Measurement of the $K^+ \to \pi^+\nu\bar{\nu}$ decay

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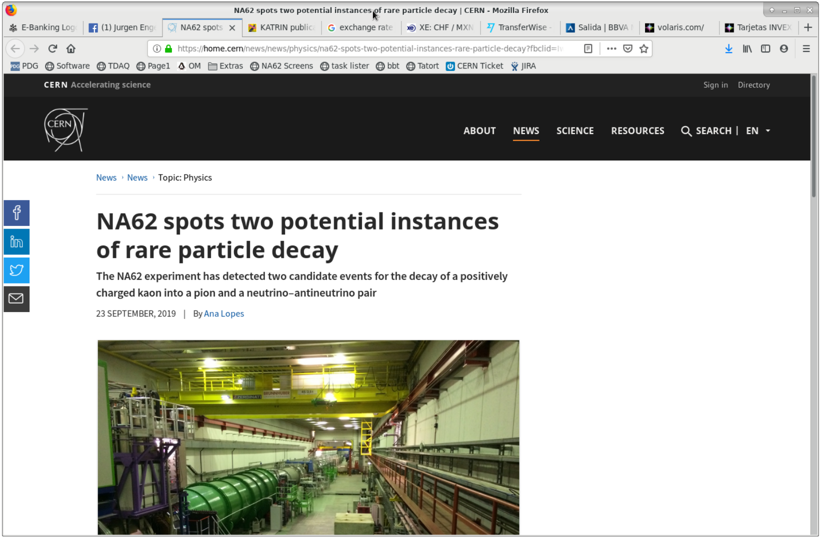
ICN-UNAM, IF-UNAM
April 21, 2021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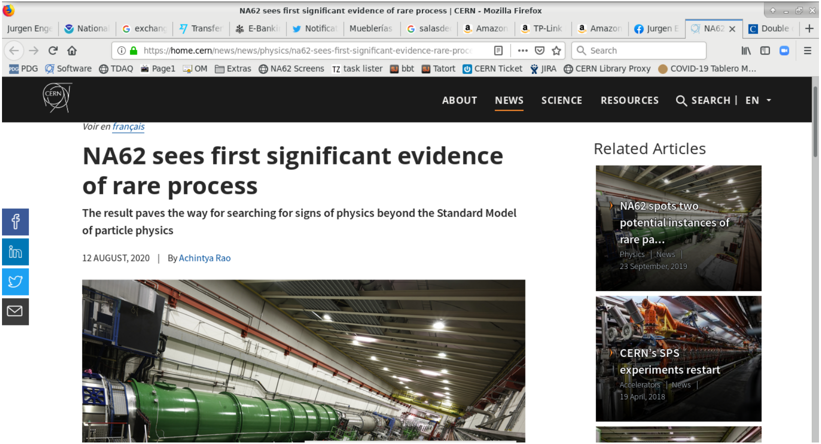
NA62 spots two potential instances of rare particle decay

The NA62 experiment has detected two candidate events for the decay of a positively charged kaon into a pion and a neutrino–antineutrino pair

23 SEPTEMBER, 2019 | By Ana Lopes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March 27, 2021

Measurement of the very rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay

The NA62 Collaboration

Abstract

The NA62 experiment reports the branching ratio measurement $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$ at 68% CL, based on the observation of 20 signal candidates with an expected background of 7.0 events from the total data sample collected at the CERN SPS during 2016–2018. This provides evidence for the very rare $K^+ \to \pi^+\nu\bar{\nu}$ decay, observed with a significance of 3.4σ. The experiment achieves a single event sensitivity of $(0.839 \pm 0.054) \times 10^{-11}$, corresponding to 10.0 events assuming the Standard Model branching ratio of $(8.4 \pm 1.0) \times 10^{-11}$. This measurement is also used to set limits on $\mathrm{BR}(K^+ \to \pi^+ X)$, where X is a scalar or pseudo-scalar particle. Details are given of the analysis of the 2018 data sample, which corresponds to about 80% of the total data sample.

Outline

- Introduction
- $K \to \pi\nu\bar{\nu}$ theory
- The NA62 experiment
- $K^+ \to \pi^+\nu\bar{\nu}$ new result
- Other NA62 measurements

Important Symmetries in Particle Physics

- Parity

$$\mathcal{P}\Psi(\vec{r}) \rightarrow \Psi(-\vec{r})$$

  Strong and Electromagnetic Interactions conserve Parity
  Weak Interaction violates Parity (1957)

- Charge Conjugate $\mathcal{C}$
  exchange sign of electric charge and magnetic moment
  exchange particle with antiparticle
- Time Reversal $\mathcal{T}$

Until 1964: All Interactions are invariant under $\mathcal{CP}$

$$\begin{aligned} K_L^0 &\rightarrow \pi^0\pi^0\pi^0 \quad (\mathrm{BR} = 21\%) \quad \mathcal{CP} = +1 \\ &\rightarrow \pi^+\pi^-\pi^0 \quad (\mathrm{BR} = 13\%) \quad \mathcal{CP} = +1 \\ &\rightarrow \pi^+\pi^- \quad (\mathrm{BR} = 0.2\%) \quad \mathcal{CP} = -1 \end{aligned}$$

$\mathcal{CP}$ Violation!!!

Where is all the Antimatter?

Sakharov (1967):
Need 3 Conditions for Matter/Antimatter Asymmetry:

- Violation of $\mathcal{C}$ and $\mathcal{CP}$
- Violation of Baryon Number
- Non-Equilibrium Condition in the Early Universe

Weak Interaction

$\approx$ 1960 weak decay of strange particles

- Why "strange"?
  - produced abondandly
  - long living
- Explanation:
  - produced in pairs by Strong Interaction
  - decay by Weak Interaction suppressed
    eigenstates to Strong Interaction and mass are
    NOT eigenstates to Weak Interaction

$\Longrightarrow$ Cabbibo theory (1963) (before quarks!)

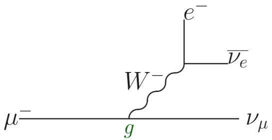
- 2×2 rotation matrix for quarks (not! for leptons, but later yes)

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

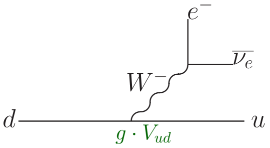
θ_c : Cabbibo angle $\qquad \cos\theta_c = V_{ud}$

Examples of Weak Decays

$\mu^- \to e^- \nu_\mu \bar{\nu}_e$: μ lifetime determines g



$n \to p e^- \bar{\nu}_e$
on quark level: $d \to u\, e^- \bar{\nu}_e$



In principle determines V_{ud}, but quarks are not alone!

Some more History

≈ 1970:	Are there more quarks? (most people: NO!) If yes, how to change Cabbibo theory?
1972:	Kobayashi and Maskawa: If there are 6 quarks, we can describe $\mathcal{CP}$ Violation (3×3 matrix)
1974:	"September Revolution" charm quark discovered (Brookhaven, SLAC)
1976:	b quark (Fermilab)
1994:	t quark (Fermilab)
2008:	Nobel Prize for Kobayashi & Maskawa (but not for Cabbibo)

Cabibbo-Kobayashi-Maskawa (CKM) Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Theory (Standard Model): Matrix is unitary.

$\Longrightarrow$ Need only 3 real and one imaginary parameters

Current fit to all experimental data incl. unitarity[1]

$$|V| = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

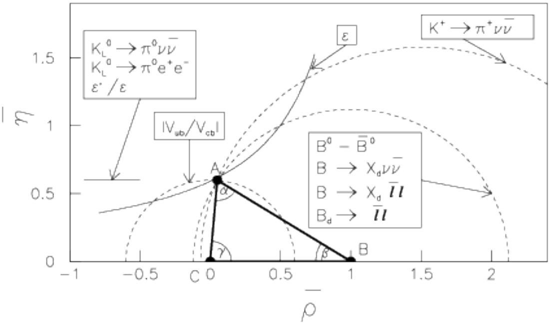
Jarlskog Constant $J = (3.18 \pm 0.15) \times 10^{-5}$

[1] PDG, 2018

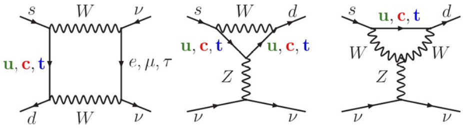
Wolfenstein parameterization:

$$V = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$\bar{\rho} = \frac{\rho}{A\lambda^3}$, $\quad \bar{\eta} = \frac{\eta}{A\lambda^3}$



Calculated[2] by weak isospin rotation from $K^+ \to \pi^0 e^+ \nu$



$$\frac{Br[K^+ \to \pi^+ \nu \bar{\nu}]}{Br[K^+ \to \pi^0 e^+ \nu]} = \frac{3\alpha^2}{8\pi^2 \sin^4 \theta_W} |V_{cs}^* V_{cd} D(X_c) + V_{ts}^* V_{td} D(X_t)|^2 \frac{1}{|V_{us}|^2}$$

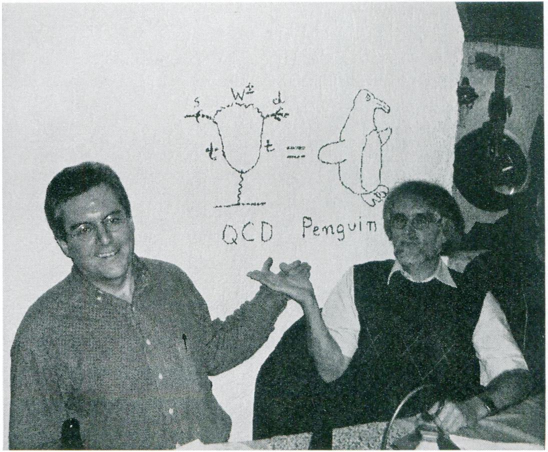
$$D(X) = \frac{1}{8}\{1 + \frac{3}{(1-X)^2} - \frac{(4-X)^2}{(1-X)^2}\} X ln(X) + \frac{X}{4} - \frac{3X}{4(1-X)}$$

$$X_j = \{\frac{m_j}{m_W}\}^2; \quad j = c, t.$$

$$Br[K^+ \to \pi^+ \nu \bar{\nu}] = 0.55 \times 10^{-10}[(1.35 - \bar{\rho})^2 + (1.05\bar{\eta})^2] = (0.75 \pm 0.29) \times 10^{-10}$$

[2] T. Inami and C.S. Lim, Progress of Theoretical Physics **65** (1981) 297-314

[4] A.J. Buras, Proceedings Zacatecas 2001



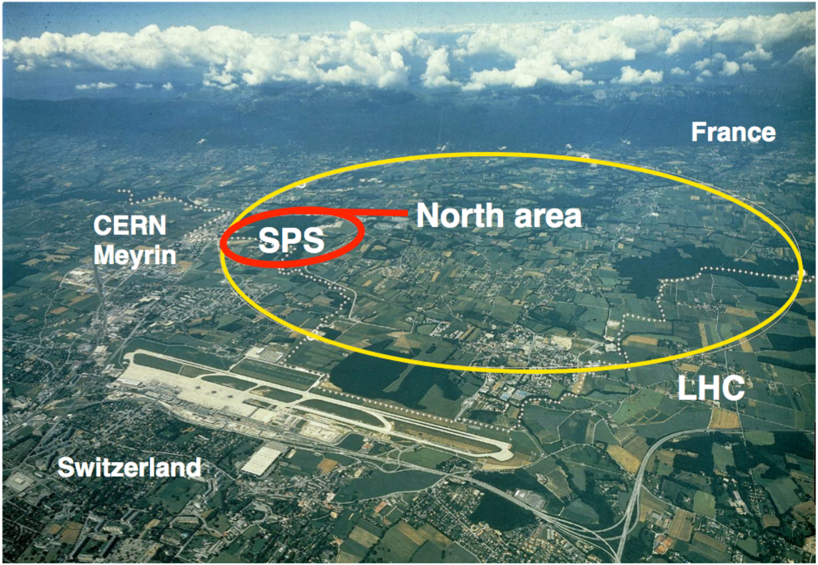
Andrei Buras (right, with John Conway), Restaurante “Mamá Inés”, Zacatecas, Mexico, November 2001

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

$\sim$ 200 collaborators

Hopefully soon also Guanajuato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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^-)	$R_K = K^\pm_{e2}/K^\pm_{\mu 2}$
2014–2025	NA62 (K^+)	$K^+ \to \pi^+\nu\bar{\nu}$ Rare K^+, π^+, and π^0 decays

NA62 (cont.)

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

NA62 Data Taking periods

2014 Pilot run

2015 Commissioning run

2016 Commissioning + Physics run

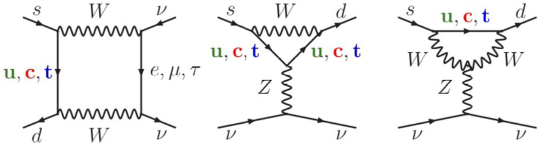
2017 Physics run

2018 Physics run
Results from 2016-8 Data shown here

2021-25 Physics run (NEWS: approved last week to run until LS3)

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

- 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. JHEP 1511 (2015) 033

$$\mathcal{B}(K^+ \to \pi^+ \nu\overline{\nu}) = (8.39 \pm 0.30) \times 10^{11} \left(\frac{|V_{cb}|}{0.0407}\right)^{2.8} \left(\frac{\gamma}{73.2^\circ}\right)^{0.74} = (0.84 \pm 0.10) \times 10^{-10}$$

$$\mathcal{B}(K^0 \to \pi^0 \nu\overline{\nu}) = (3.04 \pm 0.06) \times 10^{-11}$$

$K \to \pi\nu\bar{\nu}$: Experimental Status

- E949, E787 (Brookhaven), Stopped Kaon technique:
  $\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$
  [Phys.Rev. D77, 052003 (2008), D78,092004 (2009)]

- KOTO (JPARC) $\mathcal{B}(K^0 \to \pi^0\nu\overline{\nu}) < 3.0 \times 10^{-9}$ @90% CL
  - Result from 2015
  - Announced observation of 4 candidate events at *Kaon 2019*, all explained as background since then

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

- Simplified Z, Z' models (sensitive up to $M_{Z'} \sim 500\,TeV$)
  [Buras, Buttazzo,Knegjens, JHEP 1511 (2015) 166]
- Littlest Higgs with T-parity
  [Blanke, Buras, Recksiegel, EPJ C76 (2016) 182]
- Custodial Randall-Sundrum
  [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- MSSM non-MFV
  [Tanimoto, Yamamoto, PTEP 2016 (2016)no.12, 123B06;
  Blazek, Matak, IntJModPhysA 29 (2014) 1450162;
  Isidori et al. JHEP 0608 (2006) 064]
- LFU violating models [Isidori et al., EPJ C77 (2017)]

Constraints from existing measurements: Kaon mixing and CPV, CKM fit, K,B rare decays, direct searches

Back-of-the-envelope design

- $\mathcal{B}(K^+ \to \pi^+ \nu \overline{\nu}) \sim 10^{-10}$
- Precision 10% ($\Rightarrow |V_{td}|$ to 5%)
- Statistics: $\sim$100 events, $<$ 10 background
- Signal acceptance $\sim$10%
- $\Rightarrow$ Need to observe 10^{13} Kaon decays

- $\sim$10% of K^+ decay in fiducial 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 $K^+ \to \pi^+\nu\overline{\nu}$

Main Background are the other Kaon decay modes:

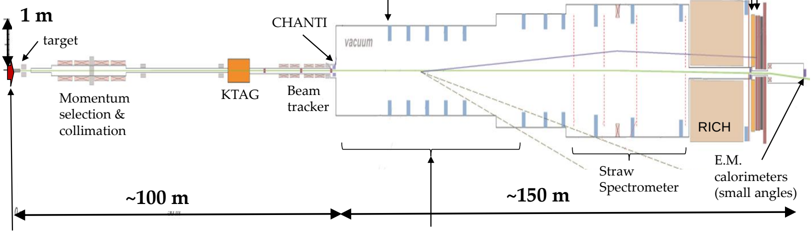
$K^+ \to \mu^+\nu_\mu(\gamma)$	$\mathcal{B} = 63.5\%$
$K^+ \to \pi^+\pi^0(\gamma)$	$\mathcal{B} = 20.7\%$
$K^+ \to \pi^+\pi^+\pi^-$	$\mathcal{B} = 5.6\%$
$K^+ \to \pi^0 e^+\nu_e$	$\mathcal{B} = 5.1\%$
$K^+ \to \pi^0\mu^+\nu_\mu$	$\mathcal{B} = 3.3\%$
$K^+ \to \pi^+\pi^- e^+\nu_e$	$\mathcal{B} = 4.1 \times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

Other Backgrounds: beam related (upstream Kaon decays, beam π^+)

Background suppression: $> 10^{12}$ requiered

NA62 Apparatus

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



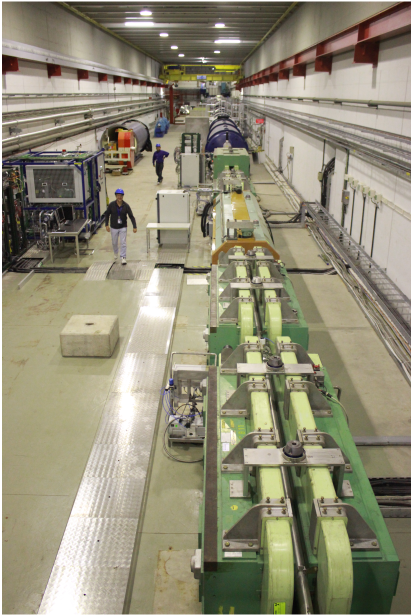
SPS proton
400 GeV
10^{12} p/s
3.5 s spill

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


ZERBINATI
BRUNNHUBER
45/2,5 t



Some more about Data Taking

- Beam for $\sim$ 3 s every 15-40s (“burst”)
- Select by trigger (“hardware” and software) $\sim$ 300000 events, $\sim$ 4 GByte
- In 2016-8: $\sim$ 1000000 bursts, $\sim$ 4 PBytes

- Offline Processing: Full processing lasts $\sim$ 4 monts with $\sim$ 10000 cores en parallel, another $\sim$ 1.5 PBytes in different filter streams.

Triggers and Analysis

Trigger streams (hardware L0 + software L1)

- “PNN”:
  - L0: presence of a charged particle, photon and muon veto
  - L1: kaon identification, photon veto, STRAW track reconstruction
- “Control”: minimum bias, presence of a charged particle downscaled by 400
- More triggers for other physics topics, but total size “small”

Offline analysis for $\pi\nu\nu$:

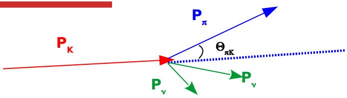
- Data samples: PNN; Control: $K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\nu$, $K^+ \to \pi^+\pi^+\pi^-$, $K^+ \to \pi^+\pi^- e^+\nu$
- Blind analysis procedure: signal/validation regions masked during the analysis

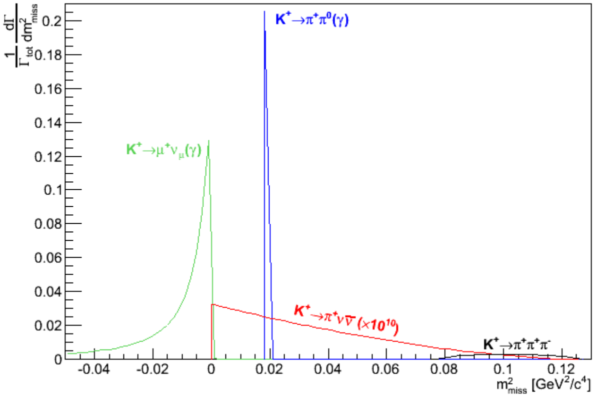
Analysis strategy

Decay-in-flight technique

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

π^+ mass hypothesis





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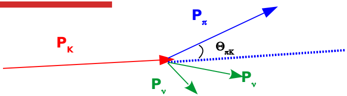

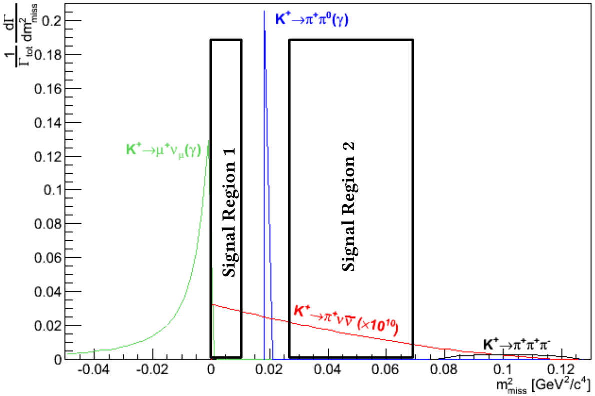

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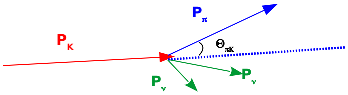
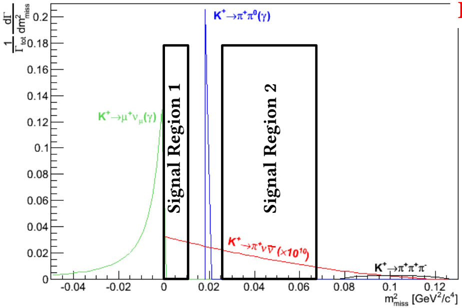


Process	Branching ratio
$K^+ \to \pi^+\pi^0$	0.2066
$K^+ \to \mu^+\nu_\mu$	0.6356
$K^+ \to \pi^+\pi^+\pi^-$	0.0558
$K^+ \to \pi^+\pi^- e^+\nu_e$	4.3×10^{-5}
$K^+ \to \pi^+\nu\nu$ (SM)	**8.4×10^{-11}**



$15 < P_{\pi^+} < 35$ GeV/c

+ Particle ID(Cherenkov detectors)

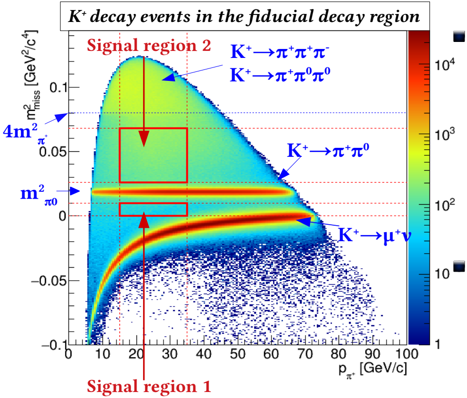
Particle ID(Calorimeters)

Photon veto

Keystones of the analysis

- Muon suppression > 10^7
- π^0 suppression (from $K^+ \to \pi^+\pi^0$) > 10^7
- Excellent time resolution O(100ps)
- Kinematic suppression ~ $O(10^4)$

Signal selection



m^2_{miss} computed under π^+ mass hypothesis

- Selection criteria
  - single track decay topology
  - π^+ identification
  - photon rejection
  - multi-track rejection
- Performance
  - $\epsilon_{\mu^+} \sim 10^{-8} (64\% \ \pi^+ \text{ efficiency})$
  - $\epsilon_{\pi^0} = (1.4 \pm 0.1) \cdot 10^{-8}$
  - $\sigma(m^2_{miss}) = 1 \cdot 10^{-3} \text{ GeV}^2/c^4$
  - $\sigma_T \sim O(100 \text{ ps})$

Analysis Strategy for 2016/7/8 Data

- With 2016 Data: Make sure experimental idea works
- With 2017 Data: Push Single Event sensitivity
- with every order of magnitude you could find a new background
- First: Cut-based analysis, to find (and fix) problems.
- With 2018 Data:
  - Most important background reduced with new beam collimator
  - Much more statistics with increased beam intensity and longer running time
  - Increased momentum range in Region II
  - Optimized cuts
- Prepare for 2021-25 Data: Use highest intensity data to investigate (and reduce) random veto losses, other intensity related effects

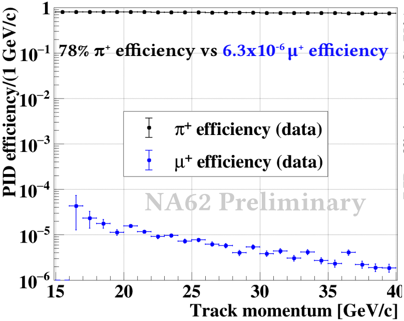
Keystones of the analysis: Particle identification

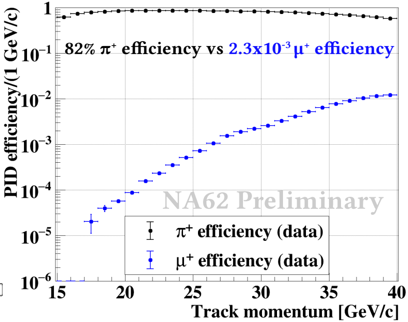
Calorimetric PID

- Machine learning approach (BDT)
  - Energy deposition
  - Energy sharing
  - Shower shape profiles

RICH PID

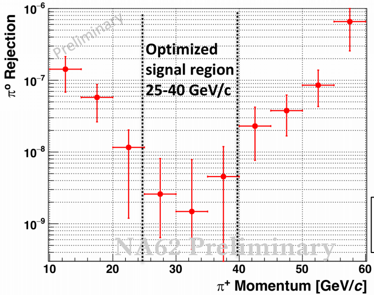
- Track driven likelihoods discriminant for π/μ/e separation
- Particle mass using track momentum
- Momentum measurement under mass hypothesis (velocity spectrometer)





π^0 suppression and search for $\pi^0 \rightarrow$ invisible

- A priori evaluation of π^0 suppression of $K^+ \rightarrow \pi^+\pi^0$ decays ($0.015 < m^2_{miss} < 0.021$ GeV^2/c^4)
  - Selection and trigger stream identical to $K^+ \rightarrow \pi^+\nu\nu$ (1/3 of the data set used)
  - Single-γ detection efficiency from control $K^+ \rightarrow \pi^+\pi^0$ data (Tag & Probe)
  - π^0 suppression evaluated from convolution with MC $K^+ \rightarrow \pi^+\pi^0(\gamma)$
  - Validation: side bands with expected rejection O(10^{-7}) where **$\pi^0 \rightarrow$ invisible** excluded [E949, PRD72 (2005)]
- π^0 suppression expected = $(2.8^{+5.9}_{-2.1})\times10^{-9}$ (π^+ momentum region 25-40 GeV/c)



- Results
  - BR($\pi^0 \rightarrow$invisible) normalized to $\pi^0 \rightarrow \gamma\gamma$
  - Expected background: 10^{+22}_{-8} events
  - Observed: 12 events

BR($\pi^0 \rightarrow$invisible) < 4.4×10^{-9} @ 90% CL

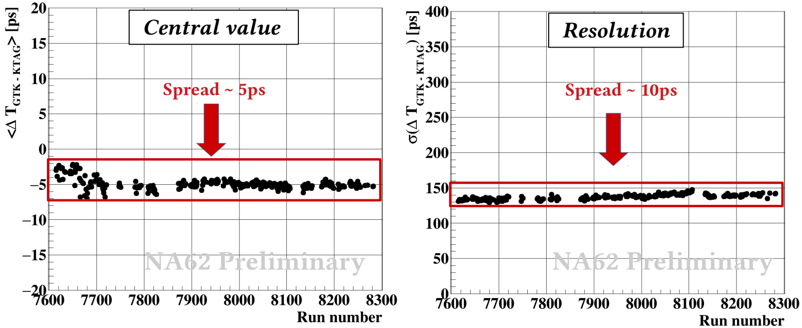
UL 60 times stronger than previous measurements

NA62 Preliminary

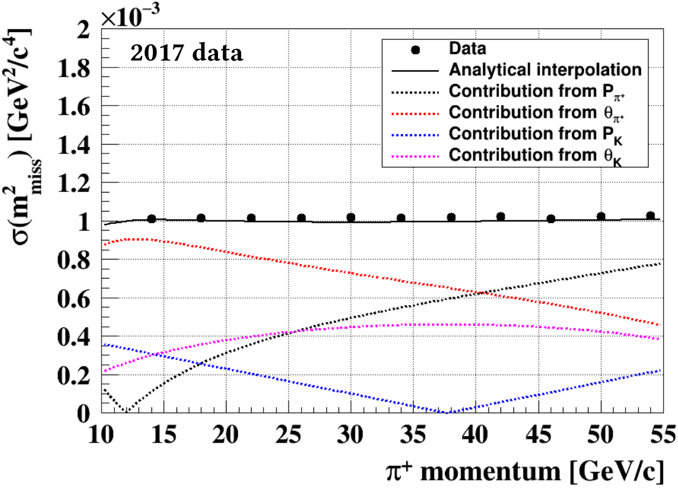
Keystones of the analysis: Time resolution

Time calibration stability

- Excellent calibration at the processing level in 2017
- Stable central value and time resolution
- Single-detector time resolution ~ 90ps



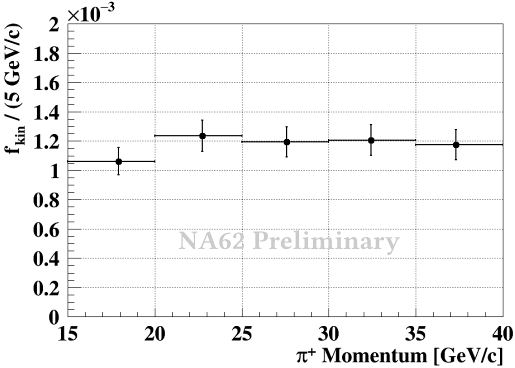
Keystones of the analysis: Kinematic resolution



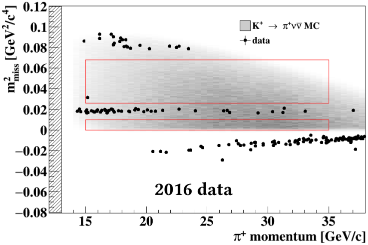
Keystones of the analysis: Kinematic suppression

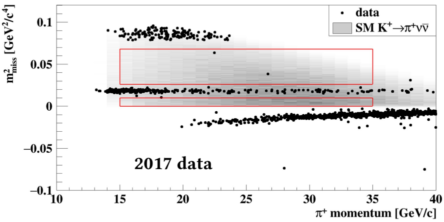
$K^+ \longrightarrow \pi^+\pi^0$

- Kinematic suppression measured on $K^+ \longrightarrow \pi^+\pi^0$ decays in data
- Fraction of events $\pi^+\pi^0$ entering m^2_{miss} signal region



Reminder: 2016 and 2017 data results



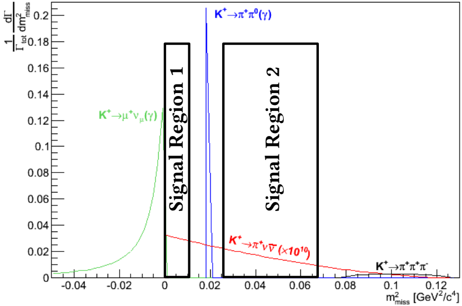


- 1 events observed
- Br($K^+ \longrightarrow \pi^+ \nu\nu$) < 14×10^{-10} @ 90% CL
  Phys. Lett. B 791 (2019) 156-166

- 2 events observed
- Br($K^+ \longrightarrow \pi^+ \nu\nu$) < 1.78×10^{-10} @ 90% CL
  [arXiv:2007.08218 [hep-ex]](submitted to JHEP)

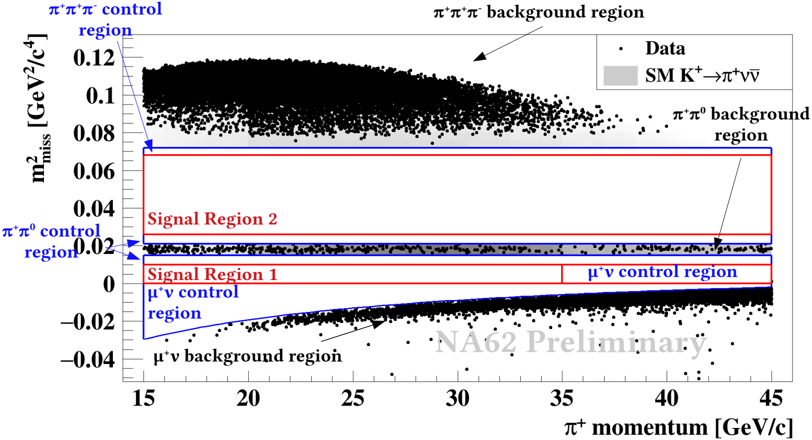
Analysis strategy

- **Analysis improvements in 2018**
  - Analysis performed in 7 separate categories
  - Category definition depends on hardware configurations (S1 and S2) and momentum
  - Selection optimized separately for each category
  - Improved signal sensitivity with respect to the 2017 analysis
  - Particle identification and upstream background rejection using MVA



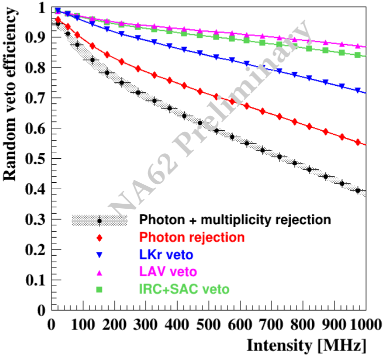
Process	Branching ratio
$K^+ \to \pi^+\pi^0$	0.2066
$K^+ \to \mu^+\nu_\mu$	0.6356
$K^+ \to \pi^+\pi^+\pi^-$	0.0558
$K^+ \to \pi^+\pi^- e\, \nu_e$	4.3×10^{-5}
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	**8.4×10^{-11}**

2018 data after signal selection



Single Event Sensitivity

$$N^{exp}_{\pi\nu\nu} \approx N_{\pi\pi}\epsilon_{trigger}\epsilon_{RV}\frac{A_{\pi\nu\nu}}{A_{\pi\pi}}\frac{Br(\pi\nu\nu)}{Br(\pi\pi)} \Rightarrow \text{S.E.S.} = \frac{Br(\pi\nu\nu)}{N^{exp}_{\pi\nu\nu}}$$

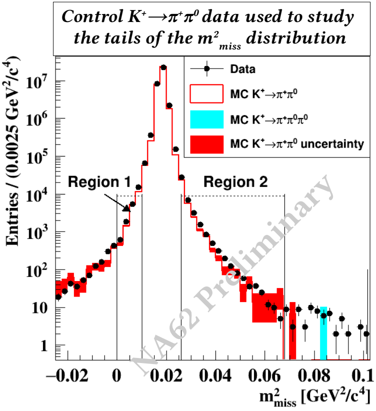


	Error budget S.E.S.
Trigger efficiency	5%
MC acceptance	3.5%
Random Veto	2%
Background(normalization)	0.7%
Instantaneous intensity	0.7%
Total	**6.5%**

- $K^+ \to \pi^+\pi^0$ decay used for normalization
- Cancellation of systematic effects (PID, Detector efficiencies, kaon ID and beam-related acceptance loss)

$$S.E.S. = (1.11 \pm 0.07_{syst.}) \times 10^{-11}$$

Background from kaon decays



Data in $\pi^+\pi^0$ region after $\pi\nu\nu$ selection (including π^0 rejection)

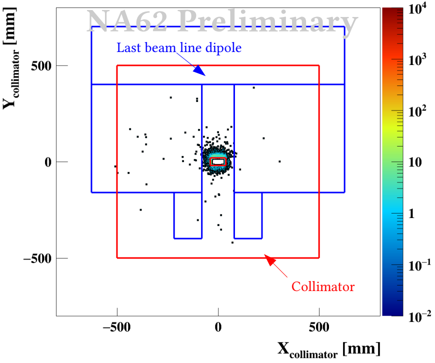
$$N^{exp}_{\pi\pi}(region) = N(\pi^+\pi^0) \cdot f_{kin}(region)$$

Expected $K^+ \rightarrow \pi^+\pi^0$ in signal regions after the $\pi\nu\nu$ selection

Fraction of $\pi^+\pi^0$ in signal region measured on control data

- Same procedure used for $K^+ \rightarrow \mu^+\nu$ and $K^+ \rightarrow \pi^+\pi^+\pi^-$ backgrounds
- $K^+ \rightarrow \pi^+\pi^-e^+\nu_e$ estimation entirely using MC simulations normalized to the S.E.S.

Upstream background



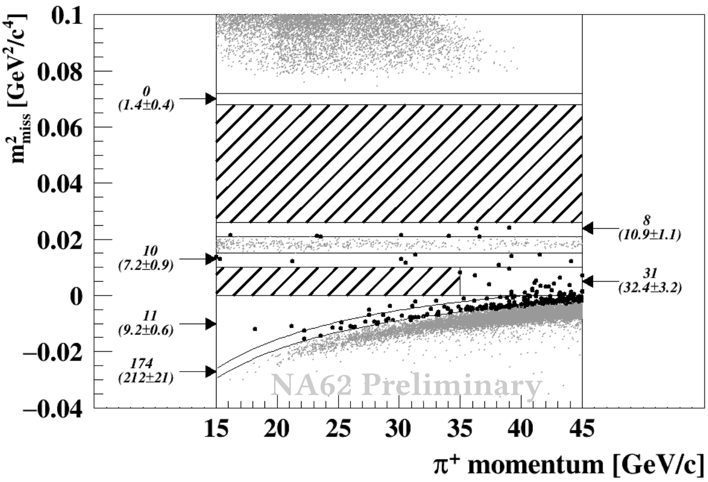
- Pions produced upstream of the fiducial volume (FV)
  - Early K^+ decays (upstream of the FV)
  - Interactions of beam particles with the beam spectrometer material
- Detected pions are associated to an accidental particle from the beam line
- Dangerous if coupled with pion scattering in the first spectrometer chamber
- Kaon-pion association and geometrical cuts effective
- The geometrical origin of those events allows us to define samples for background validation
- Data driven background estimation

Total expected background

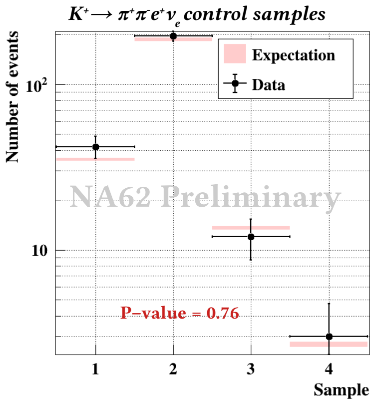
	2018 data
Expected SM signal	**$7.58(40)_{syst}(75)_{ext}$**
$K^+ \longrightarrow \pi^+\pi^0(\gamma)$	0.75(4)
$K^+ \longrightarrow \mu^+\nu(\gamma)$	0.49(5)
$K^+ \longrightarrow \pi^+\pi^- e^+\nu$	0.50(11)
$K^+ \longrightarrow \pi^+\pi^+\pi^-$	0.24(8)
$K^+ \longrightarrow \pi^+\gamma\gamma$	< 0.01
$K^+ \longrightarrow \pi^0 l^+\nu$	< 0.001
Upstream	$3.30^{+0.98}_{-0.73}$
Total background	$\mathbf{5.28^{+0.99}_{-0.74}}$

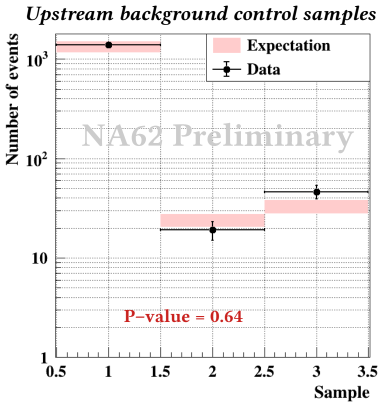
- Background expectations validated in control regions using a blind procedure

Control regions: $K^+ \to \pi^+\pi^0$, $\mu^+\nu_\mu$ and $\pi^+\pi^+\pi^-$



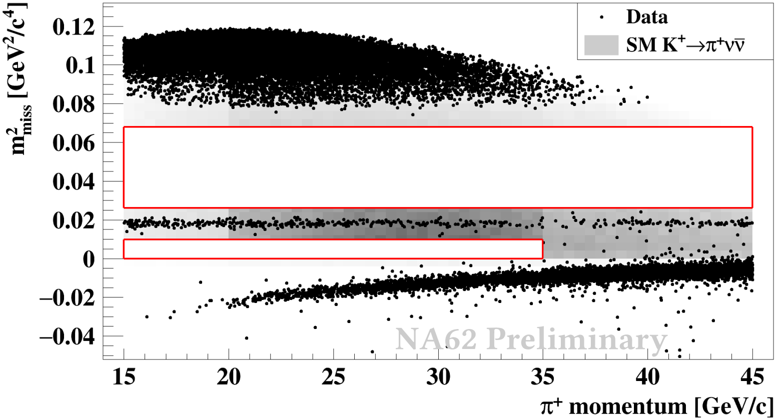
Control regions: $K^+ \to \pi^+\pi^-e^+\nu_e$ and upstream



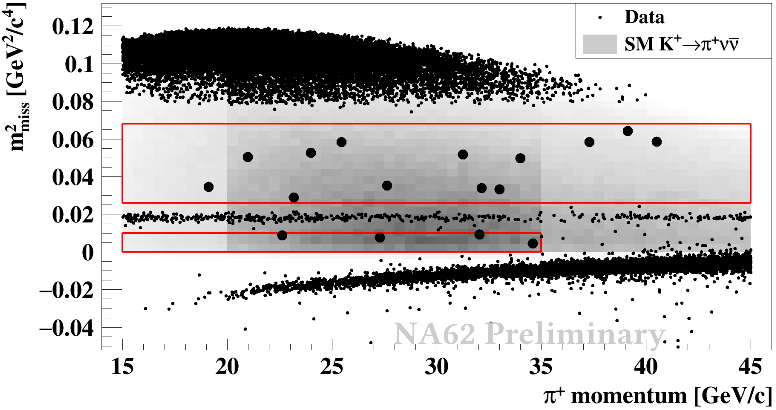


- Data samples defined by inverting signal selection criteria
- The sensitivity of some control samples comparable to the S.E.S.

2018 data before unblinding

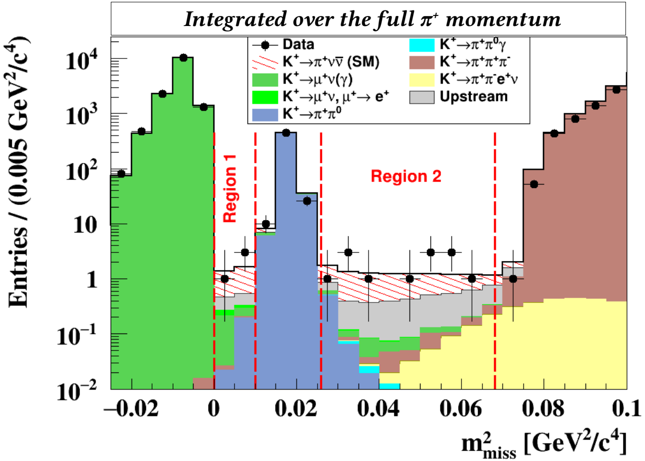


Opening the box in the 2018 data

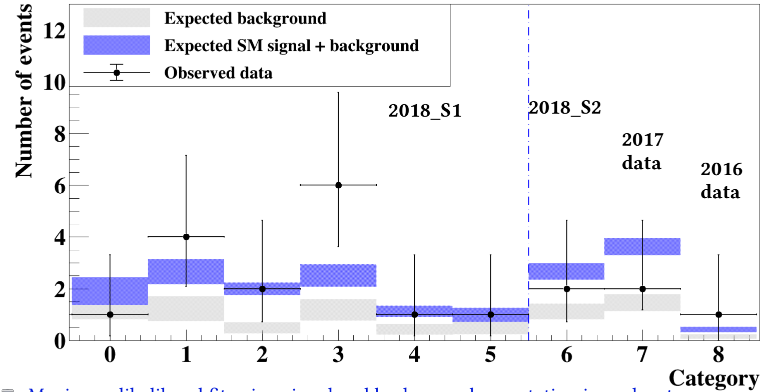


5.3 background + 7.6 SM signal events expected, 17 events observed

m^2_{miss} signal and background in the 2018 data

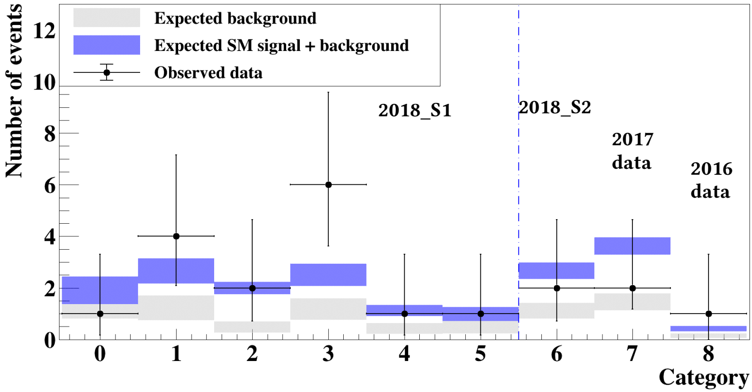


Results



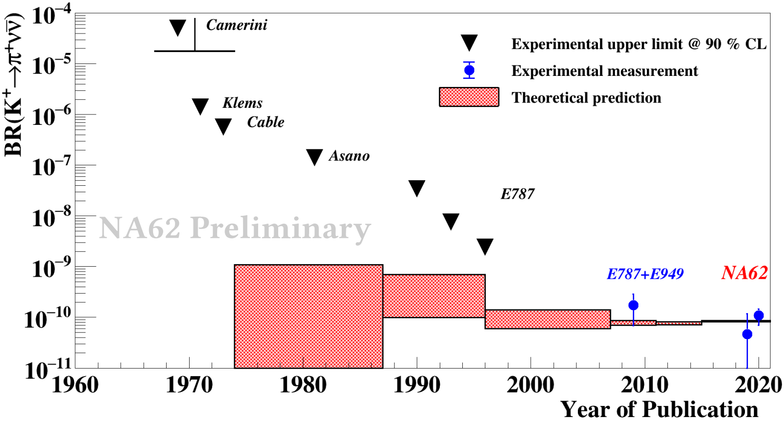
- Maximum likelihood fit using signal and background expectation in each category
- Two samples with different hardware configurations in 2018
  - 2018_S1 ~ 80% of the 2018 dataset, 5 GeV/c wide bins from 15-45 GeV/c
  - 2018_S2 ~ 20% of the 2018 dataset, integrated over momentum
  - 2016 and 2017 datasets, integrated over momentum added as separate categories

Results

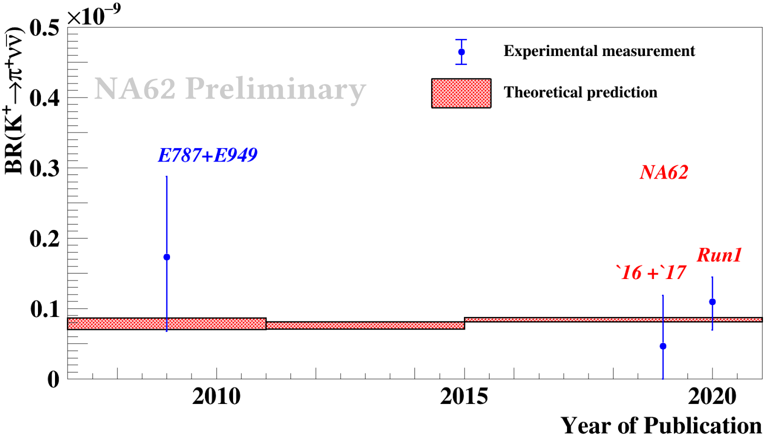


- **NA62 Run1(2016 + 2017 + 2018) result:**
  - ☆ $Br(K^+ \to \pi^+ \nu\bar{\nu}) = (11.0^{+4.0}_{-3.5\,stat.} \pm 0.3_{syst.}) \times 10^{-11}(3.5\sigma \text{ significance})$

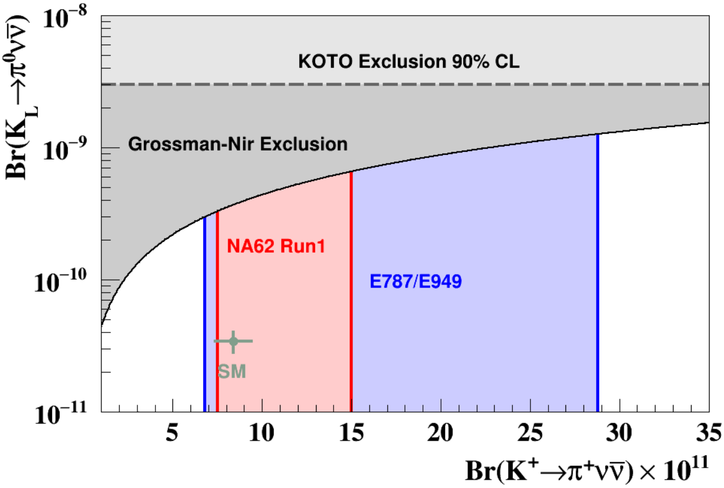
$K^+ \to \pi^+ \nu\nu$ decay: Historical context



$K^+ \rightarrow \pi^+ \nu\nu$ decay: Historical context



Grossman-Nir limit



Summary and conclusions

- NA62 result from the complete Run 1(2016 + 2017 + 2018)
  - Observed events: 1 (2016) + 2 (2017) + 17(2018) = 20 (Run 1)
  - Expected background ~ 0.2(2016) + 1.5(2017) + 5.3(2018) = 7 (Run 1)
  - $Br(K^+ \to \pi^+ \nu\bar{\nu}) = (11.0^{+4.0}_{-3.5}{}_{stat.} \pm 0.3_{syst.}) \times 10^{-11}(3.5\sigma \text{ significance})$
  - The most precise measurement of the BR obtained so far
- The result is compatible with the SM prediction within one standard deviation

- Towards the 2021 run
  - NA62 will resume data-taking in 2021
  - Modifications of the NA62 beam line, installation of an additional beam spectrometer station and a veto counter to reduce upstream background
  - New calorimeter downstream of MUV and upstream of the beam dump to further suppress kaon decay background
  - More information can be found in the NA62 SPSC addendum

Other NA62 Measurements

NA62 is the experiment with the most Kaons ever, by far. In the next few years we will rewrite the K^+ section of the PDG.

- Precision measurements of branching ratios
- Precision measurements of form factors (tests of chiral pertubation theories)
- Lepton Universality Tests ($K^+ \to e^+\nu_e/K^+ \to \mu^+\nu_\mu$, and others)
- Search for heavy neutral leptons
- Search for lepton (family) number violating decays
- π^0 decays (from $K^+ \to \pi^+\pi^0$)
    - EM transition form factor (important for muon $g-2$)
    - Search for dark photons
    - Search for $\pi^0 \to \gamma\nu\bar{\nu}$ (SM: BR 10^{-18}), $\pi^0 \to \nu\bar{\nu}$
- π^+ decays (beam is mostly π^+)
- Hadroproduction with π^+, K^+ with GTK3 as target
- In dump mode: Searches for Axions, dark Higgs, ALP, . . .
- . . .

NA62 Physics Publications

- Test of Lepton Flavour Universality in $K^+ \to \ell^+\nu$ Decays. Physics Letters B 698 (2011) 105-114
- Precision Measurement of the Ratio of the Charged Kaon Leptonic Decay Rates. Physics Letters B 719 (2013) 326-336.
- Study of $K^\pm \to \pi^\pm\gamma\gamma$ decay by the NA62 experiment. Physics Letters B 732 (2014) 65-74.
- Measurement of the π^0 electromagnetic transition form factor slope. Physics Letters B 768 (2017) 38-45.
- Search for Heavy Neutrinos in $K^+ \to \mu^+\nu_\mu$ Decays. Physics Letters B 772 (2017) 712-718.
- Search for heavy neutral lepton production in K^+ Decays. Physics Letters B 778 (2018) 137-145
- Searches for lepton number violating K^+ decays. Physics Letters B 797 (2019) 134794.
- Search for production of an invisible dark photon in π^0 decays. Journal of High Energy Physics 05 (2019) 182.
- First search for $K^+ \to \pi^+\nu\bar{\nu}$ using the decay-in-flight technique. Physics Letters B 791 (2019) 156-166
- An investigation of the very rare $K^+ \to \pi^+\nu\bar{\nu}$ decay. Journal of High Energy Physics 11 (2020) 042.
- Search for heavy neutral lepton production in K^+ decays to positrons. Physics Letters B 807 (2020) 135599
- Search for K^+ decays to a muon and invisible particles. Physics Letters B 816 (2021) 136259.
- Search for a feebly interacting particle X in the $K^+ \to \pi^+X$ decay. Journal of High Energy Physics 03 (2021) 058.
- Search for π^0 decays to invisible particles. Journal of High Energy Physics 02 (2021) 201.
- Measurement of the very rare $K^+ \to \pi^+\nu\bar{\nu}$ decay. arXiv:2103.15389 [hep-ex].

Conclusions

- NA62 sees first evidence (3.5 σ) for the very rare $K^+ \to \pi^+\nu\bar{\nu}$ decay
  $BR(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$
- Decay-in-flight technique works
- New limits for dark-sector particles

- Many more physics analysis from 2016-18 data to be published soon

- In full preparation to resume datataking this July
- Approved to run until Long Shutdown 3 ($\sim$2025)
- We should reach goal to observe 100 $\pi\nu\nu$ events