Physics Beyond the Standard Model with NA62

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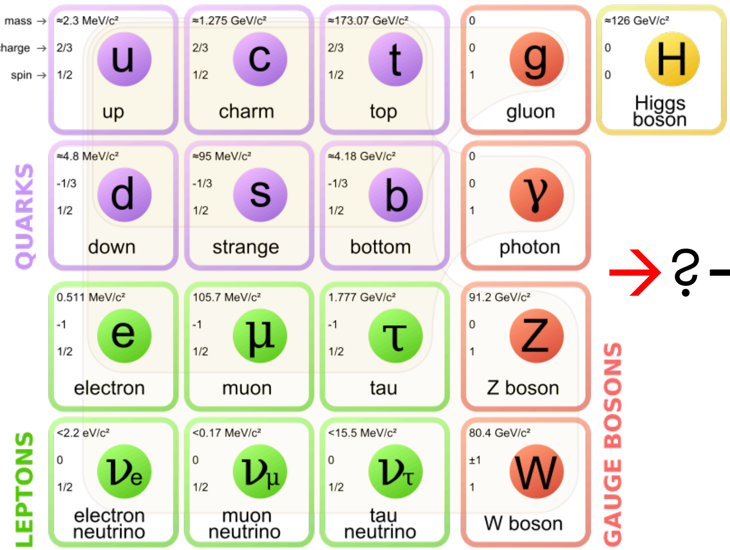
Outline

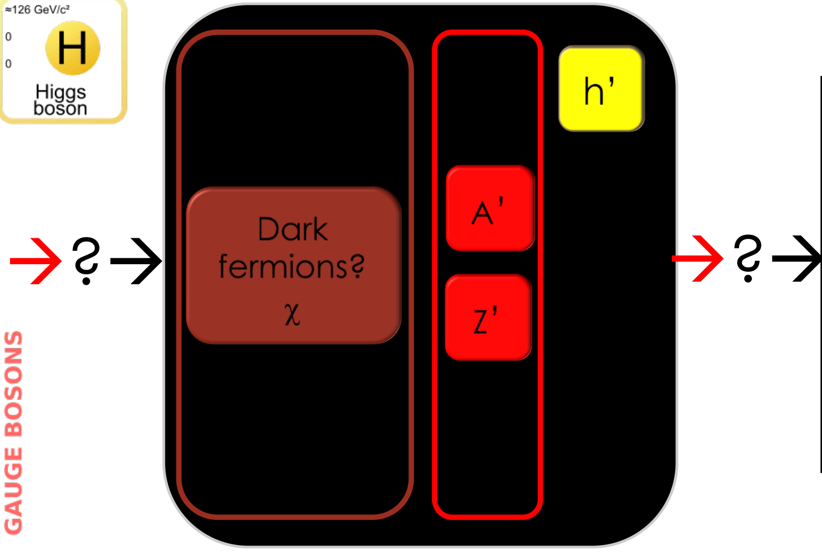
- **Dark sectors**
- The **NA62 experiment at CERN**
- Search for **feebly interacting particles** in **K^+ decays**:
  - $\boldsymbol{K}+\rightarrow\boldsymbol{\pi}+e+e-e+e-$
- Search for **feebly interacting particles NA62 "beam-dump experiment"** mode :
  - Search for A' –> e^+e^- and A'–> $\mu^+\mu^-$

What is the universe made of?

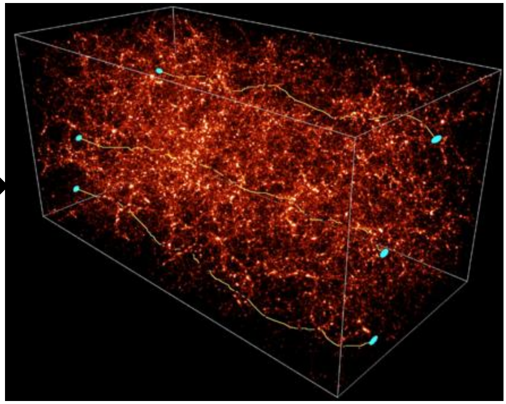
Standard model



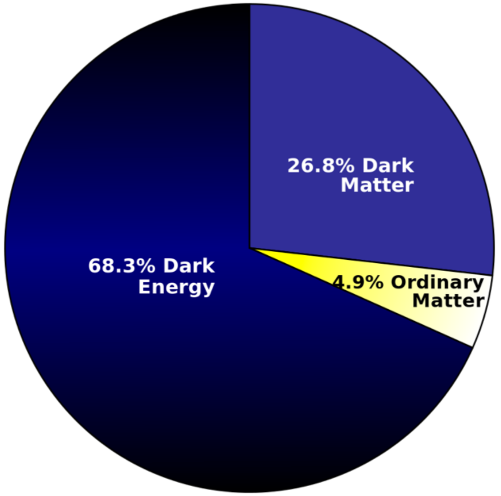
???Dark Sector???



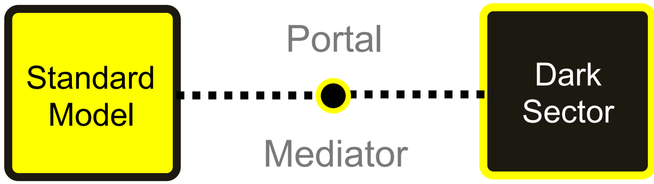
???Dark Matter???



- Standard model only includes <20% of the matter in the universe
  - We only know dark matter interacts gravitationally
- Many open questions:
  - What is dark Matter made of?
  - How dark matter interact, if it does, with SM particles?
  - Does one or more new dark force exist?
  - How complex is the dark sector spectrum?

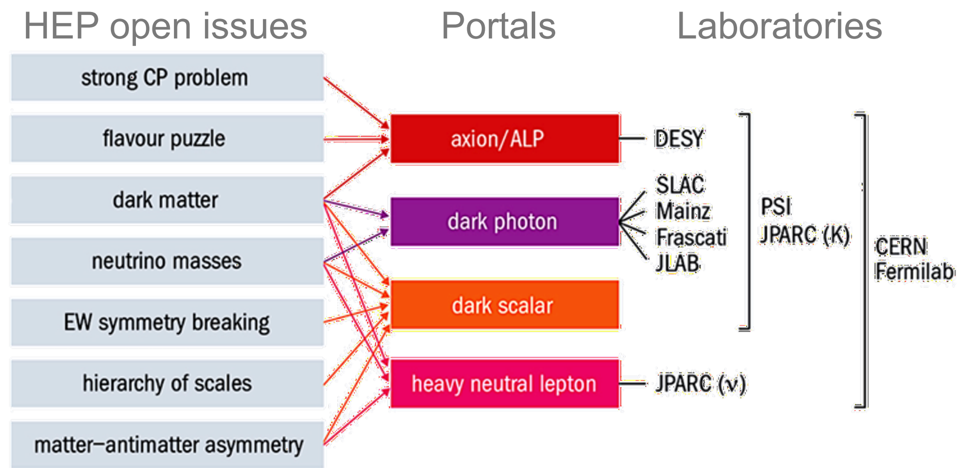


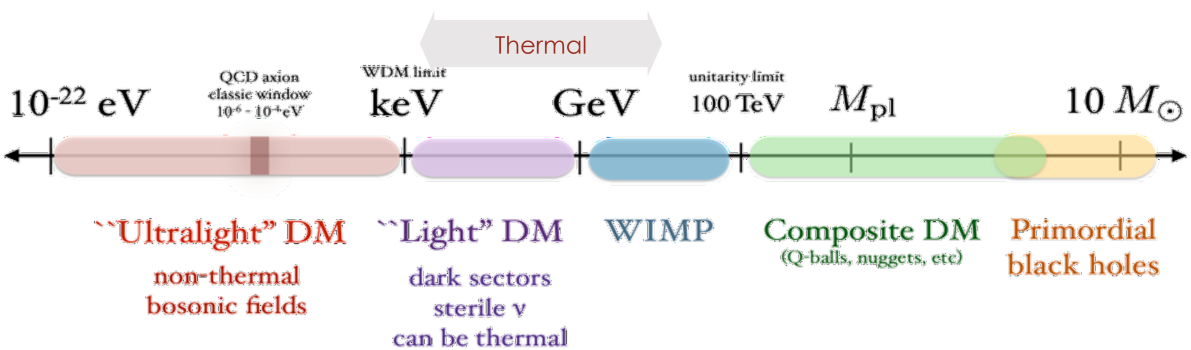
The dark sector paradigm



Feeble, non-gravitational interaction with ordinary matter

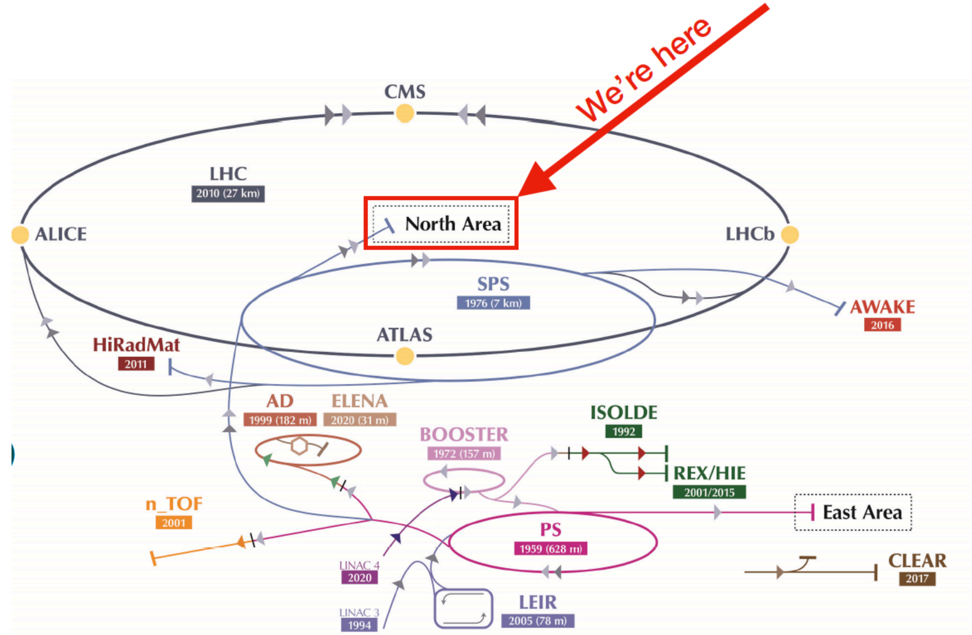
- **Dark matter**
- Dark forces
- Other dark particles





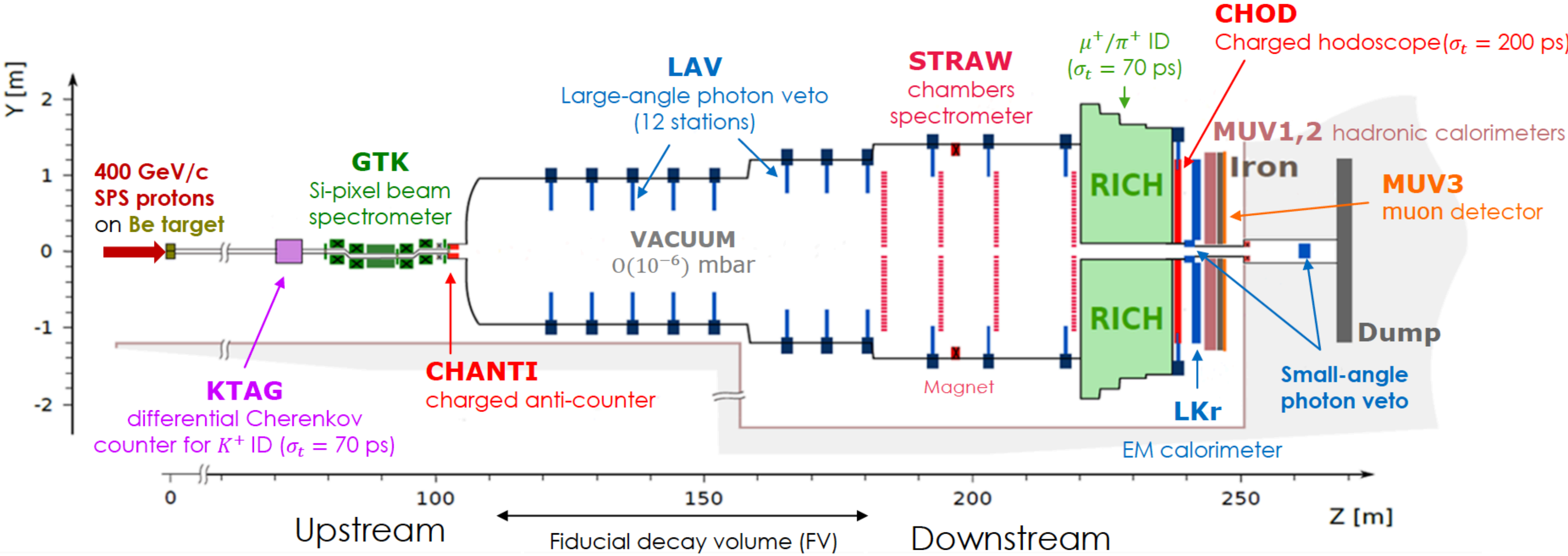
- Dark sector candidates can explain SM anomalies: (g-2)μ, ^{8}Be, proton radius
- The mediator can have a **small mass (MeV -100 MeV)**
- Due to its **small mass** the mediator can be **produced at low energy accelerators**
- It can **decay back to ordinary matter "visible"** on **not "invisible"**

NA62 experiment at CERN SPS



- The **NA62 experiment at CERN** running since 2016 to search for $K^+ \to \pi^+\nu\nu$ decay
- In addition the experiment has excellent sensitivity for **feebly interacting particles (FIPs)**
- Search for **FIPs** in K^+ decays:
  - Axion Like Particles in $\boldsymbol{K^+\to\pi^+ 4e}$ through $\boldsymbol{K^+\to\pi^+ aa}$, followed by $\boldsymbol{a\to e^+e^-}$
- **NA62 "beam-dump"** experiment mode :
  - Search for **dark photons** (**DP**) in $A' \to e^+e^-$ and $A' \to \mu^+\mu^-$

NA62 detector in Kaon Mode



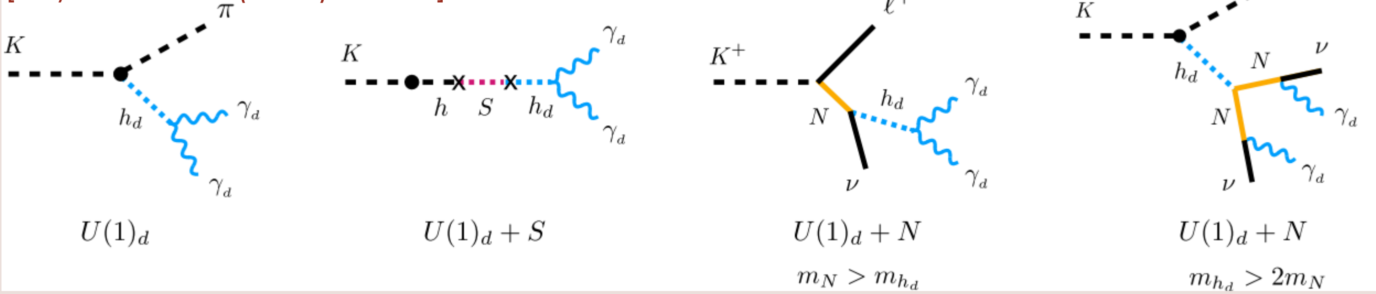
- 75 GeV K^+ beam measured by the **Giga Tracker** silicon pixel detector
- Excellent momentum measurement using **straw chambers** based spectrometer
- Excellent photon energy resolution using **Liquid Kripton Calorimeter (LKr)**
- PID capability using RICH, LKr, MUV,
- Hermetic veto system for both charged and neutral Particles.

The NA62 detector is well-suited to measure any rare SM and beyond SM processes

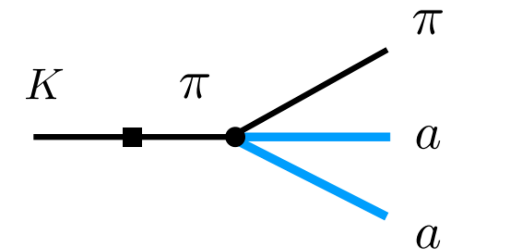
Search for $K^+ \to \pi^+ e^+ e^- e^+ e^-$: motivations

- K^+ decays in prompt dark cascade with multiple DS mediators
  - $K^+ \to \pi^+ S, S \to A'A', A' \to e^+ e^-$ involving a dark scalar (S) promptly decaying into DP (A')

[Phys.Rev.D105(2022)015017]



- Probe short-lived QCD axions (a) through the $K^+ \to \pi^+ aa$, $a \to e^+ e^-$ process



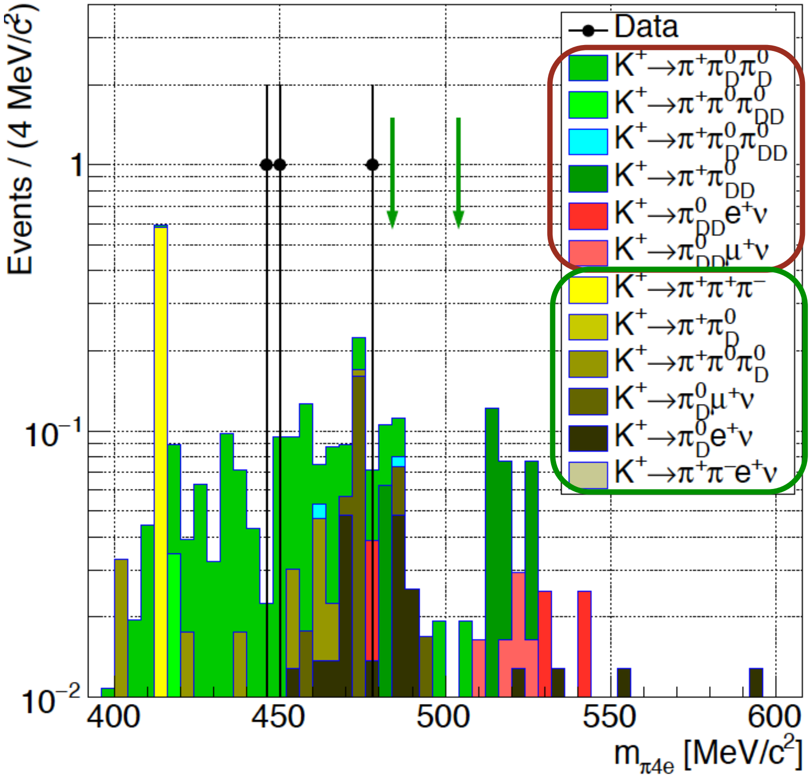
[Phys.Rev.D105(2022)015017]

  - If m_a=17 MeV, $BR(K^+ \to \pi^+ aa) > 2 \times 10^{-8}$ is predicted
  - possibility for a conclusive test of QCD axion explanation for the "17 MeV" anomaly [Phys.Rev.D103(2021)055018, Eur.Phys.J.C83(2023)230]
- $K^+ \to \pi^+ e^+ e^- e^+ e^-$: heavily suppressed SM process (outside the π^0 pole)
  - $BR^{SM}{}_{LO}(K^+ \to \pi 4e, \text{non res.}) = (7.2 \pm 0.7) \times 10^{-11}$

SM non RES. $K^+\to\pi^+e^+e^-e^+e^-$ NEW

- K^+_{flux}= $(8.58\pm0.19_{stat}\pm0.07_{MC}\pm0.41_{ext})\times10^{11}$ measured using $\boldsymbol{K^+\to\pi^+\pi^0_{DD}}$
- **Events with 5-track** vertex Q_{ToT}=+1
- Total momentum consistent with K⁺ beam one
- **Invariant mass $\boldsymbol{m_{\pi4e}}$** used as discriminant variable and blind analysis strategy
- Expected background and signal acc. from MC

- **Backgrounds from 5 & 7 tracks K^+ decays**
- **Backgrounds from 3-tracks K^+decays** with a $K_{3\pi+}$ in time
- Observed events in Signal Region = 0
- Expected bkg events in SR = (0.18 ± 0.14)



$BR(K+\to\pi^+4e,\text{non res.})<1.4\times10^{-8}$ @ 90% CL NEW

limit is O(200) larger w.r.t. SM expectations

arXiv:2307.04579 [hep-ex] - submitted to Phys.Lett.B

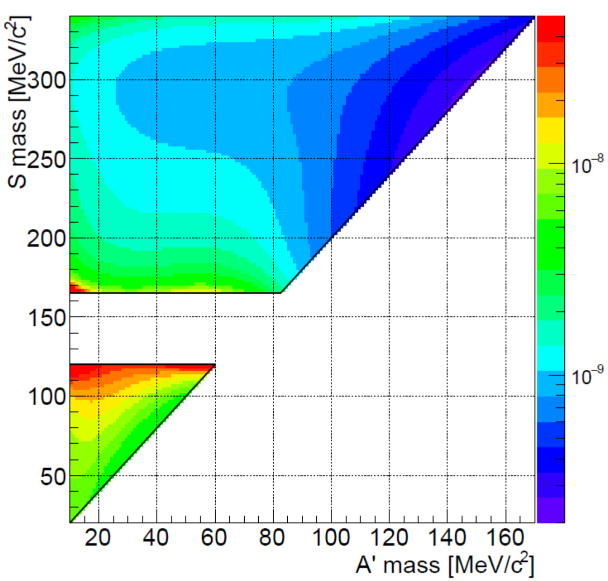
Dark sectors in $K^+ \to \pi^+ 4e$ Run1

Same $K\pi 4e$ selection + 2 identical m_{e+e-} masses.
Use the same signal region as $K\pi 4e$:

Exp. bkg events in SR = (0.0004 ± 0.0004) Observed events in SR = 0

Whole NA62 Run1 data set. Axion/dark scalar mass scan in step of 5 MeV/c^2.

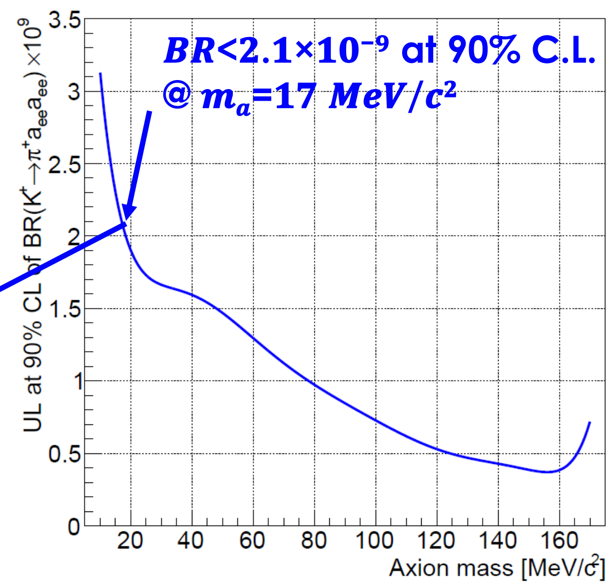
S dark scalar (A' dark photon)
$K^+ \to \pi^+ S, S \to A'A', A' \to e^+e^-$



arXiv:2307.04579 [hep-ex]
submitted to Phys.Lett.B

exclude the QCD axion as a solution for the X17 anomaly.
Theory: $BR(K^+ \to \pi^+ aa) > 2\times10^{-8}$ @ $m_a = 17\ MeV/c^2$

Short-lived QCD axion:
$K^+ \to \pi^+ aa$ with prompt $a \to e^+e^-$



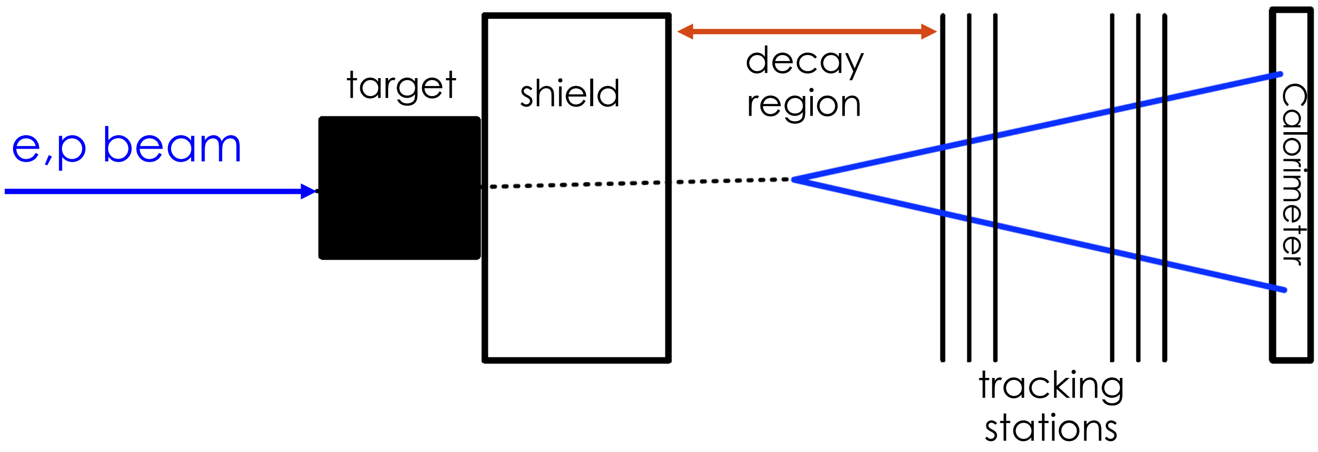
What’s a beam dump experiment?

High intensity beam impinging a thick high Z target (high production rates)

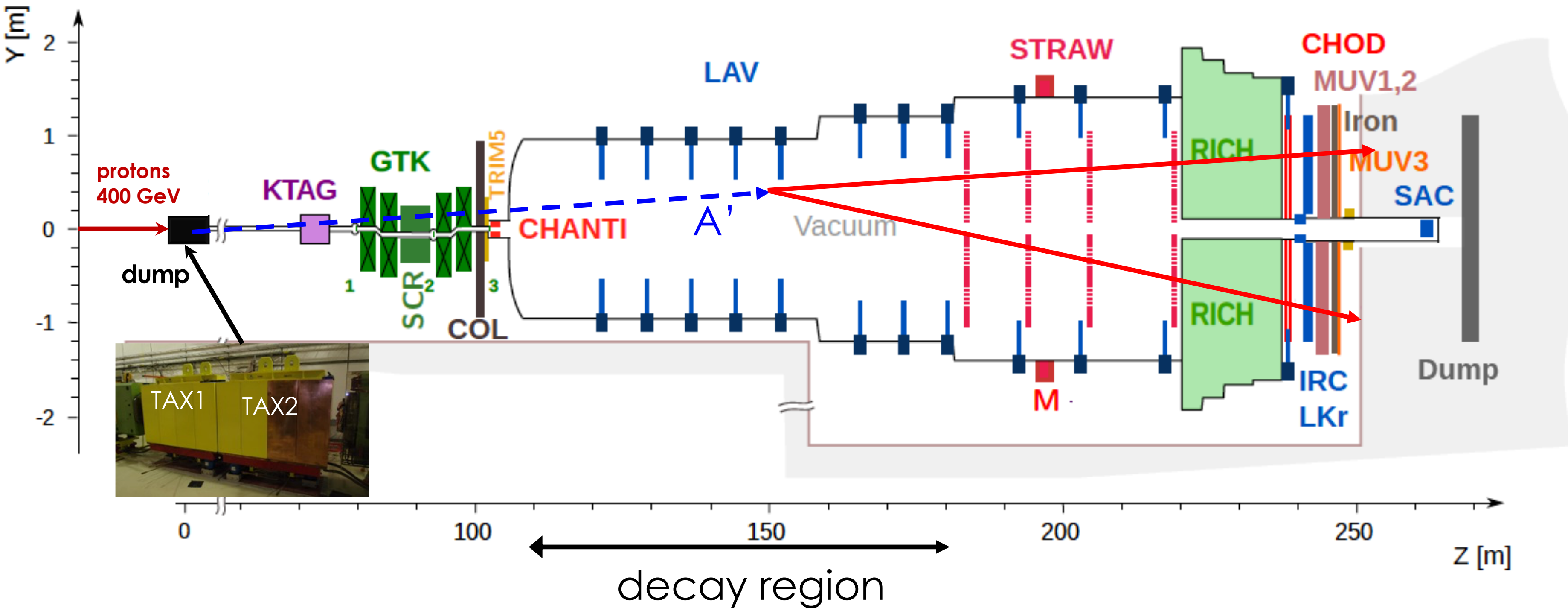
Shield absorbs SM background but not A’, weekly interacting with shield material (0 BG)

A’ decays in the decay region into lepton pairs e^+e^-,$\mu^+\mu^-$ (long lifetime low couplings)

A tracking or calorimetric system detects the decay products to reconstruct A’ decay

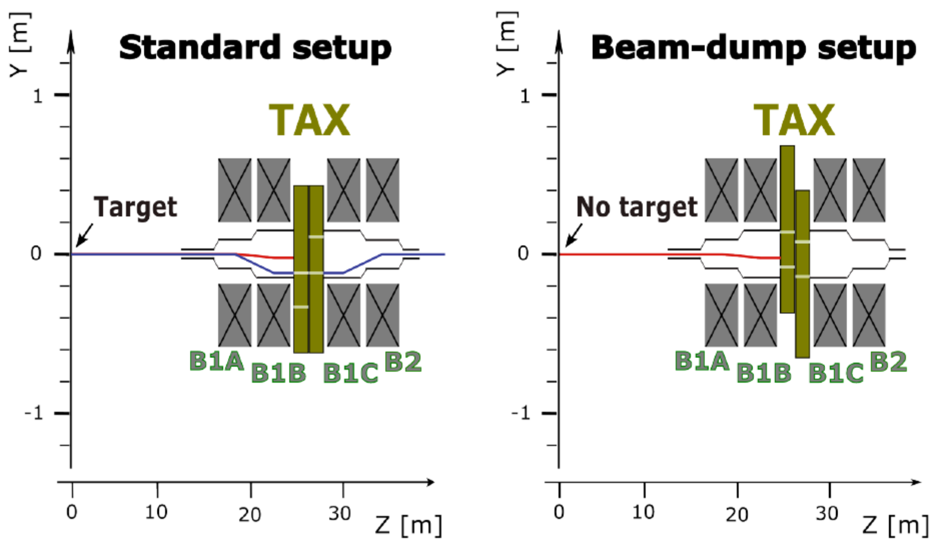


NA62 beam dump mode



- **400 GeV SPS protons** absorbed by K12 TAX copper collimators: **Target + dump**
- **A'** produced by proton strahlung or meson decays
- **A' decays** in the decay region if $\gamma c\tau$ is big enough (γ >1000)
- **Lepton pairs (e^+e^-, $\mu^+\mu^-$)** are detected by NA62 exp.
- Total of **$1.4\text{x}10^{17}$** protons on dump collected **in 2021**

How to move NA62 to dump mode



Red line **400 GeV protons**

Blue line **75 GeV secondary beam**

Tax are the copper dumps

B1X and B2 are dipole magnets

Kaon mode (standard)
proton pass through the target
75 GeV beam pass in the aligned TAX holes
Protons are dumped on Tax
B1C and B2 realign the 75 GeV beam

Dump mode
Target is removed
TAX holes are misaligned
Protons are dumped on TAX
B1C and B2 sweep out low energy particles

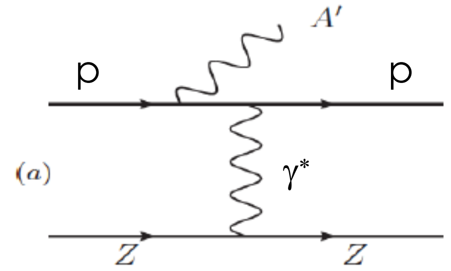
Results in this talk based are on 1.4x10^{17} protons in dump mode collected in 2021

Dark photon production and decays

A' production proceeds via p-bremsstrahlung or mesons decays

p-bremsstrahlung

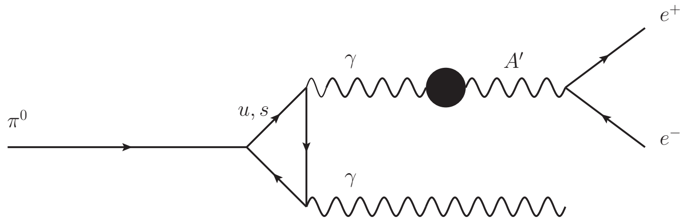
$\gamma^* p \to A' p',$



Meson decays

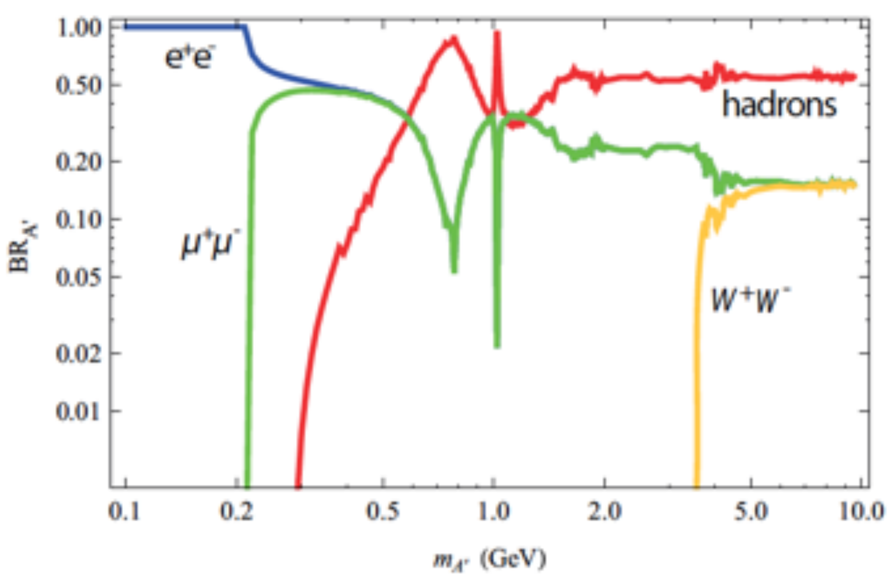
$pN \to MX$, where $M = \pi^0, \eta^{(\prime)}, \rho, \omega, \phi,$

$$
\begin{array}{llll}
M \to & \gamma A' & \text{for } M = & \pi^0, \eta^{(\prime)}; \\
M \to & \pi^0 A' & \text{for } M = & \eta', \rho, \omega, \phi; \\
M \to & \eta A' & \text{for } M = & \rho, \omega, \phi.
\end{array}
$$



A' decays to leptons pairs for $M_{A'}$<500 MeV

Dominant decays at NA62 are:
A' → e^+e^- (100% for $M_{A'}$<210 MeV)
A' → $\mu^+\mu^-$ (only if$M_{A'}$>210 MeV)



NA62 A' → $\mu^+\mu$ search technique

Event selection: Track quality, timing coincidence, PID with calorimeter and muon detector

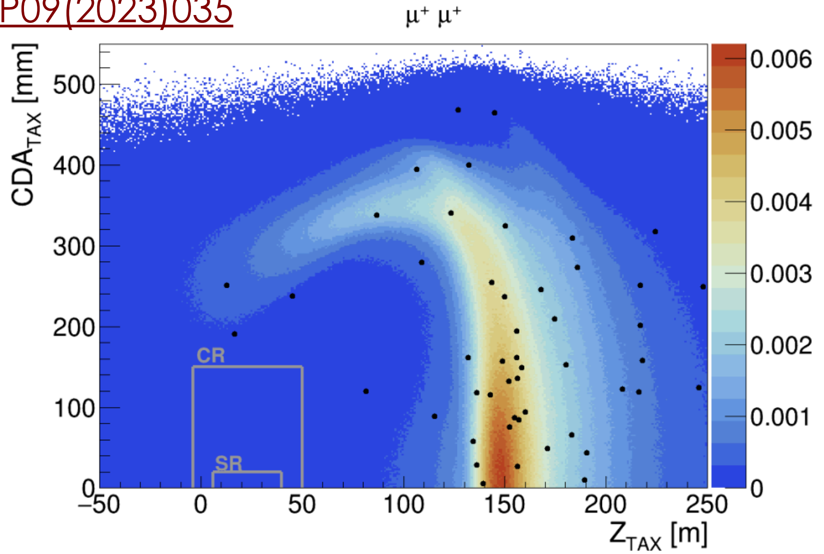
No Photons No in-time activity in Large Angle Vetos

Decay Vertex match: A' decay point P_{CDA} compatible with beam extrapolation
Closest Distance of Approach (CDA) between the dark photon line of flight and the proton beam direction at the TAX entrance.

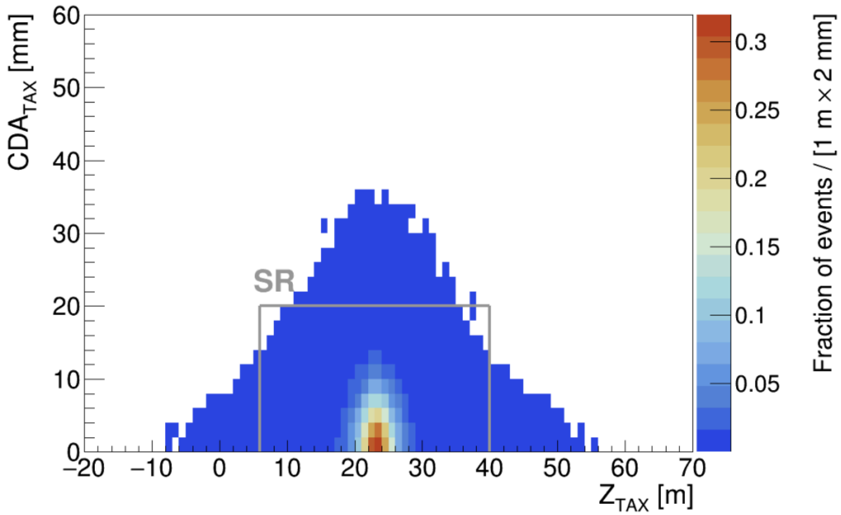
Blind analysis with control regions used for MC background estimate validation

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

JHEP09(2023)035



same sign event MC BG validation



MC: signal region definition

A’ → $\mu^+\mu^-$ results opening the box

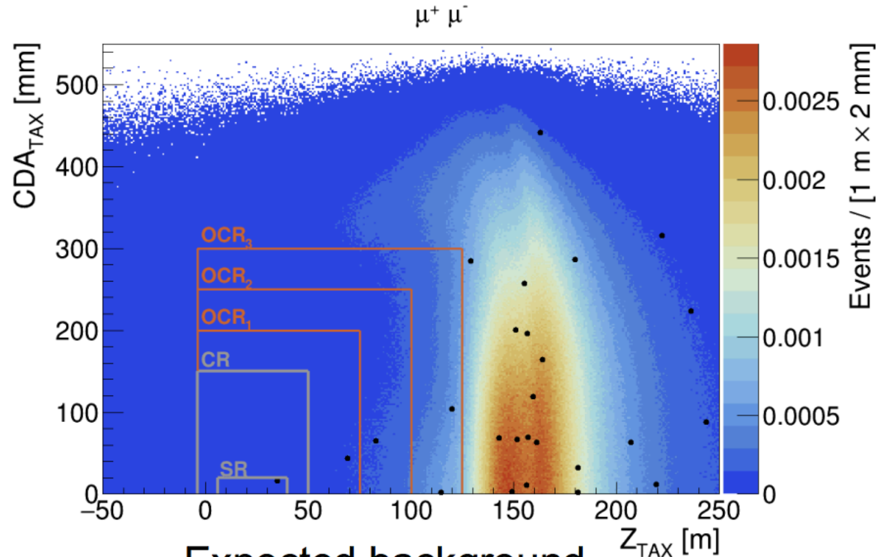
Open Signal and Control Regions:
0 events in CR 1 event in SR, black dot

Probability to observe **SM** event in SR is only **1.6%**

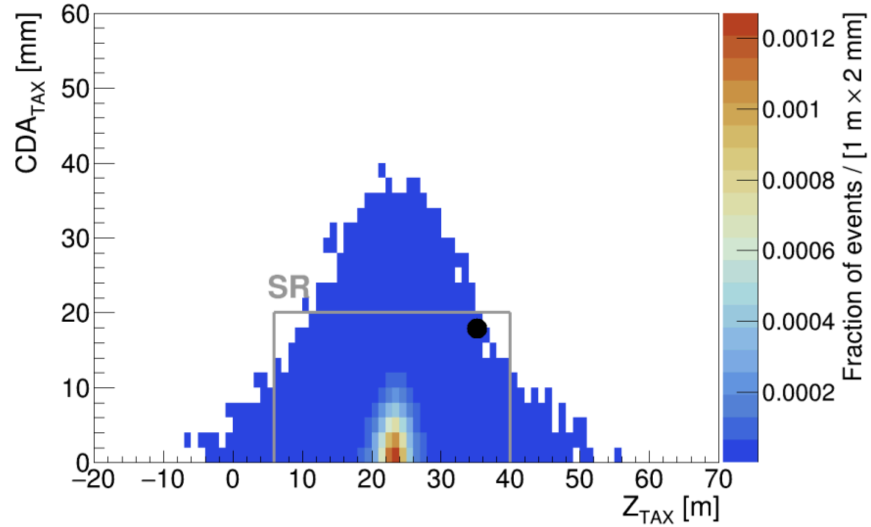
However, event on **tail end of SR** and is **ΔT** tracks is **2σ** away form zero

Invariant mass of event was 411 MeV

Observed event could be interpreted as **combinatorial background fluctuation**



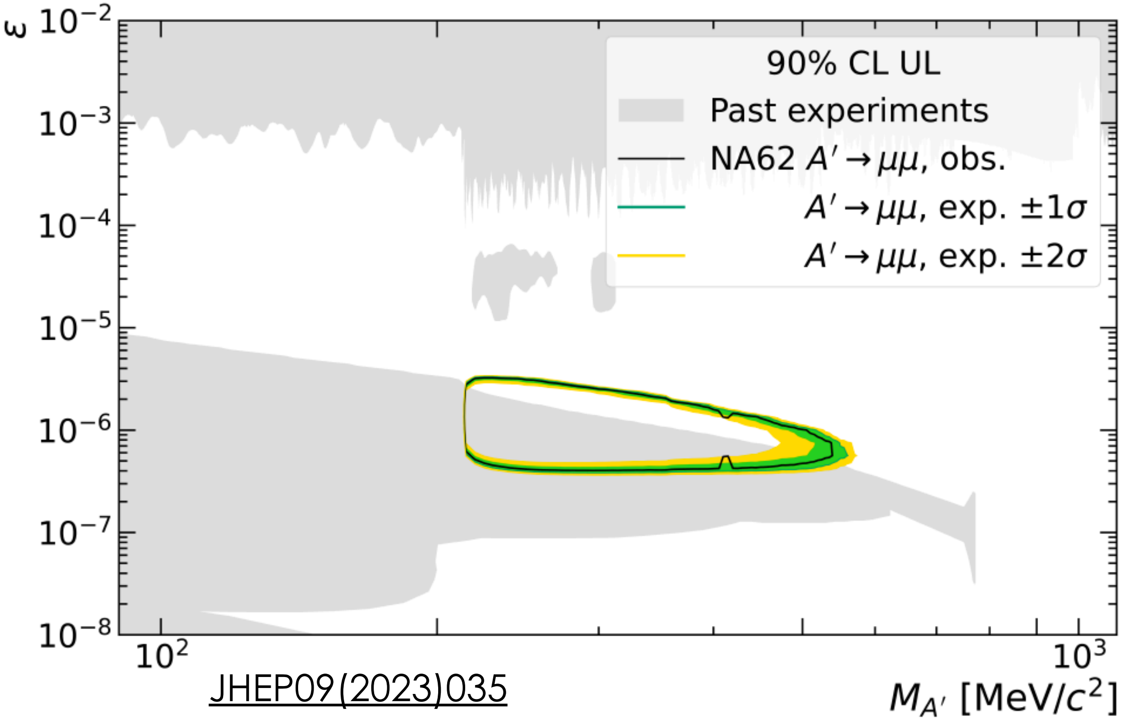
Expected background



Expected signal sensitivity

Exclusion limits

Black line: observed limit
Green filled: 1σ confidence level
Yellow filled: 2σ confidence level
Grey filled: Already excluded regions



JHEP09(2023)035

Improved 90% CL limit on DP in the mass range **215 MeV/c^2 <$M_{A'}$<550 MeV/c^2**

The A’ → e^+e^- channel

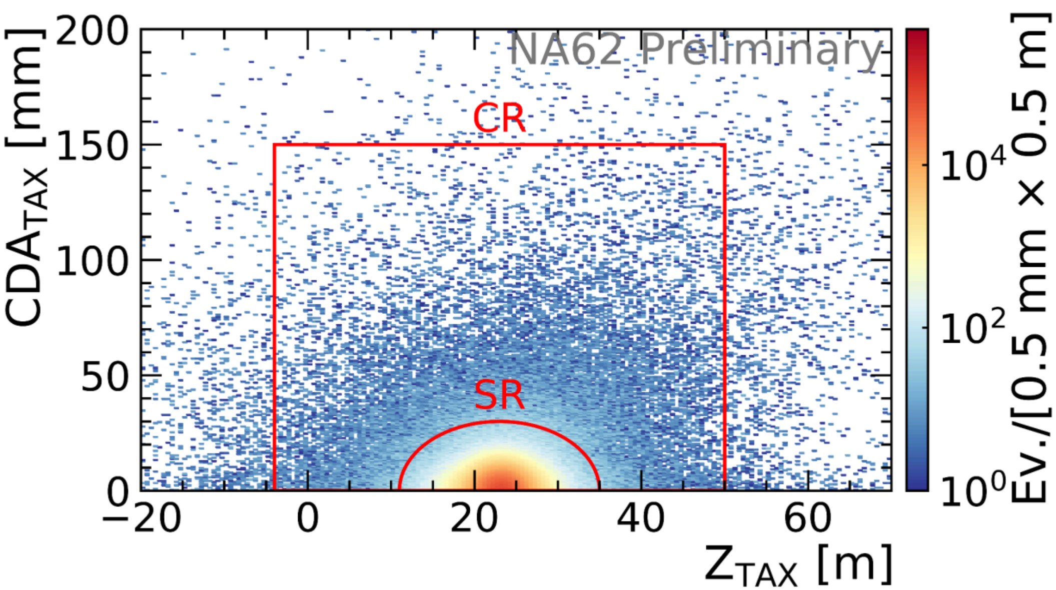
Access to the mass region $M_{A'} < 210$ MeV/c^2

Signal and control regions redefined (different kinematics)

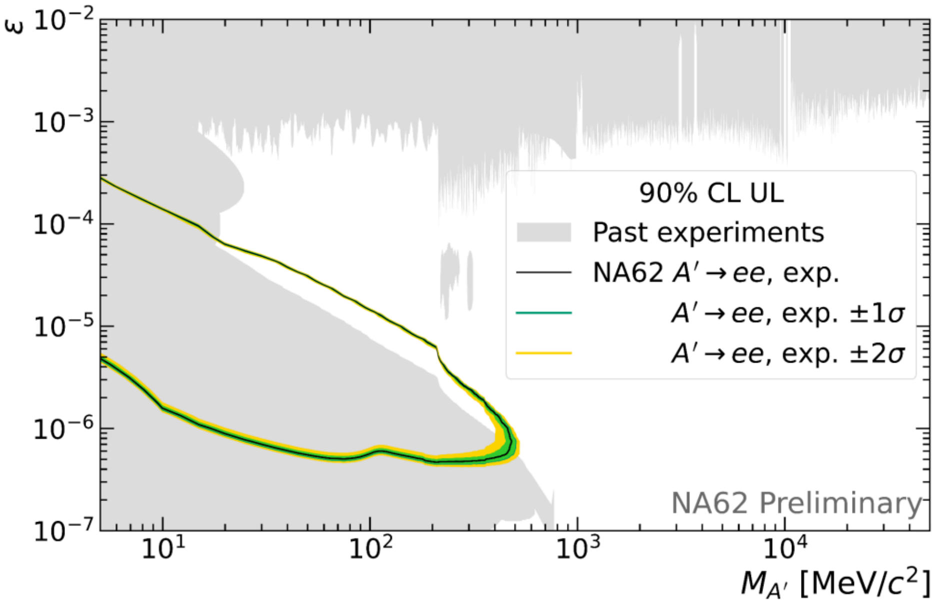
Veto on in-time activity in the muon veto detector (MUV3), Anti0, and LAV

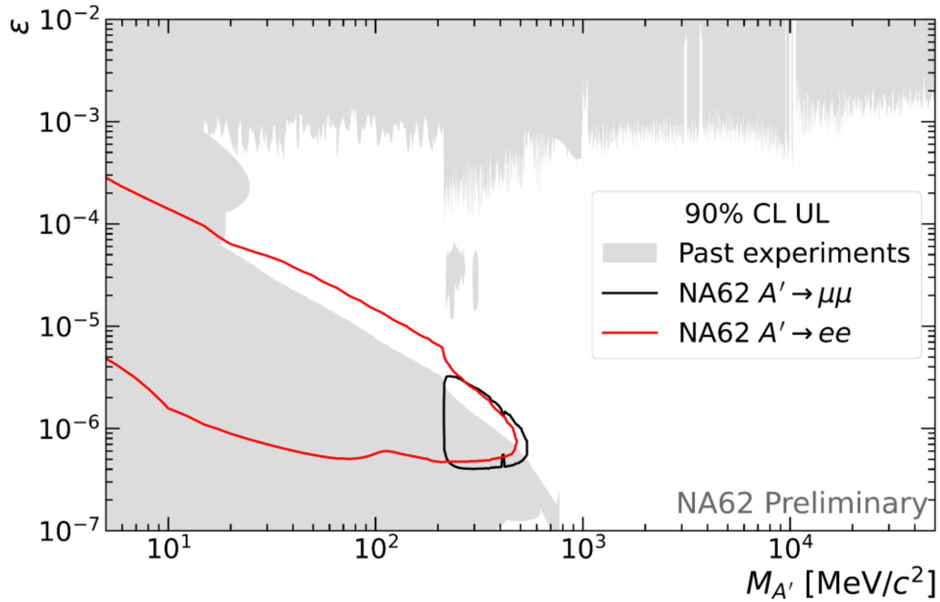
Same blind analysis technique as in A’→ $\mu^+\mu^-$

No events found in the SR after unblinding!



Combined results A'→ℓ⁺ℓ⁻





Results for **A' → e^+e^- channel only**

Combined results for **A'→e^+e^-** and **A'→$\mu^+\mu^-$**

muons extend region towards higher masses

NA62 dump mode results for 2-leptons decays improve 90% CL limit on DP in the mass range **20 MeV/c² <$M_{A'}$<550 MeV/c²**

Analysis on additional final states γγ, π π γ, μπ… ongoing on 2021 data set

Conclusions

The NA62 experiment reported the best limit for the **ultra-rare $K^+ \to \pi^+ e^+ e^- e^+ e^-$** using the 2017-2018 dataset.

$\boldsymbol{BR(K^+ \to \pi^+ 4e, \text{non res.}) < 1.4 \times 10^{-8}}$ @ 90% CL NEW arXiv:2307.04579v1

~10^{-9} UL @ 90% CL on the process: $K^+ \to \pi^+ aa$, $a \to e^+ e^-$ NEW
The QCD axion is excluded as a possible explanation of the "X17 anomaly"

The NA62 exp. in dump mode obtained its first exclusions limit on A' parameter space using 2021 dump data set (1.4×10^{17} PoT) (JHEP09(2023)035) NEW

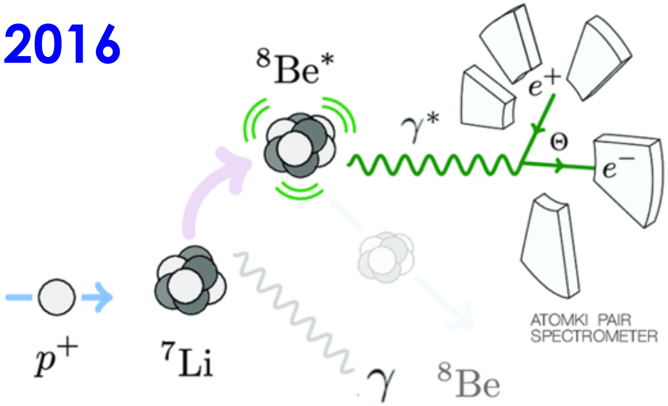
Using combined 2-leptons decays NA62 improved the 90% CL limit on DP coupling in the mass range **$20\ \text{MeV}/c^2 < M_{A'} < 550\ \text{MeV}/c^2$**

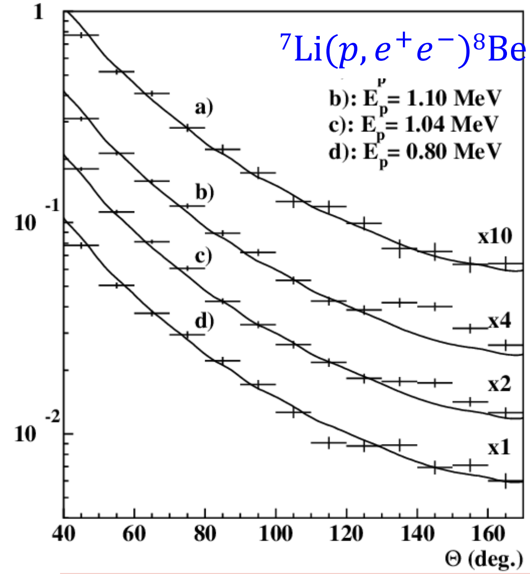
A new data set in dump mode has been collected in 23, increasing the total PoT to ~4×10^{17}

Backup Slides

The ^{8}Be and ^{4}He Atomki anomaly

2016

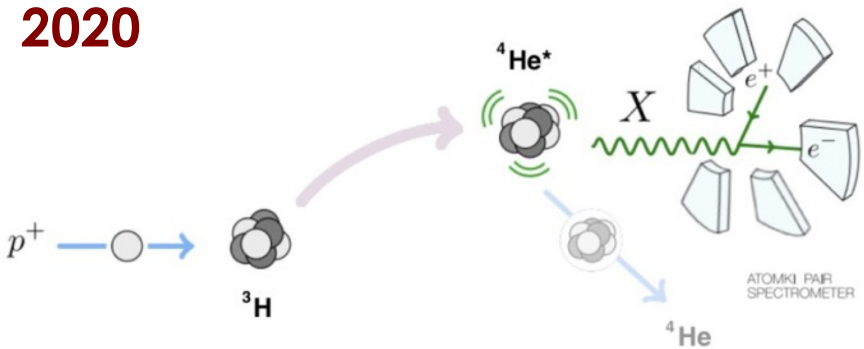


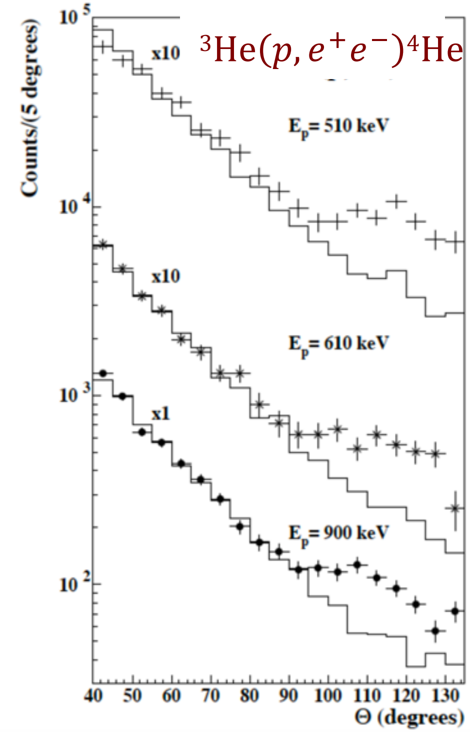


$m_X c^2 = 17.01 \pm 0.16(\text{tot})$ MeV

PRL 116, 042501 (2016)

2020





$m_X c^2 = 16.98 \pm 0.16(\text{stat}) \pm 0.20(\text{syst})$ MeV

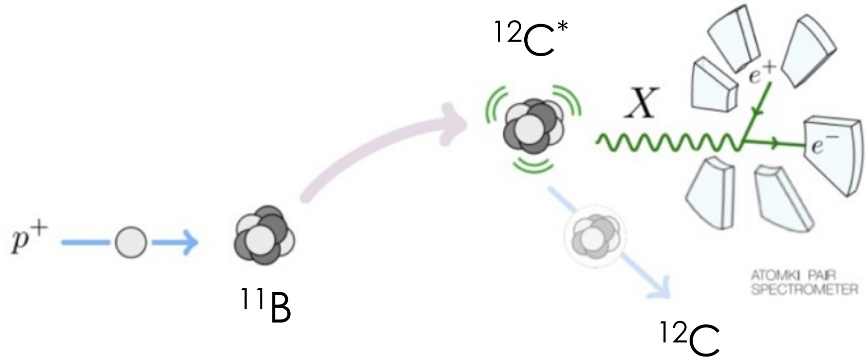
Phys. Rev. C 104, 044003 (2021)

ATOMKI has confirmed the anomalous peak in the angular distribution of internal pair creation in **^{8}Be with a similar** one in the **^{4}He** transitions, with different kinematics but at the **same invariant mass value.**

The ^{12}C anomaly and the vector portal

New anomaly observed in ^{12}C supports the existence and the vector character of the hypothetical X17 boson

Phys. Rev. C 106, L061601
Dec 2022



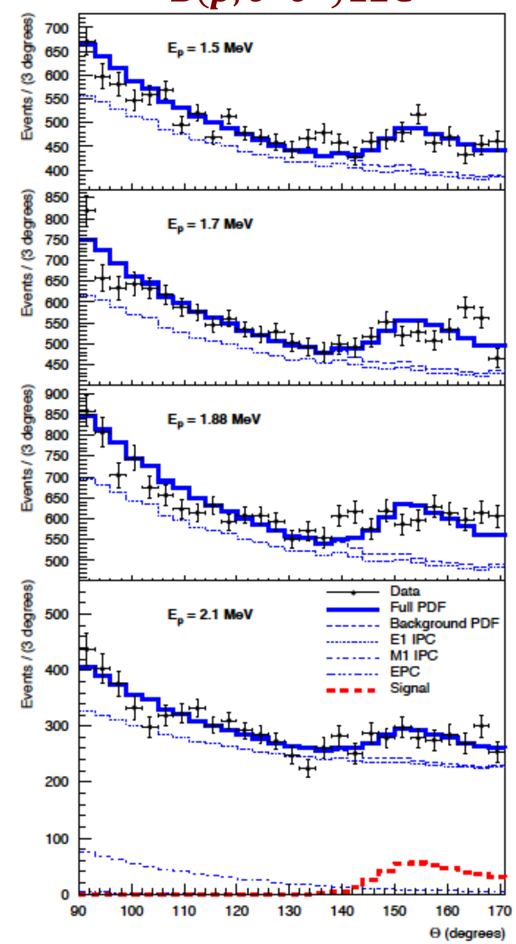
E = 17.23 MeV excited state of ^{12}C

TABLE I. X17 branching ratios (B_x), masses, and confidences derived from the fits.

E_p	B_x	Mass	Confidence
(MeV)	$\times 10^{-6}$	(MeV/c^2)	
1.50	1.1(6)	16.81(15)	3σ
1.70	3.3(7)	16.93(8)	7σ
1.88	3.9(7)	17.13(10)	8σ
2.10	4.9(21)	17.06(10)	3σ
Averages	3.6(3)	17.03(11)	
Previous [14]	5.8	16.70(30)	
Previous [31]	5.1	16.94(12)	
Predicted [33]	3.0		

4 different p bombarding energies with strong significance

$^{11}B(p, e^+e^-)12C$



On the nature of X17

PHYSICAL REVIEW D **102**, 036016 (2020)

Dynamical evidence for a fifth force explanation of the ATOMKI nuclear anomalies

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Department of Physics and Astronomy, University of California, Irvine, California 92697-4575, USA

J. Feng and collaborators suggested that the X17 should be observed in ^{12}C transitions
X17 observations in ^{12}C will point to a vector or axial vector nature for X17
Pseudo Scalar X17 killed by ^{12}C observation now confirmed

TABLE III. Nuclear excited states N_*, their spin-parity $J_*^{P_*}$, and the possibilities for X (scalar, pseudoscalar, vector, axial vector) allowed by angular momentum and parity conservation, along with the operators that mediate the decay and references to the equation numbers where these operators are defined. The operator subscripts label the operator's dimension and the partial wave of the decay, and the superscript labels the X spin. For example, $\mathcal{O}_{4P}^{(0)}$ is a dimension-four operator that mediates a P-wave decay to a spin-0 X boson.

N_*	$J_*^{P_*}$	Scalar X	Pseudoscalar X	Vector X	Axial Vector X
^{8}Be(18.15)	1^+	…	$\mathcal{O}_{4P}^{(0)}$ (27)	$\mathcal{O}_{5P}^{(1)}$ (37)	$\mathcal{O}_{3S}^{(1)}$ (29), $\mathcal{O}_{5D}^{(1)}$ (34)
^{12}C(17.23)	1^-	$\mathcal{O}_{4P}^{(0)}$ (27)	…	$\mathcal{O}_{3S}^{(1)}$ (29), $\mathcal{O}_{5D}^{(1)}$ (34)	$\mathcal{O}_{5P}^{(1)}$ (37)
^{4}He(21.01)	0^-	…	$\mathcal{O}_{3S}^{(0)}$ (39)	…	$\mathcal{O}_{4P}^{(1)}$ (40)
^{4}He(20.21)	0^+	$\mathcal{O}_{3S}^{(0)}$ (39)	…	$\mathcal{O}_{4P}^{(1)}$ (40)	…

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