Recent results from the NA62 experiment at CERN

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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

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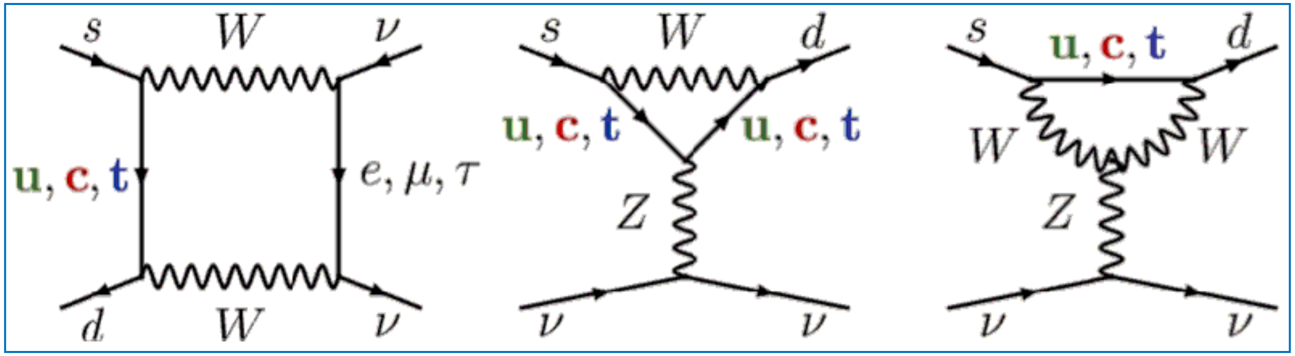
$K \to \pi\nu\nu$ in the Standard Model

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.

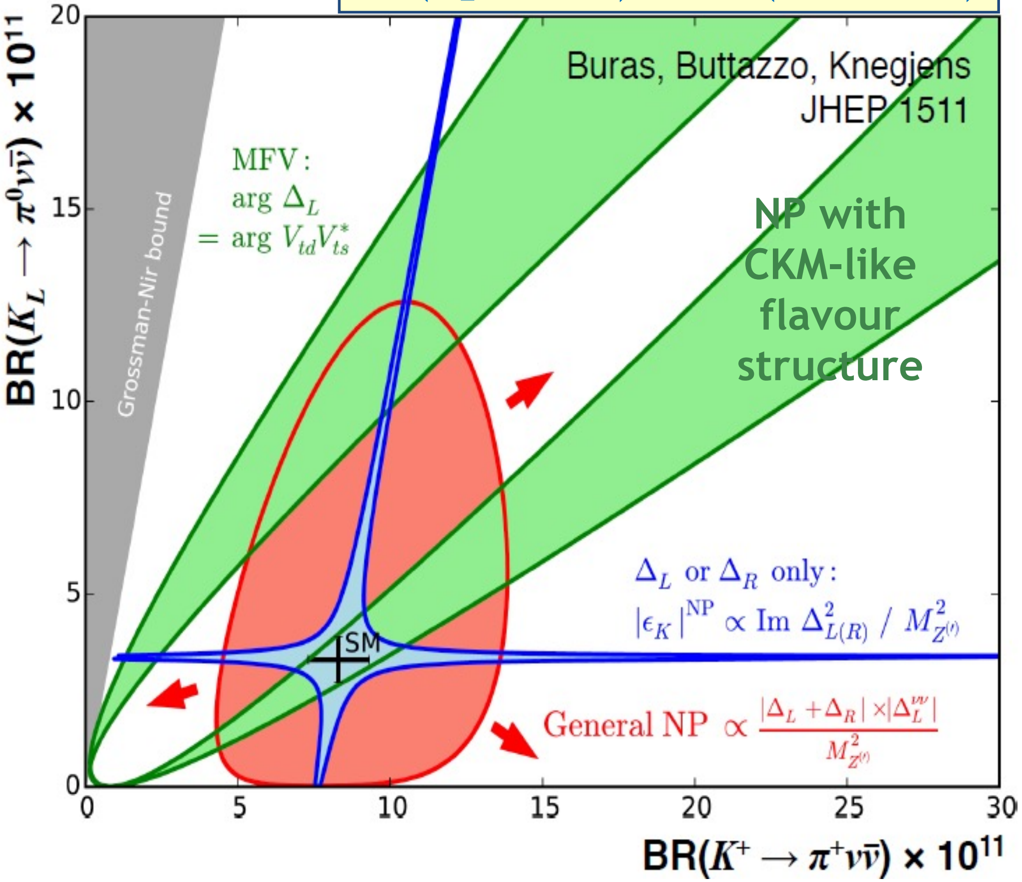
Mode	Standard Model BR	Experimental status
$K^+\to\pi^+\nu\nu$	$(8.60\pm0.42)\times10^{-11}$	$(10.6\pm4.0)\times10^{-11}$ (NA62 Run 1)
$K_L\to\pi^0\nu\nu$	$(2.94\pm0.15)\times10^{-11}$	$BR<300\times10^{-11}$ at 90% CL (KOTO 2015 data)

Standard Model BR: a new $|V_{cb}|$ and γ-independent determination.
[Buras and Venturini, arXiv:2109.11032]

$K \to \pi\nu\nu$ 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

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

Kaons: other opportunities

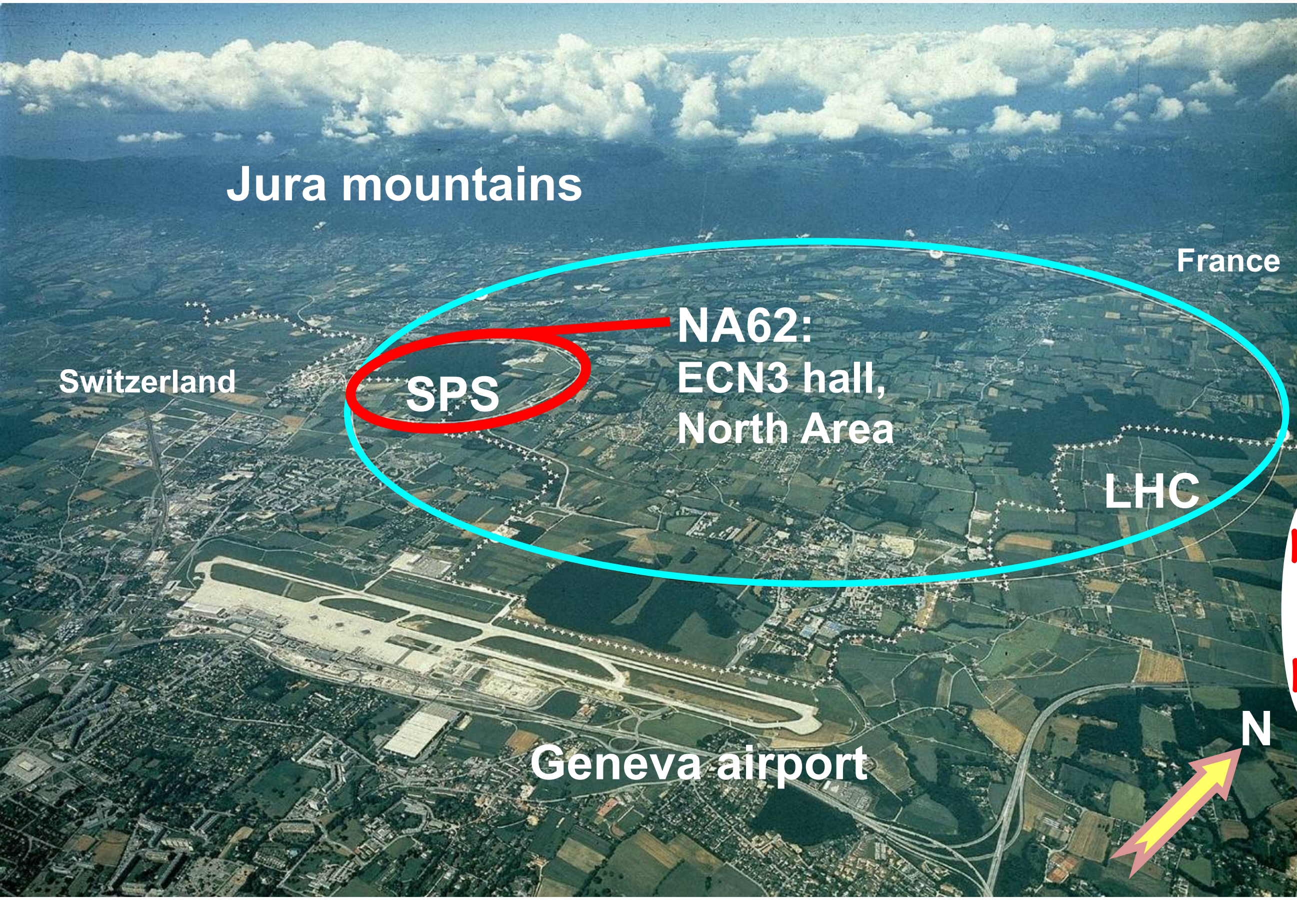
- Direct and indirect CP violation in $K^0 \to \pi\pi$ decays (ε, ε'), and the $K_L - K_S$ mass difference (ΔM_K) [no experiments planned]
  - ✓ Improving capabilities of lattice QCD to provide accurate SM predictions: opportunities for discovery of new physics.
  - ✓ SM precision on ε'/ε can match that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



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	

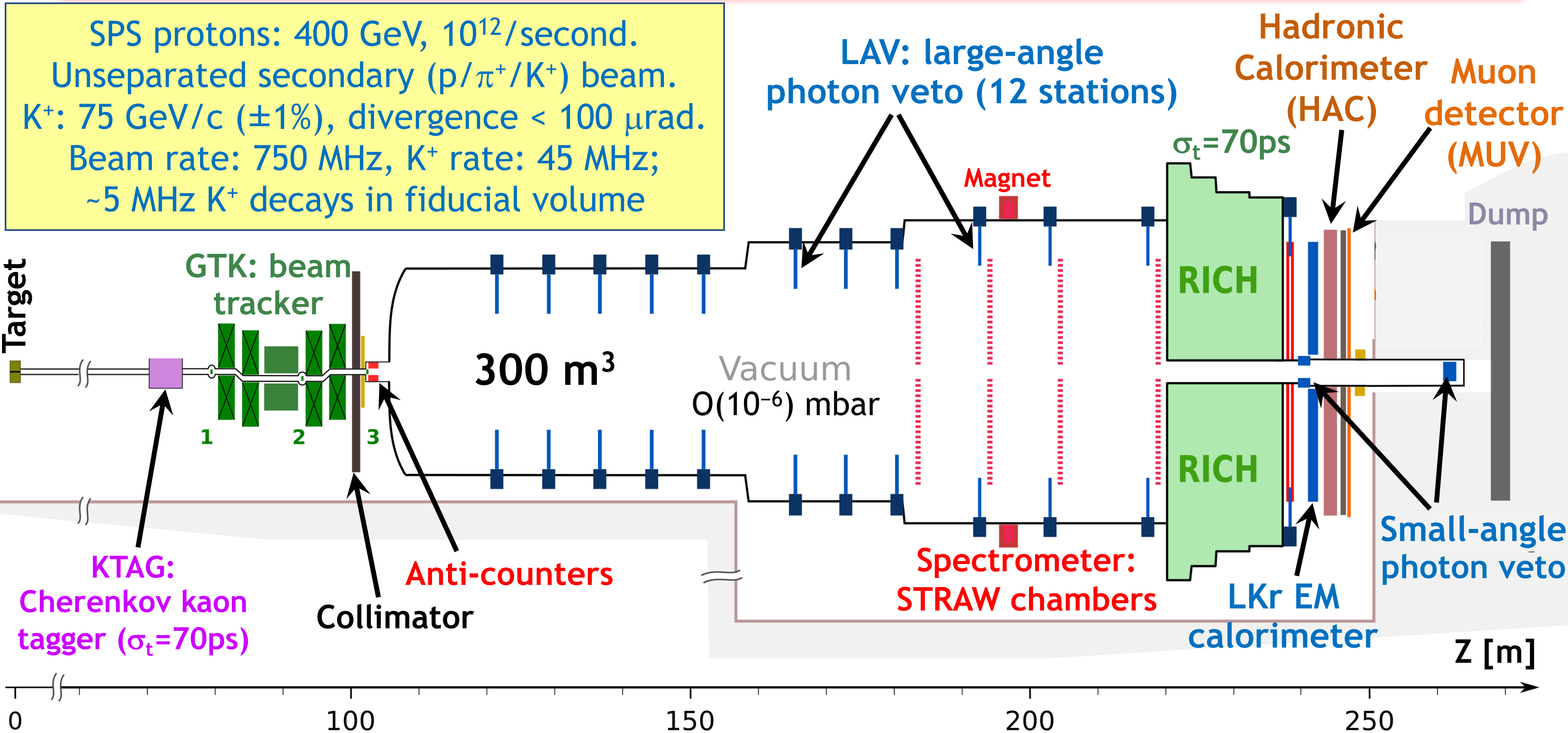
Main NA62 goal: $K^+\to\pi^+\nu\nu$ measurement to 10% precision with a novel decay-in-flight technique.

Currently ~300 participants from ~30 institutions.

NA62 collaboration,
JINST 12 (2017) P05025

The NA62 experiment

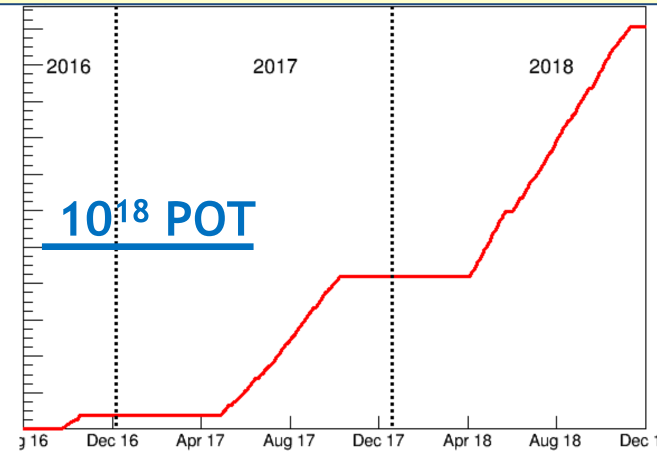
SPS protons: 400 GeV, 10^{12}/second.
Unseparated secondary ($p/\pi^+/K^+$) beam.
K^+: 75 GeV/c (±1%), divergence < 100 μrad.
Beam rate: 750 MHz, K^+ rate: 45 MHz;
~5 MHz K^+ decays in fiducial volume



- ❖ 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 $E_{\pi0}$>40 GeV) ~10^{-8}.
- ❖ Particle ID (RICH+LKr+HAC+MUV): ~10^{-8} muon suppression.

NA62 Run 1 dataset: 2016–18

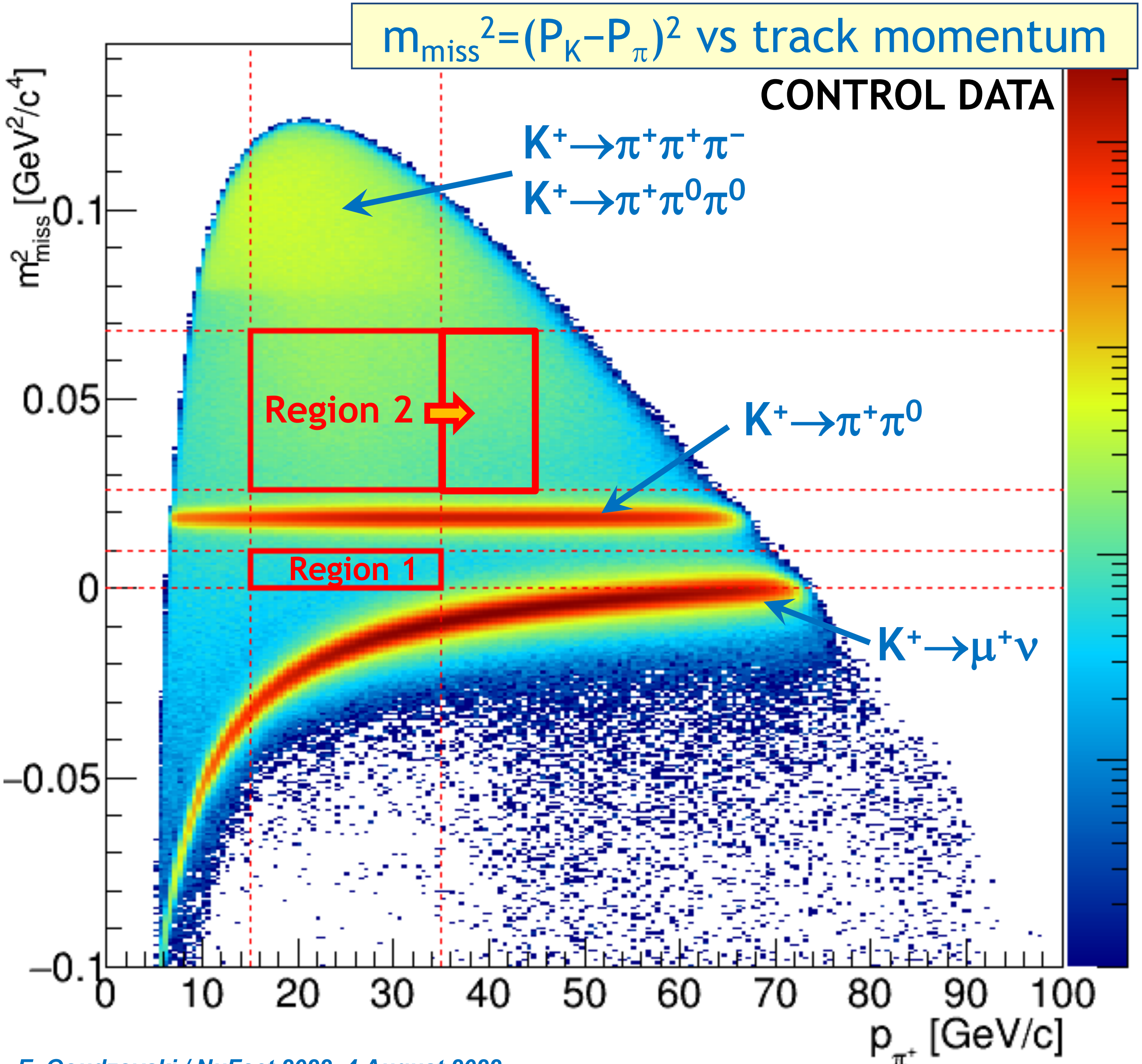
Run 1 integrated luminosity



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	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$
$BR_{SES}\times10^{10}$	**0.54±0.04**	**0.14±0.01**
$N^{exp}_{\pi\nu\bar{\nu}}$	**1.56±0.21**	**6.02±0.82**

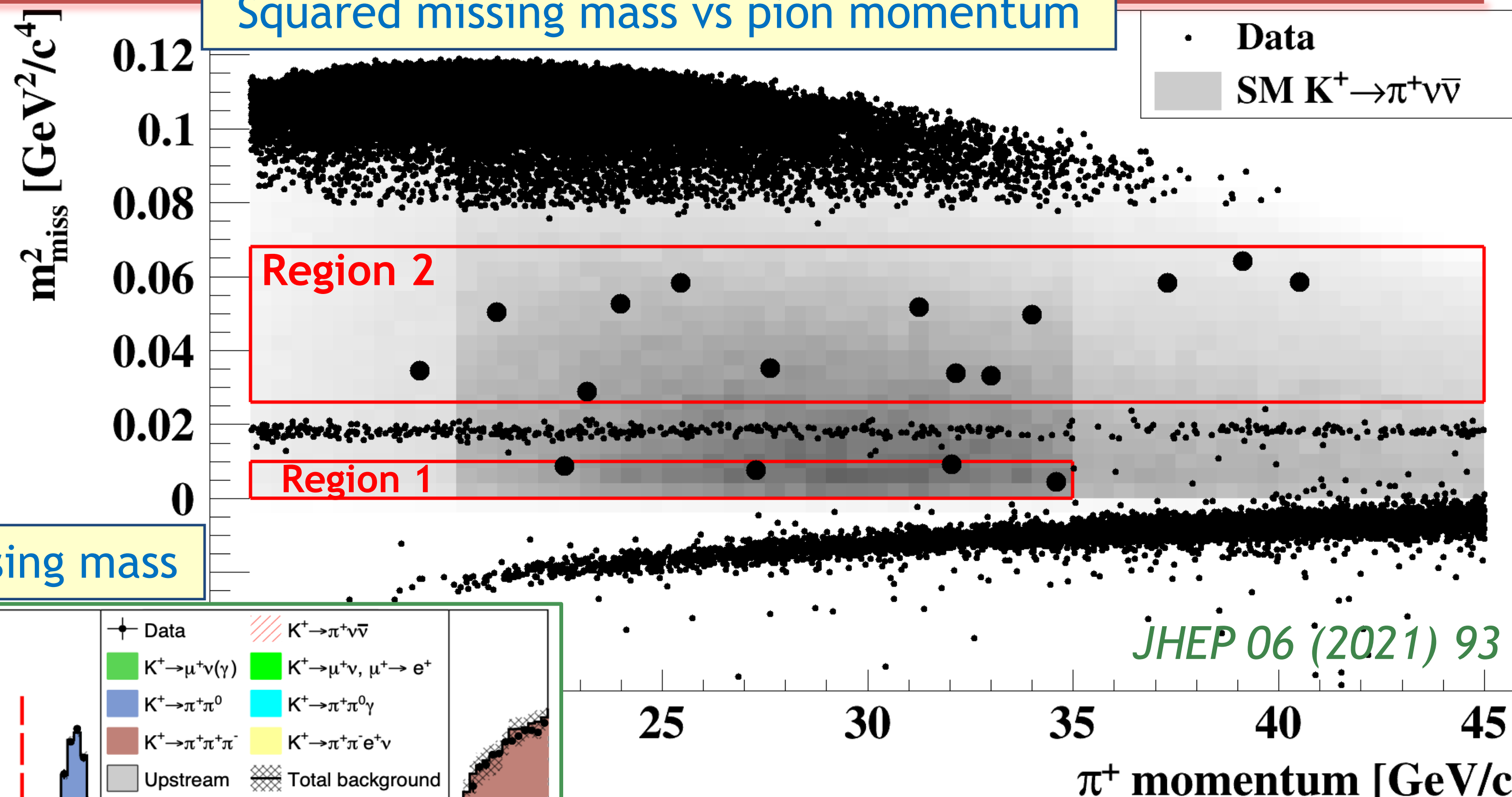
Data-driven background estimates

Dominant background: a data-driven estimate

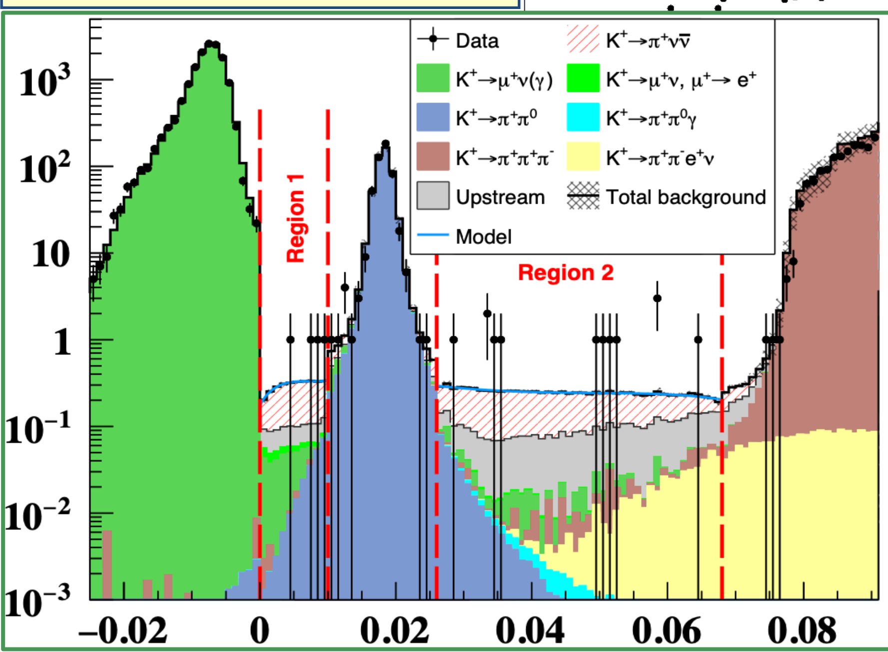
- Most background is not due to K^+ decays in the vacuum tank.
- Improved the beamline layout and new upstream veto detectors bring the Run 2 measurement into a low-background regime.

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

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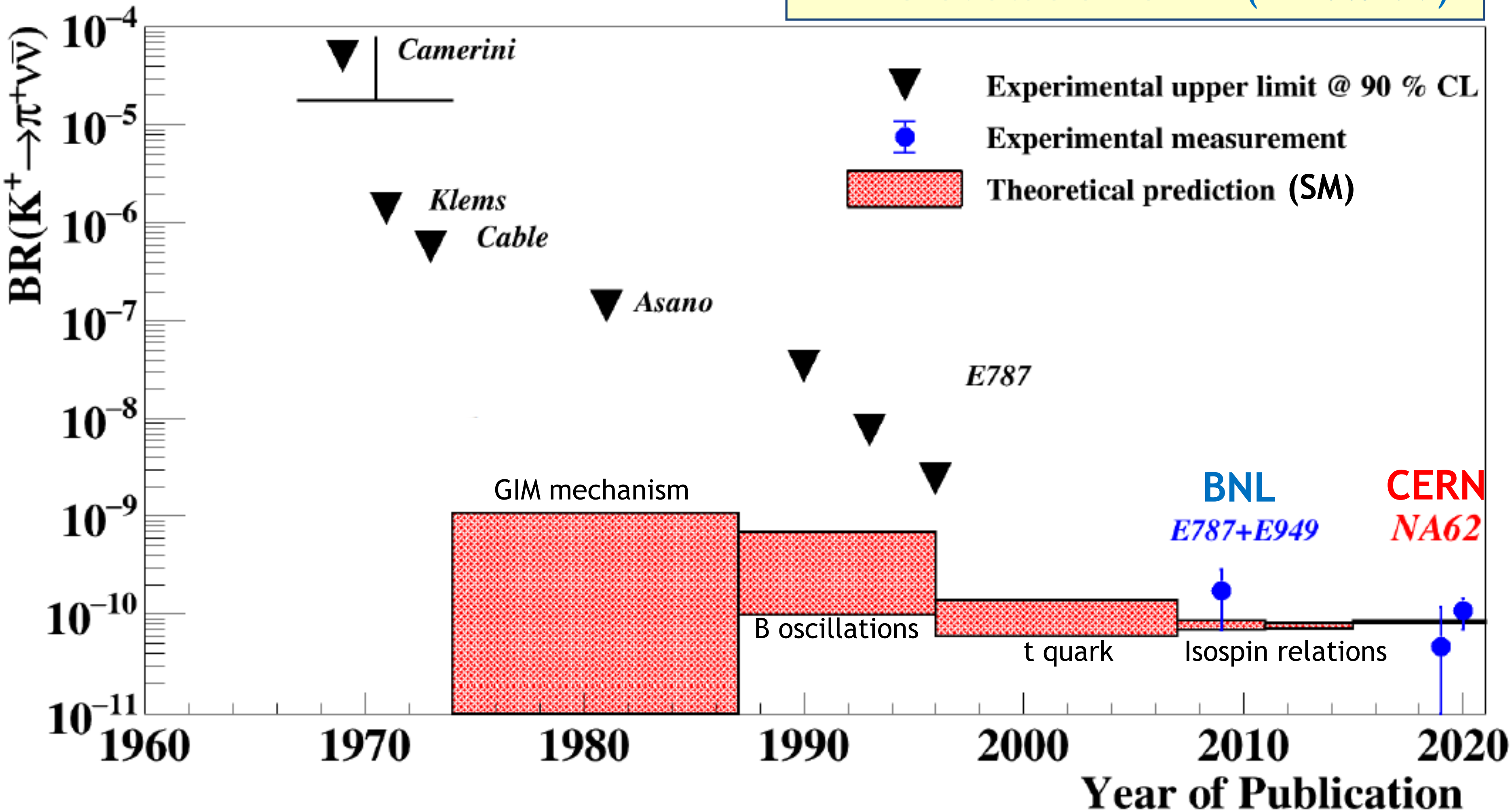
Time evolution of $BR(K^+ \to \pi^+ \nu\nu)$

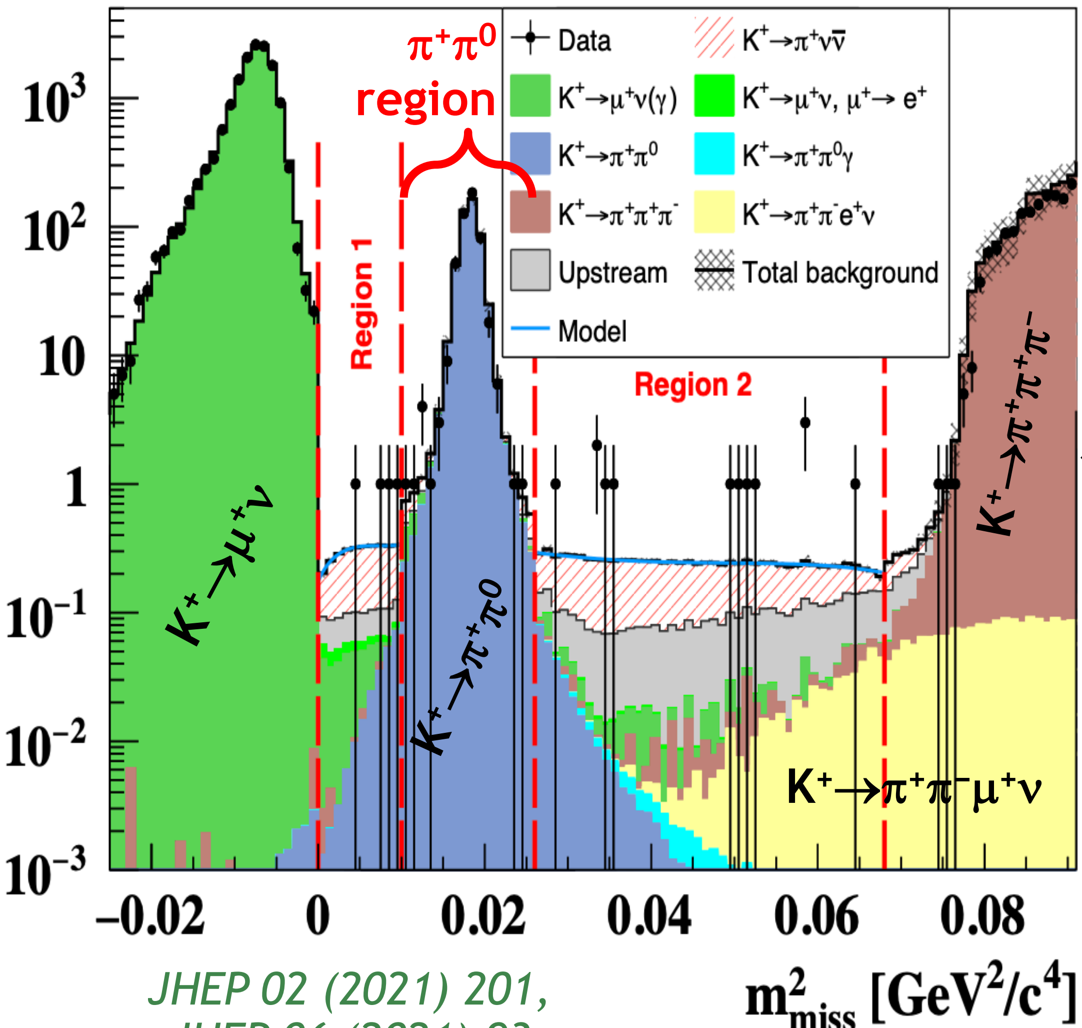


NA62 Run 1: $$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$$

(3.4σ significance)

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

Squared missing mass (2018 data)

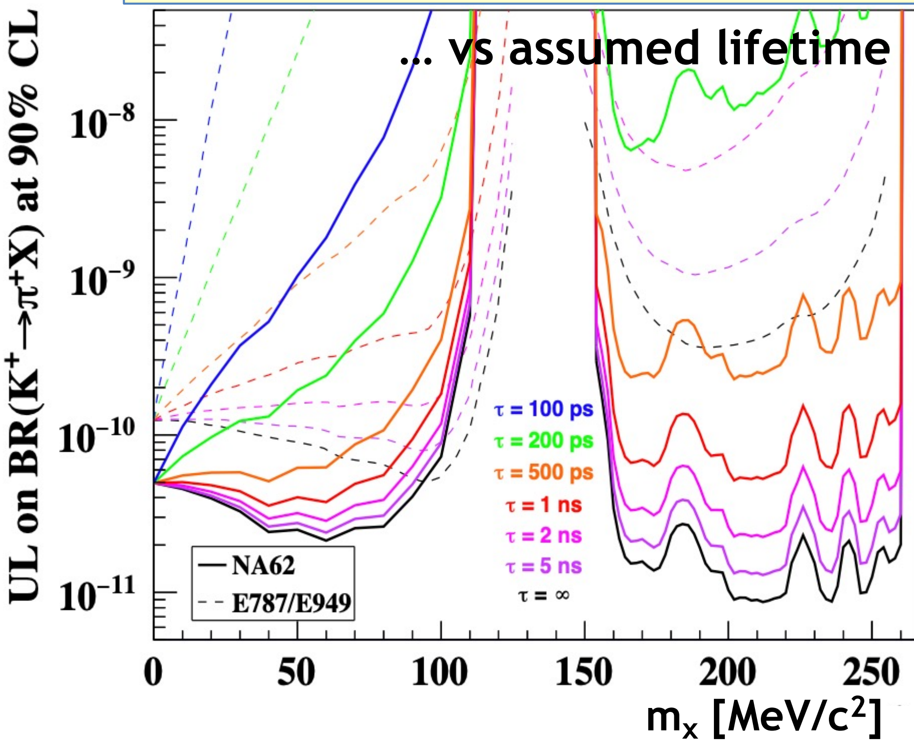


JHEP 02 (2021) 201,
JHEP 06 (2021) 93

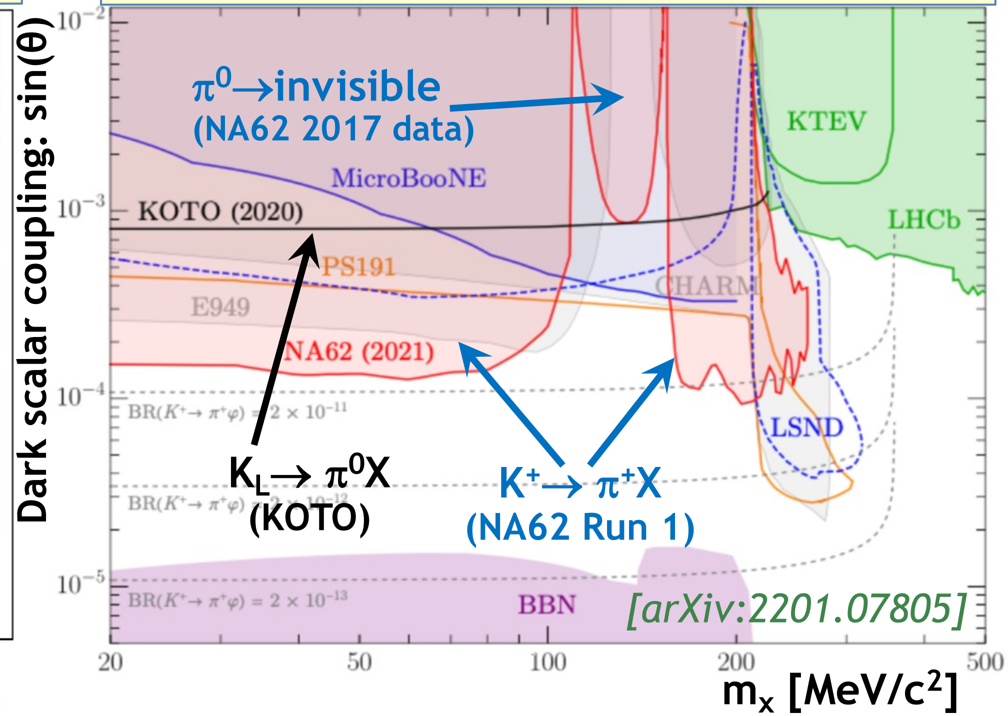
- Signal regions **R1**,**R2**: search for $K^+ \to \pi^+ X$ (X=invisible), **$0 \le m_X \le 110$ MeV/c^2** and **$154 \le m_X \le 260$ MeV/c^2**.
  - ✓ Interpretation: dark scalar, ALP, QCD axion, axiflavon.
  - ✓ Main background: $K^+ \to \pi^+ \nu\nu$.
- The $\pi^+\pi^0$ region: search for **$\pi^0 \to$ invisible**.
  - ✓ SM rate: $BR(\pi^0 \to \nu\nu) \sim 10^{-24}$.
  - ✓ 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 $K^+ \to \pi^+ X$ (Run 1)

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



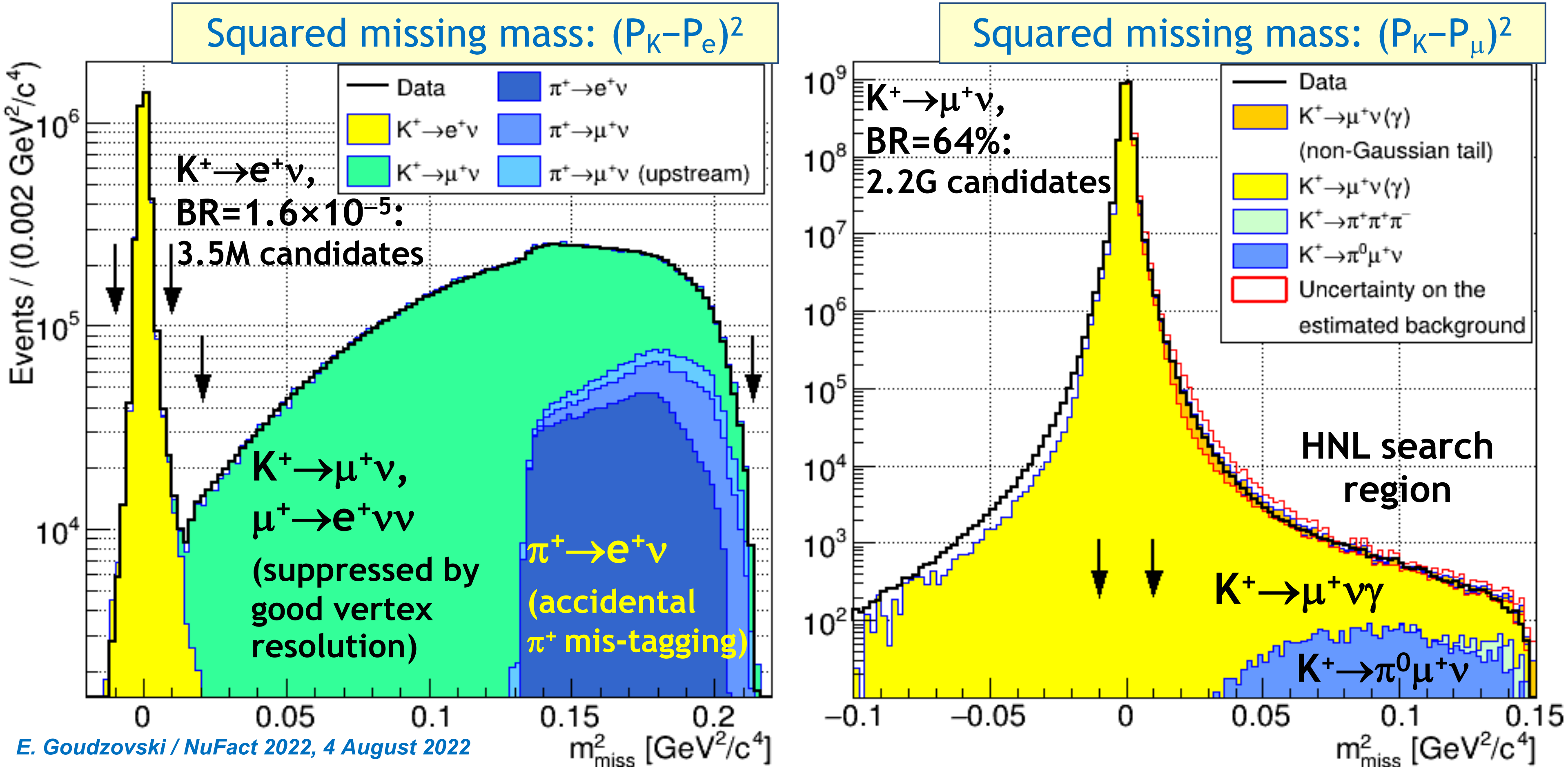
Dark scalar searches below the K mass



- Mass resolution improves with m_X and is $\delta m_X \sim 40$ MeV/c^2 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]*

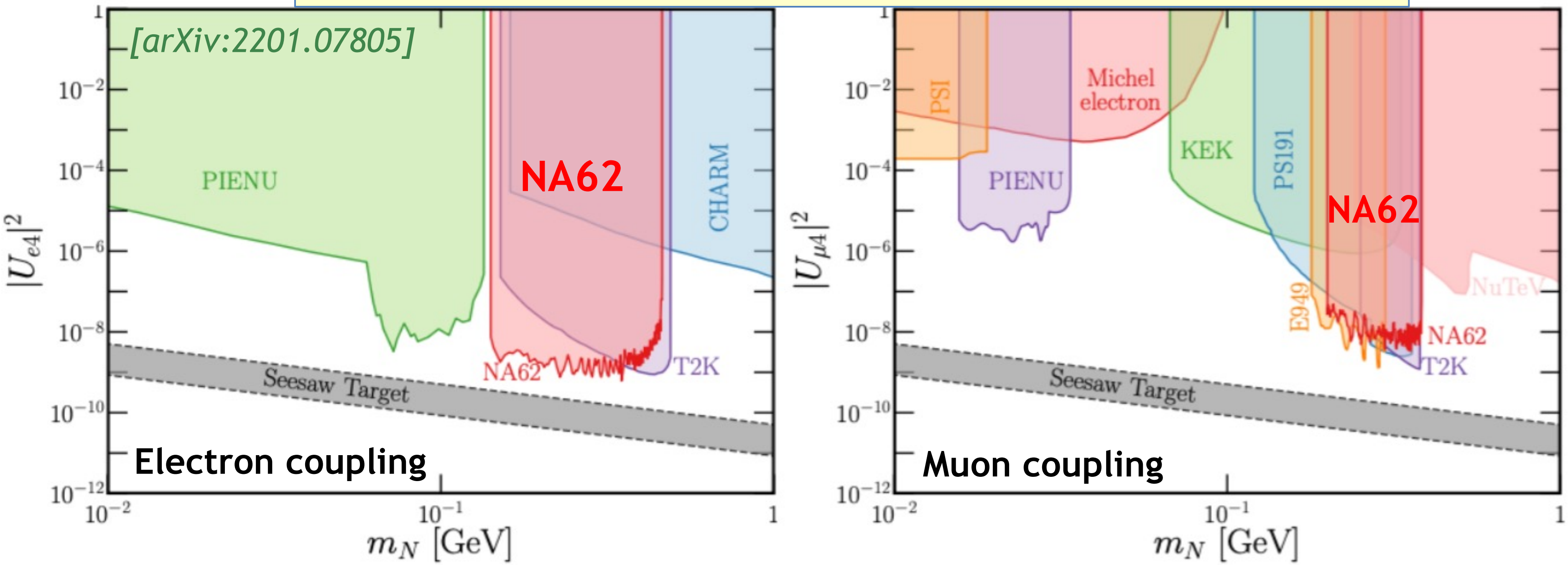
HNL production search: data sample

- 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**.



HNL production search: results

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



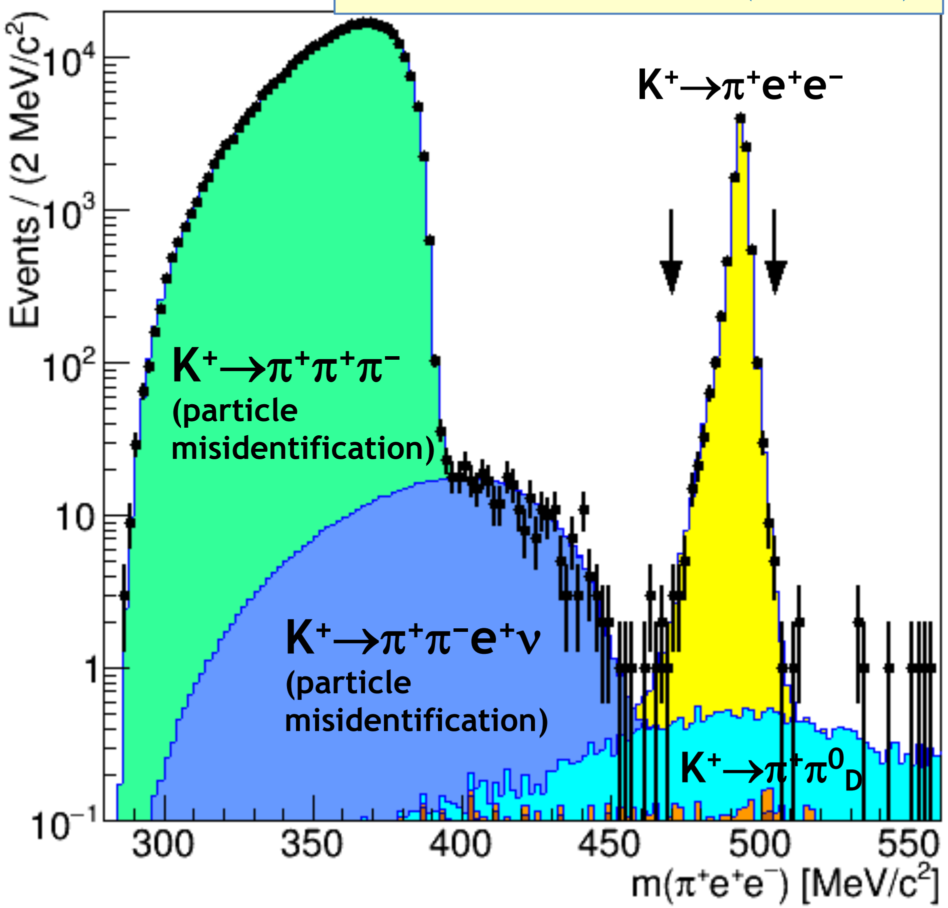
- For $|U_{e4}|^2$, complementary to search for $\pi^+ \to e^+ N$ at PIENU.
- For $|U_{\mu 4}|^2$, complementary to search for $K^+ \to \mu^+ N$ at BNL-E949.
- In both cases, complementary to HNL *decay* searches at T2K.
- Future kaon and pion experiments will approach the seesaw bound.

- 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]

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

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

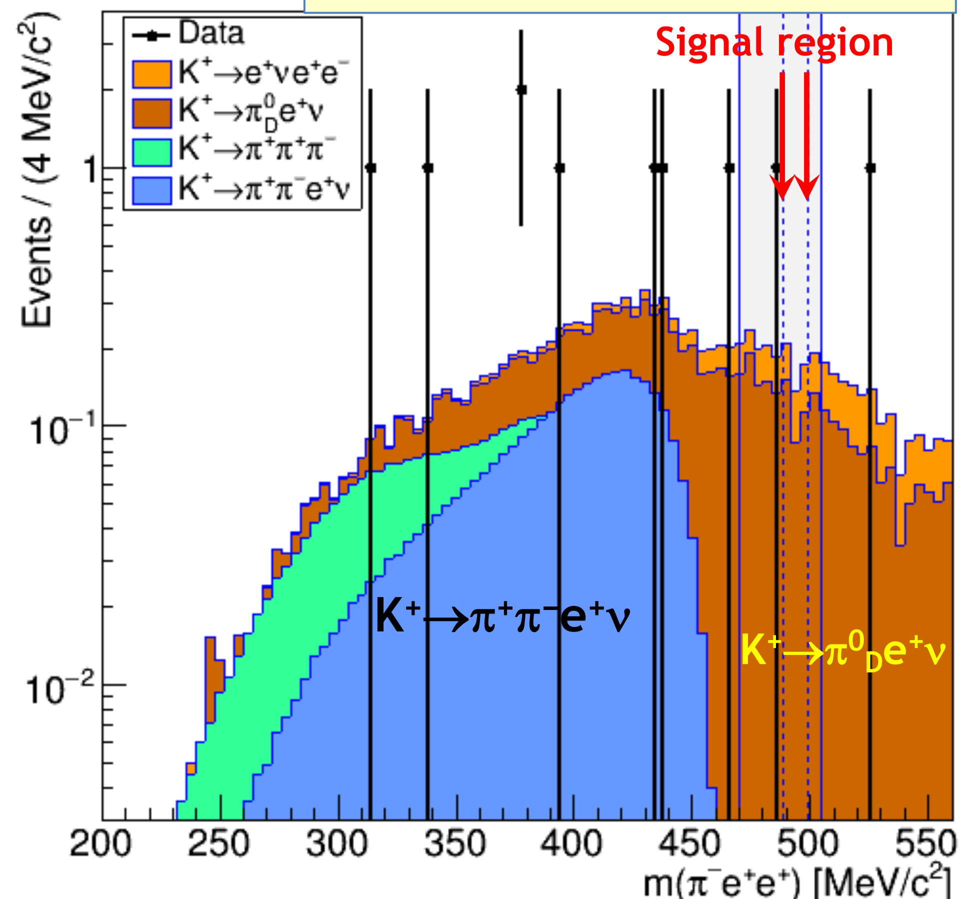


Candidates observed: **11041**

$BR(K^+ \to \pi^+ e^+ e^-) = (3.00 \pm 0.09) \times 10^{-7}$

K^+ decays in FV: **$(1.015 \pm 0.032) \times 10^{12}$**

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



Expected background: **0.43 ± 0.09** evt

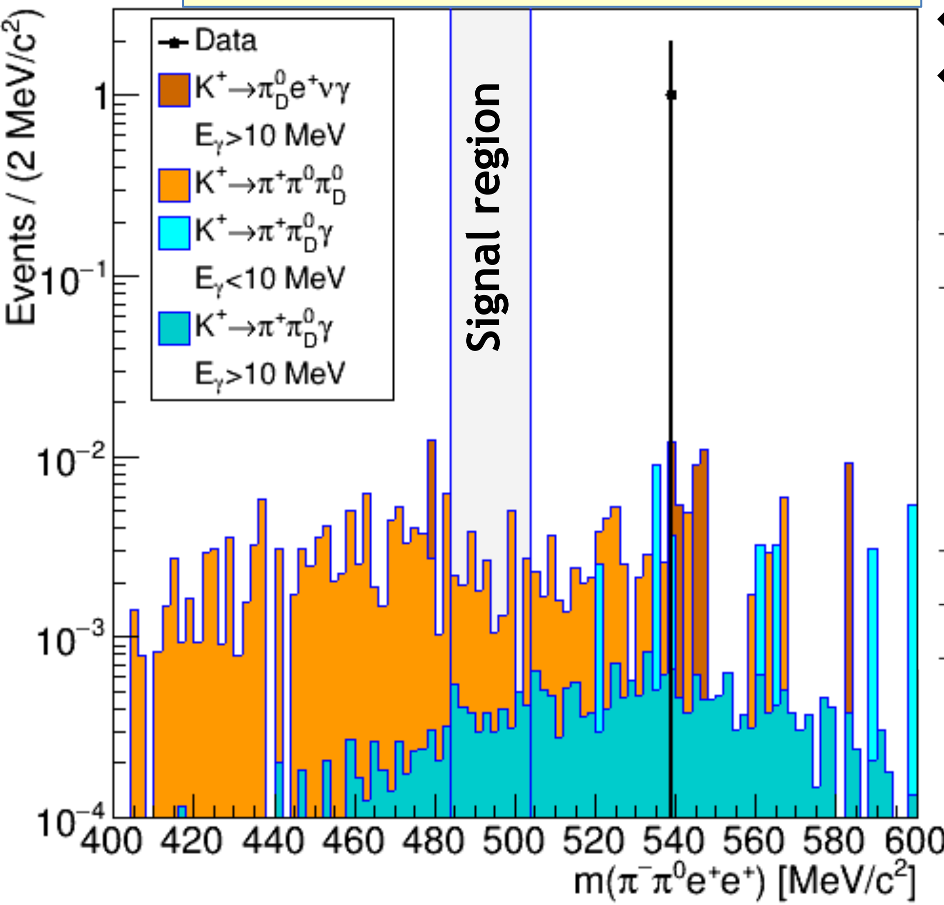
Candidates observed: **0**

$BR(K^+ \to \pi^- e^+ e^+) < 5.3 \times 10^{-11}$ at 90% CL

[PLB830 (2022) 137172]

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

LNV selection: $m(\pi^-\pi^0 e^+ e^+)$



[PLB830 (2022) 137172]

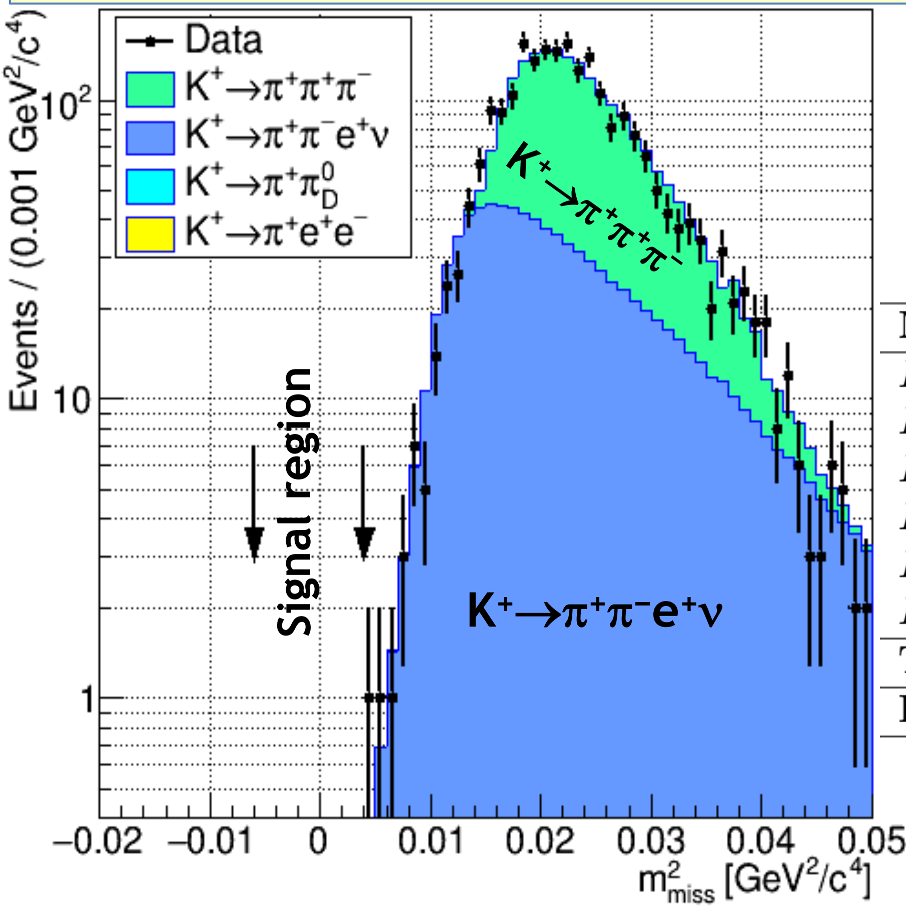
- Normalisation to the SM decay $K^+\to\pi^+e^+e^-$.
- The neutral pion is reconstructed in the LKr calorimeter via $\pi^0\to\gamma\gamma$ decay.

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
$BR(K^+\to\pi^-\pi^0e^+e^+)<8.5\times10^{-10}$ 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]

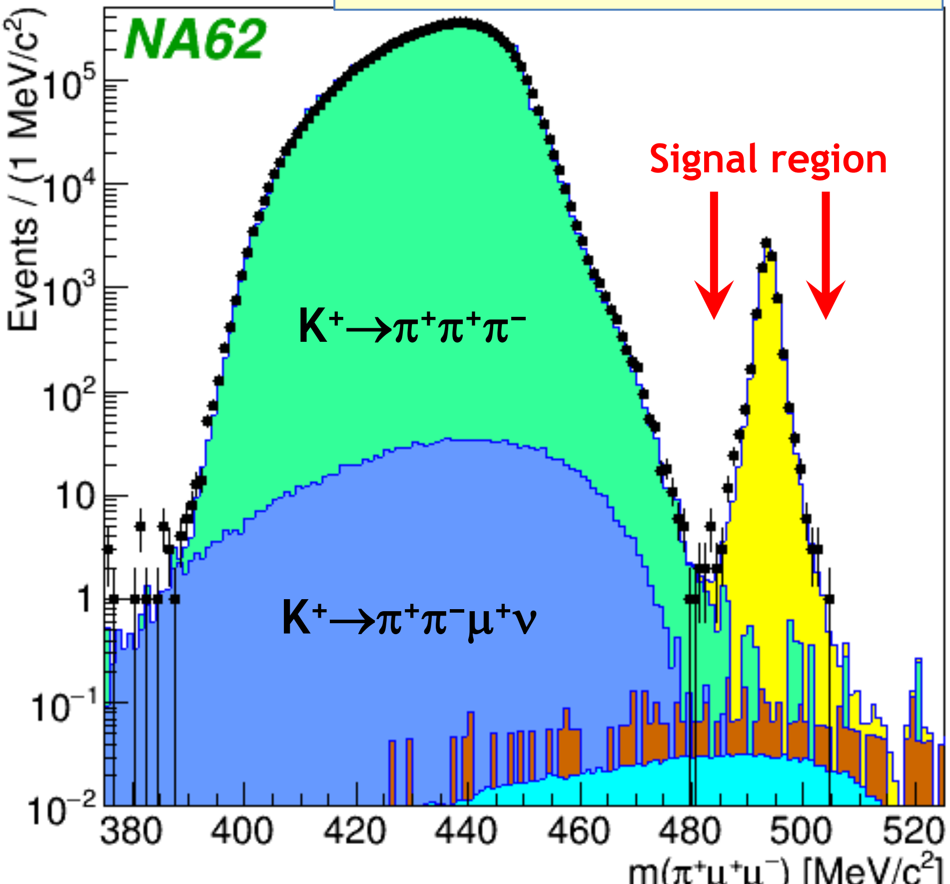
- Either lepton flavour or lepton number is violated, depending on the neutrino flavour.
- Normalisation to the SM decay $K^+ \to \pi^+ e^+ e^-$.

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

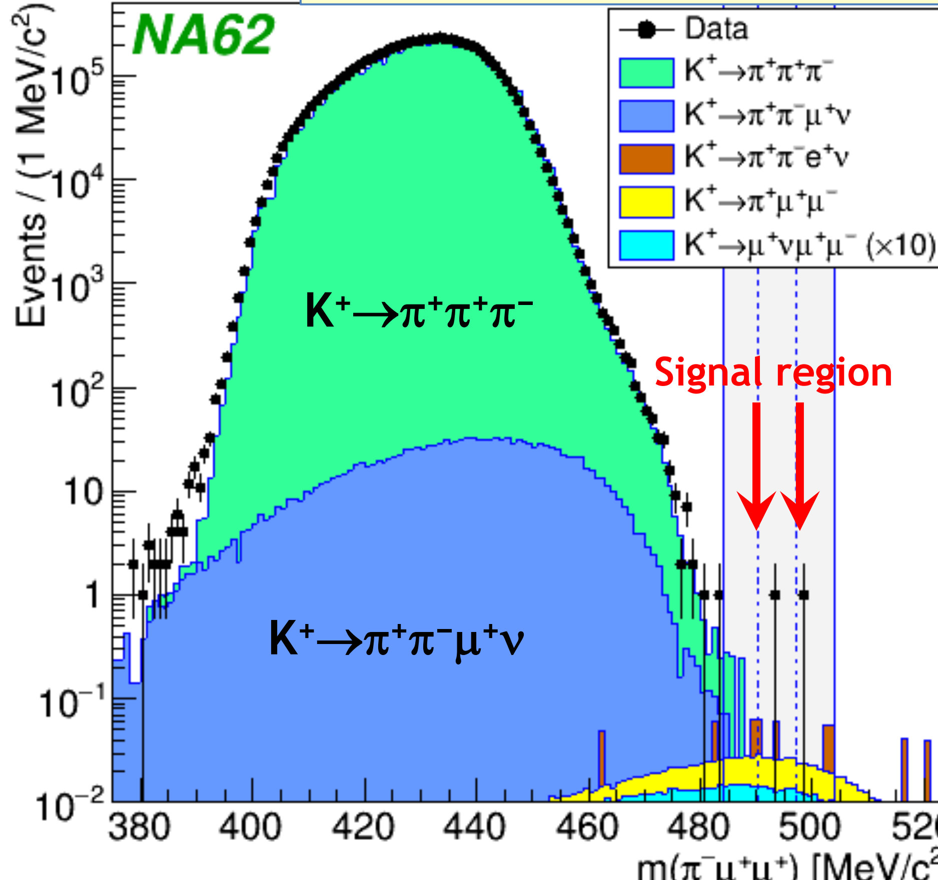
Expected background: **0.26±0.04** evt
Candidates observed: **0**
$BR(K^+ \to \mu^- \nu e^+ e^+) < 8.1 \times 10^{-11}$ at 90% CL

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

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



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



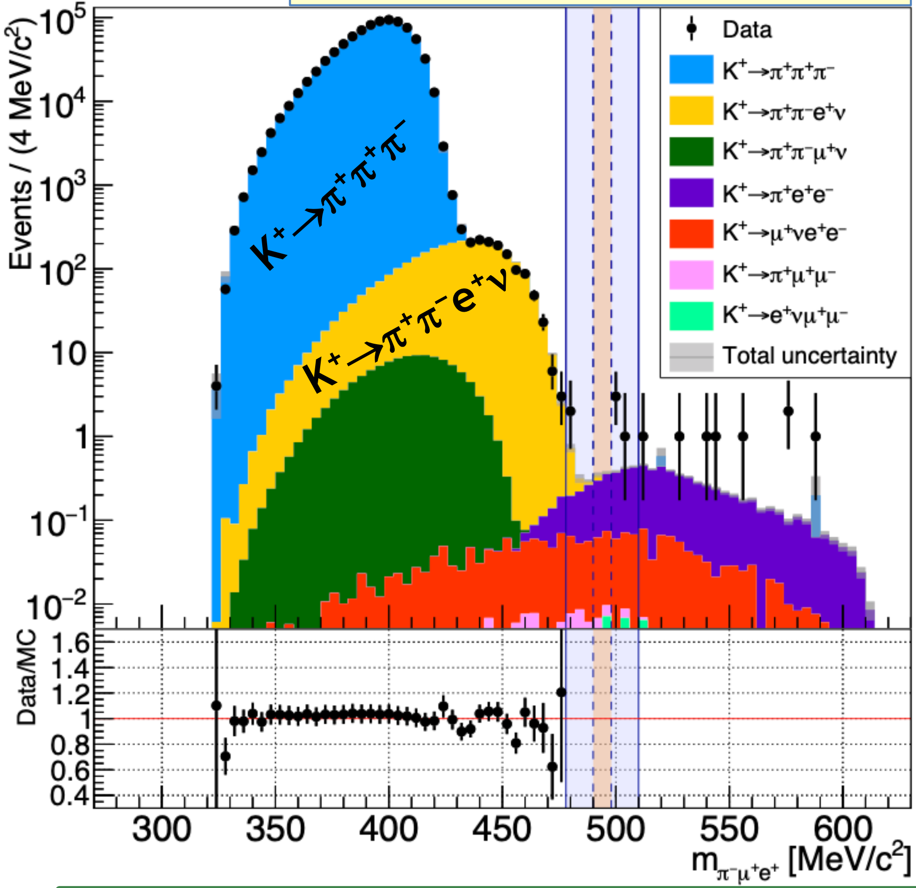
Candidates observed: **8357**
Background: **0.07%**
$BR(K^+ \to \pi^+\mu^+\mu^-) = (0.962 \pm 0.025) \times 10^{-7}$
K^+ decays in FV: $(7.94 \pm 0.23) \times 10^{11}$

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

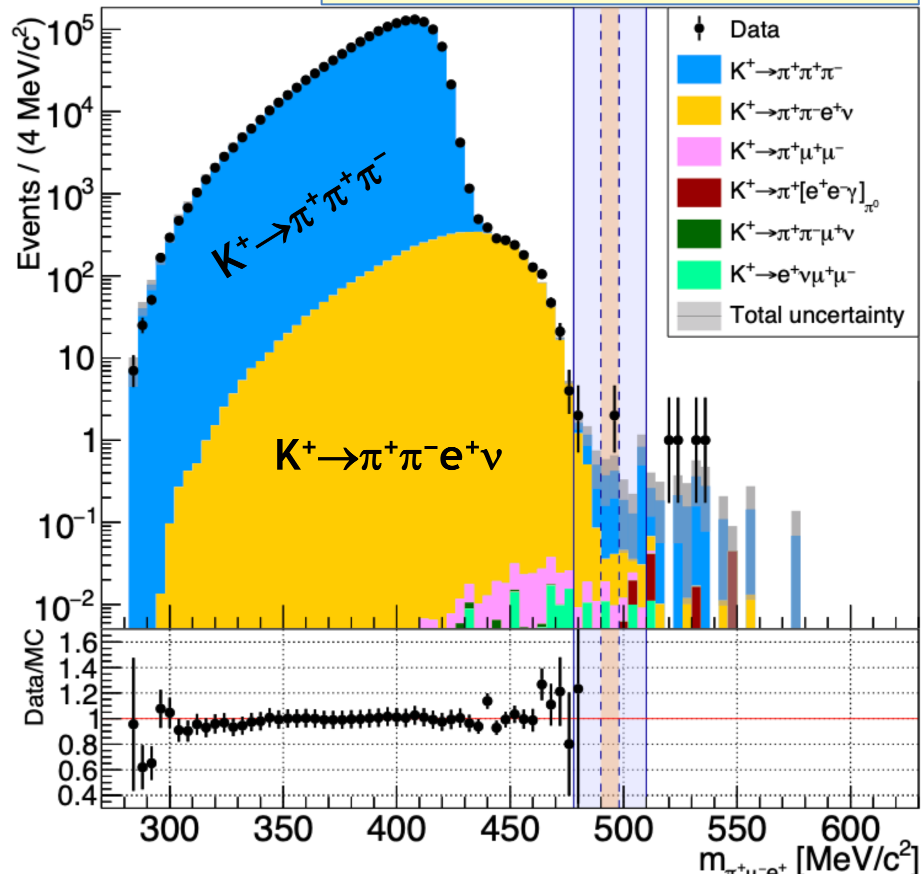
[PLB797 (2019) 134794]

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

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



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



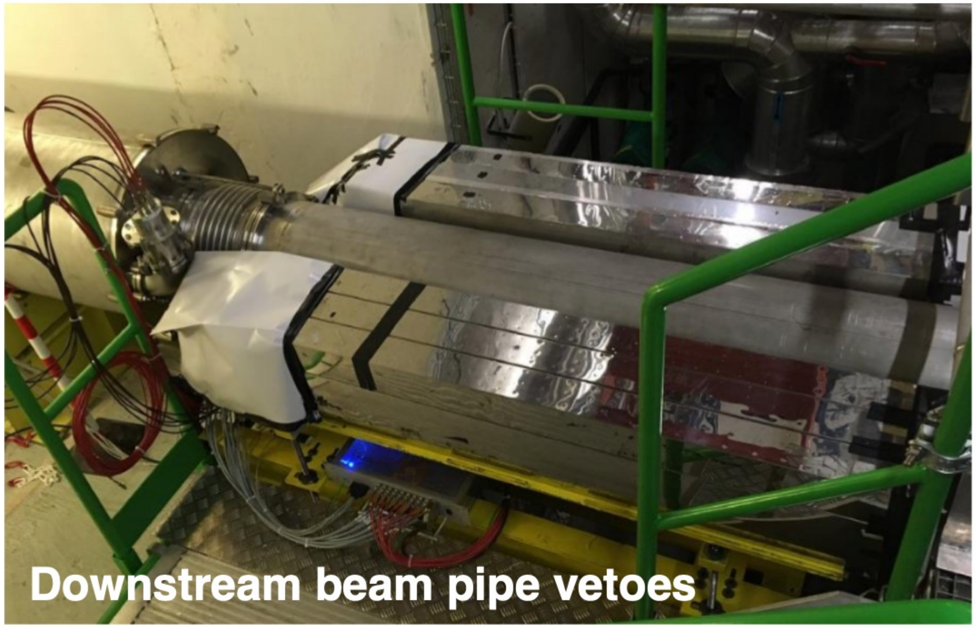
K^+ decays in FV: $(1.33\pm0.02)\times10^{12}$
Expected background: 1.07 ± 0.20 evt
Candidates observed: 0
$BR(K^+\to\pi^-\mu^+e^+)<4.2\times10^{-11}$ at 90% CL

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]

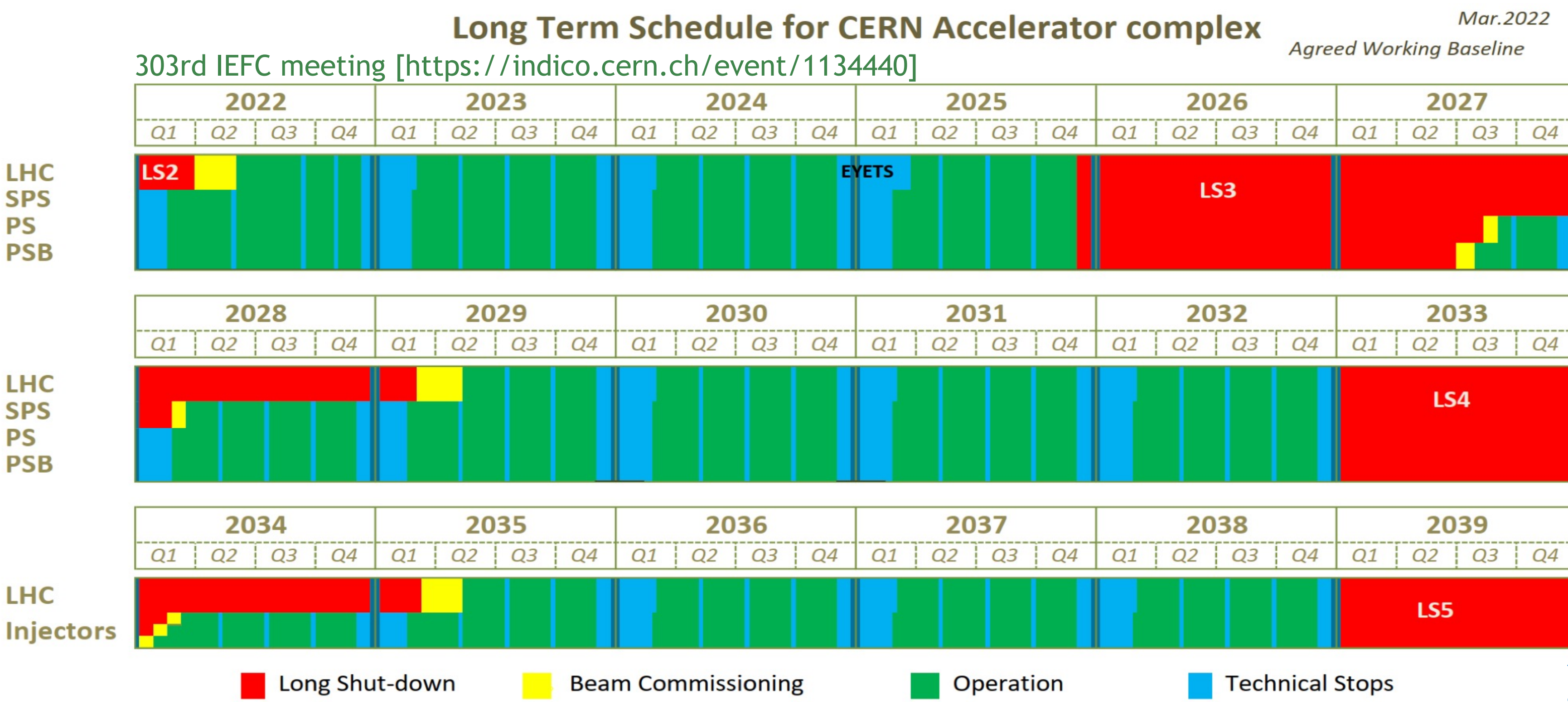
NA62 Run 2: 2021–LS3

- **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**.



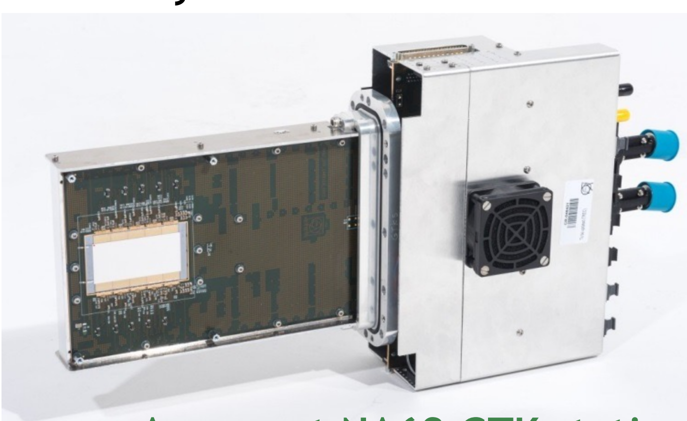
Long-term plan: $K^+ \to \pi^+ \nu\nu$ at CERN

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):

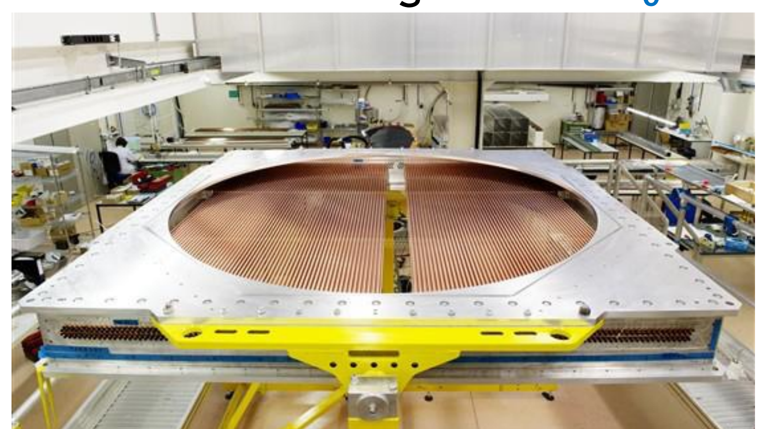
time resolution: <50 ps per plane;
pixel size: <300×300 μm²;
efficiency: >99% per plane (incl.fill factor);
material budget : 0.3–0.5% X_0;
beam intensity: >3 GHz on 30×60 mm²;
peak intensity: >8.0 MHz/mm².



A current NA62 GTK station

New STRAW spectrometer:

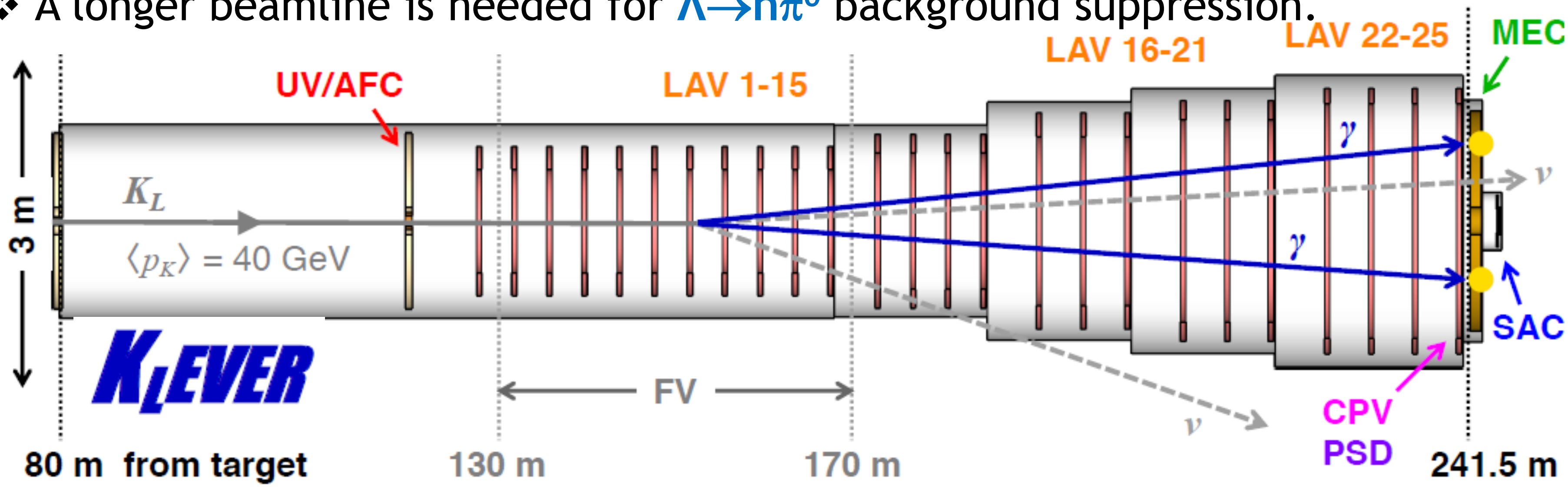
operation in vacuum;
straw diameter/length: 5 mm/2.2 m;
trailing time resolution: ~6 ns per straw;
maximum drift time: ~80 ns;
layout: ~21000 straws (4 chambers);
total material budget: 1.4% X_0.



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!**

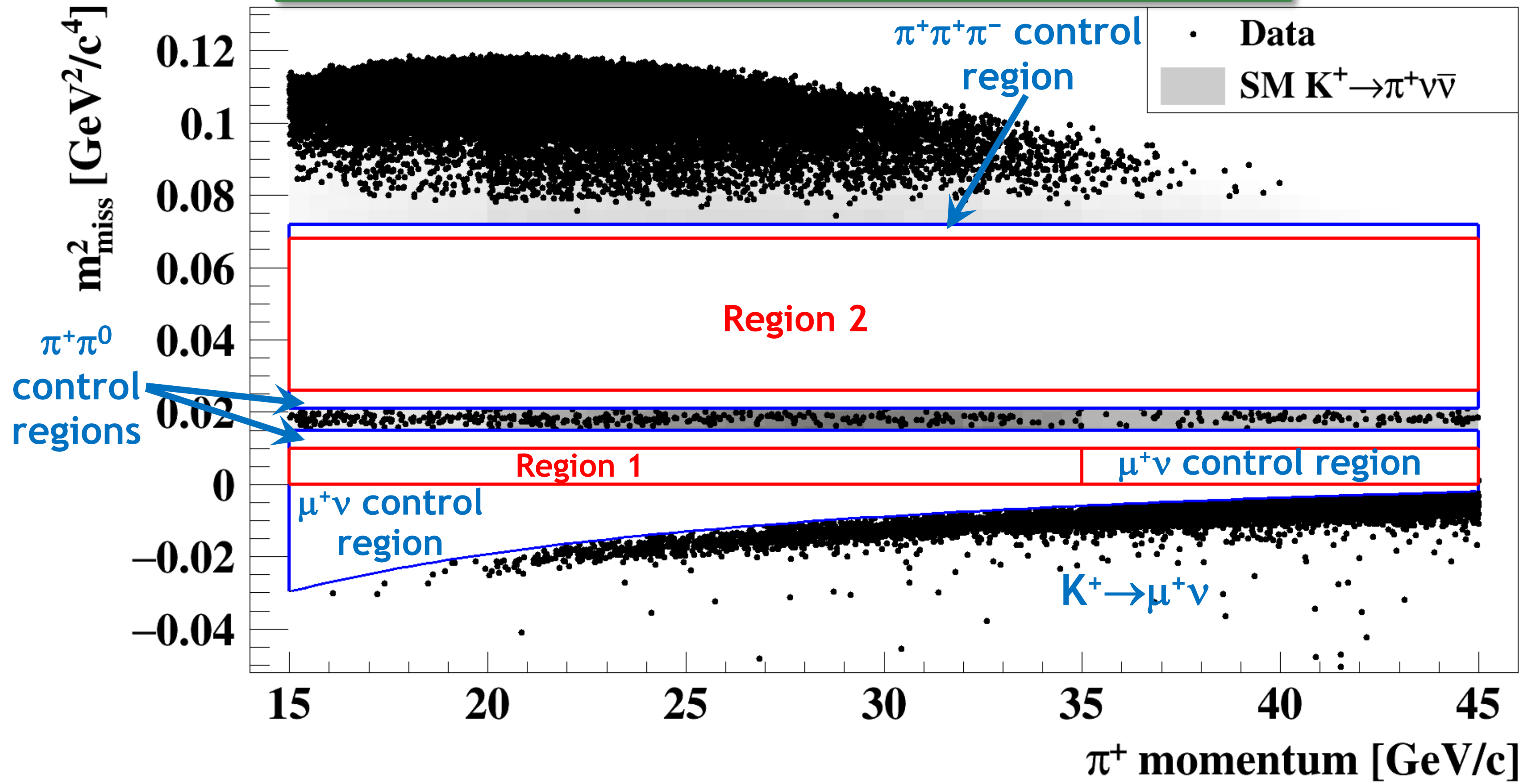
Summary and outlook

- 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

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

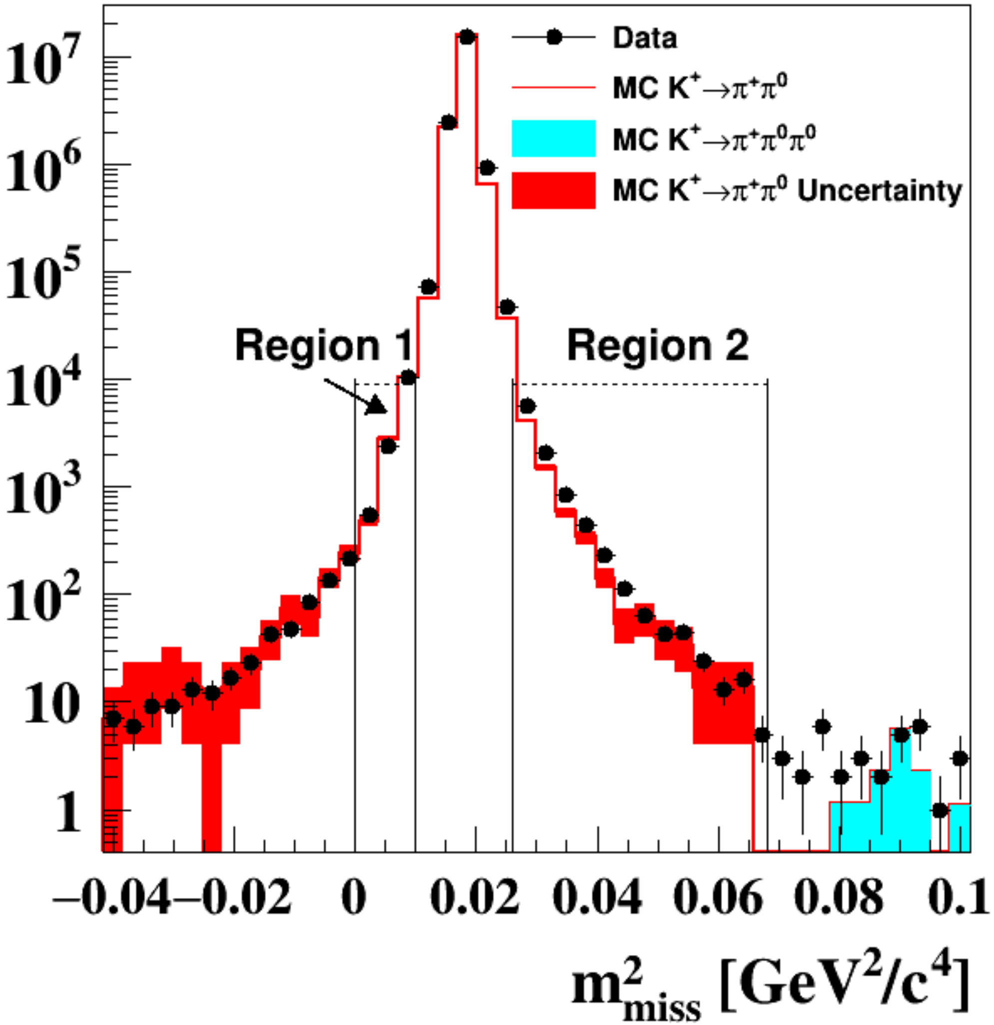
Signal and control regions are blinded



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)

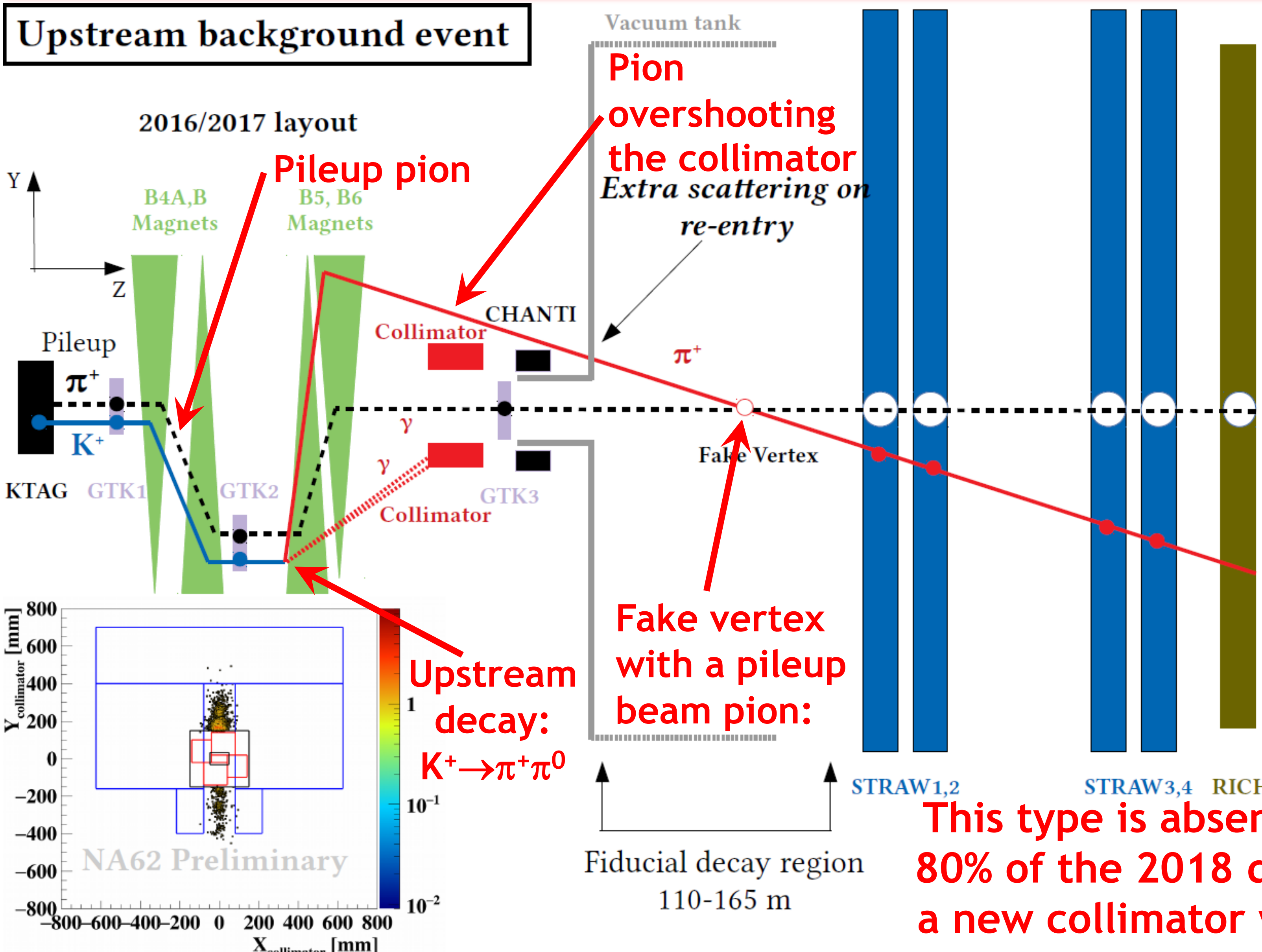
Data events in the $\pi^+\pi^0$ region after the $K_{\pi\nu\nu}$ selection (including π^0 rejection)

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

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

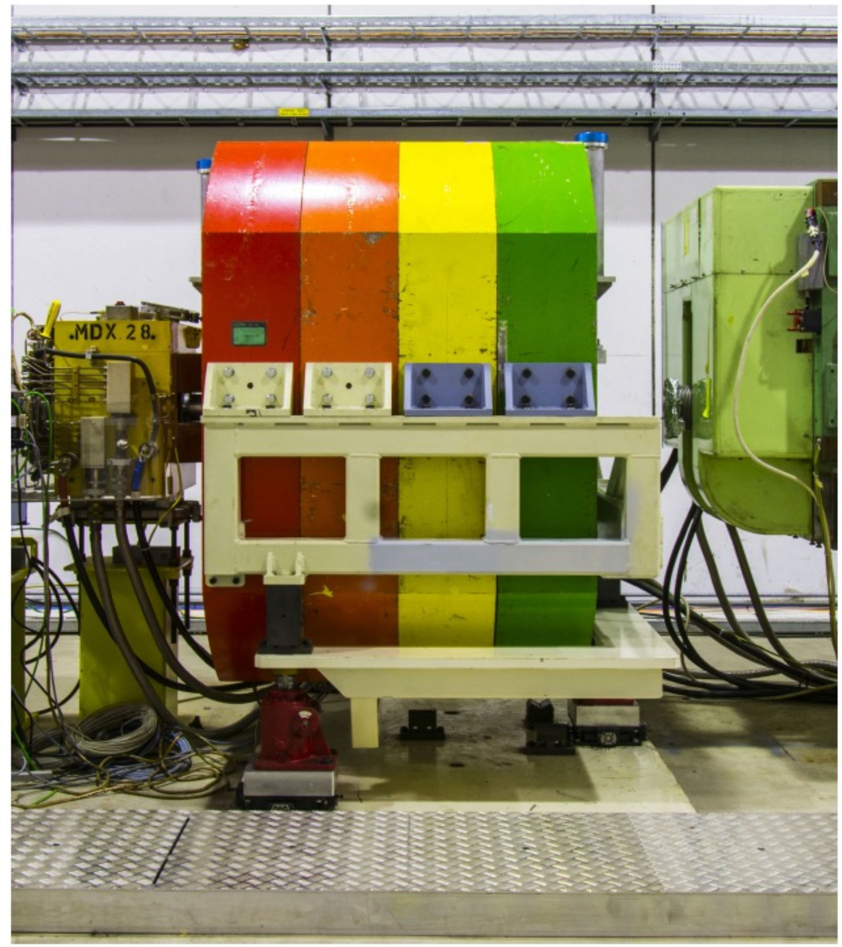


This type is absent in 80% of the 2018 data: a new collimator with larger transverse size

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%.