Recent results from the NA62 experiment at CERN*

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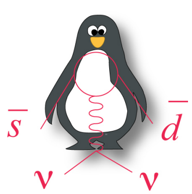
* with slides gratefully liberated from E. Goudzovski

Outline:

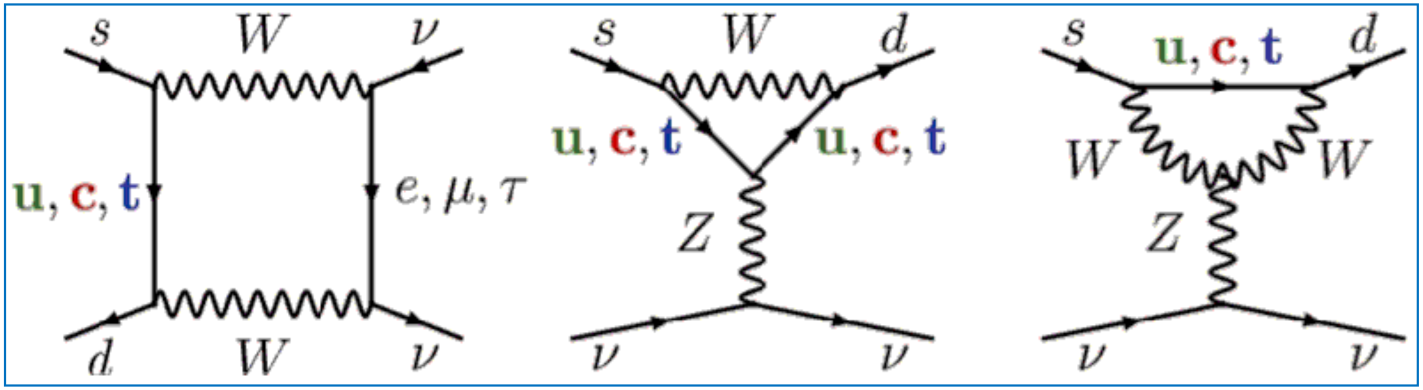
1) Introduction: rare kaon decays
2) The $K^+ \to \pi^+ \nu\nu$ measurement at NA62
3) Other NA62 results: hidden sectors, lepton flavour violation
4) Long-terms plans for kaon experiments at CERN
5) Summary and outlook



DIS2023 conference
MSU, 29 March 2023

$K \to \pi\nu\nu$ 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)

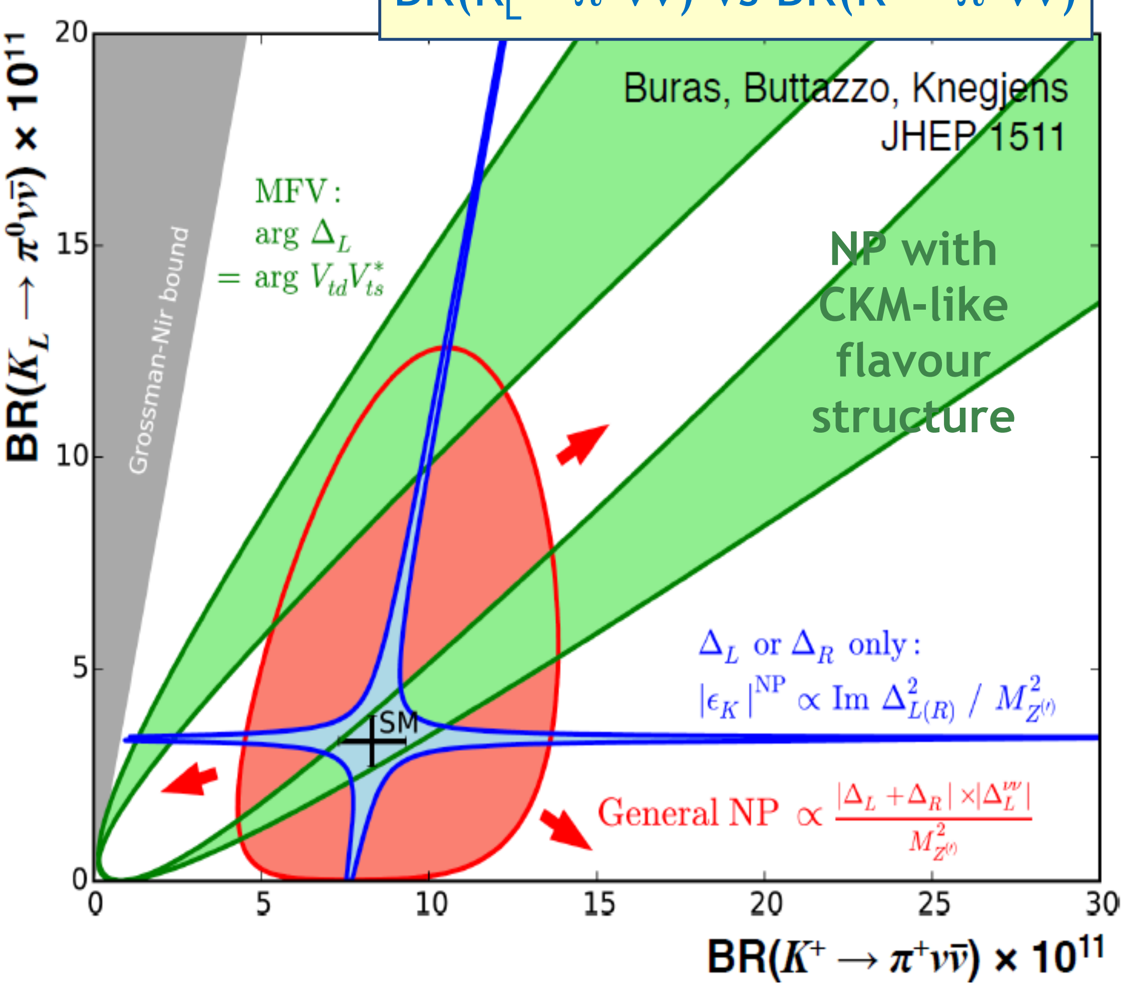
Standard Model BR: a new $|V_{cb}|$ and γ-independent determination.

[Buras and Venturini, arXiv:2109.11032]

K→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

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

Kaons: other opportunities

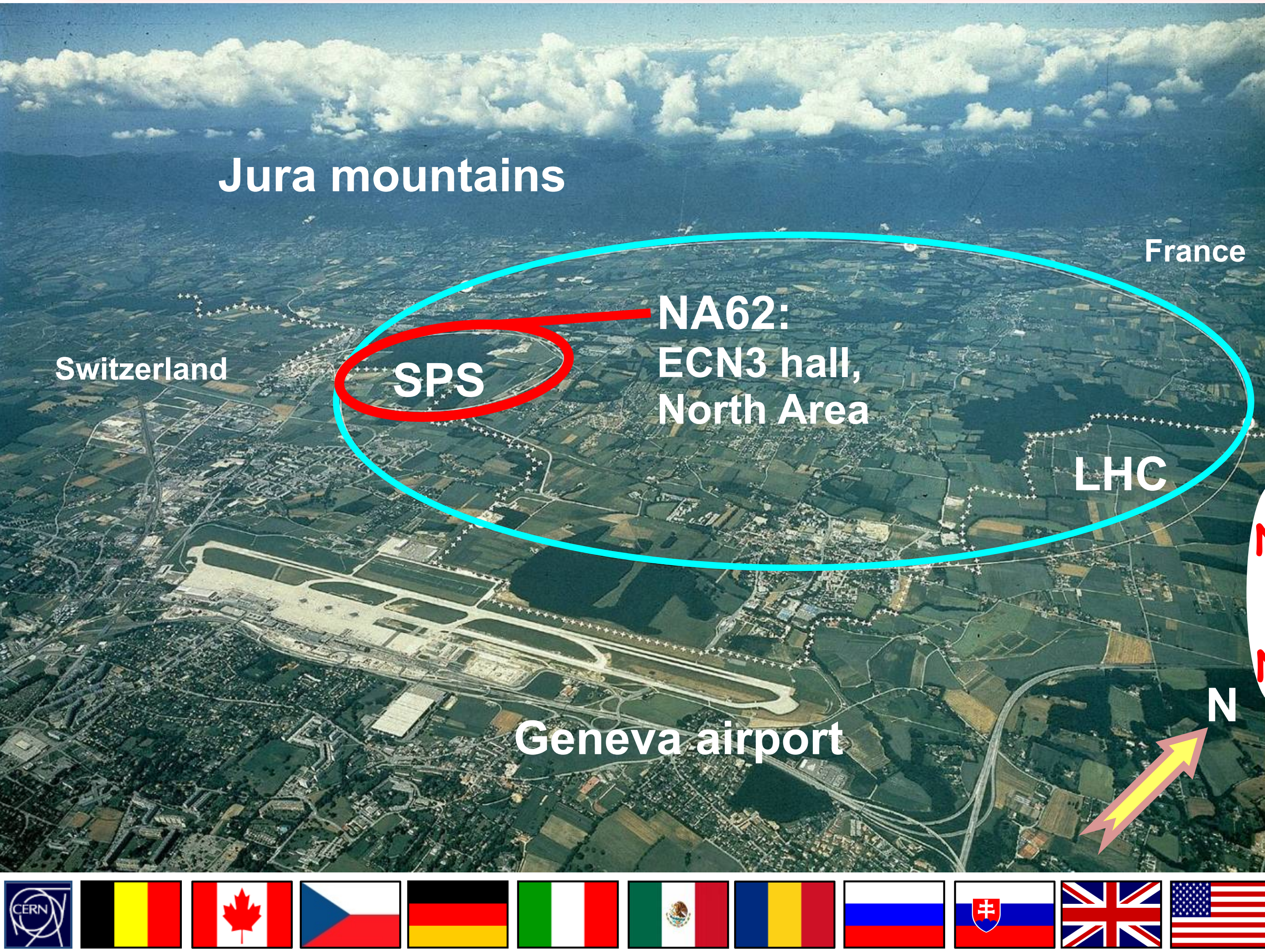
- Direct and indirect CP violation in $K^0 \to \pi\pi$ decays (ε, ε'), and the $K_L - K_S$ mass difference (ΔM_K) [no experiments planned]
  - ✓ Improving capabilities of lattice QCD to provide accurate SM predictions: opportunities for discovery of new physics.
  - ✓ SM precision on ε'/ε can match that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



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

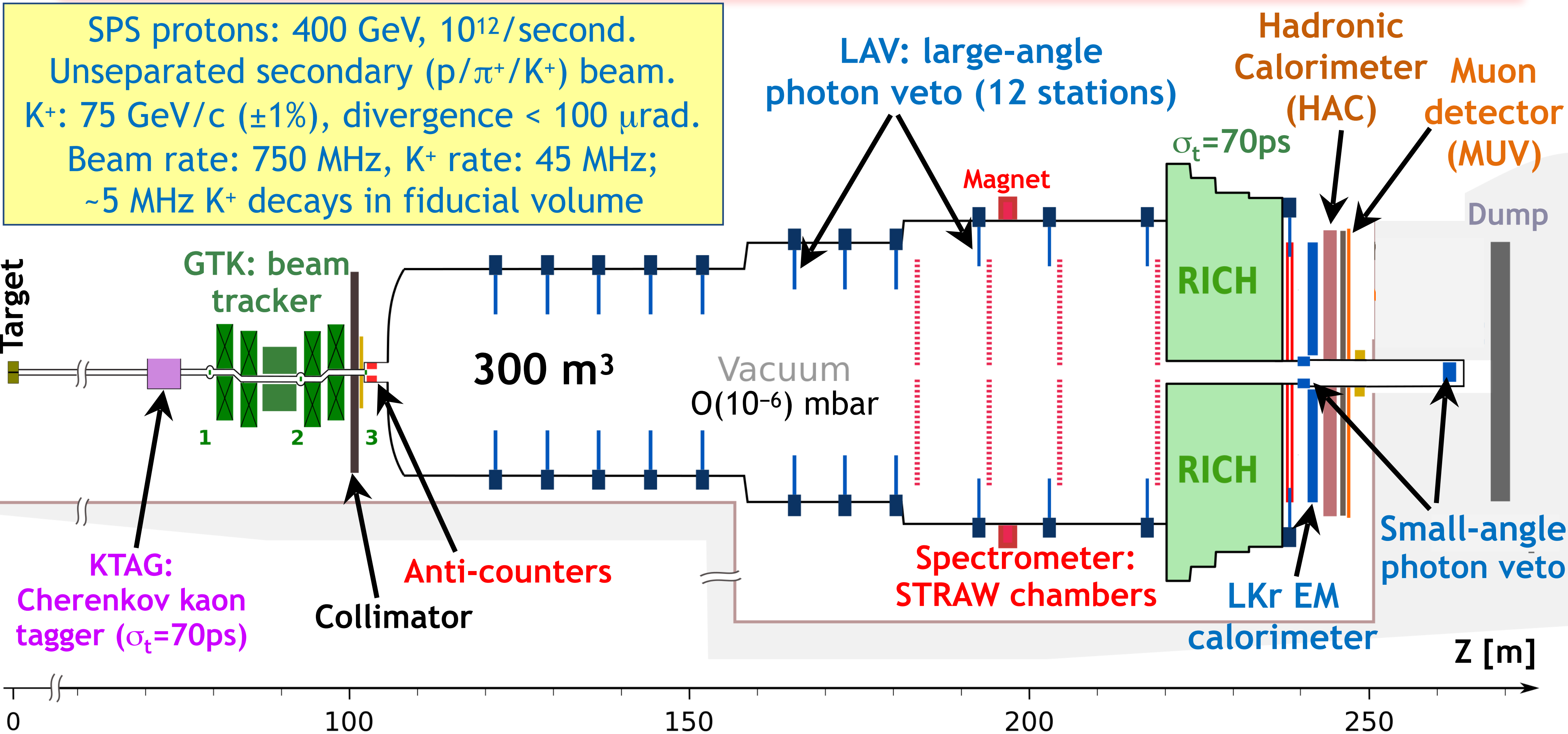
Main NA62 goal: $K^+ \rightarrow \pi^+ \nu\nu$ measurement to 10% precision with a novel decay-in-flight technique.

Currently ~300 participants from ~30 institutions.

NA62 collaboration,
JINST 12 (2017) P05025

The NA62 experiment

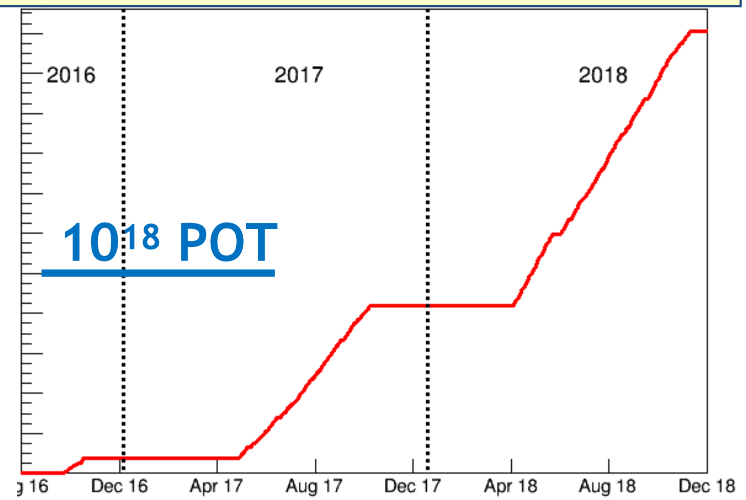
SPS protons: 400 GeV, 10^{12}/second.
Unseparated secondary ($p/\pi^+/K^+$) beam.
K^+: 75 GeV/c (±1%), divergence < 100 μrad.
Beam rate: 750 MHz, K^+ rate: 45 MHz;
~5 MHz K^+ decays in fiducial volume



- 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

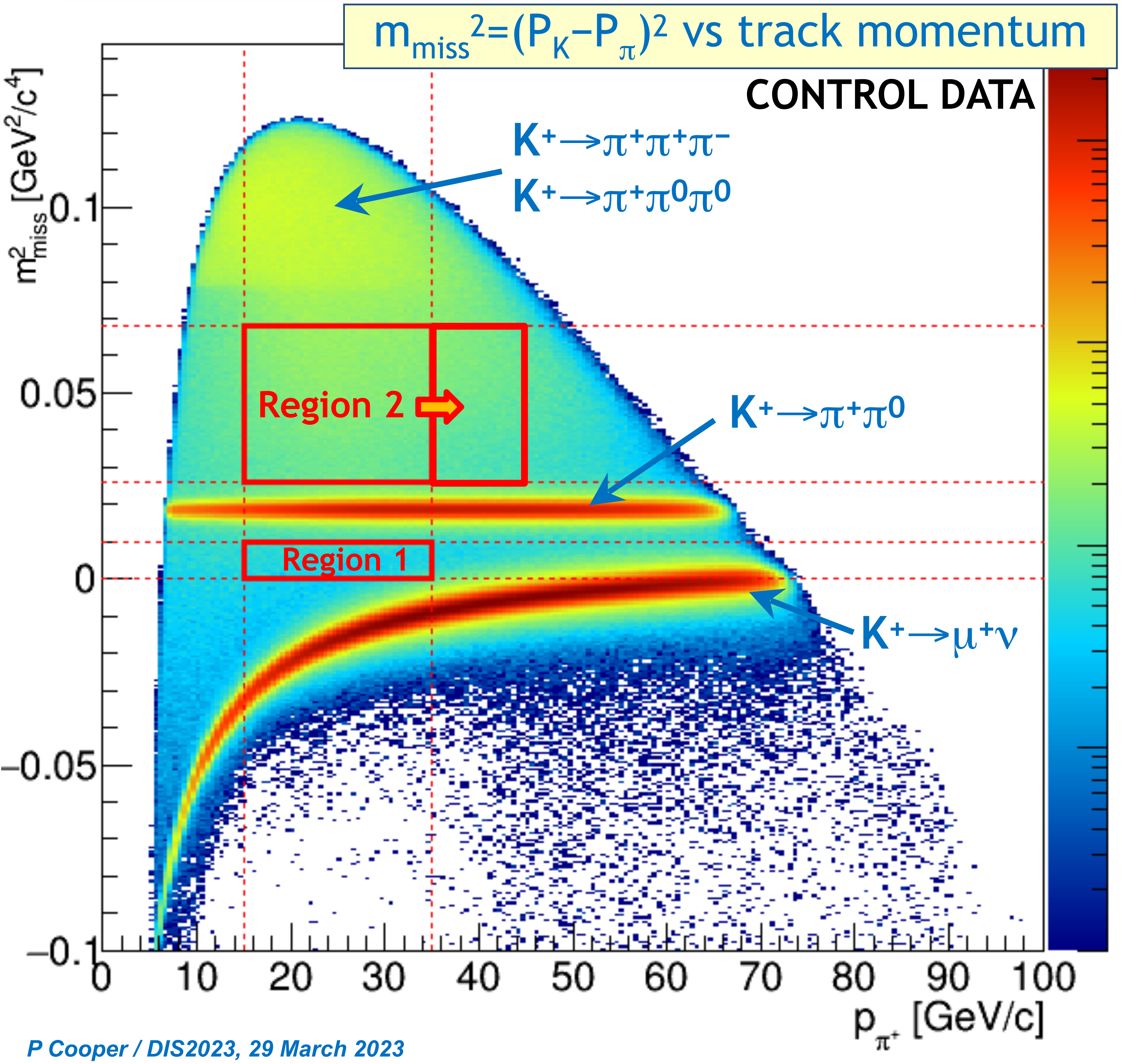


2.2×10^{18} POT collected

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

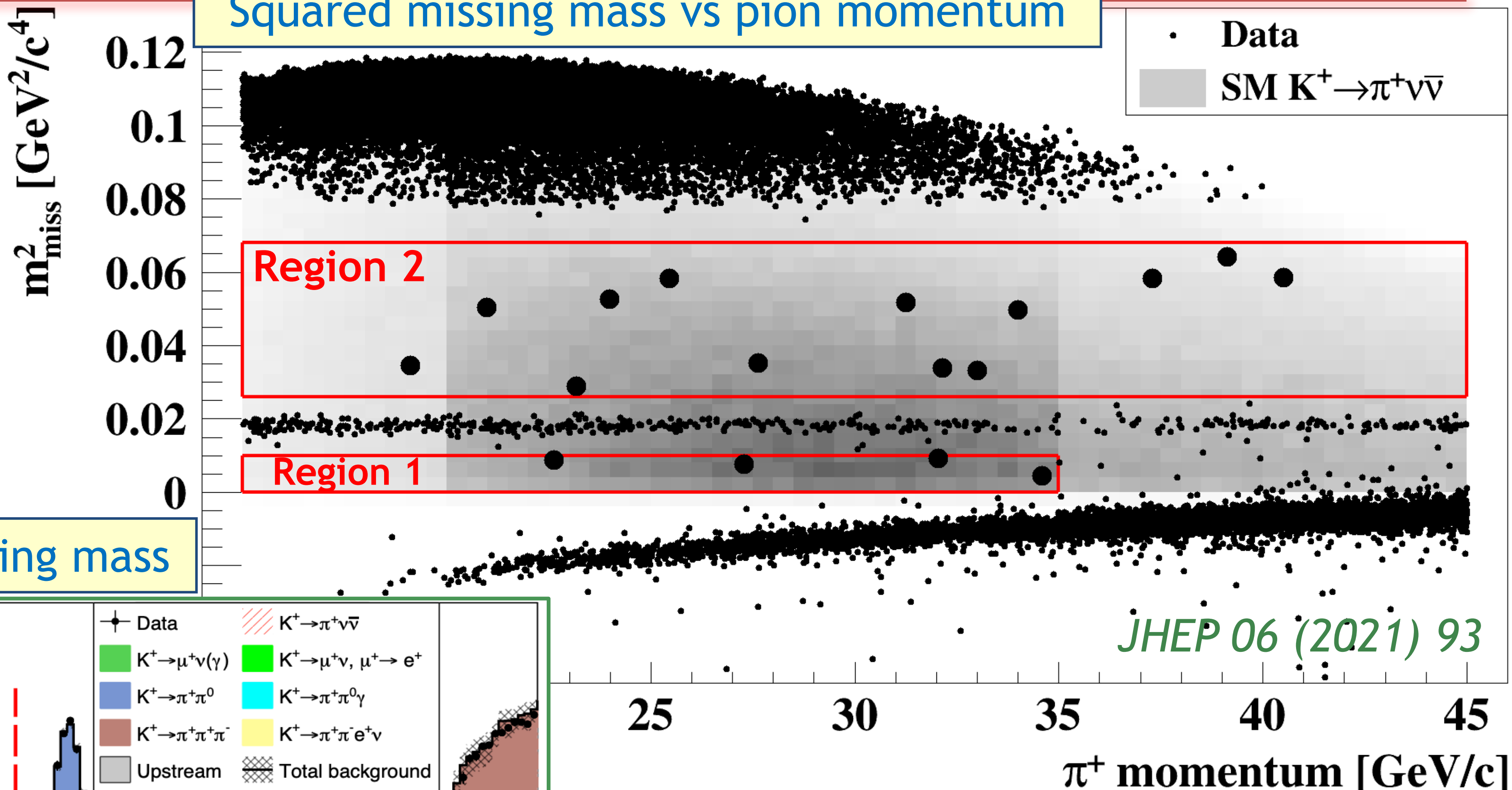
Data-driven background estimates ($\pi^+\pi^0$, $\mu^+\nu$, $\pi^+\pi^+\pi^-$)

Dominant background: a data-driven estimate (Upstream)

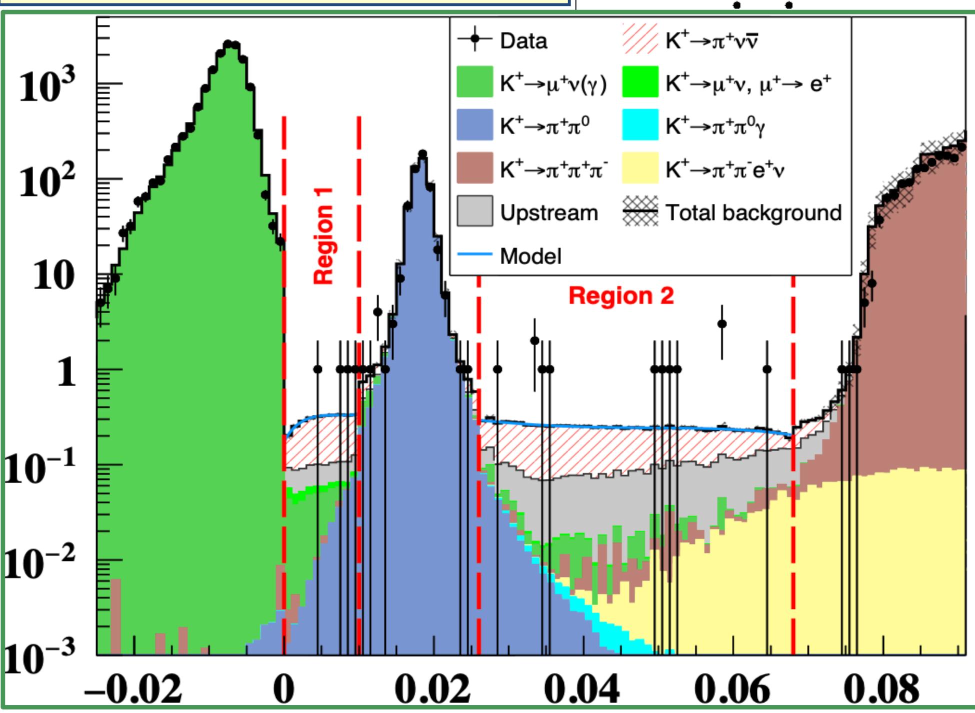
- Most background is not due to K^+ decays in the vacuum tank.
- Improved the beamline layout and new upstream veto detectors bring the Run 2 measurement into a low-background regime.

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

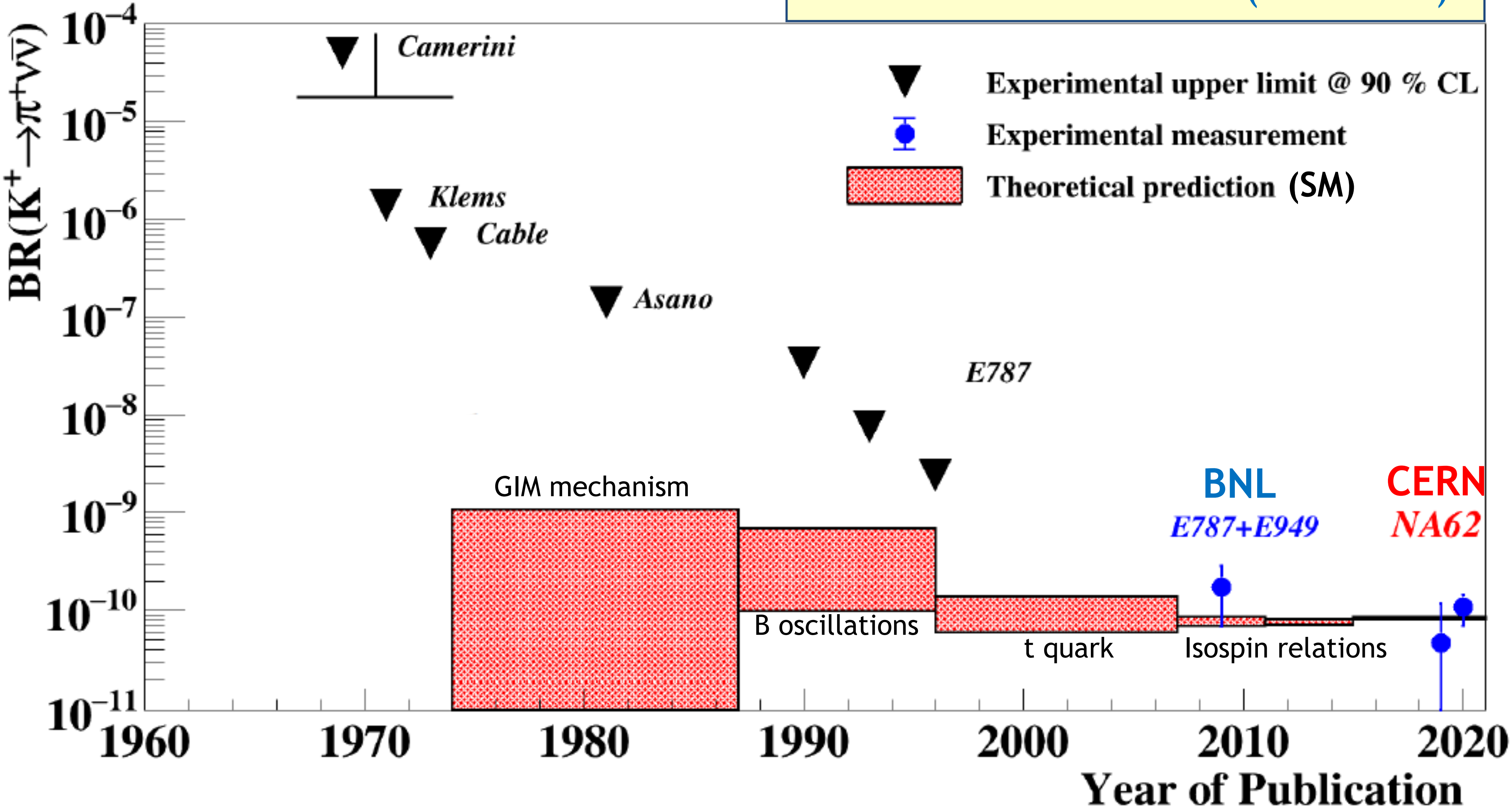
Expected SM events:

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

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

JHEP 06 (2021) 93

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

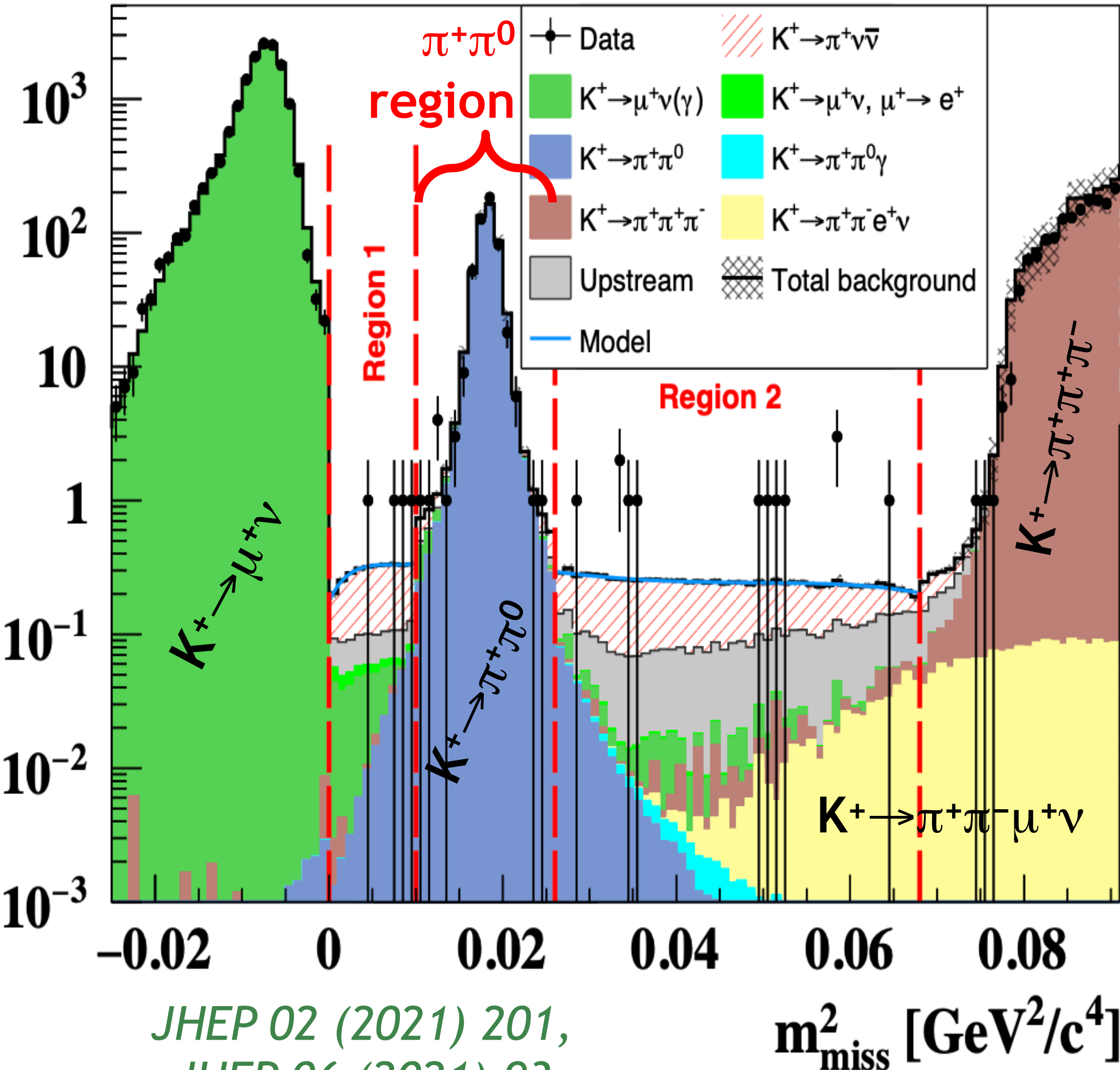


NA62 Run 1: $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$

(3.4σ significance)

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

Squared missing mass (2018 data)

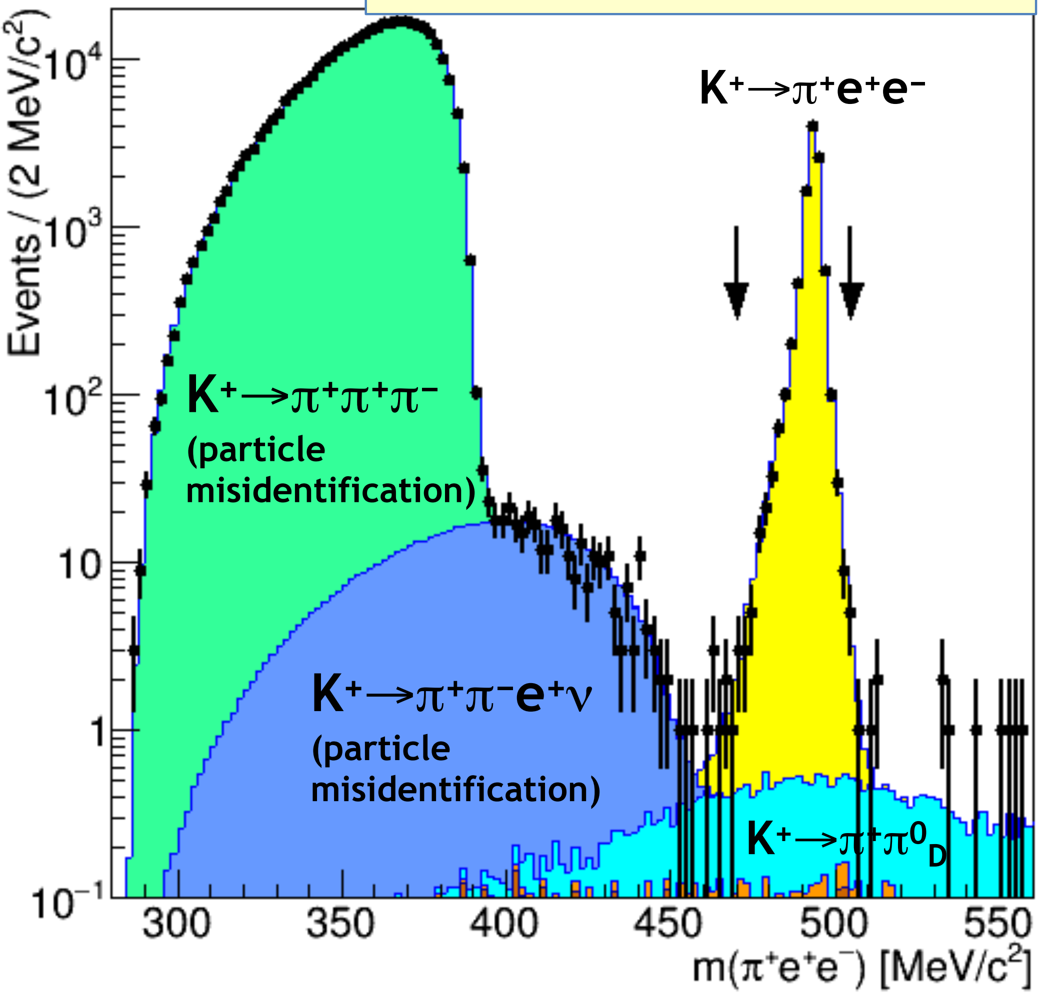


JHEP 02 (2021) 201, JHEP 06 (2021) 93

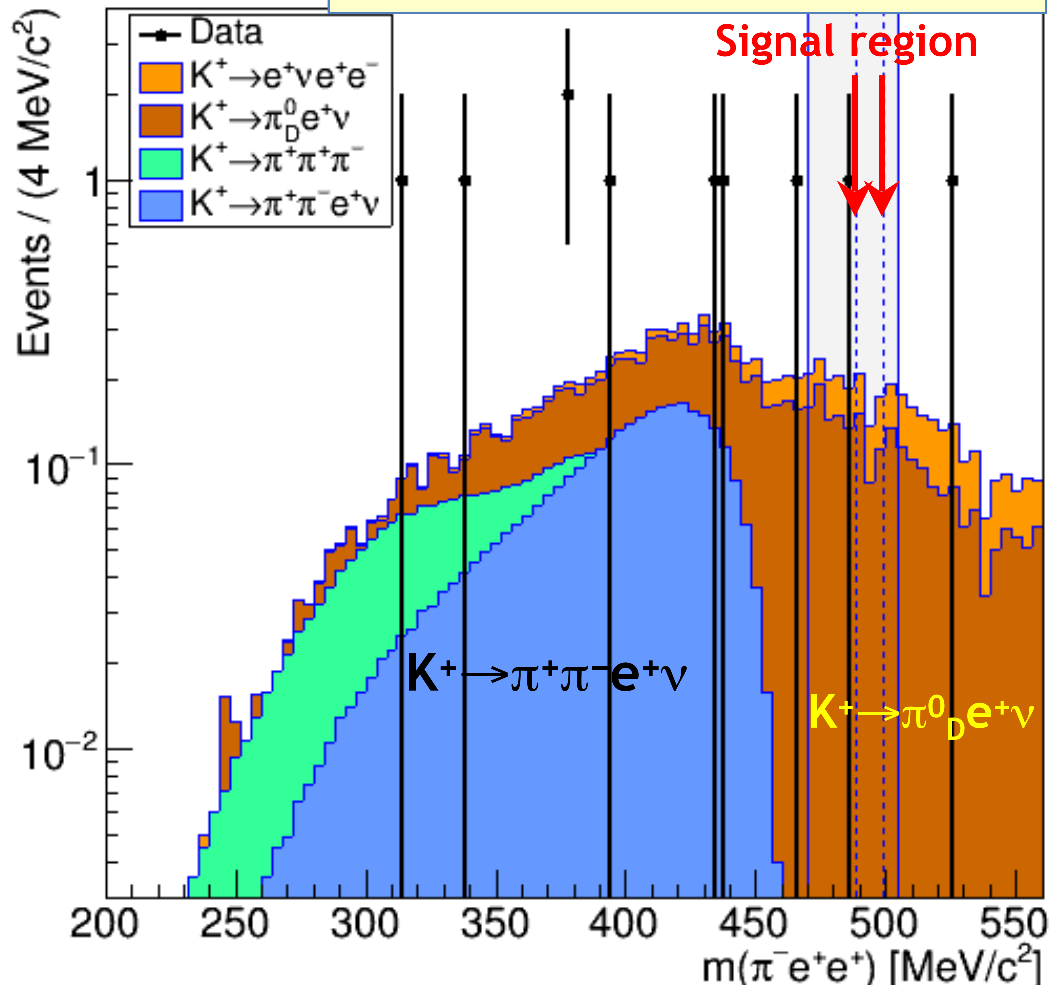
- Signal regions **R1**,**R2**: search for $K^+ \to \pi^+ X$ (X=invisible), $0 \leq m_X \leq 110$ MeV/c^2 and $154 \leq m_X \leq 260$ MeV/c^2.
  - ✓ Interpretation: dark scalar, ALP, QCD axion, axiflavon.
  - ✓ Main background: $K^+ \to \pi^+ \nu\nu$.
- The $\pi^+\pi^0$ region: search for $\pi^0 \to$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

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



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



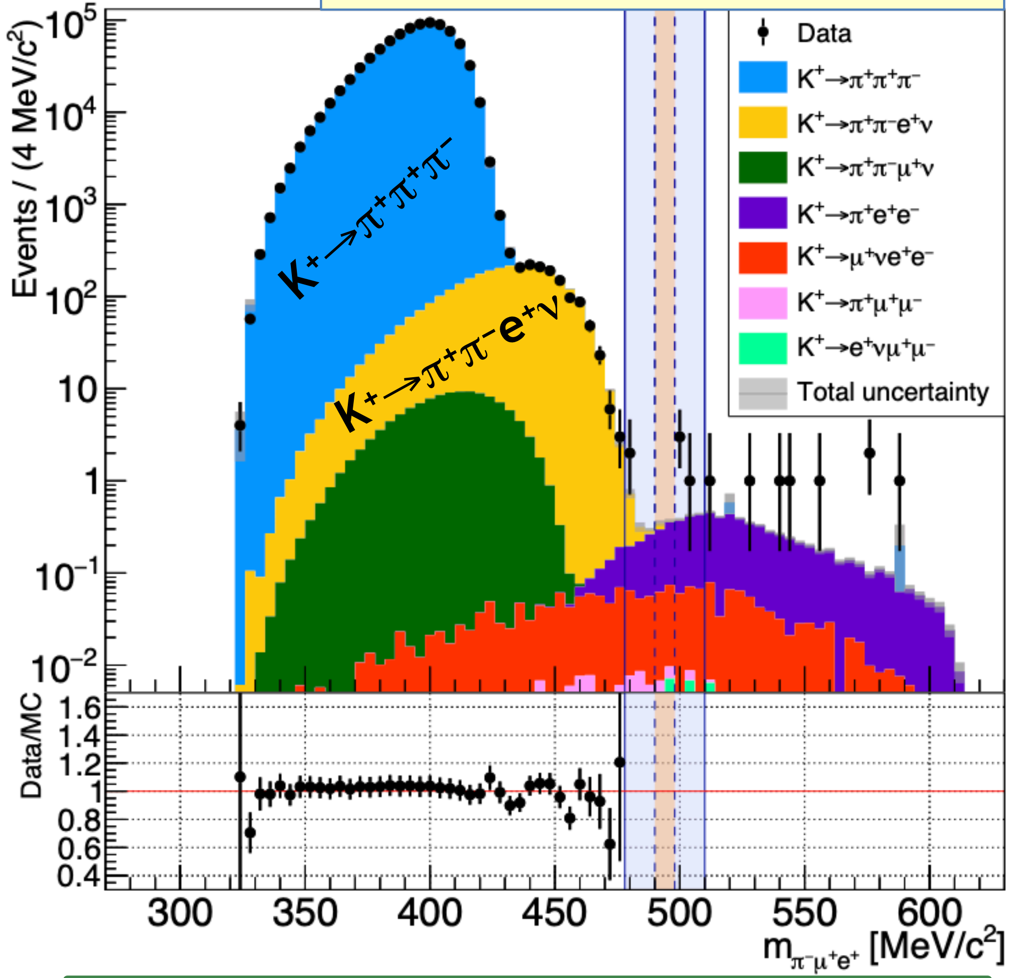
Candidates observed: **11041**
$BR(K^+ \to \pi^+ e^+ e^-) = (3.00 \pm 0.09) \times 10^{-7}$
K^+ decays in FV: $(1.015 \pm 0.032) \times 10^{12}$

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

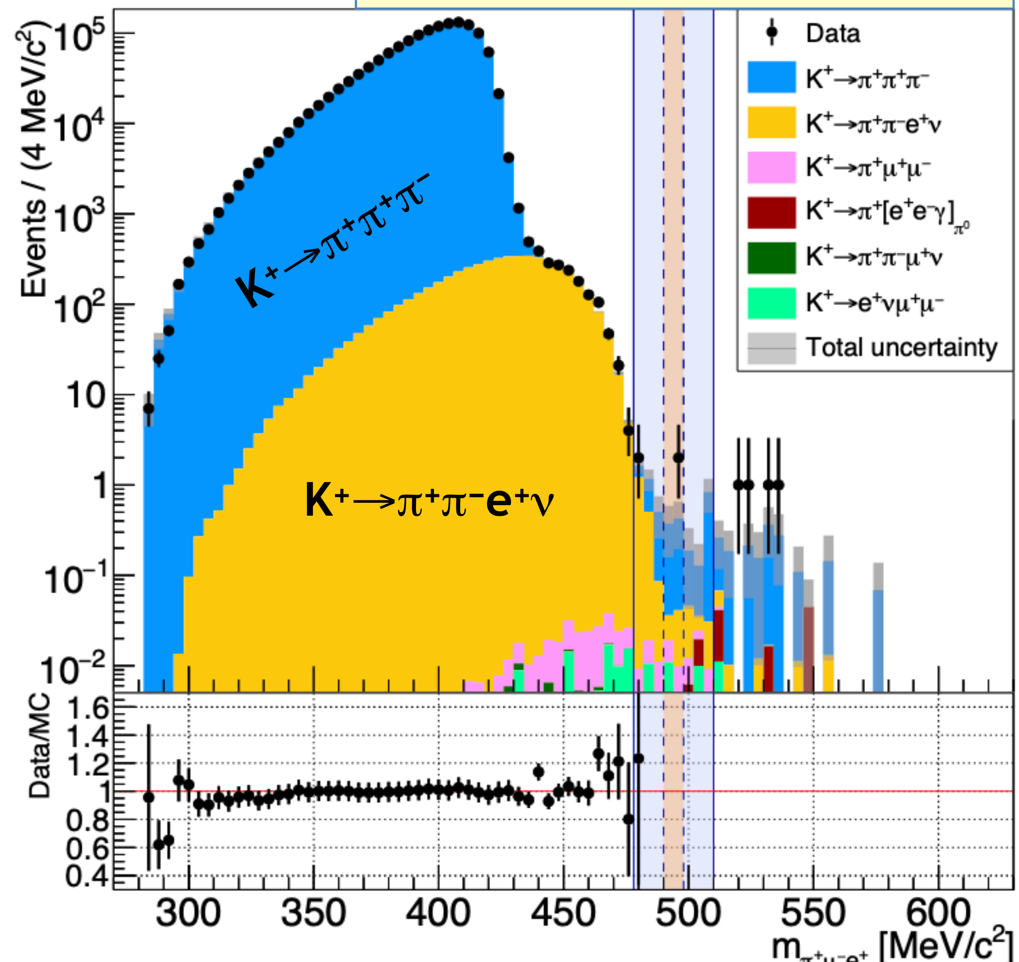
[PLB830 (2022) 137172]

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

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



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



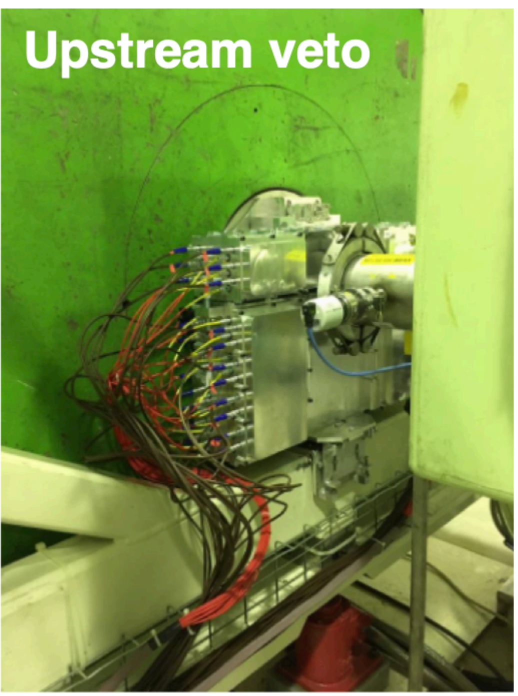
K^+ decays in FV: $(1.33\pm0.02)\times10^{12}$
Expected background: 1.07 ± 0.20 evt
Candidates observed: 0
$BR(K^+\to\pi^-\mu^+e^+)<4.2\times10^{-11}$ at 90% CL

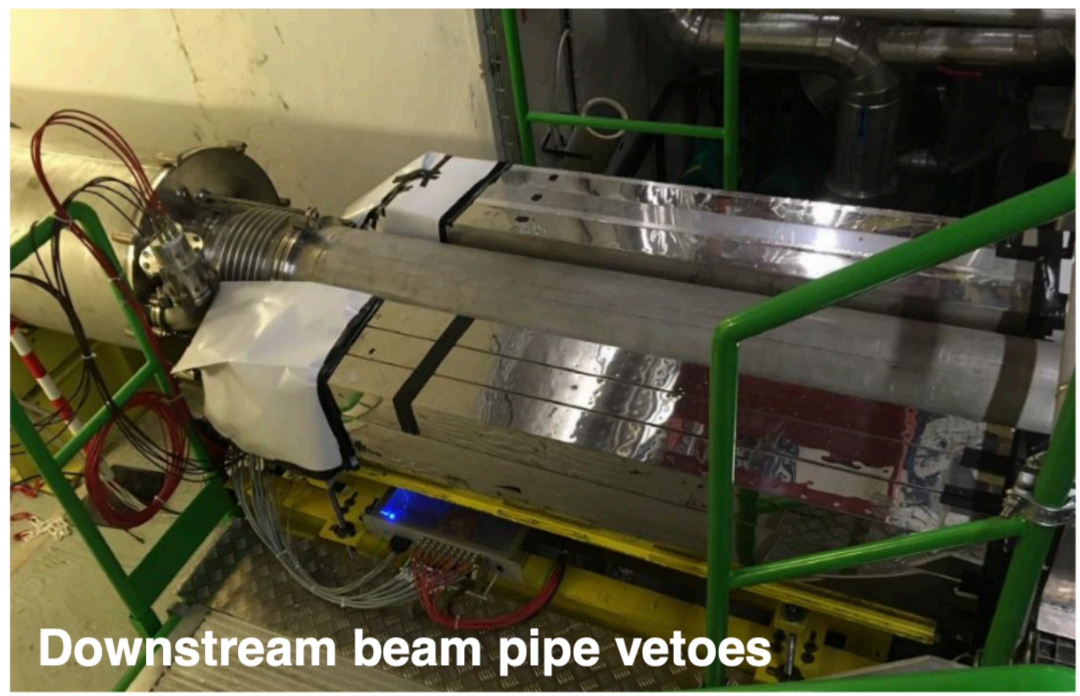
Expected background: 0.92 ± 0.34 evt
Candidates observed: 2
$BR(K^+\to\pi^+\mu^-e^+)<6.6\times10^{-11}$ at 90% CL
$BR(\pi^0\to\mu^-e^+)<3.2\times10^{-10}$ at 90% CL

[PRL 127 (2021) 131802]

NA62 Run 2: 2021–LS3

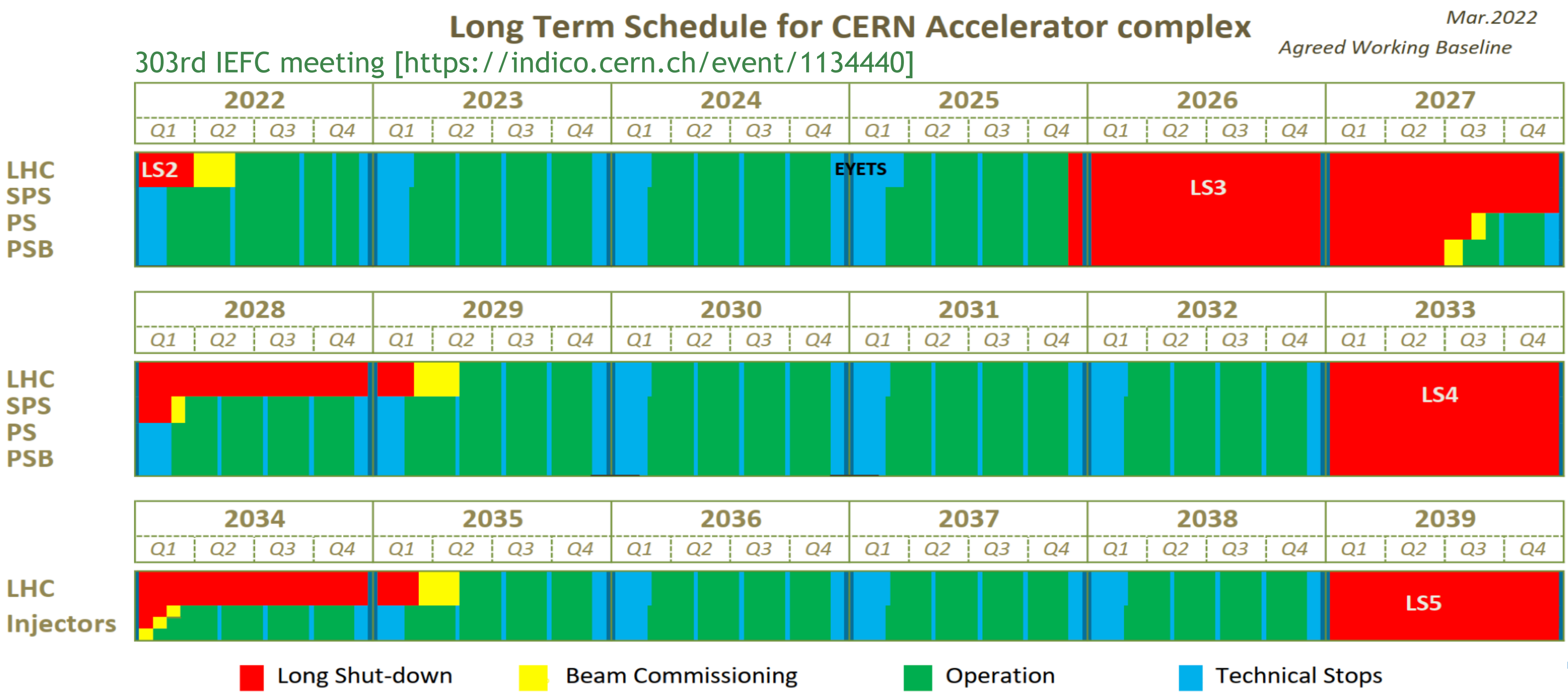
- **The technique is firmly established**. Run 2: $K^+ \to \pi^+ \nu\nu$ measurement in a low-background, high-acceptance regime, at **O(10%)** precision.
- Modifications of the setup for background reduction:
  - ✓ fourth kaon beam tracker (GTK) station;
  - ✓ rearrangement of beamline elements around 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.



303rd IEFC meeting [https://indico.cern.ch/event/1134440]

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.