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

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on behalf of the NA62 Collaboration

Kaons at the forefront of new physics

Identification/prediction of new effects using kaons strongly influenced SM building:

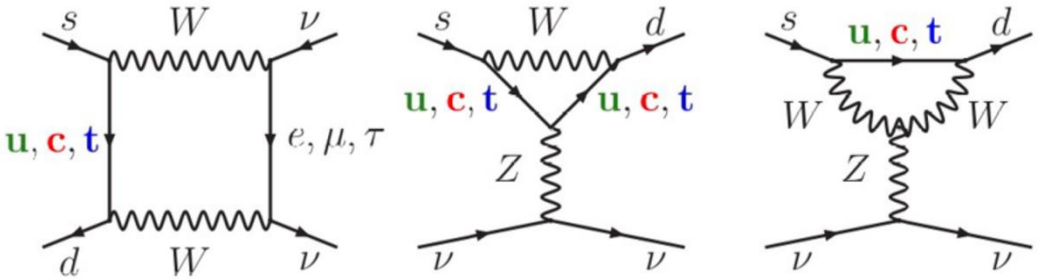
- **Parity violation predictions involving kaons: Lee, Yang PR 104 (1956) 254**
- **Theory of flavour: Cabibbo PRL 10 (1963) 531**
- **No FCNC at tree level, c-quark prediction: Glashow, Iliopoulos, Maiani PRD 2 (1970) 1285**
- **Indirect CP violation: Fitch, Cronin PRL 13 (1964) 138**
- **Theory of flavour mixing: Kobayashi, Maskawa Prog. Theor. Phys. 49 (1973) 652**
- **Direct CP violation, first evidence by NA31: PLB 206 (1988) 169**
- **CPV confirmed: KTeV PRL 83 (1999) 22, NA48 PLB 465 (1999) 335 and ($K^+ \rightarrow 3\pi$) NA48/2 EPJC 52 (2007) 875**

Kaons can continue to answer to standing questions, e.g.: hierarchies, BAU, DM, etc.

How:

- **relating new-physics at TeV or above to low-energy flavour-changing processes**
- **searching for new-physics light degrees of freedom**

The K→πνν transition in the SM



Checks all the requirements to be highly sensitive to new-physics effects:

- ✓ **Semileptonic process dominated by quark vector-current FCNC operators**
- ✓ **FCNC process hard-GIM suppressed:** A ~ $m_q^2/m_W^2\ V_{qs}^*\ V_{qd}$ with q = *u*, *c*, *t*
- ✓ **Dominantly short distance**: no contribution from *u*-quark line, nor from intermediate γ's
- ✓ **Precision SM estimate:** hadronic matrix element related to precisely measure processes

Leading-contribution effective Hamiltonian ($\lambda_i = V_{is}^*\ V_{id}$):

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

SM prediction for $K^+ \to \pi^+ \nu\nu$: error budget

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

$A^2 \bar{\eta}$ -1 $A^2 (\bar{\rho} - 1)$

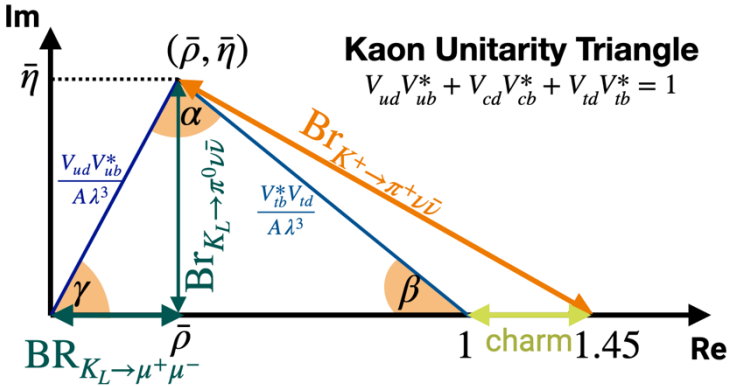
SM estimate with a 6% relative uncertainty:

- **±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]

K→πνν as a precision flavour test

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

$A^2\,\bar{\eta}$ $\quad -1 \quad$ $A^2\,(\bar{\rho} - 1)$



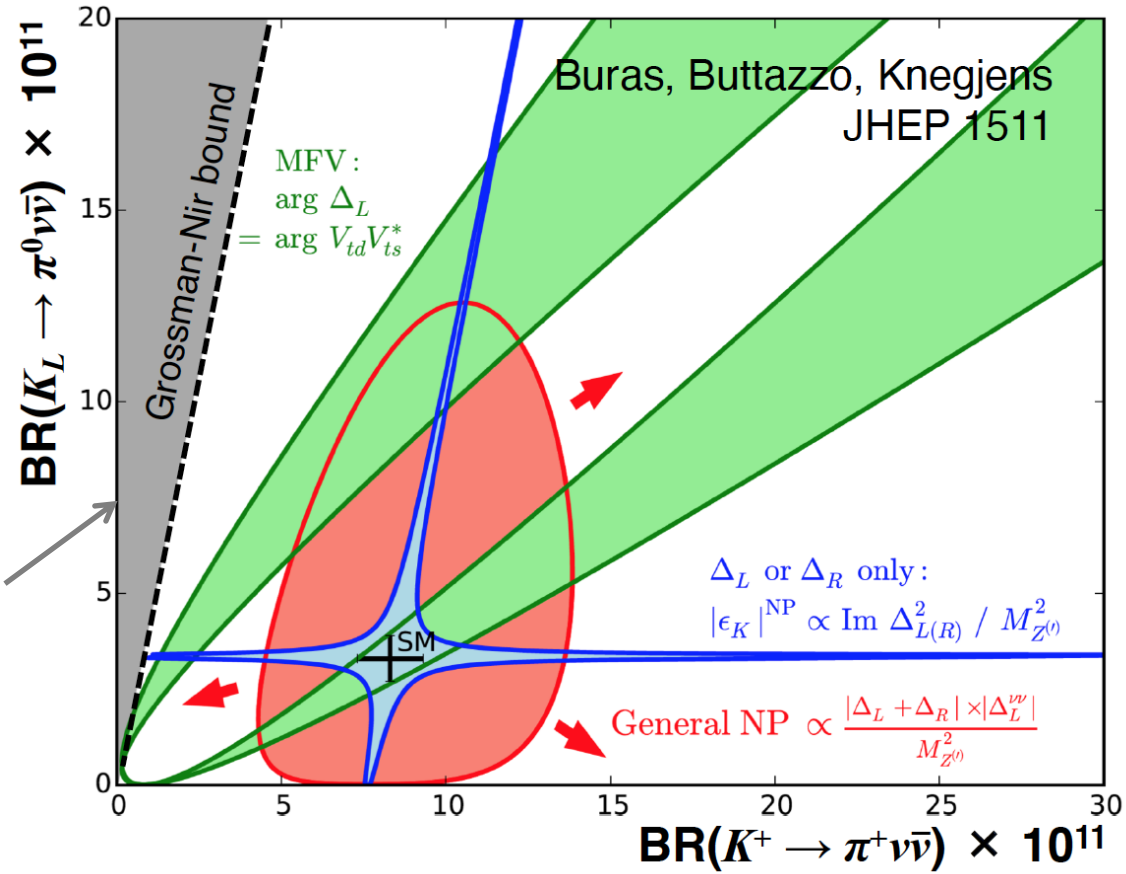
Interplay with $K_L \to \pi^0\nu\nu$ under study at the KOTO experiment

	BR($K^+ \to \pi^+\nu\nu$) × 10^{11}	BR($K_L \to \pi^0\nu\nu$) × 10^{11}
Input from CKM fit [JHEP 09 (2022) 148]	7.86 ± 0.61	2.68 ± 0.30
Lattice input to solve inclusive vs exclusive Vcb [EPJ C 82 (2022) 615]	8.60 ± 0.42	2.94 ± 0.15
Experiment	$13.0^{+3.3}_{-3.0}$ NA62 2016—22 [JHEP 02 (2025) 191]	< 220 @ 90% CL KOTO 2021 [PRL 134 (2025) 081802]

K→πνν sensitivity to NP effects

$$\frac{\Gamma(K_L \to \pi\nu\nu)}{\Gamma(K^+ \to \pi\nu\nu)} < 1$$

[PLB 398, 163 (1997)]



Models with CKM-like flavor structure

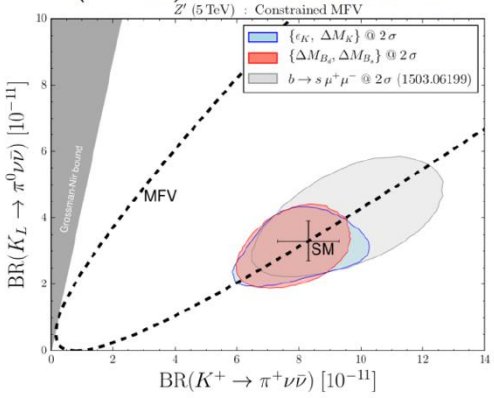
Models with new LH/RH dominating flavour structure

K→πνν: reduced list of NP models

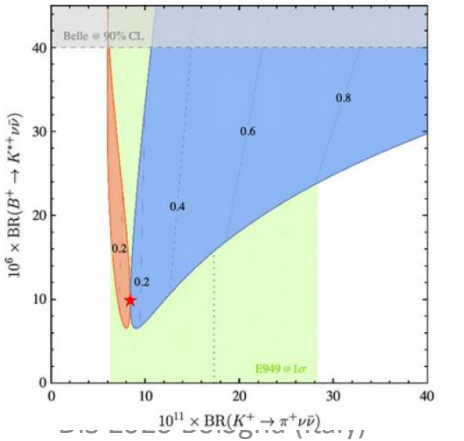
NP effects expected to correlate with other flavour observables in a number of scenarios

- 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]

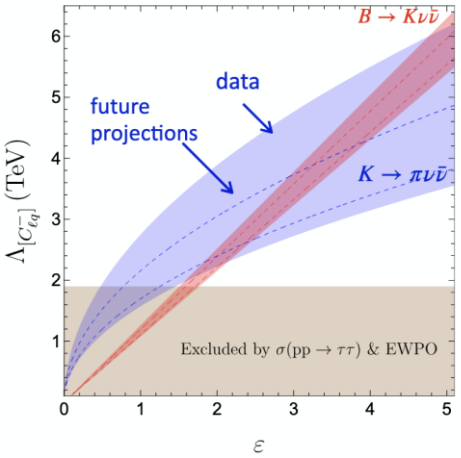
Z'(5 TeV) in Constrained MFV



LFU violation



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



The effort to reach the needed sensitivity

2005 EoI of P-326

2008 Experiment approved as NA62

2011 MoU ratified by funding agencies

2015 Detector built and operational, first test run

2016 — 2018 Run I: First evidence for $K^+ \rightarrow \pi^+\nu\nu$ [JHEP 06 (2021) 093]

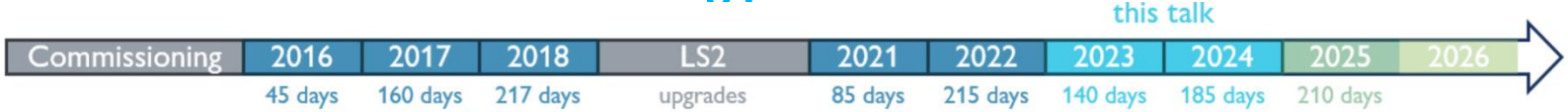
2019 — 2020 Detector upgrade

Additional veto detectors installed

2021 — 2026 Second physics run

2016—2022 Observation of $K^+ \rightarrow \pi^+\nu\nu$ & BR measurement [JHEP 02 (2025) 191]

2023—2024 The new result being presented

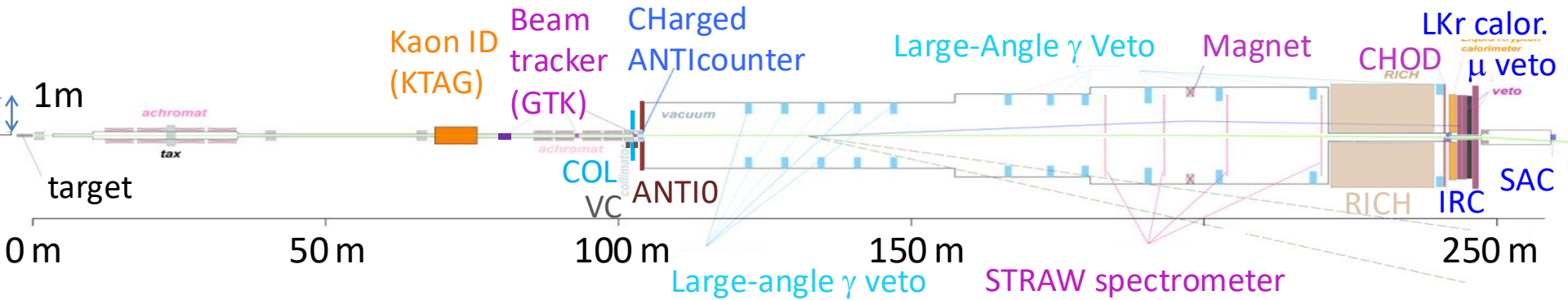


NA62: a high-intensity setup

High-intensity proton-produced charged hadron beam:

3 × 10^{12} 400-GeV protons in 4.8 s SPS spills onto a Be target

Secondary 75-GeV beam selected: 1% momentum bite, X,Y divergence < 100 μrad @ KTAG



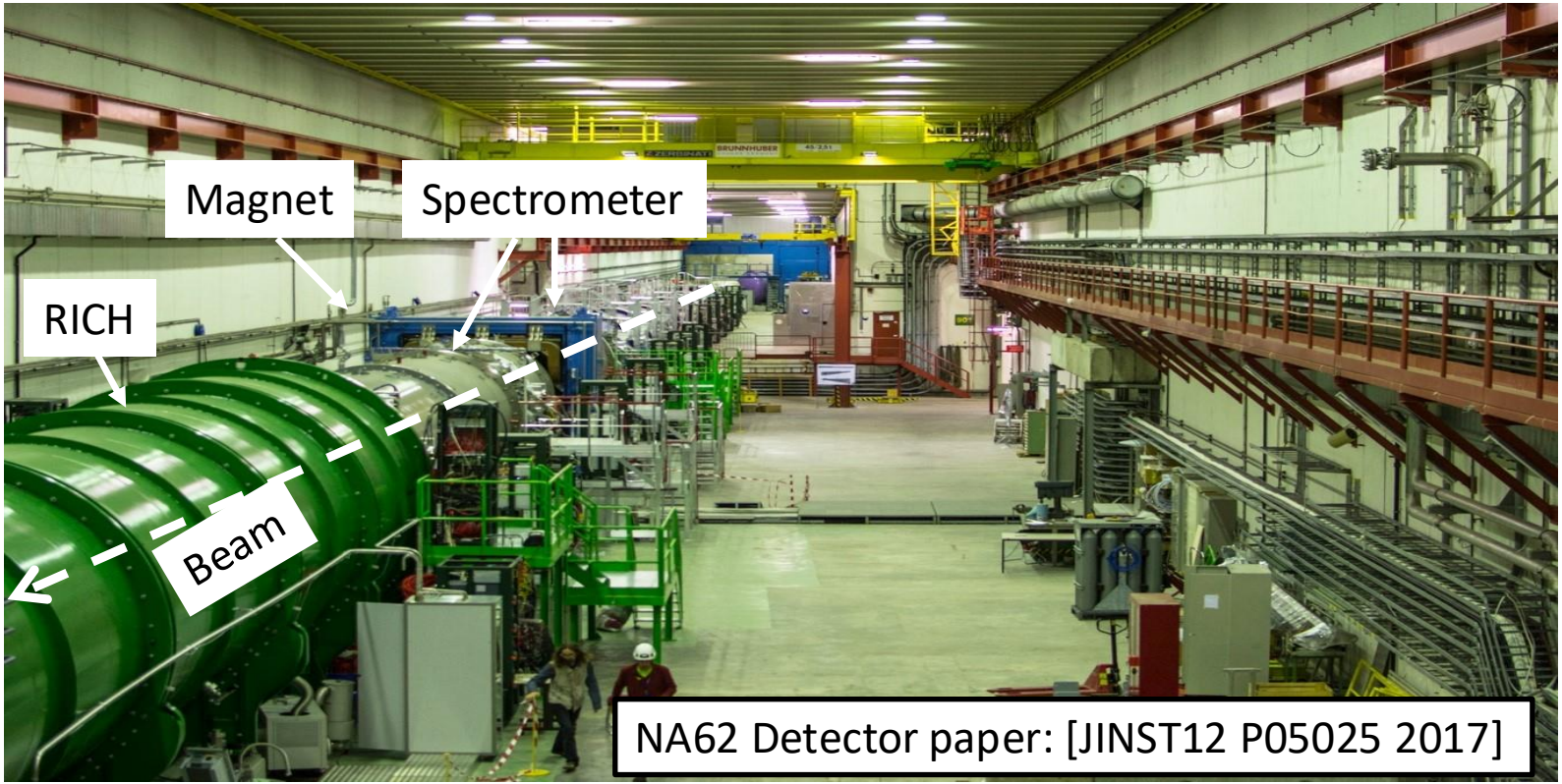
Can **track 600 MHz beam** (6% K^+) and sustain ~5 MHz K^+ decay in a **60-m long volume in vacuum**

Kinematics, rejection of main K modes 10^4—10^5 via kinematic reconstruction

PID capability, μ vs π rejection of O(10^7) for 15 < p(π^+) < 45 GeV

High-efficiency veto of additional photons, O(10^8) rejection of π^0's for E(π^0) > 40 GeV

NA62: a high-intensity setup



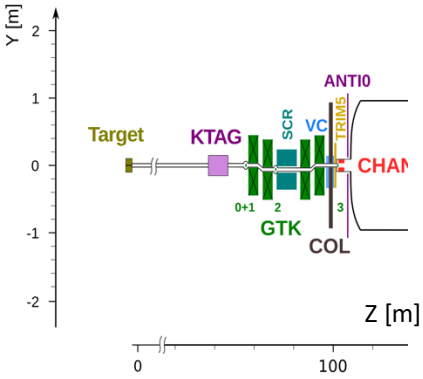
NA62 pillars: beam particle-ID, KTAG

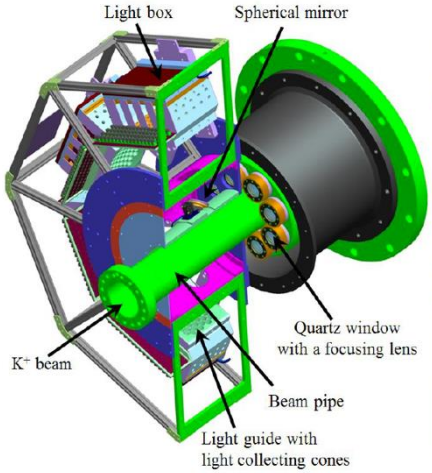
Differential Cerenkov, ID with signals in time coincidence in > 4 sectors

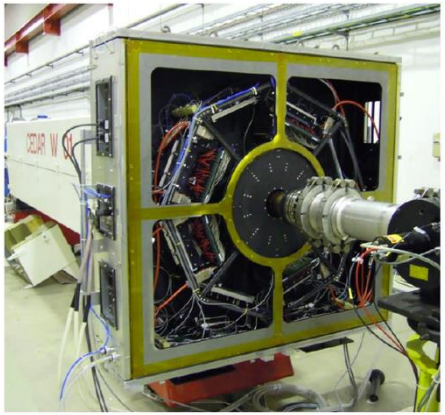
Measure beam time with σ_t = **70 ps**

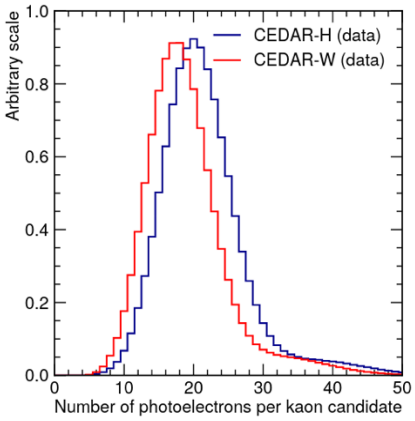
Reject pions/protons to < 10^{-4}

- 2016 – 2022: N2 @ 1.71 bar, 3.9% X_0, ε_K > 99.5% [NIM A 824 (2016) 96]
- **2023 – 2026**: H2 @ 3.85 bar, 0.7% X_0, ε_K > 99.7% [JINST 19 (2024) 05, C05026]









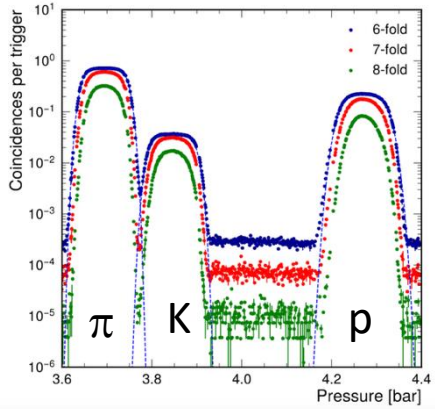
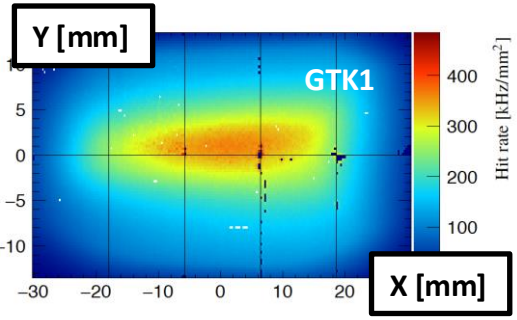


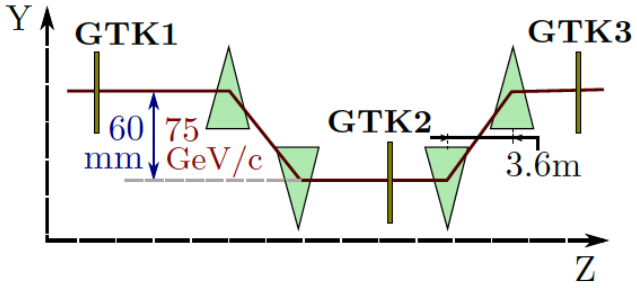
Figure 8. Left: drawing of the upstream part of the CEDAR and the KTAG. Right: KTAG and CEDAR in the NA62 beam line during a test run in 2012, with four of the eight sectors equipped.

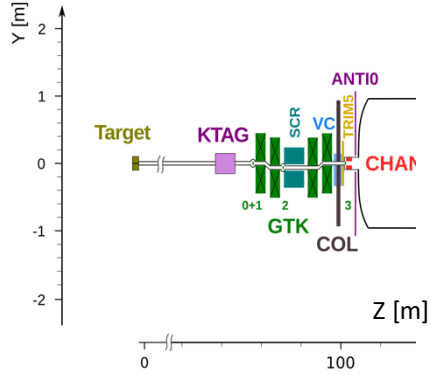
(Italy)

NA62 pillars: beam tracking, GTK

3 stations* of Si detectors in a magnetic achromat: σ_t = **100 ps**, σ_p = 0.15 GeV/*c*, σ_θ = 16 μrad



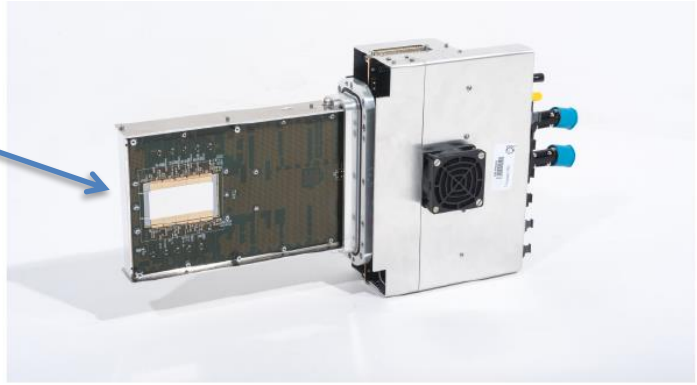




σ_Y @ GTK2 ~ 600 μm / (Δp/p [%])

62×27 mm² sensor area:
200×90 pixels, each
300×300 μm² in size

[NIM A 958 (2020) 162127]



Thickness in active area 510 μm:

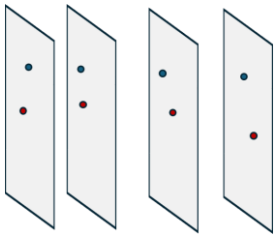
- sensor: 200 μm
- RO chip: 100 μm
- Cooling plate: 210 μm

***For redundancy, added GTK0 in 2021**

NA62 pillars: new ML-based beam tracking

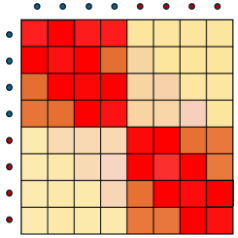
New tool for analysis of 2023-24 data

GTK hit Clusters



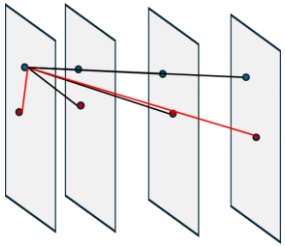
Transformer

Features

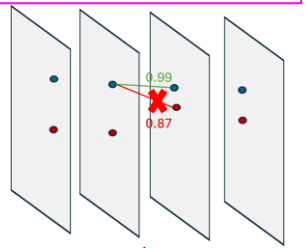


Classifier

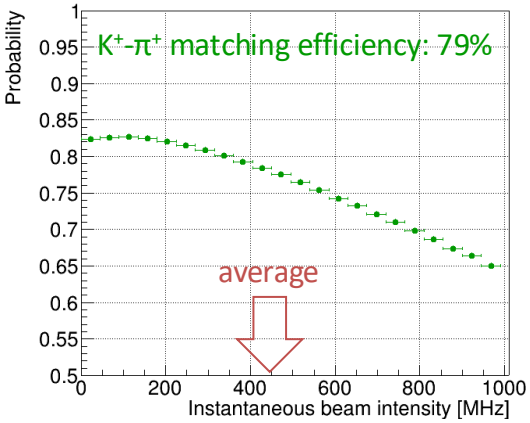
Link existence score



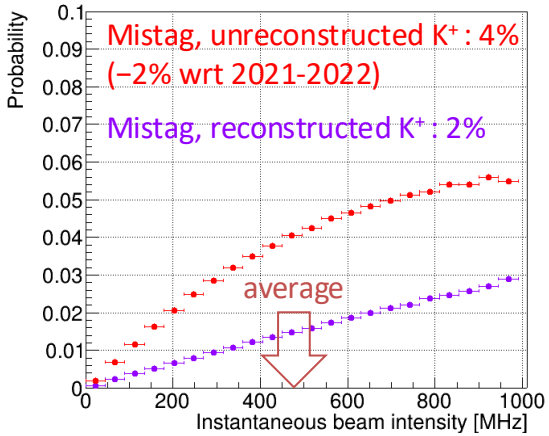
Max edge selection



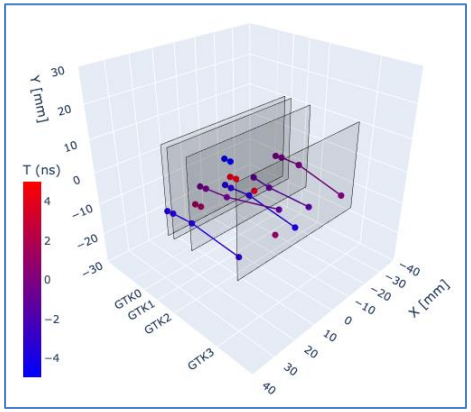
NA62 preliminary, $K^+ \to \pi^+\pi^+\pi^-$ data sample



NA62 preliminary



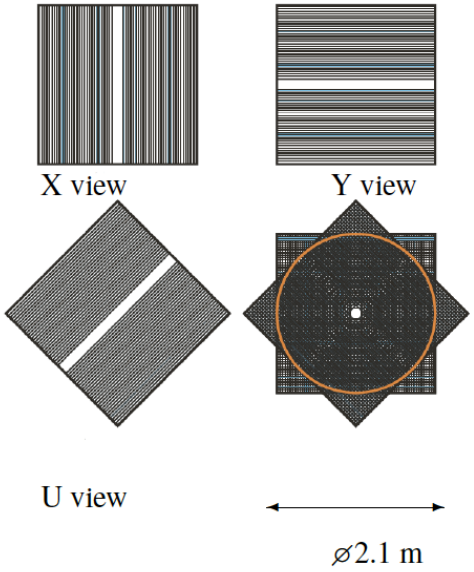
4D tracks



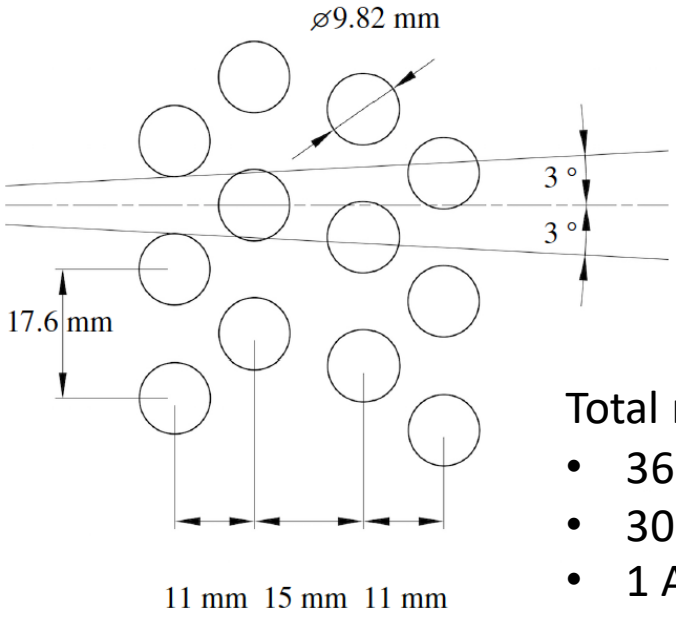
NA62 pillars: downstream tracking, STRAW

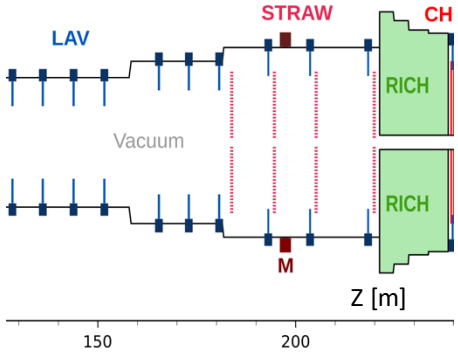
Track in vacuum: 2+2 stations of straw tubes, 270 MeV magnet Δp_t: σ_p/p = 0.3—0.4%, σ_t ~ 5 ns

4 views / chamber



2 double layers / view





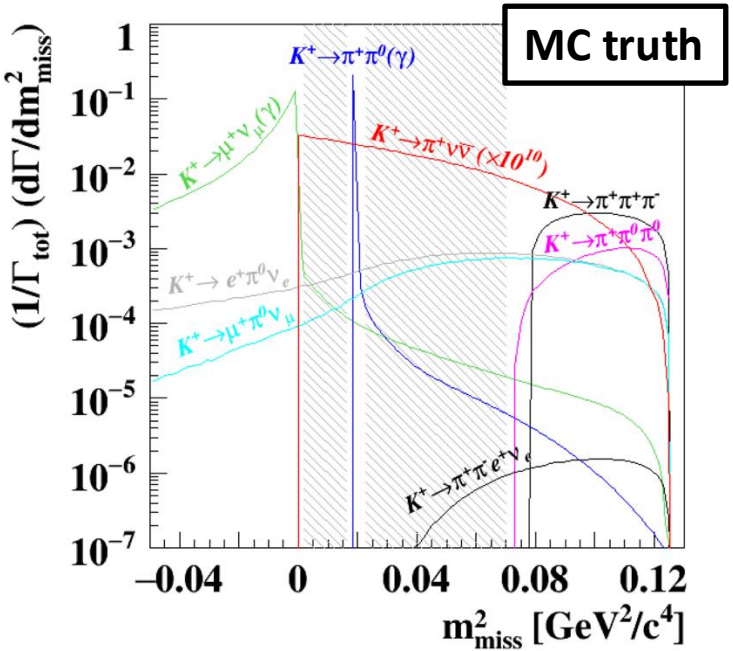
typical K^+ daughter tracks

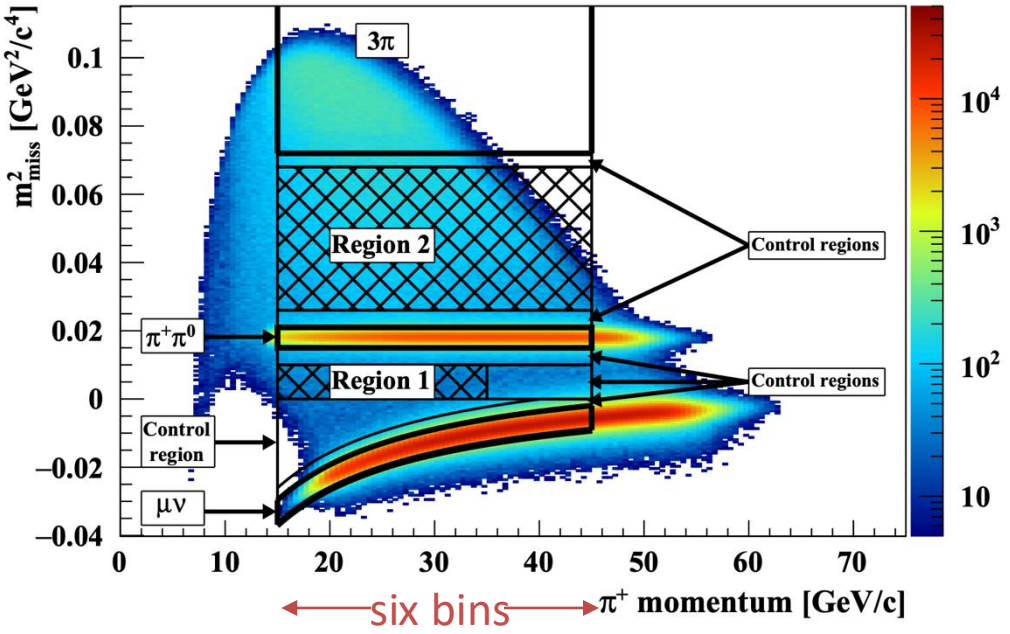
Total material ~1.8% X_0:

- 36 μm PET
- 30 μm W anode wire
- 1 Atm Ar:CO_2 70:30

Matching K^+ and π^+ tracks: kinematics

Space-time match K^+ and daughter tracks in $105 < Z_{vtx} < 165$ m, access $m_{miss}^2 = (p_K - p_\pi)^2$

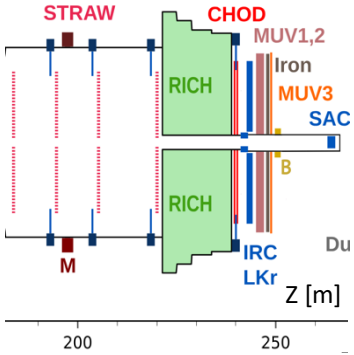


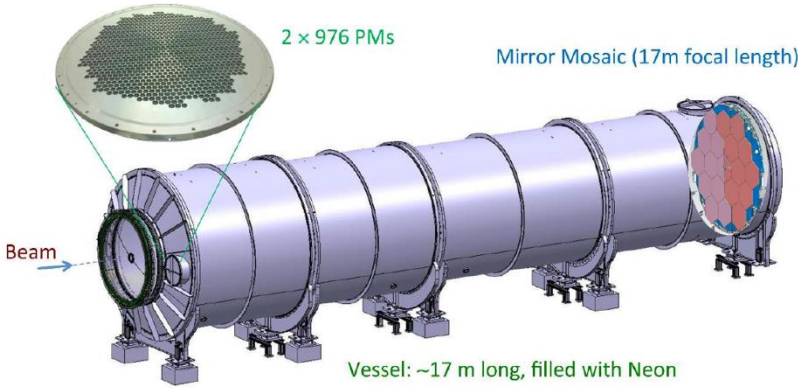


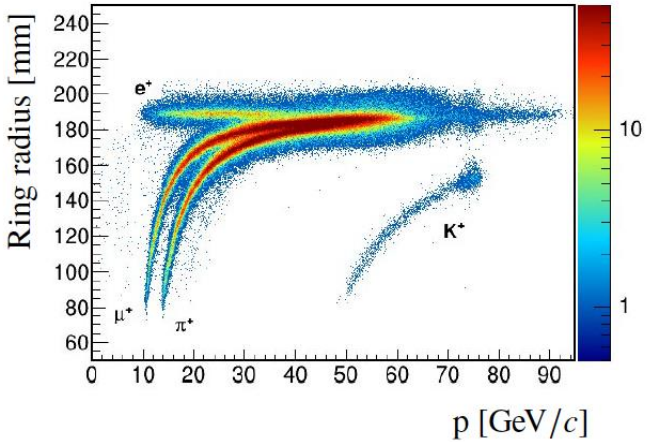
Retaining R1—R2 achieves a rejection factor of ~ 10^4 for K^+ decay backgrounds

NA62 pillars: downstream PID, RICH

Downstream particle identification: 17 m long RICH, 1 bar Ne, n-1 ~ 6.7×10^{-5}, $\sigma_t < 100$ ps







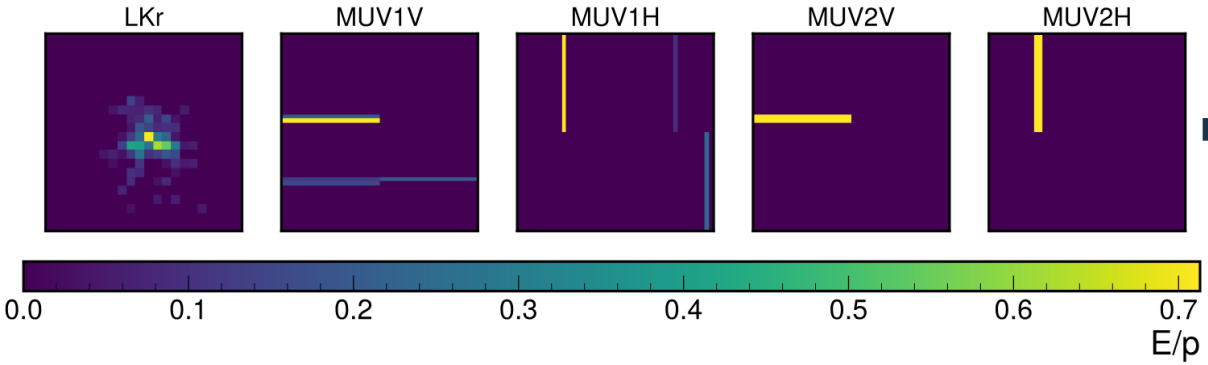
Identify π^+ mesons with > 85% efficiency, mis-ID for μ^+ to $\pi^+ < 10^{-2}$ for $15 < p_\pi < 35$ GeV/*c*

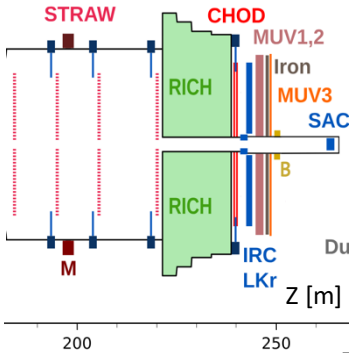
NA62 pillars: new ML calorimetric PID

Further π^+ ID from calorimeters and muon veto after Fe absorber

Downstream PID based on a Convolutional Neural Network

- Inputs: Calo E/p images in time slices (19k numbers)
- Model: ResNet architecture (2.8M parameters)





$N(K^+ \to \mu^+\nu)$ reduced by 16%

$N(K^+ \to \mu^+\nu\gamma)$ reduced by 70%

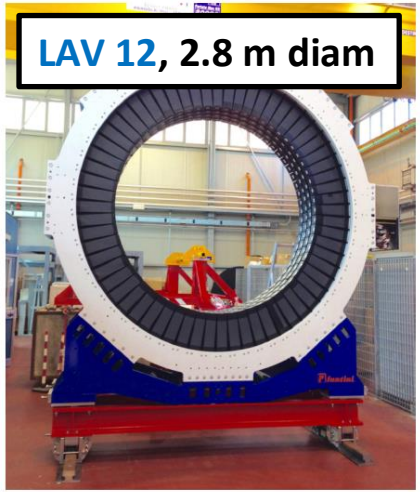
New tool for analysis of 2023-24 data

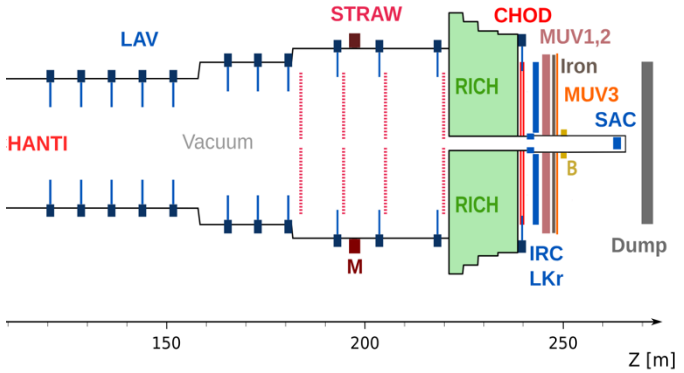
Identify π^+ mesons with > 80% efficiency, mis-ID for μ^+ to $\pi^+ < 10^{-5}$ for $15 < p_\pi < 45$ GeV/*c*

NA62 pillars: hermetic particle veto

Hermetic veto system to achieve O(10^8) rejection of π^0 mesons:

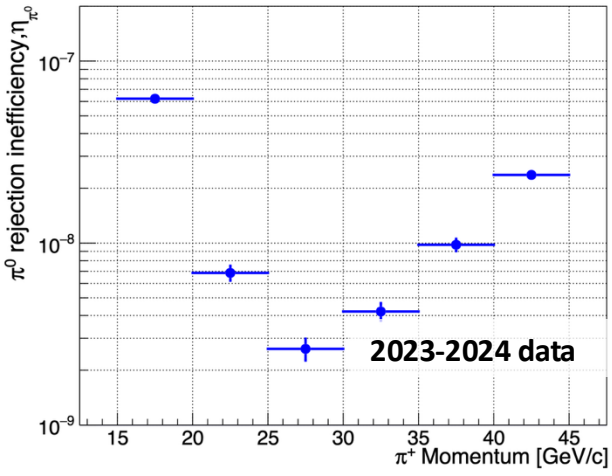
- **LKr calorimeter**: σ_t ~ 0.5--1 ns, inefficiency < 10^{-5} for γ's E > 10 GeV, 1 < θ < 8.5 mrad (from NA48)
- **12 LAVs**: 2496 refurbished OPAL PbGl blocks, σ_t ~ 1 ns, 1-ε ~ 10^{-4} for Eγ > 200 MeV, 8 < θ[mrad] < 50
- **IRC-SAC**: 2 scintillator-Pb shashlik calorimeters, 1-ε < $10^{-3\text{--}4}$ for γ's with 0 < θ < 2 mrad
- **HASC**: low-angle shashlik calorimeters at extremely low angles further downstream around beam pipe

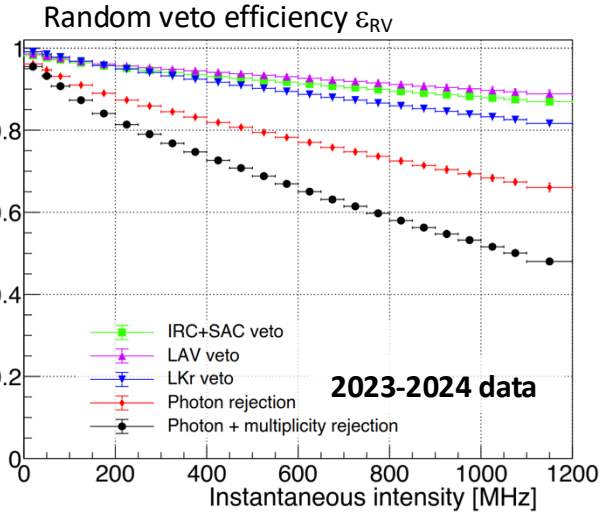


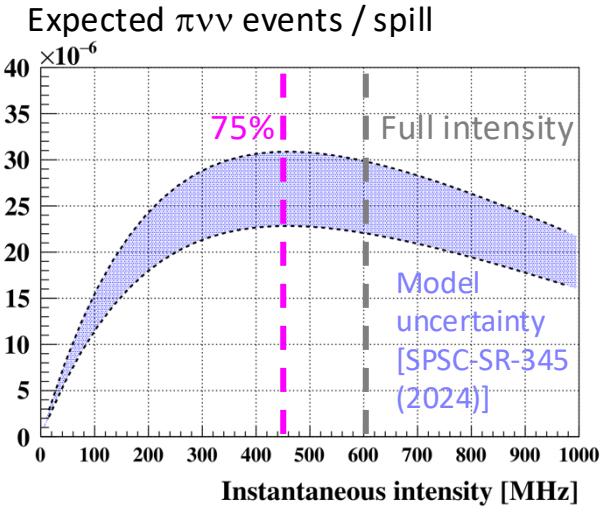


Photon veto and implications

Rejection inefficiency on π^0's from K->$\pi\pi^0$: 1.24(4)×10^{-8}, improved in 2023-2024 by >20%







Probability 1-ε_{RV} of signal event to be veto by accidental activity increases with instantaneous intensity

Intensity-tuned data taking after 2023 study: average lowered from 600 to 450 MHz

- **The efficiency for K^+-to-π^+ matching increases as well and the mis-match decreases**
- **TDAQ and data-quality efficiencies increase as well**

$K^+ \rightarrow \pi^+\nu\nu$ analysis scheme

Analysis pillars

Normalize background-subtracted $\pi\nu\nu$ to $\pi\pi^0$
Counting analysis, data-driven background expectation
Blind analysis, validated in data control regions

Trigger

"1 Track" + Emiss

L0: RICH, CHOD positive, MUV3 and LKr veto
L1: In-time K^+ in KTAG, $p_{track}^{STRAW} < 65$ GeV, q=+1 (isolated), veto LAV activity

"1 Track" downscaled

L0: RICH, CHOD positive, MUV3 veto
L1: In-time K^+ in KTAG, $p_{track}^{STRAW} < 65$ GeV, q=+1

Offline

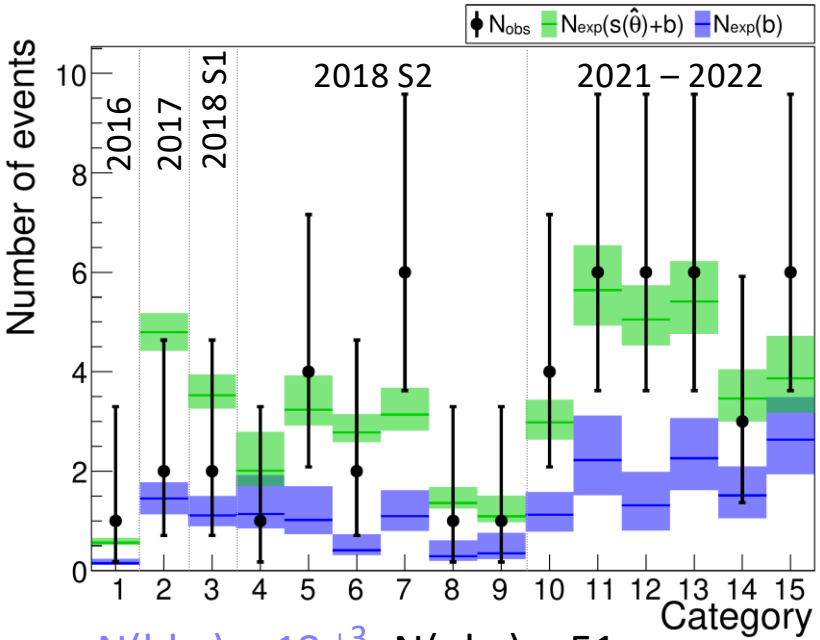
1. Vertex reconstruction
2. Kinematics ($\pi\nu\nu$ regions 1, 2)
3. Enforce π PID (RICH & LKr-MUVs)
4. Reject in-time signals upstream and downstream: γ veto, multiplicity CHOD, etc.

1. Vertex reconstruction
2. Kinematics ($\pi\pi^0$ region)
3. Enforce π PID (RICH & LKr-MUVs)
4. Reject in-time signals upstream

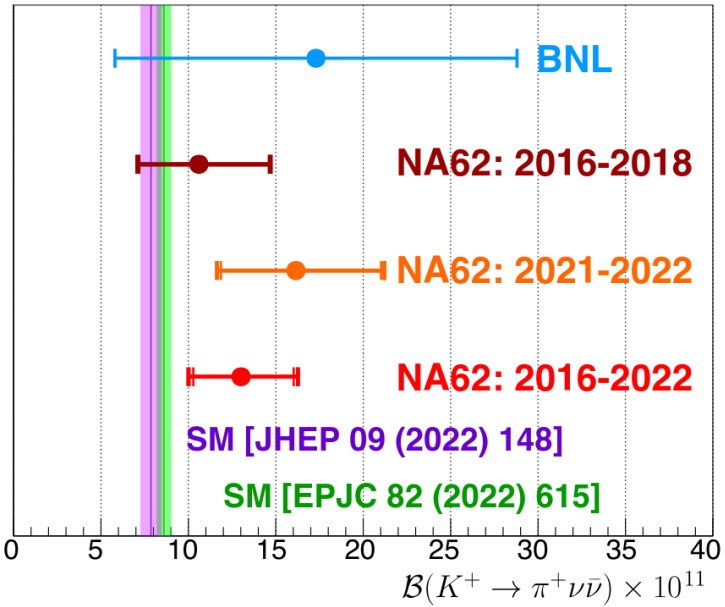
$\pi\nu\nu$ candidates

$\pi\pi^0$ candidates

Result from 2016—2022 data set



N(bkg) = $18\ ^{+3}_{-2}$, N(obs) = 51



[PRD 79 (2009) 092004]

[JHEP 06 (2021) 093]

[JHEP 02 (2025) 191]
Smallest BR ever measured at >5σ signal significance

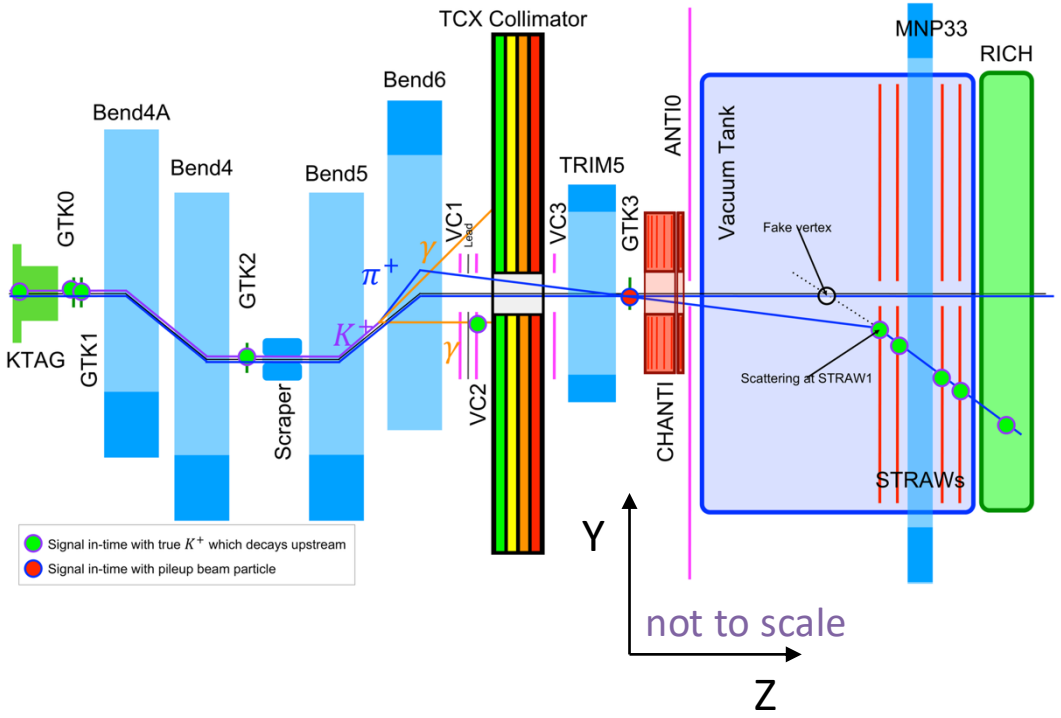
$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})^{\text{NA62}}_{2016-2022} = (13.0\ ^{+3.0}_{-2.7}|_{\text{stat}}\ ^{+1.3}_{-1.3}|_{\text{syst}}) \times 10^{-11} = (13.0\ ^{+3.3}_{-3.0}) \times 10^{-11}$$

Background budget, 2021-2022 data

	2021-2022 [JHEP 02 (2025) 191]
$K^+ \to \pi^+\pi^0(\gamma)$	0.83 ± 0.05
$K^+ \to \mu^+\nu(\gamma)$	1.70 ± 0.47
$K^+ \to \pi^+\pi^+\pi^-$	0.11 ± 0.03
$K^+ \to \pi^+\pi^-e^+\nu$	$0.89\ ^{+0.33}_{-0.27}$
Upstream	$7.4\ ^{+2.1}_{-1.8}$
Background	$11.0\ ^{+2.1}_{-1.9}$
N(πνν,exp)	9.9 ± 0.3

Decays/interactions of beam particles upstream of fiducial volume are > 60% of background and dominate uncertainty

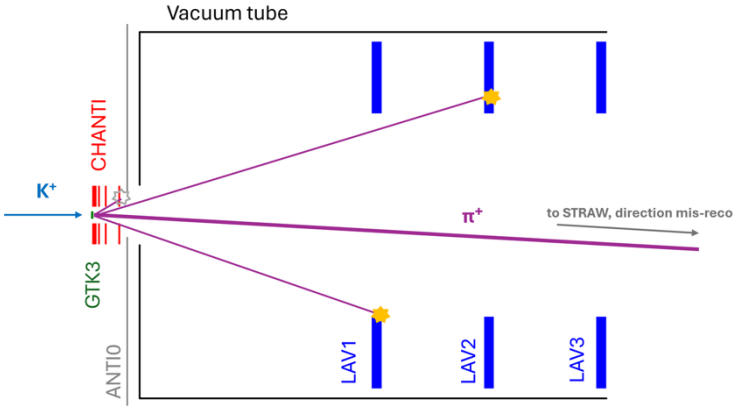
Upstream background event sketch:



Improved veto for upstream in 2023-2024

Past analysis: veto in-time signals from LAV2—LAV12 at trigger level, CHANTI offline veto

New analysis: loosened trigger-level LAV veto, offline veto using LAV1+ and CHANTI



Inelastic interactions control sample up ×10

LAV1 veto very effective in 2023-2024 dataset:

- **O(%) signal loss**
- **Total background down by 30%**

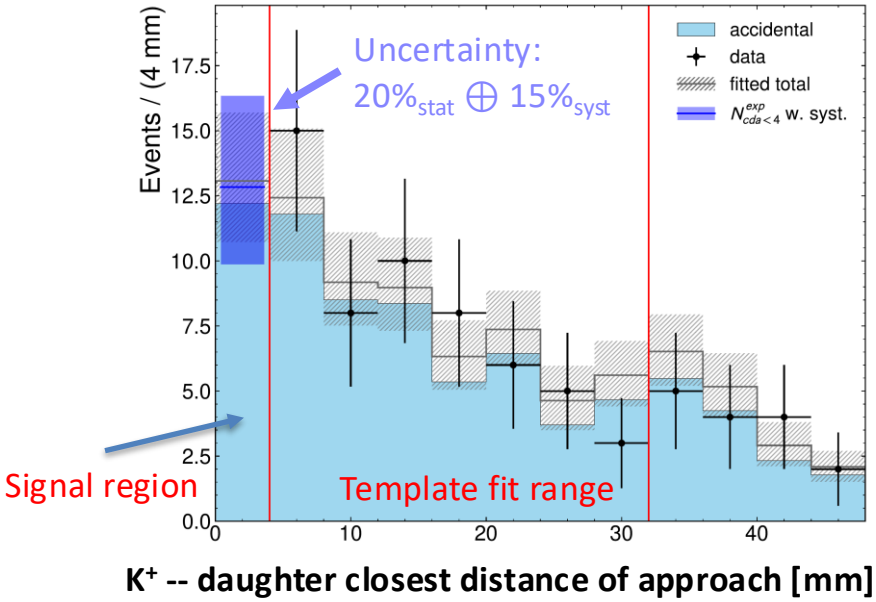
Upstream background improved evaluation

Fully data-driven estimation using upstream reference sample enriched of all known upstream background mechanisms

Old analysis: evaluate expectation in Signal Region using linear approximation

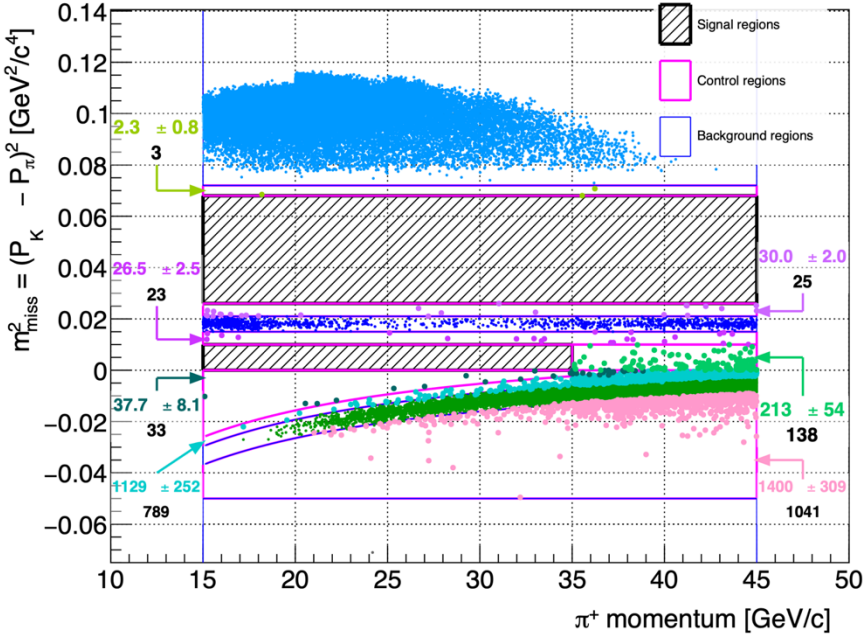
New analysis: extrapolation to Signal Region via template fit using accidental and interaction-like data

Background understood to be dominated by accidental-like events

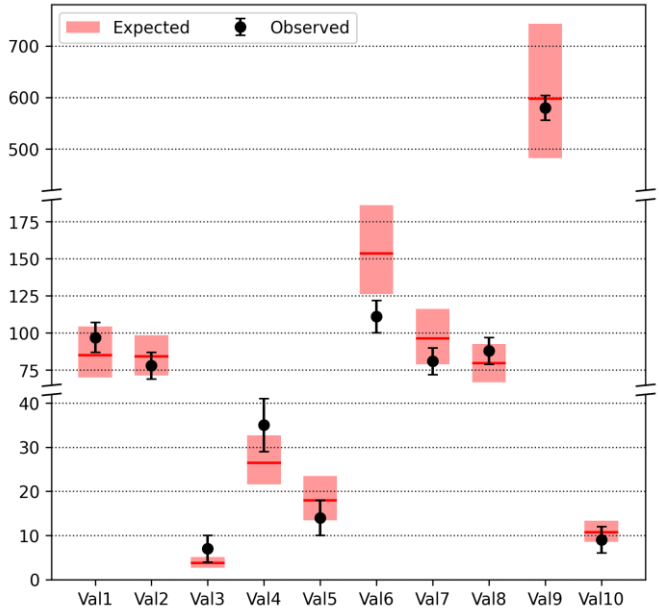


Background validation

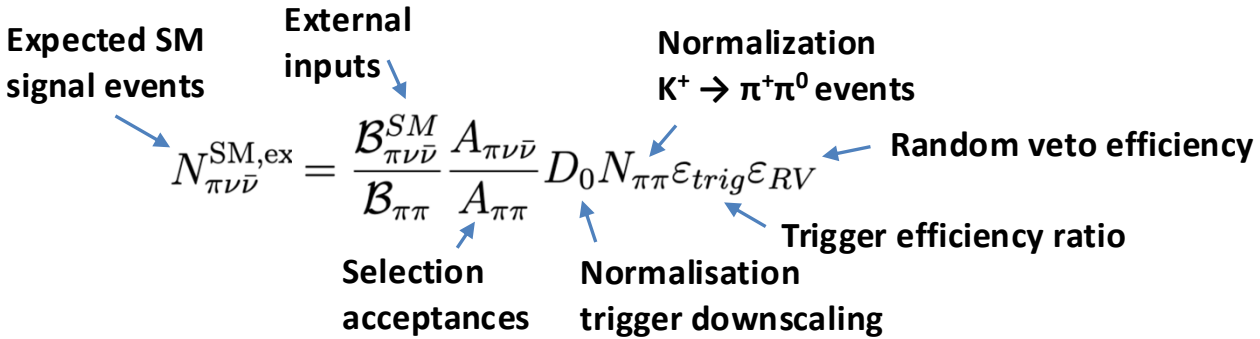
Kinematic sidebands
p-value: 0.65



Upstream background-enriched samples
p-value: 0.79



Performance of new and old analyses



	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

Performance of new and old analyses

Dramatic improvement of figure of merit $(S+B)^{1/2}/S$ = 0.26 vs 0.46

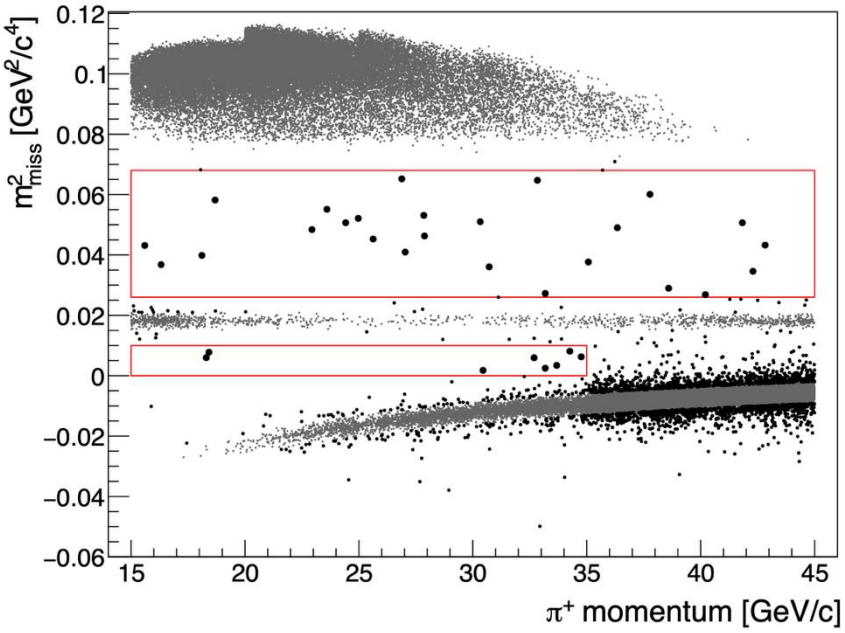
Exp. background	2021-2022 [JHEP 02 (2025) 191]	2023-2024 (this analysis)
$K^+ \to \pi^+\pi^0(\gamma)$	0.83 ± 0.05	1.19 ± 0.10
$K^+ \to \mu^+\nu(\gamma)$	1.70 ± 0.47	1.39 ± 0.29
$K^+ \to \pi^+\pi^+\pi^-$	0.11 ± 0.03	0.24 ± 0.05
$K^+ \to \pi^+\pi^-e^+\nu$	$0.89\ ^{+0.33}_{-0.27}$	$1.59\ ^{+0.51}_{-0.43}$
Upstream	$7.4\ ^{+2.1}_{-1.8}$	$7.4\ ^{+2.8}_{-2.2}$
Background	$11.0\ ^{+\mathbf{2.1}}_{-\mathbf{1.9}}$	$11.9\ ^{+\mathbf{2.9}}_{-\mathbf{2.3}}$
N(πνν,exp)	9.9 ± 0.3	22.9 ± 1.1

Improved π^0 rejection by >20%

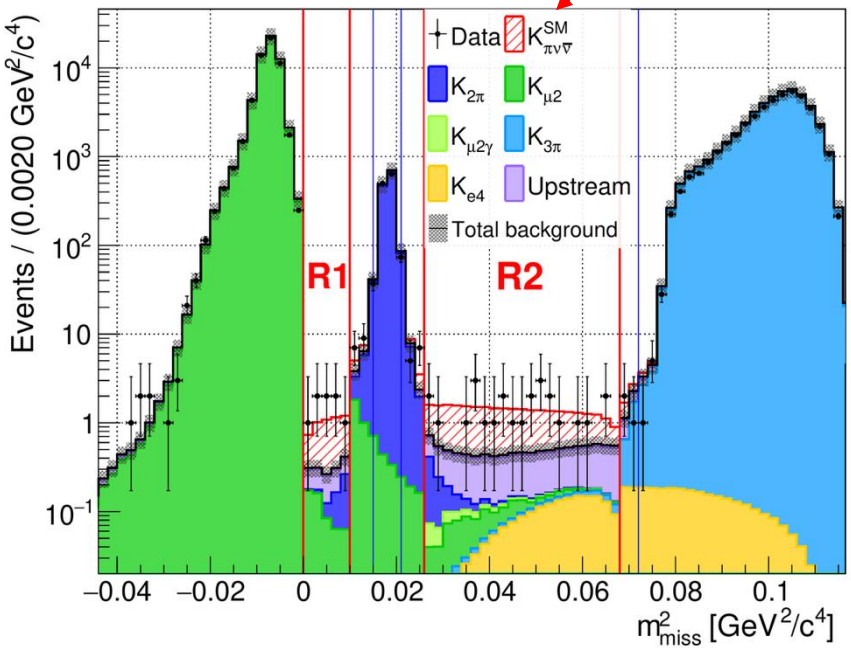
Reduced $\mu^+ \to \pi^+$ mis-ID

Improved upstream bkg rejection

Signal region opened, 2023-24 data



Not a fit: expected with BR_{SM}



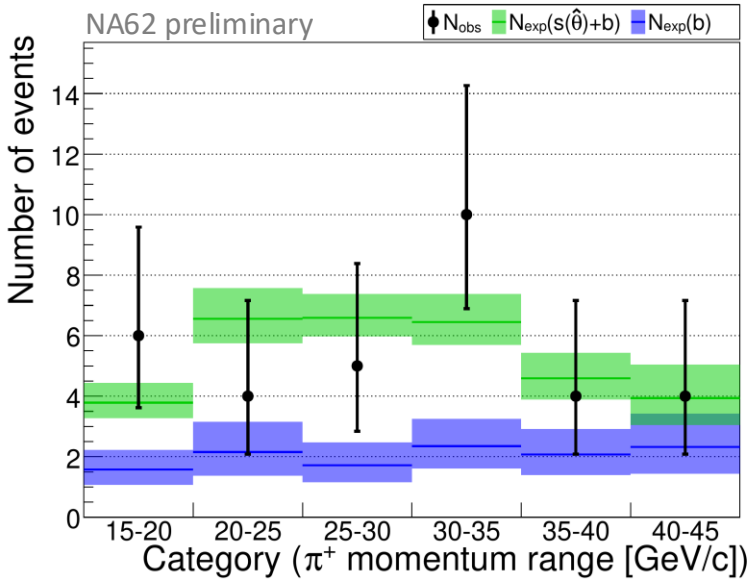
Expected ππνν signal events 22.9 ± 1.1 (with $BR_{SM} = 4.8\times10^{-11}$)

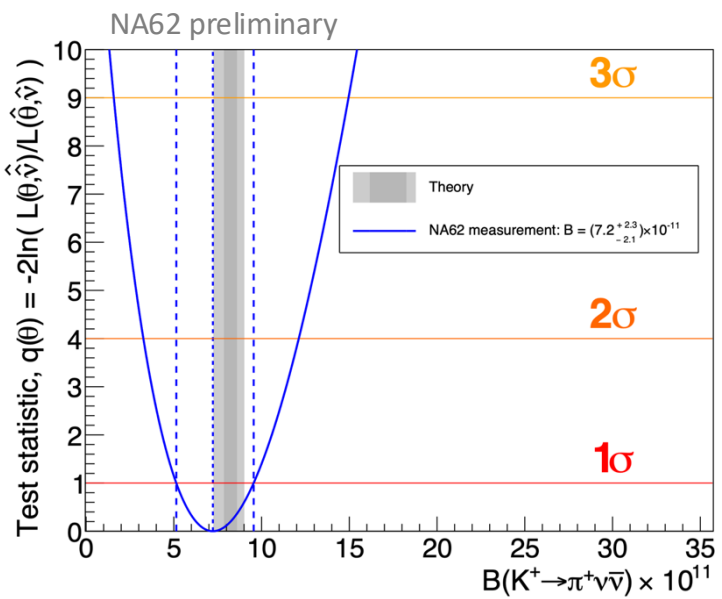
Expected background $11.9\ ^{+2.9}_{-2.3}$

- **Observed events: 33**

Result from 2023-2024 dataset

Fit in π^+ momentum with a profile likelihood ratio test statistic

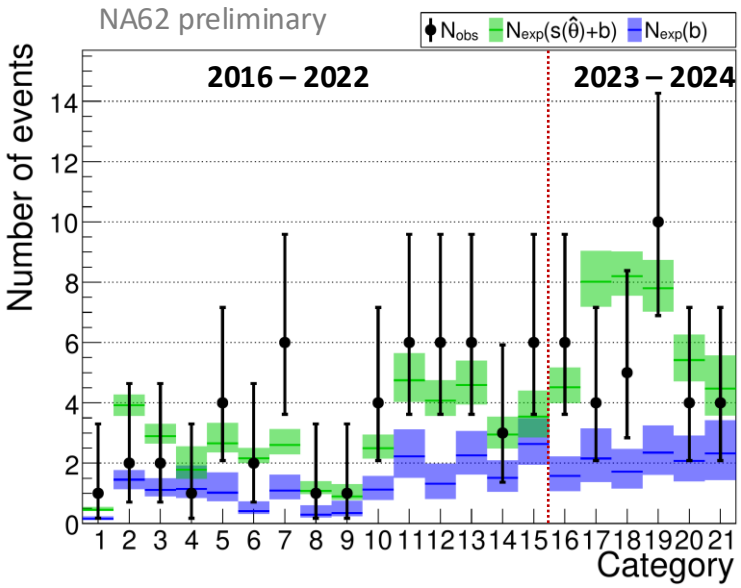


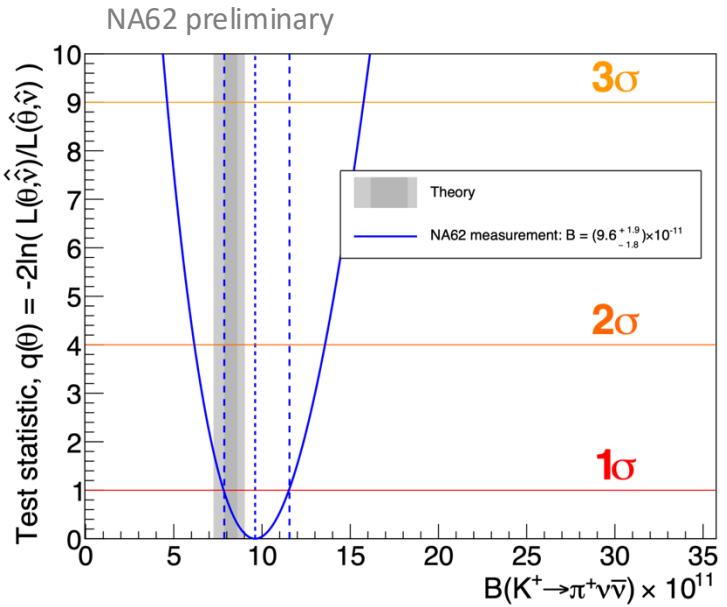


$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})^{\text{NA62}}_{2023-2024} = (7.2\,^{+2.2}_{-1.9}|_{\text{stat}}\,^{+0.9}_{-0.9}|_{\text{syst}}) \times 10^{-11} = (7.2\,^{+2.3}_{-2.1}) \times 10^{-11}$$

Combined result 2016-2024 dataset

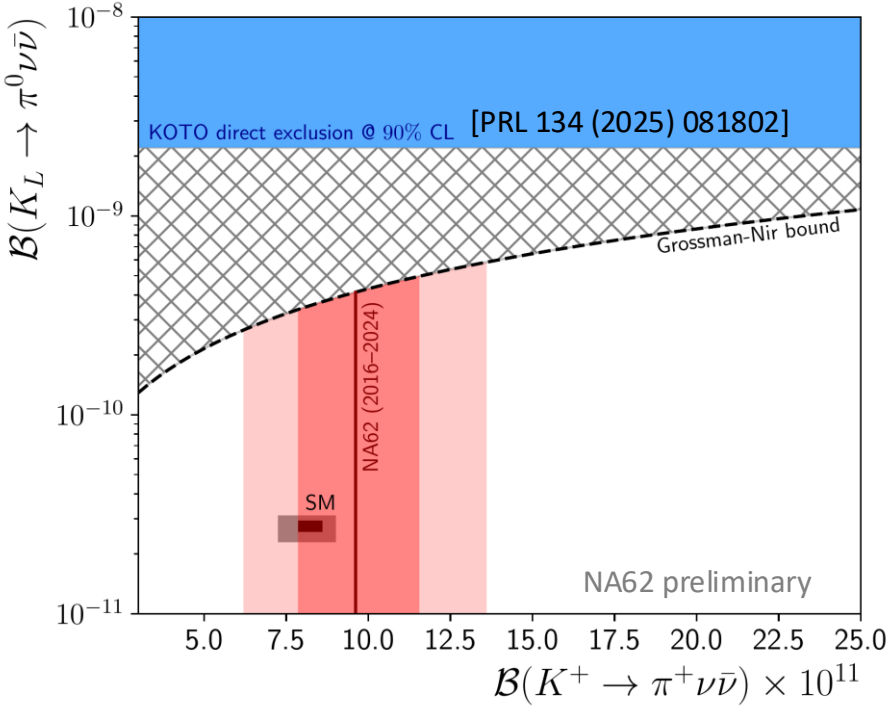
Fit in π^+ momentum with a profile likelihood ratio test statistic





$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})^{\text{NA62}}_{2016-2024} = (9.6\,^{+1.8}_{-1.6}|_{\text{stat}}\,^{+0.8}_{-0.6}|_{\text{syst}}) \times 10^{-11} = (9.6\,^{+1.9}_{-1.8}) \times 10^{-11}$$

Combined result 2016-2024 dataset



$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})^{\text{NA62}}_{2016-2024} = (9.6\,^{+1.8}_{-1.6}|_{\text{stat}}\,^{+0.8}_{-0.6}|_{\text{syst}}) \times 10^{-11} = (9.6\,^{+1.9}_{-1.8}) \times 10^{-11}$$

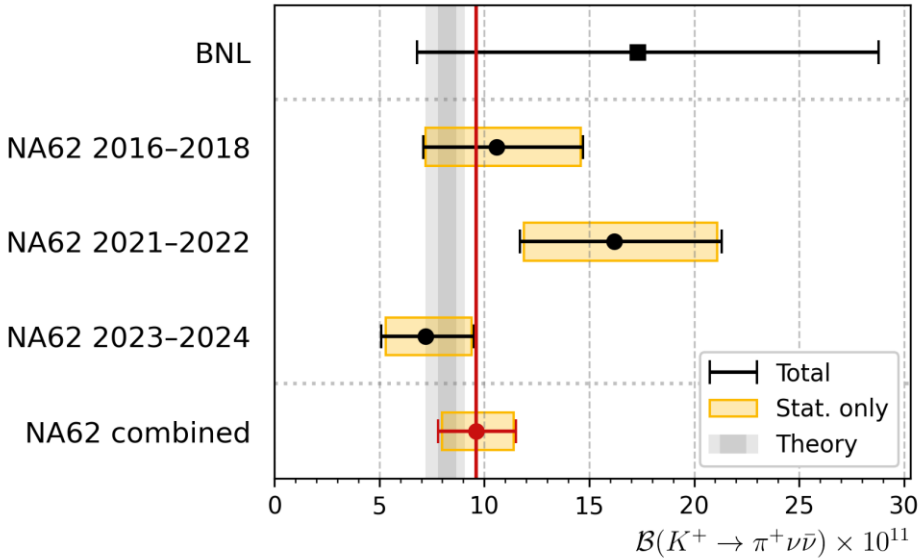
Conclusions

New result presented including 2023-24 data

- **Major sensitivity increase achieved**
- **BR measured to within 20%**

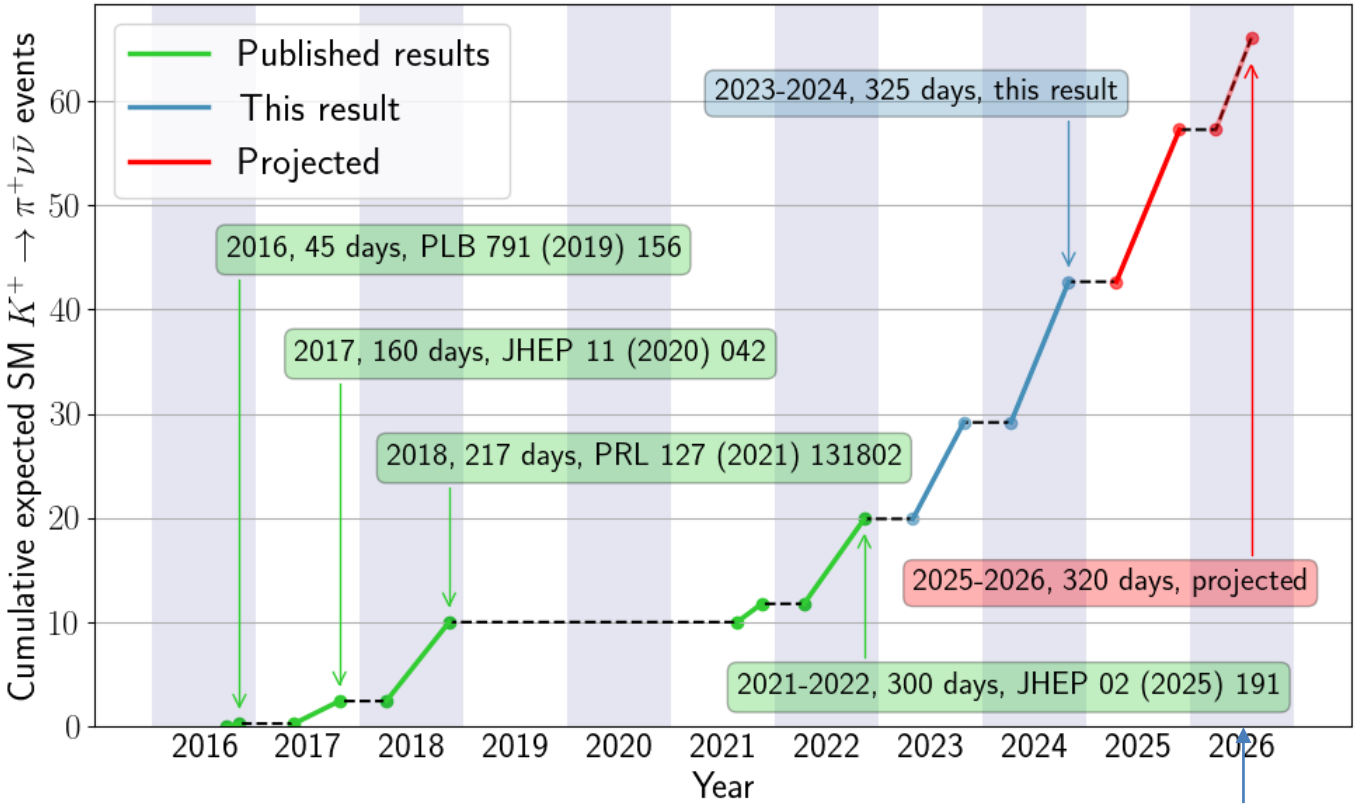
Result compatible with SM

Data sets of 2025-2026 under way…



Spare slides

The NA62 data taking and prospects



NA62 broader physics program

Precision measurements & rare decays

- $K^+ \to \pi^+\mu^+\mu^-$ JHEP 11 (2022) 011
- $K^+ \to \pi^0 e^+\nu\gamma$ JHEP 09 (2023) 040
- $K^+ \to \pi^+ e^+ e^- e^+ e^-$ PLB 846 (2023) 138193
- $K^+ \to \pi^+\gamma\gamma$ PLB 850 (2024) 138513
- $\pi^0 \to e^+e^-$ MORIOND2024
- $K^+ \to \mu^+\nu\mu^+\mu^-$ KAON2025
- $K^+ \to e^+\nu\gamma$ KAON2025
- $K^+ \to \pi^+\pi^+\pi^-\gamma$ KAON2025

Forbidden decays

- $K^+ \to \pi^-\ell^+\ell^+$ PLB 797 (2019) 134794
- $K^+ \to \pi\mu e^+$ & $\pi^0 \to \mu^- e^+$ PRL 127 (2021) 131802
- $K^+ \to \pi^-(\pi^0)e^+e^+$ PLB 830 (2022) 132172
- $K^+ \to \mu^-\nu e^+e^+$ PLB 838 (2023) 137679
- $K^+ \to \pi^0\pi\mu e$ PLB 859 (2024) 139122

Invisible particles

- $\pi^0 \to \gamma A'$ JHEP 05 (2019) 182
- $K^+ \to e^+N$ PLB 807 (2020) 135599
- **$\pi^0 \to$ inv. JHEP 02 (2021) 201**
- $K^+ \to \mu^+ +$ inv. PLB 816 (2021) 136259
- **$K^+ \to \pi^+ +$ inv. JHEP 11 (2025) 143**
- $\pi^+ \to e^+N$ PLB 872 (2026) 140119

Dump mode, see Daniel Grewe's talk in this conference

- FIPs search $\to \mu^+\mu^-$ JHEP 09 (2023) 035
- FIPs search $\to e^+e^-$ PRL 133 (2024) 111802
- FIPs search $\to$ hadrons EPJC 85 (2025) 571
- HNL search $\to$ semileptonic decays, Moriond QCD

Neutrino tagging

- PLB 863 (2025) 139345

NA62 pillars: hermetic particle veto

Hermetic veto system to achieve O(10^8) rejection of π^0 mesons:

LKr calorimeter, σ_t ~ 0.5--1 ns, inefficiency < 10^{-5} for γ's E > 10 GeV, 1 < θ < 8.5 mrad

Reused from NA48, read-out in zero-suppression mode via FADC

New readout + custom FPGA processing to allow L0 trigger operation

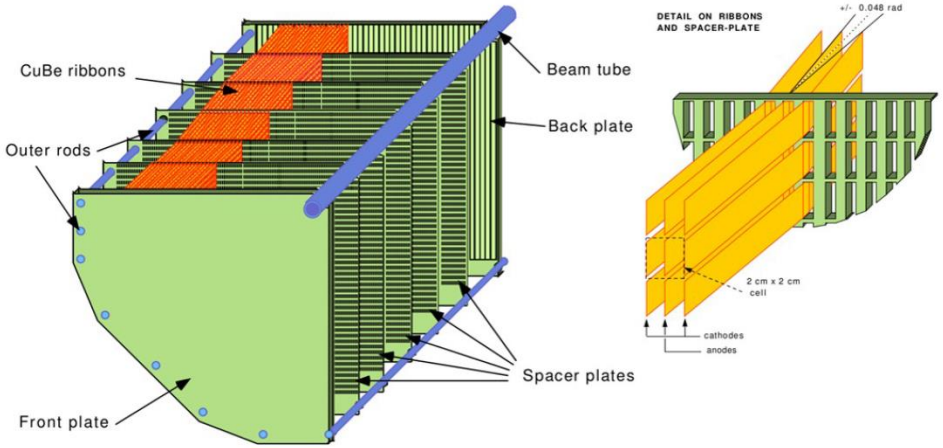


Figure 34. Left: schematic of the calorimeter structure (one quadrant). Right: detail of the calorimeter cells.

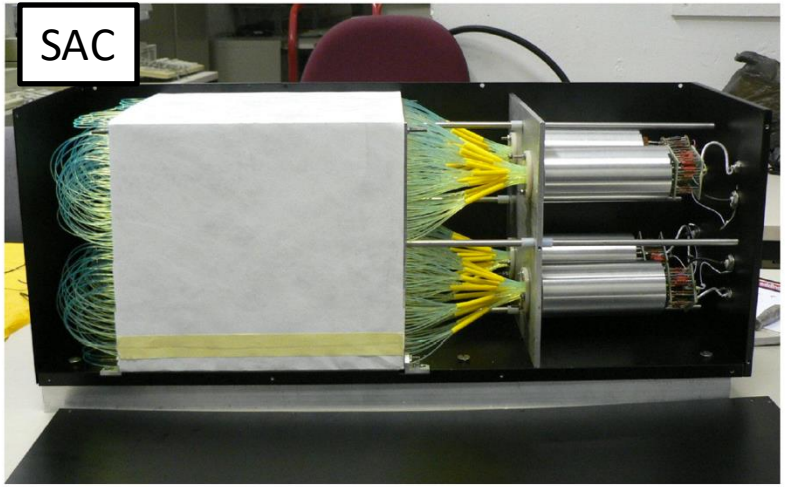
NA62 pillars: hermetic particle veto

Hermetic veto system to achieve O(10^8) rejection of π^0 mesons:

2 scintillator-Pb shashlik cal., IRC-SAC, inefficiency < $10^{-3\text{--}4}$ for γ's with $0 < \theta < 2$ mrad

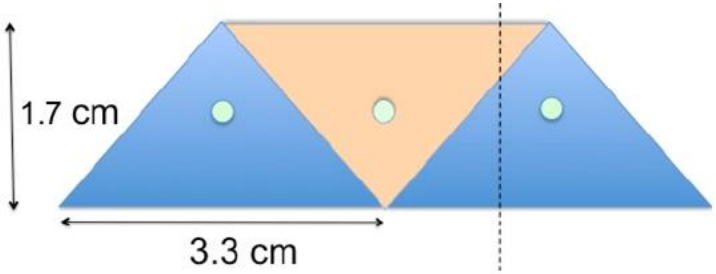
IRC: 2 annular rings, O ~120 -- 290 mm

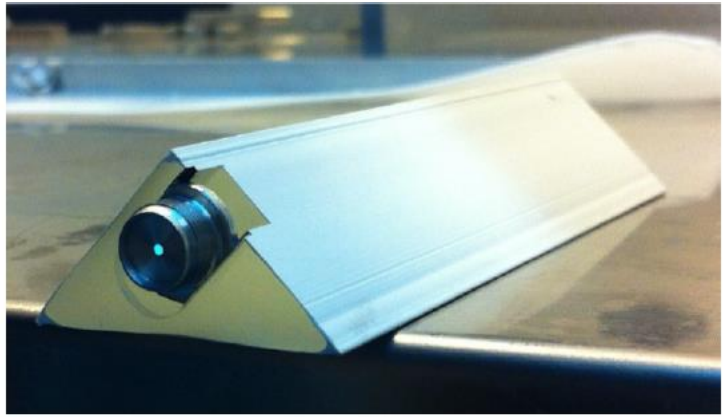
SAC: 205×205 mm^2 soon upstream of the beam dump

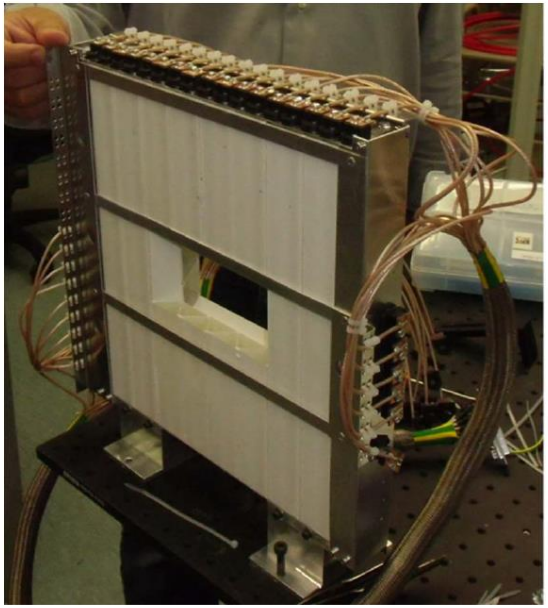


NA62 pillars: additional veto capability

6 stations of scintillator bars, SiPM RO, 99% efficiency, σ_t ~ 1 ns against interactions in GTK3
2 additional counters MUV0, HASC against multi-track final states



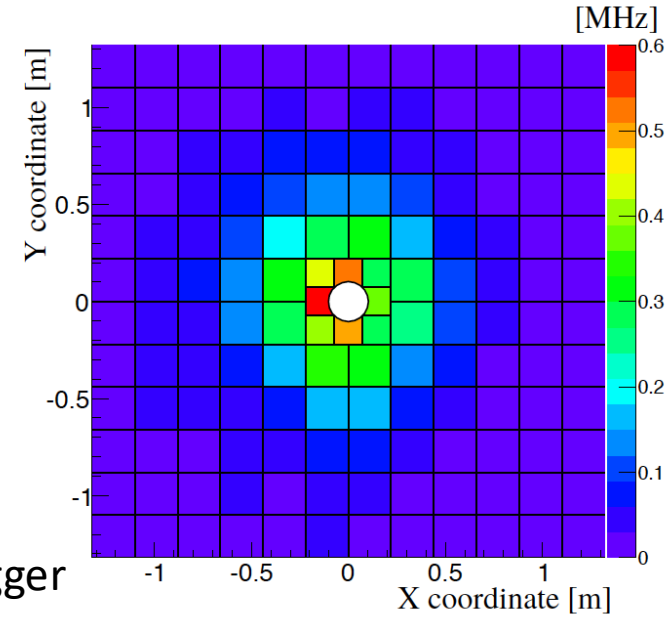




NA62 pillars: additional PID capability

Additional particle identification: 2 hadronic calorimeters, 80 cm Fe, MUV3 hodo. σ_t = 400 ps

Detector	Description	Thickness (interaction length)
MUV1	iron/scintillator	4.1
MUV2	iron/scintillator	3.7
Muon filter	80 cm iron	4.8
MUV3	scintillator tiles	—



LKr + MUV1,2 as a compensated hadronic calorimeter:

$\sigma E / E = 0.115 + 0.38 / \sqrt{E[GeV]} + 1.37 / E[GeV]$

MUV3 rate up to 600 KHz / tile, again participating at L0 trigger

After MUV3 veto, π^+ vs μ^+ ID with ε >75% vs few 10^{-3} with calorimeters, for 15 < p < 35 GeV

NA62 pillars: downstream timing

Downstream time measured by two scintillator hodoscope soon upstream of LKr, σ_t ~ 200 ps

scintillator tiles, SiPM RO (CHOD) + re-used NA48-CHOD

At nominal intensity, rates up to **1 MHz** / tile

Detectors used to initiate the L0 trigger

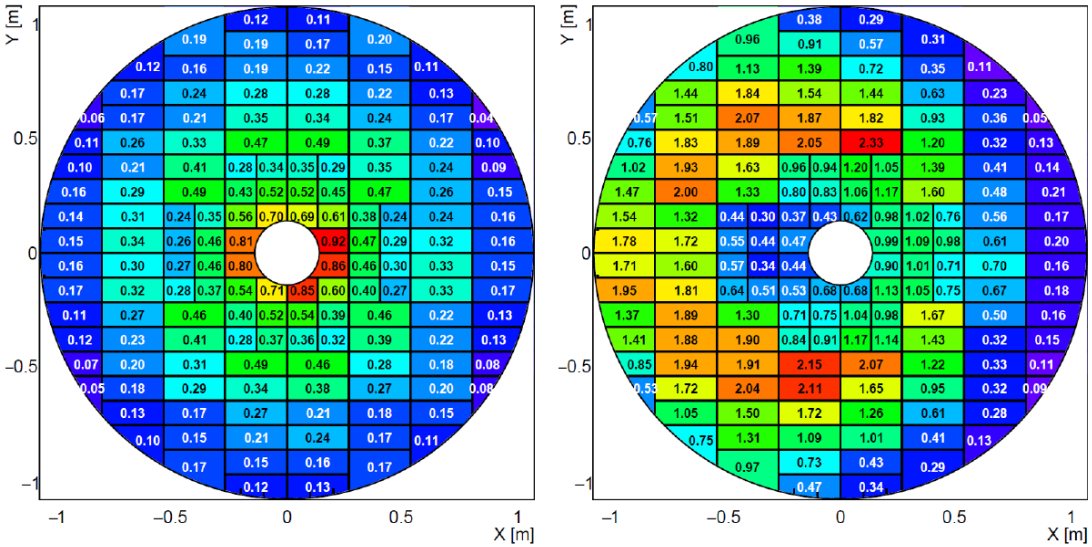


Figure 49. Left: expected rates in CHOD tiles at nominal beam intensity (in MHz). Right: probability of detecting a signal in each CHOD tile for $K^+ \to \pi^+ \nu\bar{\nu}$ decays satisfying the signal selection conditions 105 m < Z_{vertex} < 165 m and 15 GeV/c < p_π < 35 GeV/c in each tile (in percent). Both are calculated with MC simulations.