NA62 – The Kaon Factory

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Introduction and Motivation

Two approaches to test New Physics Scenarios:

- Brut Force: Highest Energy Collisions to produce new heavy particles
- Elegant: High Precision experiment to measure indirect effects of new particles

The two approaches are complimentary and both are necessary to disentagle what really is the new physics.

Introduction and Motivation

Some examples:

- Masses of $W^{\pm}$, Z^0, top-quark, Higgs, ..., known before real production
- $B_s^0 \to \mu\mu$, $\mathcal{B} = (3.1 \pm 0.7) \times 10^{-9}$ excludes most of SUSY (MSSM) phase space
- Smallest $\mathcal{B}$ ever measured: $K_L^0 \to e^+ e^-$, $\mathcal{B} = (9^{+6}_{-4}) \times 10^{-12}$
- Null measurements (upper limits) also provide a lot a information on new physics scenarios.

History of Kaon Experiments

Since the first accelerators

- CERN PS: Precision measurements
- Brookhaven: Several experiments, rare decays.
  Most famous: Indirect CP Violation $K^0_{\pi 2}/K^0_{\pi 3}$ (Cronin, Fitch)
- Fermilab (E732, KTeV), CERN SPS (NA32, NA48): Direct CP Violation $\epsilon'/\epsilon \neq 0$
- KEK, J-PARC: Rare Kaon decays
- In last 15 years several proposals in the US:
  CKM, K0PI0, KPLUS, ORKA.
  All killed by different P5 processes.
- CERN SPS: Continuation of NA48: NA62

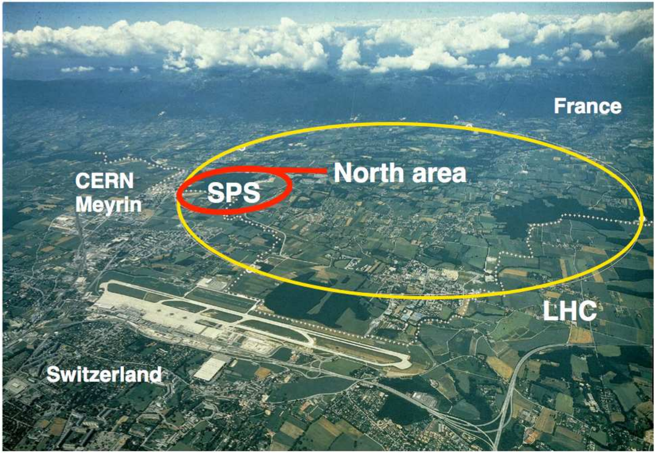
Outline

1. Introduction and Motivation
2. NA62: $K^+ \rightarrow \pi^+\nu\bar{\nu}$
3. Physics Results
   - π^0 Transition Form Factor
   - Lepton Universality
   - $K^\pm \rightarrow \pi^\pm\gamma\gamma$
4. Summary

The NA62 Collaboration

- Birmingham
- Bratislava
- Bristol
- Bucharest
- CERN
- Dubna
- George Mason
- Ferrara
- Firenze
- Frascati
- Glasgow
- Liverpool
- Louvain-la-Neuve
- Mainz
- Merced
- INR Moscow
- Napoli
- Perugia
- Pisa
- Prague
- Protvino
- Roma I
- Roma II
- San Luis Potosí
- SLAC
- Sofia
- Torino
- TRIUMF
- Vancouver

approx 250 collaborators


France
CERN
Meyrin
SPS
North area
LHC
Switzerland

Recent history of CERN North Area experiments

1997–2001	NA48 (K_S/K_L)	Re(ϵ'/ϵ) Discovery of direct CPV
2002	NA48/1 (K_S/hyperons)	Rare K_S and hyperon decays
2003–2004	NA48/2 (K^+/K^-)	Direct CPV, Rare $K^\pm$ decays
2007–2008	NA62 R_K-phase (K^+/K^-)	$R_K = K^\pm_{e2}/K^\pm_{\mu 2}$
2014–2018	NA62 (K^+)	$K^+ \to \pi^+ \nu \bar{\nu}$ Rare K^+, π^+, and π^0 decays

NA62

- Uses (most of the) beamline, and some detector from NA48
- Adds new detectors: GigaTracker, Straw, Photon Veto (Leadglass), RICH, muon veto, ...
- Data Taking with the available detectors before all detectors were ready.
- Physics Topics include: R_K (Lepton Universality), $K^\pm \to \pi^\pm \gamma\gamma$, π^0 transition form factor, ...

NA62 (cont.)

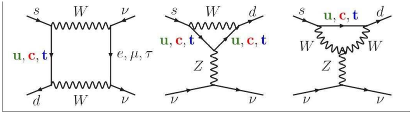
- Main Goal: $K^+ \to \pi^+ \nu \bar{\nu}$, 100 events ($\sim$ 40/year)
- A long list of other rare K^+, π^+, and π^0 decays

$K^+ \to \pi^+ \nu \bar{\nu}$

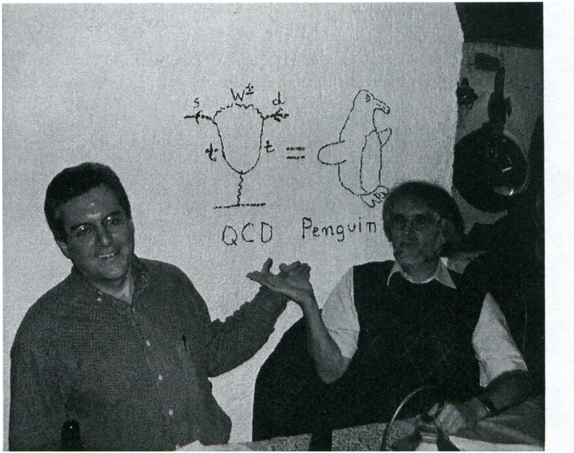
- An “old” dream: CKM finally…

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

- FCNC loop: $s \to d$ coupling, high CKM suppression



- Theoretically very clean: Short distance contribution. No hadronic uncertainties via weak isospin rotation of $K^+ \to \pi^0 e^+ \nu$
- SM Prediction: Buras et al., arXiv:1502.02693 [hep-ph], JHEP 1511 (2015) 033
  $\mathcal{B}(K^+ \to \pi^+ \nu \overline{\nu}) = (9.11 \pm 0.72) \times 10^{-11}$
  $\mathcal{B}(K^0 \to \pi^0 \nu \overline{\nu}) = (3.00 \pm 0.30) \times 10^{-11}$
- Experiments: $\mathcal{B}(K^+ \to \pi^+ \nu \overline{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$
  Phys.Rev. D77, 052003 (2008), D78,092004 (2009)
  $\mathcal{B}(K^0 \to \pi^0 \nu \overline{\nu}) < 2.6 \times 10^{-8}$ Phys.Rev D81, 072004 (2010)



Andrei Buras (right, with John Conway), Restaurante “Mamá Inés”, Zacatecas, November 2001

$K \to \pi\nu\bar{\nu}$: Sensitivity to New Physics

- Simplified Z, Z' models (sensitive up to $M_{Z'} \sim 500\,TeV$)
  [Buras, Buttazzo,Knegjens, arXiv:1507.08672 (2015)]
- Littlest Higgs with T-parity
  [Blanke, Buras, Recksiegel, arXiv:1507.06316 (2015)]
- Custodial Randall-Sundrum
  [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- MSSM non-MFV
  [Tanimoto, Yamamoto arXiv:1503.06270, Isidori et al. JHEP 0608 (2006) 064]

Back-of-the-envelope design

- $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) \sim 10^{-10}$
- Precision 10% ($\Rightarrow |V_{td}|$ to 5%)
- Statistics: $\sim$100 events, $<$ 10 background
- Signal acceptance $\sim$10%
- $\Rightarrow$ Need 10^{13} Kaon decays
- $\sim$10% of K^+ decay in decay volume
- Running time $\sim$2 CERN years, Duty cicle $\sim$30% (if no LHC fill)
- Unseparated beam contains 6% Kaons
- $\Rightarrow$ 750 Million beam particles per second! On average every 1.3 nsec one particle! Non-synchronous. (LHC: collision every 26 nsec synchronous)

Design (cont.): Backgrounds to $K^+ \to \pi^+ \nu \bar{\nu}$

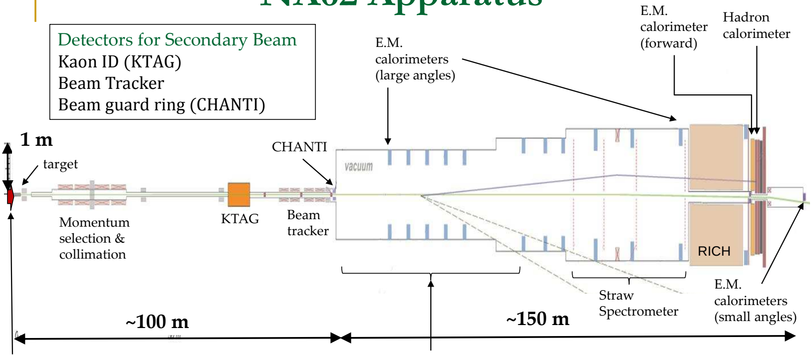
Main Background are the other Kaon decay modes:

$$
\begin{array}{ll}
K^+ \to \mu^+ \nu_\mu (\gamma) & \mathcal{B} = 63.5\% \\
K^+ \to \pi^+ \pi^0 (\gamma) & \mathcal{B} = 20.7\% \\
K^+ \to \pi^+ \pi^+ \pi^- & \mathcal{B} = 5.6\% \\
K^+ \to \pi^0 e^+ \nu_e & \mathcal{B} = 5.1\% \\
K^+ \to \pi^0 \mu^+ \nu_\mu & \mathcal{B} = 3.3\% \\
K^+ \to \pi^+ \pi^- e^+ \nu_e & \mathcal{B} = 4.1 \times 10^{-5} \\
K^+ \to \pi^0 \pi^0 e^+ \nu_e & \mathcal{B} = 2.2 \times 10^{-5} \\
K^+ \to \pi^+ \pi^- \mu^+ \nu_\mu & \mathcal{B} = 1.4 \times 10^{-5} \\
K^+ \to e^+ \nu_e (\gamma) & \mathcal{B} = 1.5 \times 10^{-5}
\end{array}
$$

Other Backgrounds: beam related (mostly upstream muons)
Background suppression: $> 10^{12}$ requiered

NA62 Apparatus

Detectors for Secondary Beam
Kaon ID (KTAG)
Beam Tracker
Beam guard ring (CHANTI)

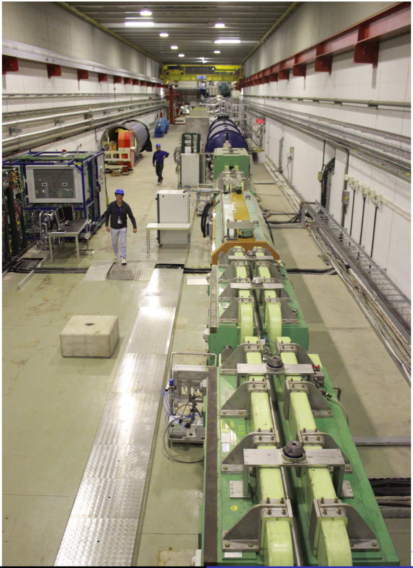


SPS proton
400 GeV
10^{12} p/s
3.5 s spill

Secondary Beam
75 GeV/c, $\Delta p/p \sim 1\%$
X,Y Divergence < 100 μrad
K(6%), π(70%), p(23%)
Total rate: 750 MHz
Beam size: 6.0 × 2.7 cm²

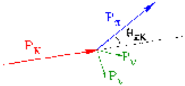
Kaon Decay
~5 MHz
$4.5 \times 10^{12}/year$
60 m length
10^{-6} mbar vacuum

Detectors for decay products
Charged particle tracking
Charged particle time stamping
Photon detection
Particle ID

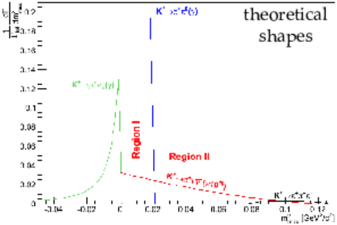


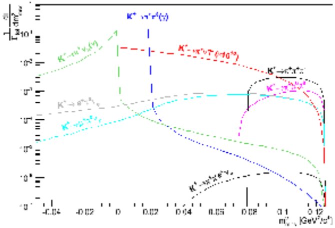
Scheme for $K^+ \to \pi^+ \nu \bar{\nu}$ Analysis

- Signal



- Background: K⁺ decay modes; beam activity
- Kinematics: $m^2_{miss} = (P_K - P_{\pi^+})^2$

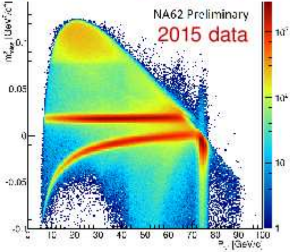




- Experimental principles:
  1) Precise kinematic reconstruction
  2) PID: K upstream, $e/\mu/\pi$ downstream
  3) Hermetic γ detection
  4) Sub-ns timing
- Key analysis requirements
  - 2 signal regions in m^2_{miss}
  - $15 < P_\pi < 35$ GeV/c
  - 65 m long decay region

Expected 45 SM signal events / year with < 10 background [O(10^{-12}) SES]

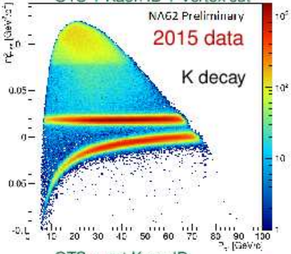
Signal Topology and Kaon ID



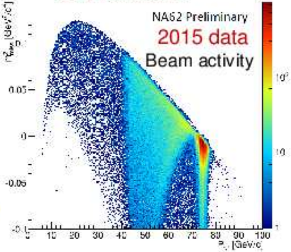
Kaon ID
Track origin in the fiducial region

Not Kaon ID

OTS + Kaon ID + Vertex cut



OTS + not Kaon ID



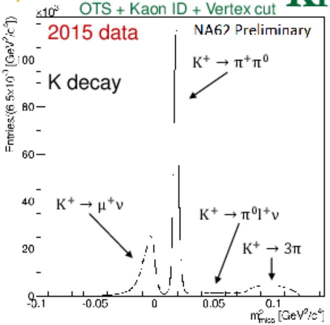
One – track selection (OTS)

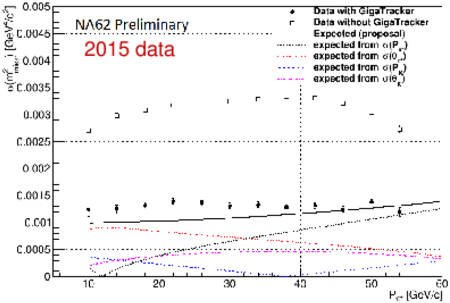
- Single downstream track topology
- Beam track matching the downstream track
- Beam track matching a K signal in Kaon ID
- Downstream track matching energy in calorimeters

Time resolutions:

- Kaon ID < 100 ps
- Beam track < 200 ps
- Downstream track < 200 ps
- Calorimeters 1-2 ns

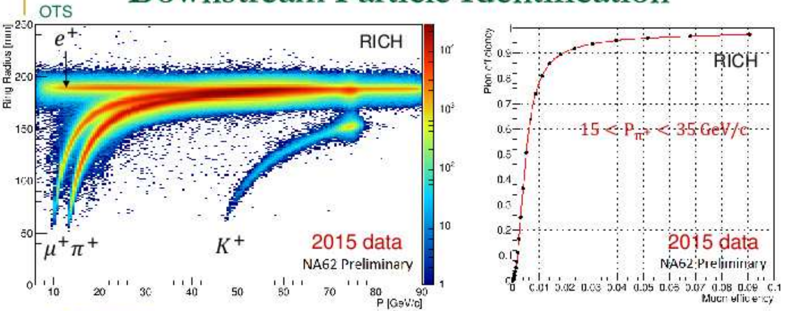
Kinematics





- Technique: Si - pixel tracker; Straw tube tracker in vacuum
- Goal: $O(10^4 \div 10^5)$ suppression factor of the main kaon decay modes
- $P_{\pi^+} < 35$ GeV/c: best $K^+ \to \mu^+ \nu$ suppression.
- Kinematics studied on $K^+ \to \pi^+ \pi^0$ selected using LKr calorimeter.
- Resolutions close to the design.
- $O(10^3)$ kinematic suppression factor in 2015.

Downstream Particle Identification



- Technique: RICH and calorimeters
- Goal: O(10^7) μ/π separation to suppress mainly $K^+ \to \mu^+ \nu$
- $15 < P_{\pi^+} < 35$ GeV/c: best μ/π separation in RICH
- Pure samples of pions and muons selected using kinematics
- RICH: O(10^2) π/μ separation, 80% π^+efficiency in 2015.
- Calorimeters: ($10^4 \div 10^6$) μ suppression, (90% ÷ 40%) π^+efficiency in 2015 using a cut analysis. Room for improvements.

Further NA62 Physics Program

- Standard Kaon Physics
  - Precision measurements of the branching ratio of all the main K decay modes
  - χPT studies: $K^+ \to \pi^+\gamma\gamma$, $K^+ \to \pi^+\pi^0 e^+ e^-$, $K^+ \to \pi^{0(+)}\pi^{0(-)} l^+ \nu$
  - LU study with the precision measurement of $R_K = \Gamma(K^+ \to e^+\nu)/\Gamma(K^+ \to \mu^+\nu)$
- LFV with Kaons:
  - $K^+ \to \pi^+\mu^\pm e^\mp$, $K^+ \to \pi^-\mu^+ e^+$, $K^+ \to \pi^- l^+ l^+$
- Heavy neutrino searches:
  - $K^+ \to l^+ \nu_h$
  - ν_h from K, D decays and $\nu_h \to \pi l$
- π^0 decays:
  - $\pi^0 \to$ invisible, $\pi^0 \to 3/4\gamma$, $\pi^0 \to U\gamma$
- Dark sector searches:
  - Long living dark photon decaying in $l^+ l^-$ and produced by $\pi^0/\eta/\eta'/\Phi/\varrho/\omega$ decays
  - Long living axion-like decaying in $\gamma\gamma$ produced in a beam-dump configuration

NA62 sensitivity for LFNV decays

Decays in FV in 2 years of data: **1×10^{13} K^+ decays**, **2×10^{12} π^0 decays**

Single-event sensitivity 1/(decays × acceptance)

Mode	UL at 90% CL	Experiment	NA62 acceptance*
$K^+ \to \pi^+\mu^+e^-$	1.3×10^{-11}	BNL 777/865	~10%
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}	BNL 865	
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}	BNL 865	~10%
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}	BNL 865	~5%
$K^+ \to \pi^-\mu^+\mu^+$	1.1×10^{-9}	NA48/2	~20%
$K^+ \to \mu^-\nu e^+e^+$	2.0×10^{-8}	Geneva Saclay	~2%
$K^+ \to e^-\nu\mu^+\mu^+$	no data		~10%
$\pi^0 \to \mu^+e^-$	3.6×10^{-10}	KTeV	~2%
$\pi^0 \to \mu^-e^+$			

* From fast Monte Carlo simulation with flat phase-space distribution. Includes trigger efficiency.

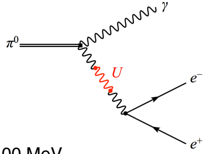
NA62 single-event sensitivities: **~10^{-12} for K^+ decays**, **~10^{-11} for π^0 decays**

Rare π^0 decays in NA62

2×10^{12} π^0 decays in FV in 2 years of data will allow substantial improvement of results in many channels

Mode	Current knowledge	Experiment	Expectation in SM	Physics interest
Neutral modes				
$\pi^0 \to 3\gamma$	$BR_{90CL} < 3.1\times10^{-8}$	Crystal Box	Forbidden	Violates C
$\pi^0 \to 4\gamma$	$BR_{90CL} < 2\times10^{-8}$	Crystal Box	$BR \sim 10^{-11}$	Scalar states $\pi^0 \to SS$
$\pi^0 \to$ inv	$BR_{90CL} < 2.7\times10^{-7}$	BNL 949	$BR < 10^{-13}$ (cosm. limit)	N_ν, LFV
Charged modes				
$\pi^0 \to e^+e^-e^+e^-$	$BR = 3.34(16)\times10^{-5}$	KTeV	$3.26(18)\times10^{-5}$	Off-shell vectors
$\pi^0 \to e^+e^-\gamma$	$BR_{95CL}(\pi^0 \to U\gamma)$: $< 1\times10^{5}$, $M_U = 30$ MeV; $< 3\times10^{6}$, $M_U = 100$ MeV	WASA/COSY	Null result	Dark forces

Rare π^0 decays in NA62



Search for U boson in $\pi^0 \to e^+e^-\gamma$ decay

New, light vector gauge boson with weak couplings to charged SM fermions

Could mediate interactions of dark-matter constituents

Expect to collect ~10^8 $\pi^0 \to e^+e^-\gamma$ decays/year

Mass resolution $M_{ee} \sim 1$ MeV

Potential for ~100× improvement in BR limit for $30 < M_U < 100$ MeV

Search for $\pi^0 \to$ invisible

$\pi^0 \to \nu\bar{\nu}$ forbidden by angular momentum conservation if νs are massless
For a given flavor of massive $\bar{\nu}$, BR($\pi^0 \to \nu\bar{\nu}$) directly related to m_ν

Direct experimental limit:

BNL 949 (2005)

BR($\pi^0 \to$ inv) $< 2.7 \times 10^{-7}$ 90%CL

Inferred limits on BR($\pi^0 \to \nu\bar{\nu}$) from:

Measured ν_τ mass: $< 5 \times 10^{-10}$

Astrophysics/cosmology: $< 3 \times 10^{-13}$

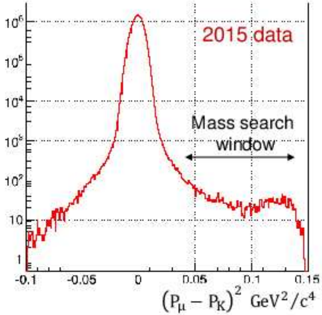
Experimental signature identical to $K^+ \to \pi^+\nu\bar{\nu}$

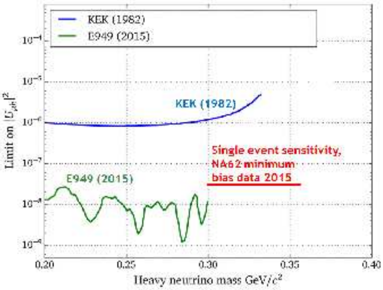
Only difference: in $K^+ \to \pi^+\pi^0$, $\pi^0 \to$ invisible, π^+ has 2-body decay kinematics

Limit BR($\pi^0 \to$ invisible) to less than 10^{-9}, ~100× better than present limits

NA62 and Heavy Neutrino

- Search for heavy neutrinos produced in $K^+ \to \mu^+ \nu_h$ and $K^+ \to e^+ \nu_h$
- NA62 is perfectly suited to search for ν_h in 100 – 380 MeV/c^2 mass range:
  - $K^+ \to l^+ \nu_h$ decays kinematically enhanced wrt to $K^+ \to \mu^+ \nu_{SM}$
  - Background in the mass region search ~5 order of magnitude below the $K^+ \to l^+ \nu_{SM}$ peak





NA62 Physics Analysis and Papers

Data taken in 2007/2008, with (partially) rearranged detectors from NA48

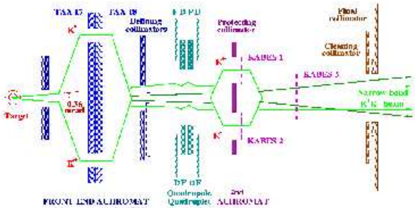
Physics topics:

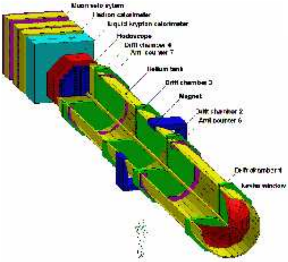
- R_K (Lepton Universality):
  PLB 719 326-336 (2013), PLB 698 105-114 (2011)
- $K^\pm \to \pi^\pm \gamma\gamma$, Chiral Pertubation tests:
  PLB 732 65-74 (2014)
- π^0 transition form factor (for $(g-2)_\mu$):
  Preliminary results, to be published later this year
- Others: Dark photon, heavy neutrino – mostly checks to prepare for full data taking

NA62

NA62 2007 Layout

- $K^\pm$ beams:
  - $P_K = 75 \pm 2$ GeV/c

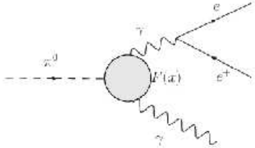




- Main Detectors (NA48):
  - Magnetic Spectrometer:
    $\sigma(P)/P = 0.48\% \oplus 0.009\ P(\mathrm{GeV/c})\%$
  - Hodoscope: Fast trigger for charged particles and timing for the event ($\sigma(t) = 200$ ps)
  - Liquid Kripton e.m. calorimeter (LKr):
    $\sigma(E)/E = 3.2\%/\sqrt{E} \oplus 9\%/E \oplus 0.42\%$ (GeV)

NA62

$\pi^0 \to \gamma\gamma^*$ Transition Form Factor

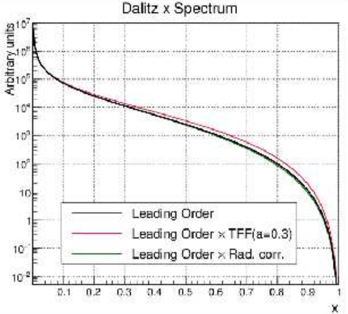


$$\frac{1}{\Gamma(\pi^0_{2\gamma})}\frac{d\Gamma(\pi^0_D)}{dx} = \frac{2\alpha}{3\pi}\frac{(1-x)^3}{x}\left(1+\frac{r^2}{2x}\right)\sqrt{1-\frac{r^2}{x}}\,(1+\delta(x))\,(1+ax)^2$$

$x = \frac{(p_{e^+}+p_{e^-})^2}{m^2_{\pi^0}}$ $r^2 = (2m_e/m_{\pi^0})^2$ δ(x) radiative correction $F(x) \approx 1 + a\,x$

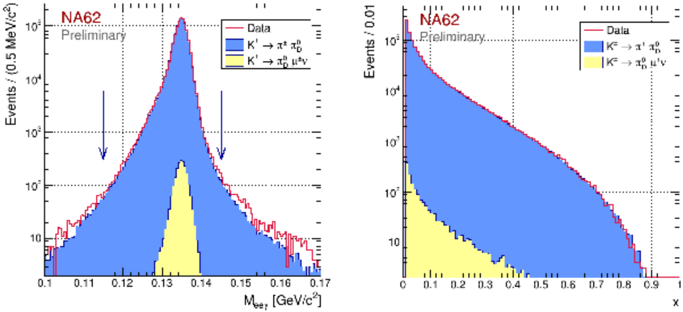
- TFF measurement: test prediction from theoretical models
- TFF models used for the hadronic light by light scattering contribution to $(g-2)_\mu$

- NA62 2007 data
- Data taking conditions optimized for $K^\pm \to e^\pm \nu$ [Phys. Lett. B 719 (2013) 326]
- $K^\pm \to \pi^\pm \pi^0$, $\pi^0 \to \gamma e^+ e^-$



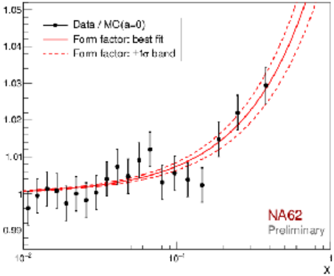
$\pi^0 \to \gamma e^+ e^-$ TFF: Selection

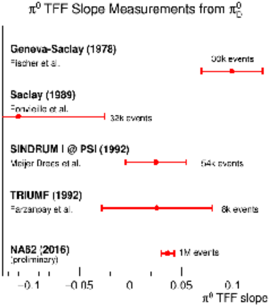
- Selection: 3-track topology, photon in LKr, full kinematic closure, $x > 0.01$
- 1.05×10^6 fully reconstructed $\pi^0 \to \gamma e^+ e^-$
- TFF obtained by adjusting the simulation to the data x spectrum.



$\pi^0 \to \gamma e^+ e^-$ TFF: Preliminary Result

$$a = (3.70 \pm 0.53_{stat} \pm 0.36_{syst}) \times 10^{-2}$$





- TFF Theory expectations:
- $a = (2.90 \pm 0.50) \times 10^{-2}$, χPT, [K. Kampf et al. EPJ C46 (2006), 191]
- $a = (3.07 \pm 0.06) \times 10^{-2}$, dispersion theory, [M. Hoferichter et al. EPJ C74 (2014), 3180]
- $a = (2.92 \pm 0.04) \times 10^{-2}$, two-hadron saturation, [T. Husek et al. EPJ C75 (2015) 12, 586]

Lepton Universality

R_K: $K^\pm \to e^\pm \nu_e$, $K^\pm \to \mu^\pm \nu_\mu$

R_K: $K^\pm \to e^\pm \nu_e$, $K^\pm \to \mu^\pm \nu_\mu$

- Fermi's Golden Rule for decay of particle with mass M:

$$d\Gamma = \frac{(2\pi)^4}{M} \cdot |\mathcal{M}_{fi}|^2 \cdot \mathrm{PS}$$

- $\mathcal{M}_{fi}$: describes the physics of the decay (weak interaction, helicity suppressed) and "should" be identical for both decay modes:
  "Lepton Universality": μ and e are identical except for the mass.
- PS: Phase Space, describing the density of final states.
- for 2-body decays: PS simple to calculate

R_K: $K^\pm \to e^\pm \nu_e$, $K^\pm \to \mu^\pm \nu_\mu$

SM width of $P^\pm \to \ell^\pm \nu$ ($P = \pi, K, D, B$)

$$\Gamma^{\text{SM}}(P^\pm \to \ell^\pm \nu) = \frac{G_F^2 M_P M_\ell^2}{8\pi} \left(1 - \frac{M_\ell^2}{M_P^2}\right)^2 f_P^2 |V_{qq'}|^2,$$

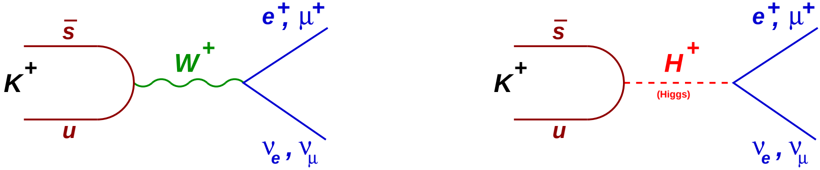
G_F: Fermi constant; M_P, M_ℓ: meson and lepton masses
f_P meson decay constant; $V_{qq'}$: CKM matrix element

$$\frac{\Gamma(K^\pm \to e^\pm \nu_e)}{\Gamma(K^\pm \to \mu^\pm \nu_\mu)} = R_K^{\text{SM}} = \left(\frac{M_e}{M_\mu}\right)^2 \left(\frac{M_K^2 - M_e^2}{M_K^2 - M_\mu^2}\right)^2 (1 + \delta R_{\text{QED}}) =$$

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

$\delta R_{\text{QED}} = (-3.79 \pm 0.04)\%$ EM (radiative) correction.

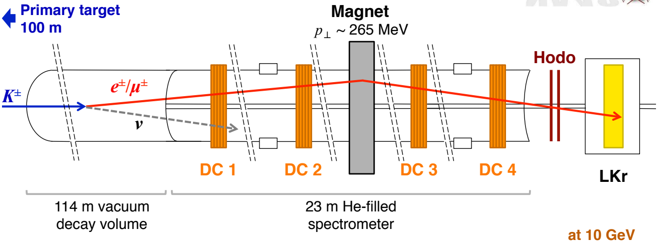
R_K beyond the Standard Model (one example)



- Charged Higgs boson exchange
- MSSM: R_K enhanced by $\sim 1\,\%$.
  But also constraint by $B_s \to \mu^+\mu^-$ and $B^+ \to \tau^+\nu_\tau$.
- R_K also sensitive to 4. generation and sterile neutrinos.

$\Rightarrow$ Need to measure R_K to better than $1\,\%$

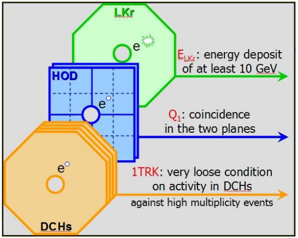
NA48 setup used by NA62 for R_K



		at 10 GeV
Drift chambers	$\sigma(p)/p = 0.48\% \oplus 0.009\%\ p$ [GeV] $\sigma_{x,y} = 90$ µm	0.48%
LKr calorimeter	$\sigma_E/E = 3.2\%/\sqrt{E}$ [GeV] $\oplus$ $9\%/E$ [GeV] $\oplus$ 0.42% $\sigma_x = \sigma_y = 4.2$ mm$/\sqrt{E} \oplus 0.6$ mm	1.4% 1.5 mm
Hodoscope	Fast trigger, good time resolution (150 ps)	

Kaon beam: 74 GeV$/c$, $10^5/sec$

R_K Trigger Logic



Electron Trigger:

- Hodoscopes
- low multiplicity in DCH
- $>$ 10 GeV in LKr

Muon Trigger:

- Hodoscopes
- low multiplicity in DCH
- Downscale by 150

Data Samples, Backgrounds

- $\sim 2 \times 10^{10}$ K decays collected over 4 months
- Main backgrounds for K_{e2}:
  - Beam halo muons
  - Miss-Id of μ as e (also: $\mu \to e\nu_e\nu_\mu$)
  - Strategy: Block one of the beams, measure the background
- Backgrounds for $K_{\mu 2}$:
  - Miss-Id of μ as e (also: $\mu \to e\nu_e\nu_\mu$)
  - Strategy: Clean sample of μ to measure Miss-Id in LKr add Pb block in front to absorb e.

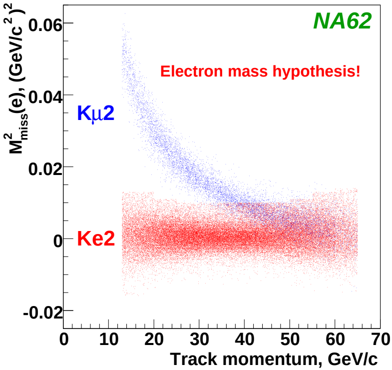
Analysis Strategy

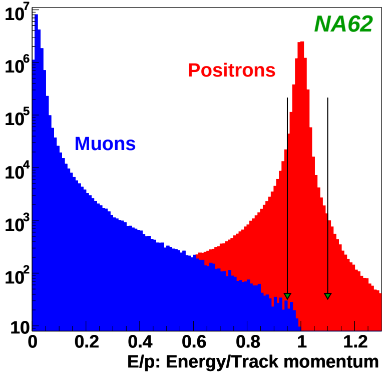
Acceptances different for K^+, K^-, with/without Pb, function of lepton momentum
$\Rightarrow$ 40 independent measurements of

$$R_K = \frac{1}{D} \cdot \frac{N(K_{e2}) - N_{\mathrm{B}}(K_{e2})}{N(K_{\mu 2}) - N_{\mathrm{B}}(K_{\mu 2})} \cdot \frac{A(K_{\mu 2})}{A(K_{e2})} \cdot \frac{f_\mu \times \epsilon(K_{\mu 2})}{f_e \times \epsilon(K_{e2})} \cdot \frac{1}{f_{\mathrm{LKr}}}$$

$N(K_{\ell 2})$: selected candidates; $N_{\mathrm{B}}(K_{\ell 2})$: background events; $A(K_{\mu 2})/A(K_{e2})$: ratio of the geometrical acceptances; f_ℓ; lepton identification efficiencies; $\epsilon(K_{\ell 2})$ trigger efficiencies; f_{LKr}: Global efficiency of the LKr readout; $D = 150$: $K_{\mu 2}$ trigger downscaling factor.

Signal Events

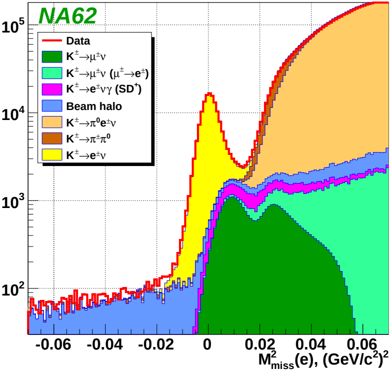


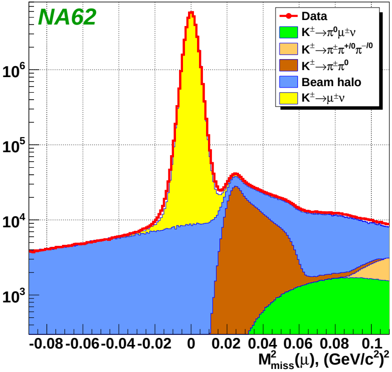


Backgrounds

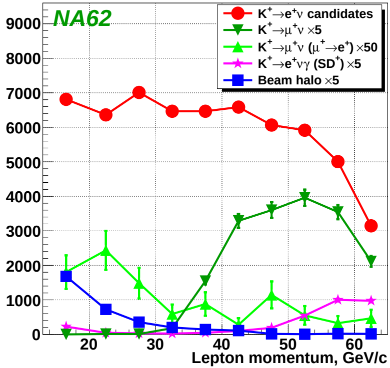
- $K_{\mu 2}$ in K_{e2} sample: Measured via Pb
- $K^\pm \to e^\pm \nu \gamma$ in K_{e2} sample: Determined via MC based on NA48 measurement
- $K^\pm \to \pi^0 e^\pm \nu$, $K^\pm \to \pi^\pm \pi^0$: Missing mass, measured missid of an $\pi^\pm$ as $e^\pm$
- $K^\pm \to \pi^0 \ell^\pm \nu$, $K^\pm \to \pi^\pm \pi^0$, with $\pi^0 \to \gamma e^+ e^-$: MC simulations.

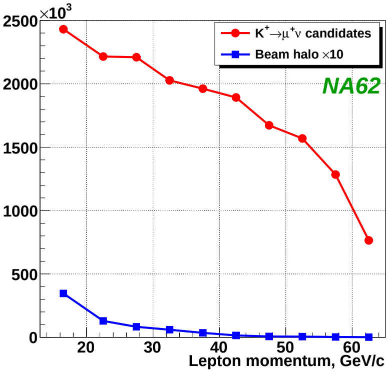
Missing Mass Spectra



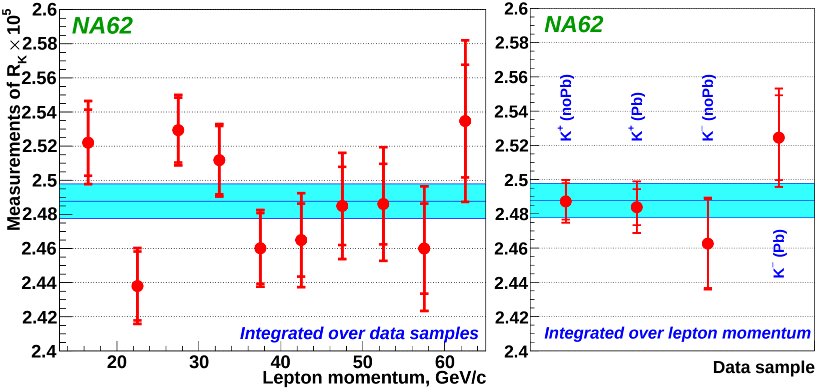


Number of Events





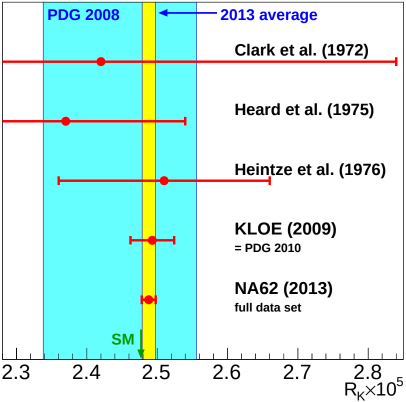
Systematics of R_K



Final result

$$R_K = (2.488 \pm 0.007_{\text{stat.}} \pm 0.007_{\text{syst.}}) = (2.488 \pm 0.010) \times 10^{-5}$$

Published: PLB 719, 326
Precision 0.4 %,
still factor 10 more than theory precision.
$\Rightarrow$ New measurement with improved statistics



$K^\pm \to \pi^\pm \gamma\gamma$

$K^\pm \to \pi^\pm \gamma\gamma$

Test of Chiral Pertubation Theory.
Kinematic Variables:

$$z = \frac{(q_1 + q_2)^2}{m_K^2} = \left(\frac{m_{\gamma\gamma}}{m_K}\right)^2, \quad y = \frac{p(q_1 - q_2)}{m_K^2}$$

q_1, q_2, p: 4-momenta of photons and kaon
$m_{\gamma\gamma}$: two photon invariant mass

$$0 \leq z \leq z_{\max} = (1 - m_\pi / m_K)^2 = 0.515$$

$$0 \leq y \leq y_{\max}(z) = \frac{1}{2}\sqrt{\lambda\left(1, (m_\pi / m_K)^2, z\right)},$$

$$\lambda(a, b, c) = a^2 + b^2 + c^2 - 2(ab + ac + bc)$$

$K^\pm \to \pi^\pm \gamma\gamma$

- Considerable phenomenological understanding
- Only small samples observed: $\mathcal{B} =\sim 10^{-6}$
  - BNL E787 (1997): 31 candidates
  - NA48/2 (2014): 149 candidates, $z > 0.2$
  - This measurement: 232 candidates, $z > 0.2$

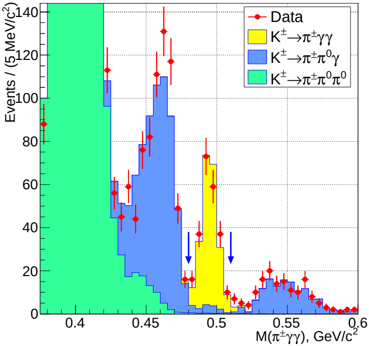
Data sample and trigger

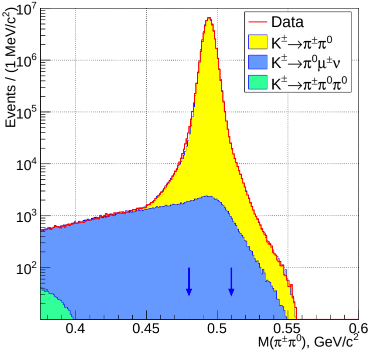
- Parallel datataking with R_K
- Minimum bias trigger, downscaled
- Branching ratio measured relativ to $K^\pm \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$

$$\mathcal{B}(K_{\pi\gamma\gamma}) = \frac{N'_{\pi\gamma\gamma}}{N'_{2\pi}} \cdot \frac{A_{2\pi}}{A_{\pi\gamma\gamma}} \cdot \frac{\varepsilon_{2\pi}}{\varepsilon_{\pi\gamma\gamma}} \cdot \mathcal{B}(K_{2\pi})\mathcal{B}(\pi^0_{\gamma\gamma}),$$

$N'_{\pi\gamma\gamma}$, $N'_{2\pi}$ signal and normalization events
$A_{\pi\gamma\gamma}$, $A_{2\pi}$: Acceptances
$\varepsilon_{\pi\gamma\gamma}$, $\varepsilon_{2\pi}$: Trigger efficiencies
$\mathcal{B}(K_{2\pi})\mathcal{B}(\pi^0_{\gamma\gamma}) = 0.204 \pm 0.001$

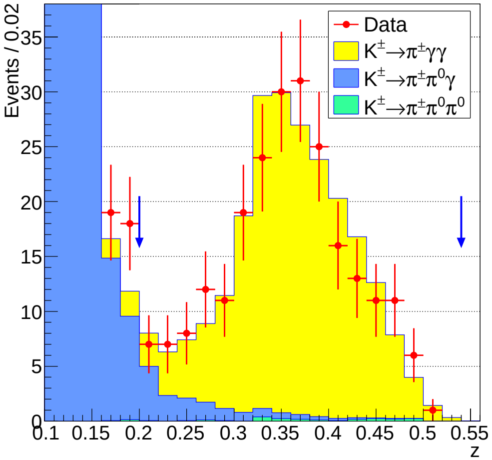
Signal Events





$\pi^\pm\gamma\gamma : z > 0.2(m_{\gamma\gamma} > 0.22\text{GeV}/c^2)$
$\pi^\pm\pi^0 : m_{\gamma\gamma} = m_{\pi^0} \pm 10\,\text{MeV}/c^2$

z distribution of signal events



Model Independent Branching Ratio in z-bins

Bin z range	N_j	N_j^B	A_j	$\mathcal{B}_j \times 10^6$
0.20–0.24	14	7.32	0.177	0.024 ± 0.013
0.24–0.28	20	3.83	0.175	0.058 ± 0.016
0.28–0.32	30	1.97	0.169	0.104 ± 0.020
0.32–0.36	54	1.93	0.160	0.204 ± 0.029
0.36–0.40	56	1.00	0.146	0.237 ± 0.032
0.40–0.44	29	0.57	0.124	0.144 ± 0.027
0.44–0.48	22	0.54	0.087	0.155 ± 0.034
$z > 0.48$	7	0.25	0.026	0.162 ± 0.064

$$\mathcal{B}_{\mathrm{MI}}(z > 0.2) = \sum_{j=1}^{8} \mathcal{B}_j = (1.088 \pm 0.093_{\mathrm{stat}}) \times 10^{-6}$$

Chiral Pertubation Theory

Differential decay rate:

$$\frac{\partial\Gamma}{\partial y\partial z}(\hat{c},y,z) = \frac{m_K}{2^9\pi^3}\Big[z^2\left(|A(\hat{c},z,y^2)+B(z)|^2+|C(z)|^2\right) + \left(y^2-\frac{1}{4}\lambda(1,r_\pi^2,z)\right)^2|B(z)|^2\Big].$$

$A(\hat{c},z,y^2)$, $B(z)$, $C(z)$ from $\mathcal{O}(p^4)$ and $\mathcal{O}(p^6)$ ChPT
Fit to z-distribution:

$$\hat{c}_4 = 1.93 \pm 0.26_{\rm stat}, \quad \hat{c}_6 = 2.10 \pm 0.28_{\rm stat}.$$

Results

This measurement:

$$\mathcal{B}_{\rm MI}(z > 0.2) = (1.088 \pm 0.093_{\rm stat} \pm 0.027_{\rm syst}) \times 10^{-6}.$$

$$\hat{c}_4 = 1.93 \pm 0.26_{\rm stat} \pm 0.08_{\rm syst}, \quad \hat{c}_6 = 2.10 \pm 0.28_{\rm stat} \pm 0.18_{\rm syst}$$

$$\mathcal{B}_{\rm ChPT} = (1.058 \pm 0.066_{\rm stat} \pm 0.044_{\rm syst}) \times 10^{-6}.$$

Combined with NA48/2 results:

$$\mathcal{B}_{\rm MI}(z > 0.2) = (0.965 \pm 0.061_{\rm stat} \pm 0.014_{\rm syst}) \times 10^{-6}.$$

$$\hat{c}_4 = 1.72 \pm 0.20_{\rm stat} \pm 0.06_{\rm syst}, \quad \hat{c}_6 = 1.86 \pm 0.23_{\rm stat} \pm 0.11_{\rm syst},$$

$$\mathcal{B}_{\rm ChPT} = (1.003 \pm 0.051_{\rm stat} \pm 0.024_{\rm syst}) \times 10^{-6} = (1.003 \pm 0.056) \times 10^{-6}.$$

Conclusions

- NA62 is a new rare kaon decay experiment at CERN SPS.
- Is taking data as we speak!
- Will measure $\sim$ 100 events of $K^+ \to \pi^+\nu\bar{\nu}$
- Single event sensitivity $\sim 10^{-12}$ for K^+ decays
- A real factory of K^+
- Also a factory of π^0 and π^+
- Already published some results
- Working on analysis of 2015 minimum bias data

- Continuation (after LS2) under discussion (K^0 beam?)