A New Measurement of the $K^+ \to \pi^+ \nu\, \nu$-bar Branching Ratio at the NA62 Experiment

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on behalf of NA62 Collaboration

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Outline

Motivation to measure $K^+ \to \pi^+ \nu \bar{\nu}$

The NA62 Experiment in Kaon Decay mode

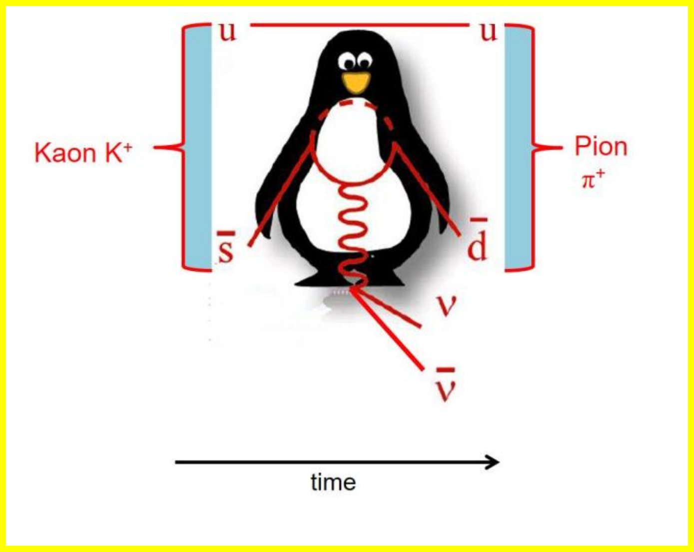
NA62 $K^+ \to \pi^+ \nu \bar{\nu}$ latest results (2023-24 data)

Motivation

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is allowed in the Standard Model (SM)

It involves s - d anti-quark conversion via FCNC

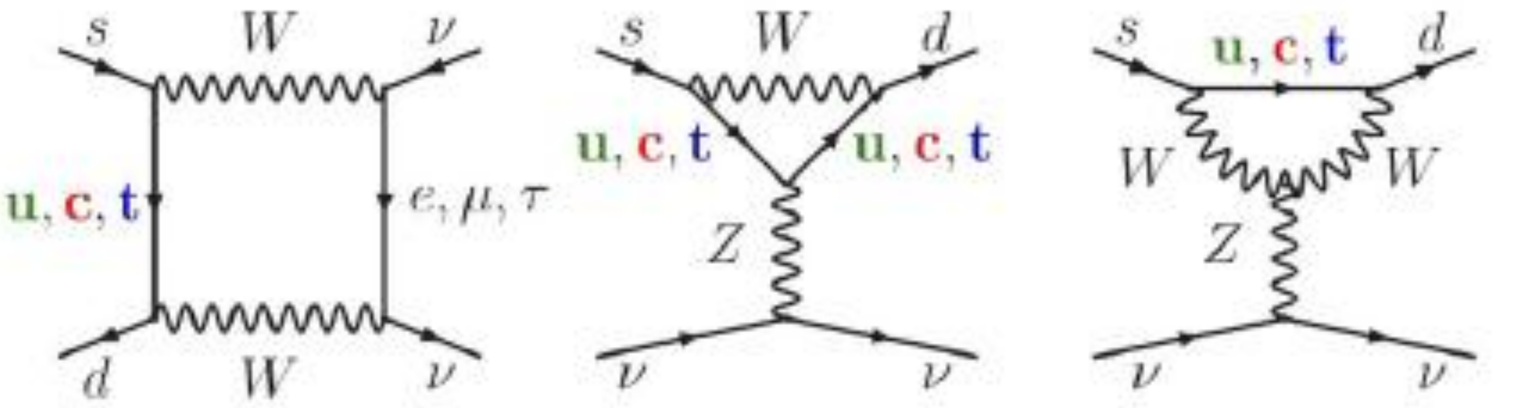
No such interaction vertex in the SM, however,
possible at loop level, via *penguin* and box diagrams



As a result it is a rare process

Motivation

$K^+ \to \pi^+ \nu \bar{\nu}$ is, in fact, ultra rare (in the SM)



Suppressed by m_q^2 / m_W^2 the top exchange in the loop dominates.
It is, however, CKM suppressed by $\lambda_t = V_{ts}^* V_{td}$:

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2\theta_w} \sum_{\ell=e,\mu,\tau} \left(\lambda_c X^\ell + \lambda_t X_t\right) (\bar{s}_L \gamma_\mu d_L)(\bar{\nu}_{\ell L} \gamma^\mu \nu_{\ell L}) + \text{h.c.}$$

SM predictions:

[Buras et al. EPJC 82 (2022) 7, 615] [D'Ambrosino et al. JHEP 09 (2022) 148]

$$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = \qquad (8.60 \pm 0.42) \cdot \underline{10^{-11}} \qquad (7.86 \pm 0.61) \cdot \underline{10^{-11}}$$

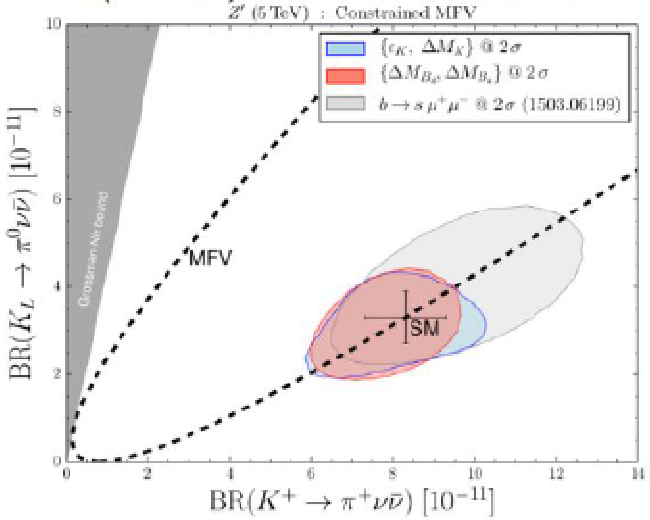
Motivation

Therefore, $K^+ \to \pi^+ \nu\bar{\nu}$ is highly sensitive to BSM contributions from NP flavor violation

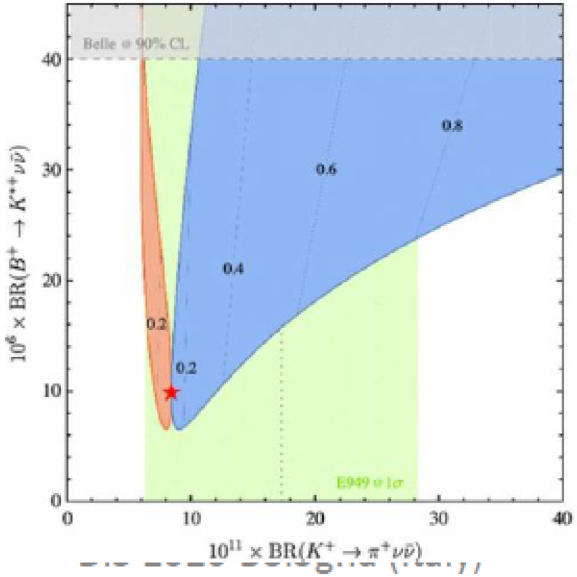
NP effects expected to correlate with other flavour observables in a number of scenarios

- Custodial Randall-Sundrum [Buras et al., JHEP 0903 (2009) 108]
- MSSM analyses [Blazek, Matak, Int.J.Mod.Phys. A29 (2014) no.27],[Isidori et al. JHEP 0608 (2006) 064]
- Simplified Z, Z' models [Buras, Buttazzo,Knegjens, JHEP11(2015)166]
- Littlest Higgs with T-parity [Blanke, Buras, Recksiegel, Eur.Phys.J. C76 (2016) 182]
- LFU violation models [Isidori et al., Eur. Phys. J. C (2017) 77: 618]
- Leptoquarks [S. Fajfer, N. Košnik, L. Vale Silva, arXiv:1802.00786v1 (2018)]
- NP aligned with 3rd generation [Allwicher, Bordone, Isidori, Piazza, Stanzione, PLB 861 (2025) 139295, update here]

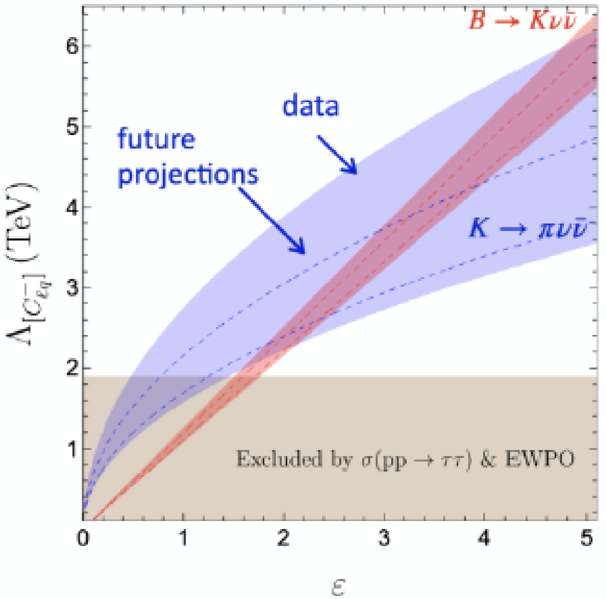
Z'(5 TeV) in Constrained MFV



LFU violation



e.g. leading $U(2)_q$ breaking (here: ϵ) can be determined by comparing b→s vs s→d



Motivation

$K^+ \to \pi^+\nu\bar{\nu}$ is, at the same time, theoretically very clean - just 6% overall SM uncertainty

$$\mathcal{B}(K^+\to\pi^+\nu\bar\nu(\gamma)) = \underline{\kappa_+}(1+\underline{\Delta_{\mathrm{EM}}})\left[\left(\overset{A^2\bar\eta}{\frac{\mathrm{Im}\lambda_t}{\lambda^5}}\underline{X_t}\right)^2 + \left(\overset{-1}{\frac{\mathrm{Re}\lambda_c}{\lambda}}(\underline{P_c}+\underline{\delta P_{c,u}}) + \overset{A^2(\bar\rho-1)}{\frac{\mathrm{Re}\lambda_t}{\lambda^5}}\underline{X_t}\right)^2\right];$$

SM estimate with a 6% relative uncertainty:

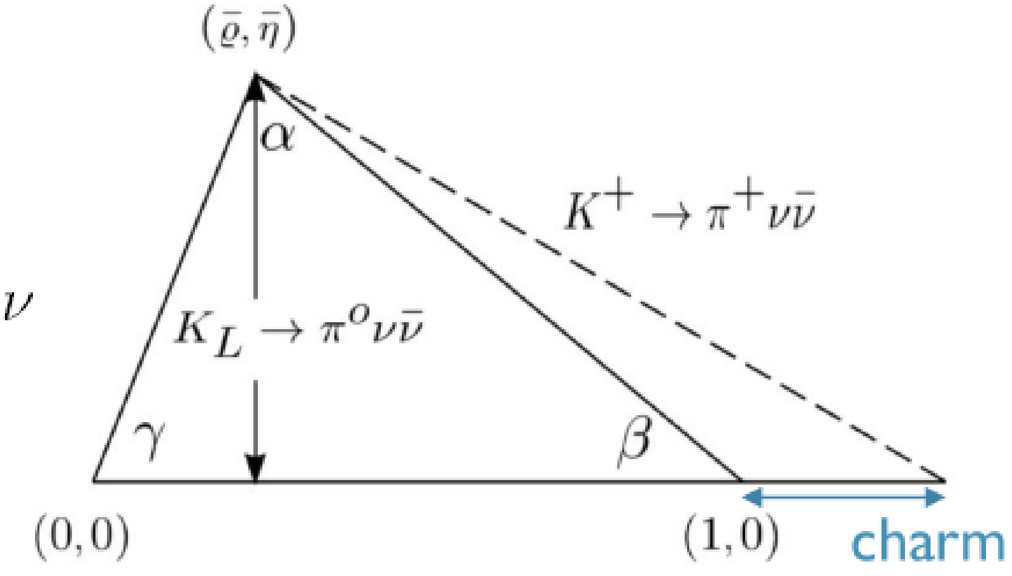
- **±0.5% Hadronic matrix element** from $K^+ \to \pi\ell\nu$ via isospin rotation at χPt O(p^4) [Mescia, Smith PRD 76 (2007) 034017; Bijnens, Ghorbani hep-ph:0711.0148 (2007)]
- **±0.1% QED correction** at NLO [Mescia, Smith PRD 76 (2007) 034017]
- **±1.7% Top contribution** at NLO QCD [Misiak, Urban PLB 451 (1999) 161; Buchalla, Buras NPB 548 (1999) 309] and NLO EW [Brod, Gorbahn, Stamou PRD 83 (2011) 034030]
- **±1.3% Charm contribution** evaluated at NNLO QCD and NLO EW [Brod, Gorbahn PRD 78 (2008) 034006]
- **±3.0% Dim-8 operators + u,c long distance** at χPt O(p^4) [Isidori, Mescia, Smith NPB 718 (2005) 319]
- **±2.0% Inputs** for m_t, m_c, α_s [EPJC 84 (2024) 4, 377]
- **±4.0% CKM inputs** for A, $\bar\rho$, $\bar\eta$ [UTfit JHEP 07 (2025) 028, CKMfitter EPJC 21 (2001) 225]

T.Spadaro's
INFN talk

Motivation

$K^+ \to \pi^+ \nu\bar{\nu}$ **Very clean theoretically**

- Short distance contribution and no hadronic uncertainties
- Hadronic matrix element extracted from well-known decay $K^+ \to \pi^0 e^+ \nu$
- Theoretical error budget dominated by CKM parameters



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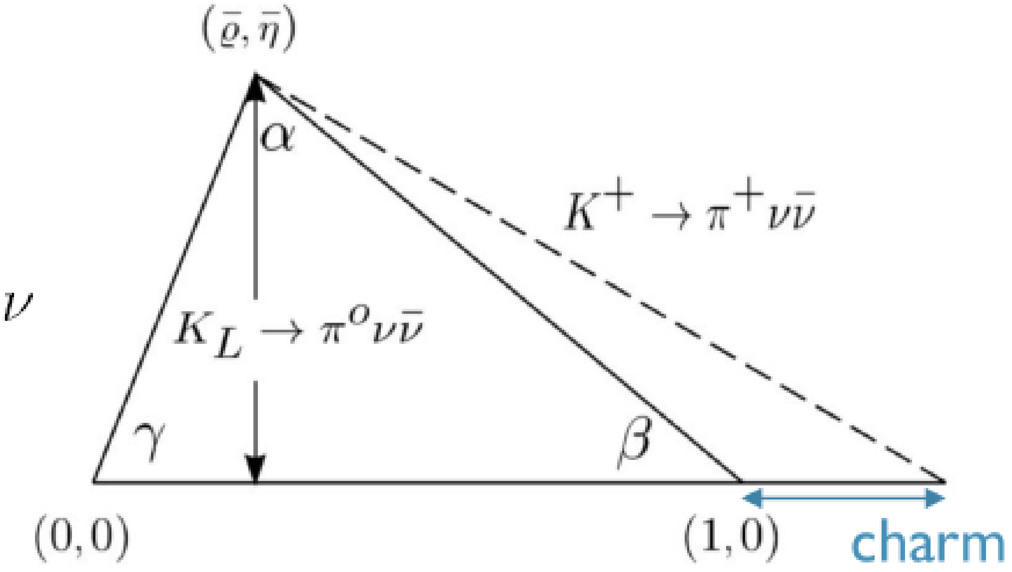

SM predictions:

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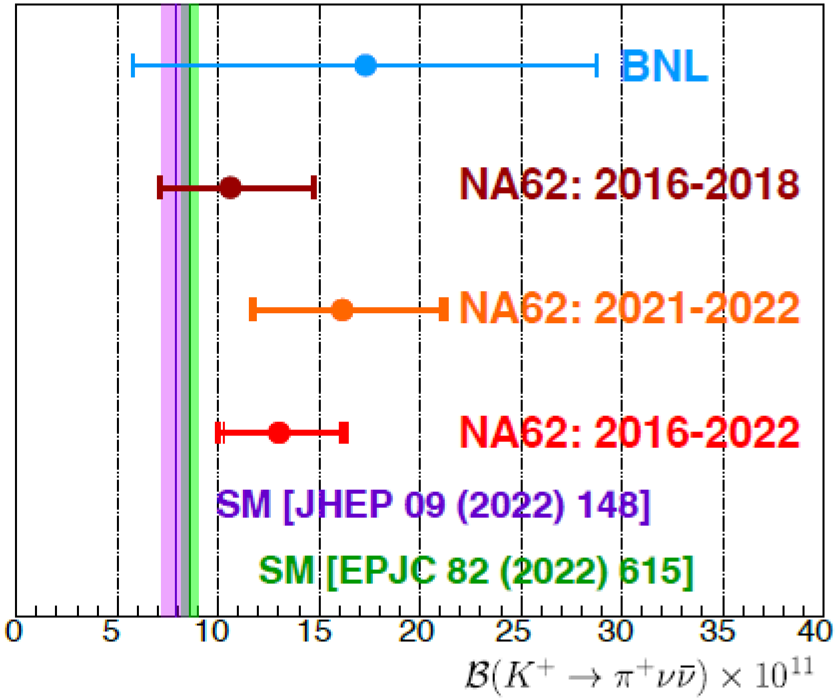
$$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (8.60 \pm \underline{\underline{0.42}}) \cdot 10^{-11} \qquad (7.86 \pm \underline{\underline{0.61}}) \cdot 10^{-11}$$

! !

Previous NA62 Results

- Integrating 2016—22 data: $N_{Bkg} = 18^{+3}_{-2}$, $N_{observed} = 51$
- **Background-only hypothesis** p–value $= 2 \times 10^{-7}$

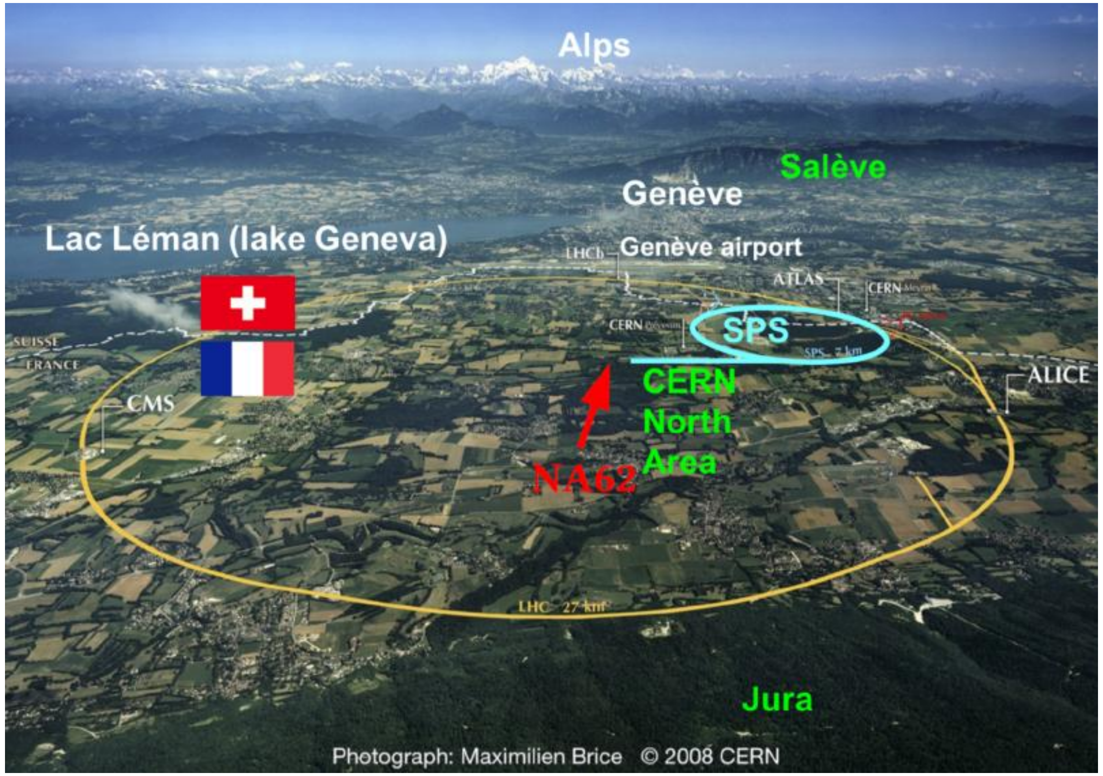
  $\Rightarrow$ significance $Z > 5$



$$\boxed{\mathcal{B}_{16-22}(K^+ \to \pi^+\nu\bar{\nu}) = (13.0^{+3.3}_{-3.0}) \times 10^{-11}} = (13.0(^{+3.0}_{-2.7})_{stat}[^{+1.3}_{-1.3}]_{syst}) \times 10^{-11}$$

[JHEP 02 (2025) 191]

The NA62 Experiment at CERN



Photograph: Maximilien Brice © 2008 CERN

~ 30 institutes, ~ 300 collaborators
K^+ decays in flight OR Beam Dumped: TAX closed & target removed (Kaon mode OR Beam Dump Mode)

Data taking **Run 1** 2017-18 **Run 2** 2021-26
2016 Comissioning + Physics run (45 days)
2017, 2018 Run 1 data taking (160+217 days)

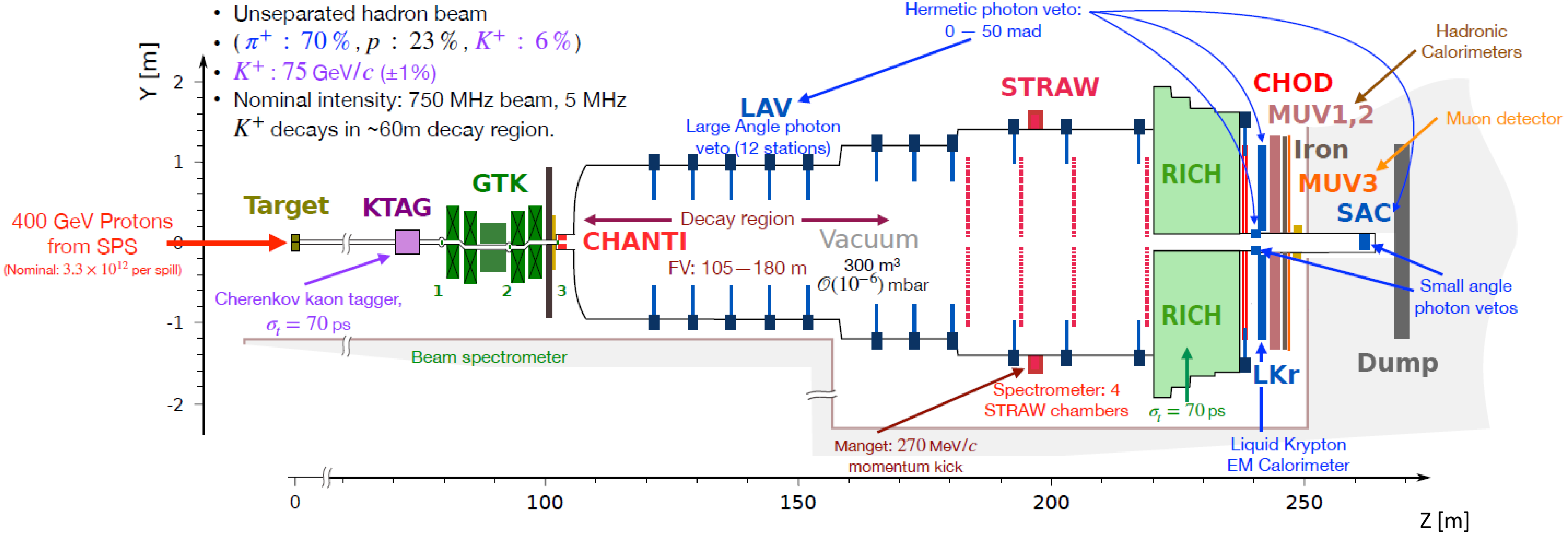
2021 Physics run (85 days, 10 days in BD mode)
2022 Physics run (215 days)
2023 Physics run (150 days, 10 days in BD mode)
2024 Physics run (204 days, 12 days in BD mode)
2025 Physics run (210 days)

Continues long history of Kaon Physics at CERN

NA62 Beamline & Detector

NA62 setup in K mode: studies of rare K^+ decays

- Unseparated hadron beam
- (π^+ : 70 %, p : 23 %, K^+ : 6 %)
- K^+ : 75 GeV/c (±1%)
- Nominal intensity: 750 MHz beam, 5 MHz K^+ decays in ~60m decay region.



JINST 12 (2017) P05025

Particle Tracking: upstream: **GTK = silicon pixel tracker**, decay region: **STRAW = tracking momentum spectrometer**

P. Identification : upstream: **KTAG**, downstream: **RICH= π/μ/e ID Cherenkov**, **LKr, MUV1,2 calorimetry**

Veto: **CHANTI = inelastic collision Anticounter**, **LAV**, **IRC**, **SAC = Large & Small Angle photon vetos**

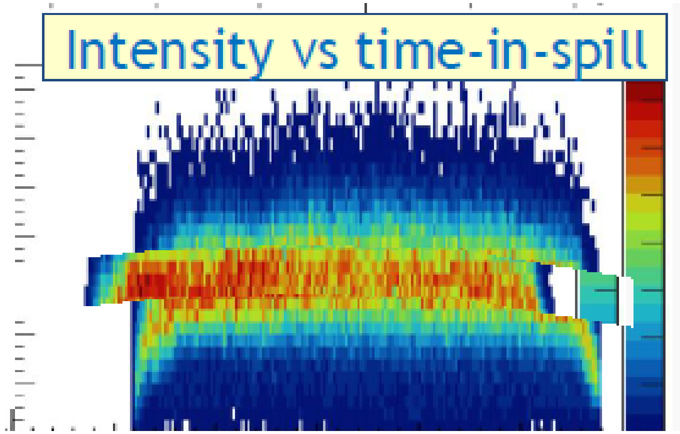
Overall experimental time resolution reaches $\mathcal{O}(100)$ps

NA62 setup in K mode: studies of rare K^+ decays

One year ≈ 1.5×10^{18} protons on target ≈ 5×10^{12} K^+ decays.

Beam structure: ideally, uniform over a 4.8 s long spill.

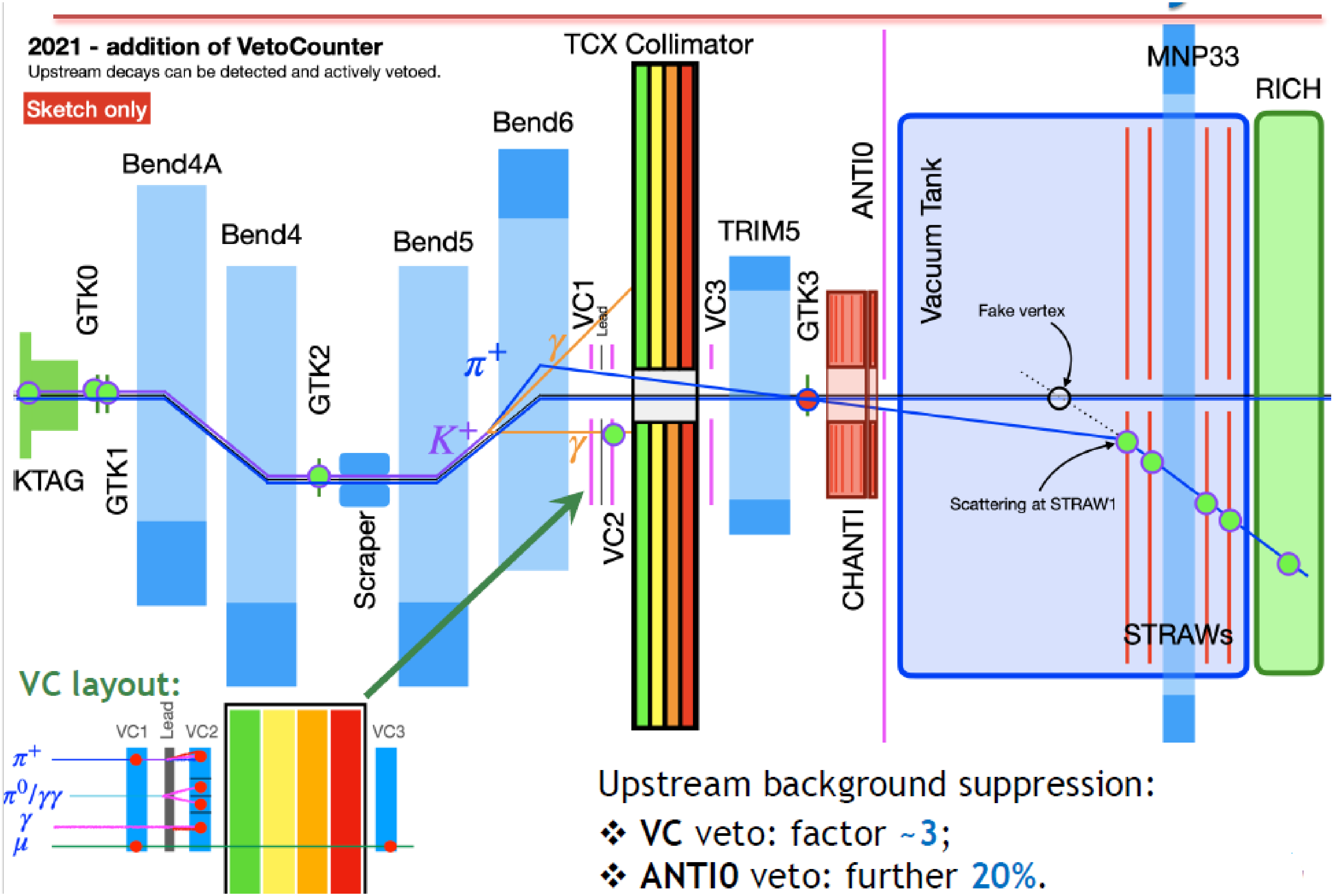
In practice, significant variations
of instantaneous beam intensity during the spill.



Main dataset (kaon mode):

- Run 1 (2016–18): 850k good SPS spills in 420 days.
- Run 2 (2021–26): so far, ~2.5M good SPS spills in 900+ days.
- Broad programme: rare K^+/π^0 decays; LNV/LFV, hidden sectors.

NA62 Upstream setup in Run 2 relevant for bkgnd analysis, more later



2021 - addition of VetoCounter

Upstream decays can be detected and actively vetoed.

Upstream background suppression:

- VC veto: factor ~3;
- ANTI0 veto: further 20%.

Experiment: How to search for ultra-rare K decays

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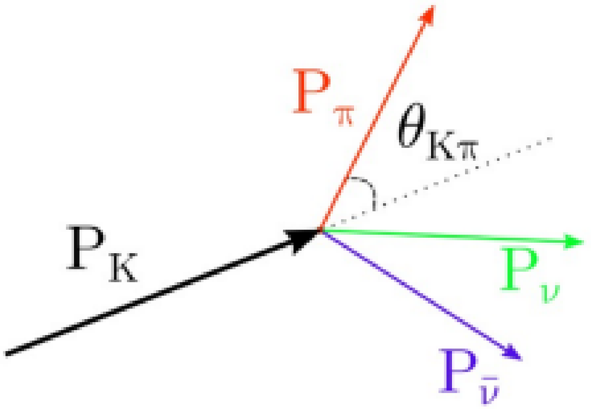
Kaon decays in flight

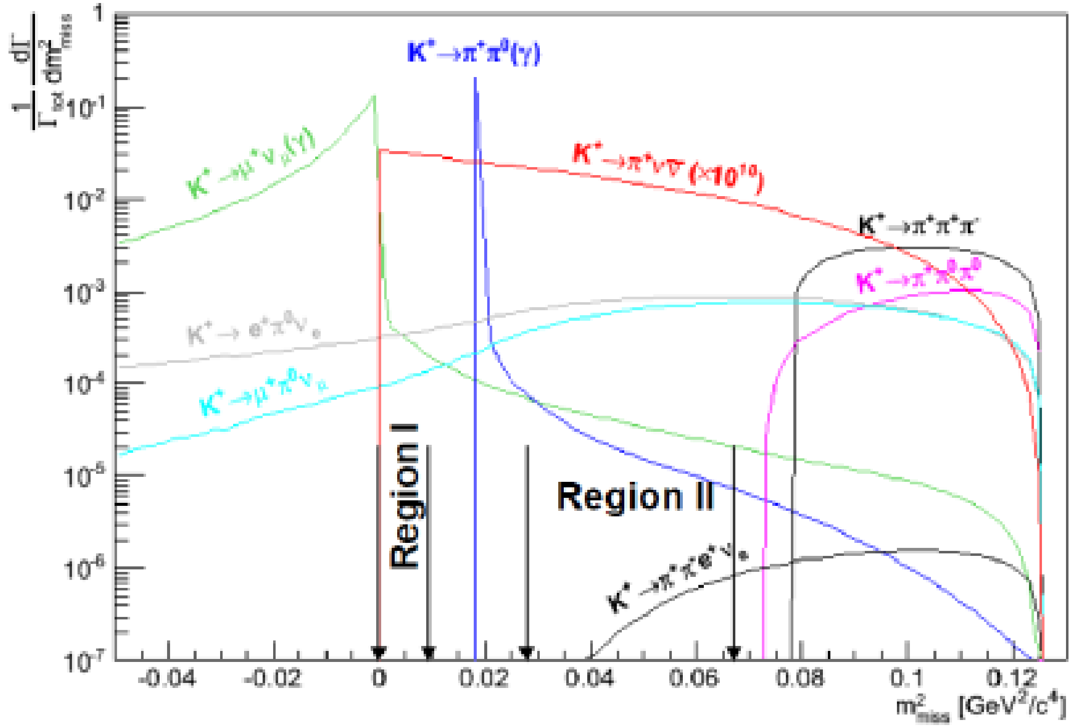
Signal: Time and space $K^+ - \pi^+$ matching

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

The analysis is mostly cut based

Blind analysis: Signal and background ctrl regions are kept blind throughout the analysis





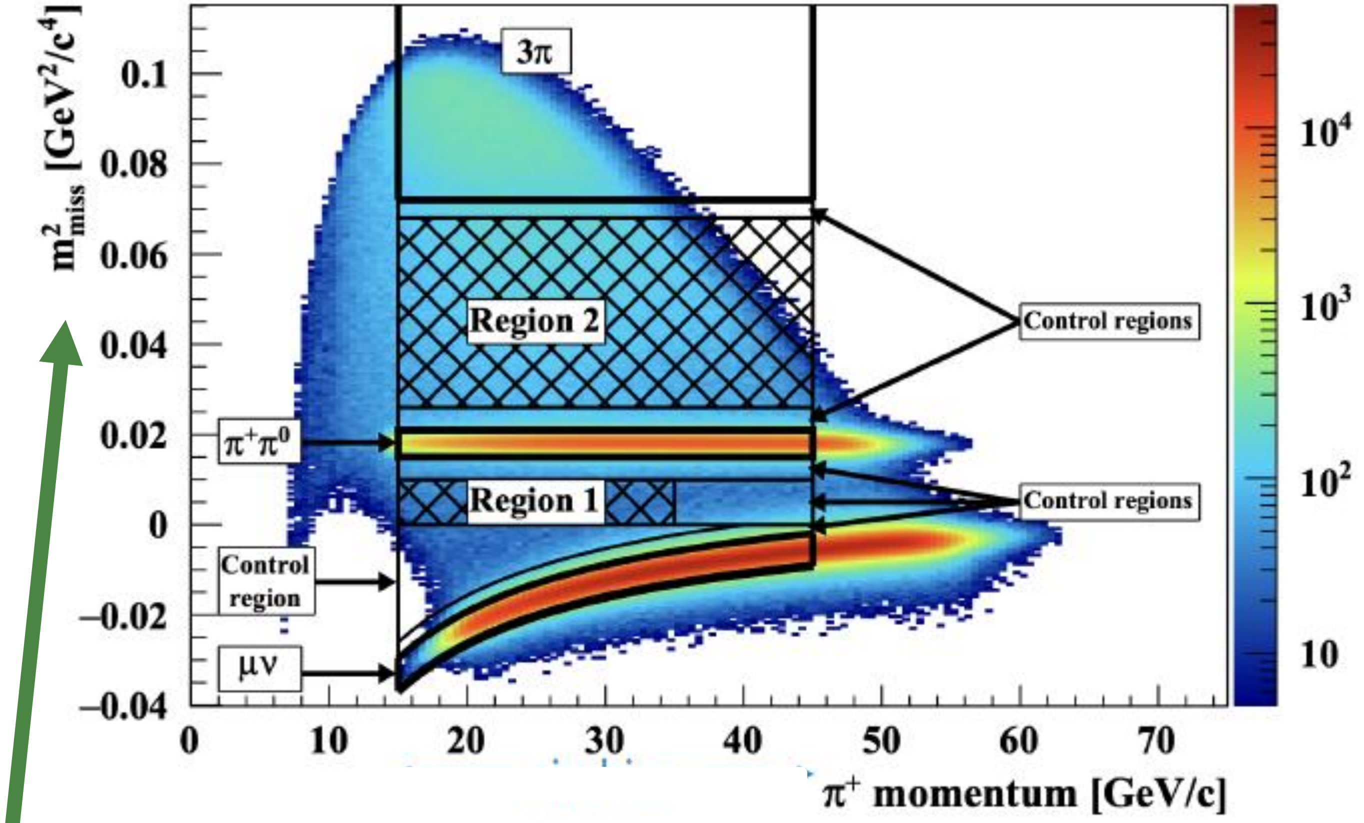
Requirements

- $\mathcal{O}(100)$ ps timing between sub-detectors

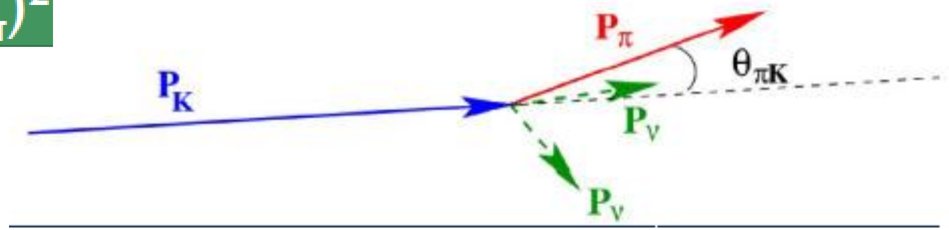
Experiment: How to search for ultra-rare K decays

Main K^+ (bkg) decay modes:

Decay mode	BR	Main rejection tools
$K^+ \to \mu^+ \nu(\gamma)$	63%	μ–ID + kinematics
$K^+ \to \pi^+ \pi^0(\gamma)$	21%	γ-veto + kinematics
$K^+ \to \pi^+ \pi^+ \pi^-$	6%	multi + kinematics
$K^+ \to \pi^+ \pi^0 \pi^0$	2%	γ-veto + kinematics
$K^+ \to \pi^0 e^+ \nu_e$	5%	e–ID + γ-veto
$K^+ \to \pi^0 \mu^+ \nu_\mu$	3%	μ–ID + γ-veto



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



Keystones

- $O(10^4)$ bkg suppression from kinematics
- $> 10^7$ muon rejection
- $> 10^7$ π^0 rejection
- $O(100$ ps$)$ timing between sub-detectors

Signal Event Sensitivity: 2023-24 improvements vs. 2021-22

Performance of new and old analyses

Expected SM signal events

External inputs

Normalization K⁺ → π⁺π⁰ events

Random veto efficiency

$$N_{\pi\nu\bar{\nu}}^{\mathrm{SM,ex}} = \frac{\mathcal{B}^{SM}_{\pi\nu\bar{\nu}}}{\mathcal{B}_{\pi\pi}} \frac{A_{\pi\nu\bar{\nu}}}{A_{\pi\pi}} D_0 N_{\pi\pi} \varepsilon_{trig} \varepsilon_{RV}$$

Trigger efficiency ratio

Selection acceptances

Normalisation trigger downscaling

	2021-2022 [JHEP 02 (2025) 191]	2023-2024 (this analysis)
N(ππ)	1.95 × 10^8	3.93 × 10^8
A(ππ)	(13.410 ± 0.005) %	(12.971 ± 0.009) %
A(πνν)	(7.62 ± 0.22) %	(7.36 ± 0.33) %
ε(trigger)	(85.9 ± 1.4) %	(86.4 ± 1.2) %
ε(RV)	(63.2 ± 0.6) %	(72.3 ± 0.7) %
N(πνν,exp)	9.9 ± 0.3	22.9 ± 1.1

Normalization statistics up by ×2

Random veto efficiency up by 14%

Expected signal counts up by ×2.3

$$S.E.S. = \frac{\mathcal{B}(\pi\nu\nu)}{N^{exp}_{\pi\nu\nu}}$$

$$S.E.S. = (0.37 \pm 0.02) \times 10^{-11} \xrightarrow{B^{SM}_{\pi\nu\bar{\nu}} = 8.4 \times 10^{-11}} N^{SM}_{\pi\nu\bar{\nu}} = 22.9 \pm 1.1$$

9.9 ± 0.3 in 2021-22

Improvements over 2021-22 data set:

- 2× the normalization statistics
- 1.14× random veto efficiency (600 → 450MHz)
- 2.3× signal statistics expected

Backgrounds Summary

Background type	**2021–22**	**2023–24**
$K^+ \to \mu^+\nu(\gamma)$	1.70 ± 0.47	1.39 ± 0.29
$K^+ \to \pi^+\pi^0(\gamma)$	0.83 ± 0.05	1.19 ± 0.10
$K^+ \to \pi^+\pi^- e^+\nu$	$0.89^{+0.34}_{-0.28}$	$1.59^{+0.51}_{-0.43}$
$K^+ \to \pi^+\pi^+\pi^-$	0.11 ± 0.03	0.25 ± 0.05
$K^+ \to \pi^+\gamma\gamma$	0.01 ± 0.01	0.04 ± 0.04
$K^+ \to \pi^0\ell^+\nu$	< 0.001	< 0.001
Upstream	$7.4^{+2.1}_{-1.8}$	$7.4^{+2.8}_{-2.2}$
Total	$\mathbf{11.1^{+2.1}_{-1.9}}$	$\mathbf{11.9^{+2.9}_{-2.3}}$
$N^{\text{expected}}_{\pi\nu\nu}$	9.9 ± 0.3	22.9 ± 1.1

- Better π^0 rejection
- Better μ^+ mis-ID
- Improved upstream background rejection

$$\sqrt{S+B}/S \approx 0.25$$

previous analyses: ~ 0.5

By far, the most sensitive dataset analyzed

Combining with previous datasets:

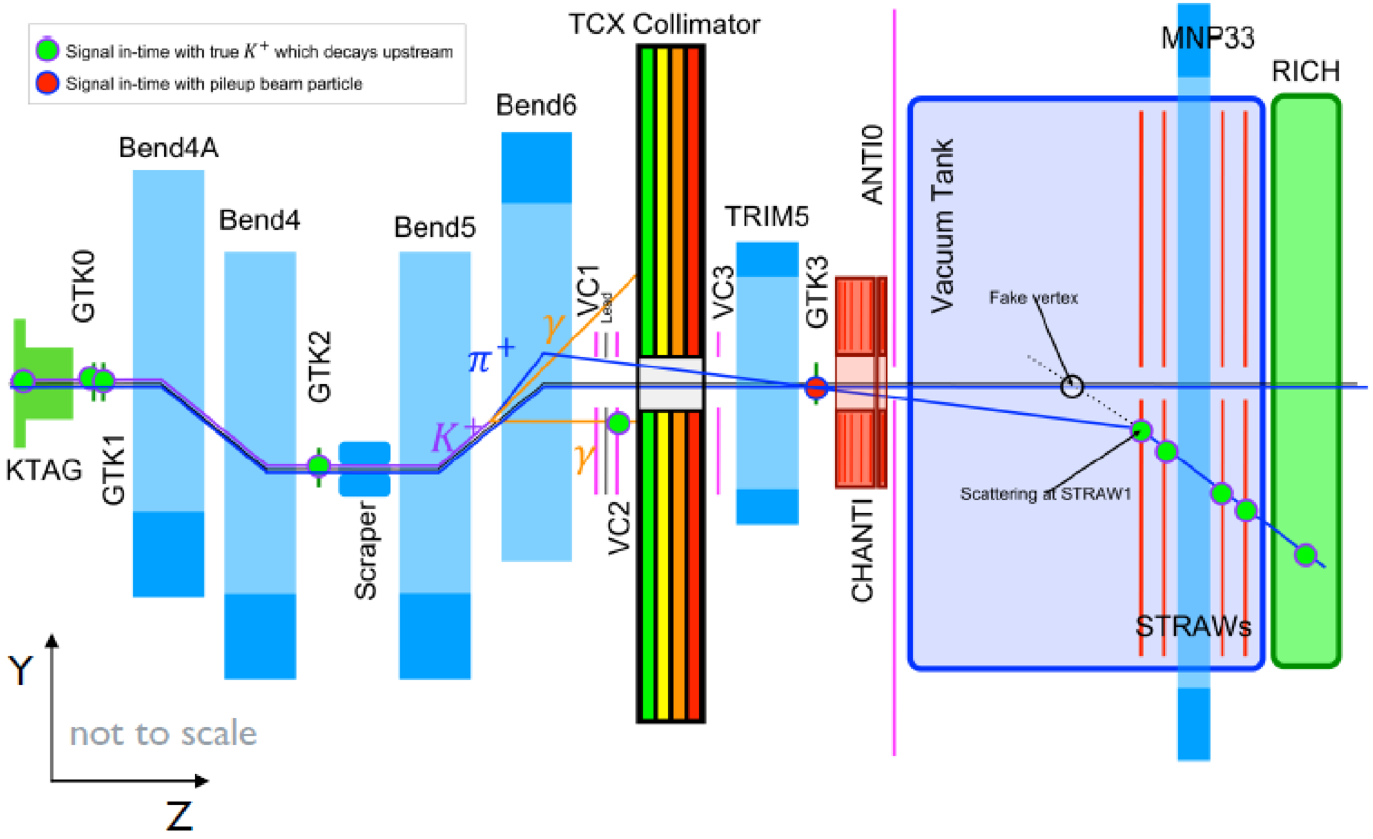
$$N_{\text{bkg}} = 30^{+4}_{-3}, \quad N^{\text{exp}}_{\pi\nu\bar{\nu}} = 43 \pm 1$$

$$\Downarrow$$

expected SM significance $> 5\sigma$

Background

UPSTREAM BACKGROUND



$N(\text{Upstream}) = 7.4^{+2.1}_{-1.8}$

Suppression

- Δt between K^+ and π^+ reconstructed tracks
- Upstream vetoes (VC, CHANTI, ANTI0)
- BDT using spatial infos of K^+, π^+

Estimation

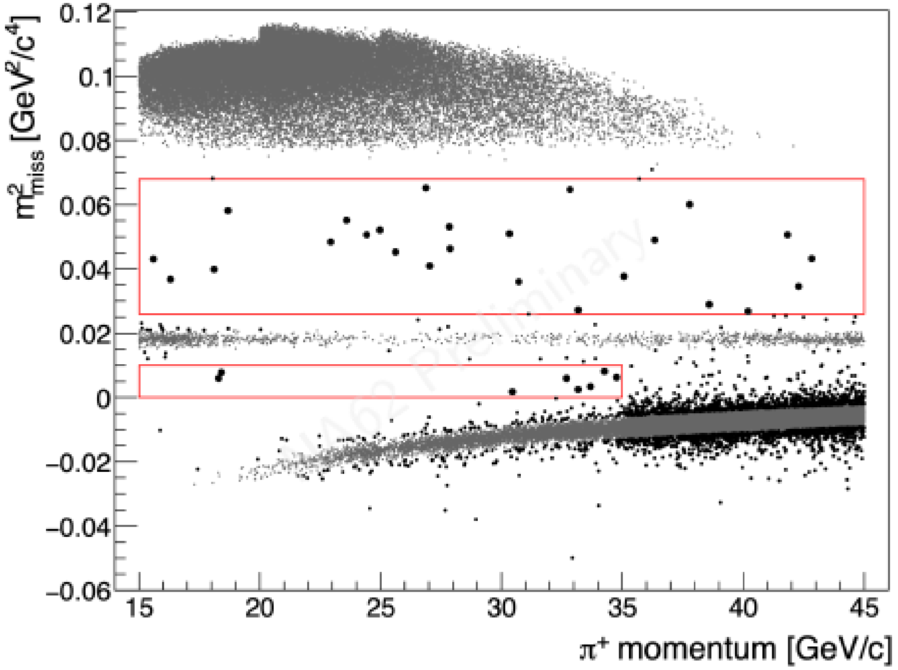
- Fully data-driven
- "Upstream Reference Sample" contains all known generation mechanisms
- Bkg-to-signal probability from data

Validation

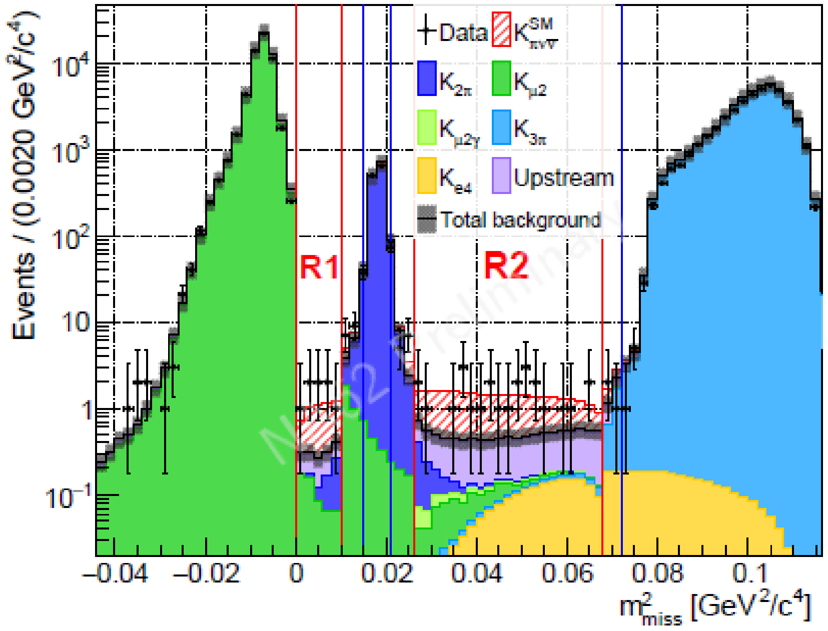
- 10 independent samples enriched with different mechanisms

2023-24 Signal Regions - Opening the Box

Distribution of observed events



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

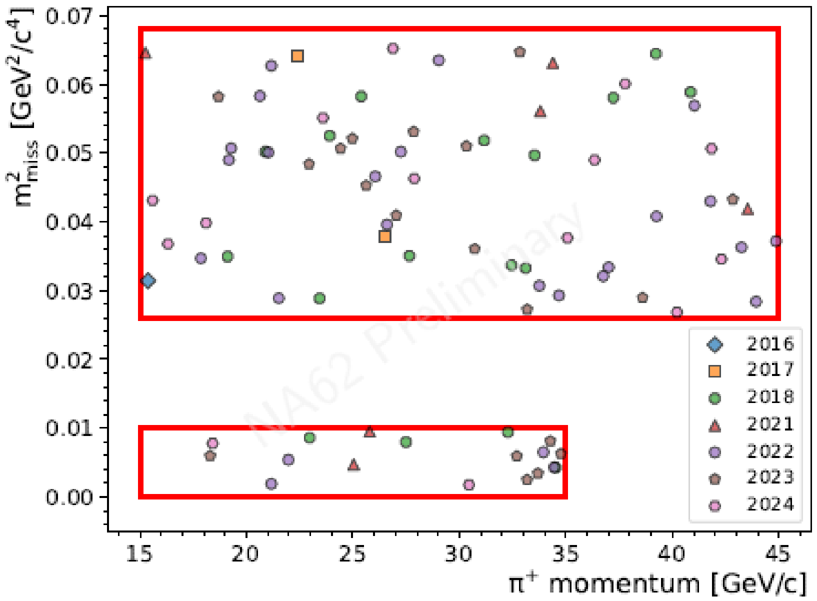


$N^{exp}_{bg} = 11.9^{+2.9}_{-2.3}$ · $N^{SM}_{\pi\nu\bar{\nu}} = 22.9 \pm 1.1$ · $N_{obs} = 33$

$$\mathcal{B}^{NA62}_{23-24}\left(K^+ \to \pi^+\nu\bar{\nu}\right) = \left(7.2^{+2.2}_{-1.9}\,|_{stat}\,{}^{+0.9}_{-0.9}\,|_{syst}\right) \times 10^{-11} = \left(7.2^{+2.3}_{-2.1}\right) \times 10^{-11}$$

2016 - 2024 Dataset

Distribution of observed events



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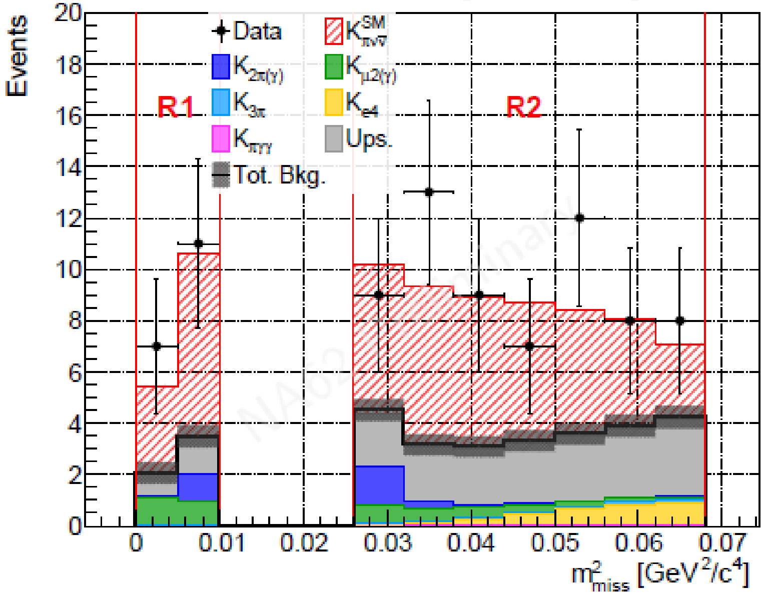


$N_{\text{bg}}^{\text{exp}} = 30^{+4}_{-3}$ · $N_{\pi\nu\bar{\nu}}^{\text{SM}} = 43 \pm 1$ · $N_{\text{obs}} = 84$

$$\mathcal{B}^{NA62}_{16-24}\left(K^+ \to \pi^+\nu\bar{\nu}\right) = \left(9.6^{+1.8}_{-1.6}\big|_{\text{stat}}\,{}^{+0.8}_{-0.6}\big|_{\text{syst}}\right) \times 10^{-11} = \left(9.6^{+1.9}_{-1.8}\right) \times 10^{-11}$$

Conclusions

The main goal of the NA62 Experiment remains the $K^+ \to \pi^+ \nu\bar{\nu}$ measurement, with the potential to provide a hint of BSM Physics

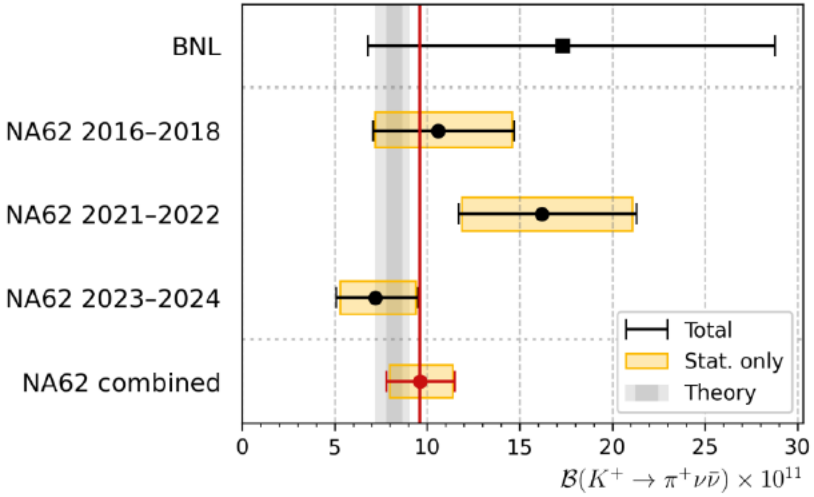
Expected SM signal more than doubled compared to the 2021-2022

Background got lower with respect to the previous analysis, leading to a significant sensitivity boost

Expected SM significance > 5σ

BR($K^+ \to \pi^+ \nu\bar{\nu}$) measured with < 20% precision

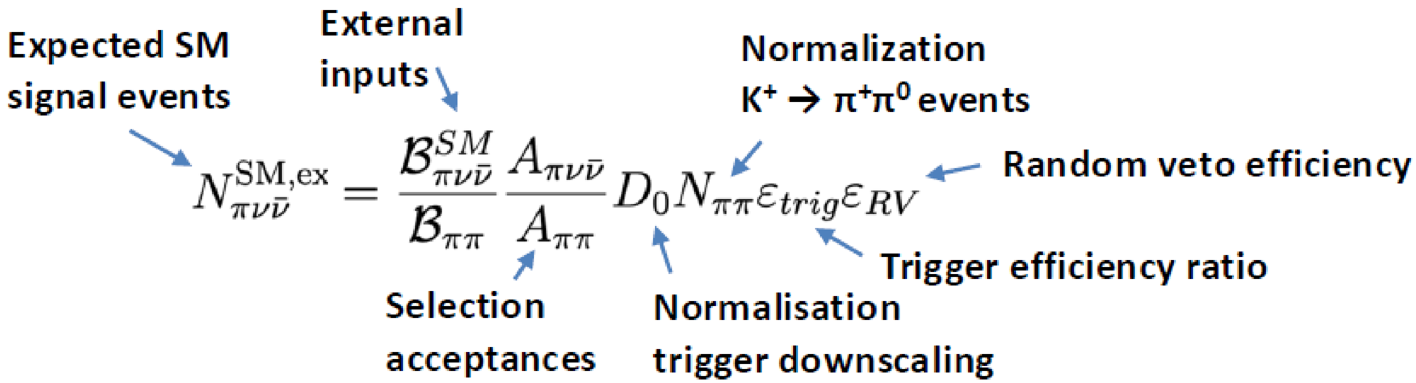
The result is compatible with the SM prediction



2025-2026 datasets are under way
The current NA62 Run will last by Summer 2026

Spares

Performance of new and old analyses



$$N_{\pi\nu\bar{\nu}}^{\mathrm{SM,ex}} = \frac{\mathcal{B}_{\pi\nu\bar{\nu}}^{SM}}{\mathcal{B}_{\pi\pi}} \frac{A_{\pi\nu\bar{\nu}}}{A_{\pi\pi}} D_0 N_{\pi\pi} \varepsilon_{trig} \varepsilon_{RV}$$

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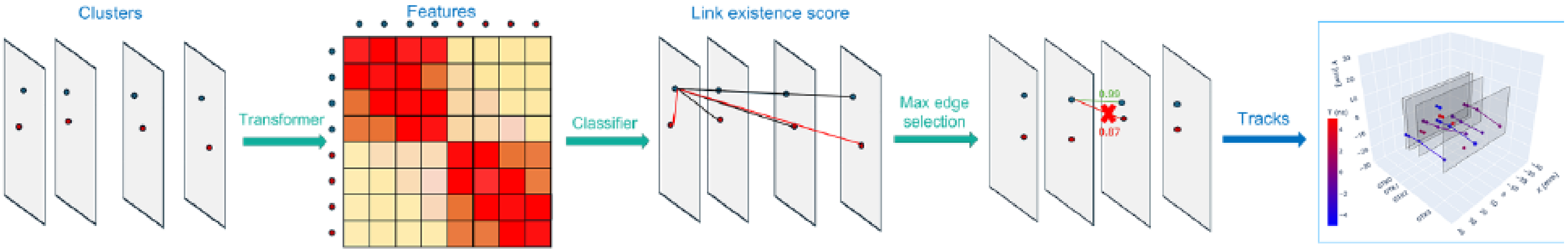
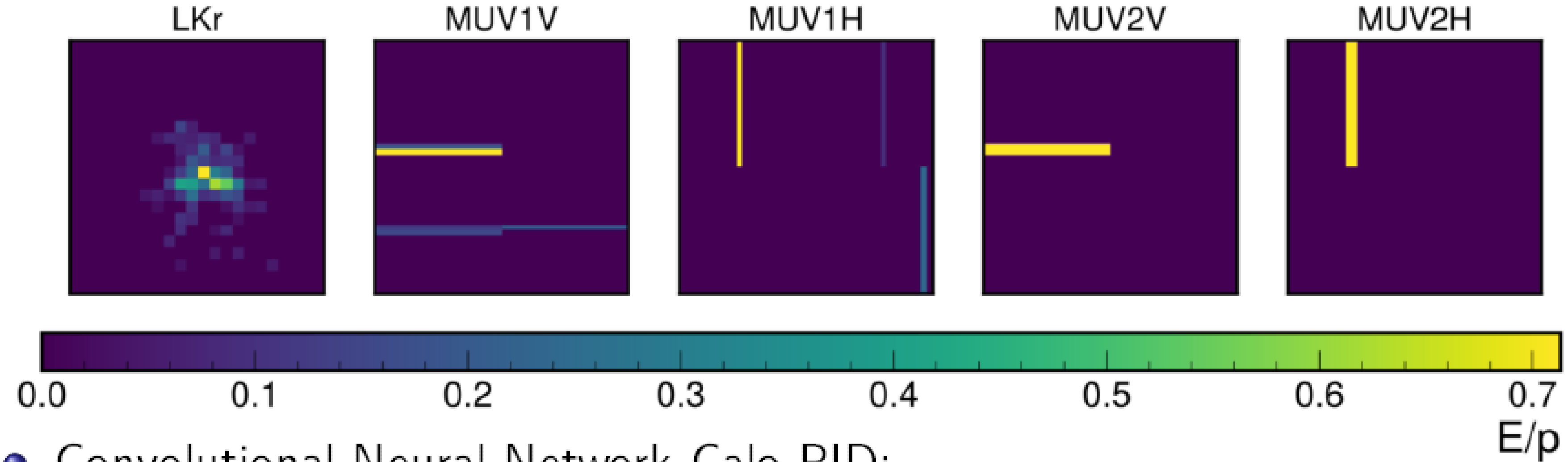
Main Improvements in the Analysis



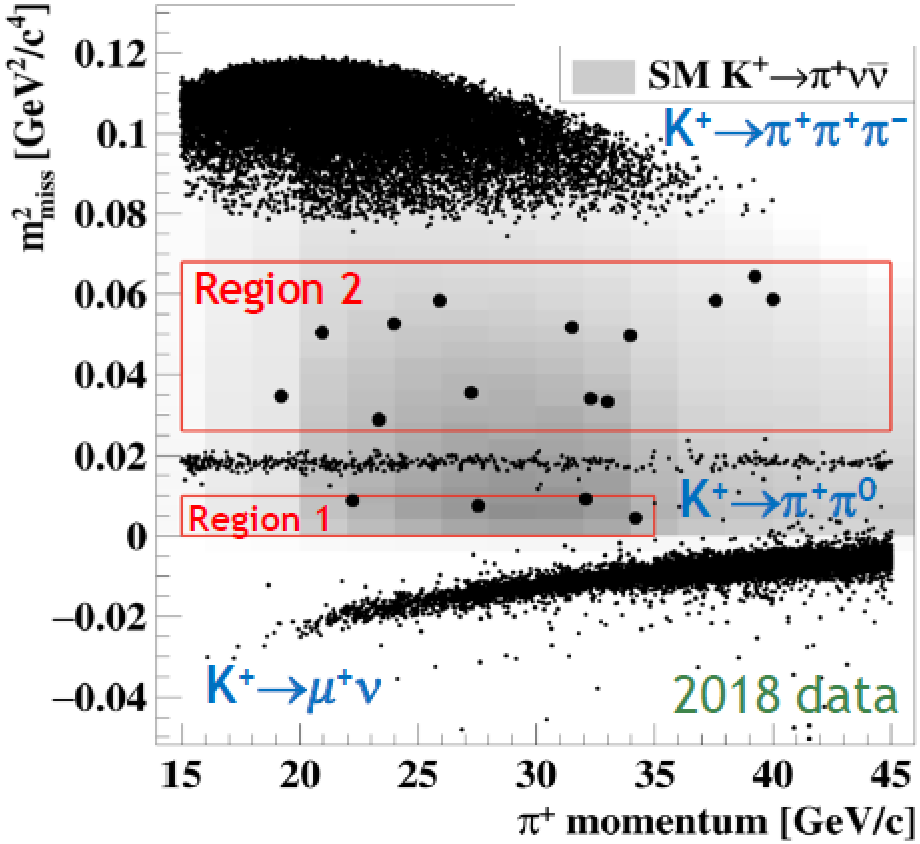
Transformer GTK reco: $K-\pi$ mis–match prob. (K not reconstructed): 6% → 4%.



- Convolutional Neural Network Calo PID:
  - ResNet model architecture with 2.8 M trained parameters
  - $\sim 16\%$ less $K^+ \to \mu^+\nu_\mu$ background.
  - $\sim 70\%$ less $K^+ \to \mu^+\nu_\mu\gamma$ background with μ^+ and γ overlap in LKr.

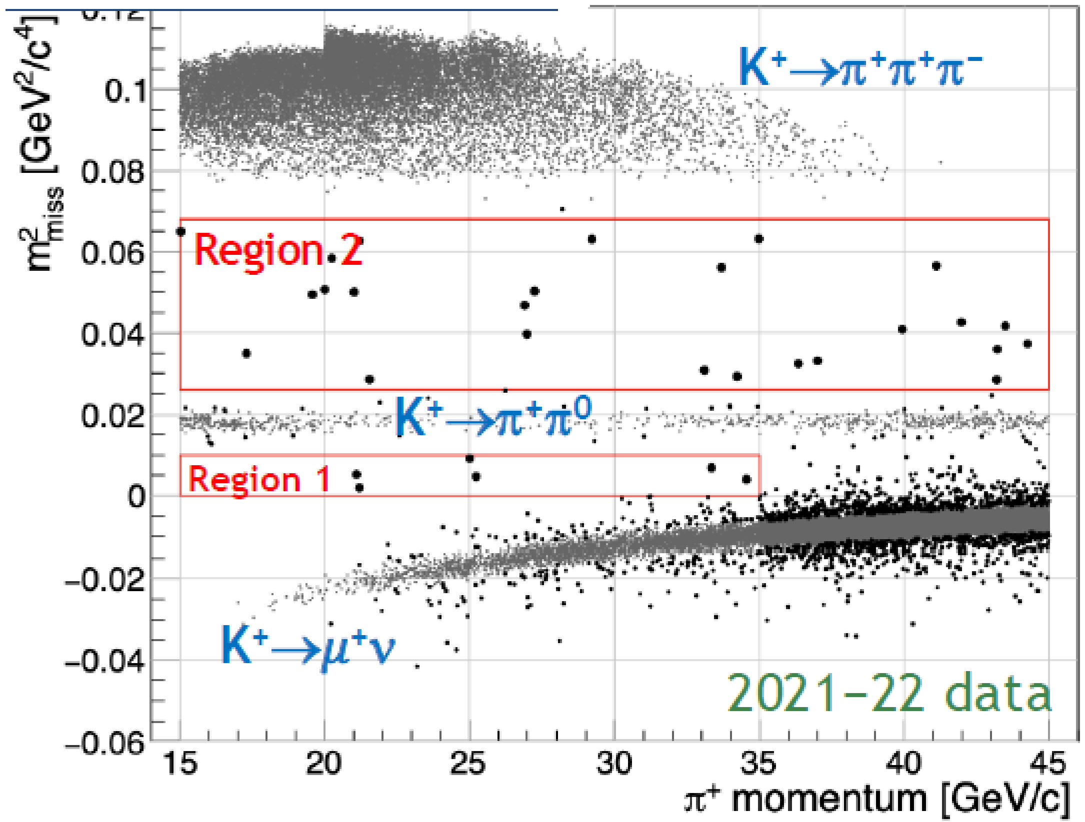
$K^+ \to \pi^+ \nu \bar{\nu}$ Results (2016 – 2022 data)

2016 – 2018 data



20 events in the Signal Regions

2021 – 2022 data



31 events in the Signal Regions

33 events in the two Signal Regions, the 2023-2024 data

$K^+ \to \pi^+ \nu \bar{\nu}$ Results (2016 – 2022 data)

51 signal candidates, expected background: $\mathbf{18^{+3}_{-2}}$

$$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = \left(13.0^{+3.0}_{-2.7}\Big|_{\mathrm{stat}} {}^{+1.3}_{-1.3}\Big|_{\mathrm{syst}} \right) \times 10^{-11} = \left(13.0^{+3.3}_{-3.0} \right) \times 10^{-11}$$

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The rarest particle decay observed ever at 5σ significance

Consistent with the SM expectation at 1.7σ