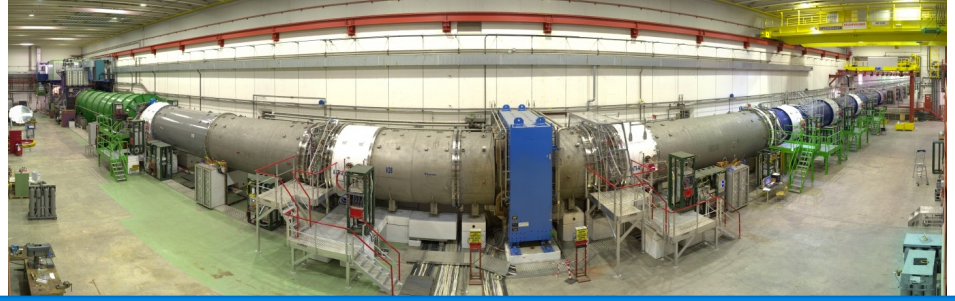

Recent results and precision measurements by the NA62 experiment at CERN

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Aspen 2023 WINTER CONFERENCE

Prospecting for New Physics through Flavour, Dark Matter, and Machine Learning

Aspen, CO, March 26-31, 2023

* On behalf of the NA62 Collaborations

Outline

- ★ Measurement of the ultra rare process $K^+ \to \pi^+ \nu \bar{\nu}$ — *JHEP 06 (2021) 093*

- ★ Precision measurements of the rare decays:
  - $K^+ \to \pi^+ \mu^+ \mu^-$ — *JHEP 11(2022) 011*
  - $K^+ \to \pi^+ \gamma \gamma$ — *preliminary result*

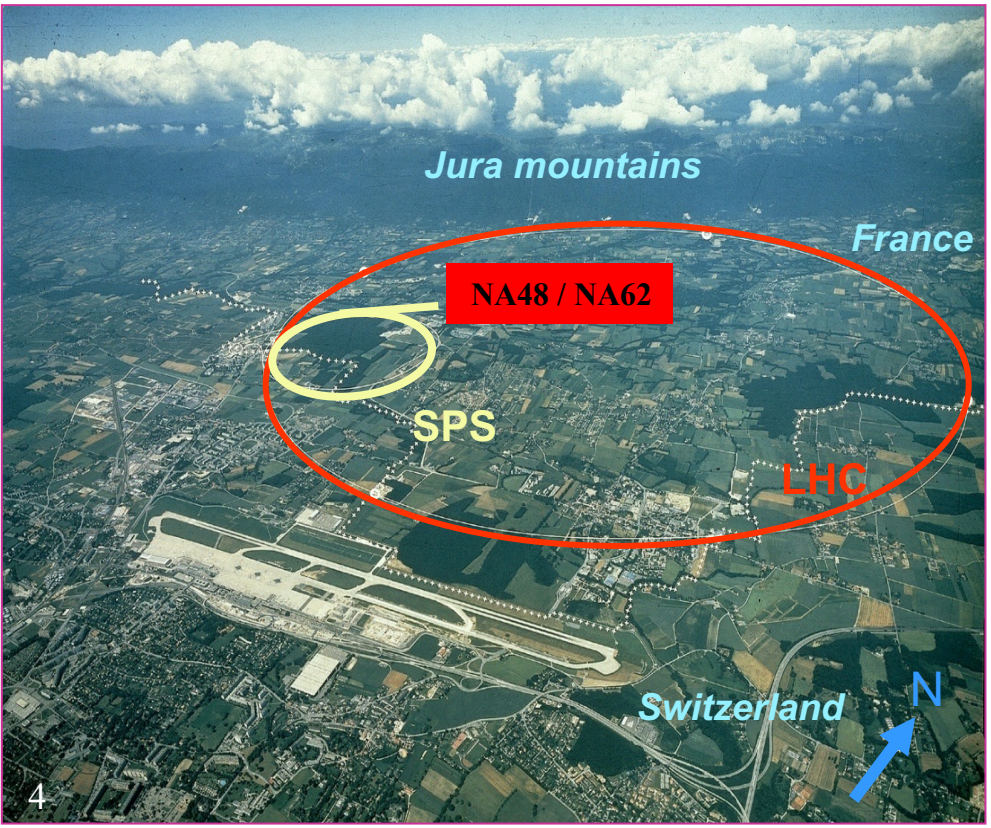
- ★ Searches for LFV/LNV processes — *PLB 797 (2019) 134794*, *PRL 127 (2021) 13, 131802*, *PLB 830 (2022) 137172*, *PLB 838 (2023) 137679*

- ★ Dark photon searches (2021 data): $A' \to \mu^+ \mu^-$ and $A' \to e^+ e^-$ — *arXiv: 2303.08666*, *NEW - preliminary result*

★ The NA62 experiment at the CERN kaon beam facility

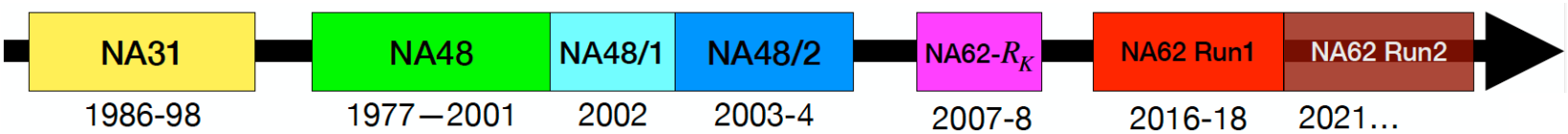
The NA62 experiment at CERN

A fixed target experiment at the CERN SPS dedicated to the study of rare decays in the kaon sector.

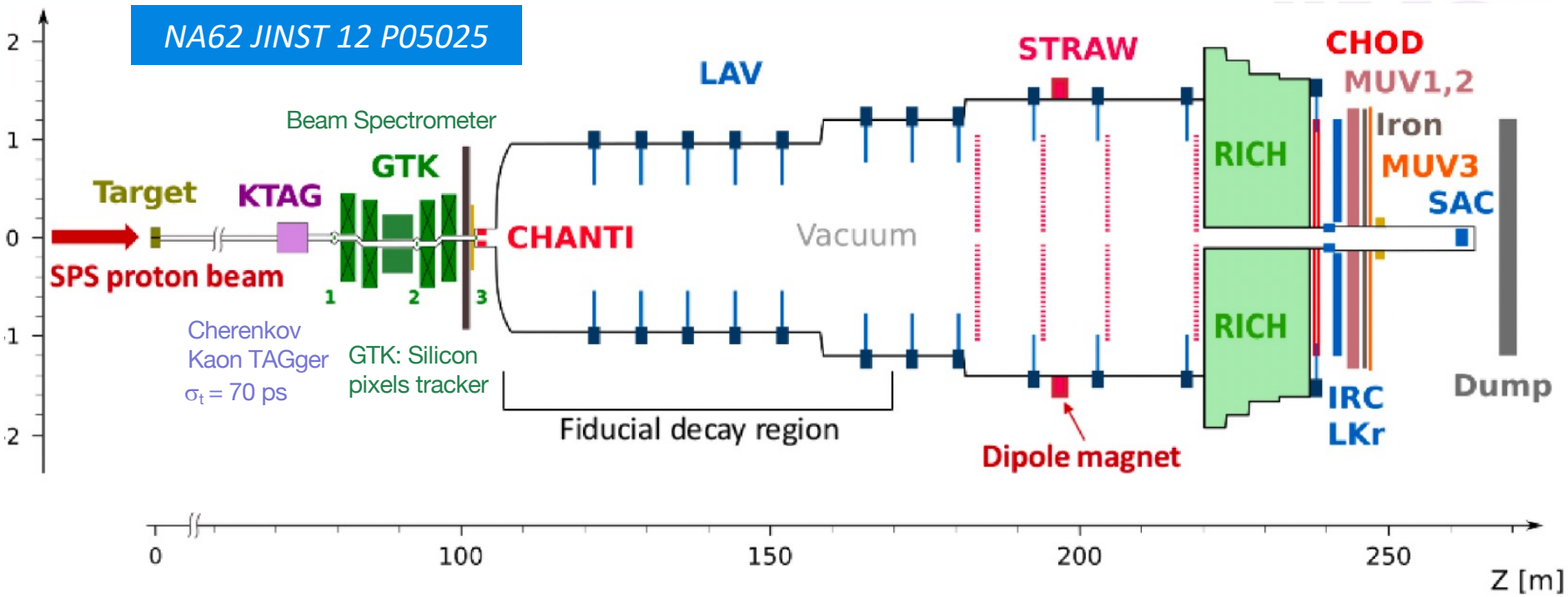


- Detector installation completed in 2016
- Physics runs in 2016, 2017 and 2018
- Data taking resumed in July 2021, approved up to CERN Long-Shutdown-3…
- Main goal: BR($K^+ \to \pi^+ \nu\nu$) measurement
- Broad physics program thanks to unprecedented statistics for many decay modes

~300 physicists from 31 institutes in 11 countries



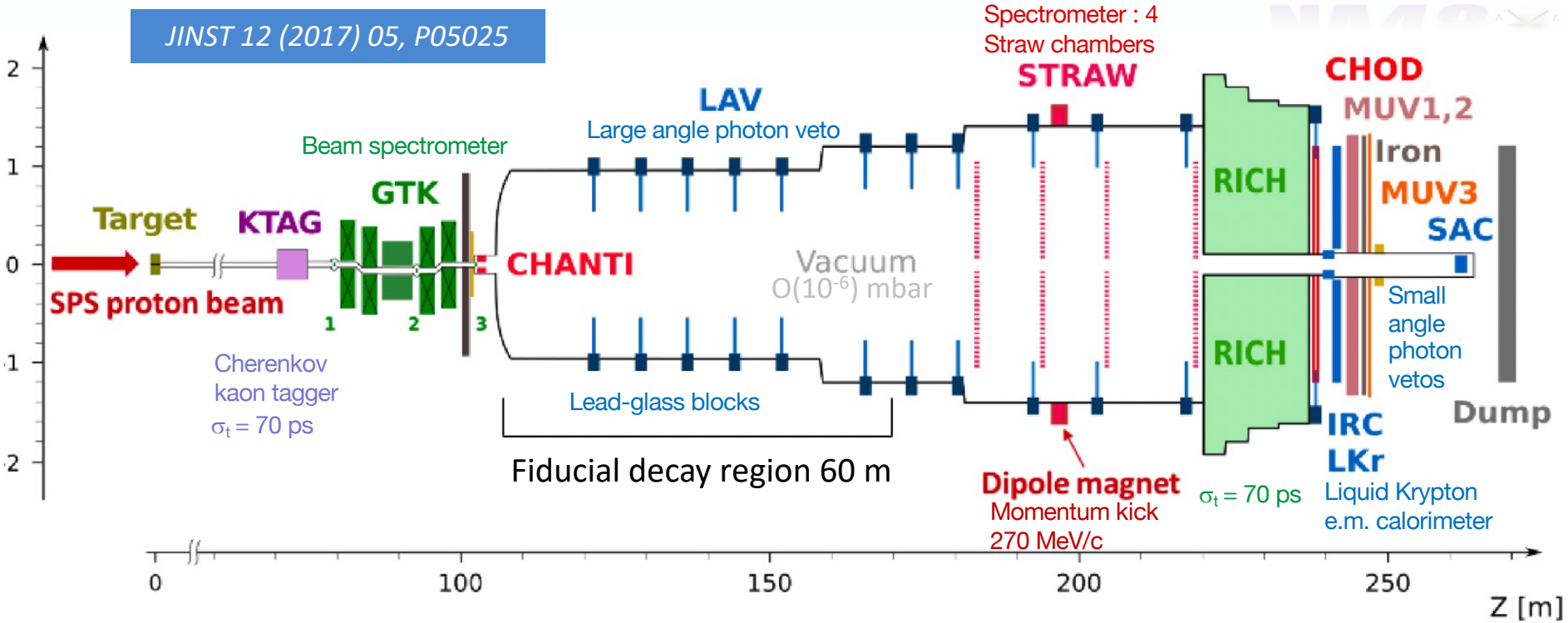
The NA62 kaon beam



- SPS beam: 400 GeV/c proton on beryllium target
- 75 ± 1 GeV/c unseparated secondary hadron beam (70% pions, 24% protons, 6% kaons)
- **Decay in-flight technique**: the high energy kaons decay in a ~60 m fiducial region

- Nominal beam particle rate (at GTK3): 750 MHz, O(10^{12}) pot per spill, ~3.5 s effective spill
- Average beam particle rate during 2018 data-taking: 500-750 MHz
- K^+ decay rate ~ 5 MHz

The NA62 detector



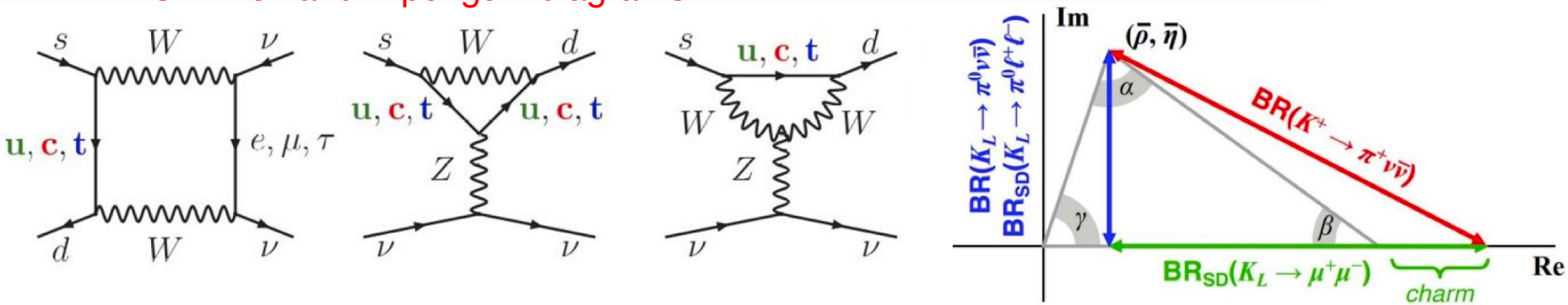
- Beam Si pixel spectrometer (**GTK**)
- Decay products magnetic spectrometer (**STRAW**)
- Particle identification system (**KTAG, RICH, MUVs**)
- **LKr**: electromagnetic calorimeter
- Veto system (**LAV, iRC, SAC, CHANTI, MUV, HASC**)
- CHOD: scintillator hodoscopes
- Multi level (**L0, L1, L2**) trigger

★ Measurement of the ultra rare process $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

JHEP 06 (2021) 093

$K^+ \to \pi^+ \nu \bar{\nu}$: a golden decay mode

SM: Box and Z-penguin diagrams



- Ultra rare FCNC: s → d transition, loop + hard GIM suppression
- Theoretically clean dominated by short-distance physics
- Negligible hadronic uncertainties
- K^+ - π^+ Form Factor (FF) extracted from $K^\pm \to \pi^0 l^\pm \nu_l$: sub % precision
- Sensitive to new physics in the lepton sector as well: involves ν_e ν_μ and ν_τ

Extremely rare process in the SM:

arXiv:2105.02868

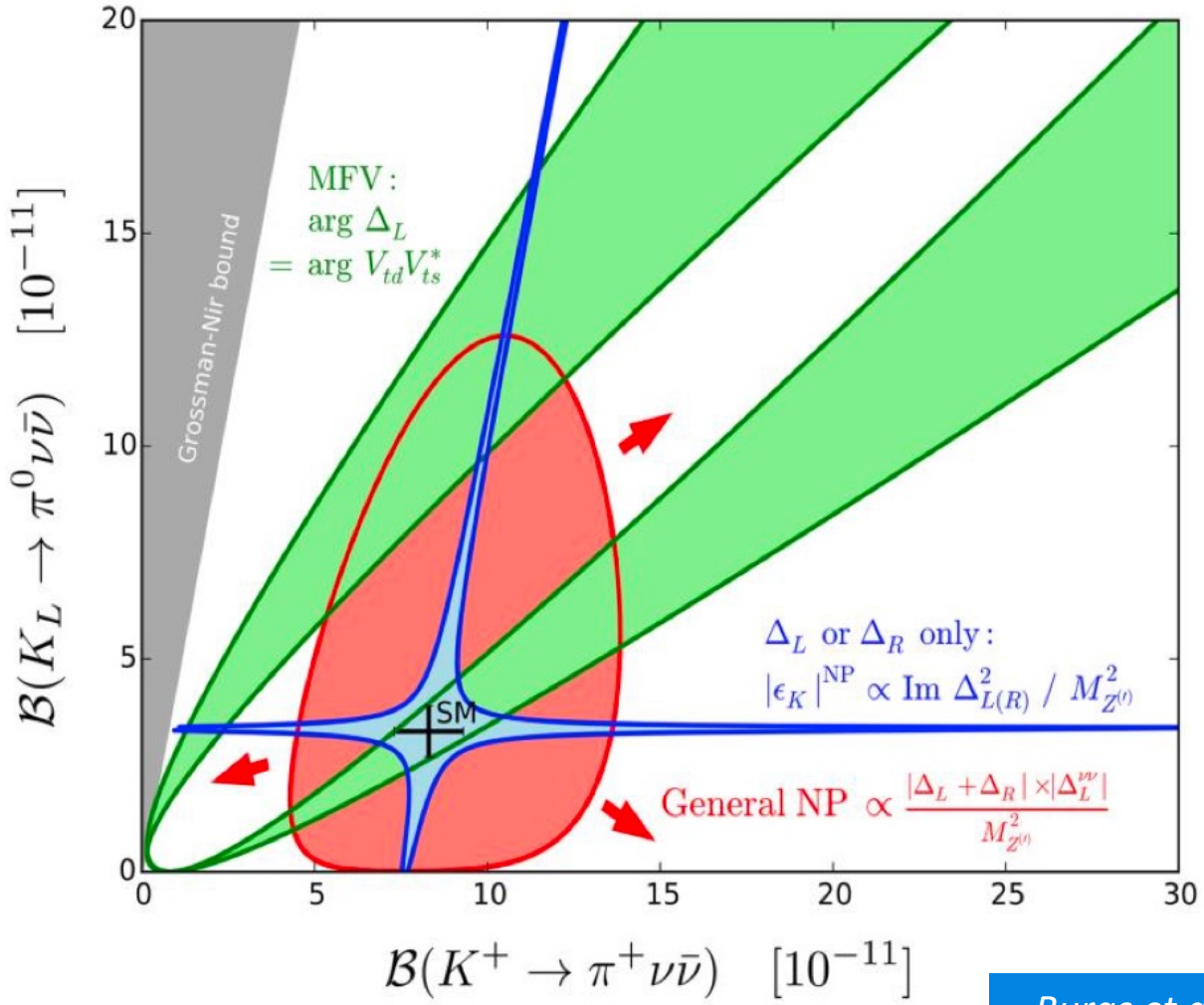
$$BR_{SM}(K^+ \to \pi^+ \nu \bar{\nu}) = 7.73 \pm 0.16_{SD} \pm 0.25_{LD} \pm 0.54_{param.} \times 10^{-11}$$

arXiv:2109.11032

$$BR_{SM}(K^+ \to \pi^+ \nu \bar{\nu}) = (7.92 \pm 0.28_{theory}) \times 10^{-11} \times [|V_{cb}|/41.0 \times 10^{-3}]^{2.8} \times [\sin\gamma/\sin 67°]^{1.39}$$

Impact in the context of BSM models

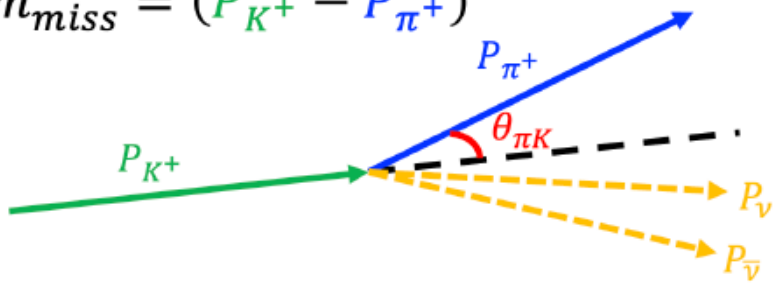
Simplified models

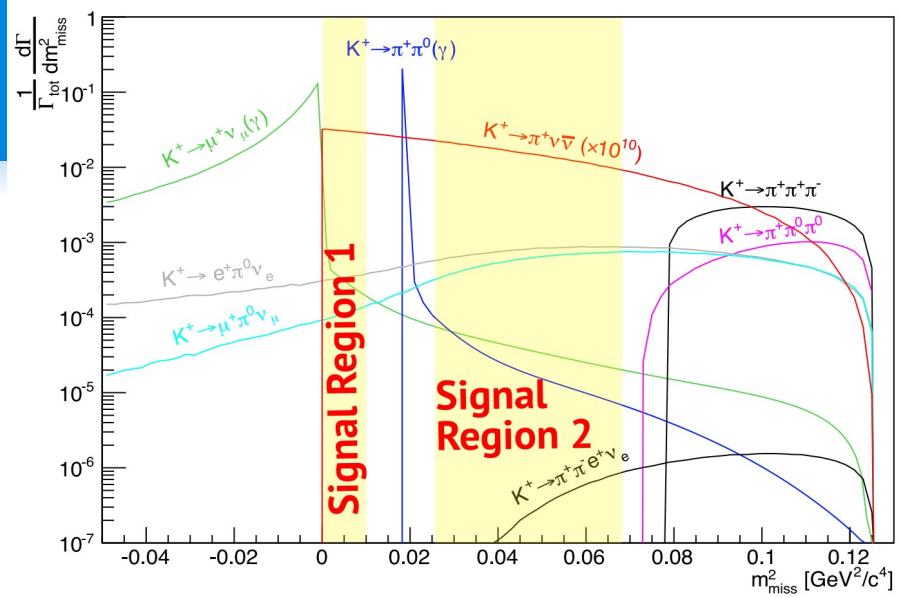


Buras et al. JHEP 11(2015) 166

Measurements strategy

$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$



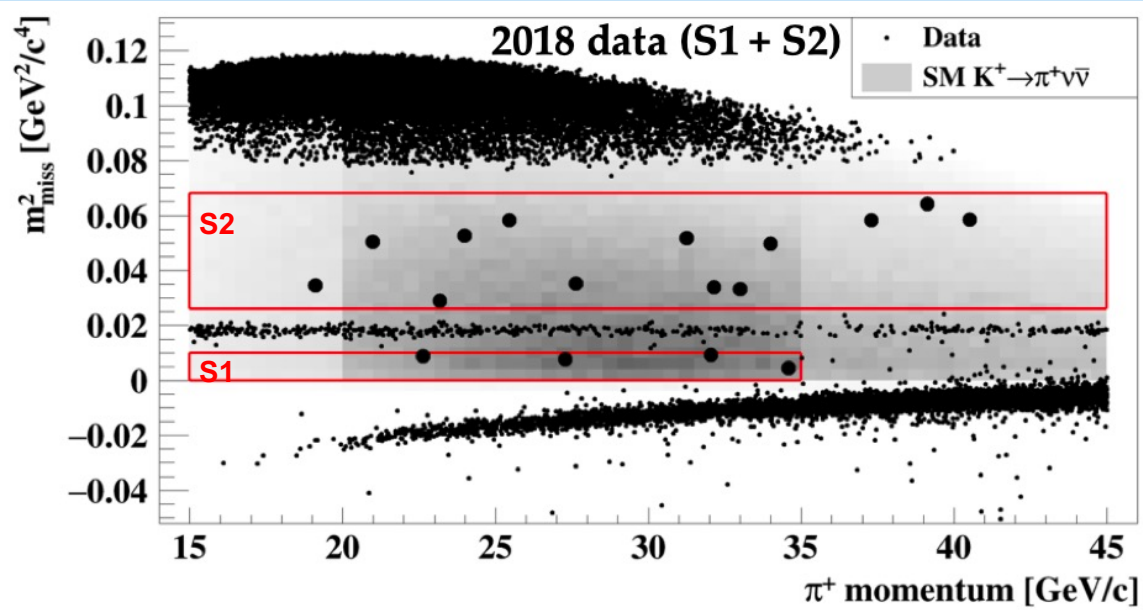


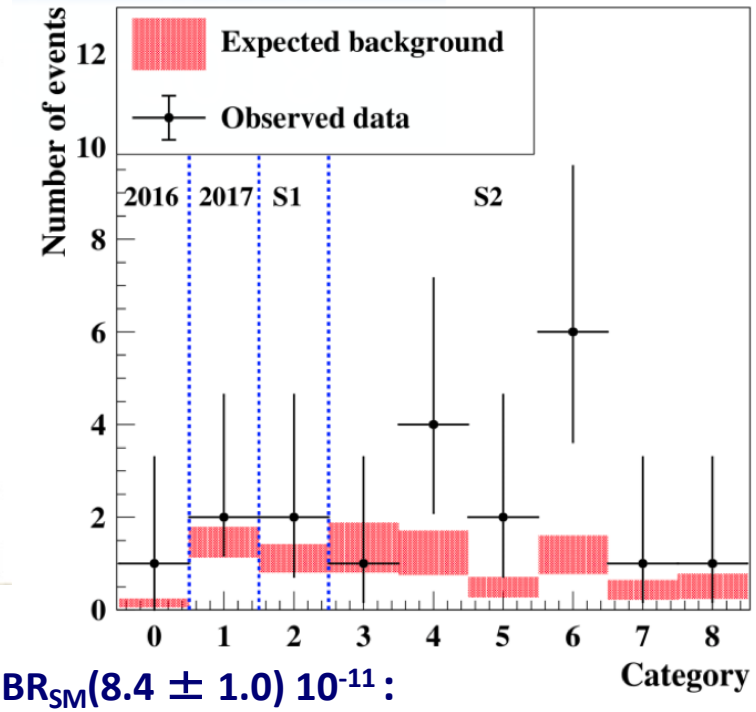
- ✓ Highly boosted decay: **K^+@(75 ± 1) GeV/c (γ ~150)**
- ✓ Large undetectable missing energy carried away by the neutrinos
- ✓ All energy from visible particles must be detected + Particle ID (calorimeters, Cherenkov, muon-ID, photon veto)
- ✓ **π^+ momentum range 15-45 GeV/c (E_{miss} > 30 GeV)**
- ✓ **Hermetic detector coverage and O(100%) detector efficiency needed**

Requirements on background rejection:

- O(10^4) suppression from kinematic conditions
- O(10^7) from μ+ rejection
- O(10^7) from π^0 rejection
- O(100 ps) timing between sub-detectors

NA62 results from Run 1 (2016-2018)





- **20 events observed in the signal region**
- Combining the complete Run 1 data set and assuming **$BR_{SM}(8.4 \pm 1.0)\ 10^{-11}$:**

$$N^{exp}_{\pi\nu\nu} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$$

$$N^{exp}_{background} = 7.03\ ^{+1.05}_{-0.82}$$

$$SES = (0.839 \pm 0.053_{syst}) \times 10^{-11}$$

JHEP 06 (2021) 093

$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (10.6\ ^{+4.0}_{-3.4}\ |_{stat} \pm 0.9_{syst}) \times 10^{-11}$$ **3.4σ significance**

★ Precision measurement of the rare processes:

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

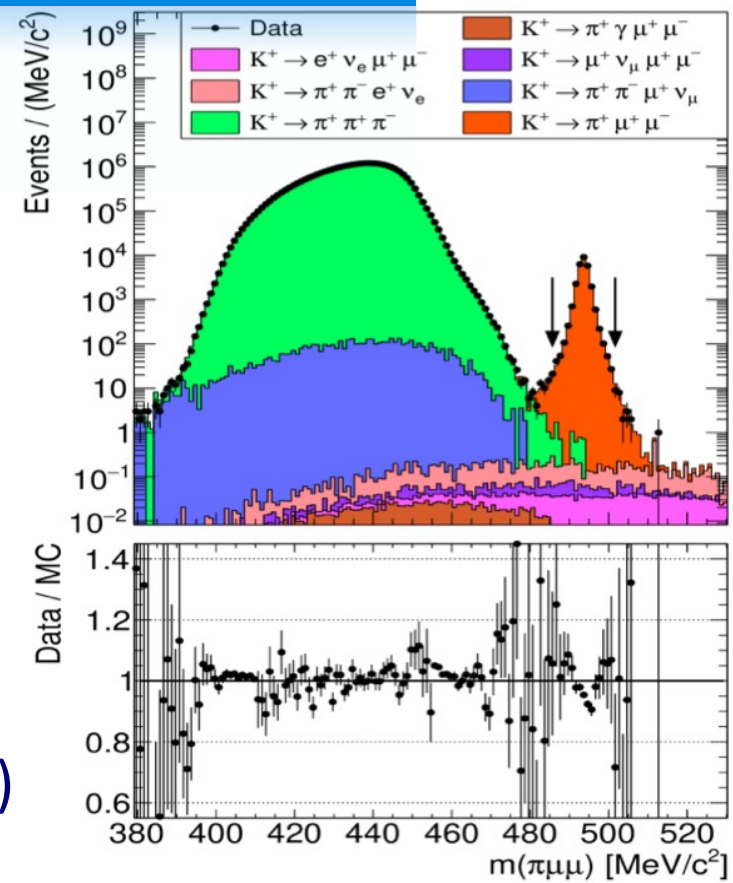
JHEP 11(2022) 011

preliminary result

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

- Heavily suppressed FCNC transition: $s \to d\, l^+ l^-$
- Main kinematic variable: $z = \dfrac{m^2(l^+l^-)}{m^2_K}$
- Form Factor of the $K^\pm \to \pi^\pm \gamma^*$ transition: W(z)
- Chiral Perturbation Theory (ChPT) parametrization of W(z) at $O(p^6)$:

$$W(z) = G_F\, m^2_K\, (a_+ + b_+ z) + W^{\pi\pi}(z)$$



Main goals of the measurement with NA62:

- Model independent measurement of the $B(\pi\mu\mu)$
- Measurement of the function $|W(z)|^2$
- Determine the Form Factor parameters a_+ and b_+
- Forward-backward asymmetry

Effective number of Kaons $N_K = 3.48\ 10^{12}$ (measured from $K3\pi$)

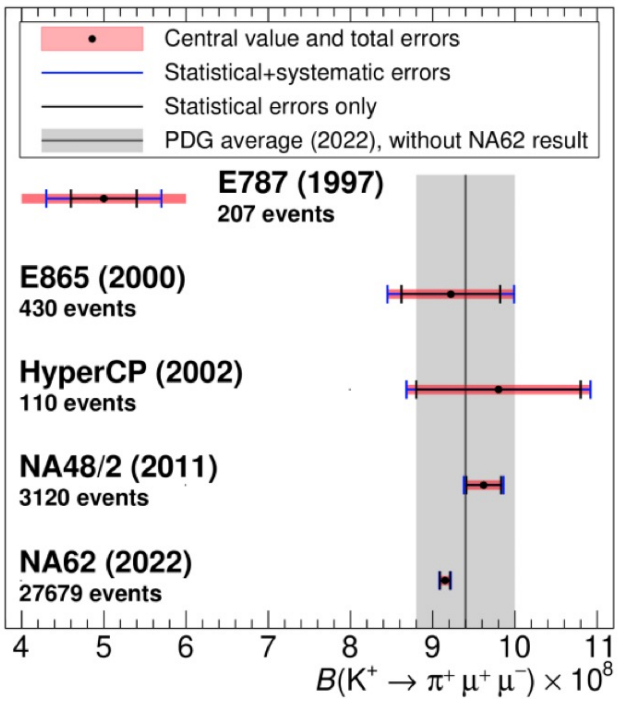
After signal selection:

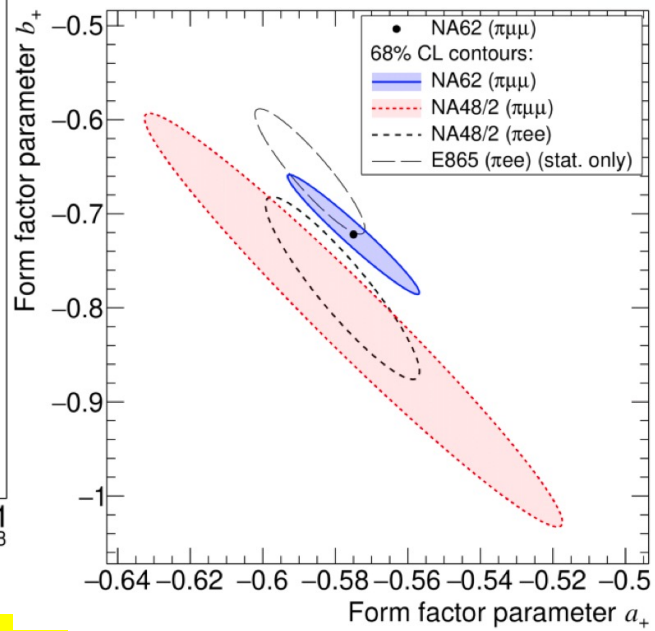
N_{obs} = 27,679 events

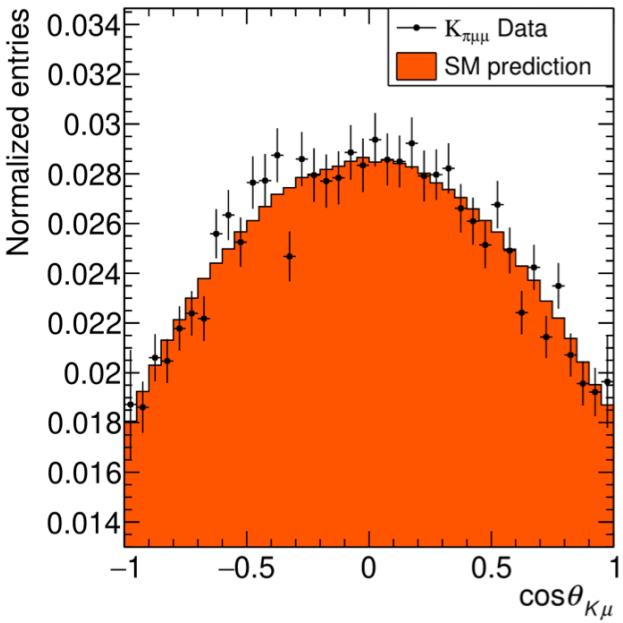
N_{bg}^{exp} = 8 events

The $K^+ \to \pi^+ \mu^+ \mu^-$ decay results

JHEP 11 (2022) 011







$B_{\pi\mu\mu} = (9.15 \pm 0.06_{stat} \pm 0.03_{syst} \pm 0.04_{ext}) \times 10^{-8}$

$a_+ = -0.575 \pm 0.012_{stat}$

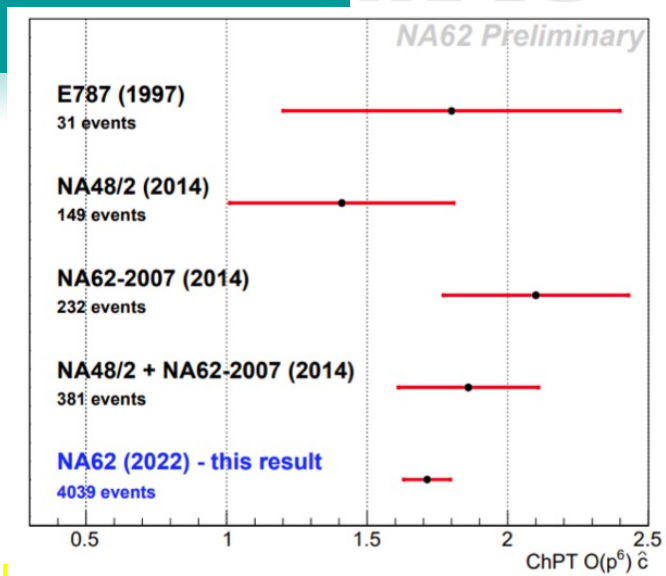
$b_+ = -0.722 \pm 0.040_{stat}$

$A_{FB} = (0.0 \pm 0.7_{stat}) \times 10^{-2}$
68% CL measurement

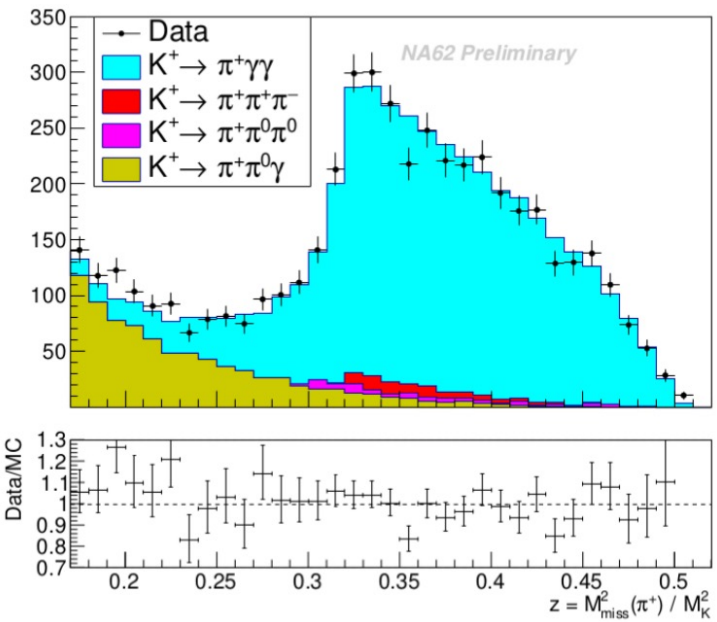
$|A_{FB}| < 0.9\ 10^{-2}$
90% CL upper limit (*)
(*) requested by PDG, to be published as addendum

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

- Rare decay that allows ChPT tests at $O(p^6)$
- Main kinematic variable: $z = \dfrac{m^2_{\gamma\gamma}}{m^2_K}$; $y = \dfrac{P_K(Q_{\gamma 1}-Q_{\gamma 2})}{m^2_K}$
- $BR(K^+ \to \pi^+\gamma\gamma)$ at $O(p^6)$ parametrized by a real **parameter $\hat{c}$**



$\hat{c} = 1.713 \pm 0.075_{stat} \pm 0.037_{syst}$



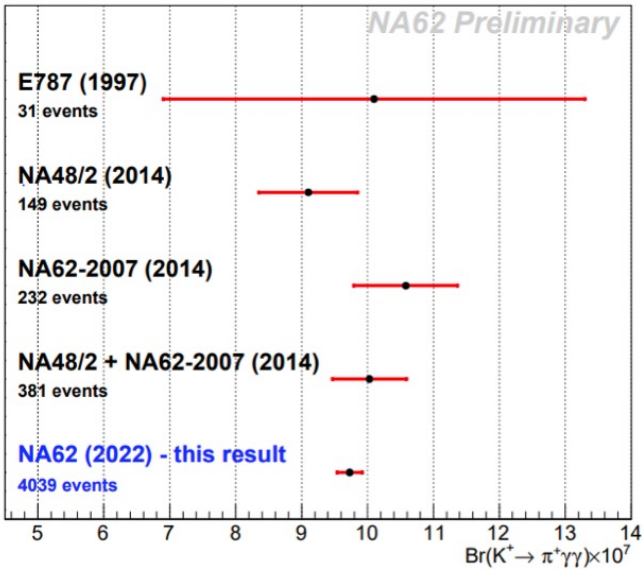
After signal selection:

N_{obs} = 4,039 events

N_{bg}^{exp} = 393 ± 20 events

Main background:

Cluster merging in the e.m. calorimeter



$B_{\pi\gamma\gamma}=(9.73 \pm 0.17_{stat} \pm 0.08_{syst})\times 10^{-7}$

★ Searches for Lepton Flavour and Lepton Number violation

PLB 797 (2019) 134794

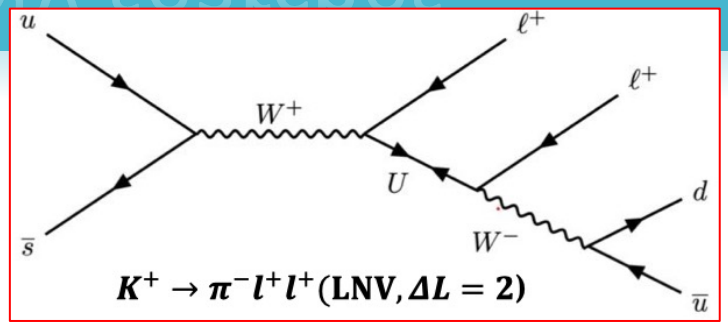
PRL 127 (2021) 13, 131802

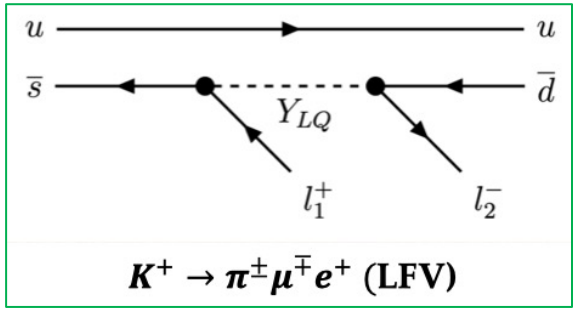
PLB 830 (2022) 137172

PLB 838 (2023) 137679

LFV/LNV searches

LNV - Type-I seesaw mechanism





LFV - leptoquark mechanism

- Lepton Number (L) → accidental U(1) symmetry of the SM. Conserved for each one flavour L_e, L_μ, L_τ in the SM.
- Notable example of LF Violation are the *neutrino oscillations.*
- There are several scenarios generating LFV/LNV in charged processes.

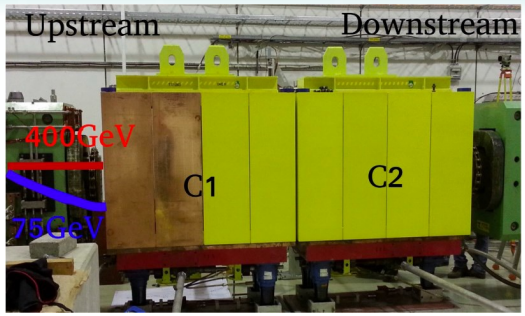
	Decay channel	Previous UL	NA62 UL @90% CL
PRL 127 (2021) 13, 131802	$K^+ \to \pi^- \mu^+ e^+$	BR < 5.0×10^{-10}	BR < 4.2×10^{-11}
PRL 127 (2021) 13, 131802	$K^+ \to \pi^+ \mu^- e^+$	BR < 5.2×10^{-10}	BR < 6.6×10^{-11}
PRL 127 (2021) 13, 131802	$\pi^0 \to \mu^- e^+$	BR < 3.4×10^{-9}	BR < 3.2×10^{-10}
PLB 797 (2019) 134794	$K^+ \to \pi^- \mu^+ \mu^+$	BR < 8.6×10^{-11}	BR < 4.2×10^{-11}
PLB 830 (2022) 137172	$K^+ \to \pi^- e^+ e^+$	BR < 6.4×10^{-10}	BR < 5.3×10^{-11}
PLB 830 (2022) 137172	$K^+ \to \pi^- \pi^0 e^+ e^+$	NA	BR < 8.5×10^{-10}
PLB 838 (2023) 137679	$K^+ \to \mu^- \nu e^+ e^+$	NA	BR < 8.1×10^{-11}

★ Exotics: Beam Dump Mode and Dark photon searches: $A' \rightarrow \mu^+ \mu^-$

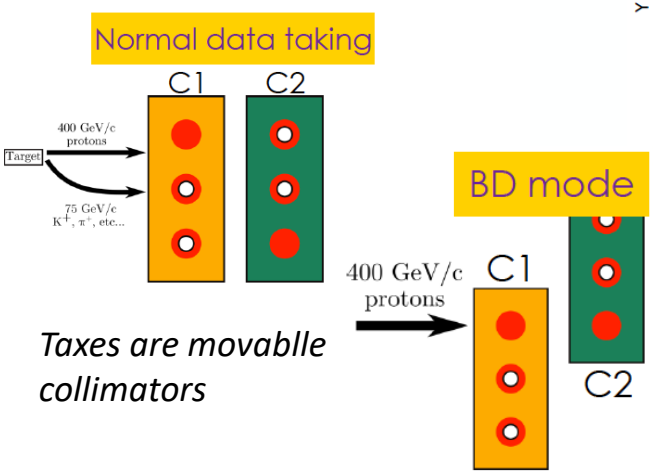
2021 data - arXiv: 2303.08666

2021 data - preliminary result

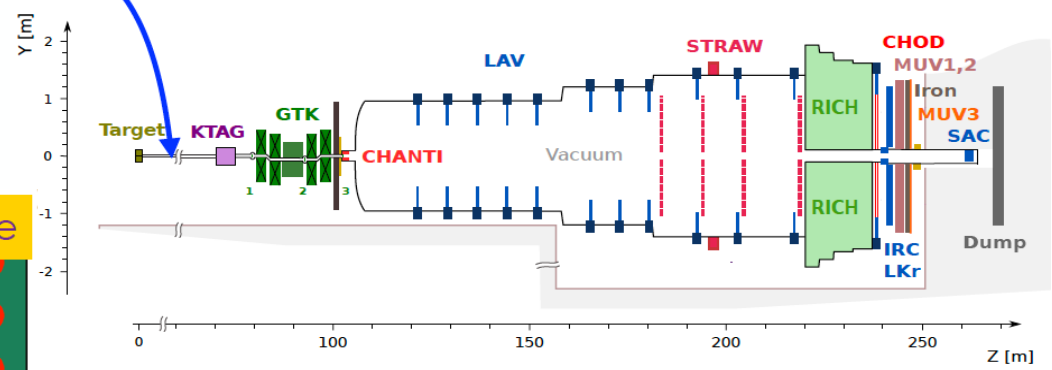
Exotics: Beam Dump Mode & A' → $\mu^+\mu^-$



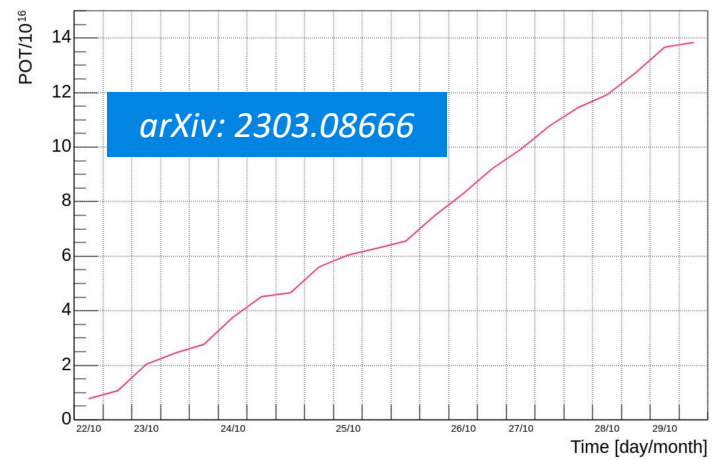
- Feebly interacting dark photon with free mass and coupling ε
- **Beam dump mode:** 3.2m Cu-Fe collimators (TAX) used as target
- Search for dark photon production in interactions with TAXs
- **(1.40 ± 0.28) x 10^{17} POT collected in ~10 days in 2021**



Taxes are movablle collimators

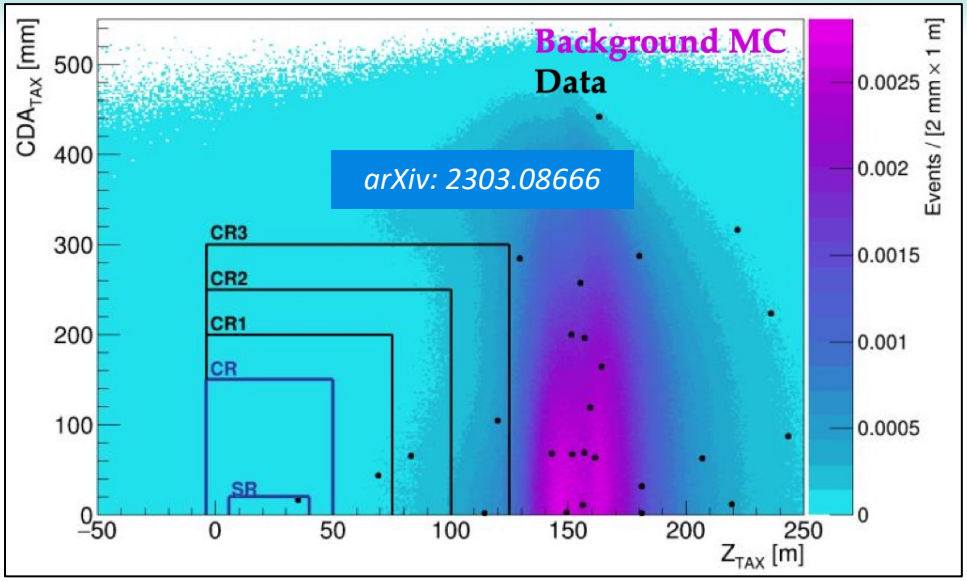


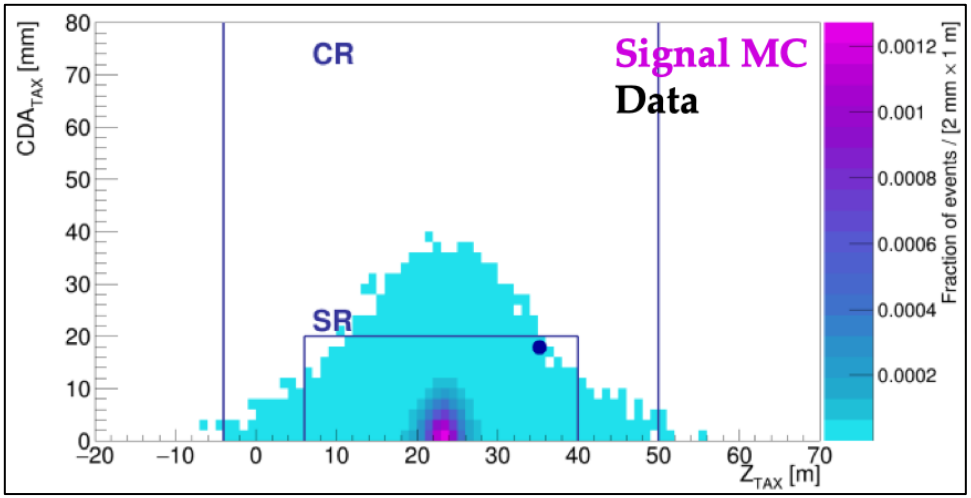
- Beam-line optimised in 2021: Improved sweeping & higher intensity
- Single & 2-track triggers.
- Search for Dark photon decays: $A' \rightarrow \mu^+\mu^-$



POT measured by beam secondary emission monitor

Dark photon searches: A' → $\mu^+ \mu^-$





Signal shape not taken into account for the significance

Probability to observe 1 or more events in the SR is 1.59%

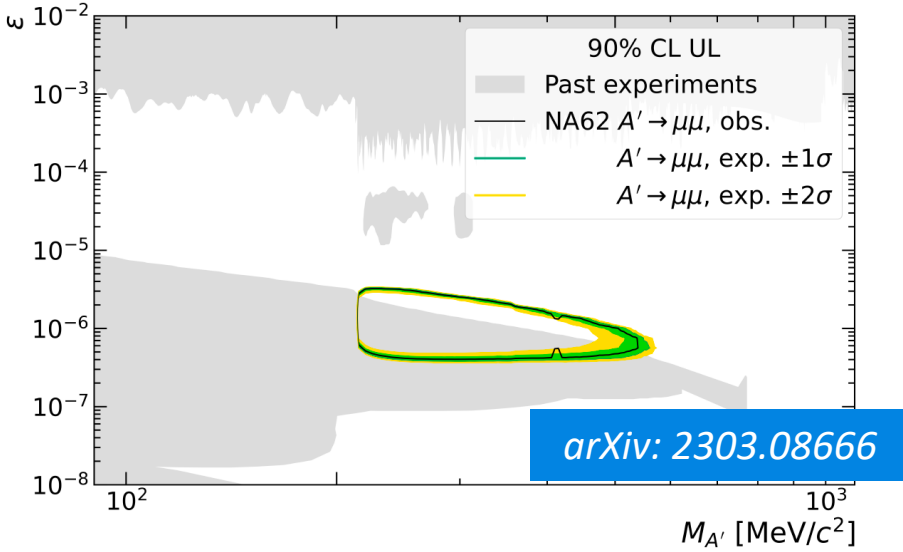
After signal selection:

$N_{bg}^{expected} = 0.016 \pm 0.002$ events

$N_{observed} = 1$ event

2.4 σ significance (counting experiment)

The region enclosed by the contour shown is excluded at 90% CL



Dark photon searches: A' → e⁺ e⁻

NEW

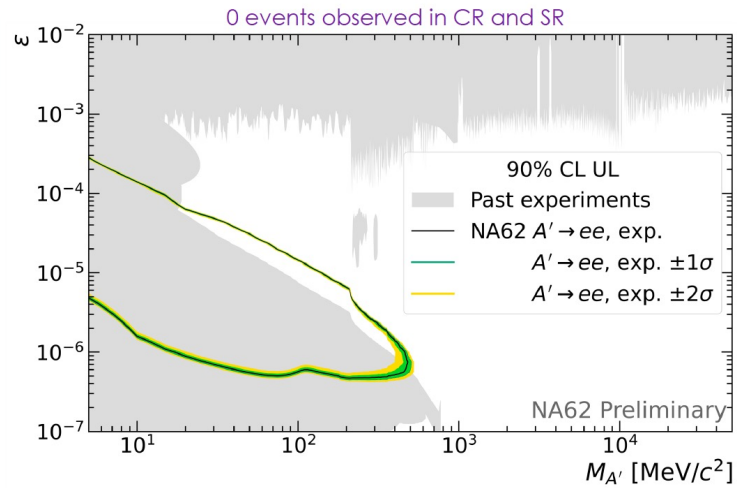
Expected events A' → e⁺ e⁻ in the CR and SR:

$N^{CR}_{background} = 0.0097^{+0.049}_{-0.009}$ @90% CL

$N^{SR}_{background} = 0.0094^{+0.049}_{-0.009}$ @90% CL

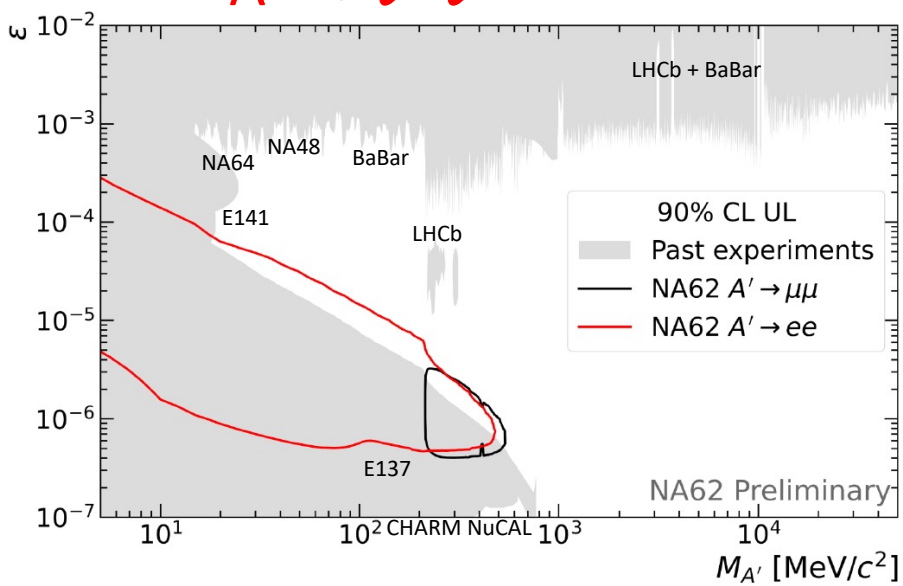
preliminary result

A' → e⁺ e⁻



The region enclosed by the contour shown is excluded

A' → ℓ⁺ ℓ⁻



Summary

Decay channel	Data set	
$K^+ \to \pi^+ \nu \bar{\nu}$	NA62 Run 1	JHEP 06 (2021) 093
$K^+ \to \pi^+ \mu^+ \mu^-$	NA62 Run 1	JHEP 11 (2022) 011
$K^+ \to \pi^+ \gamma \gamma$	NA62 Run 1	preliminary
$K^+ \to \pi^- \mu^+ e^+$	NA62 Run 1	PRL 127 (2021) 131802
$K^+ \to \pi^+ \mu^- e^+$	NA62 Run 1	PRL 127 (2021) 131802
$\pi^0 \to \mu^- e^+$	NA62 Run 1	PRL 127 (2021) 131802
$K^+ \to \pi^- \mu^+ \mu^+$	NA62 Run 1	PLB 797 (2019) 134794
$K^+ \to \pi^- e^+ e^+$	NA62 Run 1	PLB 830 (2022) 137172
$K^+ \to \pi^- \pi^0 e^+ e^+$	NA62 Run 1	PLB 830 (2022) 137172
$K^+ \to \mu^- \nu e^+ e^+$	NA62 Run 1	PLB 838 (2023) 137679
$A' \to \mu^+ \mu^-$ $A' \to e^+ e^-$	NA62 2021 data NA62 2021 data	arXiv: 2303.08666 preliminary

Thank you for your attention