Latest results from Kaon experiments at CERN

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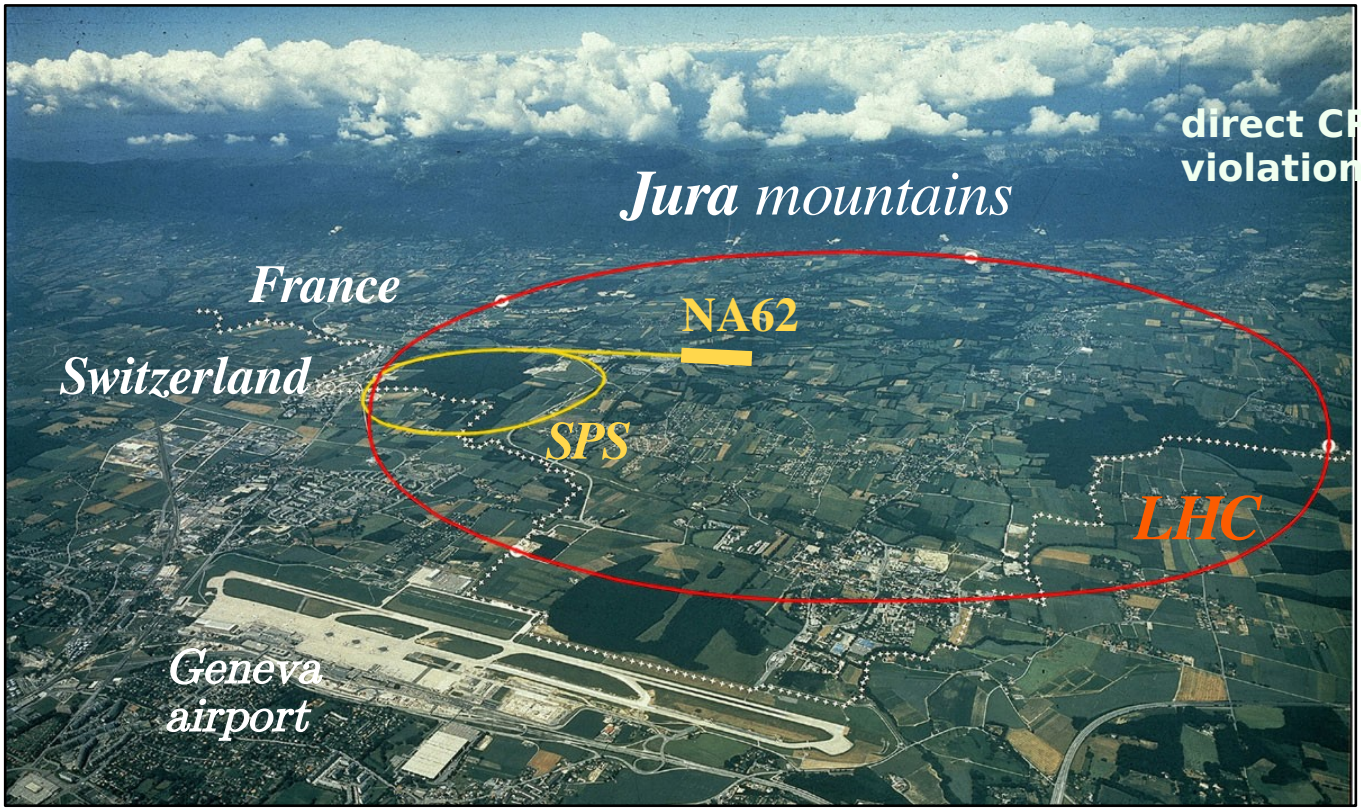
Kaon decay experiments @ CERN



direct CP violation

NA31: K_L/K_S

1987 - 1989:

NA48: K_L/K_S

1997 - 2001:

NA48/1: K_S/hyperons

2002:

NA48/2: K^+/K^-

2003-04:

NA62 – Rk: K^+/K^-

2007-08: $K^{\pm}_{e2}$ / $K^{\pm}_{\mu 2}$

NA62: K^+

2014 : pilot run
2015 : commissioning run
2016 – 18 : Physics Run 1
2021 – … : Physics Run 2

NA62: ~ 300 participants from 31 institutes

Outline:

New results from the NA48/2:

the first observation of the decay $K^{\pm}\to\pi^0\pi^0\mu^{\pm}\nu_{\mu}$ (K00μ4)

Results from the NA62 Run 1:

- ⇛ $K^+\to\pi^+\nu\bar{\nu}$ decay.
- ⇛ Precision measurements
- ⇛ LNV/LFV decays
- ⇛ Beam-dump mode

~~Summary~~ Current status of the NA62 and prospects for the future

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the first observation of the decay $K^{\pm}\to\pi^0\pi^0\mu^{\pm}\nu_{\mu}$ (K00μ4) Refer to the Anna's talk

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The NA62 apparatus

Physics Goal: Measuring Br($K^+ \to \pi^+ \nu\bar{\nu}$) with 10% precision

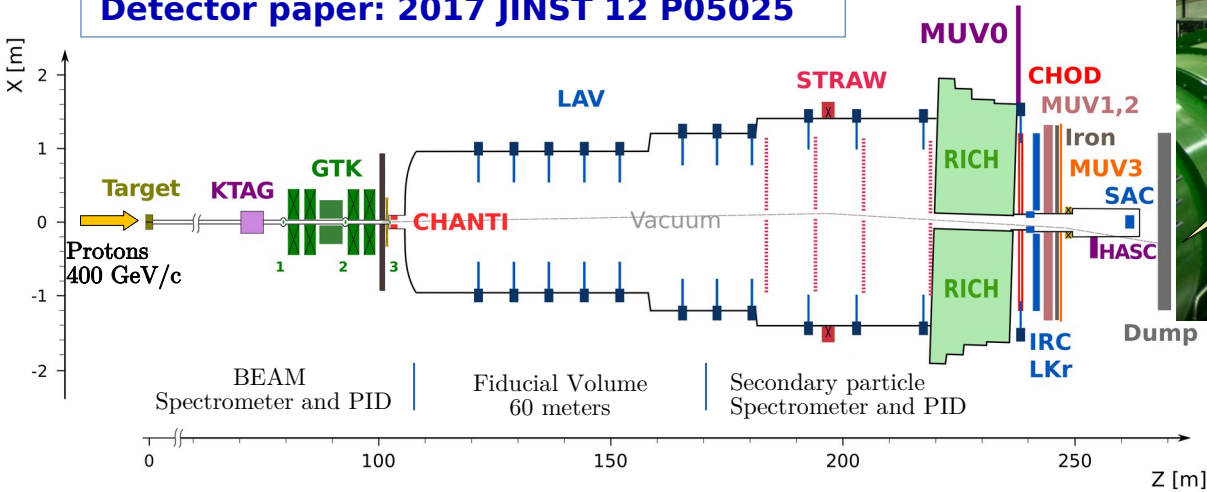
Kaon decay in flight technique

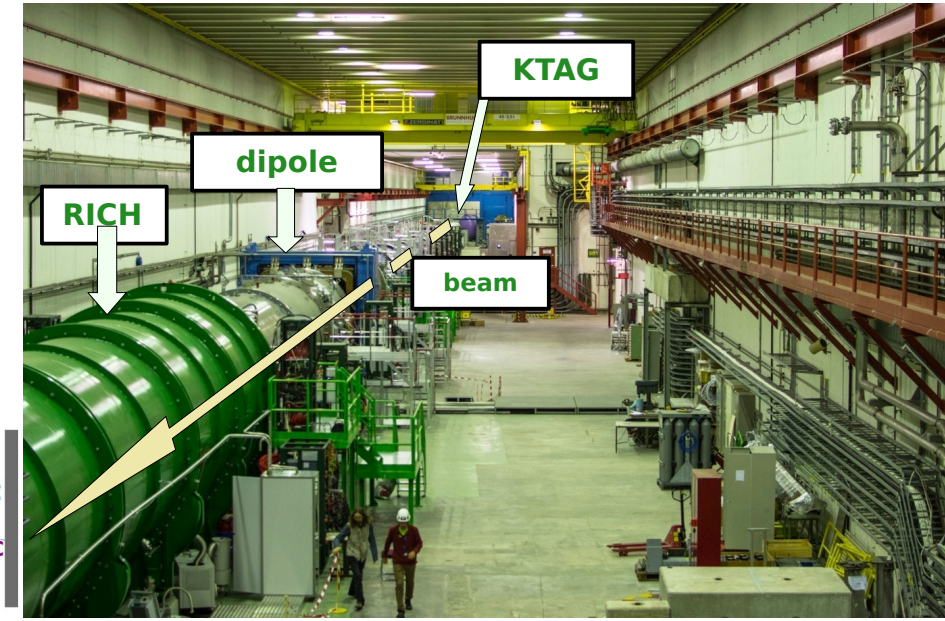
Unseparated hadron beam: (70% π^+, 24% p, **6% K^+**)

Primary beam: 400 GeV/c protons from SPS, 3.5 s spill

Secondary beam: 75 GeV/c (dp/p ~ 1%), 750 MHz rate

Detector paper: 2017 JINST 12 P05025





1y of operation: ~ 10^{18} POT, 4×10^{12} K^+ decays

Single event sensitivity for K^+ decays: Br ~ 10^{-12}

KTAG – Beam PID (σ_t ~ 70ps)

GTK – Beam spectrometer (σ_t ~ 100ps)

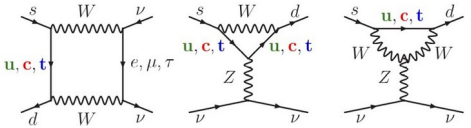
Vetos – LAVs, CHANTI, IRC, SAC, MUV

LKr – electro-magnetic calorimeter

PIDs – LKr, RICH, MUV

Hermetic photon veto for 0 - 50mrad

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

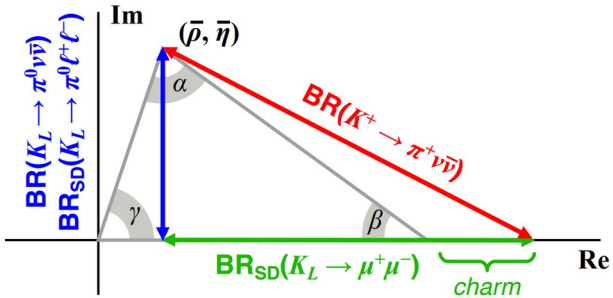


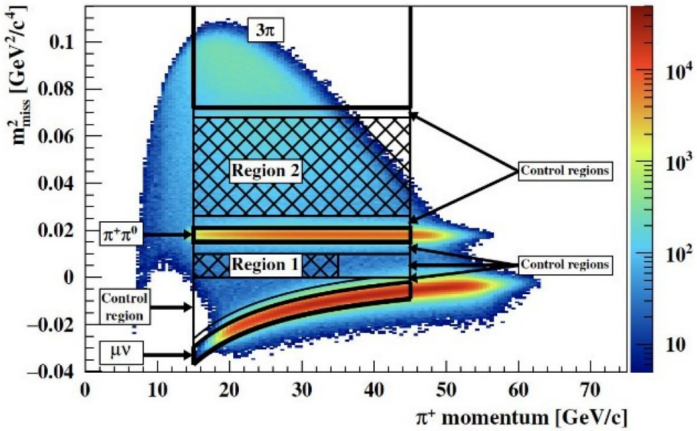
- Dominant uncertainties for SM BRs are from CKM matrix elements
- Intrinsic theory uncertainties ~ few percent
- Measuring both K^+ and K_L BRs can determine the CKM unitarity triangle independently from B inputs
- Over-constrain CKM matrix → reveal NP
- Complementary to B sector

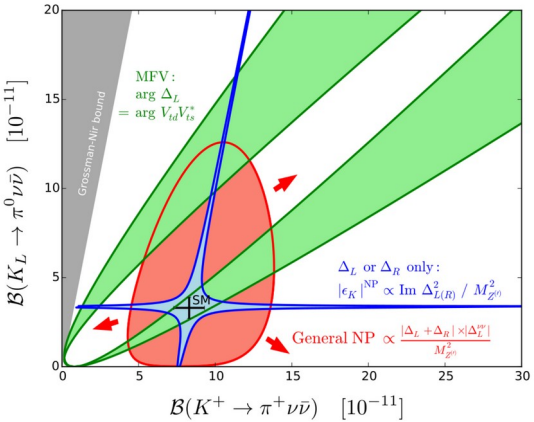
$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2.8} \cdot \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

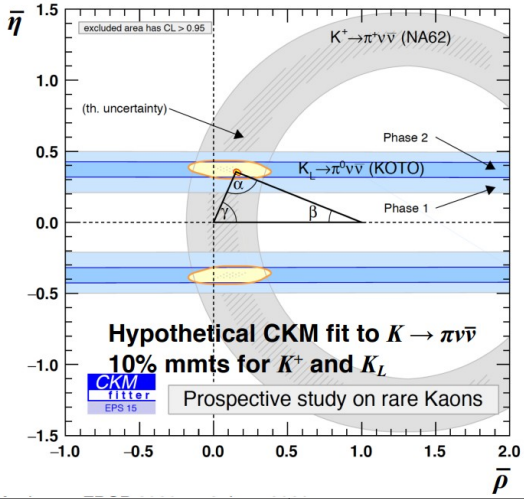
JHEP 1511 (2015) 033

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2} \cdot \left[\frac{\sin\gamma}{\sin 73.2^\circ}\right]^{2}$$





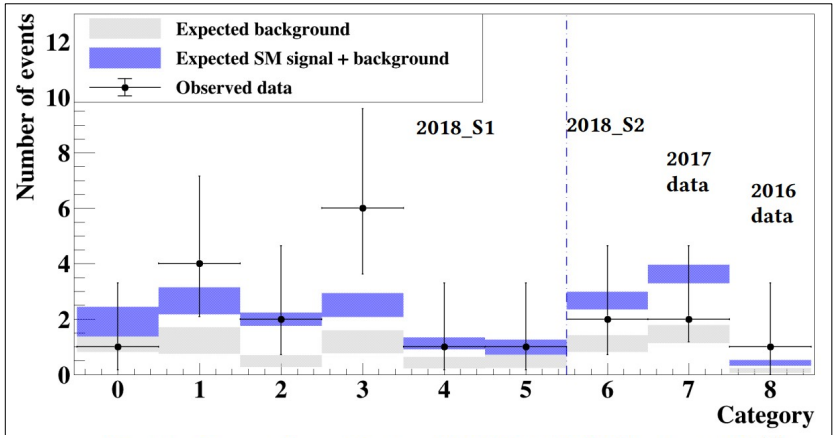


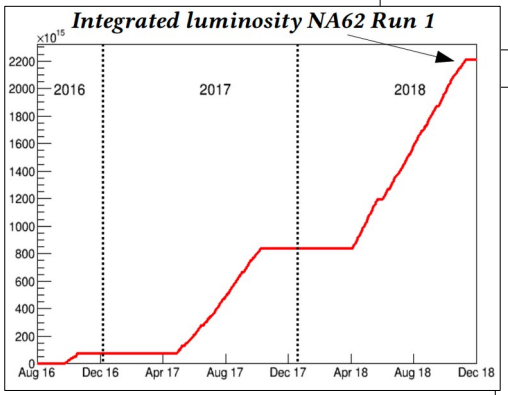


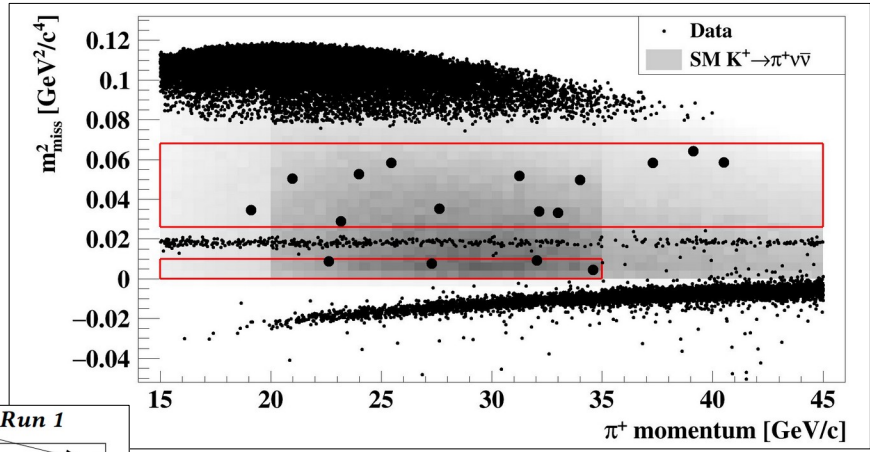
$K^+ \to \pi^+ \nu\bar{\nu}$

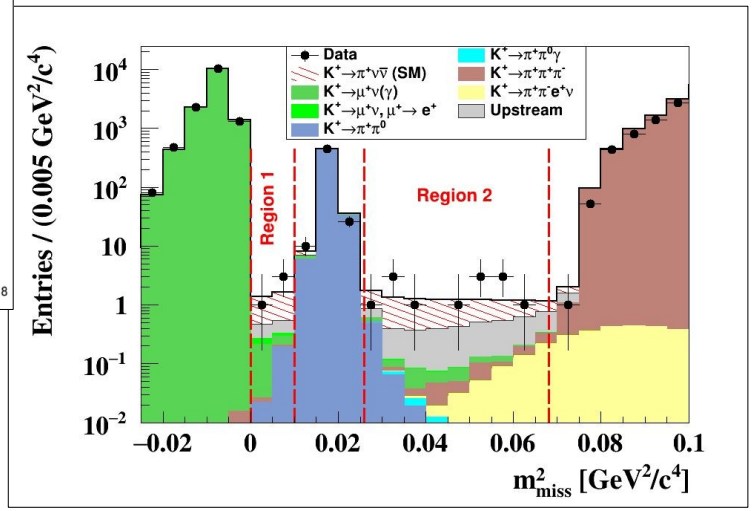
2016 data (30 days): PBL 791 (2019) 156
2017 data (160 days): JHEP 11 (2020) 042
2018 data (217 days): JHEP 06 (2021) 093

$N_K(2018) \simeq (0.8_{OLDCOL} + 1.9_{NEWCOL}) \cdot 10^{12} = 2.7 \cdot 10^{12}$









- Single Event Sensitivity: $(0.839 \pm 0.053_{syst}) \times 10^{-11}$
- Expected SM signal events: $10.01 \pm 0.42_{syst} \pm 1.19_{ext}$
- Expected background events: $7.03^{+1.05}_{-0.82}$
- Observed events: 20

$$BR(K^+ \to \pi^+ \nu\bar{\nu})^{NA62}_{16+17+18} = (10.6\ ^{+4.0}_{-3.8}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$$

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$K^+ \to \pi^+\mu^+\mu^-$

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- FCNC decay with dominant contributions mediated by virtual photon exchange:

$$K^\pm \to \pi^\pm\gamma^* \to \pi^\pm\ell^+\ell^-$$

- Form factor parametrized in ChPT at (p^6):

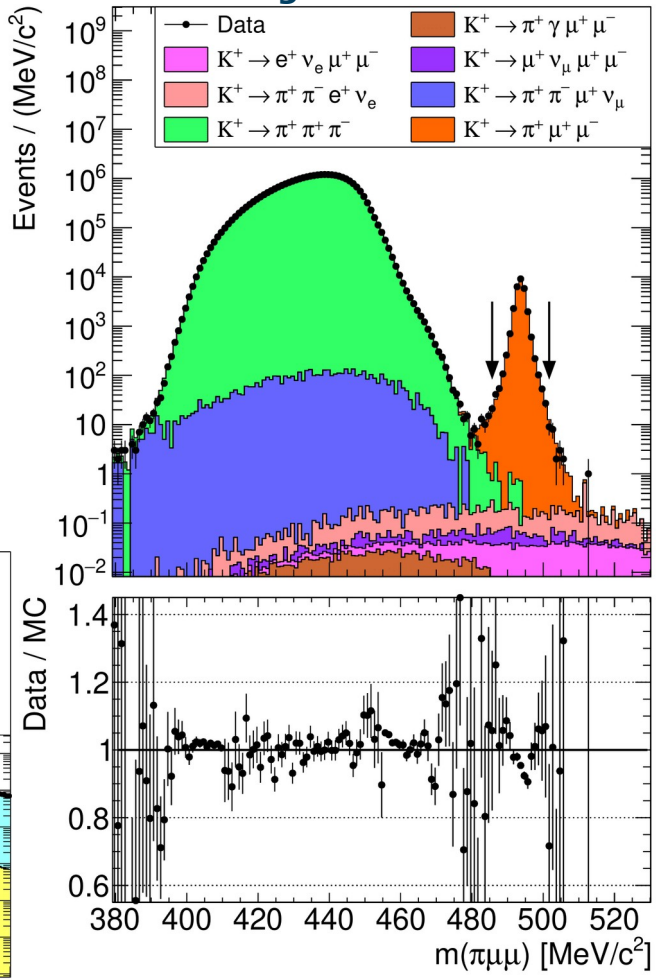
$$W(z) = G_F m_K^2(a_+ + b_+ z) + W^{\pi\pi}(z) \qquad z = m^2(\mu^+\mu^-)/m_K^2$$

[JHEP 08 (1998) 004]

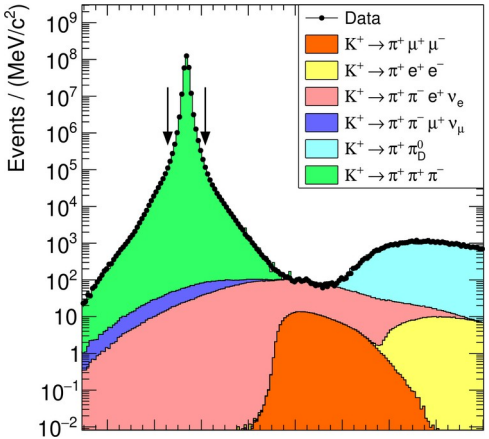
- 2017-18 data
- Normalized to $K_{3\pi}$ ($N_K \sim 3.5\times10^{12}$)
- **Observed 27679 events**
- **Expected background events: 8**

  $K\to 3\pi$ with two $\pi\to\mu\nu$ (decay in-flight)

Signal selection



Normalization selection



$K^+ \to \pi^+\mu^+\mu^-$

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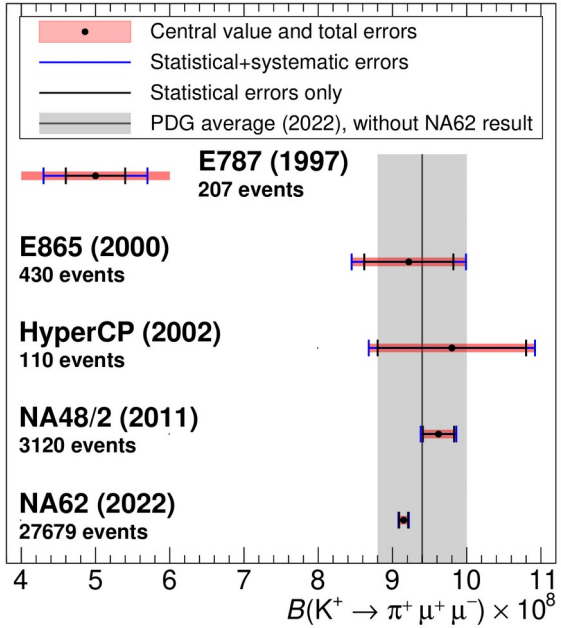
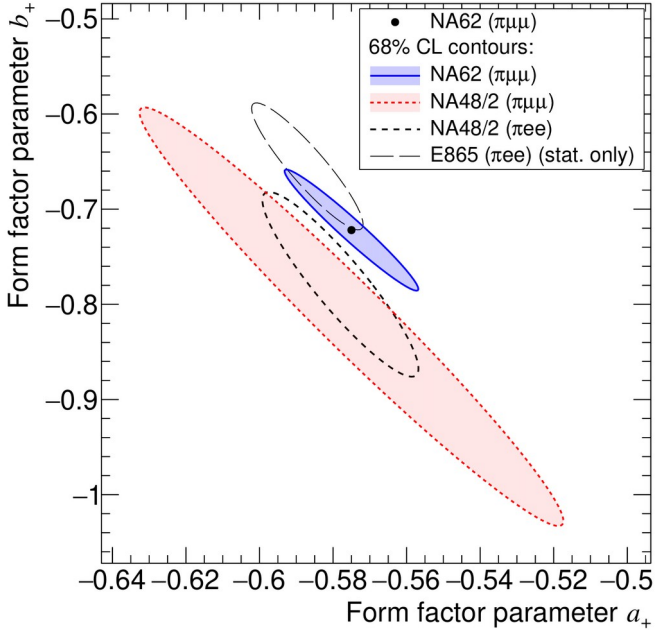
Model independent BR

- ✓ $BR(K^+ \to \pi^+\mu^+\mu^-) = (9.15 \pm 0.08)\cdot 10^{-8}$
- ✓ Improved by a factor ≥ 3
- ✓ Consistent with the previous measurements



ChPT form factor parameters

- ✓ $a_+ = -0.575 \pm 0.013$, $b_+ = -0.722 \pm 0.043$
- ✓ Compatible with previous measurements (as expected by LFU) in and ee channel

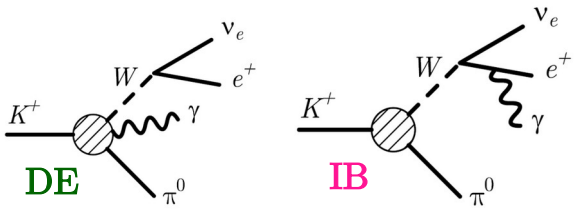


$K^+ \to \pi^0 e^+ \nu \gamma$

Precision test of ChPT up to O(p⁶)

$$R_j = \frac{\mathrm{BR}(K^+ \to \pi^o e^+ \nu \gamma \mid E_\gamma^j, \theta_{e,\gamma}^j)}{\mathrm{BR}(K^+ \to \pi^o e^+ \nu)}$$

[Eur. Phys. J. C 48 (2006)]



Process described by **DE** + **IB** + **INT**

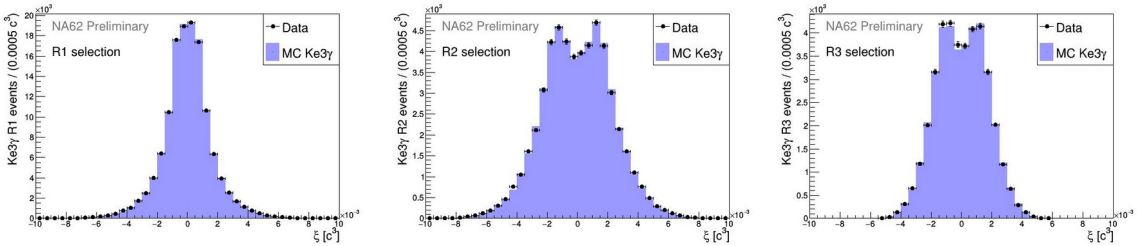
BR predicted and measured in 3 regions of the phase space

T-odd observable $\xi = \frac{\vec{p_\gamma} \cdot (\vec{p_e} \times \vec{p_\pi})}{M_K^3}$; $A_\xi = \frac{N_+ - N_-}{N_+ + N_-}$ → test of T-asymmetry

Normalization to $K^+ \to \pi^0 e^+ \nu$

Main background: accidental activity in the LKr

estimated using signal sidebands

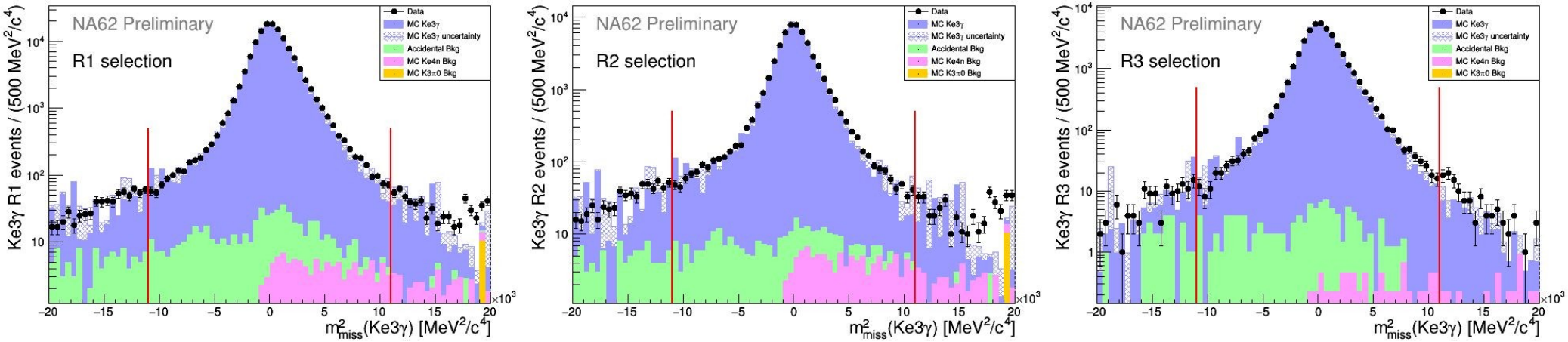


Range	E_γ cut	$\theta_{e,\gamma}$ cut	$O(p^6)$ $ChPT$ $[10^{-2}]$	$ISTRA+$ $[10^{-2}]$	OKA $[10^{-2}]$
R_1	$E_\gamma > 10\ MeV$	$\theta_{e,\gamma} > 10°$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$
R_2	$E_\gamma > 30\ MeV$	$\theta_{e,\gamma} > 20°$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$
R_3	$E_\gamma > 10\ MeV$	$0.6 < \cos\theta_{e,\gamma} < 0.9$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$

$K^+ \to \pi^0 e^+ \nu\gamma$

Events selected: **130K** (R1), **54K** (R2) and **39K** (R3)

Background contamination B/S: R1: 0.5% , R2 : 0.6% and R3~0.3%



	$O(p^6)$ *ChPT*	ISTRA+	OKA	**NA62 preliminary**
R_1 $(\times 10^2)$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$	$1.684 \pm 0.005 \pm 0.010$
R_2 $(\times 10^2)$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$	$0.599 \pm 0.003 \pm 0.005$
R_3 $(\times 10^2)$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$	$0.523 \pm 0.003 \pm 0.003$

$K^+ \to \pi^+\gamma\gamma$

described by two kinematic variables

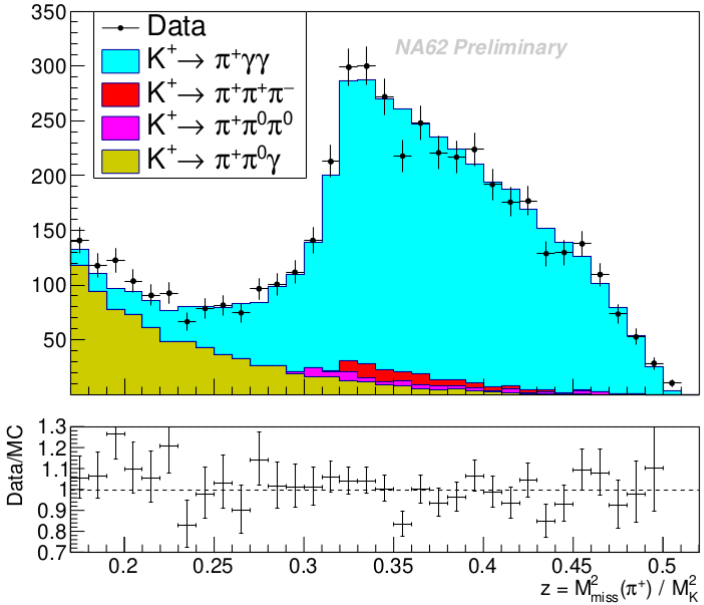
$$z = \frac{(q_1+q_2)^2}{m_K^2} = \left(\frac{m_{\gamma\gamma}}{m_K}\right)^2, \qquad y = \frac{p(q_1-q_2)}{m_K^2}$$

$$\frac{\partial\Gamma}{\partial y\partial z}(\hat{c},y,z) = \frac{m_K}{2^9\pi^3}\left[z^2\left(\left|A(\hat{c},z,y^2)+B(z)\right|^2+\left|C(z)\right|^2\right) + \left(y^2-\frac{1}{4}\lambda(1,r_\pi^2,z)\right)^2\left|B(z)\right|^2\right].$$

appears at $O(p^6)$

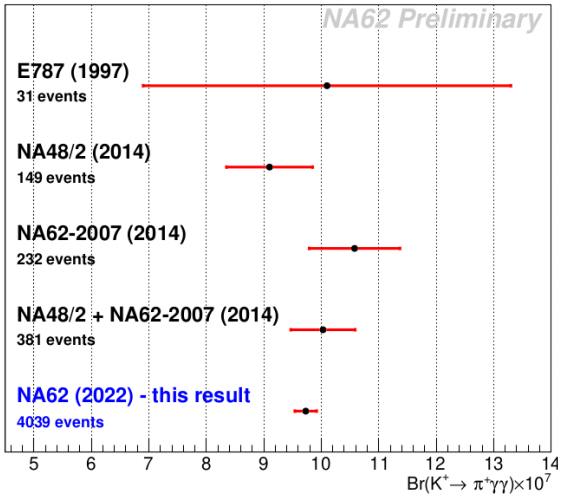
Data: 4039 events

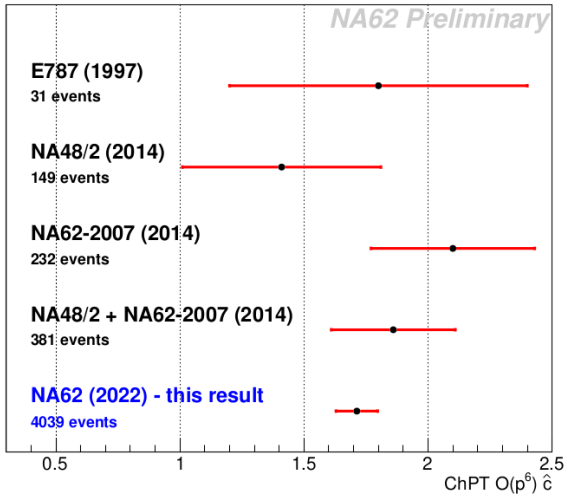
Total background: 393±9(stat.)±18(syst.)



$\hat{c}_6$ = 1.713±0.075stat.±0.037syst.

$Br(K^+\to\pi^+\gamma\gamma)=(9.73\pm0.17\text{stat.}\pm0.08\text{syst})\times10^{-7}$





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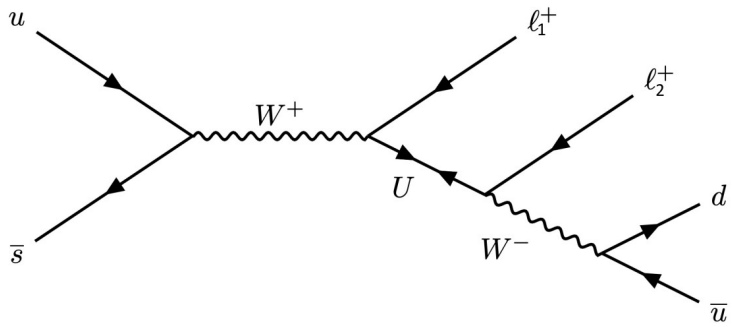
LFV and LNV in Kaon decays

Lepton number (L) and Lepton flavour (L_e, L, L) are foreseen in some BSM theories.



$K^+ \to \pi^- l^+ l^+$ (l = e, μ)

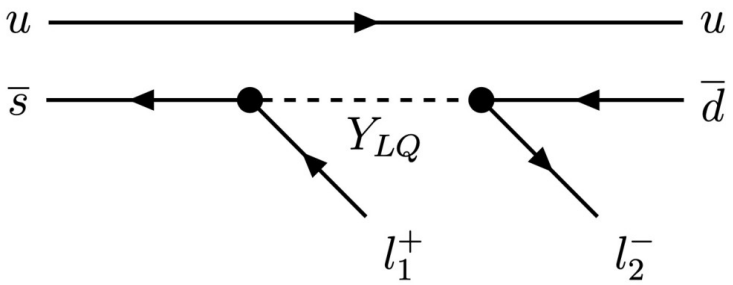
Lepton number violation:

L = 2 via Majoranna neutrinos U

(analogue to 0ν2β decays)

NPB 176 (1980) 135

JHEP 12 (2019) 089



$K^+ \to \pi^\pm \mu^\pm e^+$

Lepton flavour violation: $L_e = 1$ and $L_\mu = 1$

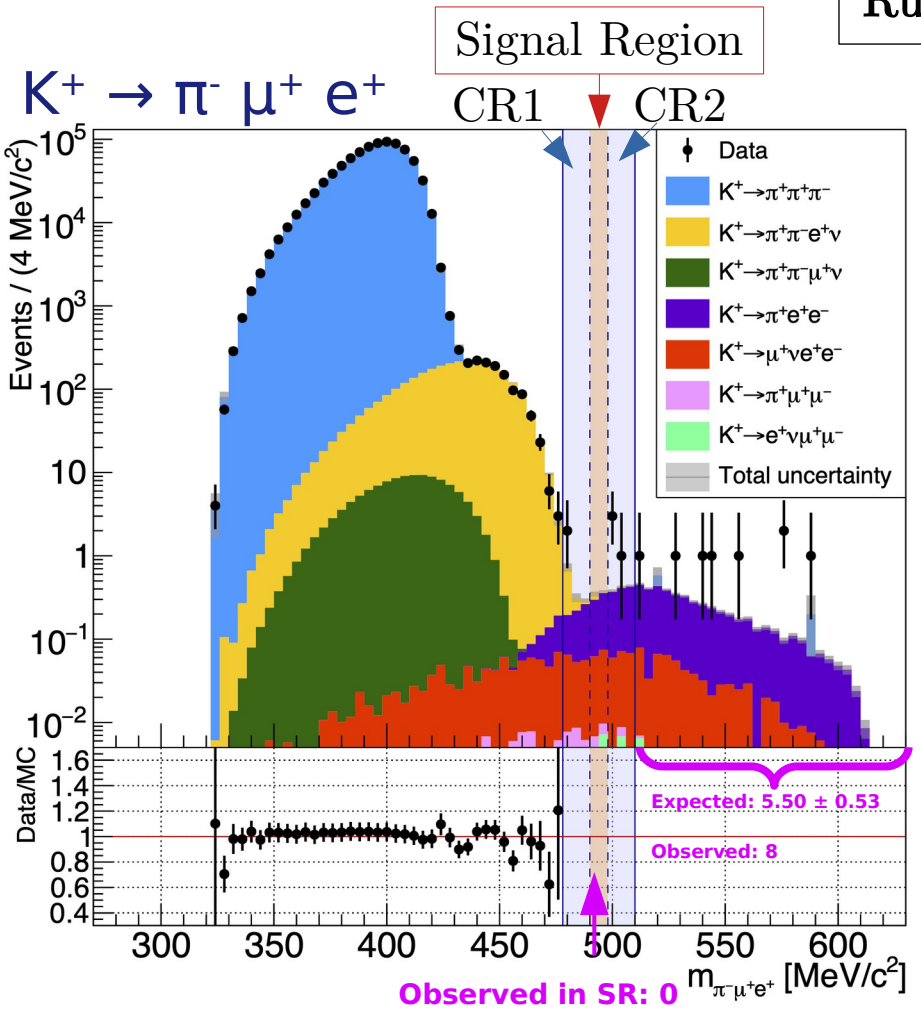
Mediated by a leptoquark

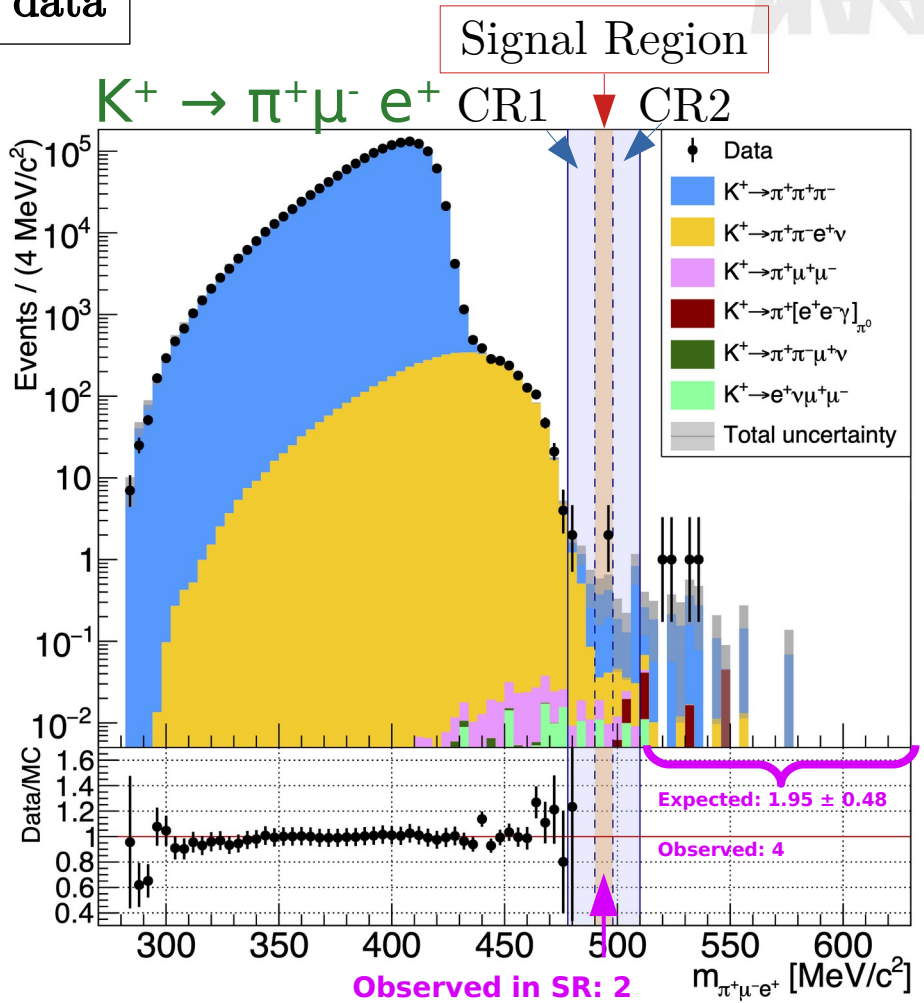
JHEP 12 (2019) 089

PLB 491 (2000) 285

LFV: $K^+ \to \pi^\pm \mu^\mp e^+$

Run1 data





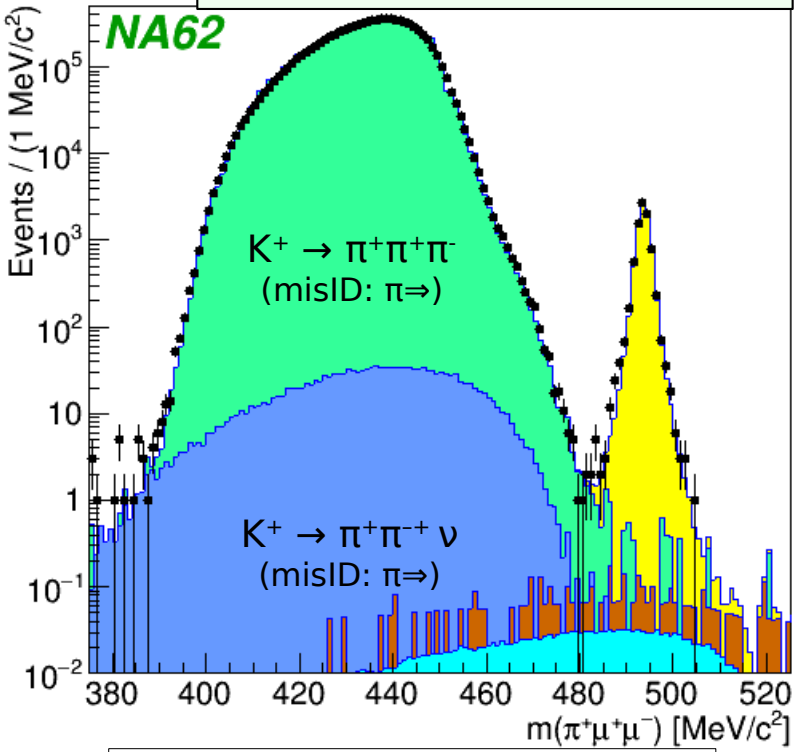
LFV: $K^+ \to \pi^\pm \mu^\mp e^+$

	$K^+ \to \pi^- \mu^+ e^+$	$K^+ \to \pi^+ \mu^- e^+$	$\pi^0 \to \mu^- e^+$
Signal Acceptance	(4.90 ± 0.02) %	(6.21 ± 0.02)%	(3.11 ± 0.02)%
SES	$(1.82 \pm 0.08) \times 10^{-11}$	$(1.44 \pm 0.05) \times 10^{-11}$	$(13.9 \pm 1.0) \times 10^{-11}$
Bkgd. expectation	1.07 ± 0.20	0.92 ± 0.34	0.23 ± 0.15
Events observed	0	2	0
BR Upper limit @ 90%CL	4.2×10^{-11}	6.6×10^{-11}	3.2×10^{-10}
Previous result [PRL 85 (2000) 2877]	5.0×10^{-10}	5.2×10^{-10}	3.4×10^{-9}

Published in PRL 127 (2021) 13, 131802

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

SM: $M(\pi^+\mu^-\mu^+)$

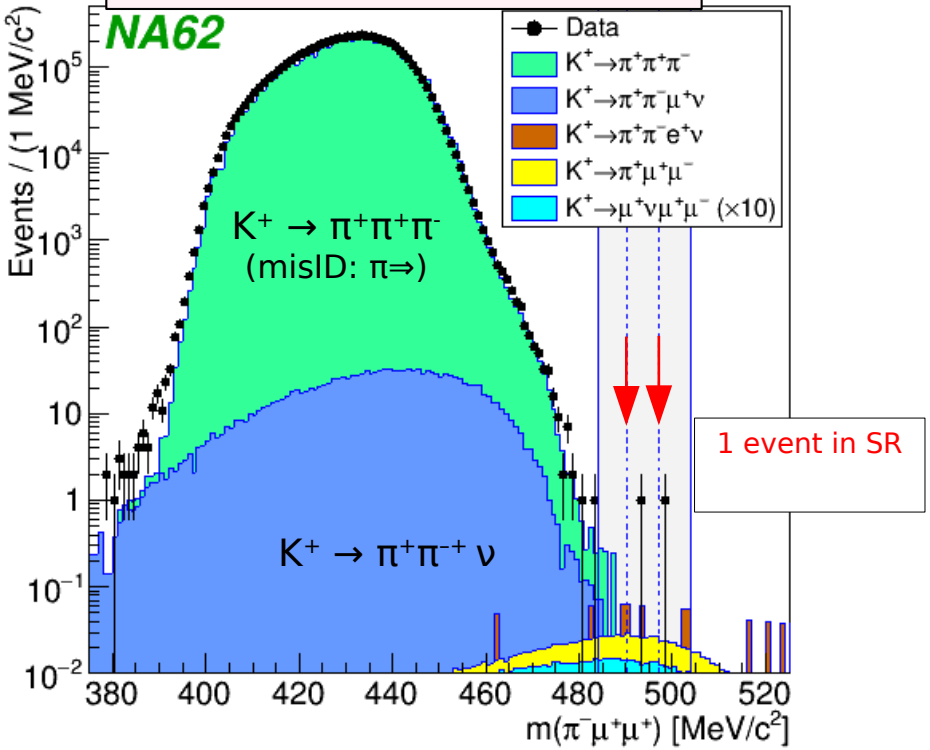


Candidates: 8357

$N_{K+} = (7.94 \pm 0.23) \times 10^{11}$

$BR = (0.962 \pm 0.025) \times 10^{-7}$

LNV: $M(\pi^-\mu^+\mu^+)$



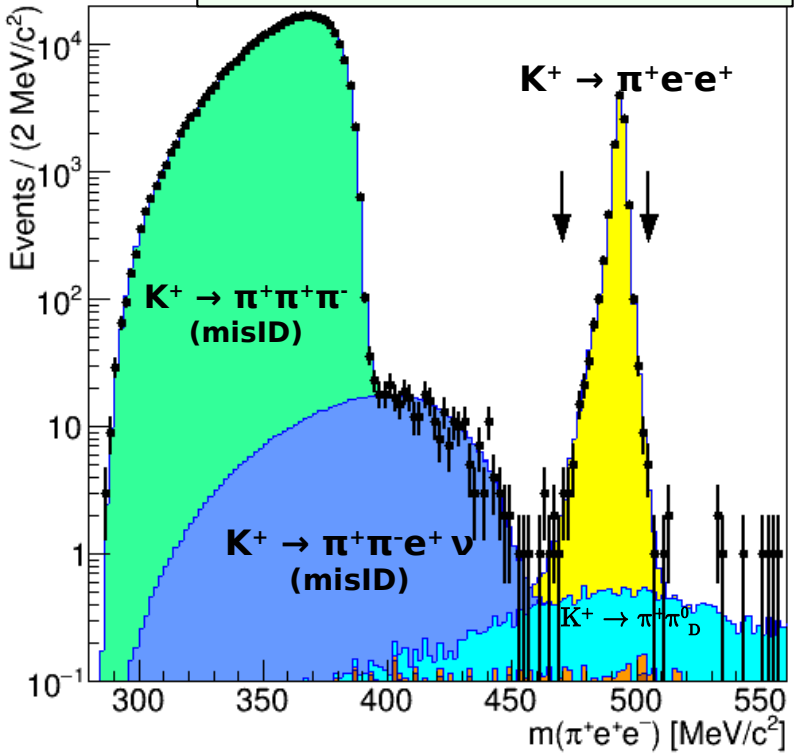
Candidates: 1

Exp.background: 0.91 ± 0.41

$BR < 4.2 \times 10^{-11}$ @ 90% CL

LNV: Search for $K^+ \to \pi^- e^+ e^+$ (Run1 data)

SM: $M(\pi^+ e^- e^+)$

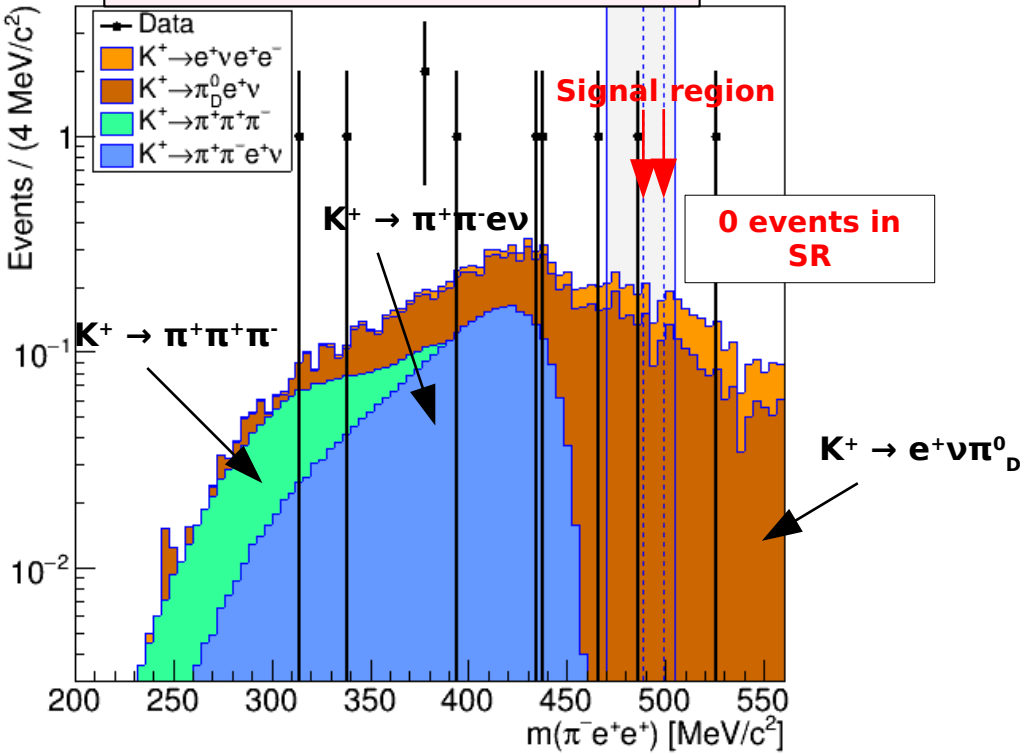


Candidates: 11041

$N_{K+} = (1.015 \pm 0.0032) \times 10^{12}$

$BR = (3.00 \pm 0.09) \times 10^{-7}$

LNV: $M(\pi^- e^+ e^+)$

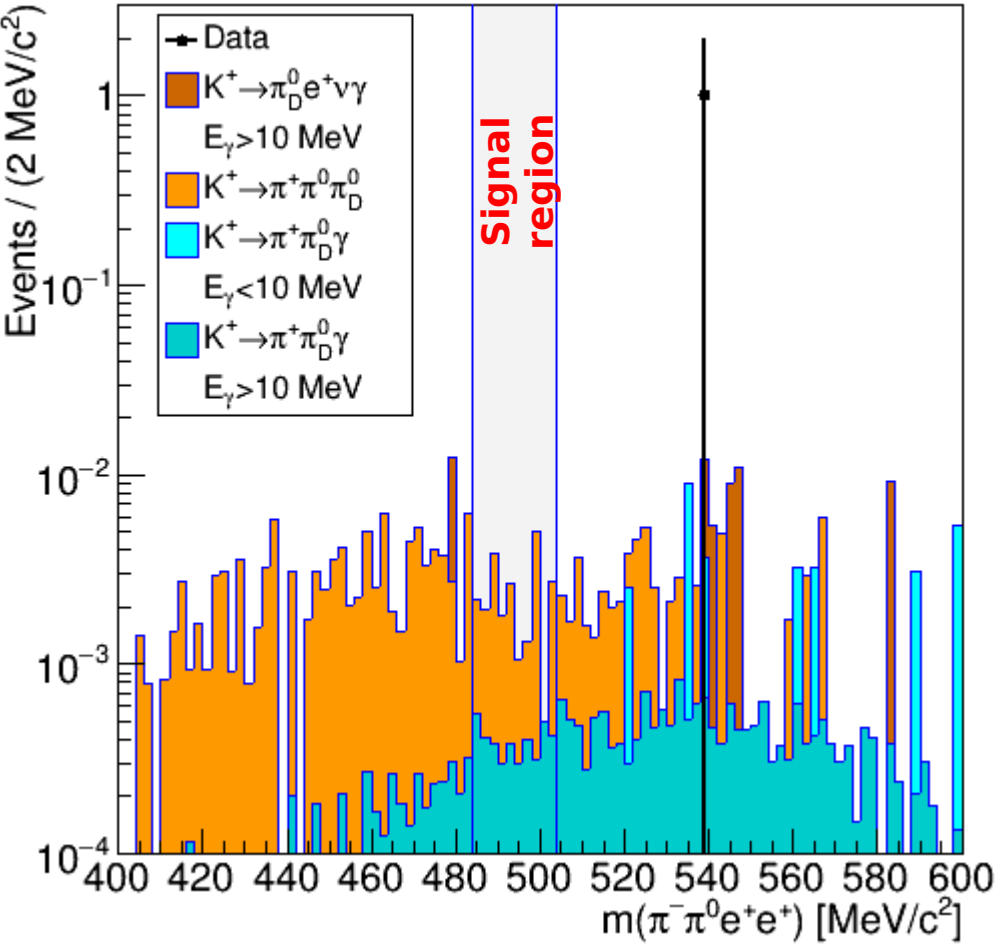


Candidates: 0

Exp.background: 0.43 ± 0.09

$BR < 5.3 \times 10^{-11}$ @ 90% CL

LNV: Search for $K^+ \to \pi^- \pi^0 e^+ e^+$ (Run1 data)

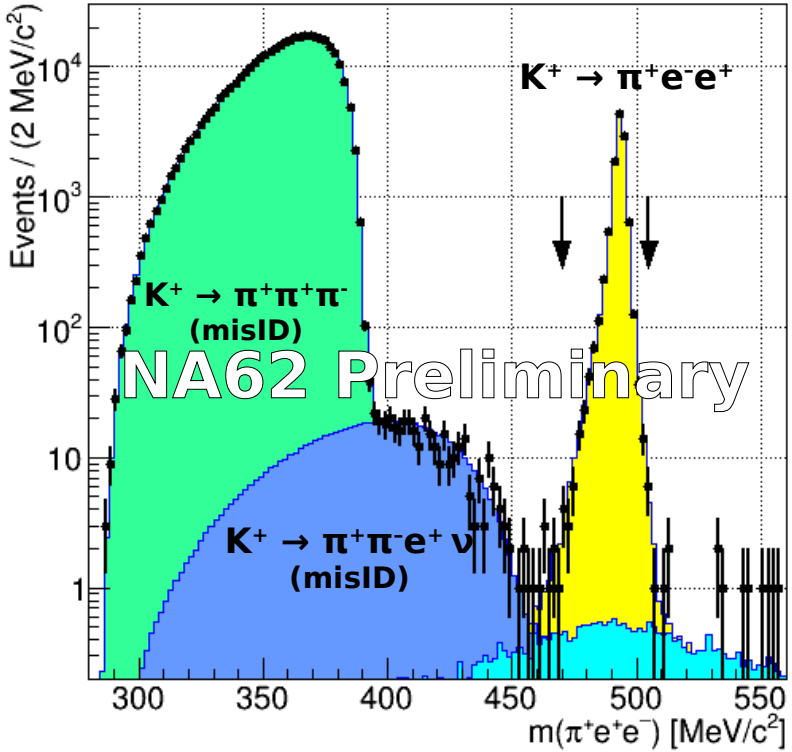


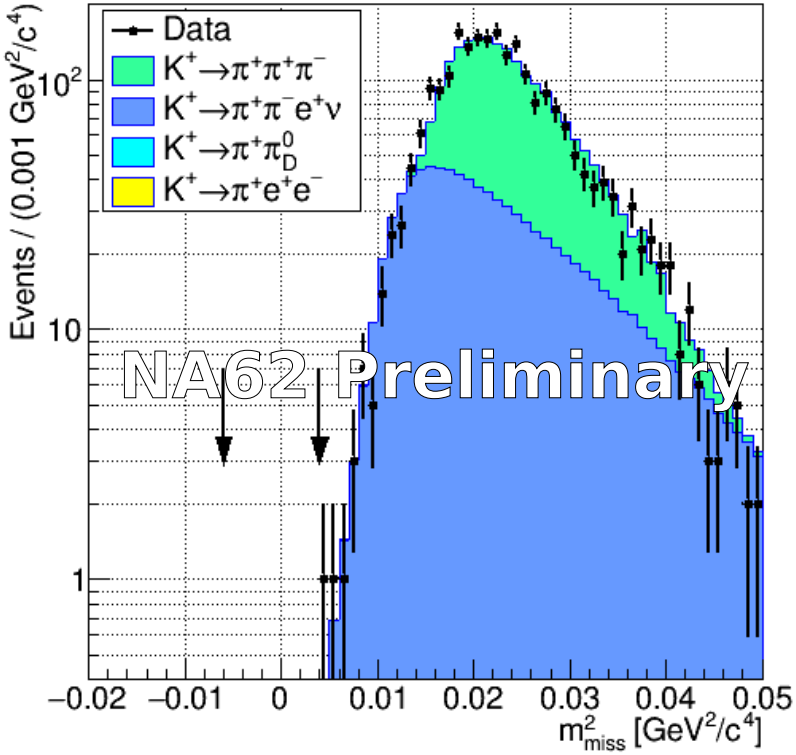
Normalization channel **$K^+ \to \pi^+ e^+ e^-$**

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

Candidates: 0
Expected background: 0.044 ± 0.020 events
BR < 8.5 x 10^{-10} at 90% CL

LFV/LNV: Search for $K^+ \to \mu^- \nu e^+ e^+$ (Run1 data)





Normalization Channel

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

$N_K = (1.97 \pm 0.02\text{stat} \pm 0.02\text{ sys} \pm 0.06\text{ext}) \times 10^{12}$

Candidates: 0

BR < 8.1×10^{-11} @ 90% CL

NA62 LNV/LFV decays

Decay	Previous BR UL [pdg]	NA62 BR UL @ 90% CL	Comment
$K^+ \to \pi^- \mu^+ \mu^+$	8.6×10^{-11}	4.2×10^{-11}	PLB 797 (2019) 134794
$K^+ \to \pi^- e^+ e^+$	6.4×10^{-10}	5.3×10^{-11}	PLB 797 (2019) 134794
$K^+ \to \pi^- \mu^+ e^+$	5.0×10^{-10}	4.2×10^{-11}	PLB 127 (2021) 131802
$K^+ \to \pi^+ \mu^- e^+$	5.2×10^{-10}	6.6×10^{-11}	PLB 127 (2021) 131802
$K^+ \to \pi^+ \mu^+ e^-$	1.3×10^{-11}	-	Not yet competitive
$\pi^0 \to \mu^- e^+$	3.4×10^{-9}	3.2×10^{-10}	PLB 127 (2021) 131802
$K^+ \to \pi^- \pi^0 e^+ e^+$	-	8.5×10^{-10}	PLB 830 (2022) 137172
$K^+ \to \mu^- \nu e^+ e^+$	- Preliminary	8.1×10^{-11}	**First search for this mode!**

Outline:

New results from the NA48/2:

the first observation of the decay $K^{\pm}\to\pi^0\pi^0\mu^{\pm}\nu_{\mu}$ (K00μ4)

Results from the NA62 Run 1:

⇛ $K^+\to\pi^+\nu\bar{\nu}$ decay.

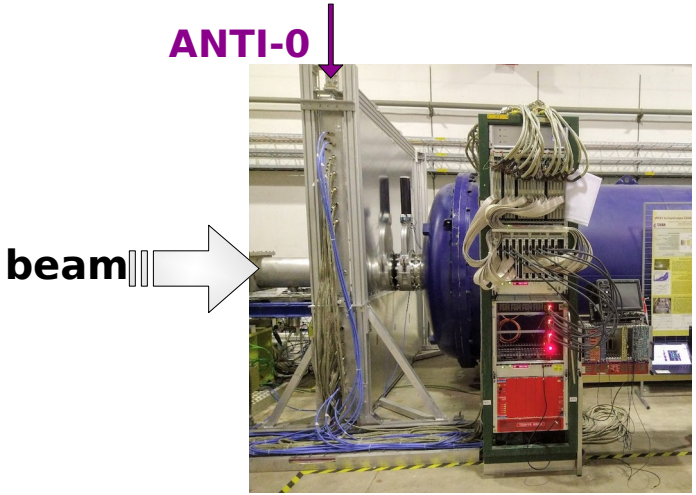
⇛ Precision measurements

⇛ LNV/LFV decays

⇛ Beam-dump mode

~~Summary~~ Current status of the NA62 and prospects for the future

NA62 in beam-dump mode: search for A`→ μμ

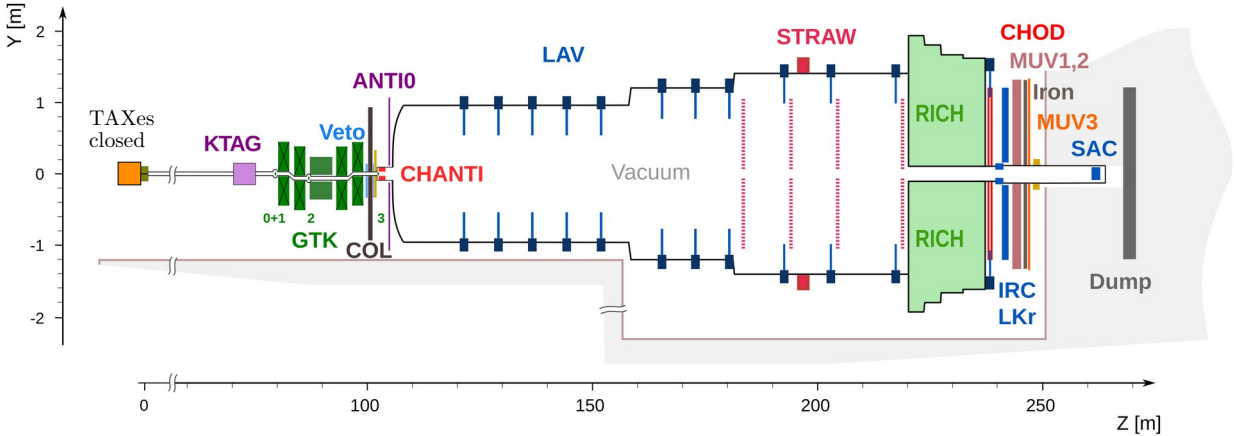


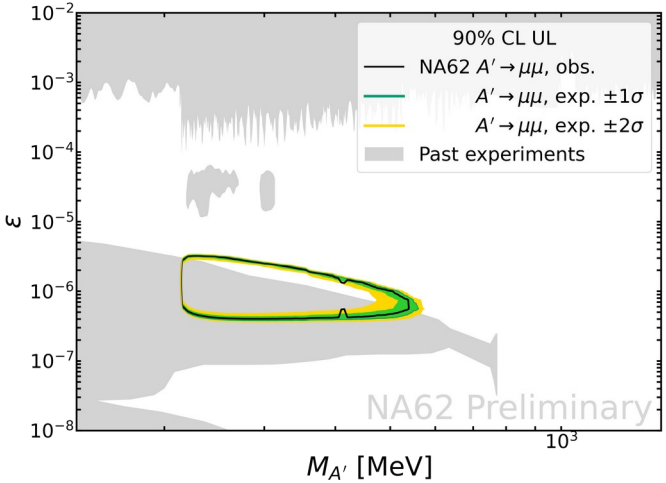
Two production mechanisms are in action in proton-nucleus interaction scenario:

- Bremsstrahlung production in pN → X A′
- Meson mediated production as pN→M X , M→γA′,

  where M= π^0, ω, ρ, ...

In 2021, NA62 **collected 1.40 ± 0.28 × 10^{17} POT** in beam-dump mode





Outline:

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⇛ LNV/LFV decays

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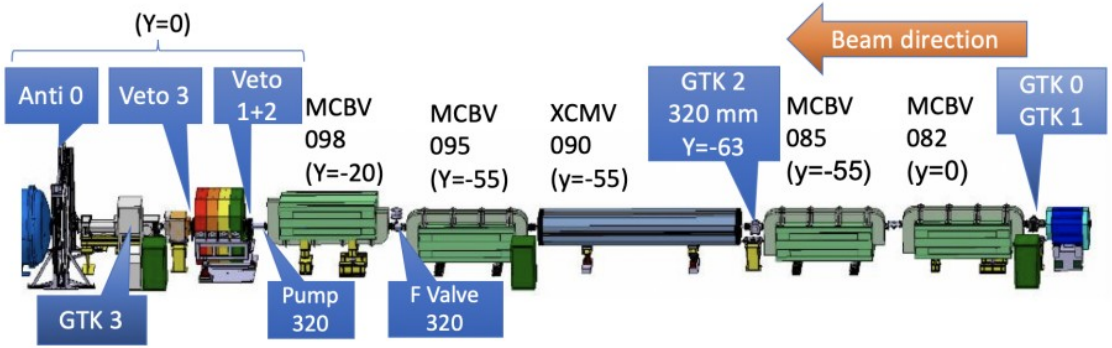
~~Summary~~ Current status of the NA62 and prospects for the future

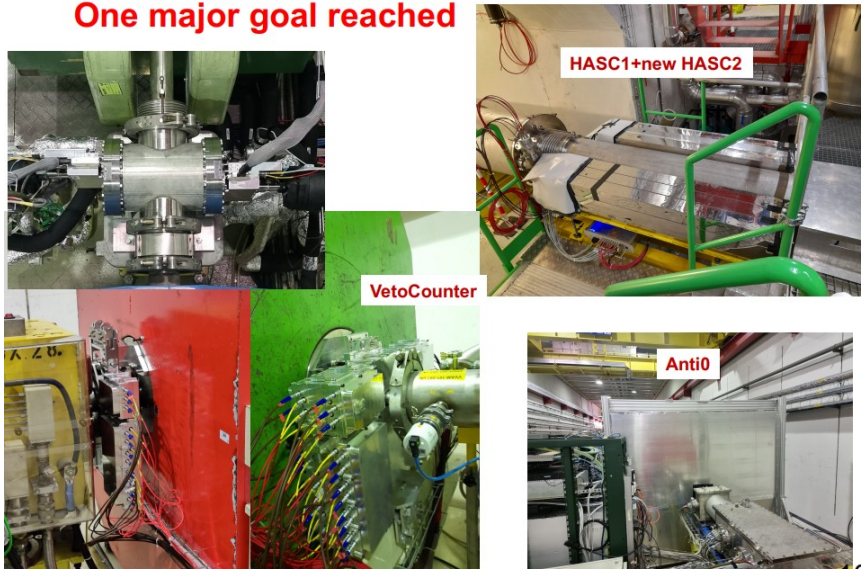
NA62: current status

NA62 is fully committed and approved to continue data-taking (Run2) in 2021-2025 (until LS3)

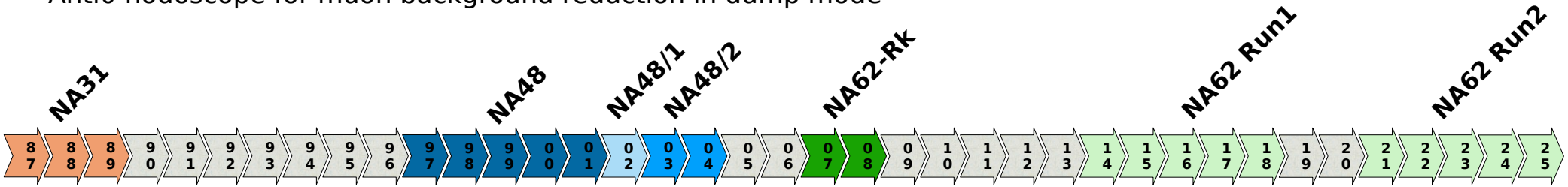


New detector installed and commissioned

One major goal reached



- 2nd achromat optimized for background rejection,
- 4th GTK station (GTK0),
- VetoCounter before/after last collimator,
- 2nd HASC module
- Anti0 hodoscope for muon background reduction in dump mode



High Intensity Kaon Experiments (HIKE)

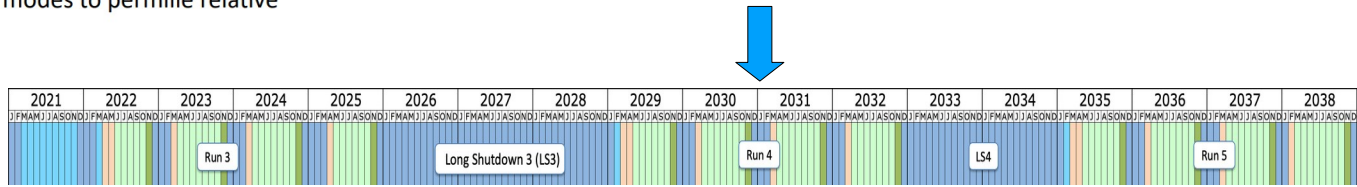
Phase 1: K^+

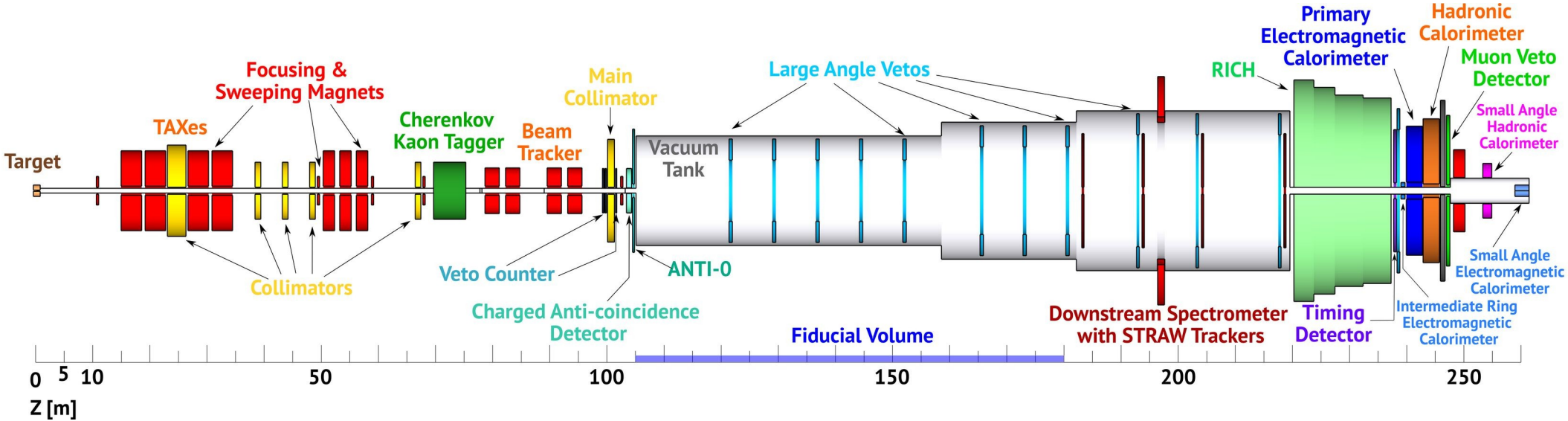
A multi-purpose K^+ experiment (after LS3)

Scrutiny the K^+ physics with the highest precision:

- Measurement of the $K^+ \to \pi^+ \nu \bar{\nu}$ branching ratio to a 5% relative precision, matching the SM theoretical uncertainty.
- Precision measurements of $K^+ \to \pi^+ l^+ l^-$ decays, and a precision lepton universality test.
- Searches for lepton flavour/number violating decays and lepton universality tests
- Measurement of the ratios of the branching ratios of the main decay modes to permille relative precision
- Improvement of other existing rare decay modes
- Searches for production of feebly-interacting particles in K^+ decays.
- Collection of a dataset in the beam-dump mode

HIKE Phase 1





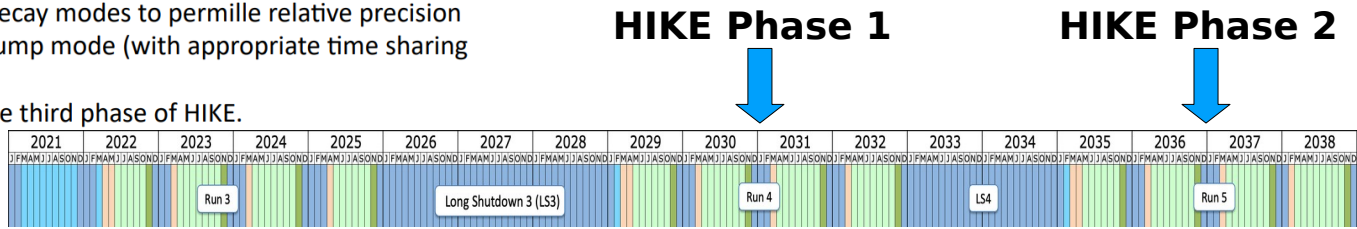
High Intensity Kaon Experiments (HIKE)

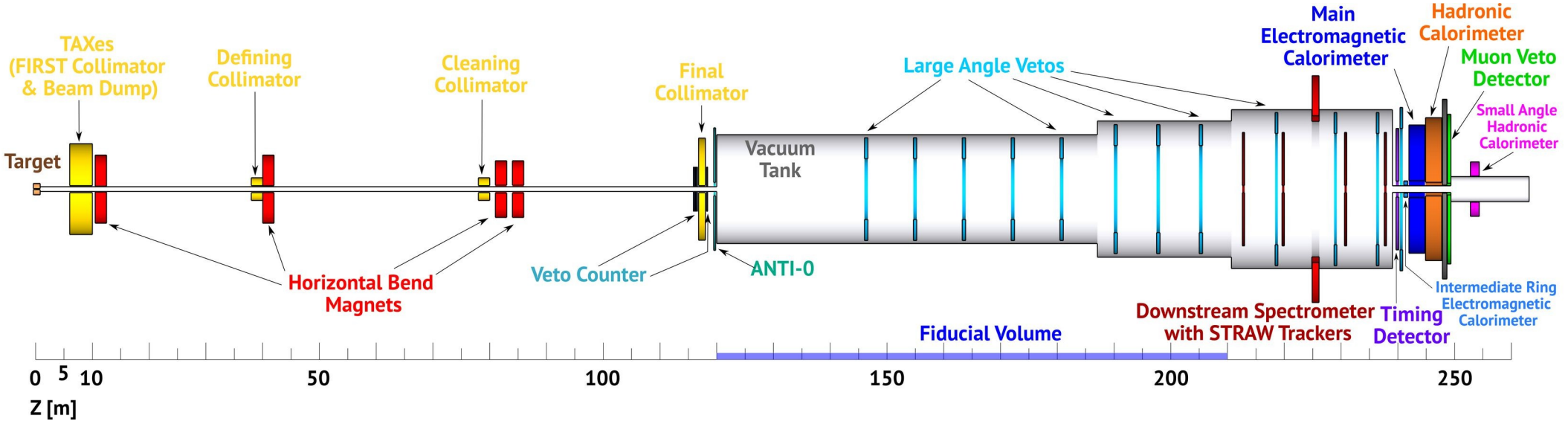
High Intensity Kaon Experiments

Phase 2: a multi-purpose K_L experiment

Measure K_L modes of particular interest:

- Observation of the ultra-rare decays $K_L \to \pi^0 l^+ l^-$ or establishment of stringent upper limits at $O(10^{-11})$ level
- Measurement of the $K_L \to \mu^+\mu^-$ decay branching ratio to a 1% relative precision
- Search for lepton flavour violating decays at the $O(10^{-12})$ sensitivity
- Measurement of the ratios of the branching ratios of the main decay modes to permille relative precision
- Collection of a further dataset (up to 5×10^{19} POT) in the beam-dump mode (with appropriate time sharing with kaon mode)
- Characterisation of the neutral beam necessary to proceed to the third phase of HIKE.





High Intensity Kaon Experiments (HIKE)

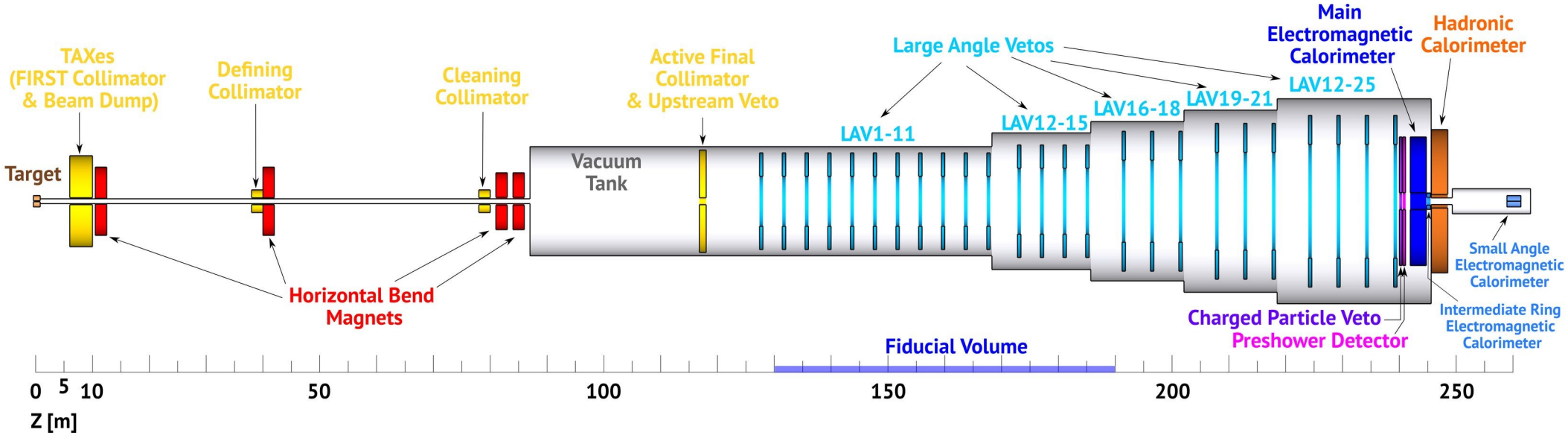
Letter of Intent: http://cds.cern.ch/record/2839661

Slides on SPSC Open Session (November 22)

Phase 3 (KLEVER):

Measure $K_L \rightarrow \pi^0 \nu\bar{\nu}$ to 20% relative precision

- Search for production and decay of feebly-interacting particles
- Search for additional FCNC K_L decays and forbidden K_L decays



High Intensity Kaon Experiments (HIKE) @ CERN

Letter of Intent: http://cds.cern.ch/record/2839661

Slides on SPSC Open Session (November 22)

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Measure $K_L \to \pi^0 \nu\bar{\nu}$ to 20% relative precision

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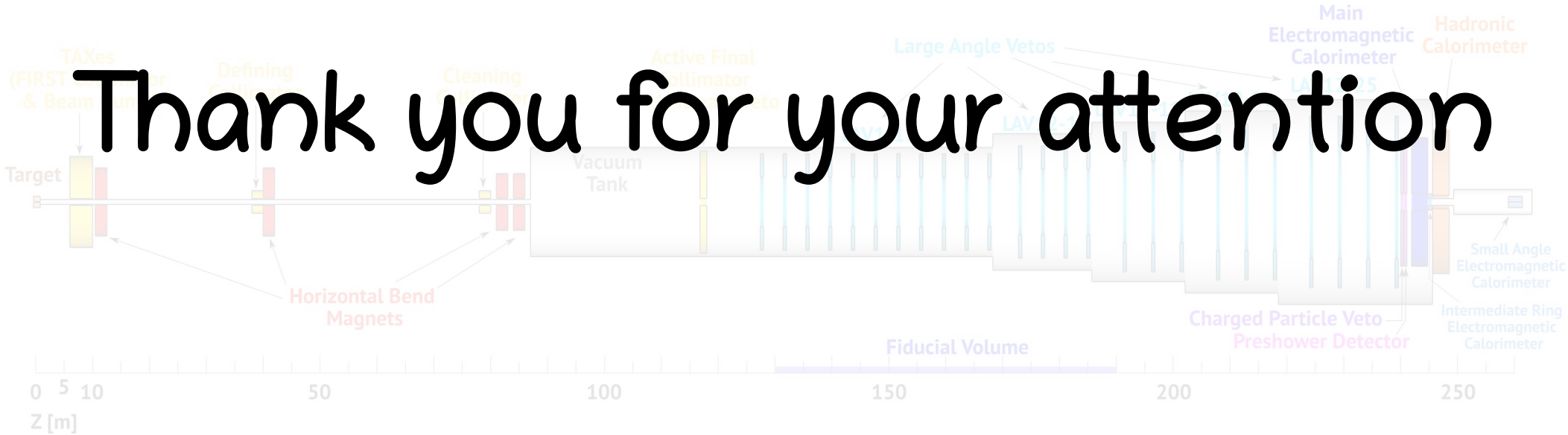

Thank you for your attention