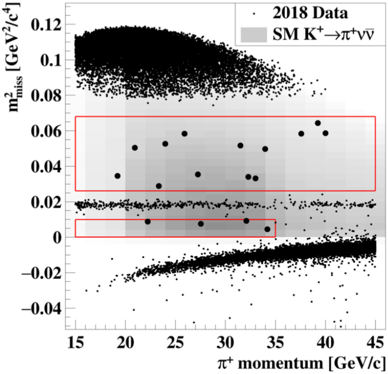


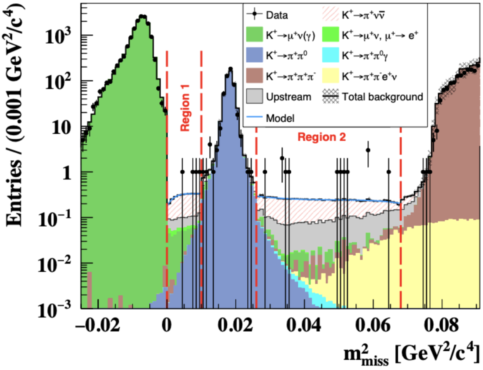


Lead Glass from CERN-LEP Experiment OPAL

NA62 2016-2018 Data JHEP 06 (2021) 093 arXiv:2103.15389 [hep-ex]

17(2018)+2(2017)+1(2016) = 20 Candidates Observed



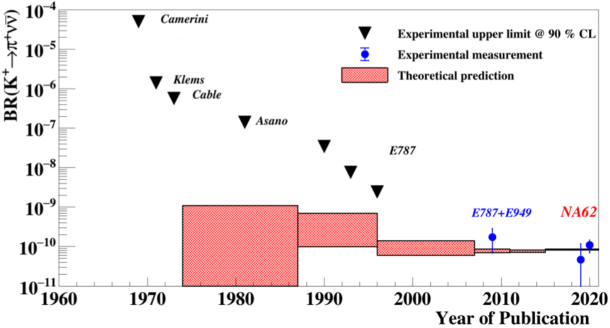


$$SES = (0.839 \pm 0.053_{syst}) \times 10^{-11},\ N^{Exp}_{back} = 7.03^{+1.05}_{-0.82}$$

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}\ (stat) \pm 0.9\ (syst)) \times 10^{-11}$$

$$B_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.60 \pm 0.42) \times 10^{-11}$$ [Buras, Venturini, 2021]

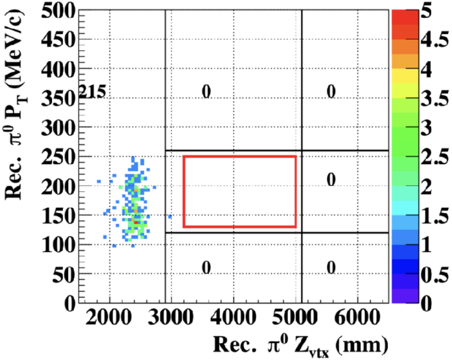
Historical



- A. V. Artamonov *et al.* [BNL-E949] Phys. Rev. D **79** (2009), 092004
  Adler S, *et al.* [E949 and E787] *Phys. Rev. D* 77:052003 (2008)
- NA62 2016 data
  E. Cortina Gil *et al.* [NA62], Phys. Lett. B **791**, 156-166 (2019) doi:10.1016/j.physletb.2019.01.067 [arXiv:1811.08508 [hep-ex]
- NA62 2017 data
  E. Cortina Gil *et al.* [NA62], JHEP 11:042 (2020) [arXiv:2007.08218 [hep-ex]
- NA62 2018 data
  E. Cortina Gil *et al.* [NA62], JHEP 06 (2021) 093 arXiv:2103.15389 [hep-ex]

NA62 data taking resumed in 2021. It will continue until the end of 2025 aiming for a 15% BR measurement (if SM)

KOTO J-PARC: 2021 Result



Presented by KOJI SHIOMI on September 6, 2023: 0 candidates

$\mathrm{BR}(K_L^0 \to \pi^0 \nu\bar{\nu}) < 2\ 10^{-9}$ 90% CL

$B_{SM}(K_L^0 \to \pi^0 \nu\bar{\nu}) = (2.94 \pm 0.15) \times 10^{-11}$[Buras, Venturini, 2021]

KOTO expects to reach a sensitivity $< 10^{-10}$ over the next 3-4 years

Prospects for Future Kaon Experiments

- At CERN the North Area will be upgraded to be able to accept much larger protons intensities available from the SPS
- The proposed successor of NA62 is HIKE:
  CERN-SPSC-2023-031; SPSC-P-368. - 2023
- HIKE is meant to measure both charged and neutral kaons decays
- A decision is expected soon, possibly before the end of 2023

HIKE
High Intensity Kaon Experiments

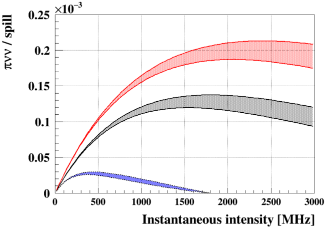
Principal HIKE Physics goals:

Phase 1:
➢ Measure BR($K^+ \to \pi^+ \nu\bar{\nu}$) at 5% precision

Phase 2:
➢ Measure ($K_L \to \pi^0 l^+ l^-$) at 20% precision

- A workshop summary - Kaons@ CERN 2023, provides an up-to-date overview of kaon physics and its world-wide prospects arXiv:2311.02923v1 [hep-ph]

HIKE Physics Prospects in Detail



HIKE

NA62 (time resolution improved x4)

NA62

HIKE: measurements of rare K^+ and K_L decays to an unprecedented level of precision

$K^+ \to \pi^+ \nu\bar{\nu}$	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 5\%$	BSM physics, LFUV
$K^+ \to \pi^+ \ell^+ \ell^-$	Sub-% precision on form-factors	LFUV
$K^+ \to \pi^- \ell^+ \ell^+$, $K^+ \to \pi\mu e$	Sensitivity $\mathcal{O}(10^{-13})$	LFV / LNV
Semileptonic K^+ decays	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 0.1\%$	V_{us}, CKM unitarity
$R_K = \mathcal{B}(K^+ \to e^+\nu)/\mathcal{B}(K^+ \to \mu^+\nu)$	$\sigma(R_K)/R_K \sim \mathcal{O}(0.1\%)$	LFUV
Ancillary K^+ decays (e.g. $K^+ \to \pi^+\gamma\gamma$, $K^+ \to \pi^+\pi^0 e^+ e^-$)	$\% - ‰$	Chiral parameters (LECs)
$K_L \to \pi^0 \ell^+ \ell^-$	$\sigma_{\mathcal{B}}/\mathcal{B} < 20\%$	Imλ_t to 20% precision, BSM physics, LFUV
$K_L \to \mu^+\mu^-$	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 1\%$	Ancillary for $K \to \mu\mu$ physics
$K_L \to \pi^0(\pi^0)\mu^\pm e^\mp$	Sensitivity $\mathcal{O}(10^{-12})$	LFV
Semileptonic K_L decays	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 0.1\%$	V_{us}, CKM unitarity
Ancillary K_L decays (e.g. $K_L \to \gamma\gamma$, $K_L \to \pi^0\gamma\gamma$)	$\% - ‰$	Chiral parameters (LECs), SM $K_L \to \mu\mu$, $K_L \to \pi^0\ell^+\ell^-$ rates

Many More Compelling Kaon Physics Topics...

- Lepton Universality
- Lepton Flavor Violation
- Lepton Number Violation
- Search for Heavy Neutral Leptons
- Search for invisible decays
- Search for invisible bosons or heavy neutral leptons
- Hadron structure / precision measurements
- Cabibbo angle: V_{us} and Unitarity → Cirigliano

Concluding Remarks

- The exquisite interplay of theory and experiment makes kaon physics quite special
- Kaon experiments have been perfect vehicles to push the detector technology (e.g. bent channelling crystal, liquid krypton calorimeter, tracking in extreme conditions,...). The future challenges are such that this trend will continue
- Kaon experiments are exceptional training grounds for the next generations
- It is remarkable that new competitive explorations can be launched relying on existing accelerators (e.g. CERN SPS, J-PARC MR)
- I had the privilege to witness the insight of Cabibbo directly when he joined CERN as guest professor in 2004. The elegance and simplicity of his reasoning, coupled to the capability to focus to the strictly essential form an important part of his unique legacy