



FACULTY  
OF MATHEMATICS  
AND PHYSICS  
Charles University



# Precision Measurements in $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ and $K^+ \rightarrow \pi^+ \gamma \gamma$ from NA62 and Exotic Searches in Beam-dump Mode

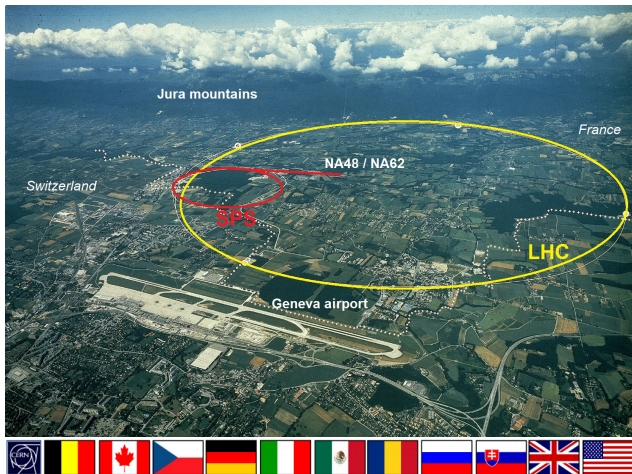
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Charles University in Prague  
on behalf of the NA62 Collaboration

57<sup>th</sup> Rencontres de Moriond, March 21, 2023

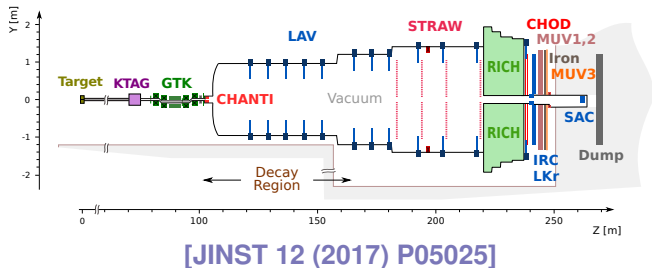
# Kaon Experiments at CERN



NA62:  $\sim 200$  participants,  $\sim 30$  institutes

- **NA31**: 1980s, *beam*:  $K_L/K_S$ 
  - *First evidence of direct CPV*
- **NA48**: 1997–2001, *beam*:  $K_L/K_S$ 
  - *Discovery of direct CPV*
- **NA48/1**: 2002, *beam*:  $K_S$ /hyperons
  - *Rare decay studies*
- **NA48/2**: 2003–2004, *beam*:  $K^+/K^-$ 
  - *Precision measurements*
- **NA62-R<sub>K</sub>**: 2007–2008, *beam*:  $K^+/K^-$ 
  - $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu2})$
- **NA62**: since 2015, *beam*:  $K^+$ 
  - 2015: commissioning run
  - 2016-2018: NA62 Physics Run 1
  - 2021-ongoing: NA62 Physics Run 2

# NA62: Beam and Detector



## Beam parameters in $K^+$ mode:

- **Beam momentum:** 75 GeV/c ( $\pm 1\%$ )
- **Nominal rate:** 750 MHz
- **Positive beam:**  $\sim 6\% K^+$

## Main subdetectors:

- **Beam tracker:** GTK ( $\sigma_p = 0.15$  GeV/c)
- **Kaon tagger:** KTAG ( $\sigma_t = 70$  ps)
- **Downstream tracker:** ( $\pi/\mu/e$ ): Straw  
 $\sigma_p/p = 0.3\% \oplus 0.005\% \cdot p[\text{GeV}/c]$
- **Photon veto detectors:** LAV, IRC, SAC
- **Cherenkov counter:** RICH
- **Trigger and timing:** CHOD ( $\sigma_t = 1$  ns), NA48-CHOD ( $\sigma_t = 200$  ps)
- **Electromagnetic calorimeter:** LKr  
 $\sigma_E/E = 4.8\%/\sqrt{E} \oplus 11\%/E \oplus 0.9\%$ ,  $[E] = \text{GeV}$
- **Hadronic calorimeters:** MUV1,2
- **Muon detector:** MUV3 ( $\sigma_t = 500$  ps)

- Measurement of the branching fraction of very rare ( $\mathcal{B}_{\pi\nu\nu} \approx 10^{-10}$ ) decay  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ 
  - Main goal of the experiment with the most recent results published in [\[JHEP06 \(2021\) 093\]](#)

- **Precision measurements:**

Decay	Dataset	Status	Reference
$K^+ \rightarrow \pi^+ \mu^+ \mu^- (K_{\pi\mu\mu})$	NA62 Run 1 (2017-2018)	Published	<a href="#">[JHEP11 (2022) 011]</a>
$K^+ \rightarrow \pi^+ \gamma\gamma (K_{\pi\gamma\gamma})$	NA62 Run 1 (2016-2018)	Preliminary	<a href="#">[Talk at KAON 2022]</a>

- Searches for exotic particles:

- **Dark photon:**

Decay	Dataset	Status	Reference
$A' \rightarrow \mu^+ \mu^- (A'_{\mu\mu})$	NA62 Run 2 (2021)	Preliminary	<a href="#">[arXiv:2303.08666]</a>
$A' \rightarrow e^+ e^- (A'_{ee})$	NA62 Run 2 (2021)	Preliminary	<a href="#">[Talk at La Thuile 2023]</a>

- Axions, HNLs,...
  - Searches for rare and forbidden (e.g. LNV or LFV)  $K^+$  decays

# $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ : Introduction

## Overview:

- FCNC decay described in the scope of ChPT, mediated by one photon exchange  $K^+ \rightarrow \pi^+ \gamma^*$  [Nucl. Phys. B291 (1987) 692–719], [Phys. Part. Nucl. Lett. 5 (2008) 76–84]
- Differential decay width:  $d\Gamma(z)/dz \sim |W(z)|^2$ ,  $z = m(\mu^+ \mu^-)^2/m_K^2$
- Parametrization of form factor (FF)  $W(z)$  in NLO ChPT [JHEP 08 (1998) 004]:

$$W(z) = G_F M_K^2 (a_+ + b_+ z) + W^{\pi\pi}(z) \quad a_+, b_+: \text{FF parameters}, \quad W^{\pi\pi}(z): K_{3\pi} \text{ pion loop term}$$

## Measurement motivation:

- Together with  $K_{\pi ee}$  allows for tests of LFU [J. Phys. Conf. Ser. 800 (2017) 1, 012014]
- Asymmetries in angular distributions could point to New Physics contributions [Phys. Rev. D 67 (2003) 074029], [Phys. Rev. D 69 (2004) 094030]

# $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ : Signal Selection

## Data sample:

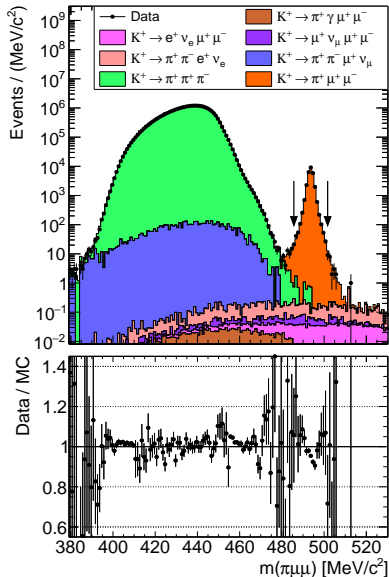
- Effective  $N_K \simeq 3.48 \times 10^{12}$  kaon decays
- Normalisation channel:  $K^+ \rightarrow \pi^+ \pi^+ \pi^-$  ( $K_{3\pi}$ )

## Signal event selection:

- Three track vertex topology
- $\pi^+$  PID: no signal in MUV3,  $E/p < 0.9$
- $\mu^\pm$  PID: signal in MUV3,  $E/p < 0.2$
- Kinematic cuts to suppress  $K_{3\pi}$  background

## Signal sample:

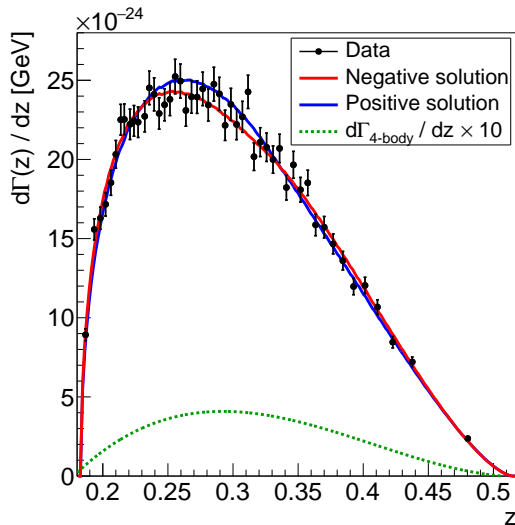
- $|m(\pi\mu\mu) - m_K| < 8 \text{ MeV}/c^2$
  - Signal region contains 27679 events
    - $\sim 9\times$  more than NA48/2
- [Phys. Lett. B 697 (2011) 107-115]
- Negligible background:  $7.8 \pm 5.6$  events



# $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ : $\mathcal{B}(K_{\pi\mu\mu})$ and Form Factor Measurement

## Model-independent $\mathcal{B}(K_{\pi\mu\mu})$ measurement:

- Reconstruct  $d\Gamma/dz$  from measured  $z$  spectrum
- Integrate to get  $\mathcal{B}(K_{\pi\mu\mu}) = (9.15 \pm 0.08) \times 10^{-8}$



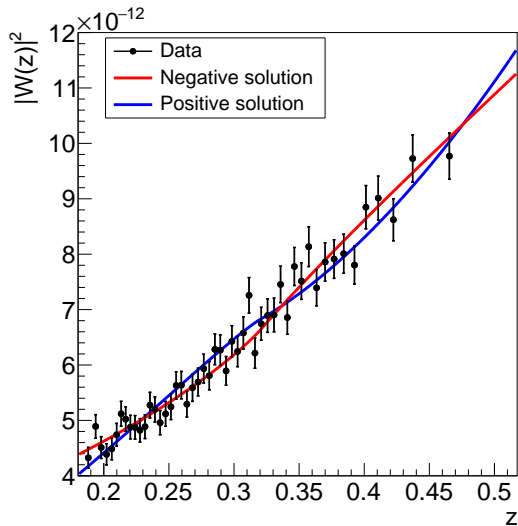
# $K^+ \rightarrow \pi^+ \mu^+ \mu^-: \mathcal{B}(K_{\pi\mu\mu})$ and Form Factor Measurement

## Model-independent $\mathcal{B}(K_{\pi\mu\mu})$ measurement:

- Reconstruct  $d\Gamma/dz$  from measured  $z$  spectrum
- Integrate to get  $\mathcal{B}(K_{\pi\mu\mu}) = (9.15 \pm 0.08) \times 10^{-8}$

## Form factor measurement:

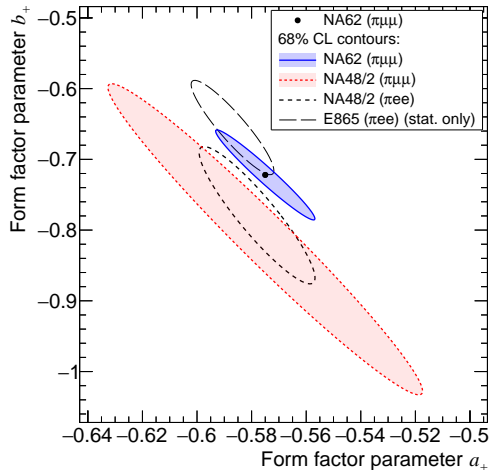
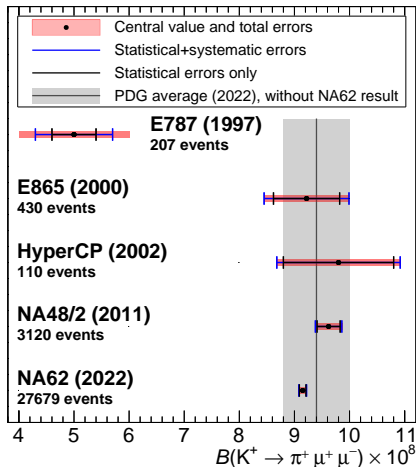
- Extract  $|W(z)|^2$  from  $d\Gamma/dz$
- Find optimal  $a_+, b_+$  by minimising  $\chi^2(a_+, b_+)$
- Results ( $\chi^2/\text{ndf} = 45.1/48$ ,  $p\text{-value} = 0.59$ ):
  - $a_+ = -0.575 \pm 0.013$
  - $b_+ = -0.722 \pm 0.043$
  - Correlation:  $\rho(a_+, b_+) = -0.972$





# $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ : Comparison with the World

- NA62  $K_{\pi\mu\mu}$  result consistent previous  $K_{\pi ee}$  FF measurements  $\rightarrow$  no tension in LFU observed



- E865,  $K_{\pi ee}$ : [[Phys. Rev. Lett. 83 \(1999\) 4482-4485](#)]
- HyperCP,  $K_{\pi\mu\mu}$ : [[Phys. Rev. Lett. 88 \(2002\) 111801](#)]

- NA48/2,  $K_{\pi ee}$ : [[Phys. Lett. B 677 \(2009\) 246-254](#)]
- NA48/2,  $K_{\pi\mu\mu}$ : [[Phys. Lett. B 697 \(2011\) 107-115](#)]

# $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ : Forward-Backward Asymmetry

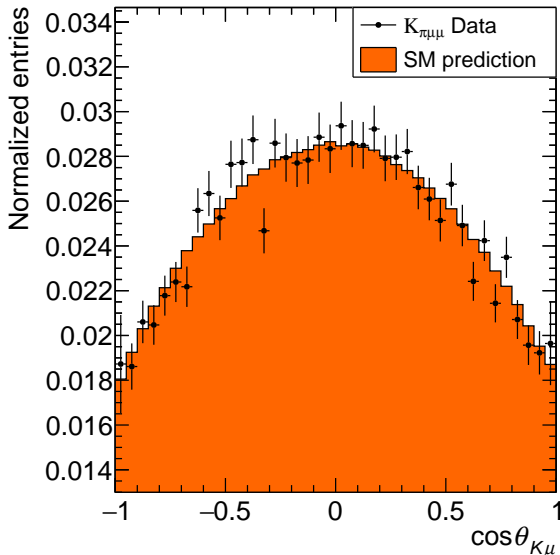
## Definitions:

- $\theta_{K\mu}$ : angle between the  $K^+$  and  $\mu^-$  three-momenta in the  $\mu^+ \mu^-$  rest frame
- Forward-backward asymmetry:

$$A_{\text{FB}} = \frac{\mathcal{N}(\cos \theta_{K\mu} > 0) - \mathcal{N}(\cos \theta_{K\mu} < 0)}{\mathcal{N}(\cos \theta_{K\mu} > 0) + \mathcal{N}(\cos \theta_{K\mu} < 0)}$$

## Results:

- 68% CL measurement:  
 $A_{\text{FB}} = (0.0 \pm 0.7) \times 10^{-2}$
- **New:** 90% CL upper limit<sup>a</sup>:  
 $|A_{\text{FB}}| < 0.9 \times 10^{-2}$



<sup>a</sup> Requested by PDG, to be published as addendum to the paper.

# $K^+ \rightarrow \pi^+ \gamma\gamma$ : Introduction

## Overview:

- Radiative non-leptonic kaon decay
- Kinematic variables:  $z = m_{\gamma\gamma}^2/m_K^2$ ,  $y = \vec{p}_K \cdot (\vec{p}_{\gamma_1} - \vec{p}_{\gamma_2})/m_K^2$
- Branching fraction of  $K_{\pi\gamma\gamma}$  parametrised in ChPT by an unknown real parameter  $\hat{c}$

$$\frac{d^2\Gamma}{dydz}(\hat{c}, y, z) = \frac{m_K}{29\pi^3} \left[ z^2 (|A(\hat{c}, z, y^2) + B(z)|^2 + |C(z)|^2) + \left( y^2 - \frac{1}{4}\lambda(1, r_\pi^2, z) \right)^2 |B(z)|^2 \right]$$

- Branching fraction and  $\hat{c}$  depend on several external parameters
  - Fixed in this analysis, recently updated  $\rightarrow$  will be accounted for in the final result

## Measurement motivation:

- Crucial test of ChPT [**Phys. Lett. B 386 (1996) 403**]
- Allows for searches of axion-like particles in decay chain  $K^+ \rightarrow \pi^+ X$ ,  $X \rightarrow \gamma\gamma$

# $K^+ \rightarrow \pi^+ \gamma\gamma$ : Signal Selection

## Data sample:

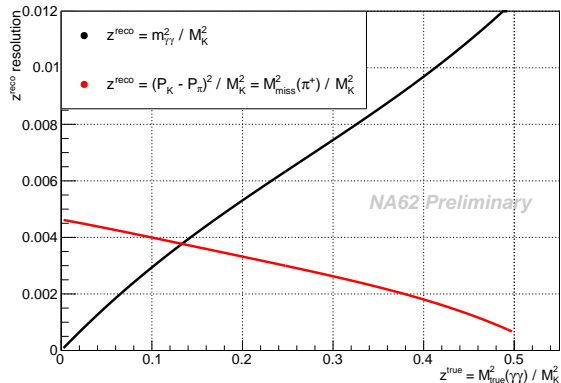
- Full NA62 Run 1 sample used
- Normalisation channel:  $K^+ \rightarrow \pi^+ \pi^0$  ( $K_{2\pi}$ )

## Signal event selection:

- One good track in Straw
- $K^+$  (GTK) –  $\pi^+$  (Straw) matching  $\rightarrow$  vertex
- Two good clusters in LKr
- Kinematic cuts on daughter particles:  
total  $E$ , total  $p_T$ ,  $m(\pi\gamma\gamma)$

## Signal sample:

- Define  $z = (P_K - P_\pi)^2 / m_K^2$   
better resolution than  $m_{\gamma\gamma}^2 / m_K^2$  definition
- Signal region:  $z > 0.25$



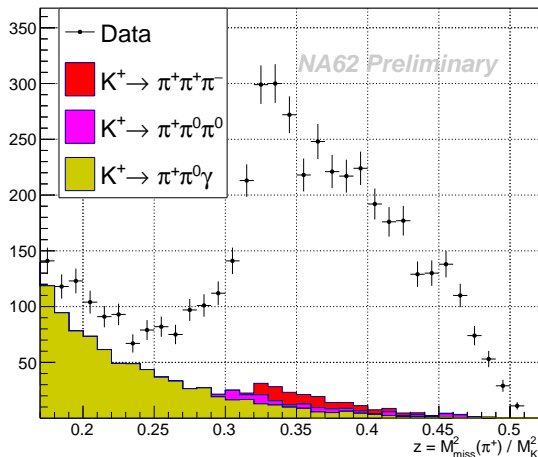
# $K^+ \rightarrow \pi^+ \gamma \gamma$ : Signal and Background

## Signal region $z > 0.25$ :

- Contains 4039 events  
→  $\sim 10\times$  more than NA48/2 + NA62-2007

## Background:

- Main background mechanisms:
  - Cluster merging in LKr:  
 $K^+ \rightarrow \pi^+ \pi^0 \gamma, \pi^0 \rightarrow \gamma \gamma$   
 $K^+ \rightarrow \pi^+ \pi^0 \pi^0, \pi^0 \rightarrow \gamma \gamma$
  - Multi-track events with tracks missing Straw acceptance: mainly  $K_{3\pi}$  decay due to large branching fraction
- Background contamination:  $393 \pm 20$  events



# $K^+ \rightarrow \pi^+ \gamma \gamma$ : Fitting the $\hat{c}$ Parameter

## Procedure:

- Find optimal  $\hat{c}$  by maximising log-likelihood:

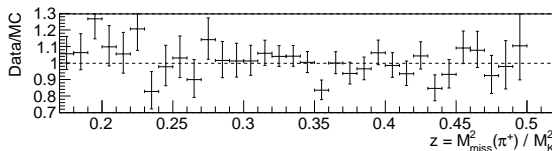
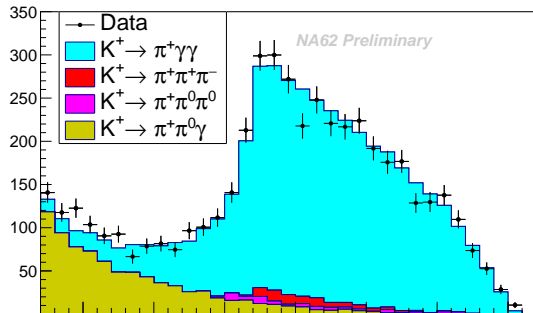
$$\ln \mathcal{L} = \sum_i (k_i \ln \lambda_i(\hat{c}) - \lambda_i(\hat{c}) - \ln(k_i!)),$$

$$\lambda_i(\hat{c}) = \lambda_i^S(\hat{c}) + \lambda_i^B$$

while reweighting the  $K_{\pi\gamma\gamma}$  MC sample

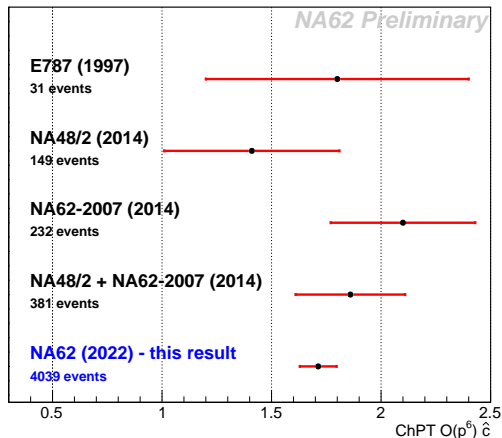
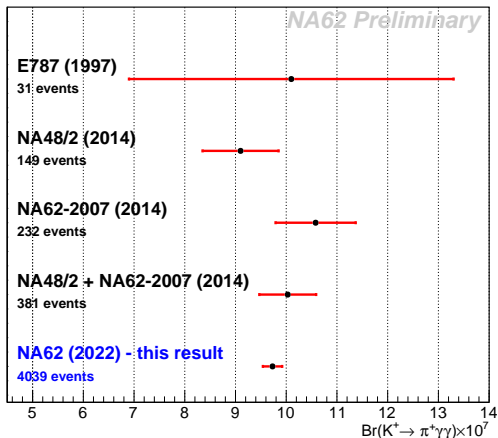
## Results:

- FF parameter  $\hat{c}$ :  
 $\hat{c} = 1.713 \pm 0.084$
- Model-dependent  $\mathcal{B}(K_{\pi\gamma\gamma})$ :  
 $\mathcal{B}(K_{\pi\gamma\gamma}) = (9.73 \pm 0.19) \times 10^{-7}$



# $K^+ \rightarrow \pi^+ \gamma \gamma$ : Comparison with the World

- Precision of the NA62  $K_{\pi\gamma\gamma}$  preliminary result better by a **factor 3** wrt NA48/2+NA62-2007
- *Final results considering updated external parameters to be published soon – stay tuned*



# $A' \rightarrow l^+l^-$ : Search Motivation and Analysis Overview

## Dark Photon (DP) model:

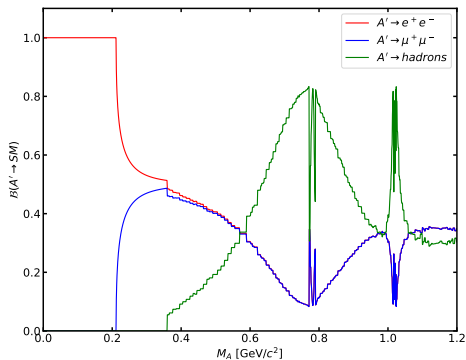
- New vector field  $F'_{\mu\nu}$  feebly interacting with SM fields
- Free parameters: mass  $m_{A'}$ , coupling  $\varepsilon$
- For  $m_{A'} < 600 \text{ MeV}/c^2$ ,  $A' \rightarrow l^+l^-$  decays dominate

## NA62 beam-dump mode:

- Target replaced by 3.2 m Cu-Fe collimators
- $\sim 1.5 \times$  nominal beam intensity
- Collected  $(1.4 \pm 0.28) \times 10^{17}$  POT

## Signal selection:

- Blind analysis technique (CRs and SR)
- Primary vertex close to  $p^+$  beam impact point
- $l^+l^-$  vertex within NA62 fiducial volume
- $l^\pm$  PID using LKr and MUV3
- No in-time activity in LAVs or ANTI0



## More details:

- $[A'_{\mu\mu}, \text{arXiv:2303.08666}]$
- $[A'_{ll}, \text{Talk at La Thuile 2023}]$
- $A'_{ll}$ , Talk at Moriond QCD 2023

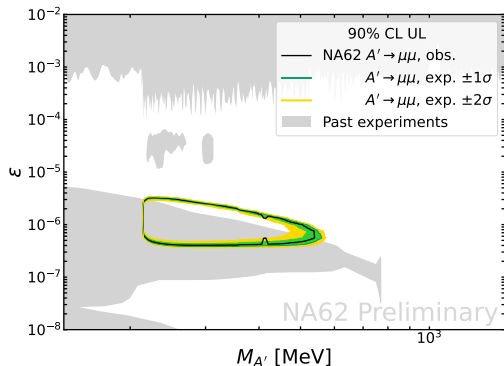


# $A' \rightarrow l^+l^-$ : 90% CL Exclusion Regions in $\varepsilon, m_{A'}$ Parameter Space

$$A' \rightarrow \mu^+\mu^-$$

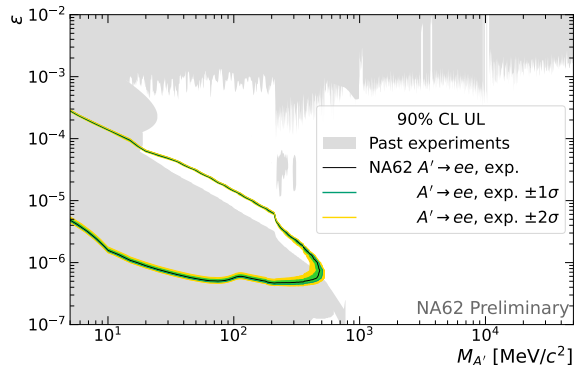
**1 event observed in the SR**

Counting experiment with  $2.4\sigma$  global significance



$$A' \rightarrow e^+e^-$$

**0 events observed in the SR**



# Summary

## Precision measurements:

- Analysis of the  $K^+ \rightarrow \pi^+ \mu^+ \mu^-$  decay (final results)
  - Sample of 27679  $K_{\pi\mu\mu}$  events collected in 2017-2018 with negligible background
  - Model-independent branching fraction:  $\mathcal{B}(K_{\pi\mu\mu}) = (9.15 \pm 0.08) \times 10^{-8}$
  - Form-factor measurement:  $|W(z)|^2$  extracted;  $a_+ = -0.575 \pm 0.013$ ,  $b_+ = -0.722 \pm 0.043$
  - Forward-backward asymmetry:  $A_{\text{FB}} = (0.0 \pm 0.7) \times 10^{-2}$ ;  $|A_{\text{FB}}| < 0.9 \times 10^{-2}$  @ 90% CL
- Analysis of the  $K^+ \rightarrow \pi^+ \gamma\gamma$  decay (preliminary results; final result and paper in preparation)
  - Sample of 4039  $K_{\pi\gamma\gamma}$  events collected with 10% background
  - Branching fraction:  $\mathcal{B}(K_{\pi\gamma\gamma}) = (9.73 \pm 0.19) \times 10^{-7}$
  - Form-factor parameter  $\hat{c} = 1.713 \pm 0.084$
- Other precision analyses at NA62 are ongoing

## Dark photon searches:

- Preliminary results have been presented using the data collected in 2021
- 90% CL exclusion regions have been established in the  $m_{A'}$ ,  $\varepsilon$  parameter space
- Searches for decays of exotic particles to  $\gamma\gamma$ ,  $\pi^+\pi^-\gamma$  final states are ongoing
- NA62 intends to take total of  $10^{18}$  POT in 2022-2025

**Stay tuned for more results from NA62!**

# Backup

# $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ : Error Budget

	$\delta a_+$	$\delta b_+$	$\delta \mathcal{B}_{\pi\mu\mu} \times 10^8$	$\delta A_{\text{FB}} \times 10^2$
<b>Statistical uncertainty</b>	0.012	0.040	0.06	0.7
Trigger efficiency	0.002	0.008	0.02	0.1
Reconstruction and particle identification	0.002	0.007	0.02	0.1
Size of the simulated $K_{\pi\mu\mu}$ sample	0.002	0.007	0.01	0.1
Beam and accidental activity simulation	0.001	0.002	0.01	—
Background	0.001	0.001	—	—
<b>Total systematic uncertainty</b>	0.003	0.013	0.03	0.2
$K_{3\pi}$ branching fraction	0.001	0.003	0.04	—
$K_{\pi\mu\mu}$ radiative corrections	0.003	0.009	0.01	0.2
Parameters $\alpha_+$ and $\beta_+$	0.001	0.006	—	—
<b>Total external uncertainty</b>	0.003	0.011	0.04	0.2
<b>Total uncertainty</b>	<b>0.013</b>	<b>0.043</b>	<b>0.08</b>	<b>0.7</b>

# $K^+ \rightarrow \pi^+ \gamma \gamma$ : Error Budget

Conditions, $z > 0.25$		
	$\delta \hat{c}_6$	$\delta \mathcal{B} \times 10^7$
Cluster merging	0.029	0.06
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$ background	0.003	<0.01
MC background stat.	0.013	0.03
z resolution	<0.001	<0.01
LKr energy calibration	0.018	0.04
Trigger emulation	0.001	<0.01
Total error	0.037	0.08
$\hat{c}_6$	$1.713 \pm 0.075_{\text{stat.}} \pm 0.037_{\text{syst.}}$	
$\mathcal{B}(K^+ \rightarrow \pi^+ \gamma \gamma) \times 10^7$	$9.73 \pm 0.17_{\text{stat.}} \pm 0.08_{\text{syst.}}$	

# $A' \rightarrow \mu^+ \mu^-$ : Analysis Summary

## Signal selection:

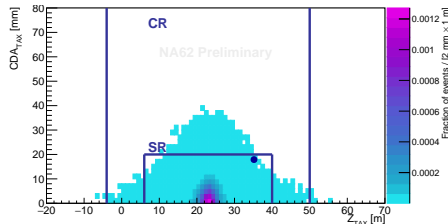
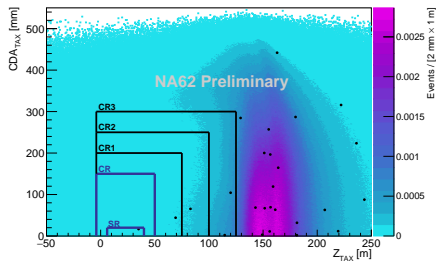
- Primary vertex close to  $p^+$  beam impact point
- $\mu^+ \mu^-$  vertex within NA62 fiducial volume
- $\mu^\pm$  PID using LKr and MUV3
- No in-time activity in LAVs

## Definitions:

- $Z_{\text{TAX}}$ : longitudinal position of the primary vertex
- $CDA_{\text{TAX}}$ : closest distance of approach between the beam direction at the TAX entrance and the  $\mu^+ \mu^-$  pair direction

## Results:

- Expected background in SR:  $0.016 \pm 0.002$  events
- Observed number of events in SR: **1**
- Counting experiment with  $2.4\sigma$  global significance (signal shape not taken into account)



- CRs and SR blinded until analysis approval

# $A' \rightarrow e^+e^-$ : Analysis Summary

## Signal selection:

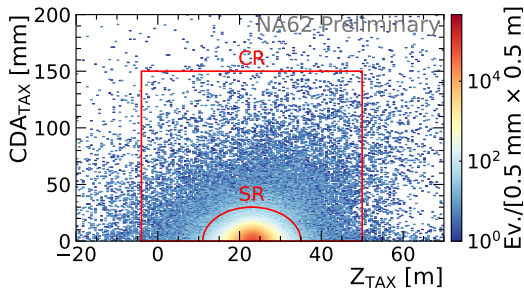
- Primary vertex close to  $p^+$  beam impact point
- $e^+e^-$  vertex within NA62 fiducial volume
- $e^\pm$  PID using LKr and MUV3
- No in-time activity in LAVs and ANTI0

## Definitions:

- $Z_{\text{TAX}}$ : longitudinal position of the primary vertex
- $CDA_{\text{TAX}}$ : closest distance of approach between the beam direction at the TAX entrance and the  $\mu^+\mu^-$  pair direction

## Results:

- Expected background in SR:  $0.0094^{+0.0049}_{-0.009}$  events
- Observed number of events in SR: **0**



- CRs and SR blinded until analysis approval