New measurement of $K^{+}\rightarrow\pi^{+}\nu\bar{\nu}$ branching ratio at the NA62 experiment

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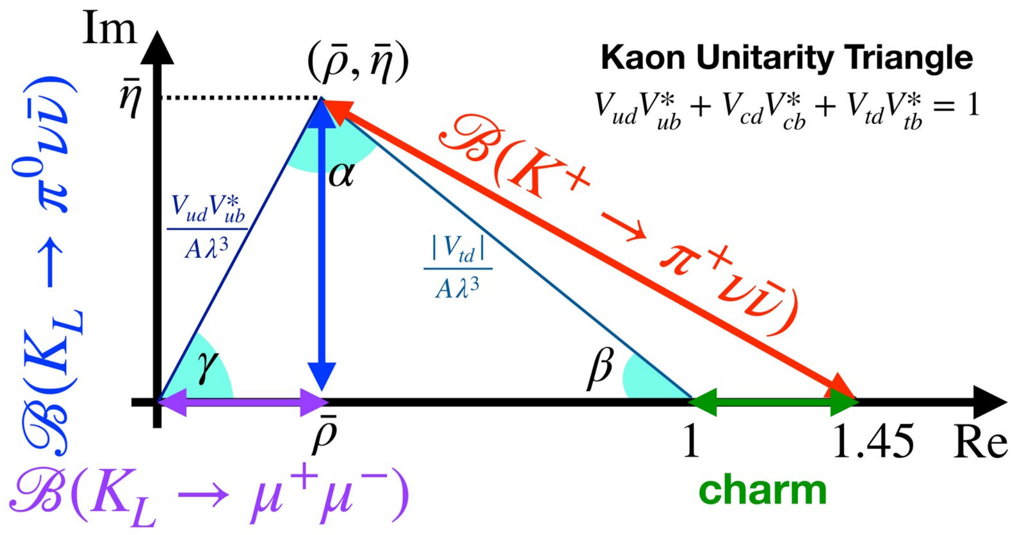
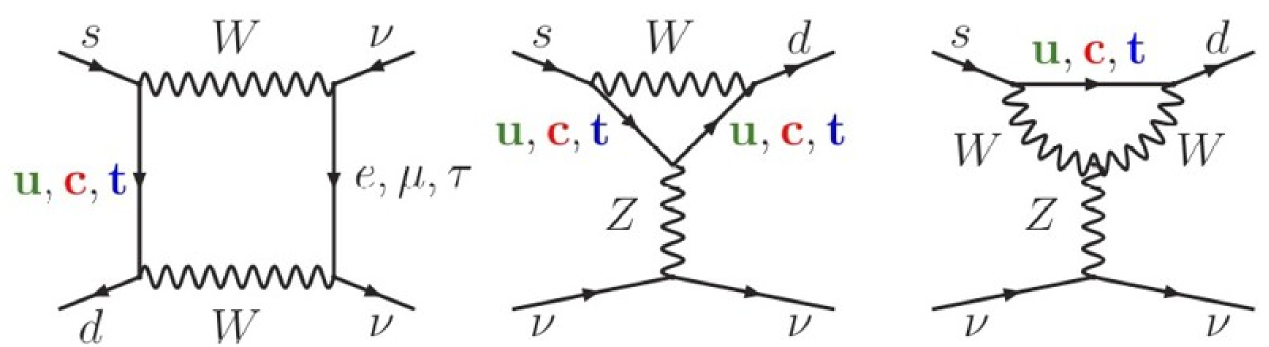
for the **NA62** collaboration

Motivation



Probabilities of the "golden decays" $K^0\to\pi^0\nu\bar\nu$ and $K^+\to\pi^+\nu\bar\nu$ are directly related to CKM parameters.



- Pure s→d FCNC process with ~ $\mathbf{sin^5\theta_C}$ suppression
- Clean theory, mainly CKM uncertainty
- Hadronic form factors from K_{l3} measurements

Mode BR	SM [Buras et al. EPJC 82 (2022) 7, 615]	SM [D'Ambrosio et al. JHEP 09 (2022) 148]	Experimental status prior to the new NA62 result
$K^+\to\pi^+\nu\bar\nu$	$(8.60 \pm 0.42)\times10^{-11}$	$(7.86 \pm 0.61)\times10^{-11}$	$(10.6^{+4.1}_{-3.5})\times10^{-11}$ NA62 data 2016-18 [JHEP 06 (2021) 093]
$K^0\to\pi^0\nu\bar\nu$	$(2.94 \pm 0.15)\times10^{-11}$	$(2.68 \pm 0.30)\times10^{-11}$	$< 2.2\times10^{-9}$ KOTO data 2021 [PRL 134 (2025) 081802]

Beyond the SM

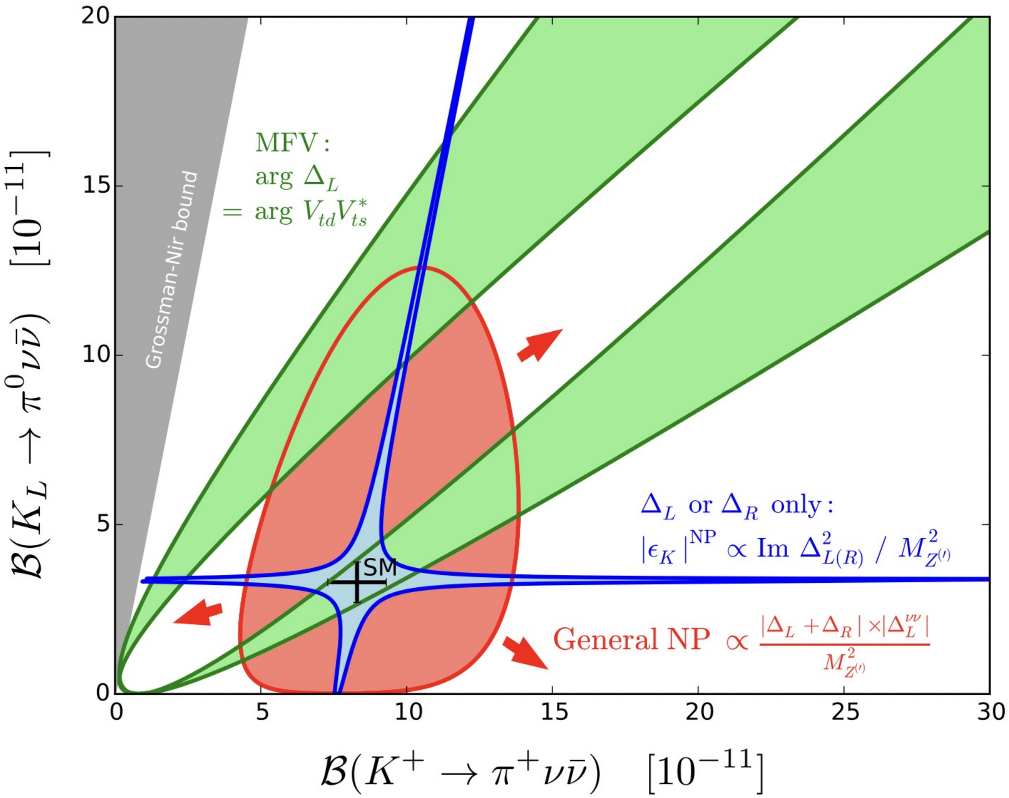
- Correlations between BSM contributions to BRs of $K^0 \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ modes [JHEP 11 (2015) 166]. Must measure both to discriminate between BSM scenarios.
- Correlations with other observables (ε'/ε, ΔM_K , B-decays) [JHEP 12 (2020) 097] [PLB 809 (2020) 135769].
- 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

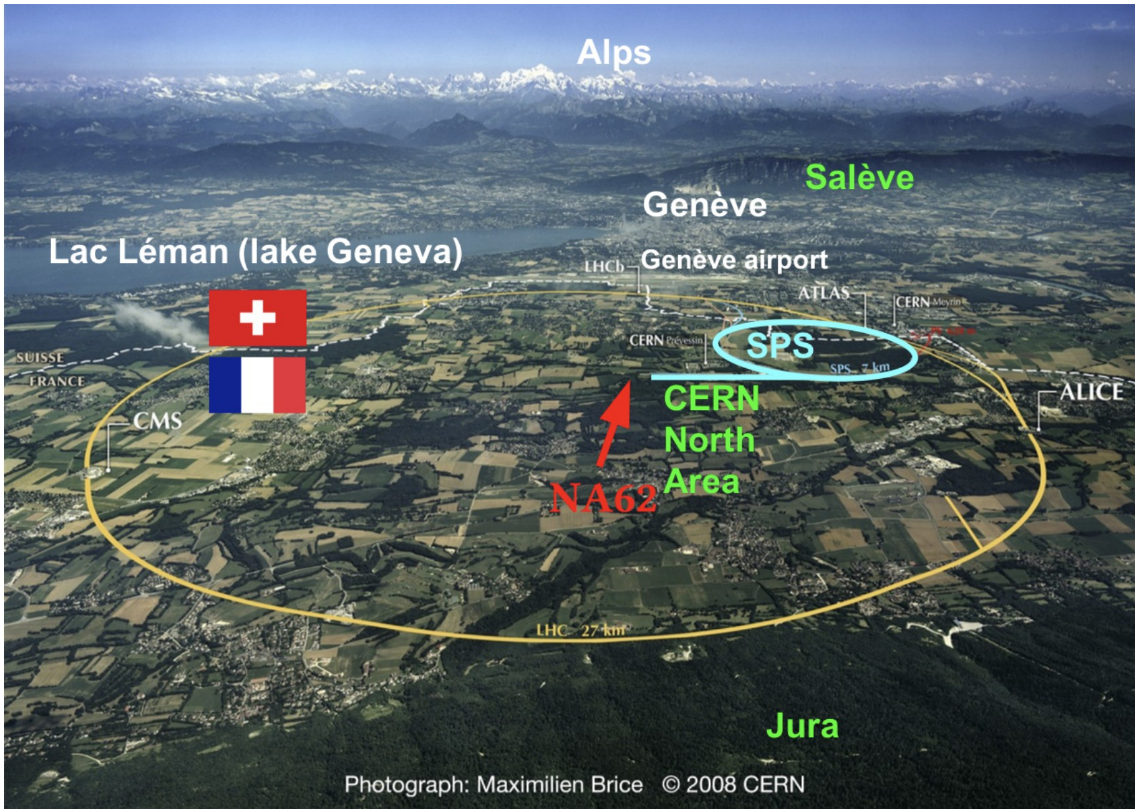
Blue: new flavour-violating interactions where LH or RH currents dominate
Models with pure LH/RH couplings

Red: general NP models without above constraints

Grossman-Nir Bound: model-independent relation



The NA62 experiment at CERN



- About 200 physicists
- 30 institutions

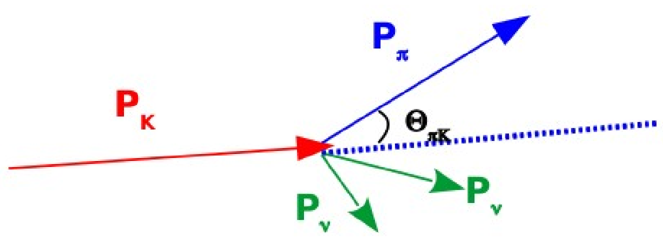
- **Primary goal:** measurement of
- **New Technique:** decay-in-flight
- **Results:** [PLB 791 (2019) 156]

  [JHEP 11 (2020) 042] [JHEP 06 (2021) 093]
- **Broader physics program:**
  - Rare decays (e.g. [PLB 850 (2024) 138513])
  - LNV/LFV decays (e.g. [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).**
  - **2022 Physics run (215 days).**
  - 2023 Physics run (150 days).
  - 2024 Physics run (204 days)
  - 2025 Physics run ongoing ...

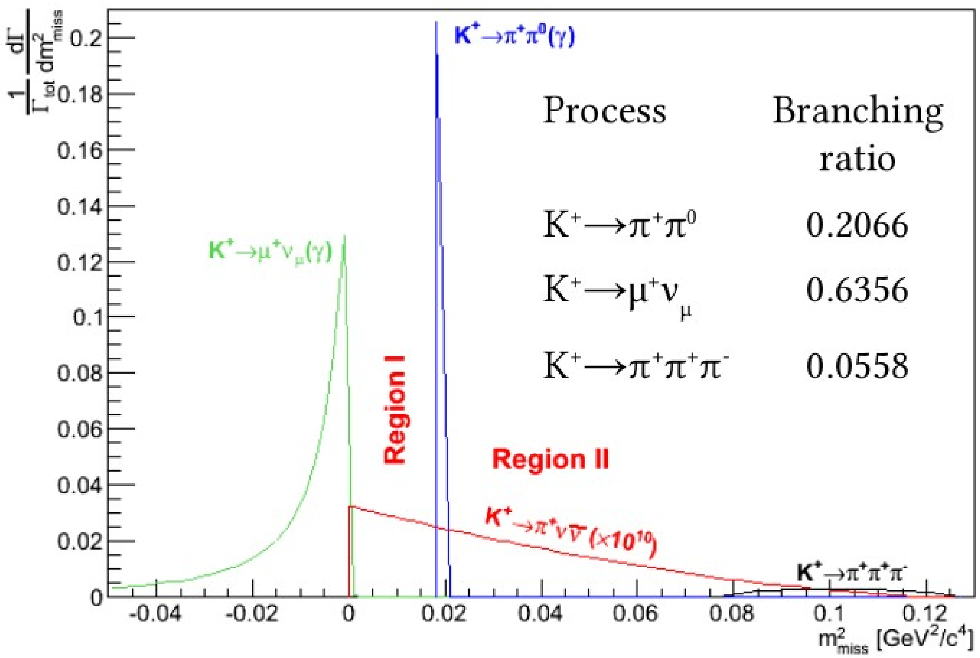
This talk :

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

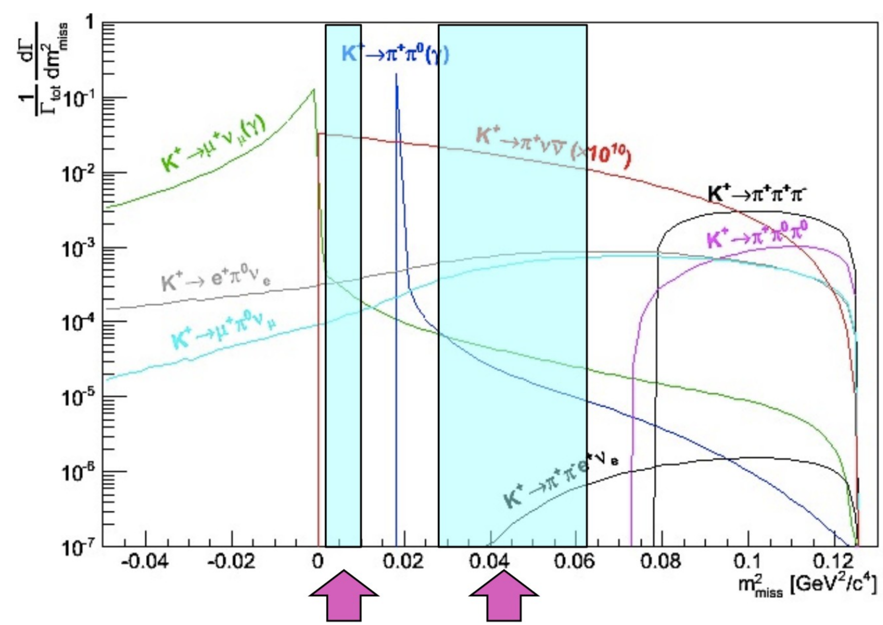
Decay in flight technique $\mathbf{m^2_{miss} = (P_K - P_{\pi^+})^2}$



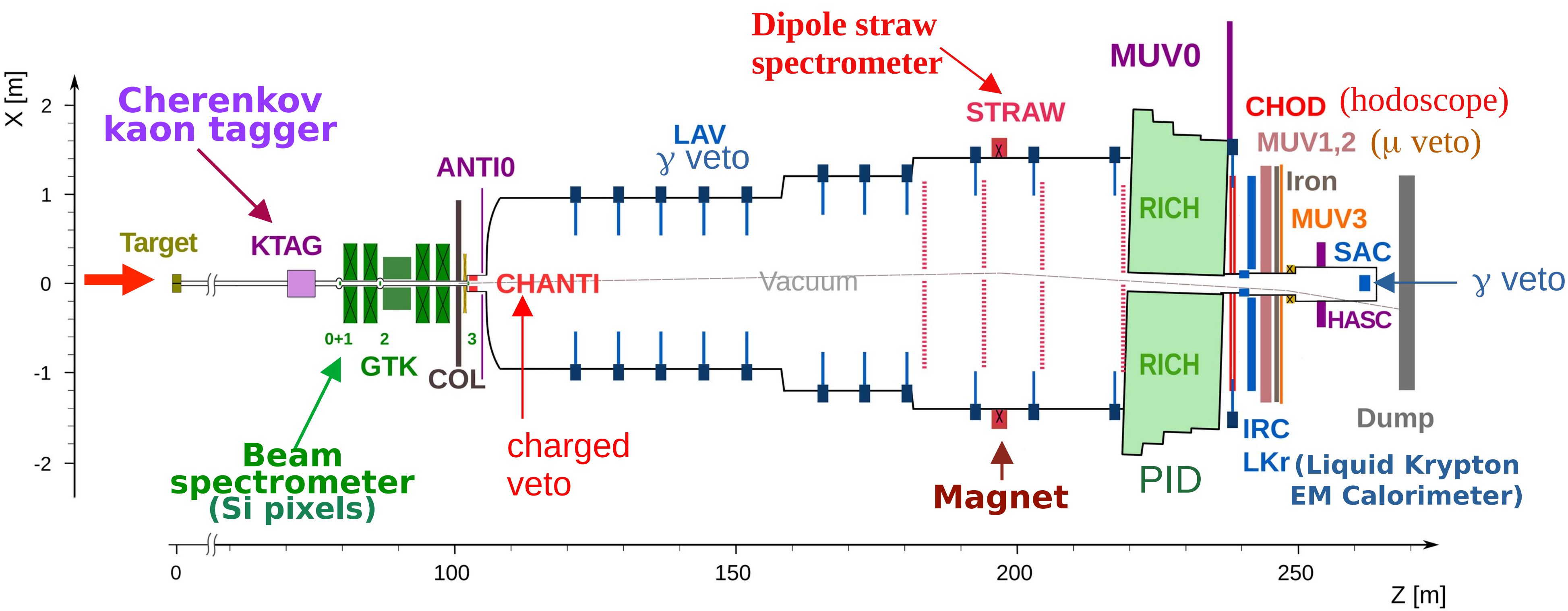
- Keystones of the analysis:
  - Timing between sub-detectors ~ O(100 ps)
  - Kinematic suppression ~ $O(10^4)$
  - Muon suppression > 10^7
  - π^0 suppression (from $K^+ \to \pi^+\pi^0$) > 10^7



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



NA62 beam and detector (final configuration 2021)



SPS proton beam

- **400 GeV/c**
- **~2×10^{12} PoT/spill**
- **4.8 sec spill**

Beam from the Target

- **75 GeV/c, 1% bite**
- **60×30 mm^2 at GTK, converging downstream**
- **K^+(6%) π^+(70%) p(24%)**

Decay region

- **~ 60 m fiducial region**
- **~ 2 MHz K^+ decays**
- **Vacuum ~ O(10^{-6}) mbar**

NA62 $\pi\nu\nu$ analysis

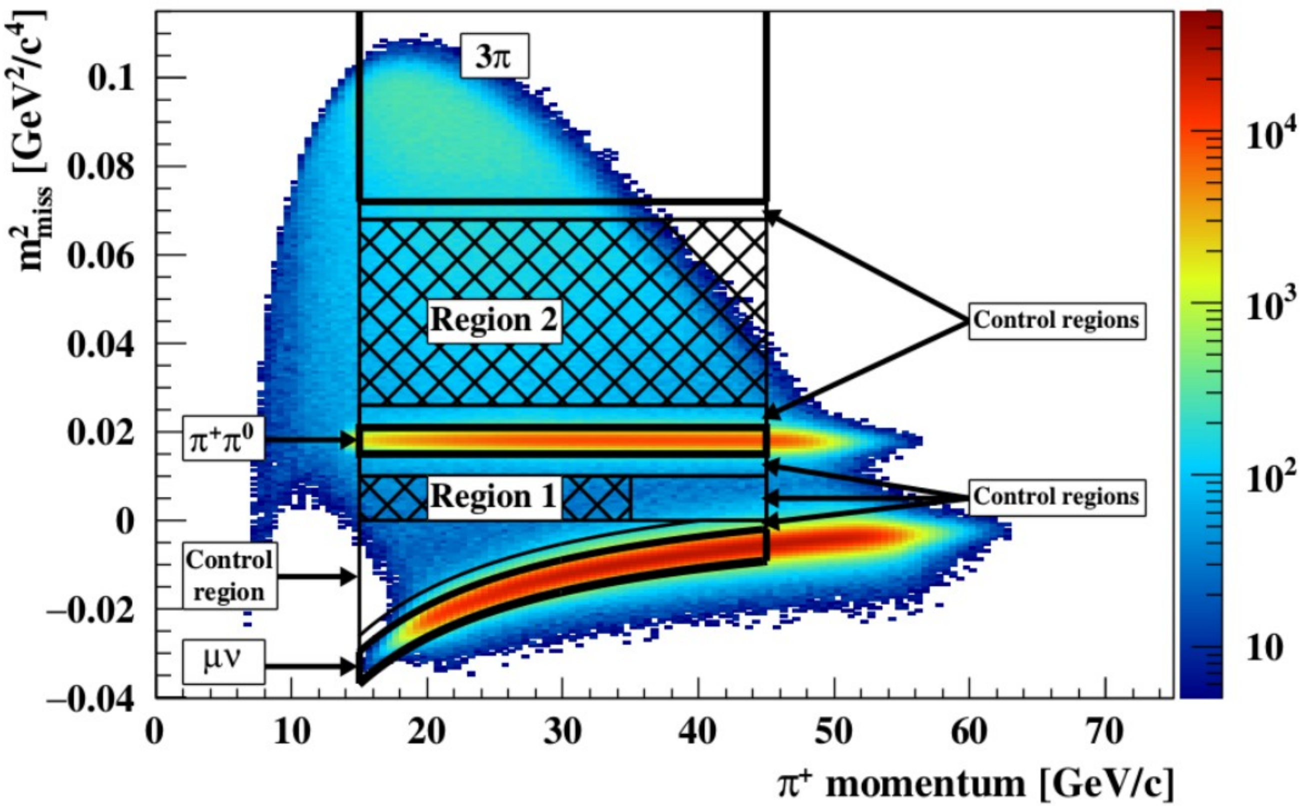
Blind analysis strategy to avoid the influence of selection criteria variation:

- 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:

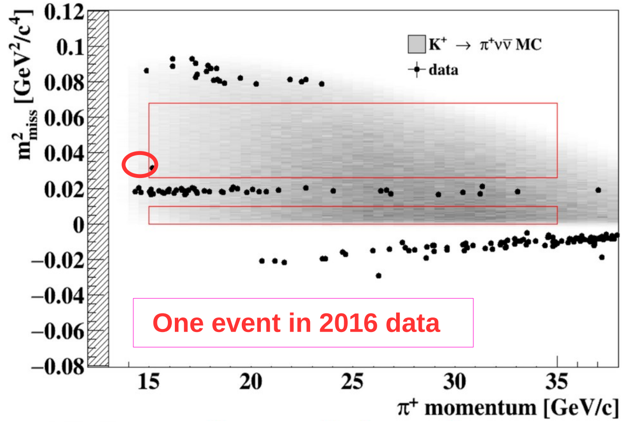
- K^+ and π^+ tracks reconstruction
- K^+ - π^+ matching
- Decay vertex reconstruction
- μ^+ rejection (π^+ identification)
- Photons rejection
- Multi-track rejection
- Kinematics plot

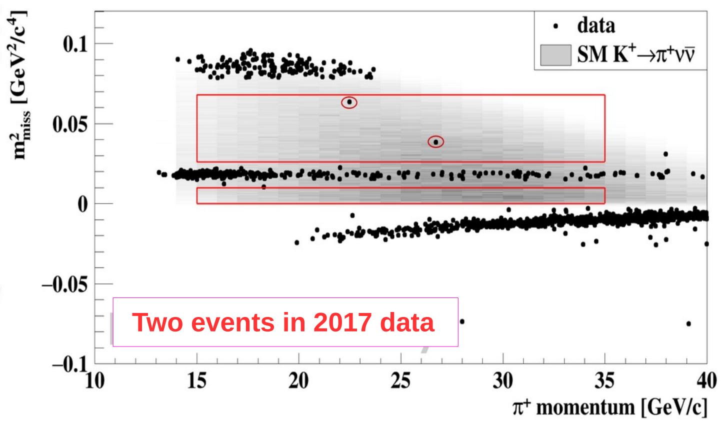
$$m^2_{miss} = (P_K - P_\pi)^2$$

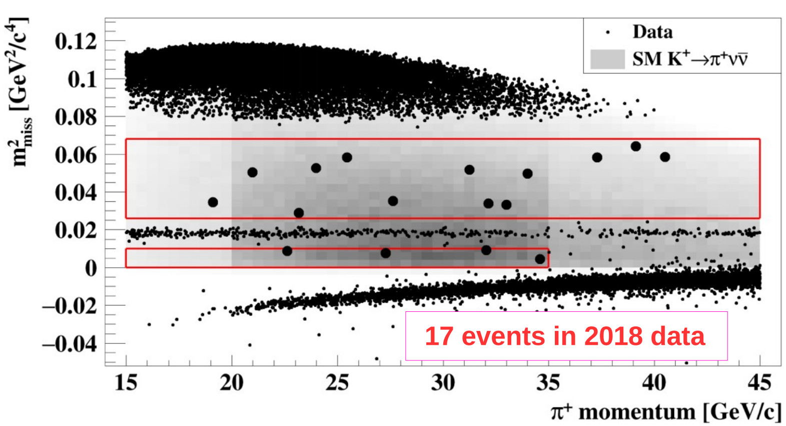


NA62 results (data 2016-2018)

Results







Data	Reference	N_{bg} estimated	$N_{\pi\nu\bar{\nu}}$ SM expected	N observed
2016	PLB 791 (2019) 156	0.152	0.267	1
2017	JHEP 11 (2020) 042	1.46	2.16	2
2018	JHEP 06 (2021) 093	5.42	7.58	17
2016-18	JHEP 06 (2021) 093	7.03	10.01	20

Statistical combination 2016-2018:

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

- Background-only hypothesis: $p = 3.4\times10^{-4}$
- Significance of 3.4 σ

Data 2021-2022

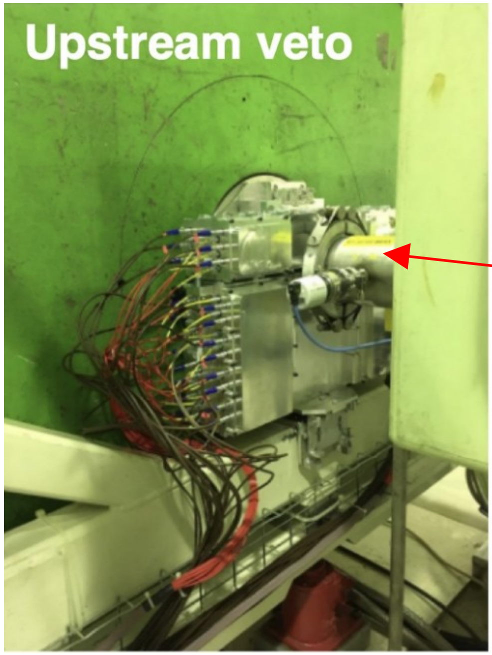
Upgrades during LS2 (2019-2020):

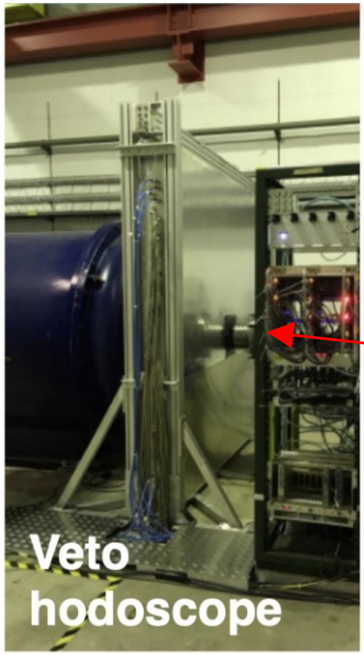
- New veto detectors upstream the fiducial volume;
- Fourth station added to beam spectrometer;
- Additional veto detector (HASC2) at the end of the beam line.

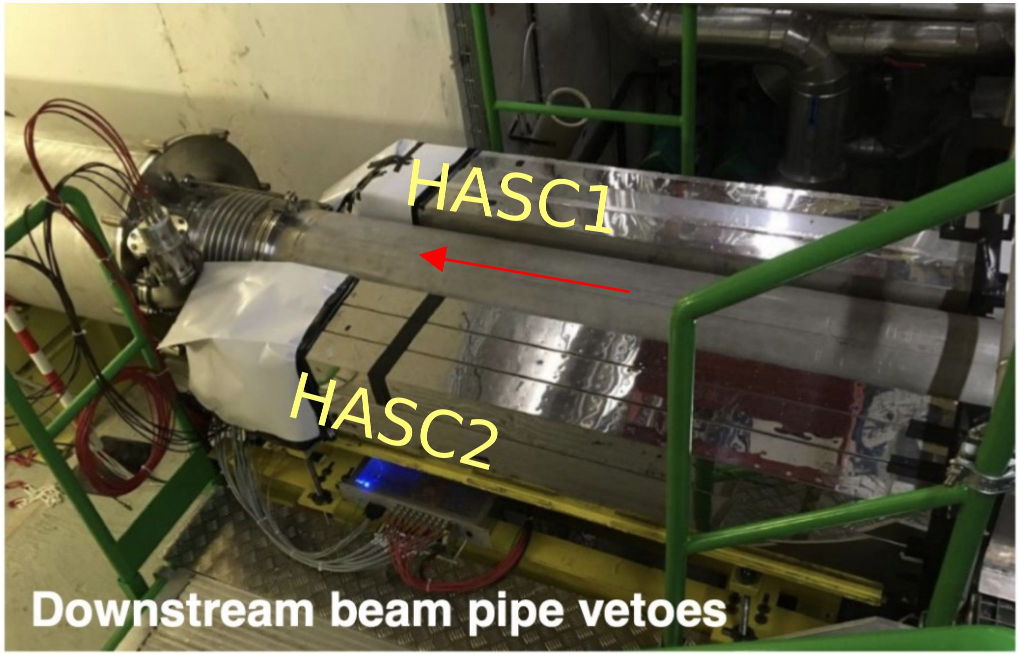
- Proton intensity +40% wrt to 16-18 data;
- 550000 spills
- Improved trigger

Selection procedure update, including the new **Bayesian classifier** for (K^+ - π^+) matching using CDA, ΔT, N_{GTK} (intensity).

← **Beam**

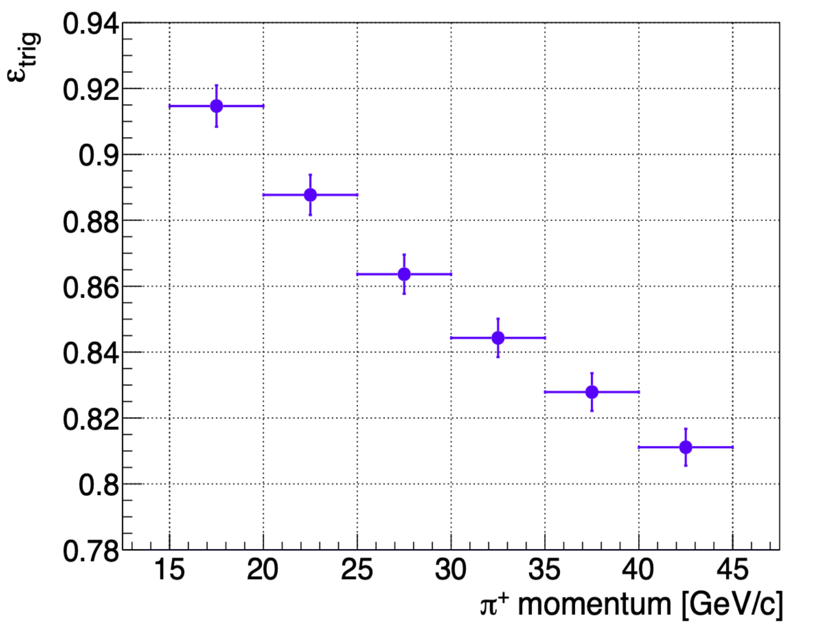






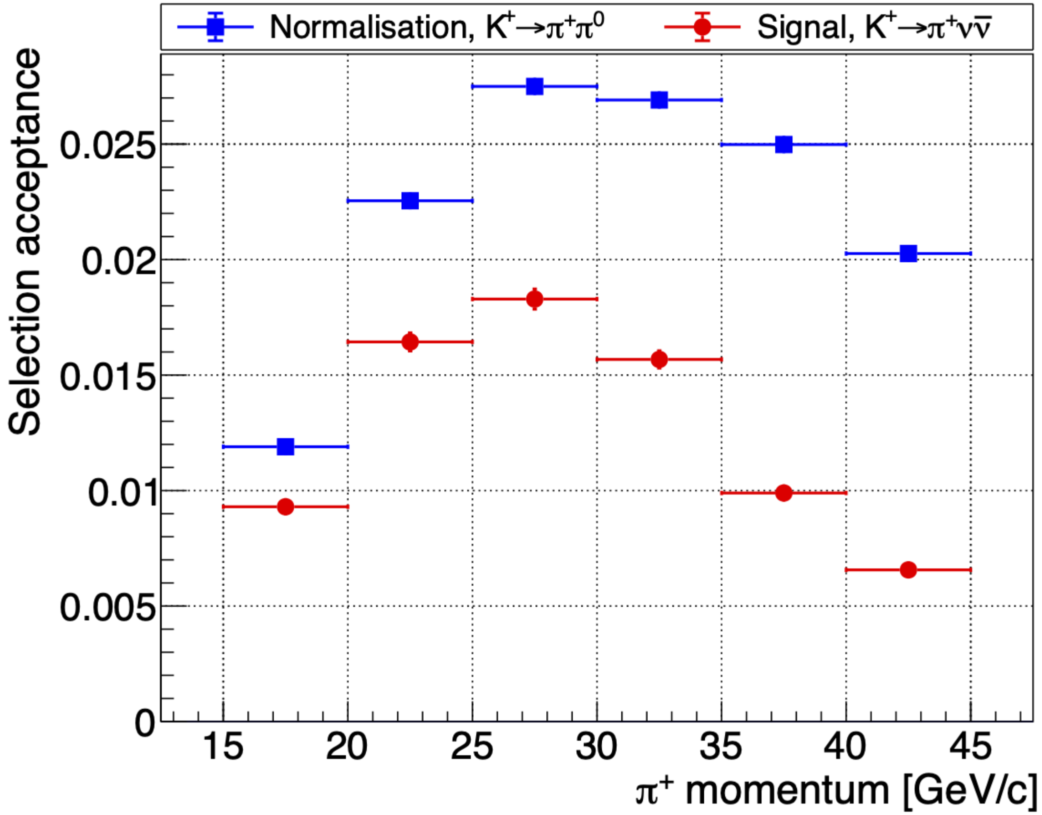
2021-2022 expected signal

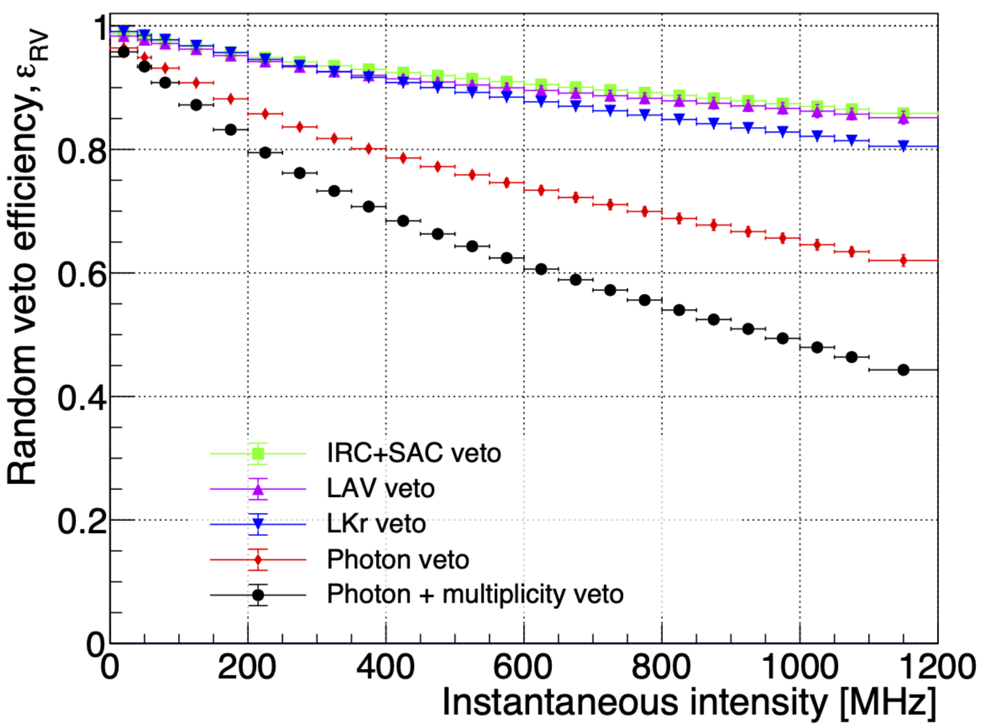
$N_{\pi\pi}$: normalization number of $K^+ \rightarrow \pi^+\pi^0$ decays collected with a downscaled (D) control trigger line.



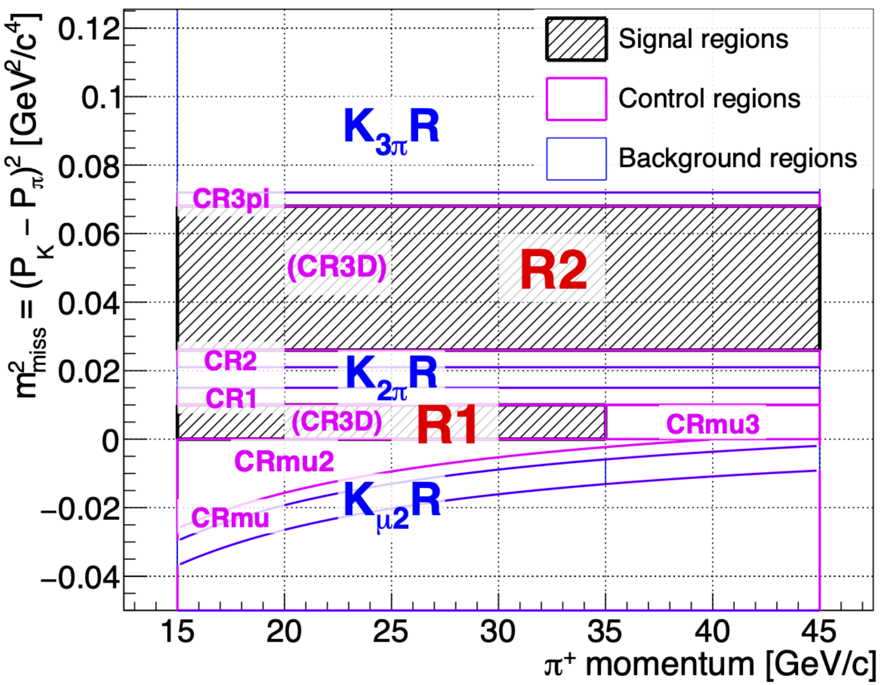
Expected number of πνν events in some region j:

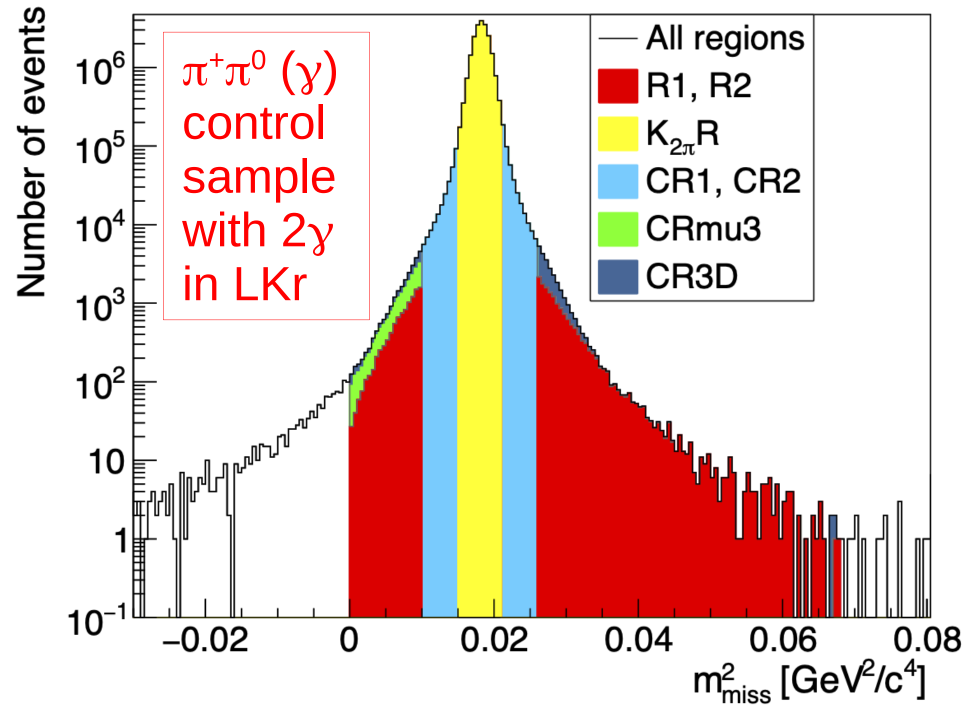
$$N^{SM,\exp}_{\pi\nu\nu} = \frac{BR(\pi\nu\nu)_{SM}}{SES} = \frac{BR(\pi\nu\nu)_{SM}}{BR(\pi\pi)} \frac{A^j_{\pi\nu\nu}}{A_{\pi\pi}} N_{\pi\pi} D\, \varepsilon^j_{trig}\, \varepsilon^j_{RV}$$



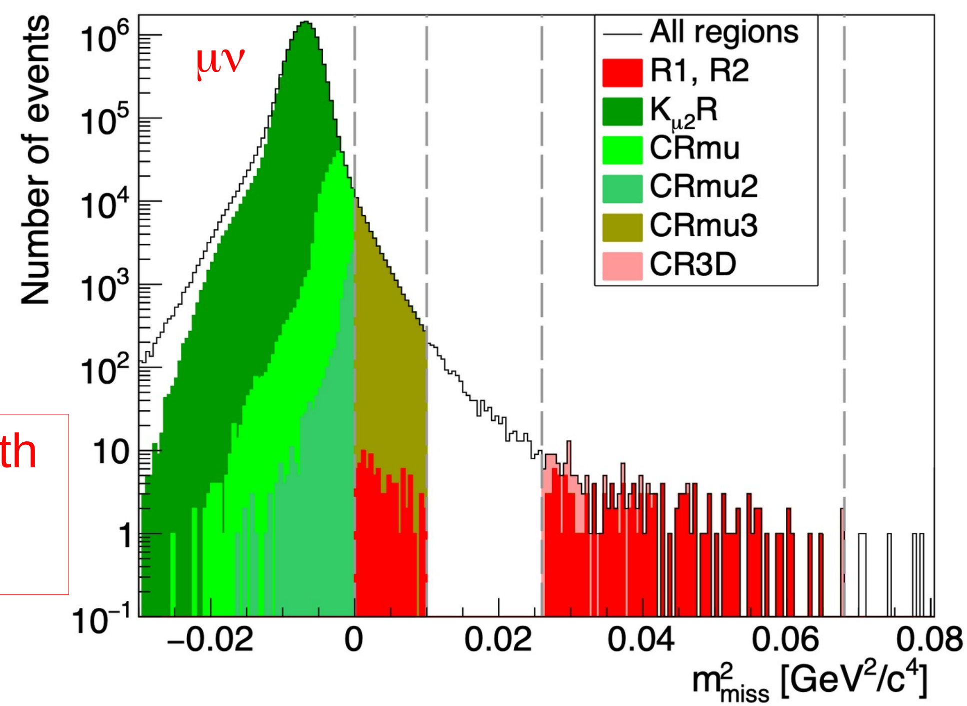


Background from kinematic tails





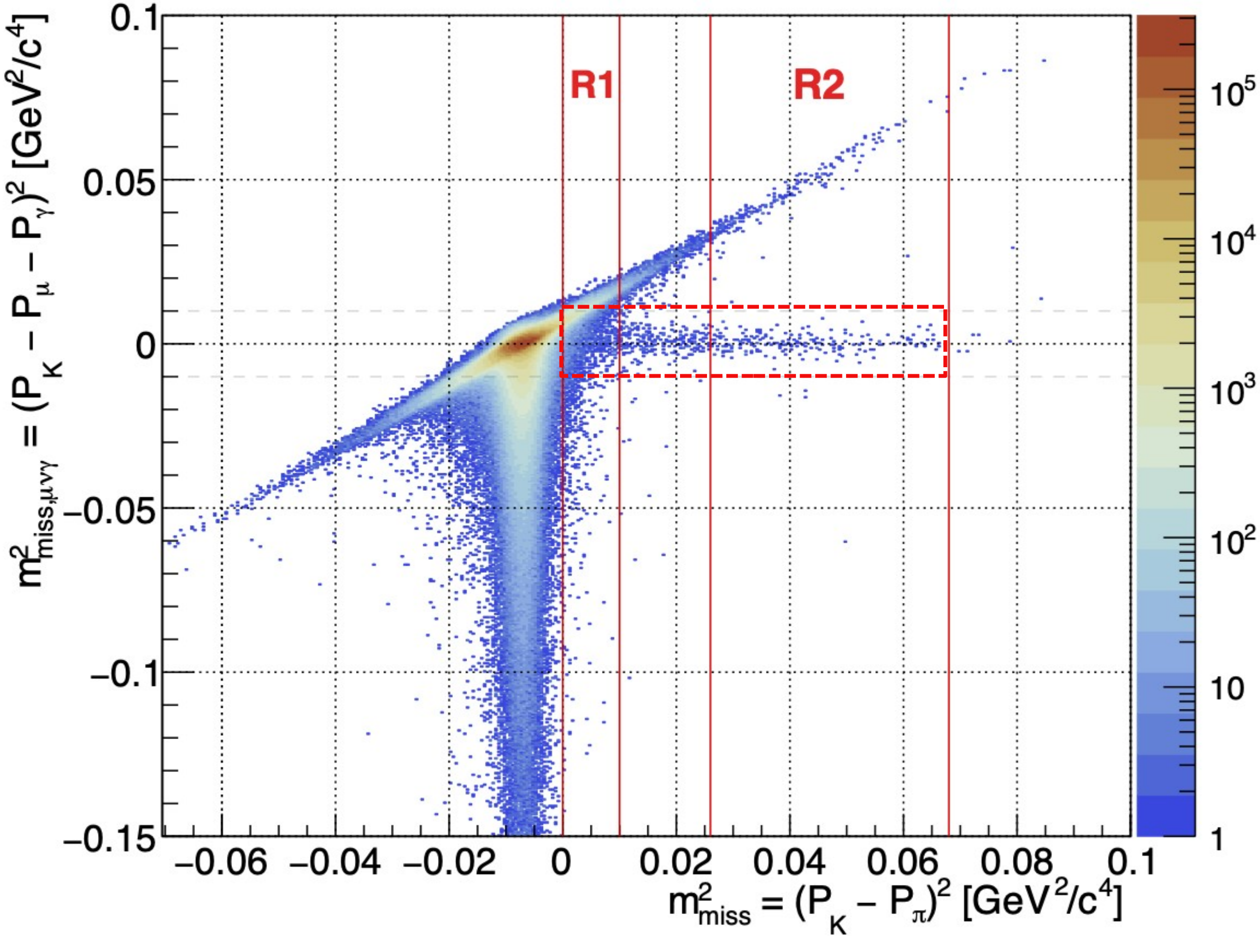
$\pi^+\pi^+\pi^-$ control sample using MC to measure f_{tail}



$\mu\nu$ control sample with RICH PID = π^+, but Calorimeter PID = μ^+

$K^+ \to \mu^+ \nu \gamma$ background

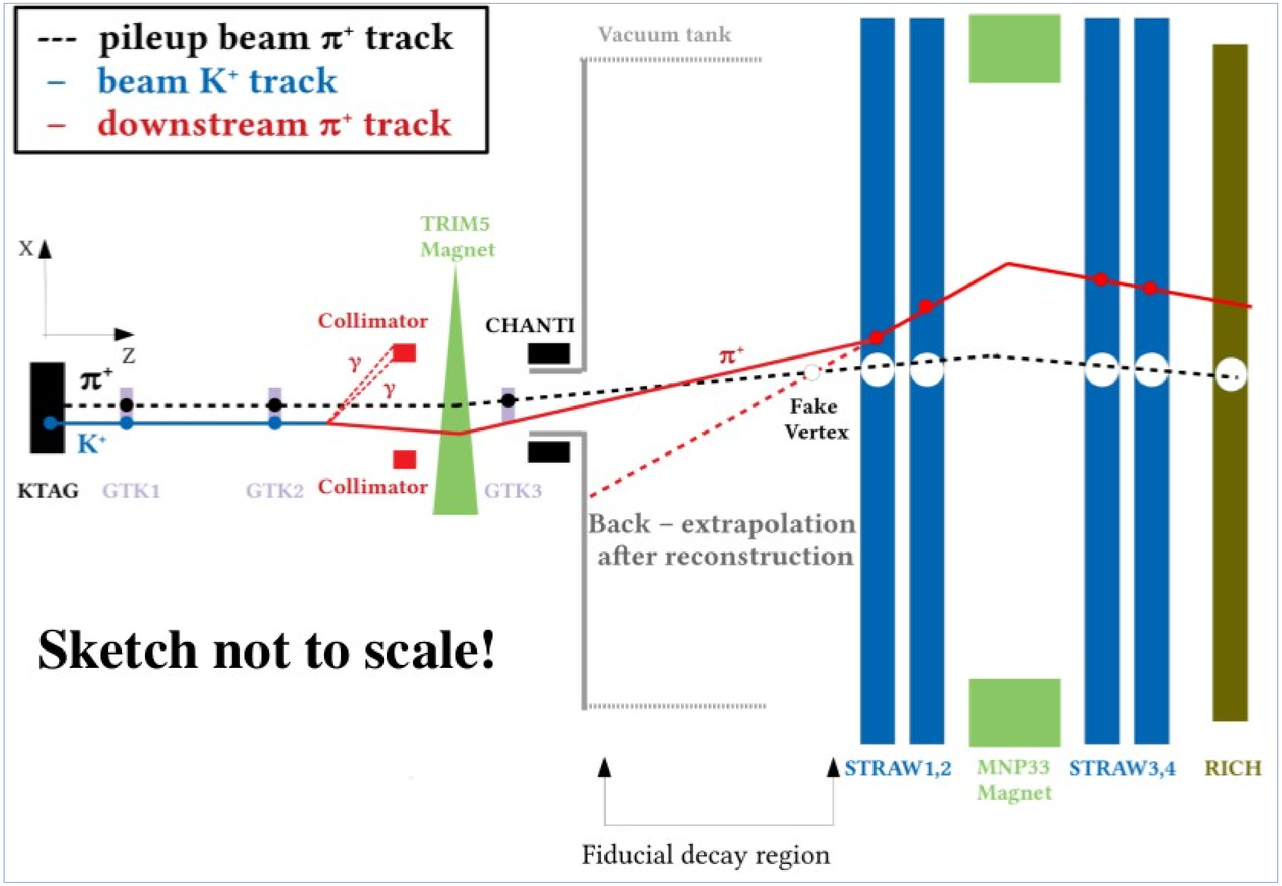
- **Excess of signal candidates at P>35 GeV/c in Region 2 relative to the 2016-2018 data.**
- Additional $K^+ \to \mu^+ \nu \gamma$ bg:
  - high-momentum μ overlap with γ in LKr leading to misID.
  - Increased due to PID worsening at higher intensity in 2021-2022.
- Selection criteria are modified, now we reject the candidate, if
  - $|m^2_{miss,\mu\nu\gamma}| < 0.01$ GeV^2/c^4
  - $E_{LKr} > 5$ GeV;
  - Not satisfying strict RICH PID.



For this background the expectation is evaluated using a control sample with Minimum Bias trigger, without calorimetric PID and with MUV3 signal.

Upstream background

- A kaon decays upstream the fiducial decay region;
- Only produced π^+ enters the fiducial region;
- An in-time pileup beam particle is registered;
- The π^+ from upstream decay is scattered in Spectrometer, and a fake vertex is found in the fiducial region.



$$N_{bg}^{upstream} = f_{CDA} \Sigma_i N_i P_i$$

Where i is a bin in (ΔT,N_{GTK}) plane;

N_i is the upstream data sample (inverted CDA cut), **51** events in total;

f_{CDA} = 0.20±0.03 extrapolation from the upstream sample distribution;

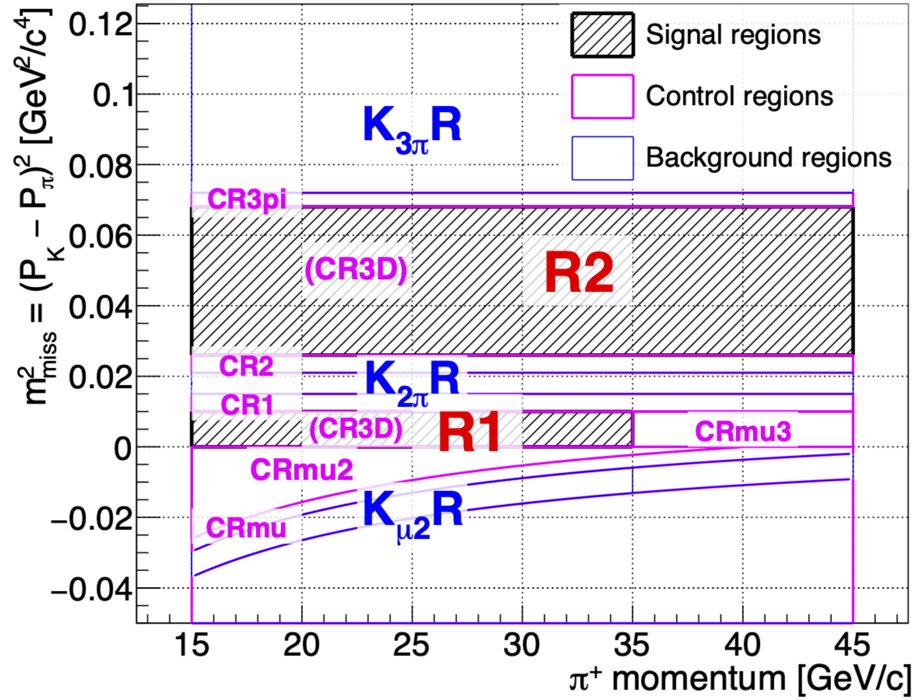
P_i is (K^+ - π^+) mismatching probability (from $\pi^0\pi^+$ control sample).

Expectations and validation

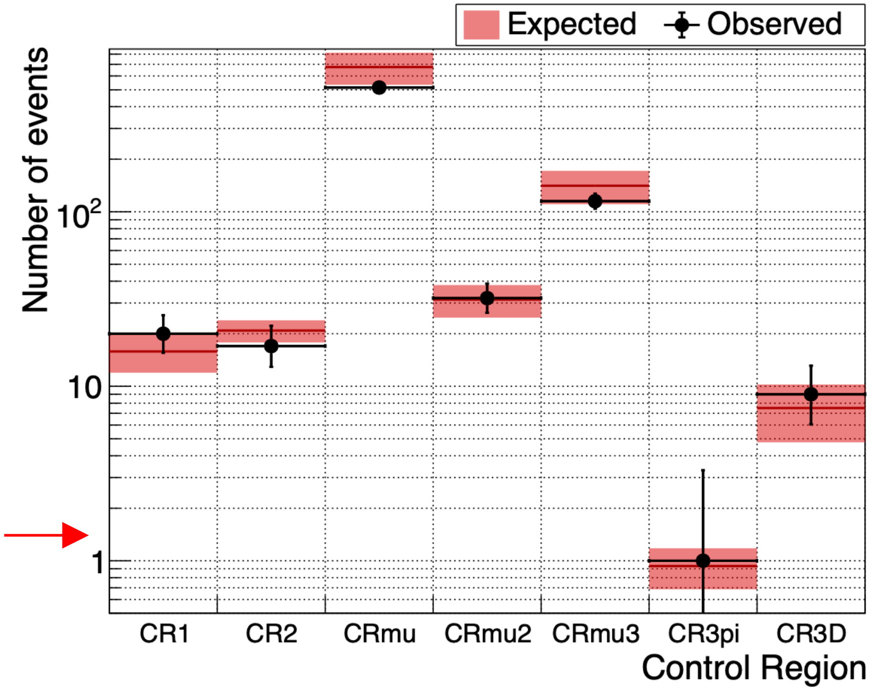
Expected in full signal region:

Background	Events	
$K^+ \to \pi^+\pi^0(\gamma)$	0.83 ± 0.05	
$K^+ \to \mu^+\nu(\gamma)$	1.70 ± 0.47	Data-driven
$K^+ \to \pi^+\pi^+\pi^-$	0.11 ± 0.03	
$K^+ \to \pi^+\pi^-e^+\nu$	$0.89^{+0.33}_{-0.27}$	
$K^+ \to \pi^+\gamma\gamma$	0.01 ± 0.01	Simulation
$K^+ \to \pi^0\ell^+\nu$	< 0.001	
Upstream	$7.4^{+2.1}_{-1.8}$	Data-driven
Total	$11.0^{+2.1}_{-1.9}$	

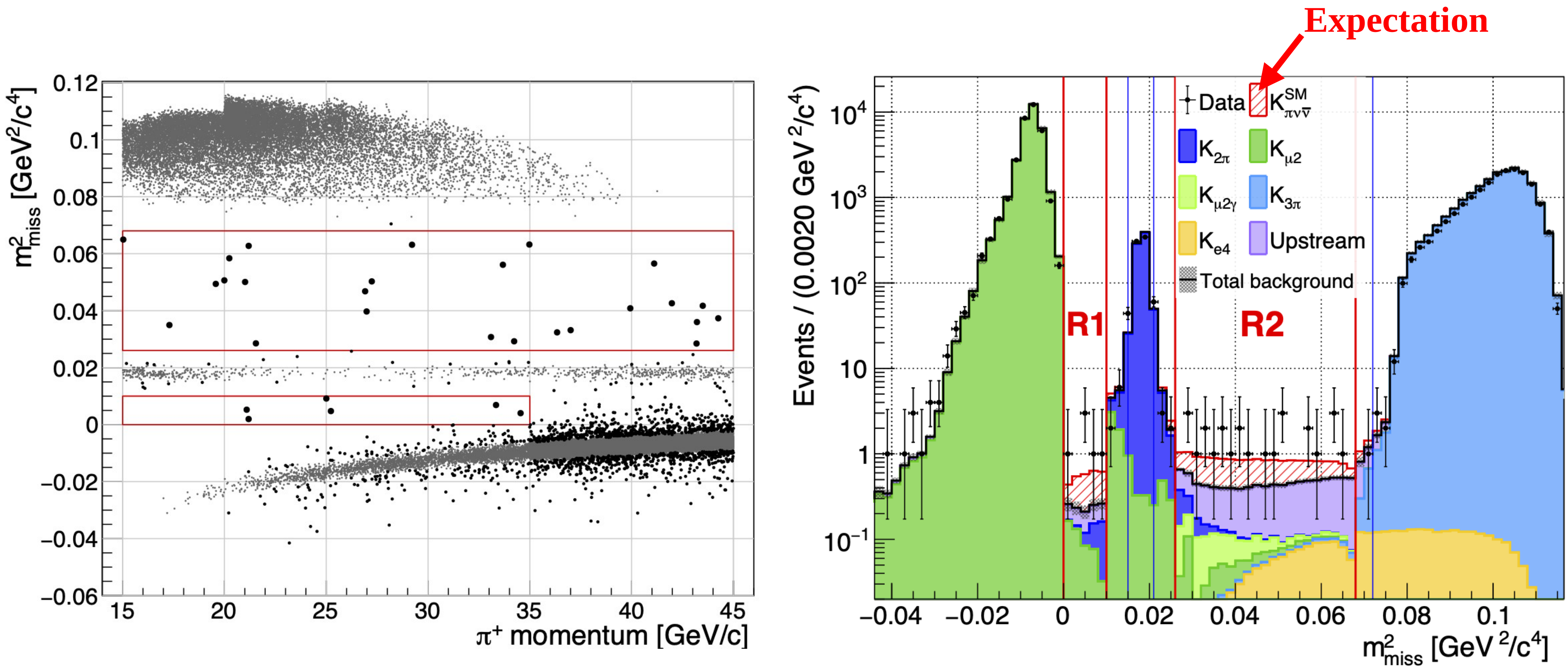
Expected SM $K^+\to\pi^+\nu\bar{\nu}$ signal: 9.91±0.34



First open the control regions:

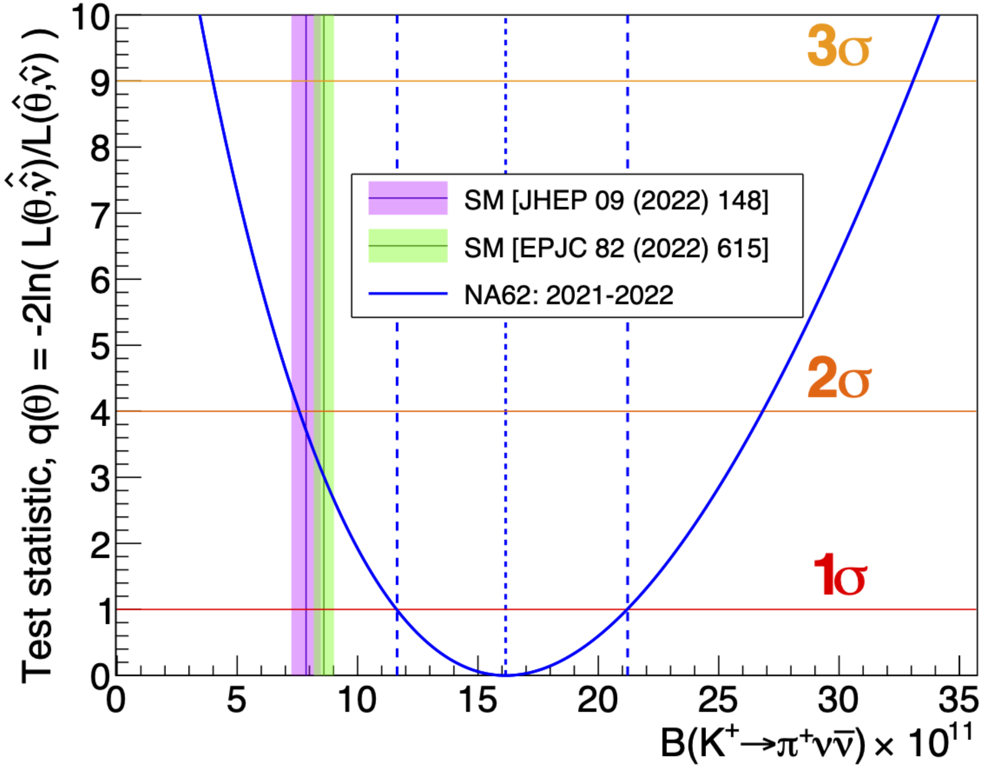


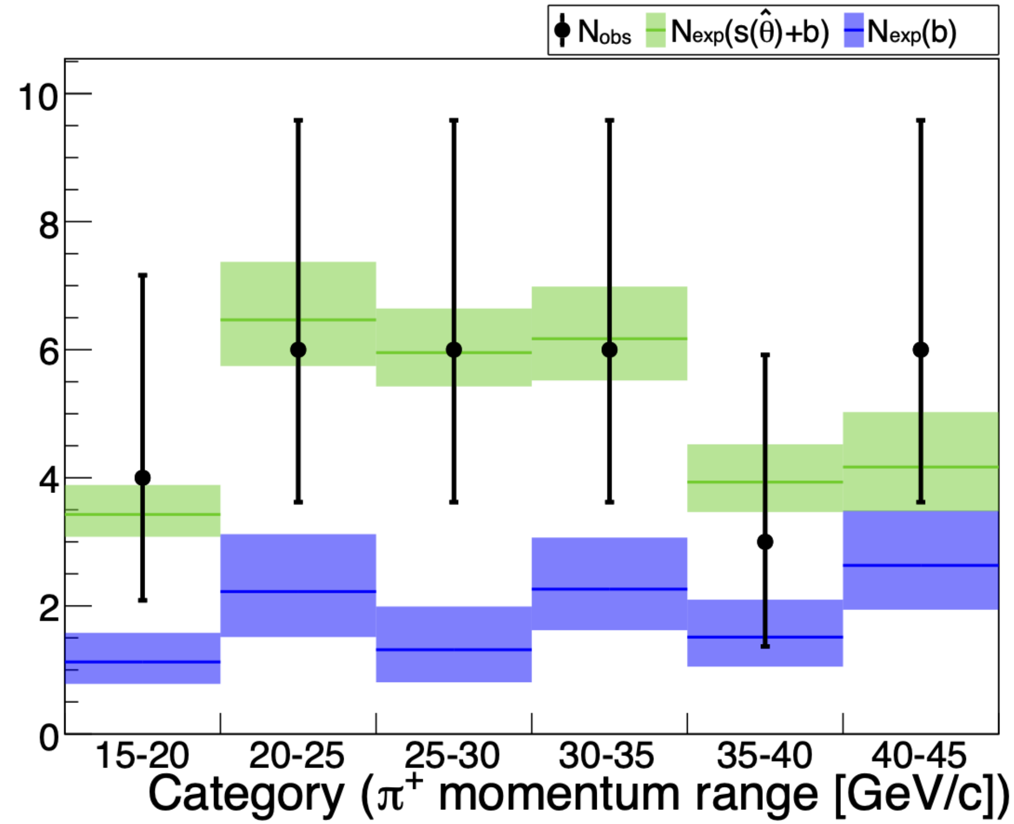
Signal regions: 2021-22 data



Observed: 31 events

Result from the data collected in 2021-2022





$N_{bkg} = 11.0^{+2.1}_{-1.9}$, $N_{obs} = 31$, significance 3.6σ

$BR_{2021-22}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = (16.2^{+4.9}_{-4.3}|_{stat}\ {}^{+1.4}_{-1.4}|_{syst}) \times 10^{-11} = (16.2^{+5.1}_{-4.5}) \times 10^{-11}$

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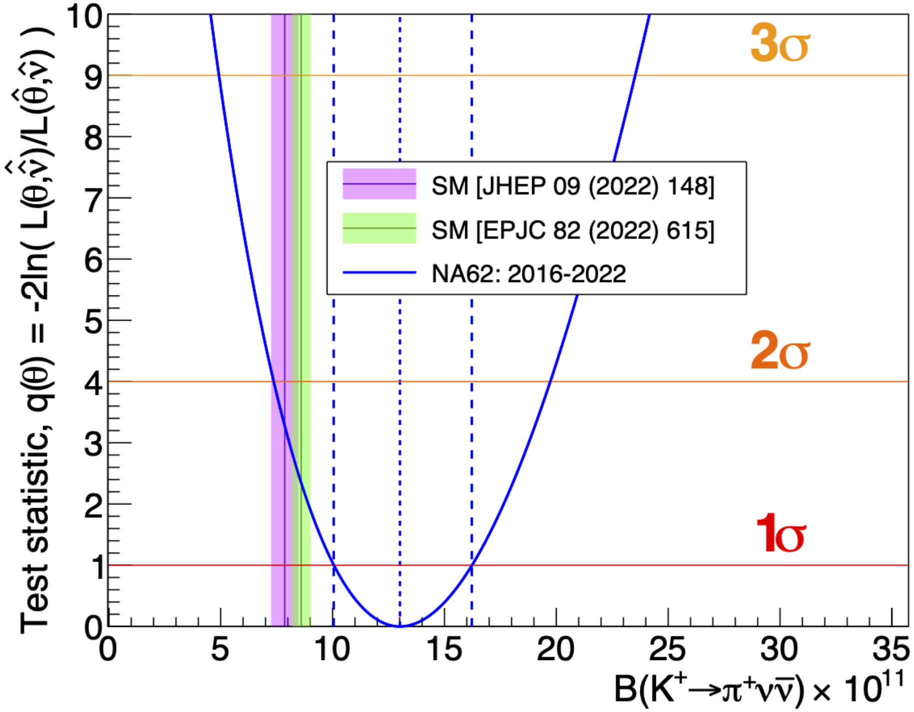
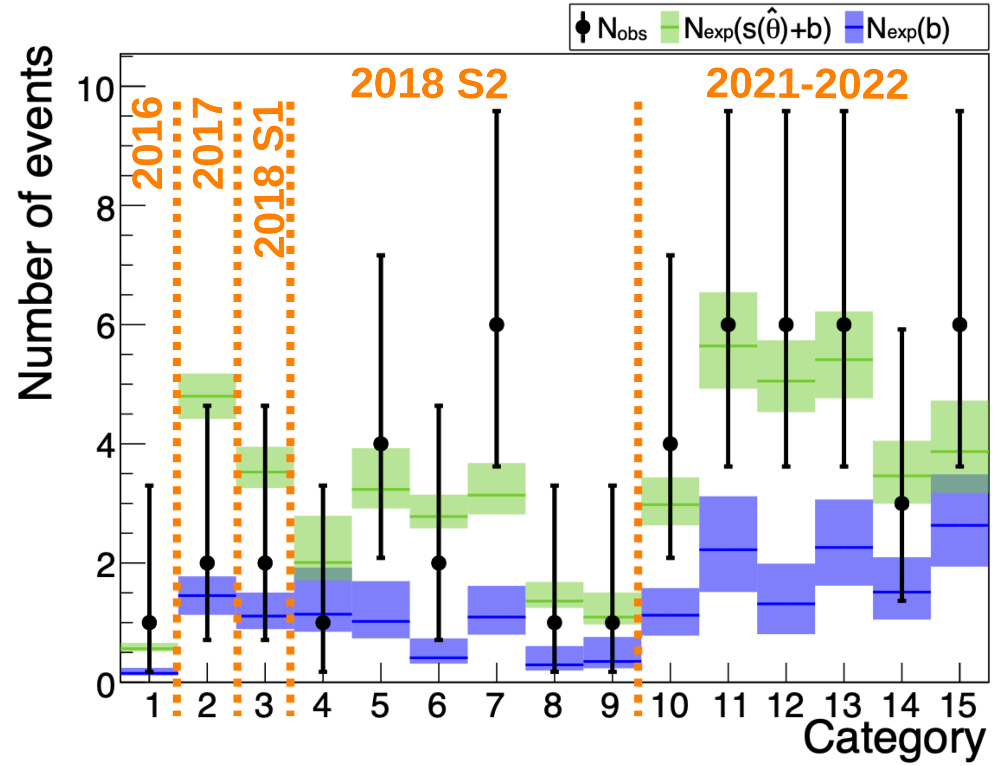
Combined result 2016-2022





Integrating 2016-2022 data: $N_{bkg} = 18^{+3}_{-2}$, $N_{obs} = 51$

Background-only hypothesis p-value = 2×10^{-7} : significance Z > 5

$BR_{2016\text{-}22}(K^+\to\pi^+\nu\bar{\nu}) = (13.0^{+3.0}_{-2.7}|_{stat}\ ^{+1.3}_{-1.3}|_{syst})\times 10^{-11} = (13.0^{+3.3}_{-3.0})\times10^{-11}$

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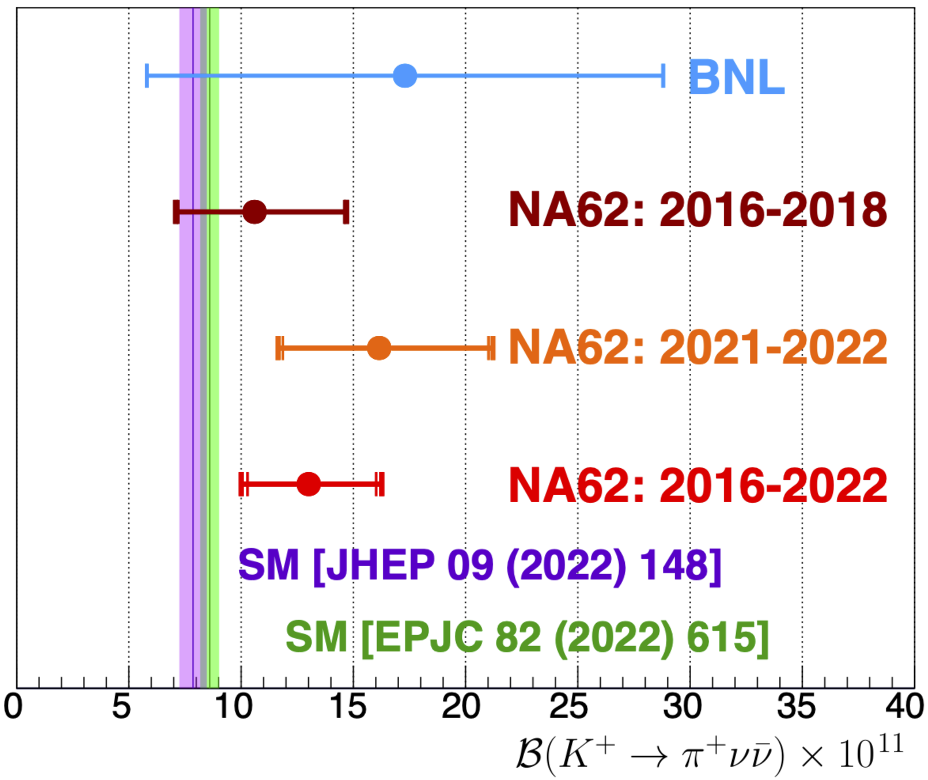
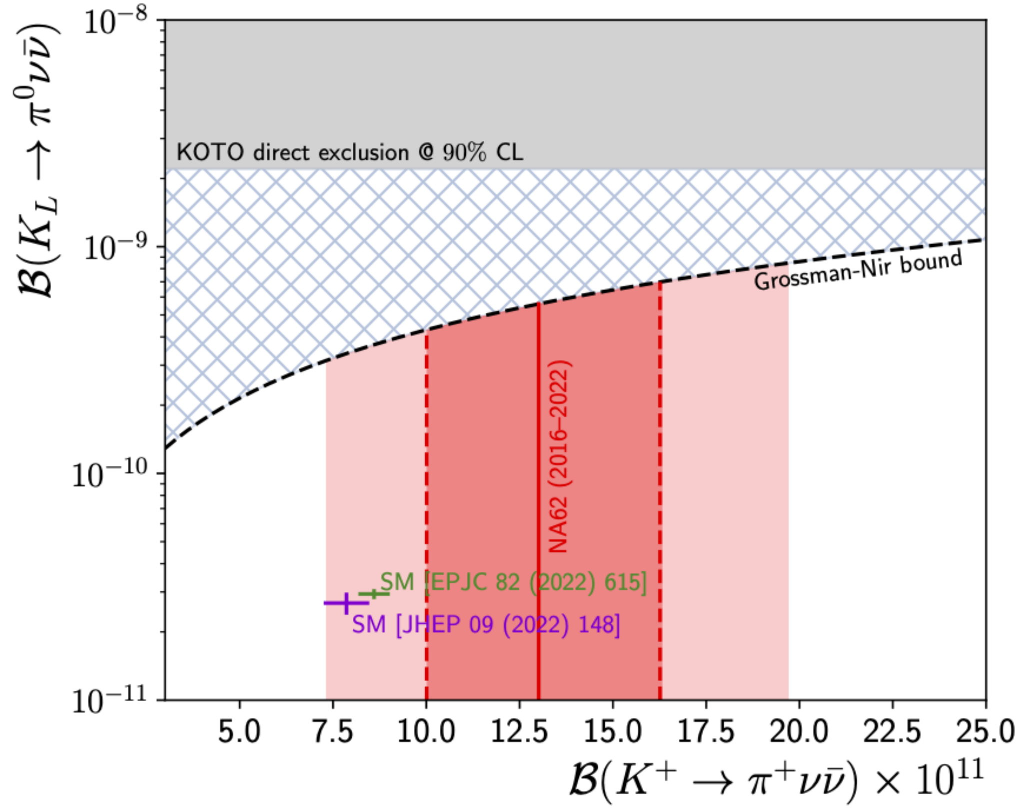
Results in context

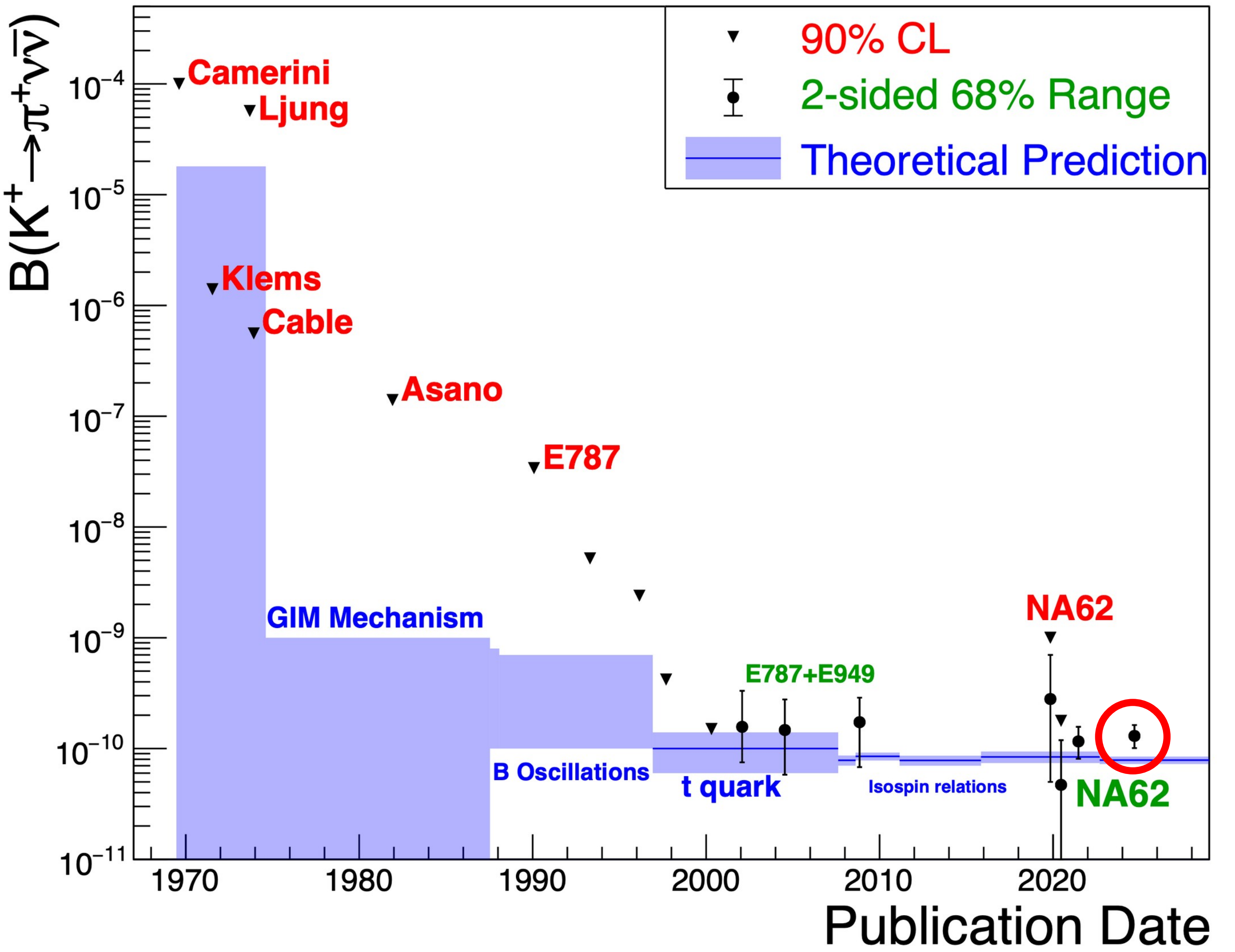




- NA62 results are consistent
- Central value moved up (now 1.5—1.7 above SM)

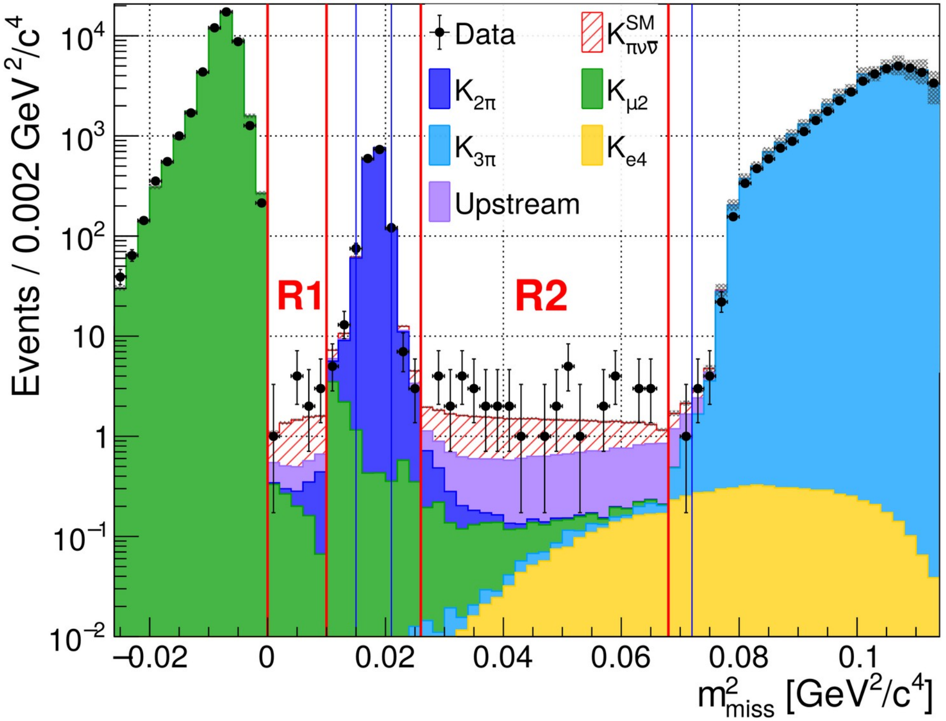
Results in context

- 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: [JHEP 02 (2025) 191]
- 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]

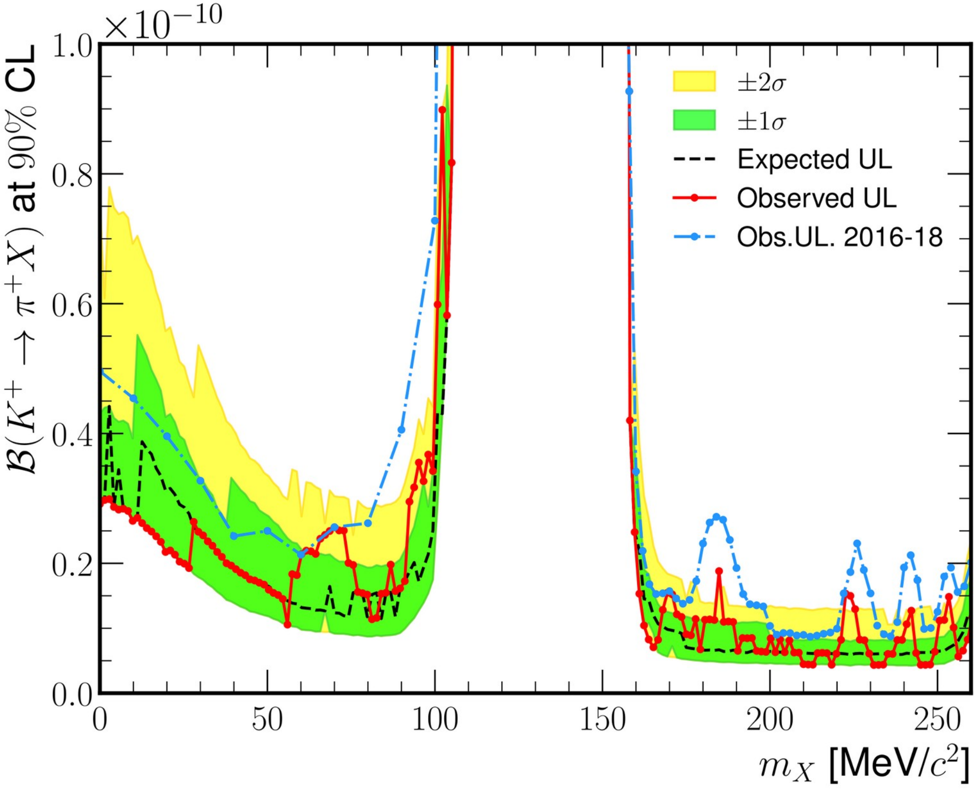


$K^+ \to \pi^+ X$, X is invisible

- Interpretation of the $K^+ \to \pi^+\nu\nu$ result (2016-2022) [arXiv:2507.17286];
- Peak search in m_{miss}^2 distribution;
- $K^+ \to \pi^+\nu\nu$ is the main background estimated using SM branching ratio.



Combined spectrum 2016-2022



Model-independent **constraints** are improved wrt **2016-2018 limits**

2023-2024 data: analysis in progress

- 2024 data-taking conditions lead to a slightly higher signal yield per spill:
  - lower random veto loss compensates the lower kaon beam intensity.
- Increase of the overall expected signal yield, given the smoother and more efficient data collection.

WORK IN PROGRESS [2025 NA62 SPSC Report]

Dataset	2022	2023	2024
Number of spills $[10^3]$	326	363	519
$<$ Beam intensity $>$ [GHz]	0.57	0.48	0.41
$< N_{\pi\pi}/\text{spill} >$ $[10^2]$	4.9	4.7	4.4
N_K $[10^{12}]$	2.3	2.5	3.3
ε_{RV}	0.63	0.68	0.73
$N_{\pi\nu\nu}$	8	9	13
$N_{\pi\nu\nu}/\text{spill}$ $[10^{-5}]$	2.5	2.5	2.6
$B_{\text{total}}/N_{\pi\nu\nu}$	1.1	1.1	1.0

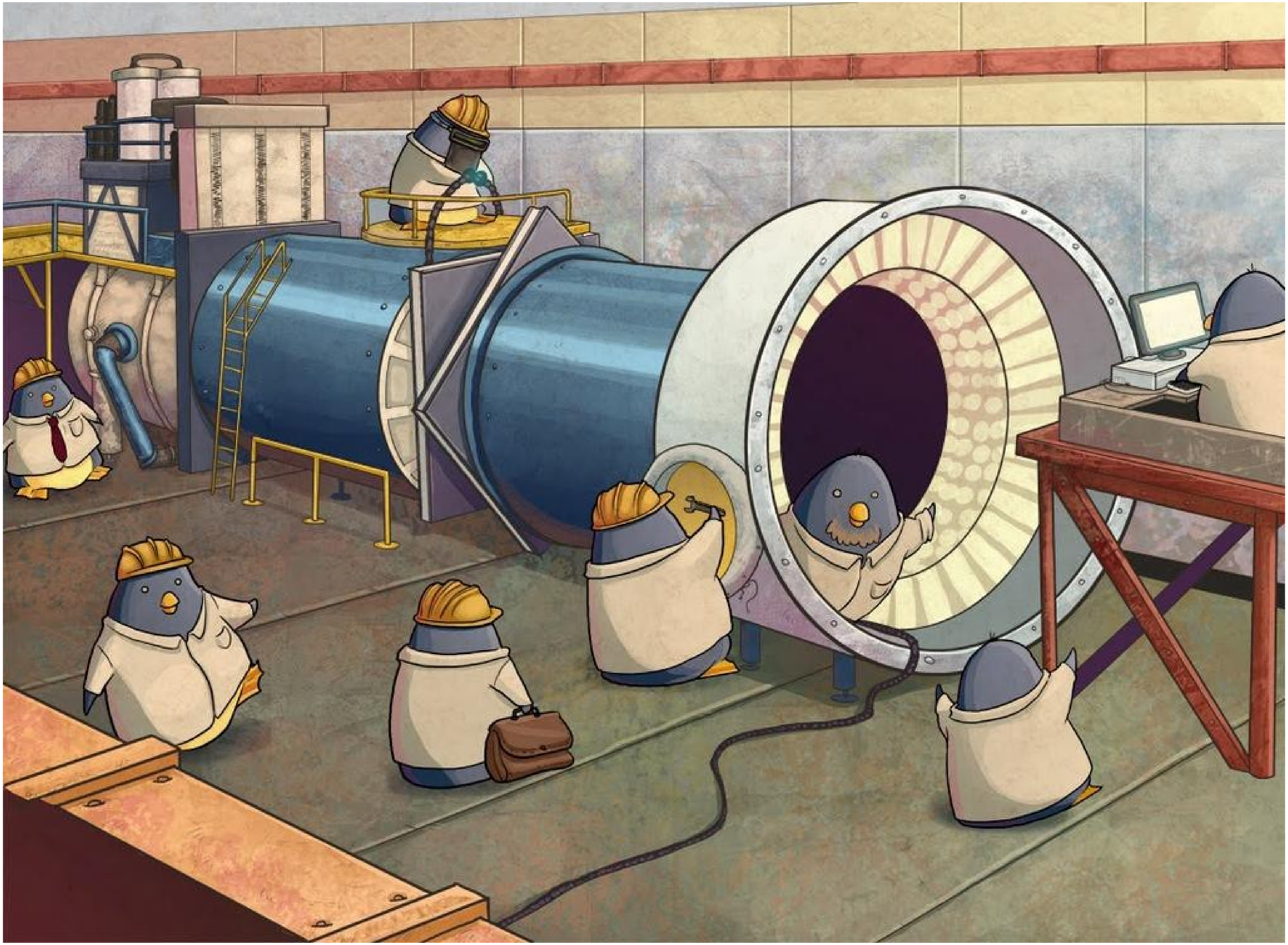
B_{total} : background events

The addition of the 2023-2024 dataset is expected at least to double the signal yield of the 2016-2022 dataset, with the same relative level of background.

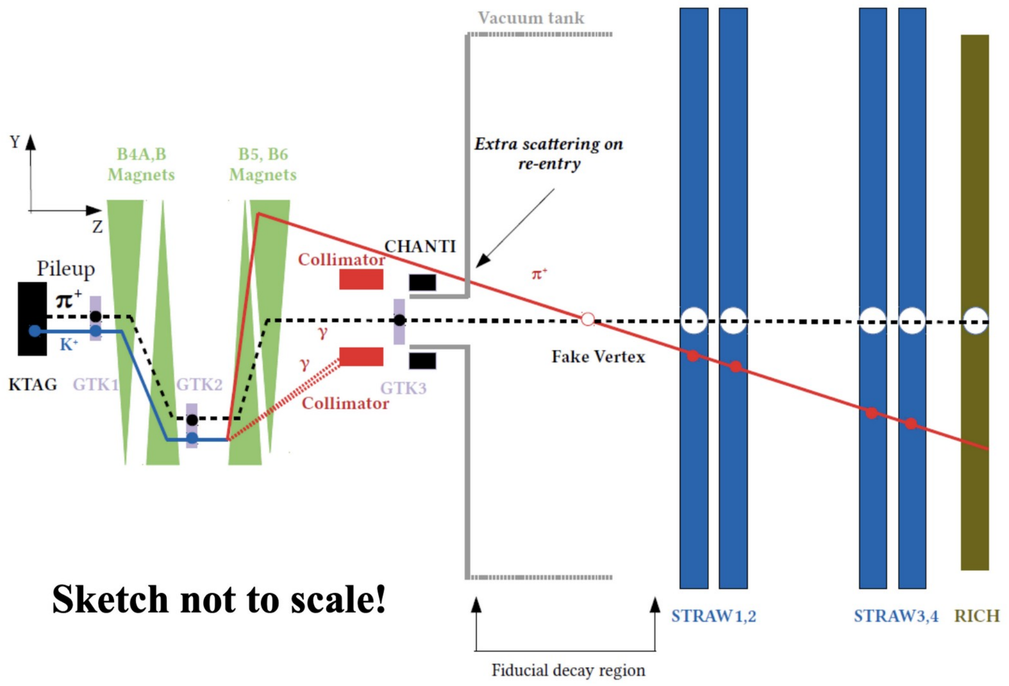
Conclusions

- New NA62 study of $K^+ \to \pi^+ \nu\bar{\nu}$ using 2021-2022 data: [JHEP 02 (2025) 191]
  - $N_{bg} = 11^{+2.1}_{-1.9}$, $N_{obs} = 31$;
  - **$BR_{2021\text{-}22}(K^+ \to \pi^+ \nu\bar{\nu}) = (16.2^{+4.9}_{-4.3}|_{stat}\ ^{+1.4}_{-1.4}|_{syst}) \times 10^{-11}$**
- Combining with the 2016-2018 result:
  - $N_{bg} = 18^{+3}_{-2}$, $N_{obs} = 51$;
  - **$BR_{2016\text{-}22}(K^+ \to \pi^+ \nu\bar{\nu}) = (13.0^{+3.0}_{-2.7}|_{stat}\ ^{+1.3}_{-1.3}|_{syst}) \times 10^{-11}$**
  - Background-only hypothesis excluded with significance of 5σ : the first statistically significant observation.
- It is the smallest BR ever observed at 5σ level.
- In agreement with SM within 1.7σ. Need full data set to confirm.
- Improved upper limits for $K^+ \to \pi^+ X$, X is invisible.
- 2023-2024 data analysis in progress, NA62 will take data until 2026.

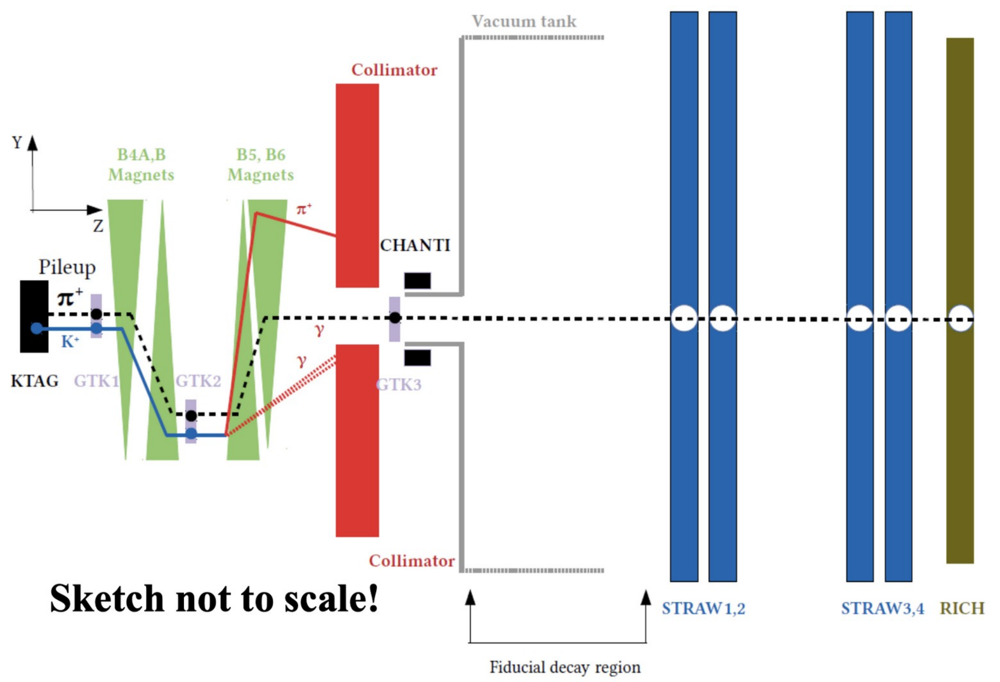
Supplemental



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.

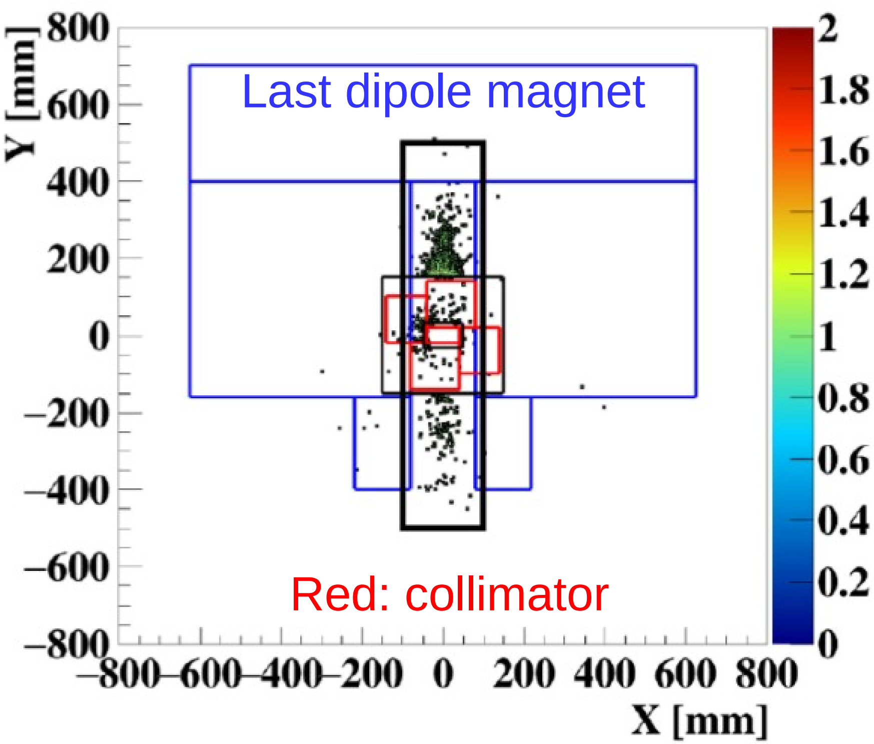


- A new final collimator from the second part (70%) of 2018 run.
- Different selections for the two parts.

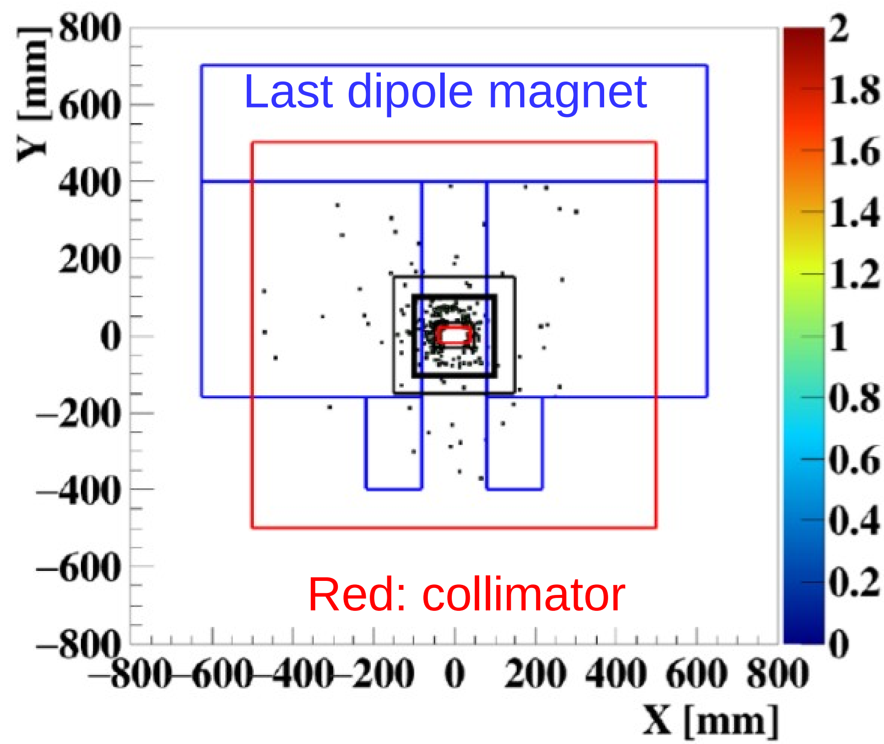
Old variable final collimator

New fixed final collimator

OLD COL



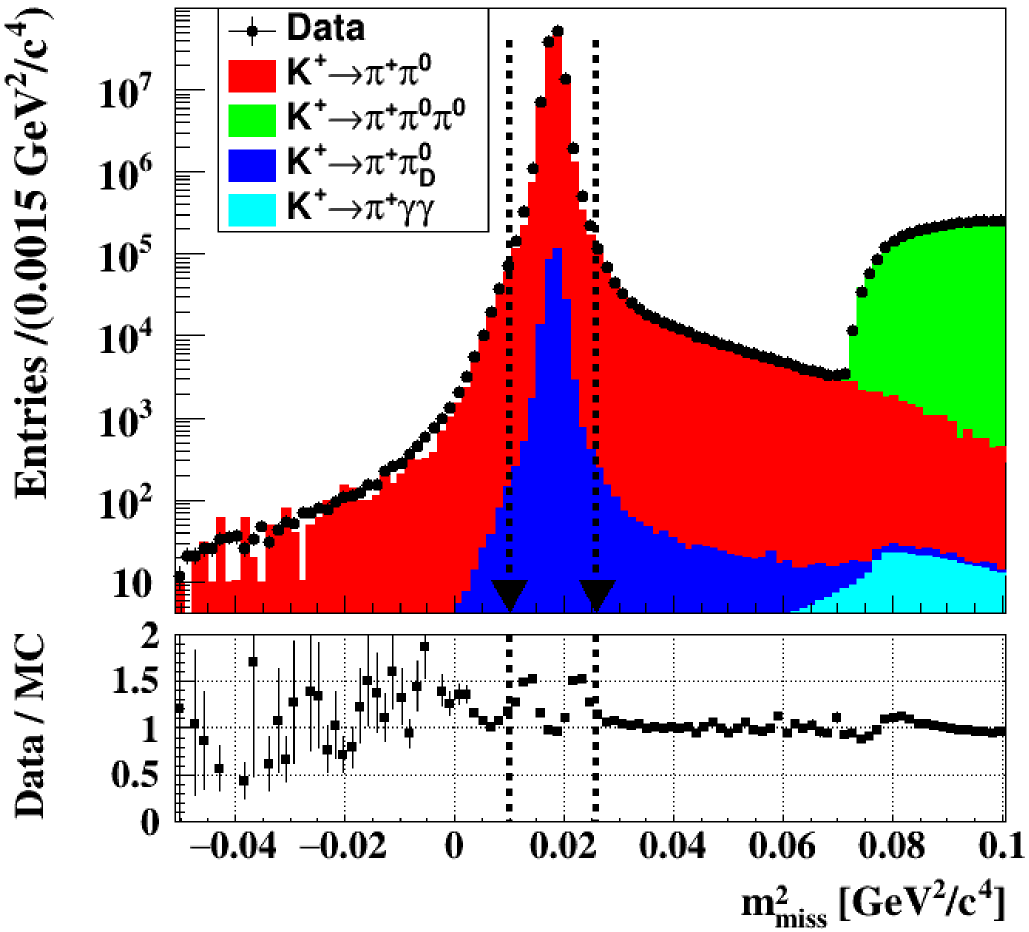
NEW COL



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

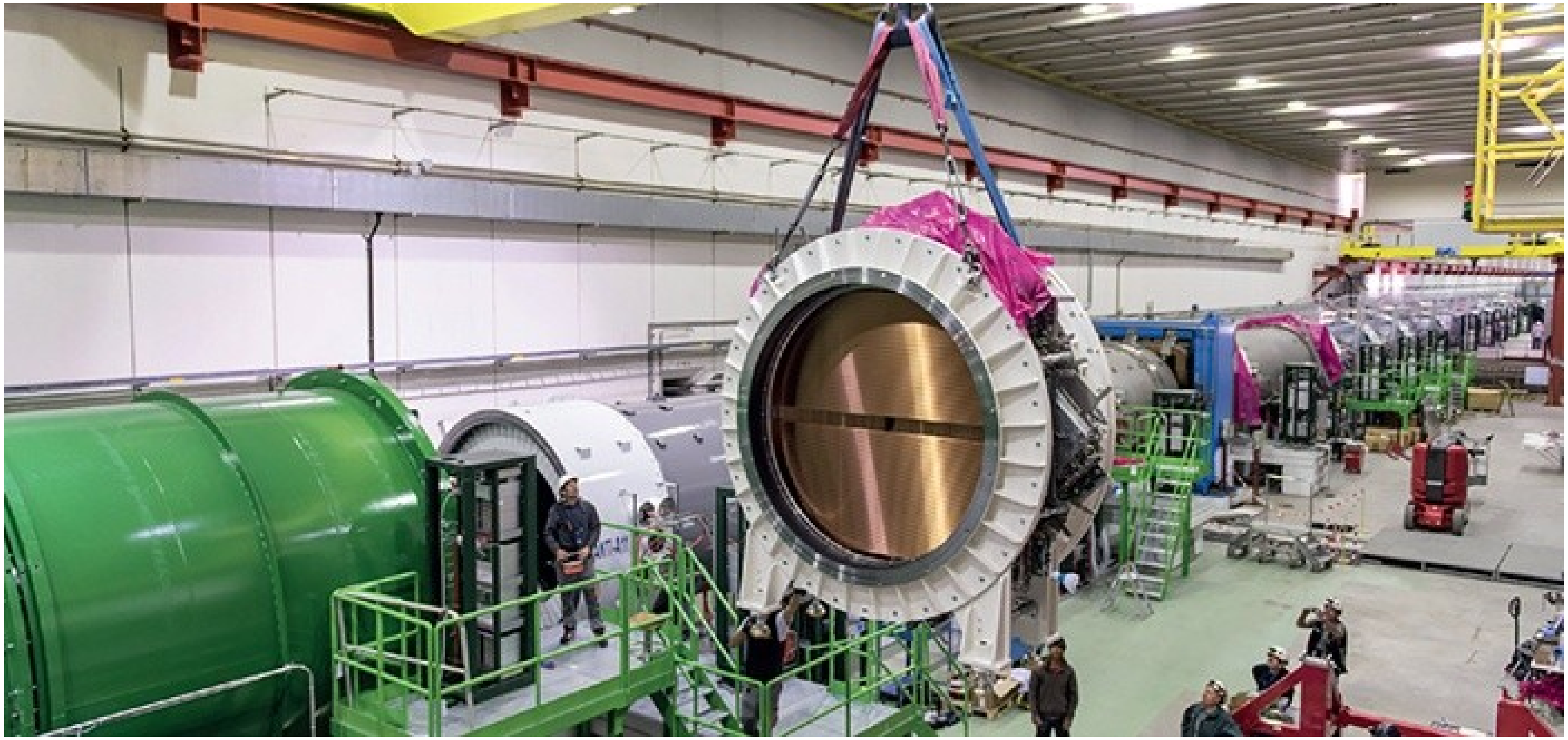
$K^+ \to \pi^+\pi^0$ normalization channel

Normalization channel: $K^+ \to \pi^+\pi^0$ ($\pi^0 \to \gamma\gamma$), same selection as the signal one, but collected with minimum bias trigger and no photon/multiplicity rejection.
Used to evaluate number of kaon events N_K



- 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;

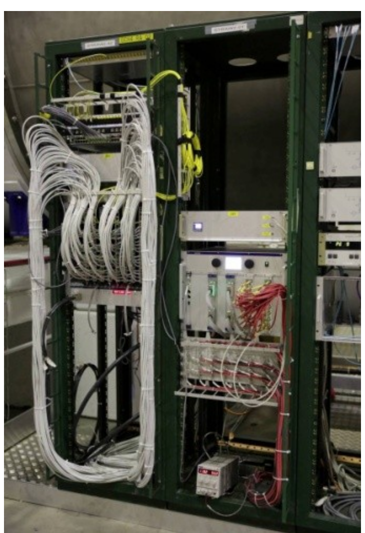
JINR+CERN responsibility :
Spectrometer made of straw tubes working in vacuum



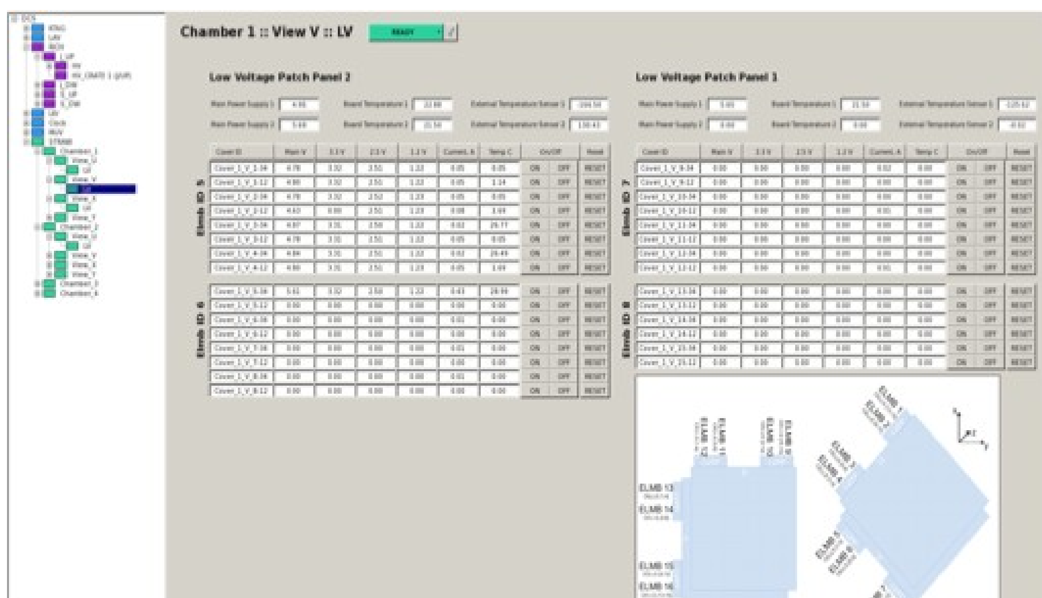
JINR contribution is very important and is defining in many aspects:

- 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