Status and Plans of the NA62 Experiment

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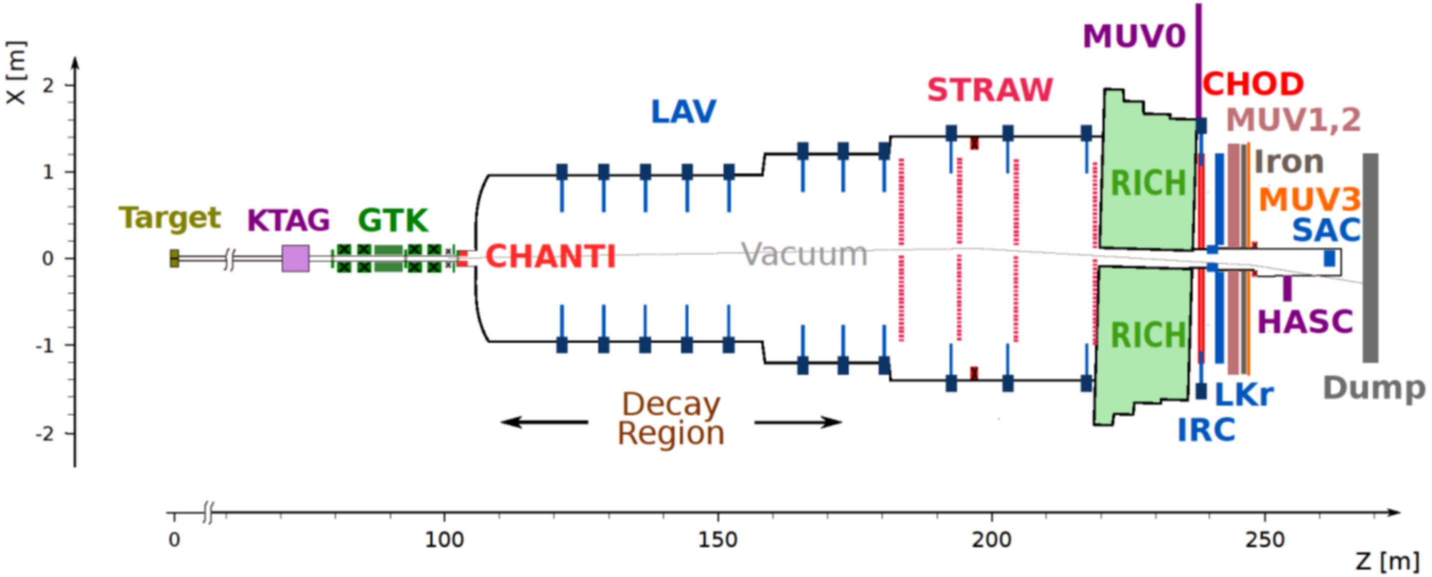
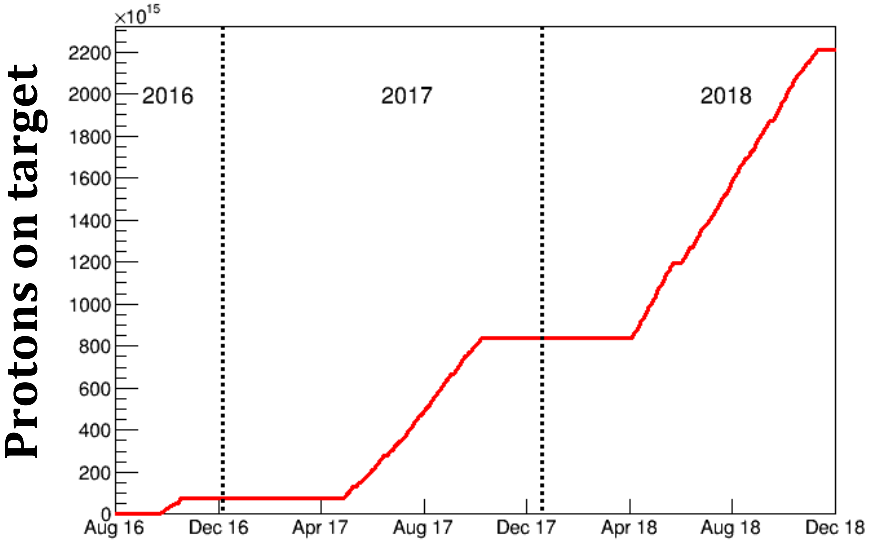
SPSC Open Session

10/05/2023

The NA62 Experiment



RUN1



- Designed to study $K^+ \to \pi^+ \nu \bar{\nu}$
- 10^{-11} Sensitivity to single π^+ events
- K and π tracking; timing; PID; calorimetry
- Broad Kaon physics program: precision measurements & searches
- Dump physics

PoT $\sim 2.2 \times 10^{18}$ recorded

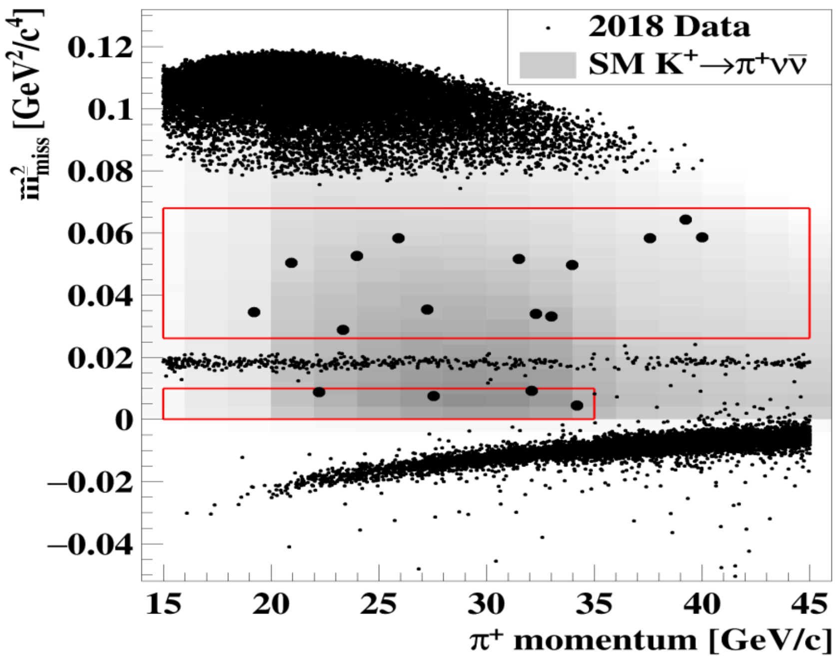
Intensity:

- 2018: 65% nominal
- 2017: 50% nominal
- 2016: 40% nominal

$K^+ \to \pi^+\nu\bar{\nu}$ from RUN1

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

$\mathcal{O}(100\ \mathrm{ps})$	Timing
$\sim 10^3$	Kinematic background suppression
$\sim 10^8$	Muon suppression
$\sim 10^8$	π^0 suppression



$$N^{\mathrm{exp}}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{\mathrm{syst}} \pm 1.19_{\mathrm{ext}},$$

$$N^{\mathrm{exp}}_{\mathrm{background}} = 7.03^{+1.05}_{-0.82}.$$

$$\boldsymbol{N_{obs} = 20}$$

3.4σ evidence $K^+ \to \pi^+\nu\bar{\nu}$

$$\boldsymbol{BR} = \left(\mathbf{10.6}^{+\mathbf{4.0}}_{-\mathbf{3.4}} \pm \mathbf{0.9}\right) \times \mathbf{10^{-11}}$$

JHEP06(2021)093

“Random Veto”

Probability of signal loss when rejecting photons

Loss due to random veto induced by accidental activity

“Upstream” background

K^+ decays upstream

Problem: lack of vetoes along the beam line

Run2: $\geq$ 2021

RUN 2

NA62 recommended by SPSC and approved from research board until LS3 (CERN-DG-RB-2021-505)

Main Goal: measurement of $\mathbf{BR}(\boldsymbol{K^+ \to \pi^+ \nu \bar{\nu}})$ (Addendum I to P326 SPSC-2019-039)

Requirements:

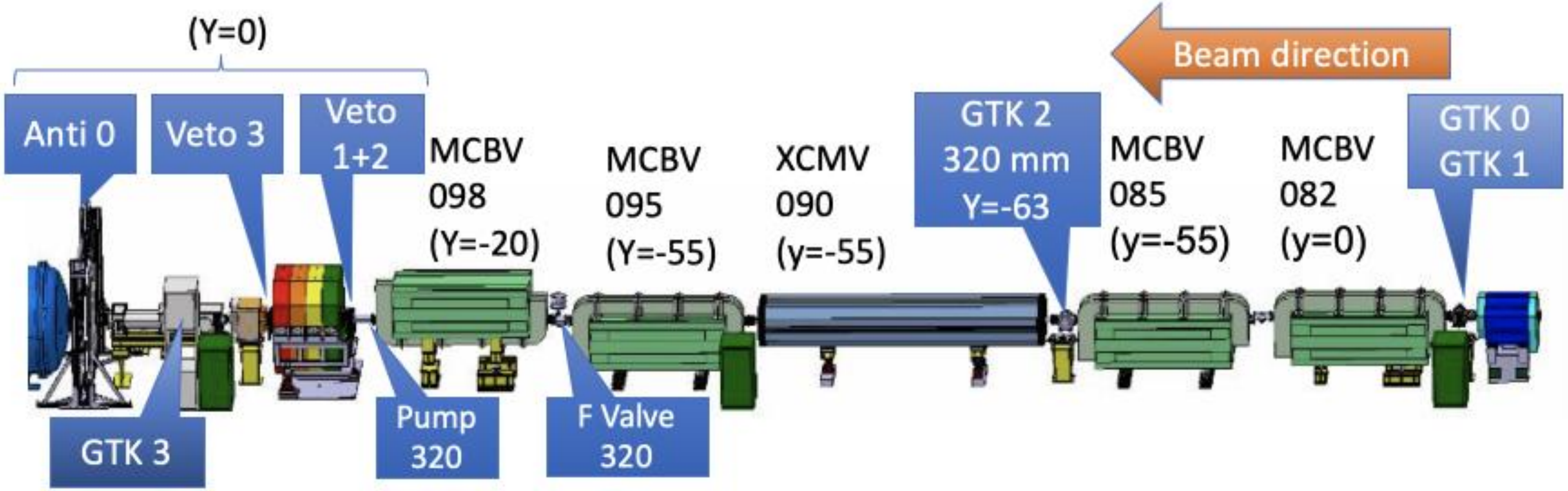
- Run at nominal intensity ($\sim \mathbf{33 \times 10^{11}}$ ppp on T10)
- Control upstream background
- Mitigate effect of random veto
- Optimize the $\boldsymbol{K^+ \to \pi^+ \nu \bar{\nu}}$ analysis to increase signal acceptance

New institutions have joined NA62 in 2022/2023

- Max Planck Institute Munich, Aix Marseille University, Ecole polytechnique federale de Lausanne, Institute of Nuclear Physics (Almaty - Kazakhstan)

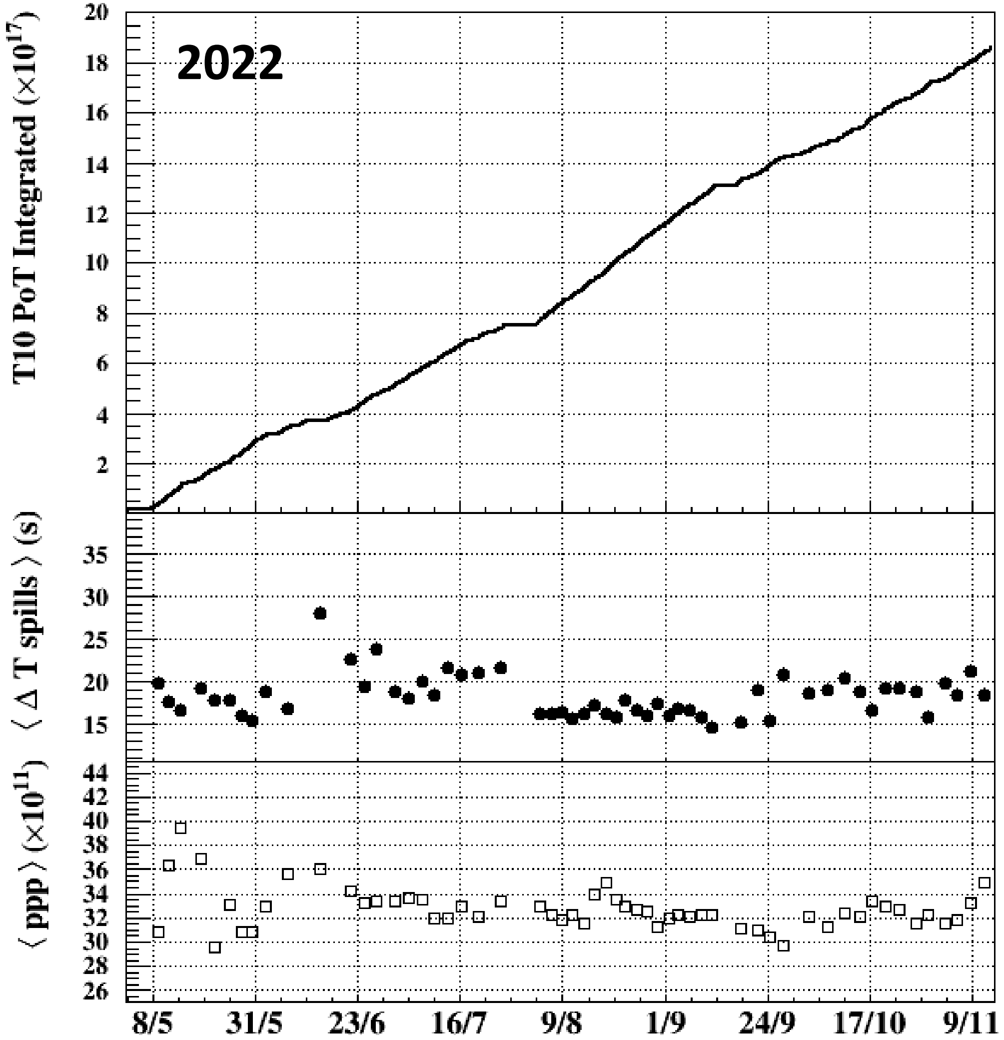
RUN 2 New Hardware

GTK0: 4th station of Gigatracker to improve kaon reconstruction efficiency	**2021**
Veto Counter: veto of K decays occurring upstream	**2021**
Anti0: veto "accidental" muons to improve background rejection in dump mode	**2021**
HASC2 (not in figure): improve photon rejection at small angles	**2021**
CEDAR - H (not in figure): reduce material along the beam line	**2023** New



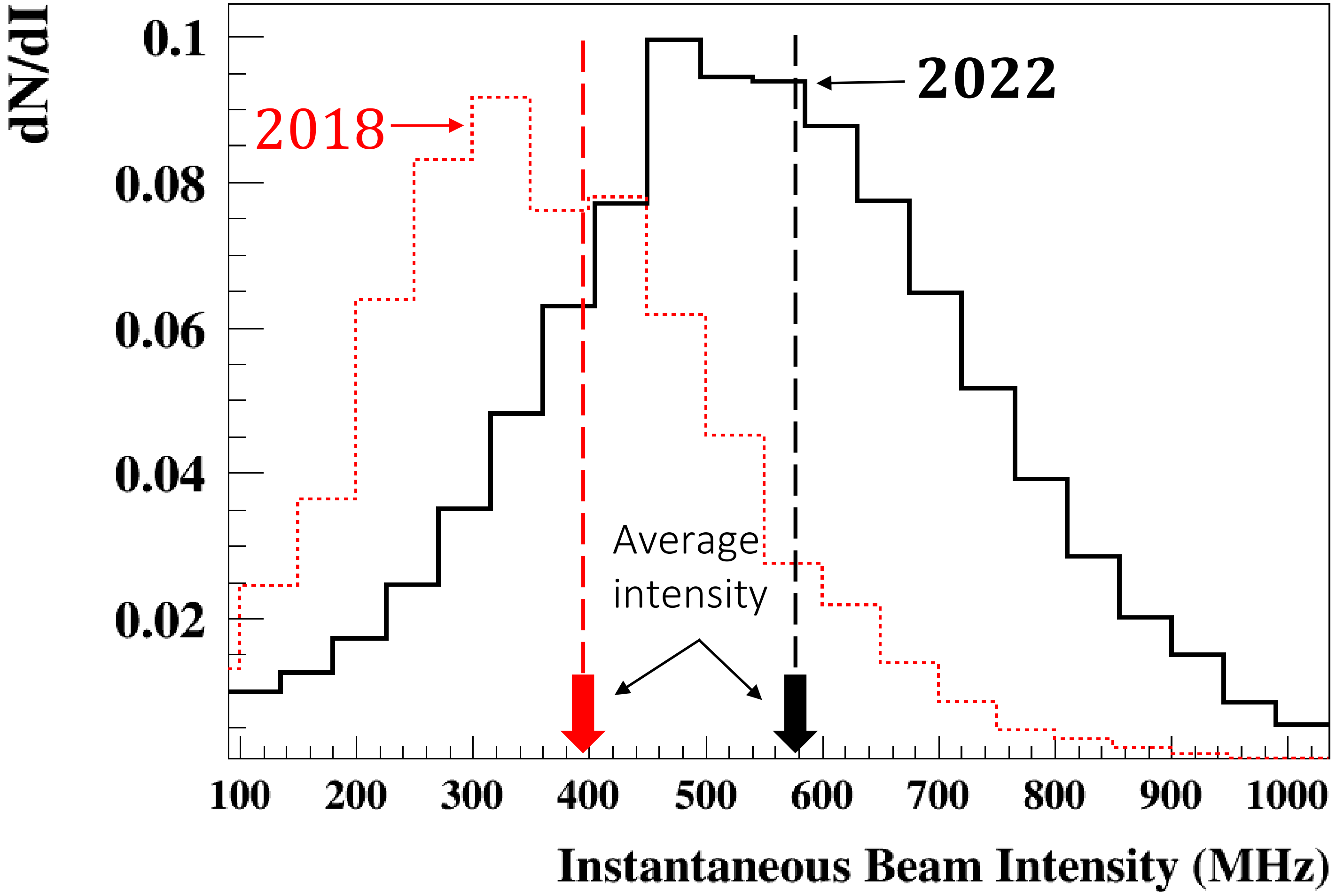
2022 Run

2022 Delivered "Luminosity"



- $\Rightarrow$ **Integrated PoT $\sim 1.8 \times 10^{18}$ on T10**
- $\Rightarrow$ $\langle \Delta t \text{ spills} \rangle \approx 18.2\ s$ **(~ 0.25 duty − cycle)**
- $\Rightarrow$ $\langle \text{ppp} \rangle \approx 32.5 \times 10^{11}$

2022 Observed Intensity (Rate at GTK)



Absolute average rate at GTK in 2022
580 MHz

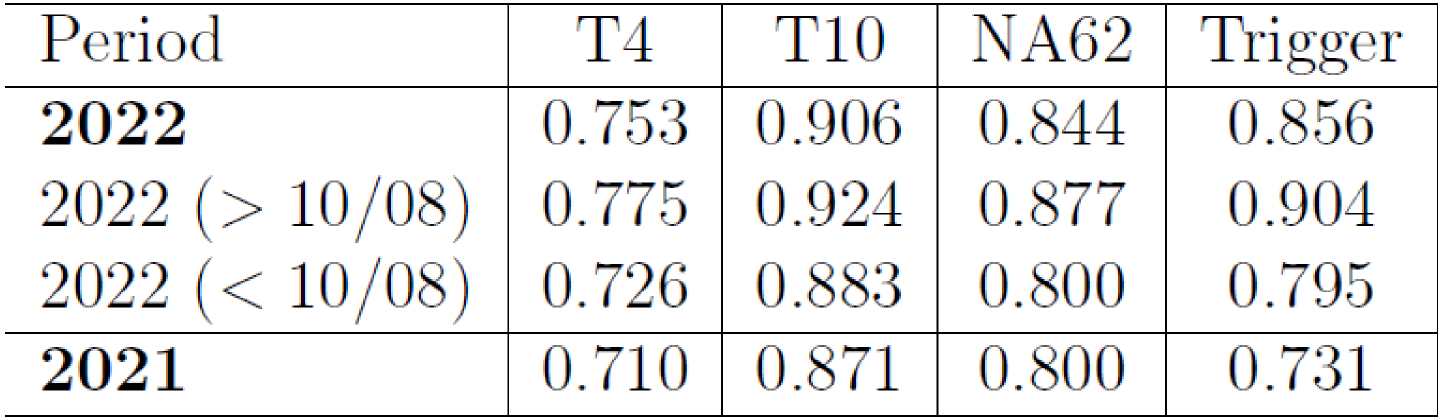
Intensity increase vs 2018: × 1.45

N.B.

Effective spill length ~4*s* (2022, 2018)

Rate at GTK corresponds to **750 MHz** at 3*s* effective spill (P326 proposal)

2022 NA62 Data Taking Efficiency



Period	T4	T10	NA62	Trigger
2022	0.753	0.906	0.844	0.856
2022 ($>$ 10/08)	0.775	0.924	0.877	0.904
2022 ($<$ 10/08)	0.726	0.883	0.800	0.795
2021	0.710	0.871	0.800	0.731

Beam	DAQ	Total
0.682	0.722	0.493
0.716	0.793	0.568
0.641	0.636	0.408
0.618	0.585	0.362

T4: (# spills with beam on T4) / (# expected spills)

T10: (# spills with beam on T4 and T10) / (# spills with beam on T4)

NA62: (# spills written on disk) / (# spills with beam on T4 and T10)

Trigger: (# events written on disk) / (< # events > that should have been written given the intensity)

DAQ: NA62 x Trigger

Total: T4 x T10 x NA62 x Trigger

2022 NA62 Data Taking Efficiency

Period	T4	T10	NA62	Trigger
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⇨

Beam	DAQ	Total
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0.716	0.793	0.568
0.641	0.636	0.408
0.618	0.585	0.362

Significant improvements vs 2021 and during 2022

- Spill quality fixed in 2022
- GTK readout instabilities fixed 10/08 (optical splitter)

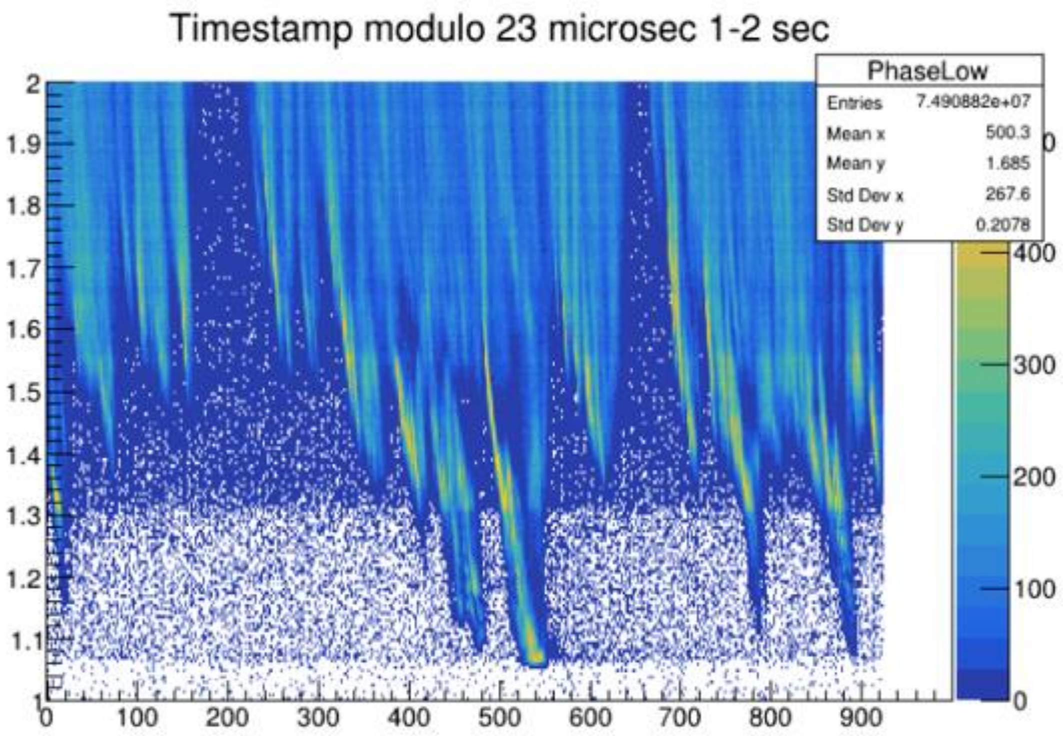
DAQ efficiency in 2018 ∼0.8

⇒ From 10/08 onwards NA62 data taking in line with 2018

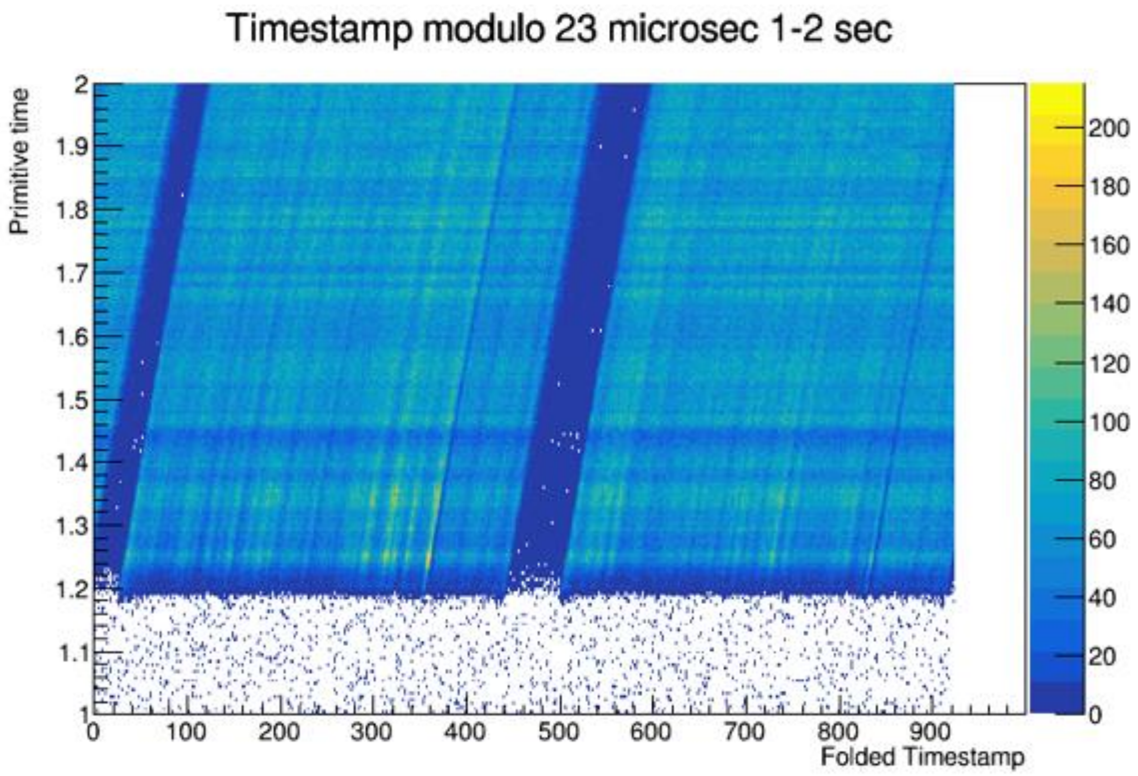
2022 Spill Quality

Intensity “bump” in 1st second (× 8 intensity) in 2021 fixed in 2022 - ***We thank the BE-OP, SY-RF groups***

2021



2022



Preparation of the 2023 Run

CEDAR - H

Reduction of material budget in the beamline: $\mathbf{N_2}$ $\mathbf{3.9\%}$ $\mathbf{X_0}$ vs $\mathbf{H_2}$ $\mathbf{0.7\%}$ $\mathbf{X_0}$

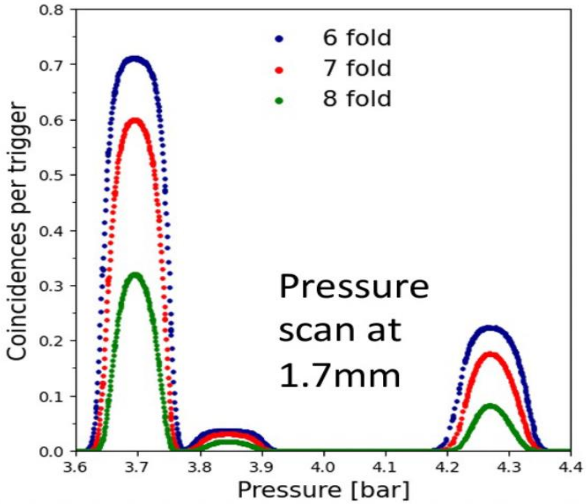
Expected 15% reduction rate at L0, Lower occupancy of detectors (to be quantified)

New optics

Tested in H6 (fall 2022)

Exhaust

Isolation of motor controls within ATEX zone

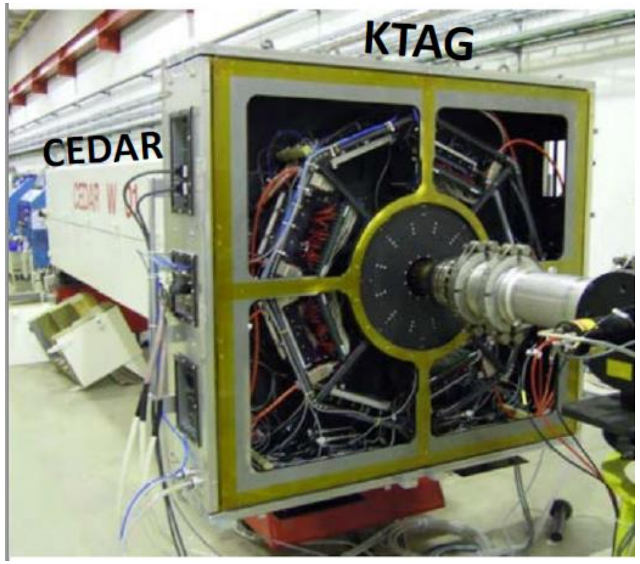


Pressure scan at 1.7mm

Photon yield	$\langle N_\gamma \rangle \approx \mathbf{18-19}$
$K-\pi$ separation	$\boldsymbol{\pi^+ ID} < \mathbf{10^{-4}}$
Time resolution	$\boldsymbol{\sigma_t^{KTAG}} \approx \mathbf{65\ ps}$

CEDAR - H

KTAG dismantled from CEDAR-W

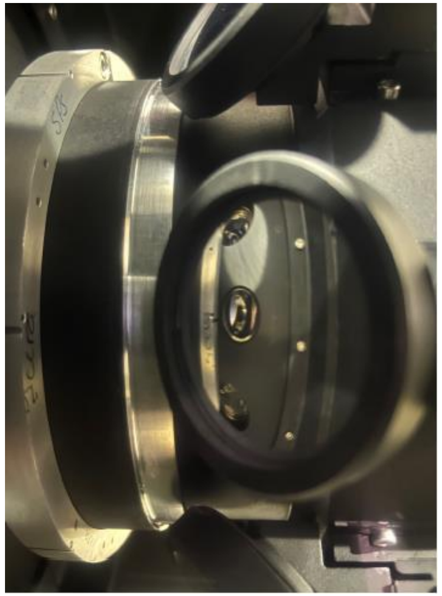


CEDAR-W removed from K12

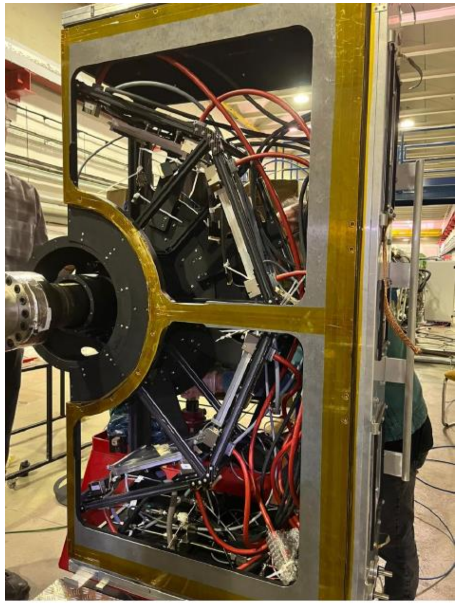
CEDAR-H installed in K12

CEDAR - H

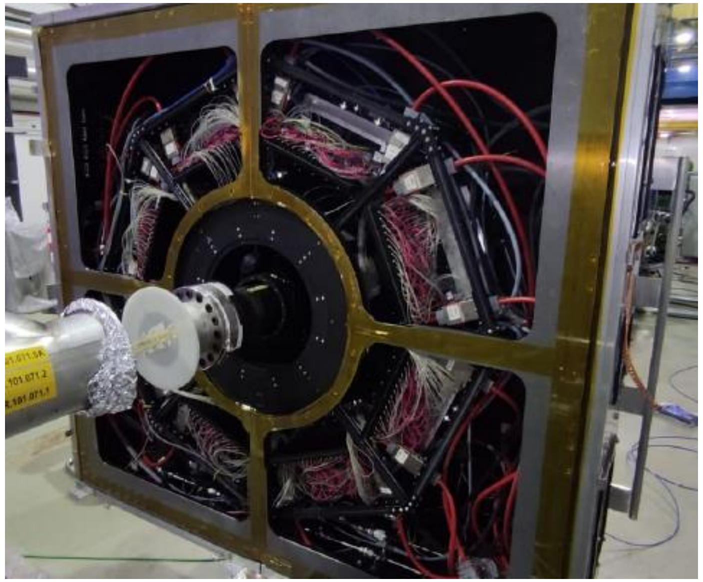
New spherical mirrors



KTAG frame reassembled



Light box installed



Cabled

Installation completed beginning of March – readout tested

Commissioning of detector for work with Hydrogen – March / April

We thank all the groups and people at CERN involved in this project

L0TP+

New L0 trigger processor board to replace the board in operation since 2015

Goal:

- Increase output bandwith
- More flexibility for different trigger algorithms

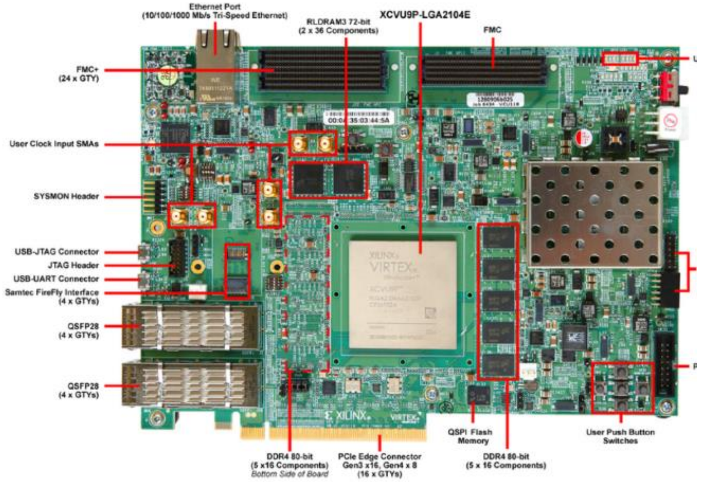
Requirements:

- Last generation FPGA; Larger on-chip memory
- PCI Express interface; FMC expansion slots
- Last generation high speed channel interfaces

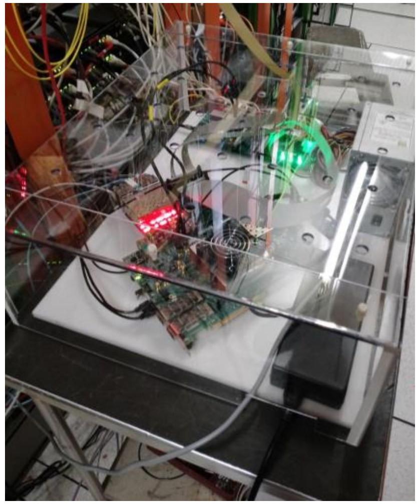
Technical solution: commodity device (Xilinx VCU118)

Project timeline:

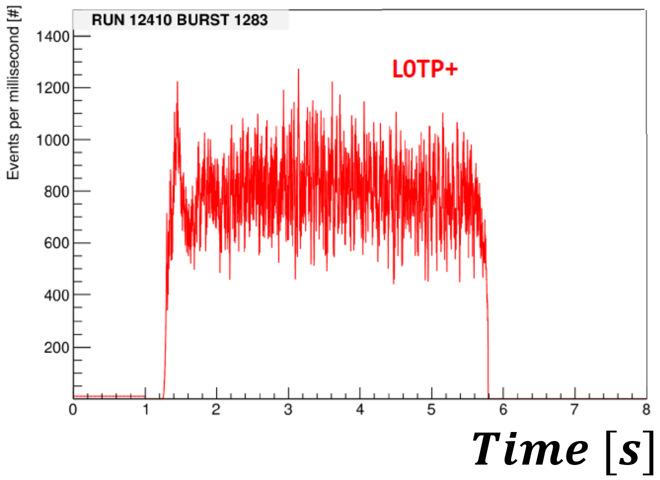
2019 – 20 design and build of the board
2021 – 22 test in parallel to L0TP, NA62 integration
2023 commissioned and fully operational



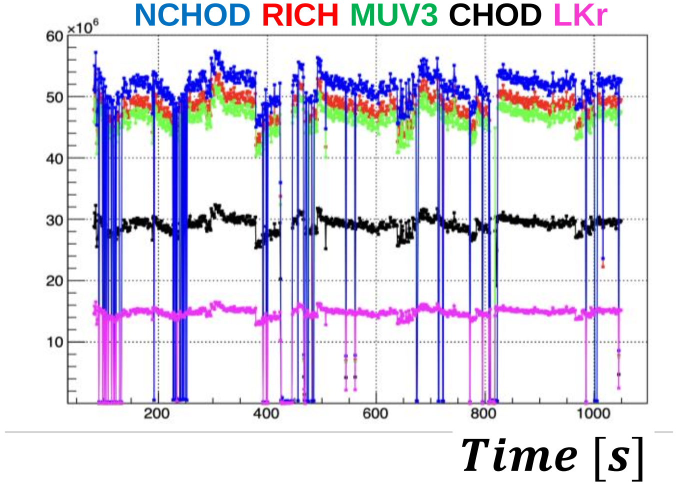
Board installed at NA62



Burst profile



Number of primitives received by L0 from detectors



Beam Preparation and Tuning

Re-alignment of the P42 beam line

Removal of not used beam line elements

Removal of a badly mis-aligned vacuum chamber after T4

Installation of addition beam instrumentation

Beam tuning completed before official start of data taking

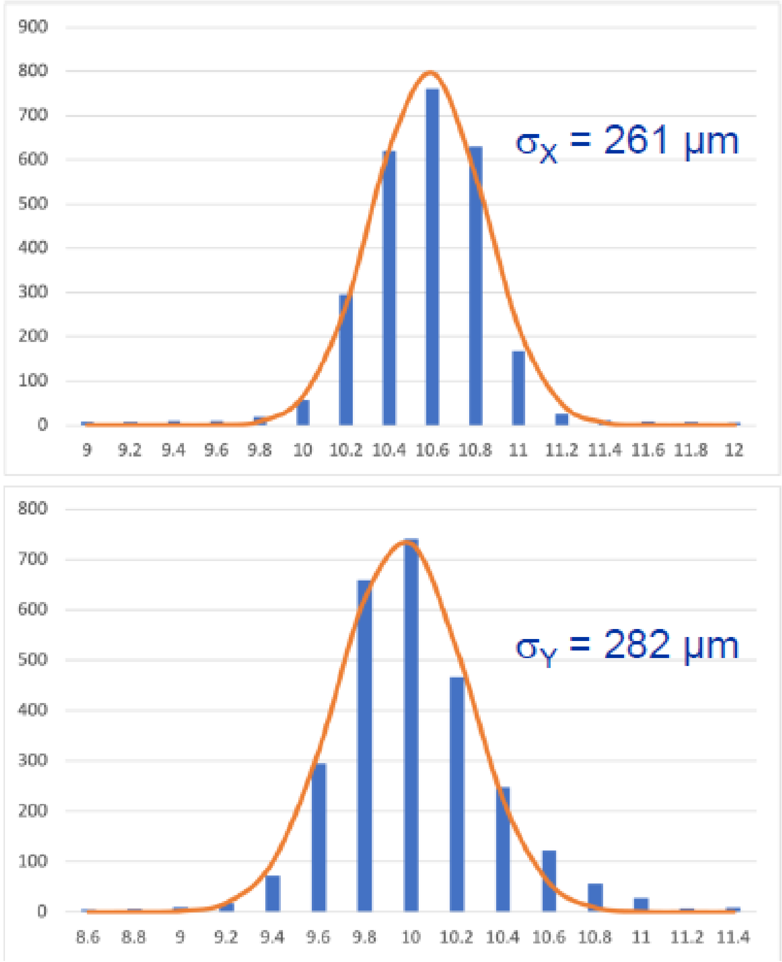
Standard magnification (0.5 - 1) (lower in 2021-2022)

Beam spot at T10 as expected (larger in 2021-2022)

20% reduction of protons on T4 for the same intensity in K12

We thank the BE-EA group and all the people involved

Beam profile at T10 - 2023



Plans for RUN 2023

25-30% shorter than 2022 due to energy saving measures

- 150 days nominal (modulus duty – cycle)

Kaon Physics

- $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ at nominal intensity
- Rare trigger and tagged neutrino trigger lines in parallel
- Possibility to optimize downscaling of non - $\pi\nu\nu$ triggers (Hydrogen + L0TP+)
- Short runs at lower intensity (65%, 80%) for $\pi\nu\nu$ if needed (to be planned)

Dump

- 1 week (+ contingency)
- $\times$ 1.5 nominal intensity
- 2021-configuration: tax closed, target removed, muon sweepers on

Computing, Software

Main upgrades

Improved online software for faster online monitoring (run 2022)

New farm PCs (run 2023)

Increase of EOS space: 1 Pbyte / year

- *We thank IT Department for the support*

Multi – threads reconstruction

- Further speeding up of the online monitor expected (run 2023)

Simulation

- Fast switching from RUN1 and RUN2 (21,22, >22) configurations
- Tuning of the intensity templates / year to simulate accidentals with overlay technique
- Biasing methods to simulate rare events sources of background
- Migration to the recent GEANT4 v.11 release

2022 Data Quality

Overview

$\mathbf{85\%}$ of data processed online in 2022 for monitoring and «express» analysis

$\mathbf{100\%}$ of 2022 data reprocessed by March 2023

Burst collected: $\sim\mathbf{403 \times 10^3}$

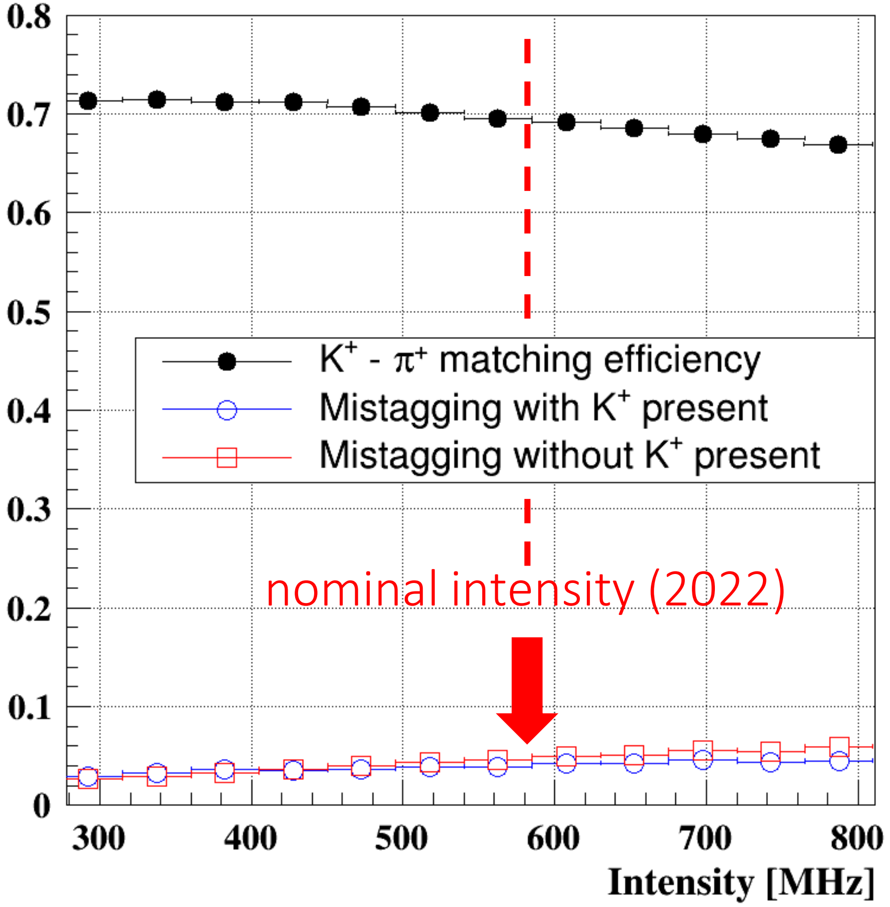
«Bad» bursts for $K^+ \to \pi^+\nu\bar{\nu}$ analysis : $\sim\mathbf{80 \times 10^3}$

- Mostly from first period due to SAV problems
- Without first period $\mathbf{10\%}$ rate of bad burst, consistent with 2017 and 2018 runs

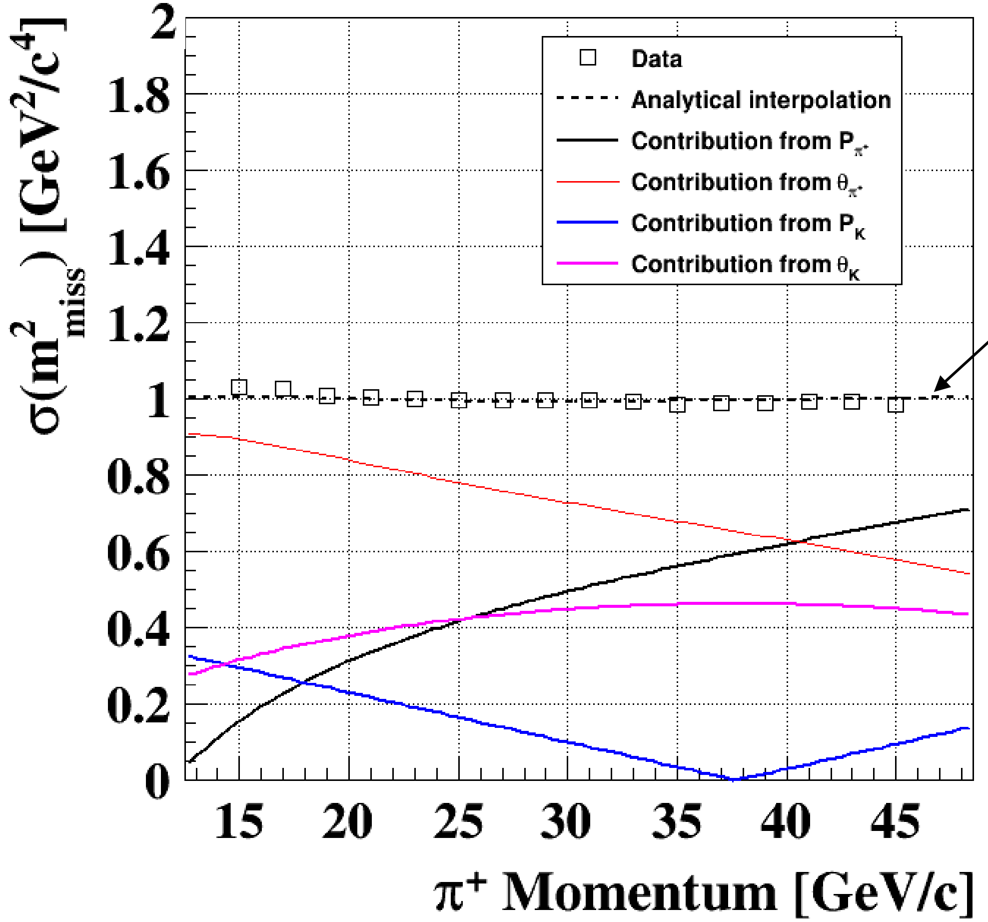
Quality of data consistent with 2018

Kinematic Reconstruction

$K - \pi$ matching



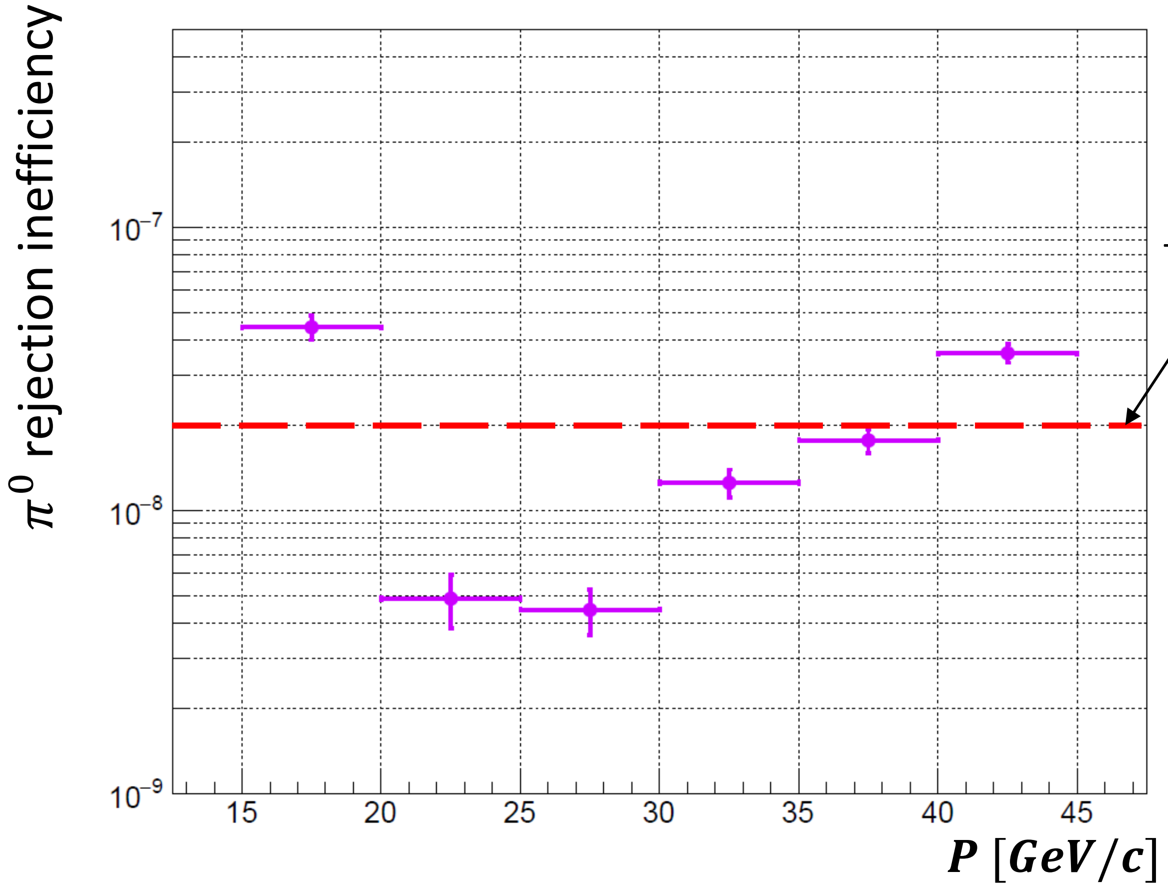
$\times 10^{-3}$ Resolution $m^2_{miss}(K^+ \to \pi^+\pi^0)$



Expected from design

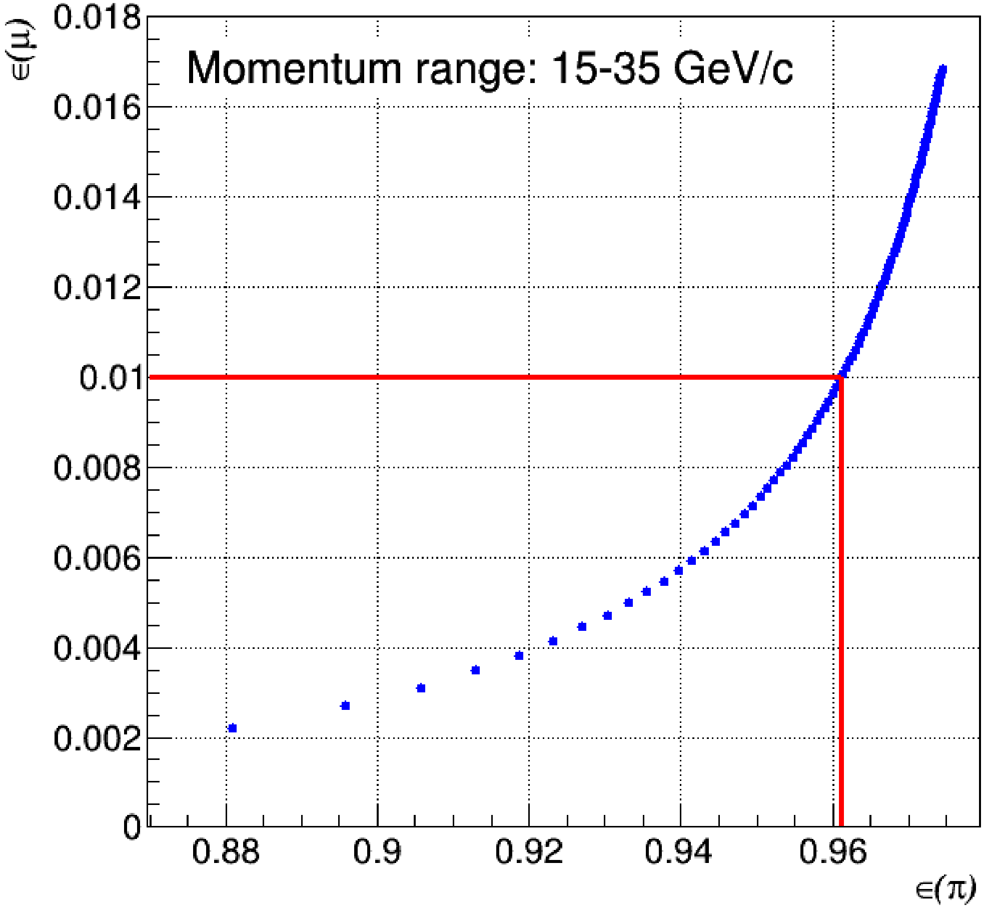
Photon Rejection and PID

Photon rejection



Expected from design

$\pi - \mu$ separation (RICH)



Status of the $K^+ \to \pi^+\nu\bar{\nu}$ analysis

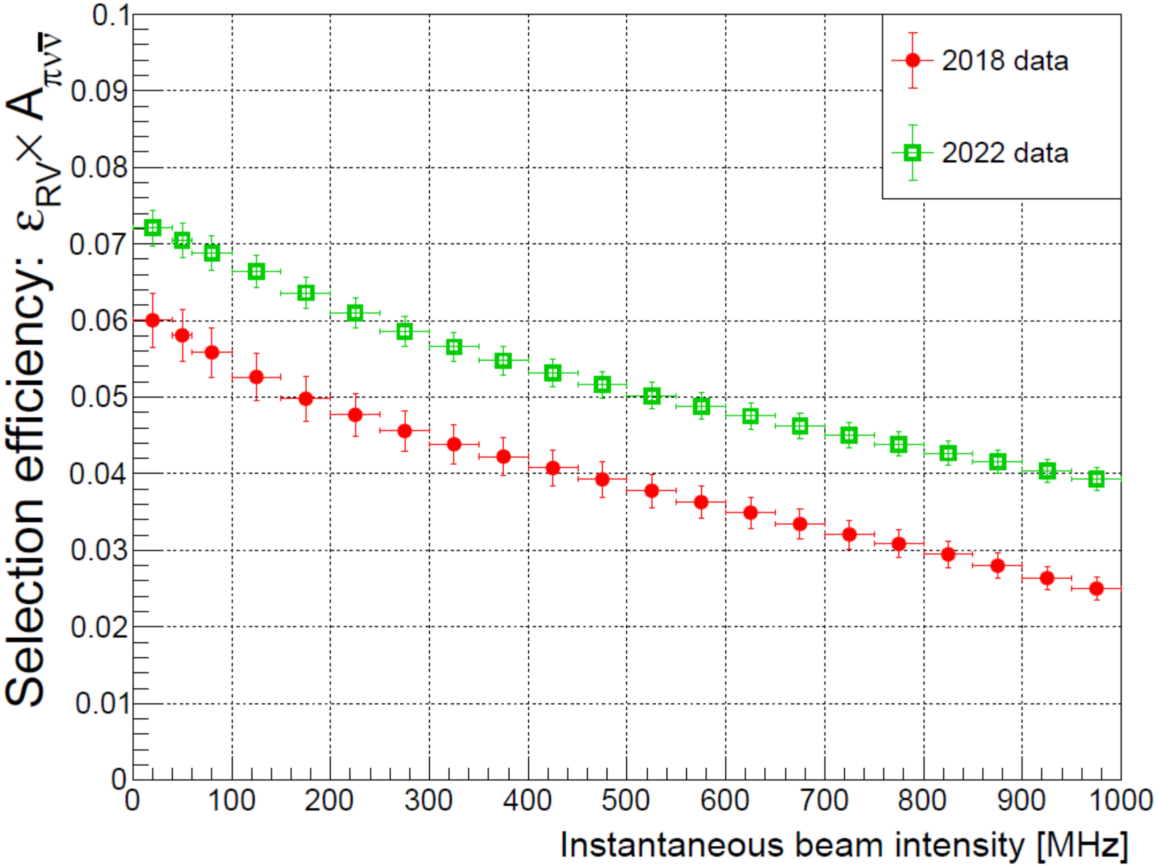
Signal Efficiency

Selection optimization → **increase of signal selection acceptance vs 2018 (× 1.2)**

Improved random veto ε_{RV} → **compensation of the effect from increased intensity vs 2018**

Decrease of reconstruction efficiency vs 2018 due to intensity increase (× 0.95)

Decrease of absolute trigger efficiency vs 2018 due to increased intensity (× 0.9)



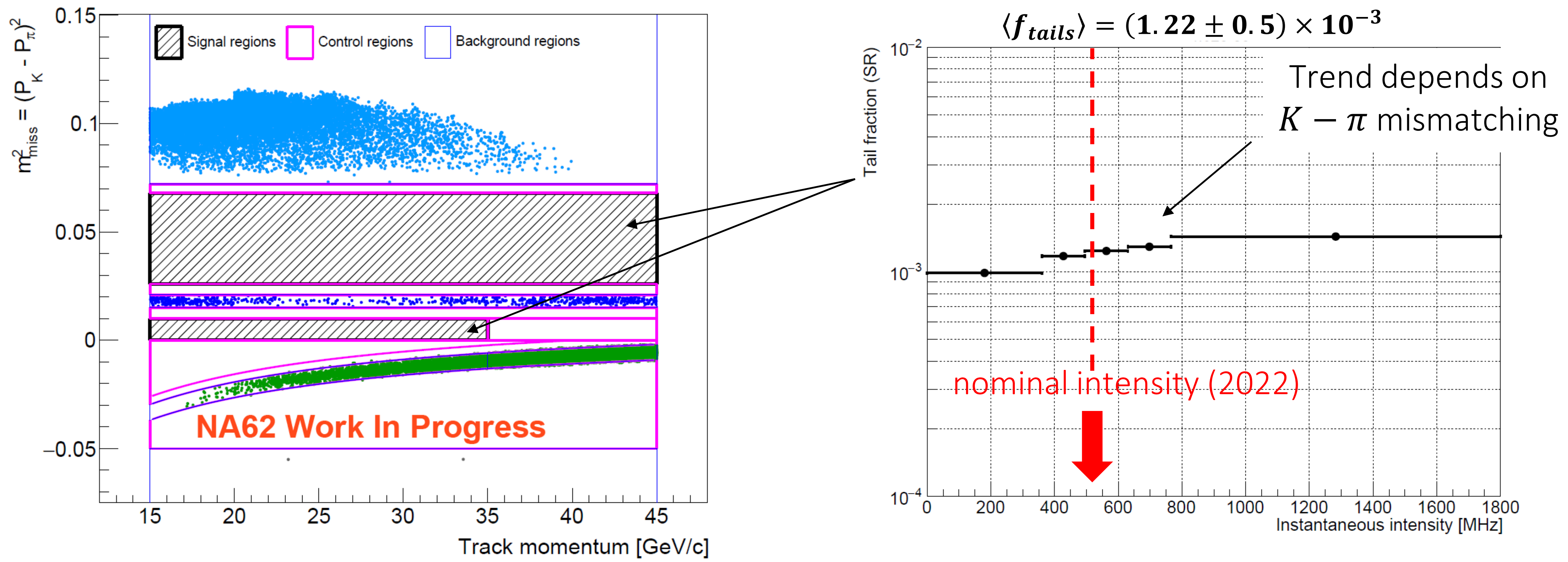
Background from Kaon Decays

e.g. $K^+ \to \pi^+\pi^0$ data driven method

Normalization: background region

Extrapolation to signal region:

Non-Gaussian tails of the m^2_{miss} resolution



$\langle f_{tails} \rangle = (1.22 \pm 0.5) \times 10^{-3}$

Trend depends on $K - \pi$ mismatching

nominal intensity (2022)

Overall Status (2022)

	Expected # events in signal region	
PROCESS	**2022**	**2018**
$K^+ \to \pi^+\pi^0$	0.82 ± 0.03	0.75 ± 0.05
$K^+ \to \mu^+\nu$	0.74 ± 0.06	0.64 ± 0.08
$K^+ \to \pi^+\pi^+\pi^-$	0.09 ± 0.02	0.22 ± 0.08
$K^+ \to \pi^+\pi^-e^+\nu$	0.31 ± 0.16	0.51 ± 0.10
Upstream	WIP	$3.30^{+0.98}_{-0.73}$
$K^+ \to \pi^+\nu\bar{\nu}$	8.0 ± 1.1	7.58 ± 0.85

$\}\to$ Data - driven

$\to$ Data + MC

$\to$ MC

Normalization: $K^+ \to \pi^+\pi^0$ from specific trigger (muon rejection in common with signal, no photon veto)

Trigger efficiency ~ 0.9 (relative between normalization and signal, main effect from photon veto)

Uncertainty # $\pi\nu\nu$: systematics from normalization/trigger + parametric uncertainty from SM branching ratio

Signal / Kaon background = 4.0 ± 0.5 (3.6 ± 0.4 in 2018)

Selected Signal yield - Summary

	Year	Weeks	# bursts collected (10^3)	# good bursts (10^3)	Beam intensity (vs nominal)	Expected PNN/good burst
	2022	29	403	320	100%	$\boldsymbol{O(2.5 \times 10^{-5})}$
	2021	18	145	120	100%	work in progress
RUN1 (published)	2018	31	520	450	65%	1.7×10^{-5}
	2017	24	300	265	50%	0.8×10^{-5}
	2016	8	84	67	40%	0.4×10^{-5}

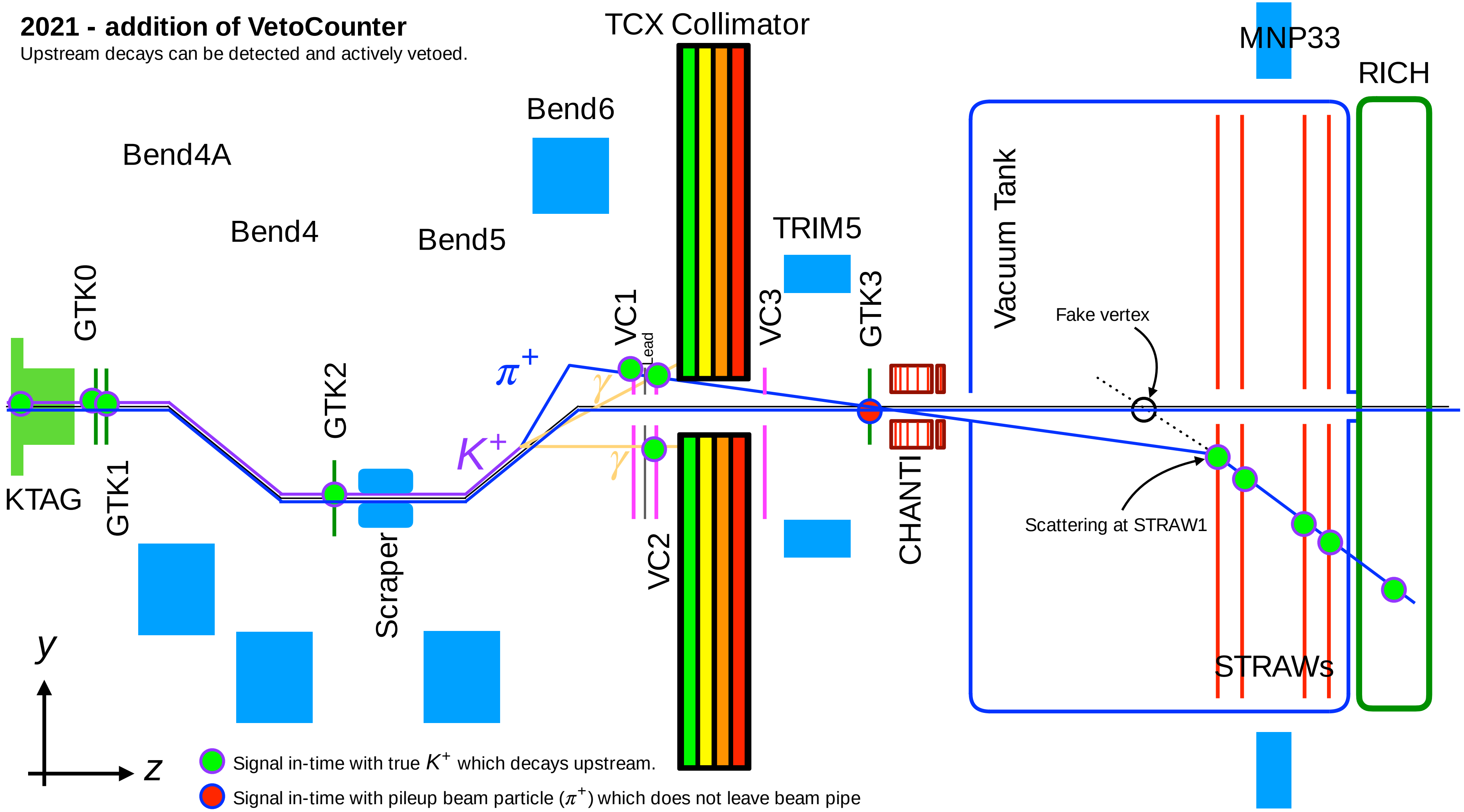
$\sim$47% increase of $\pi\nu\nu$ / burst vs 2018: ➡

$$\underbrace{1.45}_{\text{Intensity}} \times \underbrace{1.2}_{\text{Selection}} \times \underbrace{0.95}_{\text{Reconstruction}} \times \underbrace{0.9}_{\text{Trigger}} = 1.49$$

Upstream Background

2021 - addition of VetoCounter

Upstream decays can be detected and actively vetoed.



🟢 Signal in-time with true K^+ which decays upstream.

🔴 Signal in-time with pileup beam particle (π^+) which does not leave beam pipe

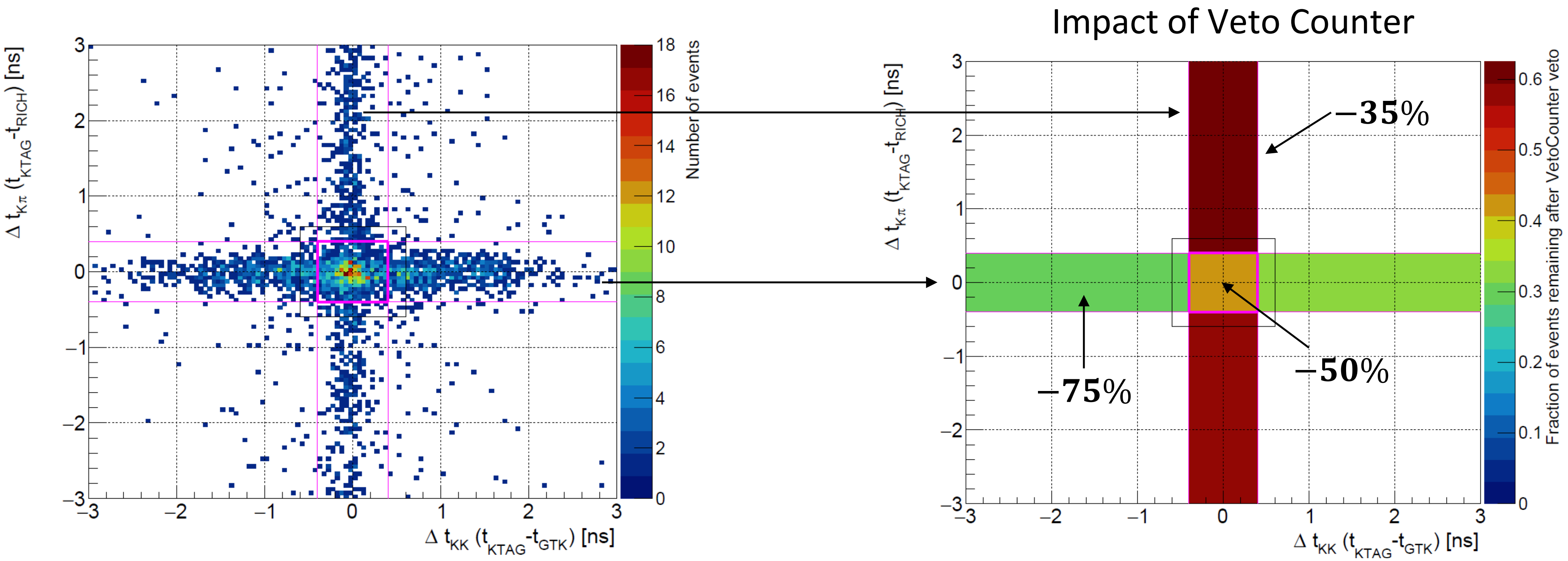
Upstream Background

Quadratic scaling with intensity increase expected: veto counter essential

Data – driven estimation; control regions from out – of – time regions and mis – reconstructed samples

Extrapolation in signal regions using PDFs for timing and mis-reconstruction probabilities

Overall procedure under review to include veto counter



Impact of Veto Counter

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

- Analysis
  - Further optimization of the selection
  - Test and possible implementation of a new algorithm for PID based on NN
  - Study of the scaling of the upstream background with intensity
  - Full implementation of the veto counter
  - Evaluation procedure of the upstream background
  - Simulation studies of the upstream background
  - Include 2021 data

- Result
  - Release of a new result based on 2021+2022 data hopefully by end-2023

Selection of Physics Results from 2022

- Precision measurements: LFUV, Chiral parameters
- NP direct search: forbidden LNV, LFV kaon decays
- Feebly interacting particles searches

$K^+ \to \pi^+ l^+ l^-$ Precision measurement

Form factors (FF)

Theory: $d\Gamma/dz \propto G_F M_K^2(\underset{\uparrow}{a} + \underset{\uparrow}{b}z) + W^{\pi\pi}(z)$ $[z = m(l^+l^-)^2/M_K^2]$ Lepton universitality: same a, b for $l = e, \mu$

Goal: Measurement of FF and $BR(K^+ \to \pi^+\mu^+\mu^-)$

Analysis: Data RUN 1, almost background-free selection

normalization $K^+ \to \pi^+\pi^+\pi^-$

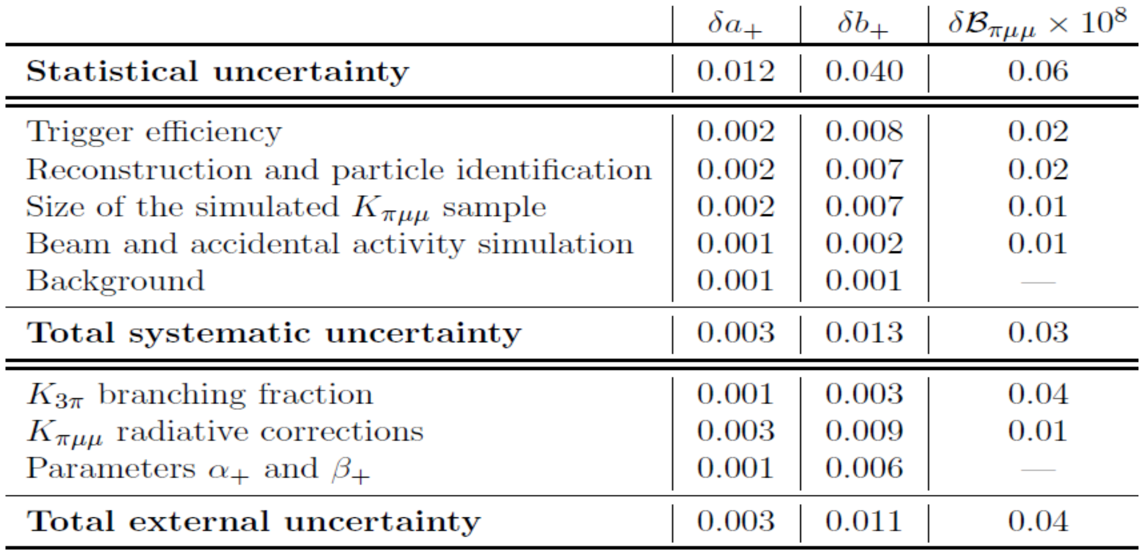
a, b from fit $d\Gamma/dz$

$N_{obs} = 27679$ JHEP11(2022)011

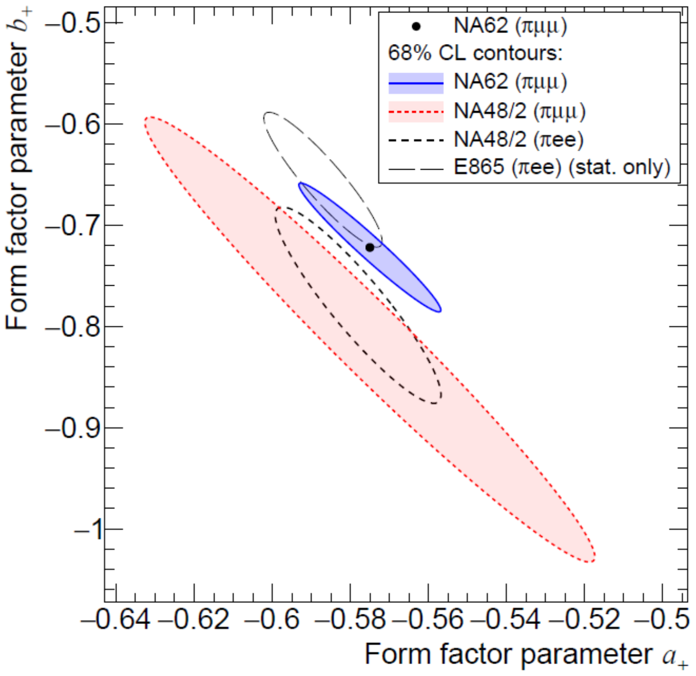
$\boldsymbol{a_+ = -0.575 \pm 0.013}$

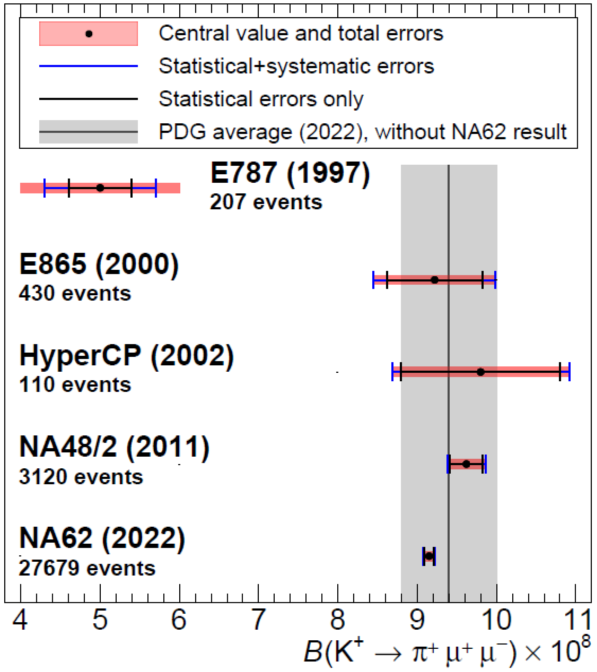
$\boldsymbol{b_+ = -0.722 \pm 0.043}$

$\boldsymbol{BR(K^+ \to \pi^+\mu^+\mu^-) = (9.15 \pm 0.08) \times 10^{-8}}$



	δa_+	δb_+	$\delta\mathcal{B}_{\pi\mu\mu} \times 10^8$
Statistical uncertainty	0.012	0.040	0.06
Trigger efficiency	0.002	0.008	0.02
Reconstruction and particle identification	0.002	0.007	0.02
Size of the simulated $K_{\pi\mu\mu}$ sample	0.002	0.007	0.01
Beam and accidental activity simulation	0.001	0.002	0.01
Background	0.001	0.001	—
Total systematic uncertainty	0.003	0.013	0.03
$K_{3\pi}$ branching fraction	0.001	0.003	0.04
$K_{\pi\mu\mu}$ radiative corrections	0.003	0.009	0.01
Parameters α_+ and β_+	0.001	0.006	—
Total external uncertainty	0.003	0.011	0.04





$K^+ \rightarrow \pi^+\gamma\gamma$ Precision measurement

Theory: Test of Chiral Perturbation Theory, $d\Gamma/(dydz)$ depends on the chiral parameter $\hat{c}$

$[z = m(\gamma\gamma)^2/M_K^2]$
$[y = p_K(p_{\gamma 1} - p_{\gamma 2})/M_K^2]$

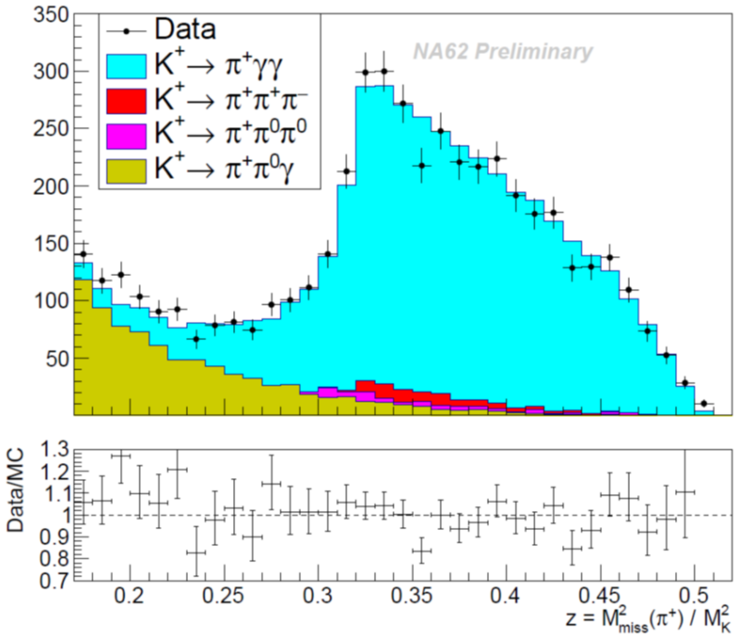
Goal: Measurement of $BR(K^+ \rightarrow \pi^+\gamma\gamma)$ and $\hat{c}$

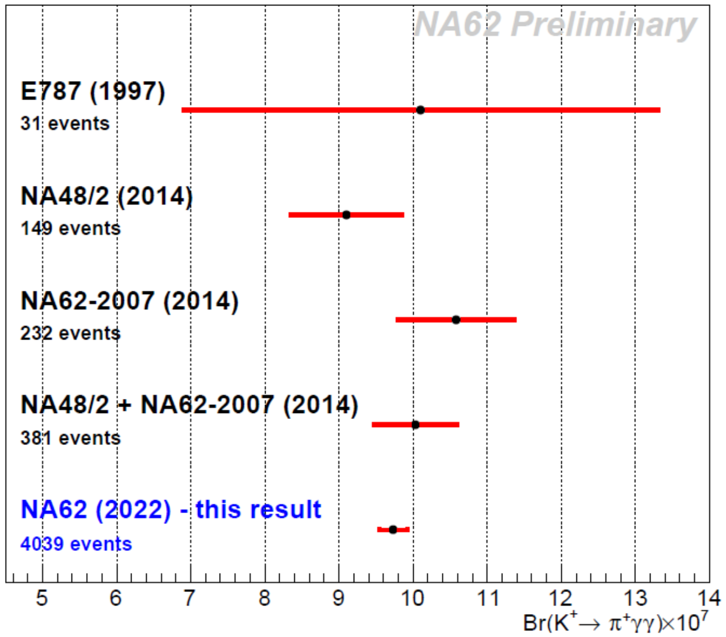
Analysis: Data RUN 1, ~10% background
normalization $K^+ \rightarrow \pi^+\pi^0$
$\hat{c}$ from $d\Gamma/(dydz)$

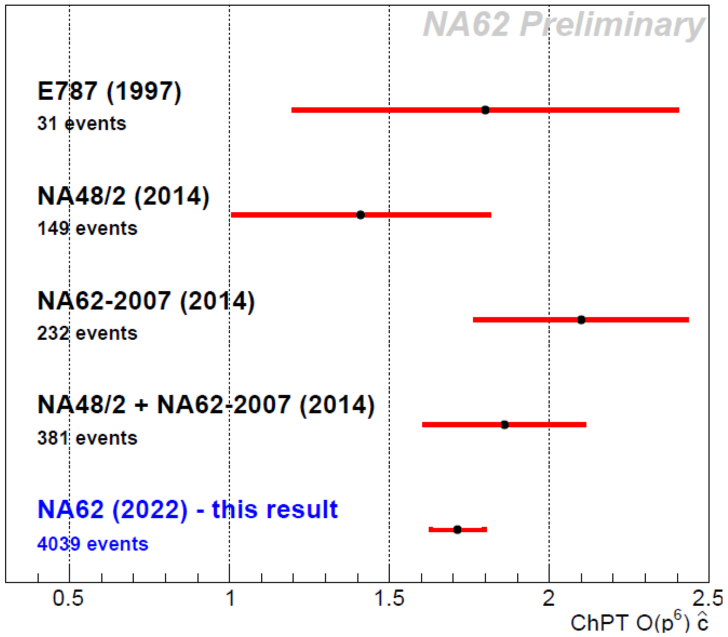
$N_{obs} = 4039$ $N_{bkg} = 393 \pm 20$ KAON2022

$\boldsymbol{\hat{c} = 1.713 \pm 0.075_{stat} \pm 0.037_{syst}}$

$\boldsymbol{BR(K^+ \rightarrow \pi^+\gamma\gamma) = (9.73 \pm 0.17_{stat} \pm 0.08_{syst}) \times 10^{-7}}$







LNV and LFV decays in RUN1

Theory: decays forbidden by SM because violate Lepton number and/or flavour
direct search of NP: Majorana neutrino (LNV), Leptonquark (LFV)

NA62: Run1 data; several channels studied

Analysis: Most recent results (90% CL)

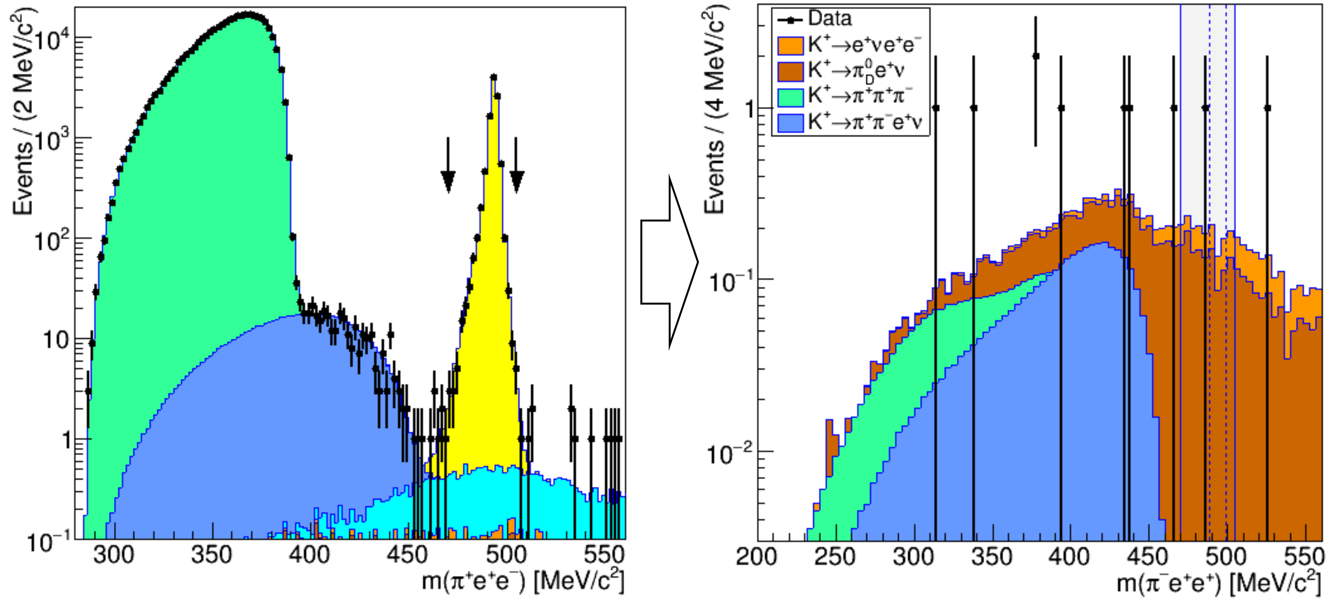
- $K^+ \to \pi^- \mu^+ \mu^+$
- $K^+ \to \mu^- \nu e^+ e^+$
- $K^+ \to \pi^- e^+ e^+$
- $K^+ \to \pi^- \pi^0 e^+ e^+$
- $K^+ \to \pi^\mp \mu^\pm e^+$
- $\pi^0 \to \mu^- e^+$

$BR(K^+ \to \mu^- \nu e^+ e^+) < 8.1 \times 10^{-11}$ (× 4 better)
PLB838(2022)137679

$BR(K^+ \to \pi^- e^+ e^+) < 5.3 \times 10^{-11}$ (× 200 better)
PLB830(2022)137172

$BR\left(K^+ \to \pi^- \pi^0 e^+ e^+\right) < 8.5 \times 10^{-11}$ (first search)
PLB830(2022)137172

$K^+ \to \pi^+ e^+ e^-$ (SM allowed) $K^+ \to \pi^- e^+ e^+$ (LNV)



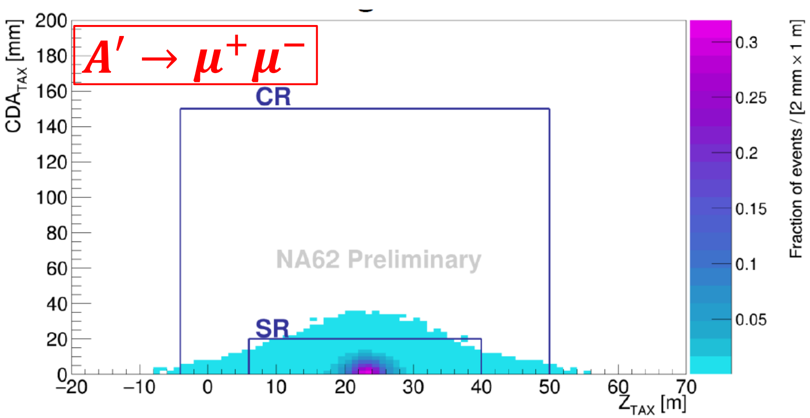
Dark Photon Search $A' \to l^+l^-$ (RUN2)

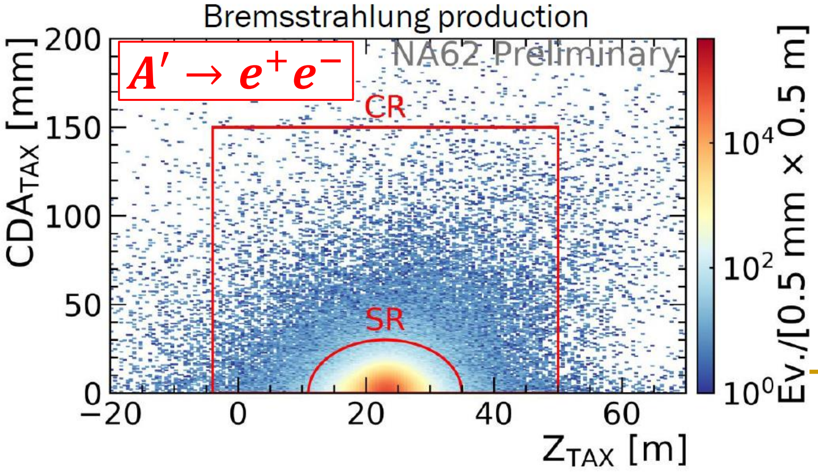
Theory: SM extension in the framework of feebly interacting particle models (FIPs)

NA62: Data taken in dump mode in **2021,** exploitation of beam optimization and ANTI0 ⇨ $(1.4 \pm 0.3) \times 10^{17}$ PoT

Analysis: 2 channels $\mu^+\mu^-$, e^+e^-; reconstructed A' compatible with production in dump; blind procedure

Expected Signal





Expected background

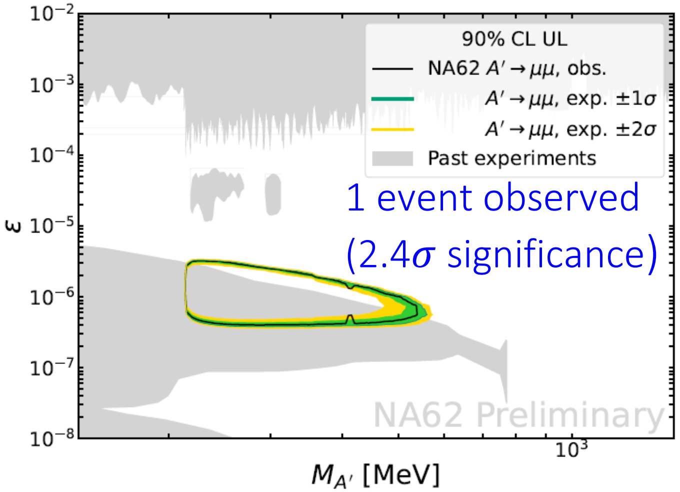
Random time superposition of two uncorrelated muons; data-driven estimation

$$0.016 \pm 0.002$$

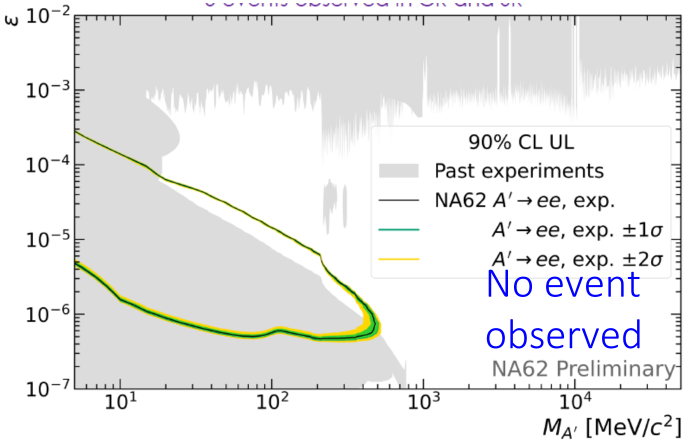
Secondaries of particle's interactions with traversed material ("prompt"); MC-data estimation

$$0.0094^{+0.049}_{-0.009} \text{ @ } 90\% \text{ CL}$$

Result



1 event observed (2.4σ significance)



No event observed

Conclusions

- Successfull run in 2022
  - ❑ NA62 runs in stable mode at full intensity
  - ❑ No evidence of loss of data taking efficiency compared to runs at lower intensity

- $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ analysis:
  - ❑ Improved compared to RUN1 analysis
  - ❑ $\sim +50\%$ increase of $\pi\nu\nu$ / burst compared to 2018
  - ❑ Background from kaon decays in line with 2018, upstream background under study

- Other physics analysis:
  - ❑ World-leading results published/released from precision, rare kaon, and dump physics
  - ❑ Several new results expected mostly from RUN1 data

Selected $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ yield / «year» matches expectations of Addendum I to P326 SPSC-2019-039

New result on $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ expected by 2023

2023 run is starting with important hardware upgrades