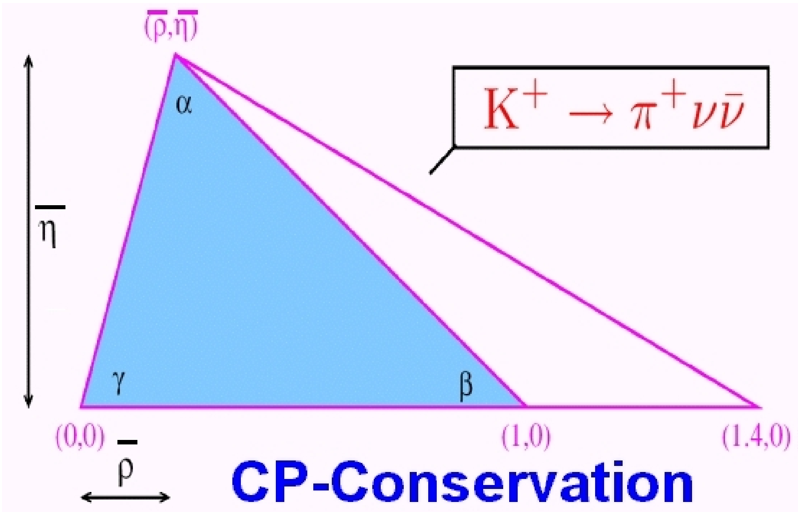
Измерение редкого распада $K^+ \to \pi^+ \nu \bar{\nu}$ в эксперименте NA62

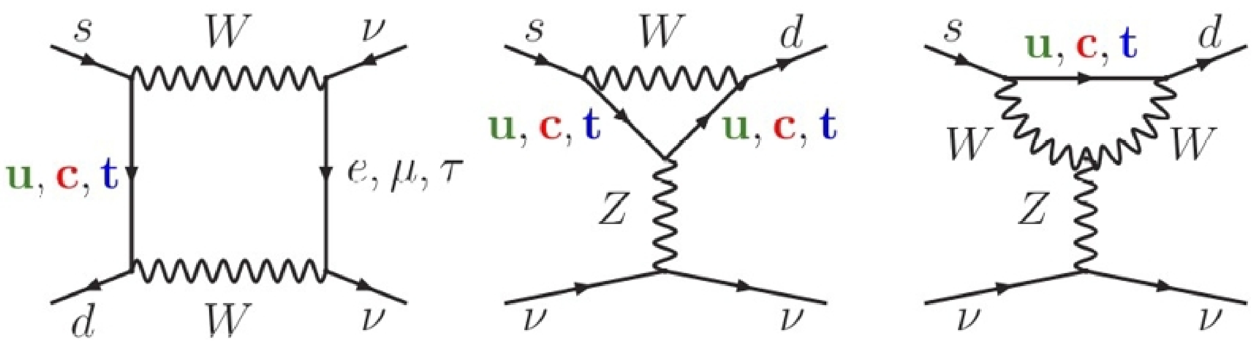
Д.Мадигожин (ОИЯИ)

коллаборация NA62

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]:

$$BR(K^+ \to \pi^+\nu\bar\nu) = (8.4 \pm 1.0) \times 10^{-11} = (0.839 \pm 0.030)\times 10^{-10} \times (|V_{cb}|/40.7\times 10^{-3})^{2.8} \times (\gamma/73.2^o)^{0.74}$$

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

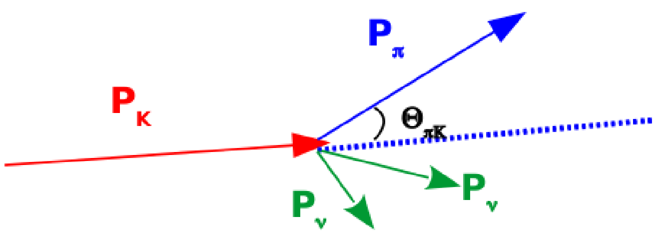
$$BR(K^+ \to \pi^+\nu\bar\nu) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$

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

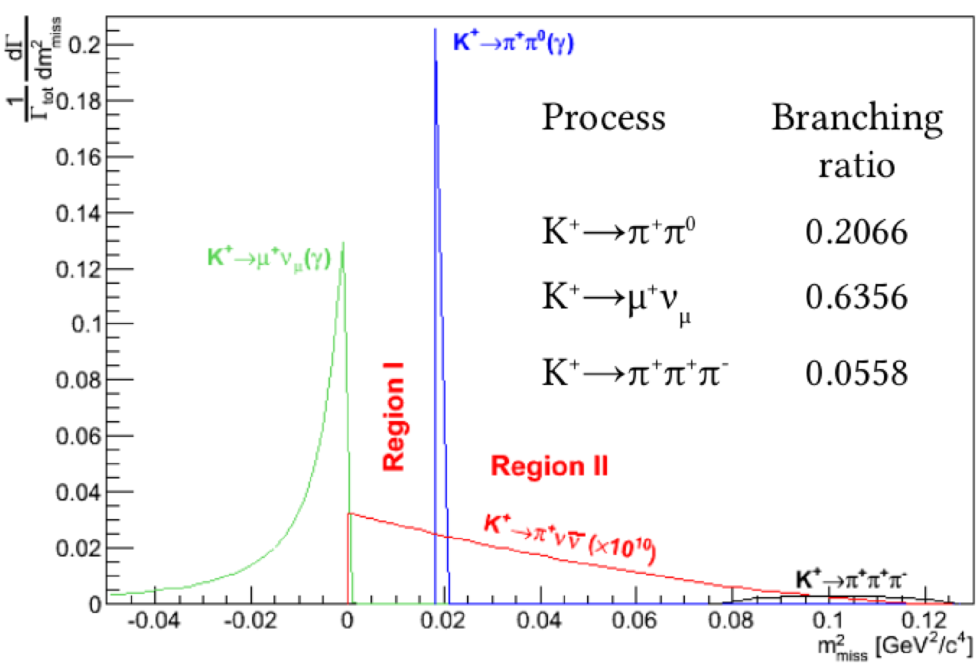
NA62 ultimate goal is ~ 10% precision for $Br(K^+ \rightarrow \pi^+\nu\bar{\nu})$ that assumes ~ 100 reconstructed events and a small background.

Decay in flight technique

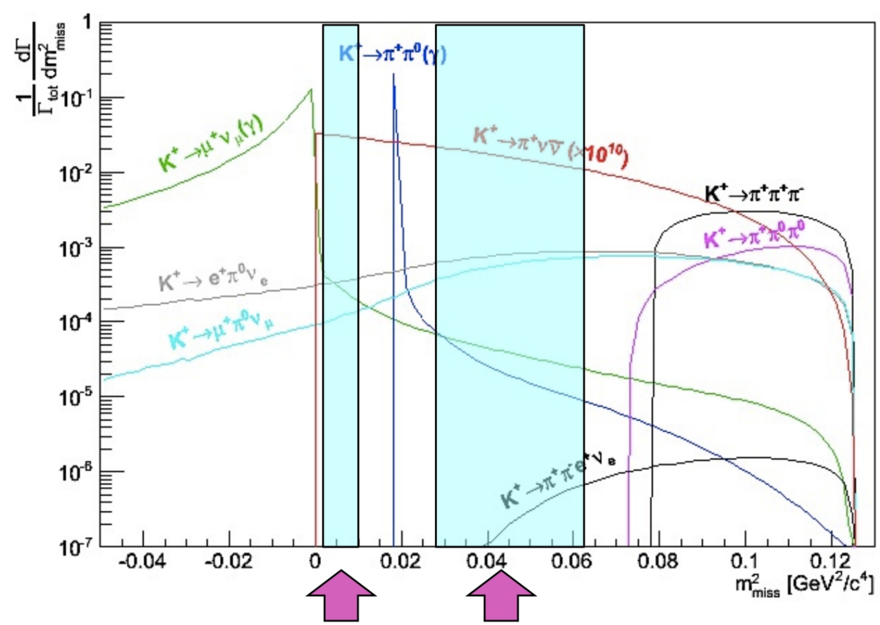
$$m^2_{miss} = (P_K - P_{\pi^+})^2$$



- 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

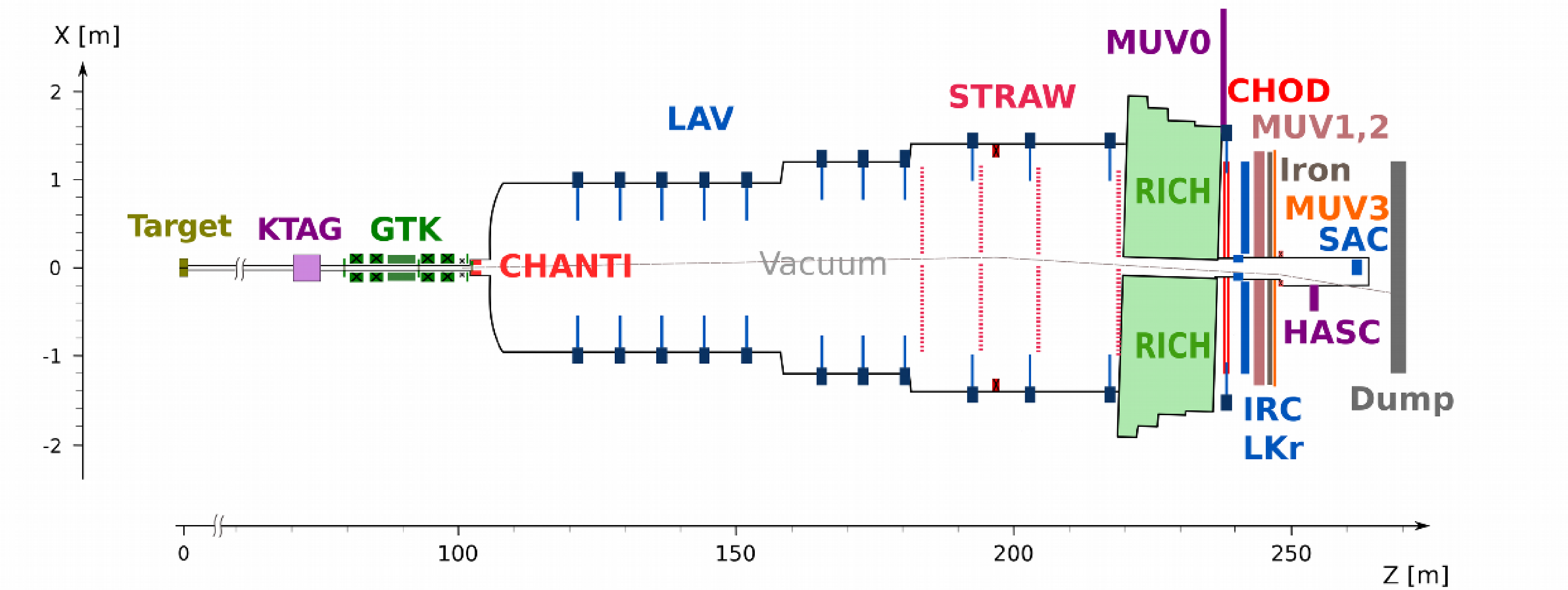


Process	Branching ratio
$K^+\rightarrow\pi^+\pi^0$	0.2066
$K^+\rightarrow\mu^+\nu_\mu$	0.6356
$K^+\rightarrow\pi^+\pi^+\pi^-$	0.0558



- History of JINR in CERN kaon decays program: NA48,NA48/1,NA48/2, NA62(R_K).
- Analysis of NA48/2 data just finished in 2024.
- NA62 inherits some elements of NA48/2, but it is a really novel setup for a new challenging task.

NA62 beam and detector

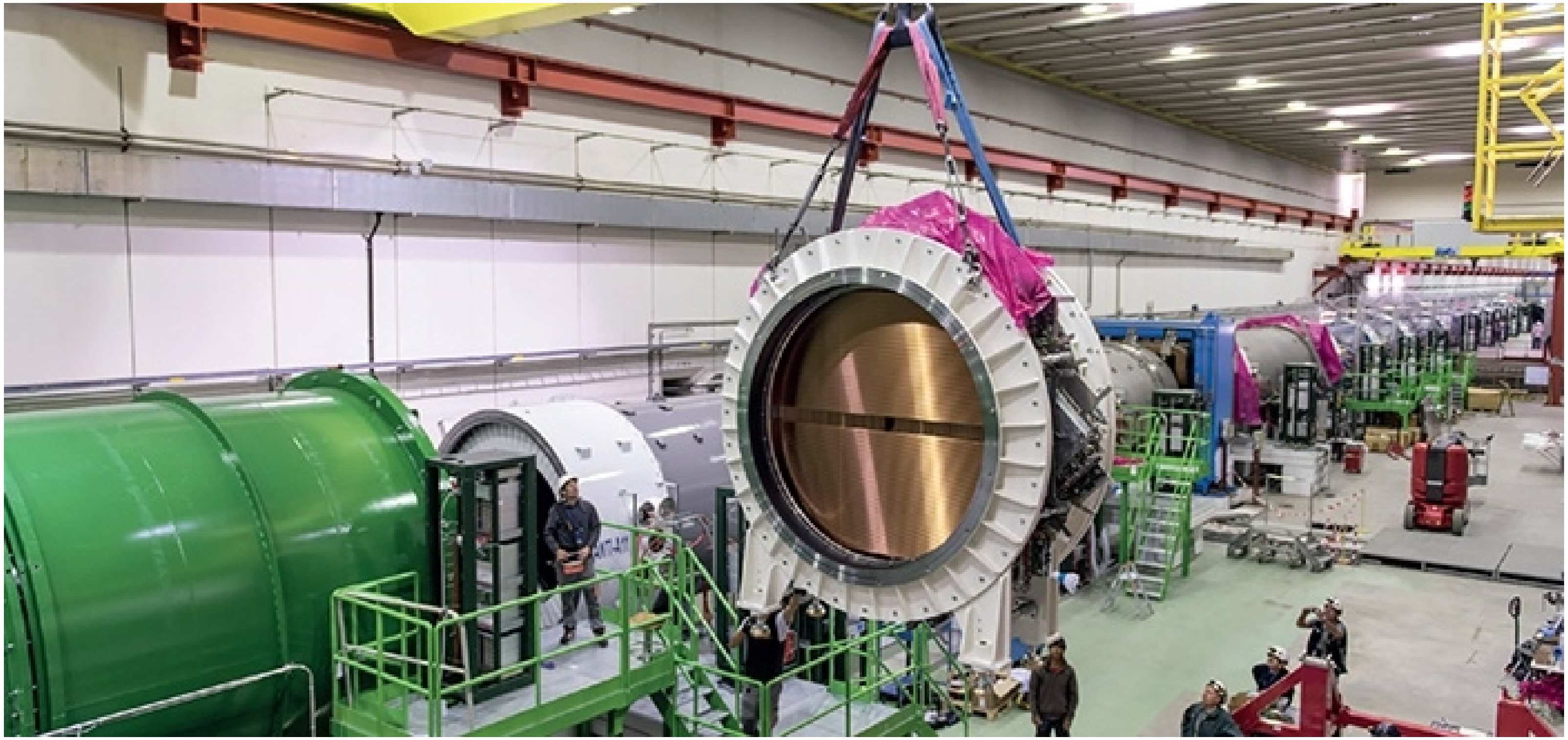


SPS Beam:
- 400 GeV/c protons
- 10^{12} protons/spill
- 3.5s spill

Secondary positive Beam:
- 75 GeV/c momentum, 1 % bite
- 100 μrad divergence (RMS)
- 60x30 mm^2 transverse size
- K^+(6%)/π^+(70%)/p(24%)
- 33x10^{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

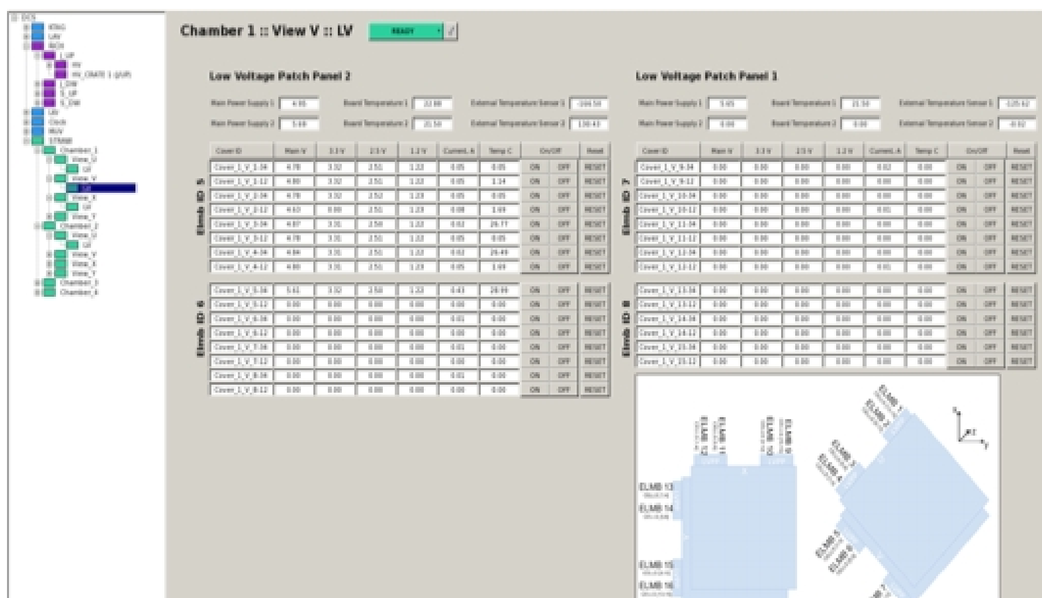


JINR contribution is very important and is defining in many aspects:

- 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 πνν analysis

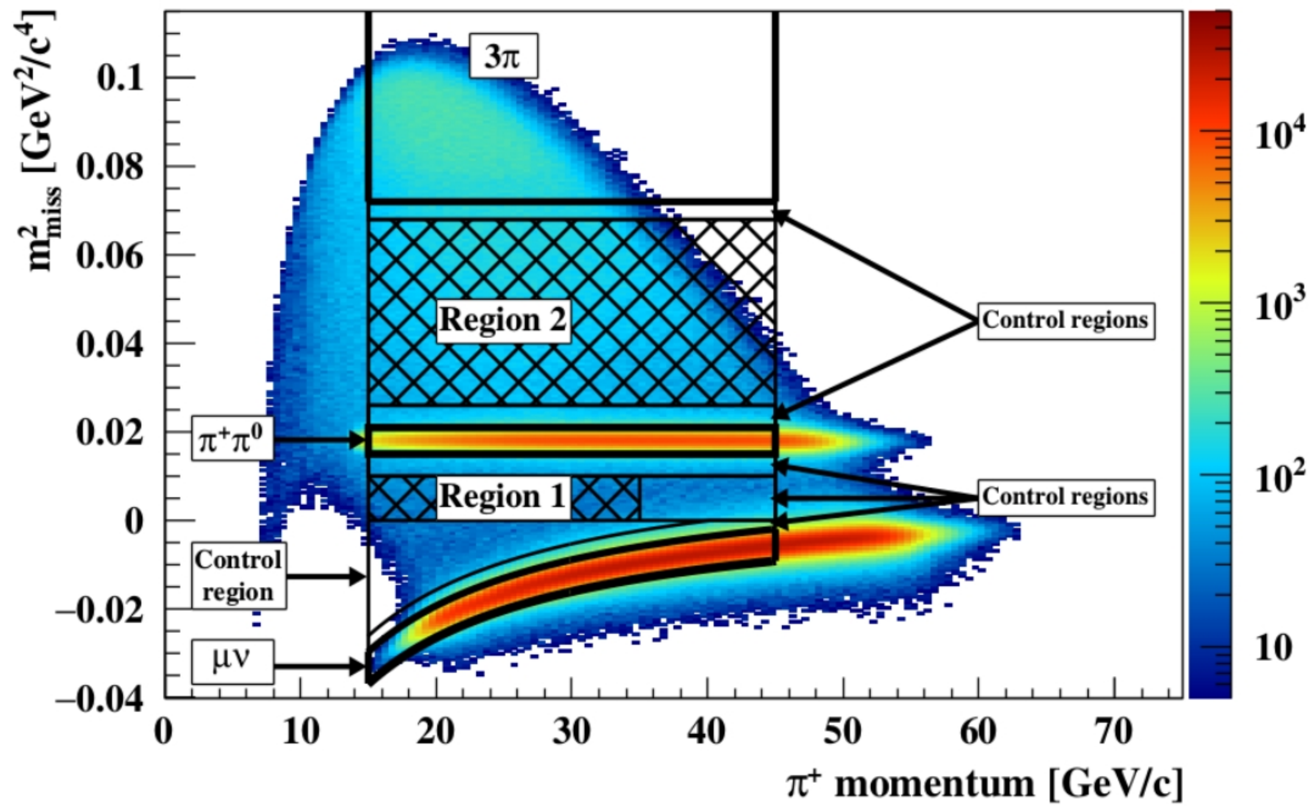
Blind analysis strategy to avoid the influence of selection criteria variation:

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

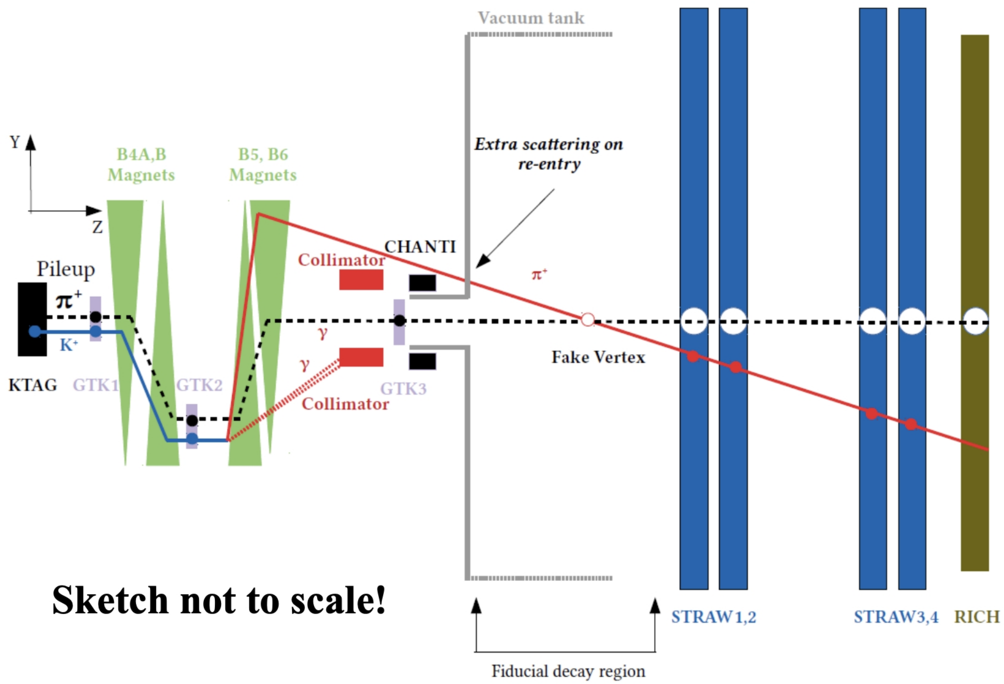
Signal selection:

- K^+ and π^+ tracks reconstruction
- K^+ - π^+ matching
- Decay vertex reconstruction
- μ^+ rejection (π^+ identification)
- Photons rejection
- Multi-track rejection
- Kinematics plot

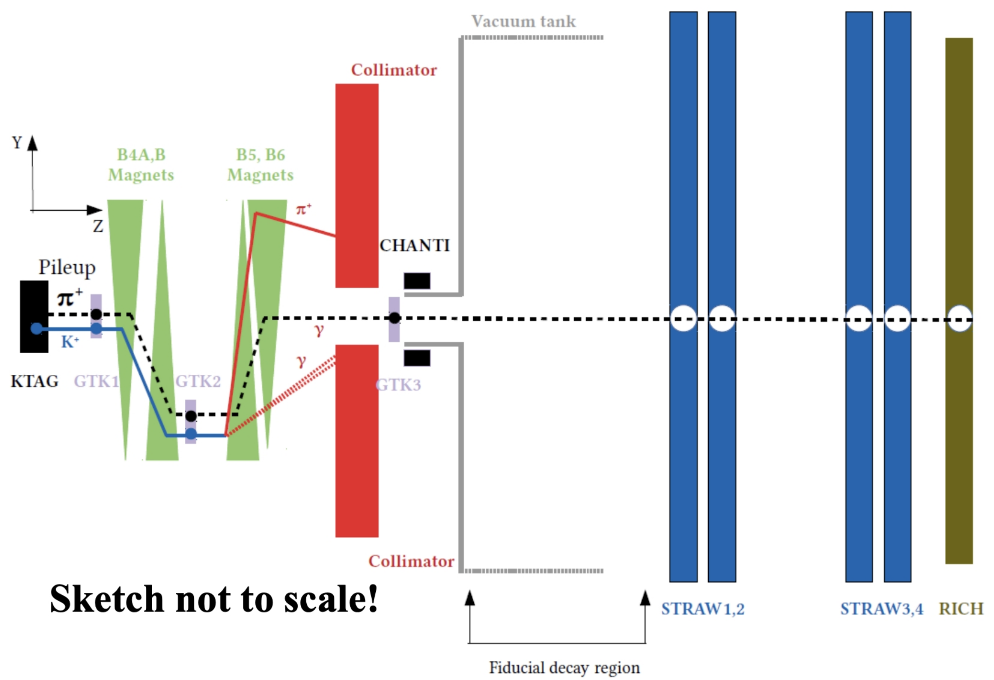
$$m^2_{miss} = (P_K - P_\pi)^2$$



Replacement of the final collimator against upstream events in June 2018



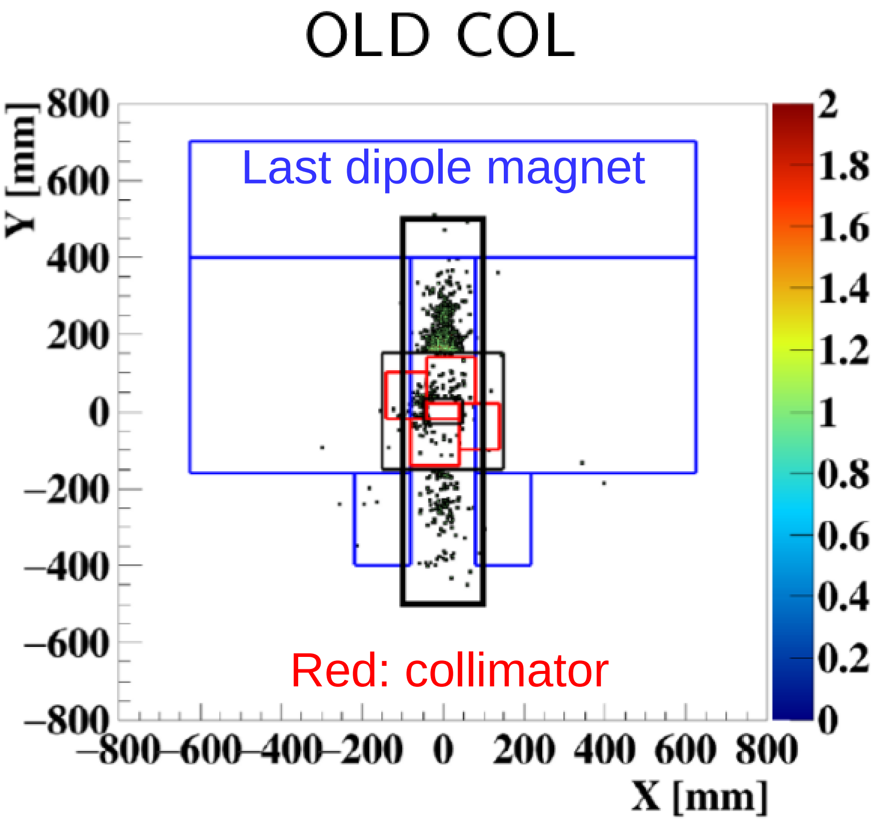
- The last dipole of the beam line changes direction of π from upstream decays (interactions) happened in the beam line.
- The pion pass the existing shielding.
- Accidentally this pion crosses some kaon path and forms a vertex in decay volume.

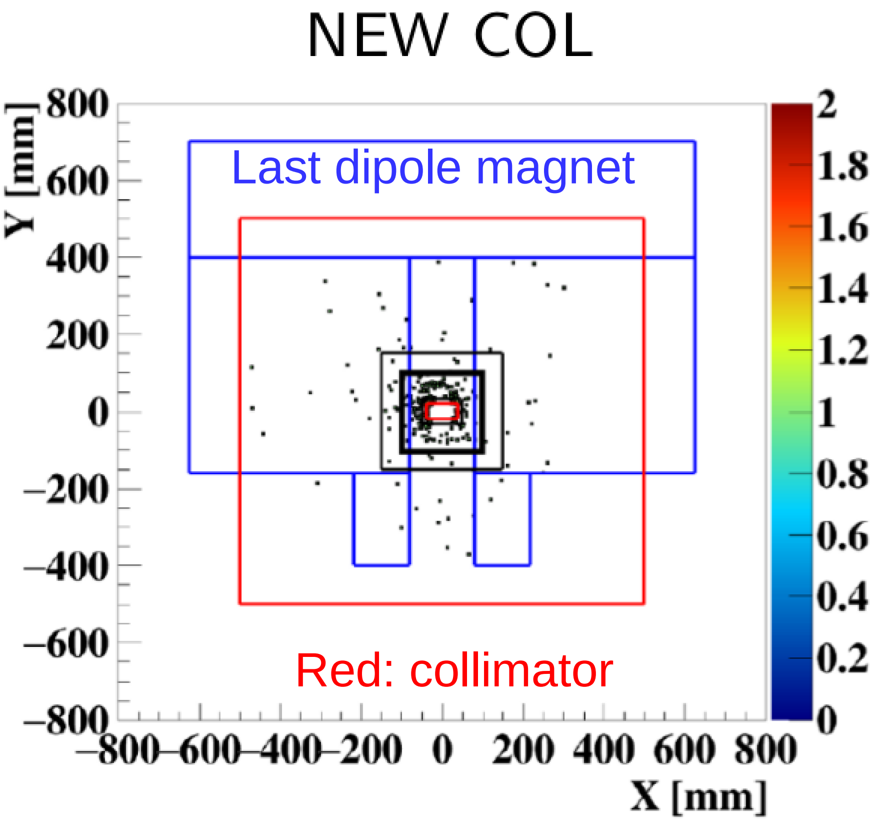


- A new final collimator from the second part (70%) of 2018 run.
- Different selections for the two parts.

Old variable final collimator

New fixed final collimator



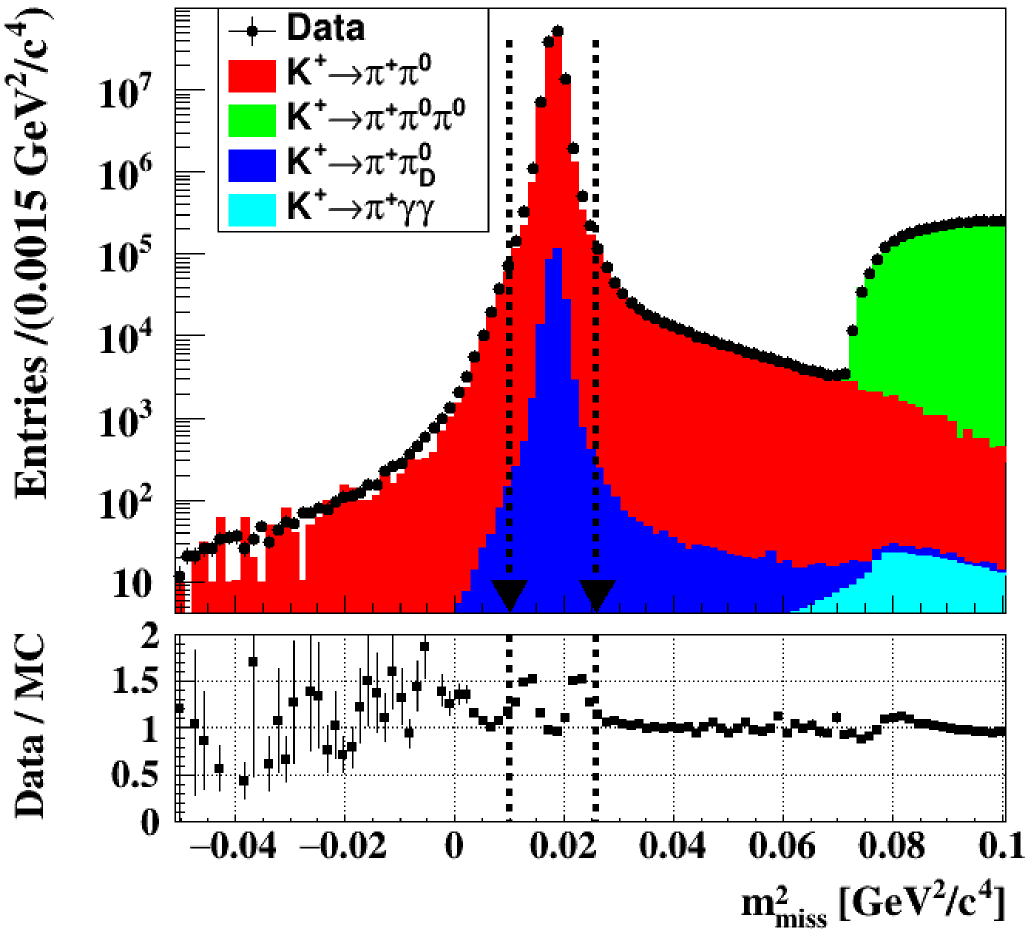


Track extrapolation at collimator in background-enriched sample of upstream events (data)

$K^+ \to \pi^+\pi^0$ normalization channel

Normalization channel: $K^+ \to \pi^+\pi^0$ ($\pi^0 \to \gamma\gamma$), same selection as the signal one, but minimum bias trigger, no photon/multiplicity rejection.

Used to evaluate number of kaon events N_K (for 2018, it is 2.7×10^{12})



- N_K systematic uncertainty of 3.5% is due to Data/MC discrepancy;
- Cancellation of systematics in the signal/normalization:
  - π^+ ID and reconstruction;
  - Detectors efficiencies;
  - K^+ ID and reconstruction;
  - Beam-related acceptance loss;

Number of kaon decays and Single Event Sensitivity

Effective number of kaon decays $N_K = (N_{\pi\pi} D)/(A_{\pi\pi} Br_{\pi\pi})$

Expected number of $\pi\nu\nu$ events $N^{exp}_{\pi\nu\nu} = Br_{\pi\nu\nu}$(SM)/SES, where

Single Event Sensitivity $SES = (N_K \, \Sigma \, A^j_{\pi\nu\nu} \, \varepsilon^j_{trig} \, \varepsilon^j_{RV})^{-1}$

$N_{\pi\pi}$: number of $K^+ \rightarrow \pi^+ \pi^0$ observed decays, D : trigger downscaling,

$A_{\pi\pi}$: norm acceptance, $A^j_{\pi\nu\nu}$: signal acceptance for π^+ momentum bin j,

ε^j_{trig} : trigger efficiency ~(89±5)%, ε^j_{RV} : random veto efficiency ~(66±1)%.

2018 data analysis

Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

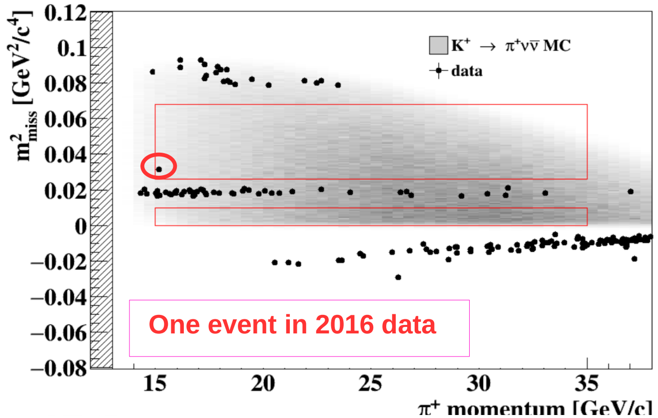
- All the expected background event numbers are evaluated prior to the signal regions opening;
- Subset S1 corresponds to the Region 1;
- Subset S2 corresponds to the Region 2 .

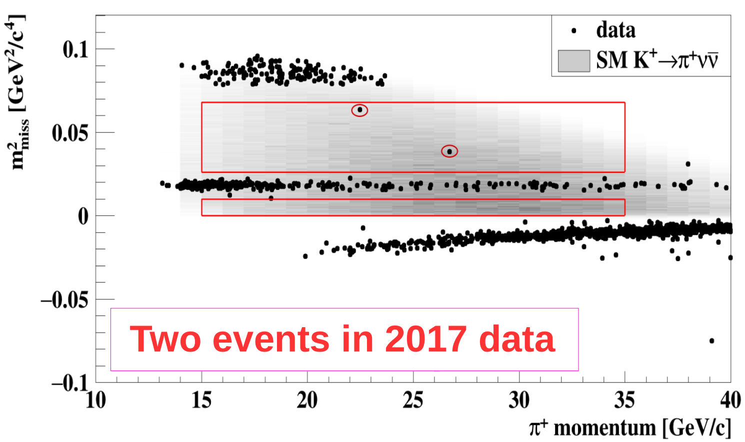
	Subset S1	Subset S2
$N_{\pi\pi} \times 10^{-7}$	3.14	11.6
$A_{\pi\pi} \times 10^2$	7.62 ± 0.77	11.77 ± 1.18
$A_{\pi\nu\bar{\nu}} \times 10^2$	3.95 ± 0.40	6.37 ± 0.64
$\epsilon_{\text{trig}}^{\text{PNN}}$	0.89 ± 0.05	0.89 ± 0.05
ϵ_{RV}	0.66 ± 0.01	0.66 ± 0.01
$SES \times 10^{10}$	0.54 ± 0.04	0.14 ± 0.01
$N_{\pi\nu\bar{\nu}}^{\text{exp}}$	$1.56 \pm 0.10 \pm 0.19_{\text{ext}}$	$6.02 \pm 0.39 \pm 0.72_{\text{ext}}$

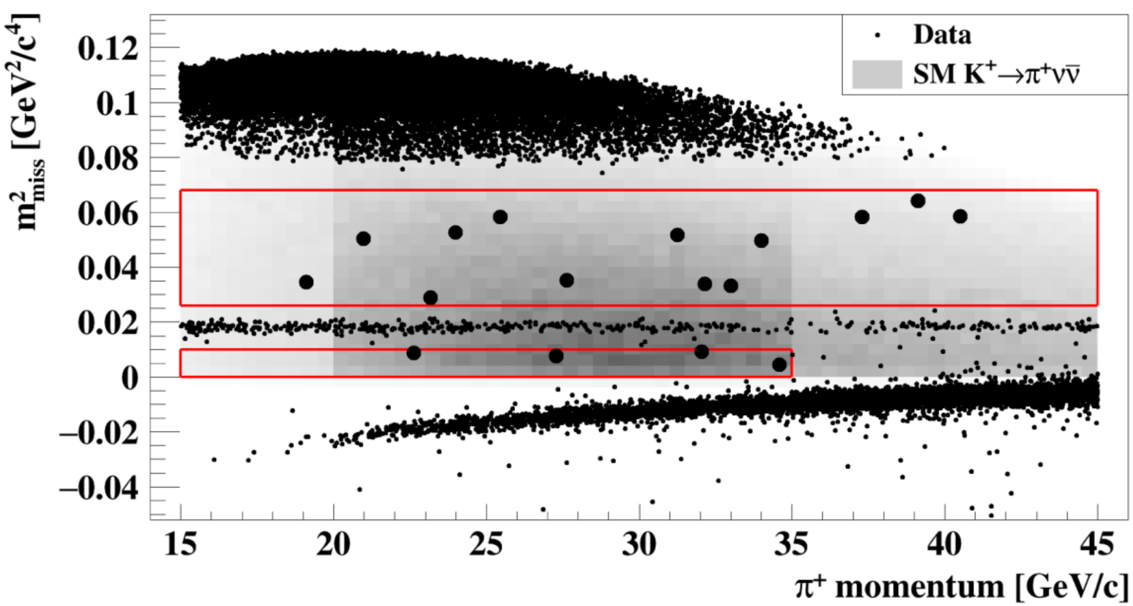
Intermediate result on $K^+ \to \pi^+ \nu\bar{\nu}$ decay

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

Results

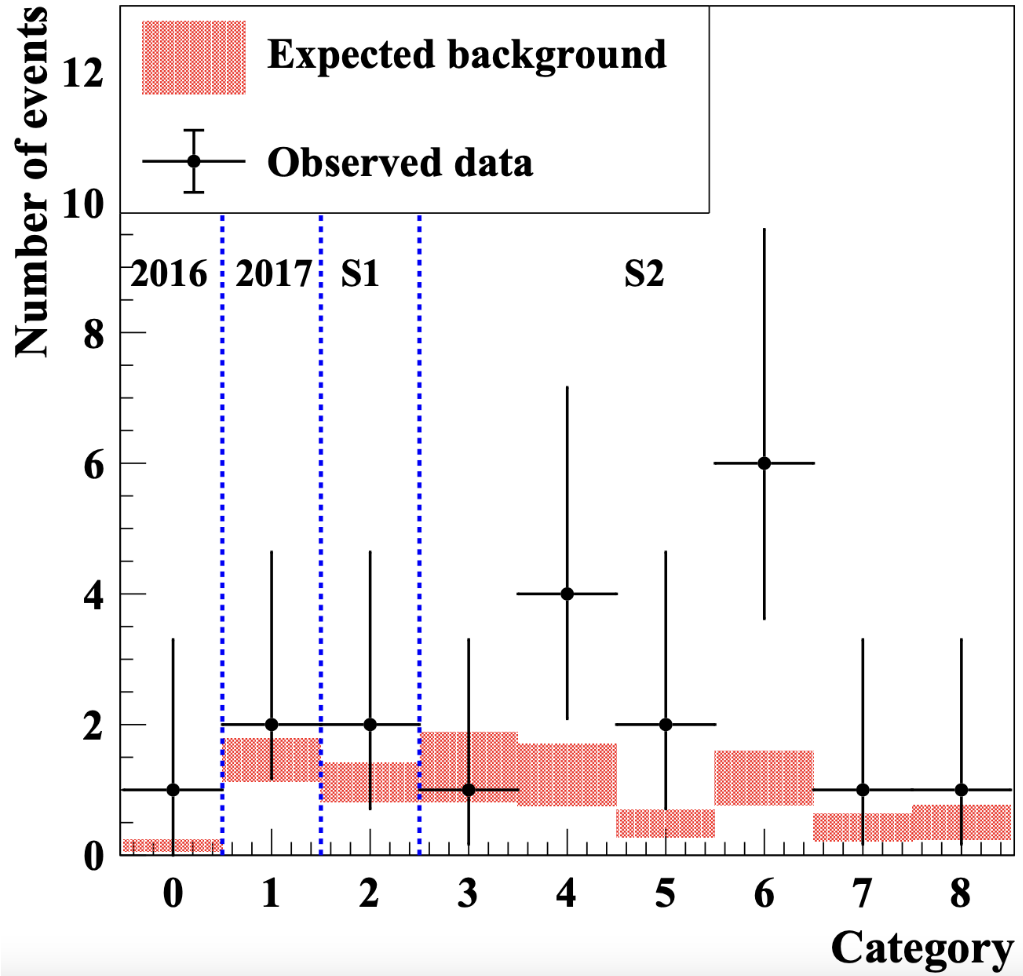






17 events in 2018 data

2016+2017+2018 result extraction



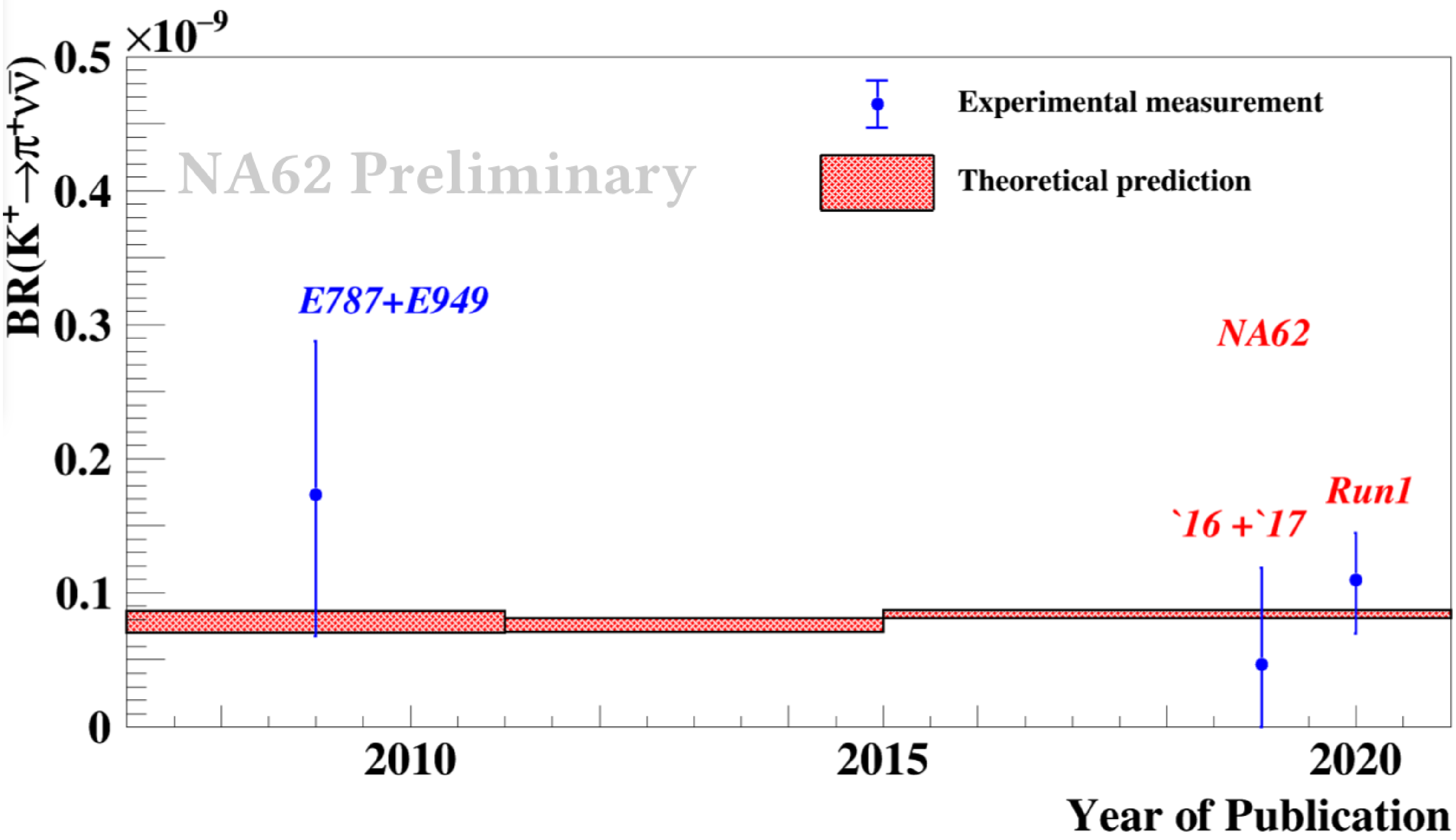
Expected signal: $10.01 \pm 0.42_{syst} \pm 1.19_{ext}$

Expected background: $7.03^{+1.05}_{-0.82}$

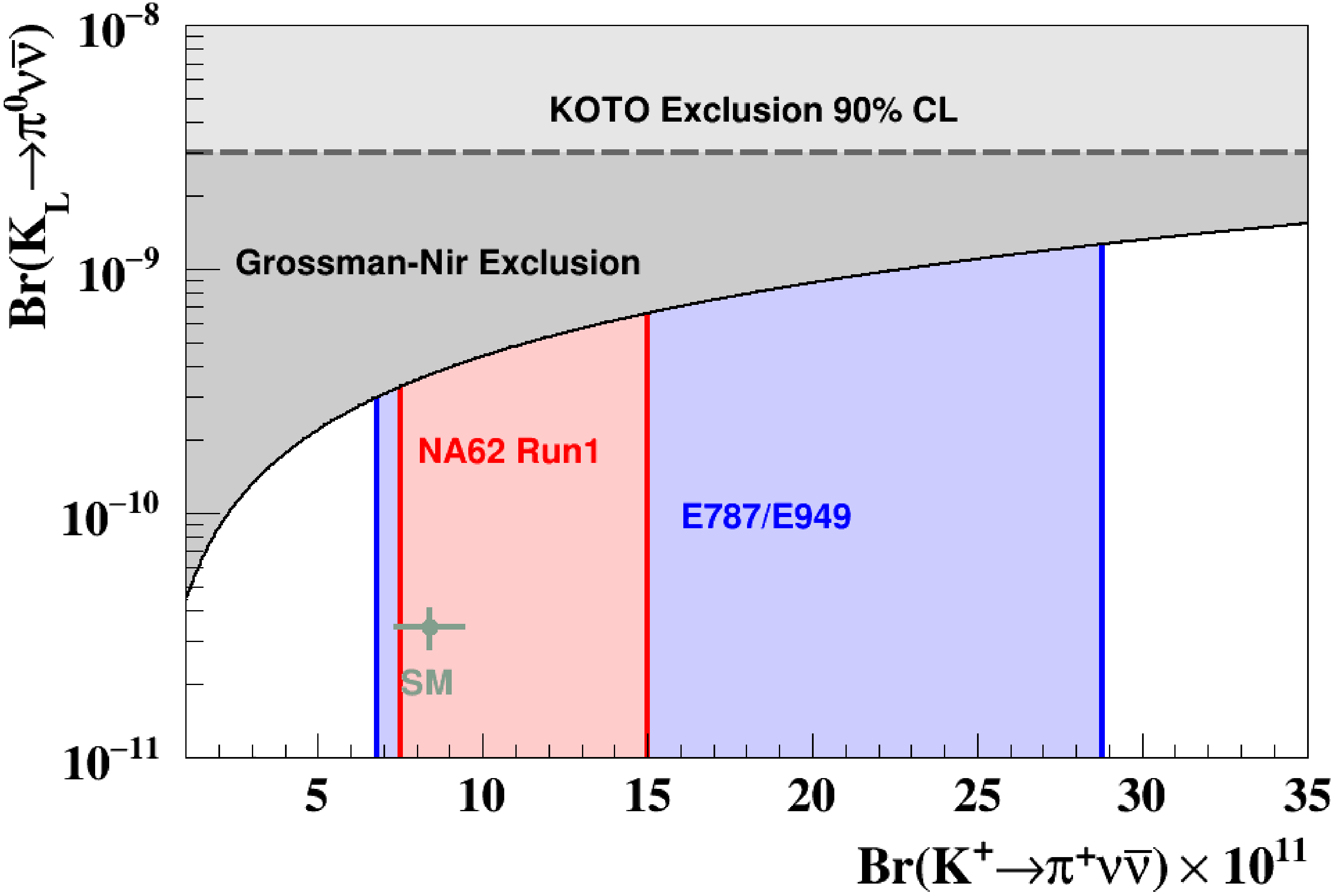
- S2 subset is split into 6 π^+ momentum bins;
- **BR($K^+ \rightarrow \pi^+\nu\nu$):** a binned maximum log-likelihood fit to the observed numbers of events in the nine categories;
- Background-only fit: p-value corresponds to 3.4 standard deviations.

[*JHEP* 06 (2021) 093]: **BR($K^+ \rightarrow \pi^+\nu\nu$) = $(10.6^{+4.0}_{-3.4} \pm 0.9_{syst}) \times 10^{-11}$**

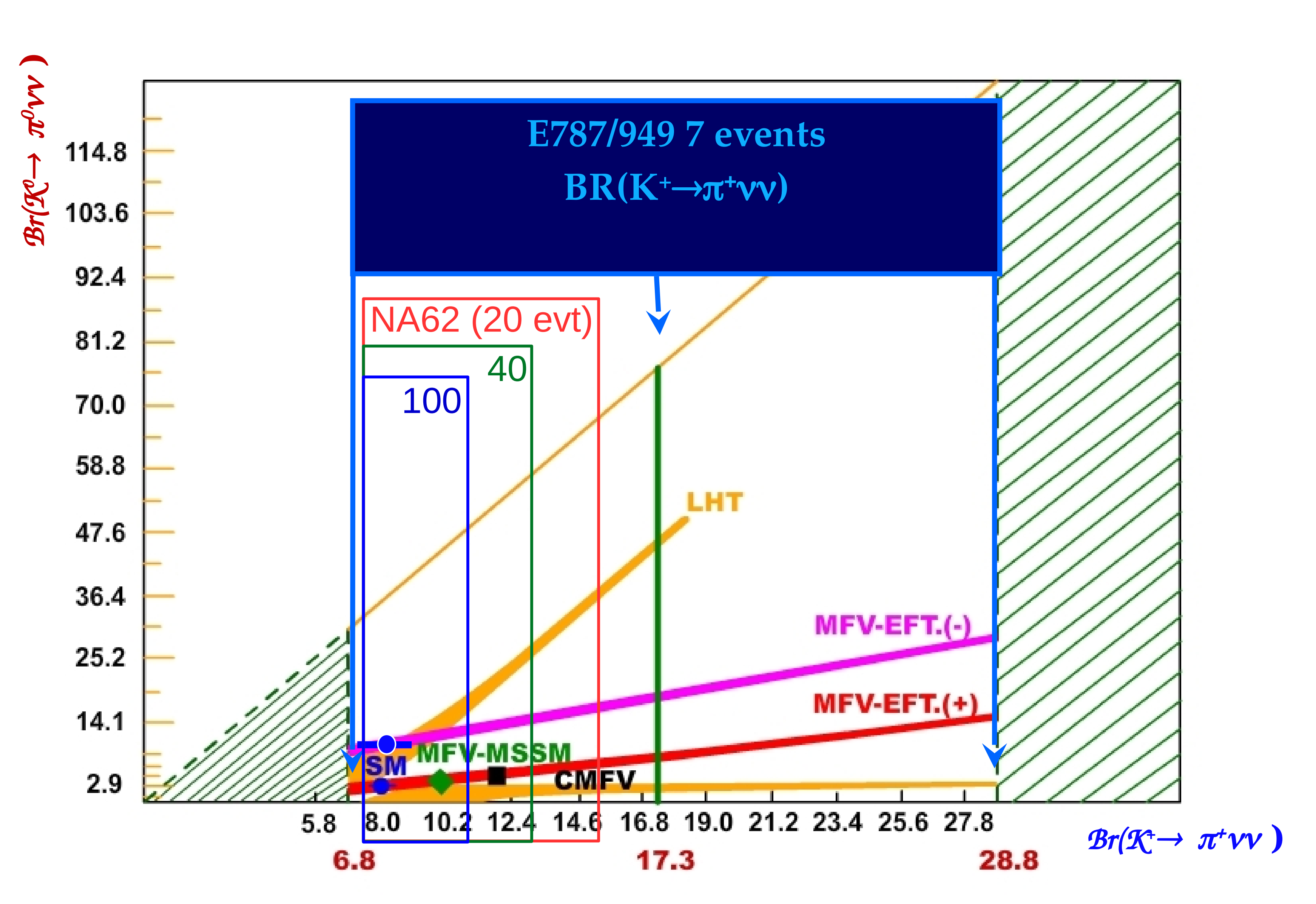
- Standard Model expectation: **$(8.4 \pm 1.0) \times 10^{-11}$**
- Best earlier result: 2009, E787/E949@BNL, 7 events : **$(17.3^{+11.5}_{-10.5}) \times 10^{-11}$**


$\times 10^{-9}$
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

Current status

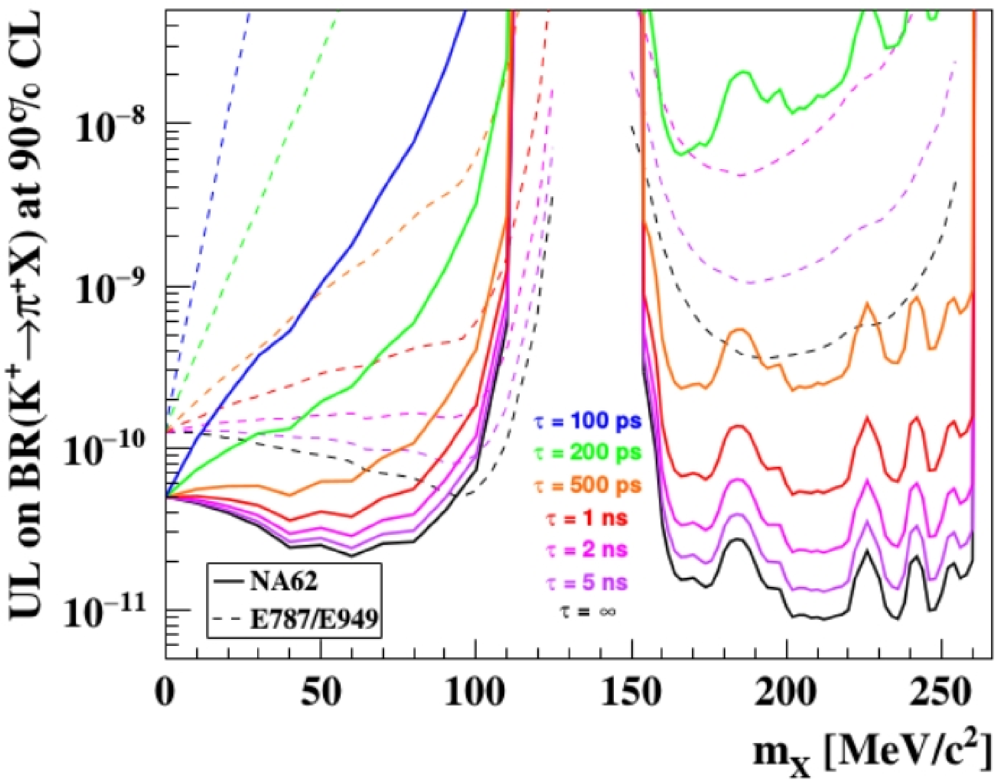


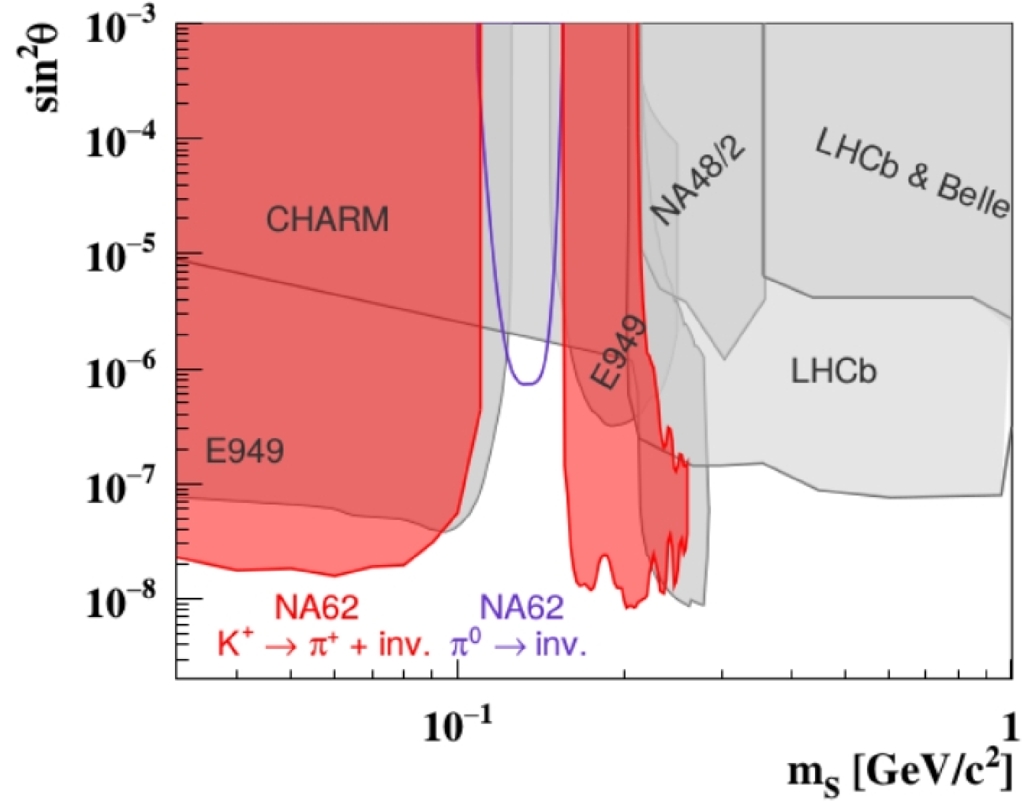
Conservative scenario: 40 SM events, initial goal: 100 SM events.



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

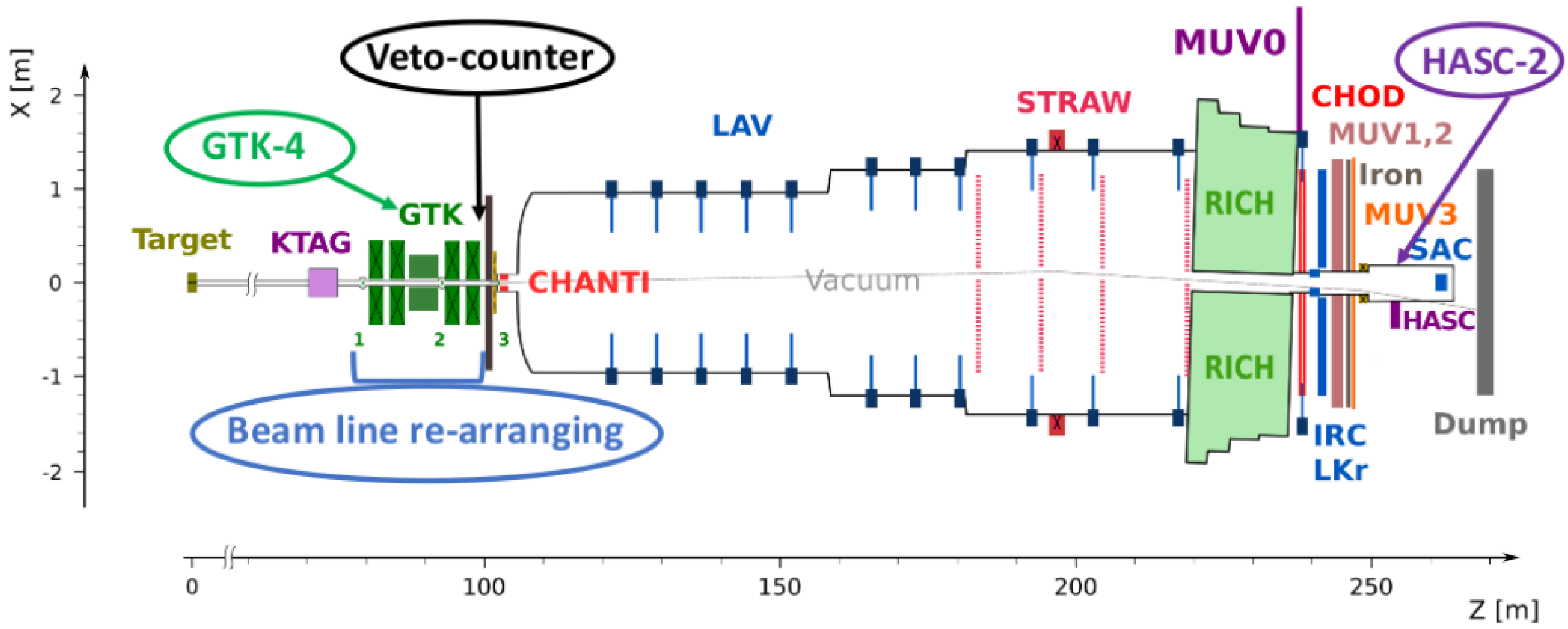
Search for $K^+ \to \pi^+ X$ (feebly interacting scalar or pseudo-scalar)





- Search for peaks in the m^2_{miss} distribution for different m_X;
- Acceptance from MC simulation;
- SM $K^+ \to \pi^+ \nu\nu$ is the main background;
- Limits for different lifetimes, assuming extra particles detection if X decays;
- If X is dark scalar, result may be interpreted in terms of limitrs for X mixing with Higgs boson θ.

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

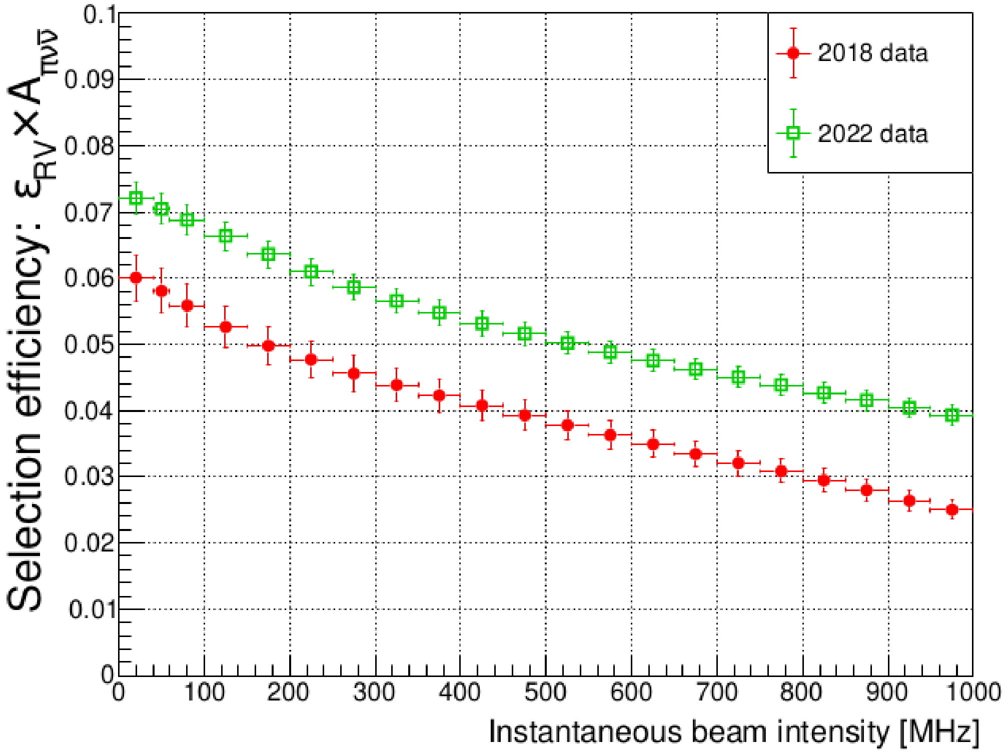


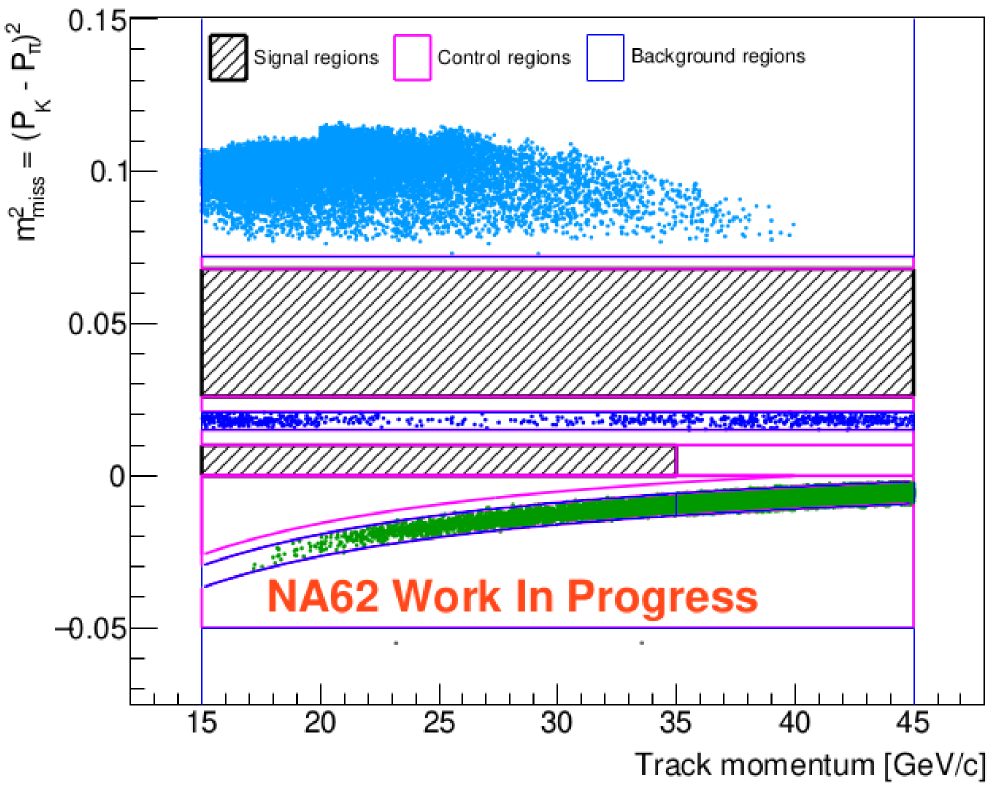
Data taking between CERN LS2 and LS3

- 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

Improvements in the data and analysis 2021-2024

- Additional GTK station – increase of kaon track reconstruction efficiency by 3%;
- Additional veto counters – decrease of background from beamline;
- New LKr reconstruction – decrease of accidental photon veto;
- Selection is re-optimized;
- Signal acceptance $A_{\pi\nu\nu}$ increased by 20% with the same level of random veto (ε_{RV} ~ 65%) despite higher intensity (2018: 400 MHz, 2022: 580 MHz);





Conclusion and plans

- The most precise measurement ever performed for the $K^+ \to \pi^+ \nu \nu$ golden mode:

$$\mathbf{BR(K^+ \to \pi^+ \nu \nu) = (10.6^{+4.0}_{-3.4} \pm 0.9_{syst}) \times 10^{-11}}\ ;$$

- First statistically significant observation (3.4 st.dev.);
- Too lagre BR starts to be improbable;
- Higher precision is needed;
- 2021+2022+2023+2024+2025 data from NA62.