On the ultra-rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay at NA62

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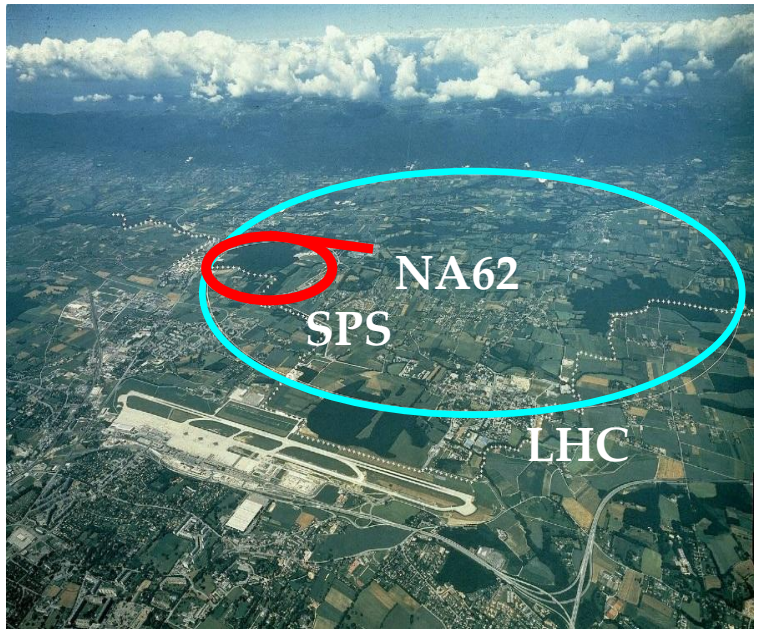
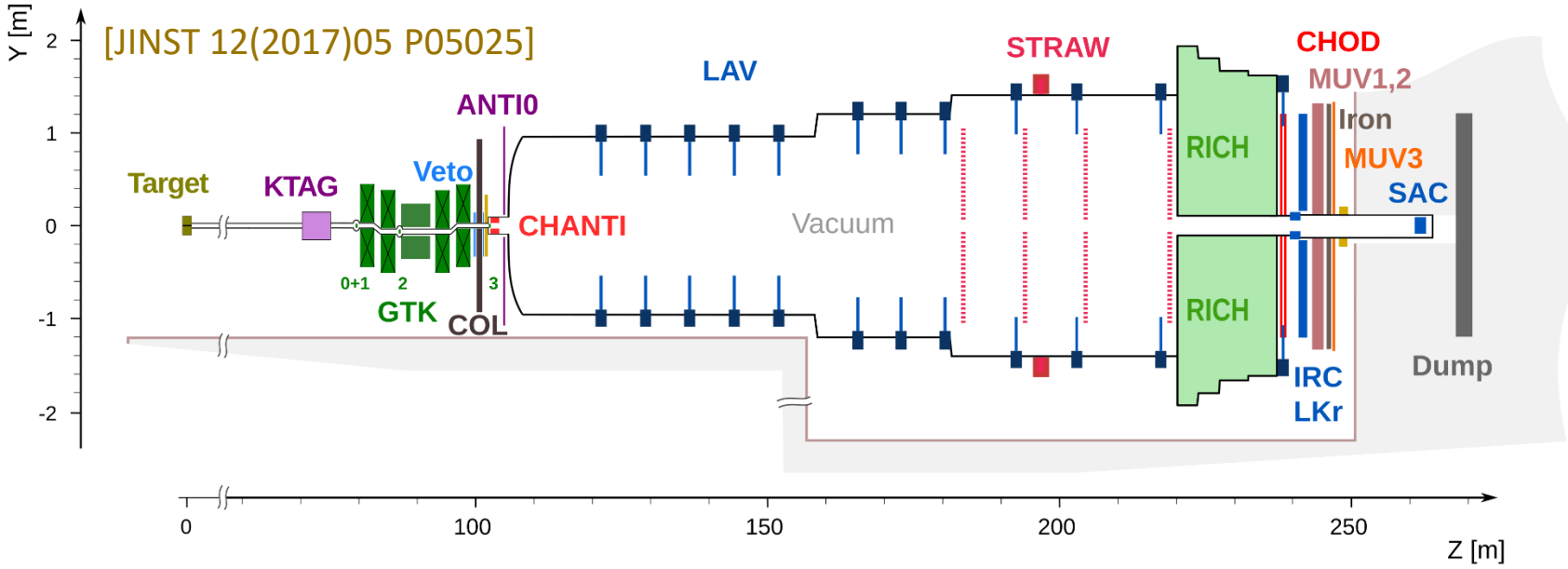
La Thuile 25/03/2025

NA62 at CERN SPS

Main goal: study of the ultra-rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay

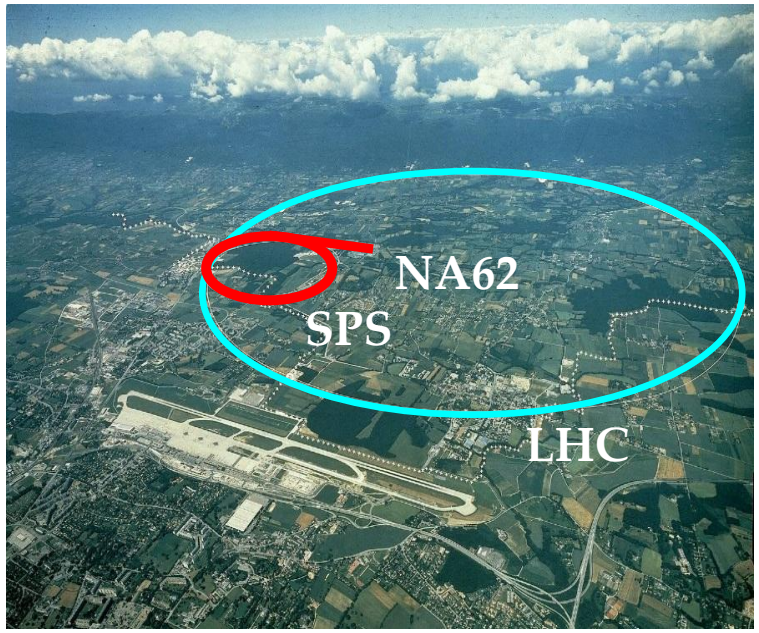




Primary beam intensity	$20 - 30 \times 10^{11}$ protons per pulse on target from SPS
Incoming K^+, 75 GeV/c, 1% rms	Timing by KTAG ($\sigma_t \sim 70$ ps); measured by GTK; rate at GTK ~ 600 MHz
Outgoing π^+	Timing by RICH ($\sigma_t \sim 70$ ps); measured by STRAW; rate at Straw ~ 5 MHz
γ/multitrack veto (LAV, LKr, IRC, SAC, HASC)	$\pi^0 \to \gamma\gamma$ suppression
Particle ID (RICH, LKr, MUV1,2,3)	μ^+ suppression

NA62 at CERN SPS: Data Taking Periods

2016 – 17 – 18	LS2 (upgrades)	2021 – 22 – 23 – 24 – 25 – 26	LS3

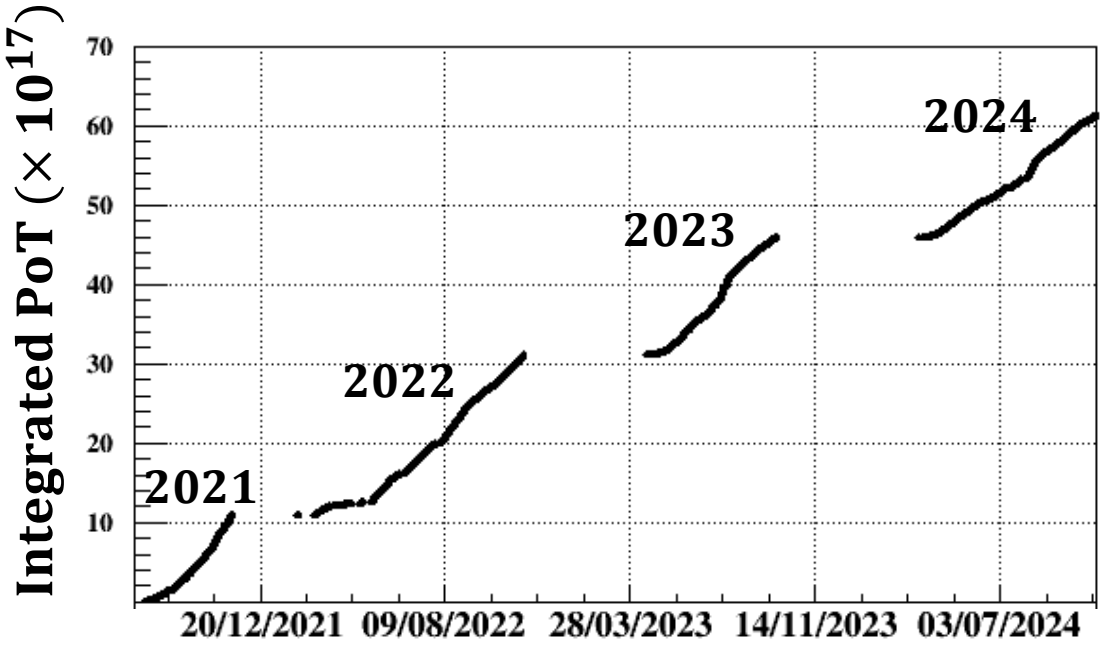


2016 – 18: $\sim 0.9 \times 10^6$ spills collected

$\sim 22 \times 10^{17}$ protons on target delivered (PoT)

$>3\sigma$ $K^+ \to \pi^+ \nu\bar{\nu}$ evidence [JHEP06(2021)093]

2021 – present: $\sim 1.5 \times 10^6$ spills collected



~ 200 physicists from 30 institutions

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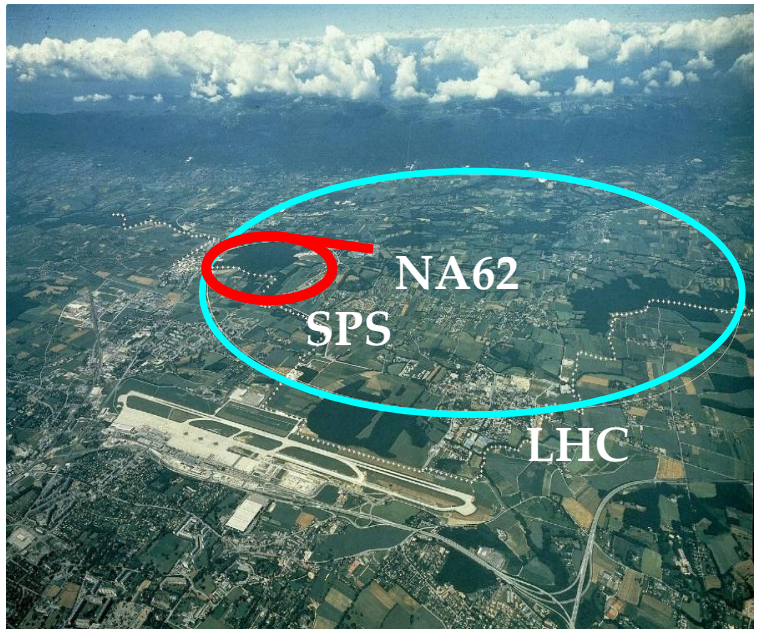

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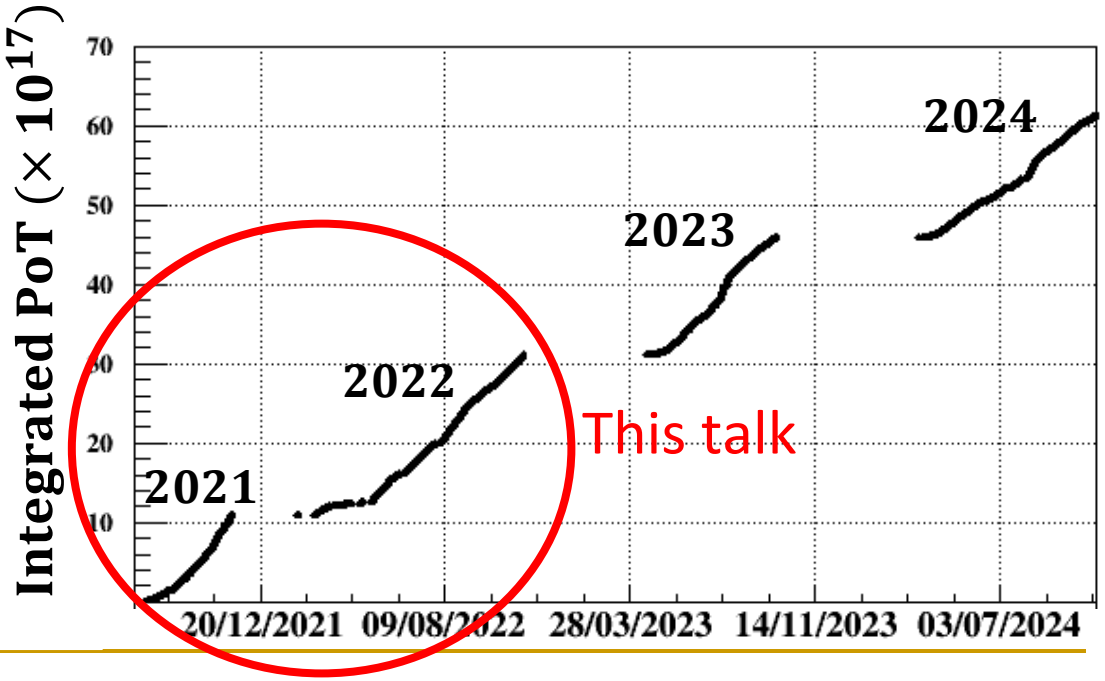
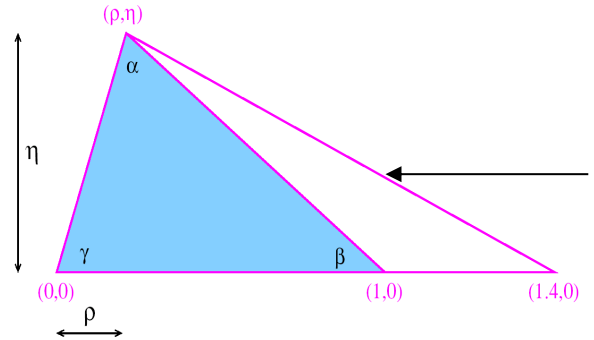


NA62 Physics Program

Flavour Physics

- Indirect search for NP at high mass scale
  - $K^+ \to \pi^+ \nu\bar{\nu}$
- Direct and indirect search for NP through LFV/LNV processes
  - $K^+ \to \pi^+ l^+ l^-$, $K^+ \to \mu^- \nu e^+ e^+$
  - $K^+ \to \pi^\pm \mu^\mp e^+$, $K^+ \to \pi^- \pi^0 e^+ e^+$
  - $K^+ \to \pi^- l^+ l^+$, $\cdots$
- Test of low-energy hadronic theories (e.g. χPT)
  - $K^+ \to \pi^+ \gamma\gamma$, $K^+ \to \pi^0 e^+ \nu\gamma$, $\cdots$



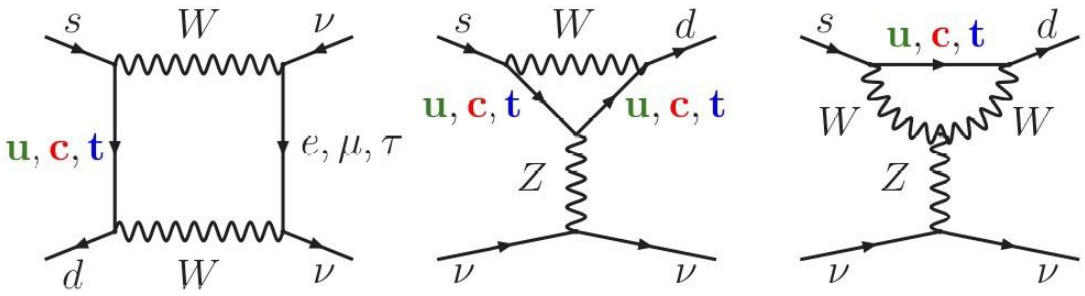
Hidden Sector Physics

- Direct searches of new particles below the EW scale
  - $K^+ \to \pi^+ X$
  - $K^+ \to l^+ N$
  - $K^+ \to \pi^+ aa, a \to e^+ e^-$
  - $A' \to l^+ l^-$
  - $N \to \pi^\pm l^\mp$
  - $\cdots$

Dump configuration

$K \to \pi\nu\bar{\nu}$ in the SM

- FCNC loop processes: s→d coupling and highest CKM suppression
- Very clean theoretically: SD dominated. Hadronic matrix element $\propto \mathrm{BR}(K_{l3})$ (precisely measured)



- SM predictions: differences in calculation from choices of CKM parameters, theory uncertainty few %

	[Buras et al. EPJC 82 (2022) 7, 615]	[D'Ambrosio et al. JHEP 09 (2022) 148]
$K^+ \to \pi^+\nu\bar{\nu}$	$(8.60 \pm 0.42) \times 10^{-11}$	$(7.86 \pm 0.61) \times 10^{-11}$
$K_L \to \pi^0\nu\bar{\nu}$	$(2.94 \pm 0.15) \times 10^{-11}$	$(2.68 \pm 0.30) \times 10^{-11}$

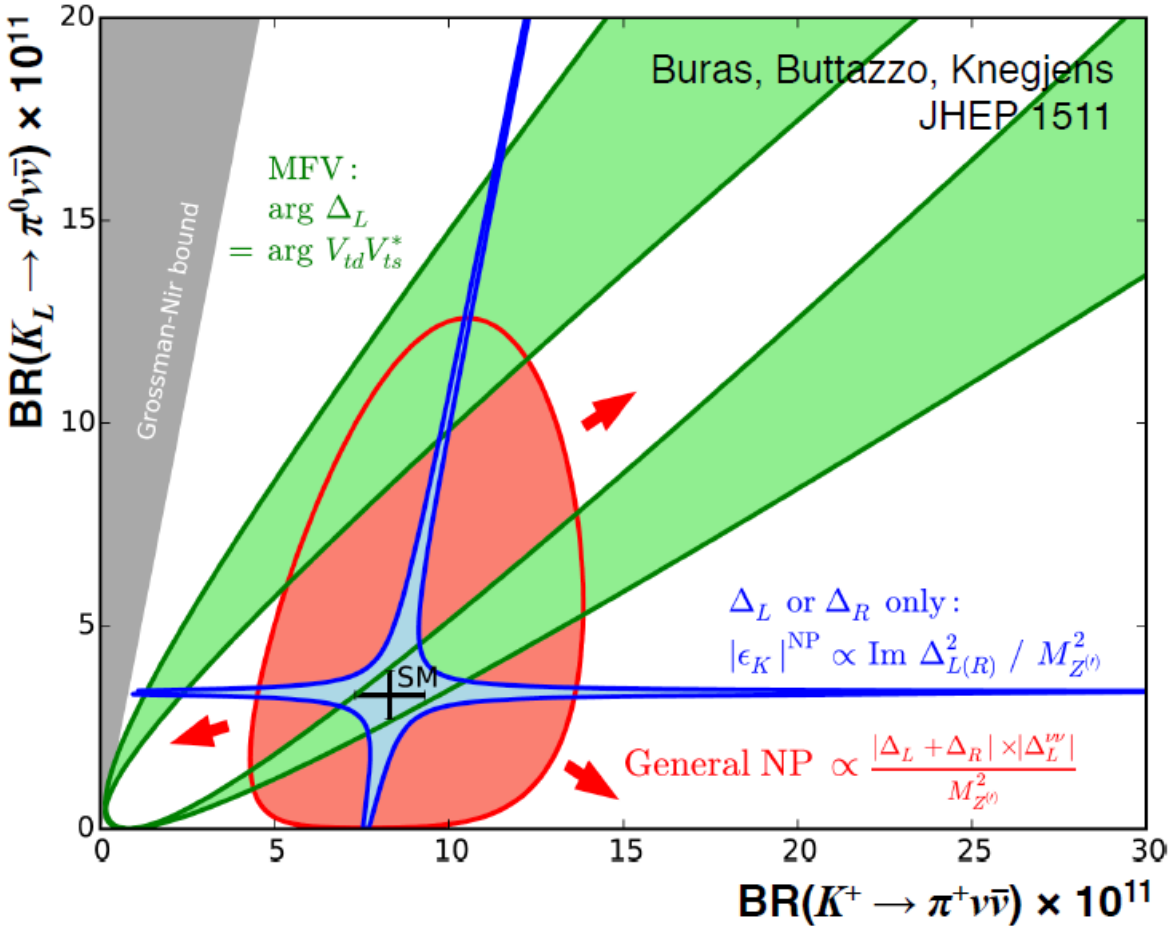
- Experimental status:

$K^+ \to \pi^+\nu\bar{\nu}$ NA62: $\left(10.6^{+4.1}_{-3.5}\right) \times 10^{-11}$ [16-18 data JHEP 06 (2021) 093]; THIS TALK [21-22 data+16-18]

$K_L \to \pi^0\nu\bar{\nu}$ KOTO: $< 2.2 \times 10^{-9}$ [21 data PRL 134, 081802]

$K \to \pi\nu\bar{\nu}$ beyond the SM

- High sensitivity to NP: significant deviation from SM predictions possible
- Weak constraints from other flavour observables
- Model-dependent correlations of variations of K^+ and K_L BR
- Sensitive to effects of lepton flavour non-universality

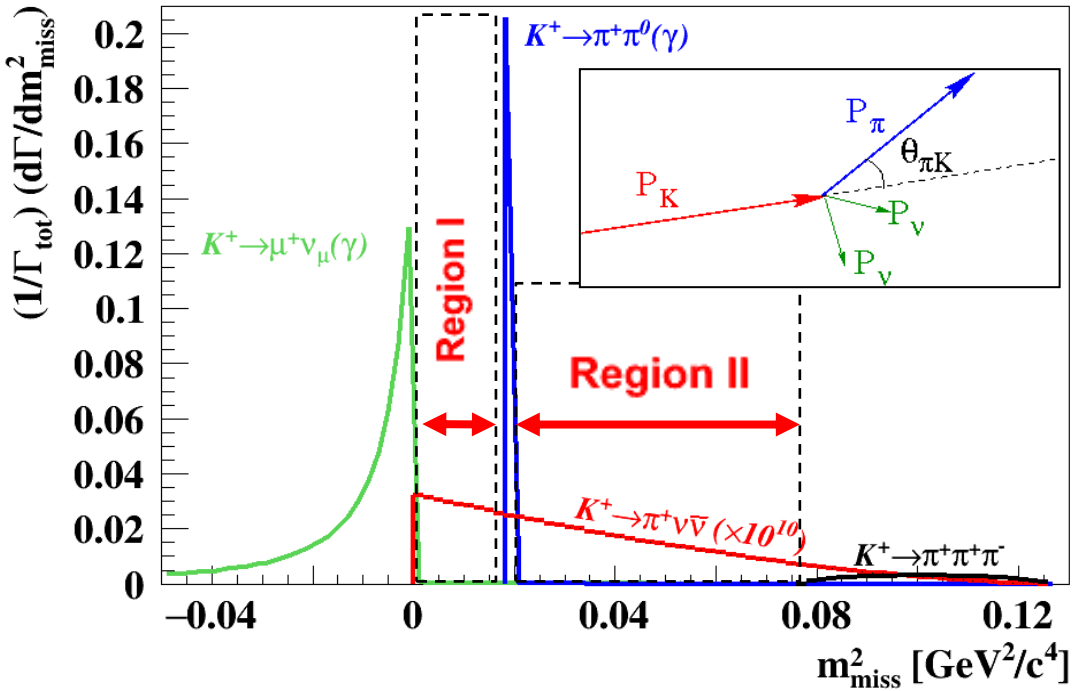


$K^+ \to \pi^+ \nu\bar{\nu}$: Analysis Strategy and Signal Selection

- ID and reconstruction of K^+ and π^+
- $K^+ - \pi^+$ matching in space (CDA) and time (Δt)
- Event classification based on

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

  π momentum [15-45] GeV/c
- Rejection of events with additional activity (no γ, charged particles)
- Analysis in 5 GeV bins of π^+ momentum



Suitable background rejection if

$\mathcal{O}(100\ \text{ps})$	Timing between sub-detectors
$\geq 10^3$	Kinematic background suppression
$\geq 10^8$	Muon suppression
$\geq 10^8$	π^0 (from $K^+ \to \pi^+\pi^0$) suppression

Decay mode	Branching Ratio [PDG]
$K^+ \to \mu^+\nu_\mu$	$(63.56 \pm 0.11)\%$
$K^+ \to \pi^+\pi^0$	$(20.67 \pm 0.08)\%$
$K^+ \to \pi^+\pi^+\pi^-$	$(5.583 \pm 0.024)\%$
$K^+ \to \pi^+\pi^- e^+\nu_e$	$(4.247 \pm 0.024) \times 10^{-5}$

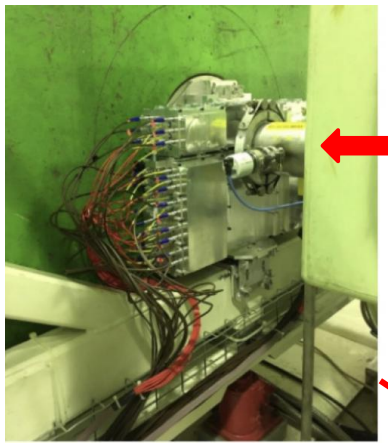
NA62 Post-LS2 Data Taking

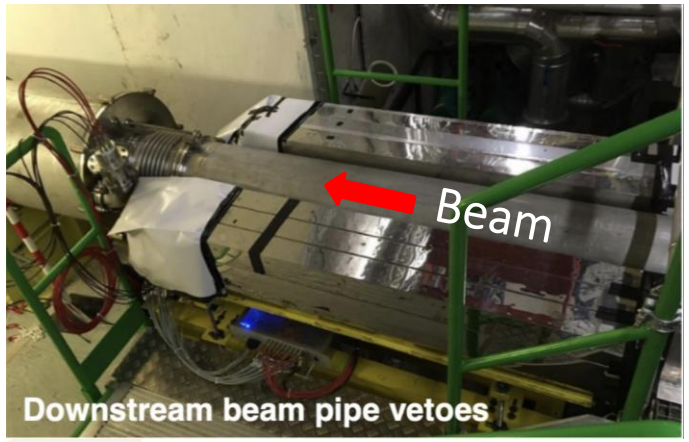
Upgrades during LS2:

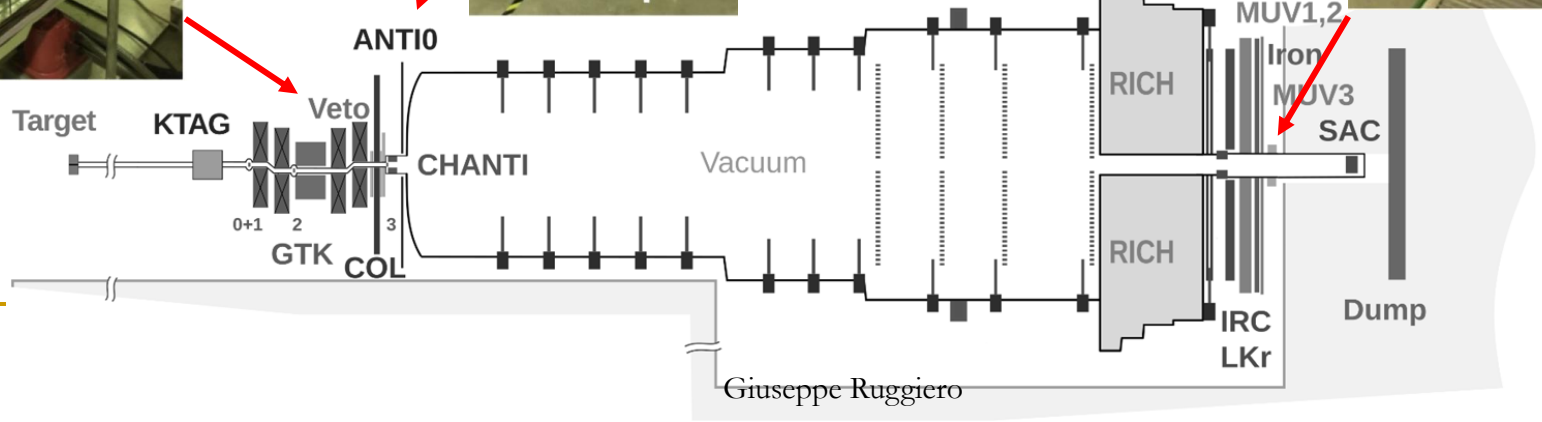
- Veto detectors upstream to the decay volume
- Fourth station added to the beam spectrometer
- Additional small angle calorimeter at the end of the beam line

2021 – 22 data taking

- Proton intensity +40% wrt 16-18 data
- 0.55×10^6 spills
- Improved trigger







Single Event Sensitivity

Normalization: $K^+ \to \pi^+\pi^0$

Online (trigger) and offline selection in common with signal except rejection of additional activity

Specific kinematic selection

π momentum bin i

8.4×10^{-11}

Acceptances at 0 intensity

Selected $\pi\pi$

1-fraction of random signal losses due to photon/multiplicity veto

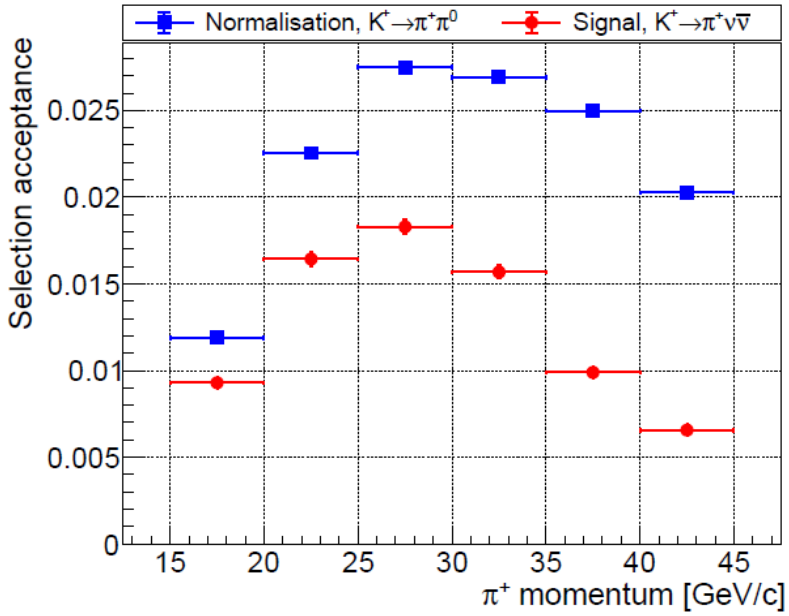
$$N_{\pi\nu\nu}^{SM}(p_i) = \frac{BR(\pi\nu\nu, SM)}{BR(\pi^+\pi^0, PDG)} \frac{\mathcal{A}(\pi\nu\nu)}{\mathcal{A}(\pi^+\pi^0)} D N_{\pi\pi}(p_i) \varepsilon_{trig}(p_i) \varepsilon_{RV}$$

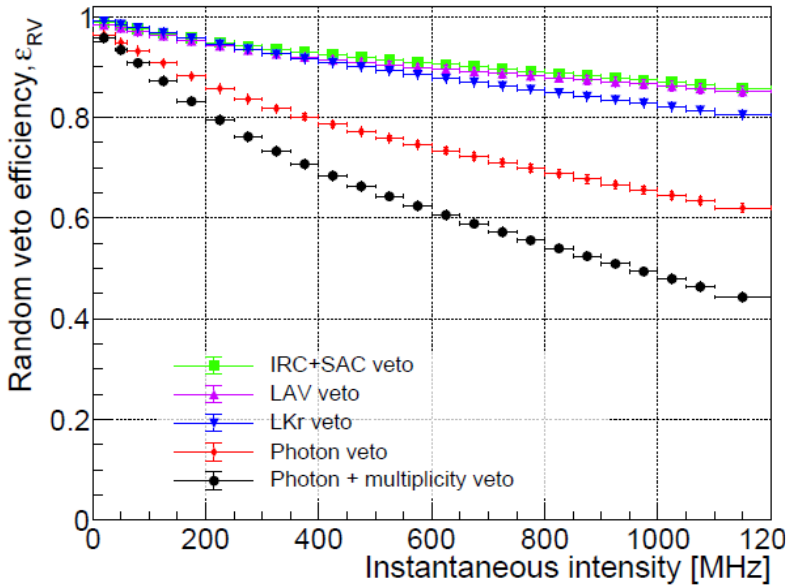
$\pi\pi$ trigger downscaling factor

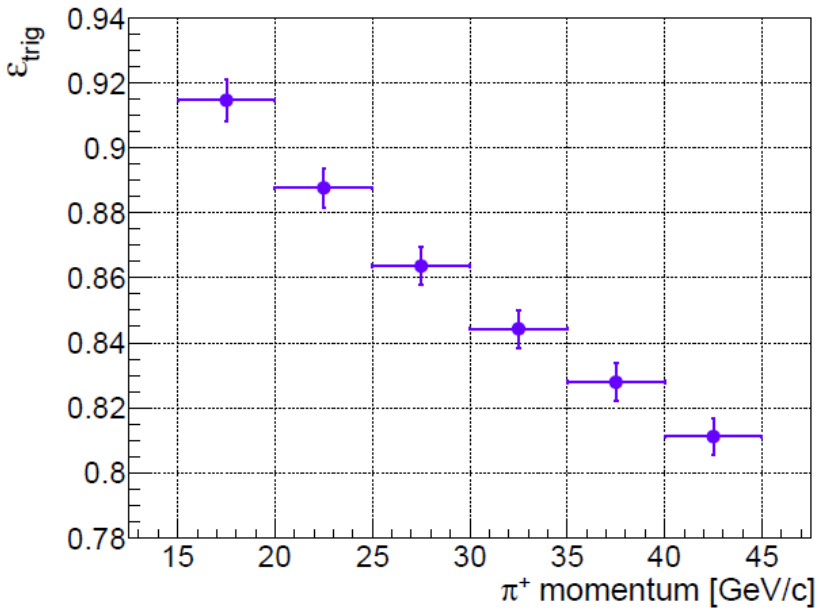
Trigger efficiency

Single Event Sensitivity (2021-22 data)

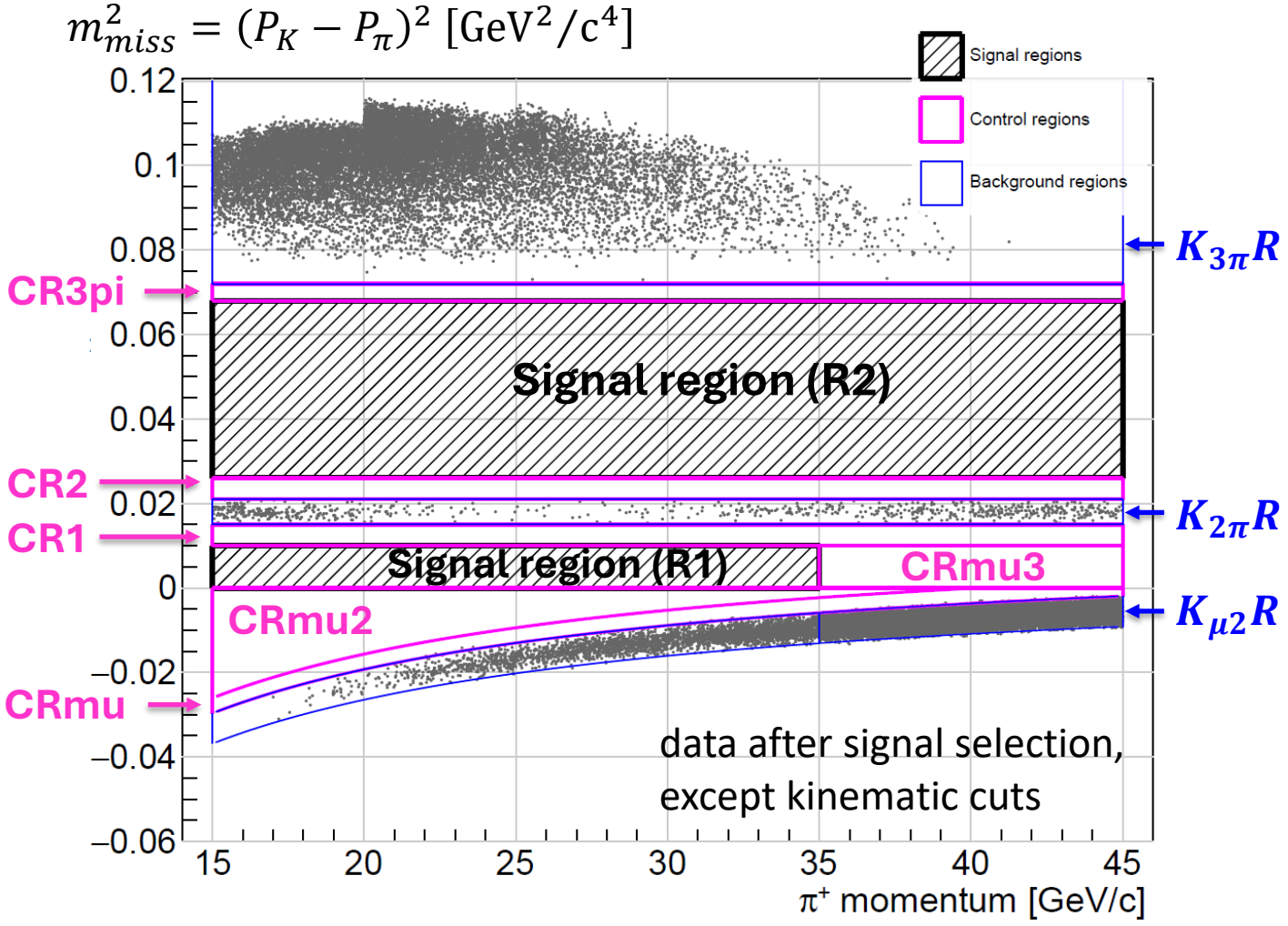
$N_{\pi\pi}^{\text{eff}}$	Effective number of normalisation events	$(1.953 \pm 0.005) \times 10^8$	
$A_{\pi\pi}$	Normalisation acceptance	$(13.410 \pm 0.005)\%$	+15% wrt 16 – 18
N_K	Effective number of K^+ decays	$(2.85 \pm 0.01) \times 10^{12}$	
$A_{\pi\nu\bar{\nu}}$	Signal acceptance	$(7.62 \pm 0.22)\%$	+20% wrt 16 – 18
$\varepsilon_{\text{trig}}$	Trigger efficiency ratio	$(85.9 \pm 1.4)\%$	× 3 better precision than 16 – 18
ε_{RV}	Random veto efficiency	$(63.2 \pm 0.6)\%$	comparable with 16 – 18
$\mathcal{B}_{\text{SES}}$	Single event sensitivity	$(8.48 \pm 0.29) \times 10^{-12}$	
$N_{\pi\nu\bar{\nu}}^{\text{SM}}$	Number of expected SM $K^+ \to \pi^+\nu\bar{\nu}$ events	9.91 ± 0.34	~10 in 16 – 18







Background (21-22 data)



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

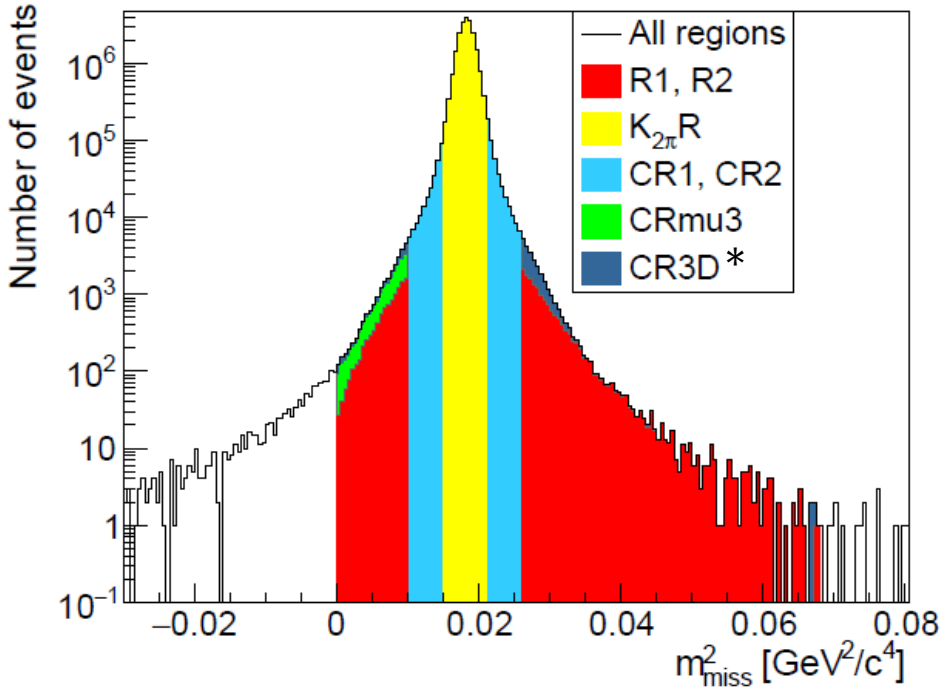
Background from $K^+ \to \pi^+\pi^0$

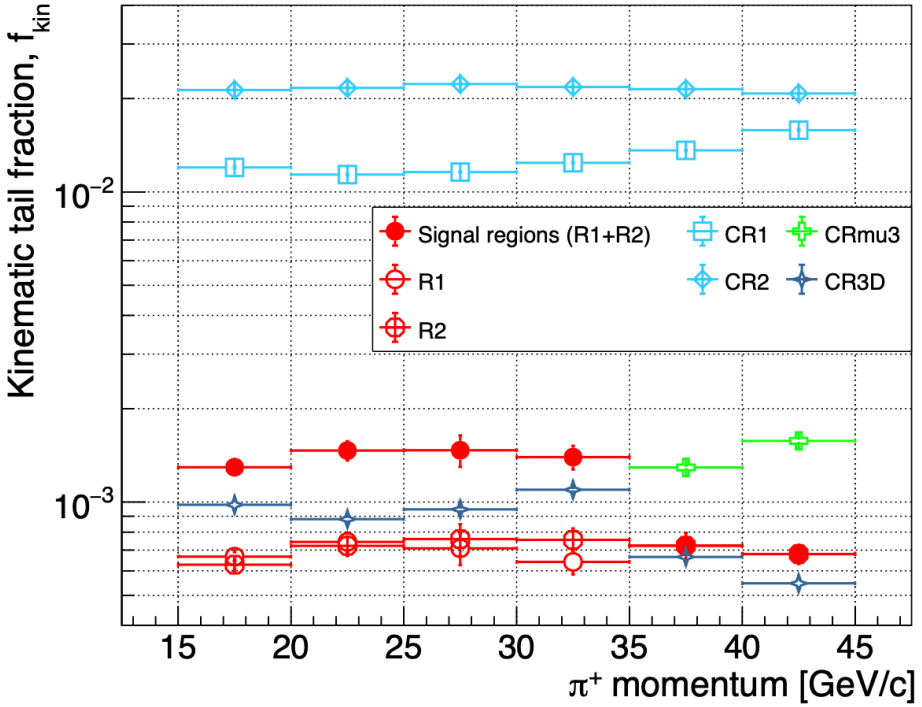
- **Suppression**: kinematics and photon vetoes
- **Estimation**: data selected tagging γ from π^0
- **Validation**: control regions in the π^+momentum, m^2_{miss} plane

⇒ Expected: $\mathbf{0.85 \pm 0.05}$

in $K_{2\pi}R$ in R1,2 or CR

$$N^{exp}_{\pi\pi}(region) = N(\pi^+\pi^0) \cdot f^{kin}(region)$$





Hypothesis: kinematics independent from photon rejection

*CR3D: control region orthogonal to the π^+momentum, m^2_{miss} plane

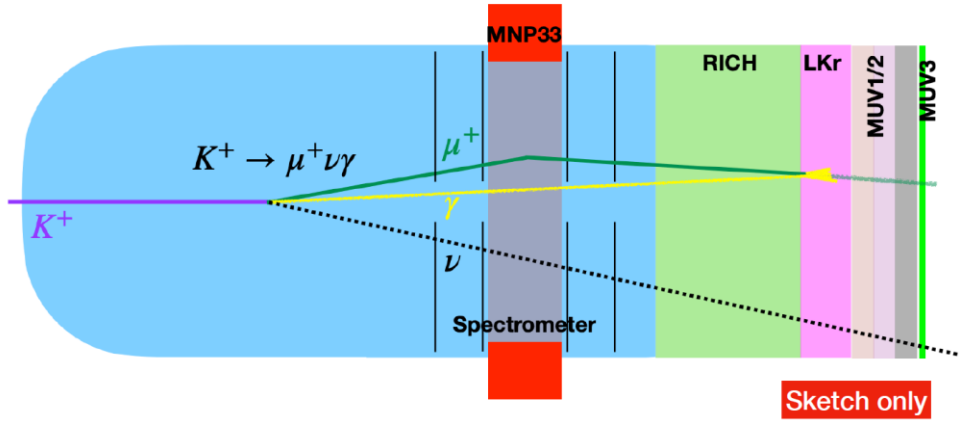
Background from $K^+ \to \mu^+\nu\gamma$

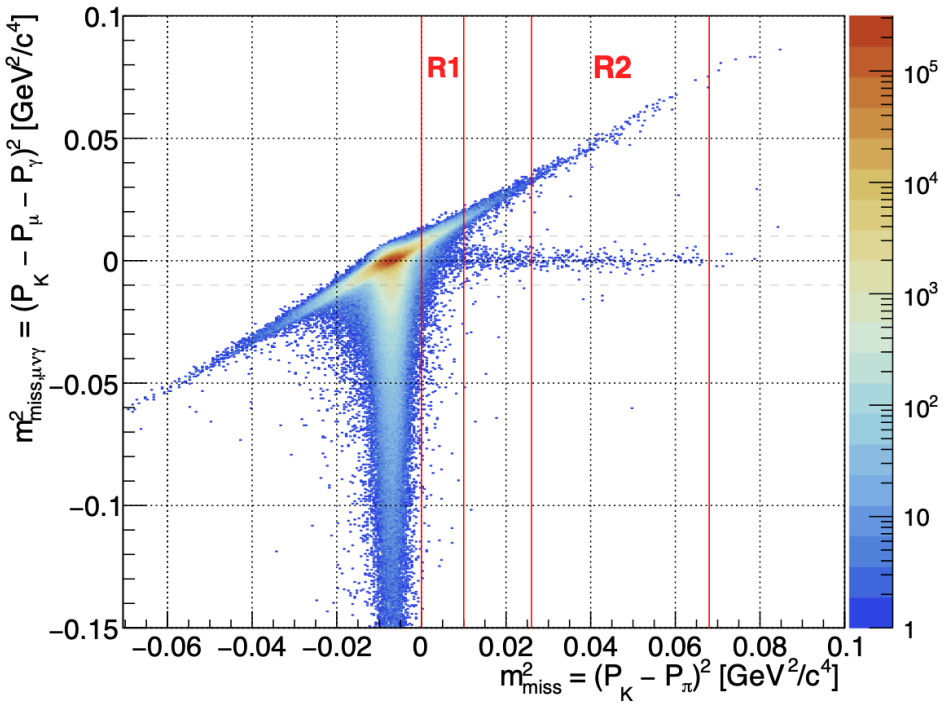
Not included in $K^+ \to \mu^+\nu$ background if γ overlaps with μ at LKr

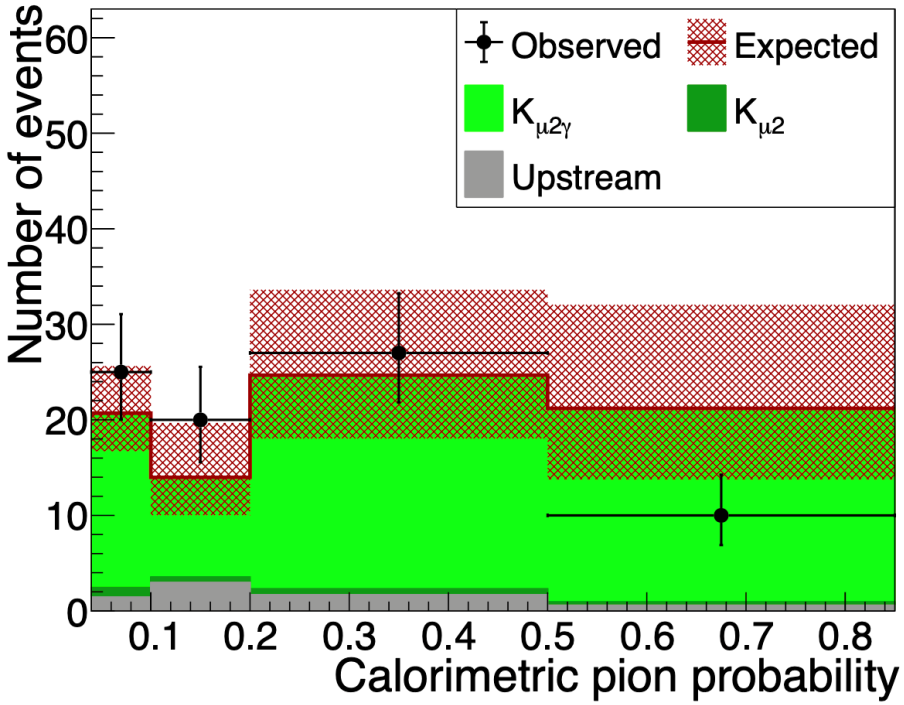
- **Suppression**: specific cuts on $\left(P_K - P_\pi - P_\gamma\right)^2$ and E_γ
- **Estimation**: data sample of events with signal in MUV3
- **Validation**: data sample with PID between μ and π

⇒ High momentum background (> 35 GeV), relevant in 21-22 data

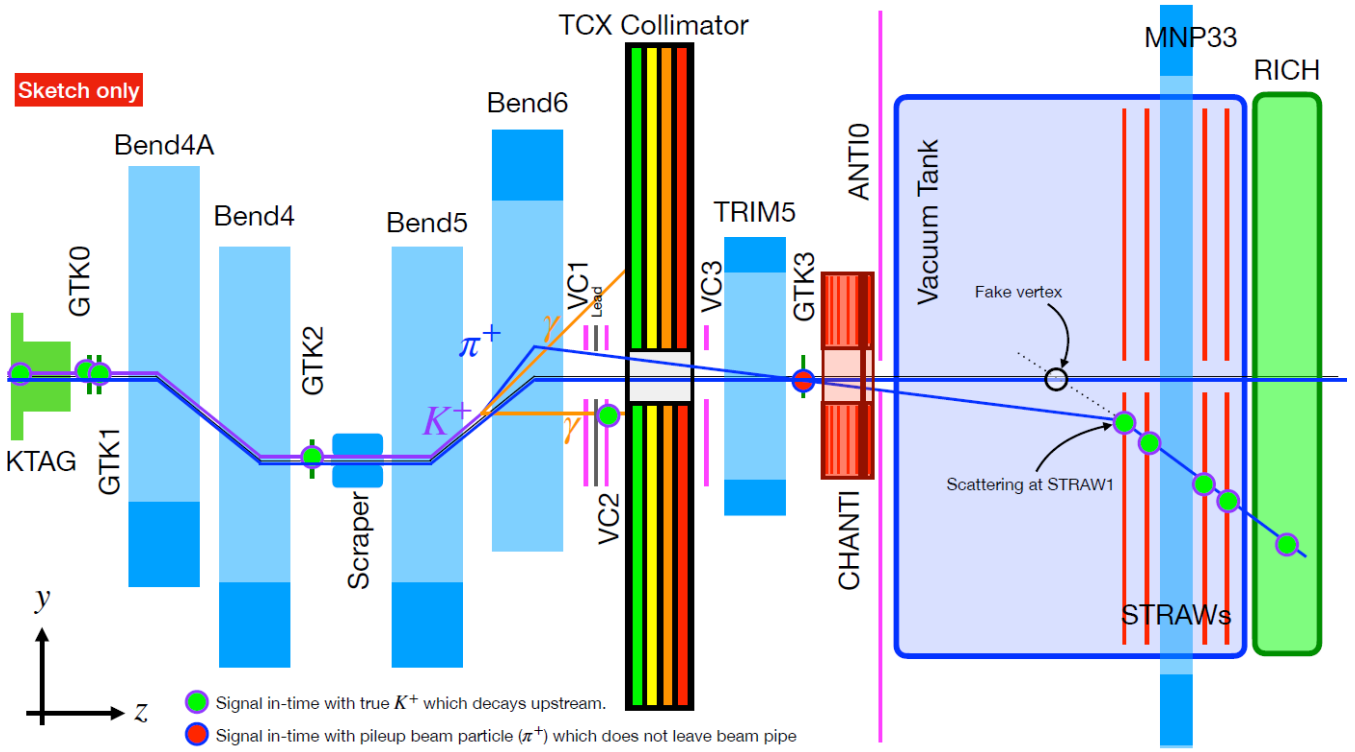
⇒ Expected: $\mathbf{0.82 \pm 0.43}$







“Upstream” Background



$$N_{bg} = f_{cda} \sum_i N_i \mathcal{P}_i^{match}$$

i	Bin in $(\Delta t, N_{GTK})$ plane
N	Upstream sample (inverted CDA cut)
f_{cda}	Scaling factor “bad-to-good” cda
$\mathcal{P}^{match}$	$K^+ - \pi^+$ mismatching probability

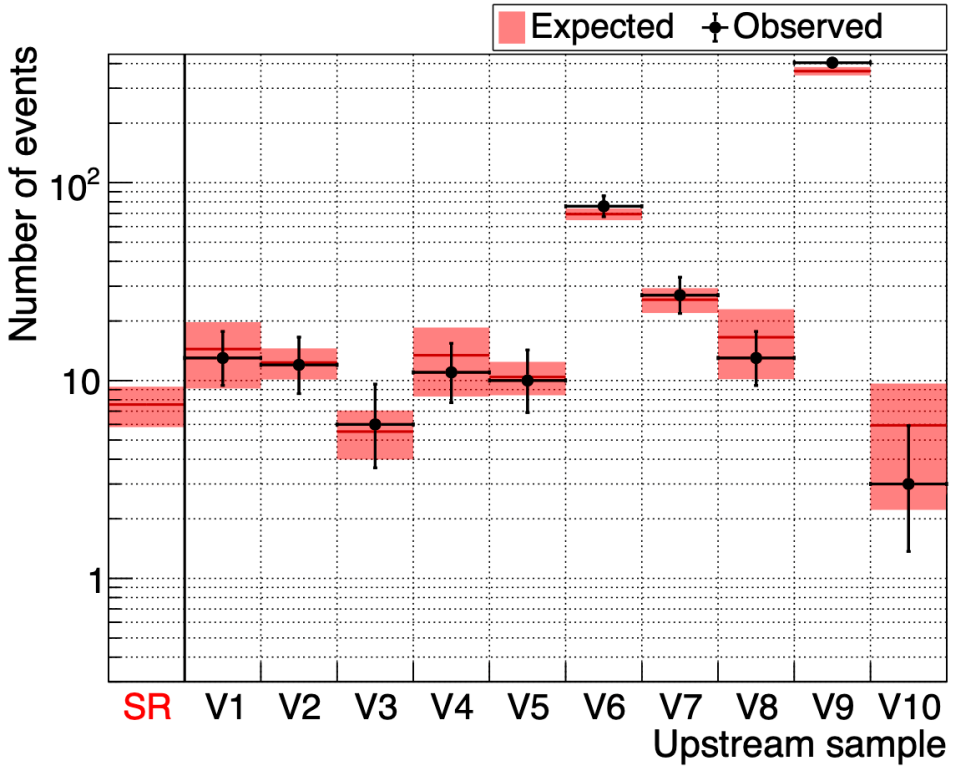
- **Suppression**: Δt kaon-pion, upstream vetoes (VC, CHANTI, Anti0), BDT using spatial infos of K^+ and π^+
- **Estimation**: data background sample and data-driven estimation of background-to-signal sample probability
- **Validation**: control sample upstream enhanced

⇒ Dominant background

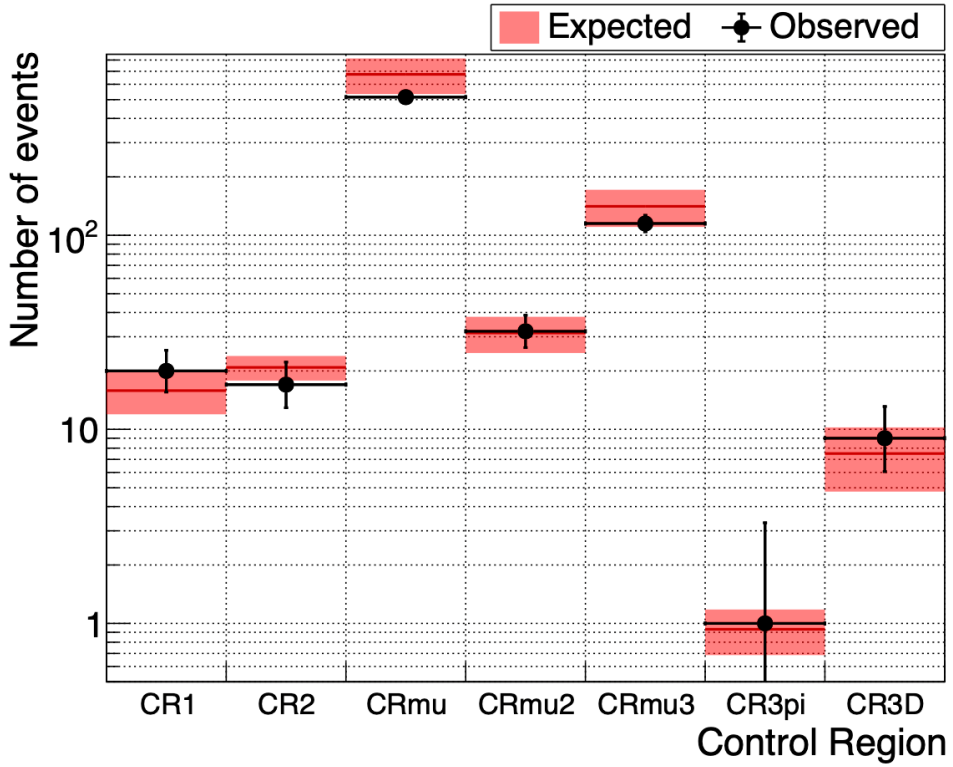
Background Validation

Upstream background validation

Sample accidental-enriched: “V3,4,5,6,9,10”
Sample interaction-enriched: “V1,2,7,8”
Signal region, masked: first bin “SR”

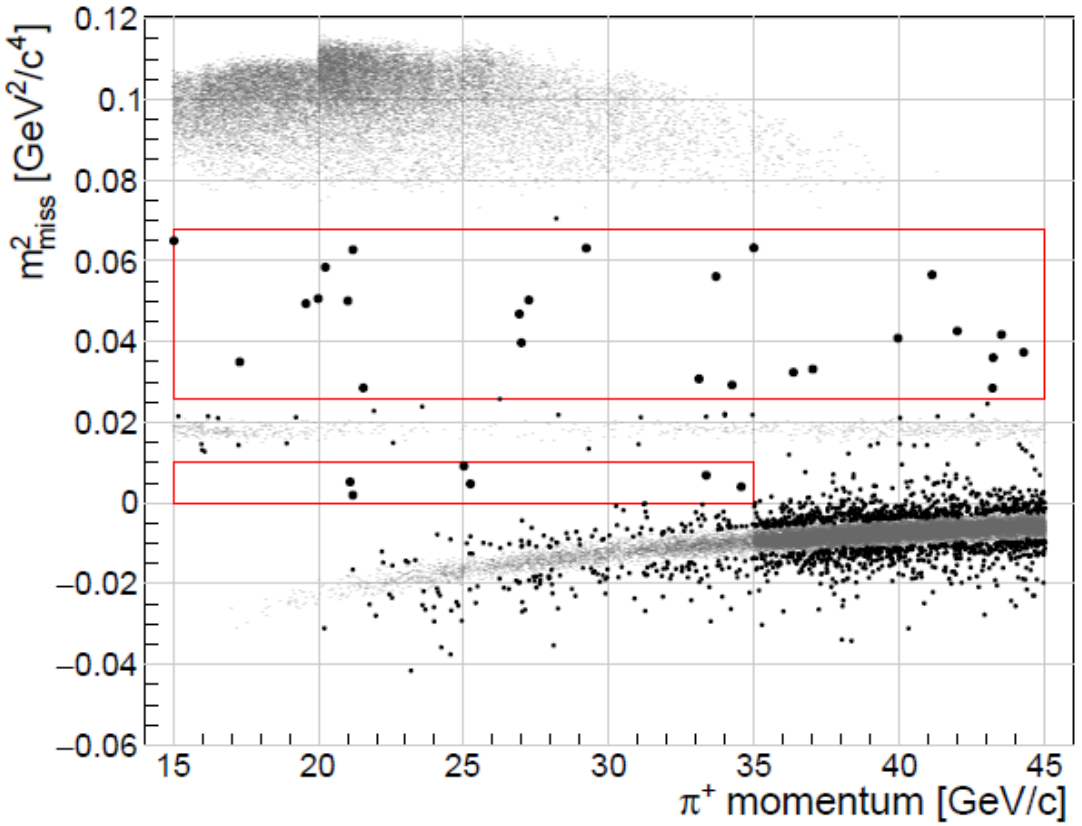


“K-decay” background validation

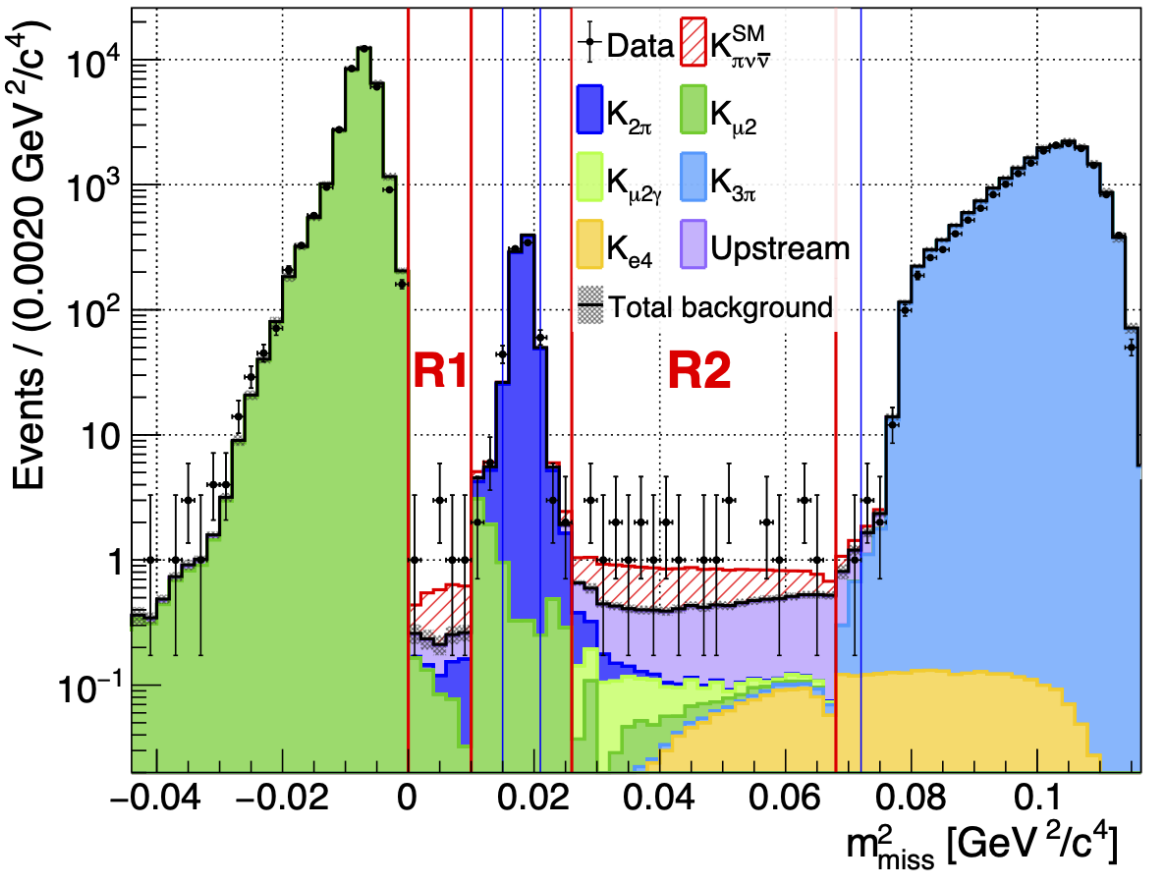


Result from 2021-22

Single Event Sensitivity	$(0.84 \pm 0.03) \times 10^{-11}$
Expected background	$11.0^{+2.1}_{-1.9}$
Observed	**31**



1D projection with differential background predictions & SM signal expectation [not a fit]



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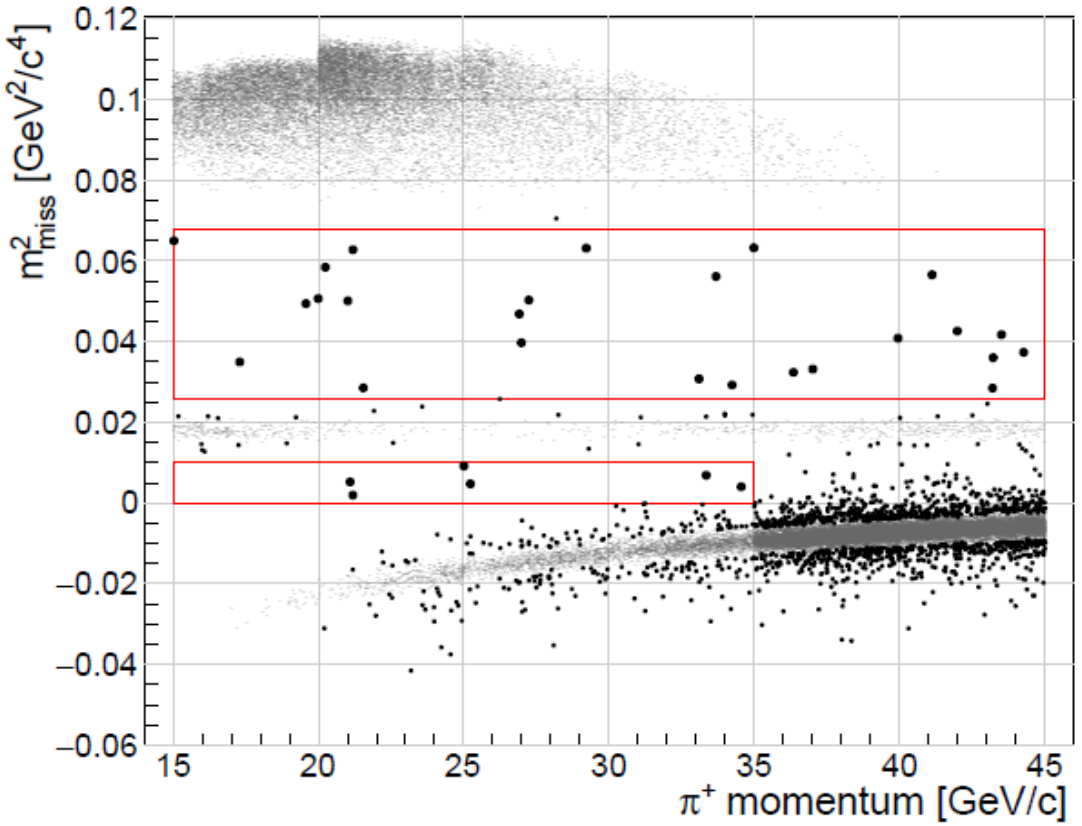
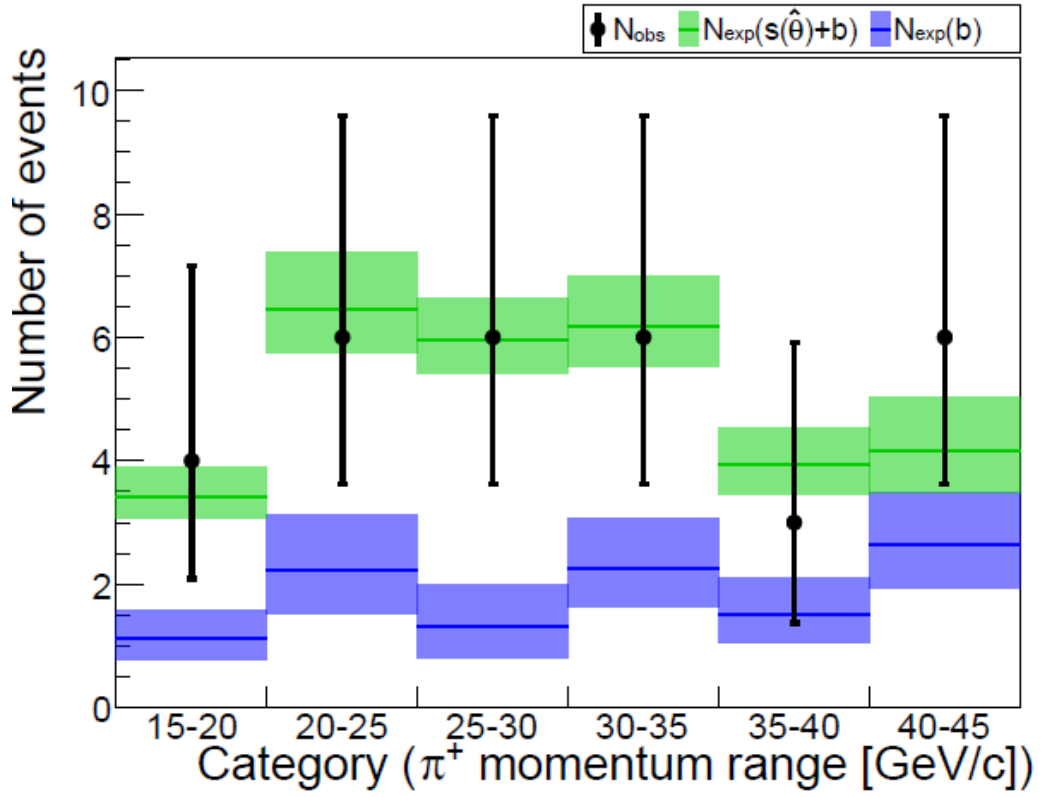
Observed	**31**

Fit to π^+ momentum with a profile likelihood ratio test statistics

$$\mathcal{B}_{\pi\nu\nu} = \left[16.0^{\,+4.8}_{\,-4.2}\,(\text{stat})\,^{+1.4}_{-1.3}\,(\text{syst})\right] \times 10^{-11}$$



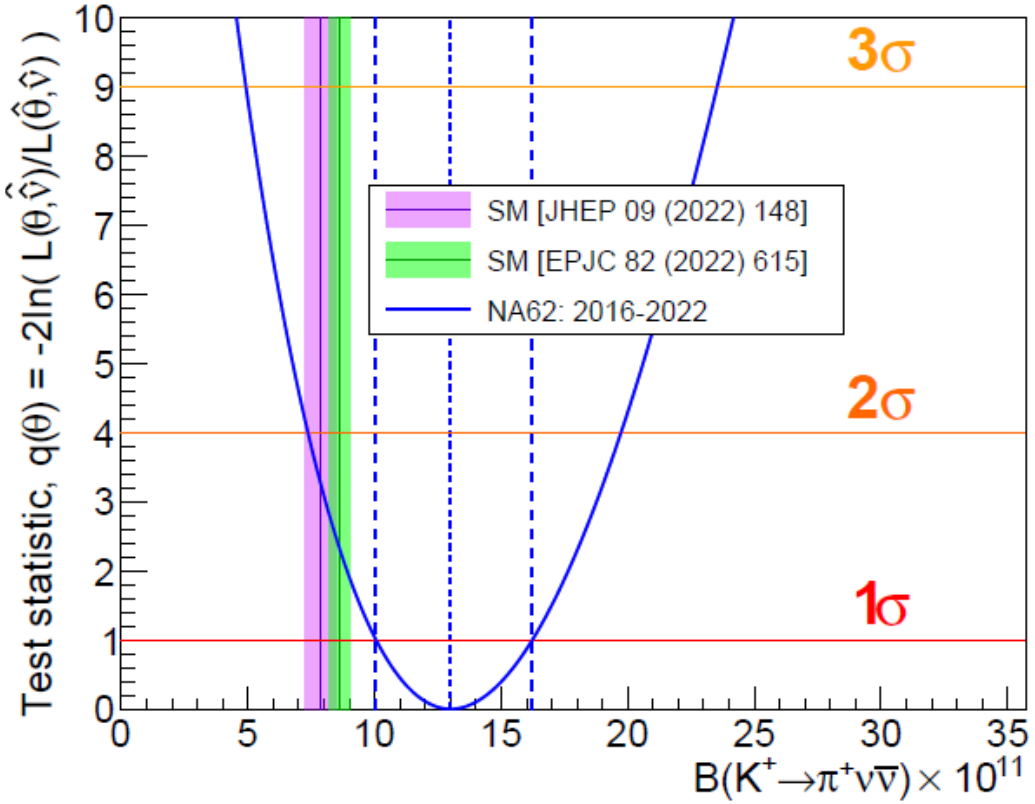


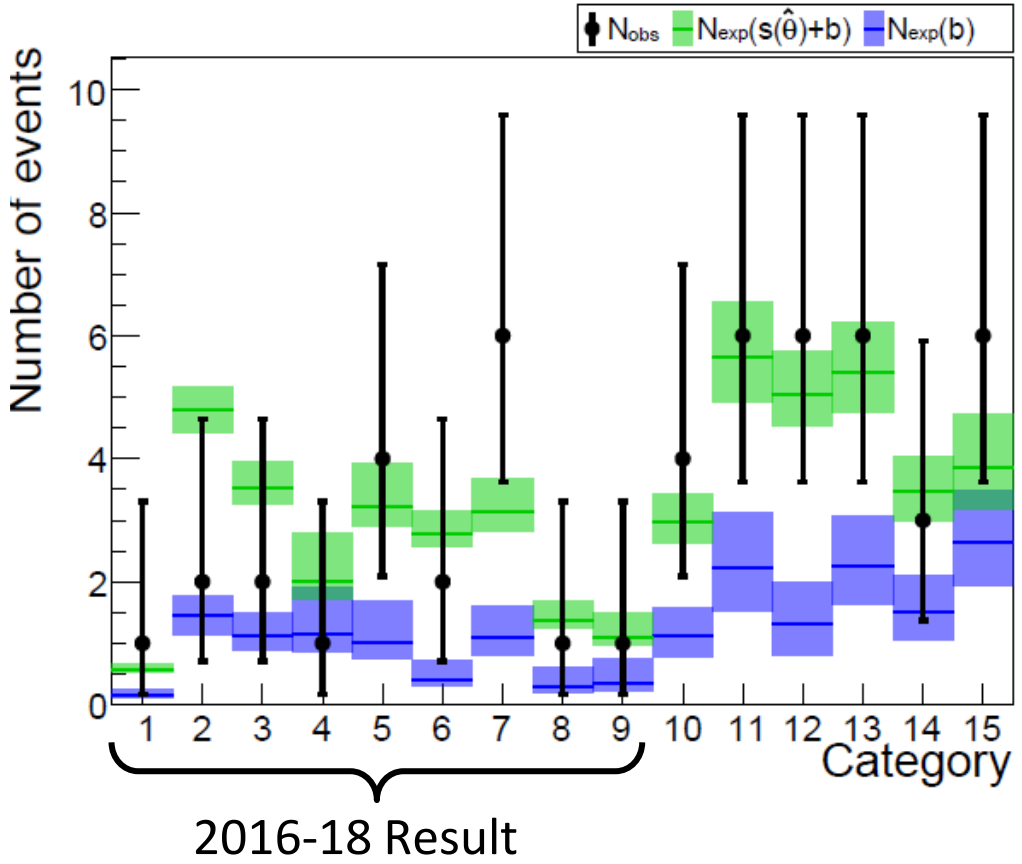
Combination with 2016-18 Results

Single Event Sensitivity	$(0.42 \pm 0.02) \times 10^{-11}$
Expected background	18^{+3}_{-2}
Observed	**51**

b-only hyp. rejection significance: $Z > 5\sigma$

$$\mathcal{B}_{\pi\nu\nu} = \left[13.0\left(^{+3.0}_{-2.7}\right)_{stat}\left(^{+1.3}_{-1.2}\right)_{syst}\right] \times 10^{-11}$$





Result in context

$$\mathcal{B}_{2016-2022}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(13.0^{+3.3}_{-3.0}\right) \times 10^{-11}$$

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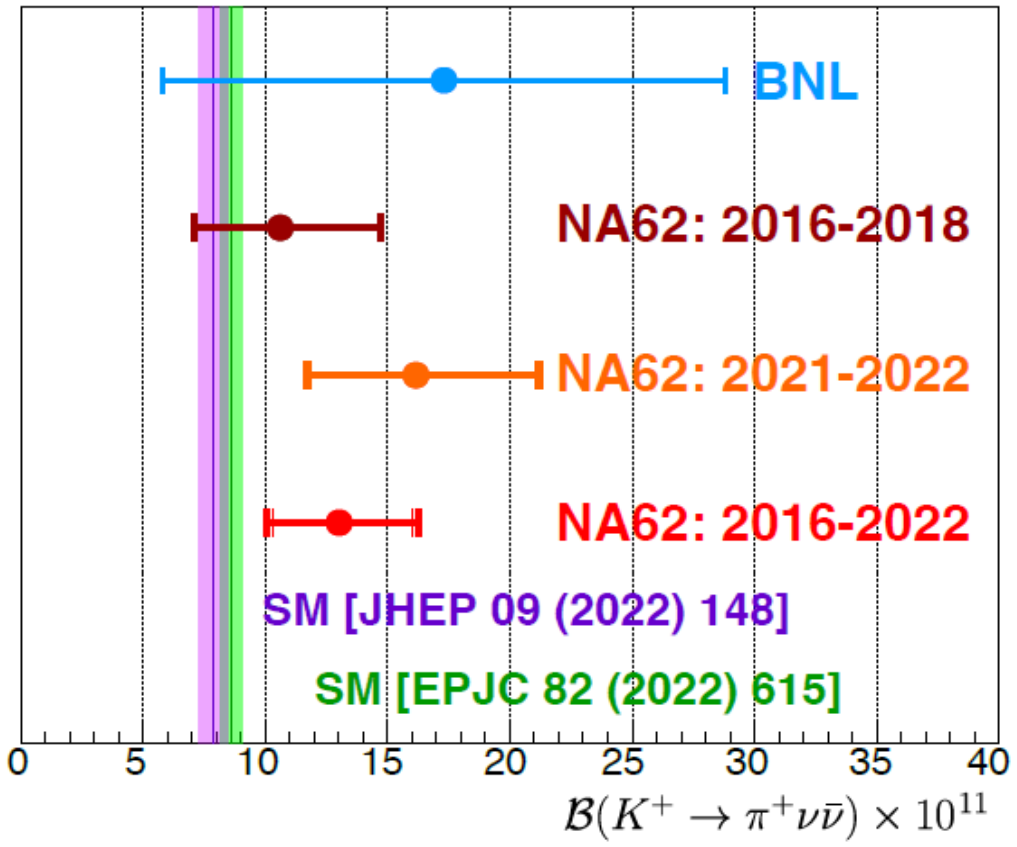

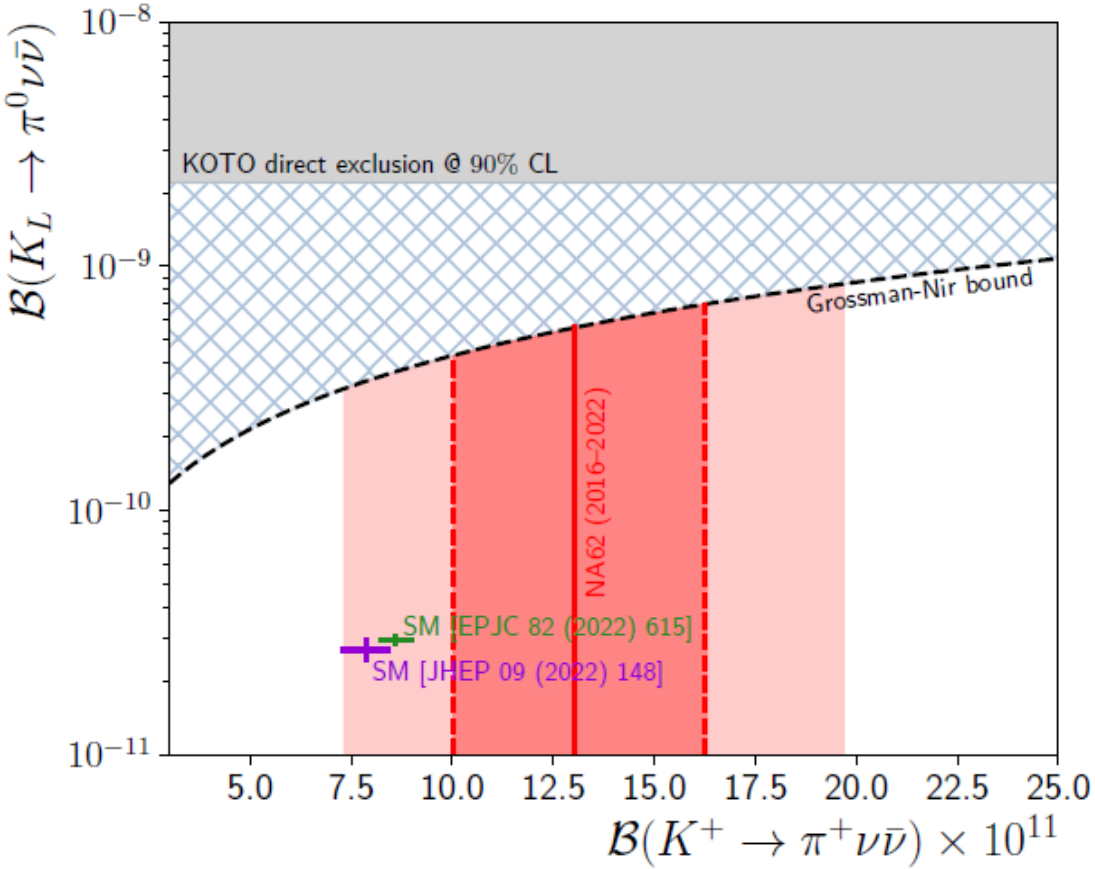

Conclusions and Prospects

- NA62 result on $K^+ \to \pi^+ \nu\bar{\nu}$ using data from 21 – 22 and combination with result from 2016 – 18 data

- First observation of $K^+ \to \pi^+ \nu\bar{\nu}$ decay with 5σ rejection of background-only hypothesis
- $BR_{2016-22} = 13.0^{+3.3}_{-3.0} \times 10^{-11}$ [JHEP 02 (2025) 191]
- In agreement with SM prediction within $1.5 - 1.7\sigma$

- 2023 – 24 data sample of the order of the 2016 – 22 data sample
- Analysis on-going

- NA62 will take data until start of LS3 (summer 2026)