The Experimental Landscape for Kaon Physics: Past and Present

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Kaons@CERN

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The Past: Historical Foreword

Strange particles provided many building blocks of the Standard Model (SM):

- Strong production and weak decays $\rightarrow$ Flavor
- $K^0 - \bar{K}^0$ oscillation $\rightarrow$ Flavor mixing
- θ/τ paradox $\rightarrow$ P-Violation
- Universality of the weak interaction $\rightarrow$ Cabibbo Theory
- Absence of FCNC $\rightarrow$ Four quarks (GIM)
- CP-Violation $\rightarrow$ Six quarks (KM)

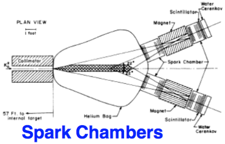
We often complain that the SM passes every test and we tend to forget that the SM was not always the same: it has been growing incorporating step by step all the new discoveries. One could say that the aim of particle physics is to continue to build the SM rather than to break it.

CP-Violation

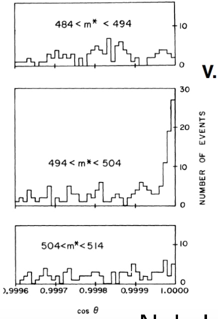
$\pi^+\pi^-$ (CP=+1) $K_1 = 1/\sqrt{2}(K_0 + \bar{K}_0)$ (CP=+1)

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

$K^0_L \rightarrow \pi^+\pi^- \Rightarrow$



Spark Chambers



V.L.Fitch R.Turlay J.W.Cronin J.H.Christenson

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

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

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

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

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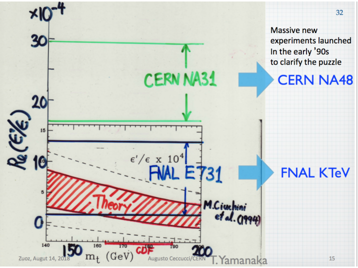
Nobel prize 1980 V. L. Fitch and J. W. Cronin

Indirect (ε) and Direct (ε') CP-Violation



Phenomenology: Wu and Yang, (1964)

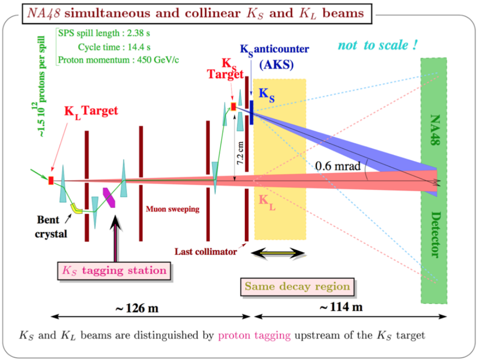
$$\eta_{\pm} = \varepsilon + \varepsilon'$$

$$\eta_{00} = \varepsilon - 2\varepsilon'$$

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

$$R = \frac{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)}{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)} \simeq 1 - 6\ \varepsilon'/\varepsilon.$$

Measuring ε'/ε: NA48@CERN



- 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

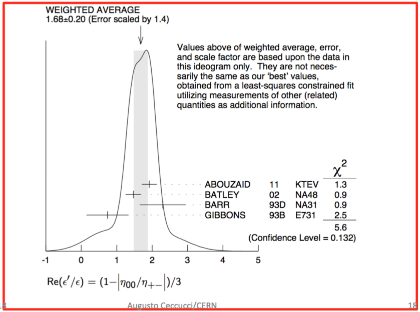
Electrode structure (half) of the Liquid Krypton Calorimeter, **now used by NA62, cold (~120 K) since 1998**

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



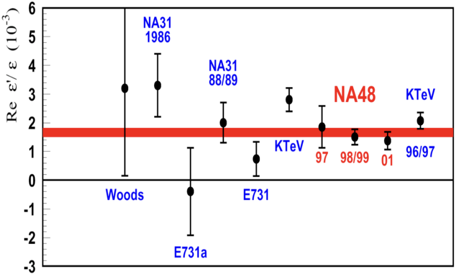
Zuoz, Augut 14, 2018 Augusto Ceccucci/CERN 18

The measurement of a non-zero ε'/ε:

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

ruled out super-weak models and was a strong endorsement for the CKM explanation of CP-violation which was then confirmed by the discovery of CP-violation in the B system

ε'/ε Timeline & Recognitions



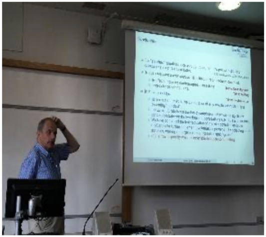
Italo Mannelli and Heinrich Wahl

EPS Young Physicist Prize 2003: G. Unal
EPS High Energy and Particle Physics Prize 2005: Heinrich Wahl and the NA31 Collaboration
APS Panofsky prize 2007: I. Mannelli, H. Wahl and B. Winstein

ε'/ε Theory

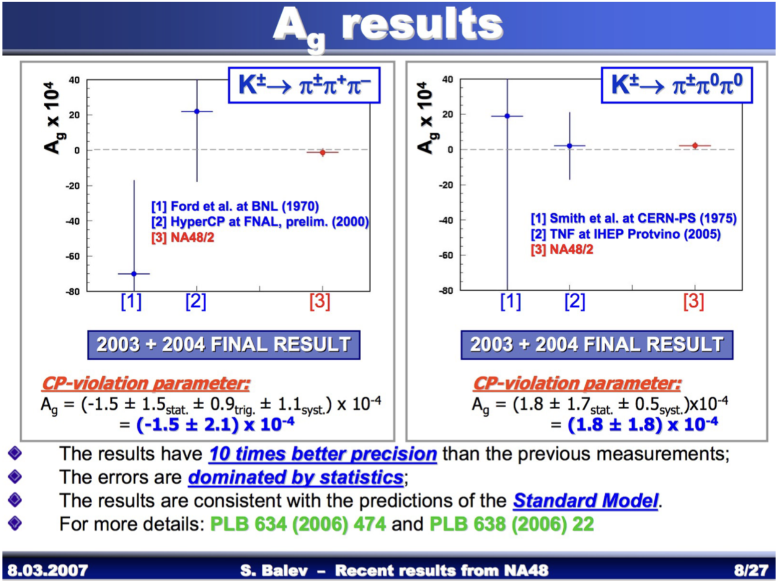
In the mean time the theorists....

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"

NA48/2: Direct CPV in Charged Kaons

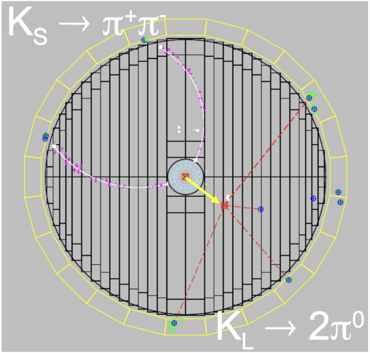


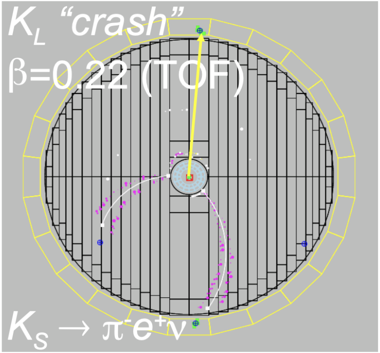
Φ Factory: tagged neutral kaon pairs

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

$$|\eta_{000}| = \sqrt{\frac{\tau_L}{\tau_S}\frac{BR(K_S \to 3\pi^0)}{BR(K_L \to 3\pi^0)}} \leq 0.0088 \quad \text{at 90 \% CL}$$

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





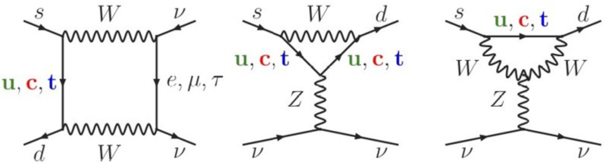
K_L tagged by
$K_S \to \pi^+\pi^-$ vertex at IP

K_S tagged by
K_L interaction in EmC

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.



- Historically a tool to look for Flavor Changing Neutral Currents (FCNC)
- Sensitivity to genuine higher order electro-weak contributions (GIM)
- Disentangling between CP-Violation models (super-weak/milliweak)
- Contributions from heavy quark masses (Inami-Lim 1981)
- Relatively larger direct CP-Violation than ε'/ε

Rare K Decays: $K^+ \to \pi^+ \nu \bar{\nu}$ A. Buras et al. JHEP 11 (2015) 033

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ (1+\Delta_{\rm EM}) \left[\left(\frac{\Im \lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\Re \lambda_c}{\lambda} P_c(X) + \frac{\Re \lambda_t}{\lambda^5} X(x_t) \right)^2 \right]$$

CP-Violating CP-Conserving

- $\Delta_{EM} = -0.003$ the electromagnetic radiative corrections
- $x_t = m_t^2 / M_W^2$ (QCD charm NNLO)
- $\lambda = |V_{us}|$, $\lambda_i = V_{is}^* V_{id}$ the relevant combinations of CKM matrix elements
- X and $P_c(X)$ the loop functions for the top and charm quark respectively
- $\kappa_+ = (5.173 \pm 0.025) \times 10^{-11} \left[\frac{\lambda}{0.225}\right]^8$ encodes the hadronic matrix element from semi-leptonic data: Theoretical error (QCD+EW)=3.6%

Removing the $|V_{cb}|$ dependence following Buras and Venturini [arXiv:2109.11032]

$$\frac{B(K^+ \to \pi^+ \nu\bar{\nu})}{|\varepsilon_K|^{0.82}} = (1.31 \pm 0.05) \times 10^{-8} \left(\frac{\sin 22.2^\circ}{\sin \beta} \right)^{0.71} \left(\frac{\sin \gamma}{\sin 64.6^\circ} \right)^{0.015}$$

and introducing the numerical values, one gets a SM prediction with a precision better than 5%:

$$B_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.60 \pm 0.42) \times 10^{-11}$$

Rare K Decays: $K_L^0 \to \pi^0 \nu \bar{\nu}$

$$B(K_L^0 \to \pi^0 \nu \bar{\nu}) = (2.231 \pm 0.013) \times 10^{-10} \left[\frac{\lambda}{0.225}\right]^8 \left(\frac{\Im \lambda_t}{\lambda^5} X(x_t)\right)^2$$

- The $B(K_L^0 \to \pi^0 \nu \bar{\nu})$ depends only on the square of the imaginary part of the top loop which is CP-violating
- The charm contributions drop out because K_L^0 is mostly an odd linear combination of K^0 and $\bar{K}^0$
- This makes the theoretical prediction for the K_L^0 rate even cleaner than the K^+ one: $\simeq 1.5\%$
- $B\left(K_L^0 \to \pi^0 \nu \bar{\nu}\right) \propto |\Im \lambda_t|^2 \to$ Jarlskog invariant J the unique measure of CP-Violation in the SM

Removing the $|V_{cb}|$ dependence following Buras and Venturini [arXiv:2109.11032]

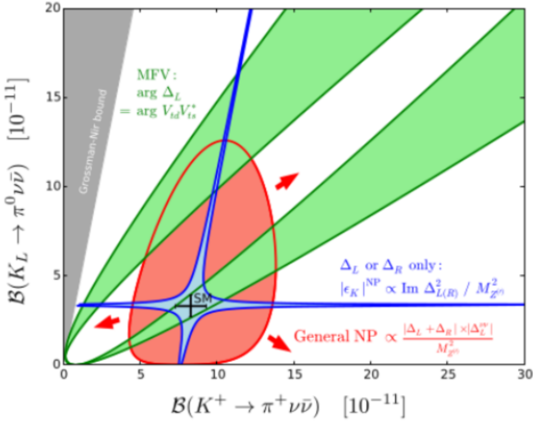
$$\frac{B(K_L^0 \to \pi^0 \nu \bar{\nu})}{|\varepsilon_K|^{1.18}} = (3.87 \pm 0.06) \times 10^{-8} \left(\frac{\sin \beta}{\sin 22.2^\circ}\right)^{0.98} \left(\frac{\sin \gamma}{\sin 64.6^\circ}\right)^{0.03}$$

and introducing the numerical values, one gets:

$$B_{SM}(K_L^0 \to \pi^0 \nu \bar{\nu}) = (2.94 \pm 0.15) \times 10^{-11}$$

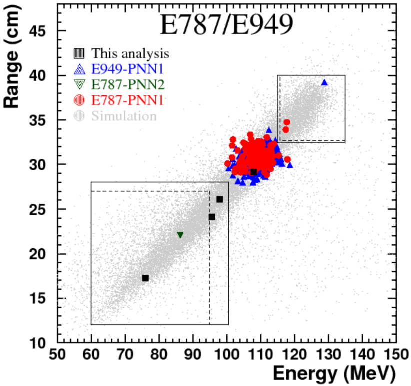
Beyond SM

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,...

BNL E787/E949: $K^+ \to \pi^+\nu\bar{\nu}$ with decays-at-rest

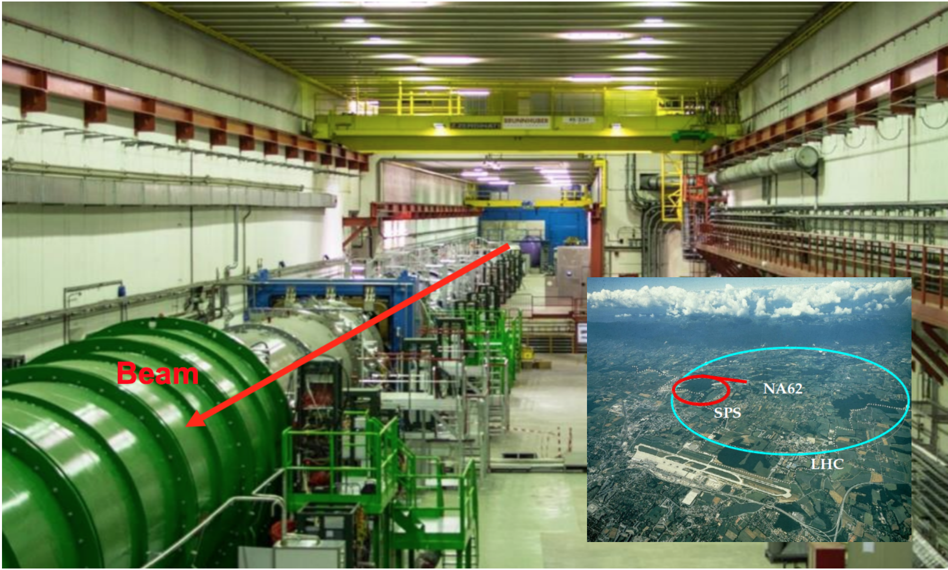


- Artamonov AV, et al. (E949 Collab.) *Phys. Rev. Lett.* 101:191802 (2008)
- Adler S, *et al.* [E949 and E787], *Phys. Rev. D* 77:052003 (2008)
- Separated beam
- full $K^+ \to \pi^+ \to \mu^+ \to e^+$ decay chain
- small acceptance
- SES $\approx$ SM

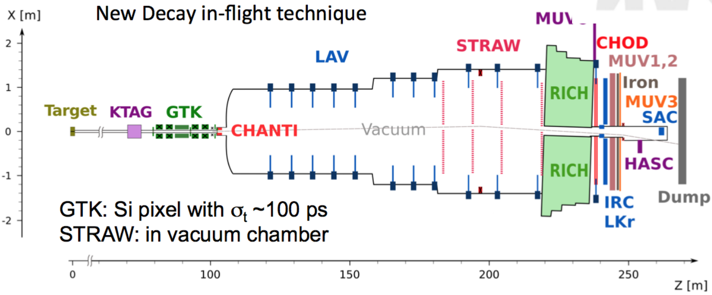
$$B(K^+ \to \pi^+\nu\bar{\nu})_{\mathrm{E787/E949}} = (17.3^{+11.5}_{-10.5}) \times 10^{-11}.$$

APS Panofsky Prize 2011: A.J. Steward Smith, Douglas Bryman and Laurence Littenberg

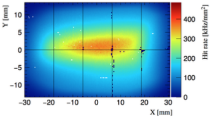
Decays-In-Flight: NA62@CERN



NA62 Beam and Layout



- **SPS Beam:**
  - 400 GeV/c protons
  - 2.10^{12} protons/spill
  - 5s spill [3s eff.] / ~16 s



- **Secondary positive Beam:**
  - 75 GeV/c momentum, 1 % bite
  - 100 μrad divergence (RMS)
  - 60x30 mm^2 transverse size
  - $K^+(6\%)/\pi^+(70\%)/p(24\%)$
  - For $33\text{x}10^{11}$ ppp on T10
  - → 750 MHz at GTK3

- **Decay Region:**
  - 60 m long fiducial region
  - ~ 5 MHz K^+ decay rate
  - Vacuum ~ $O(10^{-6})$ mbar

Detector and Performances: arXiv:1703.08501

JINST 12 P05025 (2017)

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

Jinst

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

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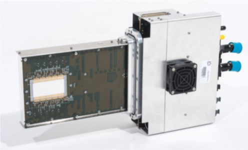
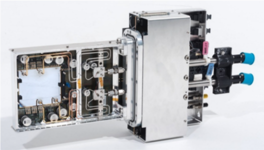
ABSTRACT: The GigaTracKer (GTK) is the beam spectrometer of the CERN NA62 experiment. The detector features challenging design specifications, in particular a peak particle flux reaching up to 2.0 MHz/mm^2, a single hit time resolution smaller than 200 ps and, a material budget of 0.5% X_0 per tracking 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.

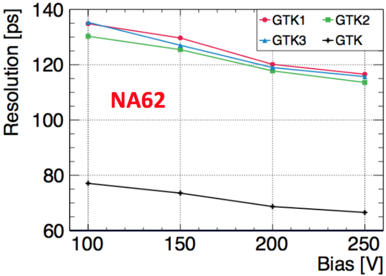
KEYWORDS: Particle tracking detectors; Particle tracking detectors (Solid-state detectors); Timing detectors; Detector cooling and thermo-stabilization

ARXIV EPRINT: 1904.12837

2019 JINST 14 P07010







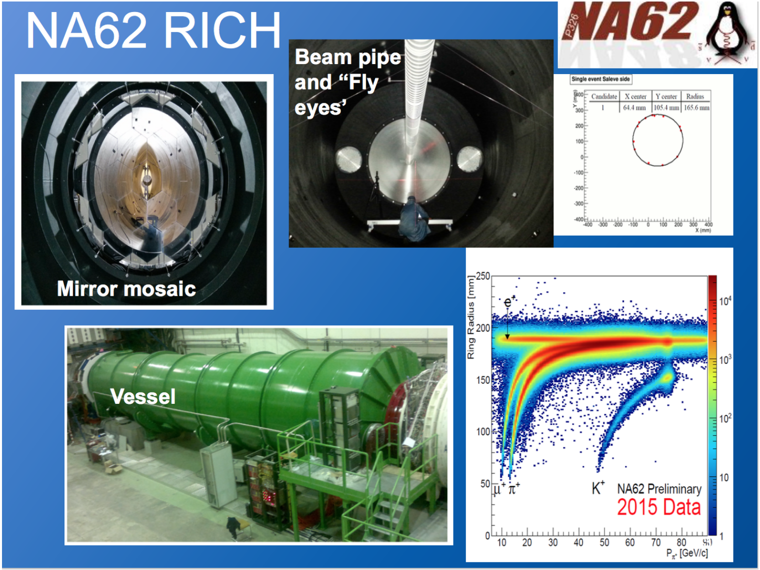
300 x 300 micron^2 time res ~ 65 ps, ~ 0.5% X_0/station

NA62 Straws Tracker

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

- Operated inside vacuum tank

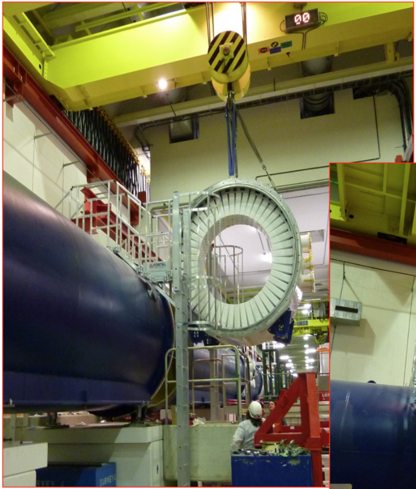
NA62: RICH

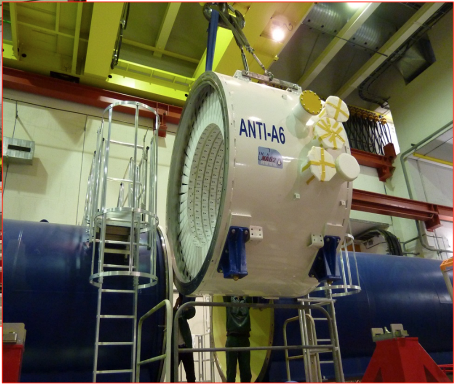


▶ Neon radiator STP, spherical mirrors f=17 m

NA62: Large Angle Vetos (LAV)

π^0 Rejection

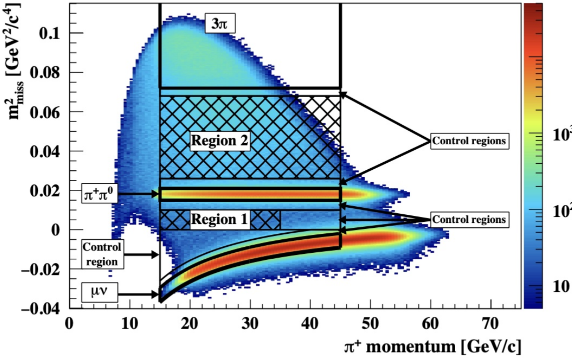


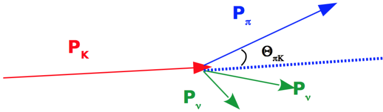


Lead Glass from CERN-LEP Experiment OPAL

NA62: Decay in Flight JHEP 06 (2021) 093 arXiv:2103.15389 [hep-ex]

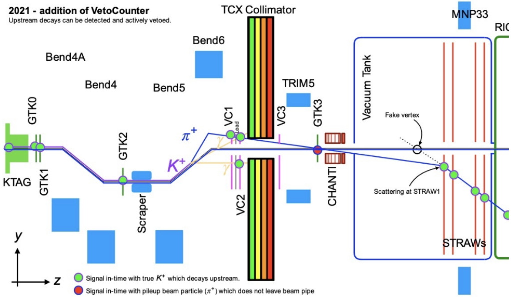
$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$

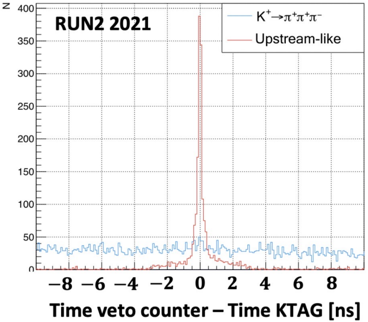




Process	Branching ratio
$K^+ \to \pi^+\pi^0$	0.2066
$K^+ \to \mu^+\nu_\mu$	0.6356
$K^+ \to \pi^+\pi^+\pi^-$	0.0558
$K^+ \to \pi^+\pi^- e\, \nu_e$	4.3×10^{-5}
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	**8.4×10^{-11}**

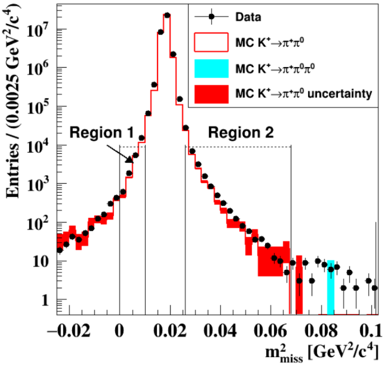
NA62: Backgrounds from Upstream Decays





- Accidental GTK tracks coupled to elastic scattering in first plane of straws $\rightarrow$ upstream decay vertex displaced into fiducial region
- New final Collimator in 2018
- Vetocounter introduced in 2021 to mitigate background
- Minimal loss of signal

NA62: Data Driven Measurement of $K^+ \to \pi^+\pi^0$ Background



- Large samples of kaons collected with minimum bias triggers are essential to measure directly the backgrounds originating from the standard decays
- Ten order of magnitude background suppression requires the combination of cuts based on kinematics, particle identification and extra particle rejection
- The most telling example is the suppression of $K^+ \to \pi^+\pi^0$ two-body decay that splits the signal region in two.
- The LKr calorimeter is not just a high performance veto. Its exquisite energy, time and energy resolutions allow one to completely reconstruct the $K^+ \to \pi^+\pi^0$ without backgrounds and without any information from the tracking system, thus enabling one to measure the kinematic tails directly
- Conversely, the reconstructing $K^+ \to \pi^+\pi^0$ using only track-based information, allows for the direct measurement of the π^0 rejection factor
- The same applies for $K^+ \to \mu^+\nu$ and $K^+ \to \pi^+\pi^+\pi^-$ decays

- Similar data driven methods for $K^+ \to \pi^+\pi^+\pi^-$ and $K^+ \to \mu^+\nu$
- Monte Carlo simulations for the rarer $K^+ \to \pi^+\pi^-e^+\nu$ and $K^+ \to \pi^+\gamma\gamma$

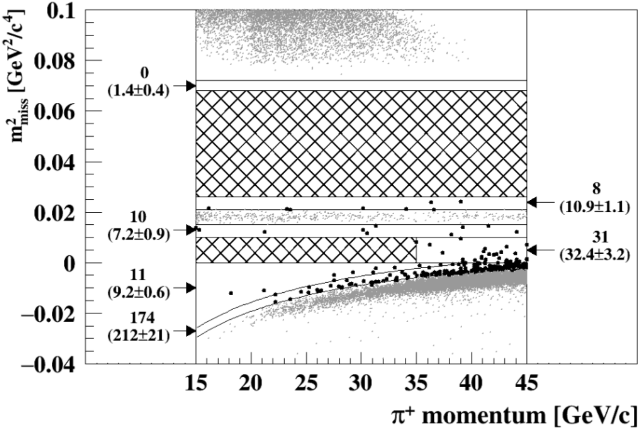
NA62: Summary of Backgrounds

JHEP 06 (2021) 093 arXiv:2103.15389 [hep-ex]

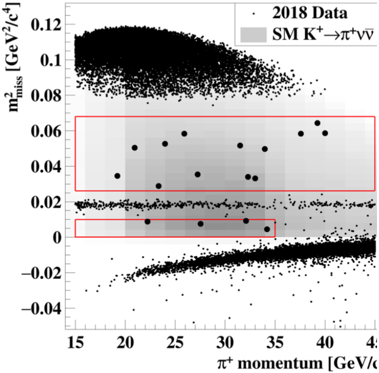
Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

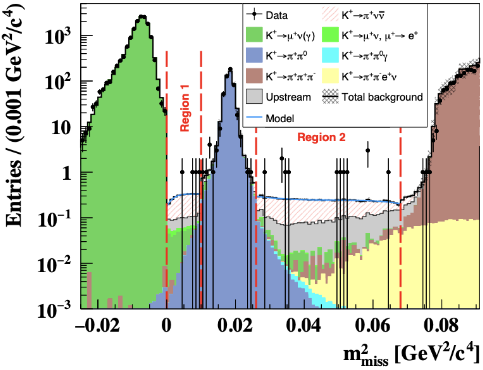
NA62: Control Regions

Observed (expected) events in control regions. Signal regions **blinded**



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

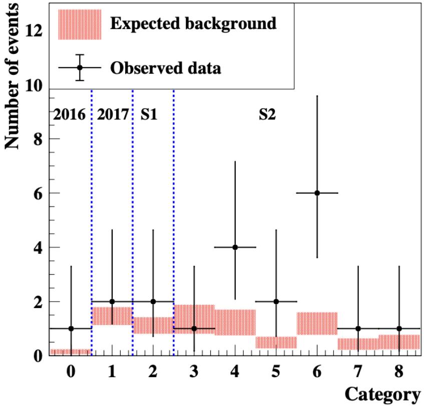




17 Candidates Observed

NA62 Combined Result (2016,2017 and 2018)

JHEP 06 (2021) 093 arXiv:2103.15389 [hep-ex]

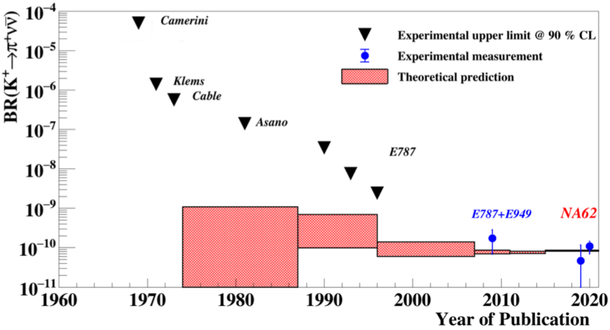


$$SES = (0.839 \pm 0.053_{\text{syst}}) \times 10^{-11},$$
$$N^{\text{exp}}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{\text{syst}} \pm 1.19_{\text{ext}},$$
$$N^{\text{exp}}_{\text{background}} = 7.03^{+1.05}_{-0.82}.$$

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

20 Candidates 3.4 σ significance, $P(back.only)\ 3.4 \cdot 10^{-4}$

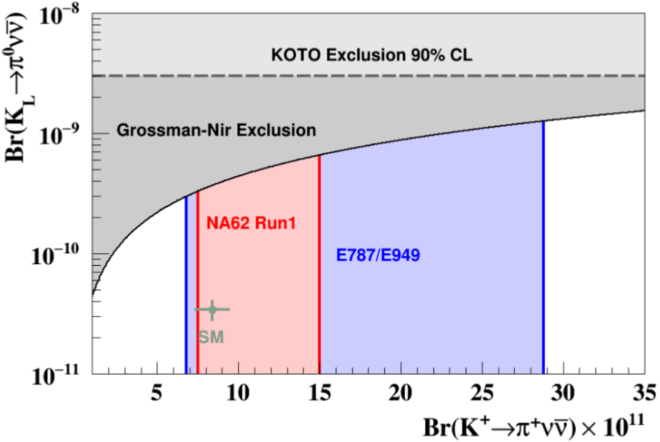
Historical



- 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]

With restricted data taking periods (end 2025) and hardware limitations at higher intensity, NA62 can aim for a 15 % BR_{SM} measurement

Grossman-Nir Bound PLB 398 163 (1997)

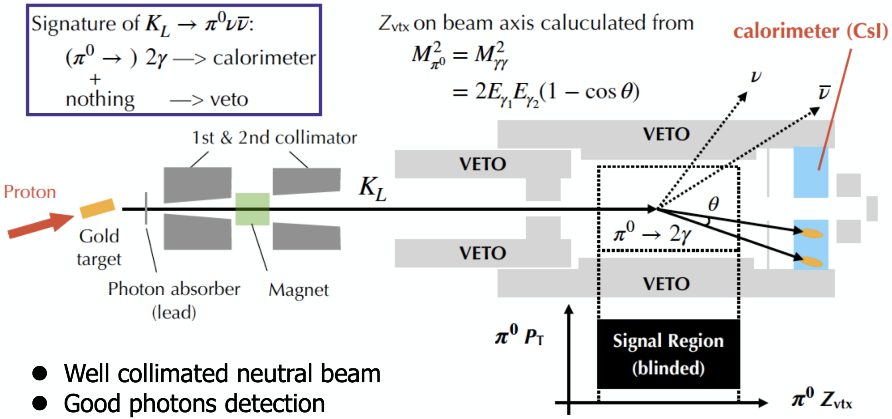


Model Independent limit assumes that the $K^+ \to \pi^+ \nu \bar{\nu}$ mode is entirely CP-violating:

$$B(K_L \to \pi^0 \nu \bar{\nu}) < 4.4 B(K^+ \to \pi^+ \nu \bar{\nu})$$

KOTO J-PARC: $K_L^0 \to \pi^0 \nu \bar{\nu}$ Principle

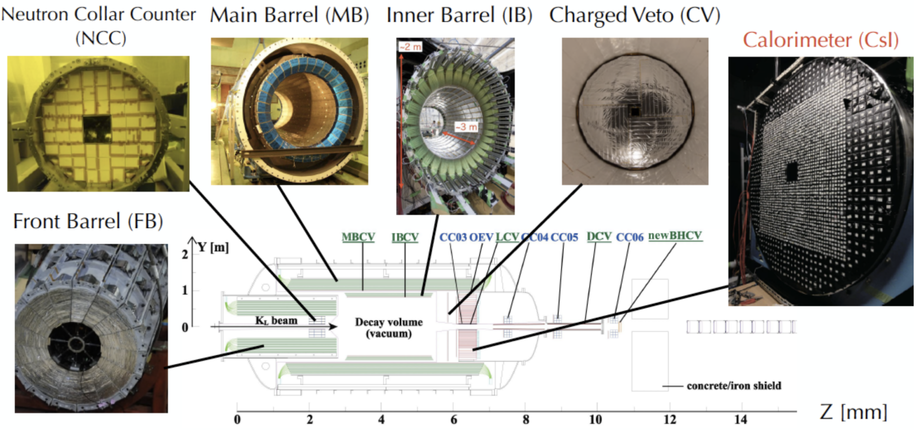
Material from Y. B. Hsiung (NTU), @WIN2023



- Well collimated neutral beam
- Good photons detection
- Hermetic vetoes in decay region

30 GeV/c protons from J-PARC Main Ring

KOTO J-PARC: $K_L^0 \to \pi^0 \nu \bar{\nu}$ Detectors



KOTO J-PARC: 2016-2018 Data

- Single Event Sensitivity:

$$SES = \frac{1}{N_{K_L} \times A_{signal}} = 7.2 \times 10^{-10}$$

- 3 events observed ==> consistent to #BG
- $BR(K_L \to \pi^0 \nu\bar{\nu}) < 4.9 \times 10^{-9}$ (90% C.L.)

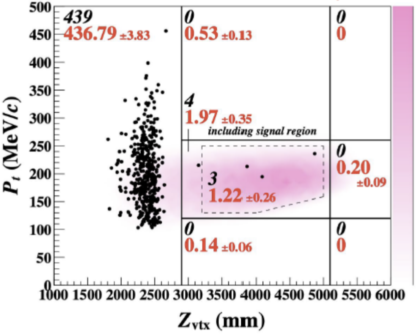
Background Table

Source		Number of events
K_L	$K_L \to 3\pi^0$	0.01 ± 0.01
	$K_L \to 2\gamma$ (beam halo)	0.26 ± 0.07[a]
	Other K_L decays	0.005 ± 0.005
$K^\pm$		0.87 ± 0.25[a]
Neutron	Hadron cluster	0.017 ± 0.002
	CV η	0.03 ± 0.01
	Upstream π^0	0.03 ± 0.03
Total		1.22 ± 0.26

Total #BG = 1.22 ± 0.26

Phys. Rev. Lett. 126, 121801
(Published in March 2021)

Black: Observed, Red: Expected



KOTO J-PARC: 2021 Result

It will be presented by Koji SHIOMI at 11.45!

Other Channels Interesting for CKM and CP-Violation

- $K_L \to \pi^0 \ell^+ \ell^-$
  - $B(K_L \to \pi^0 e^+ e^-) < 2.8 \times 10^{-10}$ (KTeV)
    $B(K_L \to \pi^0 \mu^+ \mu^-) < 3.8 \times 10^{-10}$ (KTeV)
  - Radiative backgrounds (Greenlee)
    Very little acceptance remains once the tight cuts to reject the radiative decays $K_L \to e^+ e^- \gamma\gamma$ are made. To extract a significant signal would require an enormous amount of kaon decays.
  - Indirect CP-violation from $\varepsilon A(K_S \to \pi^0 \ell^+ \ell^-)$
    $B(K_S \to \pi^0 e^+ e^-) = (5.8^{+2.8}_{-2.3} \pm 0.8) \times 10^{-9}$ (NA48/1)
    $B(K_S \to \pi^0 \mu^+ \mu^-) = (2.9^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9}$ (NA48/1)
    Short distance sensitivity is enhanced in case of positive interference of the K_S and K_L amplitudes but to determine the sign of $A(K_S \to \pi^0 \ell^+ \ell)$ lattice calculations are required. LHCb might improve on the muonic channel
  - CP-conserving contributions from $A(K_L \to \pi^0 \gamma\gamma)$

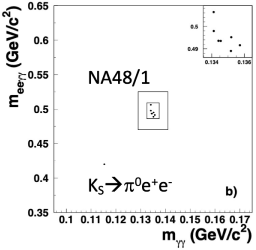
    This component seems to be small with respect to the other two because it is driven by the small

    $m_{\gamma\gamma}$ component of $K_L \to \pi^0 \gamma\gamma$ which is measured to be small.
- $K_S \to \mu^+ \mu^-$
  - $B(K_S \to \mu^+ \mu^-) < 2.1 \times 10^{-10}$ (LHCb)
  - The Short Distance contribution is CP-violating but extremely tiny ($O(10^{-13})$)
  - The Long Distance contribution is calculable: $\mathrm{B}(K_S \to \mu^+ \mu^-)_{LD} = 5.1 \times 10^{-12}$
  - So it exists a window of opportunity to be explored by LHCb for large enhancements w.r.t the SM

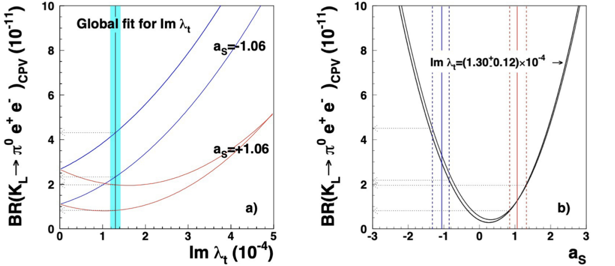
$K_{S,L} \to \pi^0 e^+ e^-$ (Similarly for $K_{S,L} \to \pi^0 \mu^+ \mu^-$)

$$\mathrm{BR}(K_L \to \pi^0 e^+ e^-)_{\mathrm{CPV}} \times 10^{12} \simeq 15.3\, a_S^2 - 6.8\, a_S \left(\frac{Im(\lambda_t)}{10^{-4}}\right) + 2.8 \left(\frac{Im(\lambda_t)}{10^{-4}}\right)^2$$

NA48/1 Collaboration, *Phys.Lett.B* 576 (2003) 43-54



K_S determines $|a_s|$
To be improved by LHCb



The sign of a_s is not known, negative is preferred phenomenologically

Assuming a constructive interference and negligible error on $|a_s|$, there is sensitivity to Im $v_{td}V_{ts}^*$

KTeV hint: $K_l \to \pi^0 e^+ e^-$ signal just behind the corner?

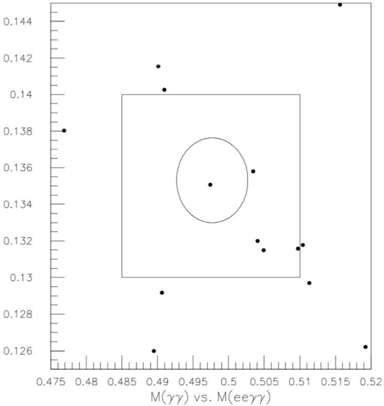


FIG. 3: $m_{\gamma\gamma}$ vs. $m_{ee\gamma\gamma}$ in GeV/c^2 for the data after all cuts have been applied. The box is open and one event appears within the signal ellipse, with a background of 0.99 $\pm$ 0.35 events

KTeV: *Phys.Rev.Lett.* 93 (2004) 021805

Measuring J from K decays

Determinations of the Jarlskog invariant J

Mode	J ($\times 10^5$)	Notes
$K_L \to \pi^0 \nu \bar{\nu}$	≤ 30	KOTO 90 % CL
$K_{S,L} \to \pi^0 e^+ e^-$	≤ 9	$\lvert \Im \lambda_t \rvert \leq 1.3 \times 10^{-3}$ [1]
$K^+ \to \pi^+ \nu \bar{\nu}$	≤ 5	GN limit, NA62 result
$\varepsilon' / \varepsilon$	3.60 ± 1.29	[2, 3, 4]
SM	3.18 ± 0.15	Global fit (PDG 2020)

Theoretical improvement on the prediction of ε'/ε and experimental progress on $K_L \to \pi^0 \nu \bar{\nu}$ may healthily compete to provide another decisive comparison between the kaon and the B system

[1] Buchalla G, D'Ambrosio G, Isidori G. *Nucl. Phys. B* 672:387 (2003)
[2] Cirigliano V, Gisbert H, Pich A, Rodríguez-Sánchez A. *JHEP* 02:032 (2020)
[3] Abbott R, et al. (RBC and UKQCD Collab.) *Phys. Rev. D* 102:054509 (2020)

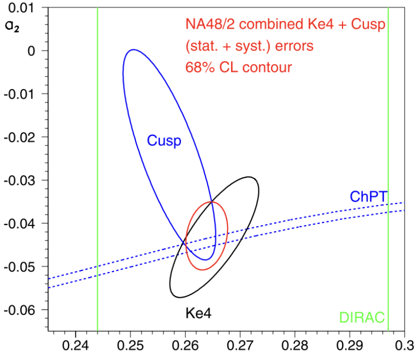
[4] Aebischer J, Bobeth C, Buras AJ, *Eur. Phys. J. C* 80:705 (2020)

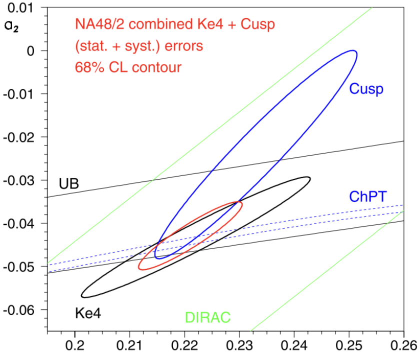
Other Compelling Topics

- $\pi\pi$ Scattering Length
- 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

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

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

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

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

Interplay between Theory and Experiment

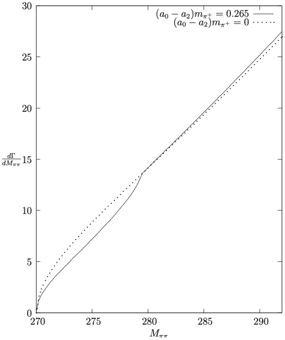
Determination of the $a_0 - a_2$ pion scattering length

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.



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

Lepton Universality

Leptonic widths of pseudoscalar mesons strongly suppressed $(V - A)$:

$$\Gamma^{SM}(K^+ \to \ell^+ \nu) = \frac{G_F^2 M_K M_\ell^2}{8\pi} \left(1 - \frac{M_\ell^2}{M_K^2}\right)^2 f_K^2 |V_{us}|^2$$

$$R_K^{SM} = \left(\frac{M_e}{M_\mu}\right)^2 \left(\frac{M_K^2 - M_e^2}{M_K^2 - M_\mu^2}\right)^2 (1 + \delta R_{QED}) = (2.477 \pm 0.001) \times 10^{-5}$$

Cirigliano V, Rosell I. *Phys. Rev. Lett.* 99:231801 (2007) [arXiv:0707.3439 [hep-ph]]

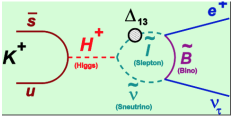
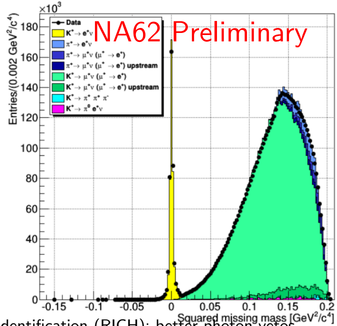


Table: Recent Determinations of R_K

Experiment	Value (10^{-5})	Year
KLOE	$2.493 \pm 0.025 \pm 0.019$	2009
NA62	$2.488 \pm 0.007 \pm 0.007$	2013
PDG	2.488 ± 0.009	

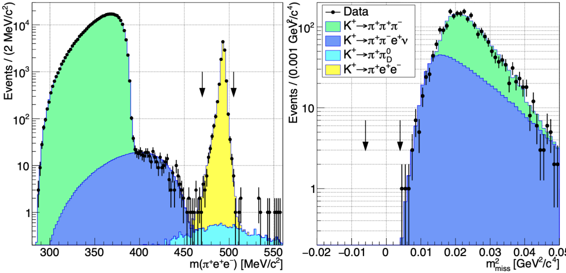


- New data NA62 (25% 2017 sample) →
- Reduced systematics: tracking in vacuum; better muon identification (RICH); better photon vetos
- Normalization to muon decay in flight

Lepton Flavor and Lepton Number Violation

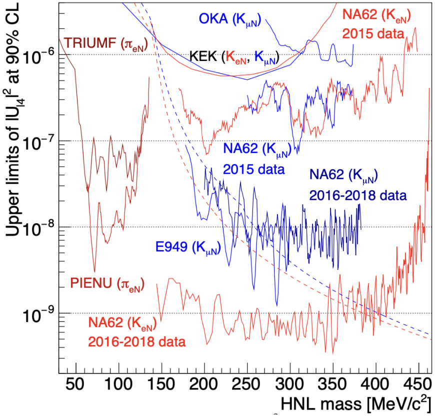
Decay	Upper Limit (90% CL)	Experiment
$K_L \to e^{\pm}\mu^{\mp}$	$< 4.7 \times 10^{-12}$	BNL 871
$\pi^0 \to \mu^- e^+$	$< 3.2 \times 10^{-10}$	CERN NA62
$K_L \to \pi^0 e^{\pm}\mu^{\mp}$	$< 7.6 \times 10^{-11}$	FNAL KTeV
$K^+ \to \pi^+ e^- \mu^+$	$< 1.3 \times 10^{-11}$	PDG
$K^+ \to \pi^+ e^+ \mu^-$	$< 5.2 \times 10^{-10}$	BNL 865
$K^+ \to \pi^- e^+ \mu^+$	$< 5 \times 10^{-10}$	BNL 865
$K^+ \to \pi^- \mu^+ \mu^+$	$< 4.2 \times 10^{-11}$	CERN NA62
$K^+ \to \pi^- \mu^+ e^+$	$< 4.2 \times 10^{-11}$	CERN NA62
$K^+ \to \pi^+ \mu^- e^+$	$< 6.2 \times 10^{-11}$	CERN NA62
$K^+ \to \mu^- \nu e^+ e^+$	$< 8.1 \times 10^{-11}$	CERN NA62
$K^+ \to \pi^- e^+ e^+$	$< 5.3 \times 10^{-11}$	CERN NA62
$\mathrm{K}^+ \to \pi^- \pi^0 e^+ e^+$	$< 8.5 \times 10^{-10}$	CERN NA62

NA62 $K^+ \to \mu^- \nu e^+ e^+$: improvement x250 (arXiv:2211.04818)



Search for Heavy Neutral Leptons (HNL)

- HNL Production: $K^+ \to \ell^+ N \quad \ell = e, \mu$
- Peak search above continuous missing mass spectrum: $m^2_{miss} = (P_{K^+} - P_\ell)^2$

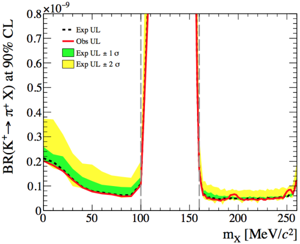


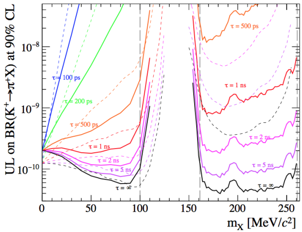
Search for: $K^+ \to \pi^+ X$ and $\pi^0 \to X$ (X *invisible*)

$K^+ \to \pi^+ X$

JHEP 03 (2021) 058

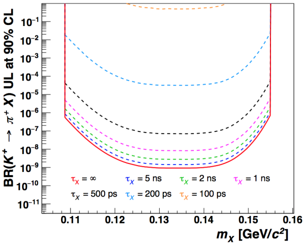
arXiv:2011.11329

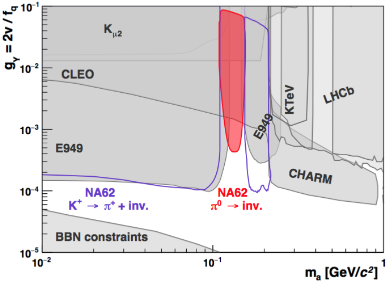




$B(\pi^0 \to invisible) < 4.4 \times 10^{-9}$ [arXiv:2010.07644 [hep-ex]]

(Improvement by $\times 60$)

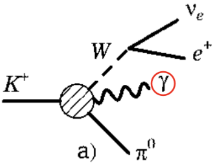




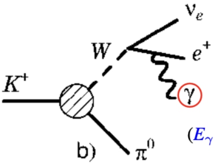
$K^+ \to \pi^+ X$ (from $\pi^0 \to$ *invisible* analysis)

ALP Interpretation

$K^+ \to \pi^0 e^+ \nu\gamma$ ($K_{e3\gamma}$) Theory



Direct Emission



Inner Bremsstrahlung

$\longrightarrow$ divergent for E_γ and $\theta_{e\gamma} \to 0$

(E_γ and $\theta_{e\gamma}$ are defined in the Kaon rest frame)

$$R_j = \frac{\mathrm{BR}(\pi^0 e^+ \nu\gamma \,|\, \text{phase space region } S_j)}{\mathrm{BR}(\pi^0 e^+ \nu(\gamma))}$$

Eur. Phys. J. C 50 (2007) 557

($E_\gamma, \theta_{e\gamma}$) region S_j		ChPT $\mathcal{O}(p^6)$
$E_\gamma > 10$ MeV, $\theta_{e\gamma} > 10°$	$R_1 \times 10^2$	1.804 ± 0.021
$E_\gamma > 30$ MeV, $\theta_{e\gamma} > 20°$	$R_2 \times 10^2$	0.640 ± 0.008
$E_\gamma > 10$ MeV, $0.6 < \cos\theta_{e\gamma} < 0.9$	$R_3 \times 10^2$	0.559 ± 0.006

T-odd observable

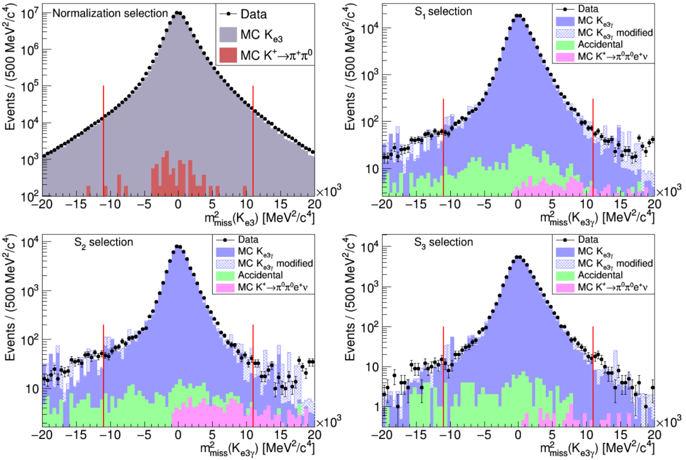
$$\xi = \frac{\vec{p}_\gamma \cdot (\vec{p}_e \times \vec{p}_\pi)}{(M_K \cdot c)^3}$$

$\longrightarrow$

Test of T symmetry

$$A_\xi = \frac{N_+ - N_-}{N_+ + N_-} \quad ; \quad A_\xi \text{ expected} \in (-10^{-4}, -10^{-5})$$

$K^+ \to \pi^0 e^+ \nu\gamma$ ($K_{e3\gamma}$) NA62 Data



$K^+ \to \pi^0 e^+ \nu\gamma$ ($K_{e3\gamma}$) Results arXiv:2304.12271

	ChPT $\mathcal{O}(p^6)$	ISTRA+	OKA	NA62
$R_1 \times 10^2$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$	$1.715 \pm 0.005 \pm 0.010$
$R_2 \times 10^2$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$	$0.609 \pm 0.003 \pm 0.006$
$R_3 \times 10^2$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$	$0.533 \pm 0.003 \pm 0.004$
$A_\xi(S_1) \times 10^3$			$-0.1 \pm 3.9 \pm 1.7$	$-1.2 \pm 2.8 \pm 1.9$
$A_\xi(S_2) \times 10^3$	-0.059		$-4.4 \pm 7.9 \pm 1.9$	$-3.4 \pm 4.3 \pm 3.0$
$A_\xi(S_3) \times 10^3$		15 ± 21	$7.0 \pm 8.1 \pm 1.5$	$-9.1 \pm 5.1 \pm 3.5$
	Eur. Phys. J. C 50 (2007) 557 Eur. Phys. J. C 48 (2006) 427	Phys. Atom. Nucl. 70 (2007) 702	Eur. Phys. J. C 81 (2021) 161 JETP Letters 116 (2022) 608	arXiv:2304.12271, submitted to JHEP

Decay rates

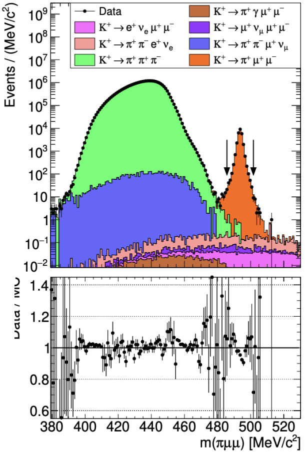
- Relative uncertainty $< 1\%$
- Factor > 2 more precise than previous measurements
- 5% ($\approx 3\sigma$) smaller than ChPT predictions

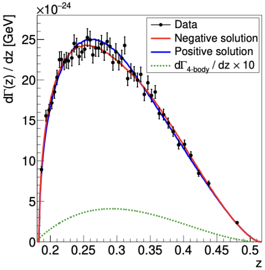
T-violating asymmetry

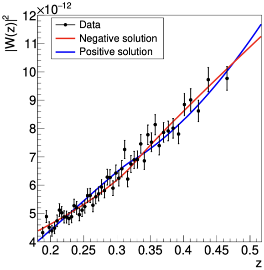
- Compatible with no asymmetry
- Improved precision
- Uncertainty still larger than theoretical predictions

$K^+ \to \pi^+\mu^+\mu^-$: NA62 data

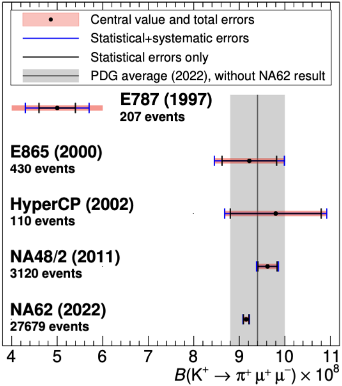
- FCNC, dominated by $K^+ \to \pi^+\gamma^*$
- Tests of ChPT, LFU, FB asymmetries,...
- $\frac{d\Gamma}{dz} = g(z)|W(z)|^2 + \frac{d\Gamma_{4-body}}{dz}$
- $z = \frac{m(\mu^+\mu^-)^2}{M_K^2}$
- in ChPT at $O(p^6)$. (JHEP 08 (1998) 004]: $W(z) = G_F M_K^2(a_+ + b_+ z) + W^{\pi\pi}(z)$



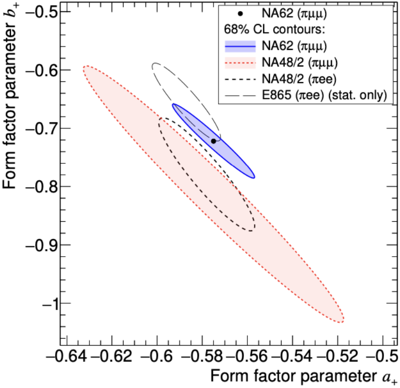




$K^+ \to \pi^+\mu^+\mu^-$



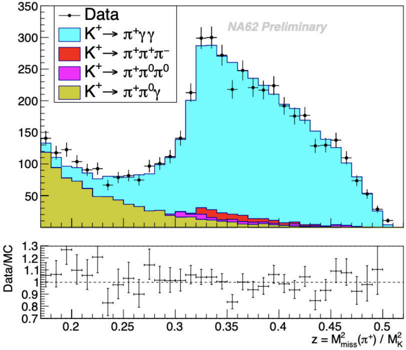
Central value and total errors
Statistical+systematic errors
Statistical errors only
PDG average (2022), without NA62 result
E787 (1997)
207 events
E865 (2000)
430 events
HyperCP (2002)
110 events
NA48/2 (2011)
3120 events
NA62 (2022)
27679 events
4 5 6 7 8 9 10 11
B(K⁺ → π⁺ μ⁺ μ⁻) × 10⁸



NA62 (πμμ)
68% CL contours:
NA62 (πμμ)
NA48/2 (πμμ)
NA48/2 (πee)
E865 (πee) (stat. only)
Form factor parameter b₊
−0.5 −0.6 −0.7 −0.8 −0.9 −1
−0.64 −0.62 −0.6 −0.58 −0.56 −0.54 −0.52 −0.5
Form factor parameter a₊

$K^+ \to \pi^+\gamma\gamma$ NA62 Preliminary

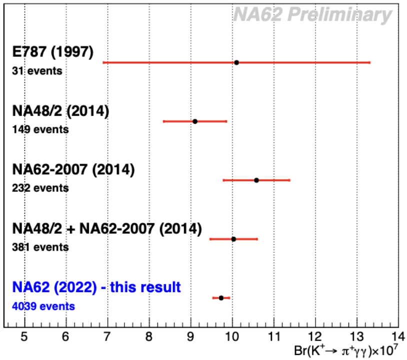
- radiative decay, determines the ChPT parameter $\hat{c}$
- $z = m^2_{\gamma\gamma}/m^2_K$ $\quad\quad y = \vec{p}\cdot(\vec{p}_{\gamma 1} - \vec{p}_{\gamma 2})/m^2_K$
- $z > 0.25$ $\quad\quad$ 4029 candidates ($\times$ 10 former statistics)

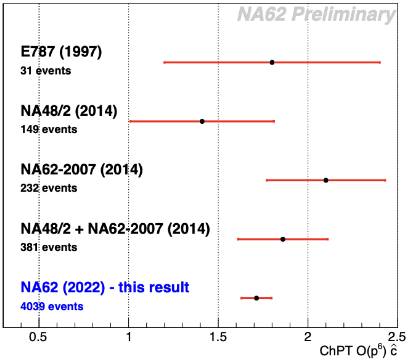


Results:

- $\hat{c} = 1.713 \pm 0.084$
- $Br(K^+ \to \pi^+\gamma\gamma) = (9.73 \pm 0.19) \times 10^{-7}$

$K^+ \to \pi^+\gamma\gamma$ Comparison

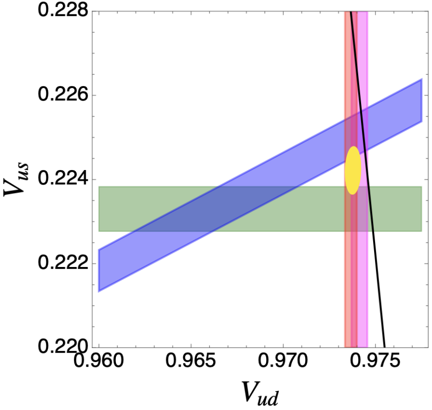




Cabibbo angle: V_{us} and Unitarity

Cirigliano, Crivellin, Hoferichter, Moulson, PLB 838 (2023) 137748

- red: $V_{ud}^{0^+\to 0^+}$
- violet: V_{ud}^{n}
- blue: $(V_{us}/V_{ud})_{K_{\ell 2}/\pi_{\ell 2}}$
- green: $V_{us}^{K_{\ell 3}}$



Tensions in unitarity and V_{us} determinations, $K_{\mu 2}$ measurement to 0.2 % would be important

Concluding Remarks

- I hope to have conveyed the message that there is no lack of compelling questions to be explored with kaons
- The exquisite interplay of theory and experiments makes kaon physics quite unique
- 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)
- This opportunity shall not be missed. It will no happen by itself. As in the past, a coherent and structured action by a strong community will be needed