Measurement of the Rare Decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at the CERN SPS

NA62 Project (Collaboration NA62)

Theme 02-1-1096-2010/2022

Extension for 2022-2024

Belgium: Université Catholique de Louvain (**Louvain-La-Neuve);**
Bulgaria: University of Sofia St. Kliment Ohridski, Faculty of Physics **(Sofia);**
Canada: TRIUMF, University of British Columbia **(Vancouver);**
Czech Republic: Charles University (**Prague);**
Germany: Johannes-Gutenberg-Universitat Mainz (**Mainz);**
Italy: Università di Ferrara (**Ferrara),** Universita e INFN (**Florence),** Istituto Nazionale di Fisica Nucleare (INFN), Laboratori Nazionali di Frascati **(Frascati),** Universita e INFN (**Naples),** Universita e INFN (**Padua),** Universita e INFN (**Perugia),** Sezione di Pisa, INFN **(Pisa),** Universita degli Studi di Roma Tor Vergata, Sezione di Roma Tor Vergata, INFN (**Rome),** Universita e INFN, Roma I, Sezione di Roma I, INFN**(Rome),** Universita e INFN (**Turin);**
Mexico: Universidad Autónoma de San Luís Potosi, Instituto de Fisica (**San Luis Potosi);**
Romania: Horia Hulubei National Institute of Physics and Nuclear Engineering (**Bucharest-Magurele);**
Russia: Joint Institute for Nuclear Research – JINR (Dubna), Institute for Nuclear Research RAS (**Moscow),** Institute for High Energy Physics, National Research Centre “Kurchatov Institute” (**Protvino);**
Slovakia: Comenius University (**Bratislava);**
Switzerland: Conseil Européen pour la Recherche Nucléaire – CERN (**Geneva)**
United Kingdom: University of Birmingham (**Birmingham),** University of Bristol, H. H. Wills Physics Laboratory (**Bristol),** University of Glasgow (**Glasgow),** University of Liverpool, Oliver Lodge Laboratory (**Liverpool);**
United States of America: Boston University (**Boston),** George Mason University (**Fairfax),** SLAC National Accelerator Laboratory (**Menlo Park),** University of California Merced (**Merced),** Brookhaven National Laboratory (BNL) (**Upton).**

Лаборатория физики высоких энергий

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Руководители проекта: Кекелидзе В.Д. (ЛФВЭ)
Потребеников Ю.К. (ЛФВЭ)

Laboratory of High Energy Physics

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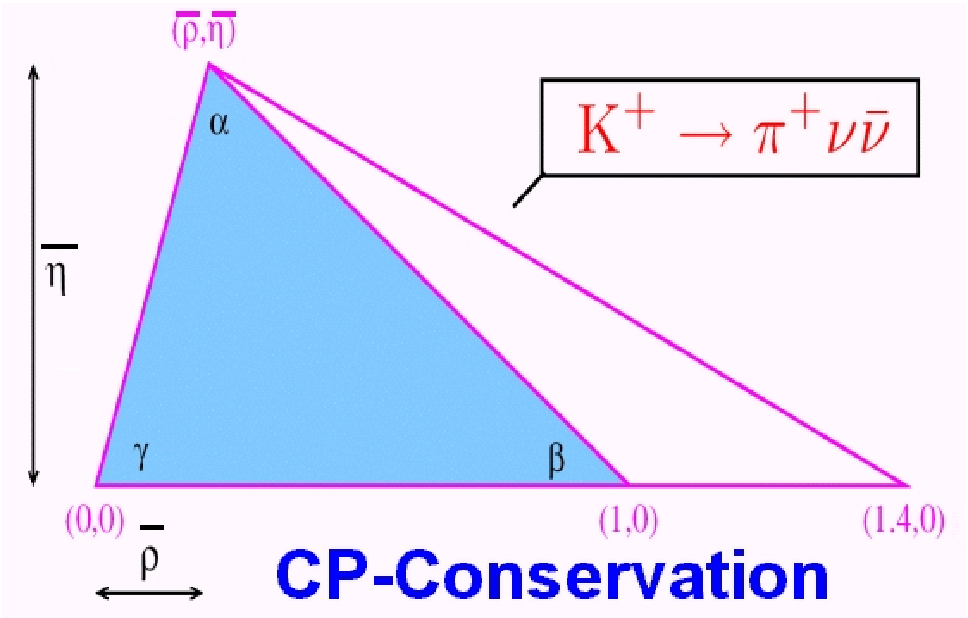
E. Goudzovski, D. Emelyanov, T. Enik, V. Falaleev, T. Mauei, V. Kekelidze, D. Kereibay, A.Korotkova, D.Madigozhin, M. Misheva, N. Molokanova, S. Movchan, I. Polenkevich,

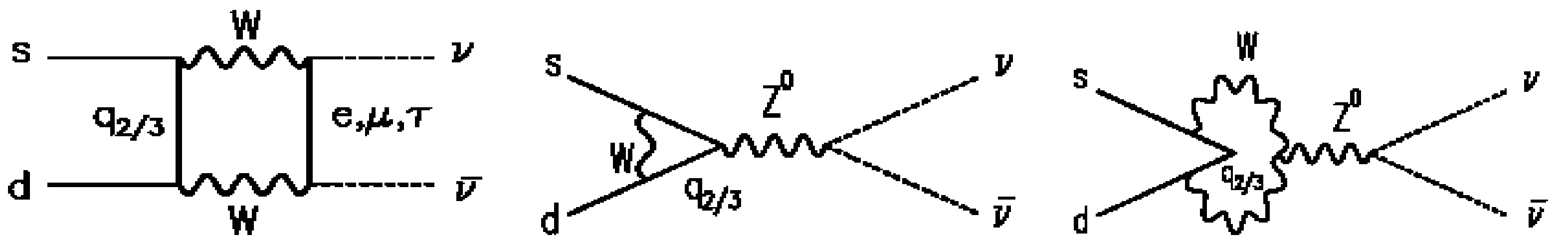
Yu. Potrebenikov, S. Shkarovskiy

Project leaders: Kekelidze V.D. (LHEP)
Potrebenikov Yu.K. (LHEP)

NA62 motivation



The "golden decays" $K^0 \to \pi^0 \nu\bar\nu$ and $K^+ \to \pi^+ \nu\bar\nu$ give an opportunity to make a very sensitive tests of SM, as their probabilities are directly related to η^2 (height of triangle) and $(\rho - 1.4)^2 + \eta^2$ in Wolfenstein notation of CKM.



- $K^+ \to \pi^+ \nu\bar\nu$ is theoretically clean, hadronic matrix element measured with K_{l3} decays
- SM predictions [Phys. Rev. D 83 034030 (2011), JHEP11 (2015) 033]:

$$BR(K^+ \to \pi^+ \nu\bar\nu) = (8.4 \pm 1.0) \times 10^{-11}$$

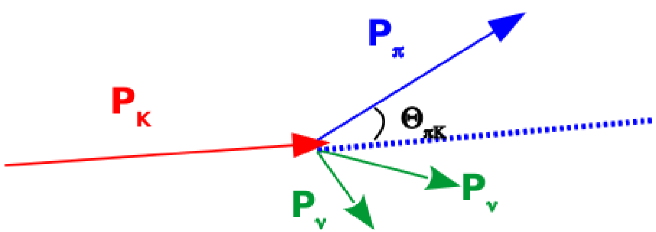
- The currently available experimental result is based on **7 events** [BNL, K decays at rest. Phys. Rev. D 79, 092004 (2009)] :

$$BR(K^+ \to \pi^+ \nu\bar\nu) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$

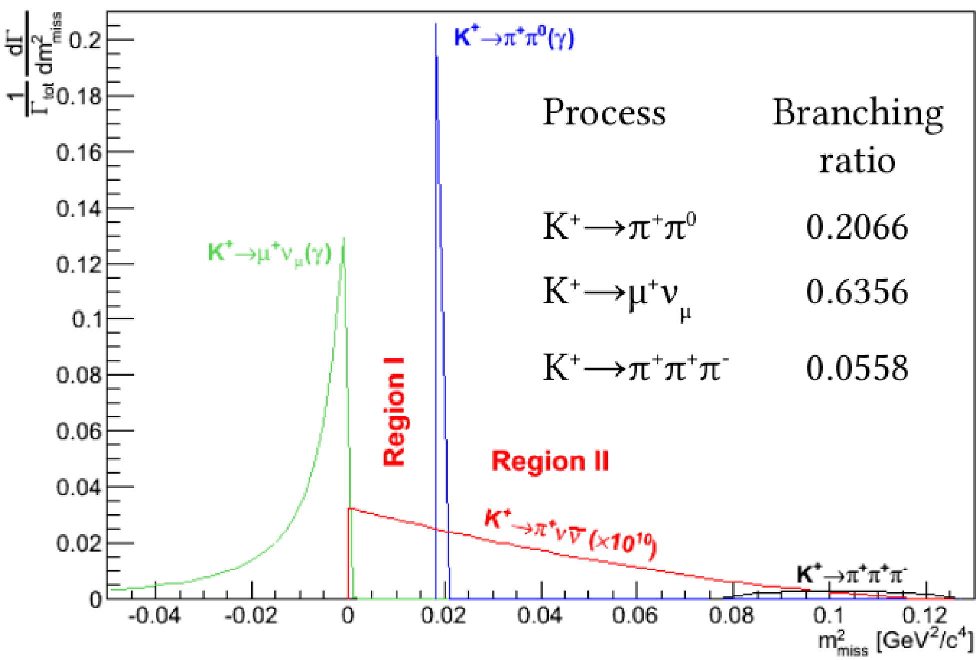
NA62 $\pi\nu\bar{\nu}$ strategy

NA62 ultimate goal is ~ 10% precision for $Br(K^+ \rightarrow \pi^+\nu\bar{\nu})$ that assumes ~ 100 reconstructed events and a small background.

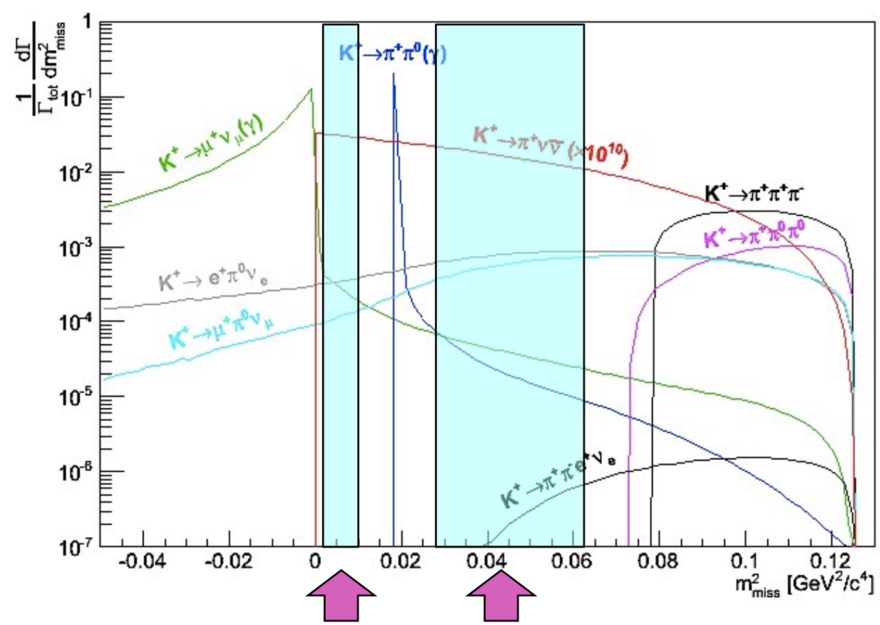
Decay in flight technique $m^2_{miss} = (P_K - P_{\pi^+})^2$



- Keystones of the analysis:
  - Timing between sub-detectors ~ O(100 ps)
  - Kinematic suppression ~ $O(10^4)$
  - Muon suppression > 10^7
  - π^0 suppression (from $K^+ \rightarrow \pi^+\pi^0$) > 10^7

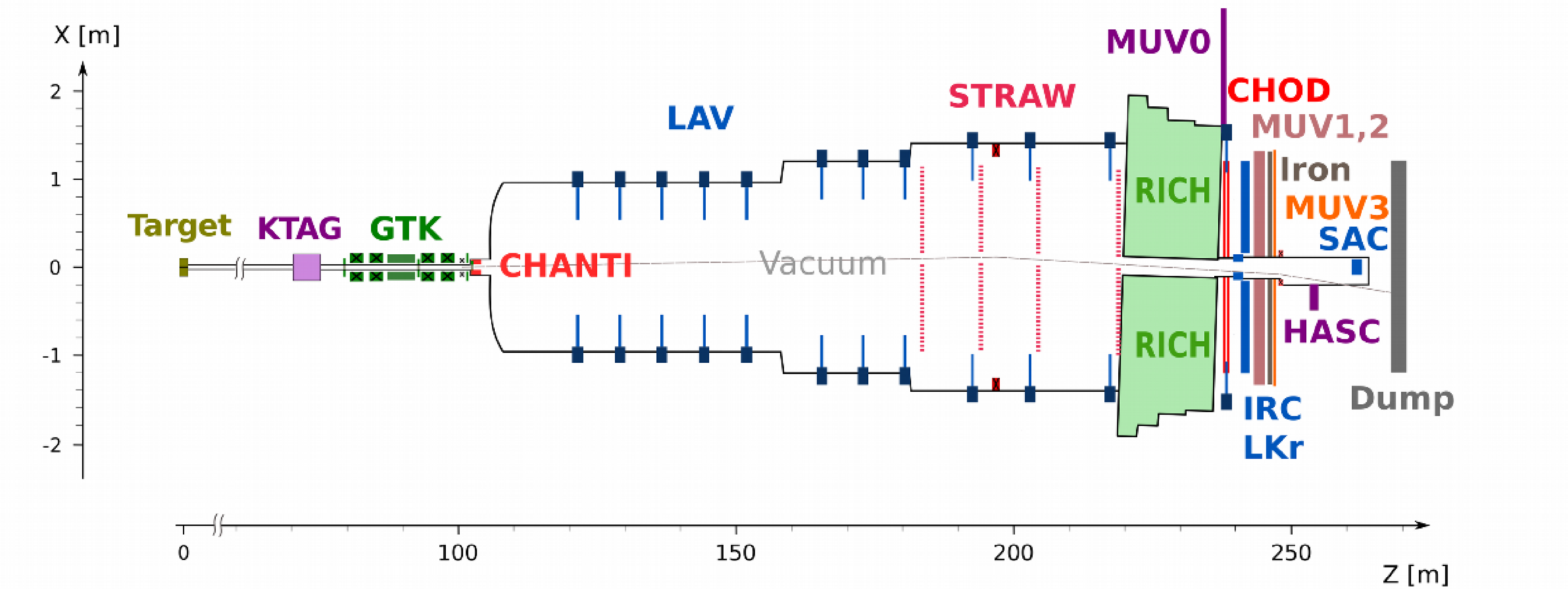


Process	Branching ratio
$K^+\rightarrow\pi^+\pi^0$	0.2066
$K^+\rightarrow\mu^+\nu_\mu$	0.6356
$K^+\rightarrow\pi^+\pi^+\pi^-$	0.0558



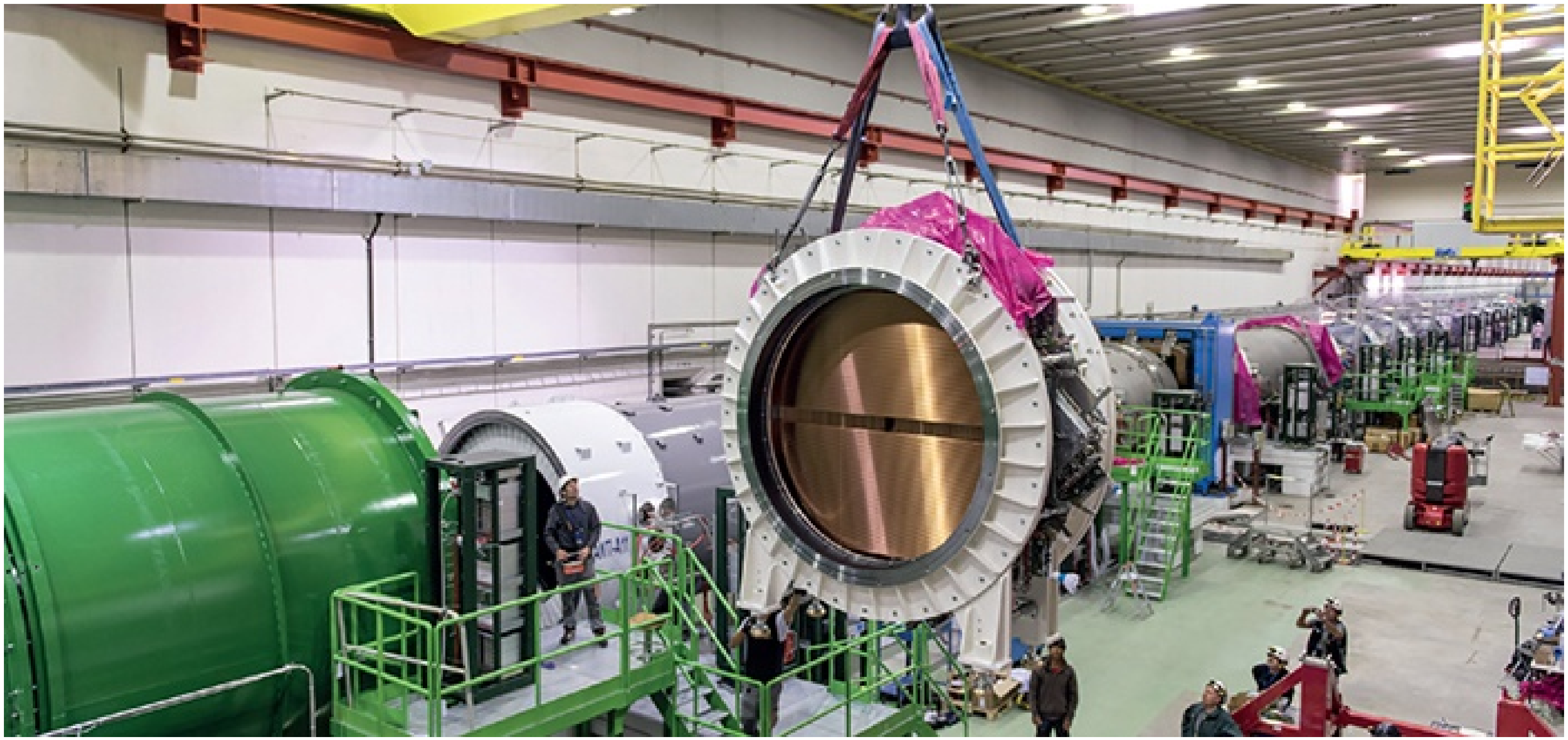
- History of JINR in CERN kaon decays program: NA48,NA48/1,NA48/2, NA62(R_K).
- Analysis of NA48/2 data is still ongoing (at final stage, and we are involved).
- NA62 inherits some elements of NA48/2, but it is a really novel setup that solves a new challenging task.

NA62 beam and detector



- **SPS Beam:**
  - 400 GeV/c protons
  - 10^{12} protons/spill
  - 3.5s spill
- **Secondary positive Beam:**
  - 75 GeV/c momentum, 1 % bite
  - 100 μrad divergence (RMS)
  - 60x30 mm² transverse size
  - $K^+(6\%)/\pi^+(70\%)/p(24\%)$
  - 33×10^{11} ppp on T10 (750 MHz at GTK3)
- **Decay Region:**
  - 60 m fiducial region
  - ~ 5 MHz K^+ decay rate
  - Vacuum ~ $O(10^{-6})$ mbar

JINR+CERN responsibility :
Spectrometer made of straw tubes working in vacuum

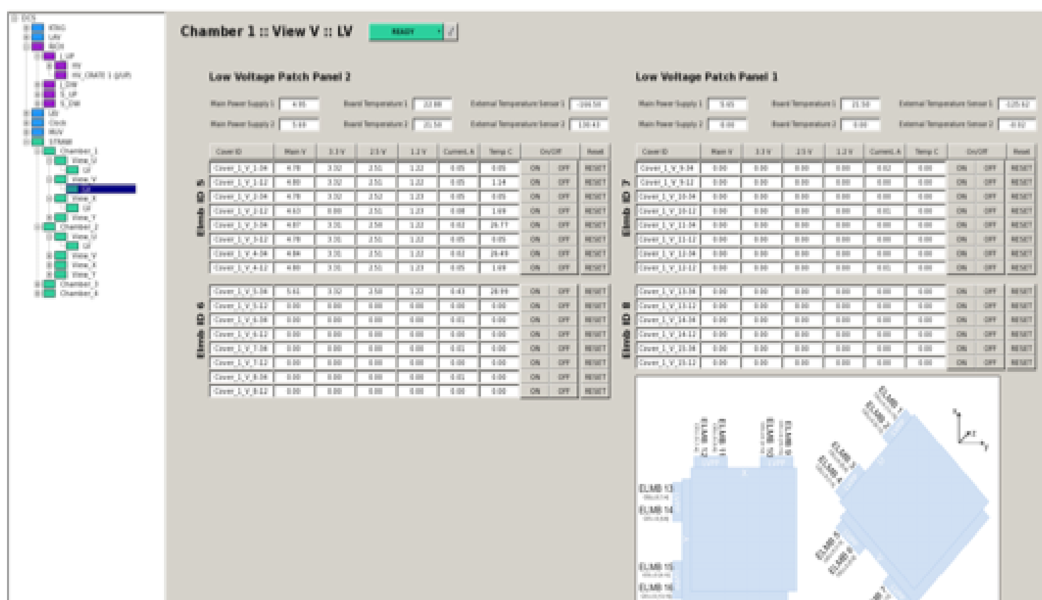


JINR contribution is very important and is defining in many aspects:

- R&D (2 prototypes),
- MC simulation,
- Straws geometry,
- Frames etc. design,
- straws production (~7000 in JINR),
- Modules assembling.

Installed in 2014.

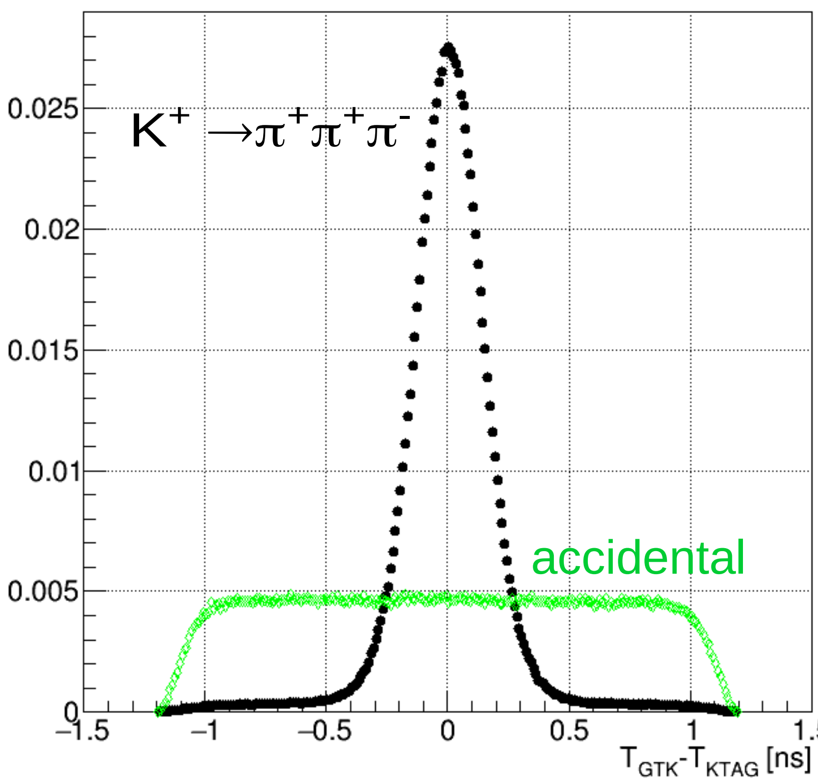
HV and LV power suppliers



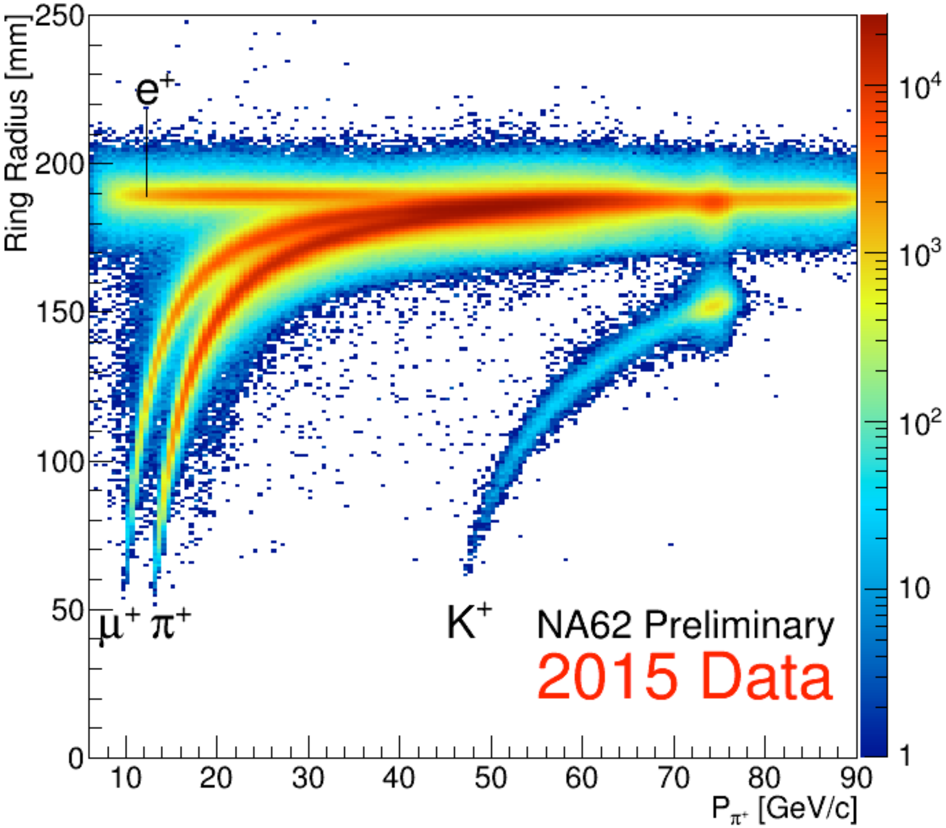
Detector Control System (DCS) for the NA62 Spectrometer

NA62 $\pi\nu\nu$

- 2014 Pilot run
- 2015 Comissioning run
- Full detector installation completed in September 2016.
- First $\pi\nu\bar{\nu}$ dataset in the end of 2016
- Continuous data taking until the end of 2018 (prolongation after 2020)



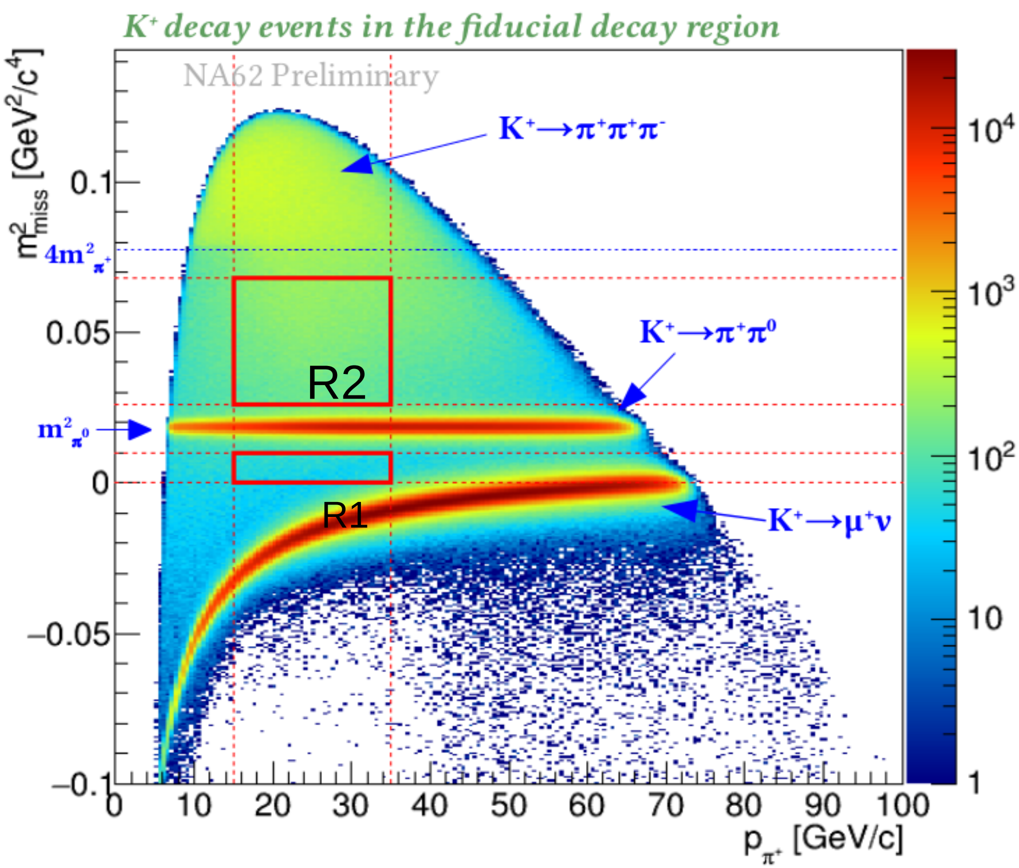
GTK and KTAG (CEDAR) time difference distributions



RICH ring radius vs the track momentum

Blind analysis strategy to avoid the influence of selection criteria variation:

- Signal region is predefined and closed.
- Selection is developed looking on the background regions and MC.
- Signal region is opened, events are counted, selection is frozen.

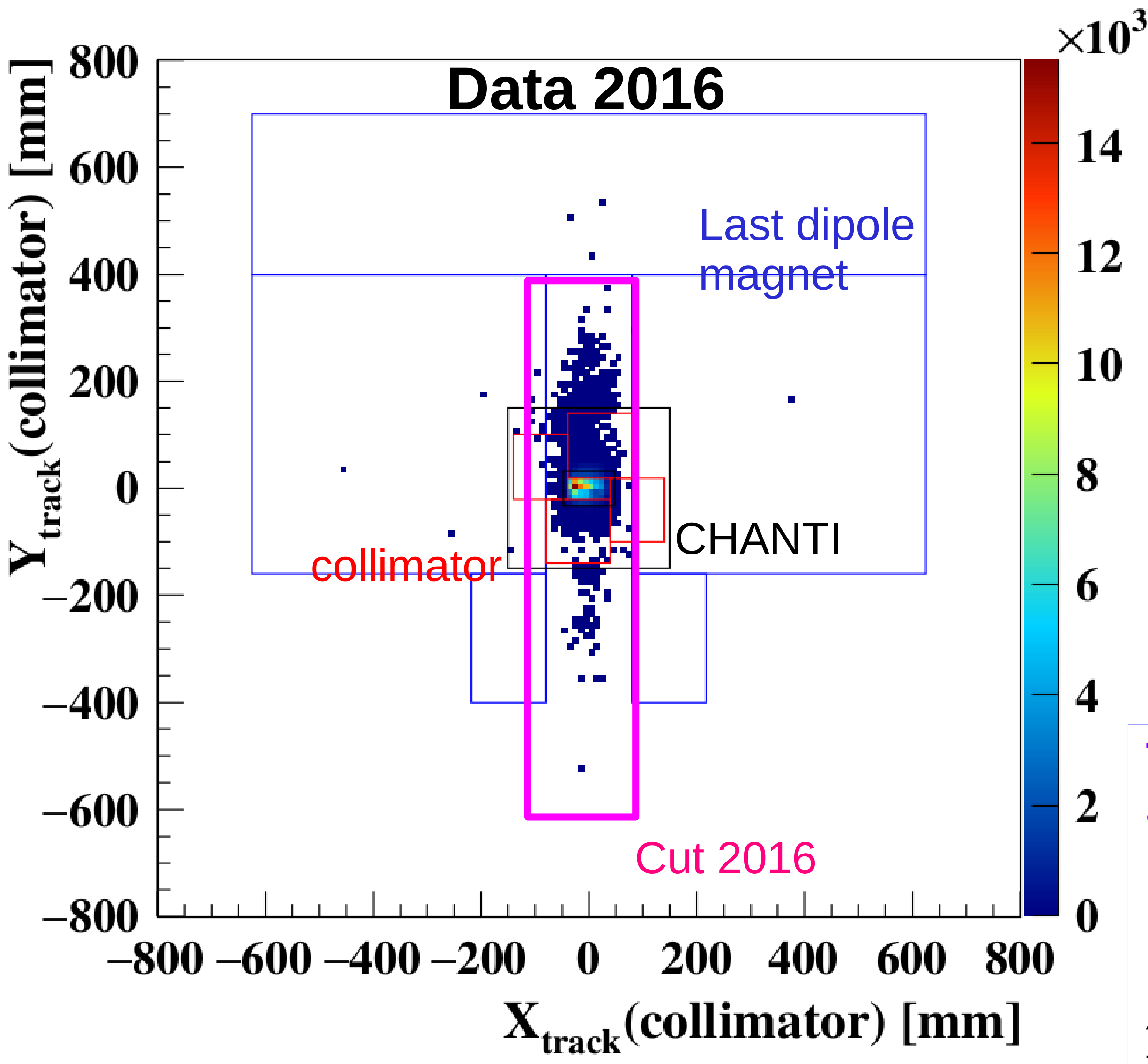


Signal regions R_1 and R_2

- **Selection criteria**
  - single track decay topology
  - π^+ identification
  - photon rejection
  - multi-track rejection

- **Performance**
  - $\epsilon_{\mu^+} = 1 \cdot 10^{-8}$ (64% π^+ efficiency)
  - $\epsilon_{\pi^0} = 3 \cdot 10^{-8}$
  - $\sigma(m^2_{miss}) = 1 \cdot 10^{-3}\ \mathrm{GeV}^2/c^4$
  - $\sigma_T \sim O(100\ \mathrm{ps})$

Unexpected "upstream background" problem



Pion track projections to the last collimator before decay volume: Artificially background-enriched by inverting tracks multiplicity cut.

- The last dipole of the beam line changes direction of π from upstream decays (interactions) happened in the beam line.
- The pion pass the existing shielding.
- Accidentally this pion crosses some kaon path and forms a vertex in decay volume.

- Additional shielding from the second part of 2017 run.
- Enlarged cut on the pion position on the last collimator.

The cost of the cut for $\pi\nu\nu$ acceptance:

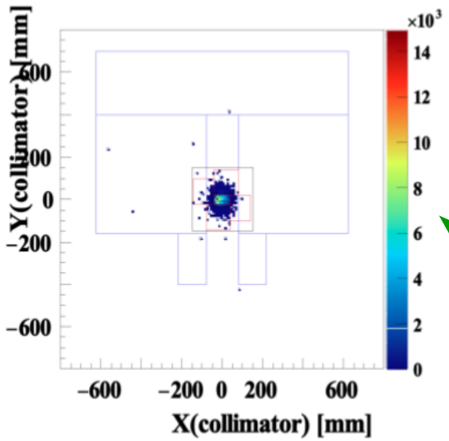
3-4% instead of 10%

A better shielding design and search for the upstream background off-line rejection where needed.

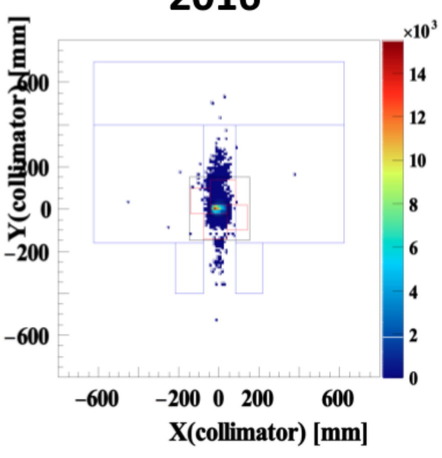
A new **Fixed collimator** (tons of iron with a hole) has improved NA62 upstream background situation dramatically.

Upstream backgrounds are significantly reduced by the introduction of The B6 plug (2017) and the fixed Collimator (2018)

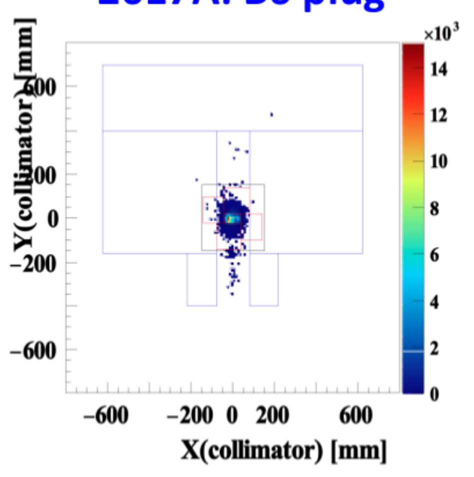
2018: New Collimator



2016



2017A: B6 plug



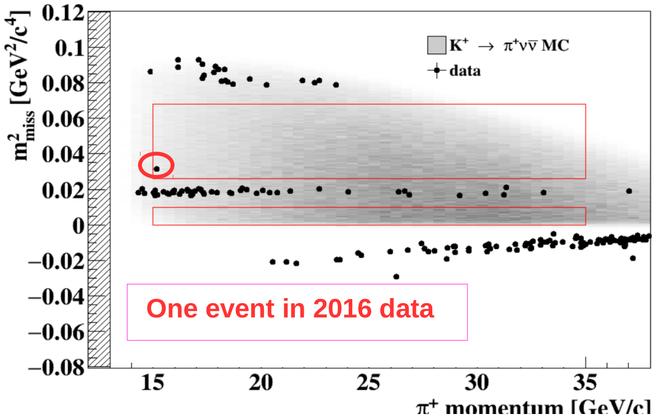
During the LS2 the upgrade of the limiting electronics was done, and now we plan to reach 100% intensity (tests at this intensity were made at the end of 2018 run).

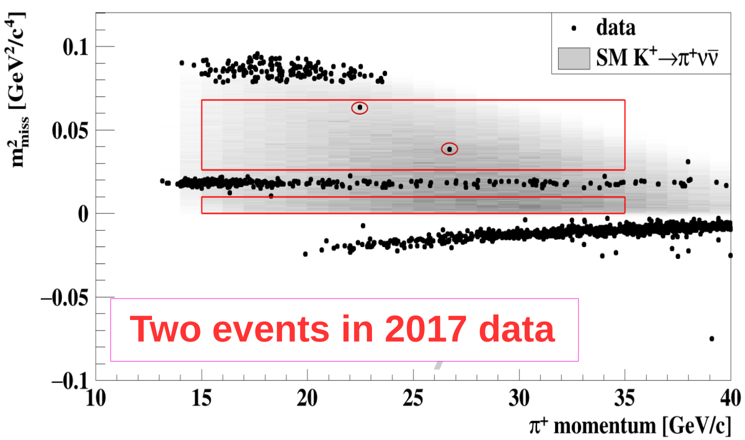
Improvements of signal efficiency (preliminary)

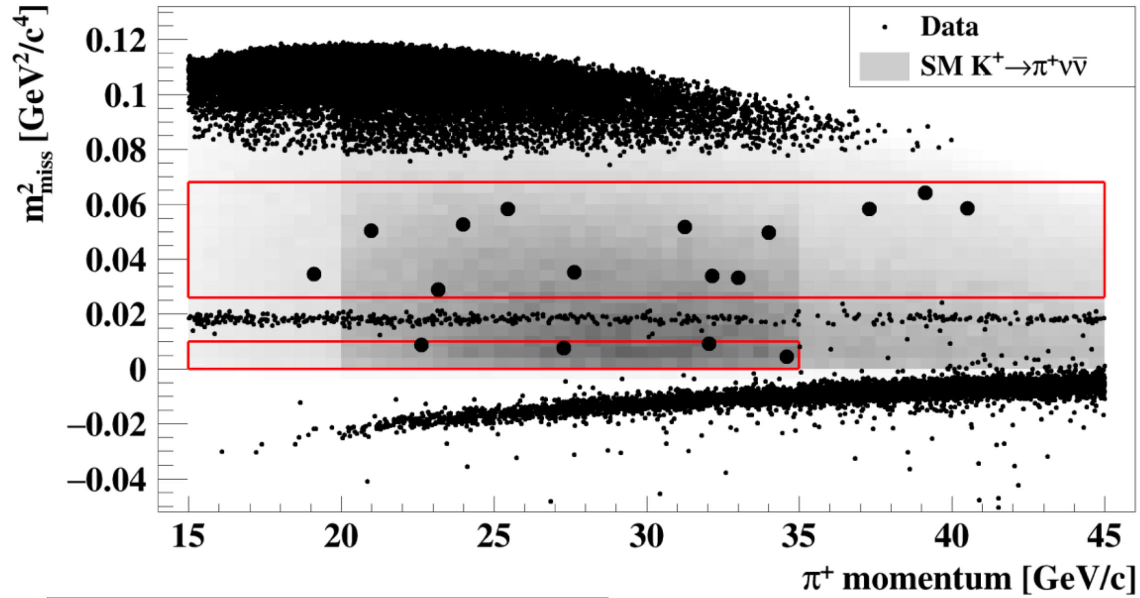
	2017	2018-OLDCOL	2018-NEWCOL
N_K	$(1.5 \pm 0.2) \cdot 10^{12}$	$(0.8 \pm 0.1) \cdot 10^{12}$	$(1.9 \pm 0.2) \cdot 10^{12}$
$A_{\pi\nu\nu}$	$(3.0 \pm 0.3)\%$	$(4.0 \pm 0.4)\%$	$(6.4 \pm 0.6)\%$
ϵ_{RV}	0.64 ± 0.01	0.66 ± 0.01	0.66 ± 0.01
ϵ_{trig}	0.87 ± 0.03	0.88 ± 0.04	0.88 ± 0.04
$N^{exp}_{\pi\nu\nu(SM)}$	2.16 ± 0.29	1.56 ± 0.21	6.02 ± 0.82
B/S	~ 0.7	~ 0.7	~ 0.7

Latest results on rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay (NA62 at CERN SPS)

2014	2015	2016	2017	2018	2019 -2020	2021 - ...
Pilot Run	Commissioning	Commissioning + Physics Run	Physics Run	Physics Run	Long shutdown 2	NA62 Run2







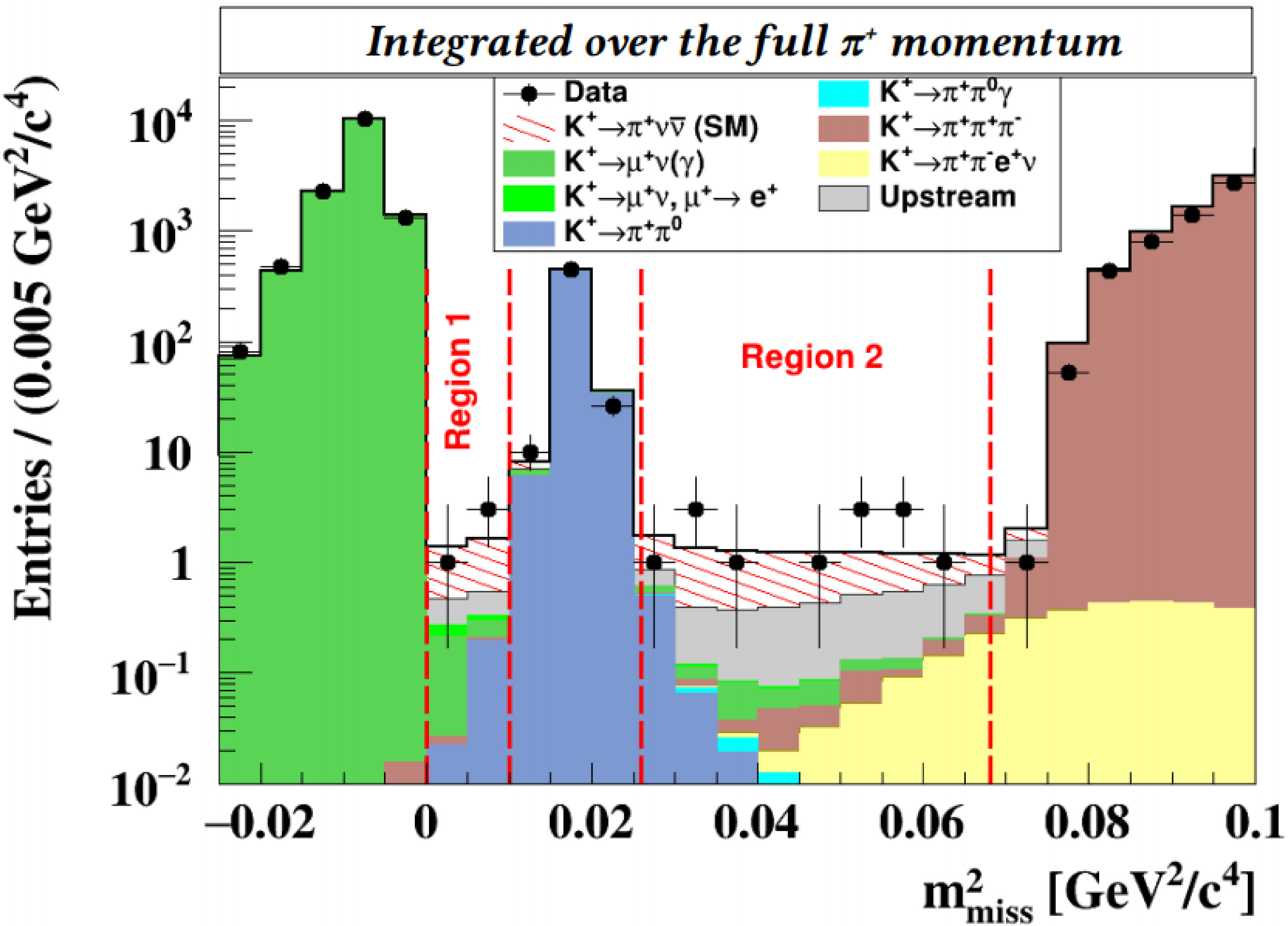
17 events in 2018 data

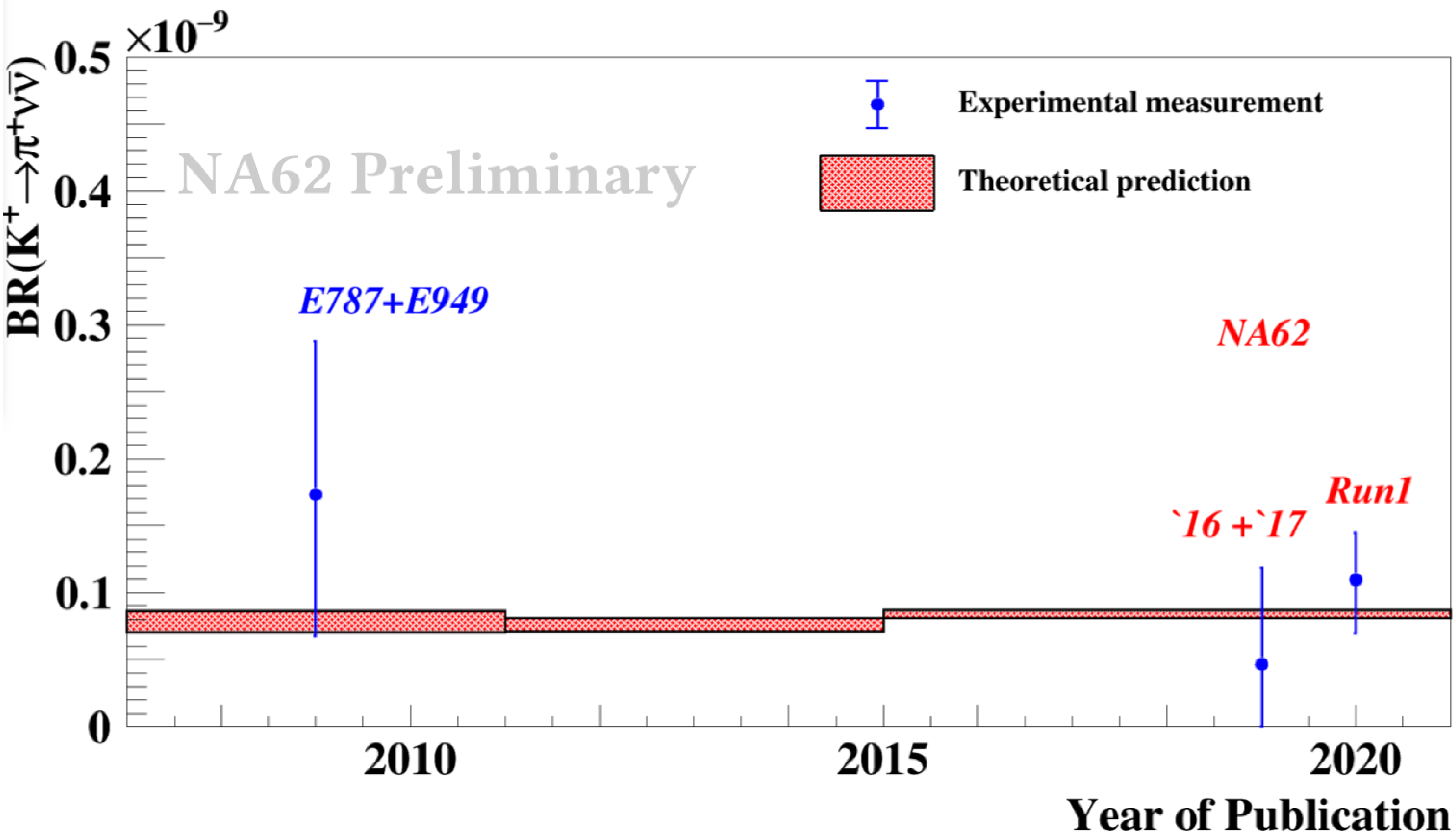
For 2018 data the expected events number (MC SM):

- $K^+ \to \pi^+\nu\bar{\nu}$: $7.58 \pm 0.40_{syst} \pm 0.75_{ext}$
- Background : $5.28\ ^{+0.99}_{-0.74}$

- 2016+2017+2018 (Run 1) [PoS(ICHEP2020)398, CERN-EP-2021-050]:
  $$BR(K^+ \to \pi^+\nu\nu) = (11.0^{+4.0}_{-3.5} \pm 0.3_{syst}) \times 10^{-11}$$
- Standard Model expectation: $(8.4 \pm 1.0) \times 10^{-11}$
- Best earlier result: 2009, E787/E949@BNL, 7 events : $(17.3^{+11.5}_{-10.5}) \times 10^{-11}$
- New runs after 2020 are approved. Initially foreseen ~ 100 events will be reached.

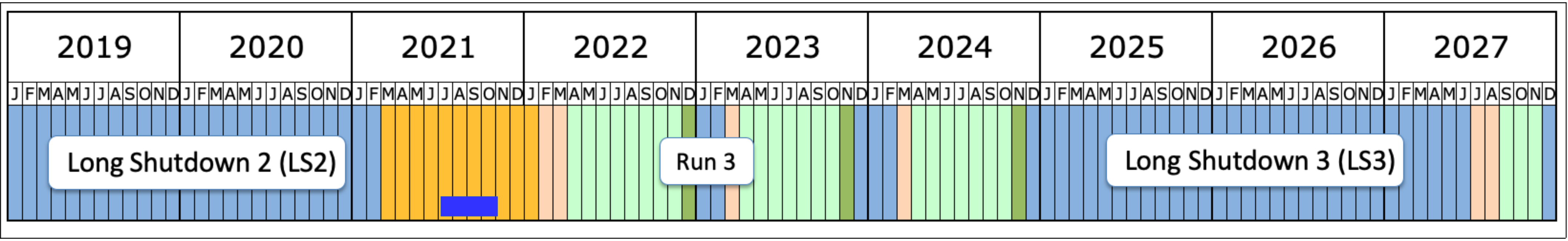
m^2_{miss} signal and background in the 2018 data




$\times 10^{-9}$
0.5
0.4
0.3
0.2
0.1
0
$BR(K^+ \to \pi^+ \nu\bar{\nu})$
NA62 Preliminary
Experimental measurement
Theoretical prediction
E787+E949
NA62
`16 +`17
Run1
2010
2015
2020
Year of Publication

In November 2018 CERN Finance Review Committee has approved a budjet, that assumes NA62 additional runs in 2021 and 2022.

NA62 runs in 2021 from July 12 till November 12

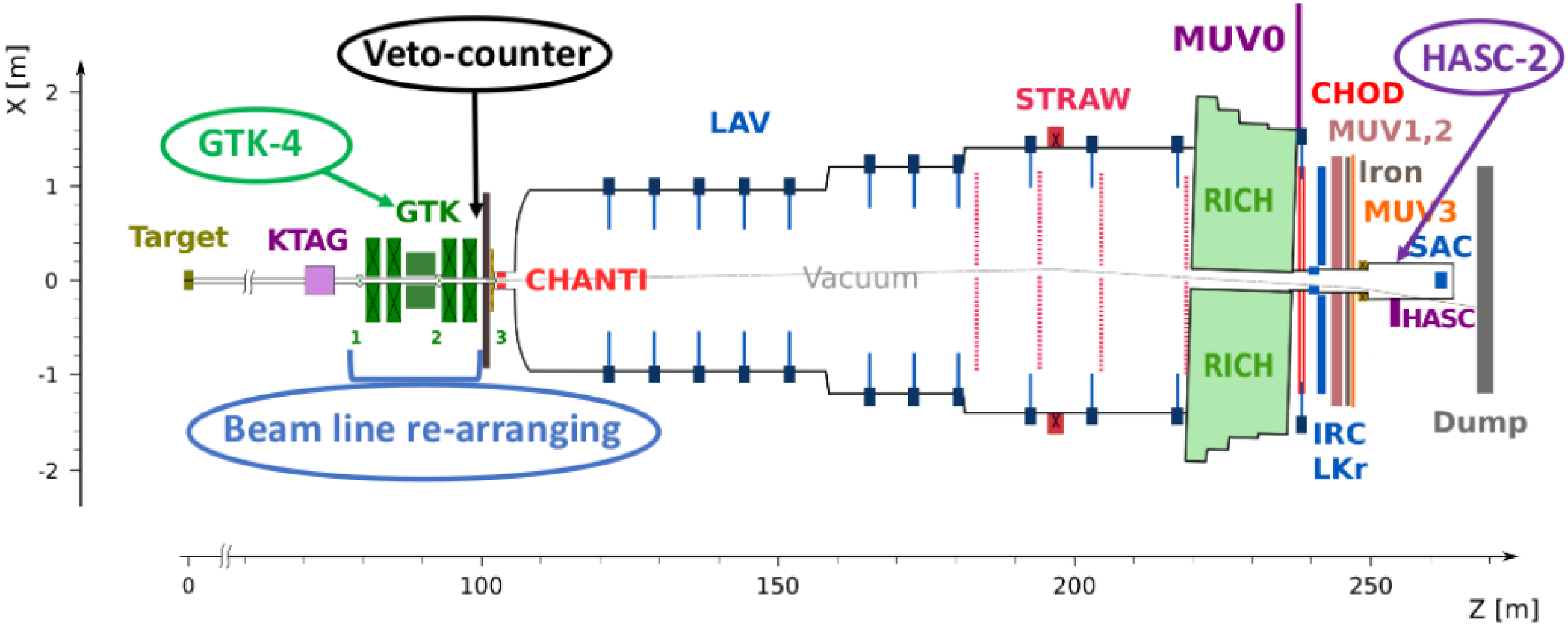


NEW! From the minutes of the CERN SPSC for the April session:

"The Committee congratulates the NA62 Collaboration for achieving the desired improvement in sensitivity and acceptance, and for the release of the (to-date) best determination of the K+->pi+ nu nubar decay rate.

The SPSC is looking forward to the additional improvements and reduction of backgrounds expected for the 2021 run, which would allow the experiment approaching the level of the theoretical uncertainties of the decay process. The Committee recognises that the experimental precision at the level of the theoretical uncertainties is only achievable with running over the full period until Long Shutdown LS3, ***thus recommends approval of NA62 up to LS3****."*

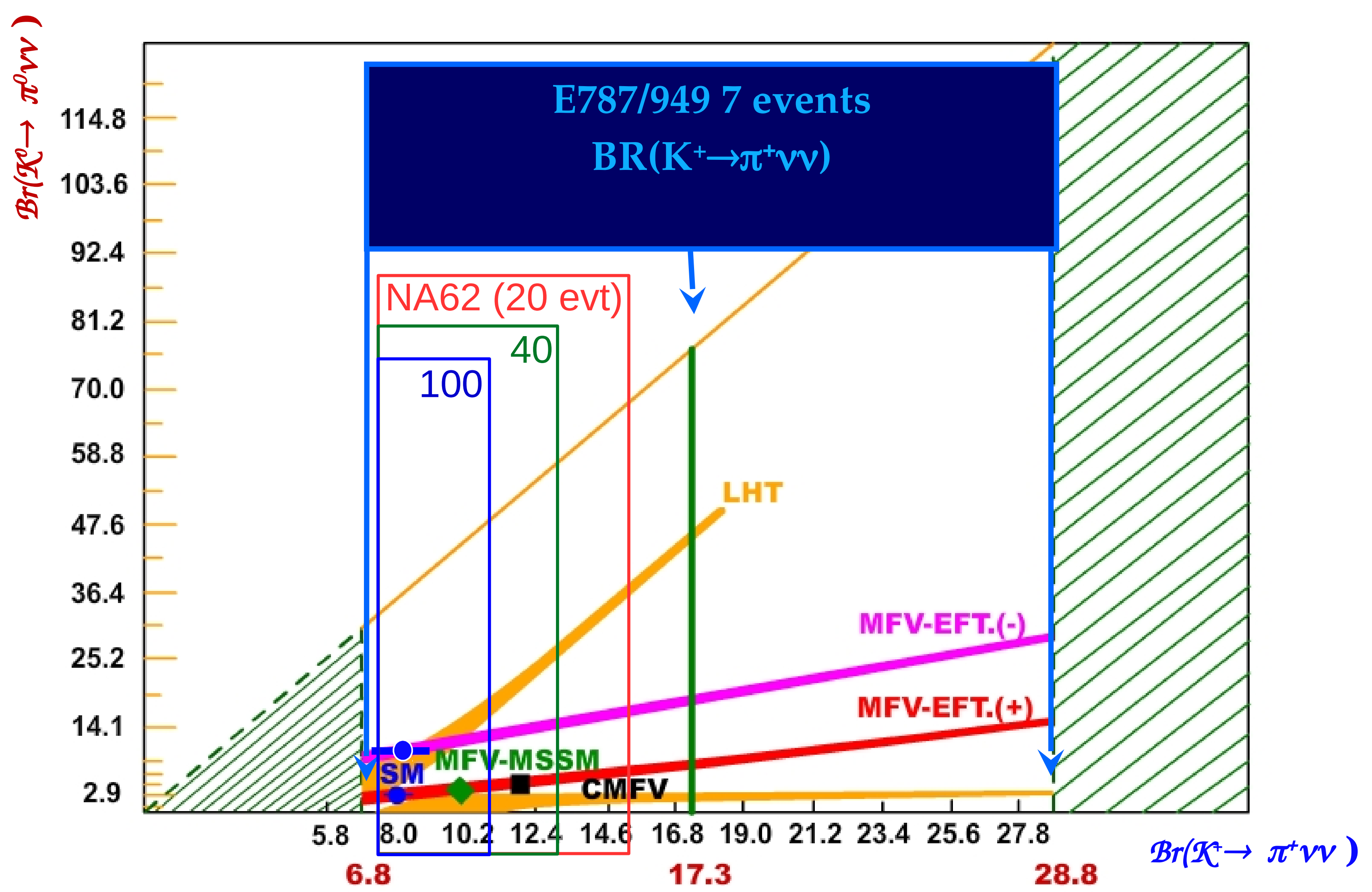
Prospects for $Br(K^+ \to \pi^+ \nu \bar{\nu})$ measurement



Data taking between CERN LS2 and LS3

- Upstream background suppression: beam line re-arranging to swip away *upstream* π^+, adding a fourth Gigatracker station (GTK-4), new veto-counter system to detect upstream decays products
- additional off-axis calorimeter (HASC-2) to further suppress $K^+ \to \pi^+ \pi^0$ background
- **goal**: $Br(K^+ \to \pi^+ \nu \bar{\nu})$ measurement with $O(10\%)$ statistical precision

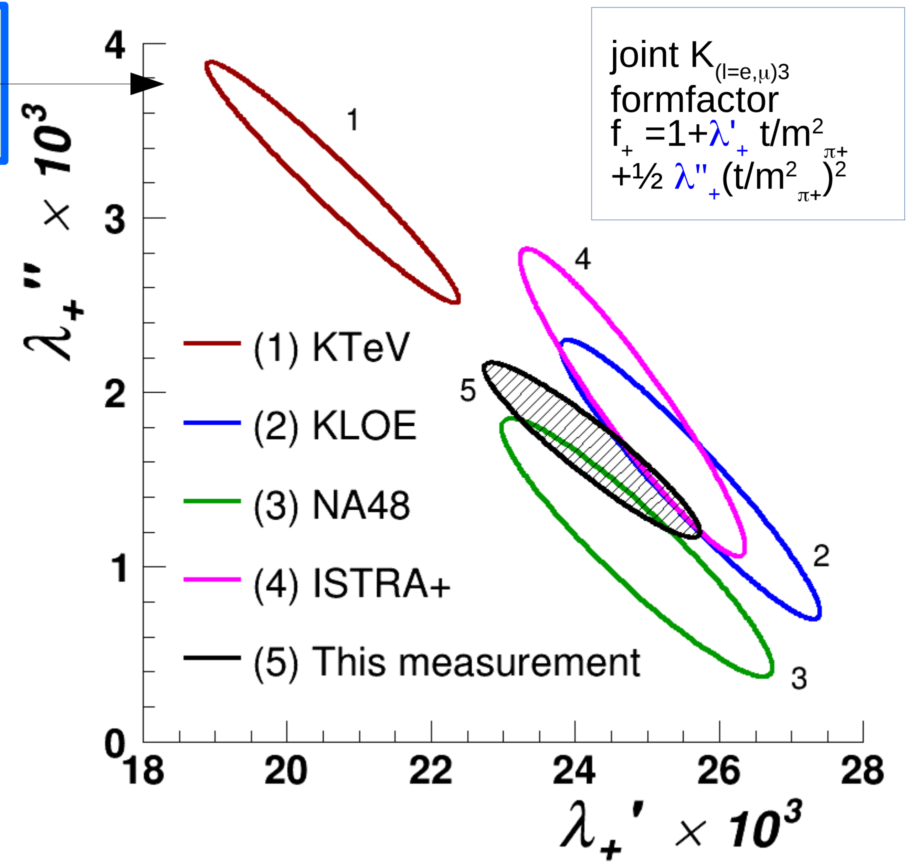
Worst scenario: 40 SM events, plan: 100 SM events.



Currently no real competition:
Old JPARC and FNAL projects were abandoned (costs)

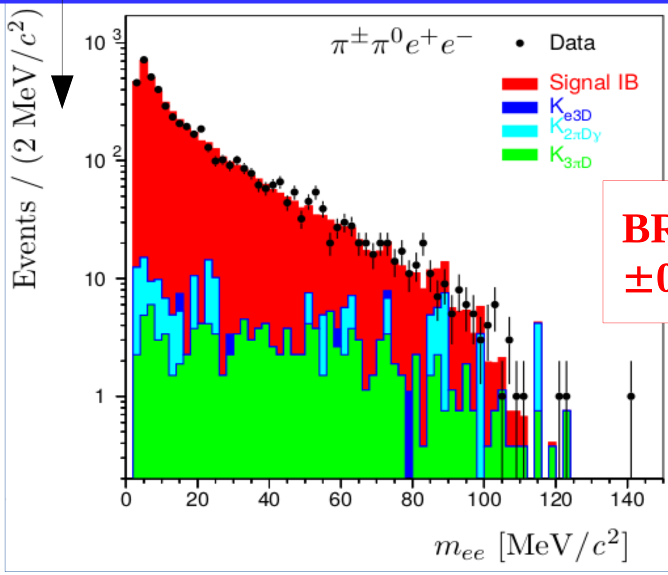
JINR II prize (2019)

$K^\pm \to \pi^0 l^\pm \nu$ (K_{l3}) form factors
JHEP 1810 (2018) 150.



NA48/2

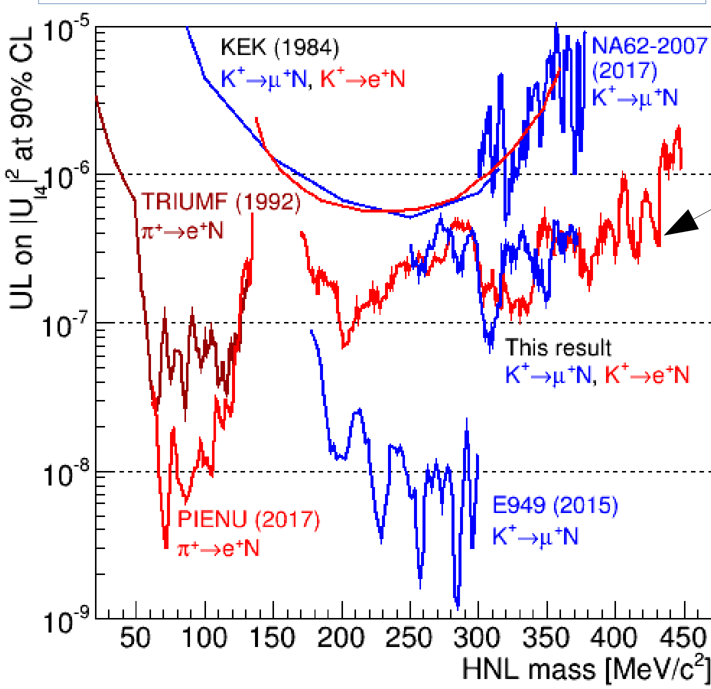
First observation $K^\pm \to \pi^\pm \pi^0 e^+ e^-$ decay
Phys.Lett. B788 (2019) 552



BR = $(4.237 \pm 0.063_{stat} \pm 0.033_{syst} \pm 0.126_{ext}) \, 10^{-6}$

NA62

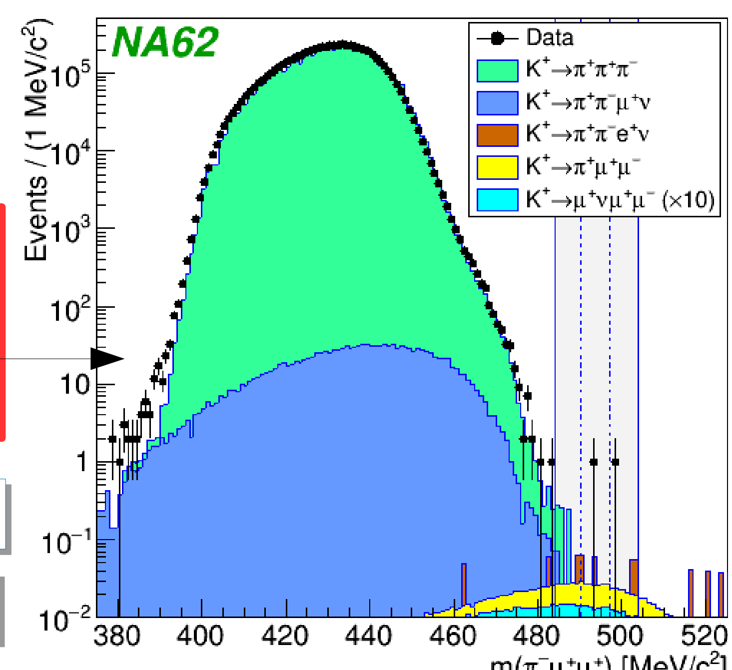
Searches for heavy neutral lepton production in K^+ decays Phys.Lett. B778 (2018) 137



Searches for lepton flavour and lepton number violation Phys.Lett. B797 (2019) 134794

$BR(K^+ \to \pi^- e^+ e^+) < 2.2 \times 10^{-10}$

$BR(K^+ \to \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11}$



- 8 journal NA62 papers have been published with the Dubna group participation in 2019-2021. In three of them the Dubna group members where the principal co-authors.
- Obtained results in 2019-2021 were presented at the international conferences, including 11 presentations given by the representatives of JINR group.
- The series of scientific works of Dubna group “Study of rare and search for forbidden decays of charged kaons” was awarded a second JINR prize (2019) in the nomination of experimental works.

Journal papers (2019-2021)

- E.Cortina Gil *et al.* (NA62). First search for $K^+ \to \pi^+\nu\nu$ using the decay-in-flight technique. Phys.Lett.B 791 (2019) 156-166.
- **J.R.Batley *et al.* (NA48/2). First observation of the $K^\pm \to \pi^\pm\pi^0 e^+ e^-$ decay. Phys.Lett.B 788 (2019) 552-561.**
- E.Cortina Gil *et al.* (NA62). Search for production of an invisible dark photon in π^0 decays *JHEP* 05 (2019) 182.
- **E.Cortina Gil *et al.* (NA62). Searches for lepton number violating K^+ decays. *Phys.Lett.B* 797 (2019) 134794.**
- **E.Cortina Gil *et al.* (NA62). Search for heavy neutral lepton production in K^+ decays to positrons. *Phys.Lett.B* 807 (2020) 135599.**
- E.Cortina Gil *et al.* (NA62). An investigation of the very rare $K^+ \to \pi^+\nu\nu$ decay. JHEP 11 (2020) 042.
- E.Cortina Gil *et al.* (NA62). Search for π^0 decays to invisible particles. JHEP 02 (2021) 201.
- E.Cortina Gil *et al.* (NA62). Search for a feebly interacting particle X in the $K^+ \to \pi^+ X$ decay. JHEP 03 (2021) 058.

Conference talks (2019-2021)

1) D. Madigozhin. Recent NA48/2 results on rare kaon decays. *EPJ Web Conf*. 206 (2019) 05001.
2) S. Shkarovskiy. New NA48/2 results on rare kaon decays. Excited QCD 2019, Schladming, Austria, 30 Jan-3 Feb 2019.
3) D. Madigozhin. Latest results from NA48/2. 31st Recontres de Blois, Blois, France, 2-7 Jun 2019.
4) E. Goudzovski. Kaon System: NA62. CLFV 2019. Fukuoka, Japan, 17-19 Jun 2019.
5) D. Madogozhin. Latest results from NA48/2. 19th Lomonosov Conference. Moscow, Russian Federation, 22-28 Aug 2019.
6) N. Molokanova. Latest results from NA48/2. ICNFP 2019, Kolymbari, Greece, 21-29 Aug 2019. IJMP A, V 35, N 36 (2020) 2044019.
7) A.Baeva. Searches for lepton flavour and lepton number violation in K^+ decays, NUFACT 2019, *Daegu, Korea, 26-31 Aug 2019. PoS* NuFact2019 (2020) 077.
8) D. Madigozhin. New measurement of the $K^+ \to \pi^+\mu^+\mu^-$ decay at NA62. ICNFP 2020. Kolymbari, Creta, Greece, 4 Sep.-2 Oct. 2020.
9) E. Goudzovski. Search for heavy neutral lepton production at the NA62 experiment. ICHEP 2020. Prague, Czech Republic, 28 Jul-6 Aug 2020.
10) E. Goudzovski. HNL searches: NA62 and other experiments. NuPhys 2019, London, United Kingdom, 16-18 Dec 2019.
11) E. Goudzovski. Exotic searches at the NA62 experiment at CERN. KAON 2019, Perugia, Italy, 10-13 Sep 2019.

NA62 JINR group contributions for 2022-2024

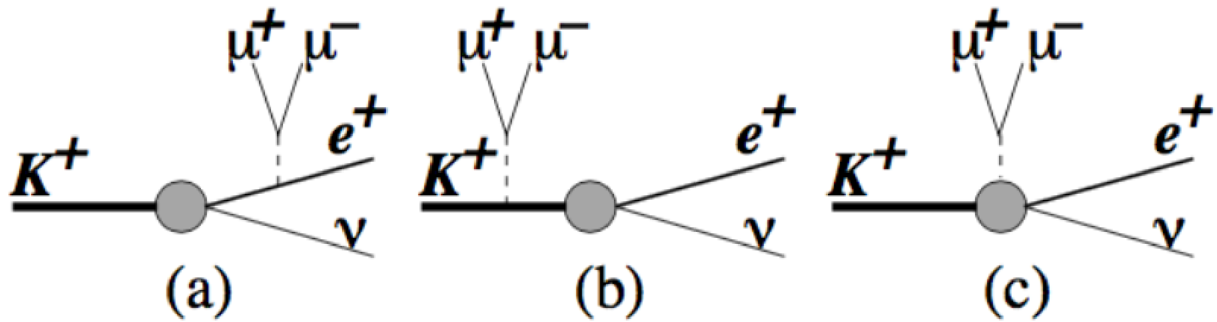
- Fine calibration and alignment of straw detector on the basis of collected data;
- Participation in the LKr fine calibration based on π^0 decays;
- Improvement of the straw detector Monte Carlo simulation used for the main NA62 analysis;
- Participation in the analysis of rare background sources for $K^+ \rightarrow \pi^+ \nu\nu$;
- Data processing and analysis of the collected experimental data to measure the four-lepton decay modes of charged kaon;
- Participation in the $K_{e3}\gamma$ analysis;
- Search for the light sgoldstio signatures;
- Diagnostics and necessary repair of the Spectrometer straw chambers and their low and high voltage power supply.
- Participation in R & D for a new straw module creation;
- Participation in the NA62 data taking runs in 2022-2024.
- Support the NA62 Spectrometer during the data taking runs in 2022-24.

Additional goals for the JINR group analysis

- Rare four-lepton decays with the branching ratios of the order of 10^{-8} (ChPT checks):
  - $K^+ \rightarrow e^+ \nu \mu^+ \mu^-$ **signal selection improvement in progress**;
  - $K^+ \rightarrow e^+ \nu e^+ e^-$ **started**;
  - $K^+ \rightarrow \mu^+ \nu e^+ e^-$ **signal selection improvement in progress**;
  - $K^+ \rightarrow \mu^+ \nu \mu^+ \mu^-$ (was not observed) **- branching fraction extraction**;

- Search for the forbidden modes $K^+ \rightarrow e^- \nu \mu^+ \mu^+$, $K^+ \rightarrow \mu^- \nu e^+ e^+$ (SM check) : **to be started**;
- $\pi^+ \gamma e^+ e^-$ (ChPT) : **started**;
- $K_{e3}\gamma$ analysis (ChPT checks, background for the main mode) **: ~ preliminary result**;
- Finalize and publish $K_{\mu 4}^{00}$ analysis results (ChPT) **: ~ preliminary result preparation**;
- $K_{\mu 4}^{+-}$ analysis (ChPT) : **signal selection improvement in progress**;
- Search for the Goldstone fermion superpartners - “sgoldstino” P in decays $K^+ \rightarrow \pi^+ \pi^0 P$ ($P \rightarrow \gamma\gamma$) : **started**.

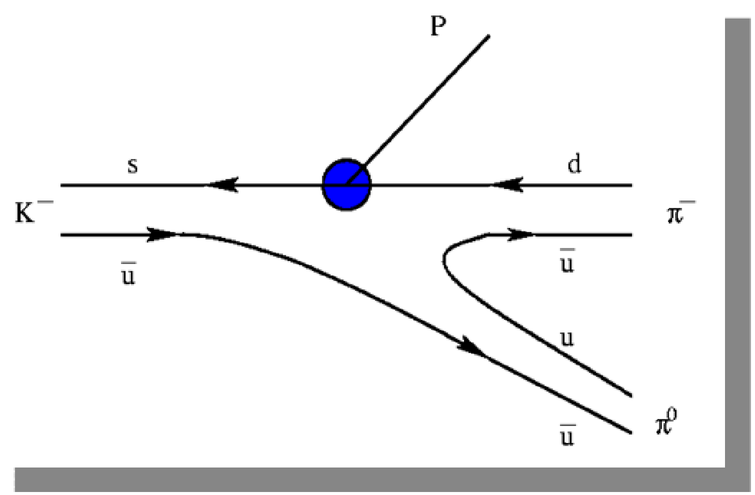
K_{l4} decays

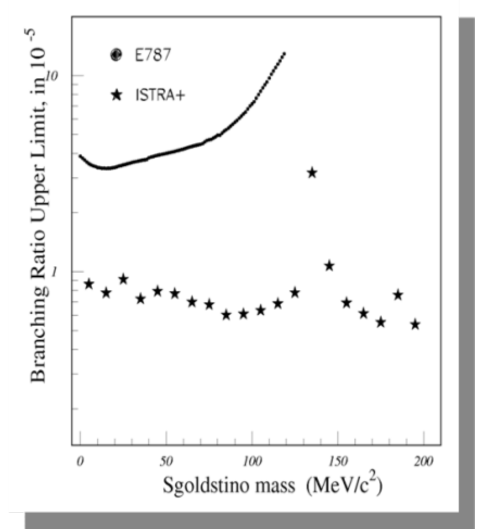


- The internally converted $K_{l2}\gamma^*$ decays, K_{l4}, are the source of information for the kaon physics.
- Within the Chiral Perturbation Theory (ChPT) these decays provide a test of the theory and the source of its parameters.
- Inner Bremsstrahlung is helicity-suppressed for $K_{e2}\gamma^*$ (better for the form factor measurements).

Light (within kaon mass) pseudoscalar sgoldstino: Goldstone fermion superpartners [D.S.Gorbunov, V.A. Rubakov. Phys.Rev.D73:035002, 2006.].

A search for New physics, and at least new limit for production will be established.





Full-time equivalent values for JINR participants

Name	FTE	PhD student	Work (apart from common duties like shifts)
D. Baygarashev	1.0	+	Data quality control, calibration, physical analysis
A. Baeva	1.0	+	Physical analysis
A. Belkova	0.5		Documentation
S. Gevorkian	1.0		Theory of rare decays, MC models development
L. Glonti	0.2		Spectrometer calibration and performance checks.
V. Gorbunova	0.5		Documentation
E. Goudzovski	0.1		MC development, analysis
D. Emelyanov	1.0	+	Software tools development, analysis
T. Enik	0.3		Hardware development and support
V. Kekelidze	0.1		Project leader
D. Kereibay	1.0	+	Physical analysis
A.Korotkova	0.7	+	Physical analysis
D.Madigozhin	1.0		MC development, data quality control, analysis
T. Mauei	1.0		Detector calibration
M. Misheva	0.2	+	Physical analysis
N. Molokanova	0.9		Physical analysis
S. Movchan	0.2		Hardware development and support
I. Polenkevich	0.5		Physical analysis
Yu. Potrebenikov	0.5		Project leader
S. Shkarovskiy	1.0	+	DCS development, hardware support, analysis
V. Falaleev	0.2		Slow control, DCS development, hardware support
TOTAL	**12.9**		

Strengths, Weaknesses, Opportunities, Threats

Strengths:

- fundamental importance of the scientific program;
- fully operating NA62 detector setup built with the JINR essential participation;
- a large amount of experimental data collected in 2016-2018;
- a strong support for the data taking prolongation from CERN side;
- experience in analysis of senior participants of the JINR team;
- young participants who will in future bring the best CERN practice into JINR projects;

Main weakness is caused by the temporary difficulties of transition from the mainly hardware activity to the data analysis stage that is overlaid with the lasting NA62 Spectrometer-related duties. This weakness is overcomed by means of the young participants training for the data analysis exploiting the existing experience of the other group members obtained earlier in the NA48/2 experiment.

The non-trivial opportunities of the project are the improved measurements of some rare decay modes based on the large statistics of kaon decays. Also there is a chance to find new physics in the case if new results will be incompatible with SM. Additionally, the participation in software development and detector calibration for NA62 will increase the qualification of young participants that may be needed in other JINR experiments.

No ongoing competition is known currently in the measurement of the charged kaon golden mode. So there are no threats to the project extension scientific importance.

Form No. 29

6. Estimated expenditures for the Project NA62 (Measurement of the Rare Decay $K^+ \to \pi^+ \nu\nu$ at the CERN SPS")

Expenditure items	Full cost	1st year	2nd year	3rd year
Direct expenses for the Project				
1. Accelerator, reactor, h				
2. Computers, h	3000	1000	1000	1000
3. Computer connection, k$	15	5	5	5
4. Design bureau, standard hour	780	480	300	
5. Experimental Workshop, st. hour	1000	500	500	
6. Materials, k$	70	30	35	5
7 Equipment, k$	35	15	10	10
8. Operational costs, k$	105	35	35	35
9. Payments for agreement-based research, k$				
10. Travel allowance, k$, including:	290	115	115	60
a) non-rouble zone countries	275	110	110	55
b) rouble zone countries	15	5	5	5
c) protocol-based				
Total direct expenses	515	200	200	115

PROJECT LEADER

LABORATORY DIRECTOR

LABORATORY CHIEF ENGINEER-ECONOMIST

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Main expenses in 2022-2024:

- participation in the runs 2022-23 and NA62 maintenance.
- development of straw detectors and on-line software systems.
- contributions to the NA62 common fund.
- computer and technical support for MC simulation, processing and analysis of experimental data.