

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

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October 24, 2025



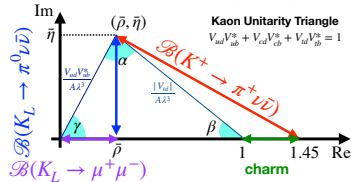
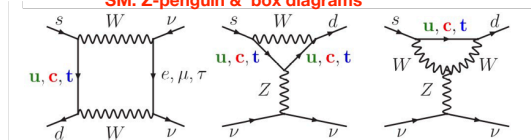
- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  in the SM and beyond
  - The Golden Modes  $K \rightarrow \pi \nu \bar{\nu}$  in the SM and beyond
  - NA62 after LS2: detector upgrades and performance
  - New measurement of  $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$
- First detection of a tagged neutrino
- Search for Heavy Neutral Leptons in  $\pi^+ \rightarrow e^+ N$  decays  
Hecho en San Luis Potosí!



# $K \rightarrow \pi \nu \bar{\nu}$ : 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)

<sup>1</sup>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](#))



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



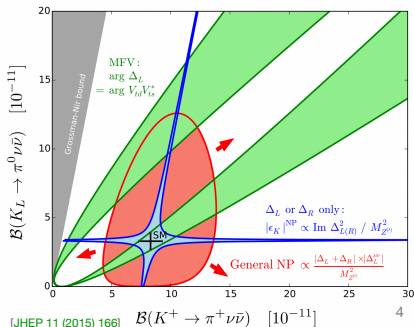
- Correlations between BSM contributions to BRs of  $K^+$  and  $K_L$  modes [JHEP 11 (2015) 166].
  - Must measure both to discriminate between BSM scenarios.
- Correlations with other observables ( $\epsilon'/\epsilon$ ,  $\Delta M_B$ , B-decays) [JHEP 12 (2020) 097][PLB 809 (2020) 135769].
- Leptoquarks [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] ...

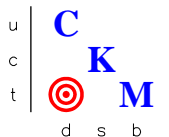
- **Green:** CKM-like flavour structure
  - Models with Minimal Flavour Violation
- **Blue:** new flavour-violating interactions where LH or RH currents dominate
  - $Z'$  models with pure LH/RH couplings
- **Red:** general NP models without above constraints
- **Grossman-Nir Bound:** model-independent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

[PLB 398 (1997) 163-168]

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

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





## 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, USA

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

J. Engelfried, A. Morelos  
 Instituto de Fisica, Universidad Autonoma de San Luis Potosi, Mexico

K. Lang, J.L. Ritchie\*  
 University of Texas at Austin, Austin, Texas 78712

† Resident at Fermilab, on leave from Tel Aviv University.

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 J.L. Ritchie, ritchie@hep.utexas.edu, (512) 471-4488

# 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	FNAL, USA
J. Dos Anjos	CBPF, Brazil
Robin Earbacher	BNL, USA
Ada Farilla	INFN-Rome, Italy
R. Flores-Mendieta	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 Panzeri	INFN, Italy
S. Pastor	Munich, Germany
J. S. Russ	Carnegie Mellon, USA
A. Santoro	LAFEX/CBPF, Brazil
N. Tarnopolski	Helsinki, Finland
A. Wagner	DESY, Germany
J. Wambach	Darmstadt, Germany
H.-J. Weber	Charlottesville, USA
A. Wirzba	FZ Julich, 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. P. Pérez	CINVESTAV

## Local Organizing Committee

J. Engelfried	IF-UASLP
A. A. Espinoza	EE-UAZ
A. Gutiérrez	EE-UAZ
M. Kerchbach	EE-UAZ (Chair)
J. Ontz Saavedra	EE-UAZ
J. M. Rivera Juárez	EE-UAZ

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

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

Design: Comunicil

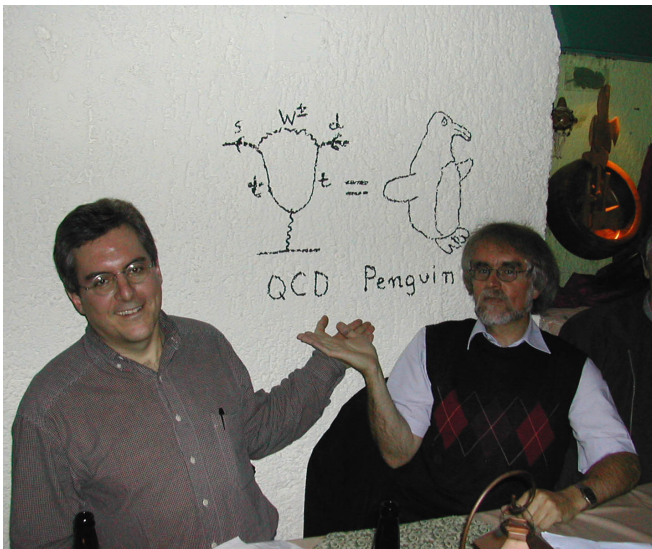
Sponsored by



Centro Latinoamericano de Física  
Centro Latinoamericano de Optoelectrónica  
Centro Americano de Física

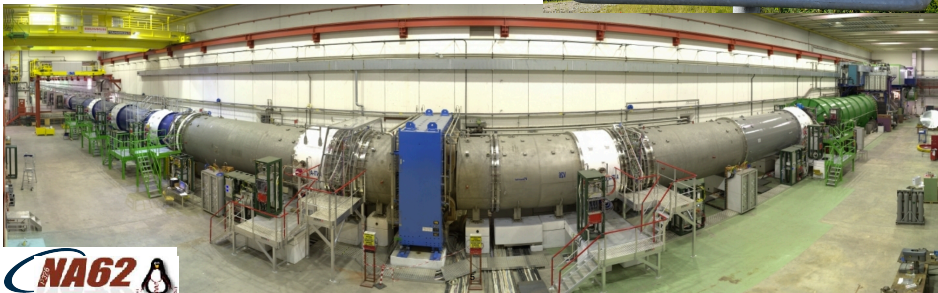


Andrzej J. Buras (Munich, Germany): *CP Violation, Rare Decays and the CKM Matrix*  
Peter S. Cooper (Fermilab): *Rare Kaon Decays*



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

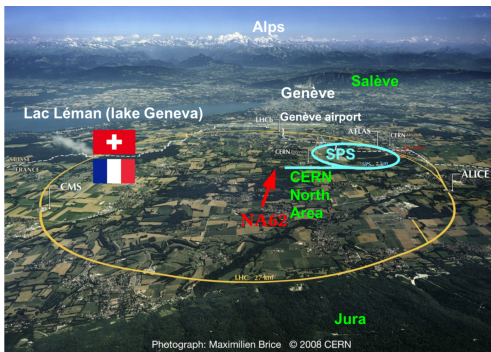
# NA62: The $K^+$ factory at the CERN north area



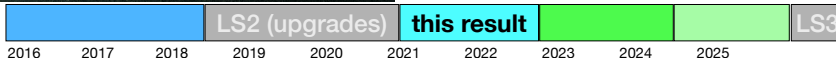
# The NA62 Experiment at CERN



~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
- Lancaster
- Louvain-la-Neuve
- EPFL Lausanne
- Mainz
- INR Moscow
- Max Planck München
- Napoli
- Perugia
- Pisa
- Prague
- Protvino
- Roma I
- Roma II
- San Luis Potosí
- Torino
- TRIUMF
- Vancouver

~ 230 collaborators



# The Mexicans in NA62



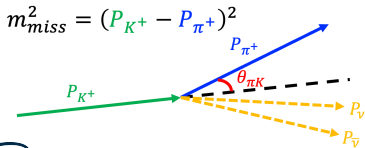
# $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at NA62

## NA62 Strategy:

- Tag  $K^+$  and measure momentum.
- Identify  $\pi^+$  and measure momentum.
- Match  $K^+$  and  $\pi^+$  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  $\pi^0$  from  $K^+ \rightarrow \pi^+ \pi^0$  decays



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

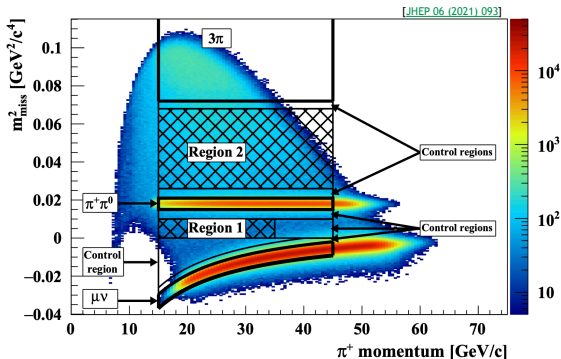
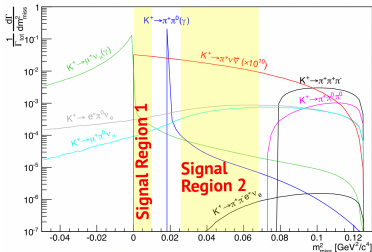
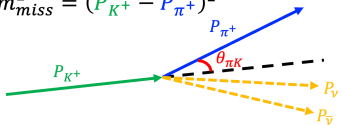
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$   $(8.60 \pm 0.42) \times 10^{-11}$  [SM]

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

# Kinematic constraints & signal regions

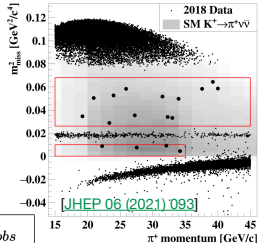
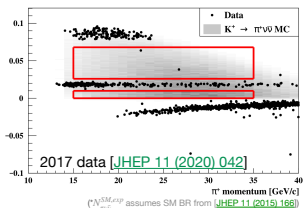
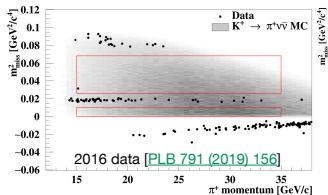
$$m_{miss}^2 = (P_{K^+} - P_{\pi^+})^2$$

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



$\pi^+$  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]	$0.152^{+0.093}_{-0.035}$	$0.267 \pm 0.020$	1
2017	[JHEP 11 (2020) 042]	$1.46 \pm 0.33$	$2.16 \pm 0.13$	2
2018	[JHEP 06 (2021) 093]	$5.42^{+0.99}_{-0.75}$	$7.58 \pm 0.40$	17
2016–18	[JHEP 06 (2021) 093]	$7.03^{+1.05}_{-0.82}$	$10.01 \pm 0.42$	20

Statistical combination:

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

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



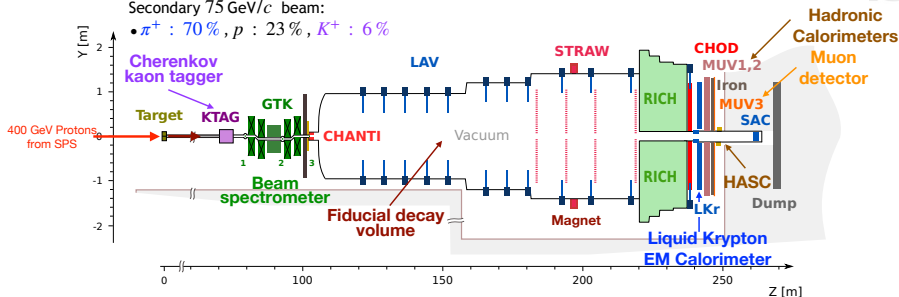
# NA62 beamline & detector

[JINST 12 (2017) 05, P05025]



Secondary 75 GeV/c beam:

- $\pi^+$  : 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,  $\pi^+$  - RICH, Calorimeters (LKr, MUV1,2), MUV3 ( $\mu$  detector)
  - Comprehensive veto systems: CHANTI (beam interactions), LAV, LKr, IRC, SAC ( $\gamma$ )



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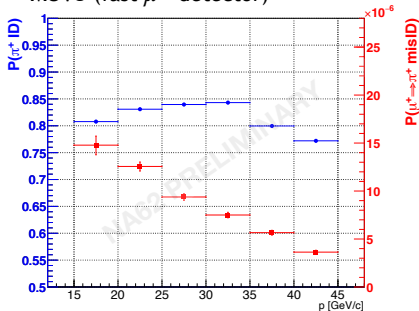


# Particle ID performance : 2021–22 data



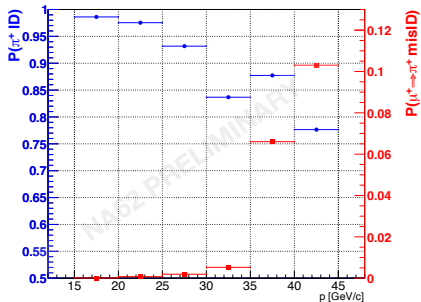
## Calorimeters

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



## RICH

Designed to distinguish between  $\pi^+/\mu^+$  with 15 – 35 GeV/c.



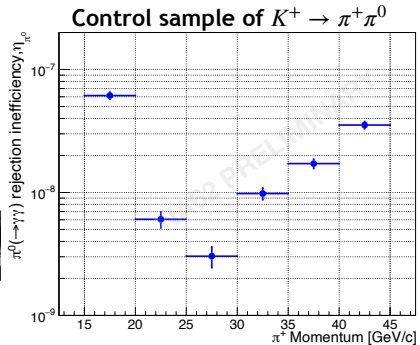
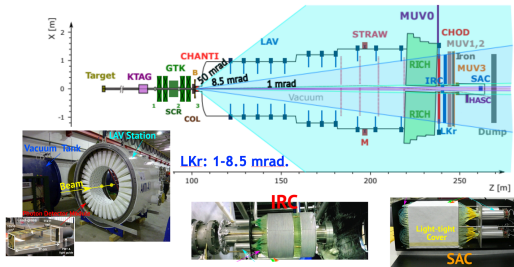
$$\varepsilon(\pi \text{ ID}) = (73.00 \pm 0.01) \%$$

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

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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  $\gamma/\pi^0$  rejection of  $\mathcal{O}(10^8)$ .

# Upgrading NA62



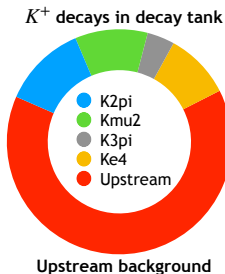
- 2016–18 analysis proved NA62 technique.
- Limitation: tight cuts to reject backgrounds  $\Rightarrow$  reduces signal efficiency.
- To improve: need new tools to control background.



# 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	$2.76^{+0.90}_{-0.70}$
$K^+ \rightarrow \pi^+ \pi^0$	$0.52 \pm 0.05$
$K^+ \rightarrow \mu^+ \nu$	$0.45 \pm 0.06$
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$	$0.41 \pm 0.10$
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	$0.17 \pm 0.08$
Total	$4.31^{+0.91}_{-0.72}$



Largest backgrounds:

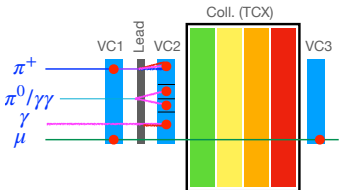
1. Upstream
2.  $K^+ \rightarrow \pi^+ \pi^0$

Veto by detecting previously missed particles...

# New upstream vetos: VetoCounter & ANTIO



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



## VetoCounter

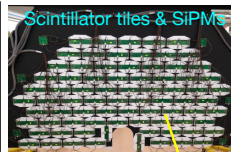
- Detect particles from decays upstream of final collimator.
- **Factor ~3 rejection** with ~2% accidental veto.

## ANTIO

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

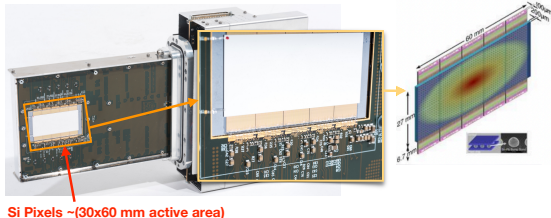
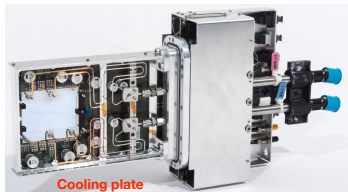
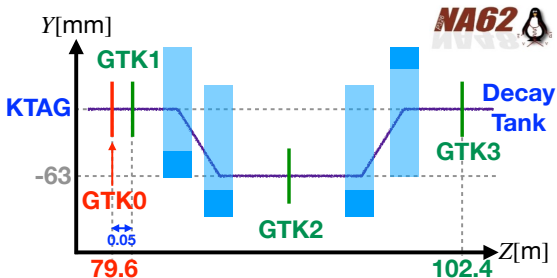
[JINST 15 (2020) C07007]

[SPSC report 2023][EP Newsletter, Dec21]



# 4th GTK station

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



More info: [\[Kleimenova\\_VERTEx2023\]](#)

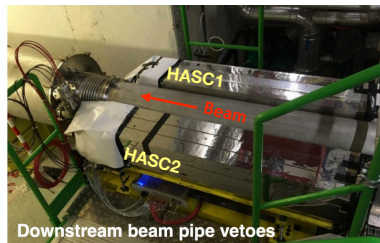
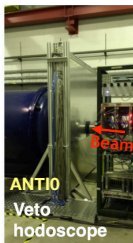
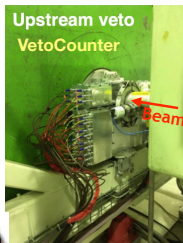
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# Summary of NA62 upgrades

- New detectors, installed during LS2:
  - 4th GTK (Kaon beam tracker) & rearrange GTK achromat (GTK2 upstream of scraper).
  - New upstream veto (**VetoCounter**) & veto hodoscope (**ANTI0**) 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:



# 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 ( $\mu$  veto)
- Tag  $K^+$  ( $\geq 5$  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  $\pi^+$ ;  $K^+ - \pi^+$  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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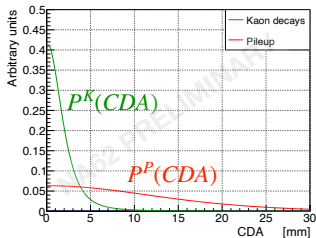


# Bayesian classifier for $K^+ - \pi^+$ matching

Example of selection update

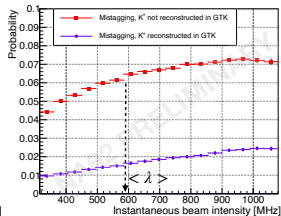
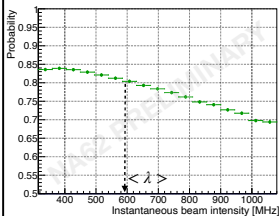


- **Inputs:** spatial (CDA) & time ( $\Delta T_+$ ) matching, intensity/pileup ( $N_{GTK}$ ) [prior]
- Models for PDFs/Prior from  $K^+ \rightarrow \pi^+\pi^+\pi^-$  data.



- **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  $p \in [15,45]$  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  $\rightarrow N_{\pi\pi} D_0$

Downscaling factor of normalisation trigger (generally 400)  $\rightarrow N_{\pi\pi} D_0$

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)

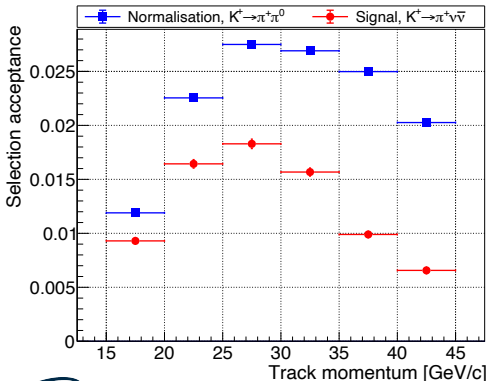
$$N_{\pi\nu\bar{\nu}}^{SM} = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{SM}}{\mathcal{B}_{SES}}$$

# Acceptances

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

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

Acceptances



Case	OLD 2018 (S2)	NEW 2021–22	
Norm.	11.8%	13.4%	+15%
Signal	(6.37±0.64)%	(7.61±0.18)%	+20%

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



Acceptances evaluated at 0 intensity.  
Intensity dependence captured in  $\epsilon_{\text{RV}}$

# Trigger Efficiencies

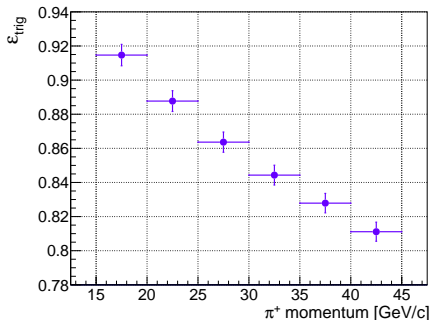
Analysis performed

in (5 GeV/c)

momentum bins

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

$$\epsilon_{\text{trig}} = \frac{\epsilon_{\text{sig}}}{\epsilon_{\text{norm}}} \quad \begin{array}{l} \epsilon(\text{new}) = (85.9 \pm 1.4) \% \\ \epsilon(2018) = (89 \pm 5) \% \end{array}$$



- Trigger efficiency ratio:

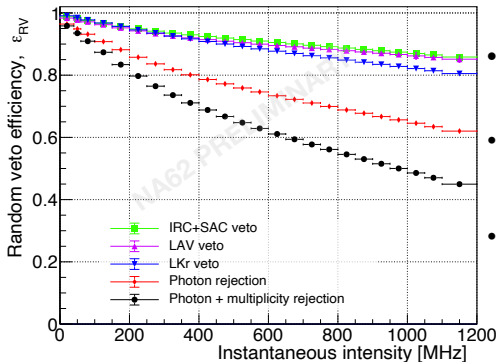
- **New:** several components in both normalization & signal triggers: **partial cancellation**
- **Old:** in 2016-18 data normalized with fully independent min bias trigger **no cancellation**

- Improved precision by factor 3 with reduced systematic uncertainty.

# Random veto

$\epsilon_{RV}$  is independent of track momentum  
(related to additional activity only)

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



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

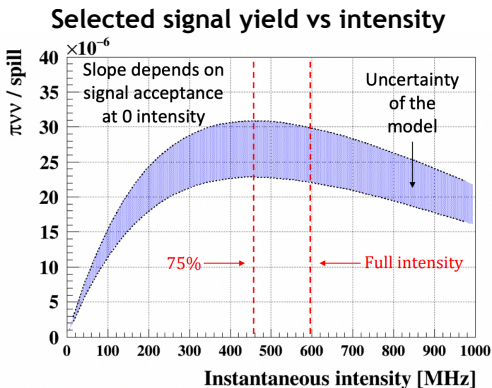
$$N_{\pi\nu\bar{\nu}}^{exp} = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{SM}}{\mathcal{B}_{SES}}$$

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  $\epsilon_{RV}$

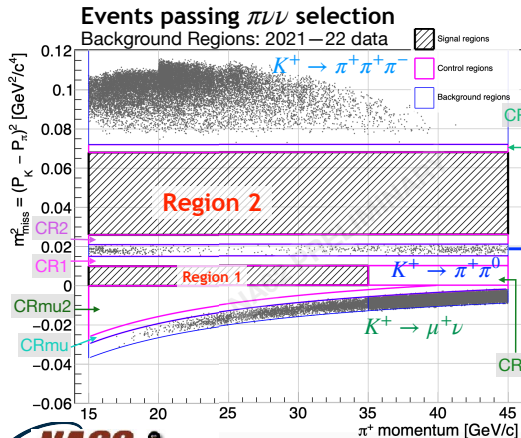
# Optimum NA62 intensity



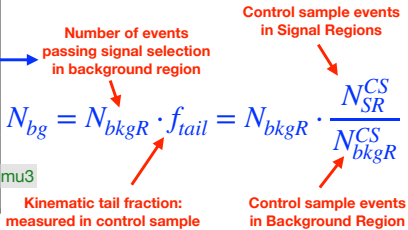
- Saturation of expected signal yield with intensity. Mainly due to:
  - Paralyzable effects from TDAQ dead time and trigger veto windows.
  - Offline selection, due to veto conditions.
- Main sources of uncertainty for model:
  - Online time-dependent mis-calibrations.
  - Fit uncertainty.
- **From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



# Background regions & background estimations

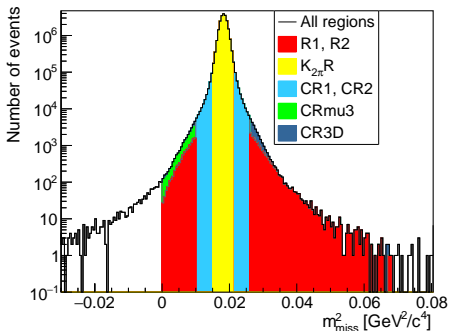


- Backgrounds from kinematic misconstruction tails in  $m_{miss}^2$



# Backgrounds from kinematic tails – Example: $K2\pi$

Control sample of  $K^+ \rightarrow \pi^+ \pi^0$  events with  $\pi^0 \rightarrow \gamma\gamma$  and 2 photons detected in LKr



$$N_{\text{bg}}(K^+ \rightarrow \pi^+ \pi^0(\gamma)) = 0.83 \pm 0.05$$

Similar:

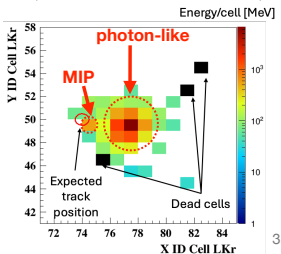
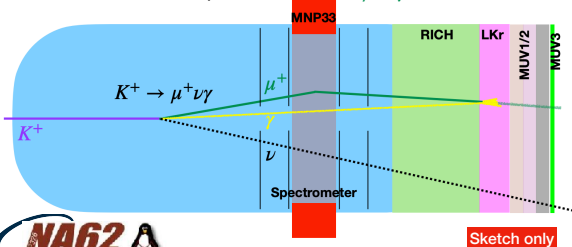
$$N_{\text{bg}}(K^+ \rightarrow \mu^+ \nu(\gamma)) = 1.70 \pm 0.47$$

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

# 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  $\gamma$  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  $\gamma$  overlaps  $\mu^+$  at LKr (leading to misID as  $\pi^+$ )
  - Suppression: based on  $(P_K - P_\mu - P_\gamma)^2$  and  $E_\gamma$  with  $\gamma =$  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  $\pi^+$  bin).



# Other backgrounds

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

- No clean control samples for  $K_{e4}$  in data: use  $2 \times 10^9$  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  $K^+ \rightarrow \pi^+ \gamma \gamma$ :

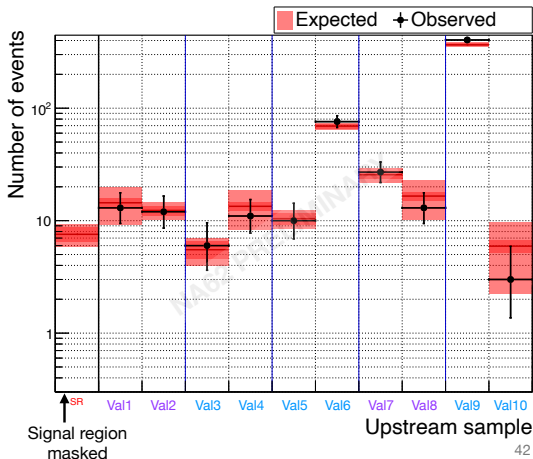
- Evaluated with simulations.
- Negligible contributions to total background.

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

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

# Upstream background 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

$K^+ \rightarrow \pi^+ \pi^0 (\gamma)$	$0.83 \pm 0.05$
$K^+ \rightarrow \pi^+ \pi^0$	$0.76 \pm 0.04$
$K^+ \rightarrow \pi^+ \pi^0 \gamma$	$0.07 \pm 0.01$
$K^+ \rightarrow \mu^+ \nu (\gamma)$	$1.70 \pm 0.47$
$K^+ \rightarrow \mu^+ \nu$	$0.87 \pm 0.19$
$K^+ \rightarrow \mu^+ \nu \gamma$	$0.82 \pm 0.43$
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	$0.11 \pm 0.03$
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$	$0.89^{+0.34}_{-0.28}$
$K^+ \rightarrow \pi^0 \ell^+ \nu$	$< 0.001$
$K^+ \rightarrow \pi^+ \gamma \gamma$	$0.01 \pm 0.01$
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 :  $N_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42$

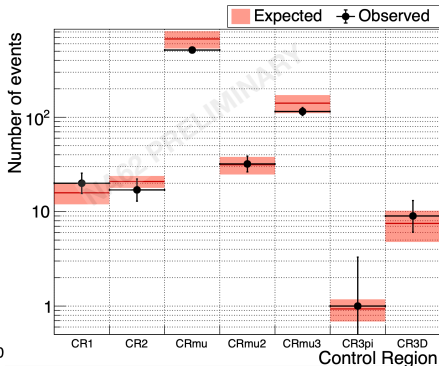
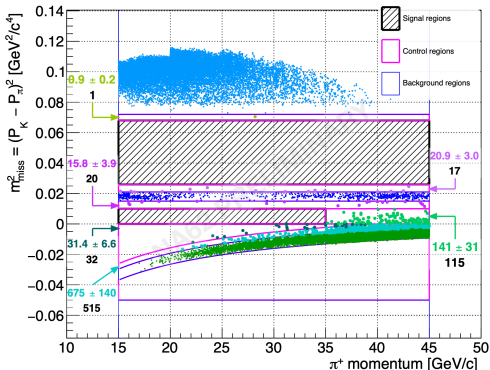
Expected signal doubled by including 2021–22 data

- $N_{\pi\nu\bar{\nu}}^{SM}$  per SPS spill:  $2.5 \times 10^{-5}$  in 2022
  - c.f.  $1.7 \times 10^{-5}$  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

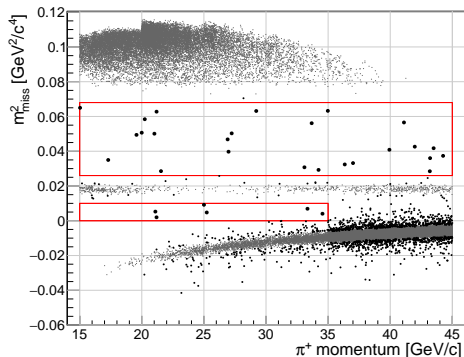
2021 – 22 data



- Good agreement in control regions validates background expectations.



2021–2022 data



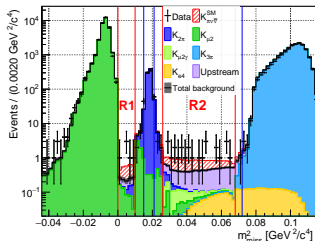
Expected SM Signal

$$N_{\pi\nu\bar{\nu}}^{\text{SM}} = 9.91 \pm 0.34$$

Expected background

$$N_{\text{bg}} = 11.0^{+2.1}_{-1.9}$$

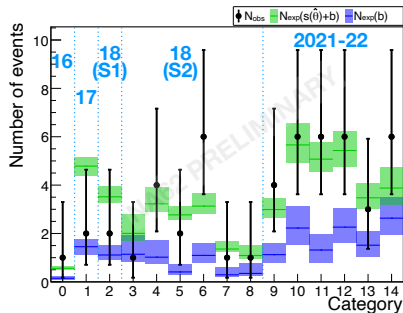
Observed  $N_{\text{obs}} = 31$



$$\mathcal{B}_{21-22}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \left( 16.2^{+4.9}_{-4.3} \Big|_{\text{stat}} \begin{array}{c} +1.4 \\ -1.4 \end{array} \Big|_{\text{syst}} \right) \times 10^{-11} = \left( 16.2^{+5.1}_{-4.5} \right) \times 10^{-11}$$

# Combining NA62 results: 2016 – 2022

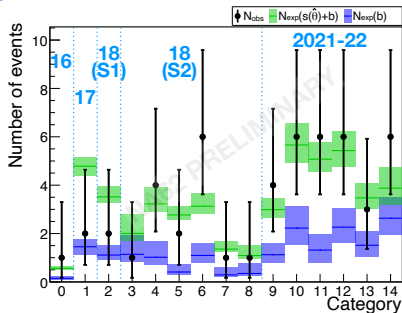
Integrating 2016-22 data:  $N_{bg} = 18_{-2}^{+3}$ ,  $N_{obs} = 51$



# Combining NA62 results: 2016 – 2022

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

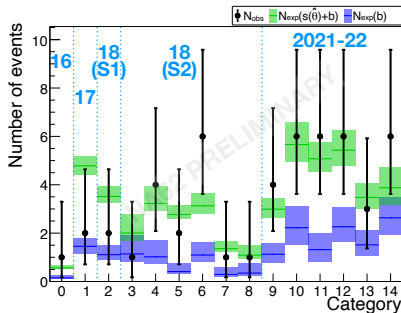
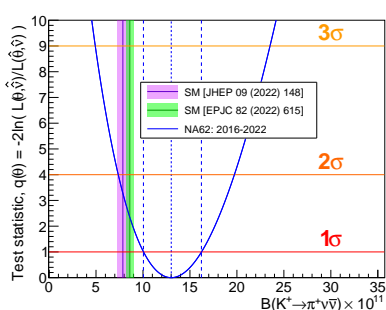
**Background-only hypothesis**  $p\text{-value} = 2 \times 10^{-7} \Rightarrow Z > 5\sigma$



# Combining NA62 results: 2016 – 2022

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

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



$$B_{16-22}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \left( 13.0_{-2.7}^{+3.0} \Big|_{\text{stat}} \quad \begin{matrix} +1.3 \\ -1.3 \end{matrix} \Big|_{\text{sys}} \right) \times 10^{-11} = \left( 13.0_{-3.0}^{+3.3} \right) \times 10^{-11}$$



# Results in Context

## BNL E781/E949

[PRD 79 (2009) 092004]

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

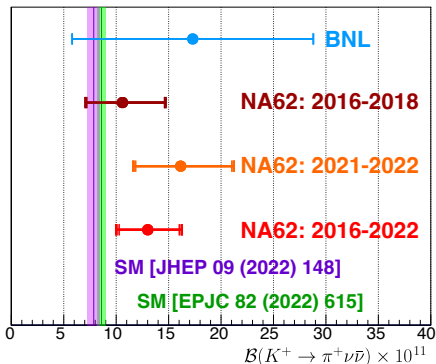
[JHEP 06 (2021) 093]

$$\mathcal{B}_{\pi\nu\bar{\nu}}^{21-22} = (16.2^{+5.1}_{-4.5}) \times 10^{-11}$$

[JHEP 02 (2025) 191]

$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = (13.0^{+3.3}_{-3.0}) \times 10^{-11}$$

[JHEP 02 (2025) 191]



- NA62 results are consistent
- Central value  $1.5 \sigma / 1.7 \sigma$  above SM
- Background-only hypothesis rejected with  $> 5 \sigma$
- Smallest BR measured with  $> 5 \sigma$  significance



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

## The NA62 collaboration

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**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  $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (13.0_{-3.0}^{+3.3}) \times 10^{-11}$  is reported. With 51 signal candidates observed and an expected background of  $18_{-2}^{+3}$  events,  $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$  becomes the smallest branching ratio measured with a signal significance above  $5\sigma$ .

**KEYWORDS:** Branching fraction, Rare Decay, Flavour Physics, Other Experiments

ARXIV EPRINT: [2412.12015](https://arxiv.org/abs/2412.12015)



# 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 %
  - $N_{\text{bg}} = 11.0_{-1.9}^{+2.1}$ ,  $N_{\text{obs}} = 31$
  - $\mathcal{B}_{21-22}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (16.2_{-4.5}^{+5.1}) \times 10^{-11}$
- Combining with 2016-2018 data for full 2016-22 result
  - $N_{\text{bg}} = 18_{-2}^{+3}$ ,  $N_{\text{obs}} = 51$
  - $\mathcal{B}_{16-22}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (13.0_{-3.0}^{+3.3}) \times 10^{-11}$
  - Background-only hypothesis rejected with  $> 5\sigma$
- **First observation of  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  decay**  
 **$\mathcal{B}$  consistent with SM prediction within  $1.7\sigma$**
- Need full NA62 data-set to clarify SM agreement or tension
  - Analysis of 2023 and 2024 to be finished soon
  - Taking more data in 2025 and 2026
  - Planning for a legacy analysis (full data set from 2016-2026)





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# Physics Letters B

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Letter

## First detection of a tagged neutrino in the NA62 experiment

The NA62 Collaboration



### ARTICLE INFO

Editor: M. Doser

### 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.

### 0. Introduction

The next generation of long-baseline neutrino experiments [1,2] will collect datasets more than ten times larger than their predecessors. Controlling systematic uncertainties in neutrino oscillation studies in these experiments becomes crucial [3], and will be vital for the precision measurements required to probe the three neutrino paradigm [4].

ties of the very rare  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  decay [17], NA62 uses a high-intensity  $K^+$  beam which copiously produces neutrinos, most importantly via  $K^+ \rightarrow \mu^+ \nu_\mu$  decays. The experiment employs a state-of-the-art beam spectrometer [18] and a liquid krypton calorimeter which can be used as an instrumented target to detect neutrino interactions. Associating neutrino interactions with the  $K^+$  and the  $\mu^+$  from their parent decays would unambiguously demonstrate the feasibility of the neutrino target-

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

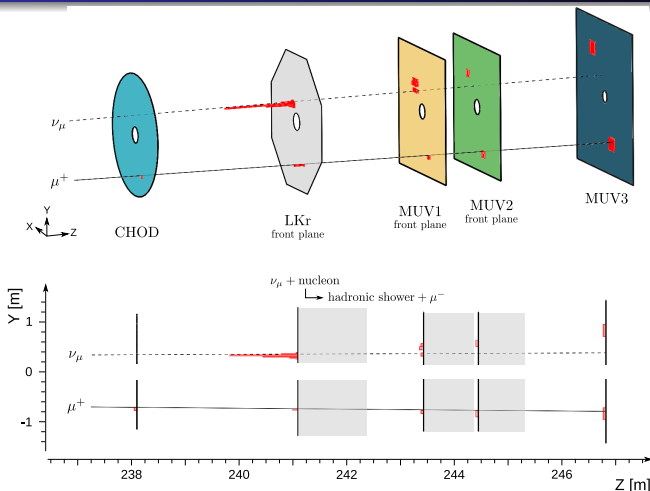


Figure 4: Display of the activity recorded in CHOD, LKr, MUV1, MUV2 and MUV3 for the signal candidate. No extra in-time activity is recorded in these detectors. The red histograms represent the activity in each detector projected at the front plane. For LKr, MUV1 and MUV2 the heights correspond to the fraction of the total energy deposited in each cell. The solid line represents the  $\mu^+$  trajectory extrapolated from the STRAW track; the dashed line represents the neutrino trajectory reconstructed using the  $K^+$  and  $\mu^+$  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/ $c$
$\mu^+$ momentum	25.26 GeV/ $c$
Decay vertex position $z_{\nu\mu}$	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 $E_{\text{LKr}}$	12.54 GeV
MUV1 energy associated with the neutrino $E_{\text{MUV1}}$	13.75 GeV
MUV2 energy associated with the neutrino $E_{\text{MUV2}}$	10.74 GeV
Inelasticity $y$	0.69
Azimuthal angle between the LKr and MUV3 signals $\varphi$	3.28 rad
$d_{\text{LKr}}$	31.4 mm
$d_{\text{MUV3}}$	567.9 mm
$m_{\text{miss}}^2$	-0.00086 GeV <sup>2</sup> / $c^4$

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

# Search for heavy neutral leptons in $\pi^+$ decays to positrons

The NA62 Collaboration \*

## Abstract

A search for heavy neutral lepton ( $N$ ) production in  $\pi^+ \rightarrow e^+ N$  in-flight decays using data collected by the NA62 experiment at CERN in 2017–2024 is reported. Upper limits for the extended neutrino mixing matrix element  $|U_{e4}|^2$  are established at the level of  $10^{-8}$  for heavy neutral leptons with mass in the range 95–126 MeV/ $c^2$  and lifetime exceeding 50 ns.

*To be submitted for publication in Physics Letters B*

## HECHO EN SAN LUIS POTOSÍ

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email: alejandro.briano.olvera@cern.ch, jurgen.engelfried@cern.ch

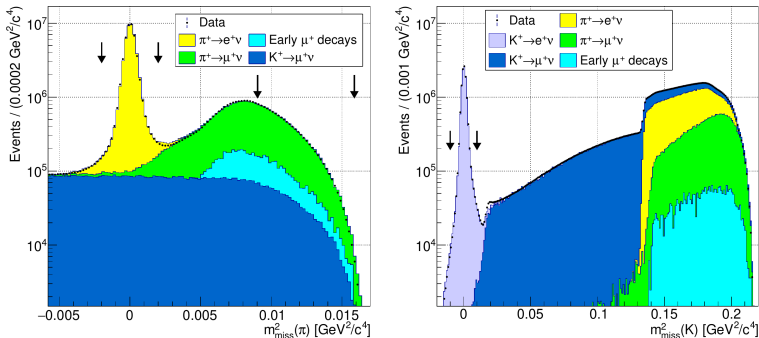


Figure 2: Squared missing mass distributions assuming the beam particle is a  $\pi^+$  (left) and a  $K^+$  (right). Pairs of vertical arrows indicate the squared missing mass ranges used for the selection of  $\pi^+ \rightarrow e^+ \nu_e$  decays and HNL search region (left), and for the selection of  $K^+ \rightarrow e^+ \nu_e$  decays (right). Kaon and pion decays to muons contribute via muon decays in flight.

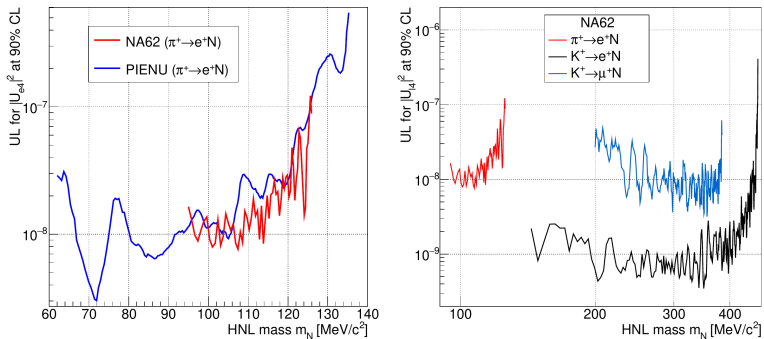


Figure 5: Left: upper limits obtained by NA62 at 90% CL for  $|U_{e4}|^2$  and upper limits established by the PIENU experiment in a wider mass range [10]. Right: summary of upper limits at 90% CL for  $|U_{e4}|^2$  and  $|U_{\mu 4}|^2$  obtained from HNL production searches at NA62 in kaon (2016–2018 data) [8, 9] and pion (2016–2024 data) decays.

# Other recent NA62 publications (1)

“Normal”  $K^+/\pi^0$  decays:

- *Search for  $K^+$  decays into the  $\pi^+ e^+ e^+ e^- e^-$  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.



## *Heavy Neutral Leptons and other BSM searches:*

- *Searches for hidden sectors using  $K^+ \rightarrow \pi^+ X$  decays.*  
Accepted in Journal of High Energy Physics,  
arXiv:2507.17286 [hep-ex].
- *First search for  $K^+ \rightarrow \pi^0 \pi \mu e$  decays.*  
Physics Letters B 859 (2024) 139122.
- *Search for  $\pi^0$  decays to invisible particles.*  
Journal of High Energy Physics 02 (2021) 201.
- *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.



## “Dump” Program:

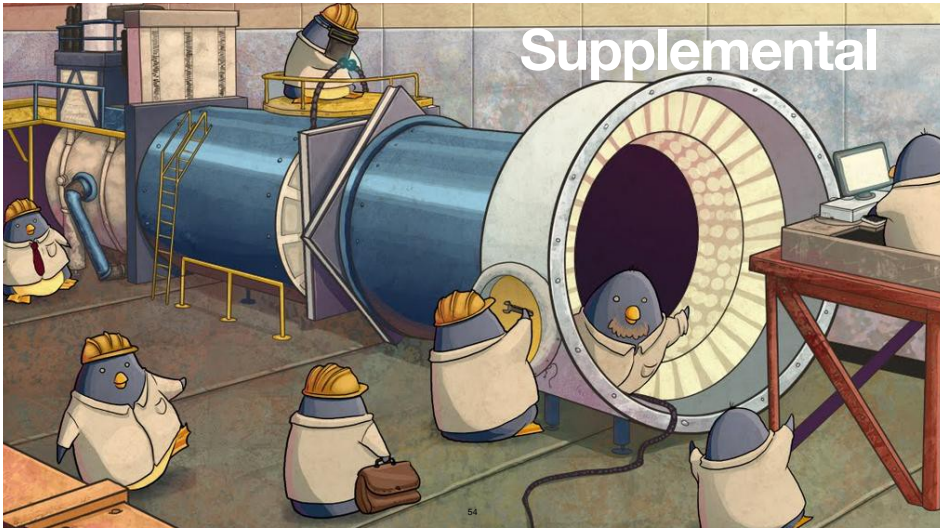
- *Search for hadronic decays of feebly-interacting particles at NA62.*  
European Physical Journal C 85 (2025), 571.
- *Search for leptonic decays of the dark photon at NA62.*  
Physical Review Letters 133, 111802 (2024).
- *Search for dark photon decay to  $\mu^+\mu^-$  at NA62.*  
Journal of High Energy Physics 09 (2023) 035.



- 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

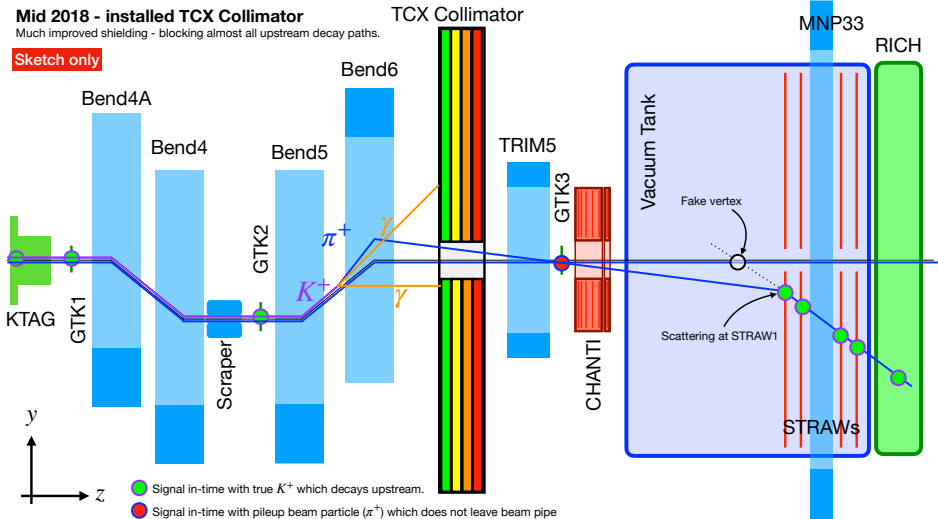


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## Mid 2018 - installed TCX Collimator

Much improved shielding - blocking almost all upstream decay paths.

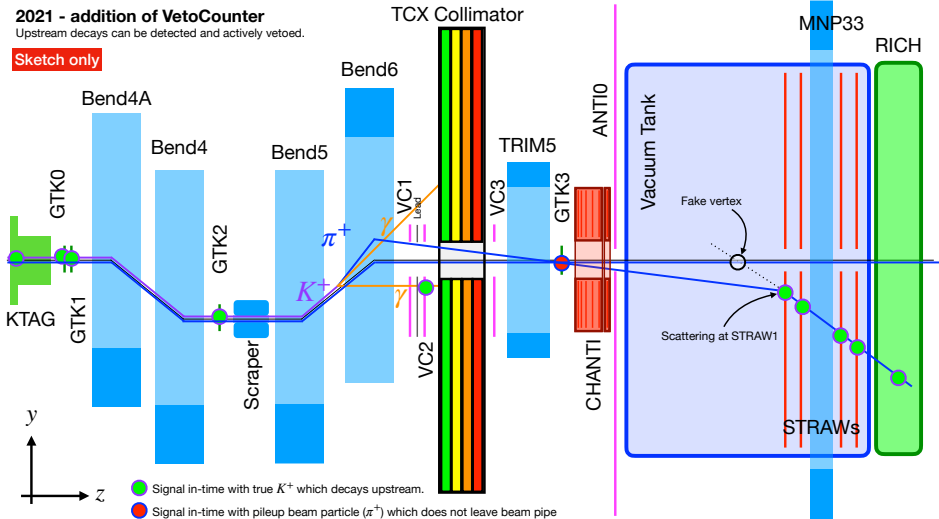
Sketch only

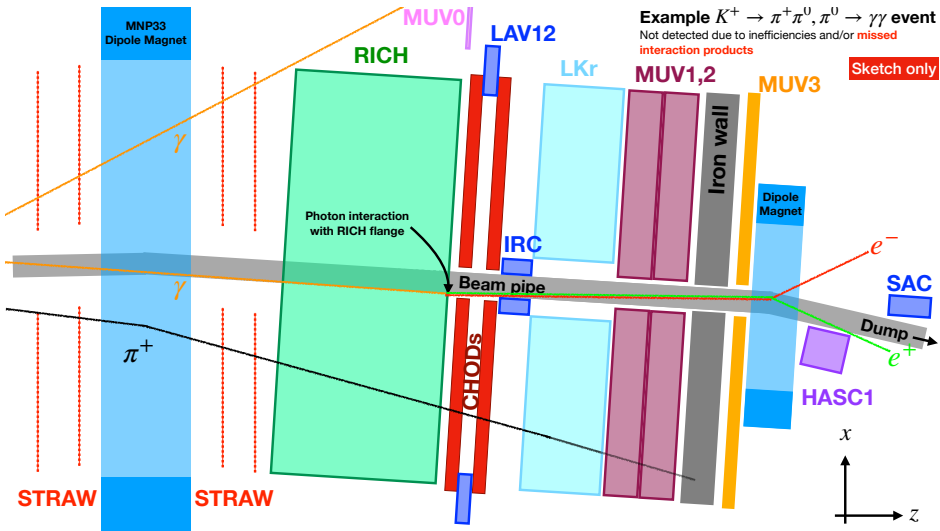


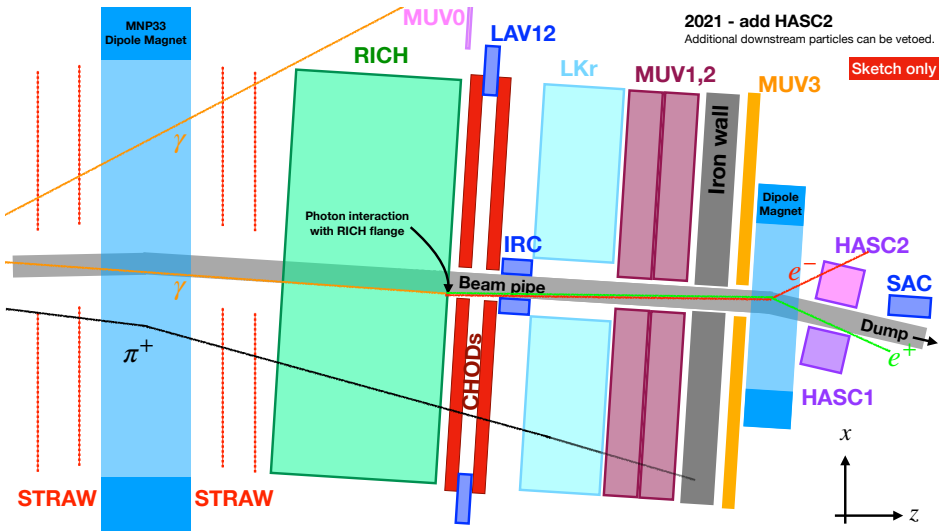
## 2021 - addition of VetoCounter

Upstream decays can be detected and actively vetoed.

Sketch only







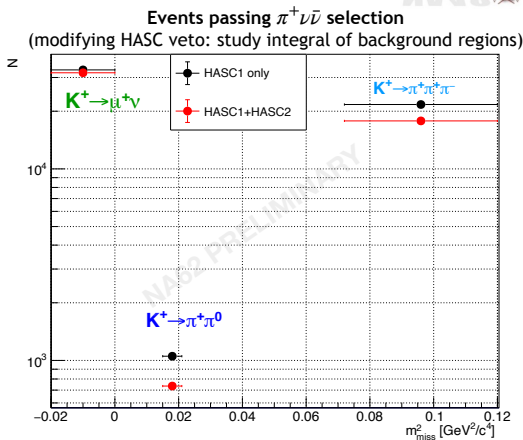
# HASC2 veto

- $K^+ \rightarrow \pi^+\pi^0$  was 2<sup>nd</sup> 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.



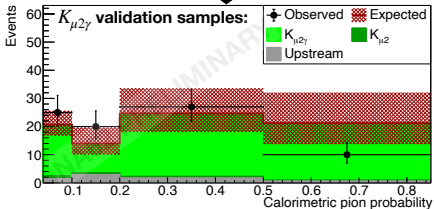
# $K^+ \rightarrow \mu^+ \nu \gamma$ Background

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

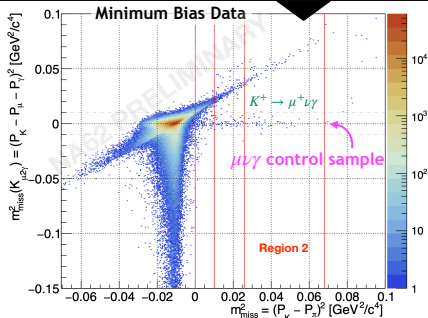
$$m_{miss}^2(K_{\mu 2\gamma}) = (P_K - P_\mu - P_\gamma)^2$$

- $P_K$ : 4-momentum of  $K^+$  from GTK (as normal)
- $P_\mu$ : 4-momentum of track with  $\mu^+$  mass hypothesis.
- $P_\gamma$ : 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  $\pi^+$  bin).



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



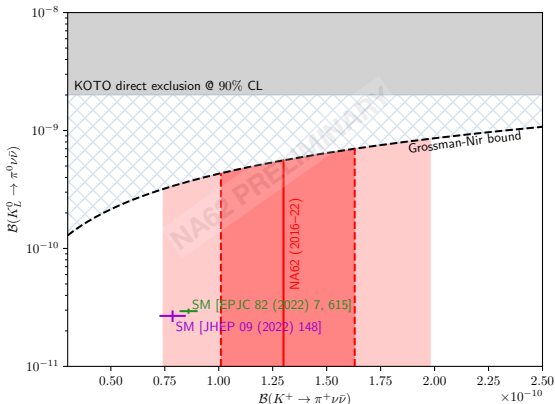
- Before  $K^+ \rightarrow \mu^+ \nu \gamma$  veto: found excess of events at  $p > 35$  GeV/c in Region 2 relative to 2016–18 data.
- Additional background identified and studied in data control samples & MC.
- $K^+ \rightarrow \mu^+ \nu \gamma$  veto added to selection criteria for final analysis.

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# Results in context



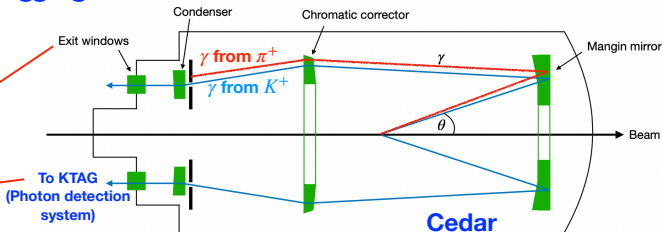
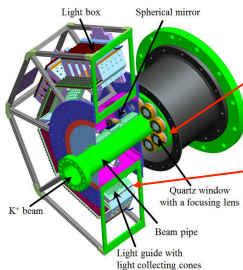
- Fractional uncertainty: 25%
- Bkg-only hypothesis rejected with significance  $Z > 5$
- **Observation of the  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  decay with BR consistent with SM prediction, within  $1.7\sigma$**
- Need full NA62 data-set to clarify SM agreement or tension



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

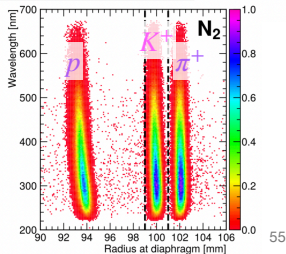
$$2\sigma \text{ range : } [7.4 - 19.7] \times 10^{-11}$$

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



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

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



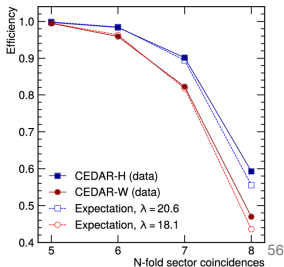
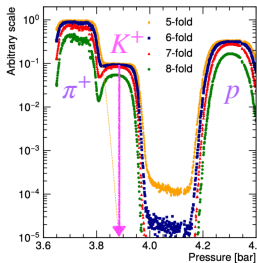
# New Cedar-H : installed in 2023



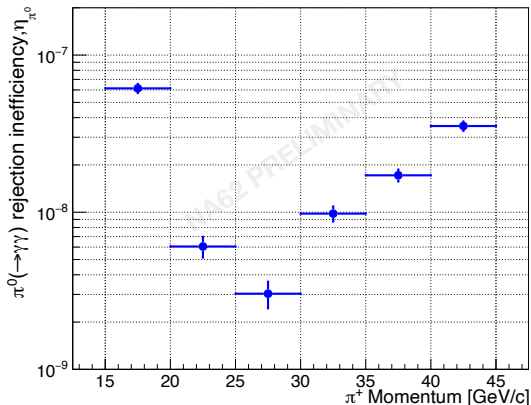
- CEDAR-W filled with  $N_2$  at 1.7 bar was biggest contributor to material in beam line ( $39 \times 10^{-3} X_0$ ).
- New CEDAR-H filled with  $H_2$  at 3.8 bar:
  - Reduces material to  $7.3 \times 10^{-3} X_0$  : reducing multiple scattering.
  - But new optics required to account for different 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.
- $\pi^+$  mistag probability:  $10^{-4}$
- **~65ps time resolution**
- **30% reduction** in elastically scattered beam particles.



# 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

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

Number of selected normalisation events

Normalisation trigger downscaling and efficiency

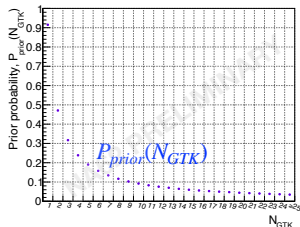
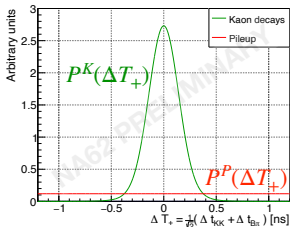
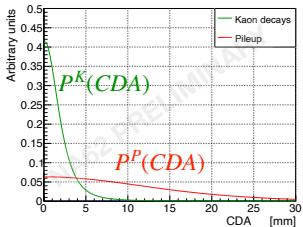
Random veto efficiency

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

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

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

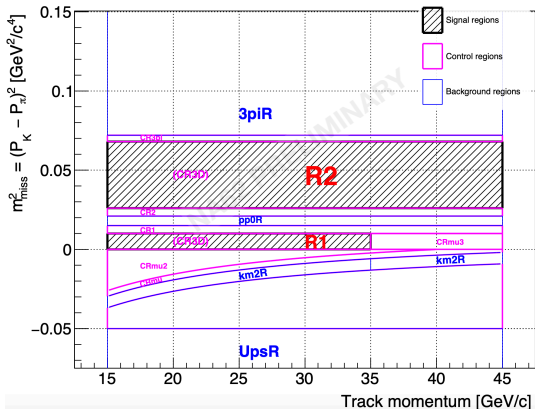
- Inputs: spatial (CDA) & time ( $\Delta T_+$ ) matching, intensity/pileup ( $N_{GTK}$ ) [prior]
  - Models for PDFs/Prior from  $K^+ \rightarrow \pi^+ \pi^+ \pi^-$  data.



Example of selection update

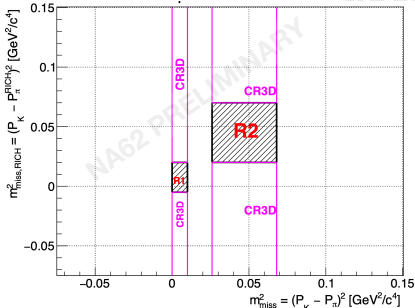
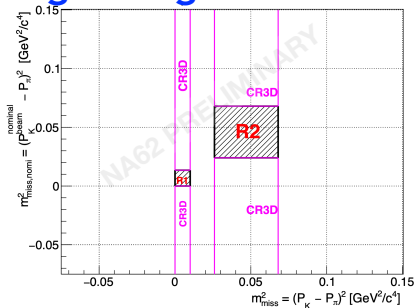
- **Output:** posterior probability of GTK track = true  $K^+$ 
  - Use likelihoods of kaons (K) and pileup (P)
  - Likelihood ratio used to select true match when  $N_{GTK} > 1$
  - Efficiency improved (+10%) and mistagging probability maintained.

# 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

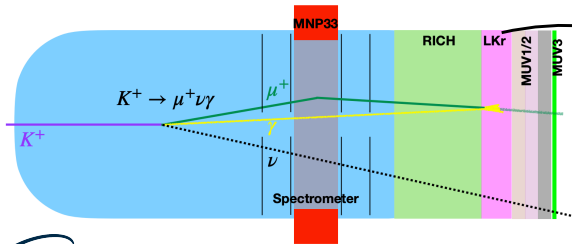
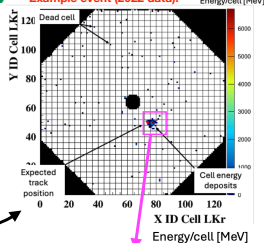
Alternative:  $|p|$  from RICH (use as a velocity spectrometer) =  $m_{miss,RICH}^2$

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

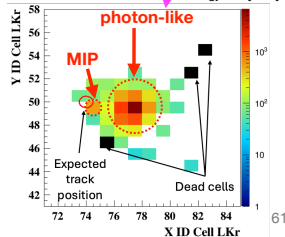


- $K^+ \rightarrow \mu^+ \nu \gamma$  decay with fairly energetic photon ( $E_\gamma > 5 \text{ GeV}$ ) and high momentum  $\mu^+$  ( $p \gtrsim 35 \text{ GeV}/c$ ).
- $\gamma$  and  $\mu^+$  hit LKr together and are misidentified as a  $\pi^+$ .
- No rejection power from photon vetos (LKr  $\gamma$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

Example event (2022 data):

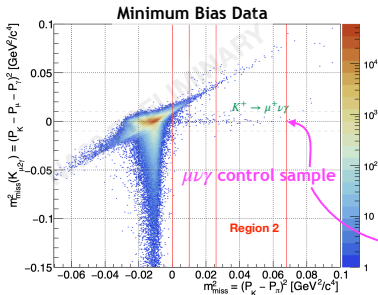


Sketch only



# 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)
- $P_\mu$ : 4-momentum of track with  $\mu^+$  mass hypothesis.
- $P_\gamma$ : reconstructed from energy (subtracting MIP energy deposit) and position of LKr cluster (and position of  $K^+ - \mu^+$  vertex).

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

Downscaling of MB trigger

Ratio of  $\pi^+ \nu \bar{\nu}$  and MB trigger efficiencies

probability of  $\gamma + \mu^+$  being misidentified as a  $\pi^+$

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

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

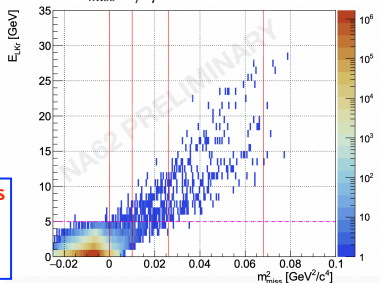


Minimum Bias Data  
Events with MUV3 association and  
 $|m_{miss}^2(K_{\mu 2\gamma})|^2 < 0.01 \text{ GeV}^2/c^4$

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  $\sim 0.0025 \text{ GeV}^2/c^4$
- $E_\gamma > 5 \text{ GeV}$
- $\mu^+$ -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

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

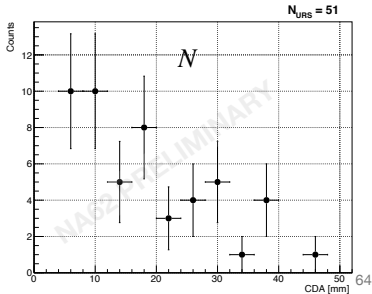
$N$  Upstream Reference Sample:  
 signal selection but invert CDA cut (CDA > 4mm)  
 $f_{cda}$  Scaling factor : bad cda  $\rightarrow$  good cda  
 $P_{match}$  Probability to pass  $K^+ - \pi^+$  matching

Calculate using bins (i) of  $(\Delta T_+, N_{GTK})$   
 [Updated to fully data-driven procedure]

$N = 51$        $f_{CDA} = 0.20 \pm 0.03$        $\langle P_{match} \rangle = 73\%$

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

- 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)

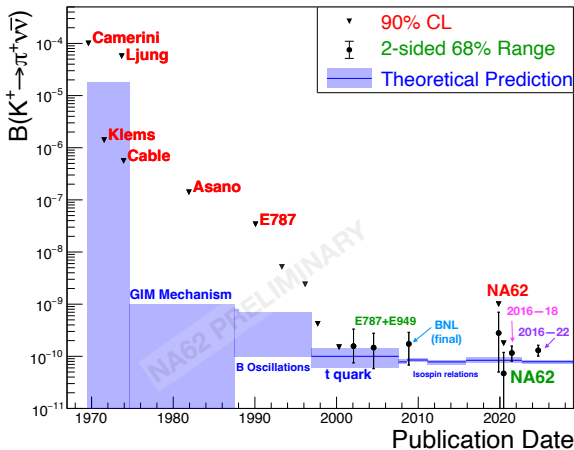
- [PRL 93 (2004) 031801]
- [PRL 101 (2008) 191802]

## 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

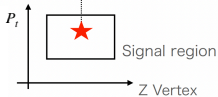
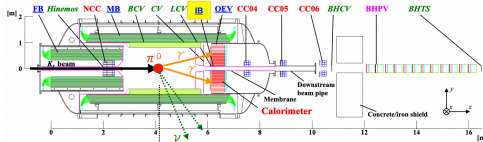
- Located at J-Park 30 GeV main ring.
- KOTO continues data-taking to reach sensitivity  $< 10^{-10}$
- Planned future program (KOTO-2) key part of high priority hadron hall extension plans at J-PARC.

[K.shiomi : Kaons @ CERN 2023]

[T.Nomura : Kaons @ J-PARC 2024]

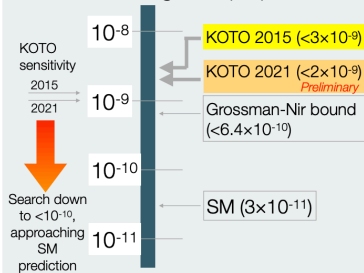


Signature of  $K_L \rightarrow \pi^0 \nu \bar{\nu} = "2\gamma + \text{Nothing} + P_t"$



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

Branching ratio (BR)



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

Latest results:

# Results of the 2021 data analysis

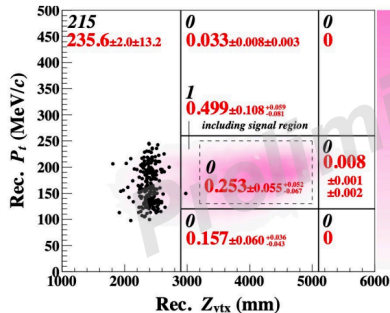


T. Nomura : Kaons @ J-PARC 2024

Final PT vs Z plot

Black: observed  
Red: expected BG  
Contour: signal MC

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



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

$BR(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 2.1 \times 10^{-9}$  (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]
- $(K^+ \rightarrow \pi^+ \pi^0, \pi^0) \rightarrow$  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]
  - $A' \rightarrow$  hadrons [prelim. Spring 2024]