ICHEP 2024

SEARCH FOR PHYSICS BEYOND THE STANDARD MODEL AT NA62

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on behalf of the NA62 collaboration

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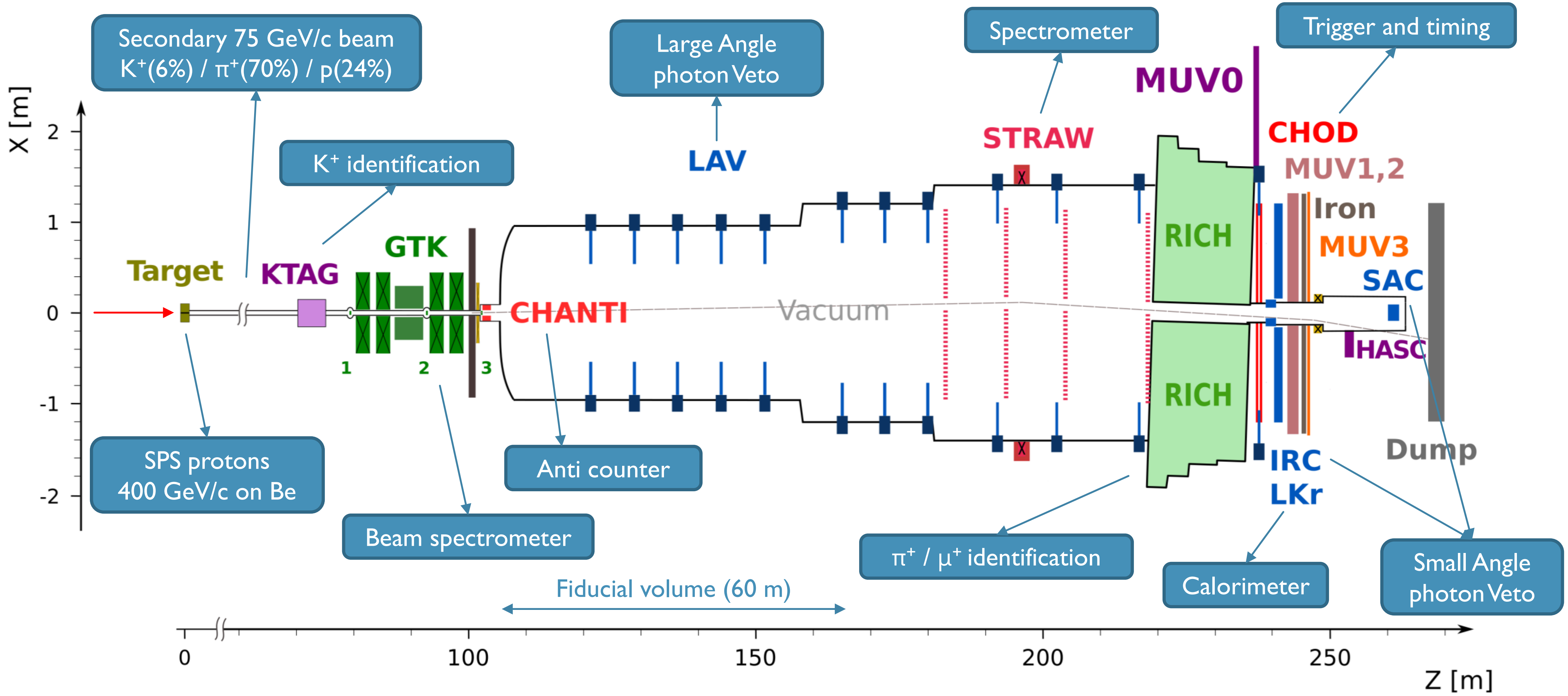
UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

INFN NAPOLI

THE NA62 EXPERIMENT

- High-precision kaon experiment
- Technique:
  - Fixed target
  - Decay-in-flight
- Broad physics program:
  - Measurement of BR($K^+ \to \pi^+ \nu\bar{\nu}$) → this talk
  - Searches for LFV / LNV → this talk
  - Precision measurements → A.T. Akmete, next talk
  - Exotic searches → S. Letzki, 20/07
- Timeline:
  - 2016 – 2018: First data taking run (2.2×10^{18} protons on target)
  - 2021 – LS3 (ongoing): Second data taking run, improved detector

THE NA62 DETECTOR



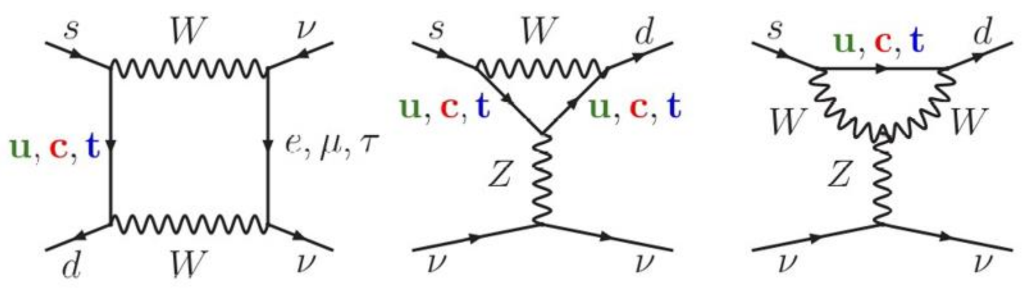
JINST 12 (2017) P05025

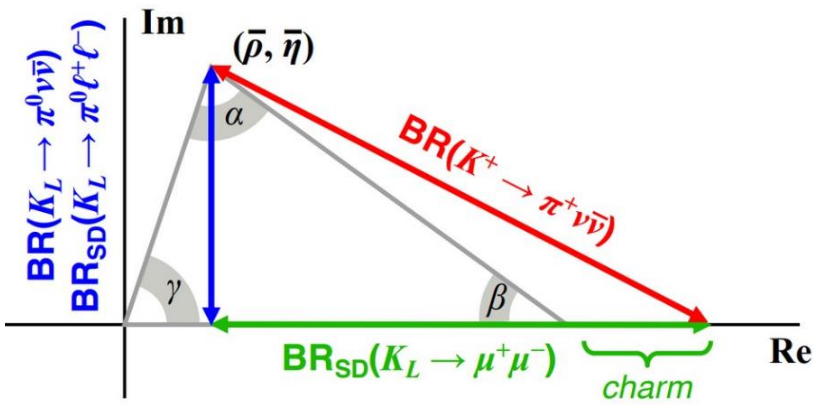
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$

RUN1 RESULTS

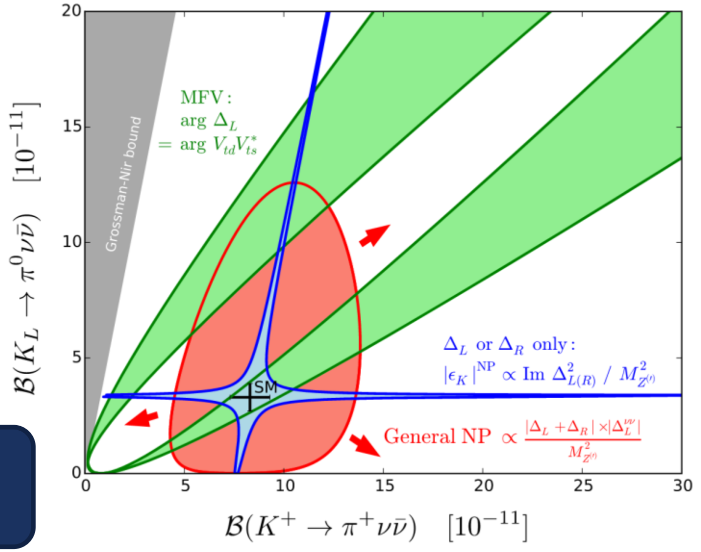
2021 – 2022 DATA ANALYSIS STATUS

$K^+ \to \pi^+ \nu\bar{\nu}$: THEORY





- FCNC s → d, high CKM suppression
- Theoretically clean, dominated by short distance
- Hadronic form factor extracted from $K_{\ell 3}$
- Uncertainty largely from CKM parameters



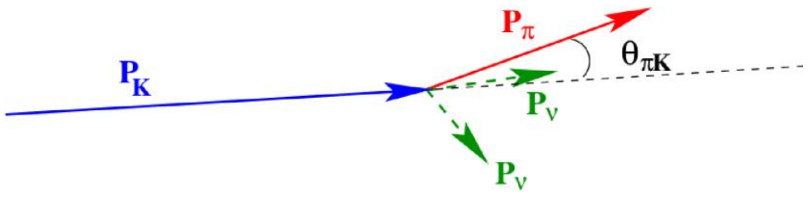
- $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ are correlated
- Very sensitive to new physics
- Kaons can constrain the UT independently from B physics

Acta Phys.Polon.B 53 6, A1 (2021)

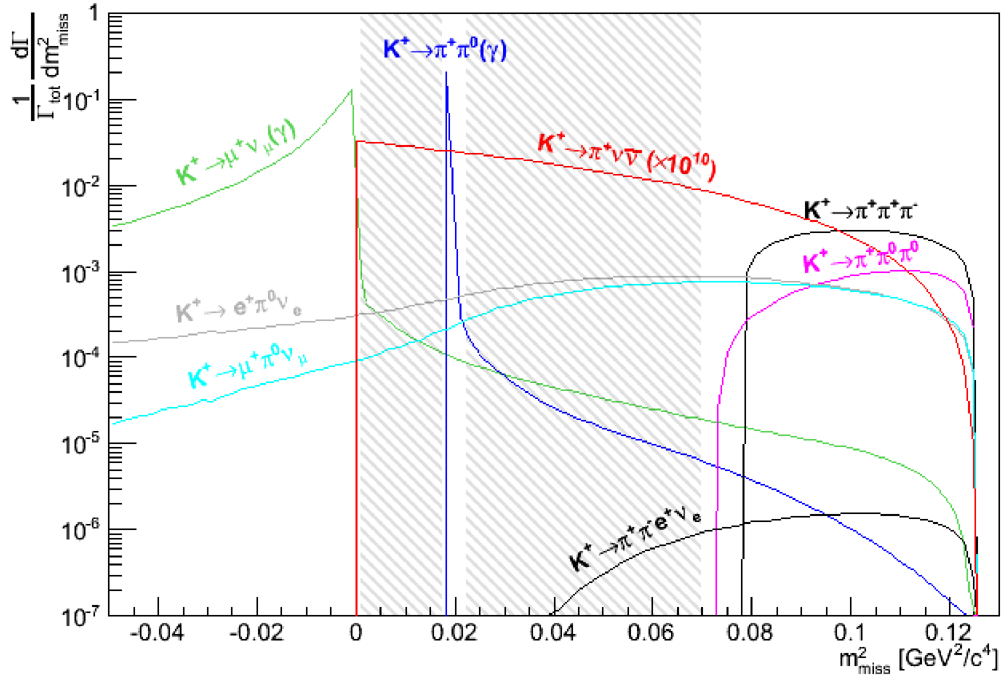
$BR(K^+ \to \pi^+ \nu\bar{\nu})_{SM} = (8.4 \pm 1.0) \times 10^{-11}$

JHEP 11 (2015) 033

$K^+ \to \pi^+ \nu \bar{\nu}$: ANALYSIS



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



Performances

- Kinematic suppression $O(10^4)$
- Muon suppression $O(10^7)$
- π^0 suppression $O(10^7)$
- Timing between sub-detectors O(100 ps)

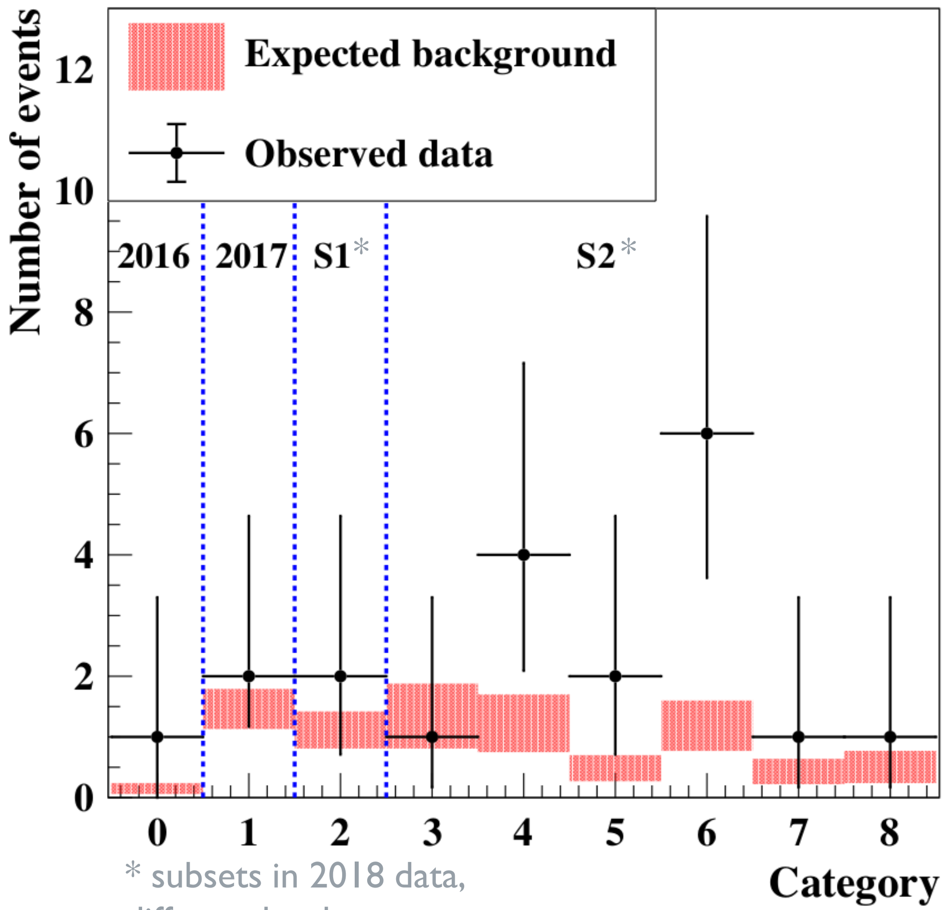
Selection

- K^+, π^+ track reconstruction
- Track matching, vertex reconstruction
- π^+ identification, μ^+ rejection
- Multi-track rejection, photon veto
- Kinematics (m^2_{miss}, p_π)

Analysis

- Momentum range: $15 < p_\pi < 45$ GeV/c
- Signal regions blinded during the analysis
- Data-driven background estimate
- Categories depending on hardware and momentum

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$: RUN1 RESULTS

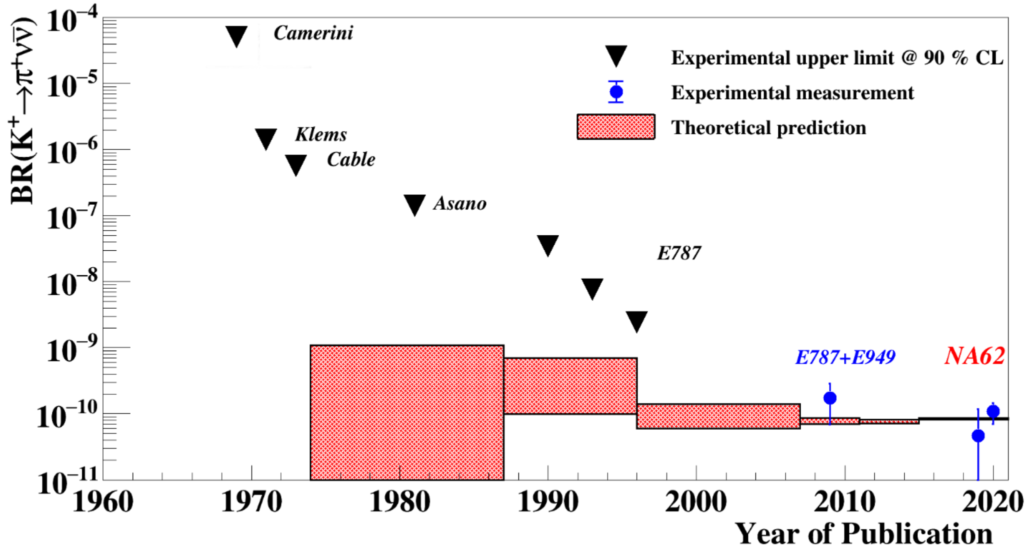


* subsets in 2018 data, different hardware

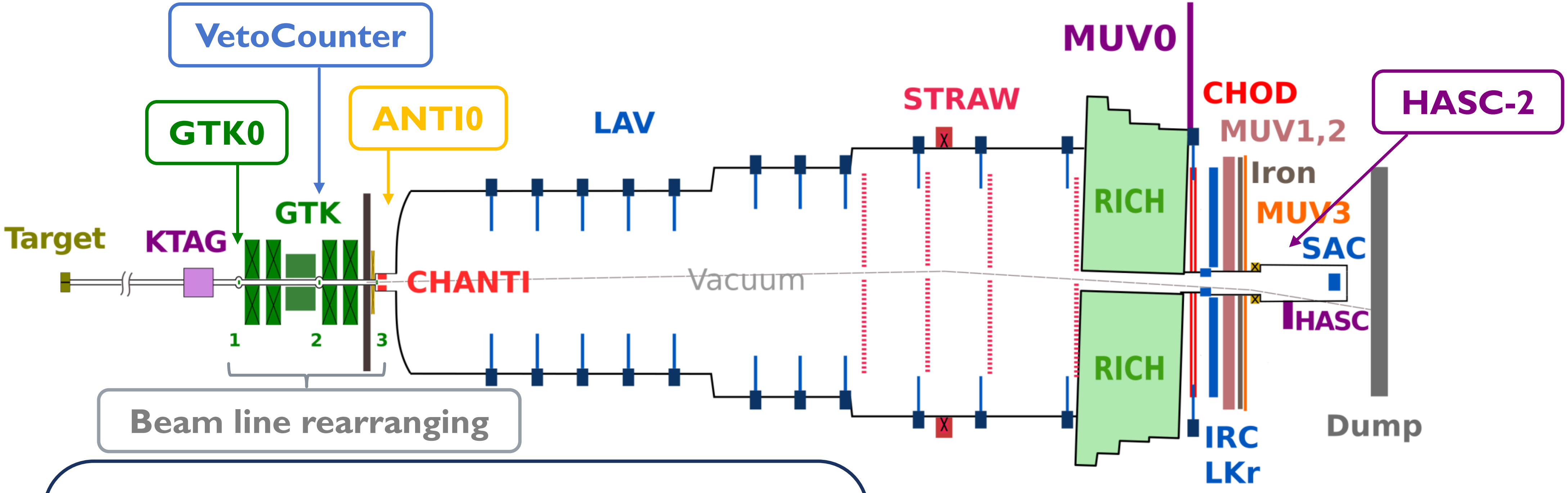
- Single Event Sensitivity: $(0.839 \pm 0.053_{syst}) \times 10^{-11}$
- Expected SM signal events: $10.01 \pm 0.42_{syst} \pm 1.19_{ext}$
- Expected background events: $7.03^{+1.05}_{-0.82}$
- Observed events: 20
- Significance: 3.4σ

$$BR(K^+ \rightarrow \pi^+ \nu\bar{\nu})^{NA62}_{16+17+18} = (10.6\ ^{+4.0}_{-3.8}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$$

JHEP 06 (2021) 093



2021 – 2022 HARDWARE IMPROVEMENTS

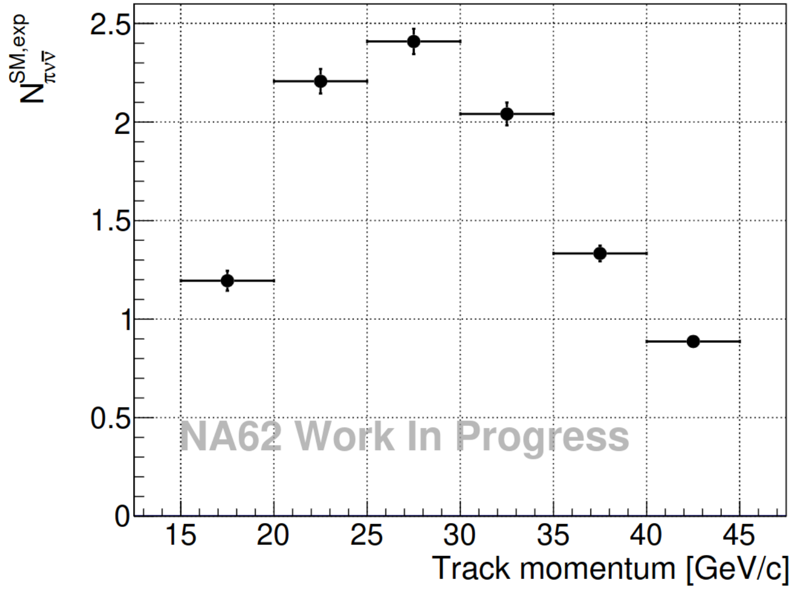


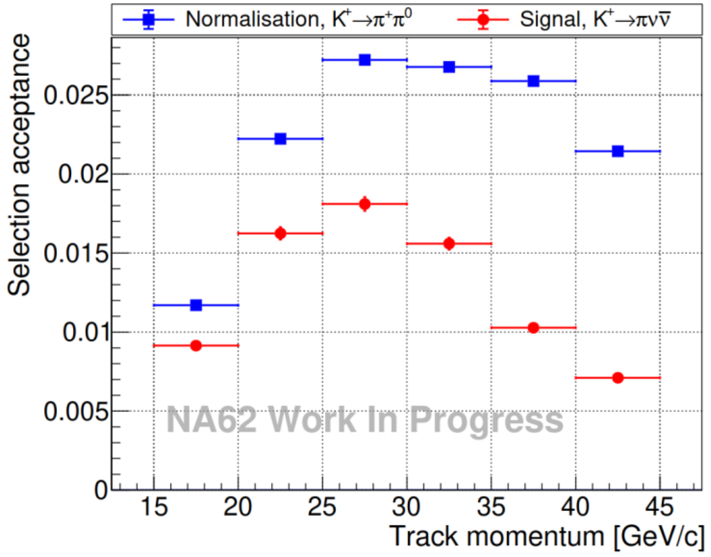
- Additional **GTK** station
- **Beam line rearranging** to swipe away upstream π^+
- **VetoCounter** to detect upstream decays
- **ANTI0** to veto accidental particles
- **HASC-2** to further suppress $K^+ \rightarrow \pi^+\pi^0$ decays
- **Intensity** increased from 60% to 100% of nominal

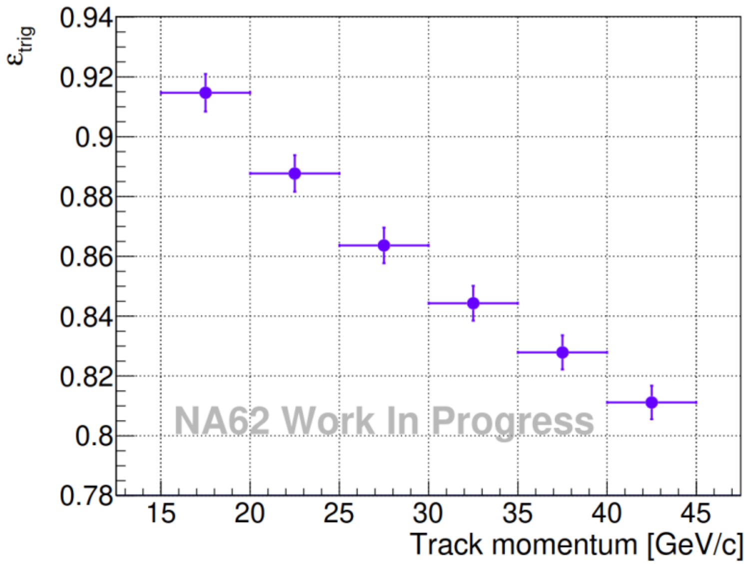
Data taken pushing to the hardware limit of intensity for NA62

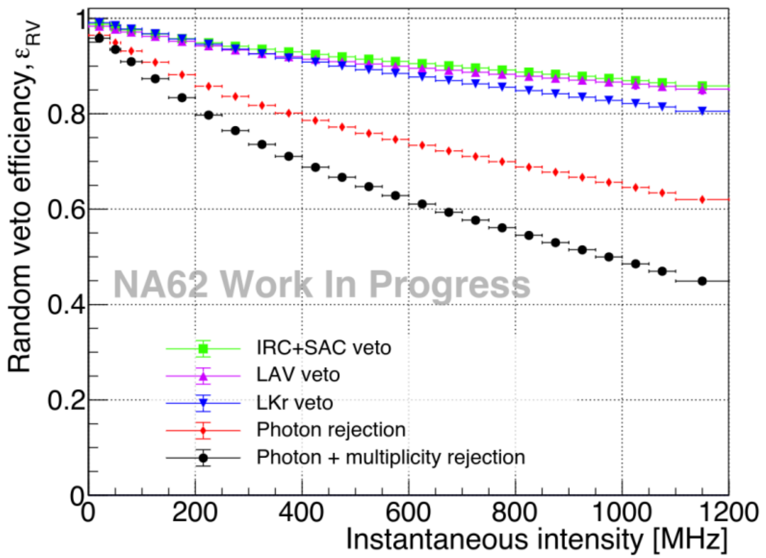
2021 – 2022 DATA: SINGLE EVENT SENSITIVITY

$$N_{\pi\nu\nu}^{SM,exp} = \frac{BR(\pi\nu\nu)_{SM}}{SES} = \frac{BR(\pi\nu\nu)_{SM}}{BR(\pi\pi)} \frac{A_{\pi\nu\nu}}{A_{\pi\pi}} (N_{\pi\pi} \times D_0)\, \varepsilon_{trig}\, \varepsilon_{RV}$$









- $K^+ \to \pi^+\pi^0$ normalization channel
- Random Veto (RV): efficiency loss due to beam activity

2021 – 2022 DATA: SINGLE EVENT SENSITIVITY

$$N^{SM,exp}_{\pi\nu\nu} = \frac{BR(\pi\nu\nu)_{SM}}{SES} = \frac{BR(\pi\nu\nu)_{SM}}{BR(\pi\pi)} \frac{A_{\pi\nu\nu}}{A_{\pi\pi}} (N_{\pi\pi} \times D_0)\, \varepsilon_{trig}\, \varepsilon_{RV}$$

	2021 ($t > 2$ s)	2022	21+22	2018
$(N_{\pi\pi}D_0)/400$ [$\times 10^7$]	3.713	16.374	20.087	
ε_{trig}	$(83.5 \pm 1.3)\%$	$(86.3 \pm 1.5)\%$	$(85.8 \pm 1.4)\%$	$(89 \pm 5)\,\%$
ε_{RV}	$(63.0 \pm 0.5)\%$	$(63.8 \pm 0.5)\%$	$(63.6 \pm 0.5)\%$	$(66 \pm 1)\,\%$
$A_{\pi\pi}$	$(13.525 \pm 0.005)\,\%$			$(11.77 \pm 0.18)\,\%$
$A_{\pi\nu\bar{\nu}}$	$(7.7 \pm 0.2)\,\%$			$(6.4 \pm 0.6)\,\%$
$\mathcal{B}_{SES}[\times 10^{-11}]$	4.68 ± 0.17	1.01 ± 0.03	0.83 ± 0.03	
$N^{SM,exp}_{\pi\nu\bar{\nu}}$	1.80 ± 0.06	8.28 ± 0.24	10.07 ± 0.31	
$N^{SM,exp}_{\pi\nu\bar{\nu}}$ per burst	1.7×10^{-5}	2.5×10^{-5}	2.3×10^{-5}	1.7×10^{-5}

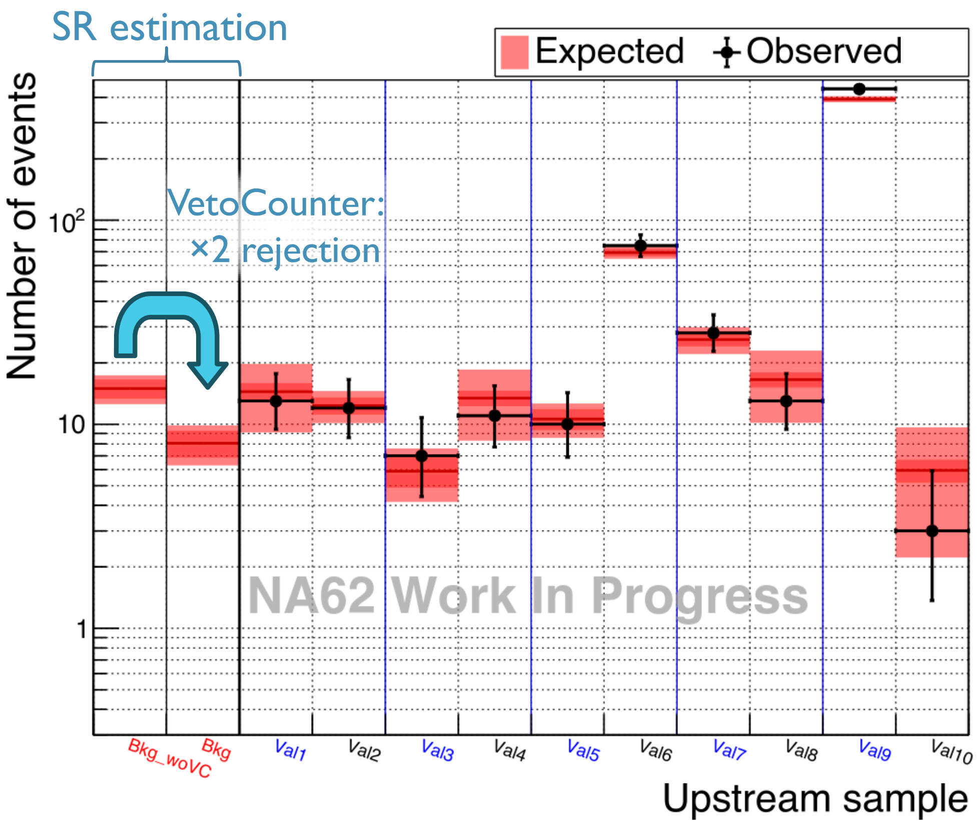
- Improvements in LKr reconstruction
- "Bayesian" K^+-π^+ matching
- Increased signal yield
- More precise ε_{trig} and ε_{RV} evaluation

- $K^+ \rightarrow \pi^+\pi^0$ normalization channel
- Random Veto (RV): efficiency loss due to beam activity

2021 – 2022 DATA: BACKGROUNDS

Upstream background

(accidental K^+-π^+ matching): fully data driven approach



Process	N_{bg}
$K^+ \to \pi^+\pi^0(\gamma)$	0.86 ± 0.06
$K^+ \to \mu^+\nu(\gamma)$	0.93 ± 0.20
$K^+ \to \pi^+\pi^+\pi^-$	0.11 ± 0.03
$K^+ \to \pi^+\pi^-e^+\nu$	$0.84^{+0.35}_{-0.28}$
$K^+ \to \pi^0\ell^+\nu$	$< 10^{-3}$
$K^+ \to \pi^+\gamma\gamma$	0.01 ± 0.01
Upstream	$8.0^{+2.2}_{-1.8}$
Total background	$10.8^{+2.2}_{-1.9}$

data driven

MC

NA62 Work In Progress

$N^{SM,exp}_{\pi\nu\nu} = 10.07 \pm 0.31$

2018 data

Upstream ≈ 3.3
Total bkg ≈ 5.4
$N^{SM,exp}_{\pi\nu\nu} \approx 7.6$

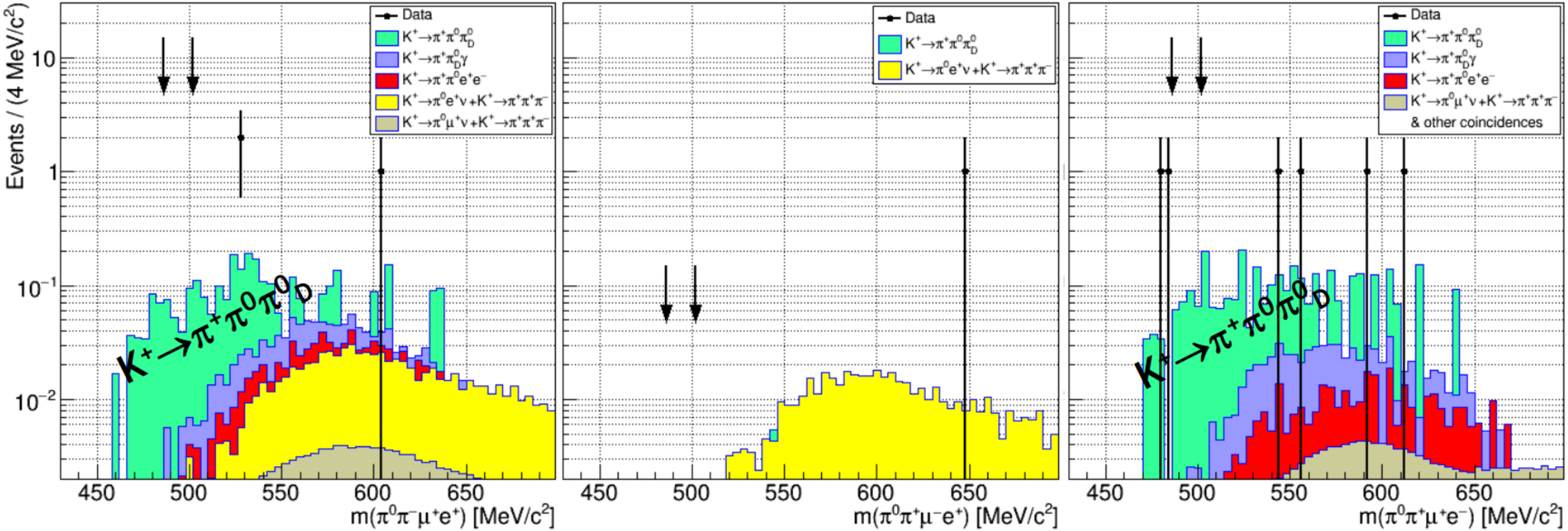
$\frac{\sqrt{S+B}}{S}$ slightly improved wrt 2018 data

Checks ongoing about scaling of backgrounds with intensity

LNV / LFV SEARCHES

RUN1 RESULTS

FIRST SEARCH FOR $K^+ \to \pi^0\pi\mu e$



$BR(K^+ \to \pi^0\pi^-\mu^+e^+) < 2.9 \times 10^{-10}$

$BR(K^+ \to \pi^0\pi^+\mu^-e^+) < 3.1 \times 10^{-10}$

$BR(K^+ \to \pi^0\pi^+\mu^+e^-) < 5.0 \times 10^{-10}$

ULs at 90% CL

First presented at BEACH 2024, paper in preparation

OTHER RESULTS

	Previous UL PDG 2019	NA62 UL at 90% CL	
$K^+ \to \pi^-\mu^+e^+$	BR < 5.0 × 10^{-10}	BR < 4.2 × 10^{-11}	PRL 127 (2021) 131802
$K^+ \to \pi^+\mu^-e^+$	BR < 5.2 × 10^{-10}	BR < 6.6 × 10^{-11}	PRL 127 (2021) 131802
$\pi^0 \to \mu^-e^+$	BR < 3.4 × 10^{-9}	BR < 3.2 × 10^{-10}	PRL 127 (2021) 131802
$K^+ \to \pi^-\mu^+\mu^+$	BR < 8.6 × 10^{-11}	BR < 4.2 × 10^{-11} (25% of dataset)	PLB 797 (2019) 134794
$K^+ \to \pi^-e^+e^+$	BR < 6.4 × 10^{-10}	BR < 5.3 × 10^{-11}	PLB 830 (2022) 137172
$K^+ \to \pi^-\pi^0e^+e^+$	N/A	BR < 8.5 × 10^{-10}	PLB 830 (2022) 137172
$K^+ \to \mu^-\nu e^+e^+$	N/A	BR < 8.1 × 10^{-11}	PLB 838 (2023) 137679

NA62 can improve ULs on LFV / LNV kaon decays by more than one order of magnitude

CONCLUSION

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- **NA62** is collecting data from 2016 until at least 2025
  - Largest multi-purpose K^+ decay sample ever $O(10^{13})$
  - Last K^+ decay experiment in the foreseeable future
- First observation of the ultra rare $\mathbf{K^+ \to \pi^+ \nu\bar{\nu}}$ decay (3.4σ)
  - Run1 result: $BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6\ ^{+4.0}_{-3.8}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$
  - Run2 result is coming soon! Expected signal to be doubled
- 10 **LFV / LNV** K^+ decay modes addressed by NA62 so far

Stay tuned for more results!

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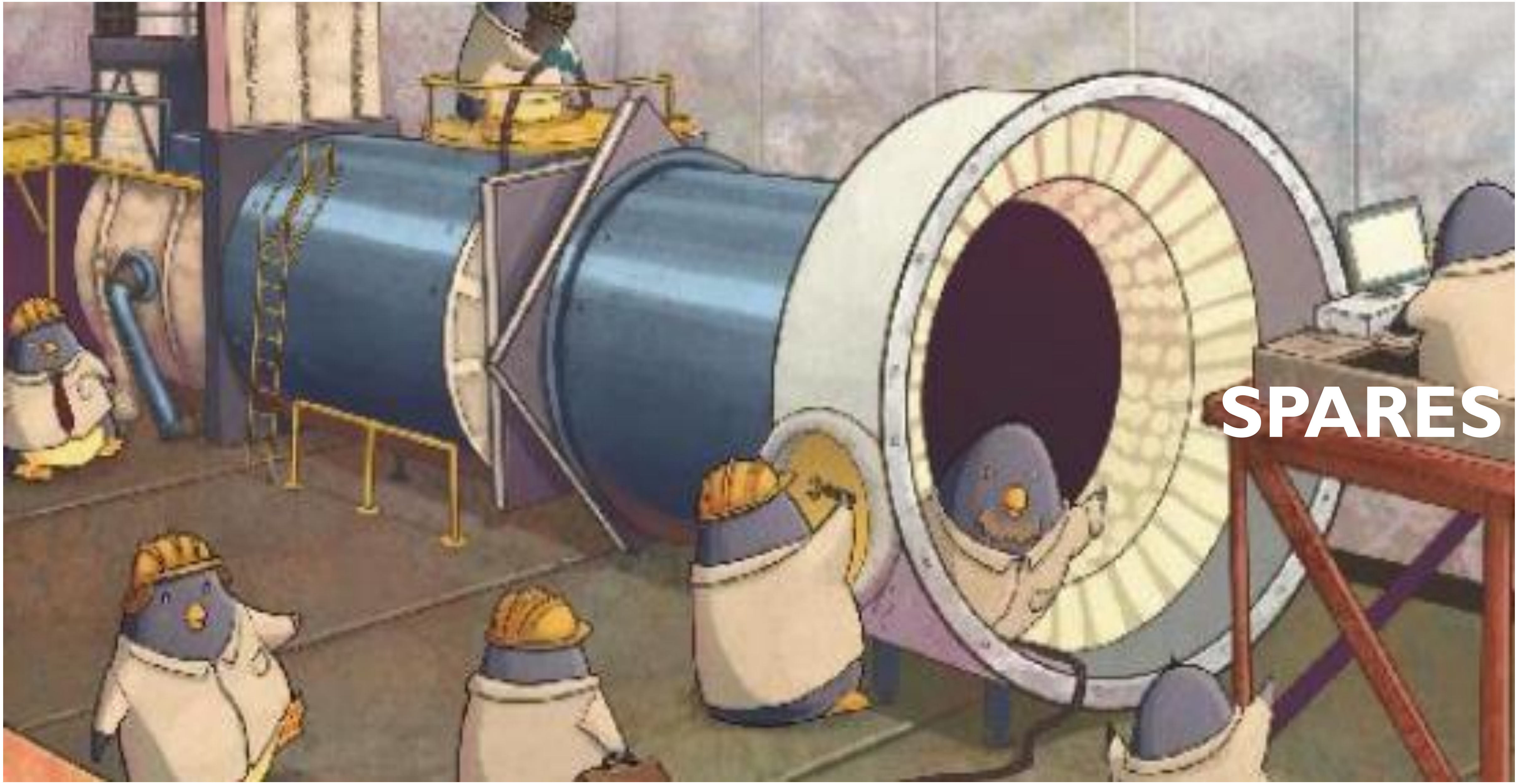
THANK YOU!



SPARES

MOST RECENT SM PREDICTIONS FOR $K \to \pi\nu\bar{\nu}$

$$BR(K^+ \to \pi^+\nu\bar{\nu}) = (8.60 \pm 0.42) \times 10^{-11}$$

$$BR(K_L \to \pi^0\nu\bar{\nu}) = (2.94 \pm 0.15) \times 10^{-11}$$

Buras and Venturini
[Eur. Phys. J. C 82 (2022) 615]
[arXiv:2109.11032]

$$BR(K^+ \to \pi^+\nu\bar{\nu}) = (7.73 \pm 0.61) \times 10^{-11}$$

$$BR(K_L \to \pi^0\nu\bar{\nu}) = (2.59 \pm 0.29) \times 10^{-11}$$

Brod, Gorbahn, Stamou
[PoS BEAUTY2020 (2021) 056]

$$BR(K^+ \to \pi^+\nu\bar{\nu}) = (7.86 \pm 0.61) \times 10^{-11}$$

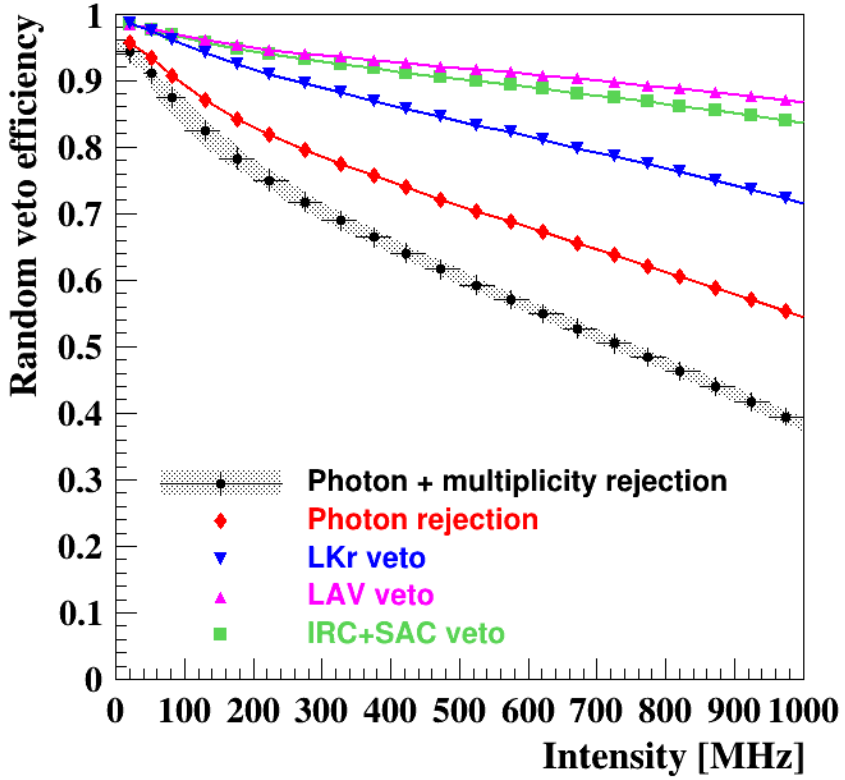
$$BR(K_L \to \pi^0\nu\bar{\nu}) = (2.68 \pm 0.30) \times 10^{-11}$$

D’Ambrosio, Iyer, Mahmoudi, Neshatpour
[JHEP 09 (2022) 148]

SINGLE EVENT SENSITIVITY, 2018 DATA

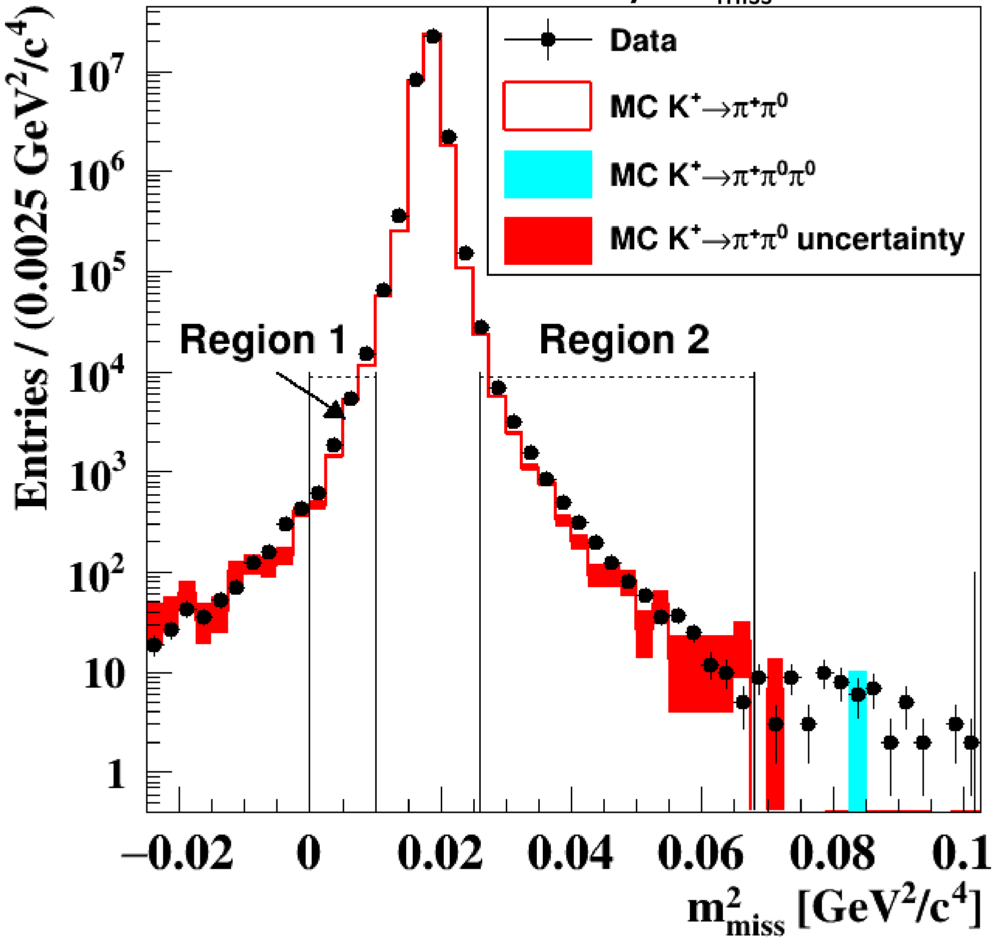
	Subset S1 *	Subset S2 *
$N_{\pi\pi} \times 10^{-7}$	3.14	11.6
$A_{\pi\pi} \times 10^{2}$	7.62 ± 0.77	11.77 ± 1.18
$A_{\pi\nu\bar{\nu}} \times 10^{2}$	3.95 ± 0.40	6.37 ± 0.64
$\epsilon_{\rm trig}^{\rm PNN}$	0.89 ± 0.05	0.89 ± 0.05
$\epsilon_{\rm RV}$	0.66 ± 0.01	0.66 ± 0.01
$SES \times 10^{10}$	0.54 ±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

* different hardware configuration



BACKGROUND FROM K^+ DECAYS

Control $\pi^+ \pi^0$ data to study m^2_{miss} distribution



$$N^{exp}_{\pi\pi}(SR) = N(\pi^+\pi^0)\, f_{kin}(SR)$$

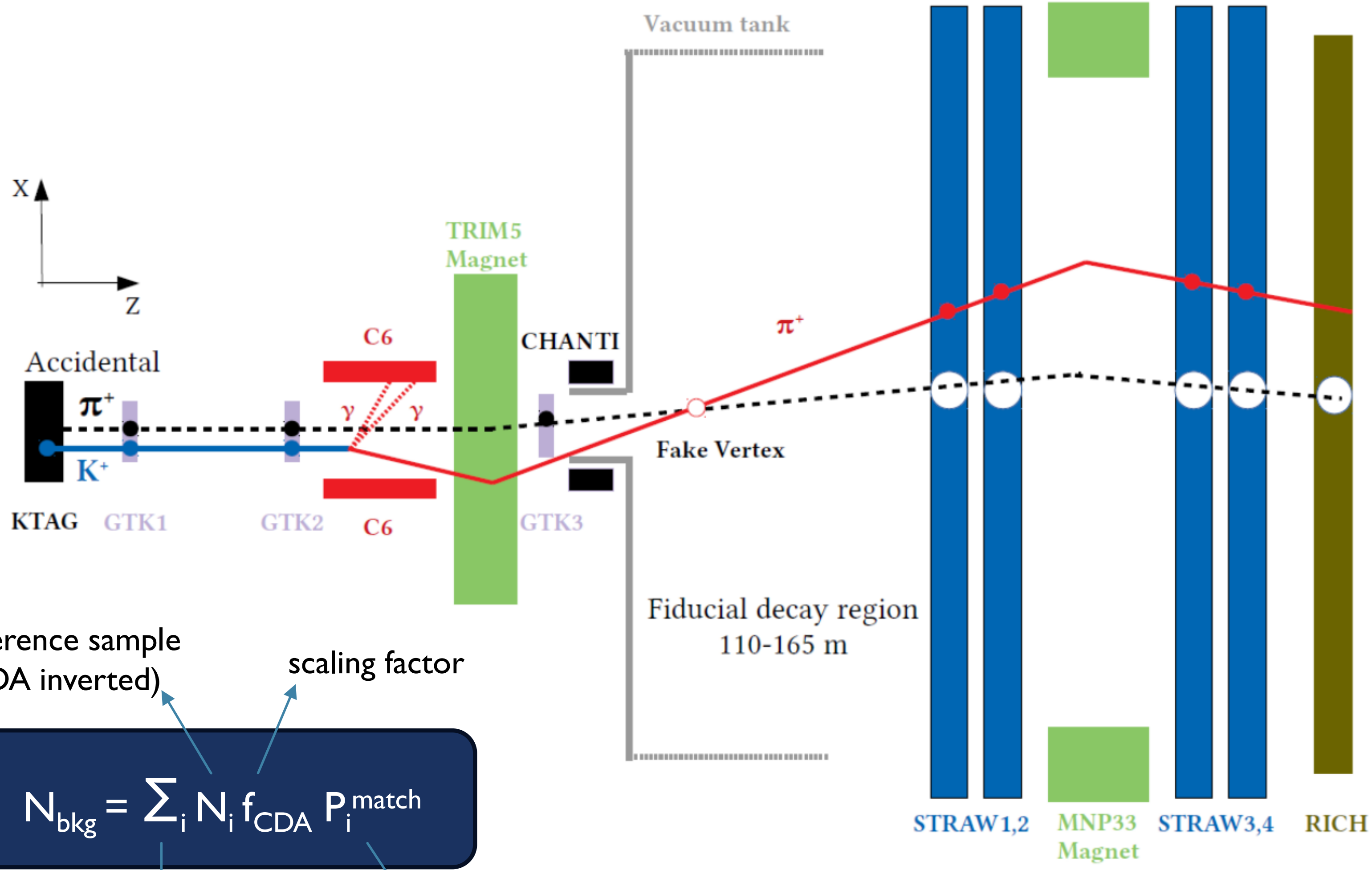
Number of events in $\pi^+ \pi^0$ region after $\pi\nu\nu$ selection

Expected $K^+ \rightarrow \pi^+ \pi^0$ events in signal region

Fraction of $\pi^+ \pi^0$ in signal region, measured on control data

- $K^+ \rightarrow \mu^+ \nu_\mu$ and $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ backgrounds: similar procedure
- $K^+ \rightarrow \pi^+ \pi^- e^+ \nu_e$ evaluated with MC simulations
- Validation with control regions

UPSTREAM BACKGROUND



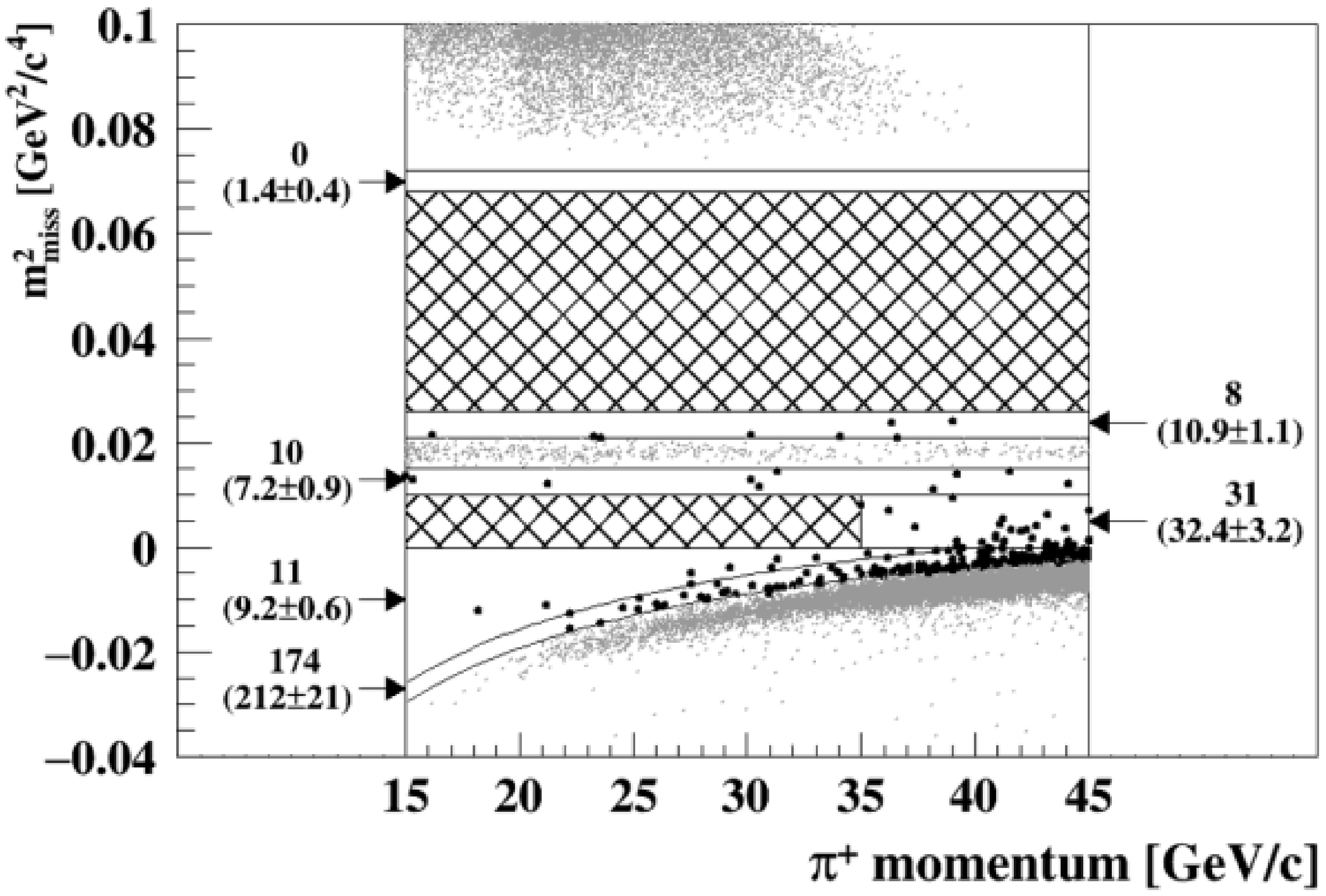
- Pions produced upstream of the fiducial volume
  - Early kaon decays
  - Interaction of beam particles with beam spectrometer material
- Fake association of detected pions to accidental particles

- Collimator installed in June 2018
- VetoCounter & ANTI0 in Run2
- Geometrical cuts & BDT cut on backtracked pion position
- Kaon-pion association effective
- Data-driven background estimation

$$N_{bkg} = \sum_i N_i \, f_{CDA} \, P_i^{match}$$

- N_i: reference sample (CDA inverted)
- f_{CDA}: scaling factor
- $\sum_i$: bins of ΔT, N(tracks)
- P_i^{match}: probability of matching

EXPECTED BACKGROUND SUMMARY, 2018 DATA



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	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$