Scientific session
of the Nuclear Physics Section
of the Department of Physical Sciences of the RAS

Search for New Physics with NA62

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on behalf of the NA62 Collaboration

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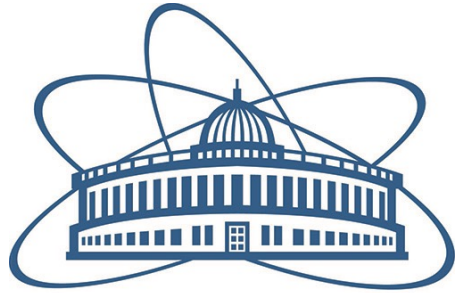

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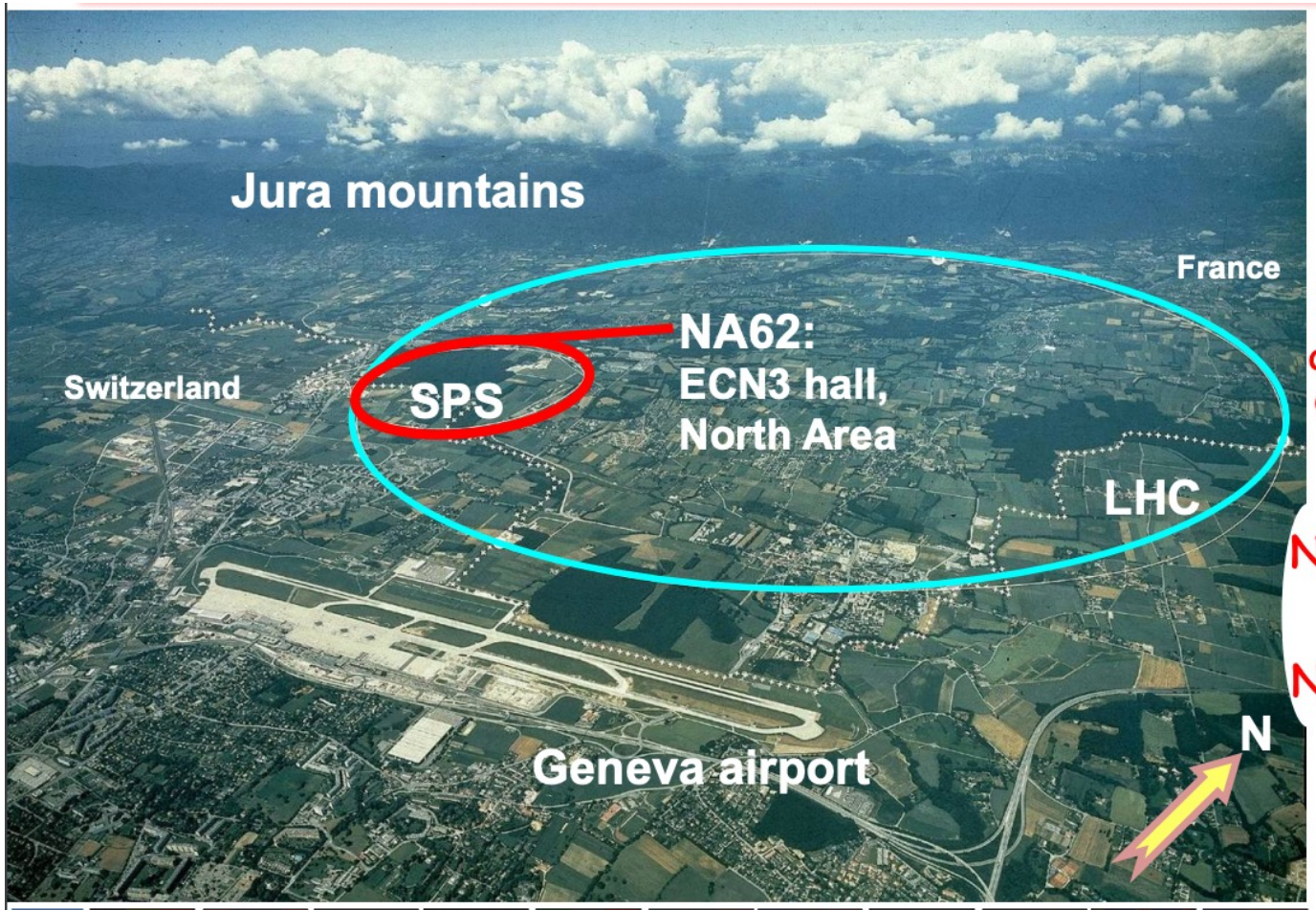
NA62 experiment (decay-in-flight): *charged kaon factory*



Earlier: NA31

NA48 discovery of direct CPV	1997: ε'/ε: K_L+K_S	
	1998: K_L+K_S	
	1999: K_L+K_S	K_S HI
	2000: K_L only	K_S HI
	2001: K_L+K_S	K_S HI
NA48/1	2002: K_S/hyperons	
NA48/2	2003: K^+/K^-	
	2004: K^+/K^-	
NA62 R_K run	2007: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$	tests
	2008: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$	tests
NA62	2015: commissioning	
	2016-18: physics run 1	
	2021-: physics run 2	

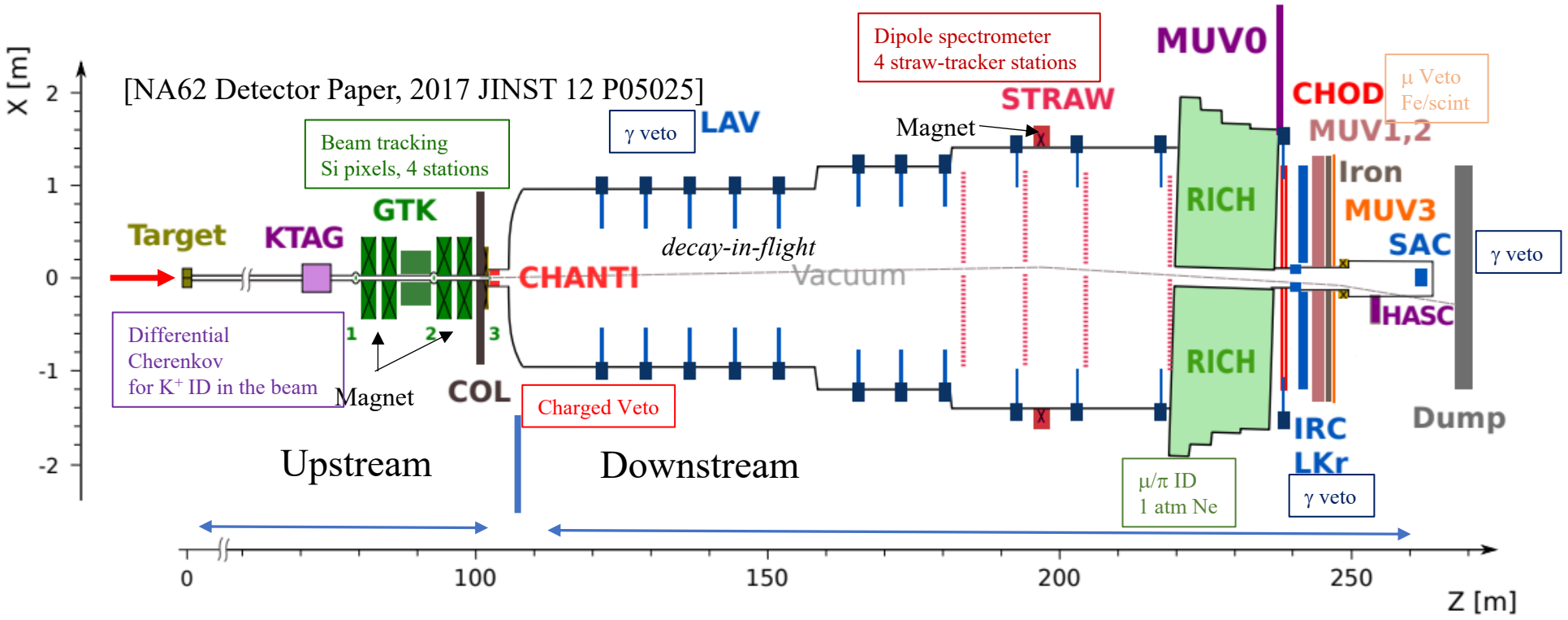
Main NA62 goal: $K^+ \to \pi^+ \nu\nu$ measurement to 10% precision with a novel decay-in-flight technique.

Currently ~300 participants from ~30 institutions.

NA62 in the standard mode

➢**SPS beam**
400 GeV/c protons
3.5s spill

➢**Secondary beam**
75 ± 1 GeV/c momentum
6% K^+ component
60 m long fiducial volume

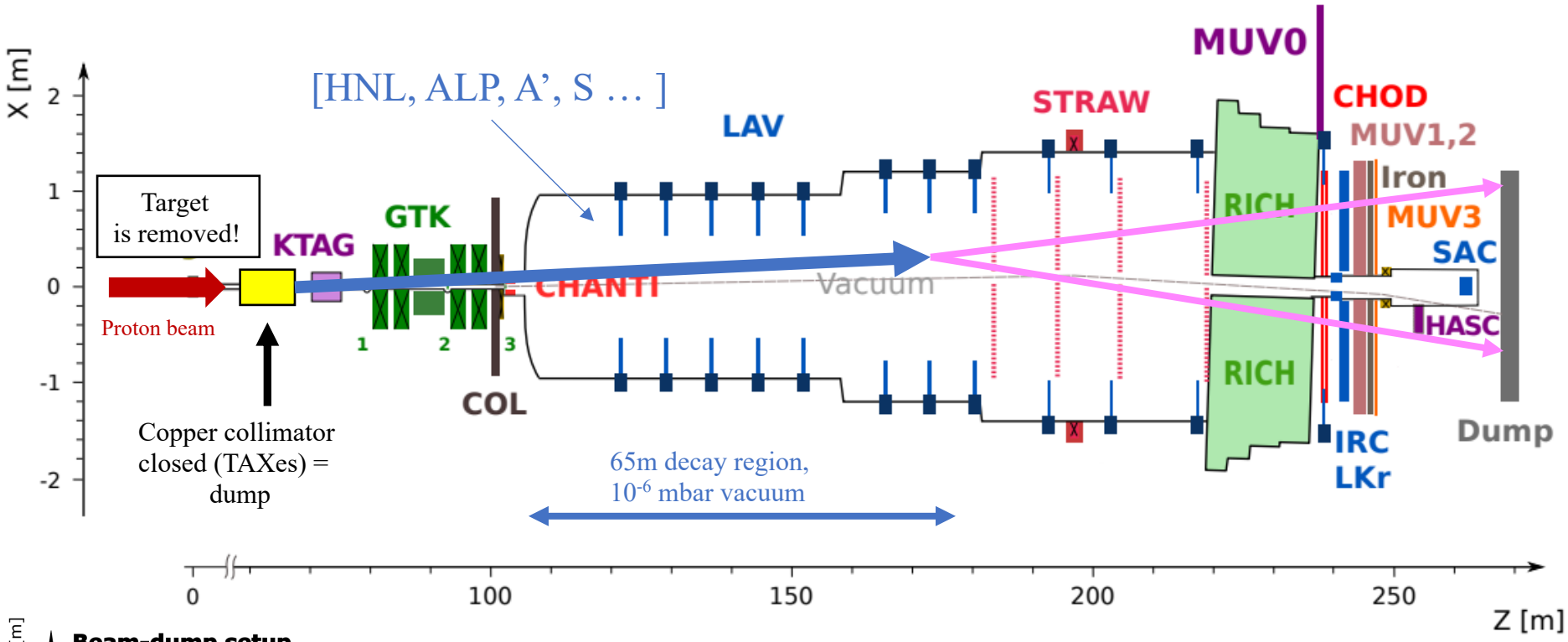


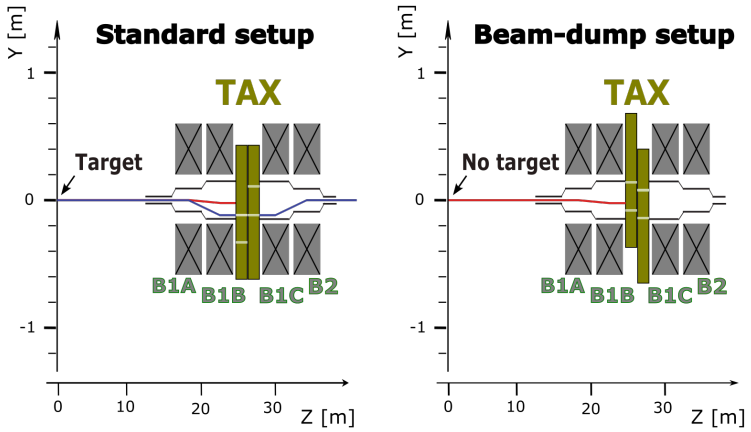
➢**Upstream detectors (K^+)**
KTAG: Differential Cherenkov counter for K^+ ID
GTK: Silicon pixel beam tracker
CHANTI: Anti-counter against inealstic beam-GTK interactions

➢**Downstream detectors (π^+)**
STRAW: track momentum spectrometer
CHOD: scintilator hodoscopes
LKr/MUV1,2: calorimeter system
RICH: Cherenkov counter for π/μ/e ID

NA62 in the beam dump mode

- **SPS beam**
  400 GeV/c protons
  3.5s spill





Beam dump prerequisites:

- Beam line optimized in 2021 (improved sweeping, higer 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 colliamtors (TAXes) used as target
- 1.4 x 10^{17} POT collected

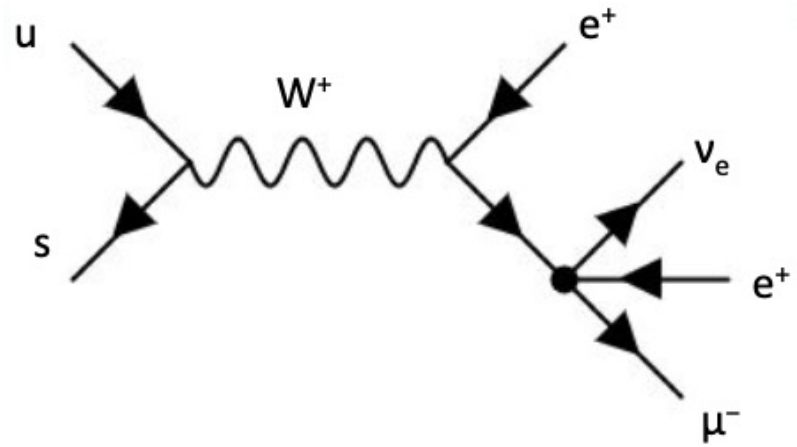
NA62 recent results

- **Main goal:**
- $K^+ \to \pi^+ \nu\bar{\nu}$ process → D. Madigozhin's talk [JHEP 06 (2021) 093; JHEP 03 (2021) 58]
- **Precision measurements of the rare decays:**
- $K^+ \to \pi^+ \mu^+ \mu^-$ [JHEP 11 (2022) 011]
- $K^+ \to e^+ \pi^0 \nu\gamma$ [JHEP 09 (2023) 040]
- $K^+ \to \pi^+ e^+ e^- e^+ e^-$ [PLB 846 (2023) 138193]
- $K^+ \to \pi^+ \gamma\gamma$ [PLB 850 (2024) 138513]
- ***LFV/LNV* processes:**
- $K^+ \to \pi \mu e$ [PRL 127 (2021) 131802]
- $K^+ \to \pi^- l^+ l^-$ [PLB 797 (2019) 134794; PLB 830 (2022) 137172]
- $K^+ \to \pi^- \pi^0 e^+ e^+$ [PLB 830 (2022) 137172]
- $K^+ \to \mu^- \nu e^+ e^+$ [PLB 838 (2023) 137679]
- **Beam dump searches for DM:**
- $A' \to \mu^+ \mu^-$ [JHEP 09 (2023) 035]
- $A' \to e^+ e^-$ [arXiv: 2312.12055]
- **Search for pair production of hidden sector meadiators X = a, S**
- $K^+ \to \pi^+ X X$, $X \to e^+ e^-$ [PLB 846 (2023) 138193]

➢ Searches for New Physics in the standard mode

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

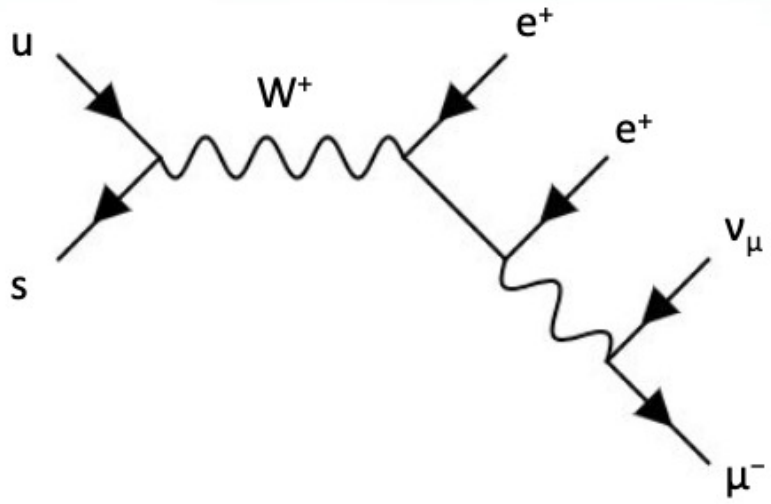
LFV



NP models:

- *Majorana* neutrino

LNV+LFV



NP models:

- ALP
- Z'

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

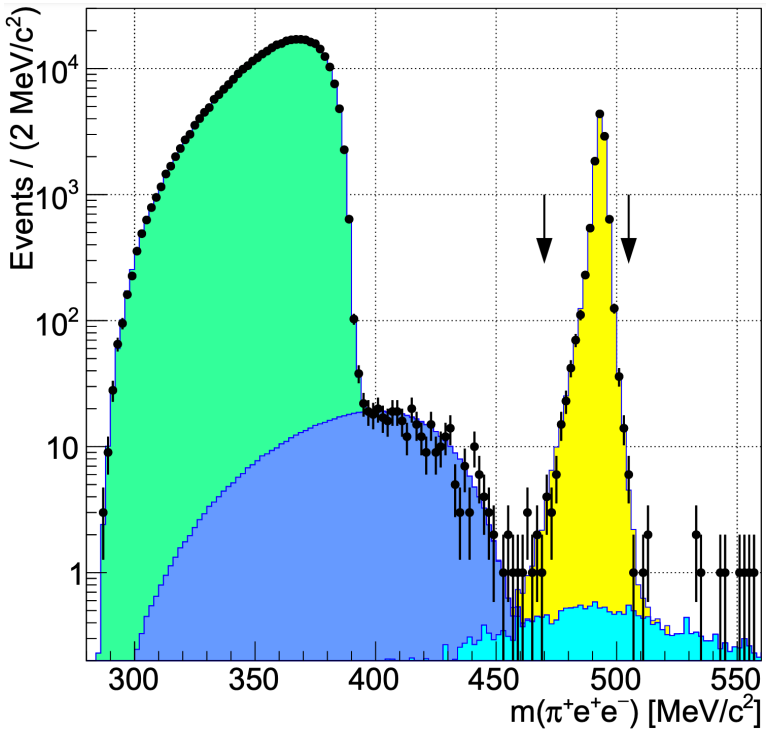
Data:
Run 1 (2016-2018)

Main features:
- Blind analysis
- $A(sig) = 1.44\%$
- $N_K = 1.97(7)\times10^{12}$
- $SES = 3.5\times10^{-11}$

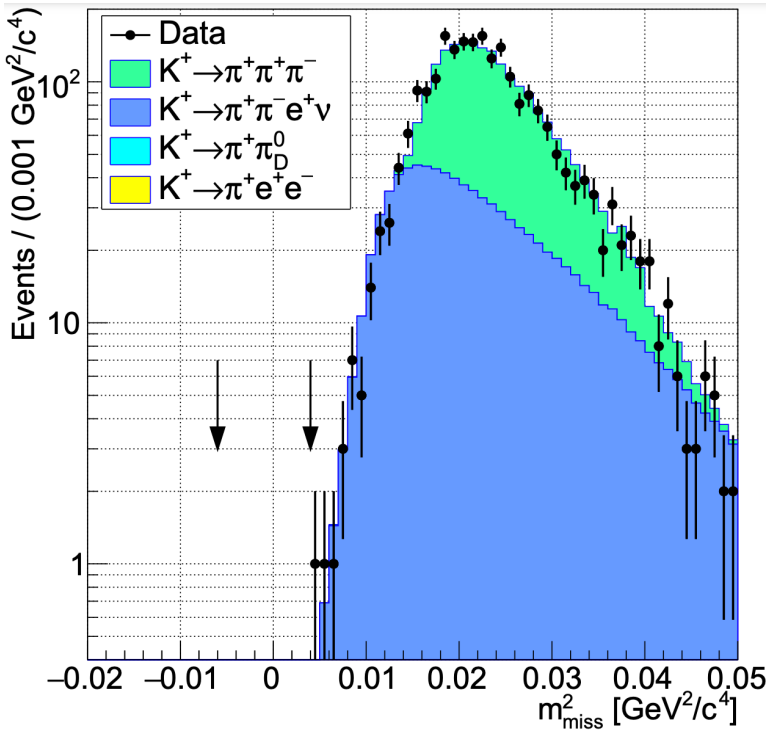
Normalisation:
- $K^+ \to \pi^+ e^+ e^-$
- $\mathrm{N}(K^+ \to \pi^+ e^+ e^-) = 10975$

Expected background:
N = 0.26(4)

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



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



SR: $N_{observed} = 0$

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

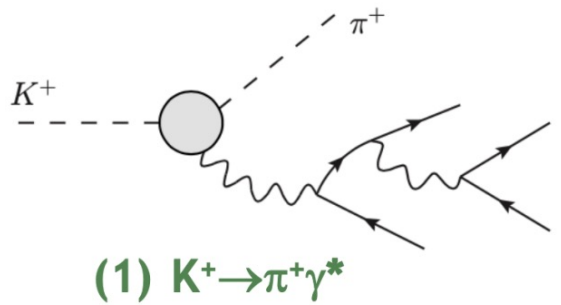
- Factor of 250 improvement wrt previous limit: $Br < 2.1\times10^{-8}$ (90% CL)
- Not sufficient to constrain *NP* modes with *Majorana* neutrinos, *ALP and* Z'

[PLB 838 (2023) 137679]

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

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

- $(\pi^+e^+e^+e^-e^-)$ final signature
- M$(e^+e^+e^-e^-)$ = M(π^0)
- $Br = (6.9 \pm 0.3)\times10^{-6}$
- Used for normalization

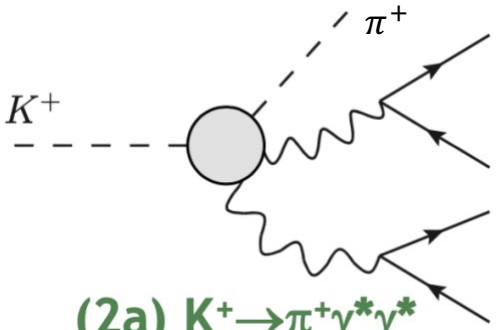


(1) $K^+ \to \pi^+\gamma^*$

One photon exchange

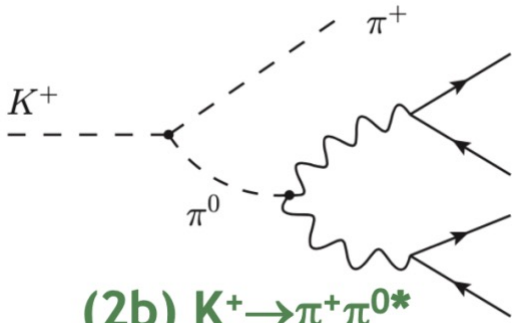
Dominant amplituted for $K^+ \to \pi^+e^+e^+e^-e^-$ in SM

- Outside M(π^0) region: one photon exchange
- Near M(π^0): resonant two photon exchange



(2a) $K^+ \to \pi^+\gamma^*\gamma^*$

Two photon exchange (non-resonant)



(2b) $K^+ \to \pi^+\pi^{0*}$

Two photon exchange (resonant)

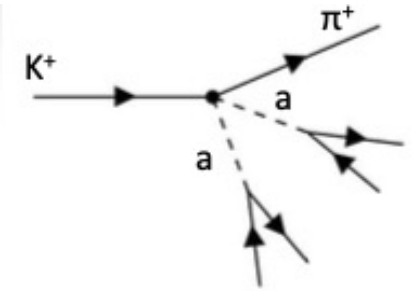
Current analysis:

- Resonant two photon exchange suppressed by kinematic cuts
- $Br(non-resonant\ SM, expected) = (7.2 \pm 0.7)\times10^{-11}$

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

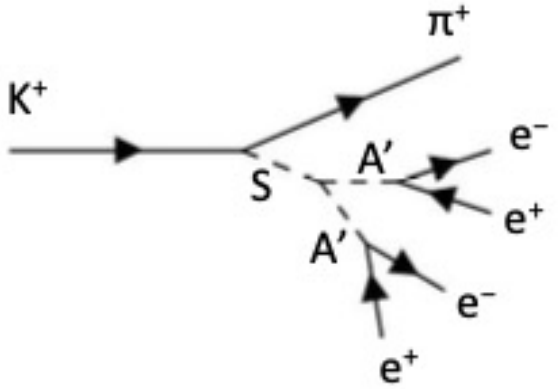
QCD axion a

- $K^+ \rightarrow \pi^+ a\, a, a \rightarrow e^+ e^-$
- Provides explanation for the 17 MeV anomaly:
  - In this case $Br(K^+ \rightarrow \pi^+ a\, a) > 2 \times 10^{-8}$



Dark scalar S and dark photon A'

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



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

Data:

Run 1 (2017-2018)

Main features:

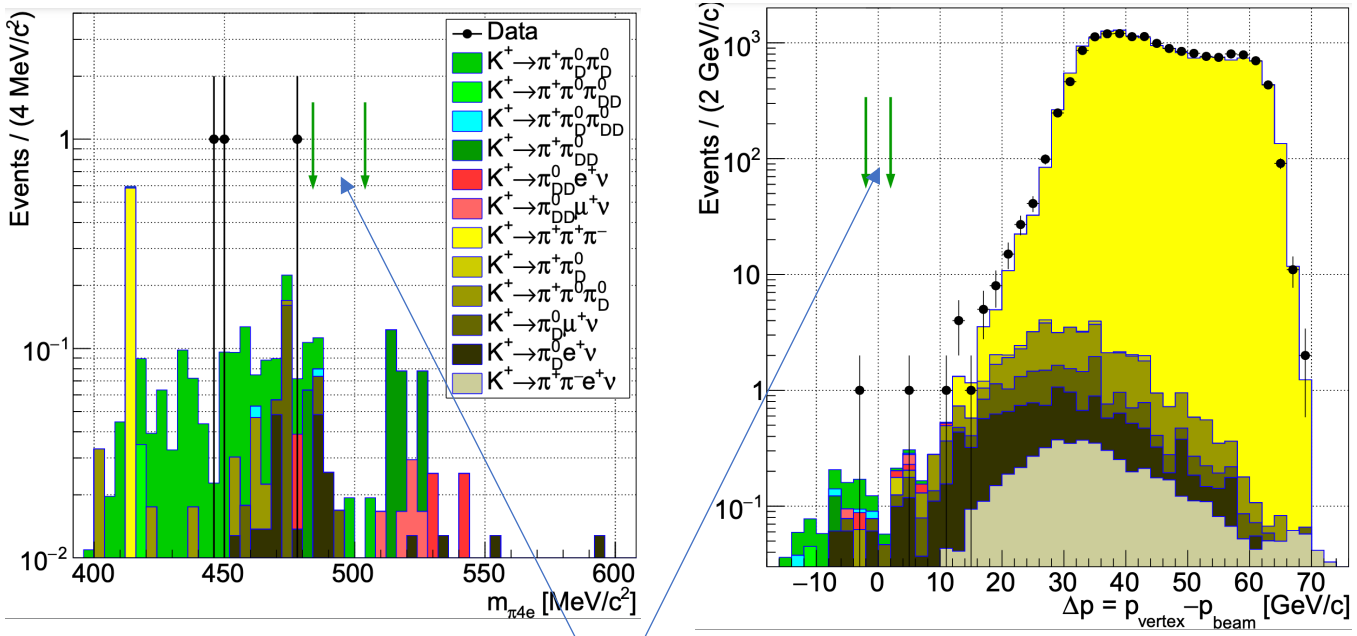
- 5 track without PID, just kinematic cuts
- Kinematic variables:
  $m_{\pi 4e} = m(\pi eeee), \Delta\, p = p(\pi eeee) - p_K$
- $|\, m_{eeee} - m_{\pi^0}| > 10\ MeV$
- Masked signal region in terms of $m_{\pi 4e}$ and $\Delta\, p$
- $A(sig, SM) = 1.85 \times 10^{-4}$
- $N_K = 8.58(46) \times 10^{11}$

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 background:

- N = 0.18(6)



SR: $N_{observed} = 0$

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

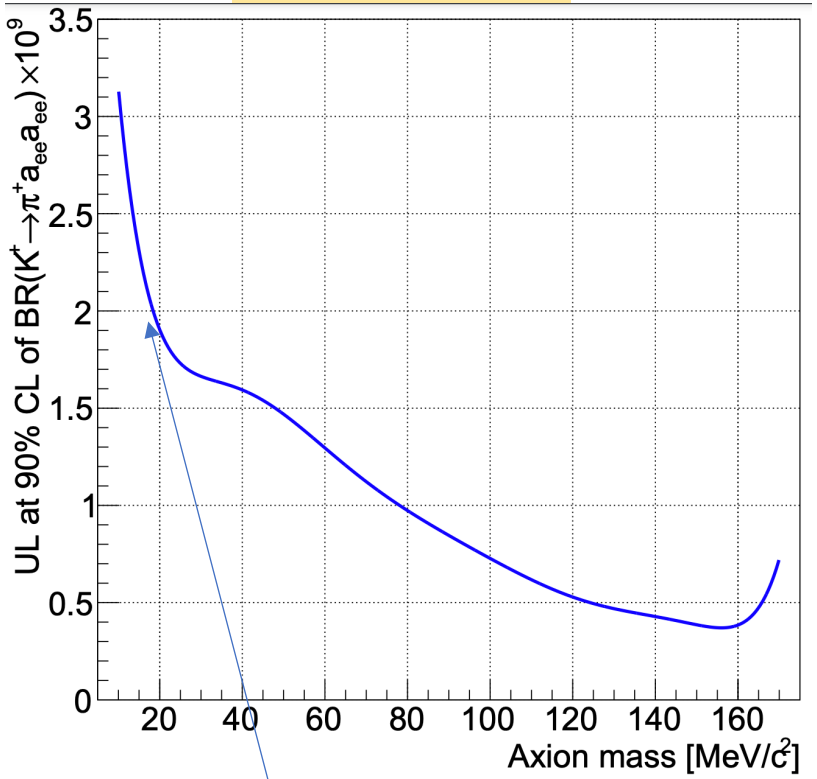
- First upper limit
- Factor of 200 far from $Br(SM, expected) = 7.2 \times 10^{-11}$

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

Mass scan:

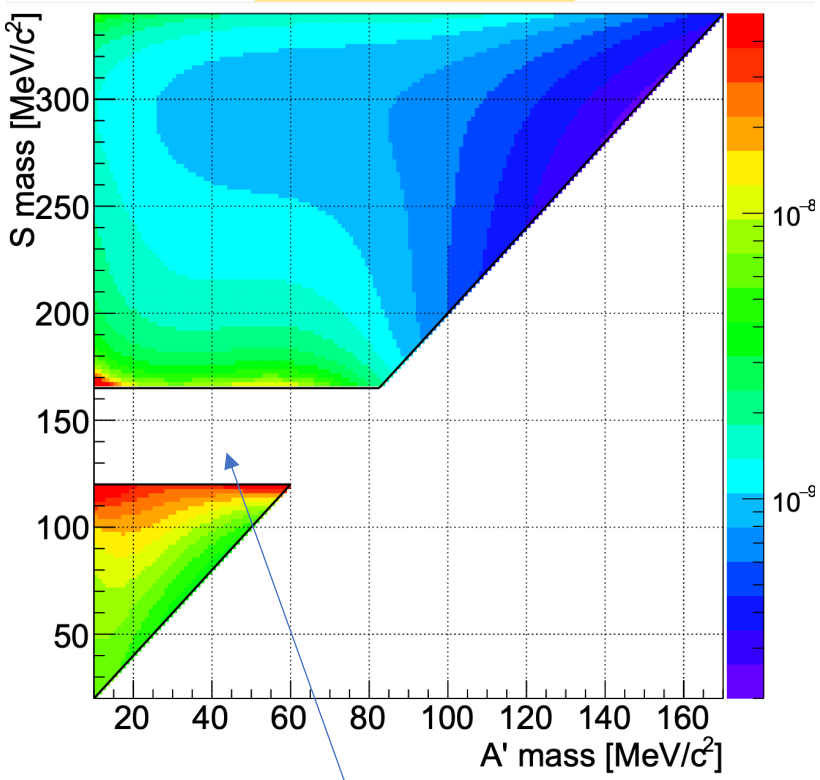
- Multiple hypotheses tested
- $10 < m_a < 170\ MeV, 5\ MeV\ step$
- $20 < m_S < 340\ MeV$ *and*
  $10 < m_{A'} < 170\ MeV, 5\ MeV\ step$
- CLs to set $UL\ (Br)$

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



17 MeV anomaly
Explanation with QCD axion excluded

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



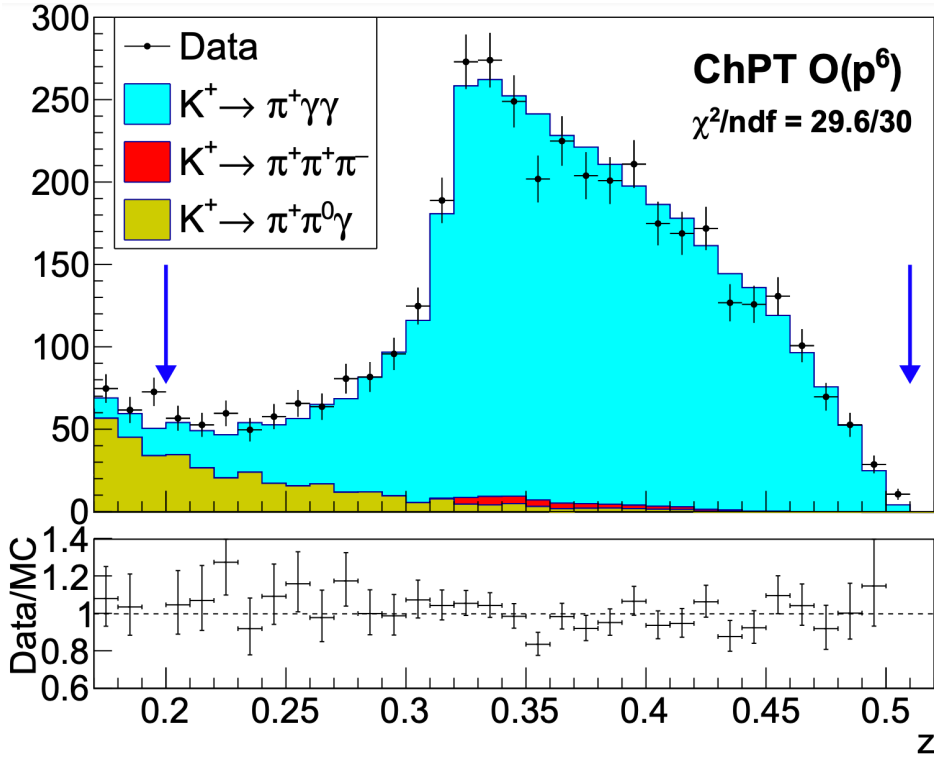
$m_{\pi^0}\ region$:

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

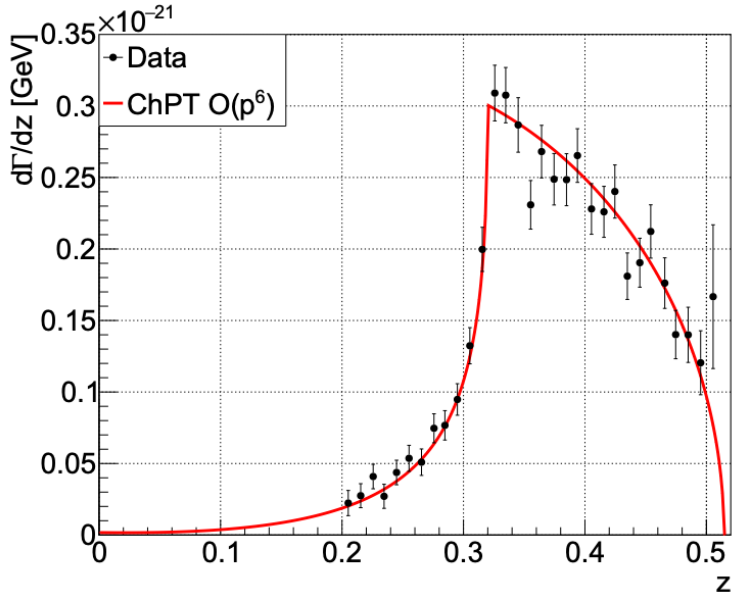
[PLB 846 (2023) 138193]

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

- Rare decay that allows ChPT tests at $O(p^6)$
- Main kinematic variable: $z = \frac{m^2_{\gamma\gamma}}{m^2_K}$, $y = \frac{P_K \times (Q_{\gamma_1} - Q_{\gamma_2})}{m^2_K}$
- $Br(K^+ \to \pi^+\gamma\gamma)$ at $O(p^6)$ parametrized by a real parameter $\hat{c}$

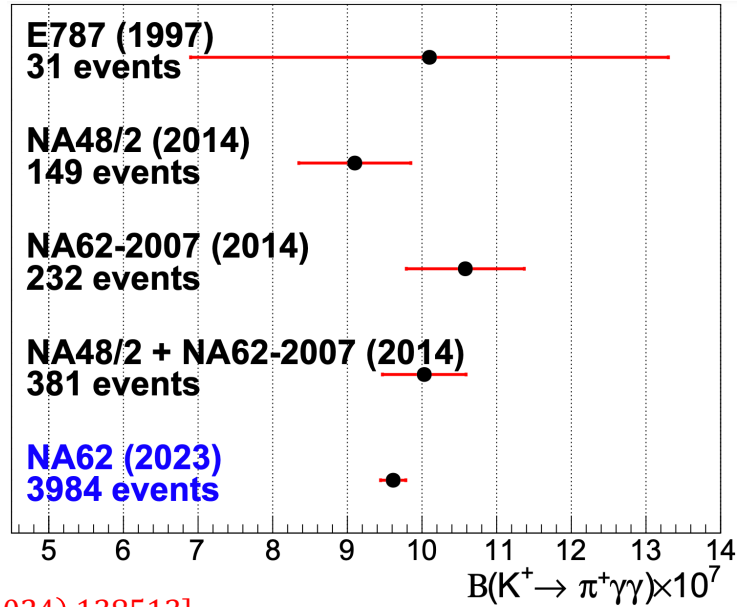


After signal selection:
N_{obs} = 3984 events
N_{bg}^{exp} = 291±14 events



$$B_{\pi\gamma\gamma} = (9.61 \pm 0.15_{stat} \pm 0.07_{syst}) \times 10^{-7}$$

Improved precision, by a factor > 3, statistically dominated



The parameter $\hat{c}$ is measured in the $ChPT\ O(p^4) and\ O(p^6)$ descriptions by performing a $minimum - \chi^2$ fit of $K^+ \to \pi^+\gamma\gamma$ MC to data:

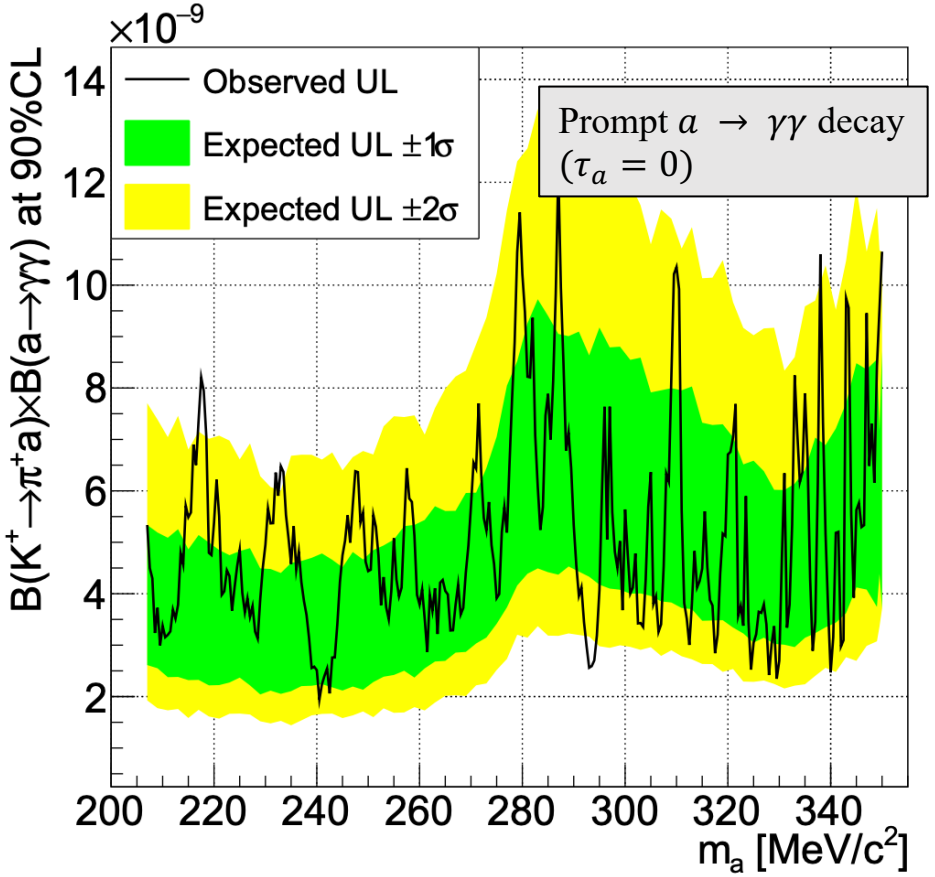
- $ChPT\ O(p^4)\ p-value$: 2.7×10^{-8} → not sufficient to describe the di-photon mass spectrum
- $ChPT\ O(p^6)\ p-value$: 0.49

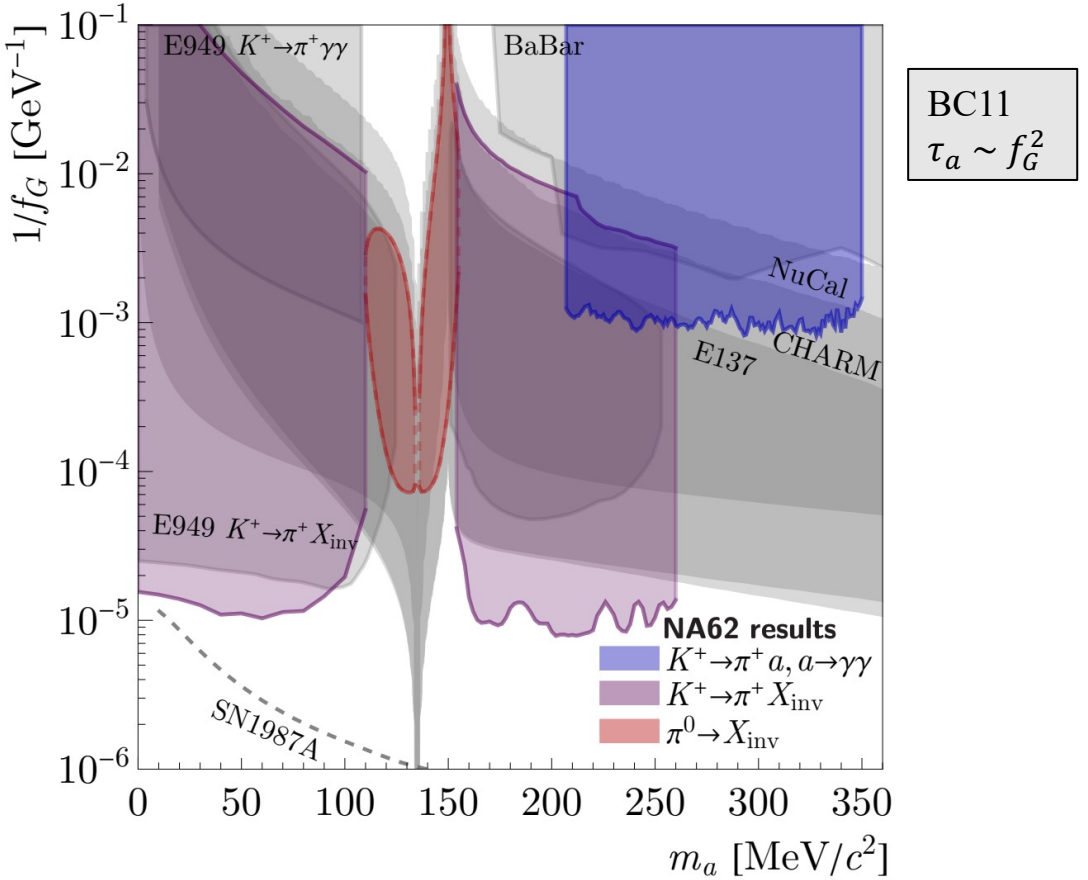
$$\hat{c} = 1.144 \pm 0.069_{stat} \pm 0.034_{syst}$$

ChPT ĉ results [*PLB* 850 (2024) 138513]

First serach for ALP in $K^+ \rightarrow \pi^+ a, a \rightarrow \gamma\gamma$ decays

- Peak search over $m_a = \sqrt{(P_K - P_\pi)^2}$ in the range 207-350 MeV/c^2 in steps of 0.5 MeV/c^2
- m_a resolution: from 2.0 MeV/c^2 to 0.2 MeV/c^2 across the search range
- In each m_a hypothesis background estimated from simulations and UL on number of signal events set using CL$_s$ method





- First UL on $Br(K^+ \rightarrow \pi^+ a)$ assuming prompt $a \rightarrow \gamma\gamma$ decay ($\tau_a = 0$)
- Limits on the coupling strength $f_G^{-1} \sim \tau_a^{-0.5}$ of the BC11 scenario

[*PLB* 850 (2024) 138513]

➢ Searches for DM in dump mode

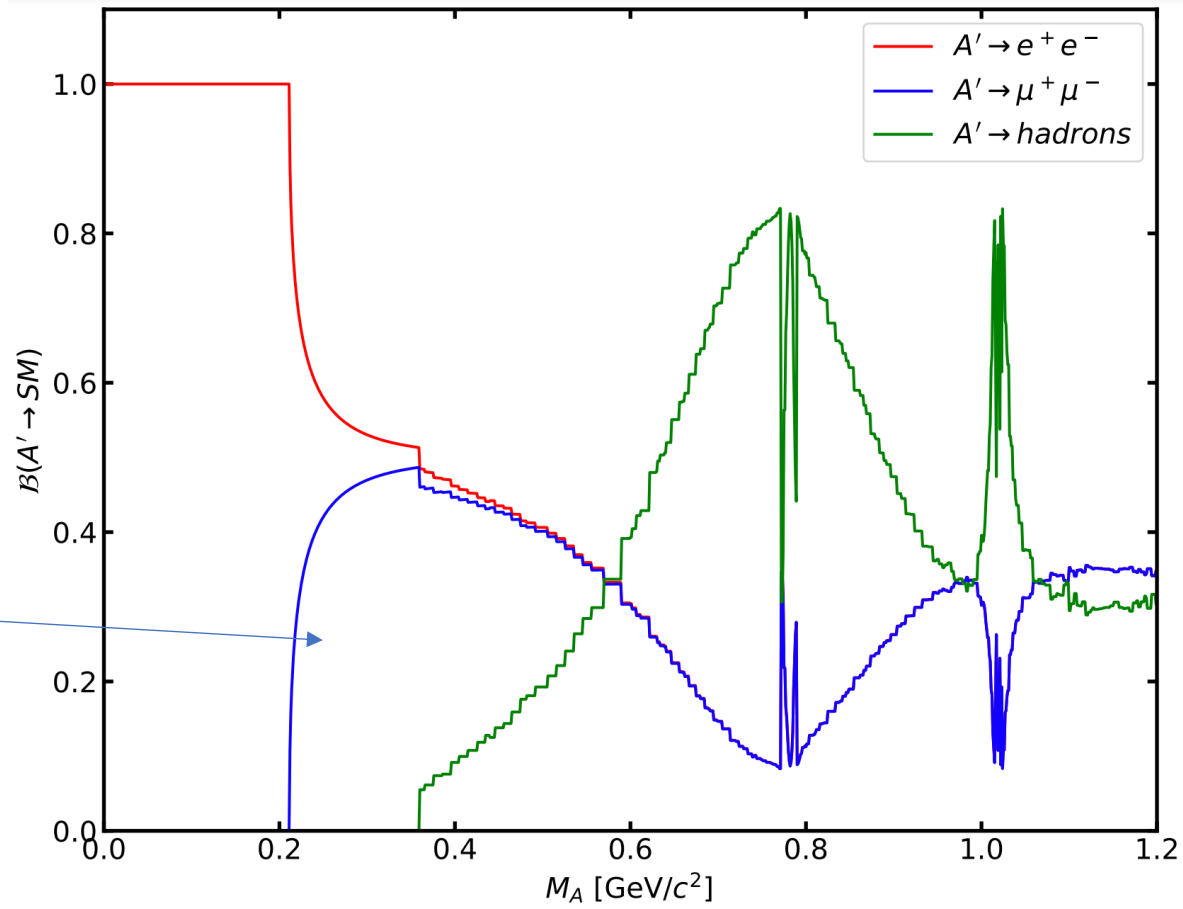
DM searches at NA62

Dark sector portals and mediators

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

DP searches @ NA62

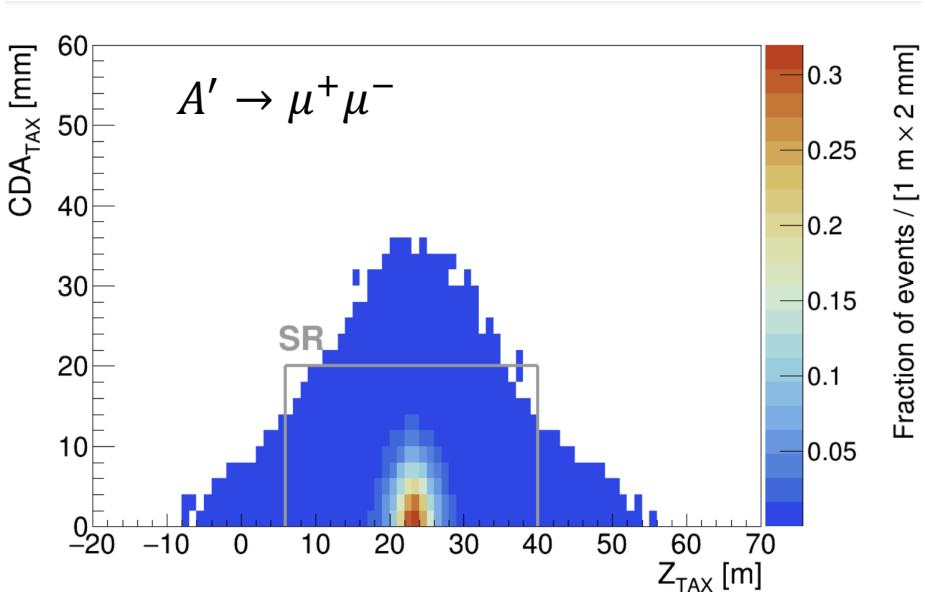
- DP produced in beam-TAX interactions
  (bremsstrahlung, decays of secondary mesons)
- **Search for DP in decays to a lepton pair**
- Two free parameters: mass and coupling ε
- Sensitive to $\boldsymbol{m < 600\ MeV}$ (where decays to leptons dominate)



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

Analysis strategy

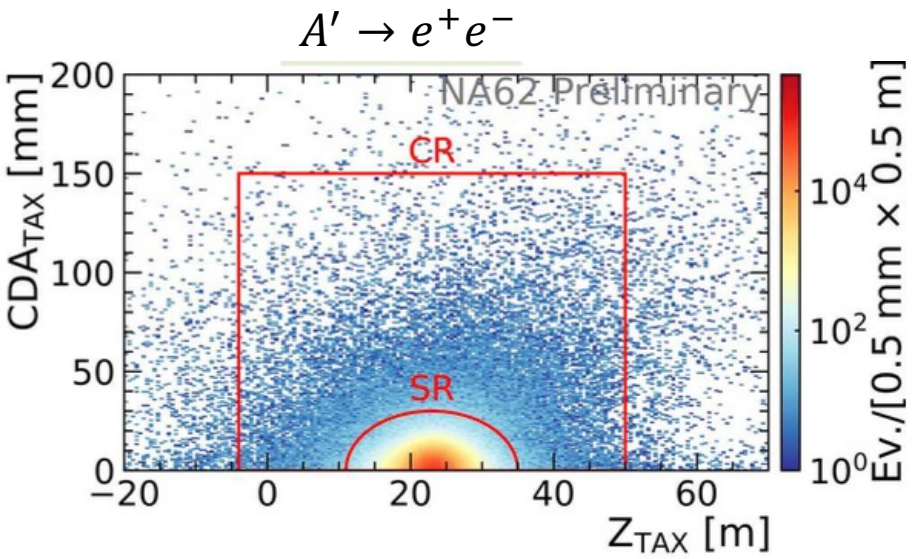
- Lepton-antilepton vertex in the NA62 decay region
- Dilepton momentum pointing back to taxes
- Kinematic variables: Z_{tax} and CDA_{tax}
- CDA_{tax}: closest distance of approach between beam and dimuon direction, $\sigma_{CDA} = 7\ mm$
- Z_{tax}: Z coordinate of the beam-TAX interaction vertex (calculated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



Expected DP yield

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

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



Background studies

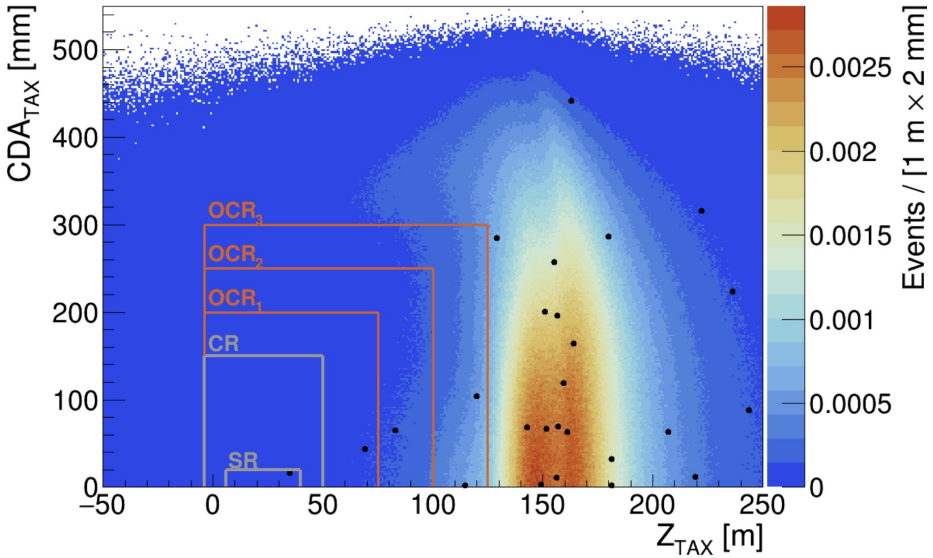
Combinatorial background

- Two uncorrelated "halo" muons
- Dominant for $A' \to \mu^+\mu^-$

Expected background for $A' \to \mu^+\mu^-$

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

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



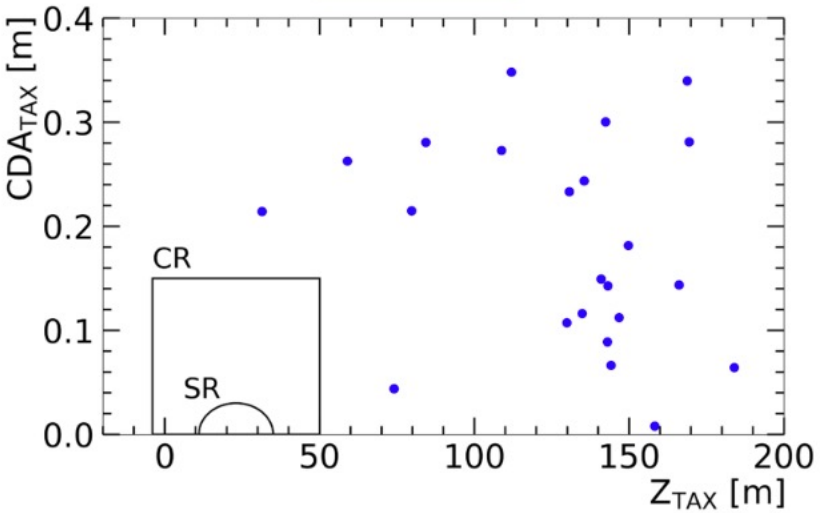
Prompt background

- Secondaries of a muon interaction with the traversed material
- Dominant for $A' \to e^+e^-$

Expected background for $A' \to e^+e^-$

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

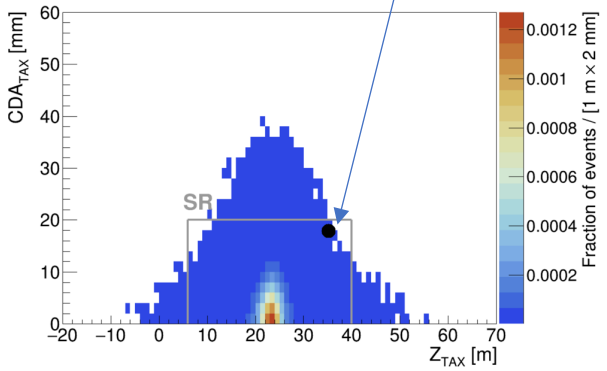
$A' \to e^+e^-$

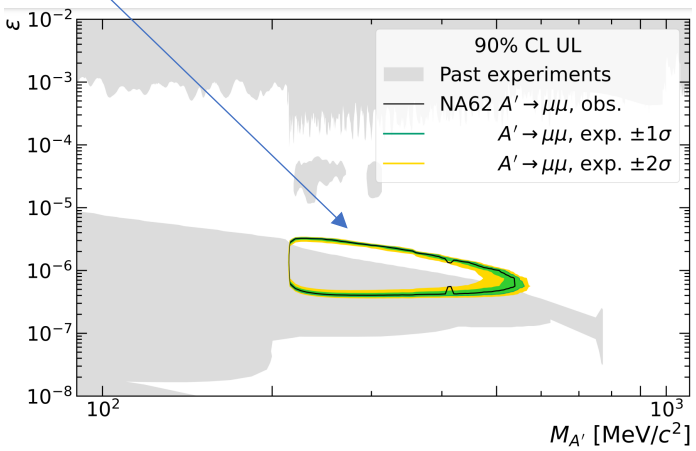


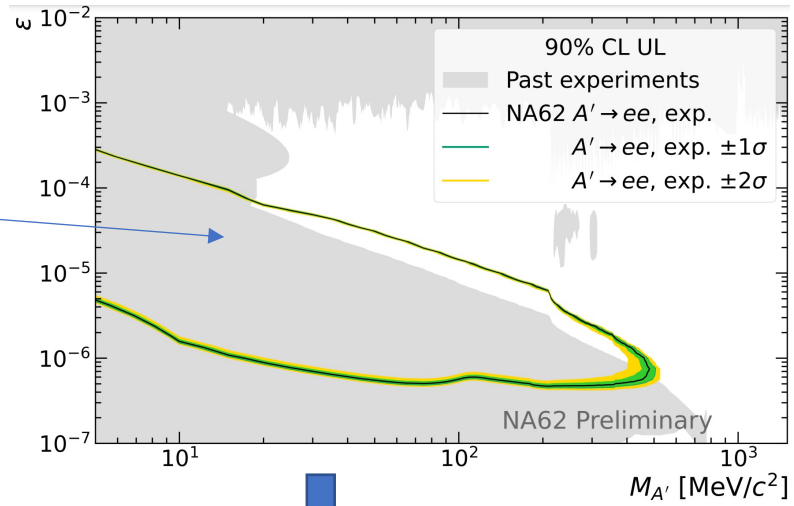
Results on DP search in $A' \rightarrow l^+l^-$

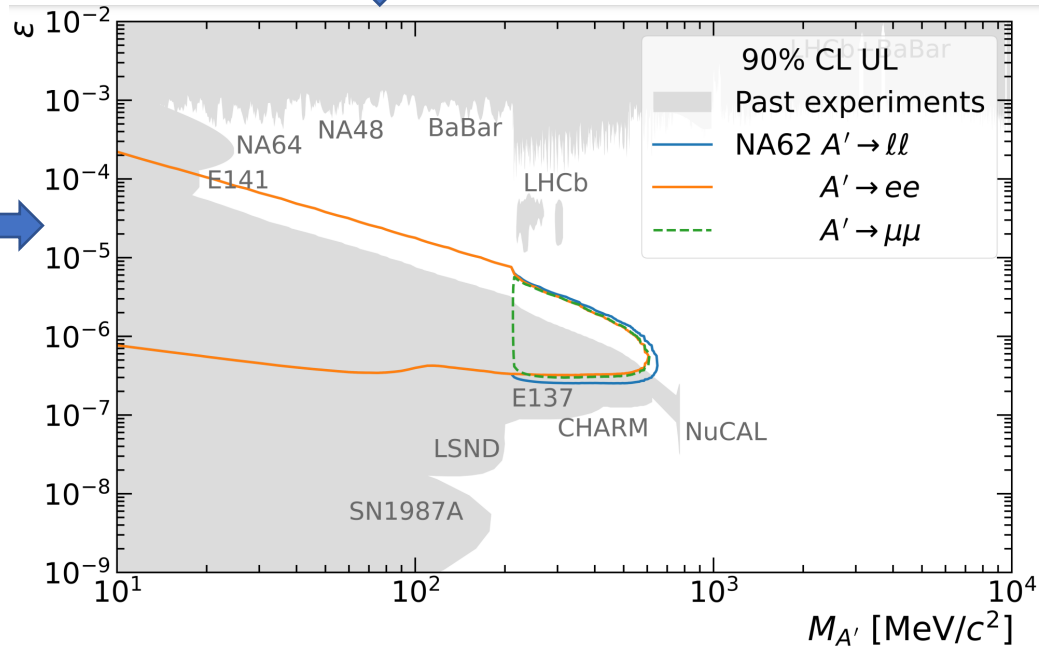
$A' \rightarrow e^+e^-: N_{obs} = 0$

$A' \rightarrow \mu^+\mu^-: N_{obs} = 1\ (2.4\sigma\ significance)$









ALP interpretation for $a \rightarrow l^+l^-$

- Previous limits extended
- See spare slides for details

Conclusions

Search for NP in the standard mode

- $K^+ \to \mu^- \nu e^+ e^-$: $UL(Br) < 8.1\times10^{-11}$, 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 exluded;
- $K^+ \to \pi^+ S \to A'A'$, $A' \to e^+e^-$: $UL(Br)\ for\ 20 < m_S < 340\ MeV, 10 < m_{A'} < 170\ MeV$

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

Plans:

- NA62 physics Run 2 started in 2021 and ongoing until CERN LS3, data analysis ongoing
- Beam dump data analysis: search for exotic particles decaying to $(\gamma\,\gamma)$, $(\pi^+\pi^-\gamma)$ states

Thank you for your attention!

Spare

Precision measurement of the rare $K^+ \to \pi^+\mu^+\mu$ and $K^+ \to \pi^+\gamma\gamma$ processes

[JHEP 11 (2022) 011], [JHEP 06 (2023) 040], preliminary, arXiv: 2304.12271

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

- Heavily suppressed FCNC transition: $s \to dl^+l^-$
- FCNC decay described in the scope of ChPT,
  mediated by one photon exchange $K^\pm \to \pi^\pm\gamma^*$
- Mainly kinematic variable: $z = \frac{m^2(l^+l^-)}{m_K^2}$
- Chiral Perturbation Theory (ChPT) parametrization of $W(z)$ at $O(p^6)$:

$$\mathbf{W(z)} = G_F m_K^2(a_+ + b_+ z) + W^{\pi\pi}(z)$$

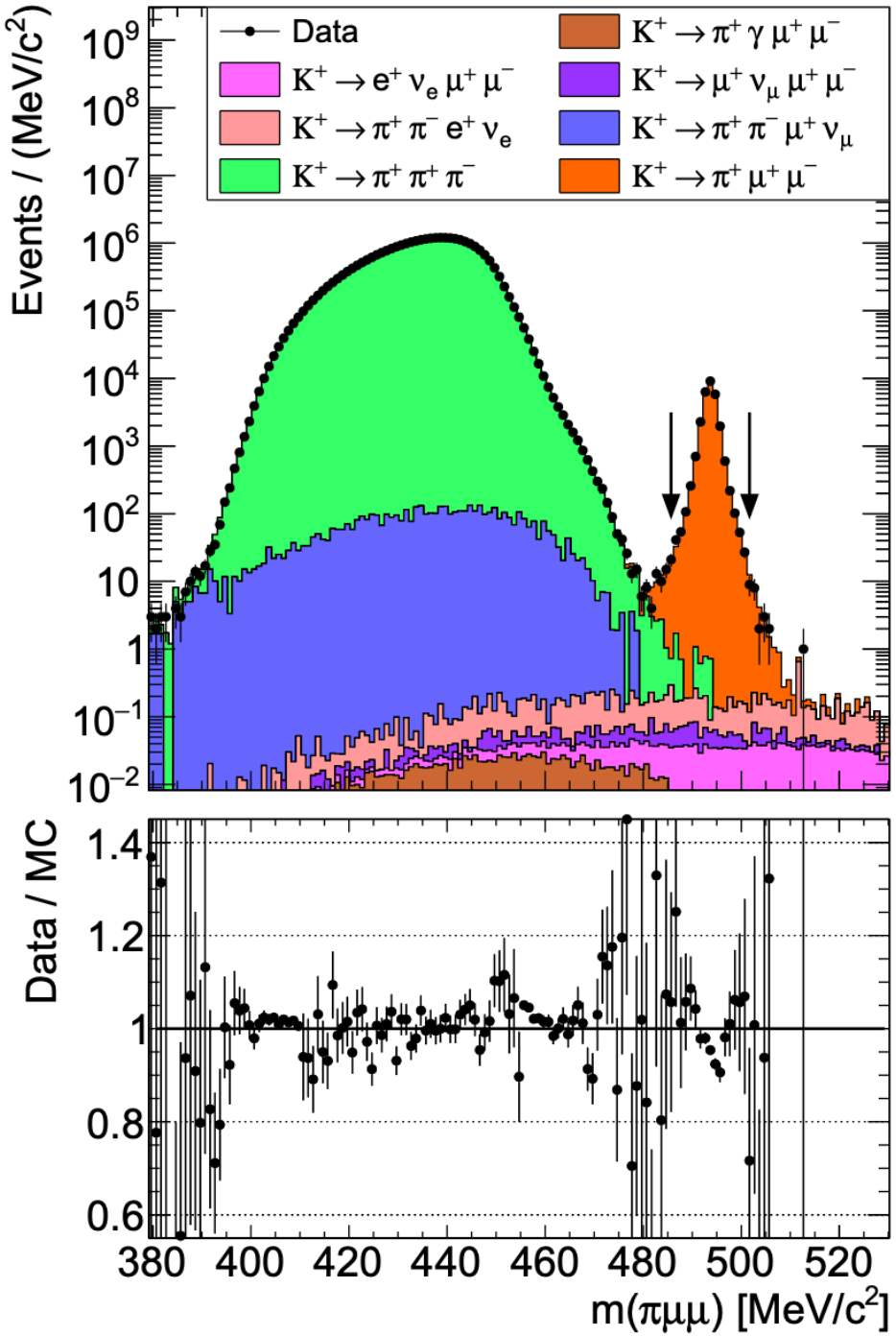
Main goals of the $K^+ \to \pi^+\mu^+\mu^-$ measurements with NA62:

- Model-independent measurement of the B(Kπμμ) branching fraction
- Measurement of the function $|W(z)|^2$
- Determine the Form Factor parameters a_+ and b_+
- Forward - backward assymetry

After signal selection:

N_{obs} = 27679 events

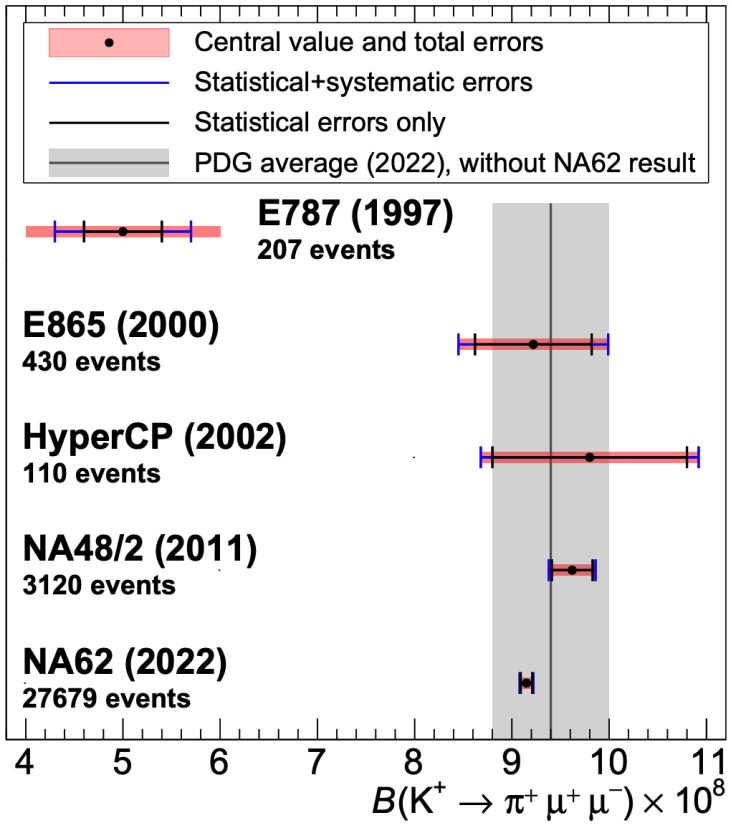
N_{bg}^{exp} = 8 events



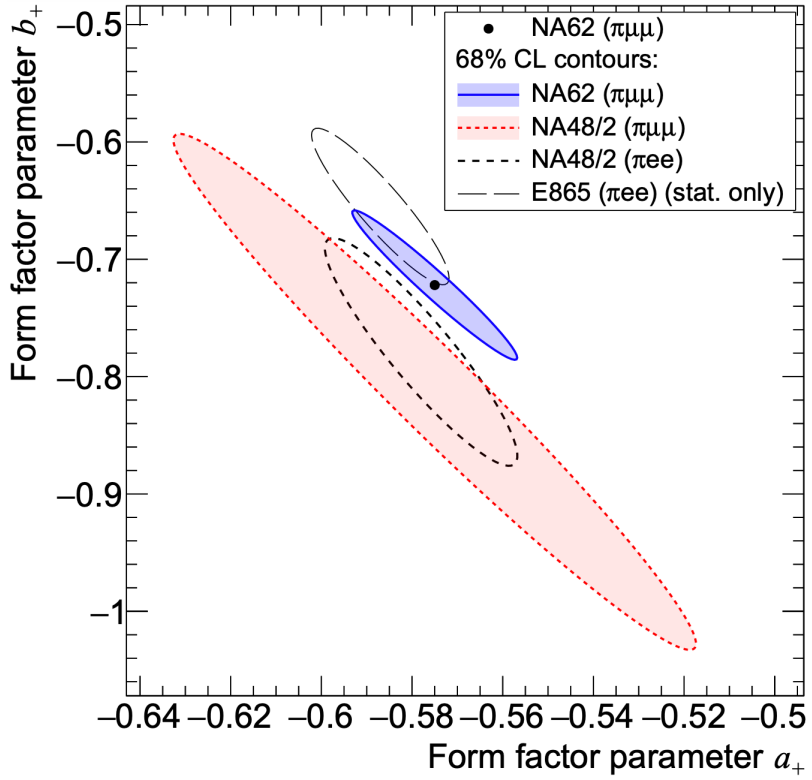
$K^+ \to \pi^+\mu^+\mu$ decays: Results

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

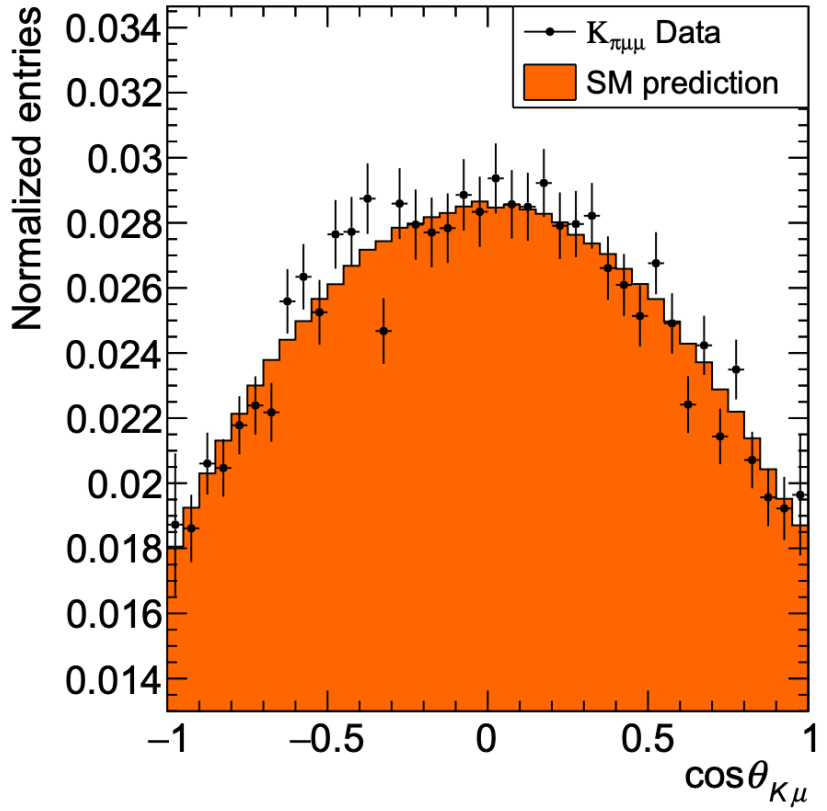
[JHEP 11 (2022) 011]



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



$a_+ = -0.575 \pm 0.012_{stat}$
$b_+ = -0.722 \pm 0.040_{stat}$



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

NEW: $|A_{FB}| < 0.9 \times 10^{-2}$
@ 90% CL *upper limit**
UL published as addendum [JHEP 06 (2023) 040]

Searches for Lepton Flavor and Lepton Number Violating (LFV/LNV) processes with NA62

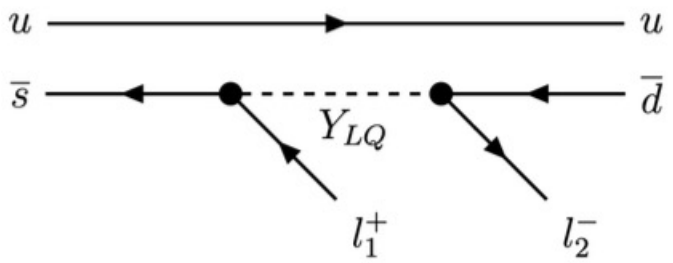
[PLB 797 (2019) 134794], [PRL 127 (2021) 13, 131802], [PLB 830 (2022) 137172], [PLB 838 (2023) 137679]

LFV/LNV searches

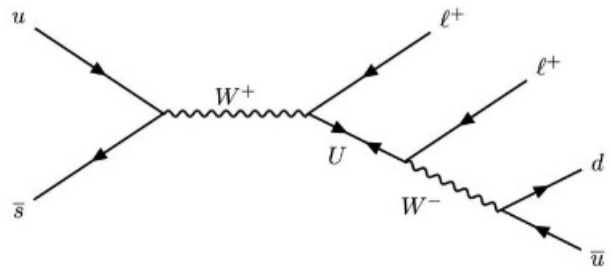
Theory: Violation of Lepton Number (LNV) and Lepton Flavor (LFV) conservation laws predicted in BSM models

(for example via Majorana neutrinos or leptoquark)

- NA62: several channels studied with RUN1 data
- Analysis: key points → tracking resolution and particle identification
- Result: no signal observed → 90% CL Upper Limit (UL) on Branching Ratios (BR)



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



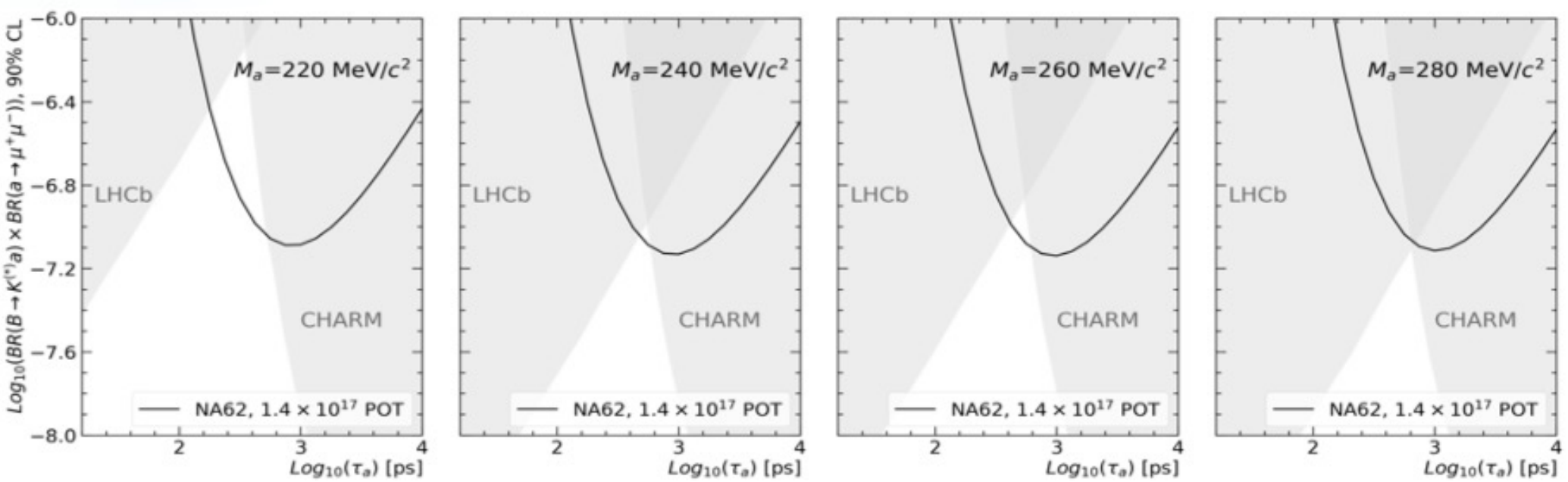
$K^+ \to \pi^- \ell^+ \ell^+$ (LNV, $\Delta L = 2$)

Decay channel	BR UL PDG 2019	BR UL NA62	Expected background	Observed	Improvement (by factor)
$K^+ \to \pi^- \mu^+ e^+$	50×10^{-11}	4.2×10^{-11}	1.07 ± 0.20	0	12
$K^+ \to \pi^+ \mu^- e^+$	52×10^{-11}	6.6×10^{-11}	0.92 ± 0.34	2	8
$\pi^0 \to \mu^- e^+$	34×10^{-10}	3.2×10^{-10}	0.23 ± 0.15	0	11
$K^+ \to \pi^- \mu^+ \mu^+$	8.6×10^{-11}	4.2×10^{-11}	0.91 ± 0.41	1	2
$K^+ \to \pi^- e^+ e^+$	64×10^{-11}	5.3×10^{-11}	0.43 ± 0.09	0	12
$K^+ \to \pi^- \pi^0 e^+ e^+$	N/A	8.5×10^{-10}	0.044 ± 0.020	0	
$K^+ \to \mu^- \nu e^+ e^+$	N/A	8.1×10^{-11}	0.26 ± 0.04	0	

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

a: (pseudo)scalar produced in B decays

- Free parameters: $m, \tau, coupling$
- Set model-independent UL on $Br(B \rightarrow K\ a) \times Br(a \rightarrow \mu^+\mu^-)$ for each (m, τ) combination

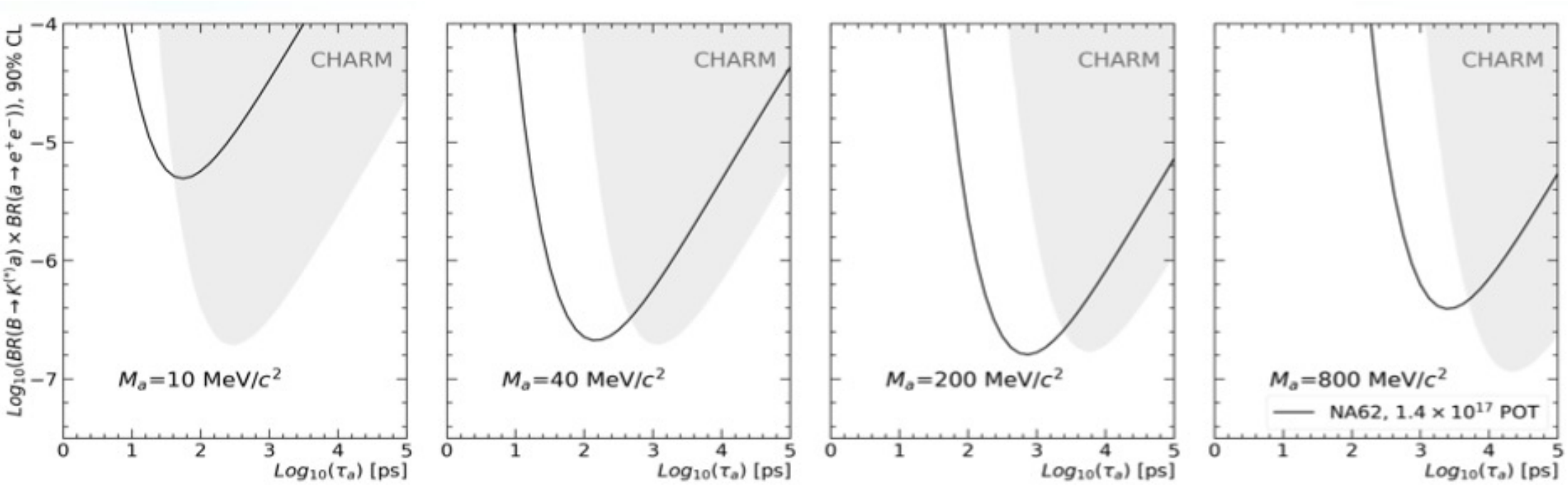


Limits of previous experiments extended for $m < 280\ MeV$

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

a: (pseudo)scalar produced in B decays

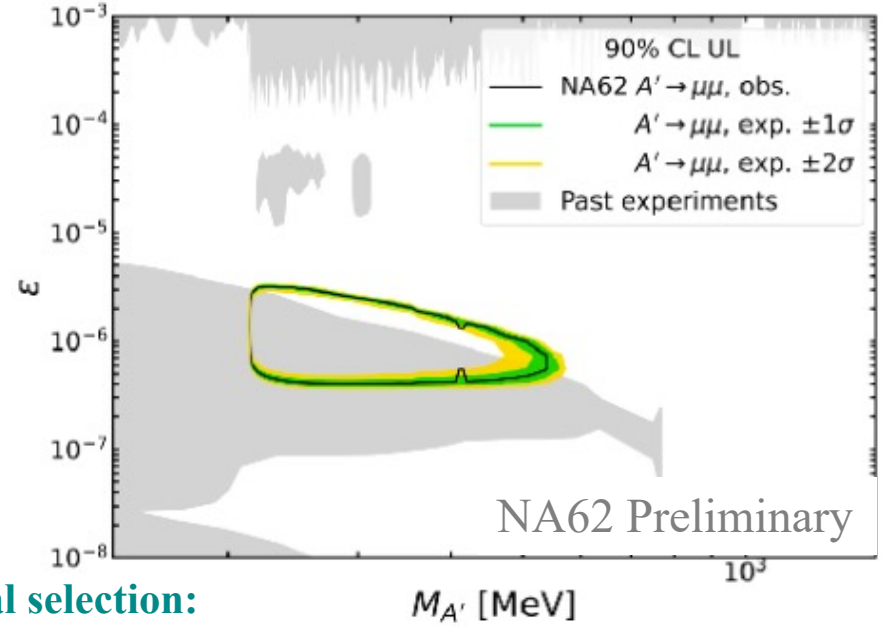
- Free parameters: $m, \tau, coupling$
- Set model-independent UL on $Br(B \rightarrow K\ a) \times Br(a \rightarrow e^+e^-)$ for each (m, τ) combination



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

Dark photon searches: $A` \rightarrow \mu^+\mu^-$

- Feebly interacting dark photon with free mass and coupling ϵ
- Beam dump mode: 3.2 m Cu-Fe collimators (TAX) used as a target
- Search for dark photon production in interaction with TAXs
- (1.4 ± 0.28) x 10^{17} POT collected in ~10 days in 2021

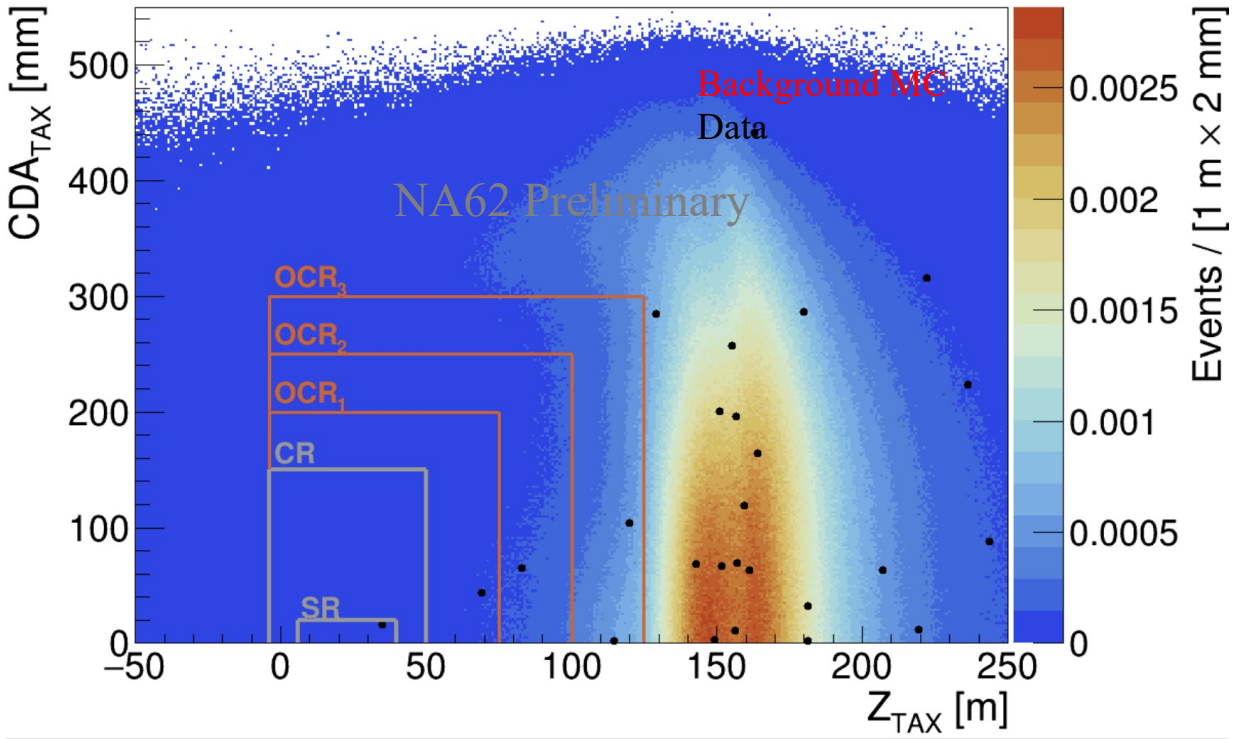


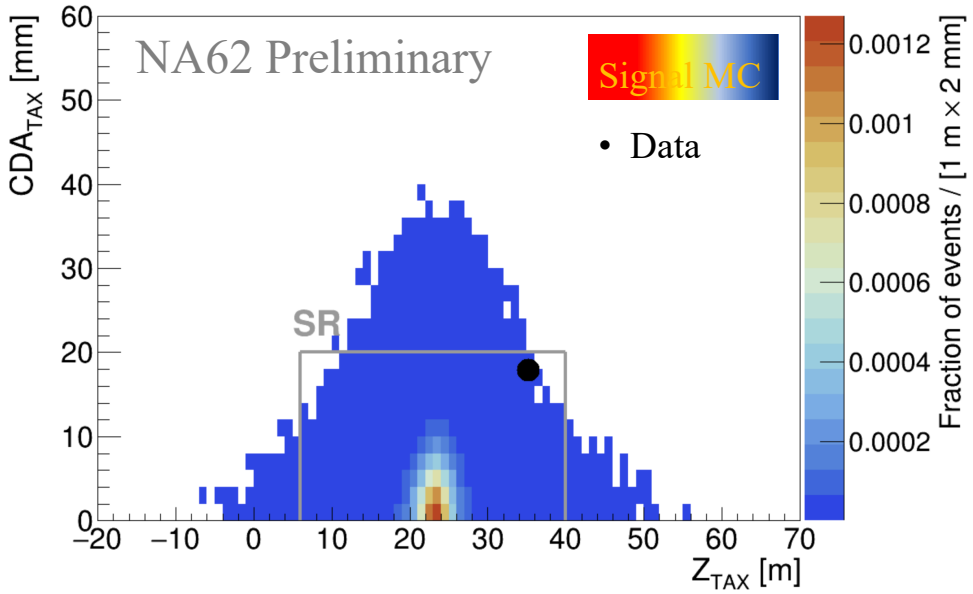
After signal selection:

N_{obs} = 1 event observed

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

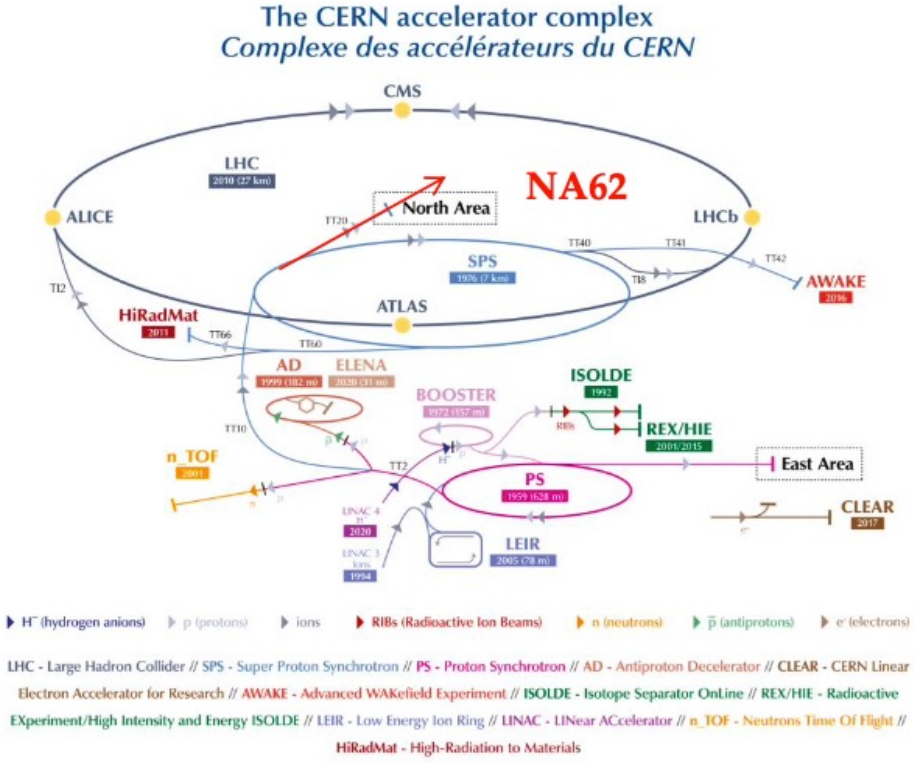
2.4 σ significance (counting experiment)

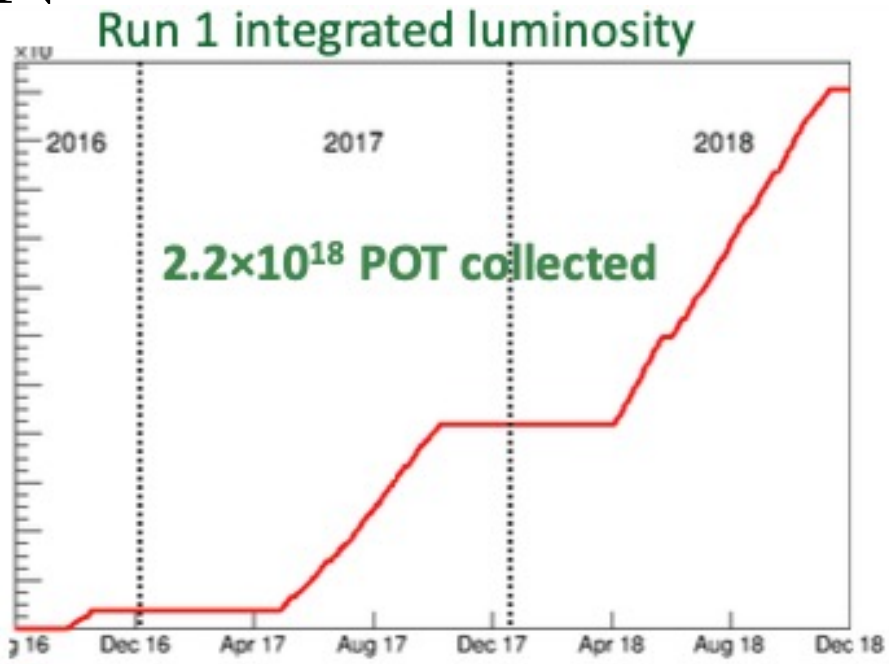




The NA62 experiment @CERN

- High precision fixed-target Kaon experiment at the CERN SPS
- Main goal: **$K^+ \to \pi^+ \nu\bar{\nu}$ decay measurement**
- Broad physics program:
  - Other rare charged kaon decays
  - Precision measurements
  - LFV/LNV searches
  - Exotic searches (FIPs, Dark photon, etc…)





- *2008: NA62 Approval*
- *2014: NA62 Pilot Run (partial layout)*
- *2015: Commissioning run*
- *2016-18: NA62 RUN 1 data-taking completed*
- 2021+: NA62 RUN 2 ongoing