Rare Kaon Decays: Results from NA62

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DESY Colloquium

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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. The aim of particle physics is to continue to build the SM rather than to break it.

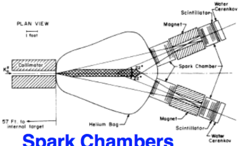
CP-Violation

$\pi^+\pi^-$ (CP=+1)

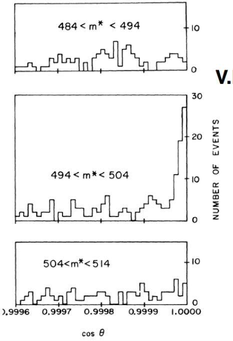
$K_1 = 1/\sqrt{2}(K_0 + \bar{K}_0)$ (CP=+1)

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

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



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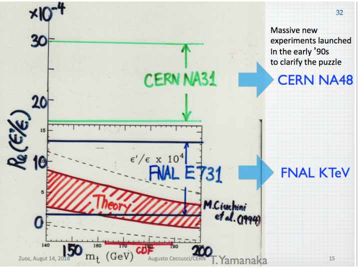
Indirect (ε) and Direct (ε') CP-Violation



Phenomenology: Wu and Yang, (1964)

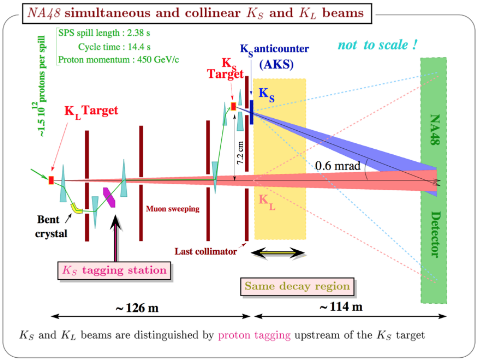
$$\eta_{\pm} = \varepsilon + \varepsilon'$$

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

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

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

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

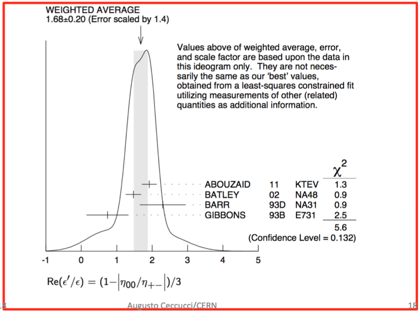
Electrode structure (half) of the Liquid Krypton Calorimeter, **now used by NA62, cold (~120 K) since 1998**

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:

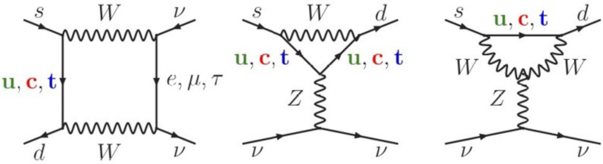
$$\varepsilon'/\varepsilon_{(\mathrm{PDG\ average})} = (1.68 \pm 0.20) \times 10^{-3}$$

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

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

Cabibbo-Kobayashi-Maskawa (CKM) Matrix

For three generations of quarks there is one irreducible complex phase (KM):
CP-Violation is automatically included!

For $n \times n$ matrix:

- $2n - 1$ unphysical phases
- $n(n-1)/2$ rotation angles
- $(n-1)(n-2)/2$ complex phases

$$\frac{-g}{\sqrt{2}}(\overline{u_L},\ \overline{c_L},\ \overline{t_L})\gamma^{\mu}\ W_{\mu}^{+}\ V_{\rm CKM}\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + {\rm h.c.},$$

$$V_{\rm CKM} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

B Unitarity Triangle:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0.$$

$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right), \qquad \alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), \qquad \gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right).$$

Kaon Unitarity Triangle:

$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^*,$$

which can be written more concisely as:

$$\lambda_u + \lambda_c + \lambda_t = 0,$$

with $\lambda_i = V_{id}V_{is}^*$.

The Jarlskog invariant is the measure of CP-Violation in the SM: $J = 2\times$ Area of (any) Unitarity Triangle

Rare K Decays: $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ 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%

Making the dependence of the CKM explicit:

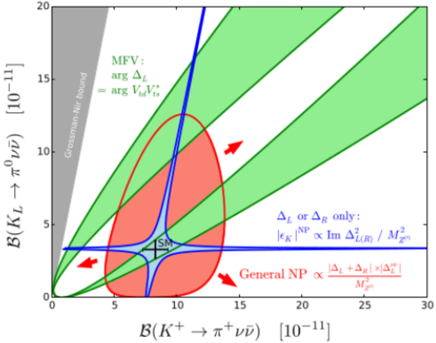
$$B(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}} \right]^{2.8} \left[\frac{\gamma}{73.2^\circ} \right]^{0.74}$$

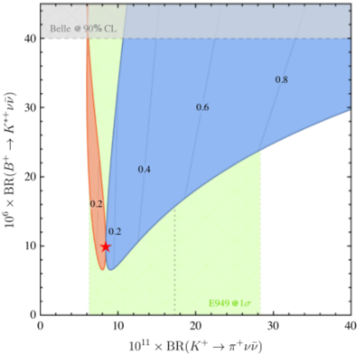
Taking $|V_{cb}|_{avg} = (40.7 \pm 1.4) \times 10^{-3}$, $|V_{ub}|_{avg} = (3.88 \pm 0.29) \times 10^{-3}$ and $\gamma = (73.2^{+6.3}_{-7.0})^\circ$:

$$B_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$

Beyond SM

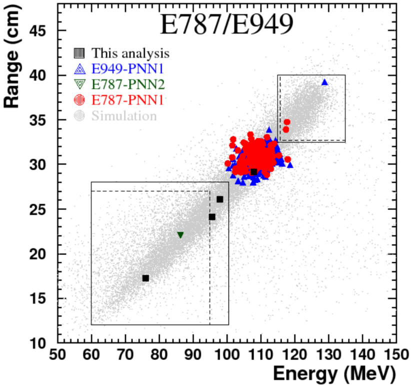
[Buras et al., JHEP11 (2015) 166] ——— *[Isidori et al., Eur.Phys.J. C (2017) 77: 618]*





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.

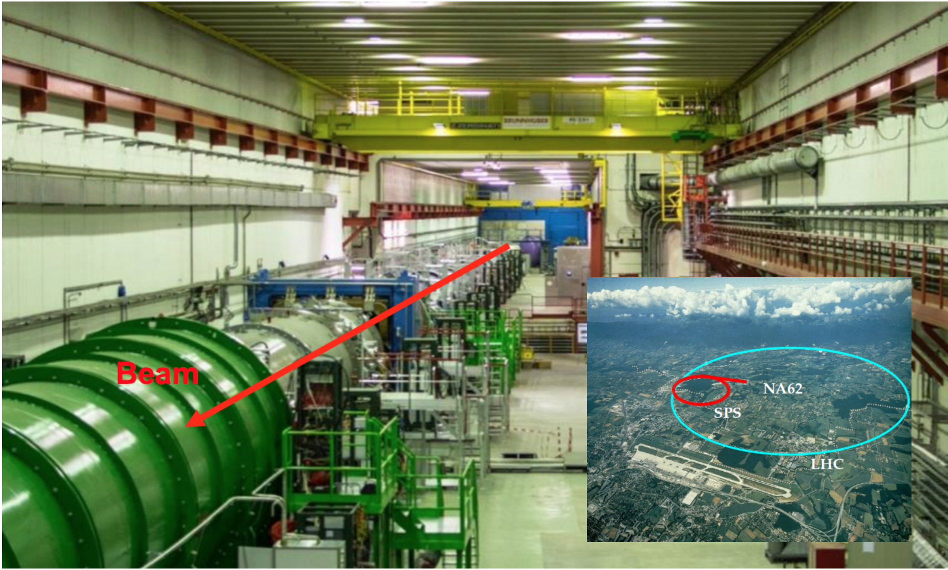
BNL E787/E949: $K^+ \to \pi^+ \nu \bar{\nu}$ with decays-at-rest



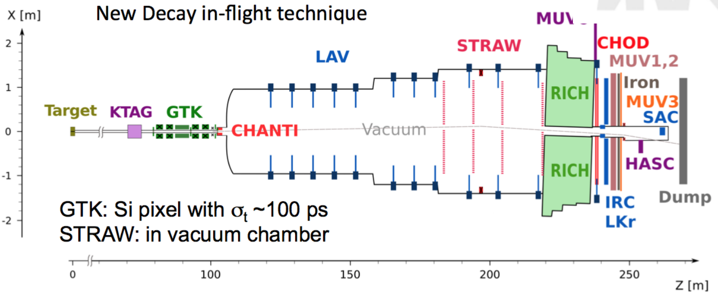
- Artamonov AV, et al. (E949 Collab.) *Phys. Rev. Lett.* 101:191802 (2008)
- Adler S, *et al.* [E949 and E787], *Phys. Rev. D* 77:052003 (2008)
- Separated beam
- full $K^+ \to \pi^+ \to \mu^+ \to e^+$ decay chain
- small acceptance
- SES $\approx$ SM

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

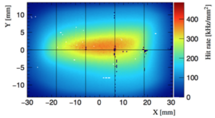
Decays-In-Flight: NA62@CERN



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%)/π^+(70%)/p(24%)
  - For 33×10^{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

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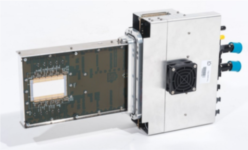
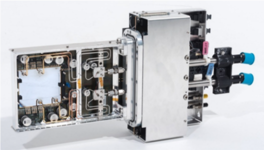
ABSTRACT: The GigaTracKer (GTK) is the beam spectrometer of the CERN NA62 experiment. The detector features challenging design specifications, in particular a peak particle flux reaching up to 2.0 MHz/mm^2, a single hit time resolution smaller than 200 ps and, a material budget of 0.5% X_0 per tracking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

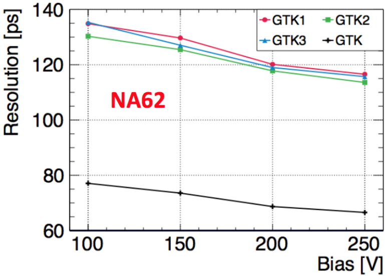
KEYWORDS: Particle tracking detectors; Particle tracking detectors (Solid-state detectors); Timing detectors; Detector cooling and thermo-stabilization

ARXIV EPRINT: 1904.12837

2019 JINST 14 P07010







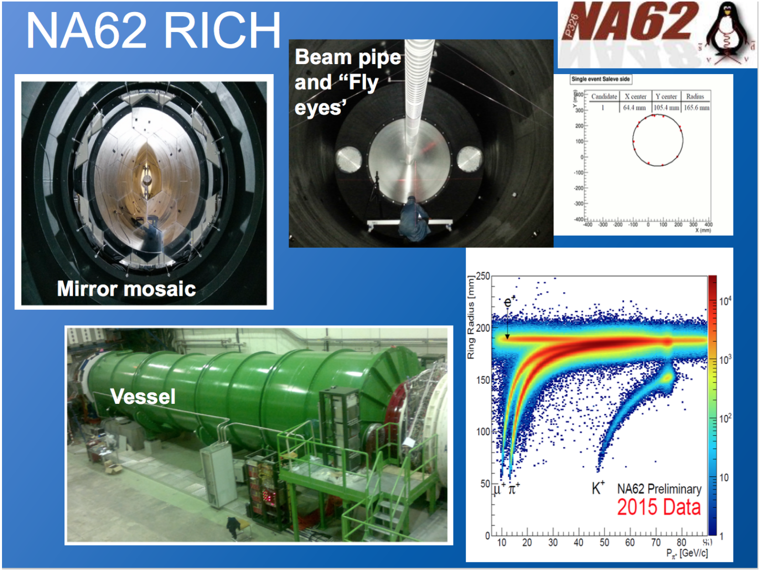
300 x 300 micron^2 time res ~ 65 ps, ~ 0.5% X_0/station

NA62 Straws Tracker

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

- Operated inside vacuum tank

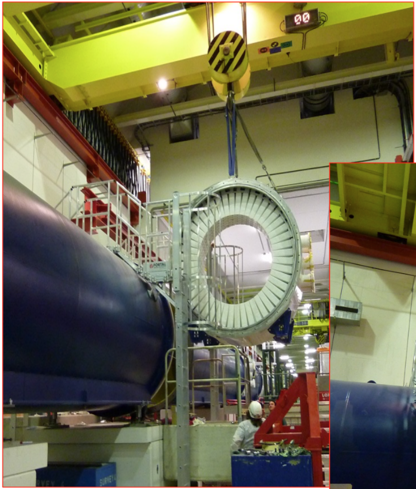
NA62: RICH

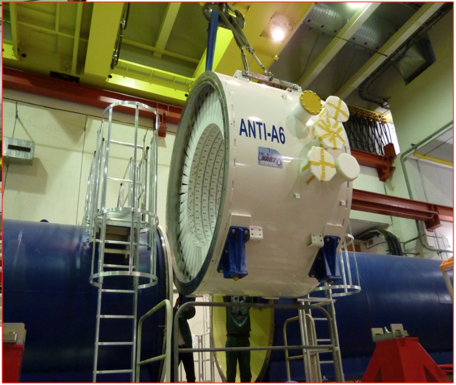


- Neon radiator STP, spherical mirrors f=17 m

NA62: Large Angle Vetos (LAV)

π^0 Rejection

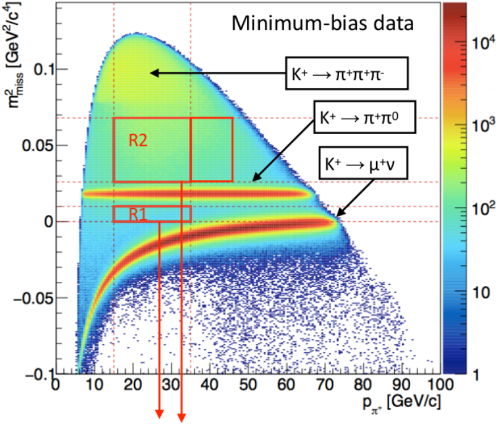




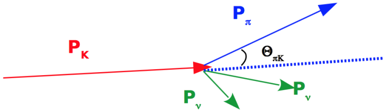
Lead Glass from CERN-LEP Experiment OPAL

NA62: Decay in Flight

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



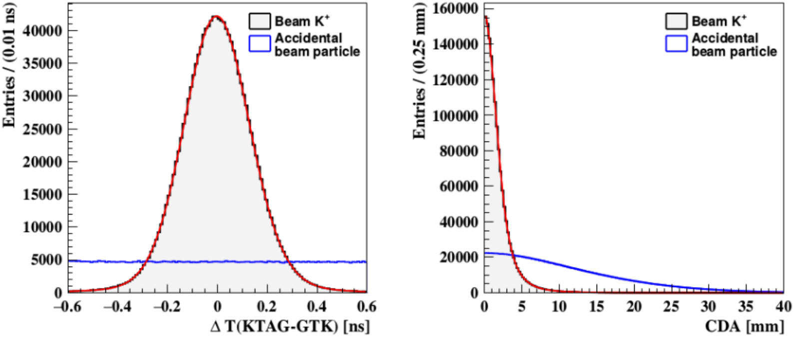
Kinematic cuts to define signal regions R1 and R2



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}**

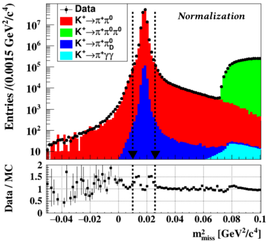
NA62: Time - Space Association

data - $K^+ \to \pi^+\pi^+\pi^-$ control sample



- KTAG: Differential Cherenkov Counter
- GTK: Gigatracker
- CDA: Closest Distance of Approach

NA62 2018: Single Event Sensitivity

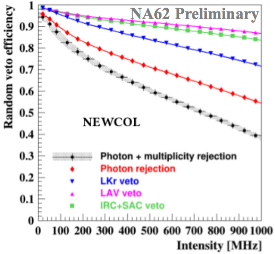


$SES = (0.111 \pm 0.007_{syst}) \cdot 10^{-10}$

SES error budget:

Source	Relative uncertainty
trigger efficiency	5%
MC acceptance	3.5%
random veto efficiency	2%
normalization background	0.7%
instantaneous intensity	0.7%
Total	6.5%

- $N_K = \frac{N_{\pi\pi} \cdot D}{A_{\pi\pi} \cdot Br_{\pi\pi}}$
- $N_{\pi\pi}$ from min. bias $K^+ \to \pi^+\pi^0$
- $N_K(2018) \simeq (0.8_{OLDCOL} + 1.9_{NEWCOL}) \cdot 10^{12}$
- Single Event Sensitivy (SES):



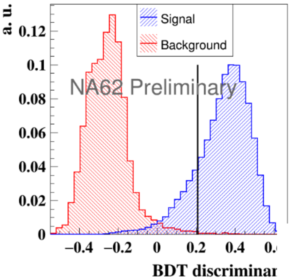
$$\mathrm{SES} = \frac{1}{N_K \cdot \sum_j \left(A^j_{\pi\nu\bar{\nu}} \cdot \varepsilon^j_{trigger} \cdot \varepsilon^j_{RV} \right)}$$

- $\varepsilon^j_{trigger} \simeq 88\%$ and $\varepsilon^j_{RV} \simeq 66\%$ from min. bias $K^+ \to \mu^+\nu$

NA62: Upstream Decays

From June 2018

Both samples normalized to 1

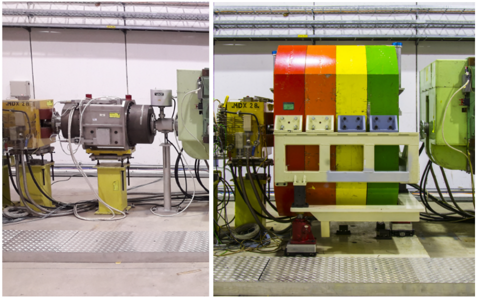


$\epsilon(sig) \sim 83\%$ @ $\epsilon(bkg) \sim 0.5\%$

BDT (New Col) based on:

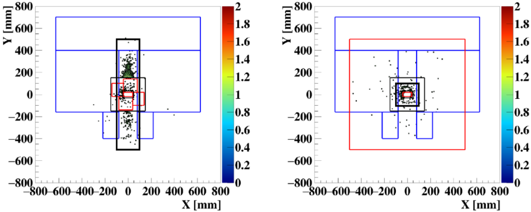
- X,Y @ Collimator
- Vertex
- Track slope

OLD COL ——————— NEW COL

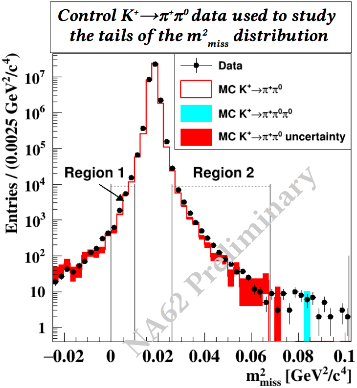


Track extrapolation at collimator in enriched sample of upstream events (data).
Red boxes: collimator coverage.

OLD COL ——————— NEW COL



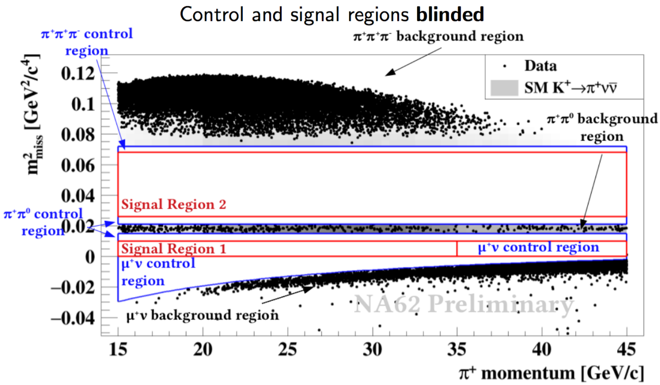
NA62: Data Driven Measurement of $K^+ \to \pi^+\pi^0$ Background



- $N^{exp}_{\pi\pi}(region) = N(\pi^+\pi^0) f_{kin}(region)$
- $N(\pi^+\pi^0)$ is the number of events found in the $\pi^+\pi^0$ region passing the $K^+ \to \pi^+\nu\bar{\nu}$ selection
- $f_{kin}(region)$ is the fraction of $K+ \to \pi^+\pi^0$ with m^2_{miss} ending up in a $K^+ \to \pi^+\nu\bar{\nu}$ region. This quantity is measured from a sample of minimum bias data by selecting pure $K^+ \to \pi^+\pi^0$ events with an algorithm independent of m^2_{miss} (that is without using information from the K^+ and the π^+ tracks):
- Using the π^0 mass as constraint, the decay vertex (assumed on the nominal beam axis) is reconstructed using the position and energies of the photons measured by the LKr calorimeter
- Using this vertex, required to be within the fiducial volume, and the energies and positions of the photons, the π^0 momentum is reconstructed (P_0).
- The pure sample to determine $f_{kim}(region)$ is selected requiring $(P_K - P_0)^2$ to be consistent with $m^2_{\pi^+}$. For P_K the nominal beam momentum is taken.

- 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: Control and Signal Blind

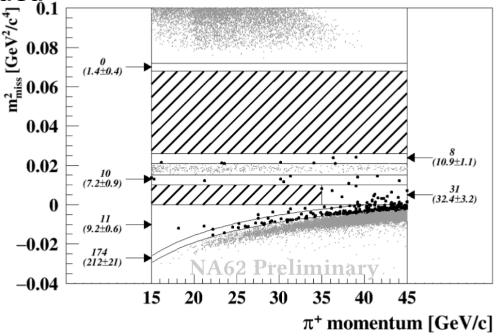


NA62: Summary of Backgrounds

Process	**Expected events in $\pi\nu\nu$ signal regions**
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	$7.58 \pm 0.40_{syst} \pm 0.75_{ext}$
$K^+ \to \pi^+\pi^0(\gamma)$	0.75 ± 0.04
$K^+ \to \mu^+\nu(\gamma)$	0.49 ± 0.05
$K^+ \to \pi^+\pi^-e^+\nu$	0.50 ± 0.11
$K^+ \to \pi^+\pi^+\pi^-$	0.24 ± 0.08
$K^+ \to \pi^+\gamma\gamma$	< 0.01
$K^+ \to l^+\pi^0\nu_l$	< 0.001
Upstream background	$3.30^{+0.98}_{-0.73}$
Total background	$5.28^{+0.99}_{-0.74}$

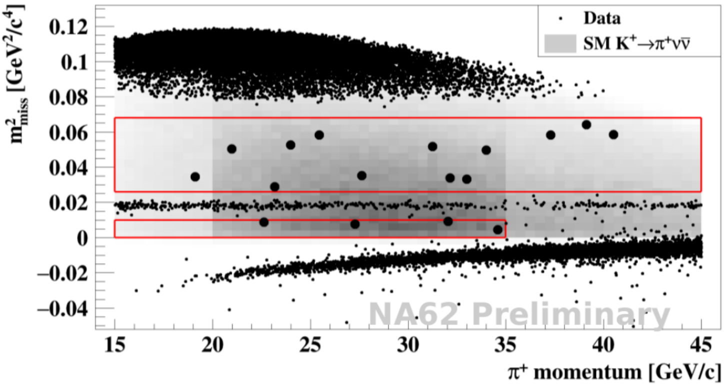
NA62: Control Region

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



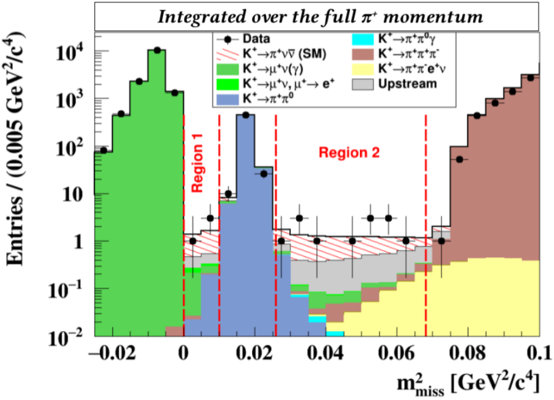
	2017	2018-OLDCOL	2018-NEWCOL
N_K	$(1.5 \pm 0.2) \cdot 10^{12}$	$(0.8 \pm 0.1) \cdot 10^{12}$	$(1.9 \pm 0.2) \cdot 10^{12}$
$A_{\pi\nu\nu}$	$(3.0 \pm 0.3)\%$	$(4.0 \pm 0.4)\%$	$(6.4 \pm 0.6)\%$
ϵ_{RV}	0.64 ± 0.01	0.66 ± 0.01	0.66 ± 0.01
ϵ_{trig}	0.87 ± 0.03	0.88 ± 0.04	0.88 ± 0.04
$N^{exp}_{\pi\nu\nu(SM)}$	2.16 ± 0.29	1.56 ± 0.21	6.02 ± 0.82
B/S	~ 0.7	~ 0.7	~ 0.7

NA62 2018 Data: Box Opened (ICHEP2020)



17 Candidates Observed

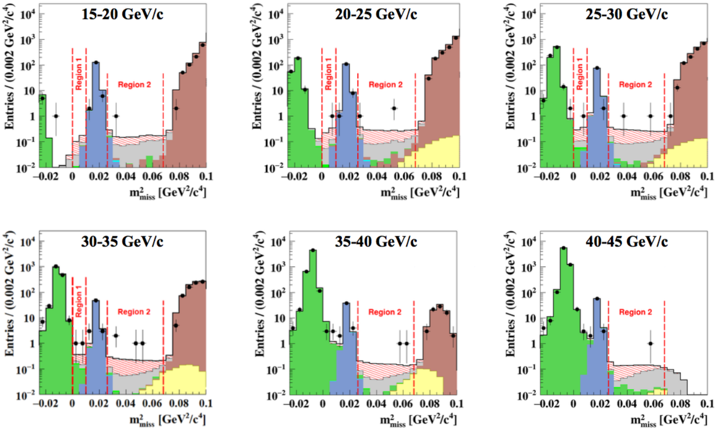
NA62 2018 Data: Box Opened



NEWCOL Data / MC Comparison

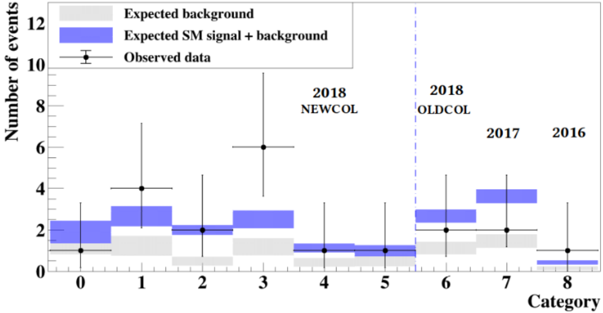
NA62 2018 Data: Momentum Bins

π^+ momentum range (15-45 GeV/c) split in six bins (5 GeV/c size)



NA62 Combined Result (2016,2017 and 2018)

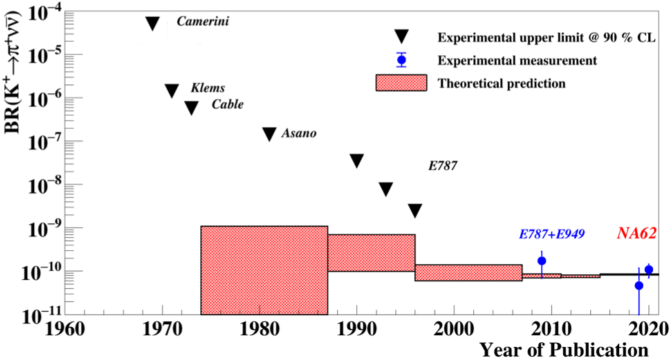
	2016 data	2017 data	2018 data
SES	$(3.15 \pm 0.24) \cdot 10^{-10}$	$(0.39 \pm 0.02) \cdot 10^{-10}$	$(0.111 \pm 0.007) \cdot 10^{-10}$
Expected SM signal	0.27 ± 0.04	2.16 ± 0.29	7.58 ± 0.85
Expected background	0.15 ± 0.09	1.50 ± 0.31	$5.28^{+0.99}_{-0.74}$
Observed events	1	2	17



$$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (11.0^{+4.0}_{-3.5}\ (stat) \pm 0.3\ (syst)) \times 10^{-11}$$

$$3.5\ \sigma \text{ significance}, \qquad P(back.only)\ 2 \cdot 10^{-4}$$

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 ICHEP2020:
  https://indico.cern.ch/event/868940/contributions/3815641/attachments/2080353/3496097/RadoslavMarchevski_ICHEP_2020.p
- NA62 2018 data: CERN EP Seminar
  https://indico.cern.ch/event/965896/

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

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

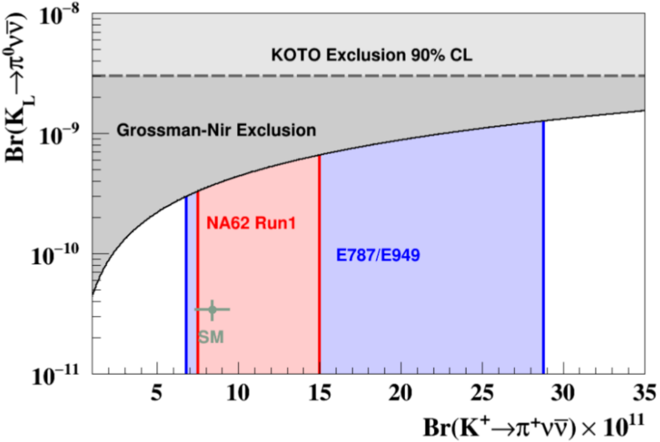
- The $B(K_L^0 \to \pi^0 \nu \bar{\nu})$ depends only on the square of the imaginary part of the top loop which is CP-violating
- The charm contributions drop out because K_L^0 is mostly an odd linear combination of K^0 and $\bar{K}^0$
- This makes the theoretical prediction for the K_L^0 rate even cleaner 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

Inserting the numerical factors and making the dependence of the CKM explicit:

$$B(K_L^0 \to \pi^0 \nu \bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^2 \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^2 \left[\frac{\sin \gamma}{\sin 73.2^\circ}\right]^2$$

$$B_{SM}(K_L^0 \to \pi^0 \nu \bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}$$

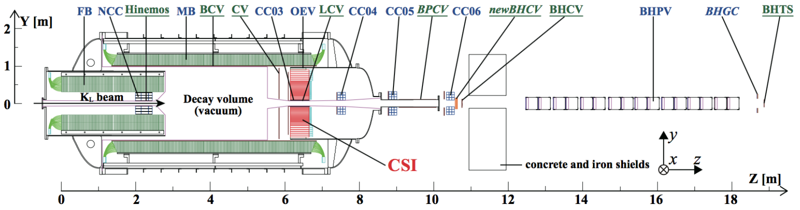
Grossman-Nir Bound PLB 398 163 (1997)

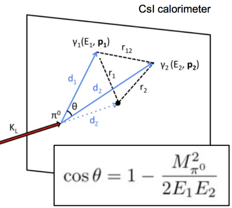


Model Independent limit assumes that the $K^+ \to \pi^+\nu\bar{\nu}$ mode is entirely CP-violating:

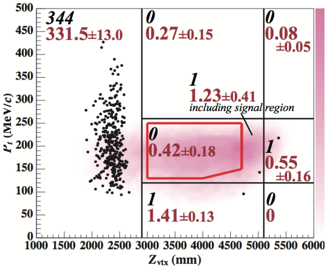
$$B(K_L \to \pi^0\nu\bar{\nu}) < 4.4B(K^+ \to \pi^+\nu\bar{\nu})$$

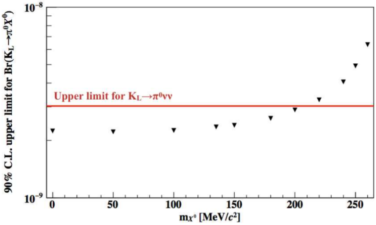
KOTO J-PARC: $K_L^0 \to \pi^0 \nu \bar{\nu}$ PRL 122 (2019) 2 [arXiv1810.09655]





$$\cos\theta = 1 - \frac{M_{\pi^0}^2}{2E_1E_2}$$





- Data 2015 (2.2×10^{19}, 30 GeV POT): $B\left(K_L^0 \to \pi^0 \nu \bar{\nu}\right) < 3.0 \times 10^{-9}$ 90% CL
- Analysis of data 2016-2019 in progress

Preliminary results: 2016-2018 data

Several important detector upgrades and analysis improvements compared to 2015 data

KOTO preliminary (KAON, Sep 2019)

SES: 6.9 × 10^{-10} (0.05 SM evts)

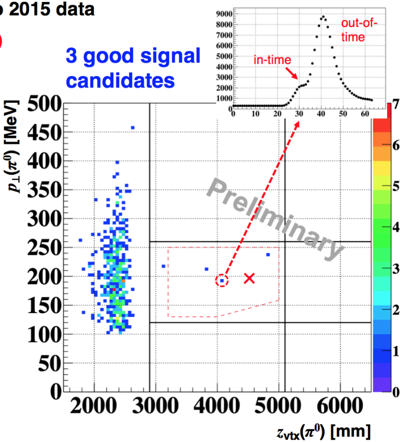
Expected bkg: 0.05 ± 0.02 evts

New background estimates

Preliminary (ICHEP 2020)

Source	Expected (68%CL)
$K_L \to \pi^0\pi^0$	< 0.05
$K_L \to \pi e \nu$ overlap pulse	< 0.05
$K_L \to ee\gamma$	< 0.05
$K_L \to \gamma\gamma$ core	< 0.06
$K_L \to \gamma\gamma$ halo	< 0.10
$K^+ \to \pi^0 e^+ \nu$	0.90 ± 0.27
$K^+ \to \pi^+\pi^0$	0.09 ± 0.09
$K^+ \to \pi^0 \mu^+ \nu$	< 0.12
π^0 from n in CV	< 0.05
Total	**1.05 ± 0.28**

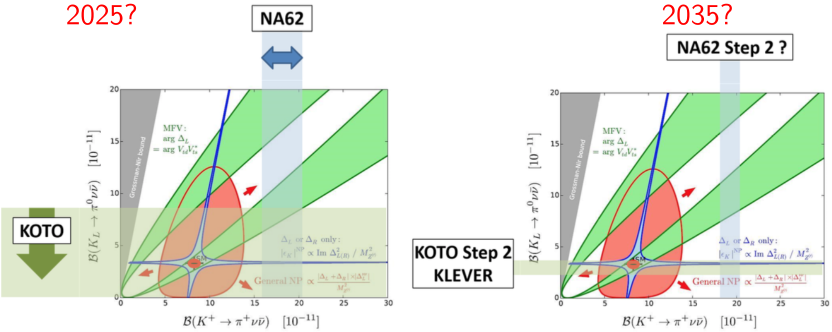
3 good signal candidates



KOTO will reach SM SES by mid-decade: Step-2 required for BR mmt

Perspectives for high-intensity kaon physics at the SPS – M. Moulson (Frascati) – CERN Detector Seminar – 23 October 2020 32

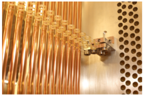
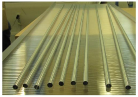
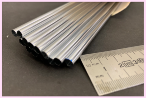
Future of $K \to \pi\nu\bar{\nu}$? CERN-ESU-004. arXiv:1910.11775



- Educated guess for experimental prospects from European Particle Physics Strategy Update Briefing Book
- Original plot from: A. J. Buras, D. Buttazzo, and R. Knegjens, JHEP 11 (2015) 166, arXiv:1507.08672 [hep-ph].
- Red: No Constraints, Green: MFV constraints (CKM-like), Blue: ϵ_K (Only Δ_R or Δ_L constraints)

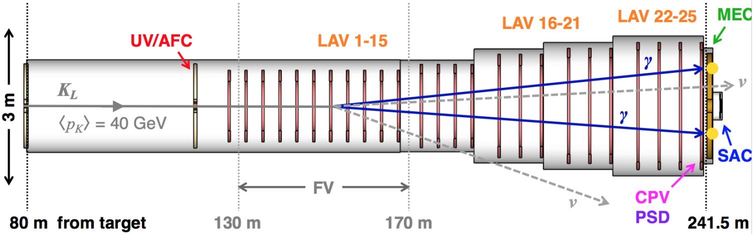
Future of NA62: $B(K^+ \to \pi^+ \nu \bar{\nu})$ towards 5%?

- Improved immunity to upstream decays from 2021 onward
- Expect NA62 to reach a precision of $\approx$ 10% by 2025
- Experiment is currently limited by 65 ps time resolution of the beam tracker
- Developments for HL-LHC can lead to detectors with better timing (20 ps?)
- Not limited by beam intensity (target to be upgraded)
- Thinner straw tracker
- Reduce random veto

	NA62	COMET Phase-I	New Straw
Straw Wall Thickness	36 μm	20 μm	12 μm
Straw Diameter	9.8 mm	9.8 mm	4.8 mm
Metal Deposition	Cu+Au, 70nm	Al, 70 nm	Al, 70 nm
Photo			
Current Status	In Operation	Under Construction	Just Developed

A $K_L \to \pi^0 \nu\bar{\nu}$ experiment at the SPS? KLEVER

400-GeV SPS proton beam on Be target at z = **0 m**



KLEVER target sensitivity:
5 years starting Run 4

~60 SM $K_L \to \pi^0 \nu\nu$
S/B ~ 1

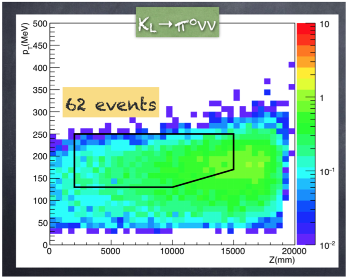
δBR/BR($\pi^0\nu\nu$) ~ 20%

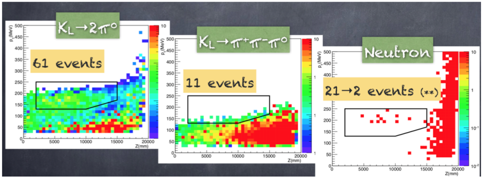
- High-energy experiment: Complementary to KOTO
- Photons from K_L decays boosted forward
  - Makes photon vetoing easier - veto coverage only out to 100 mrad
- Roughly same vacuum tank layout and fiducial volume as NA62

KOTO STEP-2?

MuscleRelax Pro

PRELIMINARY SENSITIVITY STUDY





See presentation by Tadashi Nomura at KAON 2019 (https://indico.cern.ch/event/769729/contributions/3511089) for details of the study

Nomura, KAON 2019

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: $B(K_S \to \mu^+ \mu^-)_{LD} = 5.1 \times 10^{-12}$
  - So it exists a window of opportunity to be explored by LHCb for large enhancements w.r.t the SM

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
ε'/ε	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)

Some NA62 Byproducts

- Lepton Universality
- Lepton Flavor Violation
- Lepton Number Violation
- Search for Heavy Neutral Leptons
- Search for invisible π^0 decays
- Search for invisible bosons $K^+ \to \pi^+ X$

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]]

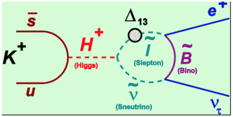
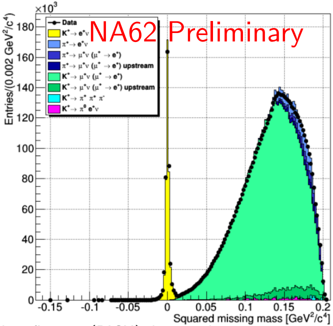


Table: Recent Determinations of R_K

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) $\rightarrow$



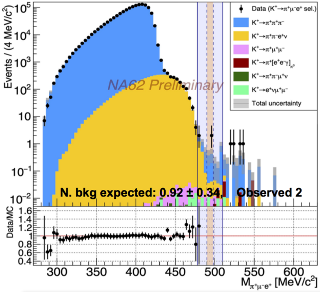
- Reduced systematics: tracking in vacuum; better muon identification (RICH); better photon vetos
- Normalization to muon decay in flight

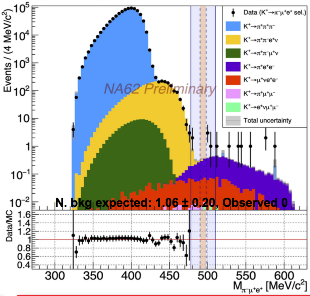
Lepton Flavor and Lepton Number Violation

Limits (90% CL)

Decay	Upper Limit	Experiment
$K_L \to e^{\pm}\mu^{\mp}$	$< 4.7 \times 10^{-12}$	BNL 871
$K_L \to \pi^0 e^{\pm}\mu^{\mp}$	$< 7.6 \times 10^{-11}$	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
$K^+ \to \pi^- e^+ e^+$	$< 2.2 \times 10^{-10}$	CERN NA62

New NA62 results recently presented:

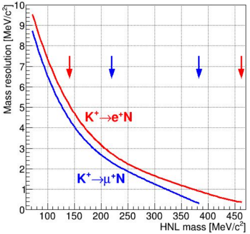


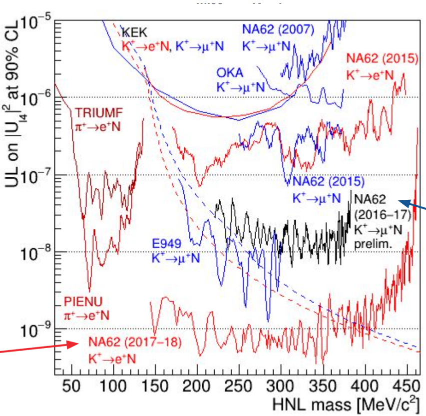


$Br(K^+ \to \pi^+\mu^-e^+) < 6.6 \times 10^{-11}$ @ 90% C.L | **$Br(K^+ \to \pi^-\mu^+e^+) < 4.2 \times 10^{-11}$ @ 90% C.L**

Search for Heavy Neutral Leptons (HNL)

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





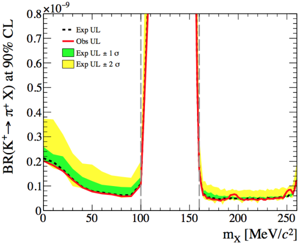
Final results
PLB 708 (2020) 135599

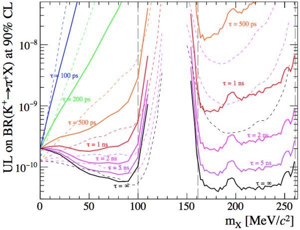
New Results
⅓ data sample

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

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

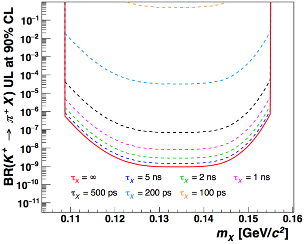
(from $K^+ \to \pi^+ \nu\bar{\nu}$ analysis)

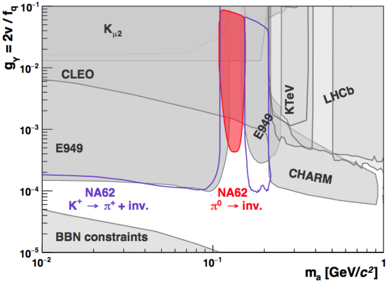




$B(\pi^0 \to invisible) < 4.4 \times 10^{-9}$ [arXiv:2010.07644 [hep-ex]]

(Improvement by $\times 60$)





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

ALP Interpretation

Conclusions

- Strong kaon program continues to help building the SM
- Moving from exploration to precision in rare K decays
- Short term goals (2025) :
  - B($K^+ \to \pi^+ \nu\bar{\nu}$) to 10% (NA62)
  - B($K_L \to \pi^0 \nu\bar{\nu}$) to SM SES (KOTO)
- Longer term goals:
  - B($K^+ \to \pi^+ \nu\bar{\nu}$) to 5% ?
  - B($K_L \to \pi^0 \nu\bar{\nu}$) to 20% ?
- Compelling byproducts: LFV, LNV, Exotics, HBL,....