Why to dump your particle beam, at least occasionally

— the example of NA62 —

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European Research Council
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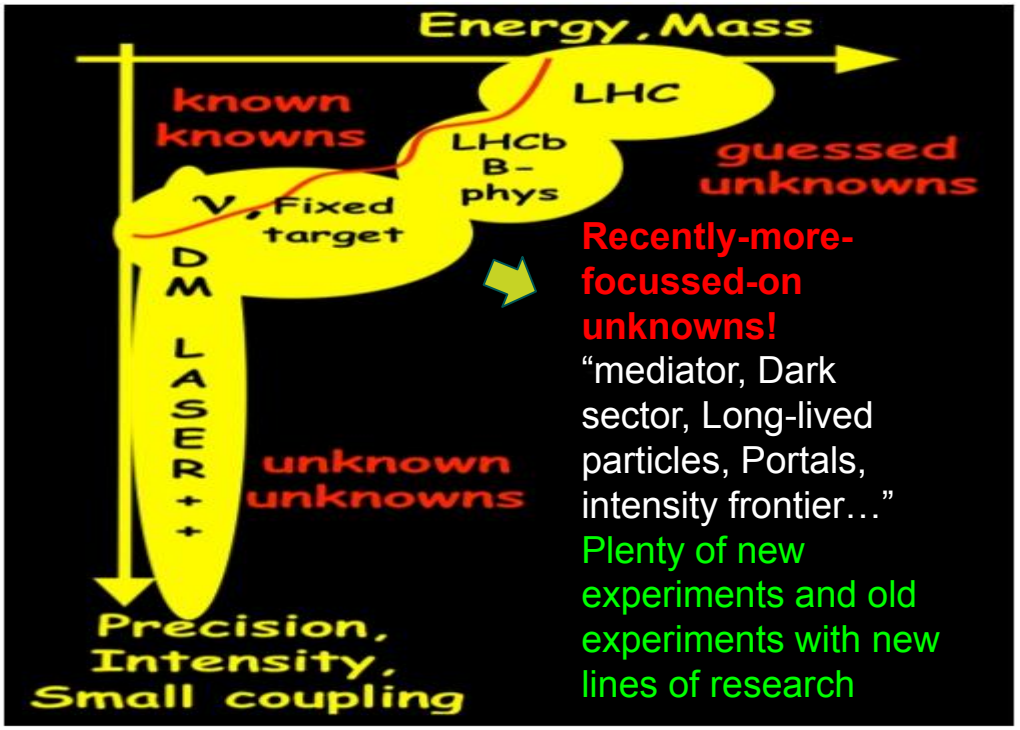
The case for weakly coupled particles at the MeV-GeV scale



Based on figure from Joerg Jaeckel, ITP Heidelberg

Light-weight Dark Matter: e.g. QCD axion, inherently stable, cannot decay into SM particles

E.g. SUSY, heavy Dark Matter protected from decay by symmetry

One case for weakly coupled particles at the MeV-GeV scale

- The most common paradigm for DM is the WIMP -> New massive particle in thermal equilibrium with the SM in the Early Universe
- Decouples at T ~ m, its abundance freezes out
- reproducing relic abundances fixes the interaction to be at the electroweak scale

$$\langle \sigma v \rangle \simeq 1 \text{ pb} \left(\frac{\alpha_W}{10^{-2}} \right)^2 \left(\frac{\text{TeV}}{m_\chi} \right)^2$$

EW scale mass

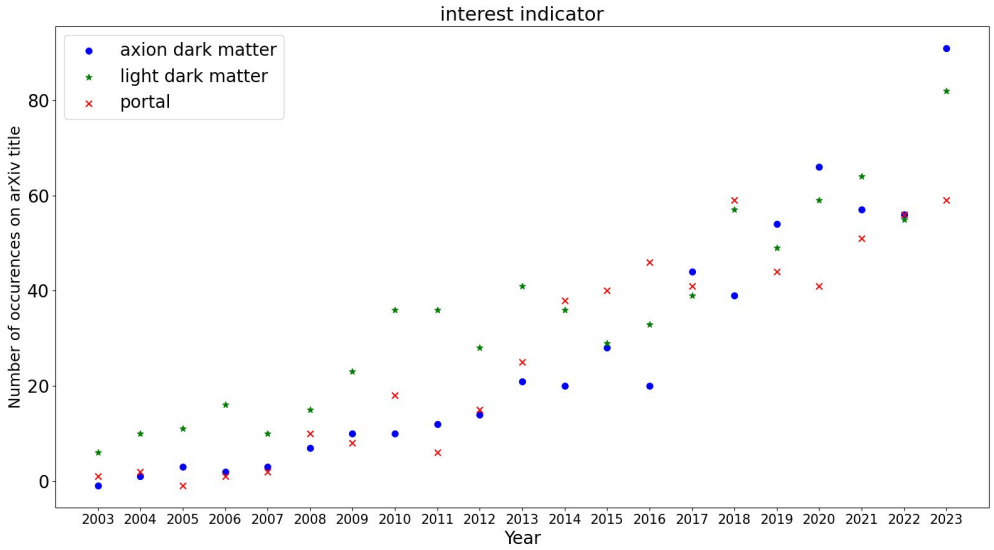
EW scale coupling

- TeV scale particle with EW coupling gives the right relic abundance

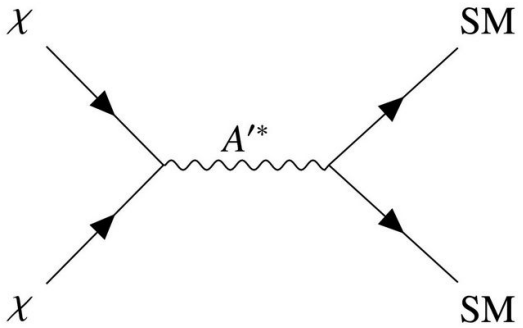
WIMP miracle

The case for weakly coupled particles at the MeV-GeV scale

- ``WIMPless miracle'' [Feng, Kumar] (and others!) : DM can be significantly lighter than TeV without overproducing it:
- Mediators that are BSM states -> “Portal”, ``light Dark Matter''
- Dark Photon: Appropriate relic abundance when mass up to 1 GeV, together with mixing ε within 10−6 to 10−3



$$L \sim \epsilon F'^{\mu\nu} B_{\mu\nu}$$

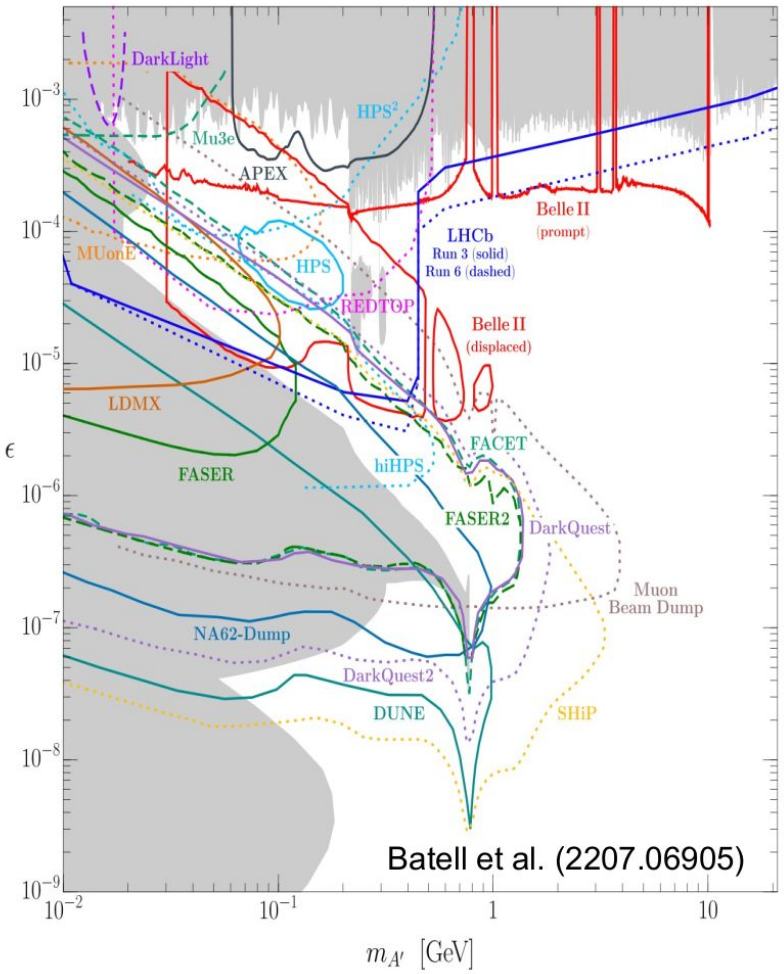


Example: The Dark Photon

- “Nose shape” sensitivity: certain decay lengths are favored by geometry

Some observations/remarks regarding plot on the r.h.s.:

1. **Clearly there is some interest/competition**
2. **Attempts have been made to make this more readable: different line-styles to indicate time-line, level of “maturity/readiness”**
3. **Still, for a non-expert, one may ask:**
   - **What’s a relevant parameter region?**
   - **Do some curves stand-out with respect to the others?**
   - **Is the plot done in a consistent fashion? I.e.: are the underlying assumptions comparable?**



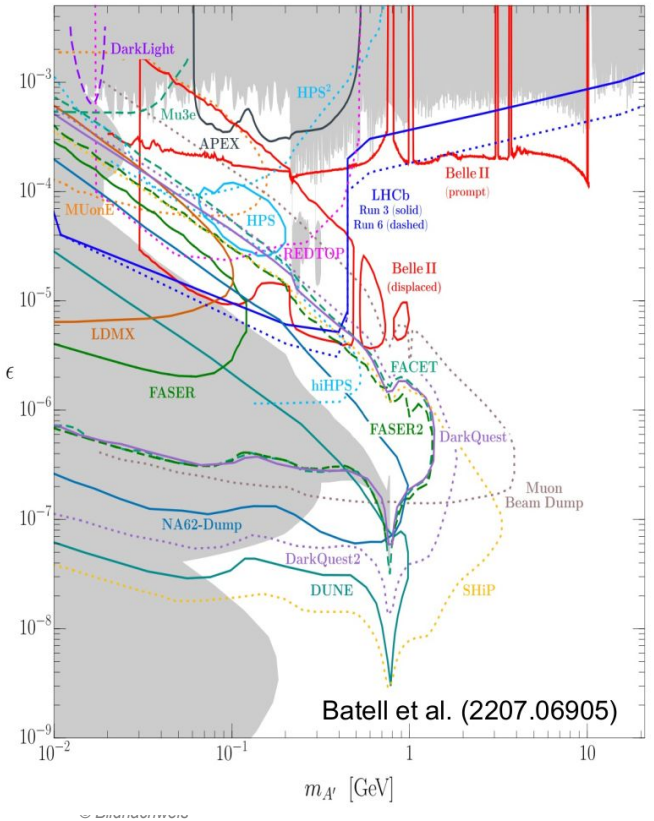
Scrutinizing Dark Sector Projections

I want to emphasize that there is a selection of aspects that is important to address when attempting to read such a plot (or produce one yourself), not only for Dark Photons

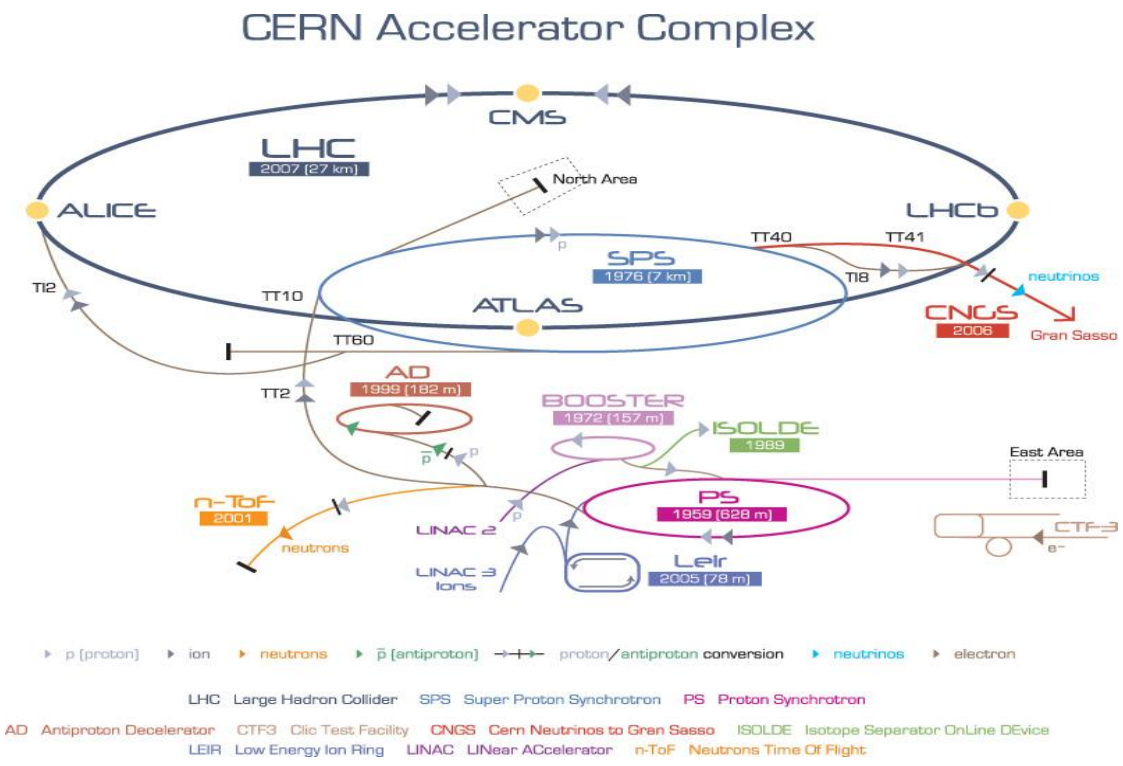
Specifically, one has to be mindful about the

1. **Comprehensiveness of input processes**
2. **Influence/options of different input shapes for exotic production (e.g. parent mesons!)**
3. **Transparency of assumptions (public code?)**
4. **Theoretical limitations (model-dependence)**
5. **Practical limitations (0 background, sufficient statistics in understanding if this is really true, MC)**

Happy to talk about these aspects as well (over dinner?) , <u>but decided to focus on some experimental results today</u>!



NA62 @ CERN/Prevessin



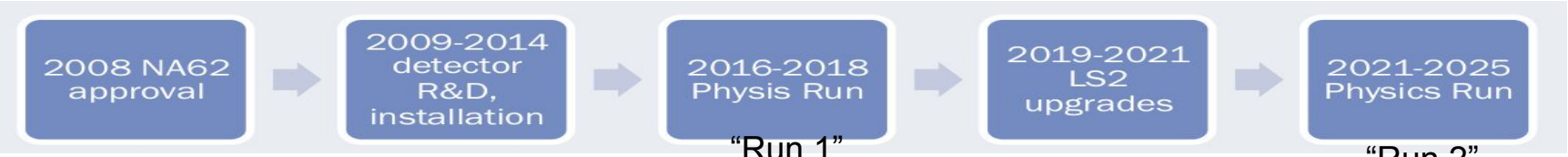
- Fixed target experiment at CERN's north area (NA)
- Around 200 participants
- **Main goal:** measure branching ratio

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

- Precision measurements
- Rare and forbidden decays
- **Beam dump/Exotics**

Each of above would warrant its own talk, focus on #3 today

NA62 experiment: timeline and impressions



"Run 1"

"Run 2"

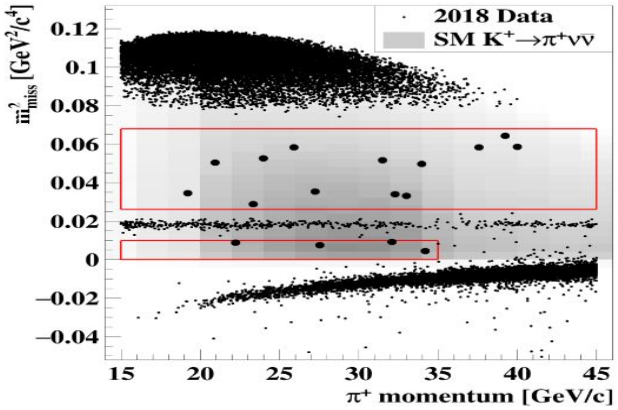
<- View of the ECN3 hall

Last [SPSC status report (G. Ruggiero, May 11th 2023)]

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

$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$

$\mathcal{O}(100\ ps)$	Timing
$\sim 10^3$	Kinematic background suppression
$\sim 10^8$	Muon suppression
$\sim 10^8$	π^0 suppression



$N^{exp}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$,

$N^{exp}_{background} = 7.03^{+1.05}_{-0.82}$.

$N_{obs} = 20$

3.4σ evidence $K^+ \to \pi^+ \nu\bar{\nu}$

$BR = (10.6^{+4.0}_{-3.4} \pm 0.9) \times 10^{-11}$

JHEP06(2021)093

"Random Veto"

Probability of signal loss when rejecting photons

Loss due to random veto induced by accidental activity

"Upstream" background

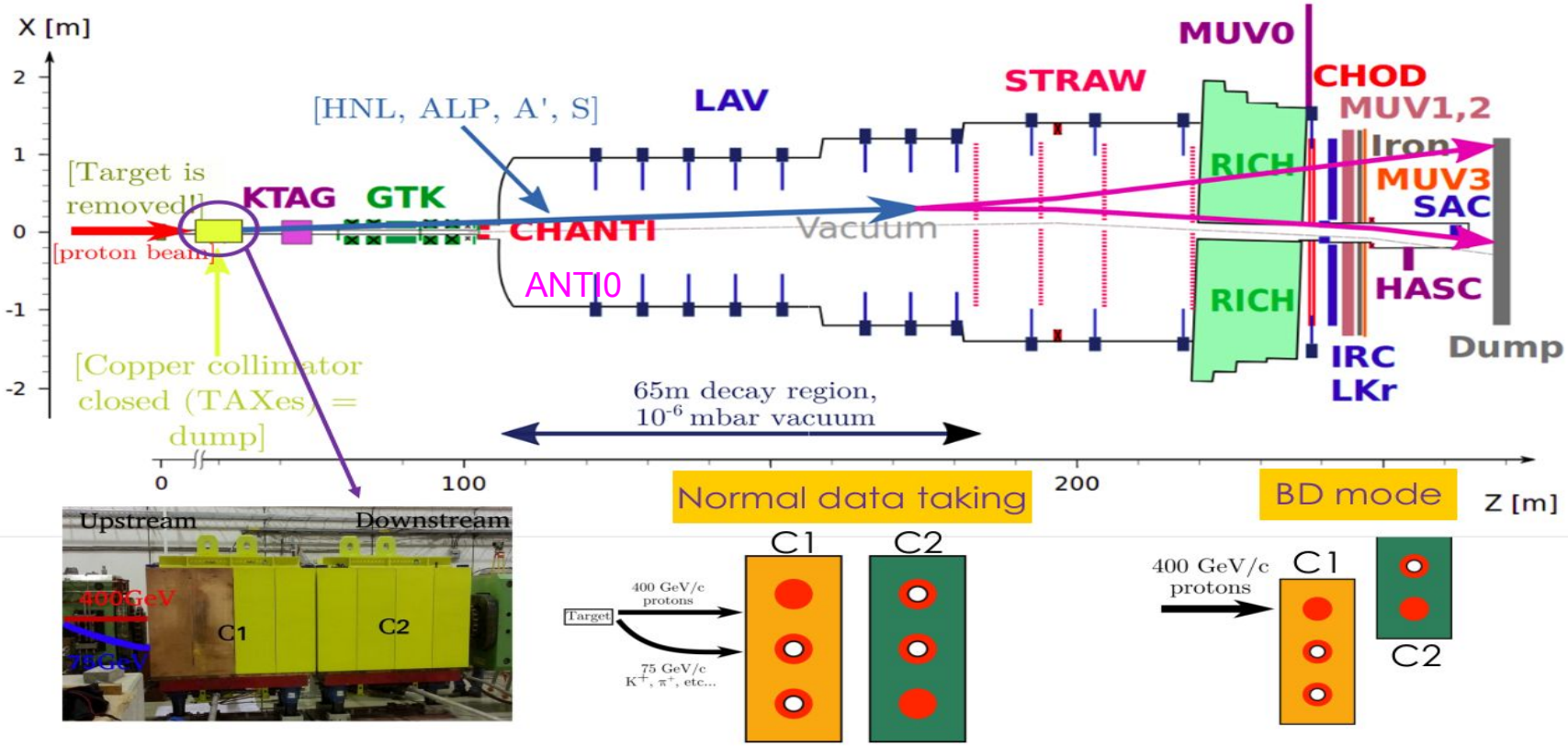
K^+ decays upstream

Problem: lack of vetoes along the beam line

The target region

- Target (hit by p+) -> Kaons of 75GeV
- Collimators after target movable & go into "closed position" within few minutes. Target itself can also be removed within few minutes
- Then, 400 GeV protons from the SPS impinge **directly** on several meters of copper/iron *(dubbed TAXes)* **-> beam dump**
- The above settings can be reverted within few minutes.
- WHY? **Produce (weakly interacting) axion like particles in p+ interaction that could decay in the experimental volume of NA62** **(e.g.** pN -> X A', **B-> K a …)!**

The NA62 experiment in Beam-Dump mode



Summarizing what we have so far

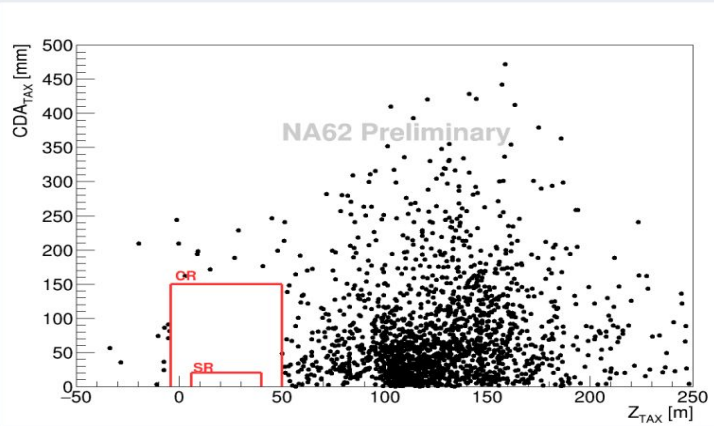
- Why to run in beam-dump: Low-risk, high-gain!
- Several physics models (Axions, Dark Photons, HNLs…) can be probed in new parameters often within only **few days of data taking**
- This holds true only if **backgrounds can be kept under control**
- **… and** one can still simulate it within accurate statistics
- Started with exploratory data-taking intervals from 2016 onwards
- Significant amounts of data collected in 2018, and again in 2021

Collected $(1.4 \pm 0.28) \times 10^{17}$ POT in around 10 days of data taking in 2021 and a slightly bigger sample in 2023

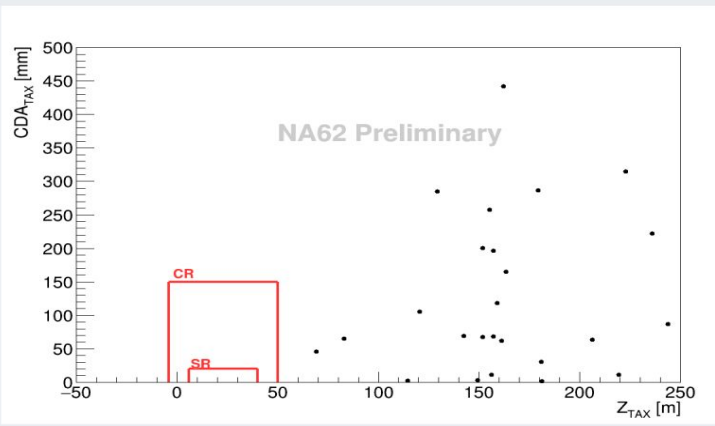
Background reduction 2018 vs 2021

- **Normally, 75GeV component retains focus, see bottom left**
- **upstream magnet tuned** to increase muon sweeping (studied with help from PBC)
- In 2021, compared to 2018, background rejection was increased by **O(200)** on most 2-track channels despite higher intensity (example below: $\mu^+\mu^-$)

2018 data: 2.6×10^{16} POT



2021 data: 1.4×10^{17} POT

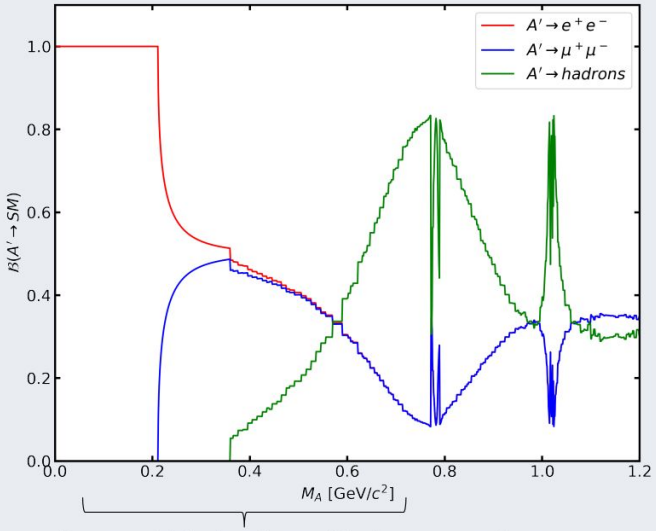


Physics reach/ final states

Model probed will depend on final state
– **Vector portal → Dark Photons (DP)**
– Scalar portal → Dark Scalars
– Neutrino portal → Heavy Neutral Leptons
– Axion portal → Axions and **Axion-like particles**

- A specific constrained model: kinetic mixing interaction with the SM hypercharge

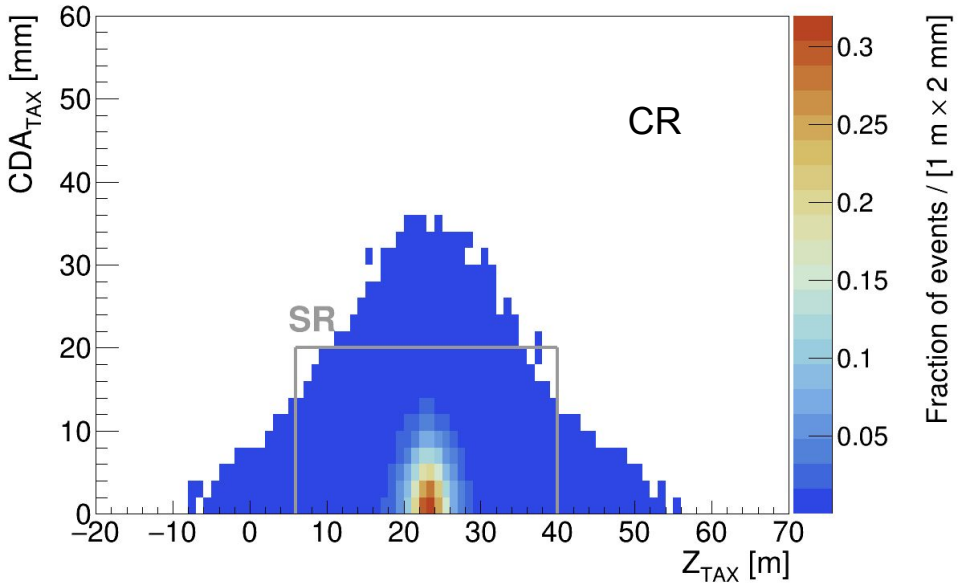
- Production modes: **Bremsstrahlung** pN -> X A' and **meson decays** pN -> X M, M -> A' $\gamma(\pi^0)$ (where M = $\pi^0, \eta, \rho, \omega$ etc)



Decay width dominated by lepton-antilepton final states for $M_{A'}$ < 700 MeV

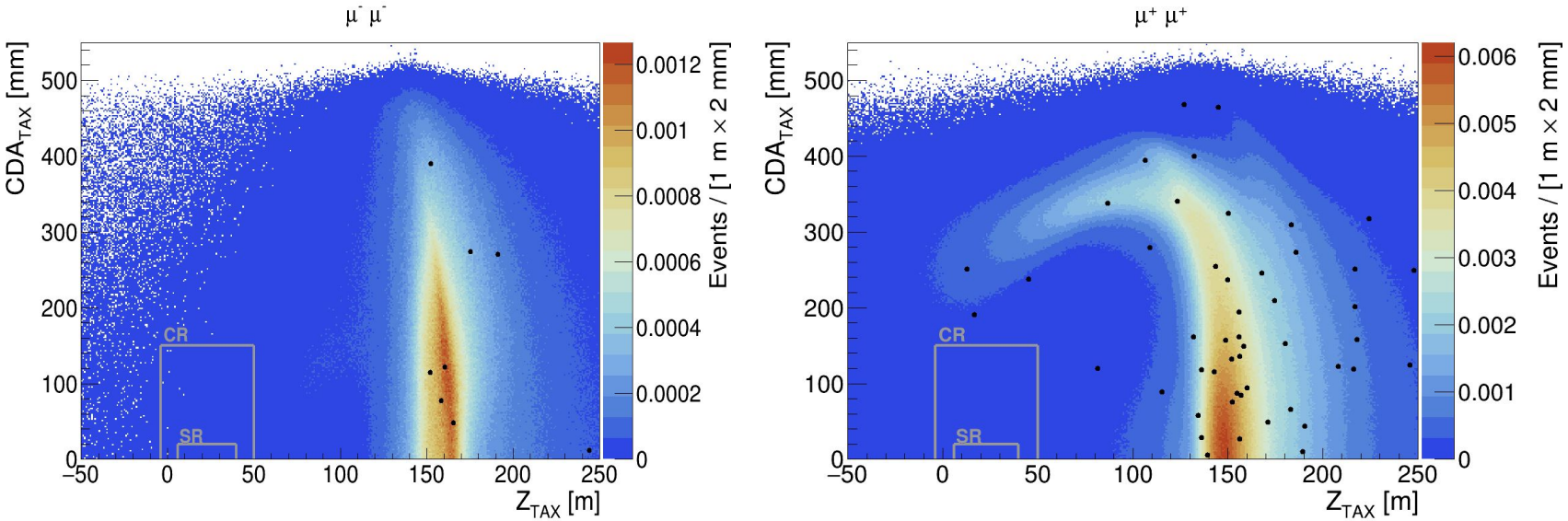
Analysis strategy for A' -> $\mu^+\mu^-$ with 2021 data

- **Pointing:** Exploit expectation of CDA between beam direction at the TAX entrance
- Event selection: track quality, timing coincidence, PID with calorimeter and muon detector, … and much more
- CR and SR kept blind up to analysis approval
- Dominant background combinatorial (well below 1 evt. In SR as well as CR)
- Build bkg artificially from single tracks (orthogonal to analysis sample - different trigger line)



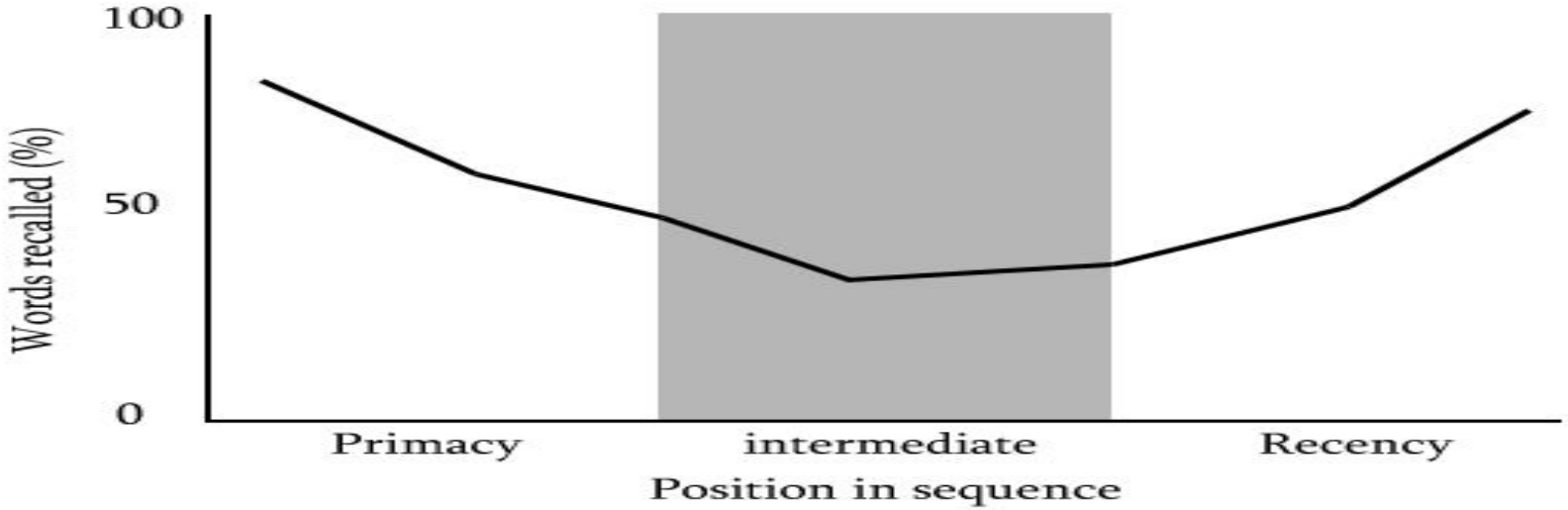
Distribution of Monte Carlo signal events for Dark Photons

Data-MC comparison: Control sample for combinatorial sample

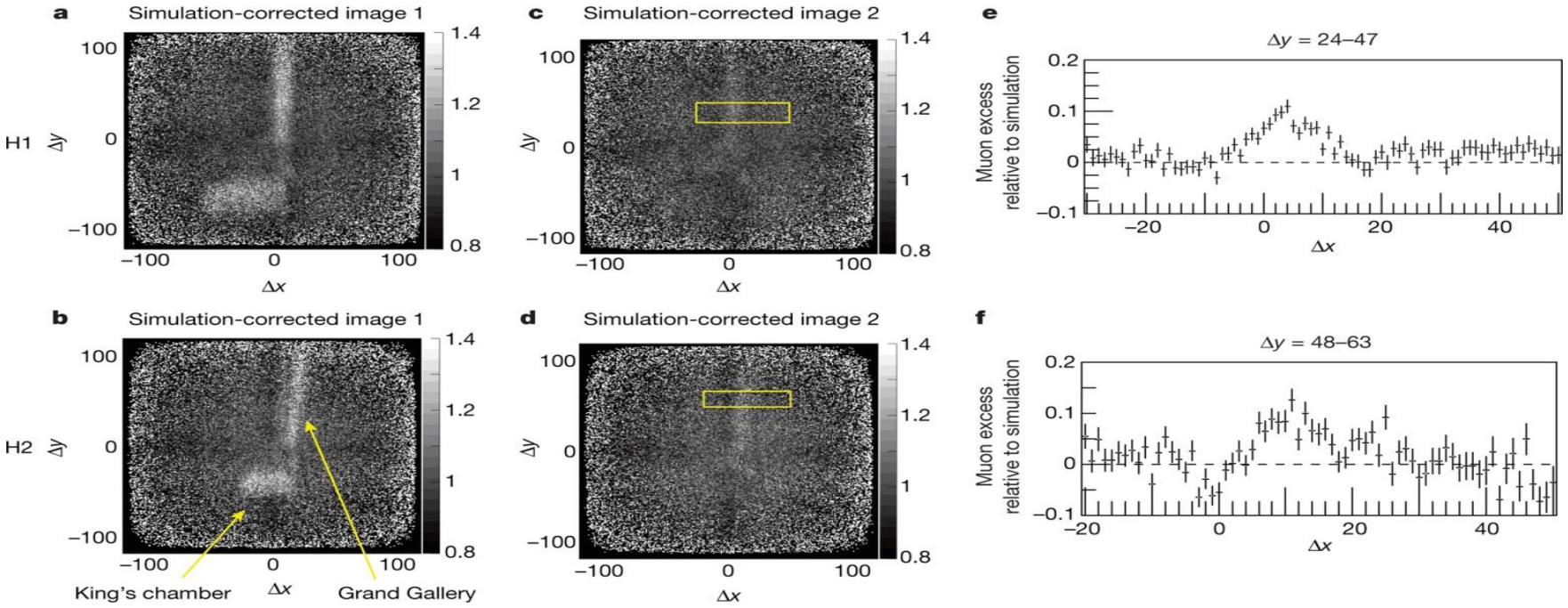


- Peculiar shape in same-sign events due to beamline element focussing effects
- That's the prompt contribution, how about in-time?

Let’s try to pause and fight the recency effect



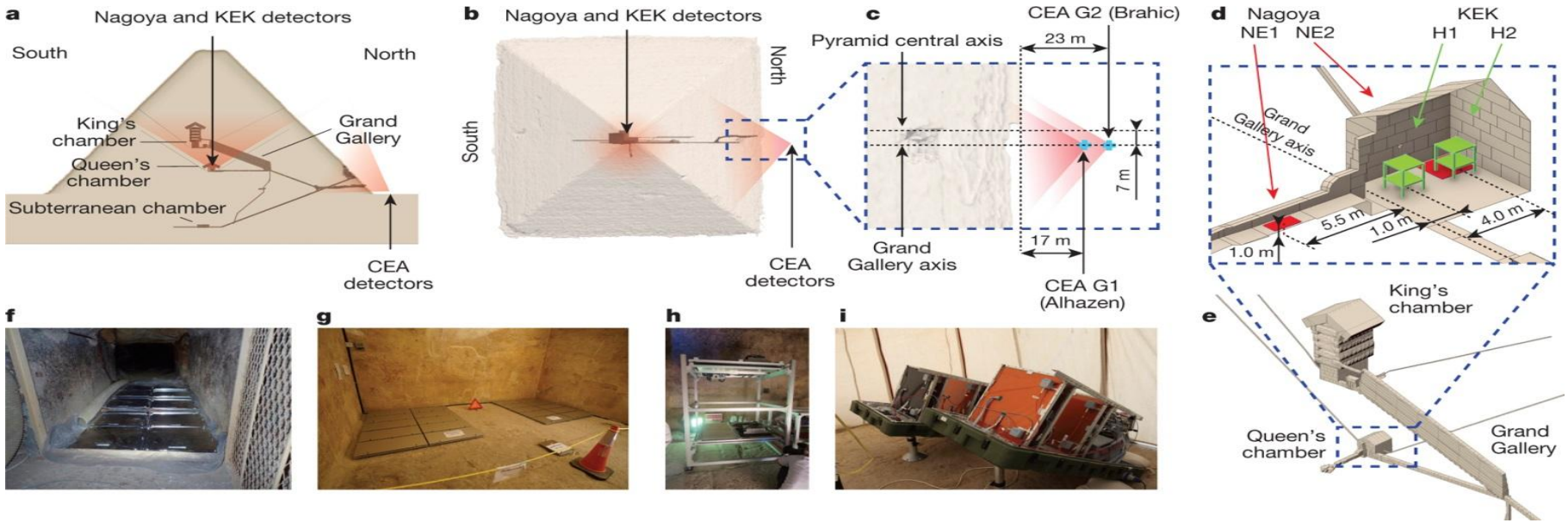
Digression: world news in 2017



K Morishima *et al. Nature* **552,** 386–390 (2017) doi:10.1038/nature24647

nature

Muography for Khufu's Pyramid



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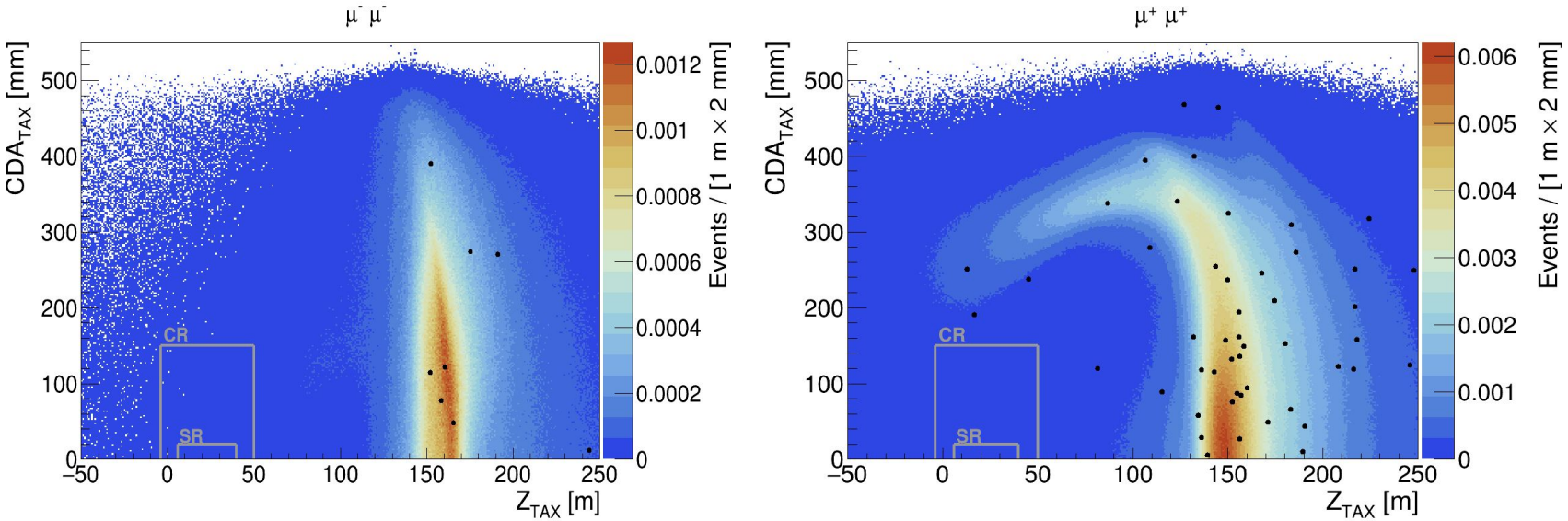
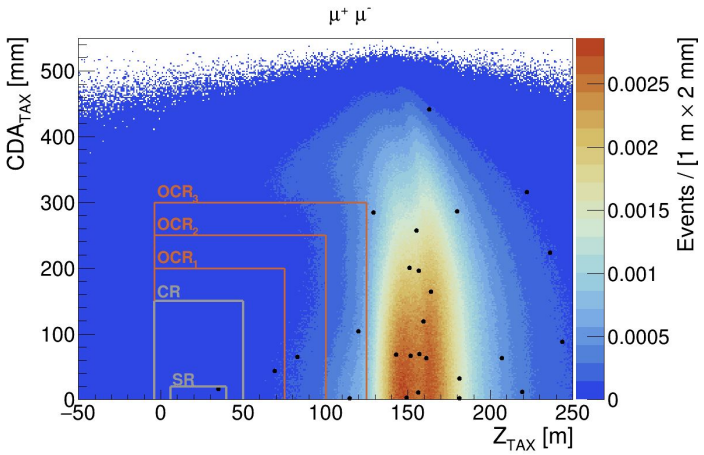
nature

Data-MC comparison: Control sample for combinatorial sample

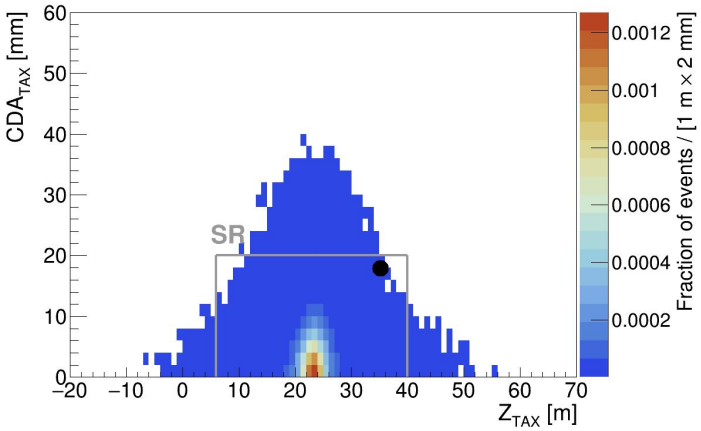


- Peculiar shape in same-sign events due to beamline element focussing effects
- For in-time (prompt) kinematics extracted from above (**backward muon MC** - PUMAS)

Data-MC comparison: SR open $\mu^+\mu^-$

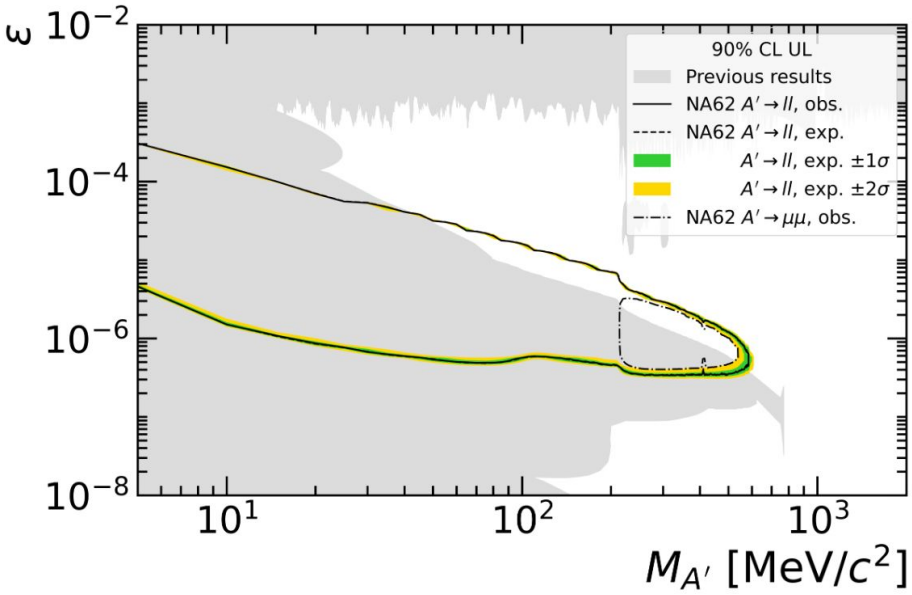


- Color scale: Expected background
- 1 event observed in SR



- Probability to observe 1 event in SR: 1.6 %:
- Invariant mass of event: 411 MeV
- Time difference ~2 sigma away from mean for signal events
- Event in far-tail of SR
- (later analysis: No events when opening SR in e^+e^-)

Complete picture: Leptonic decay of Dark Photons



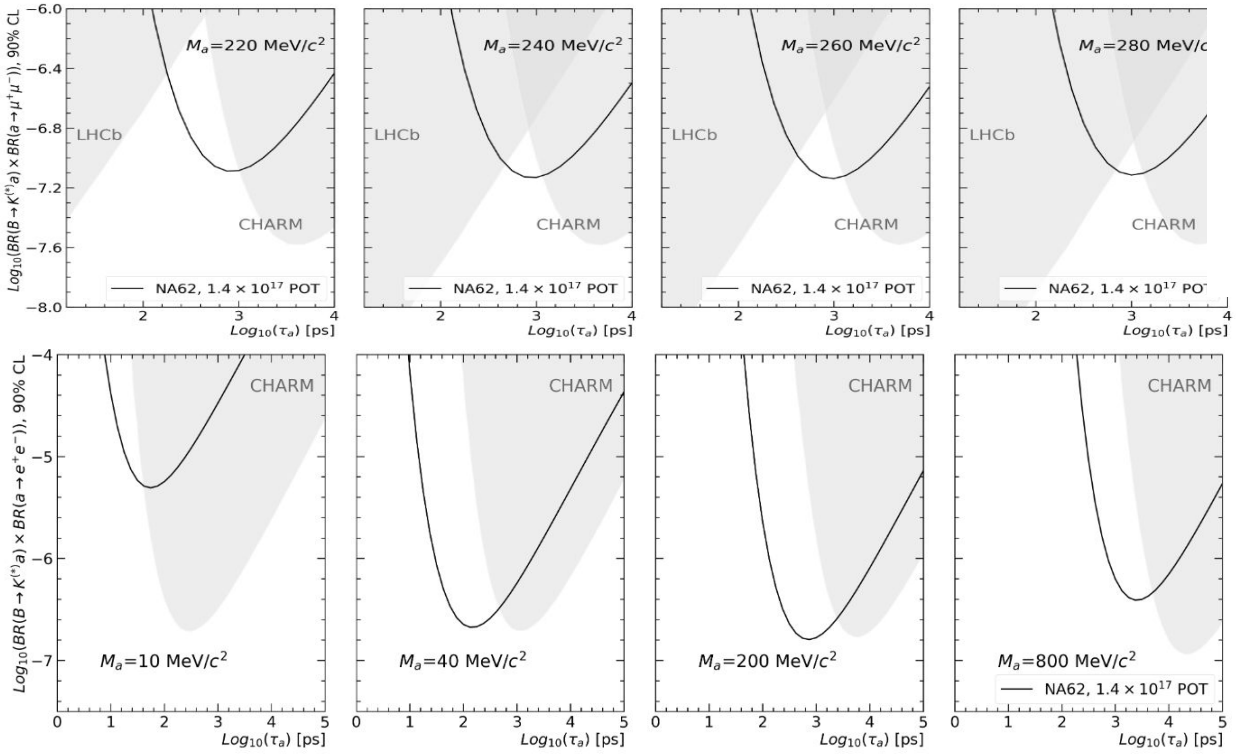
Together with FASER@LHC, first new limits in this region since the 80s!

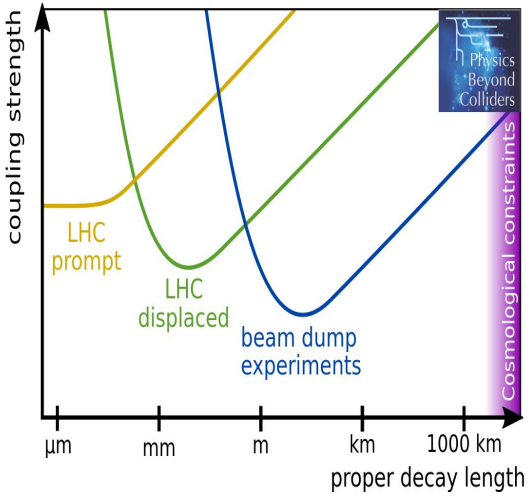
in JHEP for muons
https://link.springer.com/article/10.1007/JHEP09%282023%29035

And on the arxiv for electrons
[2312.12055]

… result for axion-like particles

fresh from the arxiv [2312.12055]





Top: $\mu^+\mu^-$,
bottom: e^+e^-

Assuming mass, lifetime and coupling to be independent parameters
see PLB 790 (2019) 537

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SEARCHES FOR NEW PHYSICS | NEWS

Searching for dark photons in beam-dump mode

24 April 2023

Intense Part of the NA62 detector in the ECN3 experimental hall in Prevessin, where beam travels from right to left. On the right-hand side is the STRAW spectrometer, with the analysing magnet in blue. Four large-angle vetoes serving to clean the samples from non-forward events are visible in white, while the green region houses the RICH detector. Credit: CERN-PHOTO-202104-059-6

Faced with the no-show of phenomena beyond the Standard Model at the high mass and energy scales explored so far by the LHC, it has recently become a much considered possibility that new physics hides "in plain sight", namely at mass scales that can be very easily accessed but at very small coupling strengths. If this were the case, then high-intensity experiments have an advantage: thanks to the large number of events that can be generated, even the most feeble couplings corresponding to the rarest processes can be accessible.

Such a high-intensity experiment is NA62 at CERN's North Area. Designed to measure the ultra-rare kaon decay $K \to \pi\nu\bar{\nu}$, it has also released several results probing the existence of weakly coupled processes that could become visible in its apparatus, a prominent example being the decay of a kaon into a pion and an axion. But there is also an unusual way in which NA62 can probe this kind of physics using a configuration that was not foreseen when the experiment was planned, for which the first result was recently reported.

Article in CERN courier from April 24th 2023:
link

Close-to-final: Hadronic final states

Projections on

Gluon-coupled ALPs using

ALPINIST [2201.05170]

Results expected for

Moriond EW/QCD,

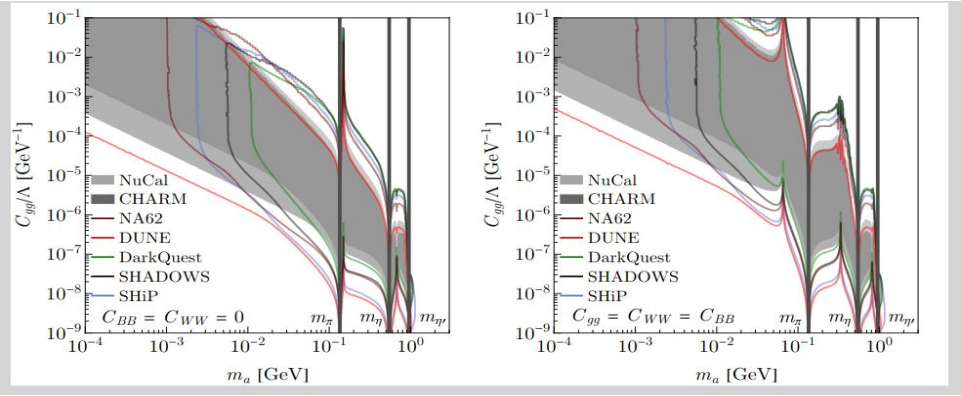
End March 2024

Main aim: search for ALPs, however other exotics have the same decay channels
Decay channels of interest ($2\pi = \pi^+\pi^-$, $2K = K^+K^-$):

- **ALP** $\to 2\pi\gamma$ / $2\pi\pi^0$ / $2\pi 2\pi^0$ / $2\pi\eta$ / $2K\pi^0$ / $\rho\rho$
- **DS** $\to 2\pi$ / $2\pi 2\pi^0$ / $2K$ / 2ρ
- **DP** $\to 2\pi$ / $2\pi\pi^0$ / $2\pi 2\pi^0$ / $2K$ / $2K\pi^0$

Production channels:

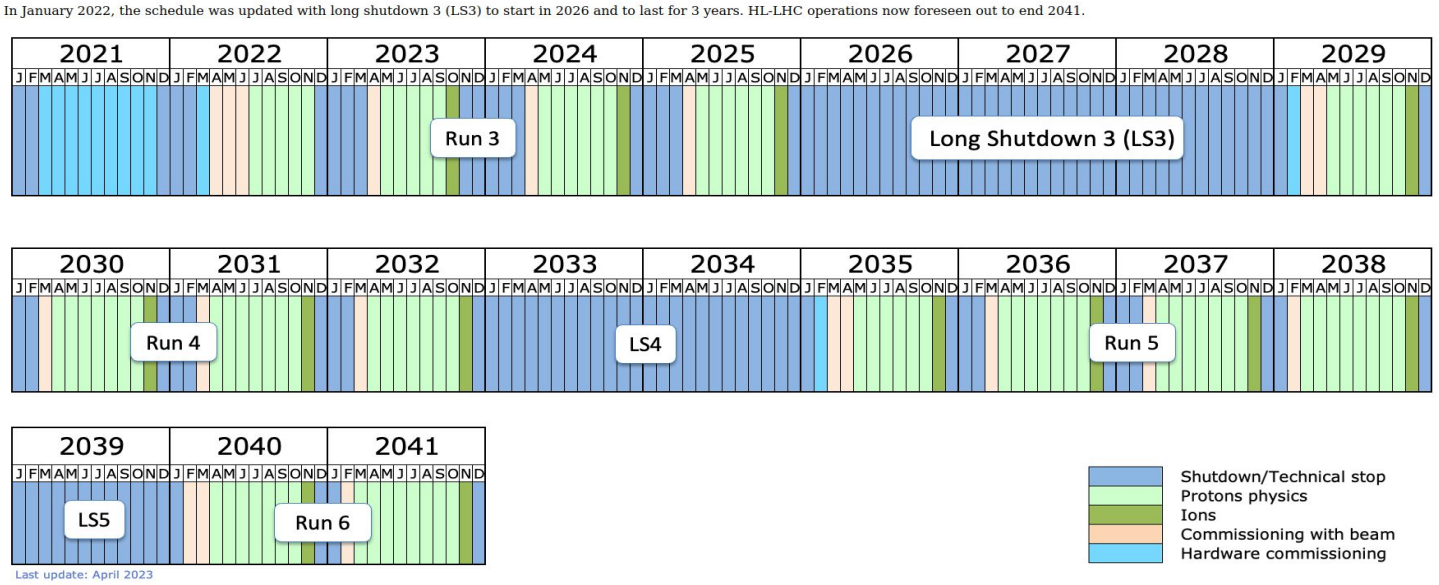
- **ALP** (5): Primakoff ($\gamma^\star\gamma^{(\star)} \to a$); $B \to K^{(\star)}a$; meson mixing ($\pi^0/\eta/\eta'$-a)
- **DS** (1): $B \to K^{(\star)}S$
- **DP** (2): Bremsstrahlung; $\pi^0/\eta/\omega/\rho/\phi \to A'\gamma$



Exotics in NA62 now and in the future

- Several additional analyses ongoing with current data-set γγ (ALPs), π π γ, μπ, possibly also open kinematics (HNLs)…
- Additional data taking during this run performed in July 2023, sample is larger than in 2021, another sample foreseen in 2024
- Exotics can also be found in Kaon decays (e.g. K -> π γγ, K -> π X)
- Data-taking ongoing and continuing until 2025
- Lively discussion ongoing about ECN3's Future: report on options in ECN3

Longer term LHC schedule



Defining plans for >2028. Currently HL-LHC operations foreseen out to end 2041 (but can still evolve very much obviously!).

ECN3 @Prevessin

- Discussion ongoing about ECN3 Future after 2029: [CERN courier article, January 2023]
- First step: experiment agnostic high-intensity facility: SPSC expressed “strong support” to the facility (February 2023)
- Second Step: decision of experimental program foreseen for December 2023 -> postponed to March 2024
- Current proposals: SHiP/BDF, HIKE + SHADOWs, see [talk by U. Wiedemann for background on decision process]

Possible extension of NA62: HIKE

- Idea: 4-fold increase on primary intensity. Requires major upgrades of the primary and secondary beamlines
- HIKE Program of multiple phases, first with charged and then neutral kaon beams, **periods in beam dump mode, combined with off-axis detector Shadows**
- Proposal released [2311.08231]

HIKE, High Intensity Kaon Experiments at the CERN SPS

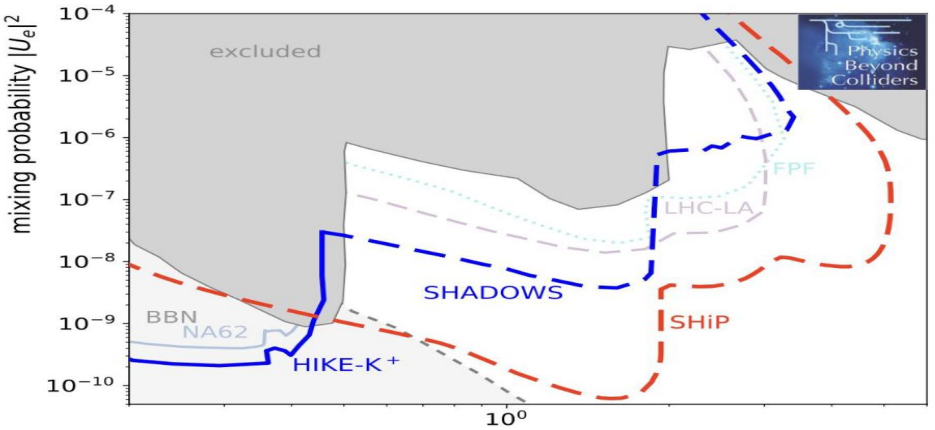
Letter of Intent

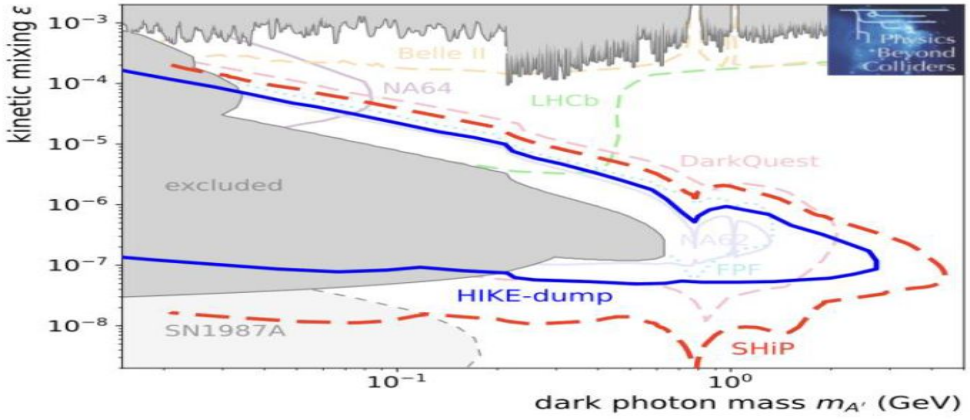
The HIKE Collaboration*

$K^+ \to \pi^+ \nu\bar{\nu}$	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 5\%$	BSM physics, LFUV
$K^+ \to \pi^+ \ell^+ \ell^-$	Sub-% precision on form-factors	LFUV
$K^+ \to \pi^- \ell^+ \ell^+, K^+ \to \pi\mu e$	Sensitivity $O(10^{-13})$	LFV / LNV
Semileptonic K^+ decays	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 0.1\%$	V_{us}, CKM unitarity
$R_K = \mathcal{B}(K^+ \to e^+\nu)/\mathcal{B}(K^+ \to \mu^+\nu)$	$\sigma(R_K)/R_K \sim O(0.1\%)$	LFUV
Ancillary K^+ decays (e.g. $K^+ \to \pi^+\gamma\gamma, K^+ \to \pi^+\pi^0 e^+ e^-$)	% – ‰	Chiral parameters (LECs)

Impressions from ECN3 document, exotics

- Working group explored both options, summarized here
- Exotics: heavy flavor: Ship, x10 accept. and x10 POT
- Exotics: good forward reach for HIKE, plus exotics from Kaons
- (Neglected Neutrino physics more details in 2310.17726)





Conclusions

- “dark/hidden sector” physics getting a lot of attention (and rightly so)
- At NA62, a running experiment, can do precision Kaon physics and possibly find new weakly coupled physics at MeV-GeV scales

Credit to work of people involved in NA62/HIKE

- NA62 intends to collect 10^18 POT in beam-dump in 2022-2025 with interesting perspectives on dark photons, ALPs, dark scalars and HNLs
- A decision about the future of ECN3/ HI facility/HIKE expected soon