

NA62: Observation of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and other recent results

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Seminario conjunto ICN-IF
Física de Altas Energías
UNAM, Mexico City
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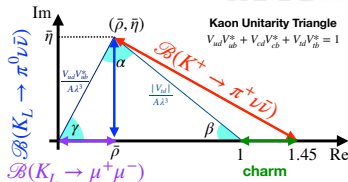
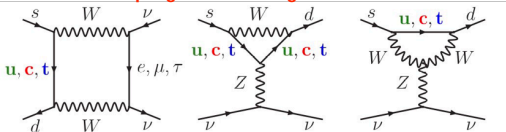
- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ in the SM and beyond
 - The Golden Modes $K \rightarrow \pi \nu \bar{\nu}$ in the SM and beyond
 - NA62 after LS2: detector upgrades and performance
 - New measurement of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$
- First detection of a tagged neutrino
- First search for $K^+ \rightarrow \pi^0 \pi \mu e$ decays



$K \rightarrow \pi \nu \bar{\nu}$: Precision test of the Standard Model



SM: Z-penguin & box diagrams



- $\mathcal{B}(K \rightarrow \pi \nu \bar{\nu})$ highly suppressed in SM

- GIM mechanism & maximum CKM suppression $s \rightarrow d$ transition: $\sim \frac{m_t}{m_W} \left| V_{ts}^* V_{td} \right|$

- Theoretically clean $\Rightarrow$ high precision SM predictions

- Dominated by short distance contributions.
- Hadronic matrix element extracted from $\mathcal{B}(K \rightarrow \pi^0 \ell^+ \nu_\ell)$ decays via isospin rotation.

Mode	SM Branching Ratio [1]	SM Branching Ratio [2]	Experimental Status
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	$(8.60 \pm 0.42) \times 10^{-11}$	$(7.86 \pm 0.61) \times 10^{-11}$	$(10.6 \pm 4.0) \times 10^{-11}$ NA62 16–18
$K_L \rightarrow \pi^0 \nu \bar{\nu}$	$(2.94 \pm 0.15) \times 10^{-11}$	$(2.68 \pm 0.30) \times 10^{-11}$	$< 2 \times 10^{-9}$ KOTO (2021 data)

[^]Recent SM calculations [1: [Buras et al. EPJC 82 \(2022\) 7, 615](#)] [2: [D'Ambrosio et al. JHEP 09 \(2022\) 148](#)]
(Differences in SM calculations from choice of CKM parameters: see [Eur.Phys.J.C 84 \(2024\) 4, 377](#))

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$K \rightarrow \pi \nu \bar{\nu}$: Beyond the Standard Model



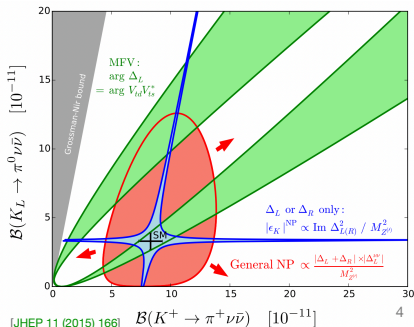
- Correlations between BSM contributions to BRs of K^+ and K_L modes [JHEP 11 (2015) 166].
 - Must measure both to discriminate between BSM scenarios.
- Correlations with other observables (ε'/ε , ΔM_B , B-decays) [JHEP 12 (2020) 097][PLB 809 (2020) 135769].
- Leptoquarks [EPJ.C 82 (2022) 4, 320], Interplay between CC and FCNC [JHEP 07 (2023) 029], NP in neutrino sector [EPJ.C 84 (2024) 7, 680] and additional scalar/tensor contributions [JHEP 12 (2020) 186][arXiv:2405.06742] ...

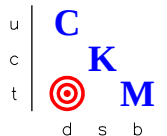
- Green:** CKM-like flavour structure
 - Models with Minimal Flavour Violation
- Blue:** new flavour-violating interactions where LH or RH currents dominate
 - Z' models with pure LH/RH couplings
- Red:** general NP models without above constraints
- Grossman-Nir Bound:** model-independent relation

[PLB 398 (1997) 163-168]

$$\frac{\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})}{\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})} \frac{\tau_{K^+}}{\tau_{K_L}} \lesssim 1$$

$$\Rightarrow \mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \lesssim 4.3 \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$$





Charged Kaons at the Main Injector

April 15, 1998

A Proposal for a Precision Measurement of the Decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and Other Rare K^+ Processes at Fermilab Using the Main Injector

R. Coleman, P.S. Cooper*, M. Crisler, C. Milstene†, E. Ramberg, R. S. Tschirhart
 Fermi National Accelerator Laboratory, Batavia, IL, U.S.A.

A. Kozhevnikov, V. Kubarovsky, V. Kurshetsov, L. Landsberg, V. Molchanov, V. Obraztsov, V. Polyakov,
 D. Vavilov, O. Yushchenko
 Institute of High Energy Physics, Serpukhov, Russia

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 Instituto de Fisica, Universidad Autonoma de San Luis Potosi, Mexico

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 University of Texas at Austin, Austin, Texas 78712

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VIII MEXICAN WORKSHOP ON PARTICLES AND FIELDS

November 14-20, 2001

Zacatecas, México

Invited Speakers

J. Bonn	Mainz, Germany
A. J. Buras	Munich, Germany
R. Cashmore	CERN, Switzerland
J. Conway	Rutgers, USA
G. Contreras	Mérida, México
P. S. Cooper	ENAF, USA
J. Dos Anjos	CBPF, Brazil
Robin Earbacher	ENAF, USA
Ada Farilla	INFN-Rome, Italy
R. Flores-Méndez	San Luis Potosí, México
N. Fornengo	Torino, Italy
Elizabeth Jenkins	San Diego, USA
W. C. Louis	LANL, USA
O. G. Miranda	CINVESTAV-IPN, México
A. Mondragón	UNAM, México
Giulia Pancheri	INFN, Italy
S. Pastor	Munich, Germany
J. S. Russ	Carnegie Mellon, USA
A. Santoro	LAFEX/CBPF, Brazil
N. Tarnqvist	Helsinki, Finland
A. Wagner	DESY, Germany
J. Wambach	Darmstadt, Germany
H.-J. Weber	Charlottesville, USA
A. Wirzba	FZ Jülich, Germany
J. Wudka	Riverside, USA
C. P. Yuan	Michigan, USA

Topics

Heavy Quarks and CP
Neutrino Physics
Chiral Dynamics
Higgs Particle

National Organizing Committee

J. L. Díaz Cruz	IF-BUAP (Chair)
G. Herrera	CINVESTAV
M. Mondragón	IE-UNAM
N. Nellen	ICN-UNAM
M. A. Pérez	CINVESTAV

Local Organizing Committee

J. Engelfried	IF-UASLP
A. A. Espinoza	EF-UAZ
A. Gutiérrez	EF-UAZ
M. Kirchbach	EF-UAZ (Chair)
J. Ortiz Saavedra	EF-UAZ
J. M. Rivera Juárez	EF-UAZ

Organized by the División Partículas
and Fields of the Sociedad Mexicana
de Física

taller2001@dpvc.smf.mx
<http://dpvc.smf.mx/Workshop/>

Design: Comunic

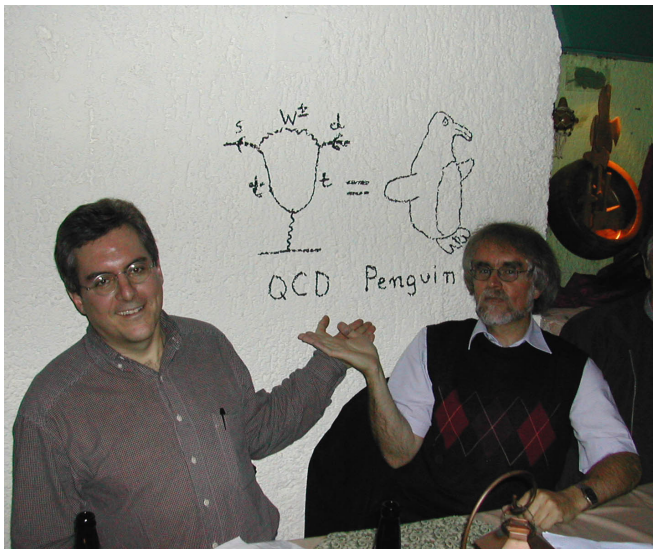
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Centro Latinoamericano de Física
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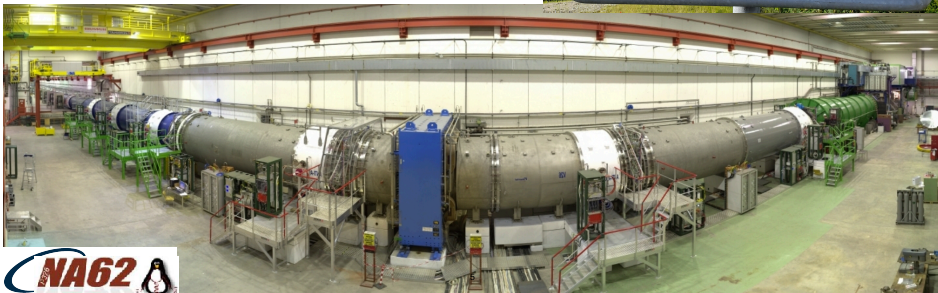
Andrzej J. Buras (Munich, Germany): *CP Violation, Rare Decays and the CKM Matrix*
Peter S. Cooper (Fermilab): *Rare Kaon Decays*



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

NA62:

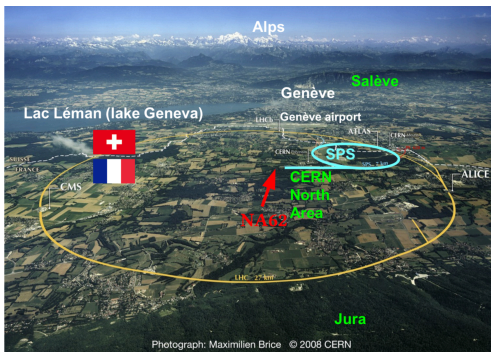
The K^+ factory at the
CERN north area



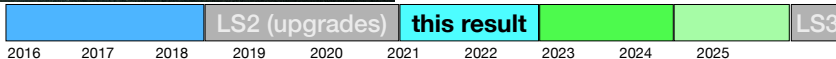
The NA62 Experiment at CERN



~200 collaborators from ~30 institutions.



- **Primary goal:** measurement of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$
- **New Technique:** K^+ decay-in-flight
- **Results:** [\[PLB 791 \(2019\) 156\]](#) [\[JHEP 11 \(2020\) 042\]](#) [\[JHEP 06 \(2021\) 093\]](#)
- **Broader physics programme:**
 - Rare K^+ decays (e.g. $K^+ \rightarrow \pi^+ \gamma \gamma$ [\[PLB 850 \(2024\) 138513\]](#))
 - LNV/LFV decays (e.g. $K^+ \rightarrow \pi^- (\pi^0) e^+ e^+$ [\[PLB 830 \(2022\) 137172\]](#))
 - Exotics (e.g. Dark photon [\[PRL 133 \(2024\) 11, 111802\]](#))
- **Data taking**
 - 2016 Commissioning + Physics run (45 days).
 - 2017 Physics run (160 days).
 - 2018 Physics run (217 days).
 - 2021 Physics run (85 days [10 beam dump]).
 - 2022 Physics run (215 days).
 - 2023 Physics run (150 days [10 beam dump]).
 - 2024 Physics run ongoing ...



The NA62 Collaboration

- Birmingham
- Bratislava
- Bristol
- Bucharest
- CERN
- Dubna
- George Mason
- Ferrara
- Firenze
- Frascati
- Glasgow
- Louvain-la-Neuve
- EPFL Lausanne
- Mainz
- IN2P3 Marseille
- INR Moscow
- Max Planck
München
- Napoli
- Perugia
- Pisa
- Prague
- Protvino
- Roma I
- Roma II
- San Luis Potosí
- SLAC
- Torino
- TRIUMF
- Vancouver

~ 230 collaborators

The Mexicans in NA62



$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at NA62

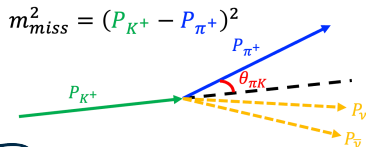


NA62 Strategy:

- Tag K^+ and measure momentum.
- Identify π^+ and measure momentum.
- Match K^+ and π^+ in time & form vertex.
 - Determine $m_{miss}^2 = (P_K - P_\pi)^2$
- Reject any additional activity.

NA62 Performance Keystones:

- $\mathcal{O}(100)$ ps timing between detectors
- $\mathcal{O}(10^4)$ background suppression from kinematics
- $> 10^7$ muon rejection
- $> 10^7$ rejection of π^0 from $K^+ \rightarrow \pi^+ \pi^0$ decays



Decay mode	Branching Ratio [PDG]
$K^+ \rightarrow \mu^+ \nu_\mu$	$(63.56 \pm 0.11) \%$
$K^+ \rightarrow \pi^+ \pi^0$	$(20.67 \pm 0.08) \%$
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	$(5.583 \pm 0.024) \%$
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu_e$	$(4.247 \pm 0.024) \times 10^{-5}$

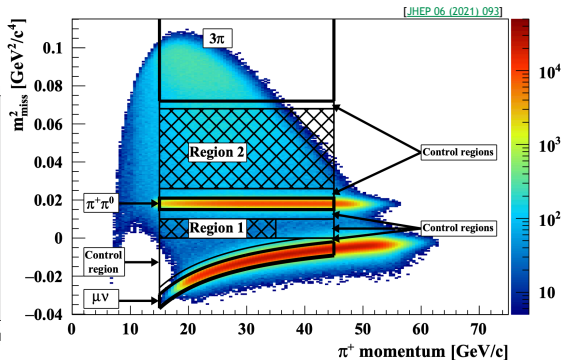
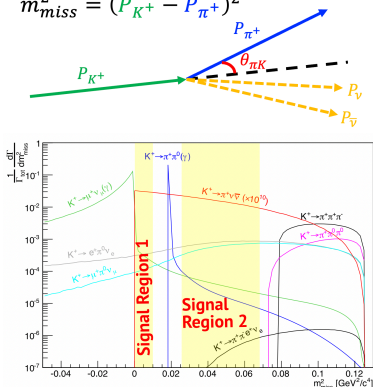
$$K^+ \rightarrow \pi^+ \nu \bar{\nu} \quad (8.60 \pm 0.42) \times 10^{-11} \text{ [SM]}$$

[Buras et al. EPJC 82 \(2022\) 7, 615](#)

Kinematic constraints & signal regions

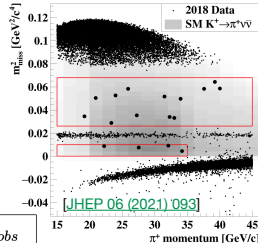
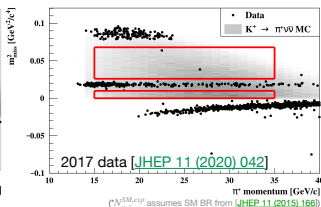
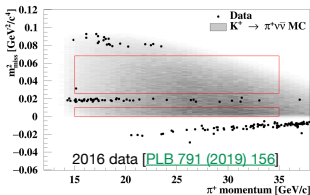
$$m_{\text{miss}}^2 = (P_{K^+} - P_{\pi^+})^2$$

$\mathcal{O}(10^4)$ background suppression from kinematics



π^+ momentum range: 15–45 GeV/c

The story so far: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ with 2016–18 data



Data-taking year	[Reference]	N_{bg}	$N_{\pi\nu\bar{\nu}}^{SM,exp}$	N_{obs}
2016	[PLB 791 (2019) 156]	$0.152^{+0.093}_{-0.035}$	0.267 ± 0.020	1
2017	[JHEP 11 (2020) 042]	1.46 ± 0.33	2.16 ± 0.13	2
2018	[JHEP 06 (2021) 093]	$5.42^{+0.99}_{-0.75}$	7.58 ± 0.40	17
2016–18	[JHEP 06 (2021) 093]	$7.03^{+1.05}_{-0.82}$	10.01 ± 0.42	20

Statistical combination:

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (10.6^{+4.0}_{-3.4})_{\text{stat}} \pm 0.9_{\text{syst}} \times 10^{-11} \text{ at } 68\% \text{ CL}$$

$$\text{In background-only hypothesis: } p = 3.4 \times 10^{-4} \Rightarrow \text{significance} = 3.4\sigma.$$



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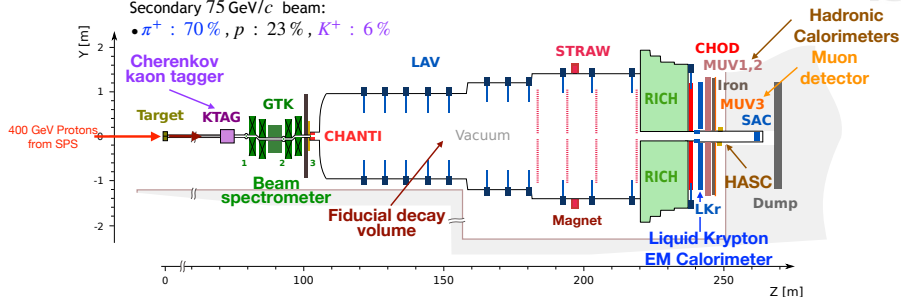
NA62 beamline & detector

[JINST 12 (2017) 05, P05025]



Secondary 75 GeV/c beam:

• π^+ : 70 %, p : 23 %, K^+ : 6 %



- Designed & optimised for study of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$:
 - Particle tracking: beam particle (GTK) & downstream tracks (STRAW)
 - PID: K^+ - KTAG, π^+ - RICH, Calorimeters (LKr, MUV1,2), MUV3 (μ detector)
 - Comprehensive veto systems: CHANTI (beam interactions), LAV, LKr, IRC, SAC (γ)



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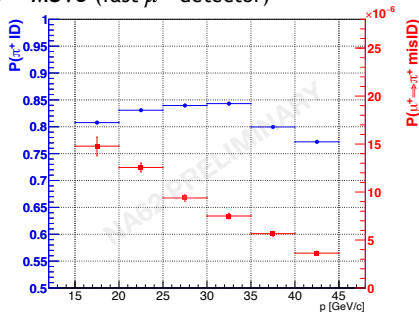


Particle ID performance : 2021–22 data



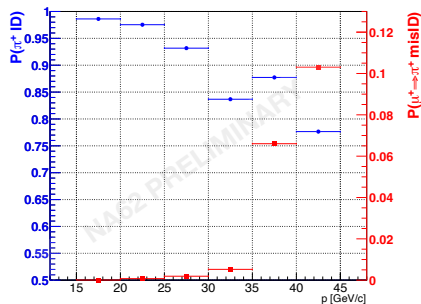
Calorimeters

- Use BDT classifier for LKr & MUV1,2
- + MUV3 (fast μ^+ detector)



RICH

Designed to distinguish between π^+/μ^+ with 15 – 35 GeV/c.



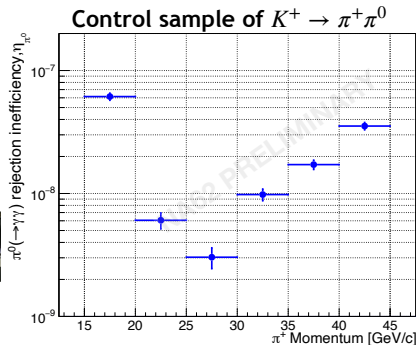
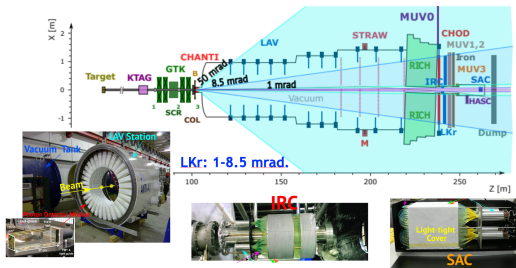
$$\varepsilon(\pi \text{ ID}) = (73.00 \pm 0.01) \%$$

$$P(\mu^+ \text{ misID as } \pi^+) = (1.3 \pm 0.2) \times 10^{-8}$$

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Comprehensive photon veto system: 2021–22 **NA62**



- Probability of $K^+ \rightarrow \pi^+ \pi^0$, $\pi^0 \rightarrow \gamma\gamma$ events passing all photon veto conditions: $\eta_{\pi^0} = (1.72 \pm 0.07) \times 10^{-8}$



- Meets target: combined γ/π^0 rejection of $\mathcal{O}(10^8)$.

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Upgrading NA62



- 2016–18 analysis proved NA62 technique.
- Limitation: tight cuts to reject backgrounds $\Rightarrow$ reduces signal efficiency.
- To improve: need new tools to control background.



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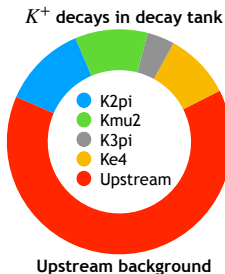


Upgrading NA62



- 2016–18 analysis proved NA62 technique.
- Limitation: tight cuts to reject backgrounds $\Rightarrow$ reduces signal efficiency.
- To improve: need new tools to control background.

Background	N(exp) 2018 (S2)
Upstream	$2.76^{+0.90}_{-0.70}$
$K^+ \rightarrow \pi^+ \pi^0$	0.52 ± 0.05
$K^+ \rightarrow \mu^+ \nu$	0.45 ± 0.06
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$	0.41 ± 0.10
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	0.17 ± 0.08
Total	$4.31^{+0.91}_{-0.72}$



Largest backgrounds:

1. Upstream
2. $K^+ \rightarrow \pi^+ \pi^0$

Veto by detecting previously missed particles...



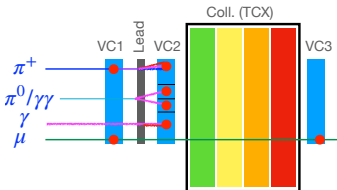
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New upstream vetos: VetoCounter & ANTIO



[FELIX readout: [Streaming Readout Workshop talk 2021](#)]



VetoCounter

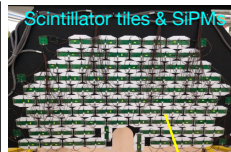
- Detect particles from decays upstream of final collimator.
- **Factor ~3 rejection** with ~2% accidental veto.

ANTIO

- Detect particles up to ~1 m from beam line.
- **Reject ~20% of upstream background** with <1% signal loss.

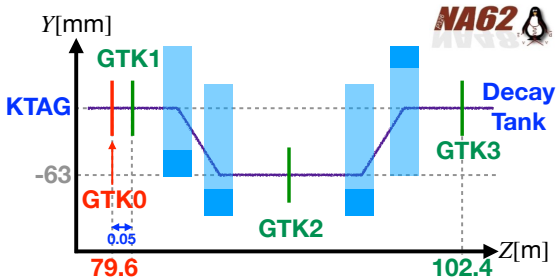
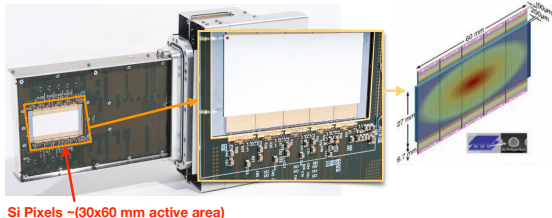
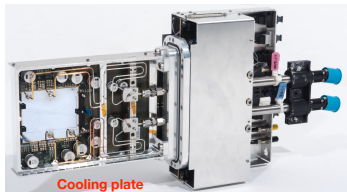
[JINST 15 (2020) C07007]

[SPSC report 2023][EP Newsletter, Dec21]



4th GTK station

- Si Pixel detector exposed to ~1GHz beam.
- Essential for $K^+ - \pi^+$ matching.
 - Measures K^+ 3-mom. & time
- 4th GTK station improves efficiency & pileup resilience.



More info: [\[Kleimenova, VERTEX2023\]](#)

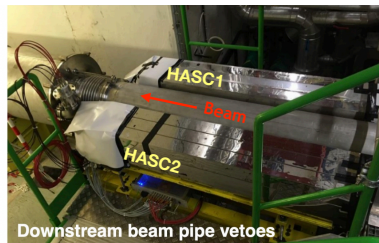
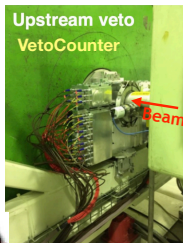
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Summary of NA62 upgrades

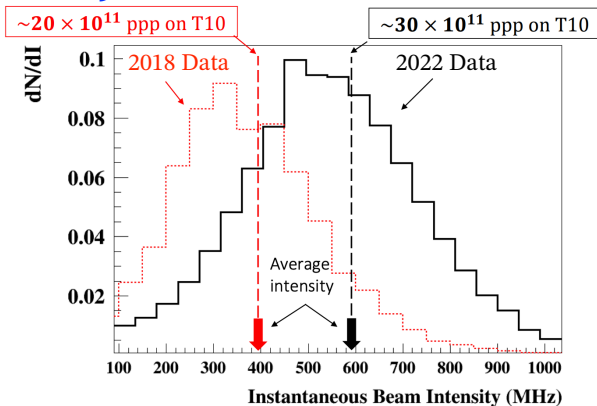


- New detectors, installed during LS2:
 - 4th GTK (Kaon beam tracker) & rearrange GTK achromat (GTK2 upstream of scraper).
 - New upstream veto (VetoCounter) & veto hodoscope (ANTIO) upstream of decay volume.
 - Additional veto detector (HASC2) at end of beam-line.
- Intensity increased by $\sim 35\%$ with respect to 2018 [450 $\rightarrow$ 600 MHz].
- Improvements to the trigger configuration.

New detectors
installed in 2021:



Beam intensity: 2018 vs 2022



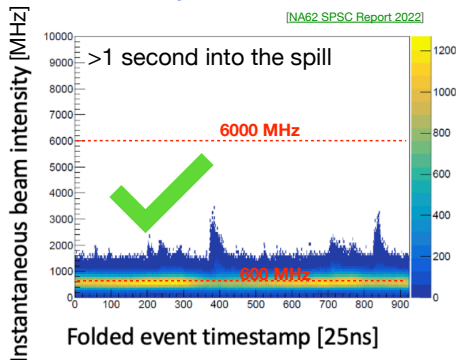
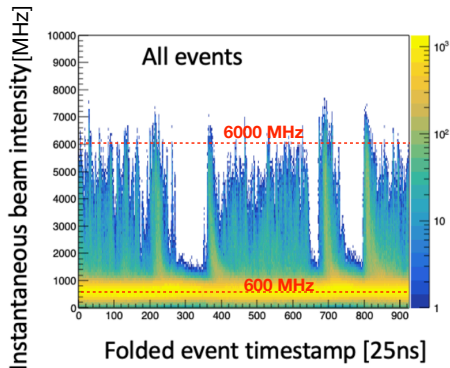
- Average beam intensity increased.
- NA62 “Full intensity” with 4.8s spill = 600 MHz



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2021 instantaneous beam intensity



- Remove events in first 1s of 4.8s spill for 2021 data only.
- DAQ overwhelmed by instantaneous rates up to 10x higher than design.

Analysis strategy



Triggers:

- Minimum Bias: $K^+ \rightarrow \mu^+ \nu$
- Normalisation: $K^+ \rightarrow \pi^+ \pi^0$
- Signal: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ candidates

- RICH multiplicity (reference time)
- Signal in CHODs
- No signal in MUV3(μ veto)
- Tag K^+ (≥ 5 KTAG sectors)
- <40 GeV in LKr ($\pi^0/\gamma/e$ veto)
- LAV veto (downstream of vertex).

Common conditions

+ add more conditions



Selection:

- Normalisation $K^+ \rightarrow \pi^+ \pi^0$: 1 downstream track (only); identified as π^+ ; $K^+ - \pi^+$ matching (space & time); upstream vetos.
- Signal $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ candidates: same as normalisation selection + full photon and detector multiplicity cuts (reject all extra activity).



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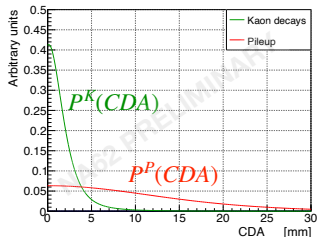


Bayesian classifier for $K^+ - \pi^+$ matching

Example of
selection update

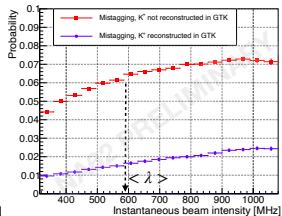
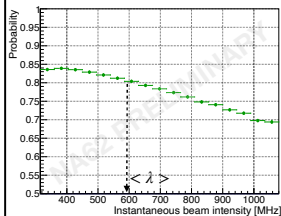


- **Inputs:** spatial (CDA) & time (ΔT_+) matching, intensity/pileup (N_{GTK}) [prior]
- Models for PDFs/Prior from $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ data.



- **Output:** posterior probability of GTK track = true K^+
 - Use likelihoods of kaons (K) and pileup (P)
 - Likelihood ratio used to select true match when $N_{GTK} > 1$

$\epsilon = 80\%$ $P^P_{mistag} = 6\%$ $P^K_{mistag} = 2\%$



- Efficiency improved (+10%) and mistagging probability maintained.



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Signal sensitivity

- Normalisation channel: $K^+ \rightarrow \pi^+ \pi^0$, momentum range $p \in [15, 45] \text{ GeV}/c$.

Effective number of K^+ decays, N_K :

$$N_K = \frac{N_{\pi\pi} D_0}{\mathcal{B}_{\pi\pi} A_{\pi\pi}}$$

Number of normalisation events $\rightarrow N_{\pi\pi}$

Downscaling factor of normalisation trigger (generally 400) $\rightarrow D_0$

Branching ratio of $K^+ \rightarrow \pi^+ \pi^0$ decay $\rightarrow \mathcal{B}_{\pi\pi}$

Acceptance of normalisation selection $\rightarrow A_{\pi\pi}$

Single event sensitivity:

(Branching ratio corresponding to expectation of 1 event)

$$\mathcal{B}_{SES} = \frac{1}{N_K \epsilon_{RV} \epsilon_{trig} A_{\pi\nu\bar{\nu}}}$$

Random veto efficiency $\rightarrow \epsilon_{RV}$

Trigger efficiency (ratio) $\rightarrow \epsilon_{trig}$

Signal selection acceptance $\rightarrow A_{\pi\nu\bar{\nu}}$

Number of expected SM events:

(For comparison to previous results use $\mathcal{B}_{\pi\nu\bar{\nu}}^{SM} = 8.4 \times 10^{-11}$ [JHEP 11 (2015) 166], but results are independent of this choice)

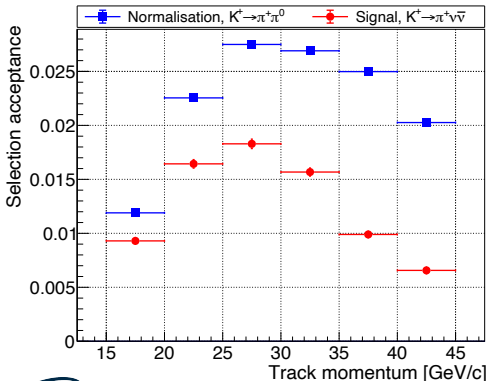
$$N_{\pi\nu\bar{\nu}}^{SM} = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{SM}}{\mathcal{B}_{SES}}$$

Acceptances

Analysis is performed in (5 GeV/c) bins of momentum:

$$N_{\pi\nu\bar{\nu}}^{\text{exp}}(p_i) = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{\text{SM}}}{\mathcal{B}_{\pi\pi}(p_i)} = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{\text{SM}}}{\mathcal{B}_{\pi\pi}} \frac{A_{\pi\nu\bar{\nu}}(p_i)}{A_{\pi\pi}(p_i)} D_0 N_{\pi\pi}(p_i) \varepsilon_{\text{trig}}(p_i) \varepsilon_{\text{RV}}$$

Acceptances



Case	OLD 2018 (S2)	NEW 2021–22
Norm.	11.8%	13.4%
Signal	(6.37±0.64)%	(7.61±0.18)%

+15%

+20%

- Increased selection efficiencies.
 - New K-pi matching technique.
 - Re-tuned vertex conditions.
 - Relaxation of some vetos.
- Improved precision (plus improved systematic uncertainty evaluation).

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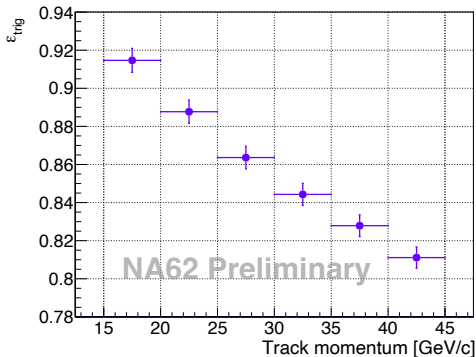
Acceptances evaluated at 0 intensity.
Intensity dependence captured in ε_{RV}



Trigger efficiencies

Analysis is performed in (5 GeV/c) bins of momentum:

$$N_{\pi\nu\bar{\nu}}^{\text{exp}}(p_i) = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{\text{SM}}}{\mathcal{B}_{\text{SES}}(p_i)} = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{\text{SM}}}{\mathcal{B}_{\pi\pi}} \frac{A_{\pi\nu\bar{\nu}}(p_i)}{A_{\pi\pi}(p_i)} D_0 N_{\pi\pi}(p_i) \boxed{\varepsilon_{\text{trig}}(p_i)} \varepsilon_{\text{RV}}$$



$$\varepsilon_{\text{trig}} = \frac{\varepsilon_{\text{sig}}}{\varepsilon_{\text{norm}}}$$

$$\varepsilon_{\text{trig}}(\text{new}) = (85.9 \pm 1.4) \%$$

$$\varepsilon_{\text{trig}}(2018) = (89 \pm 5) \%$$

- Trigger efficiency ratio:
 - **New:** several components in both normalisation & signal triggers: **partial cancellation.**
 - **Old:** in 2016–18 data normalise with fully independent min bias trigger (**no cancellation**).
- Improved precision by factor 3 with reduced systematic uncertainty.



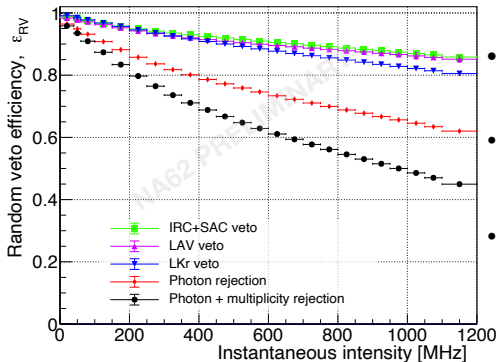
31



Random veto

ϵ_{RV} is independent of track momentum
(related to additional activity only)

$$N_{\pi\nu\bar{\nu}}^{exp}(p_i) = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{SM}}{\mathcal{B}_{SES}(p_i)} = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{SM}}{\mathcal{B}_{\pi\pi}} \frac{A_{\pi\nu\bar{\nu}}(p_i)}{A_{\pi\pi}(p_i)} D_0 N_{\pi\pi}(p_i) \epsilon_{trig}(p_i) \epsilon_{RV}$$



- ϵ_{RV} = Random Veto Efficiency:
 - $1 - \epsilon_{RV}$ = Probability of rejecting a signal event due to additional activity.
- Balance:
 - Strict vetos $\Rightarrow$ lower efficiency
 - Loose vetos $\Rightarrow$ higher background
- Operational intensity higher but re-tuning vetos means ϵ_{RV} is comparable:

$$\epsilon_{RV}(\text{new}, \overline{\lambda_{21-22}} \approx 600 \text{ MHz}) = (63.6 \pm 0.6) \%$$

$$\epsilon_{RV}(\text{old}, \overline{\lambda_{2018}} \approx 400 \text{ MHz}) = (66 \pm 1) \%$$

Signal sensitivity results

$$N_K = \frac{N_{\pi\pi} D_0}{\mathcal{B}_{\pi\pi} A_{\pi\pi}}$$

$$\mathcal{B}_{SES} = \frac{1}{N_K \epsilon_{RV} \epsilon_{trig} A_{\pi\nu\bar{\nu}}}$$

- Display integrals (15–45 GeV/c, 2021+22) for summary tables.
- * Acceptances evaluated at 0 intensity.

$N_{\pi\pi}$	Normalisation $K^+ \rightarrow \pi^+ \pi^0$	2.0×10^8
$A_{\pi\pi}$	Normalisation acceptance	$(13.410 \pm 0.005)\%$
N_K	Effective K^+ decays	2.9×10^{12}
$A_{\pi\nu\bar{\nu}}$	Signal acceptance	$(7.6 \pm 0.2)\%$
ϵ_{trig}	Trigger efficiency	$(85.9 \pm 1.4)\%$
ϵ_{RV}	Random veto efficiency	$(63.6 \pm 0.6)\%$
$\mathcal{B}_{SES}$	Single event sensitivity	$(0.84 \pm 0.03) \times 10^{-11}$

$$N_{\pi\nu\bar{\nu}}^{exp} = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{SM}}{\mathcal{B}_{SES}}$$

Assuming $\mathcal{B}_{\pi\nu\bar{\nu}}^{SM} = 8.4 \times 10^{-11}$:
2021–22: $N_{\pi\nu\bar{\nu}} = 10.00 \pm 0.34$
c.f. 2016–18 : $N_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42$

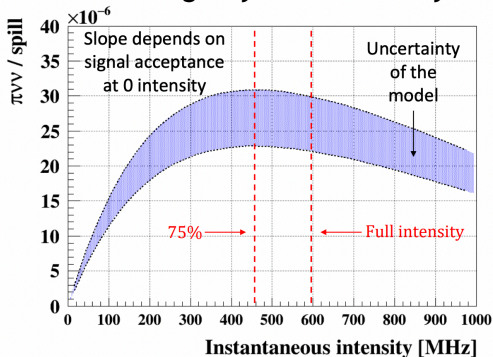
↓
Double expected signal by including 21–22 data.

- **Significant improvement in SES uncertainty:**
 - old: 6.3% → new: 3.5%. Due to:
 - trigger efficiency cancellations
 - improved procedures for evaluation of acceptances and ϵ_{RV}

Optimum NA62 intensity



Selected signal yield vs intensity



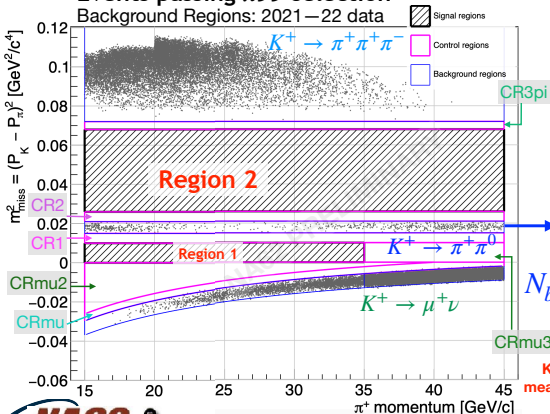
- Saturation of expected signal yield with intensity. Mainly due to:
 - Paralyzable effects from TDAQ dead time and trigger veto windows.
 - Offline selection, due to veto conditions.
- Main sources of uncertainty for model:
 - Online time-dependent mis-calibrations.
 - Fit uncertainty.
- **From August 2023 operate at optimal intensity (~75% of full) to maximise $\pi\nu\nu$ sensitivity**
 - Maximise signal yield
 - lower expected background
 - Higher DAQ efficiency
- **Studies of 2021–22 data at high intensity were crucial to establish optimal intensity.**

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Background regions & background estimations

Events passing $\pi\nu\nu$ selection

Background Regions: 2021–22 data



- Backgrounds from kinematic misconstruction tails in m_{miss}^2

Number of events passing signal selection in background region

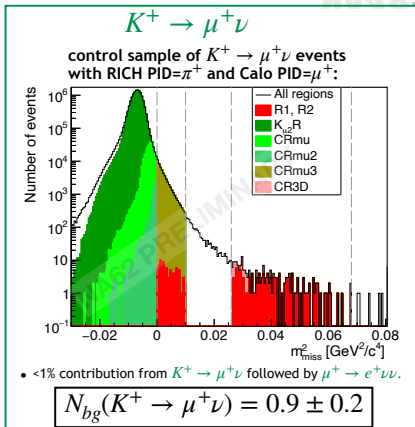
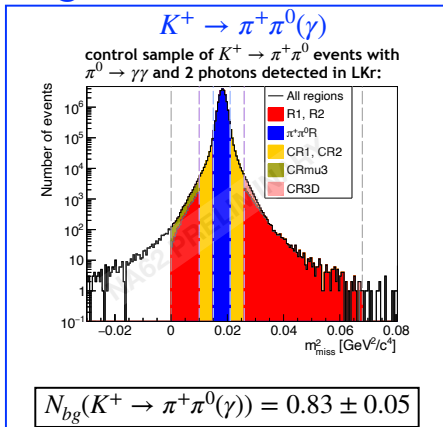
Control sample events in Signal Regions

Control sample events in Background Region

$$N_{bg} = N_{bkgR} \cdot f_{tail} = N_{bkgR} \cdot \frac{N_{SR}^{CS}}{N_{bkgR}^{CS}}$$

Kinematic tail fraction: measured in control sample

Backgrounds from kinematic tails



$K^+ \rightarrow \pi^+ \pi^+ \pi^-$

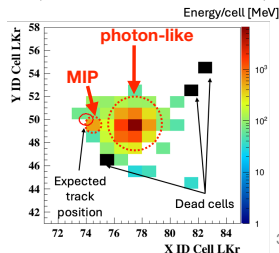
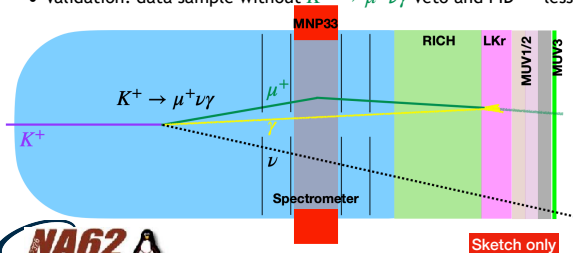
- Use MC to measure f_{tail} .

$N_{bg}(K^+ \rightarrow \pi^+ \pi^+ \pi^-) = 0.11 \pm 0.03$

Radiative decays: $K^+ \rightarrow \pi^+ \pi^0 \gamma$ & $K^+ \rightarrow \mu^+ \nu \gamma$



- $K^+ \rightarrow \pi^+ \pi^0 \gamma$: included with “kinematic tails” estimation.
 - Suppression: photon vetos, rejection with additional γ is 30x stronger.
 - Estimation: MC + measured single photon rejection efficiency : $N_{bg}(K^+ \rightarrow \pi^+ \pi^0 \gamma) = 0.07 \pm 0.01$
 - Validation: m_{miss}^2 control regions (CR1,2 - see later)
- $K^+ \rightarrow \mu^+ \nu \gamma$: not included in “kinematic tails” estimation if γ overlaps μ^+ at LKr (leading to misID as π^+)
 - Suppression: based on $(P_K - P_\mu - P_\gamma)^2$ and E_γ with γ = LKr cluster (mis)associated to muon.
 - Necessary for 2021–22 data, since Calorimetric PID degraded at higher intensities.
 - Estimation: min. Bias data control sample with signal in MUV3 : $N_{bg}(K^+ \rightarrow \mu^+ \nu \gamma) = 0.8 \pm 0.4$
 - Validation: data sample without $K^+ \rightarrow \mu^+ \nu \gamma$ veto and PID = “less pion-like” (Calo BDT bins below π^+ bin).



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Other backgrounds

- $K^+ \rightarrow \pi^+ \pi^- e^+ \nu$ (K_{e4})

- No clean control samples for K_{e4} in data: use 2×10^9 simulated decays.

$$N_{bg}(K^+ \rightarrow \pi^+ \pi^- e^+ \nu) = N_K \epsilon_{RV} \epsilon_{trig} \mathcal{B}_{K_{e4}} A_{K_{e4}}$$

Effective # of K^+ → N_K
 Random veto & trigger efficiencies → $\epsilon_{RV} \epsilon_{trig}$
 Branching ratio of K_{e4} (from PDG) → $\mathcal{B}_{K_{e4}}$
 Acceptance: $A_{K_{e4}} = \frac{N_{MC}^{sel}}{N_{MC}^{gen}} = (1.3 \pm 0.3_{stat}) \times 10^{-8}$

$N_{bg}(K^+ \rightarrow \pi^+ \pi^- e^+ \nu) = 0.89^{+0.34}_{-0.28}$

- $K^+ \rightarrow \pi^0 \ell^+ \nu$ and $K^+ \rightarrow \pi^+ \gamma \gamma$:

- Evaluated with simulations.
- Negligible contributions to total background.

$N_{bg}(K^+ \rightarrow \pi^0 \ell^+ \nu) < 1 \times 10^{-3}$

$N_{bg}(K^+ \rightarrow \pi^+ \gamma \gamma) = 0.01 \pm 0.01$

Upstream background evaluation

$$N_{bg} = \sum_i N_i f_{cda} P_i^{match}$$

N Upstream Reference Sample:
signal selection but invert CDA cut (CDA > 4mm)

f_{cda} Scaling factor : bad cda $\rightarrow$ good cda

P_{match} Probability to pass $K^+ - \pi^+$ matching

Calculate using bins (i) of $(\Delta T_+, N_{GTK})$

[Updated to fully data-driven procedure]

$$N = 51 \quad f_{CDA} = 0.20 \pm 0.03 \quad < P_{match} > = 73 \%$$

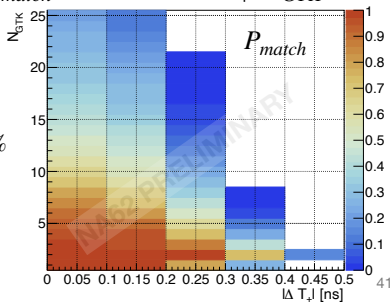
$$N_{bg}(\text{Upstream}) = 7.4^{+2.1}_{-1.8}$$

- Upstream reference sample contains all known upstream mechanisms.

- N provides normalisation.

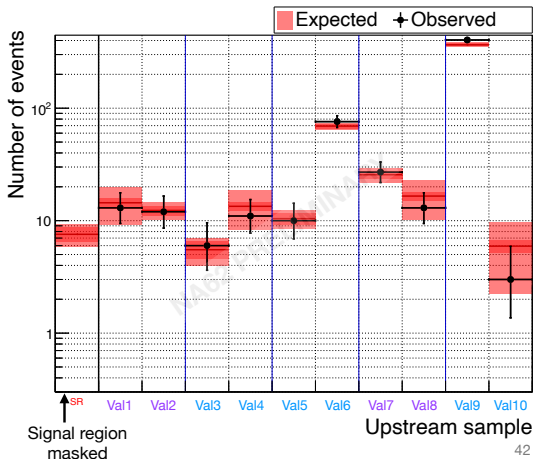
- f_{CDA} depends only on geometry.

- P_{match} depends on $(\Delta T_+, N_{GTK})$.



Upstream background validation

- Invert & loosen upstream vetos to enrich with different mechanisms:
 - Interaction-enriched: Val1,2,7,8
 - Accidental-enriched: Val3,4,5,6,9,10.
- All independent.
- Expectations and observations are in good agreement.
- Number of events rejected by VetoCounter:
 - (i.e. events in signal region with associated VC signal)
 - $N_{exp}^{VC rej.} = 6.9 \pm 1.4$, $N_{obs}^{VC rej.} = 9$
- VetoCounter is essential to control upstream background.



Summary of expectations



Backgrounds

$K^+ \rightarrow \pi^+ \pi^0 (\gamma)$	0.83 ± 0.05
$K^+ \rightarrow \pi^+ \pi^0$	0.76 ± 0.04
$K^+ \rightarrow \pi^+ \pi^0 \gamma$	0.07 ± 0.01
$K^+ \rightarrow \mu^+ \nu (\gamma)$	1.70 ± 0.47
$K^+ \rightarrow \mu^+ \nu$	0.87 ± 0.19
$K^+ \rightarrow \mu^+ \nu \gamma$	0.82 ± 0.43
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	0.11 ± 0.03
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$	$0.89^{+0.34}_{-0.28}$
$K^+ \rightarrow \pi^0 \ell^+ \nu$	< 0.001
$K^+ \rightarrow \pi^+ \gamma \gamma$	0.01 ± 0.01
Upstream	$7.4^{+2.1}_{-1.8}$
Total	$11.0^{+2.1}_{-1.9}$

Signal Sensitivity

$$\mathcal{B}_{SES} = (0.84 \pm 0.03) \times 10^{-11}$$

$$N_{\pi\nu\bar{\nu}}^{SM,exp} = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{SM}}{\mathcal{B}_{SES}}$$

Assuming $\mathcal{B}_{\pi\nu\bar{\nu}}^{SM} = 8.4 \times 10^{-11}$:

2021–22: $N_{\pi\nu\bar{\nu}} = 10.00 \pm 0.34$

c.f. 2016–18 : $N_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42$

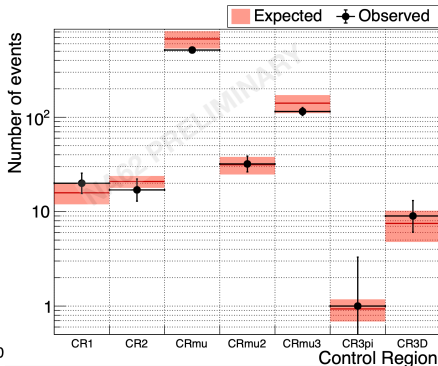
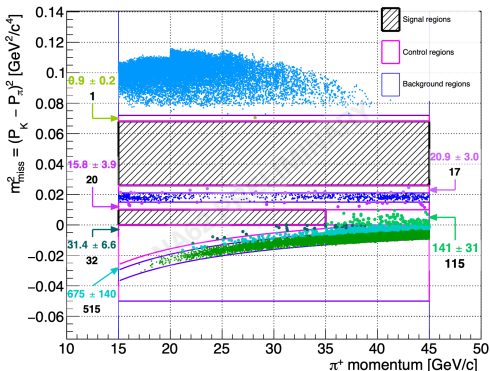
Expected signal doubled by including 2021–22 data

- $N_{\pi\nu\bar{\nu}}^{SM}$ per SPS spill: 2.5×10^{-5} in 2022
 - c.f. 1.7×10^{-5} in 2018. $\Rightarrow$ signal yield increased by 50%.
- Sensitivity for $BR \sim \sqrt{S+B}/S = 0.5$
 - Similar but improved with respect to 2018 analysis for same amount of data.



Control regions

2021 – 22 data



- Good agreement in control regions validates background expectations.

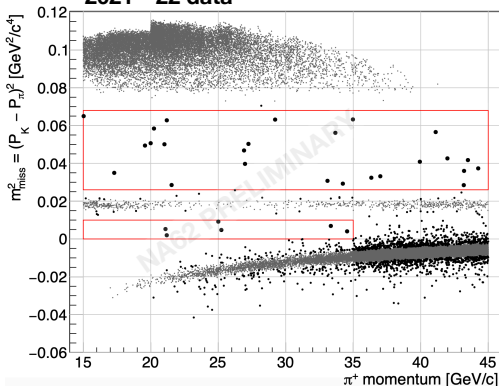


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Signal regions

2021 – 22 data

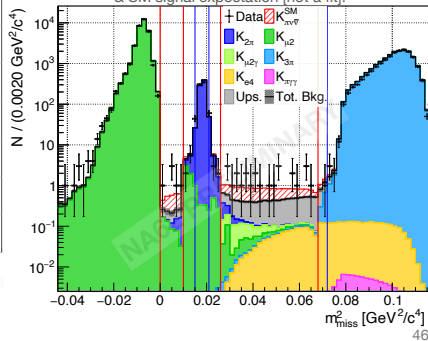


Expected SM signal, $N_{\pi\nu\bar{\nu}}^{\text{SM}} \approx 10$

Expected background, $N_{bg} = 11.0^{+2.1}_{-1.9}$

Observed, $N_{obs} = 31$

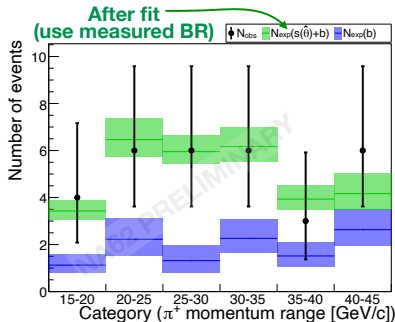
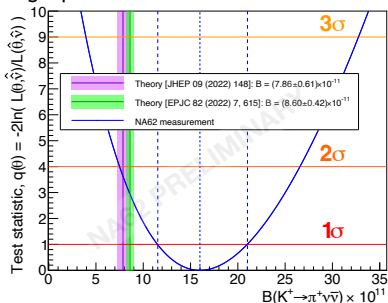
1D projection with differential background predictions
& SM signal expectation [not a fit]:



Results: 2021–22 Data



- Measure $\mathcal{B}_{\pi\nu\bar{\nu}}$ and 68% (1σ) confidence interval using a profile likelihood ratio test statistic $q(\theta)$.
- Use 6 (momentum bin) categories



$$\mathcal{B}_{21-22}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (16.0^{+5.0}_{-4.5}) \times 10^{-11} = \left(16.0 \begin{matrix} +4.8 \\ -4.2 \end{matrix} \text{stat} \begin{matrix} +1.4 \\ -1.3 \end{matrix} \text{syst} \right) \times 10^{-11}$$



Evaluate statistical-only component by repeating procedure assuming exact knowledge of signal and background expectations.

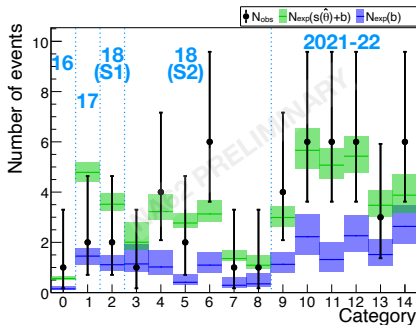
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Combining NA62 results: 2016–22



- Integrating 2016–22 data: $N_{bg} = 18_{-2}^{+3}$, $N_{obs} = 51$.



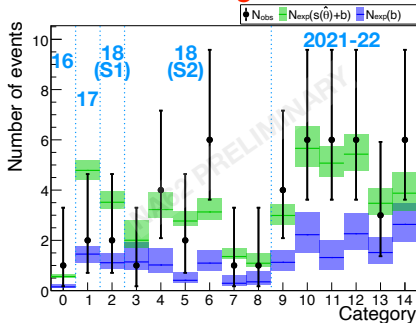
48



Combining NA62 results: 2016–22



- Integrating 2016–22 data: $N_{bg} = 18_{-2}^{+3}$, $N_{obs} = 51$.
- Background-only hypothesis **p-value** = $2 \times 10^{-7} \Rightarrow$ **significance** $Z > 5$



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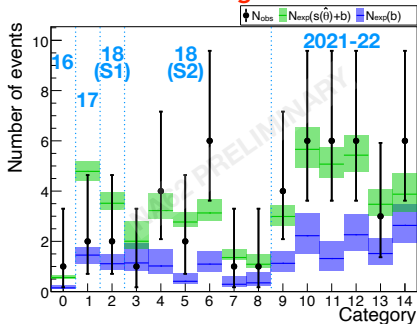
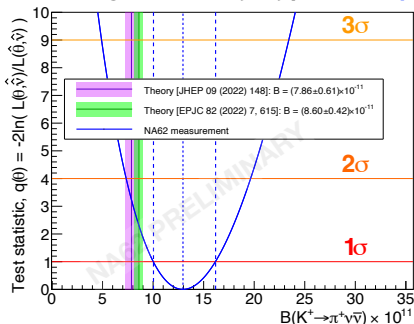


Combining NA62 results: 2016–22



- Integrating 2016–22 data: $N_{bg} = 18_{-2}^{+3}$, $N_{obs} = 51$.

- Background-only hypothesis **p-value = $2 \times 10^{-7} \Rightarrow$ significance $Z > 5$**



$$\mathcal{B}_{16-22}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (13.0_{-2.9}^{+3.3}) \times 10^{-11} = \left(13.0_{-2.7}^{+3.0} \right)_{\text{stat}} \left({}_{-1.2}^{+1.3} \right)_{\text{syst}} \times 10^{-11}$$

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Results in context



BNL E787/E949 experiment
[Phys.Rev.D 79 (2009) 092004]

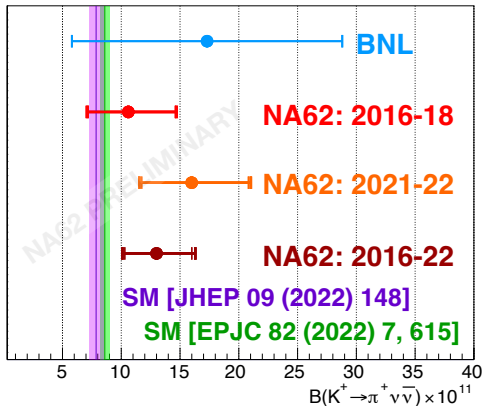
$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-18} = (10.6^{+4.1}_{-3.5}) \times 10^{-11}$$

[JHEP 06 (2021) 093]

$$\mathcal{B}_{\pi\nu\bar{\nu}}^{21-22} = (16.0^{+5.0}_{-4.5}) \times 10^{-11}$$

$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = (13.0^{+3.3}_{-2.9}) \times 10^{-11}$$

- NA62 results are consistent
- Central value moved up (now 1.5–1.7 σ above SM)
- Fractional uncertainty decreased: 40% to 25%
- Bkg-only hypothesis rejected with significance $Z > 5$



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Observation of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay and measurement of its branching ratio

The NA62 Collaboration *

Abstract

A measurement of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay by the NA62 experiment at the CERN SPS is presented, using data collected in 2021 and 2022. This dataset was recorded, after modifications to the beamline and detectors, at a higher instantaneous beam intensity with respect to the 2016–2018 data taking. Combining NA62 data collected in 2016–2022, a measurement of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (13.0^{+3.3}_{-3.0}) \times 10^{-11}$ is reported. With 51 signal candidates observed and an expected background of 18^{+3}_{-2} events, $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ becomes the smallest branching ratio measured with a signal significance above 5σ .

Conclusions $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

- Study of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay using NA62 2021-2022 data
 - Improved signal yield per SPS spill by 50 %
 - $N_{\text{bg}} = 11.0^{+2.1}_{-1.9}$, $N_{\text{obs}} = 31$
 - $\mathcal{B}_{21-22}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (16.0^{+5.0}_{-4.5}) \times 10^{-11}$
- Combining with 2016-2018 data for full 2016-22 result
 - $N_{\text{bg}} = 18^{+3}_{-2}$, $N_{\text{obs}} = 51$
 - $\mathcal{B}_{16-22}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (13.0^{+3.3}_{-2.9}) \times 10^{-11}$
 - Background-only hypothesis rejected with **significance** > 5
- **First observation of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay**
 $\mathcal{B}$ consistent with SM prediction within 1.7σ
- Need full NA62 data-set to clarify SM agreement or tension
 - Analysis of 2023 data in progress
 - Processing of 2024 data in progress
 - Taking more data in 2025 and 2026

First detection of a tagged neutrino in the NA62 experiment

The NA62 Collaboration ¹

Abstract

The NA62 experiment at the CERN SPS reports the first detection of a tagged neutrino candidate based on the data collected in 2022. The candidate consists of a $K^+ \rightarrow \mu^+ \nu_\mu$ decay where the charged particles are reconstructed and the neutrino is detected through a charged-current interaction in a liquid krypton calorimeter.

To be submitted to Physics Letters B

$$K^+ \rightarrow \mu^+ \nu_\mu, \nu_\mu + (\text{LKr}) \rightarrow \mu^+ X$$

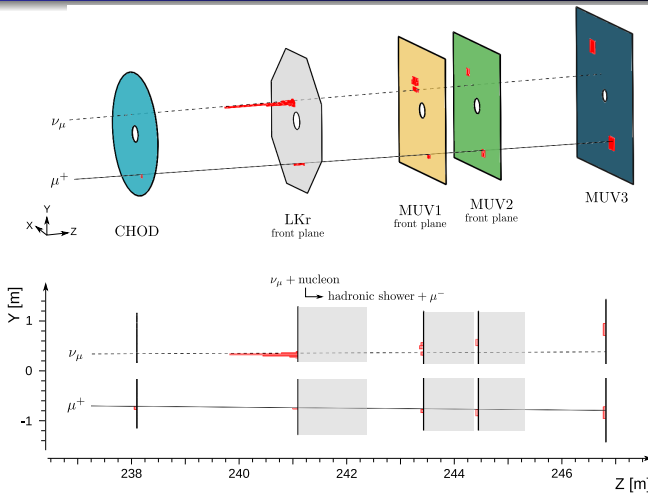


Figure 4: Display of the activity recorded in CHOD, LKr, MUV1, MUV2 and MUV3 for the signal candidate. No extra in-time activity is recorded in these detectors. The red histograms represent the activity in each detector projected at the front plane. For LKr, MUV1 and MUV2 the heights correspond to the fraction of the total energy deposited in each cell. The solid line represents the μ^+ trajectory extrapolated from the STRAW track; the dashed line represents the neutrino trajectory reconstructed using the K^+ and μ^+ momenta. The shaded areas in the projection represent the detector volumes.

$$K^+ \rightarrow \mu^+ \nu_\mu, \nu_\mu + (\text{LKr}) \rightarrow \mu^+ X$$

Table 2: Properties of the tagged neutrino candidate event. Its energy evaluated from kinematics has a relative uncertainty of 0.34% which is significantly better than the 10-30% typically achievable in neutrino detectors.

Property	Value
K^+ momentum	77.34 GeV/c
μ^+ momentum	25.26 GeV/c
Decay vertex position z_{vtx}	161.2 m
Neutrino energy $E_\nu = E_{K^+} - E_{\mu^+}$	52.09 GeV
Distance of the LKr signal to the Z axis	334.9 mm
LKr energy associated with the neutrino E_{LKr}	12.54 GeV
MUV1 energy associated with the neutrino E_{MUV1}	13.75 GeV
MUV2 energy associated with the neutrino E_{MUV2}	10.74 GeV
Inelasticity y	0.69
Azimuthal angle between the LKr and MUV3 signals φ	3.28 rad
d_{LKr}	31.4 mm
d_{MUV3}	567.9 mm
m_{miss}^2	$-0.00086 \text{ GeV}^2/c^4$

Expected $0.208 \pm 0.013_{\text{stat}} \pm 0.0009_{\text{syst}}$ Events
 observed 1 event (probab 19%)

K^+ decay to lepton pairs

Depending on lepton flavor and/or charge, could be SM allowed, Lepton number or lepton family number violating.

NA62 published upper limits for:

$$K^+ \rightarrow \pi^-(\pi^0)e^+e^+ \quad (\text{Phys. Lett. B 830 (2022) 137172})$$

$$K^+ \rightarrow \pi^-\mu^+\mu^+ \quad (\text{Phys. Lett. B 797 (2019) 134794})$$

$$K^+ \rightarrow \pi^-\mu^+e^+ \quad (\text{Phys. Rev. Lett. 127 (2021) 131802})$$

$$K^+ \rightarrow \pi^+\mu^-e^+ \quad (\text{Phys. Rev. Lett. 127 (2021) 131802})$$

$$K^+ \rightarrow \mu^-\nu e^+e^+ \quad (\text{Phys. Lett. B 838 (2023) 137679})$$

$$K^+ \rightarrow \pi^0\pi^-\mu^+\mu^+ \quad (\text{Phys. Lett. B 859 (2024) 139122})$$

$$K^+ \rightarrow \pi^0\pi^+\mu^\pm e^\mp \quad (\text{Phys. Lett. B 859 (2024) 139122})$$

$$\pi^0 \rightarrow \mu^+e^- \quad (\text{Phys. Rev. Lett. 127 (2021) 131802})$$

all permutations covered



Contents lists available at ScienceDirect

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Letter

First search for $K^+ \rightarrow \pi^0 \pi \mu e$ decays

The NA62 Collaboration



ARTICLE INFO

Editor: M. Doser

ABSTRACT

The first search for the lepton number violating decay $K^+ \rightarrow \pi^0 \pi^- \mu^+ e^+$ and lepton flavour violating decays $K^+ \rightarrow \pi^0 \pi^+ \mu^- e^+$, $K^+ \rightarrow \pi^0 \pi^+ \mu^+ e^-$ has been performed using a dataset collected by the NA62 experiment at CERN in 2016–2018. Upper limits of 2.9×10^{-10} , 3.1×10^{-10} and 5.0×10^{-10} , respectively, are obtained at 90% CL for the branching ratios of the three decays on the assumption of uniform phase-space distributions.

Related to $K^+ \rightarrow \pi^+ \nu \bar{\nu}$:

- *Search for a feebly interacting particle X in the $K^+ \rightarrow \pi^+ X$ decay.*

Journal of High Energy Physics 03 (2021) 058.

will be repeated for the latest data set.

Other recent NA62 publications (2)

“Normal” K^+/π^0 decays:

- *Search for K^+ decays into the $\pi^+ e^+ e^- e^-$ final state.*
Physics Letters B 846 (2023) 13893
- *Measurement of the $K^+ \rightarrow \pi^+ \gamma \gamma$ decay.*
Physics Letters B 850 (2024) 138513.
- *A measurement of the $K^+ \rightarrow \pi^0 e^+ \nu_e \gamma$ decay.*
Journal of High Energy Physics 09 (2023) 040
- *A measurement of the $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ decay.*
Journal of High Energy Physics 11 (2022) 011,
- *Search for π^0 decays to invisible particles.*
Journal of High Energy Physics 02 (2021) 201.

Heavy Neutral Leptons searches:

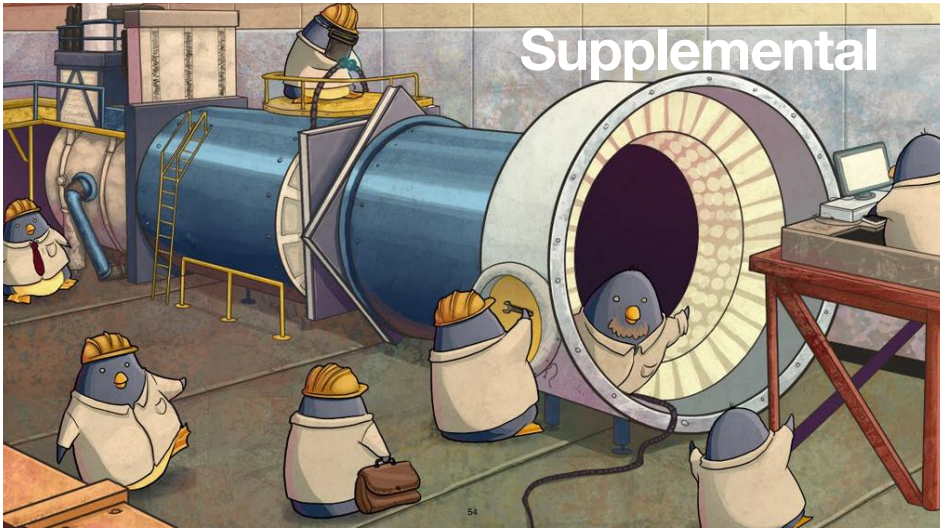
- *Search for K^+ decays to a muon and invisible particles.*
Physics Letters B 816 (2021) 136259.
- *Search for heavy neutral lepton production in K^+ decays to positrons.*
Physics Letters B 807 (2020) 135599.
- *soon: Search for heavy neutral lepton production in π^+ decays to positrons.*

“Dump” Program:

- *Search for leptonic decays of the dark photon at NA62.*
Physical Review Letters 133, 111802 (2024).
- *Search for dark photon decay to $\mu^+\mu^-$ at NA62.*
Journal of High Energy Physics 09 (2023) 035.
- soon: *Search for hadronic decays of feebly-interacting particles at NA62.*

- NA62 observed the $K^+ \rightarrow \pi + \nu \bar{\nu}$ decay.
- Has a rich program on rare kaon decays
- New limits for rare and LNV/LFV decays
- Searches for BSM particles

Supplemental

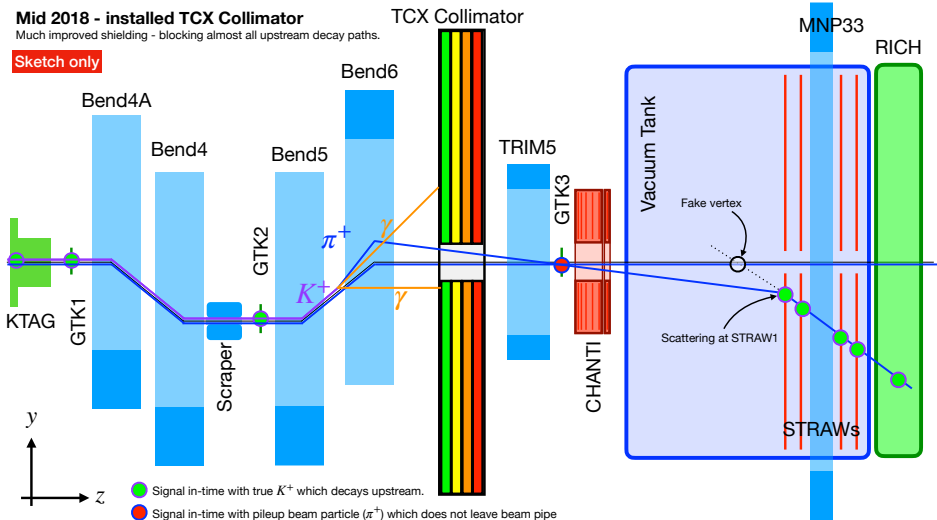


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Mid 2018 - installed TCX Collimator

Much improved shielding - blocking almost all upstream decay paths.

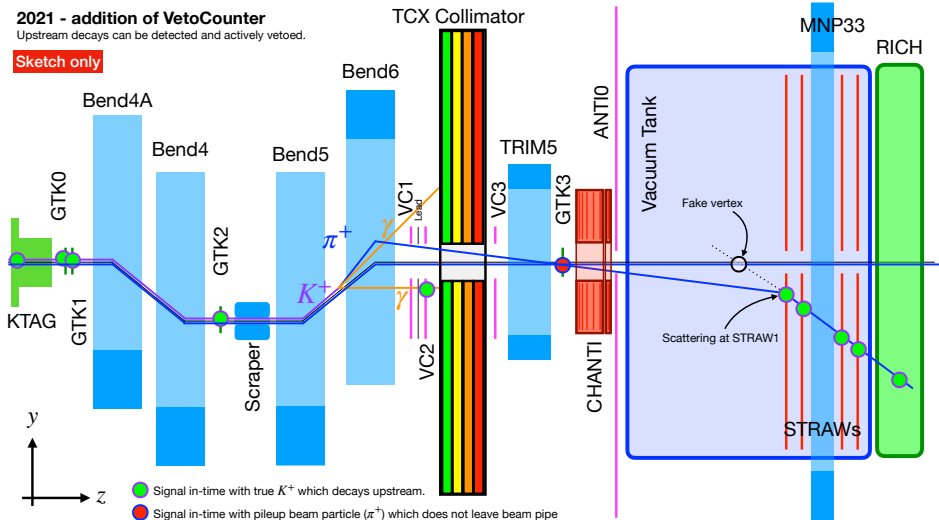
Sketch only

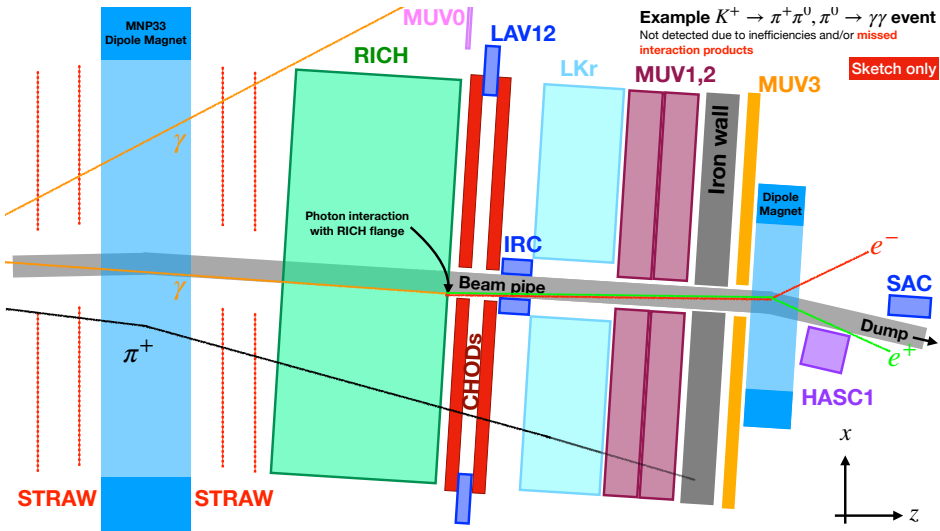


2021 - addition of VetoCounter

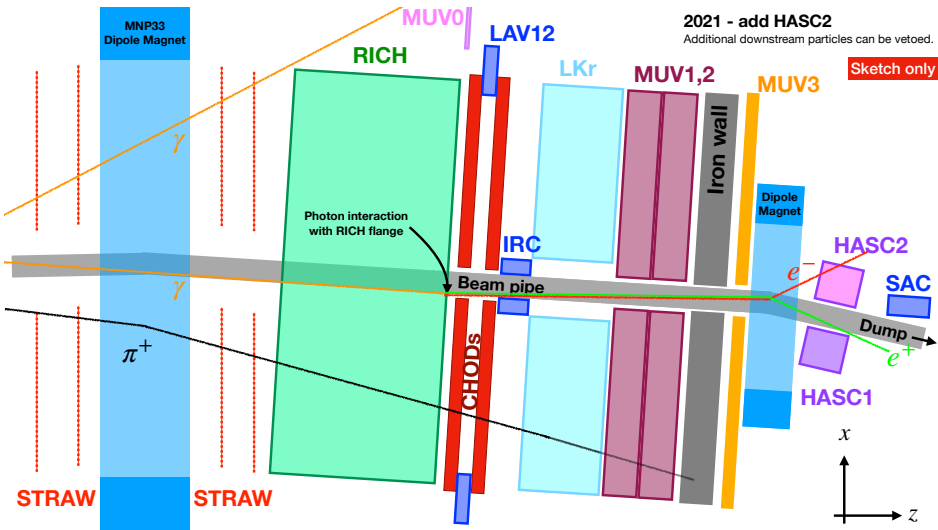
Upstream decays can be detected and actively vetoed.

Sketch only





Example $K^+ \rightarrow \pi^+ \pi^0, \pi^0 \rightarrow \gamma\gamma$ event
 Not detected due to inefficiencies and/or **missed interaction products**

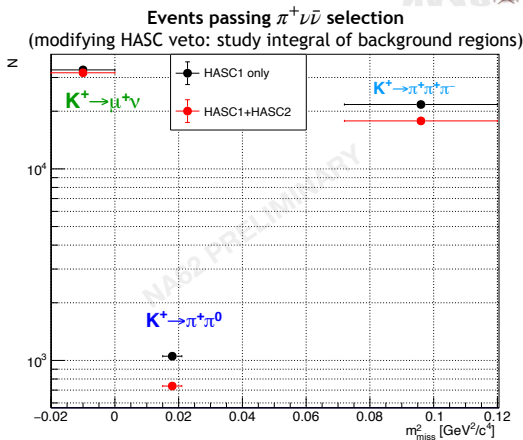


HASC2 veto

- $K^+ \rightarrow \pi^+ \pi^0$ was 2nd largest background for 2018 analysis.

- Addition of HASC2:

- 30% less $K^+ \rightarrow \pi^+ \pi^0$
- 18% less $K^+ \rightarrow \pi^+ \pi^+ \pi^-$
- 3.5% less $K^+ \rightarrow \mu^+ \nu$
- with only 1.5% signal loss.



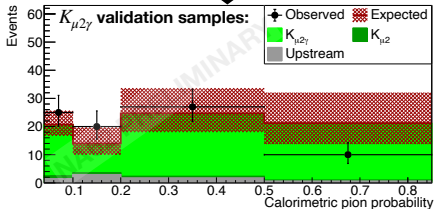
$K^+ \rightarrow \mu^+ \nu \gamma$ Background

- Kinematically select $K^+ \rightarrow \mu^+ \nu \gamma$ events:

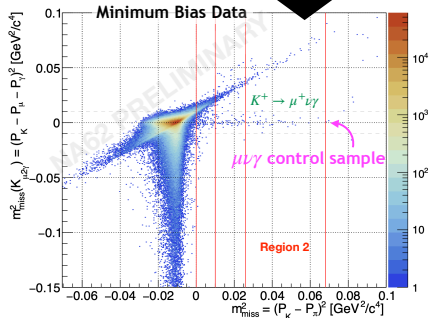
$$m_{\text{miss}}^2(K_{\mu 2\gamma}) = (P_K - P_\mu - P_\gamma)^2$$

- P_K : 4-momentum of K^+ from GTK (as normal)
- P_μ : 4-momentum of track with μ^+ mass hypothesis.
- P_γ : reconstructed from energy and position of LKr cluster (and position of $K^+-\mu^+$ vertex).

Validation: data sample with PID = “less pion-like” (Calo BDT bins below π^+ bin).



Evaluate background expectation using $\mu \nu \gamma$ control sample from MinimumBias trigger, not applying Calorimetric BDT classifier and MUV3 signal:



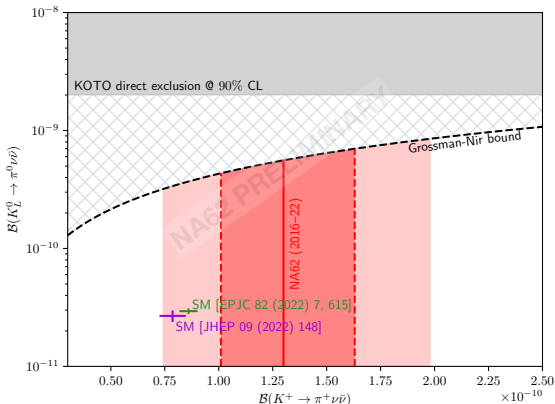
- Before $K^+ \rightarrow \mu^+ \nu \gamma$ veto: found excess of events at $p > 35$ GeV/c in Region 2 relative to 2016–18 data.
- Additional background identified and studied in data control samples & MC.
- $K^+ \rightarrow \mu^+ \nu \gamma$ veto added to selection criteria for final analysis.

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Results in context



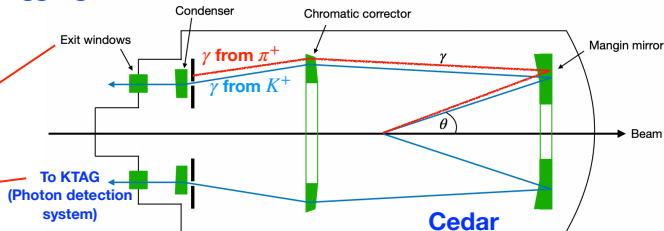
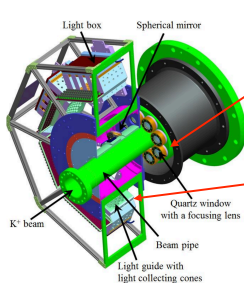
- Fractional uncertainty: 25%
- Bkg-only hypothesis rejected with significance $Z > 5$
- **Observation of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay with BR consistent with SM prediction, within 1.7σ**
- Need full NA62 data-set to clarify SM agreement or tension



$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = (13.0^{+3.3}_{-2.9}) \times 10^{-11}$$

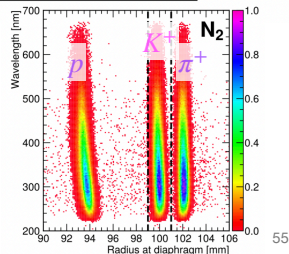
$$2\sigma \text{ range : } [7.4 - 19.7] \times 10^{-11}$$

Cedar & KTAG : K^+ tagging with threshold Cherenkov counter **NA62**



- 75 GeV Unseparated hadron beam
 π^+ : 70 % , p : 23 % , K^+ : 6 % .

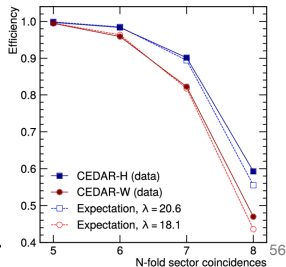
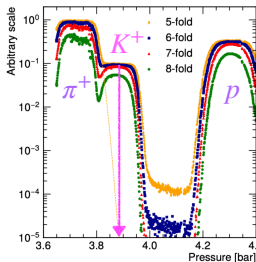
- Use fixed diaphragm to select ONLY Cherenkov light from K^+ (adjust diaphragm width and gas pressure in CEDAR to ensure powerful K^+/π^+ discrimination).



New Cedar-H : installed in 2023



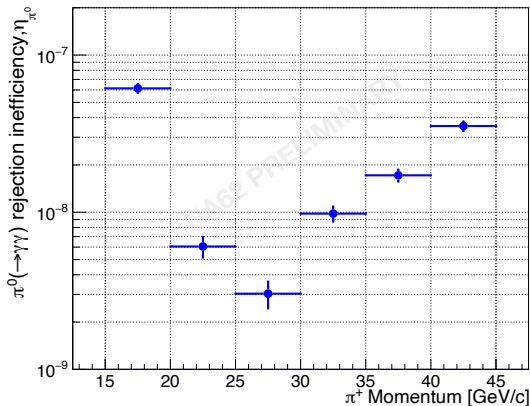
- CEDAR-W filled with N_2 at 1.7 bar was biggest contributor to material in beam line ($39 \times 10^{-3} X_0$).
- New CEDAR-H filled with H_2 at 3.8 bar:
 - Reduces material to $7.3 \times 10^{-3} X_0$: reducing multiple scattering.
 - But new optics required to account for different optical properties of H_2 .
- Successful test beam in 2022 (at CERN,H6) and installation in NA62 in **early 2023**.
- **Cedar-H Performance at NA62:**
 - **>99.5% efficiency** for 5-fold coincidence.
 - **π^+ mistag probability: 10^{-4}**
 - **~ 65 ps time resolution**
 - **30% reduction** in elastically scattered beam particles.



Joel Swallow
CERN Seminar

[JINST 19 (2024) 05, P05005]
More info: [\[Kenworthy, PM2024\]](#)

Photon veto performance



- Probability of $K^+ \rightarrow \pi^+\pi^0$ events with $\pi^0 \rightarrow \gamma\gamma$ passing full photon vetos:

Number of events passing full $\pi^+\nu\bar{\nu}$ selection in $\pi^+\pi^0$ region

$$\eta_{\pi^0} = \frac{N_{\pi^+\pi^0 R}^{sel.}}{N_{\pi\pi} D_0 \epsilon_{trig} \epsilon_{RV}}$$

Number of selected normalisation events

Normalisation trigger downscaling and efficiency

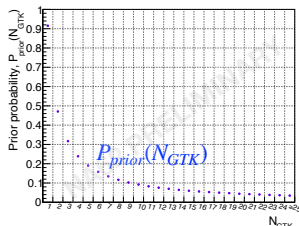
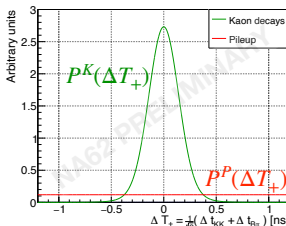
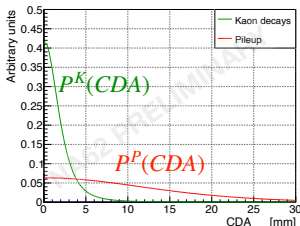
Random veto efficiency

$$\eta_{\pi^0} = (1.72 \pm 0.07) \times 10^{-8}$$

- Combined γ/π^0 rejection of $\mathcal{O}(10^8)$.

Bayesian classifier for $K^+ - \pi^+$ matching

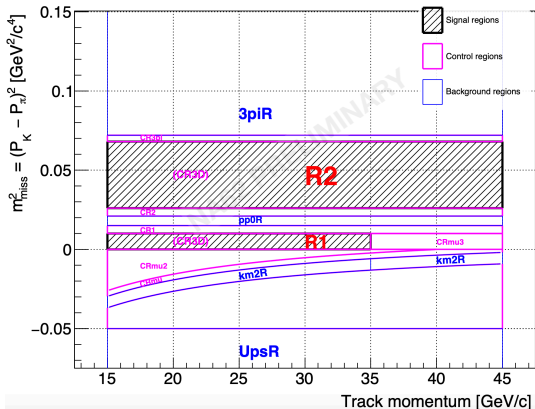
- Inputs: spatial (CDA) & time (ΔT_+) matching, intensity/pileup (N_{GTK}) [prior]
 - Models for PDFs/Prior from $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ data.



Example of
selection update

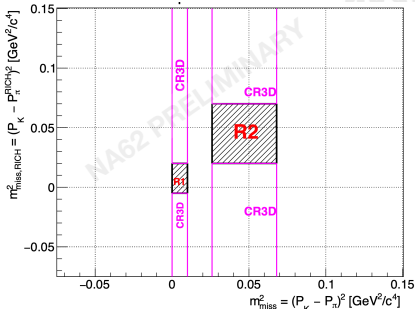
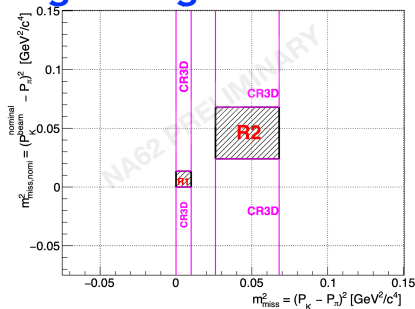
- Output: posterior probability of GTK track = true K^+
 - Use likelihoods of kaons (K) and pileup (P)
 - Likelihood ratio used to select true match when $N_{GTK} > 1$
- Efficiency improved (+10%) and mistagging probability maintained.

Kinematic regions



- **Signal regions:**
- **Control regions:**
 - Used to validate background predictions.
- **Background regions:**
 - Used as “reference samples” for some background estimates.

3D signal regions definition



CR3D: control region for events in SR in 2 out of 3 dimensions.

$$m_{miss}^2 = (P_K - P_\pi)^2$$

Default: GTK

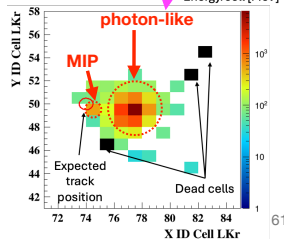
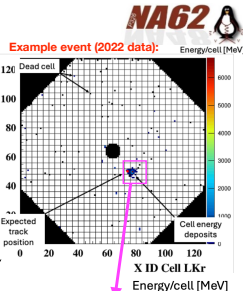
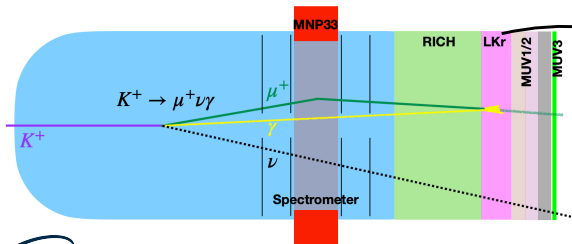
Alternative: Nominal beam = $m_{miss,nom}^2$

Default: STRAW

Alternative: $|p|$ from RICH (use as a velocity spectrometer) = $m_{miss,RICH}^2$

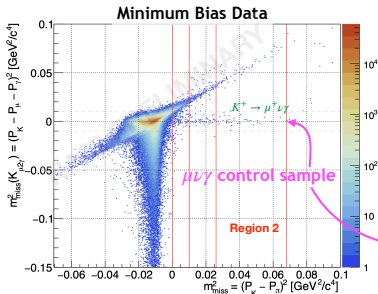
Background mechanism: $K^+ \rightarrow \mu^+ \nu \gamma$

- $K^+ \rightarrow \mu^+ \nu \gamma$ decay with fairly energetic photon ($E_\gamma > 5$ GeV) and high momentum μ^+ ($p \gtrsim 35$ GeV/c).
- γ and μ^+ hit LKr together and are misidentified as a π^+ .
- No rejection power from photon vetos (LKr γ cluster associated to track).
- Additional γ naturally shifts $m_{miss}^2 = (P_K - P_\pi)^2$ towards higher values (i.e. towards signal regions).



Background evaluation: $K^+ \rightarrow \mu^+ \nu \gamma$

- Evaluate background expectation using $\mu \nu \gamma$ control sample from MinimumBias (MB) trigger.
 - Not applying Calorimetric BDT classifier and a signal in MUV3.

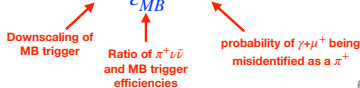


- Kinematically select $K^+ \rightarrow \mu^+ \nu \gamma$ events:

$$m_{miss}^2(K_{\mu 2\gamma}) = (P_K - P_{\mu} - P_{\gamma})^2$$

- P_K : 4-momentum of K^+ from GTK (as normal)
- P_{μ} : 4-momentum of track with μ^+ mass hypothesis.
- P_{γ} : reconstructed from energy (subtracting MIP energy deposit) and position of LKr cluster (and position of K^+ - μ^+ vertex).

$$N_{bg}(K^+ \rightarrow \mu^+ \nu \gamma) = N_{\mu \nu \gamma}^{MB} D_{MB} \frac{\epsilon_{signal}}{\epsilon_{MB}} P_{misID}$$



Not included in kinematic tails calculation because the tails sample imposes Calorimetric PID= μ^+ , while here there is misID of $\mu^+ \gamma \Rightarrow \pi^+$.

Background rejection: $K^+ \rightarrow \mu^+ \nu \gamma$

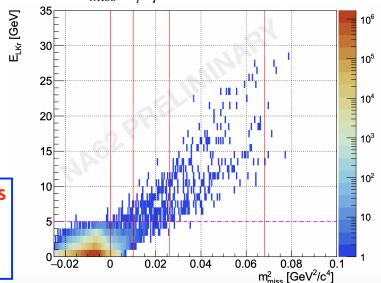


Minimum Bias Data
Events with MUV3 association and
 $|m_{miss}^2(K_{\mu 2\gamma})|^2 < 0.01 \text{ GeV}^2/c^4$

veto $K^+ \rightarrow \mu^+ \nu \gamma$ events with:

- $|m_{miss}^2(K_{\mu 2\gamma})|^2 < 0.01 \text{ GeV}^2/c^4$ → c.f. resolution $\sim 0.0025 \text{ GeV}^2/c^4$
- $E_\gamma > 5 \text{ GeV}$
- μ^+ -like RICH PID.

- Veto conditions established using data control samples and MC.
- $K^+ \rightarrow \mu^+ \nu \gamma$ Veto $\Rightarrow$ 20x background suppression with 0.4% signal loss.



- Why different to 2016–18 analysis?
 - Calorimetric PID degraded:
 - Higher intensity in 2021–22 data (in particular, affects MUV1,2).
 - Training of BDT classifier.

Upstream background evaluation

$$N_{bg} = \sum_i N_i f_{cda} P_i^{match}$$

Upstream Reference Sample:
signal selection but invert CDA cut (CDA > 4mm)

Scaling factor : bad cda → good cda

Probability to pass $K^+ - \pi^+$ matching

Calculate using bins (i) of $(\Delta T_+, N_{GTK})$

[Updated to fully data-driven procedure]

$$N = 51 \quad f_{CDA} = 0.20 \pm 0.03 \quad < P_{match} > = 73 \%$$

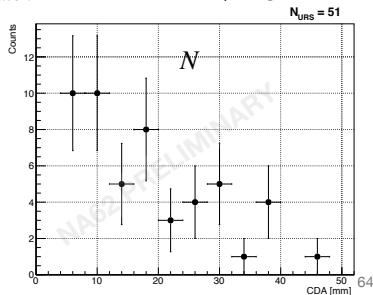
$$N_{bg}(\text{Upstream}) = 7.4^{+2.1}_{-1.8}$$

- Upstream reference sample contains all known upstream mechanisms.

- N provides normalisation.

- f_{CDA} depends only on geometry.

- P_{match} depends on $(\Delta T_+, N_{GTK})$.



Results in context: the long story of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

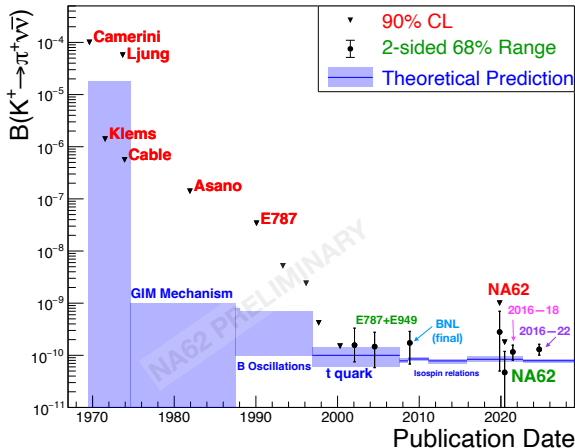


Experimental measurements:

- Camerini et al. [PRL 23 (1969) 326-329]
- Klems et al. [PRD 4 (1971) 66-80]
- Ljung et al. [PRD 8 (1973) 1307-1330]
- Cable et al. [PRD 8 (1973) 3807-3812]
- Asano et al. [PLB 107 (1981) 159]
- E787 :
 - [PRL 64 (1990) 21-24]
 - [PRL 70 (1993) 2521-2524]
 - [PRL 76 (1996) 1421-1424]
 - [PRL 79 (1997) 2204-2207]
 - [PRL 84 (2000) 3768-3770]
 - [PRL 88 (2002) 041803]
- E949 (+E787)
 - [PRL 93 (2004) 031801]
 - [PRL 101 (2008) 191802]
- NA62:
 - 2016 data: [PLB 791 (2019) 156]
 - 2016+17 data: [JHEP 11 (2020) 042]
 - 2016–18 data: [JHEP 06 (2021) 093]
 - 2016–22 data: this result.

Theory:

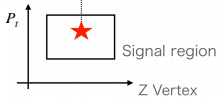
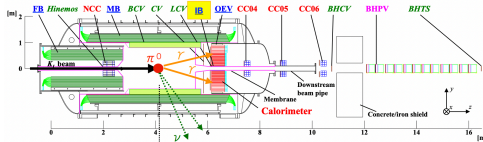
- [Phys.Rev. 163 (1967) 1430-1440]
- [PRD 10 (1974) 897]
- [Prog.Theor.Phys. 65 (1981)]
- [PLB 133 (1983) 443-448]
- [PLB 192 (1987) 201-206]
- [Nucl.Phys.B 304 (1988) 205-235]
- [PRD 54 (1996) 6782-6789]
- [PRD 76 (2007) 034017]
- [PRD 78 (2008) 034006]
- [PRD 83 (2011) 034030]
- [JHEP 11 (2015) 033]
- [JHEP 09 (2022) 148]



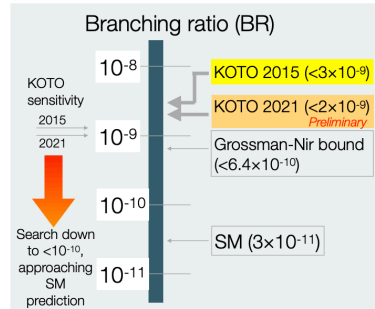
$K_L \rightarrow \pi^0 \nu \bar{\nu}$ at KOTO

- Located at J-Park 30 GeV main ring.
- KOTO continues data-taking to reach sensitivity $< 10^{-10}$
- Planned future program (KOTO-2) key part of high priority hadron hall extension plans at J-PARC.

Signature of $K_L \rightarrow \pi^0 \nu \bar{\nu} = "2\gamma + \text{Nothing} + \text{Pt}"$



Assuming 2γ from π^0 ,
Calculate z vertex on the beam axis
 $M^2(\pi^0) = 2E_1 E_2 (1 - \cos \theta)$
Calculate π^0 transverse momentum



Grossman-Nir bound:
indirect limit from relation to $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$;
Calc'd from NA62 results (2021) with 1σ region

Latest results:

Results of the 2021 data analysis

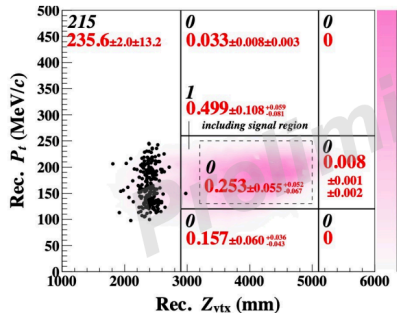


T. Nomura : Kaons @ J-PARC 2024

Final PT vs Z plot

Black: observed
Red: expected BG
Contour: signal MC

Single Event Sensitivity =
 $(9.26 \pm 0.03_{\text{stat}} \pm 0.75_{\text{syst}}) \times 10^{-10}$



$N_{\text{observed}} = 0$

$\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 2.1 \times 10^{-9}$ (90% C.L.)

Obtained the world best limit.

We will submit the paper on this result soon.

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physics programme

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

Rare Decays

Forbidden Decays

Exotics

- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$: [PLB 791 (2019) 156] [JHEP 11 (2020) 042] [JHEP 06 (2021) 093][this talk]
- $K^+ \rightarrow \pi^+ X$: [JHEP 03 (2021) 058] [JHEP 06 (2021) 093]
- $(K^+ \rightarrow \pi^+ \pi^0, \pi^0 \rightarrow \text{invisible})$ [JHEP 02 (2021) 201]

- $K^+ \rightarrow \pi^+ \pi^0, \pi^0 \rightarrow e^+ e^-$ [prelim. Spring 2024]
- $K^+ \rightarrow \pi^+ \gamma \gamma$ [PLB 850 (2024) 138513]
- Tagged neutrino [prelim. 2023]

- $K^+ \rightarrow \pi^0 \pi \mu e$ [prelim. Spring 2024]
- $K^+ \rightarrow (\pi^0) \pi^- e^+ e^+$ [PLB 830 (2022) 137172]
- $K^+ \rightarrow \mu^- \nu e^+ e^+$ [PLB838 (2023) 137679]
- $K^+ \rightarrow \pi \mu e, \pi^0 \rightarrow \mu^- e^+$ [PRL 127 (2021) 13, 131802]

- Beam dump dark photon searches:
 - $A' \rightarrow \ell^+ \ell^-$ [PRL 133 (2024) 11, 111802] [JHEP 09 (2023) 035]
 - $A' \rightarrow \text{hadrons}$ [prelim. Spring 2024]