Recent results from the NA62 experiment at CERN*

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* with slides gratefully liberated from E. Goudzovski

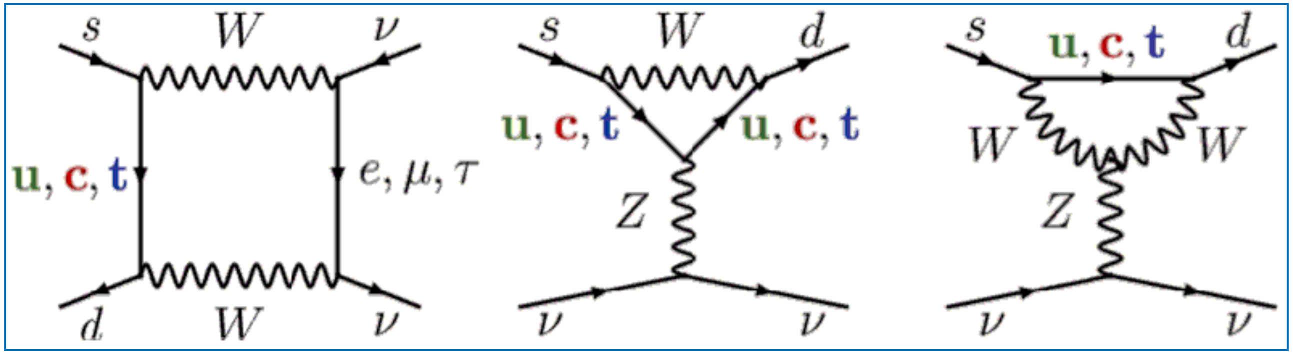
Outline:

1) Introduction: rare kaon decays
2) The $K^+ \to \pi^+ \nu\nu$ measurement at NA62
3) Other NA62 results: hidden sectors, lepton flavour violation
4) Long-terms plans for kaon experiments at CERN
5) Summary and outlook

CIPANP 2022 conference
Orlando, FL, 3 September 2022

K→πνν in the Standard Model

SM: Z-penguin and box diagrams



"Golden modes": extremely rare decays, precise SM predictions.

- Maximum CKM suppression: $\sim(m_t/m_W)^2|V^*_{ts}V_{td}|$.
- No long-distance contributions from amplitudes with intermediate photons.
- Hadronic matrix element extracted from measured BR(K_{e3}) via isospin rotation.

Mode	Standard Model BR	Experimental status
$K^+\to\pi^+\nu\nu$	$(8.60\pm0.42)\times10^{-11}$	$(10.6\pm4.0)\times10^{-11}$ (NA62 Run 1)
$K_L\to\pi^0\nu\nu$	$(2.94\pm0.15)\times10^{-11}$	BR<300×10^{-11} at 90% CL (KOTO 2015 data)

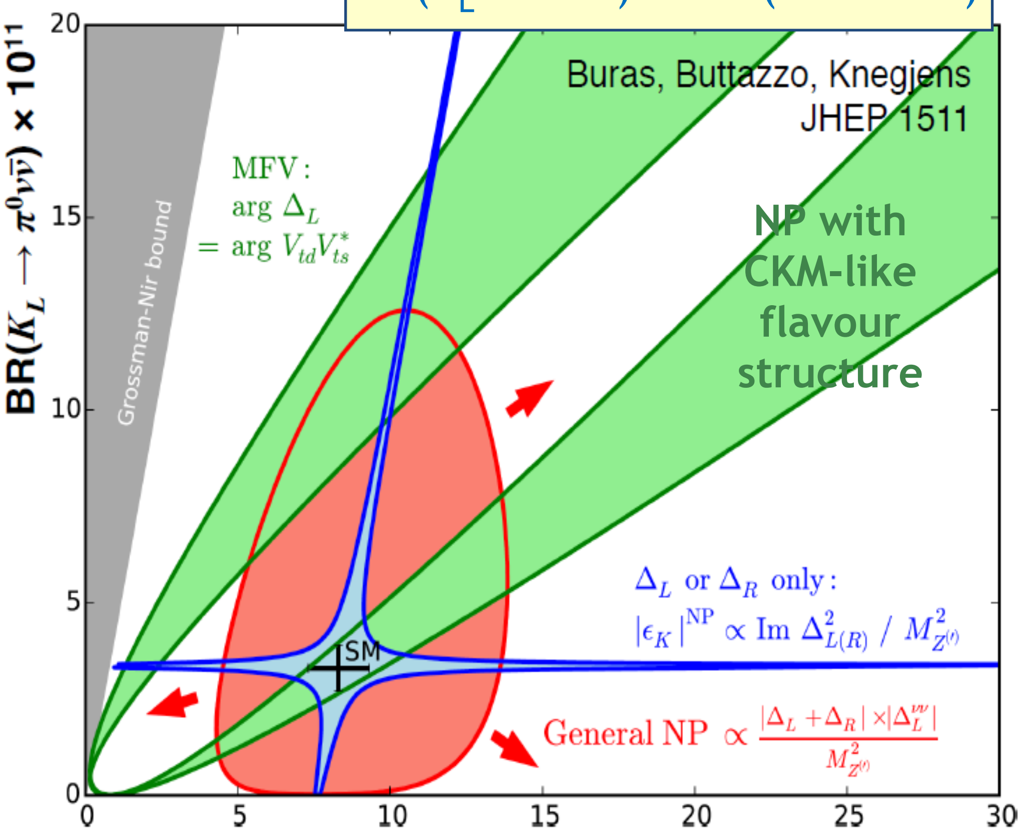
Standard Model BR: a new $|V_{cb}|$ and γ-independent determination.

[Buras and Venturini, arXiv:2109.11032]

K→πνν and new physics

- Correlations between BSM contributions to K^+ and K_L BRs. *[JHEP 11 (2015) 166]*
- Need to measure both K^+ and K_L to discriminate among BSM scenarios (within SM, this allows for a clean β angle measurement).
- Correlations with other observables (ε'/ε, ΔM_K, B decays). *[JHEP 12 (2020) 97]*

BR($K_L \to \pi^0 \nu\bar{\nu}$) vs BR($K^+ \to \pi^+ \nu\bar{\nu}$)



- **Green:** CKM-like flavour structure
  - ✓ Models with MFV
- **Blue:** new flavour-violating interactions in which LH or RH couplings dominate
  - ✓ Z′ models with pure LH/RH couplings
- **Red:** general NP models without the above constraints
- **The Grossman-Nir bound:** a model-independent relation

$$\frac{BR(K_L \to \pi^0 \nu\bar{\nu})}{BR(K^+ \to \pi^+ \nu\bar{\nu})} \times \frac{\tau_+}{\tau_L} \le 1$$

Kaons: other opportunities

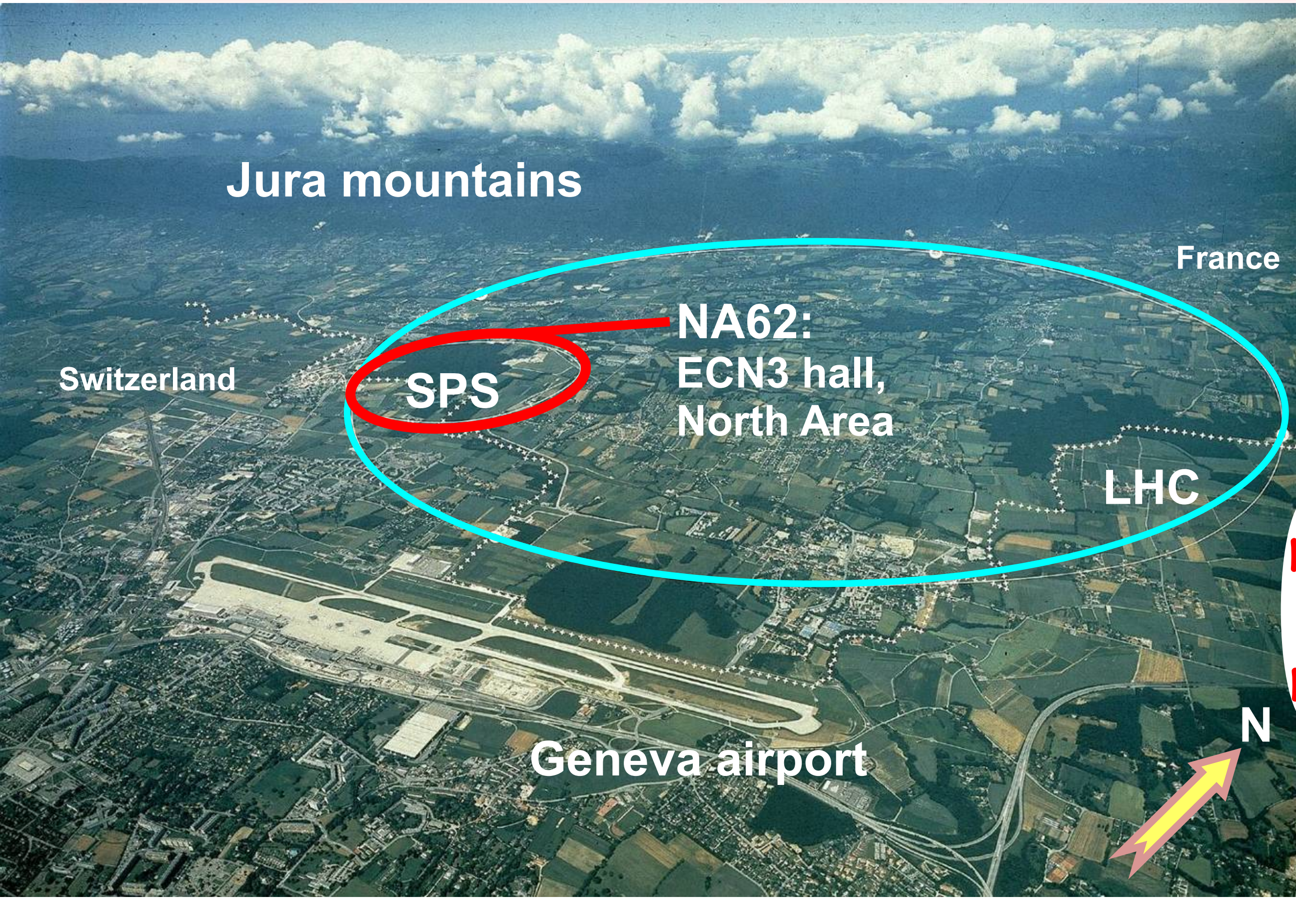
- Direct and indirect CP violation in $K^0 \to \pi\pi$ decays (ε, ε'), and the $K_L - K_S$ mass difference (ΔM_K) [no experiments planned]
  - ✓ Improving capabilities of lattice QCD to provide accurate SM predictions: opportunities for discovery of new physics.
  - ✓ SM precision on ε'/ε can match that of the experiment within a decade, motivating a new measurement.

- Measurement of V_{us} with $K \to \pi \ell \nu$ decays. [no experiments planned]
  - ✓ V_{us} accounts for **50%** of the uncertainty in the first-row CKM unitarity test.
  - ✓ Uncertainty in V_{us}: equal contributions from experiment [$BR(K \to \pi \ell \nu)$] and theory [decay constants f_K/f_π, form-factor $f_+(0)$].
  - ✓ Improvements on lattice QCD expected, motivating new measurements.

- Lepton universality tests, lepton flavour & number conservation tests.
  - ✓ $BR(K^+ \to (\pi^0) e^+ \nu)/BR(K^+ \to (\pi^0) \mu^+ \nu)$, $BR(K^+ \to \pi^+ e^+ e^-)/BR(K^+ \to \pi^+ \mu^+ \mu^-)$; searches for $K^+ \to \pi^+ (\pi^0) \ell \ell$, $K_L \to (\pi^0)(\pi^0) \mu e$, $K_L \to 2\mu 2e$, …

- Searches for light hidden sectors: unique sensitivity due to large datasets and suppression of the kaon decay width.

Kaon experiments at CERN



Main **NA62** goal: $K^+ \to \pi^+ \nu \nu$ measurement to **10%** precision
with a novel decay-in-flight technique.
Currently ~**300** participants from ~**30** institutions.

Earlier: NA31

NA48 discovery of direct CPV
- 1997: ε'/ε: $K_L + K_S$
- 1998: $K_L + K_S$
- 1999: $K_L + K_S$ | K_S HI
- 2000: K_L only | K_S HI
- 2001: $K_L + K_S$ | K_S HI

NA48/1
- 2002: K_S/hyperons

NA48/2
- 2003: K^+/K^-
- 2004: K^+/K^-

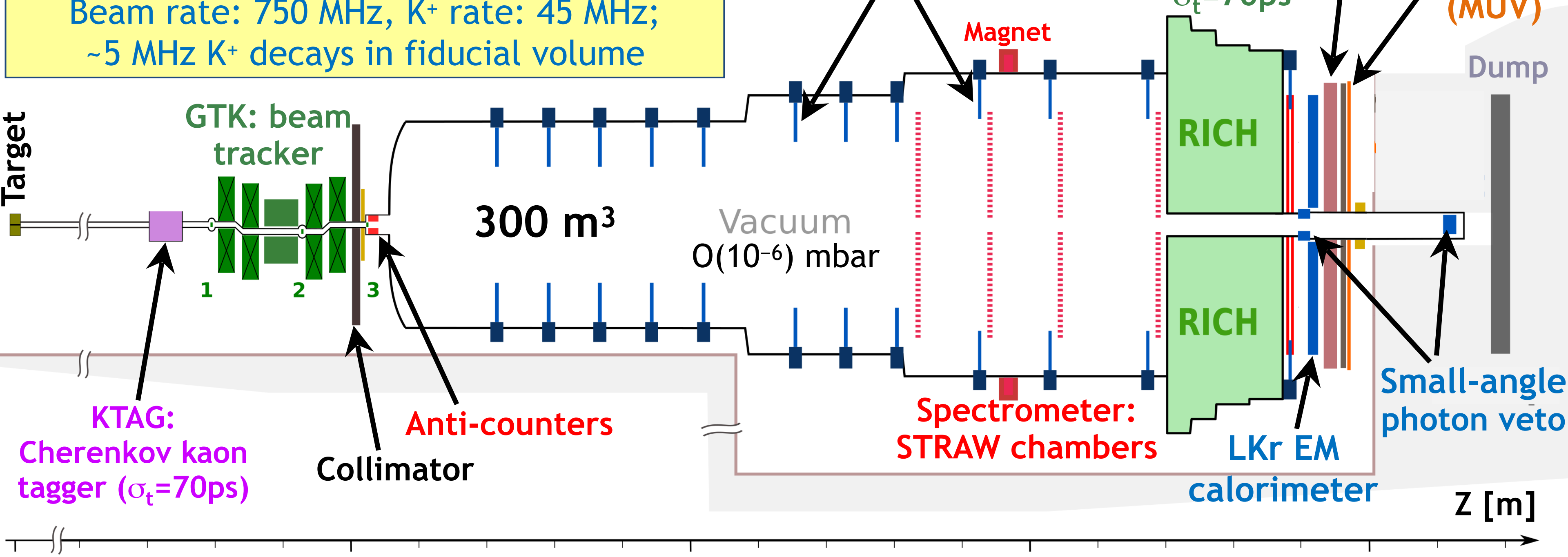
NA62 R_K run
- 2007: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ | tests
- 2008: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ | tests

NA62
- 2015: commissioning
- 2016-18: physics run 1
- 2021-: physics run 2

NA62 collaboration, JINST 12 (2017) P05025

The NA62 experiment

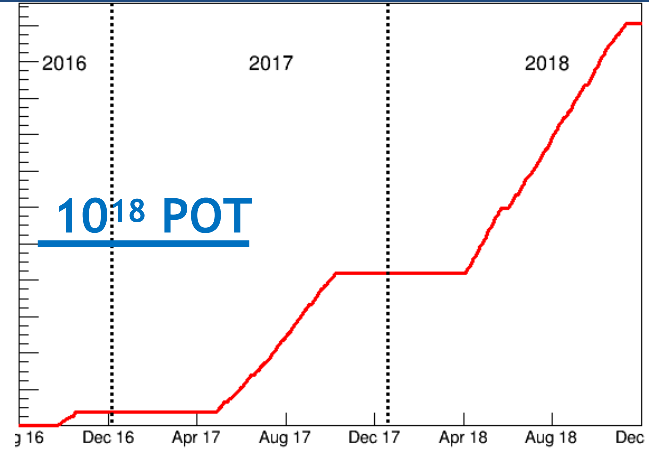
SPS protons: 400 GeV, 10^{12}/second.
Unseparated secondary ($p/\pi^+/K^+$) beam.
K^+: 75 GeV/c (±1%), divergence < 100 μrad.
Beam rate: 750 MHz, K^+ rate: 45 MHz;
~5 MHz K^+ decays in fiducial volume



- In 2018, 1 year of operation ≈ 10^{18} protons on target; 4×10^{12} K^+ decays.
- Single event sensitivities for K^+ decays: approaching BR~10^{-12}.
- Kinematic rejection factors: 1×10^{-3} for $K^+\to\pi^+\pi^0$, 3×10^{-4} for $K\to\mu^+\nu$.
- Hermetic photon veto: $\pi^0\to\gamma\gamma$ decay suppression (for $E_{\pi 0}$>40 GeV) ~10^{-8}.
- Particle ID (RICH+LKr+HAC+MUV): ~10^{-8} muon suppression.

NA62 Run 1 dataset: 2016–18

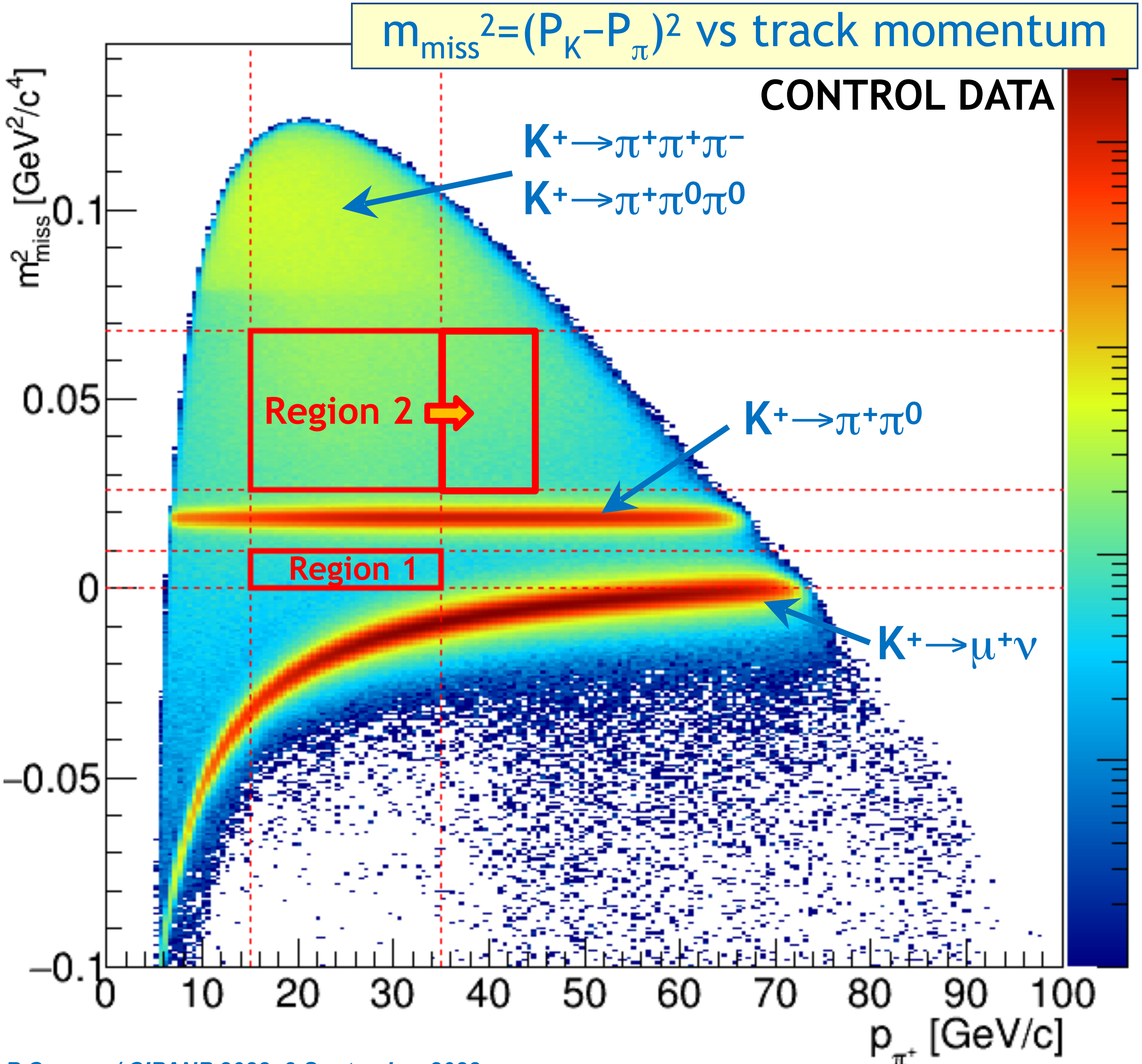
Run 1 integrated luminosity



2.2×10^{18} POT collected
(3×10^{16} from 50h in dump mode)

- Commissioning run **2015**: minimum bias data (~3×10^{10} protons/pulse).
- Physics run **2016** (30 days, ~1.3×10^{12} ppp): 2×10^{11} useful K^+ decays.
- Physics run **2017** (160 days, ~1.9×10^{12} ppp): 2×10^{12} useful K^+ decays.
- Physics run **2018** (217 days, ~2.3×10^{12} ppp): 4×10^{12} useful K^+ decays.
- Run 2 (2021–): in progress (~3×10^{12} ppp), approved till LS3.

NA62: $K_{\pi\nu\nu}$ signal regions



Main K^+ decay modes (>90% of BR) rejected kinematically.

Resolution on m^2_{miss}: $\sigma=1.0\times10^{-3}$ GeV^4/c^2.

Measured kinematic background suppression:

- ✓ $K^+\to\pi^+\pi^0$: 1×10^{-3};
- ✓ $K^+\to\mu^+\nu$: 3×10^{-4}.

Further background suppression:

- ✓ PID (calorimeters & RICH): μ suppression 10^{-8}, π efficiency = 64%.
- ✓ Hermetic photon veto: $\pi^0\to\gamma\gamma$ rejection factor = 1.4×10^{-8}.

Expected backgrounds (2018 data)

Background	Subset S1 (old collimator)	Subset S2 (new collimator)
$\pi^+\pi^0$	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	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$
$BR_{SES} \times 10^{10}$	**0.54±0.04**	**0.14±0.01**
$N^{exp}_{\pi\nu\bar{\nu}}$	**1.56±0.21**	**6.02±0.82**

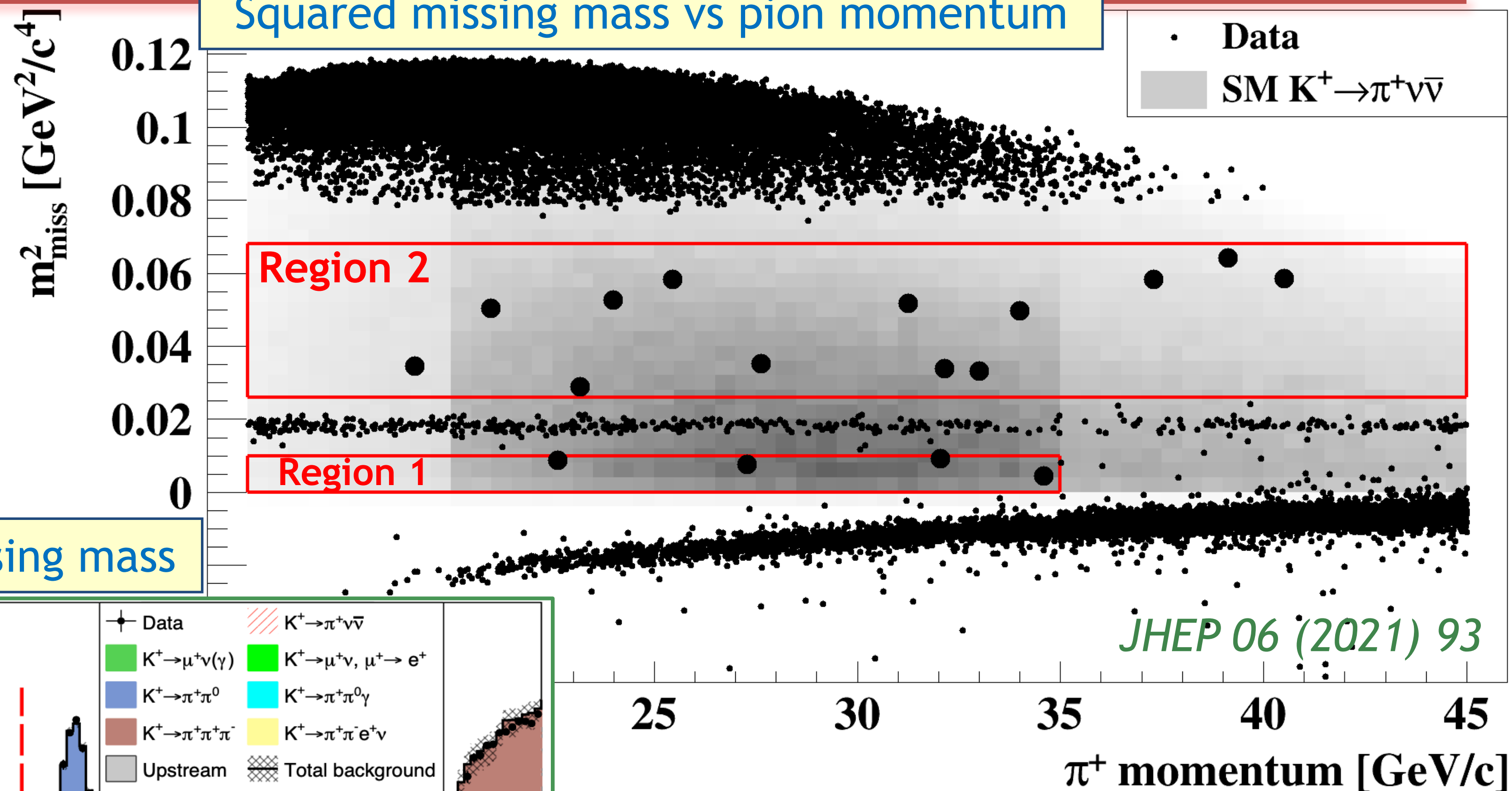
Data-driven background estimates

Dominant background: a data-driven estimate

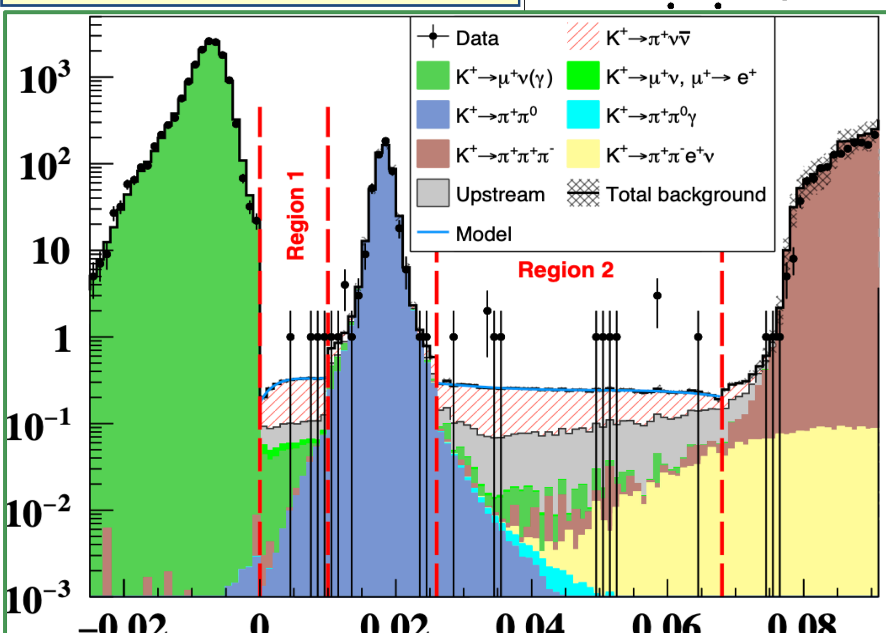
- Most background is **not due to K^+ decays in the vacuum tank**.
- **Improved the beamline layout** and **new upstream veto detectors** bring the Run 2 measurement into a low-background regime.

Opening the box (2018 data)

Squared missing mass vs pion momentum



Squared missing mass



Full Run 1 data set:

Candidates observed: **20** (**17** in 2018 data)

Expected background: $7.03^{+1.05}_{-0.82}$

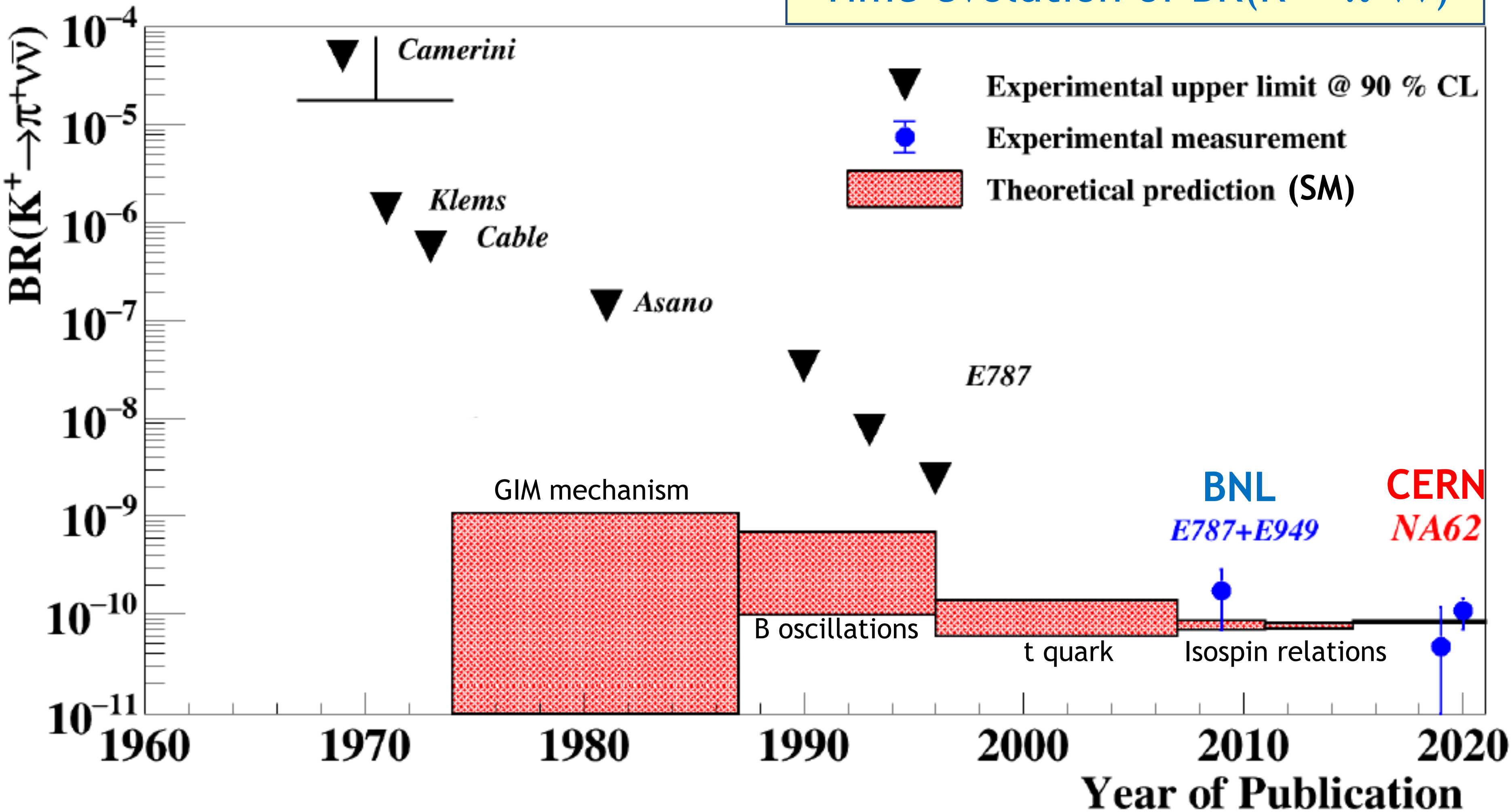
Expected SM events:

$10.01 \pm 0.42_{syst} \pm 1.19_{ext}$

History of $K^+ \to \pi^+ \nu\nu$ searches

JHEP 06 (2021) 93

Time evolution of BR($K^+ \to \pi^+ \nu\nu$)

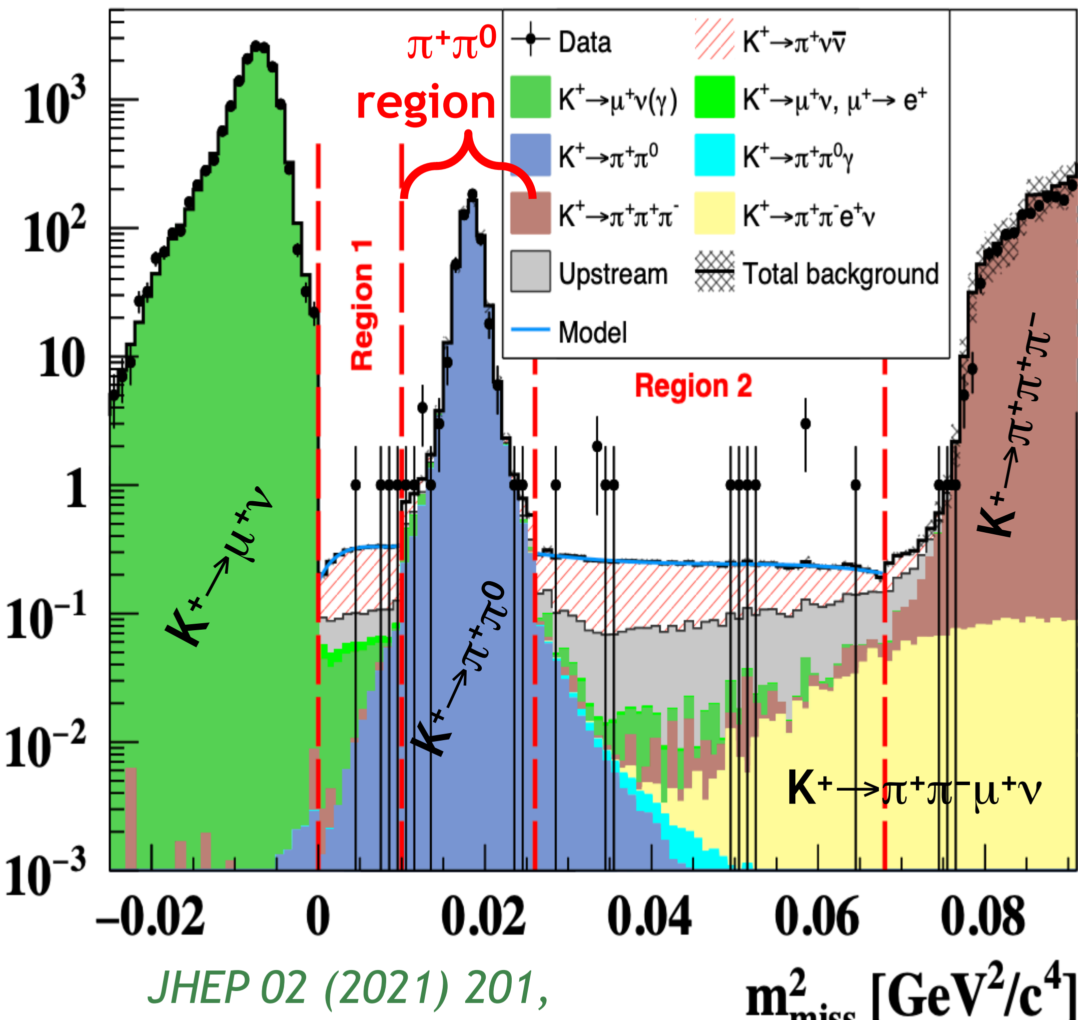


NA62 Run 1: $BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$

(3.4σ significance)

Hidden sectors with $K^+ \to \pi^+\nu\nu$

Squared missing mass (2018 data)

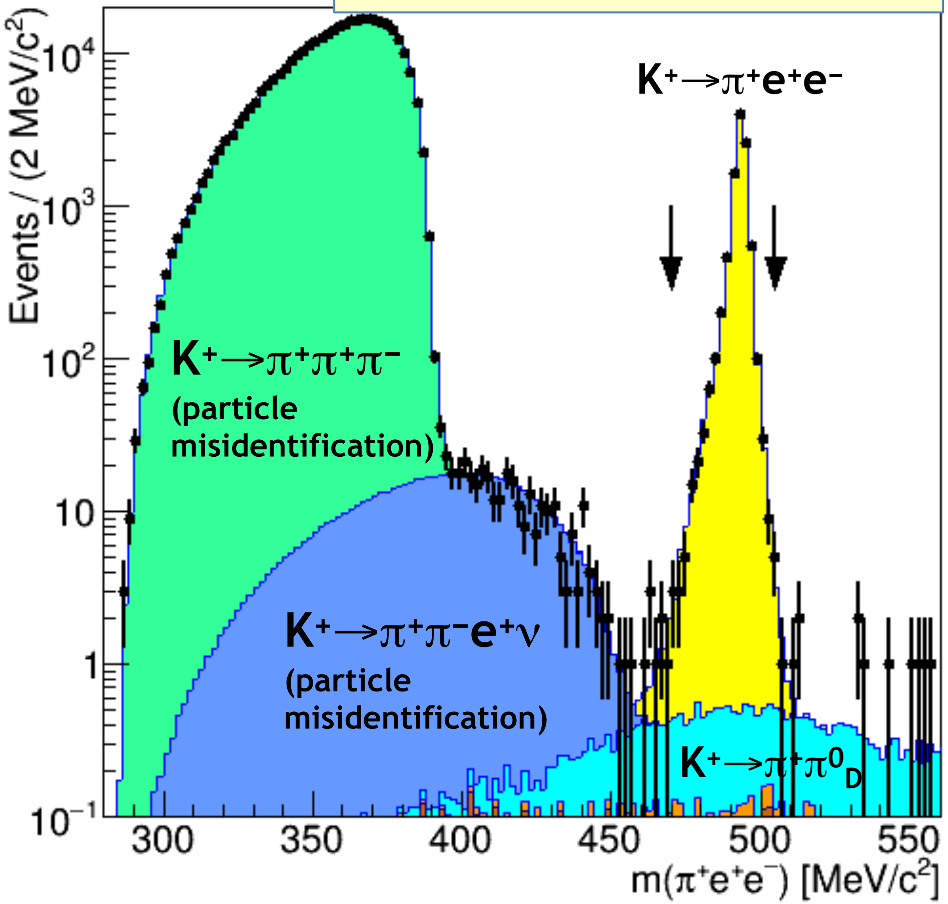


JHEP 02 (2021) 201,
JHEP 06 (2021) 93

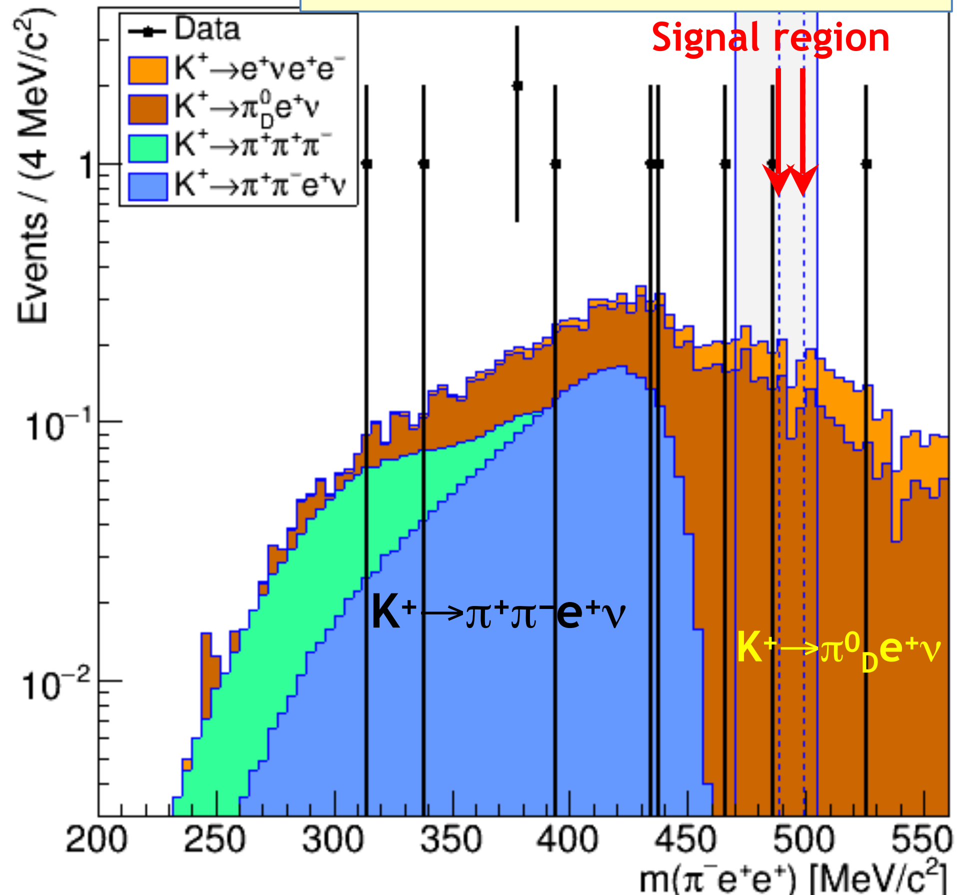
- Signal regions **R1**,**R2**: search for $K^+\to\pi^+X$ (X=invisible), $0 \le m_X \le 110$ MeV/c^2 and $154 \le m_X \le 260$ MeV/c^2.
  - ✓ Interpretation: dark scalar, ALP, QCD axion, axiflavon.
  - ✓ Main background: $K^+\to\pi^+\nu\nu$.
- The $\pi^+\pi^0$ region: search for $\pi^0\to$invisible.
  - ✓ SM rate: $BR(\pi^0\to\nu\nu)\sim10^{-24}$.
  - ✓ Observation = BSM physics.
  - ✓ Reduction of $\pi^0\to\gamma\gamma$ background: optimised π^+ momentum range.
  - ✓ Interpretation as $K^+\to\pi^+X$, with m_X between R1 and R2.

Search for $K^+ \to \pi^- e^+ e^+$ (Run 1)

SM selection: $m(\pi^+ e^+ e^-)$



LNV selection: $m(\pi^- e^+ e^+)$



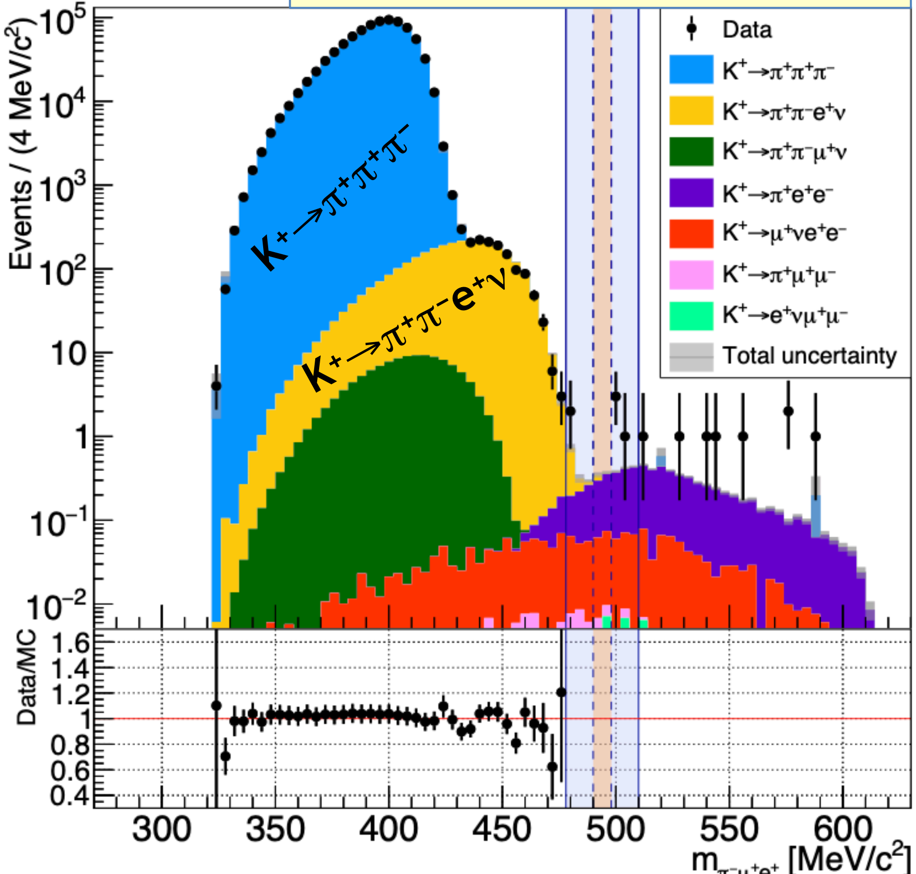
Candidates observed: 11041
$BR(K^+ \to \pi^+ e^+ e^-) = (3.00 \pm 0.09) \times 10^{-7}$
K^+ decays in FV: $(1.015 \pm 0.032) \times 10^{12}$

Expected background: 0.43 ± 0.09 evt
Candidates observed: 0
$BR(K^+ \to \pi^- e^+ e^+) < 5.3 \times 10^{-11}$ at 90% CL

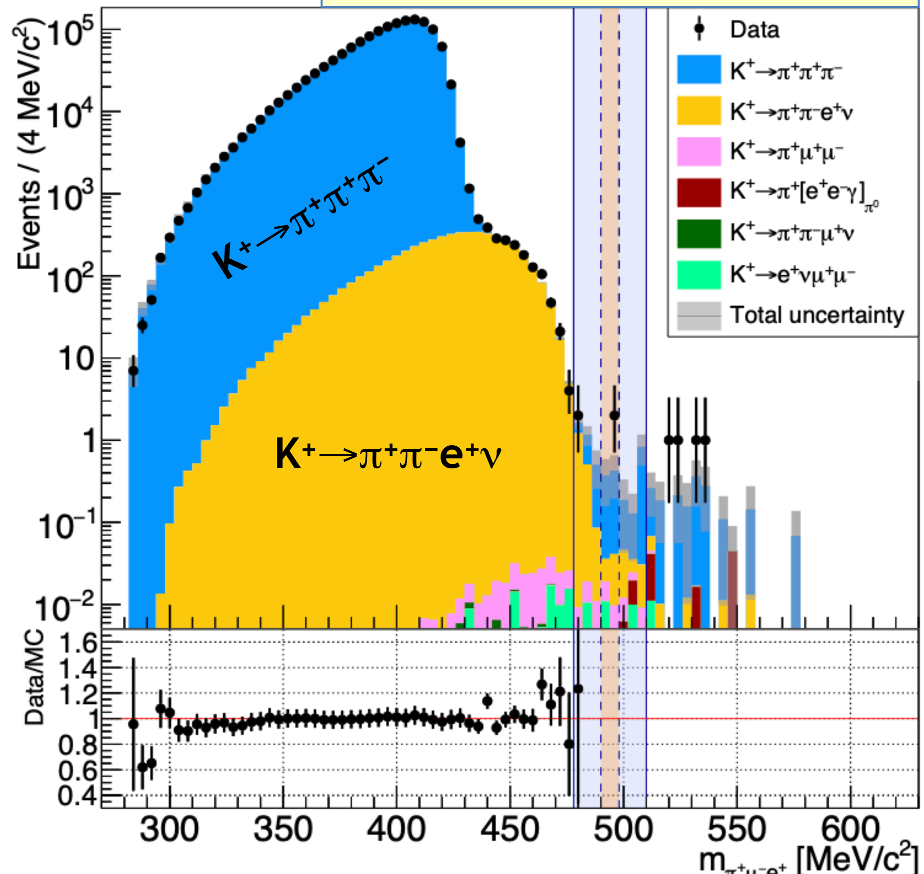
[PLB830 (2022) 137172]

Search for $K^+ \to \pi\mu e$ decays (Run 1)

LNV decay: $m(\pi^-\mu^+e^+)$



LFV decay: $m(\pi^+\mu^-e^+)$



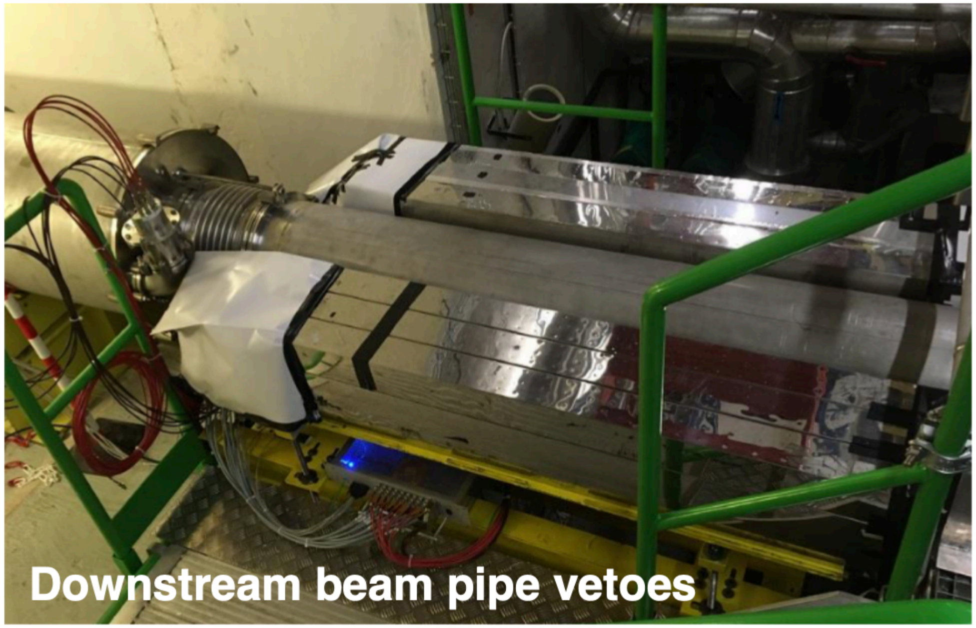
K^+ decays in FV: $(1.33\pm0.02)\times10^{12}$
Expected background: 1.07 ± 0.20 evt
Candidates observed: 0
$BR(K^+\to\pi^-\mu^+e^+)<4.2\times10^{-11}$ at 90% CL

Expected background: 0.92 ± 0.34 evt
Candidates observed: 2
$BR(K^+\to\pi^+\mu^-e^+)<6.6\times10^{-11}$ at 90% CL
$BR(\pi^0\to\mu^-e^+)<3.2\times10^{-10}$ at 90% CL

[PRL 127 (2021) 131802]

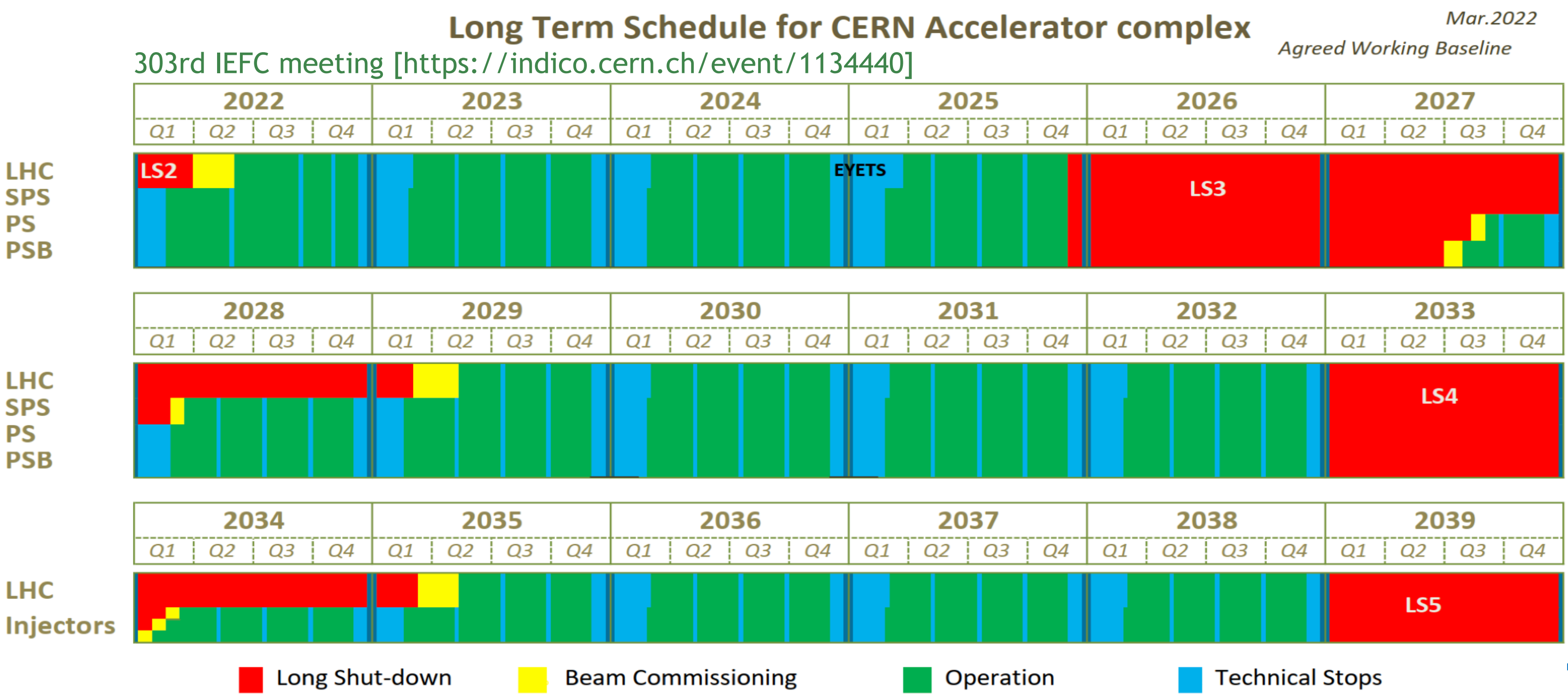
NA62 Run 2: 2021–LS3

- **The technique is firmly established**. Run 2: $K^+ \to \pi^+ \nu\nu$ measurement in a low-background, high-acceptance regime, at **O(10%)** precision.
- Modifications of the setup for background reduction:
  - ✓ fourth kaon beam tracker (GTK) station;
  - ✓ rearrangement of beamline elements around the GTK achromat;
  - ✓ new veto hodoscopes upstream of the decay volume;
  - ✓ an additional veto counter around downstream beam pipe.
- Improved TDAQ: beam intensity increased by ~30% wrt Run 1.
- Collection of 10^{18} pot in up to 90 days in beam dump mode is foreseen.



Fixed target runs at CERN SPS

- SPS fixed target operation foreseen **until at least 2038**.
- **HIKE** (*"High-Intensity Kaon experiment"*): a long-term programme at the SPS proposed to search for new physics in kaon decays.
- Measurements of rare K^+ and K_L kaon decay modes: a clear insight into the flavour structure of new physics.
- Details in a Snowmass white paper: **arXiv:2204.13394**.



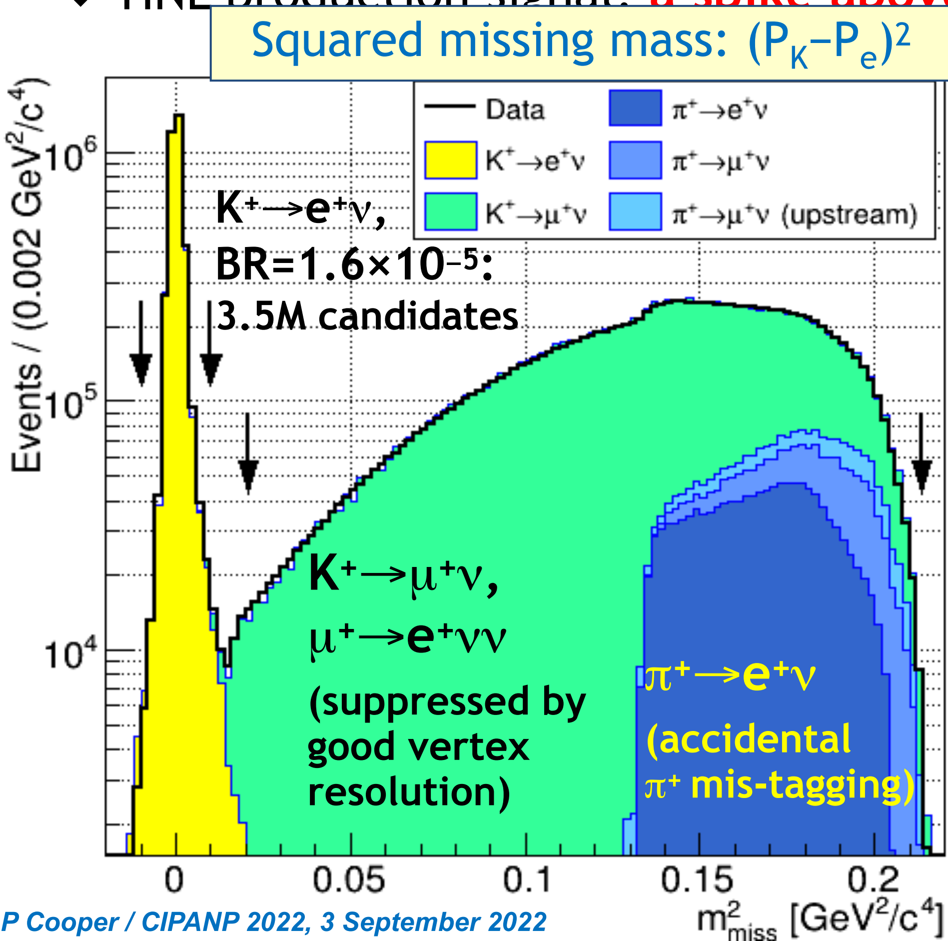
Summary and outlook

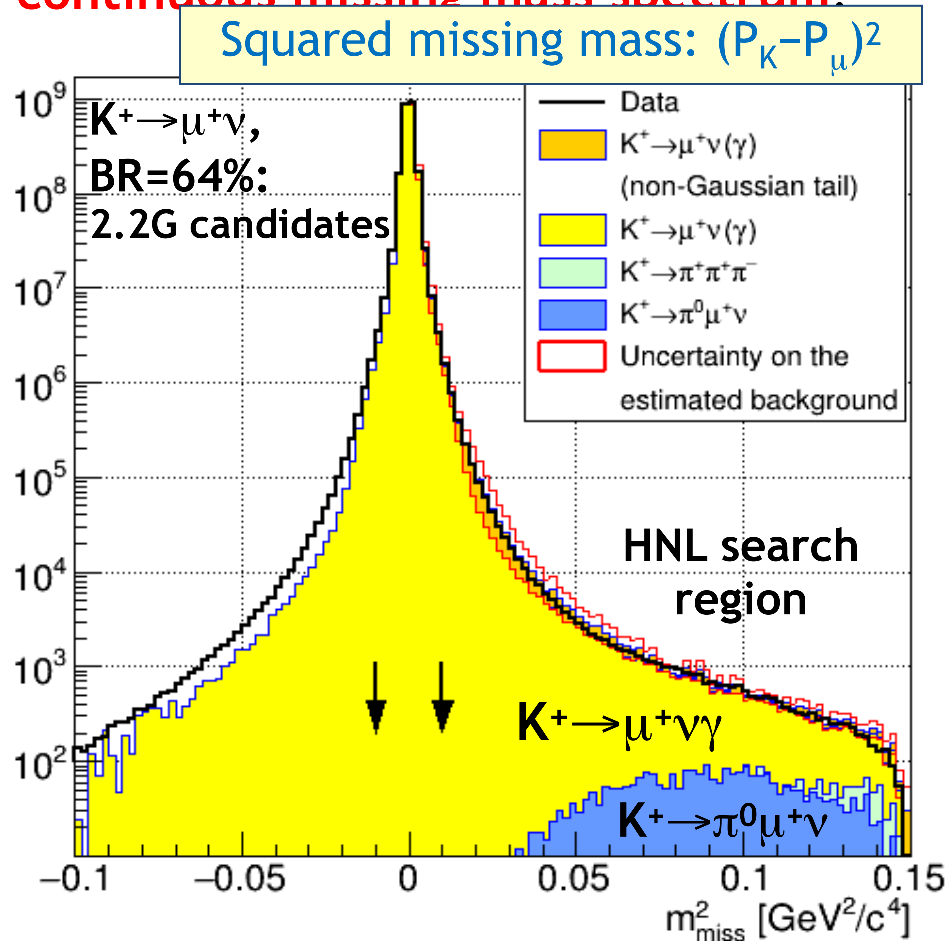
- Rare kaon decays ($K \to \pi\nu\nu$, …): unique probes for heavy new physics at the **O(100 TeV)** mass scale, and for light hidden sectors.
- Precision measurements of both **K^+** and **K^0** decays are essential.
- **NA62** is improving on **BR($K^+ \to \pi^+\nu\nu$)**, aiming at **O(10%)** precision by **2025**.
- Next generation rare kaon experiments with high-intensity beams will provide a powerful tool to search for BSM physics.
- A long-term **K^+** and **K_L** programme (**"HIKE"**) is taking shape at CERN.
- Other operating kaon experiments: **KOTO at JPARC**, **LHCb at CERN**. Both are planning ambitious future programmes.

Spares

HNL production search: data sample

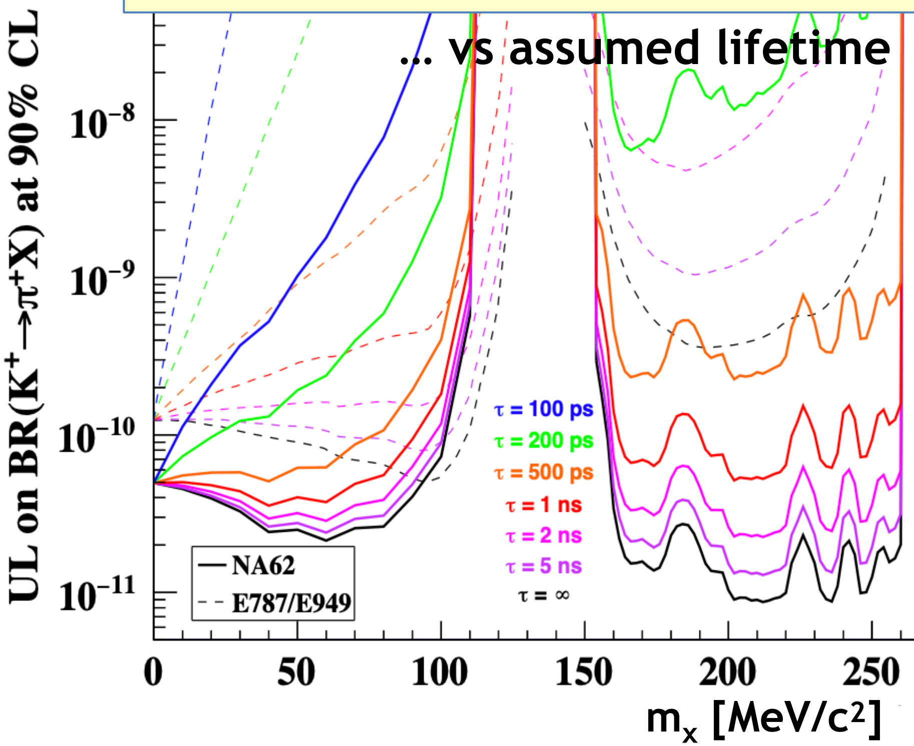
- Triggers used: $K_{\pi\nu\nu}$ for $K^+ \to e^+ N$; Control/400 for $K^+ \to \mu^+ N$.
- Numbers of K^+ decays in fiducial volume:
  $N_K = (3.52 \pm 0.02) \times 10^{12}$ in positron case; $N_K = (4.29 \pm 0.02) \times 10^9$ in muon case.
- Squared missing mass: $m^2_{miss} = (P_K - P_\ell)^2$, using STRAW and GTK trackers.
- HNL production signal: a spike above continuous missing mass spectrum.



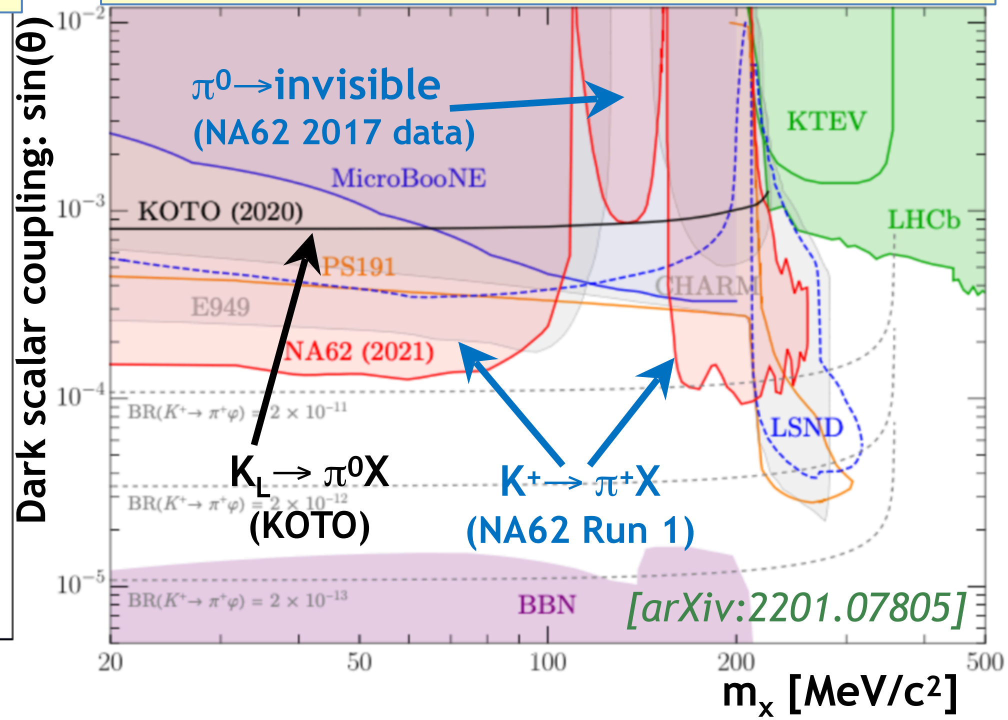


Search for $K^+ \to \pi^+ X$ (Run 1)

UL at 90% CL of $BR(K^+ \to \pi^+ X)$ vs m_X

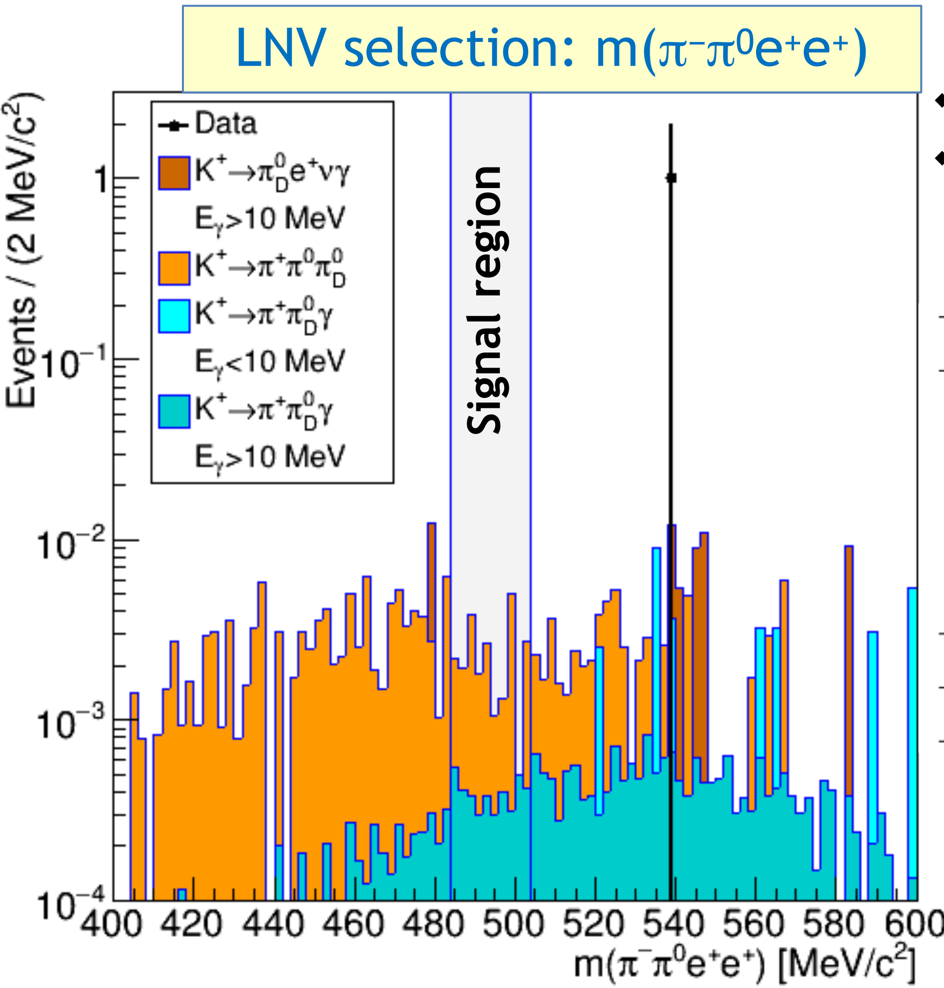


Dark scalar searches below the K mass



- Mass resolution improves with m_X and is $\delta m_X \sim 40$ MeV/c² at $m_X=0$.
- Upper limits of $BR(K^+ \to \pi^+ X)$ established depending on X mass and lifetime.
- Improvement on BNL-E949 *[PRD79 (2009) 092004]* over most of m_X range.
- Interpreted within the dark scalar and ALP (fermionic coupling) models *[EPJ C81 (2021) 1015; arXiv:2201.07805]*
- Note the **KOTO** result based on 2016–18 data. *[PRL125 (2021) 021801]*

Search for $K^+ \to \pi^- \pi^0 e^+ e^+$ (Run 1)



[PLB830 (2022) 137172]

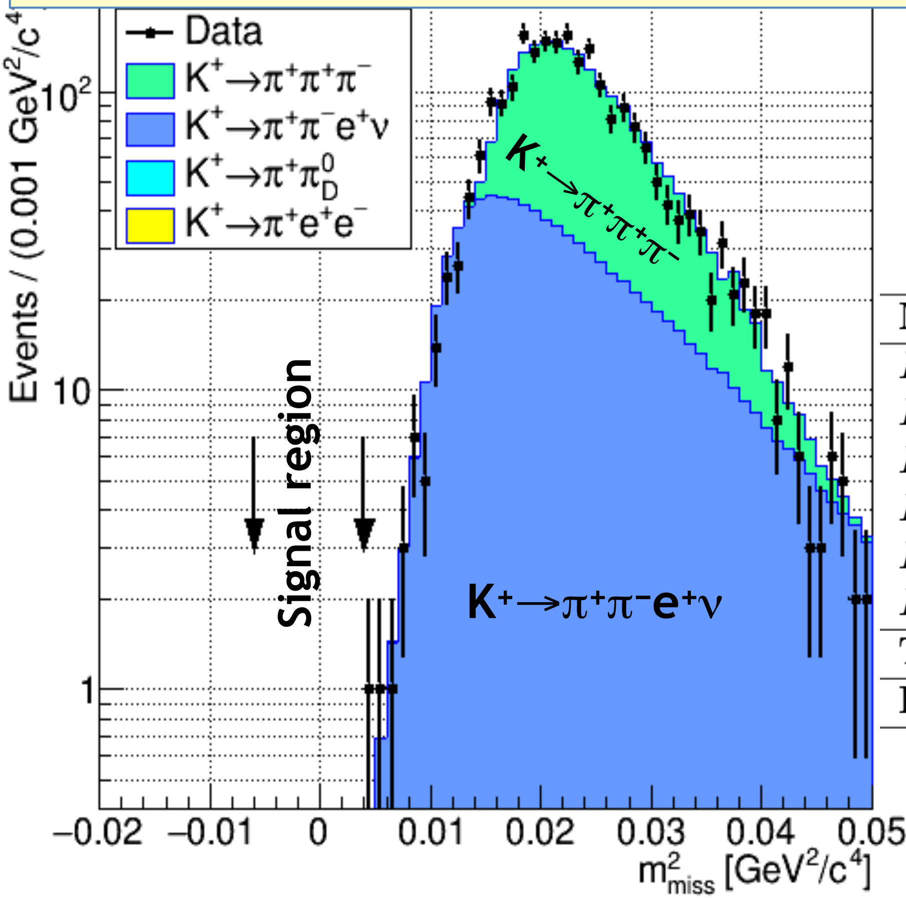
- Normalisation to the SM decay $K^+ \to \pi^+ e^+ e^-$.
- The neutral pion is reconstructed in the LKr calorimeter via $\pi^0 \to \gamma\gamma$ decay.

Mode	Control region	Signal region
$K^+ \to \pi^+ \pi^0 \pi^0_D$	0.16 ± 0.01	0.019
$K^+ \to \pi^+ \pi^0_D \gamma$	0.06 ± 0.01	0.004
$K^+ \to \pi^0_D e^+ \nu \gamma$	0.05 ± 0.02	–
$K^+ \to \pi^+ \pi^0 e^+ e^-$	0.01	0.001
Pileup	0.20 ± 0.20	0.020 ± 0.020
Total	0.48 ± 0.20	0.044 ± 0.020
Data	1	0

Expected background: **0.044±0.020** evt
Candidates observed: **0**
$BR(K^+ \to \pi^- \pi^0 e^+ e^+) < 8.5 \times 10^{-10}$ at 90% CL
First search for this mode.

Search for $K^+ \to \mu^- \nu e^+ e^+$ (Run 1)

Squared missing mass, $(P_K - P_\mu - P_{e1} - P_{e2})^2$



[NEW, to be published]

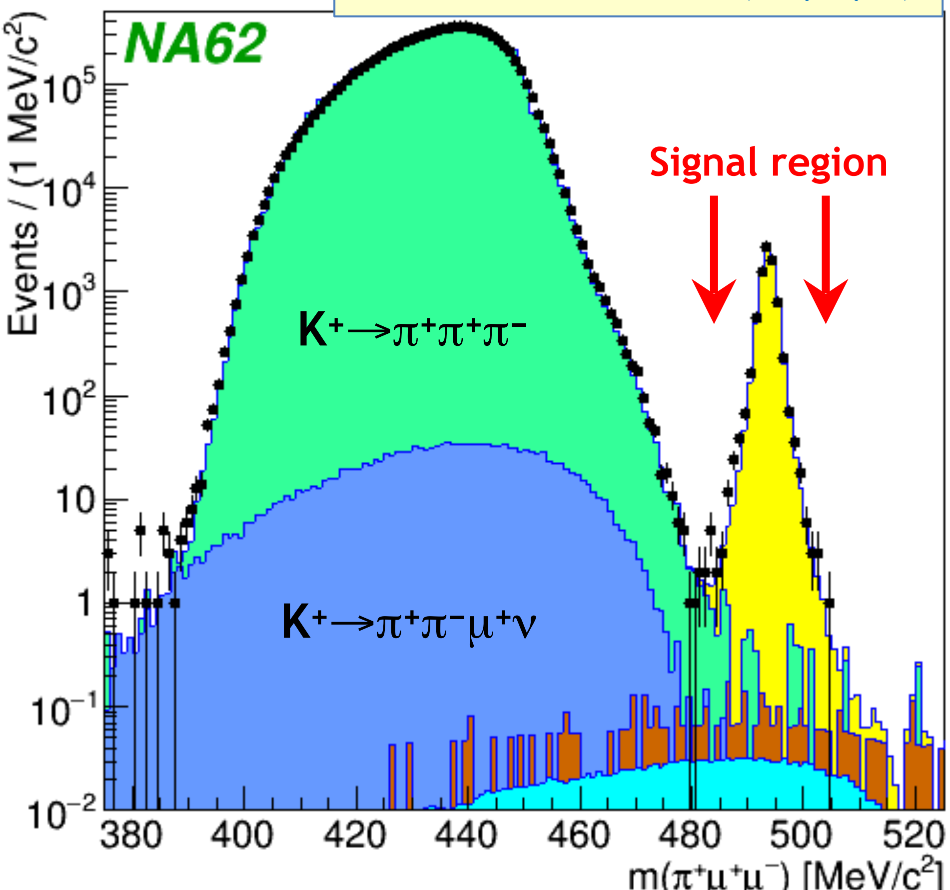
- Either lepton flavour or lepton number is violated, depending on the neutrino flavour.
- Normalisation to the SM decay $K^+ \to \pi^+ e^+ e^-$.

Mode / Region	Signal	Upper
$K^+ \to \pi^+\pi^+\pi^-$	< 0.07	1412 ± 11
$K^+ \to \pi^+\pi^+\pi^-$ (upstream)	0.06 ± 0.03	1.5 ± 0.3
$K^+ \to \pi^+\pi^- e^+\nu$	0.16 ± 0.02	867 ± 1
$K^+ \to \pi^+\pi^- e^+\nu$ (upstream)	0.01 ± 0.01	0.14 ± 0.03
$K^+ \to \pi^0_D e^+\nu$	0.01 ± 0.01	0.02 ± 0.01
$K^+ \to e^+\nu\mu^+\mu^-$	< 0.01	0.05 ± 0.02
Total	0.26 ± 0.04	2281 ± 11
Data	0	2271

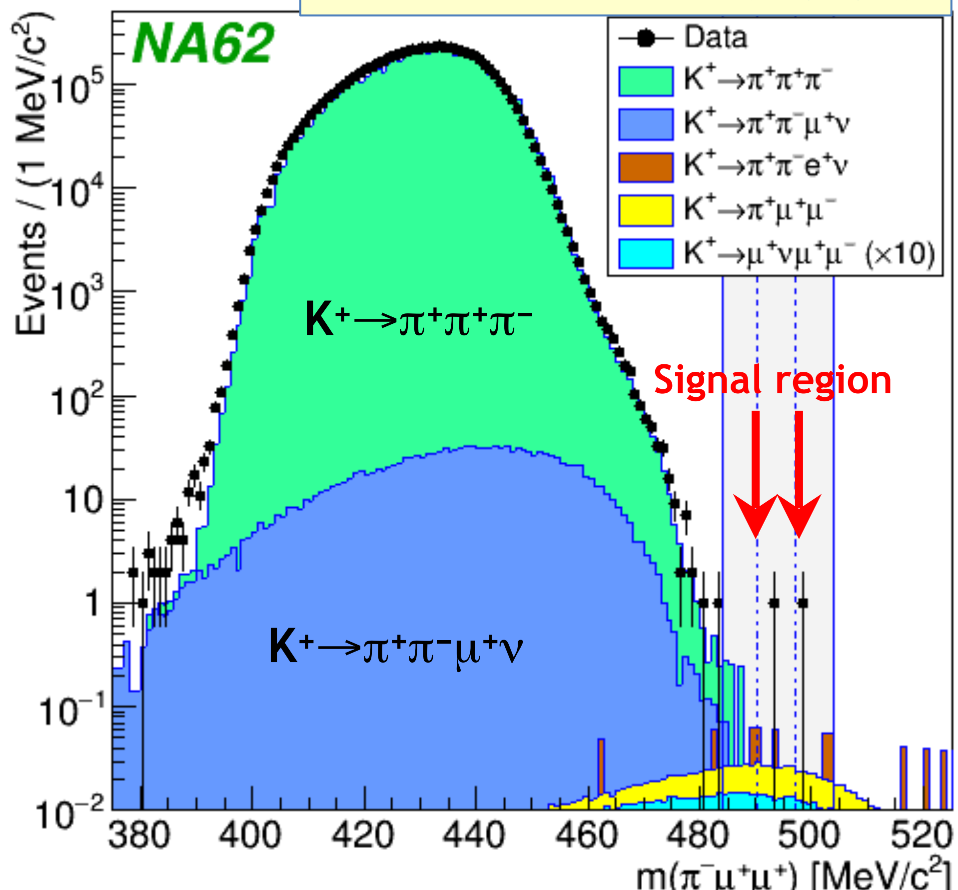
Expected background: **0.26±0.04** evt
Candidates observed: **0**
BR($K^+ \to \mu^- \nu e^+ e^+$)<$8.1 \times 10^{-11}$ at 90% CL

Search for $K^+ \rightarrow \pi^- \mu^+ \mu^+$ (2017 data)

SM selection: $m(\pi^+\mu^+\mu^-)$



LNV selection: $m(\pi^-\mu^+\mu^+)$



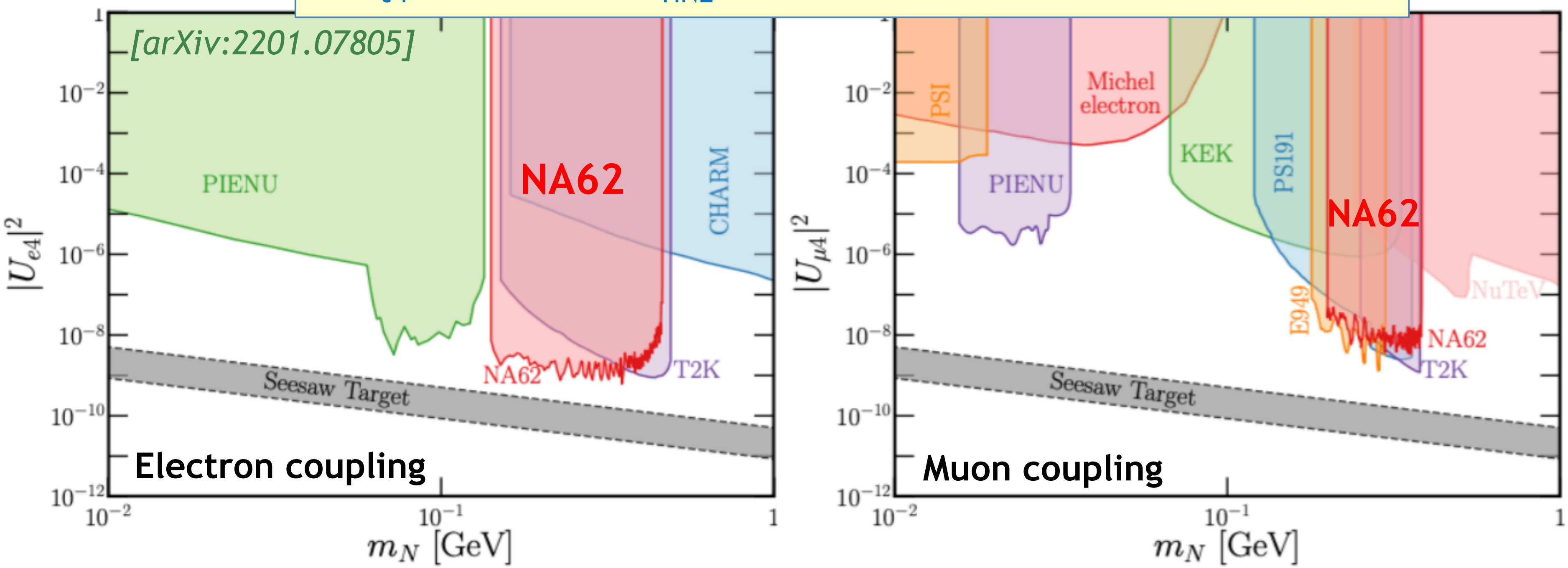
Candidates observed: **8357**
Background: **0.07%**
$BR(K^+ \rightarrow \pi^+\mu^+\mu^-) = (0.962 \pm 0.025) \times 10^{-7}$
K^+ decays in FV: **$(7.94 \pm 0.23) \times 10^{11}$**

Expected background: **0.91 ± 0.41** evt
Candidates observed: **1**
$BR(K^+ \rightarrow \pi^-\mu^+\mu^+) < 4.2 \times 10^{-11}$ at 90% CL

[PLB797 (2019) 134794]

HNL production search: results

$|U_{\ell 4}|^2$ limits vs m_{HNL} from production & decay searches



- For $|U_{e4}|^2$, complementary to search for $\pi^+ \to e^+ N$ at PIENU.
- For $|U_{\mu 4}|^2$, complementary to search for $K^+ \to \mu^+ N$ at BNL-E949.
- In both cases, complementary to HNL *decay* searches at T2K.
- Future kaon and pion experiments will approach the seesaw bound.

- An upper limit at **90%** CL: **$BR(K^+ \to \mu^+ \nu\nu\nu) < 1.0 \times 10^{-6}$**, and similar limits on **$BR(K^+ \to \mu^+ \nu X)$**, with **X=invisible**.

[PLB 807 (2020) 135599; PLB 816 (2021) 136259]

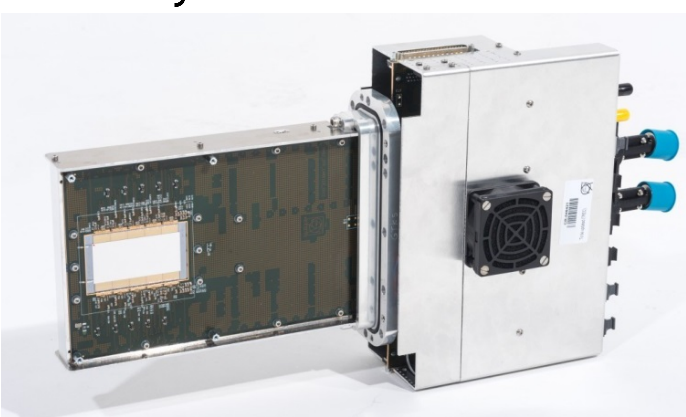
Long-term plan: $K^+\to\pi^+\nu\nu$ at CERN

An in-flight $K^+\to\pi^+\nu\nu$ experiment, up to **×6** the NA62 beam intensity, aiming at **~5%** precision.

- ✓ Challenge: **20 ps** time resolution for key detectors to keep random veto under control, while maintaining all other NA62 specifications.
- ✓ Challenges aligned with HL-LHC projects and future flavour/dark matter exp.

New pixel beam tracker (GTK):

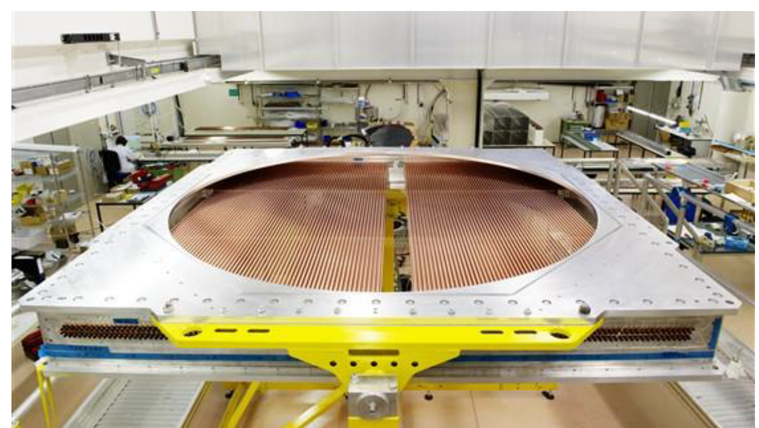
time resolution: **<50 ps** per plane;
pixel size: **<300×300 μm^2**;
efficiency: **>99%** per plane (incl.fill factor);
material budget : **0.3–0.5% X_0**;
beam intensity: **>3 GHz** on **30×60 mm^2**;
peak intensity: **>8.0 MHz/mm^2**.



A current NA62 GTK station

New STRAW spectrometer:

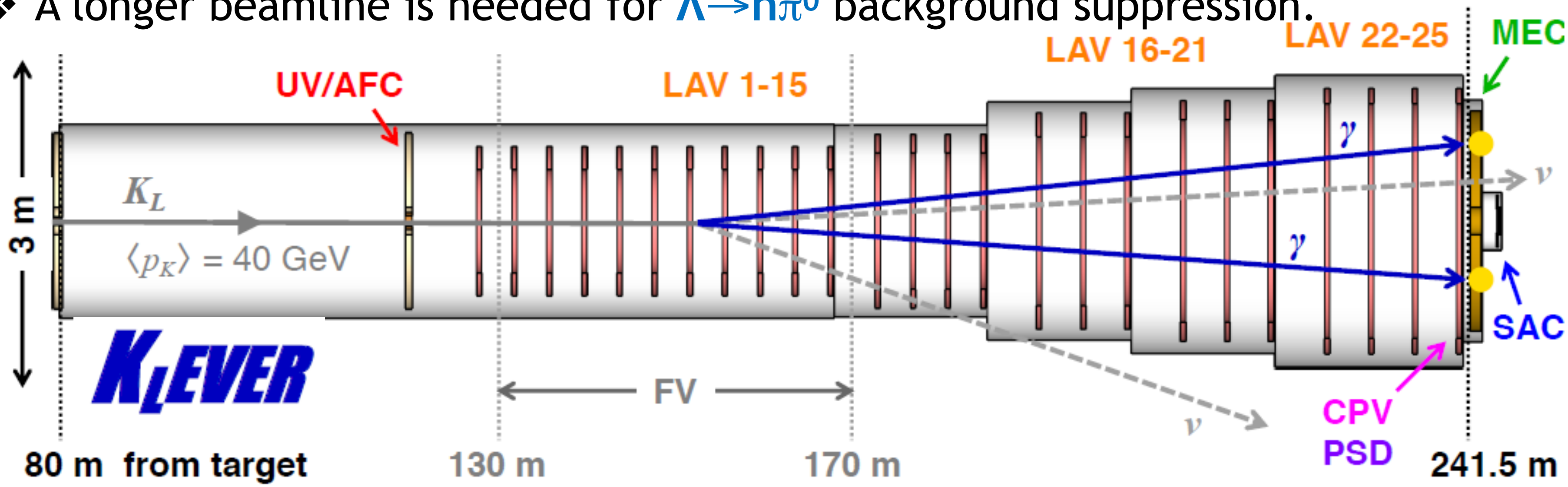
operation in vacuum;
straw diameter/length: **5 mm/2.2 m**;
trailing time resolution: **~6 ns** per straw;
maximum drift time: **~80 ns**;
layout: **~21000** straws (**4** chambers);
total material budget: **1.4% X_0**.



A current NA62 STRAW chamber

Long-term plan: $K_L \to \pi^0 \nu\nu$ at CERN

- **KLEVER**: a high-energy experiment (10^{19} pot/year) complementary to KOTO.
- Photons from K_L decays boosted forward: veto coverage only up to **100 mrad**.
- Vacuum tank layout and fiducial volume similar to NA62.
- A longer beamline is needed for $\Lambda \to n\pi^0$ background suppression.



Main detector/veto systems:

UV/AFC	Upstream veto/Active final collimator
LAV1-25	Large-angle vetoes (25 stations)
MEC	Main electromagnetic calorimeter
SAC	Small-angle vetoes
CPV	Charged particle veto
PSD	Pre-shower detector

Target sensitivity:

60 SM $K_L \to \pi^0 \nu\nu$ events with S/B~1 in 5 years of operation;

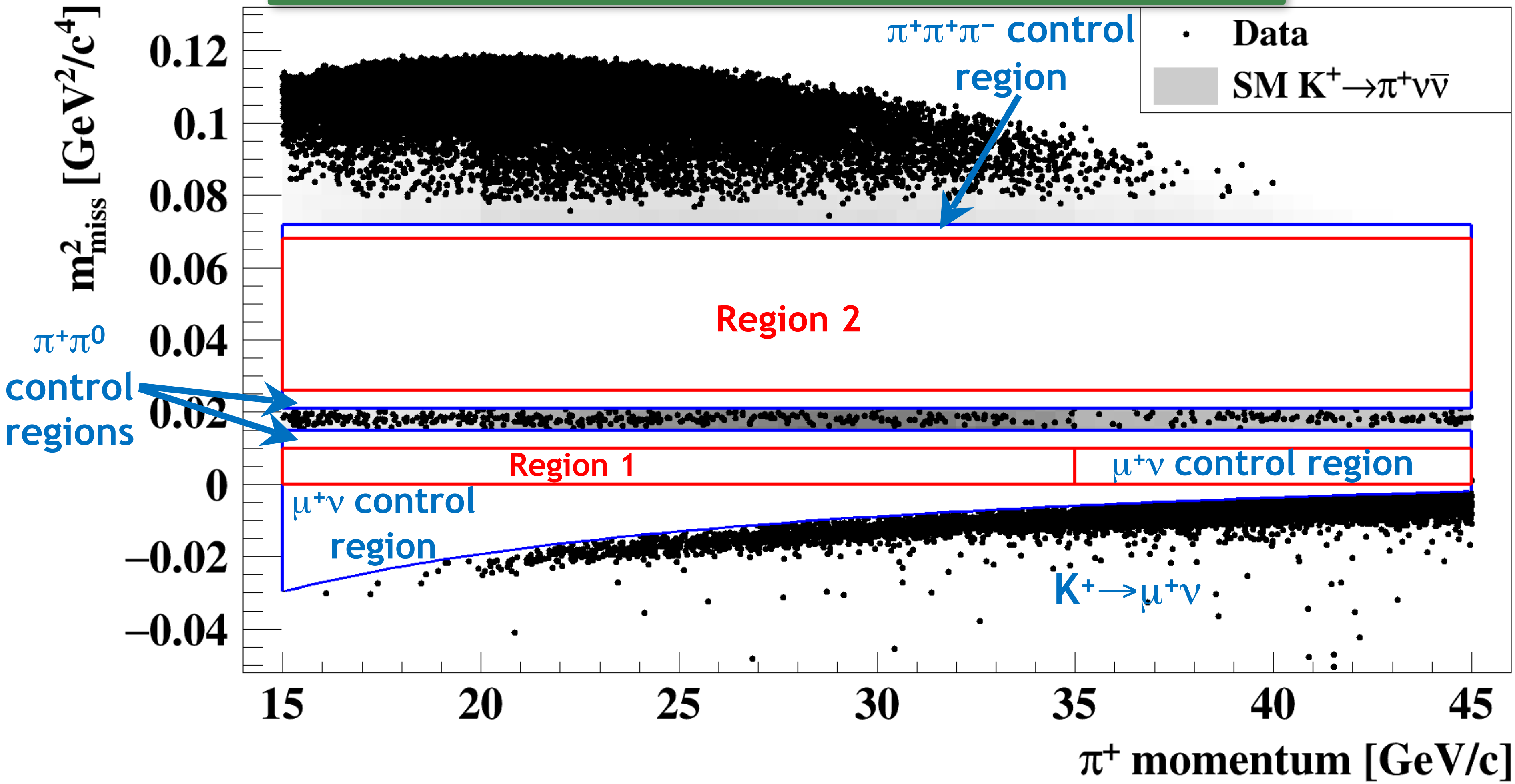
$\delta BR(K_L \to \pi^0 \nu\nu)/BR(K_L \to \pi^0 \nu\nu)$ ~ 20%.

Long-term plan: a hybrid experiment

- Availability of high-intensity K^+ and K_L beams at the SPS: measurements *at the boundary of "high-intensity NA62" and KLEVER*.
- An experiment for rare K_L decays with charged particle detection:
  - ✓ K_L beamline, as in KLEVER;
  - ✓ tracking and PID for secondary particles, as in NA62.
- Physics objectives:
  - ✓ $K_L \to \pi^0 \ell^+ \ell^-$: the excellent $\pi^0 \to \gamma\gamma$ mass resolution is essential to reduce the Greenlee background ($K_L \to \gamma\gamma \ell^+ \ell^-$);
  - ✓ lepton flavour violation: $K_L \to (\pi^0)(\pi^0)\mu e$, $K_L \to 2\mu 2e$;
  - ✓ precision measurements of rare radiative K_L decays;
  - ✓ hidden sectors in K_L decays.
- Characterisation of the neutral beam:
  - ✓ measurements of K_L, n, Λ and beam halo fluxes;
  - ✓ KOTO experience and KLEVER studies show this to be critical.
- **Just getting started!**

$K_{\pi\nu\nu}$ data after selection (2018)

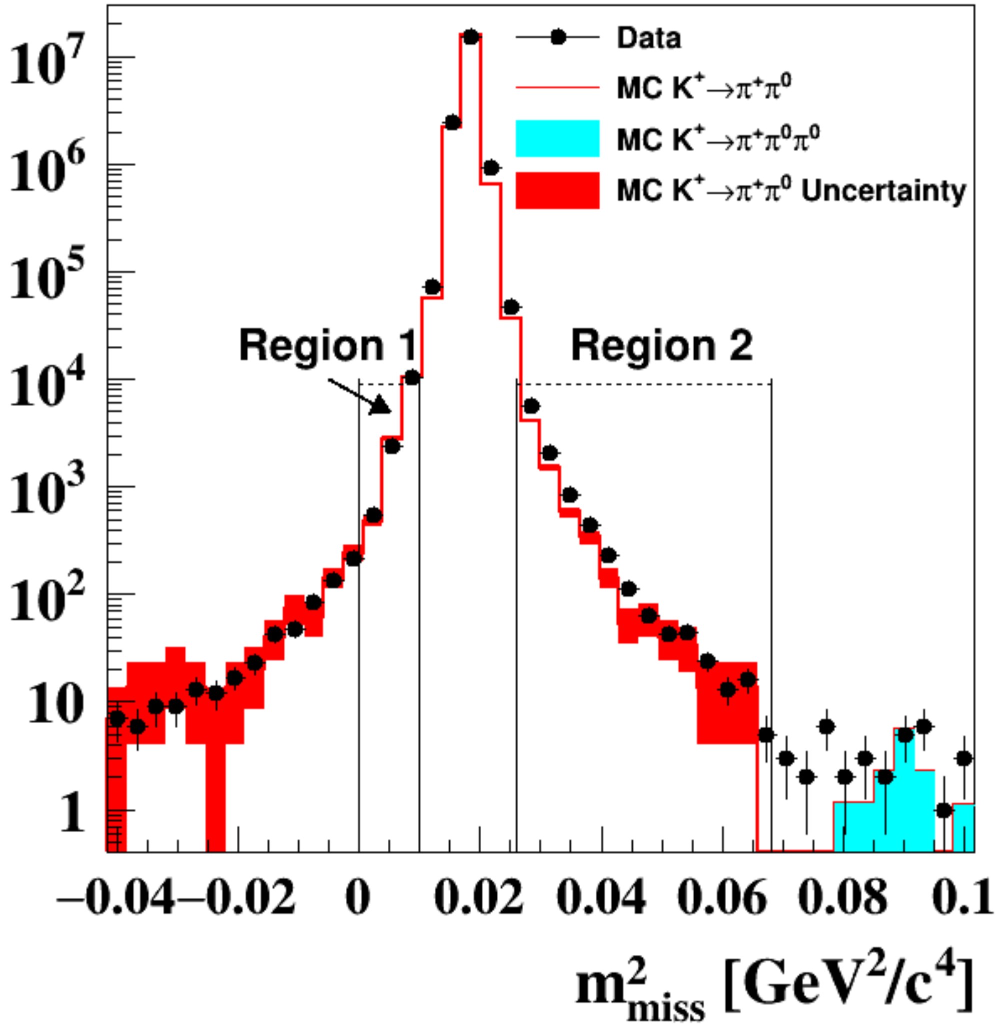
Signal and control regions are blinded



After background evaluation, the control regions are opened first, to validate background expectations with the data.

"Conventional" backgrounds

Missing mass spectrum of $\pi^+\pi^0$ events (control data)



The largest background from K^+ decays in the vacuum tank: $K^+\to\pi^+\pi^0$

($K^+\to\mu^+\nu$ is treated similarly)

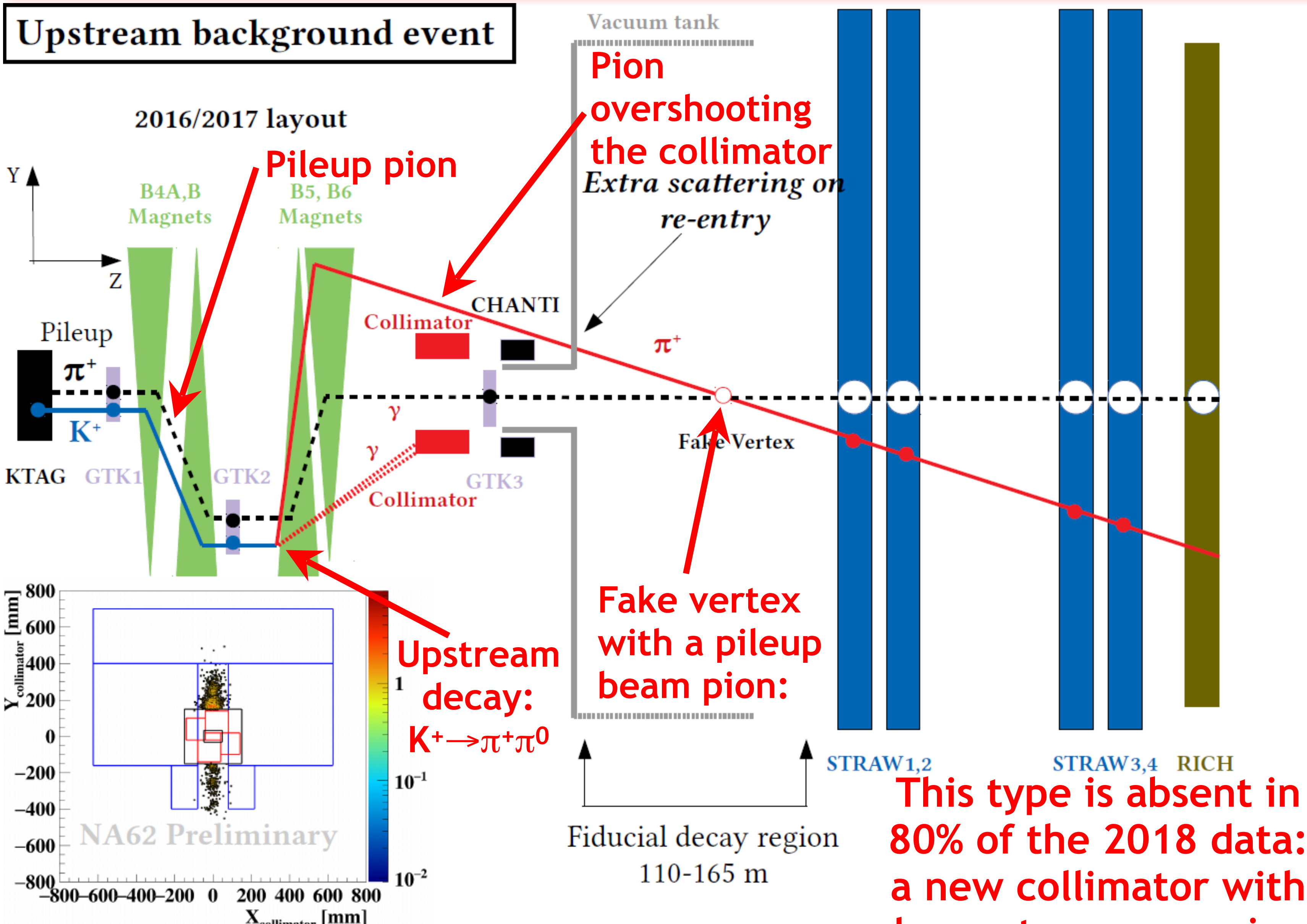
Data events in the $\pi^+\pi^0$ region after the $K_{\pi\nu\nu}$ selection (including π^0 rejection)

$$N_{BKG} = N(\pi^+\pi^0)\, f_{kin}$$

Expected numbers of $K^+\to\pi^+\pi^0$ events in signal regions after $K_{\pi\nu\nu}$ selection

Fraction of $\pi^+\pi^0$ events in signal regions measured from control data

Upstream background

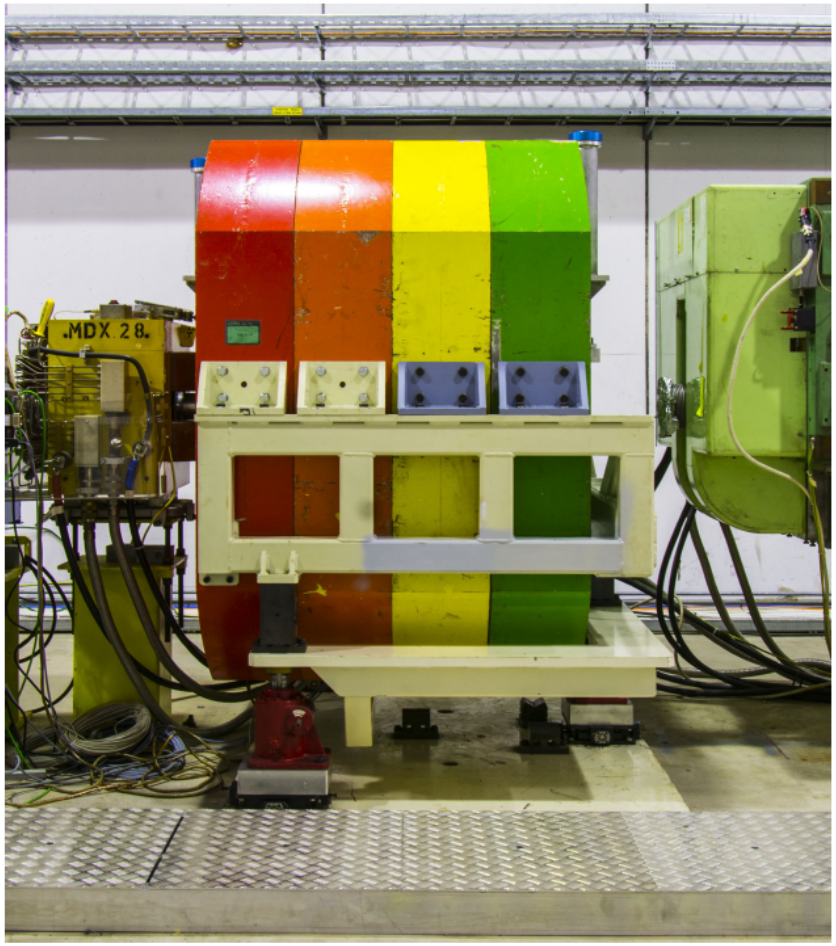


This type is absent in 80% of the 2018 data: a new collimator with larger transverse size

Collimator replacement

The old collimator

Current collimator (since June 2018)



❖ The current collimator allows for a looser event selection: signal acceptance $A_{\pi\nu\nu}$ improved from 4.0% to 6.4%.