LATEST RESULTS FROM NA62 EXPERIMENT

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on behalf of NA62 Collaboration

DISCRETE 2022

8th Symposium on Prospects in the Physics of Discrete Symmetries

7-11 November Baden-Baden

Bundesministerium
für Bildung
und Forschung

JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

OUTLINE

- NA62 experiment
- Precision measurements
  - $K^+ \to \pi^+\mu^+\mu^-$ analysis
  - $K^+ \to \pi^o e^+ \nu\gamma$ analysis
  - $K^+ \to \pi^+\gamma\gamma$ analysis
- Beyond Standard Model searches
  - Lepton Number and Flavor Violation decays $K^+ \to \pi^-(\pi^o)\ell^+\ell^-$, $K^+ \to \pi^\pm\mu^\mp e^+, \pi^o \to \mu^- e^+$
  - Heavy Neutral Lepton searches $K^+ \to \ell^+ N$, $K^+ \to \mu^+\nu X$, $K^+ \to \mu^+\nu\bar{\nu}\nu$
  - Dark Photon search in beam dump mode $A' \to \mu^+\,\mu^-$
- Conclusions

NA62 Experiment

2005 Proposal

2007 Design and construction

2015 Pilot run and commissioning

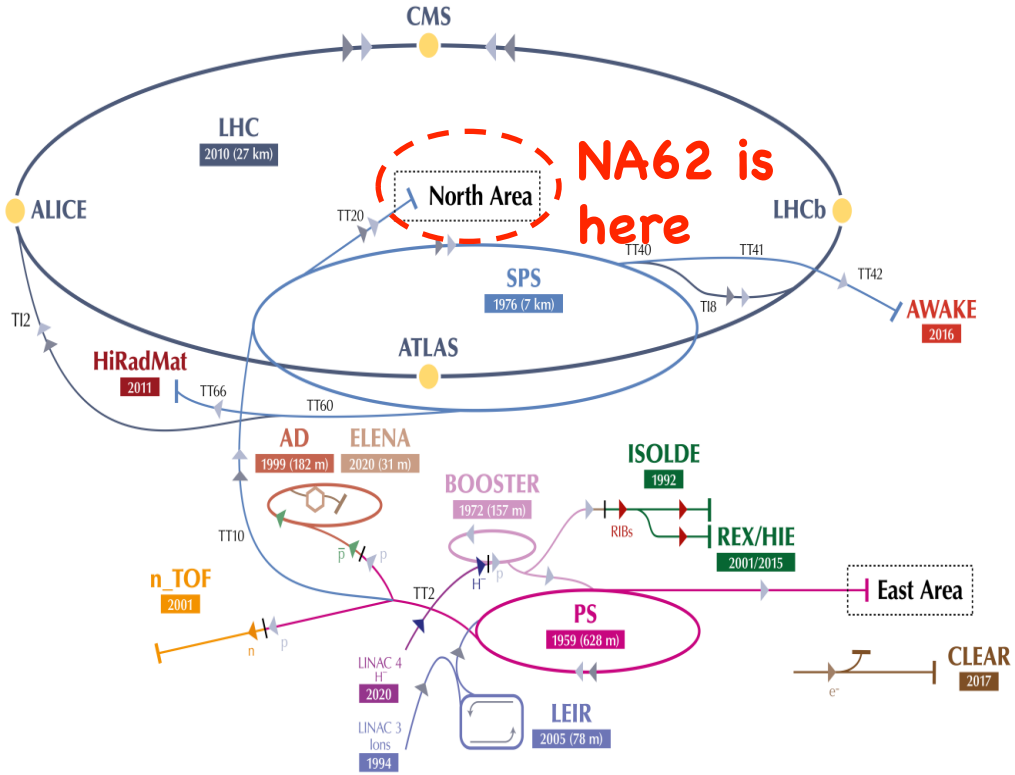
2016 Start of physics data taking

2016–2018 NA62 Physics Run 1

2019–2020 Long shutdown 2

2021– NA62 Physics Run 2

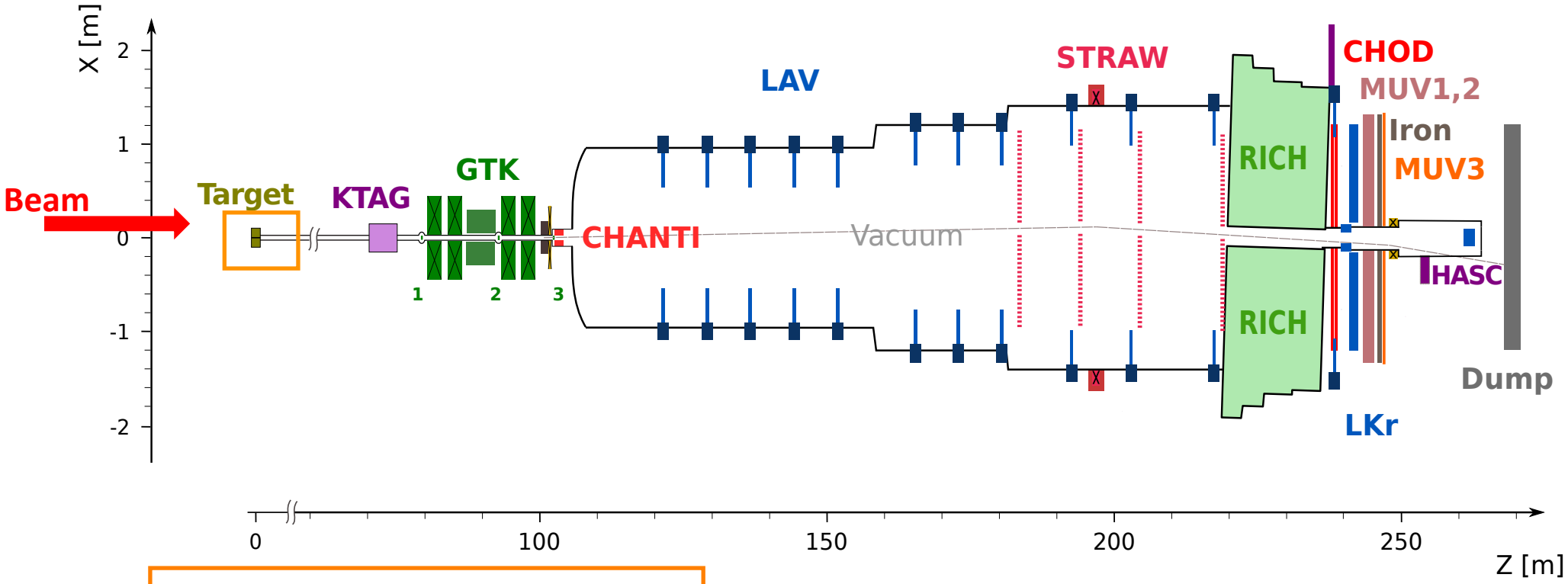
Data taking ongoing



- Kaon factory in North Area of CERN SPS
- Primary goal: precision measurement of $\mathbf{BR}(K^+ \to \pi^+ \nu\bar{\nu})$
- Excellent environment to push precision measurement and search for New Physics in kaon and pion sector
- Currently ~300 participants from ~30 institutions

NA62 Experiment

NA62 Detector Paper, 2017 JINST 12 P05025



Primary beam from SPS:

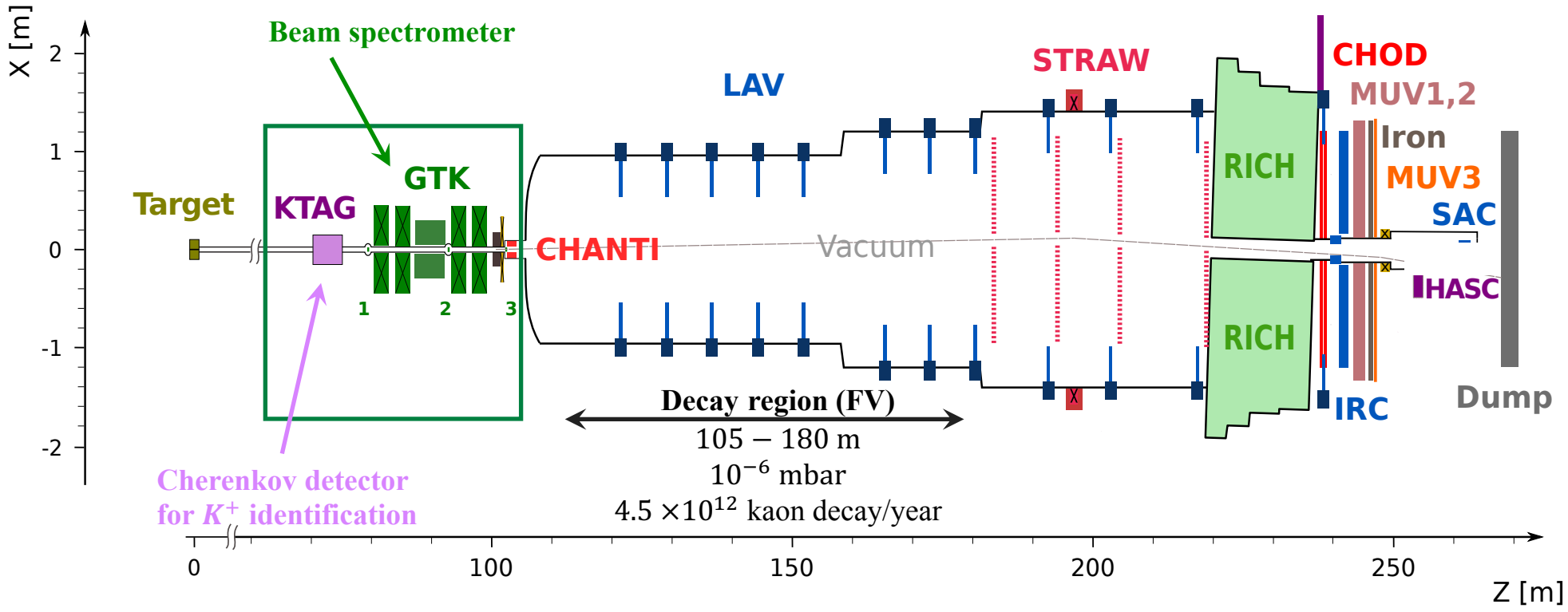
- 400 GeV/c protons

Secondary hadronic beam:

- $K^+(6\%)/p(23\%)/\pi^+(70\%)$
- 75 GeV/c ($\pm$ 1%)

NA62 Experiment

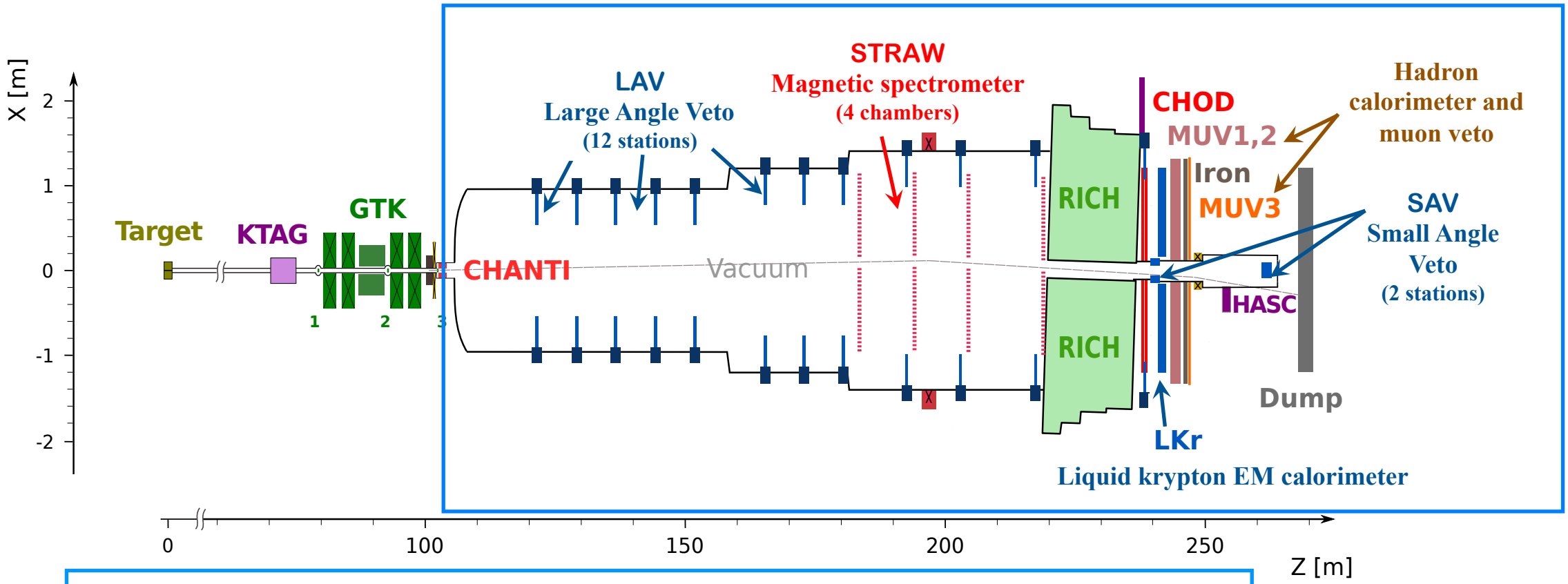
NA62 Detector Paper, 2017 JINST 12 P05025



- ✧ Kaon tagger KTAG: Cherenkov detector 70 ps time resolution
- ✧ Beam spectrometer GTK: 3 Si-pixel stations for momentum and position
- ✧ Anticounter CHANTI: veto detector

NA62 Experiment

NA62 Detector Paper, 2017 JINST 12 P05025

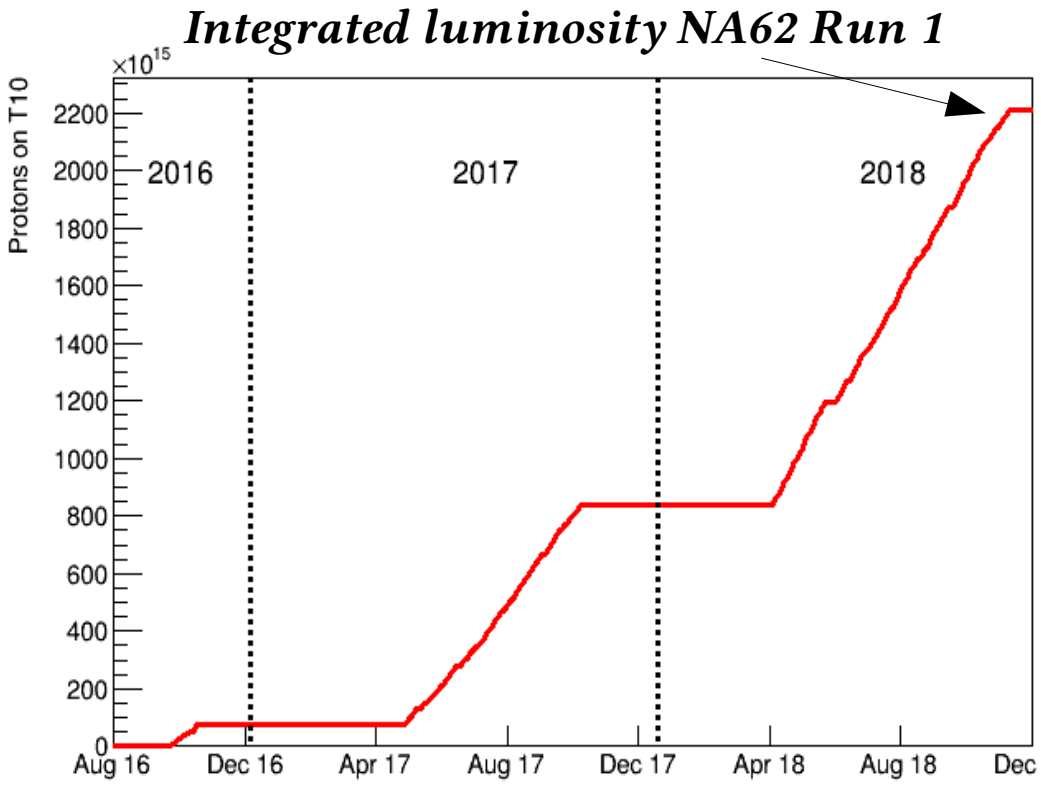


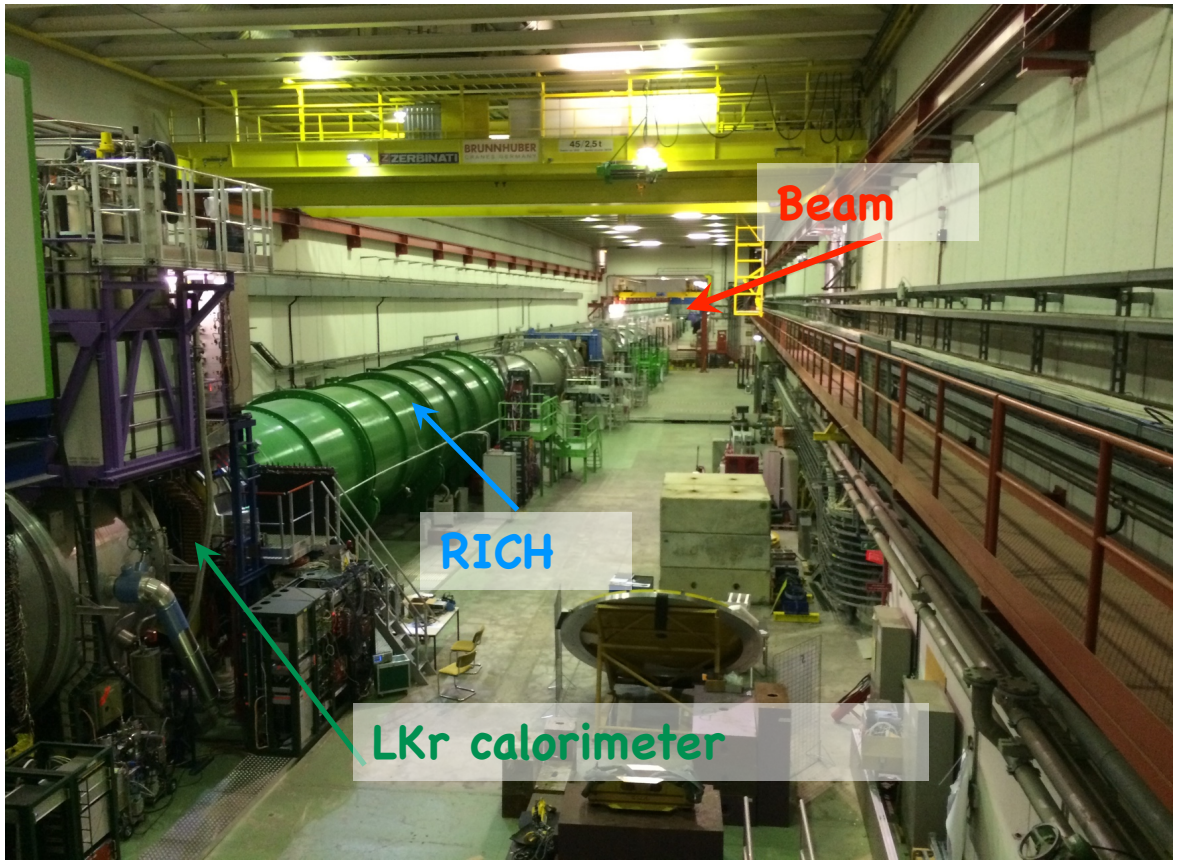
- ✧ Tracking: 4 STRAW chambers + 1 dipole magnet
- ✧ Timing and trigger hodoscopes (CHODs)
- ✧ Particle ID: RICH + calorimeters (EM + hadron) + muon veto
- ✧ Photon Veto system: hermetic veto 0-50 mrad

NA62 Experiment

- **Run1** 2016 30 days , 2017 160 days, 2018 217 days
  $\sim 2.2 \times 10^{18}$ Proton On Target (POT) collected in Run1
  6×10^{12} K^+ decays

- **Run2** 2021- larger K^+ sample expected
  1.4×10^{17} POT already collected in beam dump

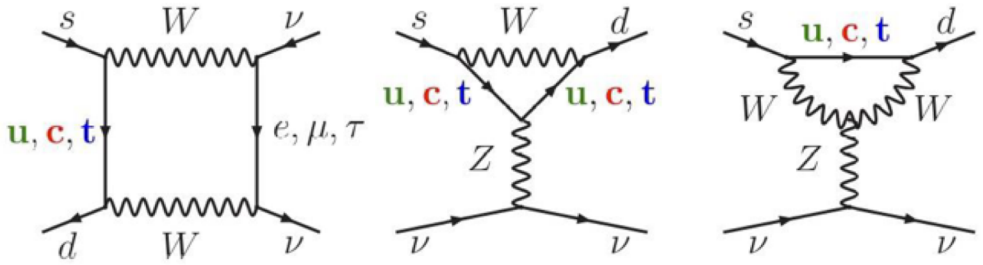




- Dedicate trigger streams to collect both single-track and multi-track final state events, based on hardware L0 and software L1 trigger

NA62 Trigger System, arXiv:2208.00897

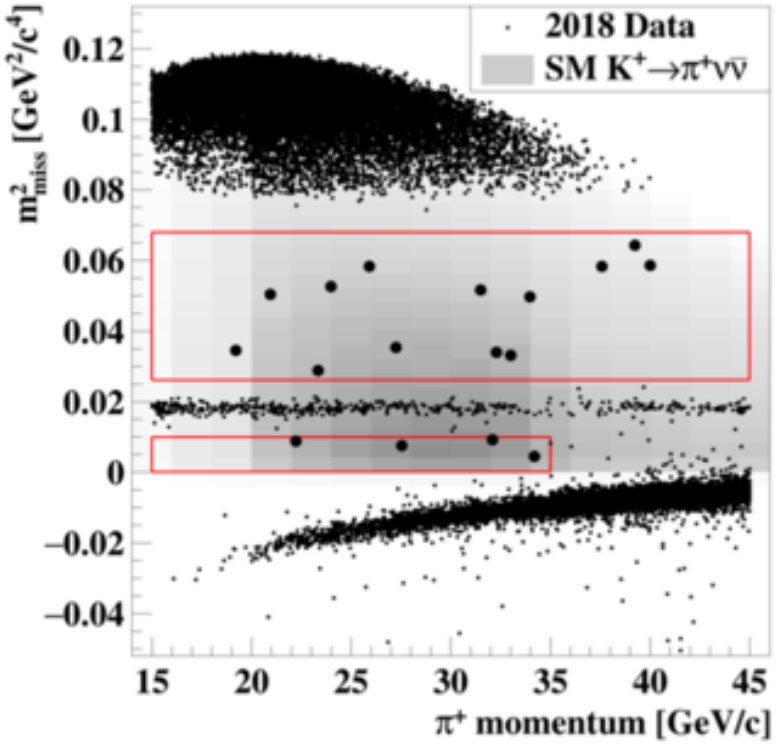
$K^+ \to \pi^+ \nu\bar{\nu}$ IN RUN1



- FCNC process
- Theoretically very clean
- SM predictions [JHEP 11 (2015) 33]

$$\mathbf{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (\mathbf{0.84 \pm 0.10}) \times \mathbf{10^{-10}}$$

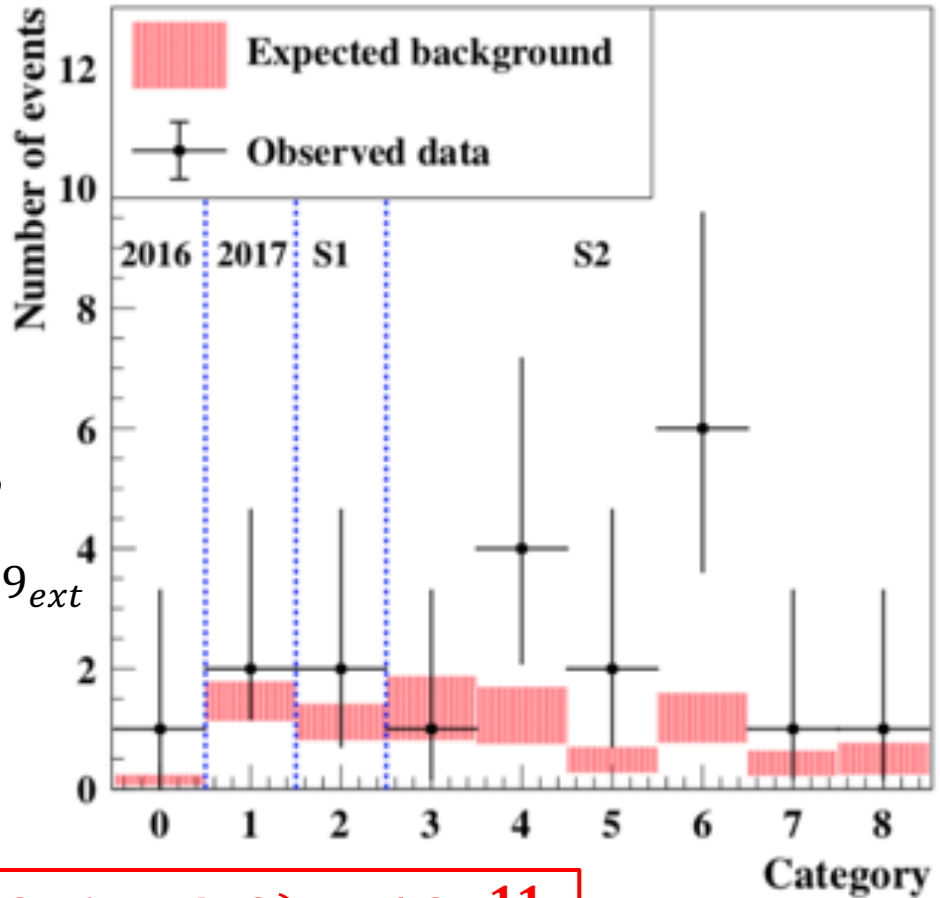
- Sensitive to New Physics in many BSM scenarios



2016 + 2017 + 2018 summary:

NA62 Coll. JHEP 06 (2021) 093

- $N_{\pi\nu\nu}^{\text{exp}} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$
- $N_{\text{bkg}}^{\text{exp}} = 7.03^{+1.05}_{-0.82}$
- **Observed 20 events**



$$\mathbf{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (\mathbf{10.6 \pm 4.0}) \times \mathbf{10^{-11}}$$

Results in precision measurements

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

- FCNC process dominated by virtual-photon exchange $K^+ \to \pi^+\gamma^* \to \pi^+\ell^+\ell^-$ [Phys. Part. Nucl. Lett. 5 (2008) 76-84] [Nucl. Phys. B291 (1987) 692-719]
- Form factor parameterized in ChPT $\mathcal{O}(p^6)$ [JHEP 08 (1998) 004]

$$W(z) = G_F m_K^2 (\boldsymbol{a}_+ + \boldsymbol{b}_+ z) + W^{\pi\pi}(z), \qquad z = \frac{m_\mu^2}{m_K^2}$$

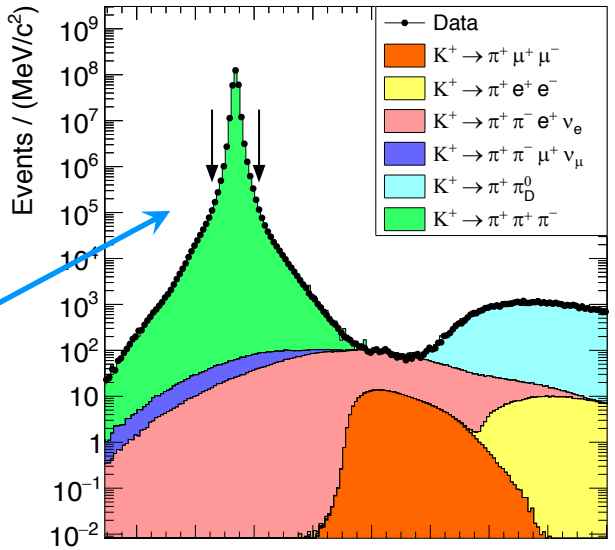
Model-independent BR

Form factor parameter a_+ and b_+

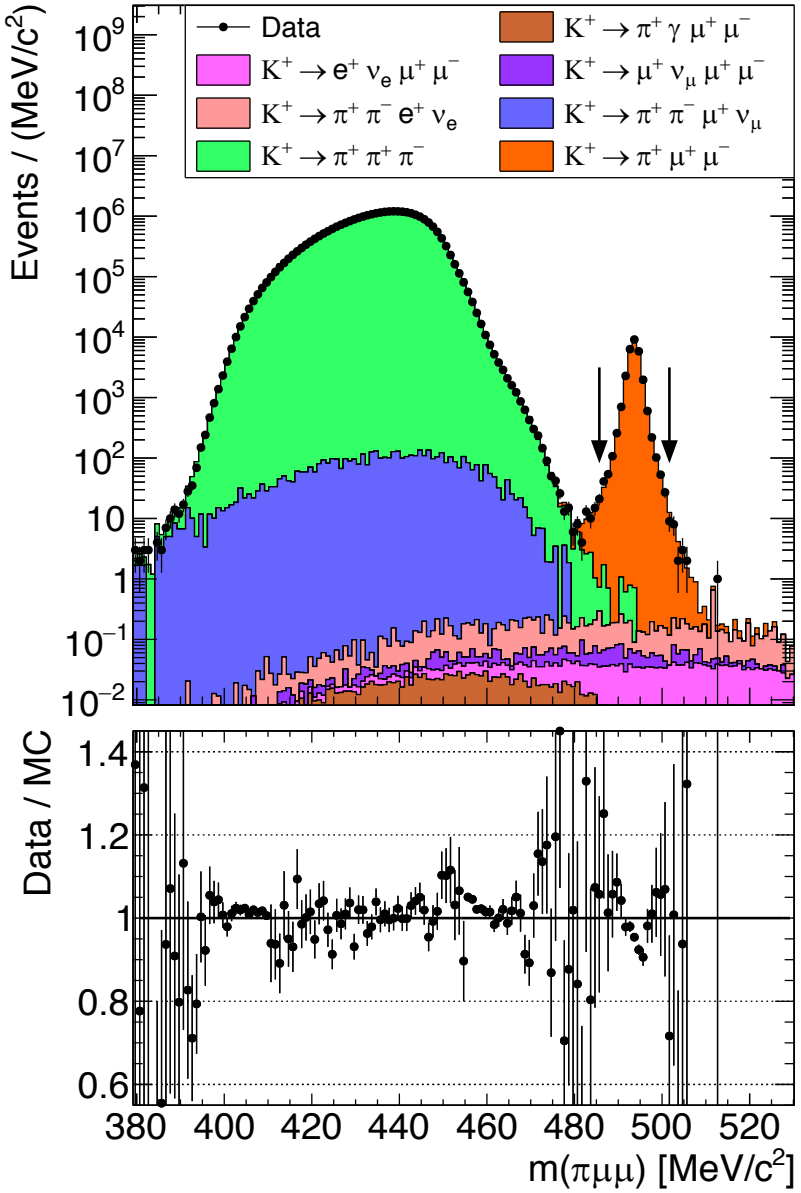
- NA62 analysis details:
  - Exploit 2017-2018 data
  - Normalized to $K^+ \to \pi^+\pi^+\pi^-$ events
    $N_K \approx 3.5 \times 10^{12}$
  - Expected 8 background events
    ($K_{3\pi}$ with 2 $\pi \to \mu\nu$ decay in-flight)
  - Observed 27679 events
  - **Improved treatment of radiative corrections**

[Eur. Phys. J. C70 (2010) 219]

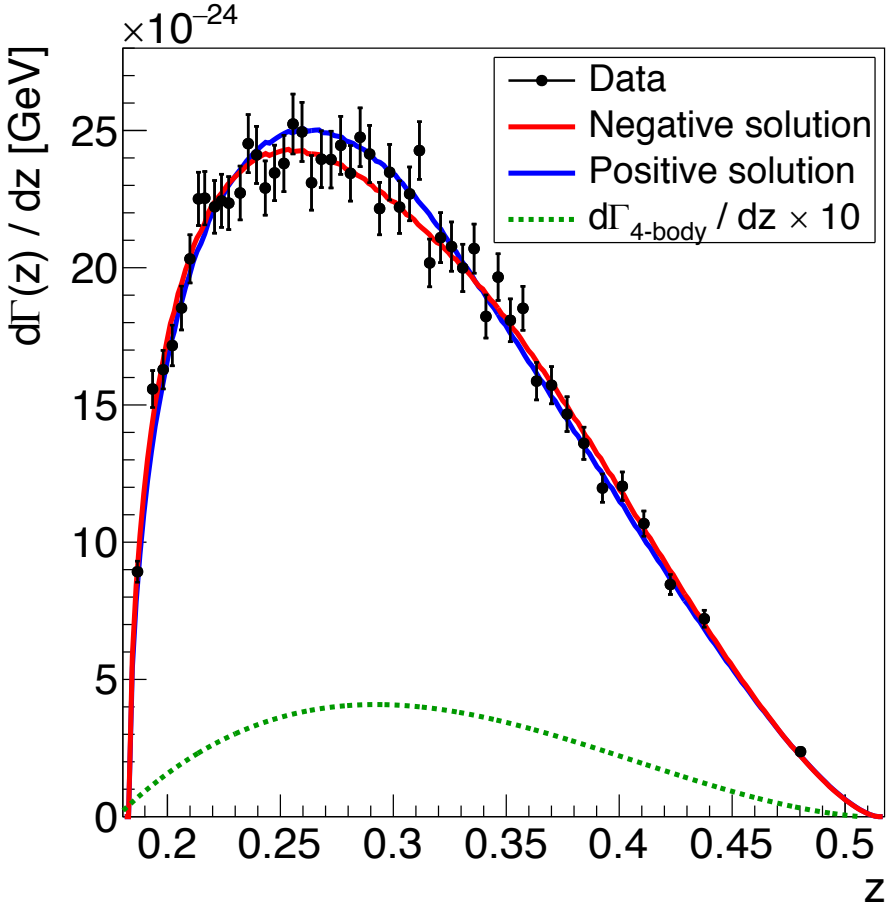
Normalization



Signal

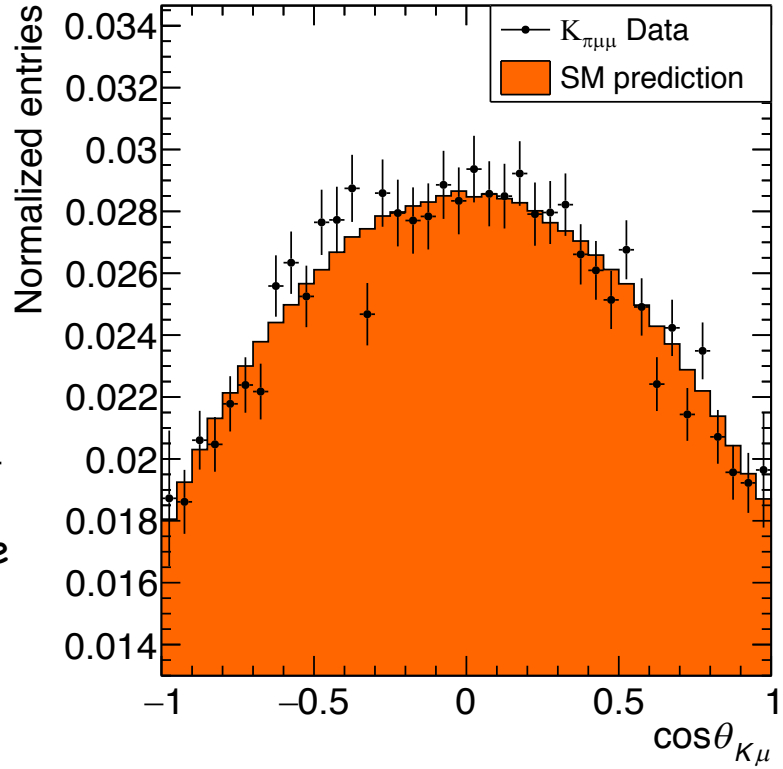


$K^+ \to \pi^+\mu^+\mu^-$ ANALYSIS



$\frac{d\Gamma(z)}{dz}$ profile in 50 equally populated bins

- **Model-independent** BR (integrate profile)
- ChPT form factor parameter a_+ and b_+
  - Fit of data points
  - Assuming linearity in $|W(z)|^2$
  - Negative solution preferred



- Forward-backward asymmetry

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

$\theta_{K\mu}$: K^+ and μ^- angle in $\mu^+\mu^-$ rest frame

$$\mathbf{A_{FB} = (0.0 \pm 0.7)\times 10^{-2}}$$

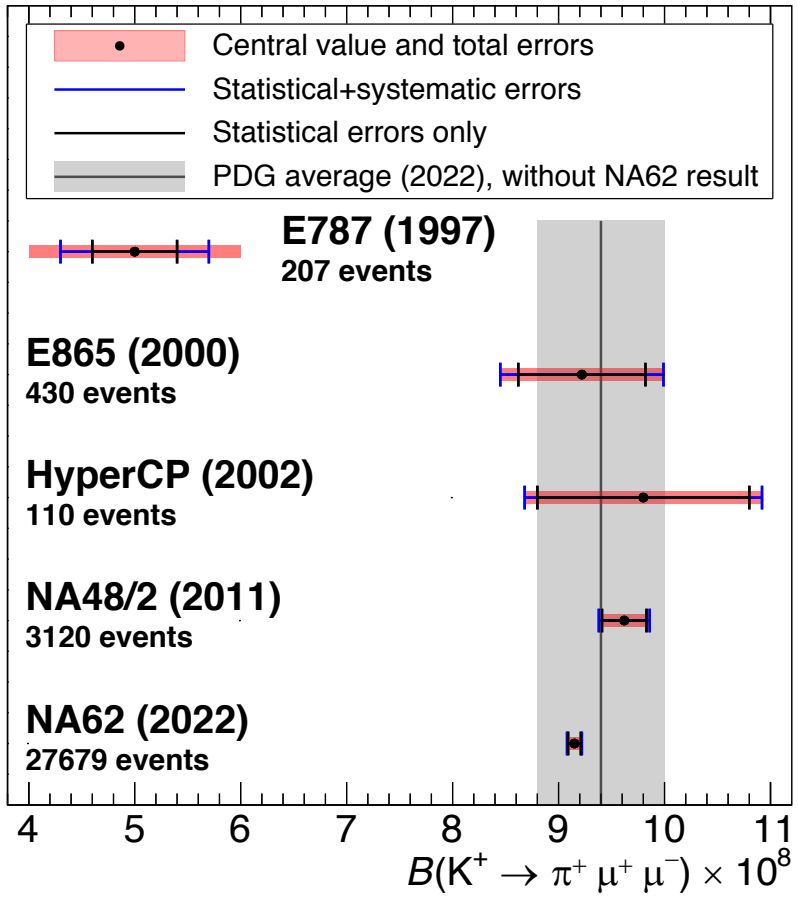
- No significant dependence in z
- **Statistical precision reaches upper limit from theory**

[Phys. Rev. D 67 (2003) 074029], [Phys. Rev. D 69 (2004) 094030]

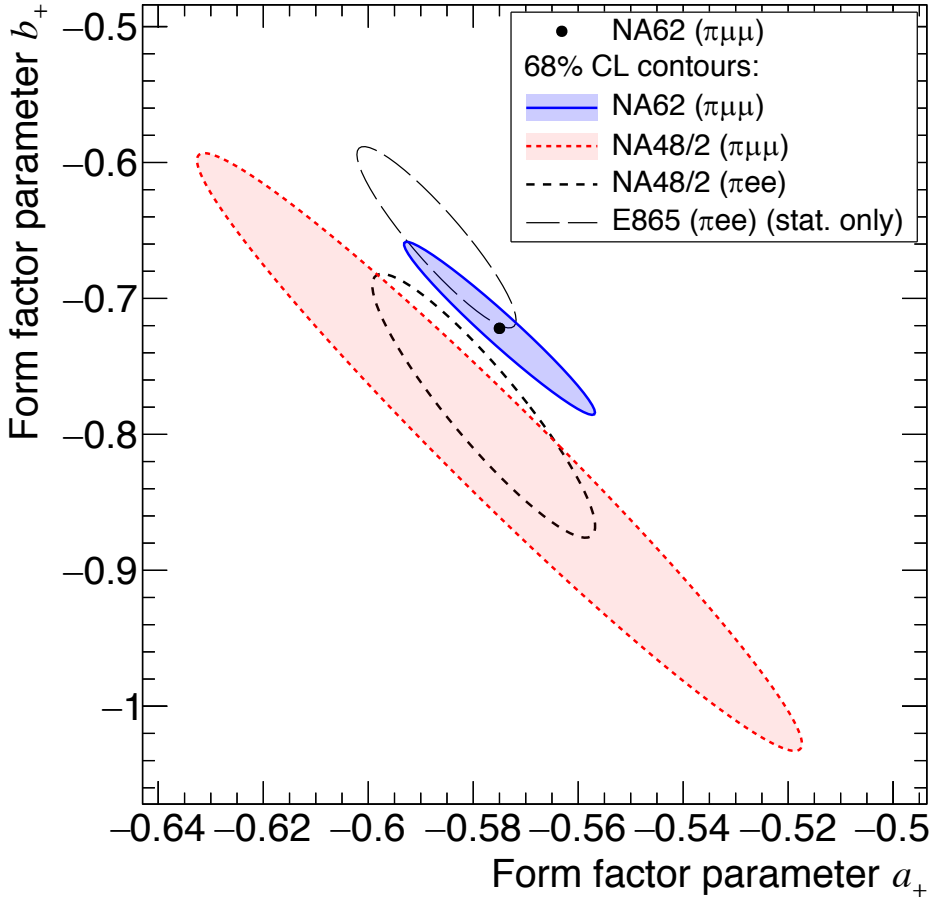
$K^+ \to \pi^+\mu^+\mu^-$ ANALYSIS

NA62 Coll. JHEP 11 (2022) 011

- Model-independent BR
  - $\mathbf{BR}(K^+ \to \pi^+\mu^+\mu^-) = (9.15 \pm 0.08) \times 10^{-8}$
  - **Improvement by a factor ≥ 3**
  - Consistent with previous measurements



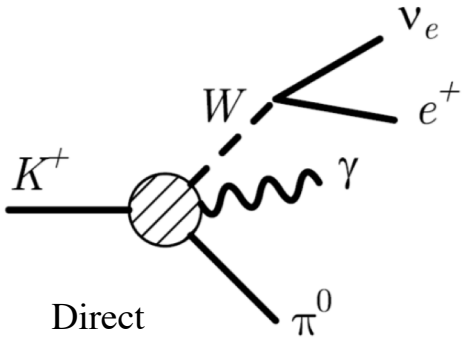
- ChPT form factor parameter
  - $a_+ = -0.575 \pm 0.013,\ b_+ = -0.722 \pm 0.043$
  - **Compatible with previous measurements (as expected by LFU) in $\mu\mu$ and ee channel**



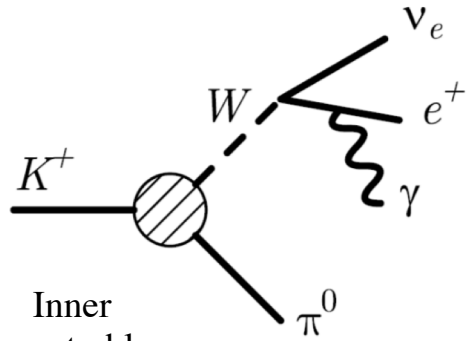
$K^+ \to \pi^o e^+ \nu\gamma$ ANALYSIS

- Precision test of ChPT up $\mathcal{O}(p^6)$ [Eur. Phys. J. C 50 (2007)]

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



Direct Emission



Inner Bremsstrahlung

- Test of **T-asymmetry** [Eur. Phys. J. C 48 (2006)]

  T-odd variable $\xi = \frac{\vec{p_\gamma} \cdot (\vec{p_e} \times \vec{p_\pi})}{m_K^3}$, $A_\xi = \frac{N_+ - N_-}{N_+ + N_-}$

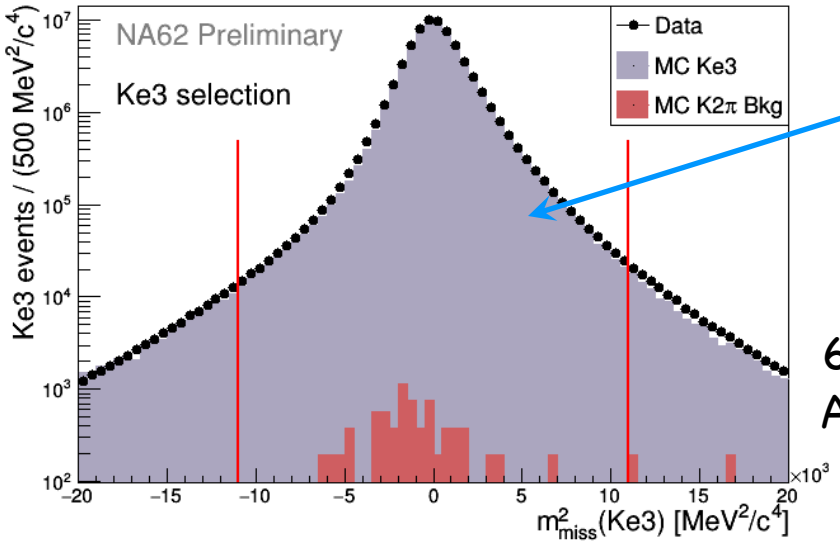
  - A_ξ theory SM and beyond $|A_\xi| < 10^{-4}$
  - Experimental measurement only for R3 $|A_\xi|$ $\mathcal{O}(10^{-2})$

- NA62 analysis details:

$$R_j = \frac{\mathrm{BR}(K^j_{e3\gamma})}{\mathrm{BR}(Ke3)} = \frac{N^{\mathrm{obs}}_{K^j_{e3\gamma}} - N^{\mathrm{bkg}}_{K^j_{e3\gamma}}}{N^{\mathrm{obs}}_{K_{e3}} - N^{\mathrm{bkg}}_{K_{e3}}} \cdot \frac{A_{K_{e3}}}{A_{K^j_{e3\gamma}}} \cdot \frac{\varepsilon^{\mathrm{trigger}}_{K_{e3}}}{\varepsilon^{\mathrm{trigger}}_{K^j_{e3\gamma}}}$$

  - Normalization $K^+ \to \pi^o e^+ \nu$ (K_{e3}) events
  - Background estimated in data and MC
  - Acceptance evaluated in MC
  - Trigger efficiency measured in data
  - Analysis of full 2017 and 2018 data sets

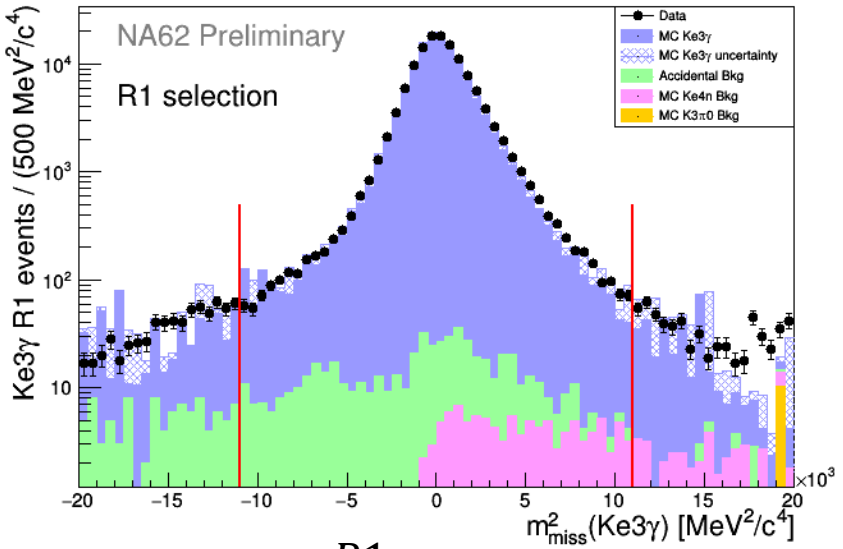
Normalization



66M normalization K_{e3} events
Almost background free: $B/S \sim 10^{-4}$

$K^+ \to \pi^o e^+ \nu\gamma$ ANALYSIS

Signal

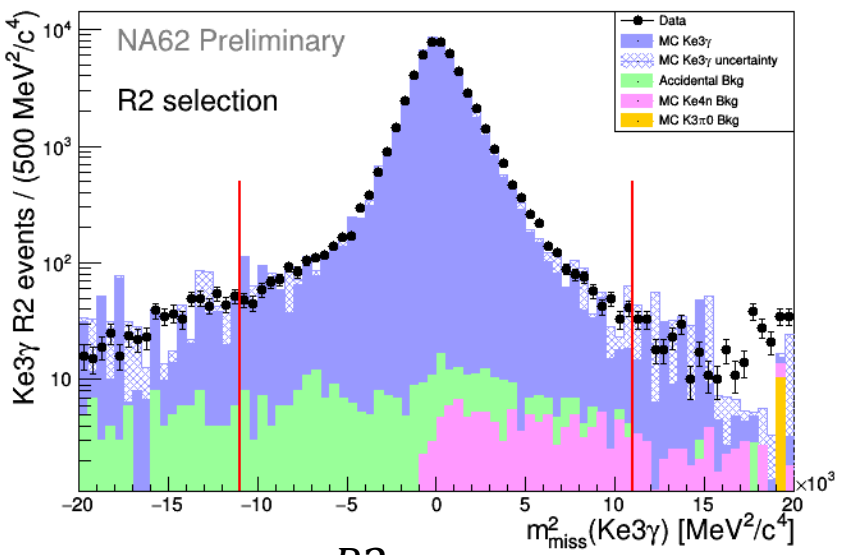


$R1$

$E_\gamma > 10$ MeV, $\theta_{e\gamma} > 10^o$

130k events

Signal

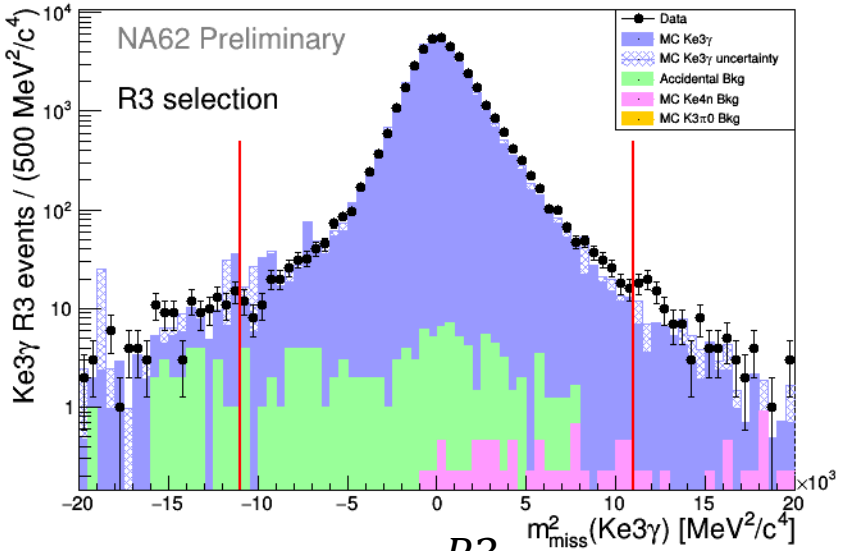


$R2$

$E_\gamma > 30$ MeV, $\theta_{e\gamma} > 20^o$

54k events

Signal



$R3$

$E_\gamma > 10$ MeV, $0.6 < cos\theta_{e\gamma} < 0.9$

39k events

- Main background from accidentals K_{e3} decay with additional LKr cluster
  Dedicated $m^2_{\mathrm{miss}}(K_{e3})$ cut

- **Low background contamination $B/S < 1\%$ in all 3 regions**
  Uncertainty of background contamination small when propagated in R_j (0.2% relative at worse)

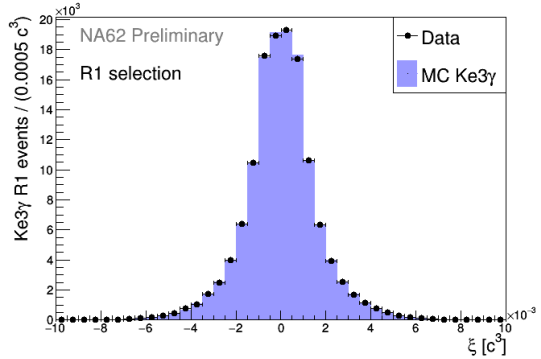
$K^+ \to \pi^0 e^+ \nu\gamma$ ANALYSIS

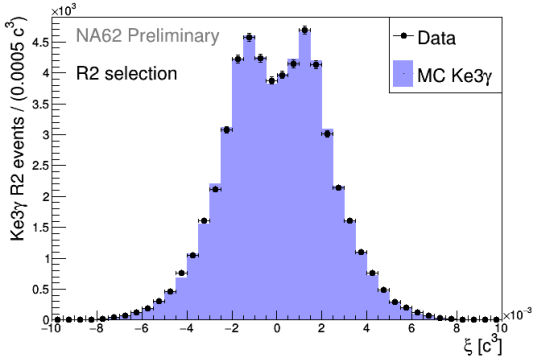
R region	$\mathcal{O}(p^6)$ ChPT (10^{-2}) [1]	ISTRA+ (10^{-2}) [2]	OKA (10^{-2})[3]	**NA62 Preliminary** $R(10^{-2})$ **measurement**
$R1$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$	$1.684 \pm 0.005 \pm 0.010$
$R2$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$	$0.559 \pm 0.003 \pm 0.005$
$R3$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$	$0.523 \pm 0.003 \pm 0.003$

NA62 Preliminary A_ξ **measurement**
$-0.001 \pm 0.003 \pm 0.002$
$-0.003 \pm 0.004 \pm 0.003$
$-0.009 \pm 0.005 \pm 0.004$

[1] [Eur. Phys. J. C 50 (2007)]
[2] [Phys. Atom. Nucl. 70 (2007)]
[3] [Eur. Phys. J. C 81.2 (2021)]

- R_j relative precision equal/better than 1% relative
  - **Improved by a factor between 2 and 3.6**
  - Relative discrepancy with theory 6-7%
- T-asymmetry
  - $R3$ precision improved by a factor > 3
  - **First ever measurements in $R1$ and $R2$**





STAY TUNED PAPER IN PREPARATION

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

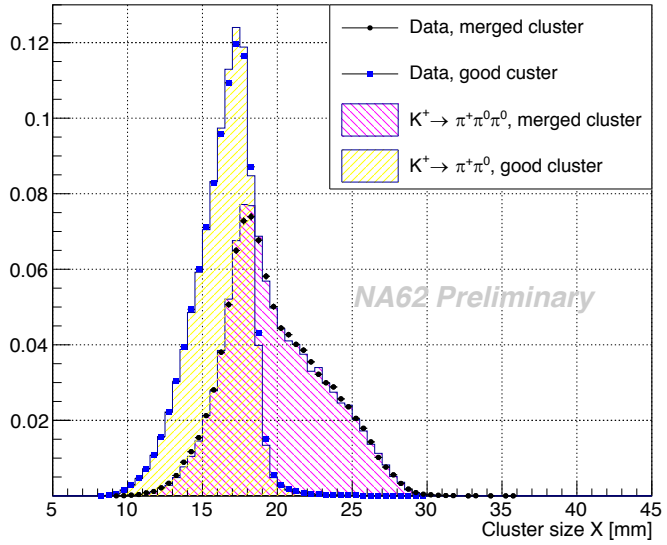
- Crucial test of ChPT $\mathcal{O}(p^6)$
- Decay described by two variables

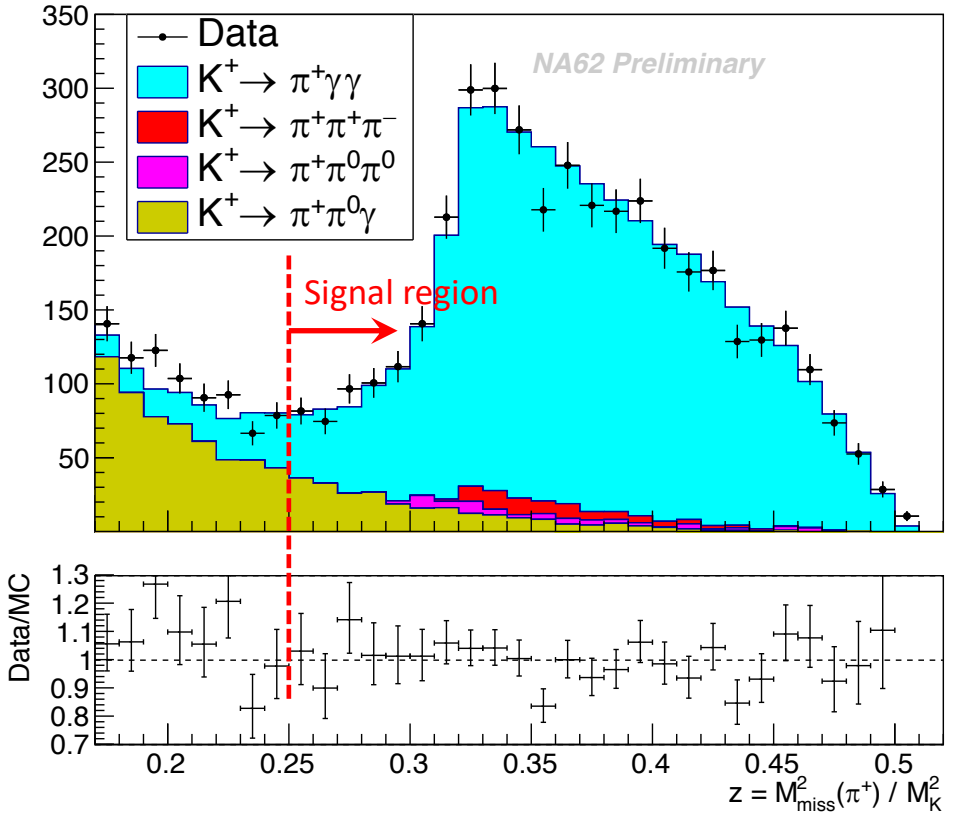
$$z = \frac{m_{\gamma\gamma}^2}{m_K^2}\,, y = \frac{p(q_1-q_2)}{m_K^2} \quad [p = p_K, q_i = p_{\gamma_i}]$$

- Decay rate and spectrum determined by a **single**, a priori unknown, $\mathcal{O}(1)$ **parameter** $\hat{c}$

[Phys. Lett. B386 (1996) 403]

- NA62 analysis details:
  - Full Run1 data sets
  - Normalize to $K^+ \to \pi^+\pi^o$ events
  - Analysis performed in $z > 0.25$ **signal region**
  - Background
    - cluster merging (e.g. $K^+ \to \pi^+\pi^o\pi^o$)
    - $K^+ \to \pi^+\pi^+\pi^-$ with 2 non reconstructed tracks
  - Validate in control regions with enhanced background and check Data/MC agreement
  - $N_{\text{obs}} = 4039$, $N_{\text{bkg}}^{\text{exp}} = 393 \pm 20$
  - **Fit to data point distribution to extract** $\hat{c}$





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

NA62 preliminary results:

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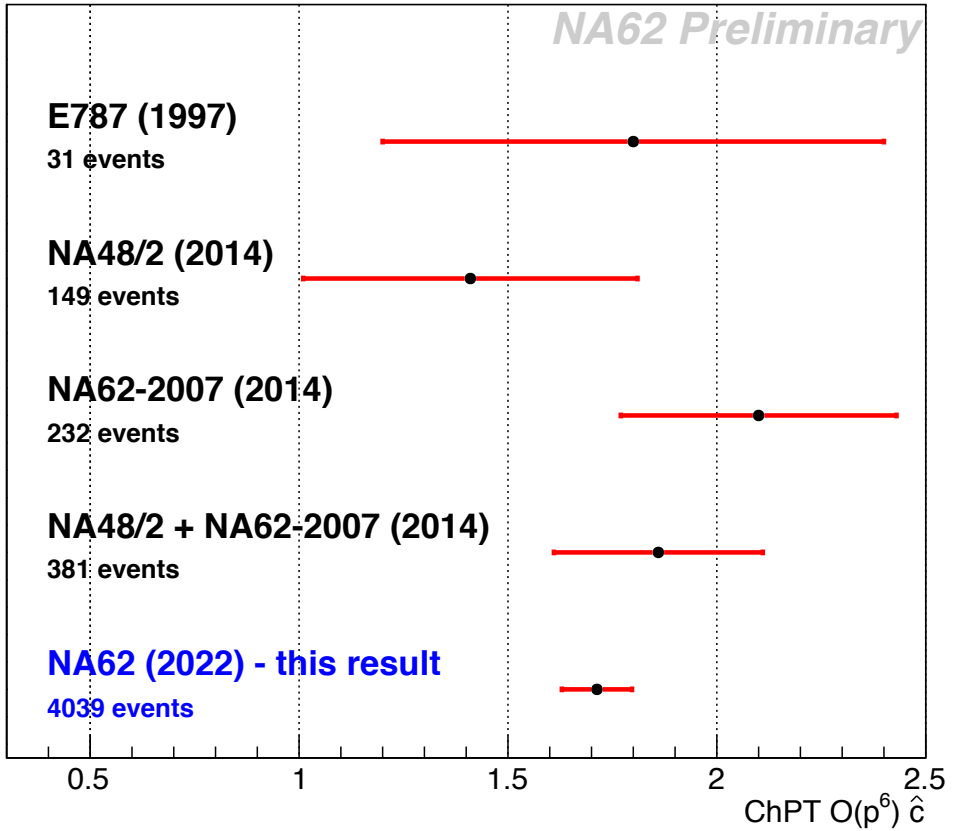
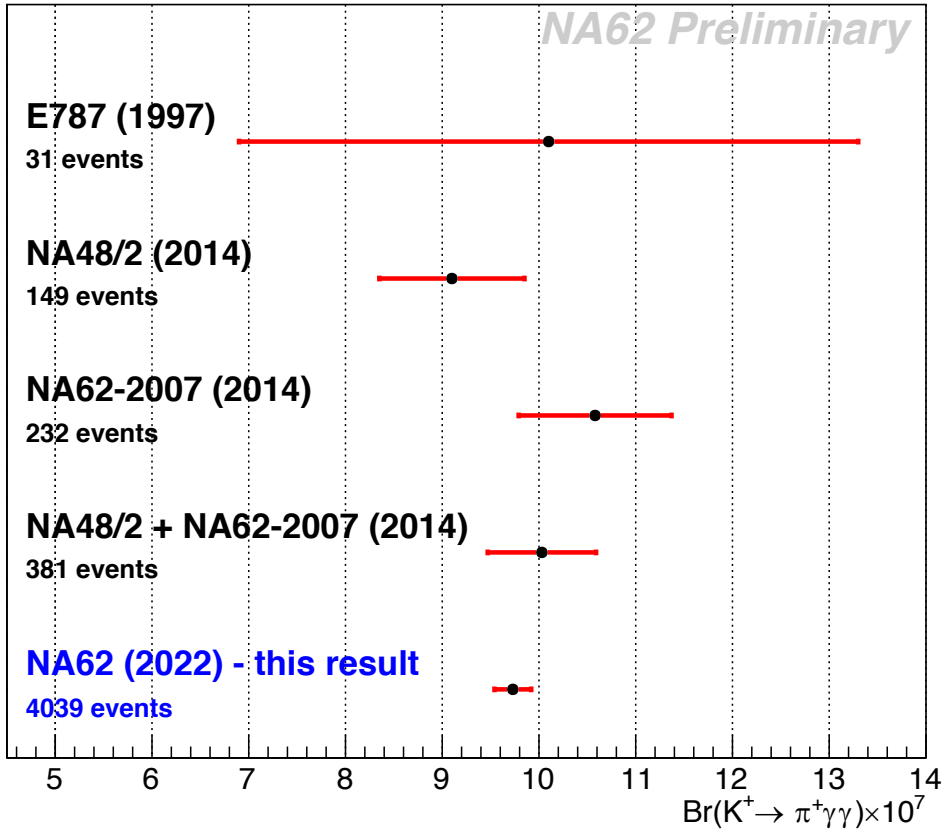
$$\hat{c} = 1.713 \pm 0.084$$

$$\mathrm{BR}(K^+ \to \pi^+\gamma\gamma) = (9.73 \pm 0.19) \times 10^{-7}$$

- Total uncertainty reduced by factor 3
- Extension to NP search $K^+ \to \pi^+ a\,, a \to \gamma\gamma$





Results in Beyond Standard Model searches

LNV/LFV ANALYSIS

- Lepton Number (LN) and Lepton Flavor (LF) conserved in SM
- Neutrino oscillation first hint of LF violation

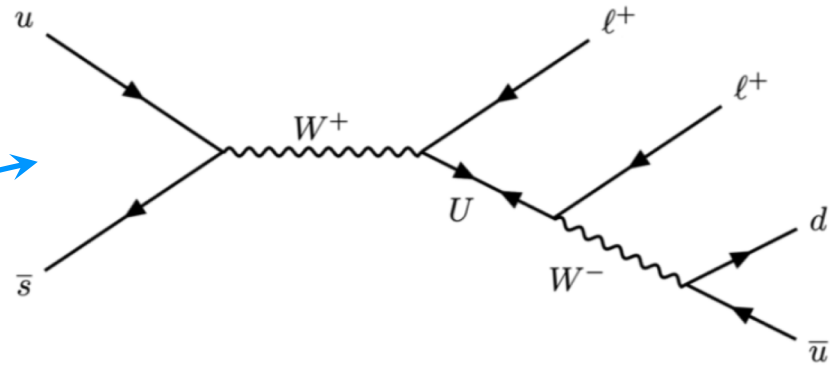
- Observations of LN and LF violation clear signs of New Physics

- Several scenario for generating LNV/LFV in charged processes

- NA62 analysis details:
  - Dedicate multi-track trigger streams with electron and/or muon in final states
  - Run1 data sets
  - Analysis carried on with blind principle
  - Different channels investigated

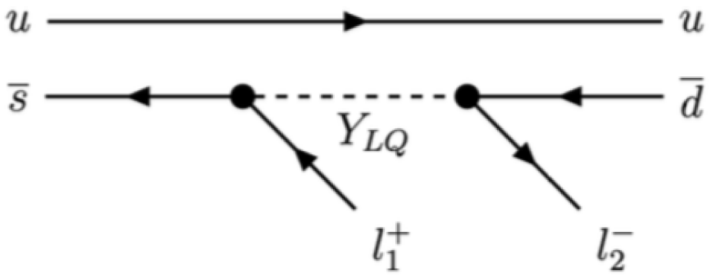
$$K^+ \to \pi^- \mu^+ \mu^+$$
$$K^+ \to \pi^- (\pi^o) e^+ e^+$$
$$K^+ \to \pi^{\mp} \mu^{\pm} e^+, \pi^o \to \mu^- e^+$$
$$K^+ \to \mu^- \nu e^+ e^+$$

Today talk



$K^+ \to \pi^- \ell^+ \ell^+ (\Delta L = 2)$ LNV process mediated by Majorana neutrino (U)

[JHEP 05 (2009) 030]



$K^+ \to \pi^+ \ell_1^+ \ell_2^-$ LFV process mediated by a leptonquark (Y_{LQ})

[JHEP 12 (2019) 089]

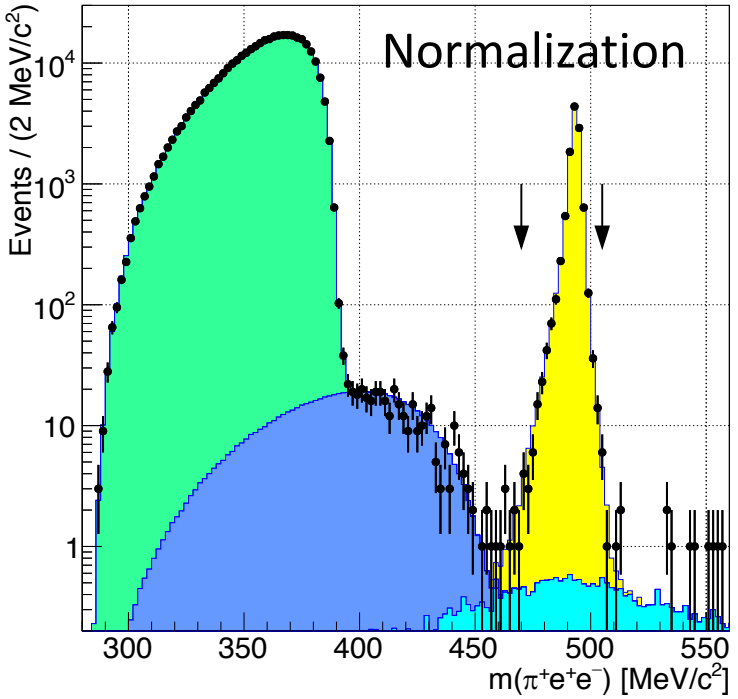
LNV/LFV ANALYSIS

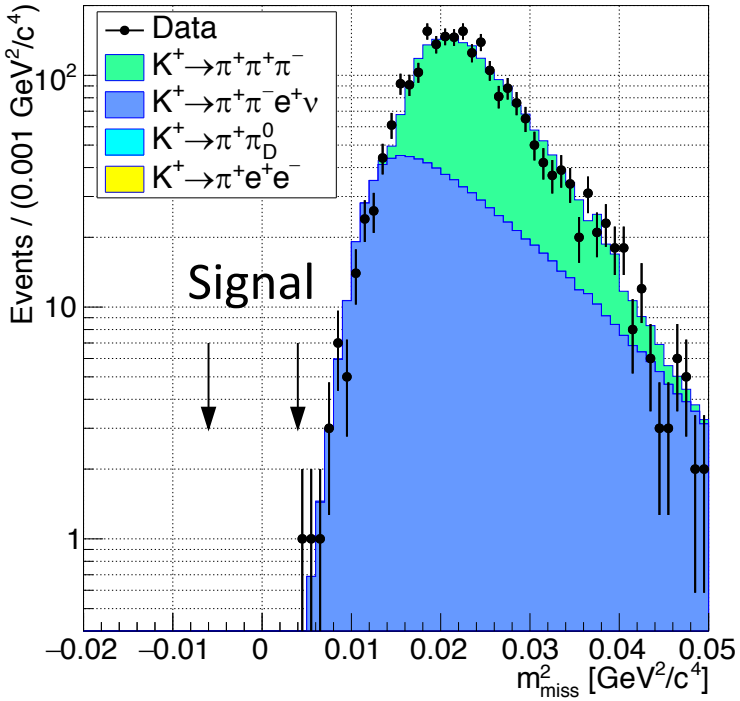
$K^+ \to \mu^- \nu e^+ e^+$ decay

- LNV or LFV process depending on neutrino flavor
- **Only one previous measurement in 1976** [Phys. Lett. B 62 (1976) 485]
- NA62 analysis details:
  - Normalized to $K^+ \to \pi^+ e^+ e^-$ SM events
    $$N_K \sim 2 \times 10^{12}$$
  - Signal region $m^2_{\text{miss}} = \left(P_K - P_\mu - P_{e_1} - P_{e_2}\right)^2$
    $$-0.006 < m^2_{\text{miss}} < 0.004\ \text{GeV}^2/c^4$$
  - Dominant background in signal region $K^+ \to \pi^+ \pi^- e^+ \nu$ with π^+ misID and $\pi^- \to \mu^- \bar{\nu}$
    $$N^{\text{exp}}_{\text{bkg}} = 0.26 \pm 0.04$$
  - $N_{\text{obs}} = 0$

NA62 preliminary result:

$$\mathbf{BR}(K^+ \to \mu^- \nu e^+ e^+) < 8.1 \times 10^{-11} \text{ @ 90 \% CL}$$





LNV/LFV ANALYSIS

NA62 summary of Run1 results in LN/LF violation

Decay channel	BR UL (PDG)	**NA62 Results**	Improvement
$K^+ \to \pi^- \mu^+ \mu^-$	8.6×10^{-11}	4.2×10^{-11} [1]	$\sim$ factor 2
$K^+ \to \pi^- e^+ e^-$	6.4×10^{-10}	5.3×10^{-11} [2]	$\sim$ factor 12
$K^+ \to \pi^- \pi^o e^+ e^+$	–	8.5×10^{-11} [2]	–
$K^+ \to \pi^- \mu^+ e^+$	5.0×10^{-10}	4.2×10^{-11} [3]	$\sim$ factor 12
$K^+ \to \pi^+ \mu^- e^+$	5.2×10^{-10}	6.6×10^{-11} [3]	$\sim$ factor 8
$\pi^o \to \mu^- e^+$	3.4×10^{-9}	3.2×10^{-10} [3]	$\sim$ factor 10
$K^+ \to \mu^- \nu e^+ e^+$	2.1×10^{-8}	8.1×10^{-11} [4]	$\sim$ factor 250

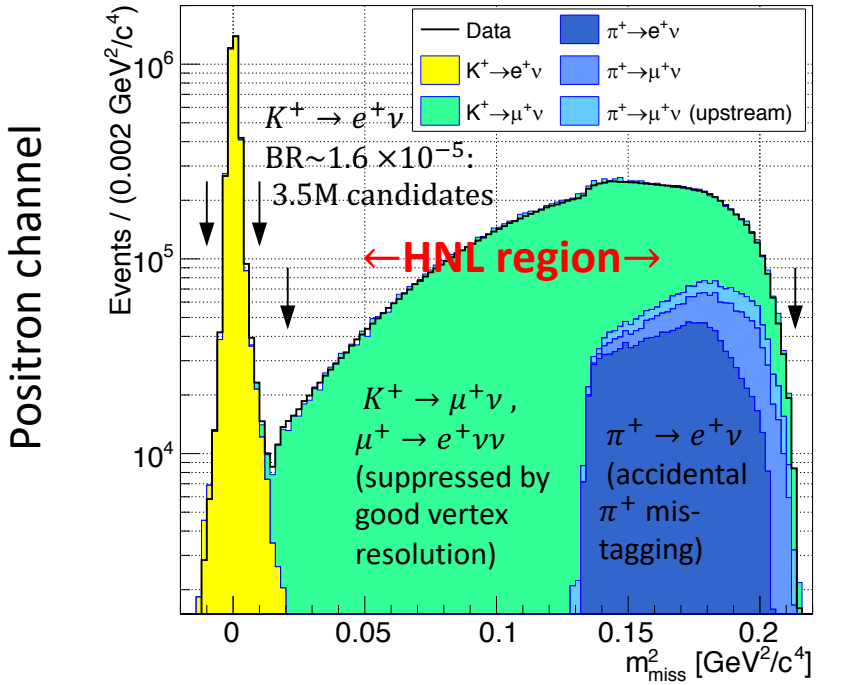
first limit for this channel

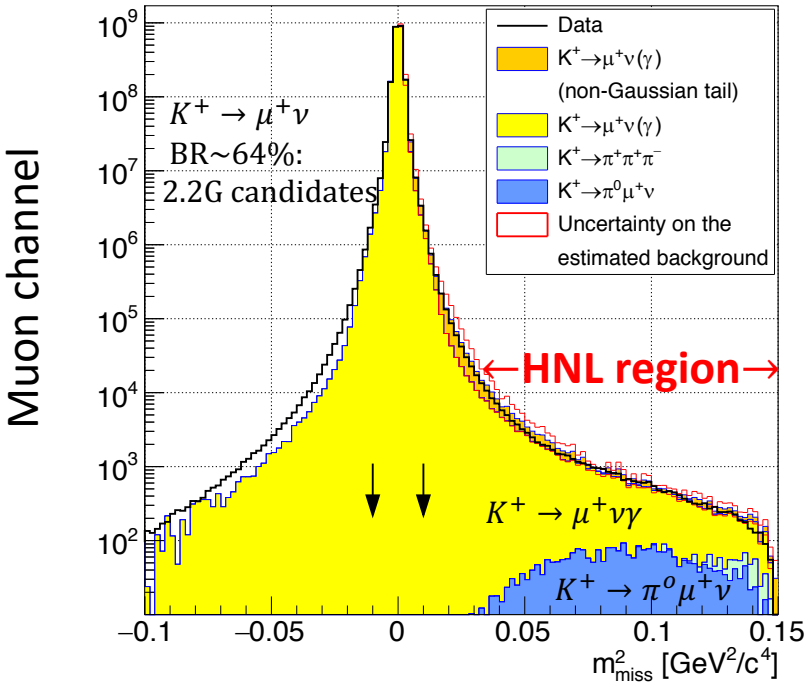
[1] NA62 Coll., Phys. Lett. B 797 (2019) 134794
[2] NA62 Coll., Phys. Lett. B 830 (2022) 137172
[3] NA62 Coll., Phys. Rev. Lett. 127 (2021) 12, 131802
[4] CERN-EP-2022-243, submitted to PLB

$K^+ \to \ell^+ N$ ANALYSIS

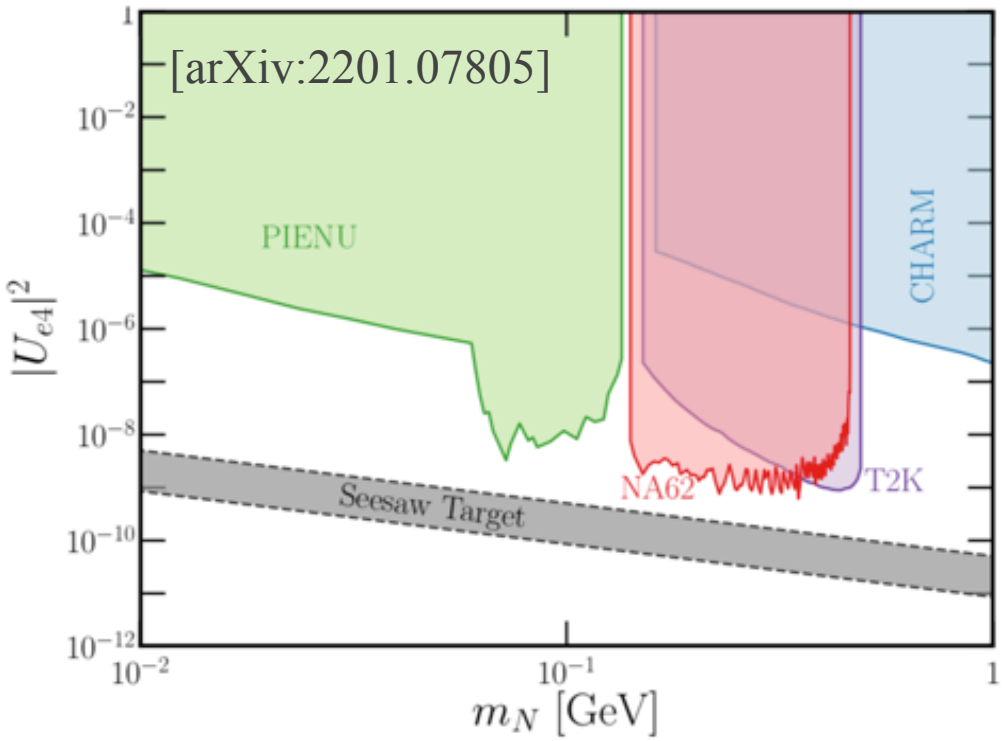
- Heavy neutral lepton (HNL) predicted in many scenario BSM to generate non-zero SM neutrino masses
- Mixing between N and ν described by $U_{\ell 4}$ parameter
- NA62 analysis details:
  - Search for **N production** in kaon decays
    $\mathbf{BR}(K^+ \to \ell^+ N) = \mathbf{BR}(K^+ \to \ell^+ \nu) \cdot \rho_\ell(m_N) \cdot |U_{\ell 4}|^2$
  - Assuming lifetime N exceeds 50 ns (**stable inside detector**)
  - Peak searching above a continuous missing mass spectrum $m^2_{\text{miss}} = (P_K - P_\ell)^2$
  - Scan m_N in step of $\mathcal{O}(1)$ MeV/c^2 in range
    $144 - 462$ MeV/c^2 positron channel
    $200 - 384$ MeV/c^2 muon channel

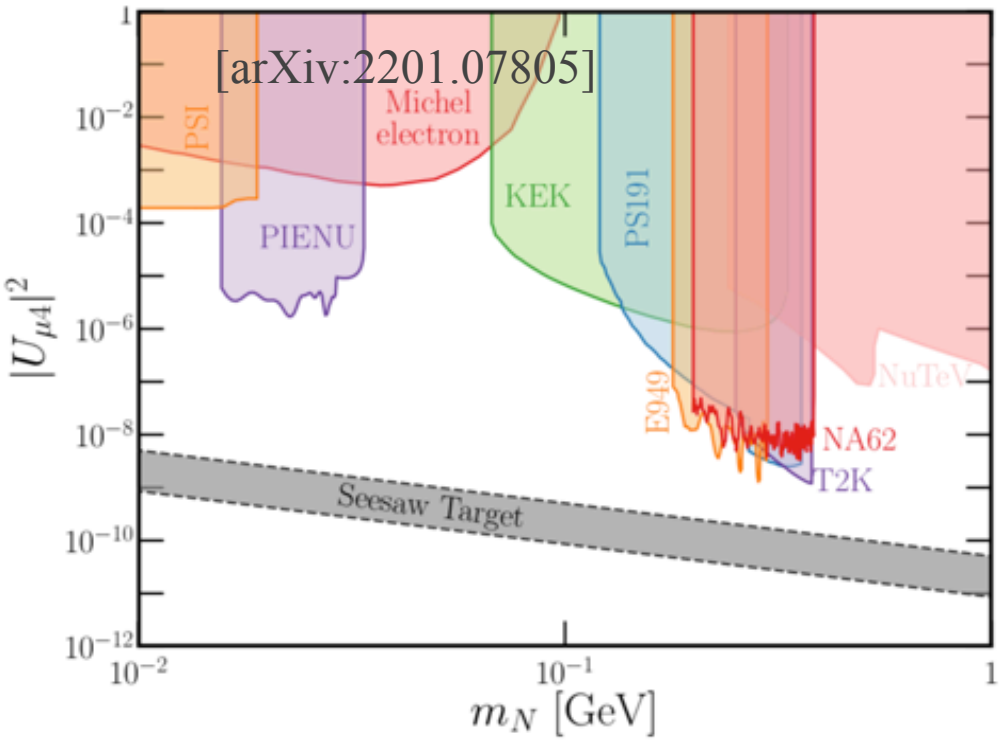
NA62 Coll., Phys. Lett. B 807 (2020) 135599 (e channel)
NA62 Coll., Phys. Lett. B 816 (2021) 136259 (μ channel)





$K^+ \to \ell^+ N$ ANALYSIS





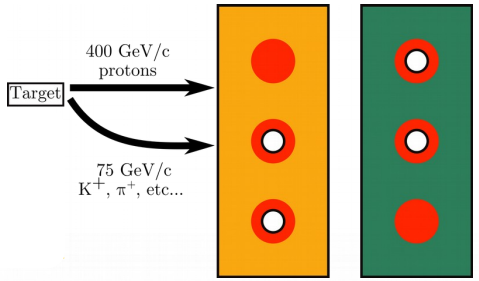
NA62 results:

- $|U_{e4}|^2$ UL $\mathcal{O}(10^{-9})$ complimentary to search for $\pi^+ \to e^+ N$
- $|U_{\mu 4}|^2$ UL $\mathcal{O}(10^{-8})$ complimentary to search for $\pi^+ \to \mu^+ N$
- Muon channel extension:
  - $K^+ \to \mu^+ \nu X$ scalar or vector with $m_X \in 10 - 310$ MeV/c^2 UL $\mathcal{O}(10^{-5} - 10^{-7})$
  - $BR(K^+ \to \mu^+ \nu\nu\bar{\nu}) < 1.0 \times 10^{-6}$ @ 90% CL

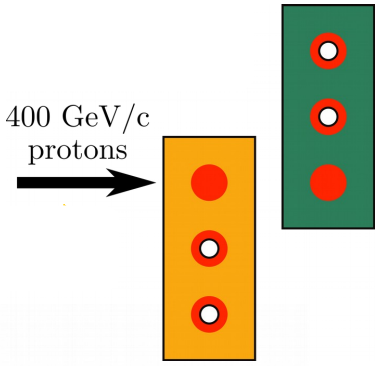
NA62 Coll., Phys. Lett. B816 (2021) 136259

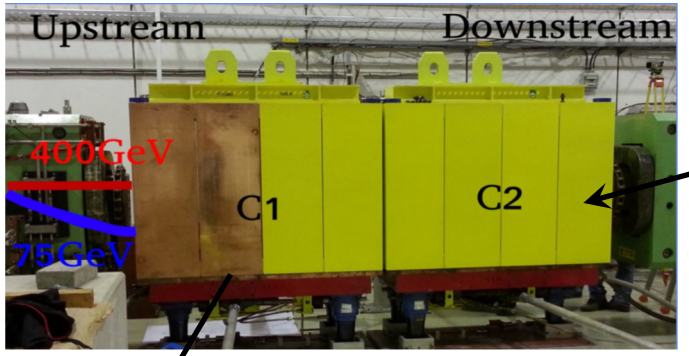
NA62 IN BEAM DUMP CONFIGURATION

Normal data taking with Be target in place

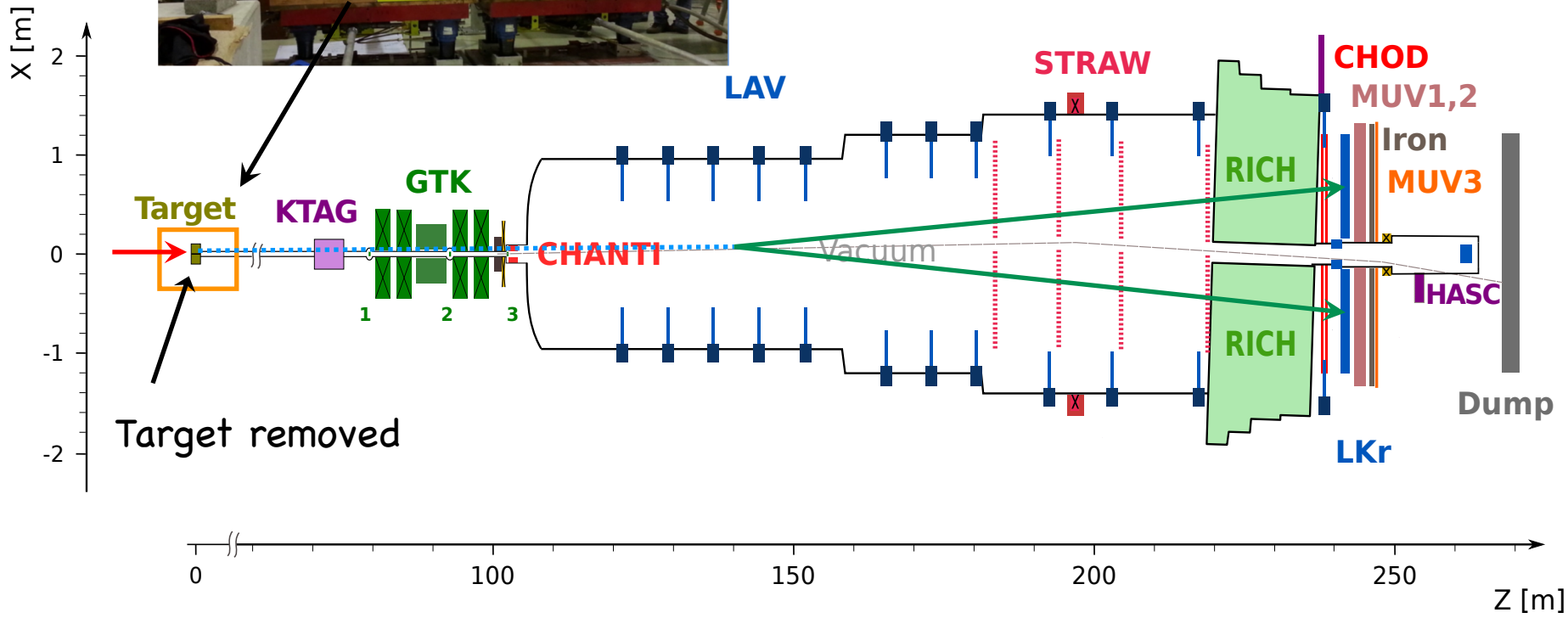


Beam Dump mode
Be target lifted and Tax collimator closed





3.2m long Cu-Fe movable collimators (TAX)



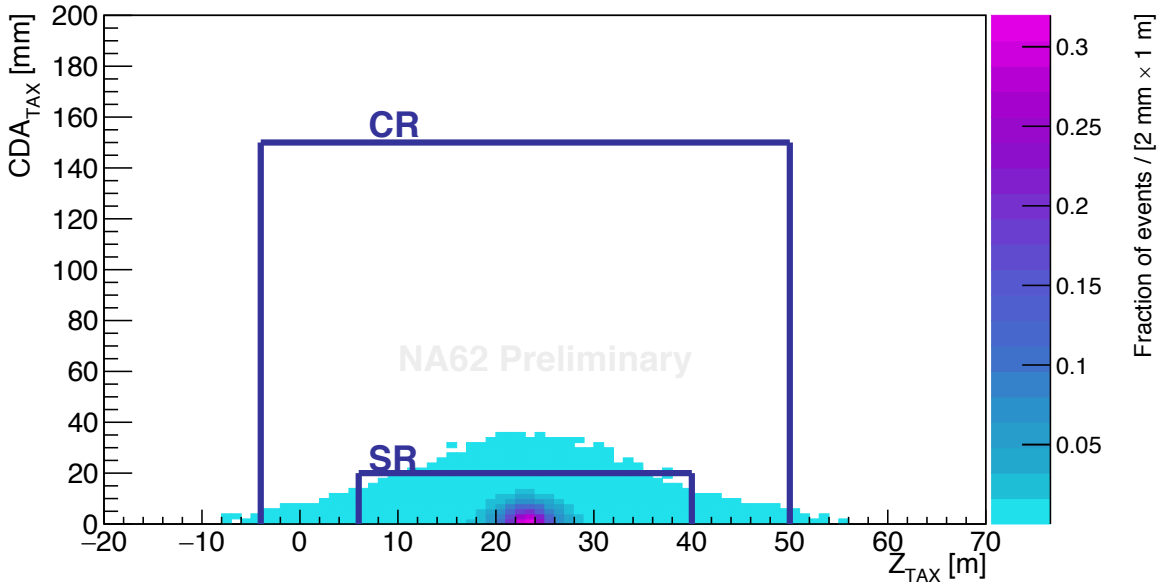
$A' \to \mu^+\mu^-$ ANALYSIS IN BEAM DUMP

CR = control region
SR = signal region

- SM extension via vector portal (dark photon)
- New vector field feebly interacting with SM particles
- **Free parameters of the model $m_{A'}$ and kinetic coupling ε**
- Dominant decay in $\ell\bar{\ell}$ pair for $m_{A'} < 700\ \mathrm{MeV/c^2}$

- NA62 analysis details:
  - **10 days** of data taking at 1.5 nominal intensity 1.4×10^{17} POT collected
  - Beam optimization in 2021: background reduction x200 wrt 2018 (although higher intensity)
  - Blind technique
  - **A' via Bremsstrahlung or meson-mediated production in the TAX**
  - Lepton-antilepton vertex reconstructed within NA62 fiducial volume, a primary vertex close to the proton beam impact at the TAX

Signal MC simulation



Z_{TAX} longitudinal position primary vertex
CDA_{TAX} closest distance of approach between beam direction (at TAX entrance) and $\ell^+\ell^-$ pair direction

SR: $CDA_{TAX} < 20$ mm & $6 < Z_{TAX} < 40$ m

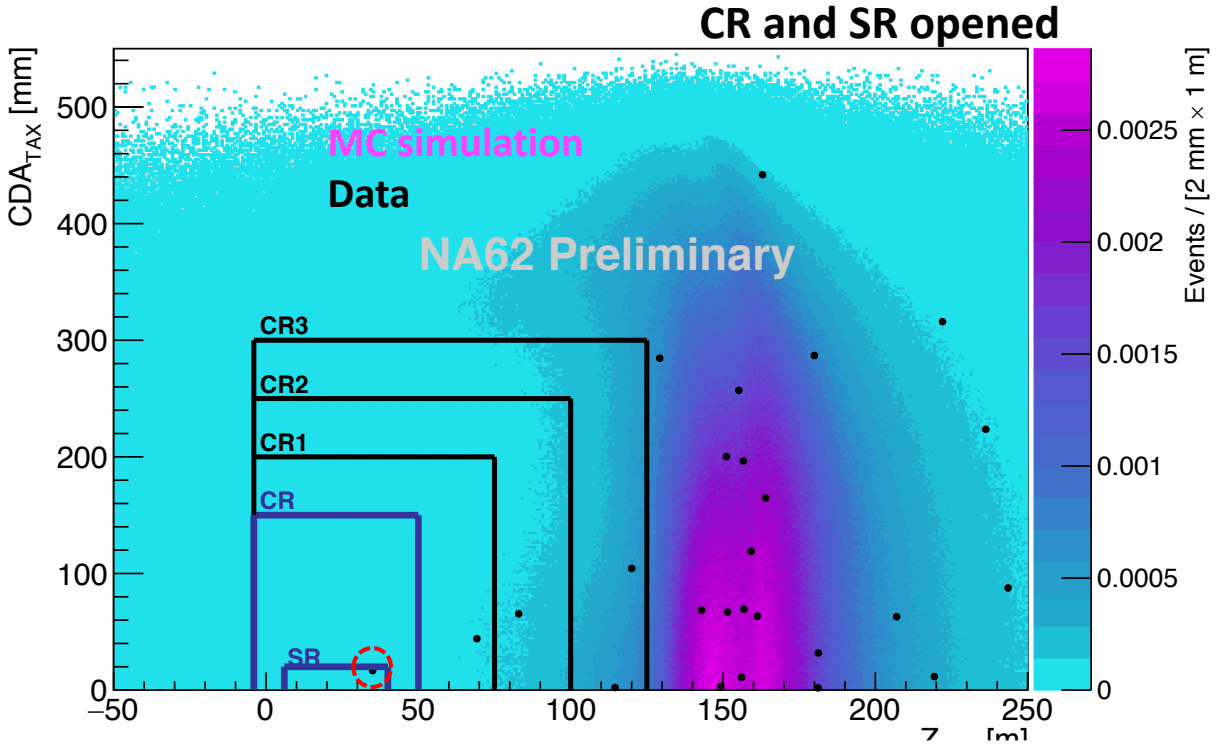
$A' \to \mu^+\mu^-$ ANALYSIS IN BEAM DUMP

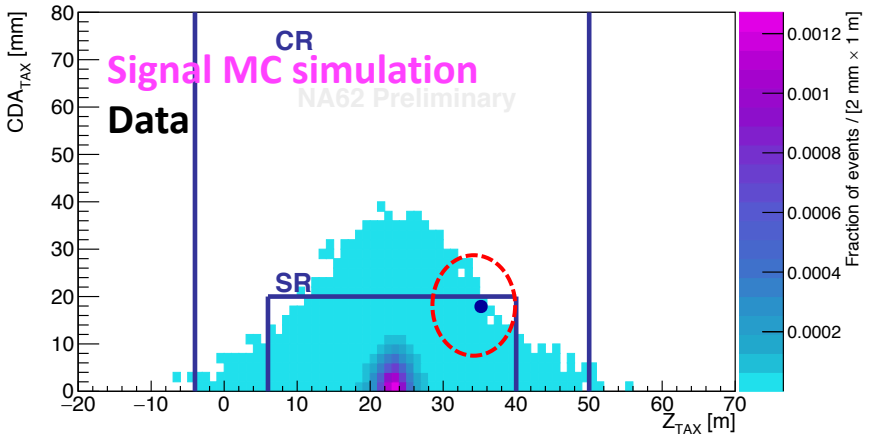
- **Dominant background from random superposition of two uncorrelated muons**
- Studied with dedicated sample in different control regions

	$N_{exp} \pm \delta N_{exp}$	N_{obs}
Outside CR	26.3 ± 3.4	28
CR1	0.29 ± 0.04	1
CR2	0.58 ± 0.07	1
CR3	1.70 ± 0.22	2
CR1+2+3	2.57 ± 0.33	4
CR	0.17 ± 0.02	0

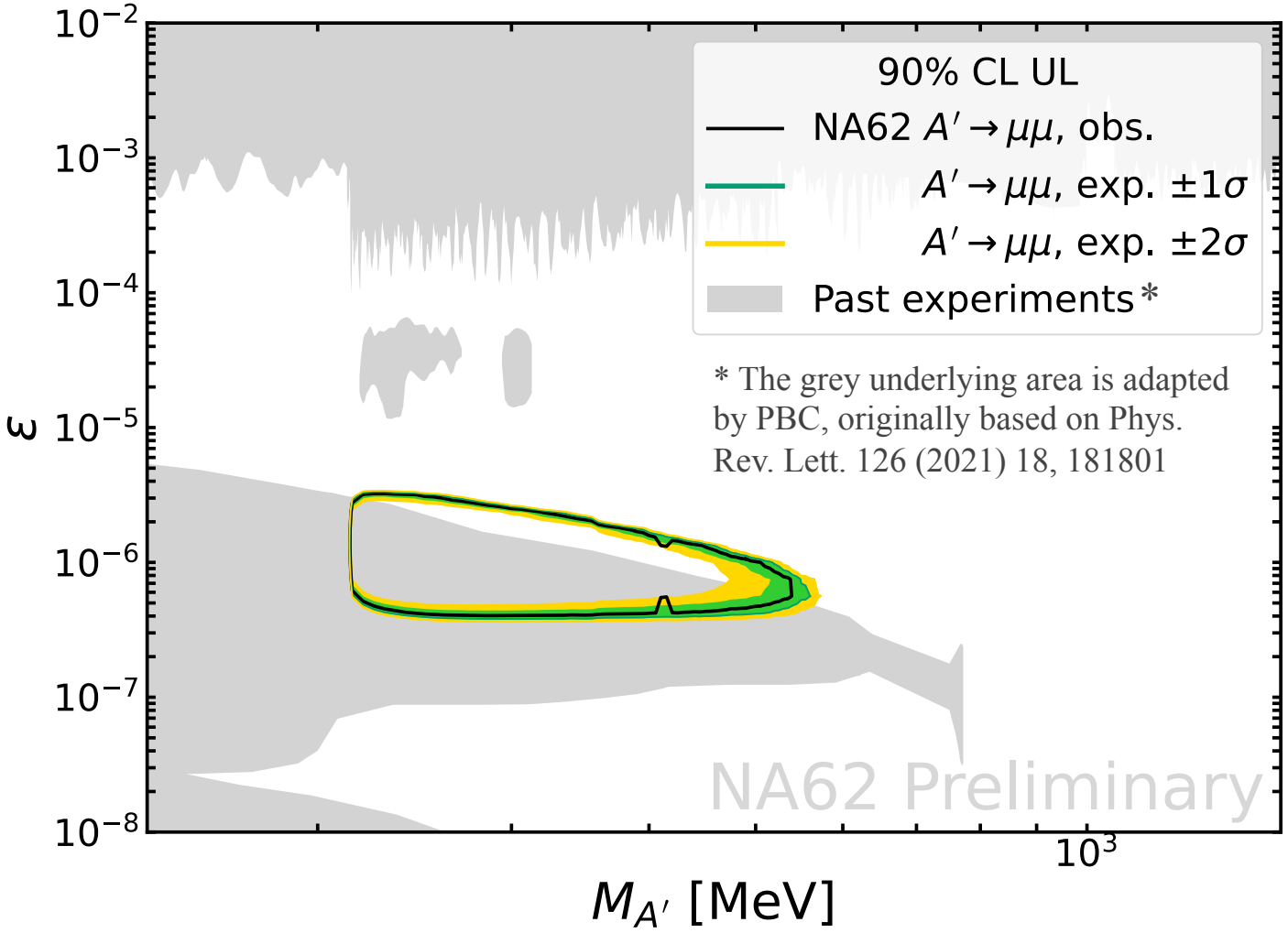
- Probability to observe 1 or more events in SR is 1.59%
- Expected background in SR $N_{\mathrm{bkg}}^{\mathrm{exp}} = 0.016 \pm 0.002$

After SR opened
- **1 events observed**
- Counting experiment with 2.4σ global significance
- Signal shape not taken into account for the significance





$A' \to \mu^+\mu^-$ ANALYSIS IN BEAM DUMP



90% CL upper limit
Region enclosed by the contour is excluded

PAPER IN PREPARATION
AND MANY OTHER RESULTS WILL COME

- searches of exotic particles to $e^+e^-, \gamma\gamma, \pi^+\pi^-\gamma$ and other hadronic final state using 2021 data are ongoing
- 10^{18} POT in beam dump expected in 2022-2025 with interesting perspectives on **dark photon, ALPs, dark scalars and HNLs**

CONCLUSIONS

- **NA62 successfully completed Run1 (2016-2018) data taking**
- Run2 ongoing since last year: broad physics program to be explored
- Plans for longer term high-intensity kaon experiments (HIKE) under preparation

  HIKE LOI CERN-SPSC-2022-031
- **New results presented:**
  - $K^+ \to \pi^+\mu^+\mu^-$ JHEP 11 (2022) 011
  - $K^+ \to \pi^o e^+ \nu\gamma$ (paper in preparation)
  - $K^+ \to \pi^+\gamma\gamma$ (paper in preparation)

    Phys. Lett. B 797 (2019) 134794
    Phys. Lett. B 830 (2022) 137172
    Phys. Rev. Lett. 127 (2021) 12, 131802
  - Lepton Number and Flavor Violation decays $K^+ \to \pi^-(\pi^o)\ell^+\ell^-$, $K^\pm \to \pi^\pm\mu^\mp e^+, \pi^o \to \mu^- e^+$
  - Heavy Neutral Lepton searches $K^+ \to \ell^+ N$, $K^+ \to \mu^+\nu X$, $K^+ \to \mu^+\nu\bar{\nu}\nu$ Phys. Lett. B 807 (2020) 135599
    Phys. Lett. B 816 (2021) 136259
  - Dark Photon search in beam dump mode $A' \to \mu^+\mu^-$ (paper in preparation)


THANK YOU FOR YOUR ATTENTION!