Search for New Physics with NA62

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Les Rencontres de Physique de la Vallée d'Aoste

NA62 experiment

NA62: fixed target experiment at CERN SPS

Technique:
Kaon decays in flight

Timeline:
- 2015: commissioning
- 2016-2018: physics runs

- 2021-2025: physics runs

Primary goal:
Measure BR($K^+ \to \pi^+ \nu\nu$)

ECN3 hall at CERN

NA62 collaboration: ~300 participants, ~30 institutions

NA62 recent results

- $K^+ \to \pi^+ \nu \nu$
  - $BR(K^+ \to \pi^+ \nu \nu)$ JHEP 06 (2021) 93
  - $K^+ \to \pi^+ X$, $X = a, S$ JHEP 03 (2021) 58
- Precision measurements
  - $K^+ \to \pi^+ \mu^+ \mu^-$ JHEP 11 (2022) 011
  - $K^+ \to e^+ \pi^0 \nu \gamma$ JHEP 09 (2023) 040
  - $K^+ \to \pi^+ \gamma \gamma$ PLB 850 (2024) 138513
- LFV/LNV decays
  - $K^+ \to \pi \mu e$ PRL 127 (2021) 131802
  - $K^+ \to \pi^- l^+ l^+$ PLB 797 (2019) 134794; PLB830 (2022) 137172
  - $K^+ \to \pi^- \pi^0 e^+ e^+$ PLB 830 (2022) 137172
  - $K^+ \to \mu^- \nu e^+ e^+$ PLB 838 (2023) 137679
- Search for pair production of hidden sector mediators X = a, S
  - $K^+ \to \pi^+ X X$, $X \to e^+ e^-$ PLB 846 (2023) 138193
- Beam dump searches for DM
  - $A' \to \mu^+ \mu^-$ JHEP 09 (2023) 035
  - $A' \to e^+ e^-$ arXiv: 2312.12055

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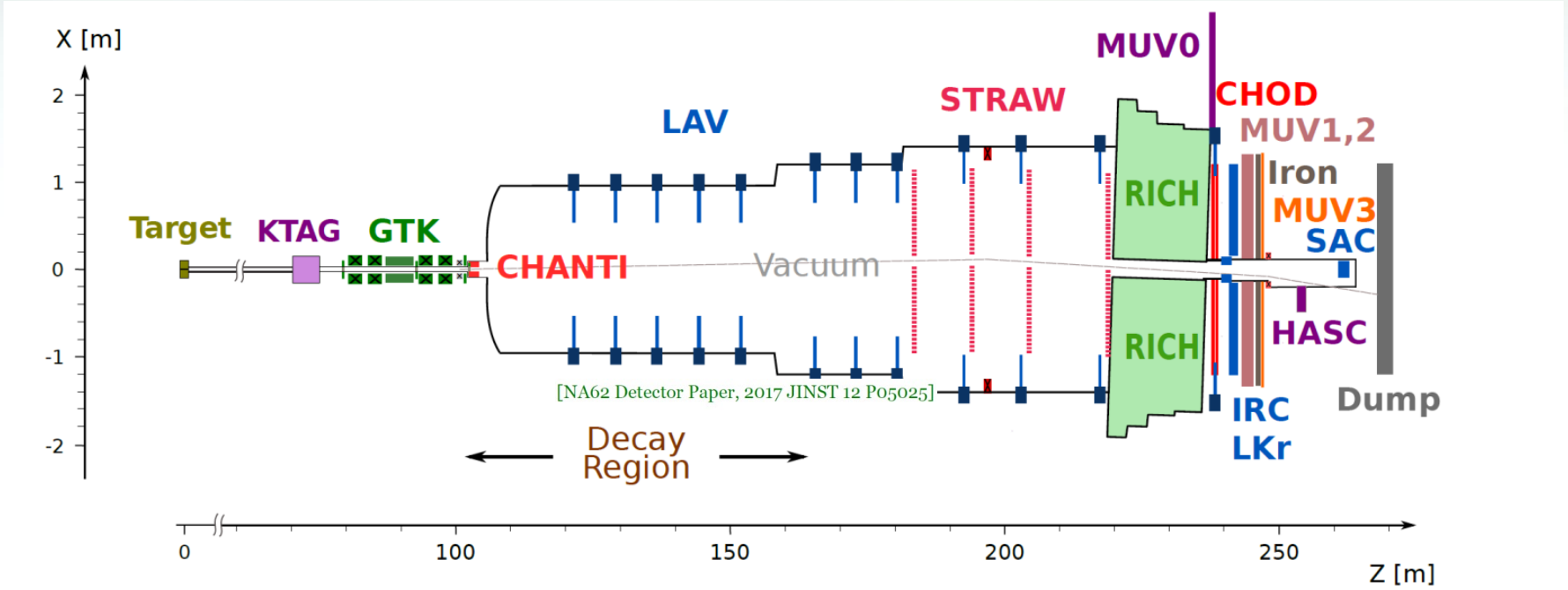
This talk

NA62 in the standard mode

[NA62 Detector Paper, 2017 JINST 12 P05025]

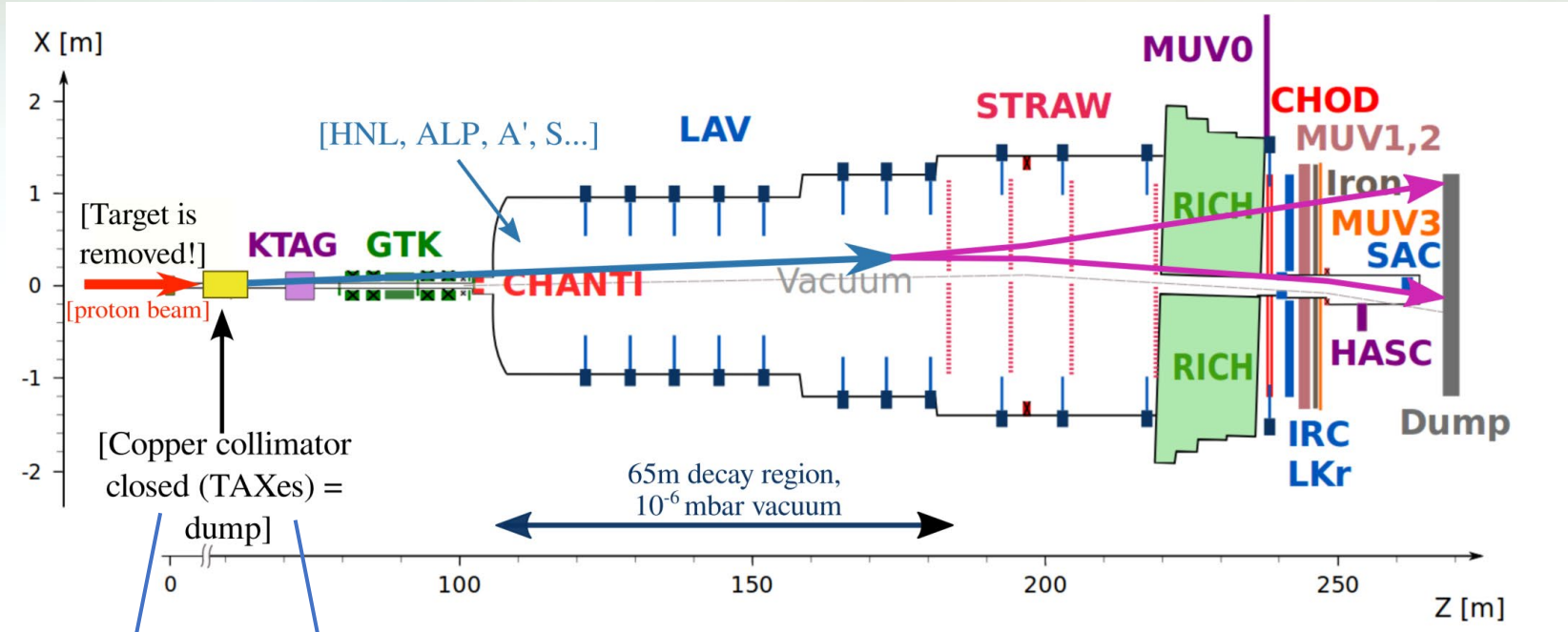


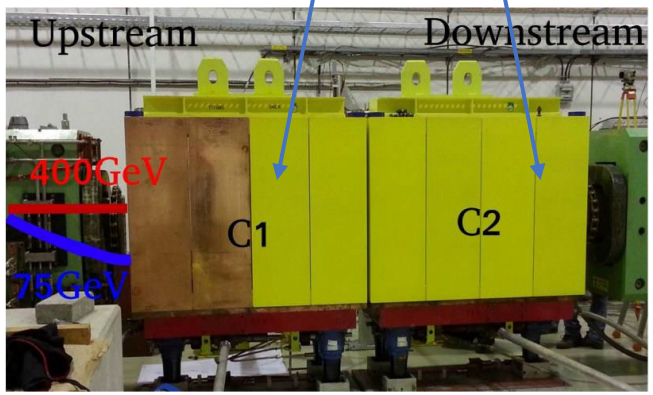
Primary beam:
- 400 GeV/c protons
- 3×10^{12} protons per spill

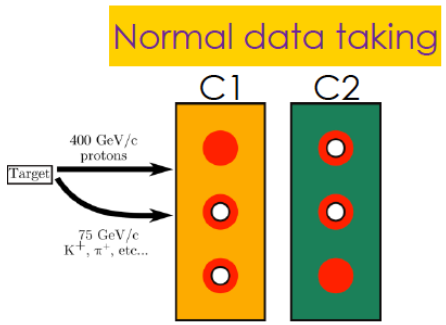
Secondary beam:
- 75 GeV/c (±1%)
- Divergency < 100 μrad
- 70% pions, **6% K^+**, 24% protons

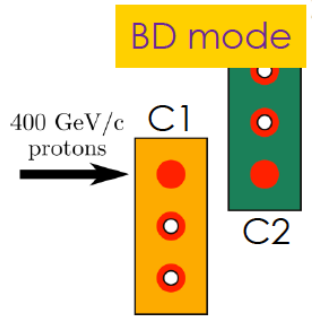
Key detectors:
- PID: KTAG, RICH, LKr, MUV1-2, MUV3
- Momentum: GTK, STRAW
- Time: GTK, KTAG, RICH, CHOD
- Photon veto: LAV, LKr, IRC, SAC

NA62 in the beam dump mode









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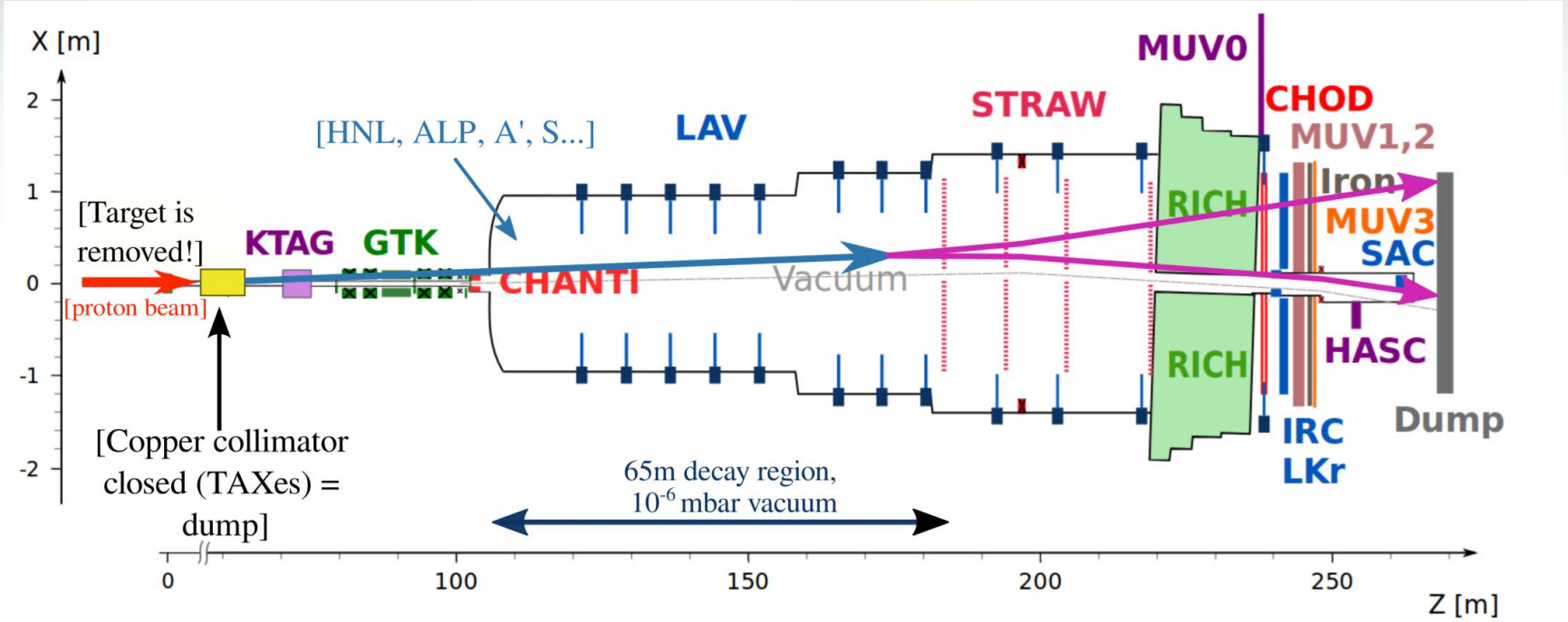


Beam dump prerequisites

- Beam line optimized in 2021 (improved sweeping, higher intensity)
- single and 2-track trigger based on CHOD
- Control trigger based on LKr

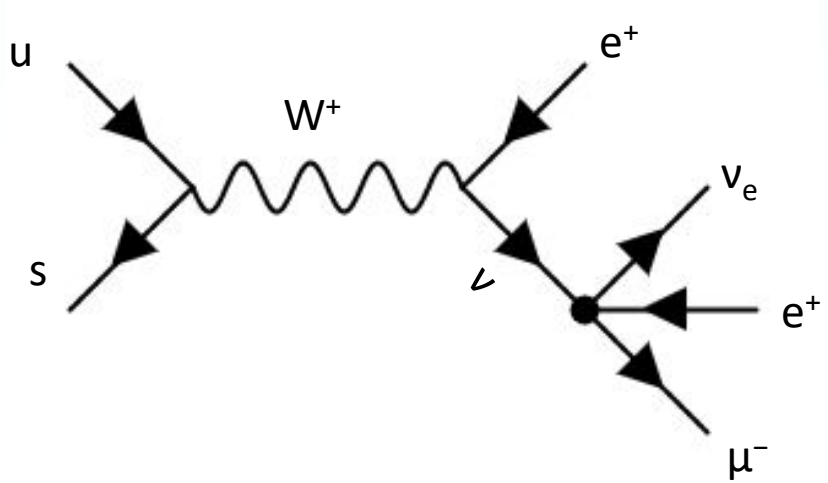
2021 run

- 10 days in beam dump mode
- 3.2 m Cu-Fe collimators (TAXes) used as target
- 1.40 x 10^{17} POT collected

Searches for New Physics in the standard mode

$K^+ \to \mu^- \nu e^+ e^+$ in New Physics

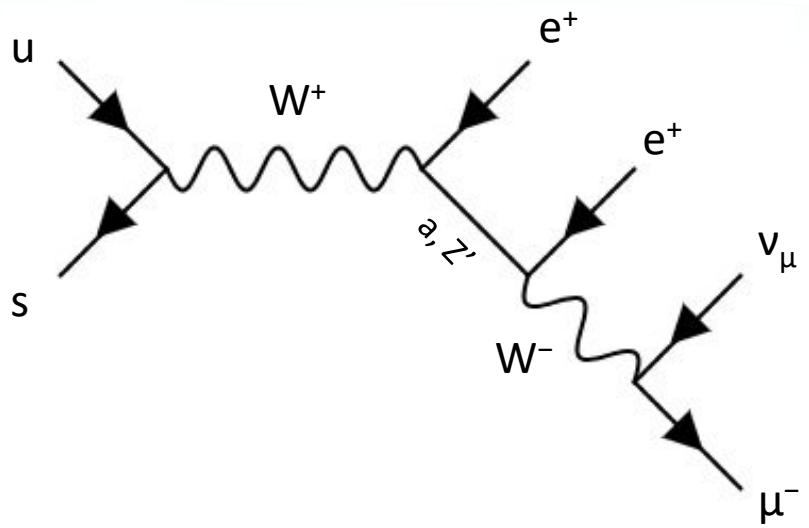
LFV



NP models

- Majorana neutrino

LNV + LFV



NP models

- ALP
- Z’

Search for $K^+ \to \mu^- \nu e^+ e^+$

Data:

- Run 1 (2016-2018)

Main features

- blind analysis
- A(sig) = 1.44%
- $N_K = 1.97(7) \times 10^{12}$ ← Number of K decays in the fiducial volume
- SES = 3.5×10^{-11}

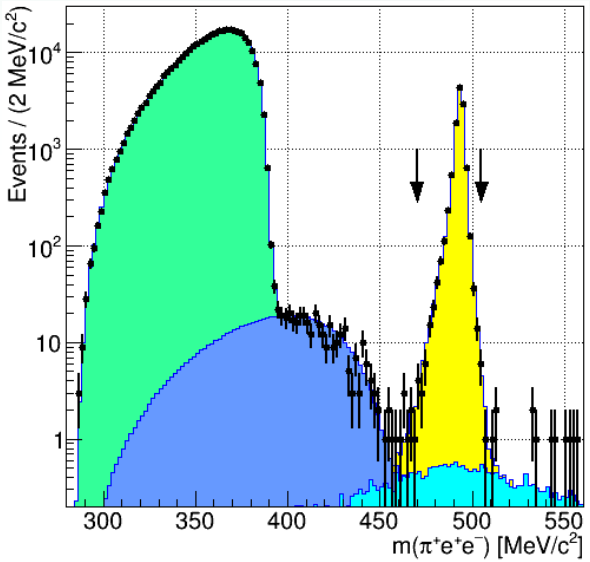
Normalisation:

- $K^+ \to \pi^+ e^+ e^-$
- $N(K^+ \to \pi^+ e^+ e^-) = 21401$

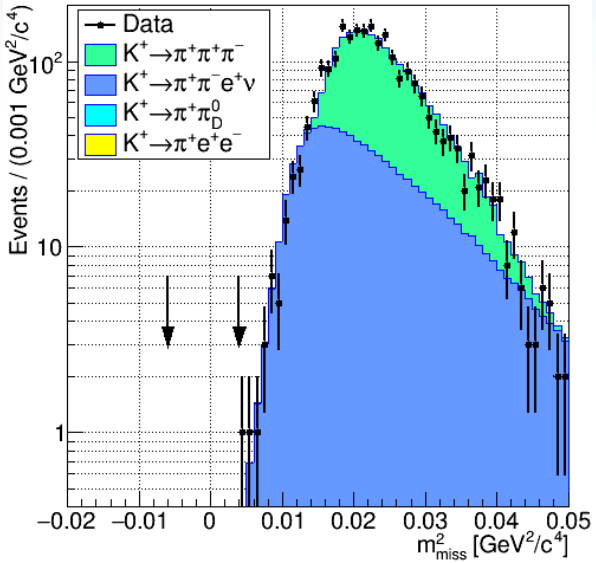
Expected bkg:

- N = 0.26(4)

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



signal: $(P_K - P_{\mu^-} - P_{e^+} - P_{e^+})^2$



SR: $N_{observed} = 0$

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

- Factor of 250 improvement wrt previous limit: $BR < 2.1 \times 10^{-8}$ (90% CL)
- Not sufficient to constrain NP models with Majorana neutrinos, ALP and Z'

$K^+ \to \pi^+ e^+ e^+ e^- e^-$ in the Standard Model

$K^+ \to \pi^+ \pi^0$, $\pi^0 \to \gamma\gamma$, $\gamma \to e^+ e^-$

- $(\pi^+ e^+ e^- e^+ e^-)$ final signature
- $m(e^+ e^- e^+ e^-) = m(\pi^0)$
- BR = $(6.9 \pm 0.3) \times 10^{-6}$
- Used for normalization

Dominant amplitudes for $K^+ \to \pi^+ e^+ e^- e^+ e^-$ in SM

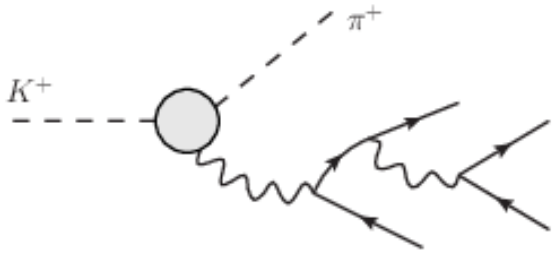
- Outside $m(\pi^0)$ region: one photon exchange
- Near $m(\pi^0)$: resonant two photon exchange

PRD 106 (2022) L071301

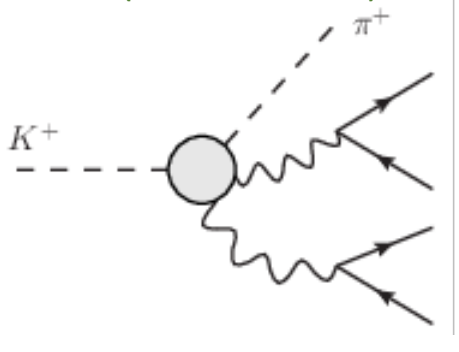
Current analysis

- Resonant two photon exchange suppressed by kinematic cuts
- BR (non-resonant SM, expected) = $(7.2 \pm 0.7) \times 10^{-11}$

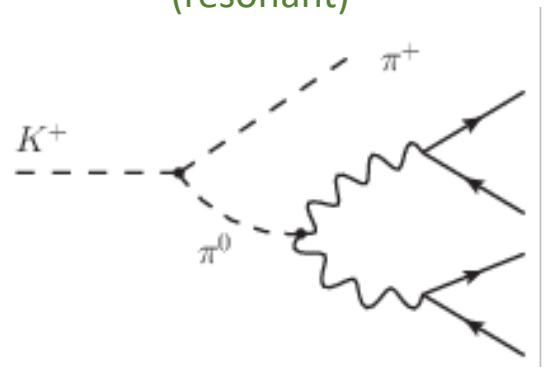
One photon exchange



Two photon exchange (non-resonant)



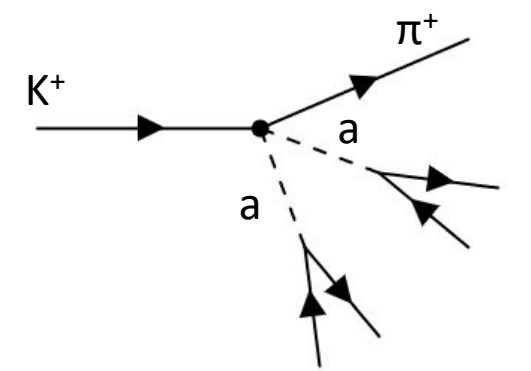
Two photon exchange (resonant)



$K^+ \to \pi^+ e^+ e^+ e^- e^-$ in New Physics

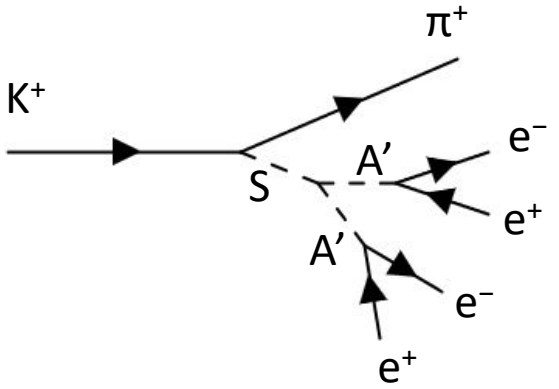
QCD axion a

- $K^+ \to \pi^+ a\ a$, $a \to e^+ e^-$
- Provides explanation for the 17 MeV anomaly: in this case BR($K^+ \to \pi^+ a\ a$) > 2×10^{-8}



Dark scalar S and dark photon A'

- $K^+ \to \pi^+ S$, $S \to A' A'$, $A' \to e^+ e^-$
- $m_S \geq 2m_{A'}$
- A' should decay promptly



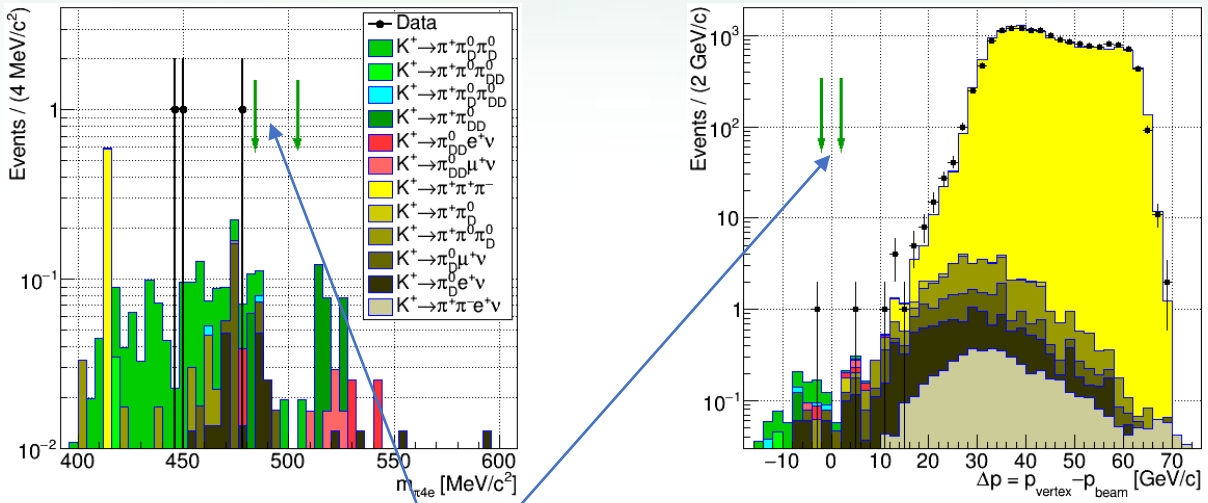
$K^+ \to \pi^+ e^+ e^+ e^- e^-$ analysis strategy

Data:

Run 1 (2017-2018)

Main features

- 5 tracks without PID, just kinematic cuts
- Kinematic variables: $m_{\pi 4e} = m(\pi eeee)$, $\Delta p = p(\pi eeee) - p_K$
- $|m_{eeee} - m_{\pi 0}| > 10$ MeV
- Masked signal region in terms of $m_{\pi 4e}$ and Δp
- $A(sig, SM) = 1.85 \times 10^{-4}$
- $N_K = 8.58(46) \times 10^{11}$



SR: $N_{observed} = 0$

Normalisation:

- $K^+ \to \pi^+ \pi^0$, $\pi^0 \to \gamma\gamma$, $\gamma \to e^+ e^-$
- $|m_{eeee} - m_{\pi 0}| < 10$ MeV
- $N(K^+ \to \pi^+ \pi^0, \pi^0 \to \gamma\gamma, \gamma \to e^+ e^-) = 2023$

Expected bkg:

N = 0.18(6)

$BR(K^+ \to \pi^+ e^+ e^- e^+ e^-) < 1.4 \times 10^{-8}$ (90% CL)

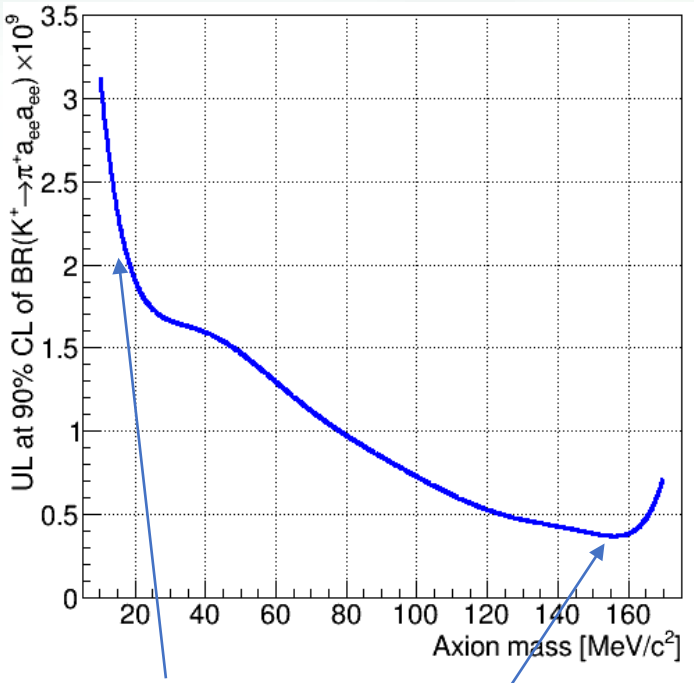
- First upper limit
- Factor of 200 far from BR(SM, expected) = 7.2×10^{-11}

$K^+ \to \pi^+ e^+ e^+ e^- e^-$: NP limits

Mass scan

- Multiple hypotheses tested
- $10 < m_a < 170$ MeV, 5 MeV step
- $20 < m_S < 340$ MeV and $10 < m_{A'} < 170$ MeV, 5 MeV step
- CLs to set UL(BR)

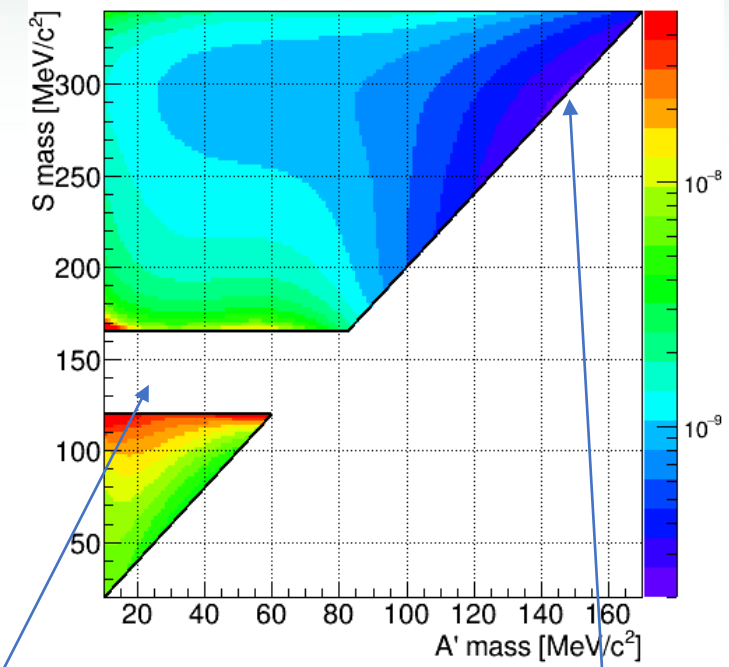
$K^+ \to \pi^+$ a a, a $\to e^+ e^-$



17 MeV anomaly
explanation with QCD axion excluded (UL = 2.1×10^{-9})

Best limit at 155 MeV
UL = 3.7×10^{-10}

$K^+ \to \pi^+$ S, S $\to$ A' A', A' $\to e^+ e^-$



$m_{\pi 0}$ region:

- low acceptance due to $|m_{eeee} - m_{\pi 0}| > 10$ MeV
- Excluded from the search

Best limit at $m_{A'} = 150$ MeV, $m_S = 300$ MeV
UL = 2.5×10^{-10}

Searches for DM in the beam dump mode

DM searches at NA62

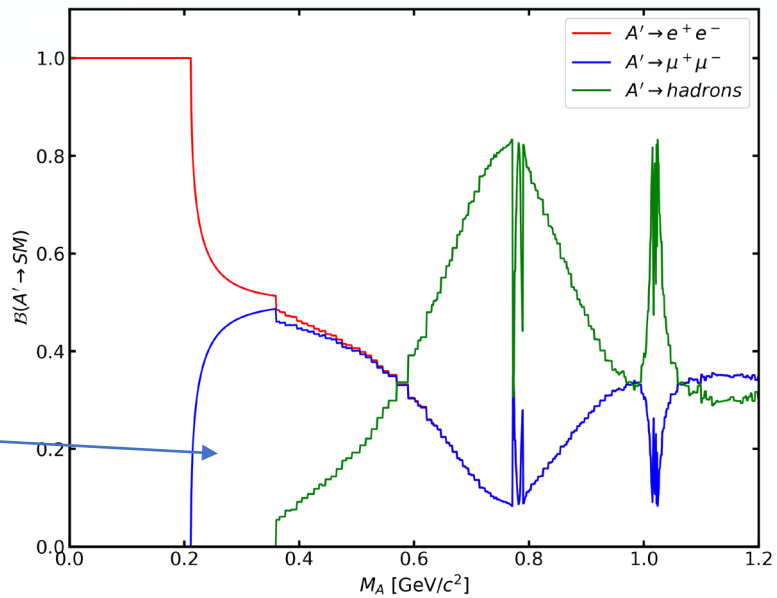
Dark sector portals and mediators

- Vector portal → dark photon
- Scalar portal → dark scalar
- Neutrino portal → HNL
- Axion portal → ALP

Dark photon (DP)

- New vector field $F'_{\mu\nu}$ feebly interacting with SM fields
- Kinetic mixing with the SM hypercharge $B_{\mu\nu}$ $\mathcal{L} \supset -\epsilon \frac{1}{2cos\theta_W} F'_{\mu\nu} B_{\mu\nu}$
- Could decay to SM particles
- m < 600 MeV: decays to leptons dominate

JHEP 06 (2018) 004



DP searches @ NA62

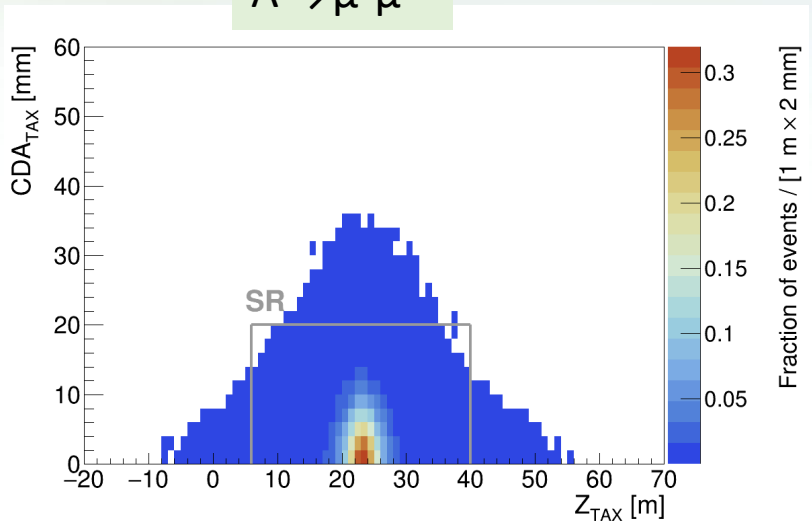
- DP produced in beam-TAX interactions (bremsstrahlung, decays of secondary mesons)
- **Search for DP in decays to a lepton pair**
- Two free parameters: mass and coupling ε
- Sensitive to **m < 600 MeV** (where decays to leptons dominate)

Dark photon search in A'→$\mu^+\mu^-$ and A'→e^+e^-

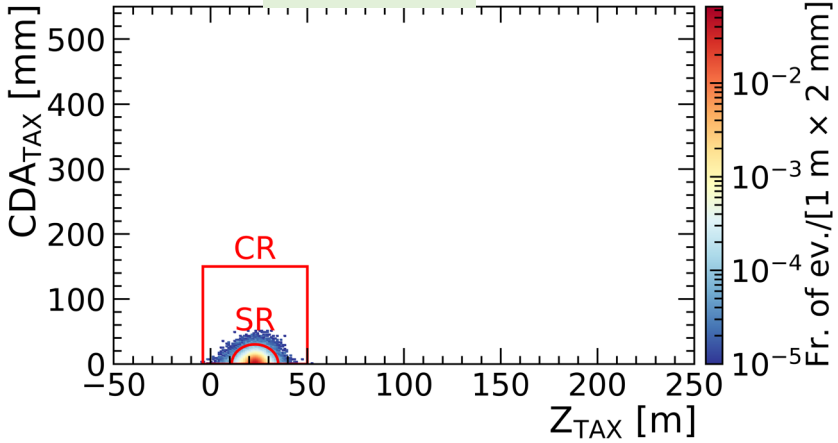
Analysis strategy

- Lepton-antilepton vertex in the NA62 decay region
- Dilepton momentum pointing back to taxes
- Kinematic variables: Z_{tax} and CDA_{tax}
- CDA_{tax}: closest distance of approach between beam and dimuon direction, σ_{CDA} = 7 mm
- Z_{tax}: Z coordinate of the beam-TAX interaction vertex (calculated using CDA), σ_Z= 5.5 m
- Signal region for A'→$\mu^+\mu^-$: 6 < Z_{tax} < 40 m & CDA_{tax} < 20 mm
- Signal region for A'→e^+e^- : ellipse centered around Z_{tax} = 23 m & CDA_{tax} = 0 mm

A'→$\mu^+\mu^-$



A'→e^+e^-



Expected DP yield

$$N_{exp} = \mathrm{POT} \times \chi(pp \to A') \times \mathrm{BR}(A' \to \mu\mu) \times Prd(\epsilon) \times A_{acc} \times A_{trig}$$

- POT = 1.40 x 10^{17}
- $\chi(pp \to A')$: DP production probability
- BR($A' \to \mu\mu$): DP decay branching fraction
- Prd(ϵ) : probability to reach the NA62 decay volume and decay there
- A_{acc}: signal selection efficiency
- A_{trig}: trigger efficiency

Background studies

Combinatorial bkg

- Two uncorrelated “halo” muons
- Dominant for A’→μ⁺μ⁻

Prompt bkg

- Secondaries of a muon interaction with the traversed material
- Dominant for A’→e⁺e⁻

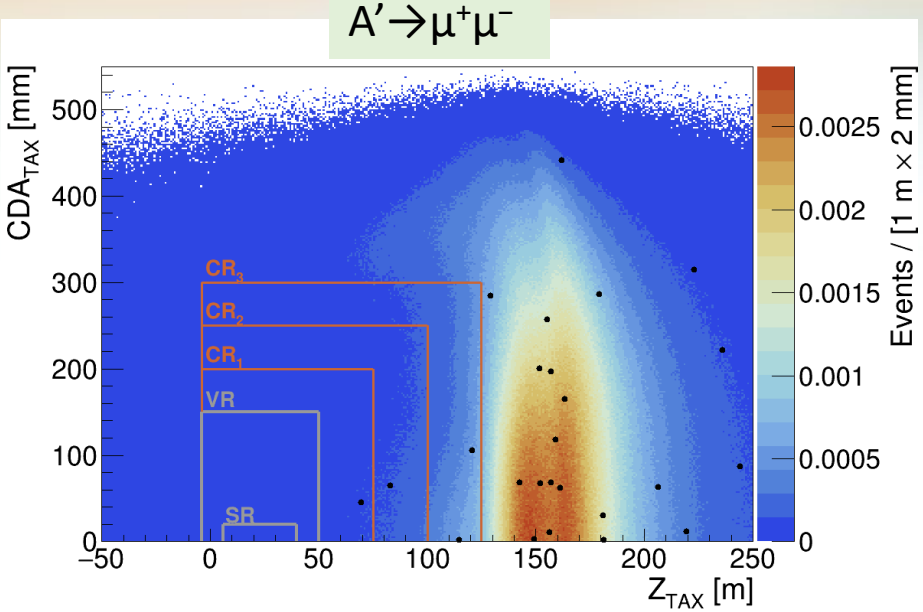
Expected bkg for A’→μ⁺μ−

Region	Combinatorial	Prompt	Upstream-prompt
VR	0.17 ± 0.02	< 0.004	< 0.069
SR	0.016 ± 0.002	< 0.0004	< 0.007

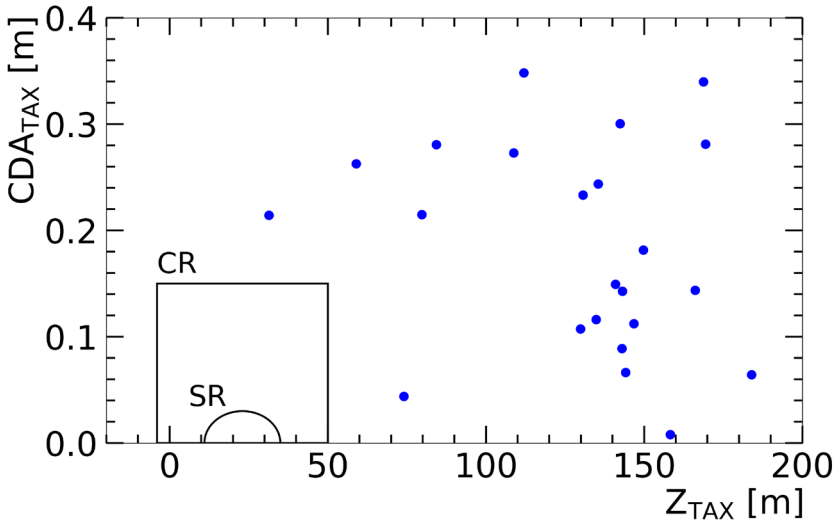
Expected bkg for A’→e⁺e⁻

$$N_{\text{bkg}}^{\text{CR}} = 9.7^{+21.3}_{-7.3} \times 10^{-3},\ N_{\text{bkg}}^{\text{SR}} = 9.4^{+20.6}_{-7.2} \times 10^{-3}$$

A’→μ⁺μ⁻



A’→e⁺e⁻

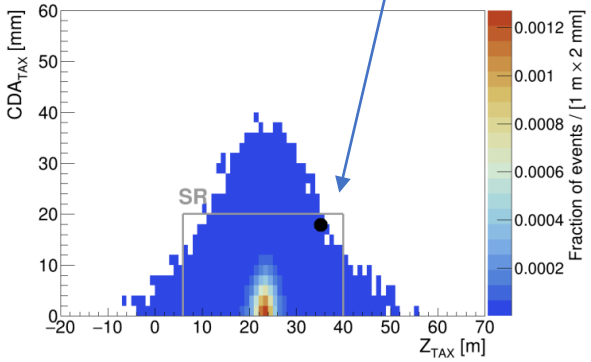


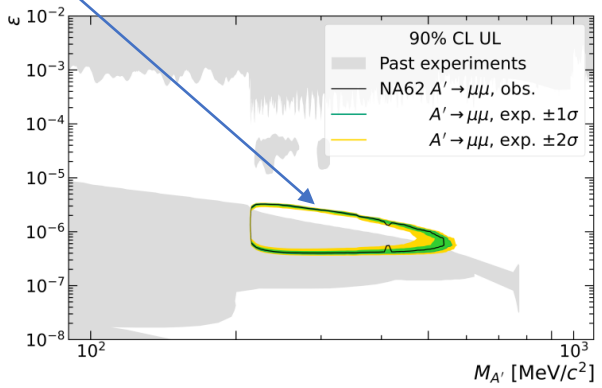
Results on the DP search in A’→l⁺l⁻

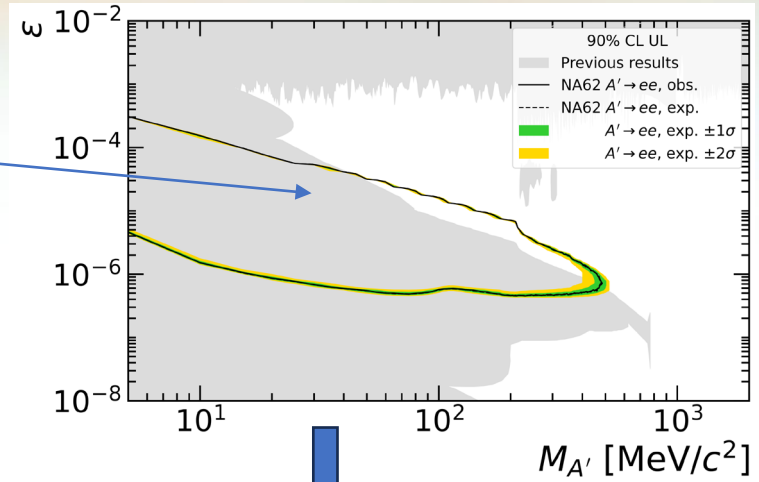
A’→e⁺e⁻ : $N_{obs} = 0$

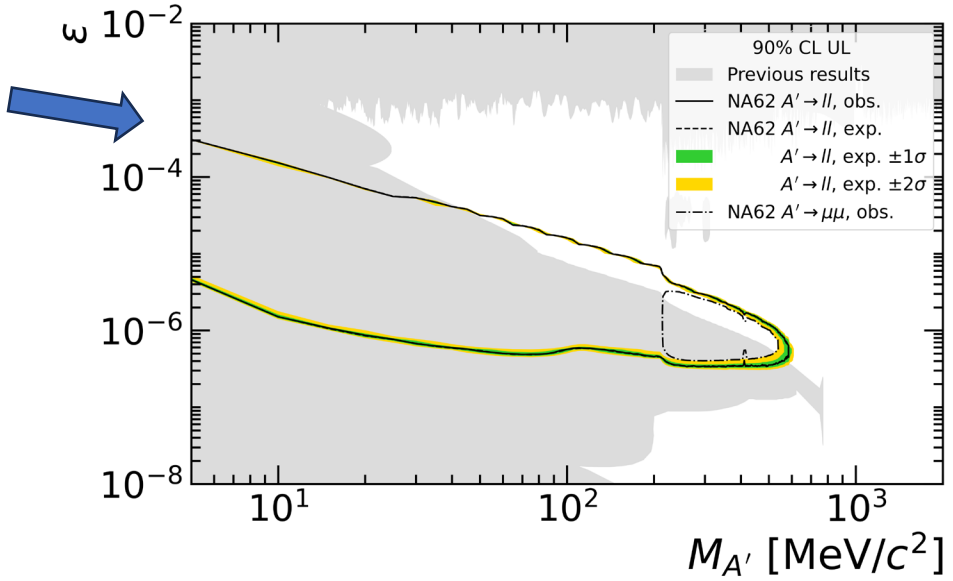
A’→μ⁺μ⁻ : $N_{obs} = 1$ (2.4σ significance)

A’→μ⁺μ⁻





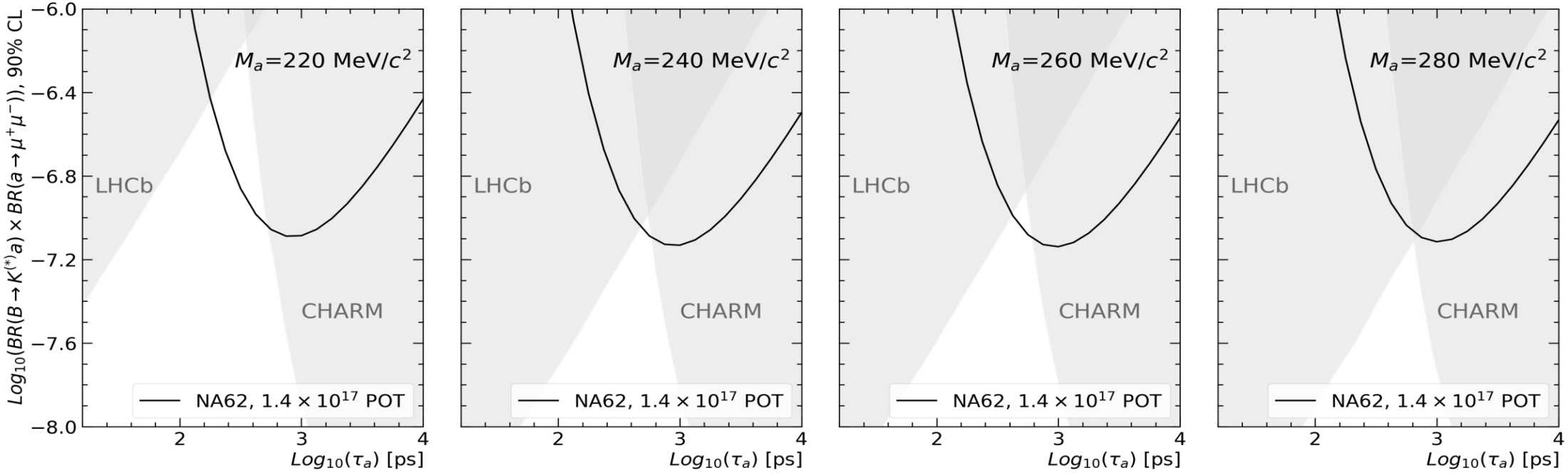




ALP interpretation of $a \to \mu^+\mu^-$

a: (pseudo)scalar produced in B decays

- free parameters: m, τ, coupling
- Set model-independent UL on BR(B→K a)xBR(a→$\mu^+\mu^-$) for each (m, τ) combination



Limits of previous experiments extended for m < 280 MeV

ALP interpretation of $a \to e^+e^-$

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- free parameters: m, τ, coupling
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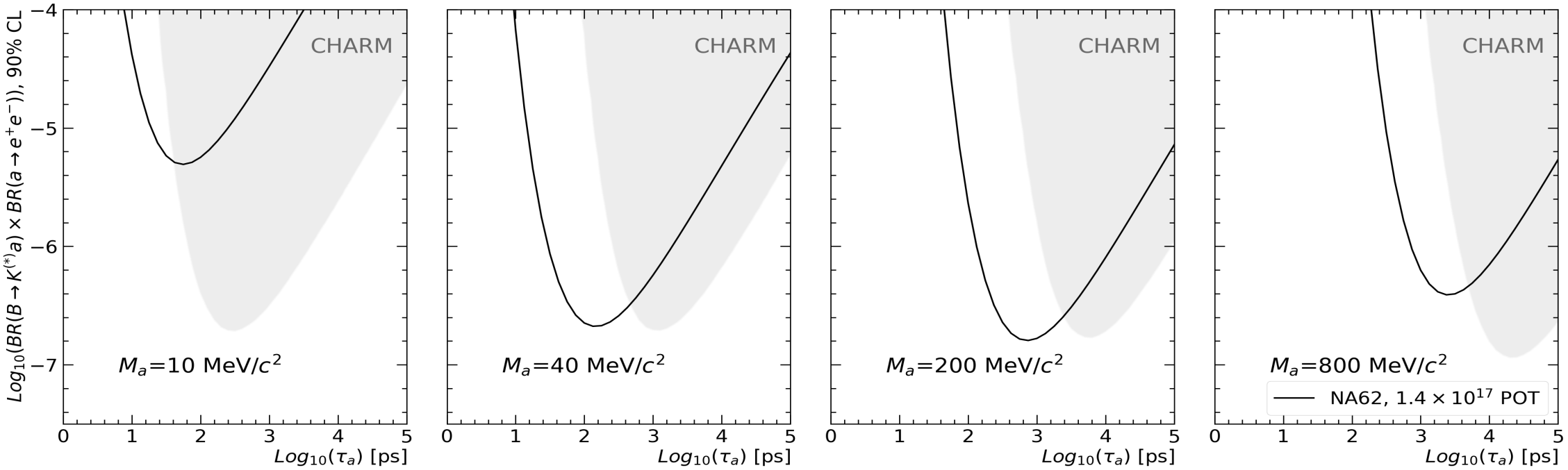


Limits of previous experiments extended for 10 < m < 800 MeV

Conclusions

Search for NP in the standard mode

- $K^+ \to \mu^- \nu e^+ e^+$: UL(BR) < 8.1×10^{-11}, factor of 250 improvement
- $K^+ \to \pi^+ a\, a$, $a \to e^+ e^-$: UL(BR) for $10 < m_a < 170$ MeV, explanation of the 17 MeV anomaly with QCD axion excluded
- $K^+ \to \pi^+ S \to A' A'$, $A' \to e^+ e^-$: UL(BR) for $20 < m_S < 340$ MeV, $10 < m_{A'} < 170$ MeV

Search for NP in the beam dump mode

- NA62 collected 1.40×10^{17} POT in the beam dump mode in 2021
- Dark photon search performed in $A' \to \mu^+\mu^-$ and $A' \to e^+e^-$ decays
- Obtained upper limits exclude new regions in the (ε, m) parameter space

Future plans

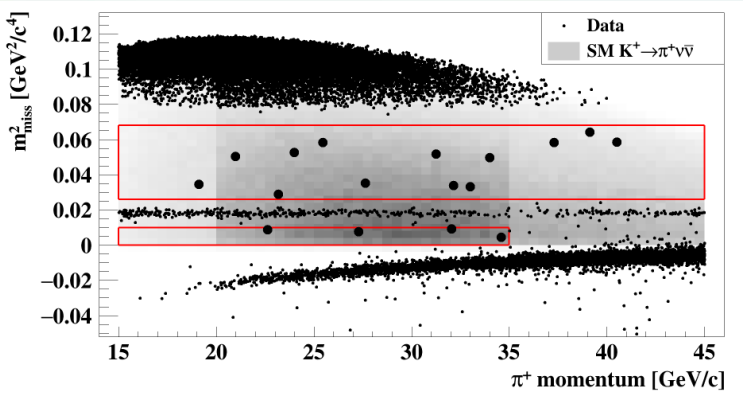
- Collect data in 2024-2025 (both standard and beam dump mode)
- Beam dump data analysis: search for exotic particles decaying to (γ γ), ($\pi^+ \pi^-$ γ) states
- …

Spare

NA62 main goal: BR($K^+ \to \pi^+ \nu\nu$)

Data	N(K decays)	N(K→πνν candidates)	publication
2016	2×10^{11}	1	PBL 791 (2019) 156
2017	2×10^{12}	2	JHEP 11 (2020) 042
2018	4×10^{12}	17	JHEP 06 (2021) 093

2018 data sample

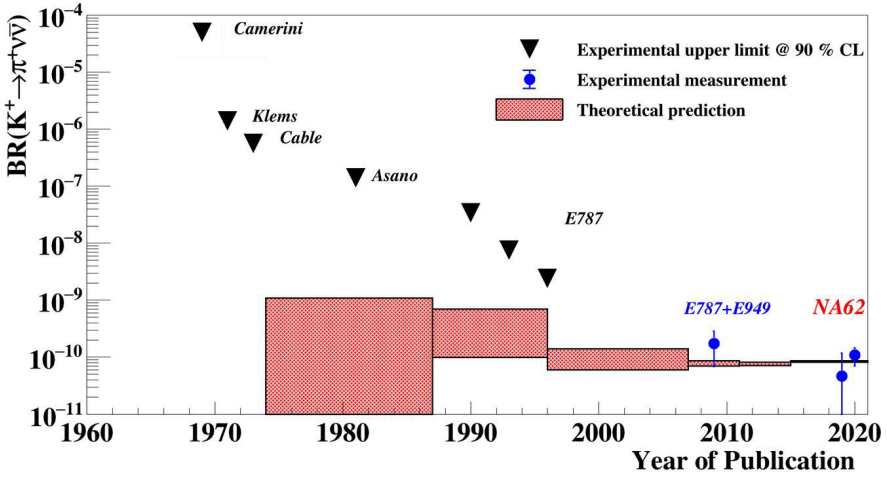


Combined result: JHEP 06 (2021) 93

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11} \text{ at } 68\% \text{ CL}$$

Statistical significance: p = 3.4×10^{-4} (3.4 σ)

First evidence of the decay



Search for $K^+ \to \pi^+ S$

Data:
Run 1 (2016-2018)

Analysis strategy
- Selection, normalisation and bkg evaluation from the πνν analysis
- Signal acceptance: generate MC samples for 200 mass hypotheses
- Shape analysis of the m_{miss}^2 distribution to search for a signal peak

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