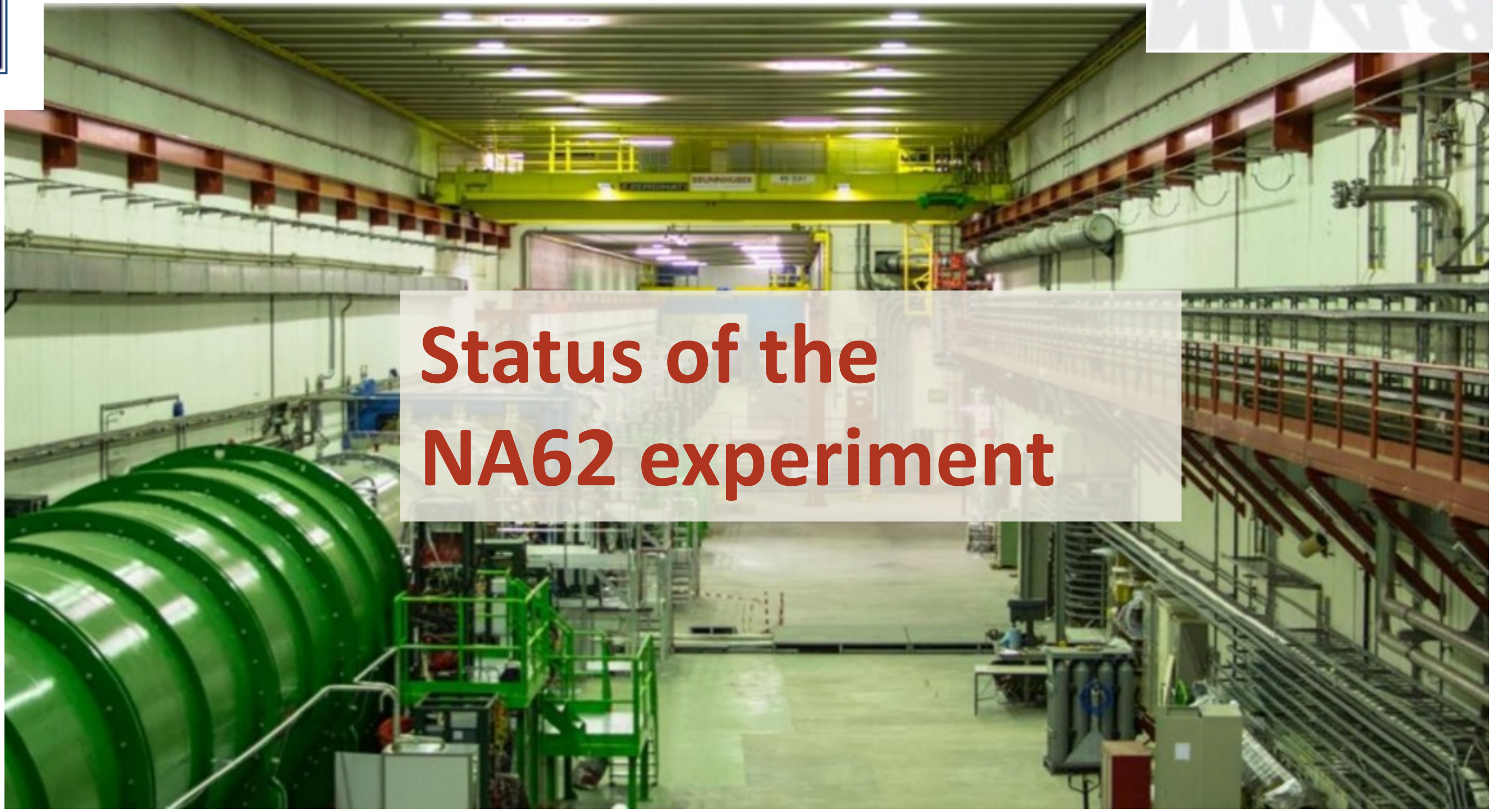
Status of the NA62 experiment



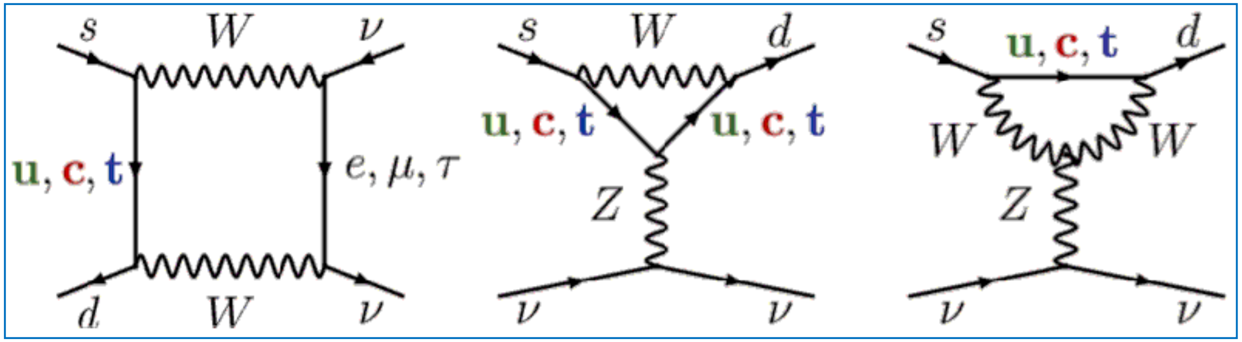
Cristina Lazzeroni (University of Birmingham)

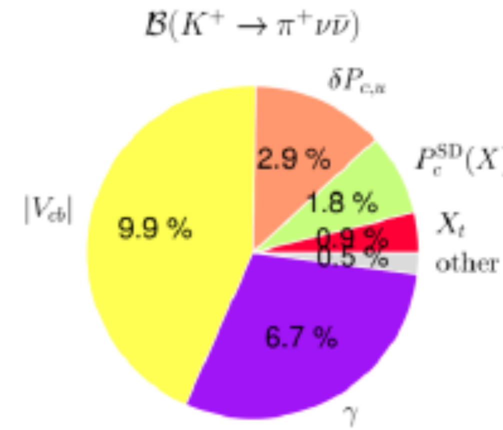
SPSC Open Session

12 April 2022

$K^+ \to \pi^+ \nu\nu$

SM: box and penguin diagrams





Theoretical error budget
Buras. et. al., JHEP11(2015)033

A high-order process with highest CKM suppression:

$A \sim (m_t/m_W)^2 |V_{ts}^* V_{td}| \sim \lambda^5$

"Free" from hadronic uncertainties

Exceptional SM precision

Sensitive to New Physics

Complementary to B sector

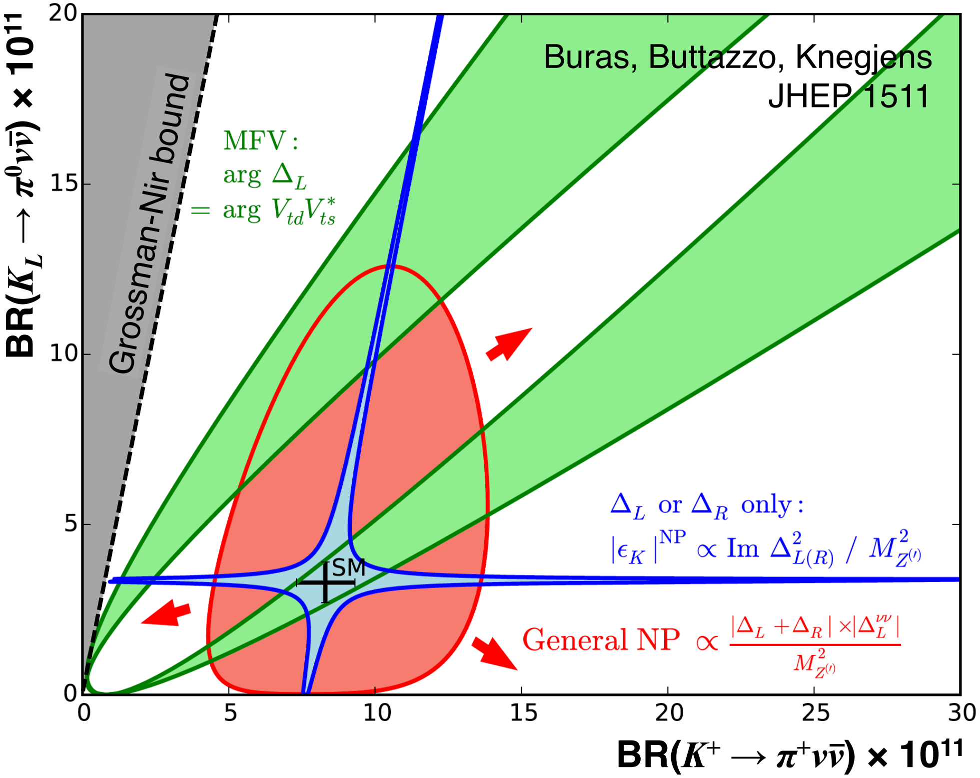
SM branching ratios

Buras et al., JHEP 1511 (2015) 033

Mode	$BR_{SM}\times10^{11}$	
$K^+\to\pi^+\nu\nu(\gamma)$	8.4±1.0	(12%)
$K_L\to\pi^0\nu\nu$	3.00±0.31	(10%)

Unreducible theory error: O(5-3%)

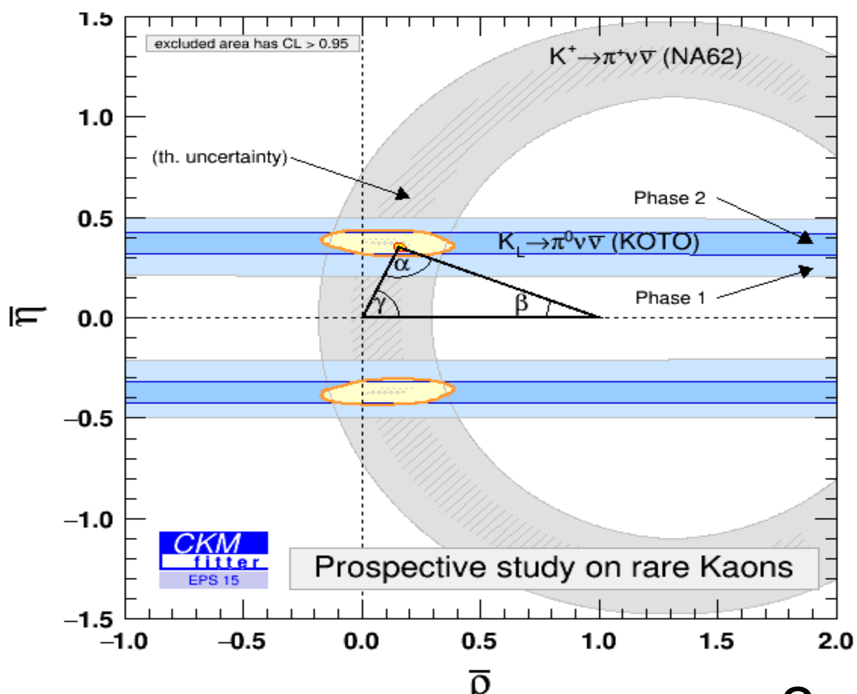
Sensitivity to new physics



- Models with CKM-like flavor structure
  - Models with MFV
- Models with new flavor-violating interactions in which either LH or RH couplings dominate
  - Z/Z' models with pure LH/RH couplings
  - Littlest Higgs with T parity
- Models without above constraints
  - Randall-Sundrum

Besides, first experiment to reach sensitivity down to 10^{-12} for single pion plus missing energy

Simplified Z,Z' models [JHEP 1511 (2015) 166]
Littlest Higgs with T-parity [EPJ C76 (2016) 182]
Custodial Randall-Sundrum [JHEP 0903 (2009) 108]
MSSM non-MFV [PEPT 2016 123B02, JHEP 0608 (2006) 064
LVF models [Eur Phys J C (2017) 77]

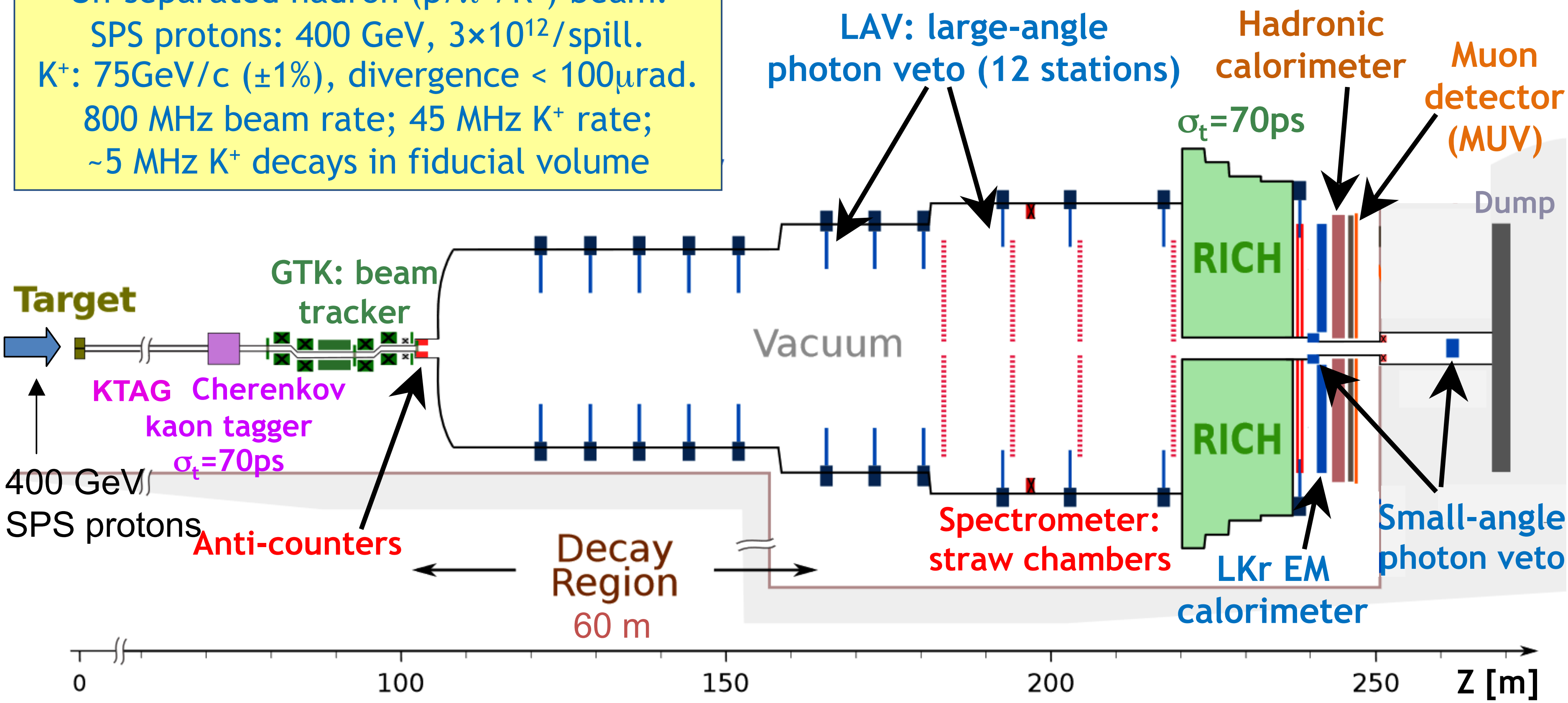


Correlations are model-dependent

The NA62 experiment

NA62 collaboration,
JINST 12 (2017) P05025

Un-separated hadron ($p/\pi^+/K^+$) beam.
SPS protons: 400 GeV, 3×10^{12}/spill.
K^+: 75GeV/c (±1%), divergence < 100μrad.
800 MHz beam rate; 45 MHz K^+ rate;
~5 MHz K^+ decays in fiducial volume



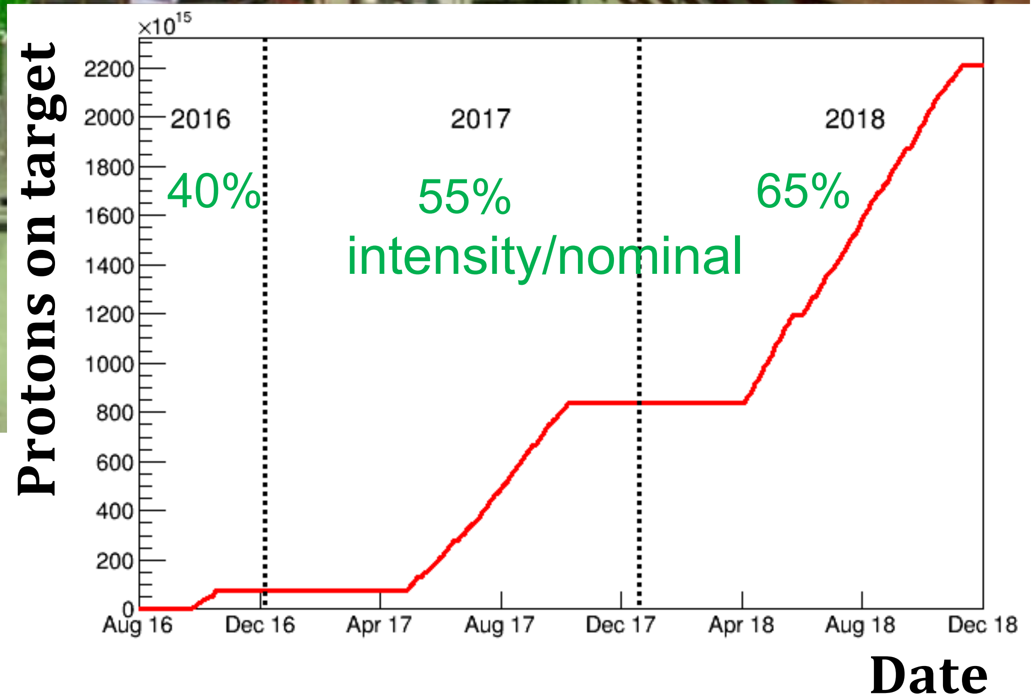
Time resolution **O(100 ps).**

Kinematic rejection **O(10^4)** for $K^+\to\pi^+\pi^0$ and $K\to\mu^+\nu$.

Photon veto: $\pi^0\to\gamma\gamma$ decay suppression from $K^+\to\pi^+\pi^0$ (10^7)

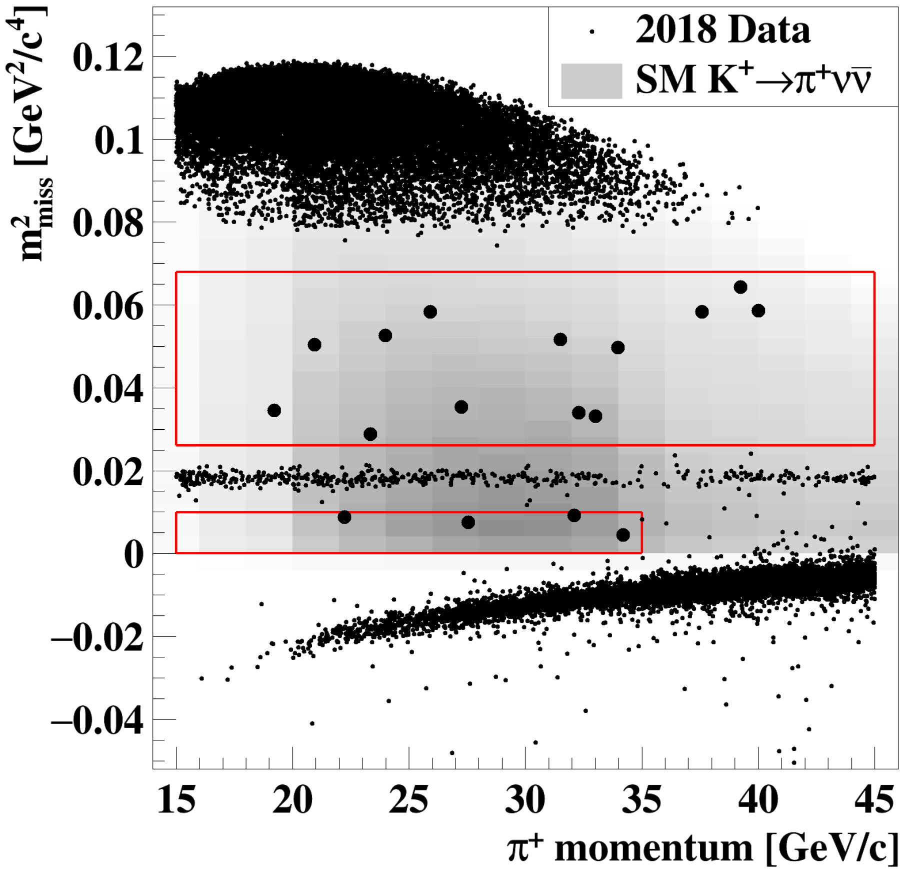
Particle ID (RICH+LKr+HAC+MUV): muon suppression from $K\to\mu^+\nu$ (10^7)

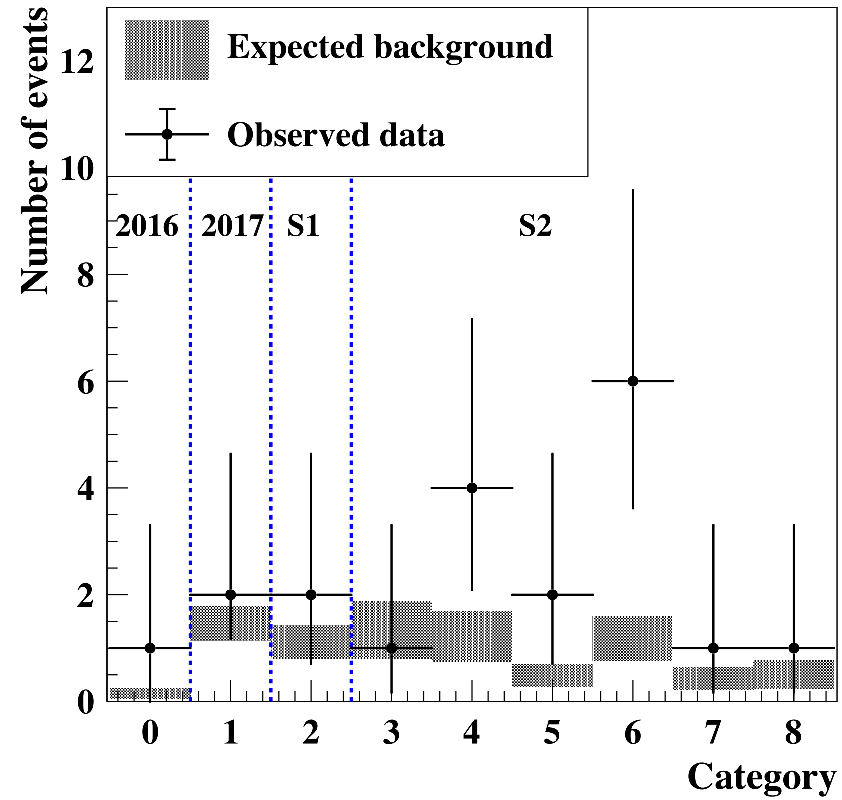
NA62 data samples in Run1



Result: 2016+2017+2018 data

[JHEP 06 (2021) 093]





$$SES = (0.839 \pm 0.053_{sys}) \times 10^{-11}$$

$$N_{obs}(2016 + 2017 + 2018) = 20$$

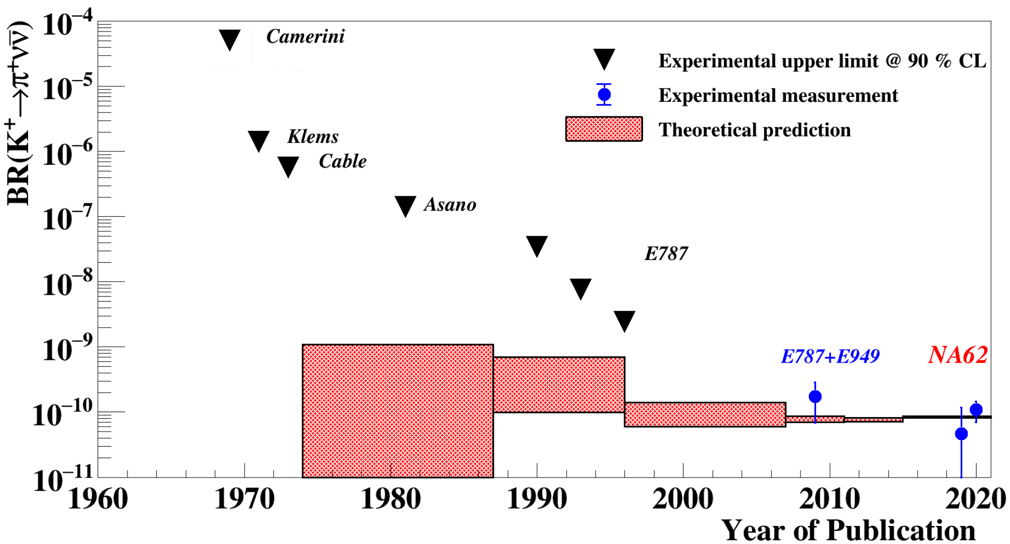
$$N^{exp}_{\pi\nu\nu} = 10.01 \pm 0.42_{sys} \pm 1.19_{ext}$$

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

$$Br(K^+ \to \pi^+ \nu\nu) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{sys}) \times 10^{-11} \text{ at } 68\% \text{ CL}$$

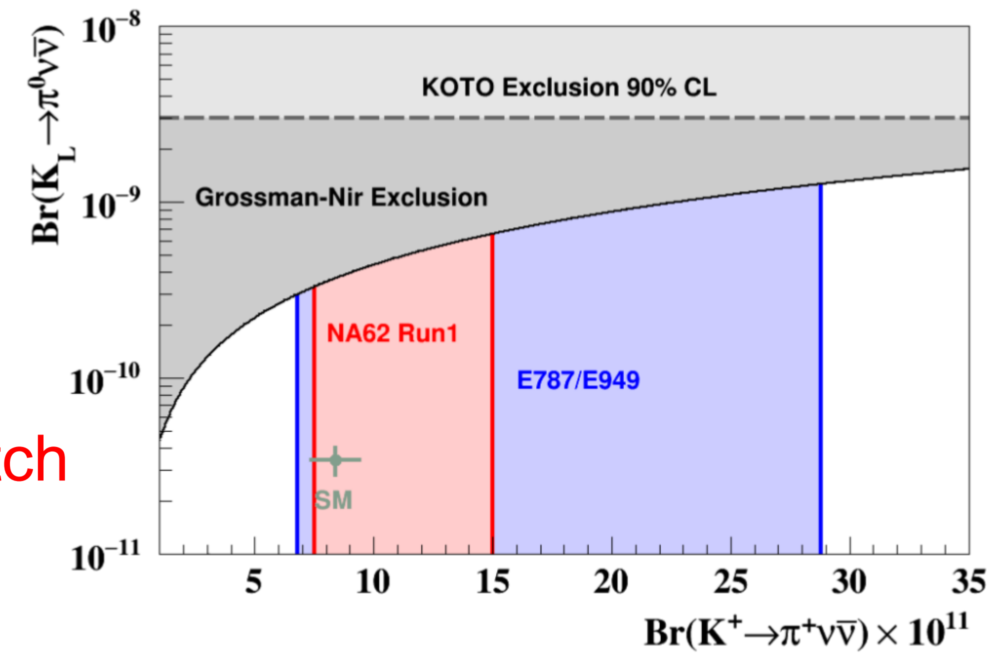
3.4σ significance

Implications of $K^+ \to \pi^+ \nu\nu$



Most precise determination of the decay rate to date
Provides strongest evidence so far (3.4 σ) for its existence

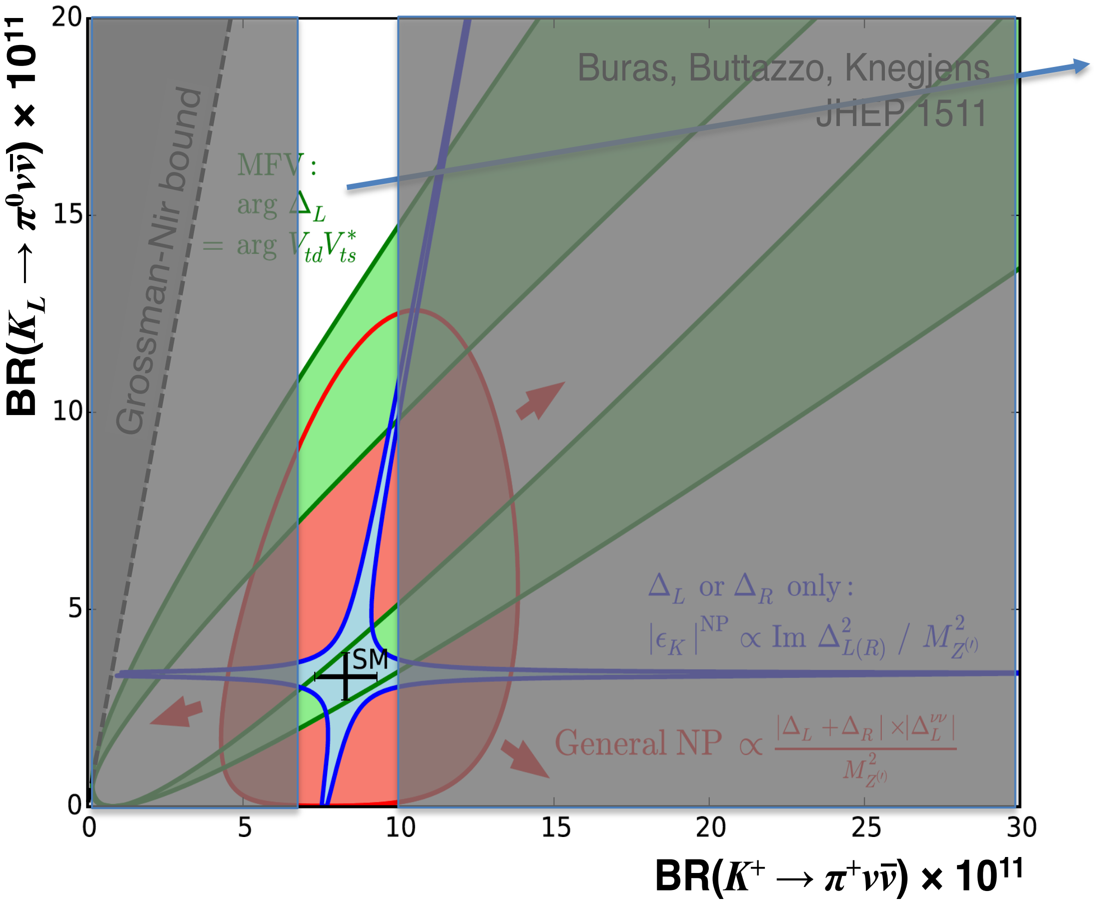
Part of parameter space already ruled out



Next target: at least x3 improved precision to match parametric theoretical uncertainty by LS3

NA62 Experiment approved until LS3 by CERN Research Board

Data taking after LS2 to reach O(10%) precision on the $K^+ \rightarrow \pi^+ \nu\nu$ measurement



NA62@LS3
O(10%) precision

Constrain New Physics models

Status of NA62 and Run2

Overview

Next target: reach our physics goal of challenging the SM, with a precision matching the theoretical one.
NA62 is fully committed to take data (Run2) in 2021-2025 to reach our physics goal.

Since the previous report in April 2021:

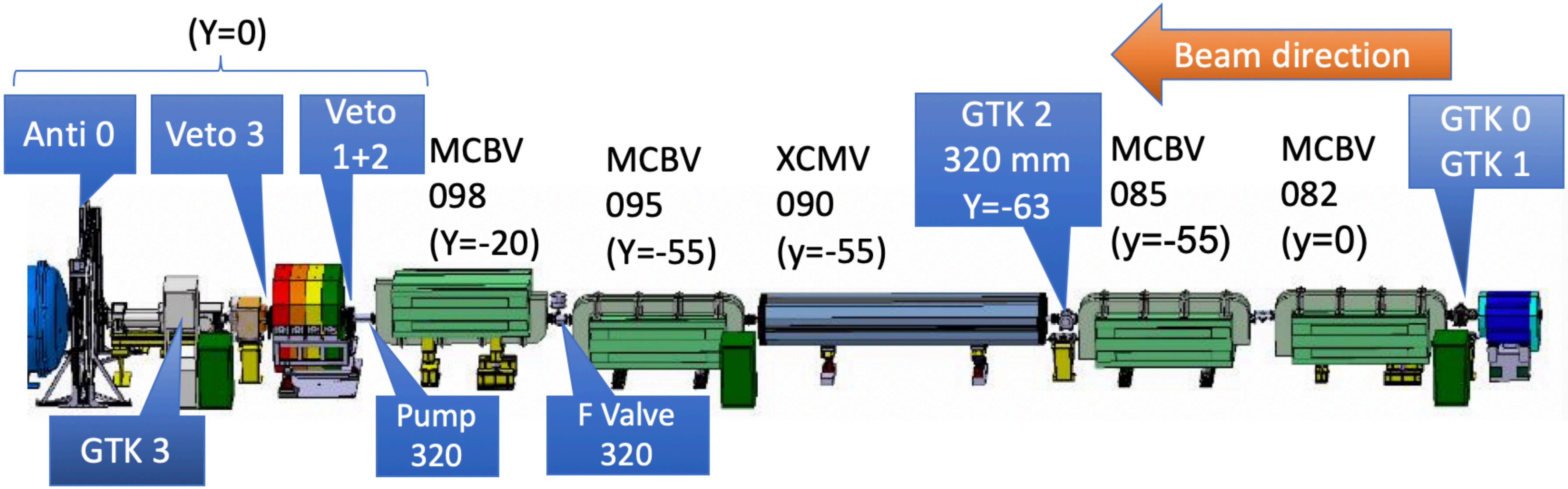
Completed the beam line modifications, the preparation and installation of new detectors.
Despite delays in beam delivery, reduced beam availability and poor spill structure, the upgraded setup was commissioned and data was successfully collected in the Summer and Autumn of 2021, reaching nominal beam intensity.

Several results published on Run1 data for rare and exotic processes.

Detector additions

For background reduction in $K^+ \to \pi^+ \nu\nu$ analysis: **re-built 2nd achromat optimized for background rejection, 4th GTK station (GTK0), VetoCounter before/after last collimator, 2nd HASC module**

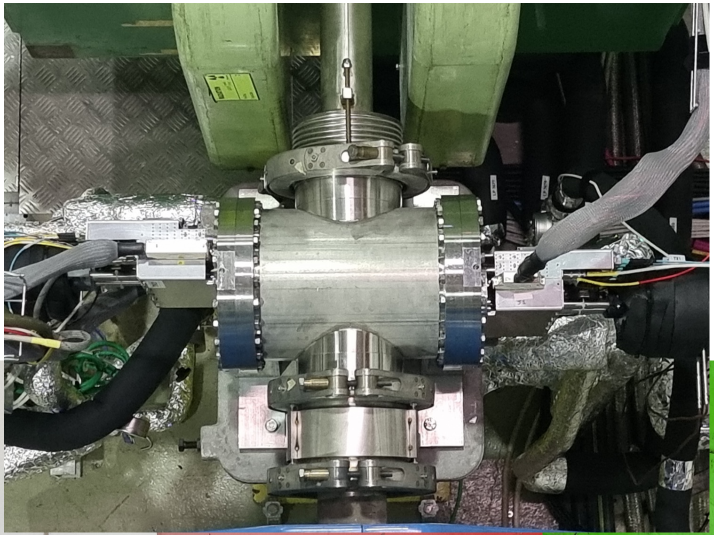
Anti0 hodoscope for muon background reduction in dump mode

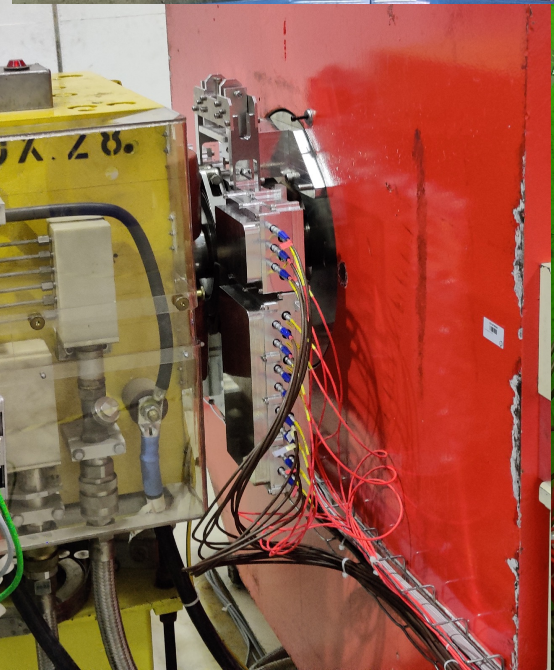


NA62 activities restarted as soon as CERN partially reopened in 2020. We worked with a tight schedule, prepared for beam in July 2021.

New detector installed and commissioned

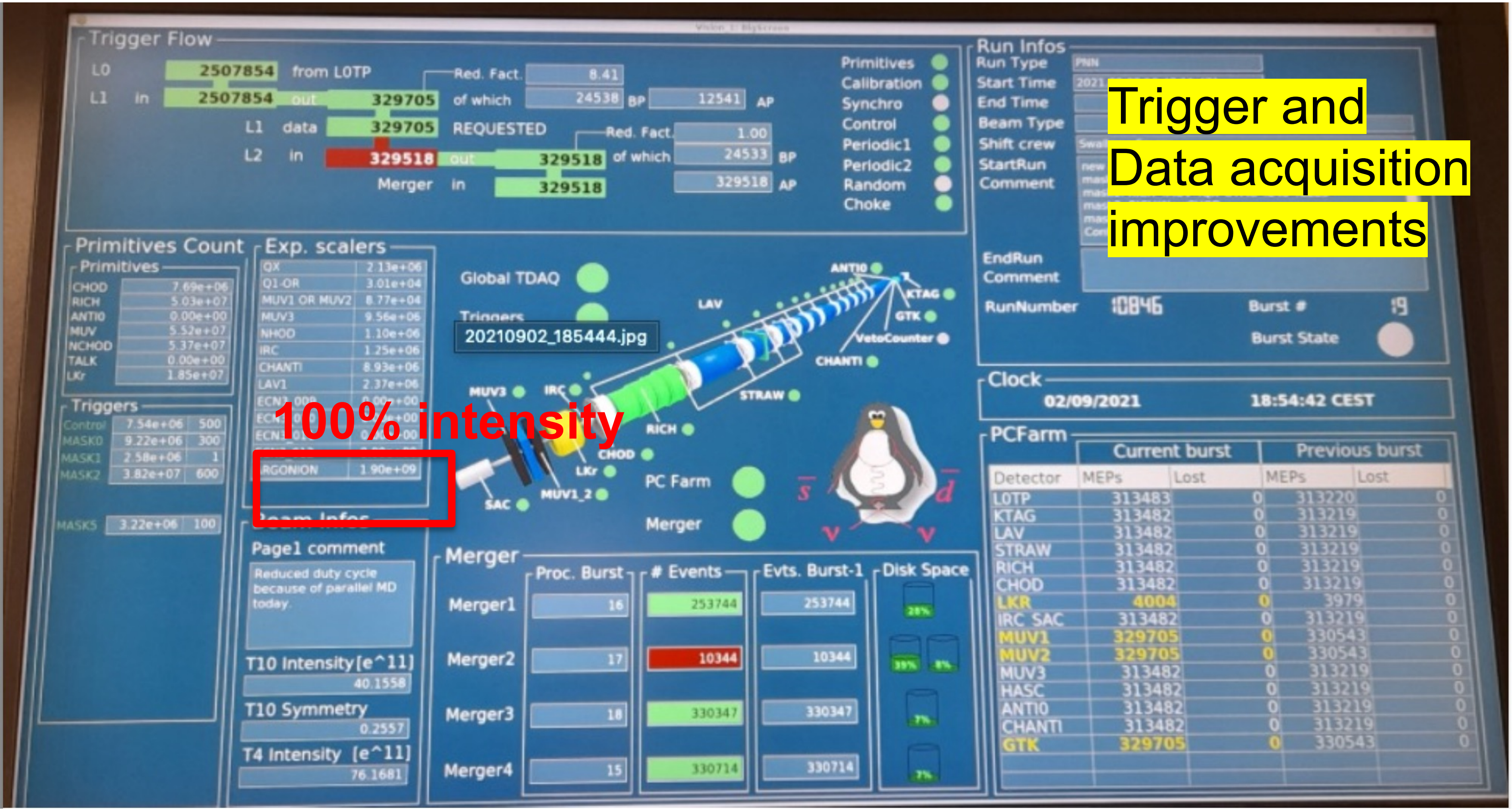
One major goal reached





Data taking at nominal intensity

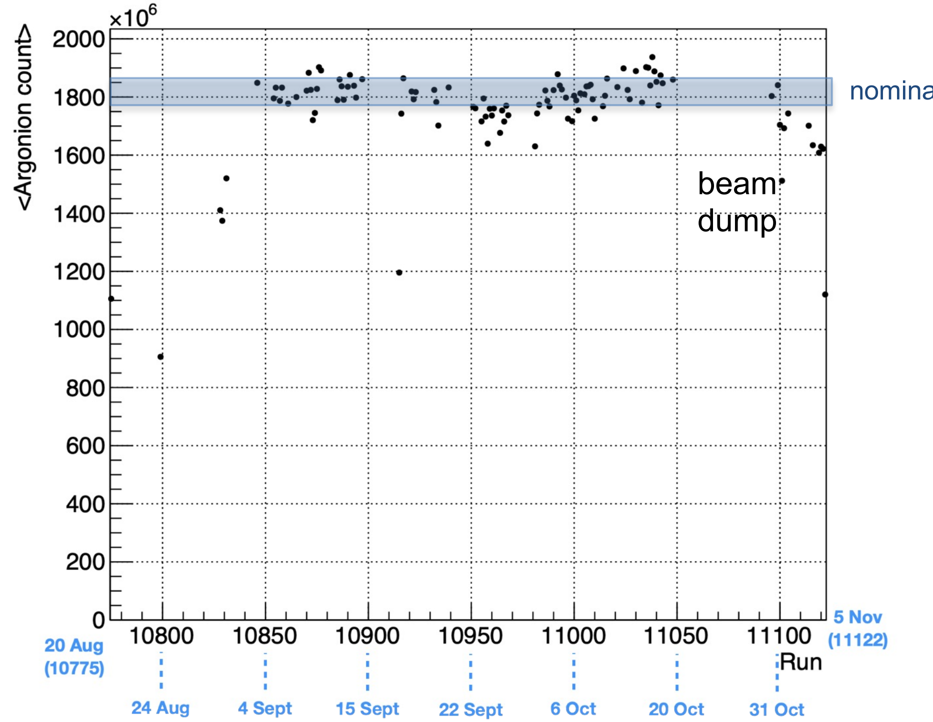
Another major goal reached



NA62 is grateful for the commitment of CERN in delivering a high-intensity beam to NA62 and for the efforts to improve the beam

Beam availability in 2021

Nominally beam available: 26/7 – 14/11
~2 weeks with no hadron beam at start
Several problems with beam tuning, also affected by instrumentation issues in K12. In August, intensity reached ~50-60% of nominal
(low T4-T10 transmission)

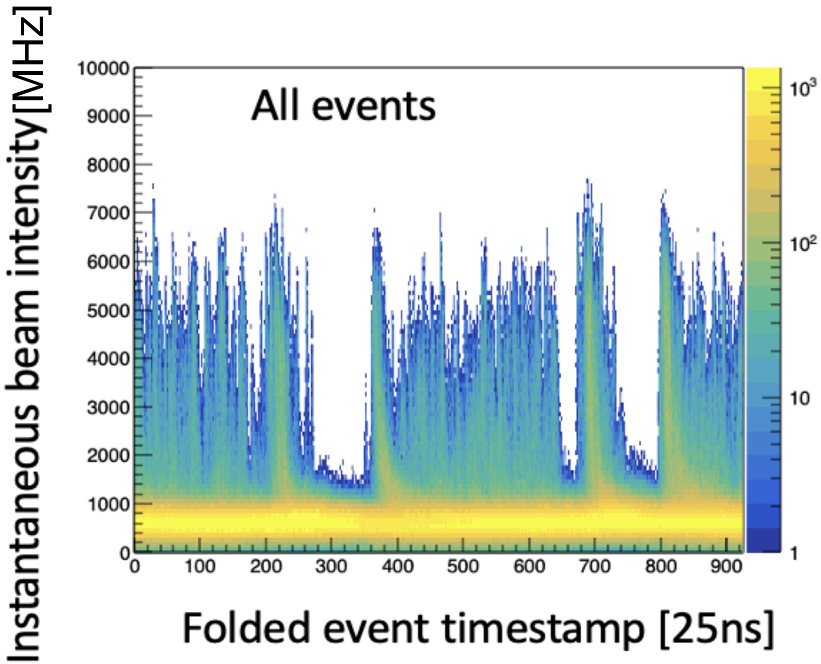


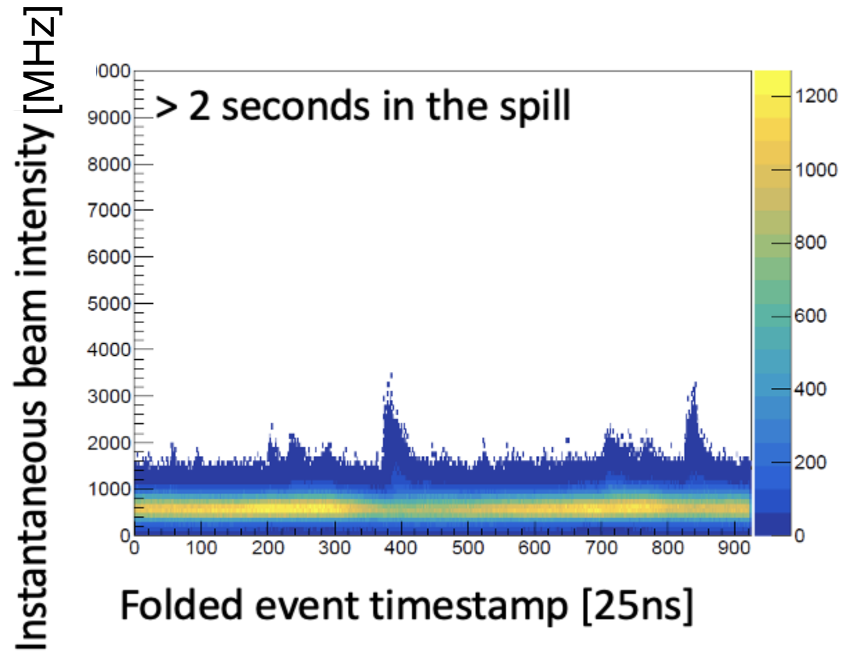
From September, beam delivered as measured by Argonion counters increased to about nominal.
T10 value @nominal intensity: newly defined in 2021 (as ~40-45 units, not 33).
This highlights the need of a trustworthy, independent instrument that can be used to record the protons on T10 target.
Several periods of beam absence and instability present throughout the year, including instability of beam magnets (faulty regulation cards in power converters).
T4 beam availability = ~70% T10 beam availability = ~87% of T4

Spill quality

Instantaneous intensity significantly higher (up to x8) in first second of spill, well above specs, causing unsustainable high rate in readouts, trigger and DAQ.

Distribution of intensity seen in GTK as a function of the modulus of the time with respect to the revolution frequency of the SPS (folded timestamp):





Quality of the spill structure severely limited protons usable for physics.

Possible origins and ways to improve: being discussed with CERN BE-OP-EA-SY.

New NA62 tools being developed to give fast feedback.

If this effect cannot be substantially reduced, other strategies being considered.

Detector Current Status

Detectors generally working well, including new ones.

GTK Inefficiency observed in 2018 due to limit on the number of hits per half-chip in each frame resolved in 2021.
Periods of instability in 2021 in all stations except GTK3, when synchronization between readout chips and boards was lost, probably due to SEUs.
2022: work on-going to solve inefficiency due to presence of the trigger at the edges of 400 ns trigger-matching window. Work ongoing to improve stability.
Production of new GTK modules progressing, to cover data taking after LS2.

New CEDAR optimized for H2: production ongoing.
Test beam in H6 to validate new optics and performances, commission the detector.
To be installed once new system is fully validated with test beam data.

2021: FPGA-based TDC system (higher rate, no dead time), read out by the ATLAS FELIX PCIe board, was installed for the new VetoCounter.
2022: to be extended to CHANTI.

TDAQ Current Status

L0 Trigger processor: planned improvements done and functioning.
"Oscillations" seen in 2018 in number of triggers due to the switches: removed.
2022: New ethernet TAPs.
Upgrade of L0 Trigger Processor with new FPGA technology in commissioning.

L0 and HLT Triggers improved with new more selective conditions.
HLT online framework created, that reproduces offline.
Work ongoing to improve selection power in order to include other trigger lines.
LKr L0 dedicated readout to output the energy and positions of clusters,
to be used in HLT in 2022.

Improved monitoring system for possible TDAQ inefficiency sources.
Warning signal (CHOKE) system sent by detectors when their buffers are almost
full now fully implemented.

Data Processing and Simulation

GTK reconstruction included GTK0, and reoptimized to reduce CPU time.
LKr reconstruction better handles the pileup, much less intensity dependance.

New Online Monitor, based on multi-layer feedback (online/fast/prompt) implemented in 2021. Performance affected by very high intensity.
To be improved in 2022.

Spill problem caused increased data size in every spill, nearly double wrt 2018.
Assuming spill problem is mitigated:
Total raw data size to CTA of about 15 PB for all the data taken by 2025.
10 PB of EOS space by 2025.

Simulation of new detectors and modified beam line configuration.
More accurate simulation of accidental activity achieved thanks to new strategy to obtain the true beam intensity (Bayesian unfolding).
Simulation code extensively modified, to allow flexible choice of layout.
MC true hit merging and hit information propagated up to analysis level.

Thanks to CERN IT for their support and assistance and services provided to NA62

$K^+ \rightarrow \pi^+ \nu\nu$ analysis and prospects

Plan for Run2: $K^+ \to \pi^+ \nu\nu$

Goal: take data at ~100% nominal intensity (good spill quality) for maximum beam time compatible with accelerators schedules. Increase further signal acceptance while decreasing background.

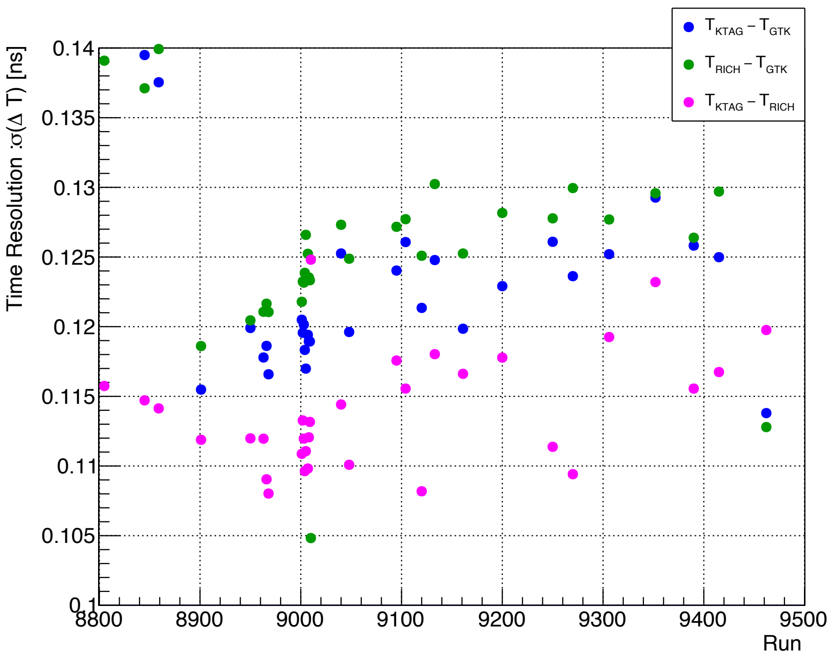
- **Keep Random Veto stable with increased intensity**
- **Background Reduction with new detectors**
- **Signal acceptance increase**

With increased sensitivity, CEDAR-H2 to reduce the beam-gas radiator nuclear scattering and reduce the radiation environment dose level

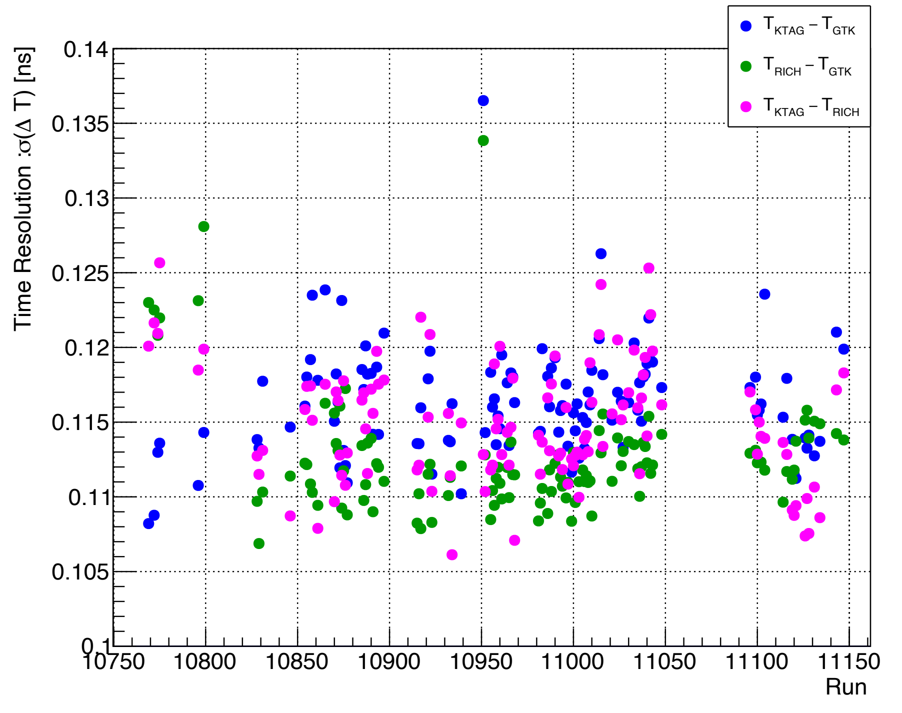
O(10%) precision is in the reach by LS3 with optimization of the analysis

NA62: 2021 data quality

We are in the process of looking at data in more depth.
The analysis has only just started.



2018 data (subsample)

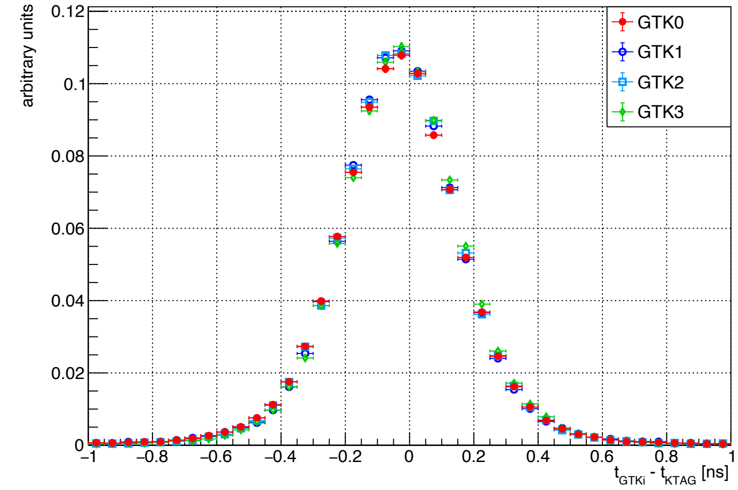


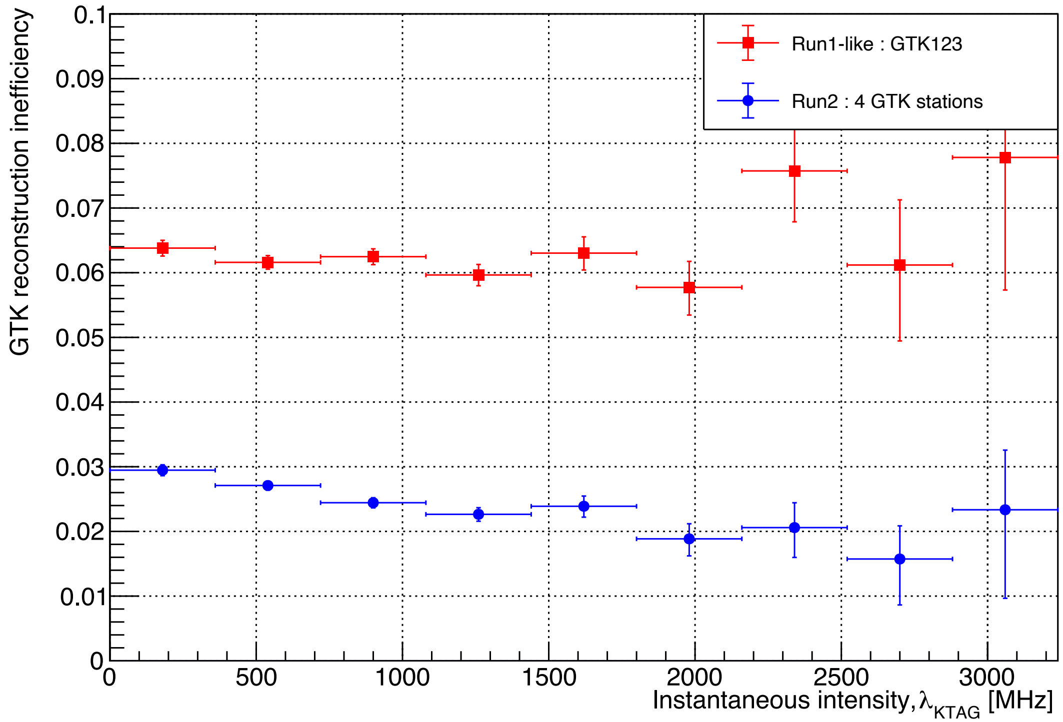
2021 data (subsample)

Factorising out the first part of the spill: good data quality.
For example, time resolutions are at least as good as in 2018.

NA62 new detectors: GTK0

New GTK station fully integrated and working as other stations.



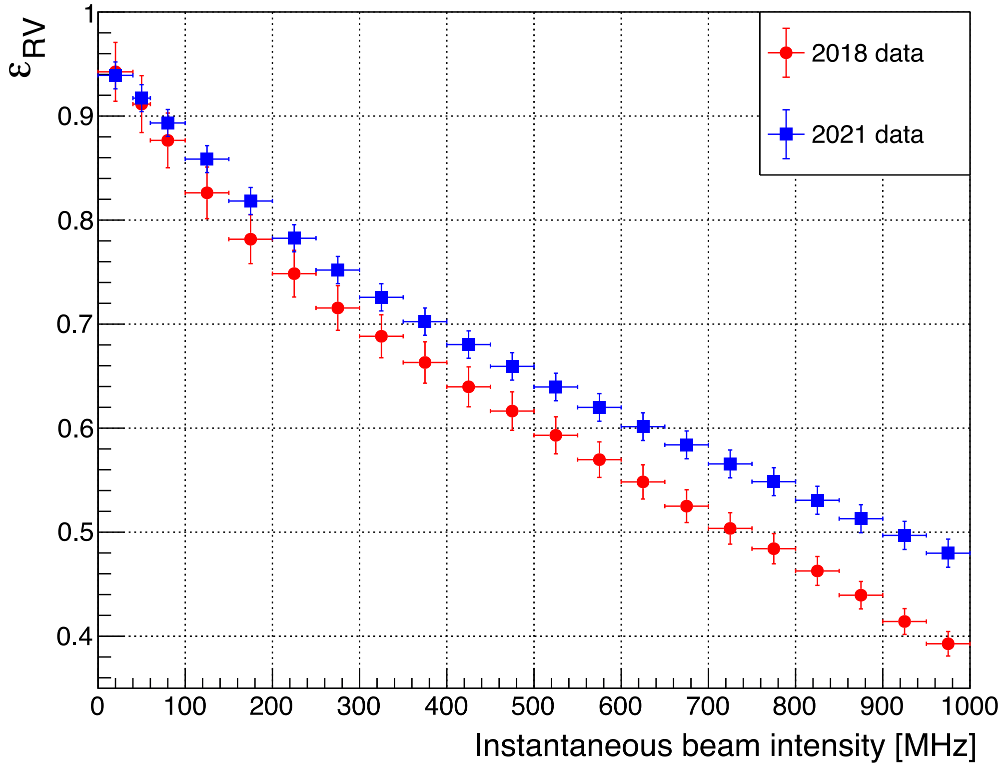


GTK reconstruction inefficiency reduced by GTK0.

Re-optimization of Kaon-to-Pion matching is in progress.

2021 data quality: Random Veto

Spill structure: signal efficiency in early part of spill is degraded.
Average instantaneous intensity for normalisation increased only by ~30%



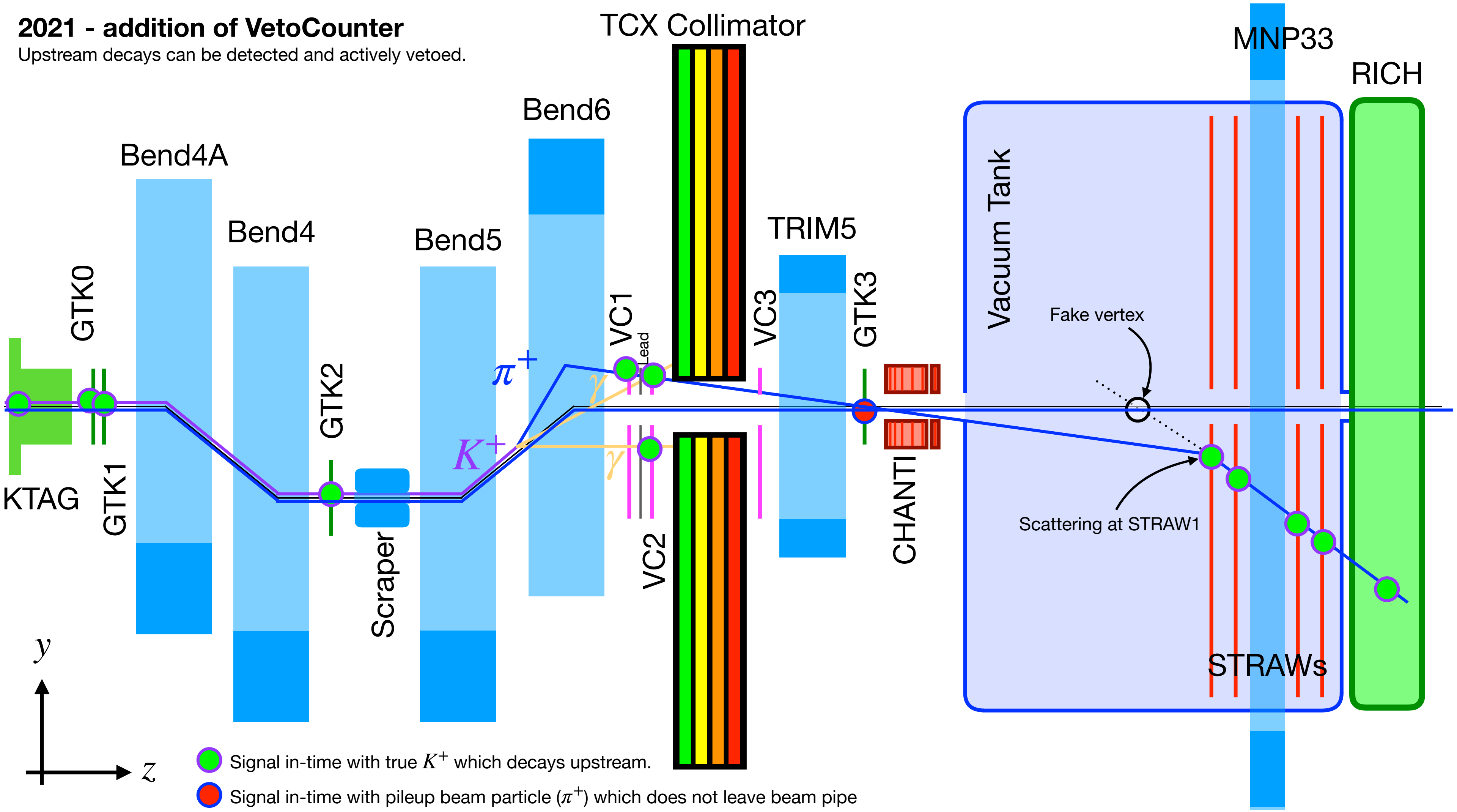
Average signal efficiency after extra-activity rejection:

$$\epsilon_{RV}^{2018} = 66\%$$

$$\boxed{\epsilon_{RV}^{2021} = 64\%}$$

Most relevant random veto effect as a function of the beam intensity is due to the photon rejection in the LKr calorimeter.
Improvements in reconstruction mean time windows for the photon veto are reduced significantly.

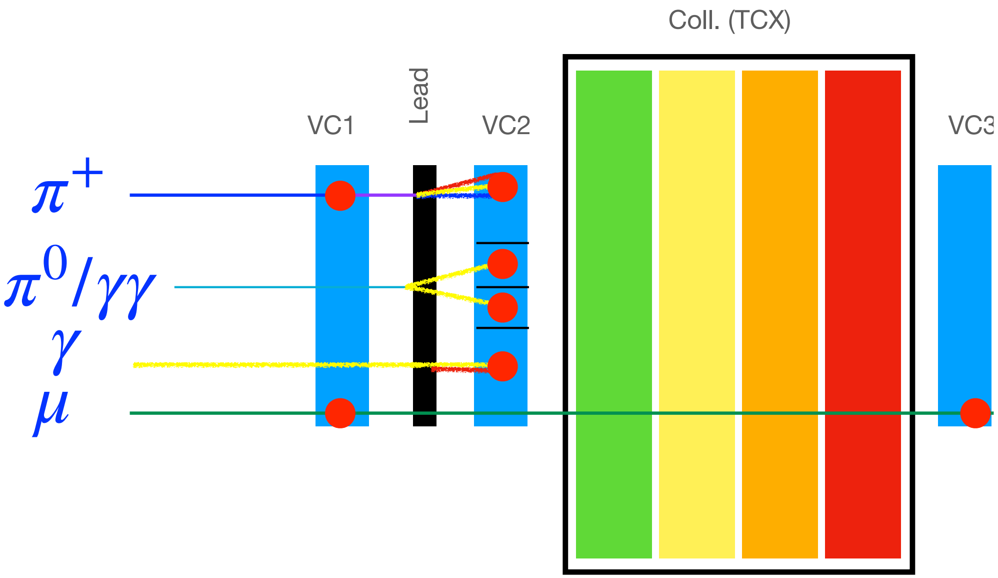
Background reduction: VetoCounter

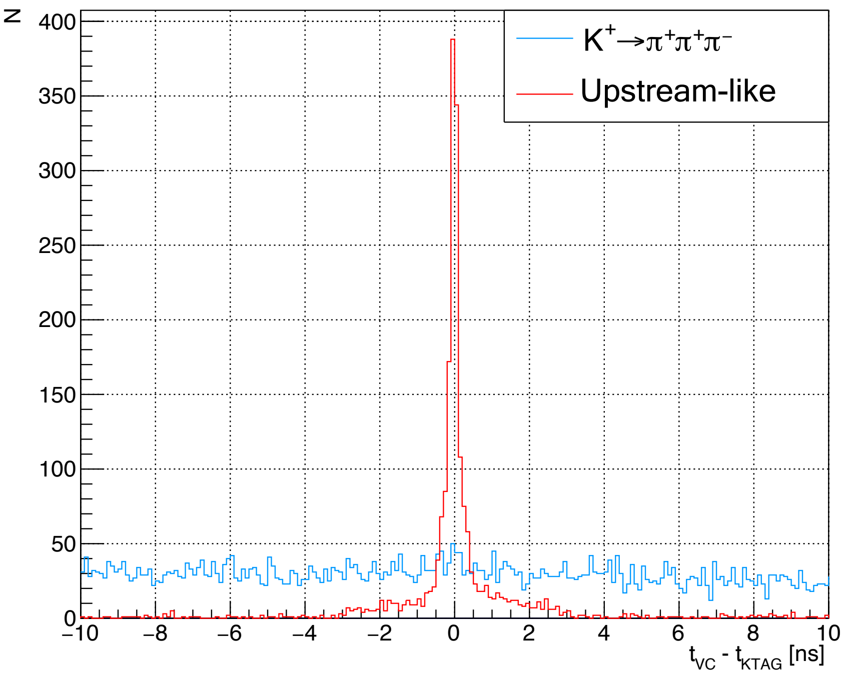


Background reduction: VetoCounter

Start with conservative veto criteria.

Initial results give suppression of upstream-like events by a factor of 2





Rough categorisation:

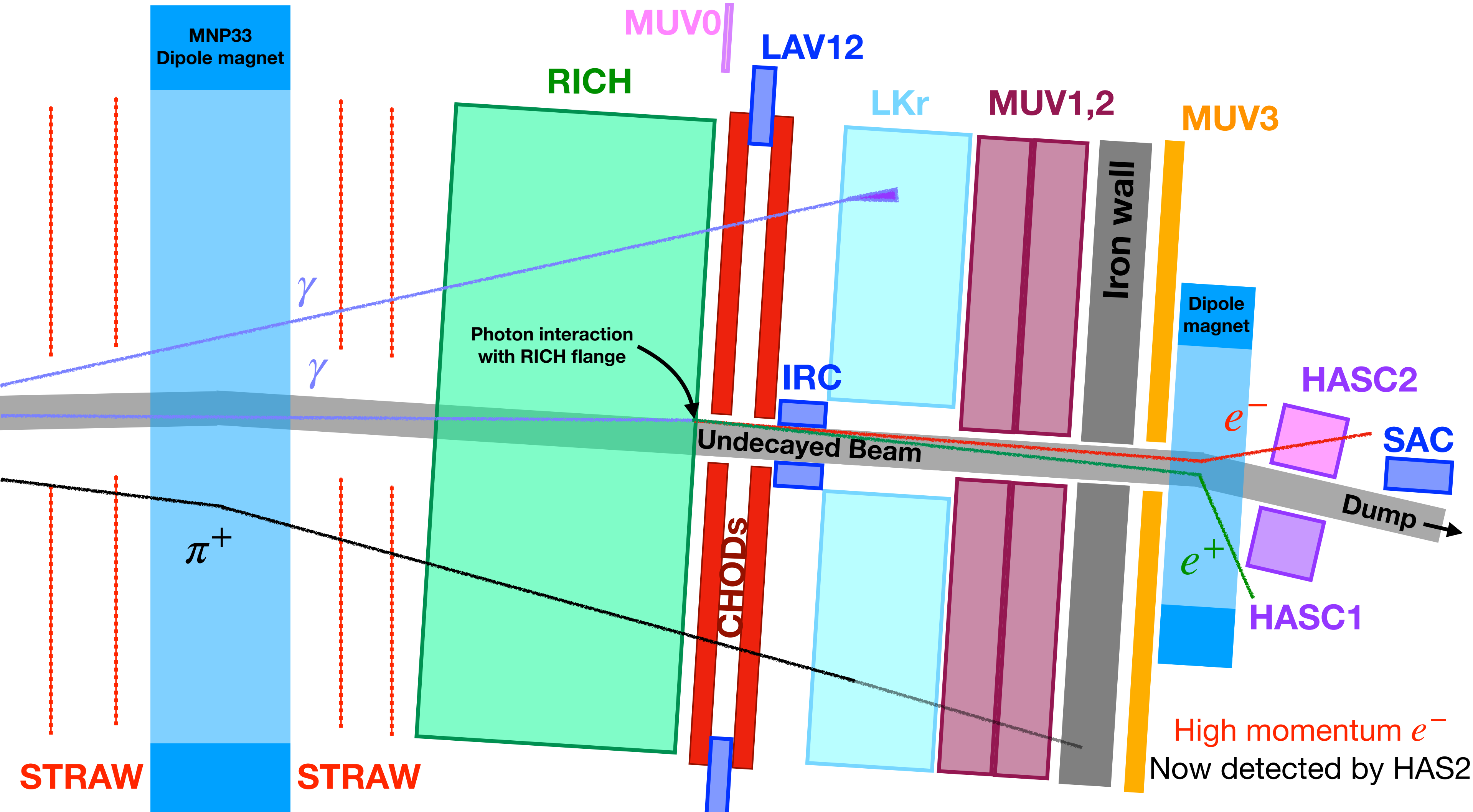
π^+-like : candidate in station 1 (+ possible shower also hitting station2 “shower-like”)

$\pi^0/\gamma\gamma$/shower -like : candidates in 2 different tiles of station 2.

μ-like : candidates in stations 1+3.

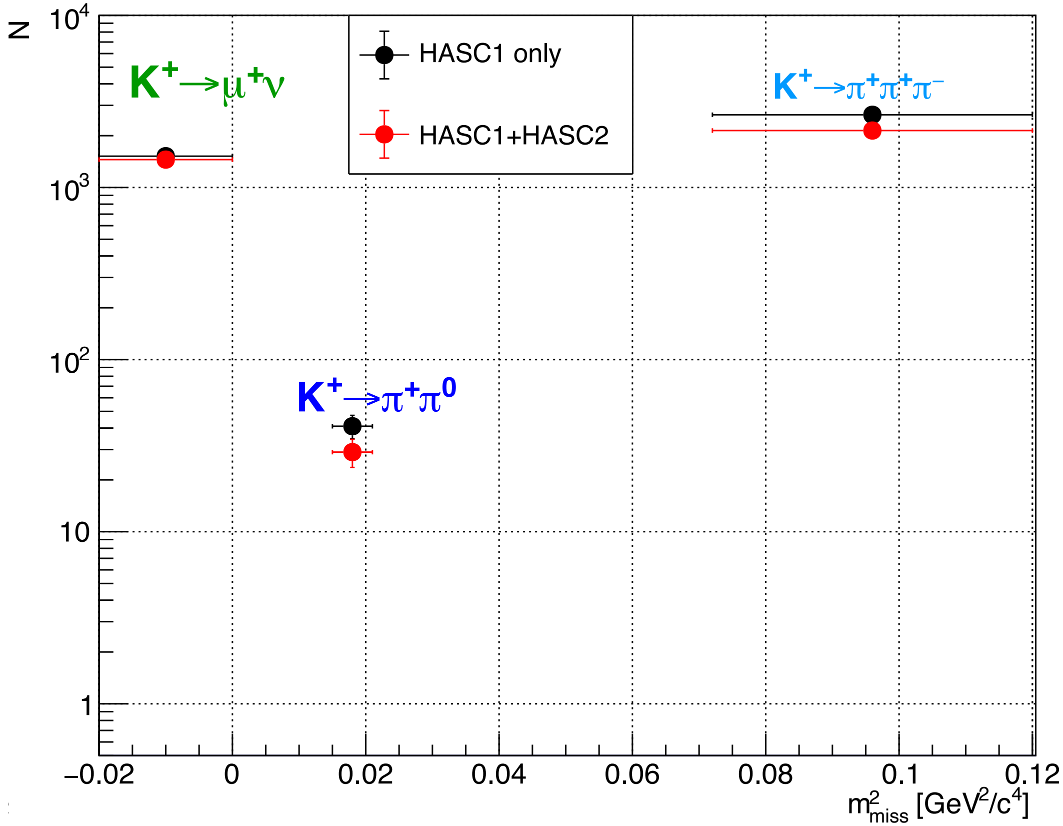
γ-like : candidate in station 2 only.

Background reduction: HASC2



Background reduction: HASC2

Addition of HASC2 suppresses the $K^+ \to \pi^+\pi^0$ and $K^+ \to \pi^+\pi^+\pi^-$ backgrounds by ~35% and ~20% respectively, without noticeable increase in random veto ($K^+ \to \mu^+\nu_\mu$)

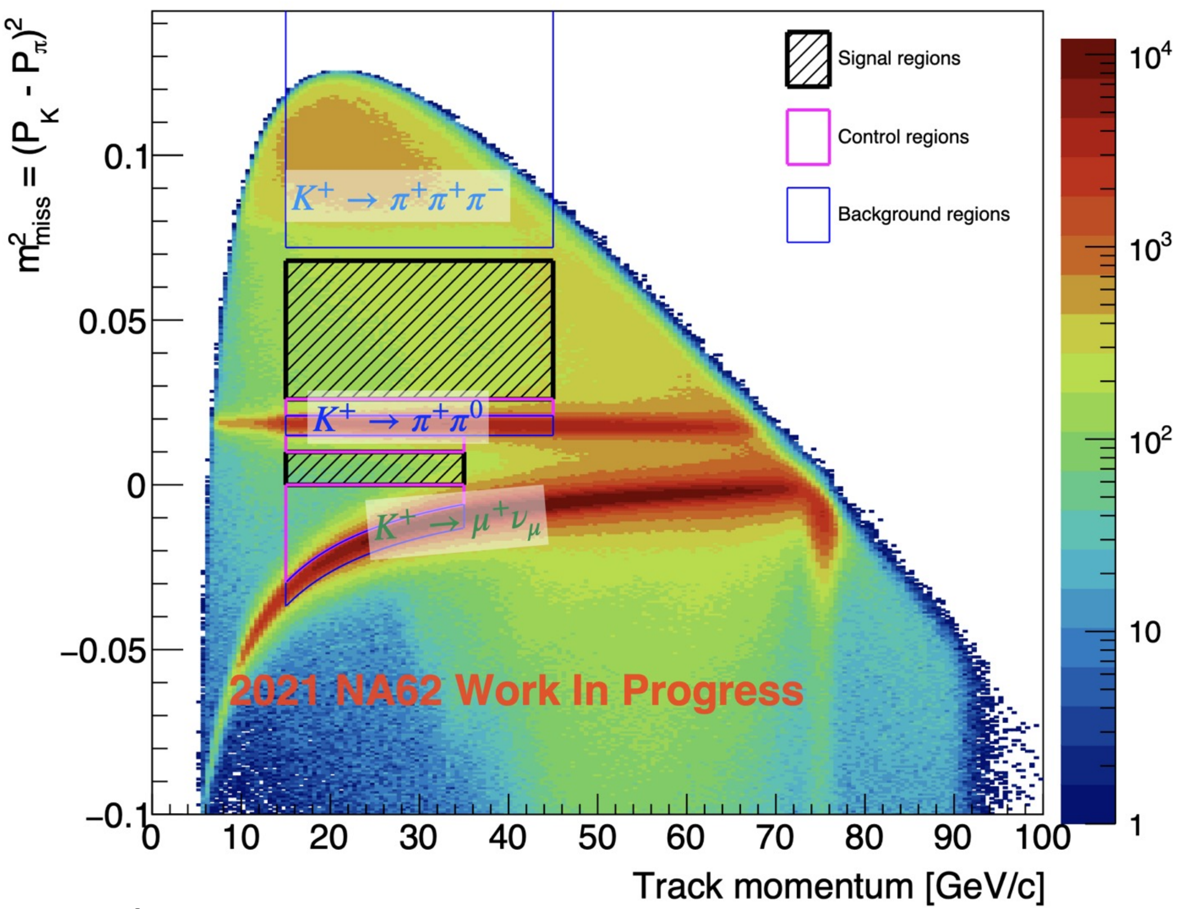


$K^+ \to \pi^+\pi^0$ background, formerly the second largest, now suppressed to a similar level to the $K^+ \to \mu^+\nu_\mu$ decay.

NA62: 2021 data quality

Control data, before selection.

First step: 2018-like analysis, same strategy and regions.



Data quality good enough.

Statistically similar to 2017

Analysis in progress.

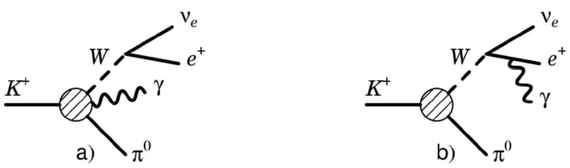
Background studies on-going. All control and signal regions kept blind.

Highlights of other analyses

NA62: Other analysis on Run1 data

Test of ChiPT with $K^+ \to \pi^0 e^+ \nu \gamma$

DE (a) + IB (b) + INT



[PoS EPS-HEP2021 553]

$$R_j = \frac{\mathcal{B}(Ke3\gamma^j)}{\mathcal{B}(Ke3)} = \frac{\mathcal{B}(K^+ \to \pi^0 e^+ \nu\gamma \mid E_\gamma^j,\, \theta_{e,\gamma}^j)}{\mathcal{B}(K^+ \to \pi^0 e^+ \nu(\gamma))}$$

	E_γ^i	$\theta_{e\gamma}^i$	ChPT $O(p^6)$	NA62 (preliminary)
$R_1 \times 10^2$	$E_\gamma > 10$ MeV	$\theta_{e\gamma} > 10°$	1.804 ± 0.021	$1.684 \pm 0.005 \pm 0.010$
$R_2 \times 10^2$	$E_\gamma > 30$ MeV	$\theta_{e\gamma} > 20°$	0.640 ± 0.008	$0.599 \pm 0.003 \pm 0.005$
$R_3 \times 10^2$	$E_\gamma > 10$ MeV	$0.6 < \cos\theta_{e\gamma} < 0.9$	0.559 ± 0.006	$0.523 \pm 0.003 \pm 0.003$

LFV and LNV searches

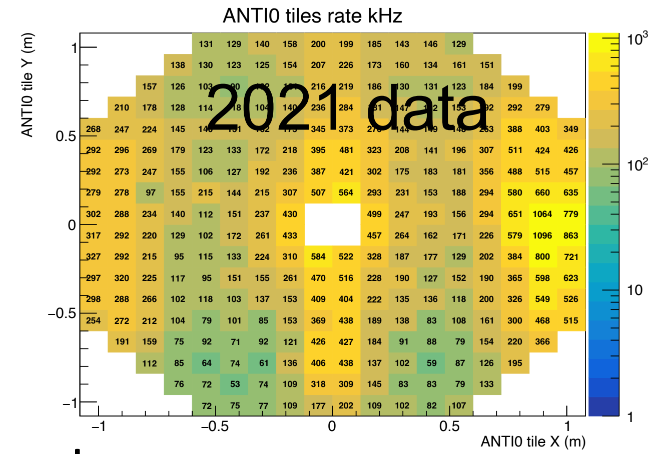
2017 and 2018 data

Blind analyses

[Phys Rev Lett 127 (2021) 131802]

$$\begin{aligned}
\mathcal{B}(K^+ \to \pi^- e^+ e^+) &< 5.3 \times 10^{-11}, \\
\mathcal{B}(K^+ \to \pi^- \pi^0 e^+ e^+) &< 8.5 \times 10^{-10}, \\
\mathcal{B}(K^+ \to \pi^- \mu^+ \mu^+) &< 4.2 \times 10^{-11}, \\
\mathcal{B}(K^+ \to \pi^- \mu^+ e^+) &< 4.2 \times 10^{-11}, \\
\mathcal{B}(K^+ \to \pi^+ \mu^- e^+) &< 6.6 \times 10^{-11}, \\
\mathcal{B}(\pi^0 \to \mu^- e^+) &< 3.2 \times 10^{-10}.
\end{aligned}$$

NA62 in dump mode



Long decay volume and detector performances: suitable to search for feebly-interacting particles

Impinge protons directly on Fe/Cu collimators.

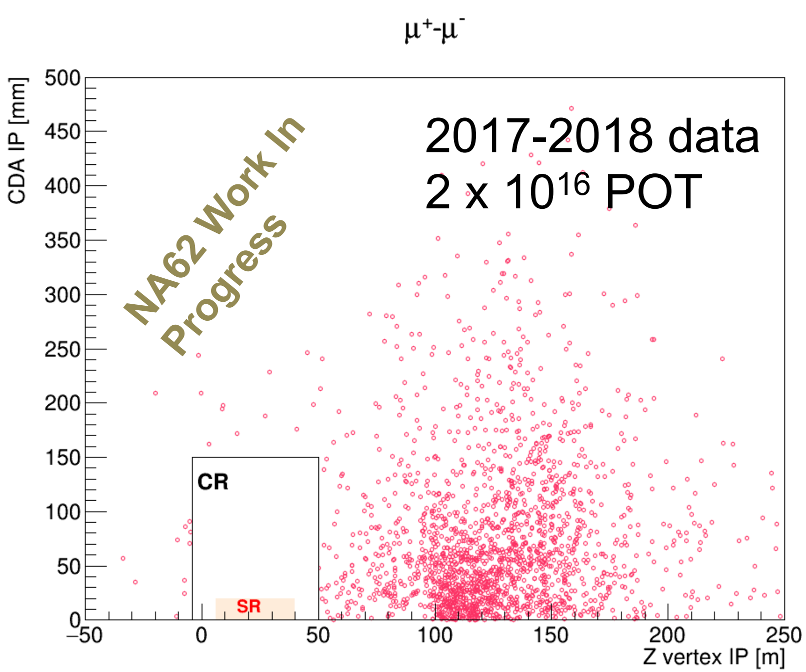
Quick to switch to dump mode.

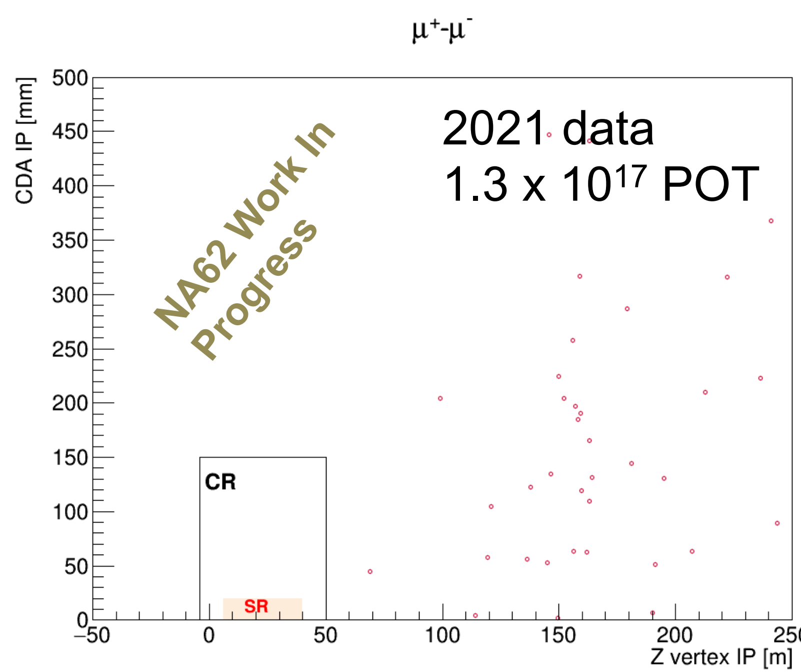
Anti0 Hodoscope instruments the entrance of decay volume.

Beam line magnet (BEND2) tuning for increased muon sweeping.

About 10 days of dump mode taken in 2021, at ~150% nominal intensity.

Collected about 1.3 x10^{17} POT. Data analysis started.

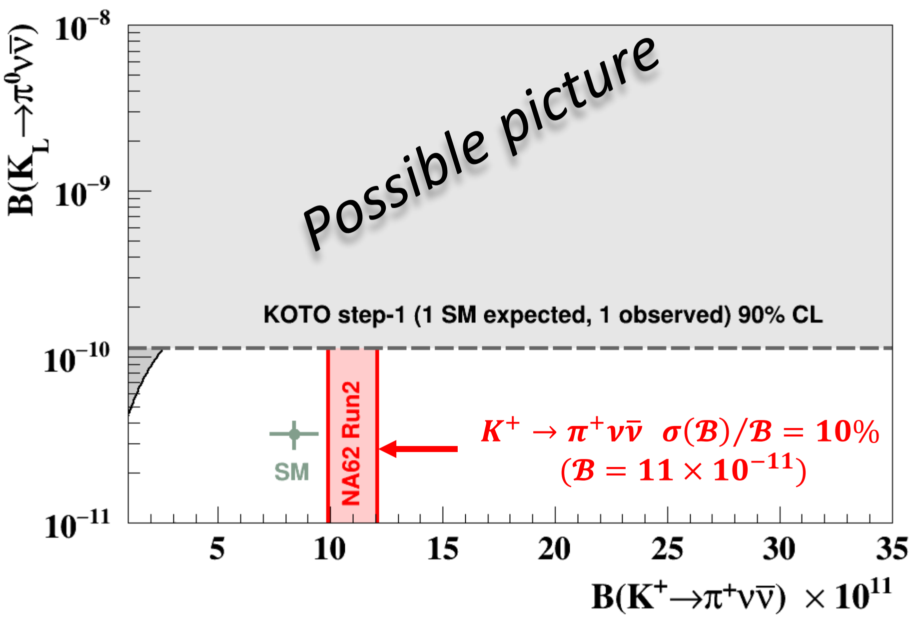


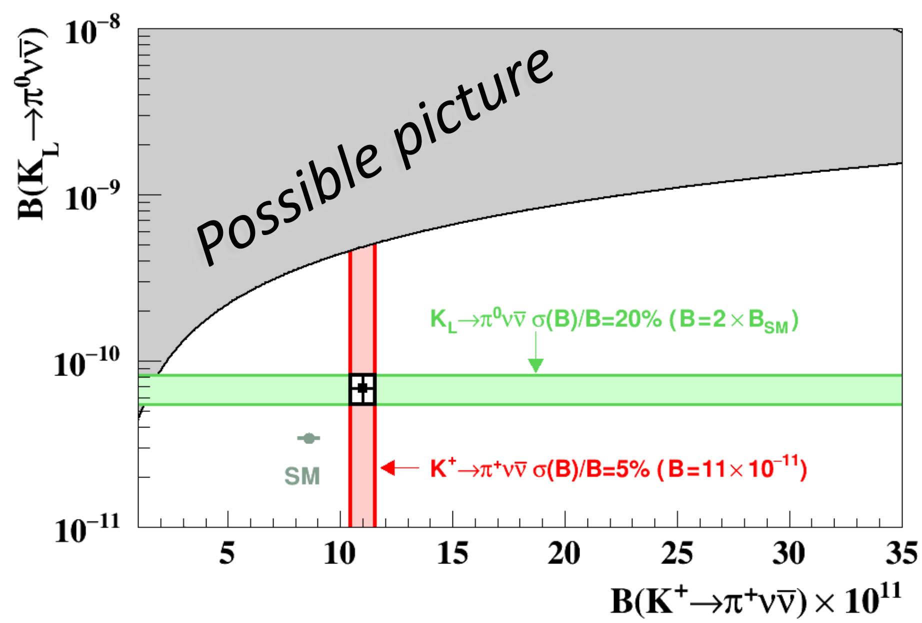


Clear opportunity in the Kaon sector

Going beyond 10% measurement on $K^+ \to \pi^+ \nu\nu$

Precision measurements of BRs can provide model-independent tests for new physics at mass scales of up to O(100 TeV)





Approach ultimate theory error, possibility to find clear evidence of deviation from SM

High-Intensity Kaon Experiments (HIKE) at the SPS

EU Strategy deliberation document: **CERN-ESU-014.** “Rare kaon decays at CERN”
mentioned: “**Other essential activities for particle physics**”

Broad programme with multiple phases, K^+ + K_L beams and dump mode.
Exceptional sensitivity to discovery new physics:
Rare K decays, precision measurements , exotic particles in K/dump
FCNC in K are complementary to B in testing LFUV with comparable sensitivity

HIKE Timeline:

Modification of Target and TAX to stand 6 x NA62 nominal intensity by 2028
Step 1 after LS3: K^+ @ 400% intensity:
Reach ultimate theory error $K^+ \to \pi^+ \nu\nu$ decays, +other K^+ physics, + dump.
Step 2: switch to K_L mode @ 600% intensity:
Transition: K_L rare decays with tracking & PID. Periodic dump mode.
$K_L \to \pi^0 \nu\nu$ decays

First phase: K^+ : ~7 x 10^{18} pot/year (4x increase wrt NA62)
Second phase: K_L : 1 x 10^{19} pot/year (6x increase wrt NA62)

LoI in preparation, aim for submission to SPSC by 2022.

Summary

Experiment restarted operation in 2021.

Detectors in good shape. Data taking reached nominal intensity.

Work to improve spill structure ongoing.

Data analysis just started.

Promising indications for random veto and background suppression.

Broad physics programme to be explored in Run2.

Plans for longer term high-intensity kaon beam experiments.

NA62 is grateful for the steady and proactive support of our Funding Agencies and for the Technical and Administrative help from CERN and all the Collaborating Institutes