THE UNIVERSITY OF BRITISH COLUMBIA

INSTITUTE OF PARTICLE PHYSICS

Searches for dark photons at accelerators

Christopher Hearty
U. British Columbia / IPP
May 26, 2022

New Scientific Opportunities with the TRIUMF ARIEL e-linac

Dark matter / dark sector / dark photons

- A natural explanation to explain observed dark matter properties is “freeze out”: dark matter and standard model matter were in thermal equilibrium in the early universe.

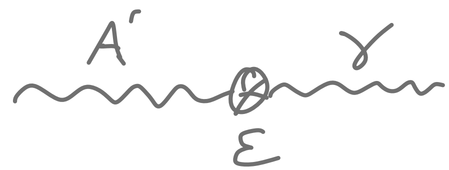
  $\chi\bar{\chi} \longleftrightarrow SM\,\overline{SM}$

- As the universe cooled, dark matter production and annihilation essential stopped, giving the observed relic density.

- For low mass dark matter, this requires a new feeble interaction: dark sector.

- Particularly simple case: dark matter χ plus dark photon A′.

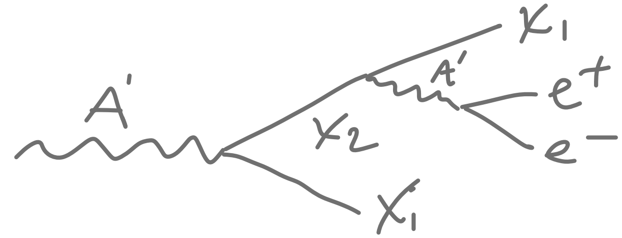
- Dark photon mixes with strength ε with the photon.



- Dark photon decays and interactions are then related to standard model interactions.

Caveats; things I am not going to discuss

- The dark photon could itself be dark matter if it were light enough to only decay to three photons.
- There are other simple cases: dark scalar S that mixes with the Higgs; heavy neutral leptons that mix with neutrinos.
- Dark sector could be much more complicated, giving more complicated experimental signatures.
  - e.g. “inelastic dark matter”



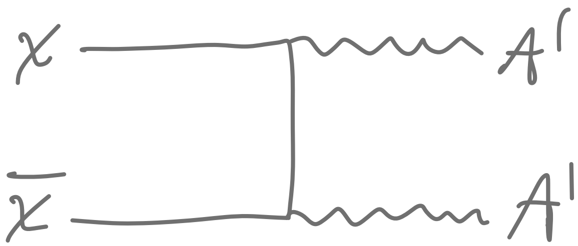
- Interactions could be more complicated, e.g., couplings to only the 2nd and 3rd generations; protophobic.

- Some of these models are motivated by anomalies other than dark matter:
  - muon g-2
  - $B \to K\ell\ell$ and related
  - ATOMKI

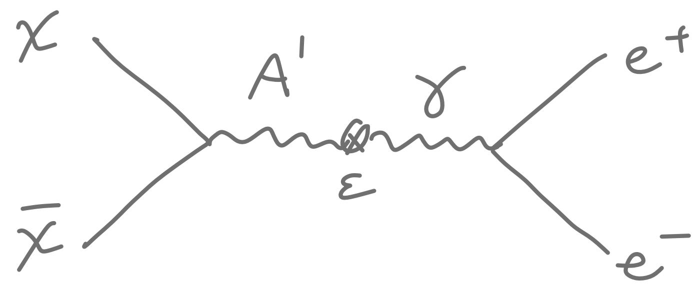
Which is heavier? Dark photon or dark matter?

- Determines how dark matter annihilates in the early universe.

dark matter is heavier than dark photon



dark photon is heavier than dark matter



- In the 2nd case, the dark matter relic density depends on the parameter $y = \varepsilon^2 \alpha_D (m_\chi / m_{A'})^4$; there are specific combinations of parameters that give the observed value.

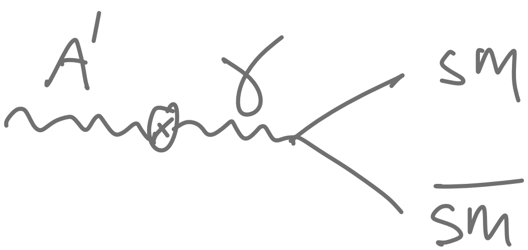
coupling of dark photon to dark matter, $\mathcal{O}(1)$

Dark photon decay (and experimental signature) also depends on relative mass

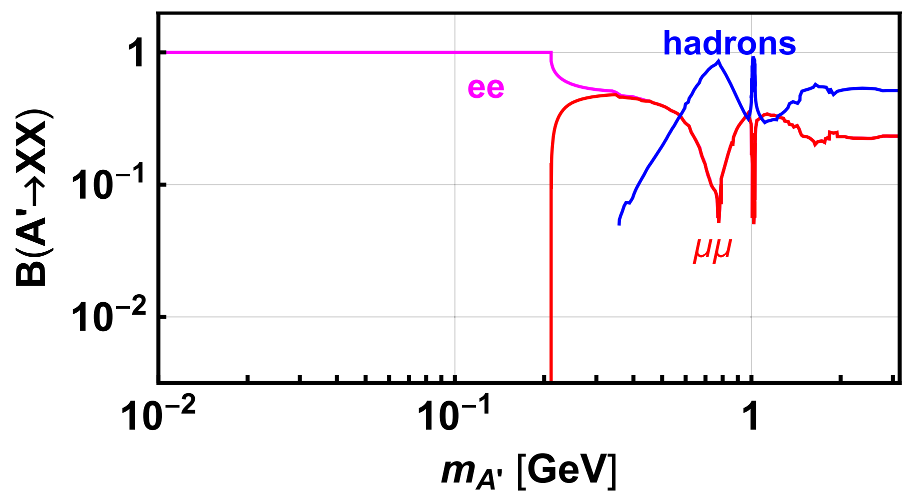
- If $m_{A'} > 2m_\chi$:
  experimental signatures:
  - missing energy / mass
  - scattering in downstream (neutrino) detectors

"invisible"

- Otherwise, dark photon decays like a virtual photon of mass $m_{A'}$.



"visible"



- Large standard model backgrounds for visible case, e.g. $\gamma^* \rightarrow \ell^+\ell^-$. Experimental signatures:
  - mass peak on a smooth background;
  - displaced vertex (non negligible dark photon lifetime);
  - extensive shielding (even longer lifetime).

- Invisible decays: relic density targets for ε.

- Visible decays: relic density targets only if $m_\chi < m_{A'} < 2m_\chi$.

Focus of my talk

- Experiments that are operating.
- $A' \to \ell^+\ell^-$ or $A' \to$ invisible.
- 10 MeV/c^2 $< m_{A'} <$ 10 GeV/c^2.
- Most of the content is based on these two papers:

B. Batell, N. Blinov, C. Hearty, and R. McGehee, *Exploring Dark Sector Portals with High Intensity Experiments*, Snowmass RF6 summary white paper "Big idea 2" (to appear on arXiv).

M. Graham, C. Hearty, and M. Williams, *Searches for Dark Photons at Accelerators*, Annu. Rev. Nucl. Part. Sci. 2021. 71:37–58.

Experiments that I should cover

Visible decay

- **LHCb**
- HPS
- **FASER**
- Mu3e

Both

- **NA64**
- **Belle II**

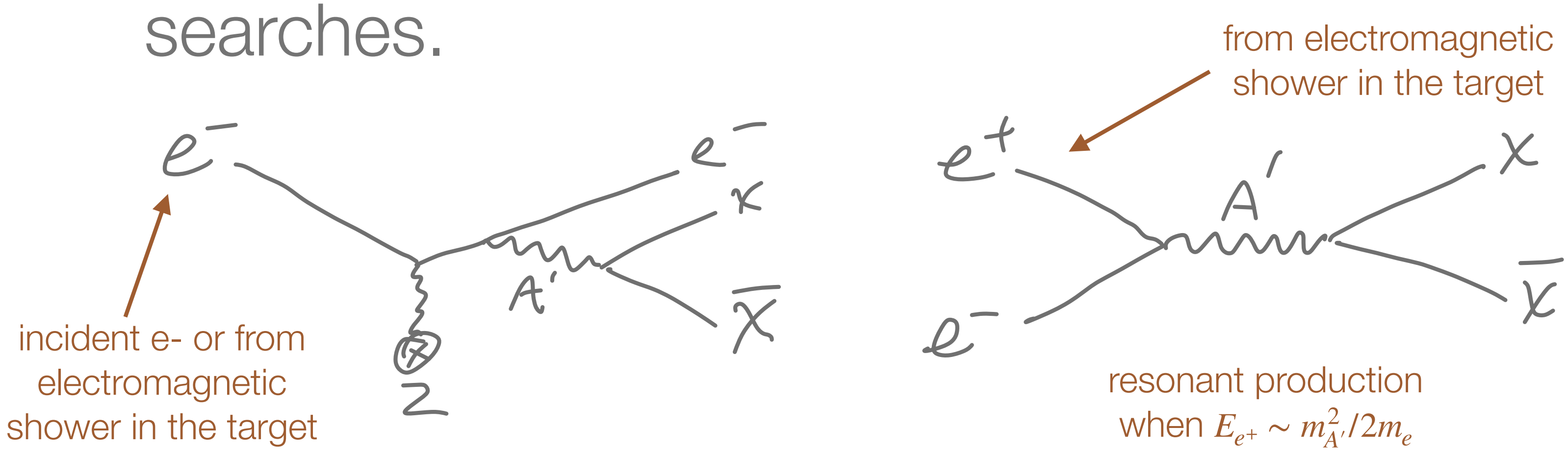
Invisible decay

- **COHERENT**
- NA62

- The experiments I am actually covering are in bold.

NA64 — electron beam fixed target experiment at CERN

- Searches for new light particles produced in electron interactions in an active target.
- 100 GeV or 150 GeV e^- beam, CERN SPS H4 line.
- Different detector configurations for visible and invisible searches.

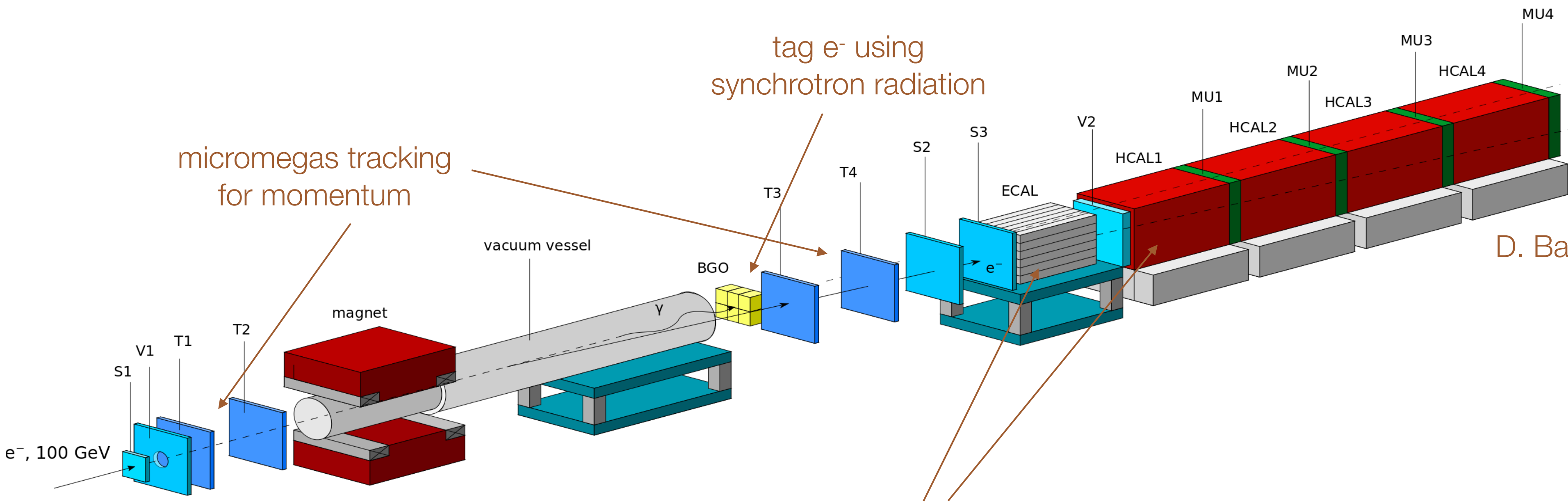


NA64 search for invisible dark photon decays

- 100 GeV e^- from H4 beam line. 3×10^9 e^- in July 2016

tag e^- using synchrotron radiation

micromegas tracking for momentum

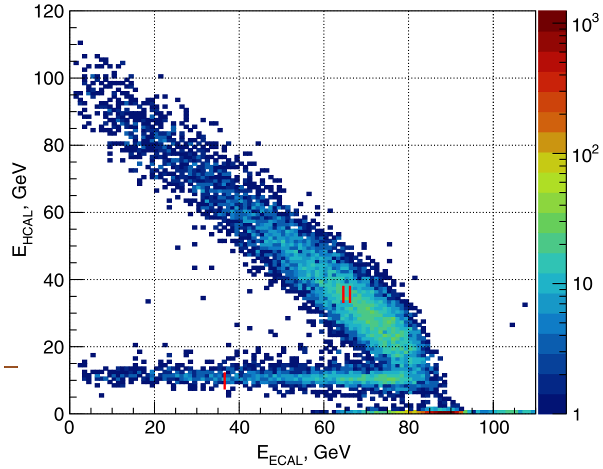


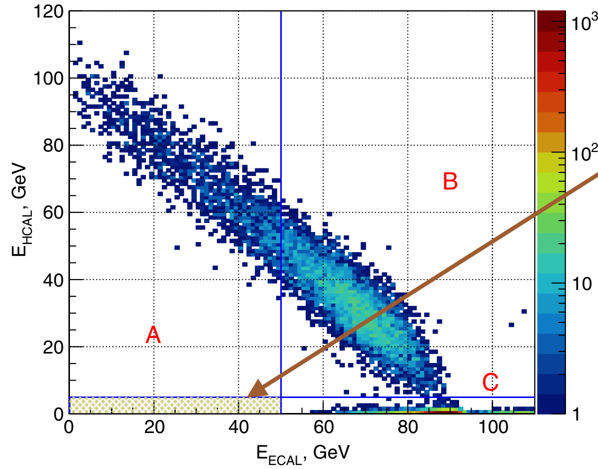
D. Banerjee

5×10^{10} e^-/month

SM processes will deposit full energy in ECAL+HCAL; A′ will give no energy in HCAL and low energy in ECAL

$e^-Z \to e^-Z\gamma; \gamma \to \mu^+\mu^-$

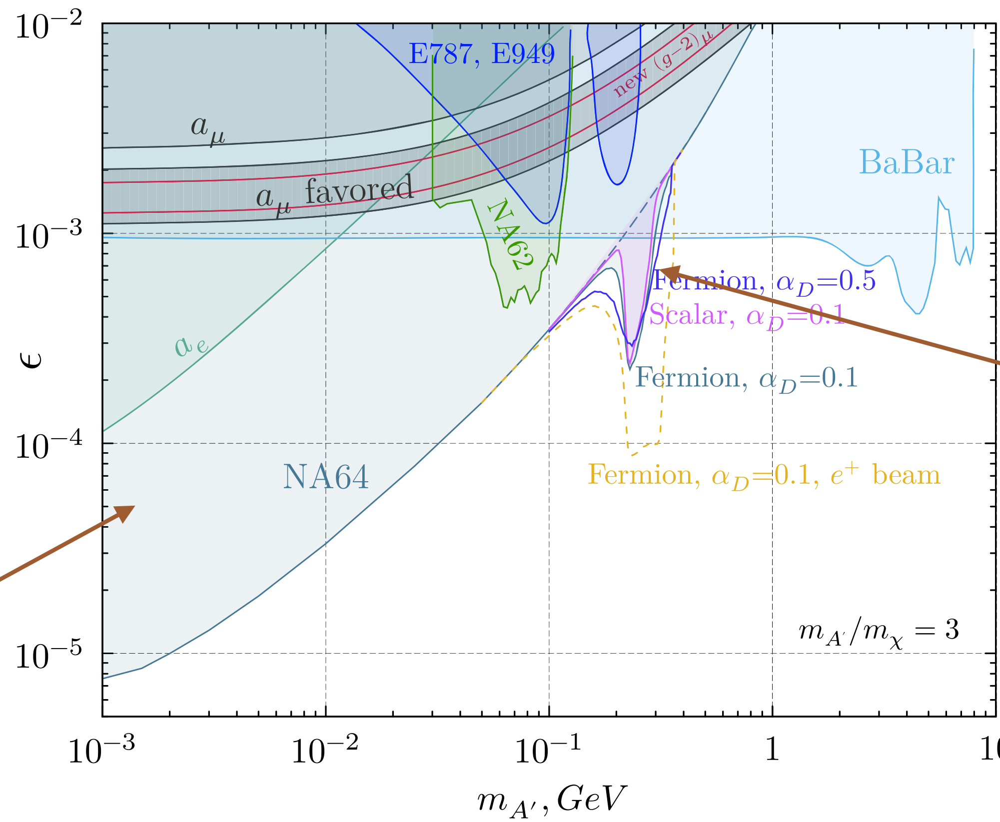




signal region; expect 0.4 background, observe 0

Dark Matter Search in Missing Energy Events with NA64, Phys. Rev. Lett. 123, 121801 (2019);

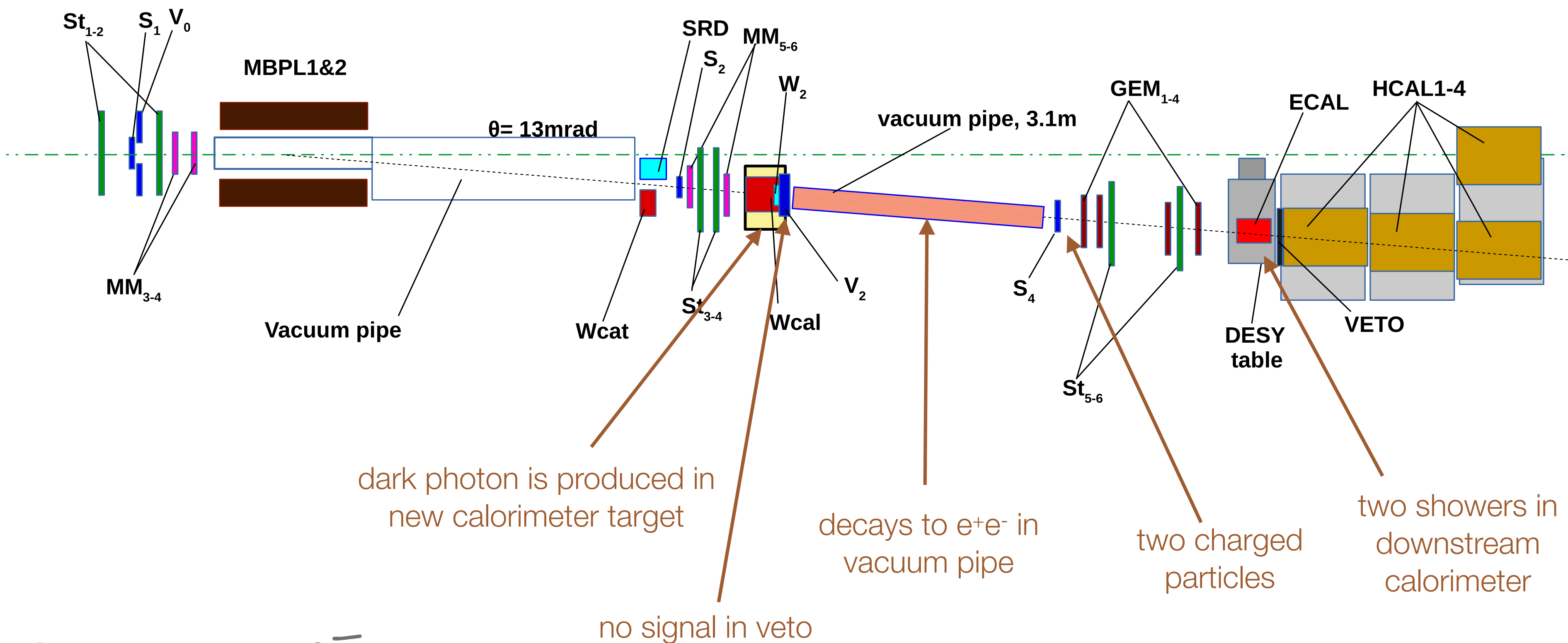
Improved exclusion limit for light dark matter from e^+e^- annihilation in NA64, Phys. Rev. D104, L091701 (2021).

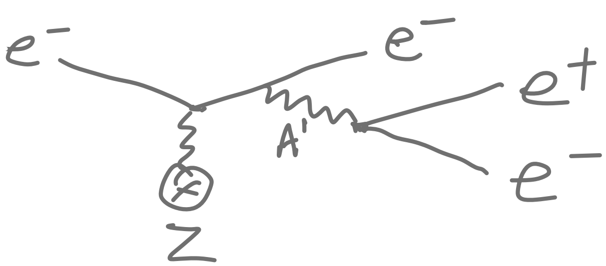


resonant production

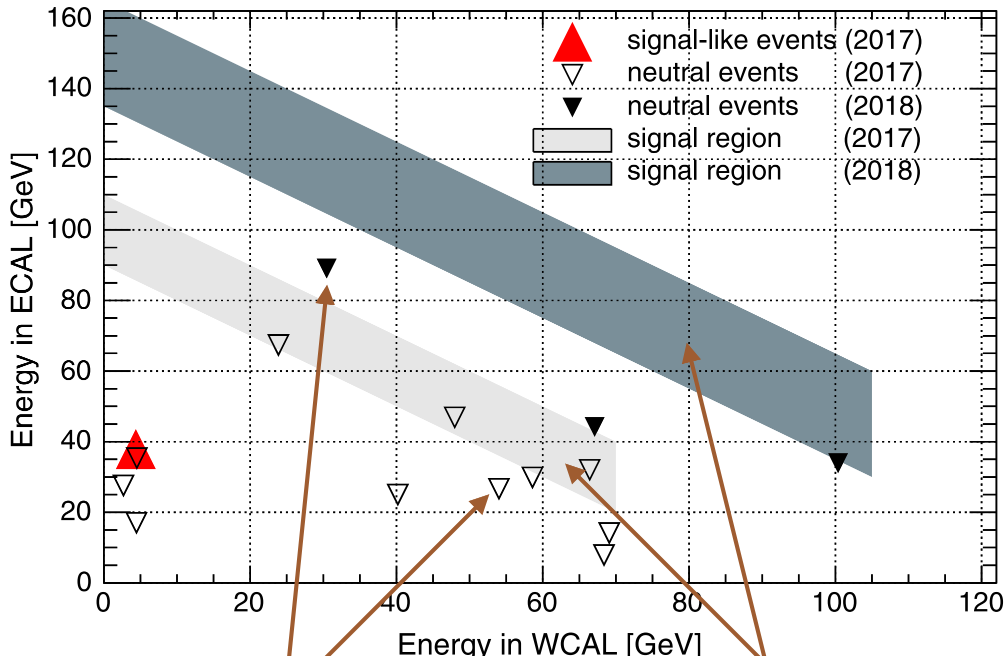
world-leading limits for mass < 300 GeV/c²

NA64 search for the X17 decaying to e^+e^-



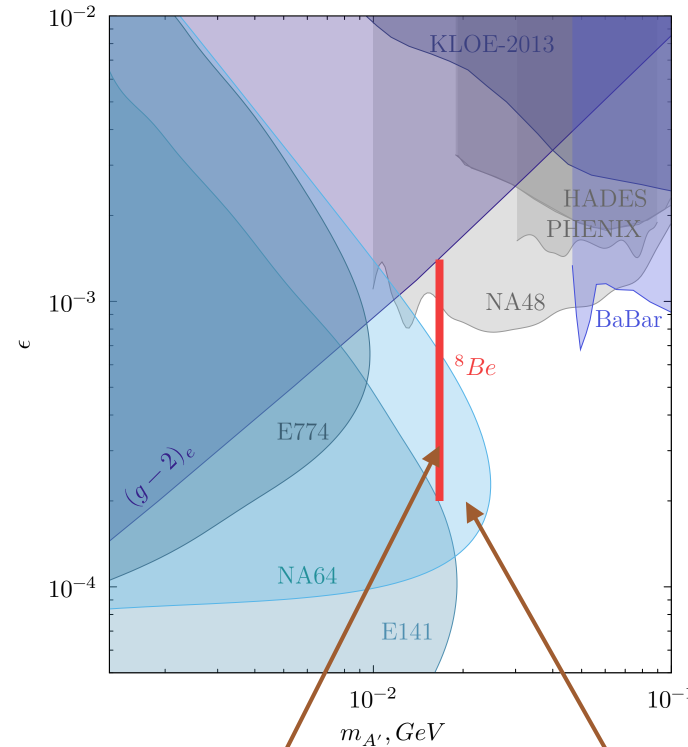


5 x 10^{10} 100 GeV e- on target in 2017
3 x 10^{10} 150 GeV e- on target in 2018



control sample with 0 charged particles

0.08 background expected; 0 events observed



parameter space of the ATOMKI anomaly

NA64 exclusion region

Improved limits on a hypothetical X(16.7) boson and a dark photon decaying into e^+e^- pairs, Phys. Rev. D101, 071101(R), 2020.

NA64 outlook

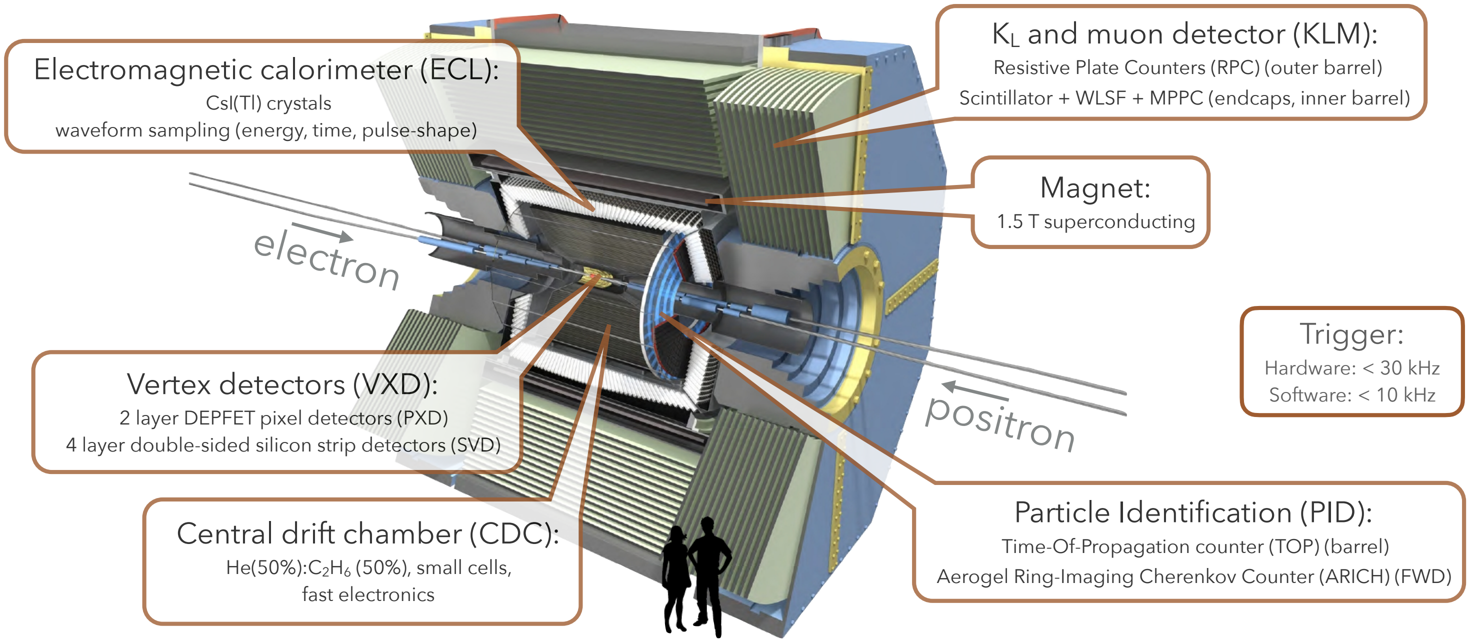
- Summer 2022: 10 week run, invisible configuration.

- Summer 2023: visible mode, modified to improve sensitivity to shorter X17 lifetime = smaller ε.
  - denser active target
  - 200 GeV beam to increase boost
  - additional magnetic spectrometer to measure electron momenta.

  - Need 7×10^{11} electrons on target to reach $\varepsilon = 1.4\times10^{-3}$.

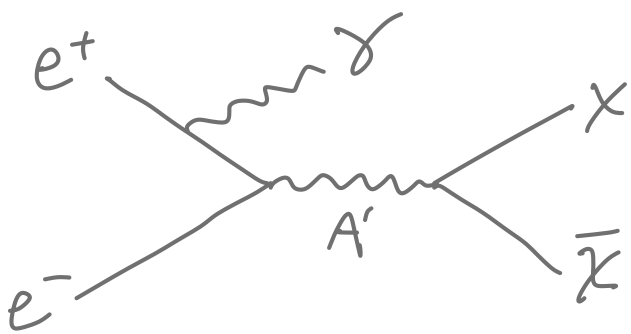
Belle II

- Located at the SuperKEKB e^+e^- collider in Japan. Operates at $\sqrt{s}$ = 10.58 GeV (Υ(4S)).
- Collecting data since 2019. Luminosity goal is 50 ab^{-1} = 100x BaBar, but ~1x BaBar so far.

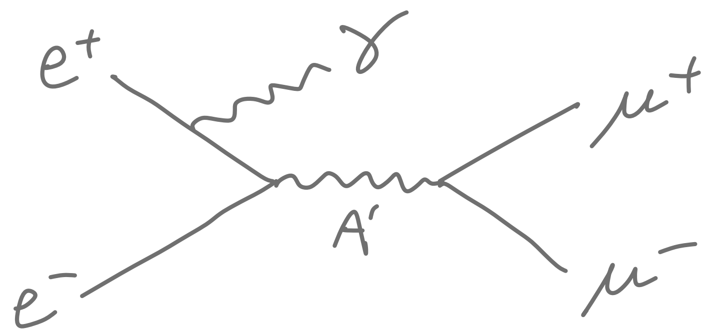


Dark photon production at Belle II

- Dark photon production via initial state radiation, followed by invisible or visible decay.



only the γ is visible in Belle II



the γ and both muons are visible

Invisible dark photon at Belle II "single photon search"

- We don't see the dark photon, but we can deduce its mass from the photon energy (momentum and energy conservation).
  $$E^*_\gamma = E^*_{beam} - \frac{m^2_{A'}}{4E^*_{beam}}$$
- Given an imperfect detector, there are many processes in the Standard Model that also result in a single detected photon:

$e^+e^- \to \gamma\,\gamma$

$e^+e^- \to \gamma\,\gamma\,\gamma$

$e^+e^- \to e^+e^-\,\gamma$

$e^+e^- \to \nu\,\bar{\nu}\,\gamma$ is negligible

if we miss these particles, we end up with a "single photon" event

- Trigger on single photons 0.5 GeV and above.

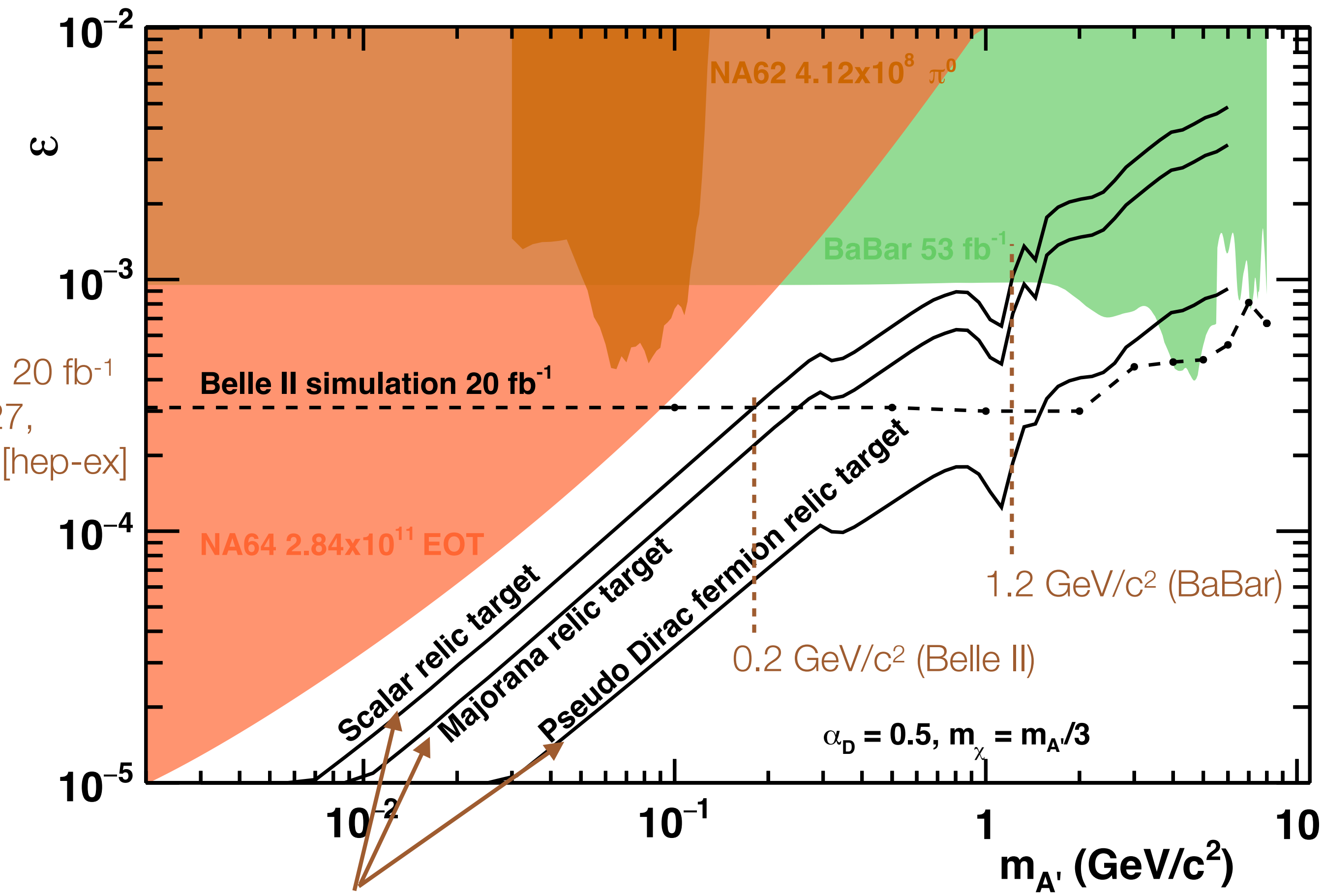
- Belle had no single photon trigger. BaBar had a trigger for ~10% of its data, but was unable to quantify background from $e^+e^- \rightarrow \gamma\ \gamma$
  - could not identify a low-mass dark photon.

- Belle II calorimeter is much more hermetic. Should be able to significantly improve on existing BaBar limits.

Limits on dark sector parameters from BaBar and projections for Belle II

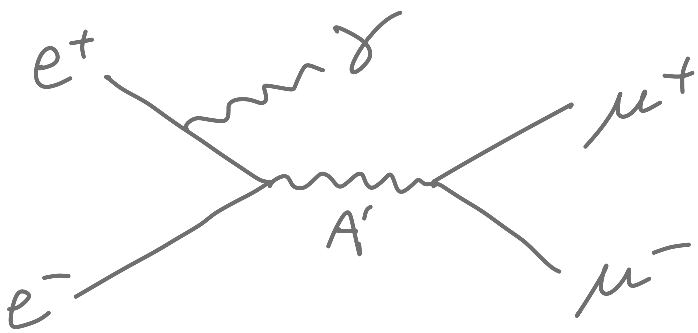
BaBar limit, 50 fb^{-1}
Phys. Rev. Lett. 119, 131804 (2017)

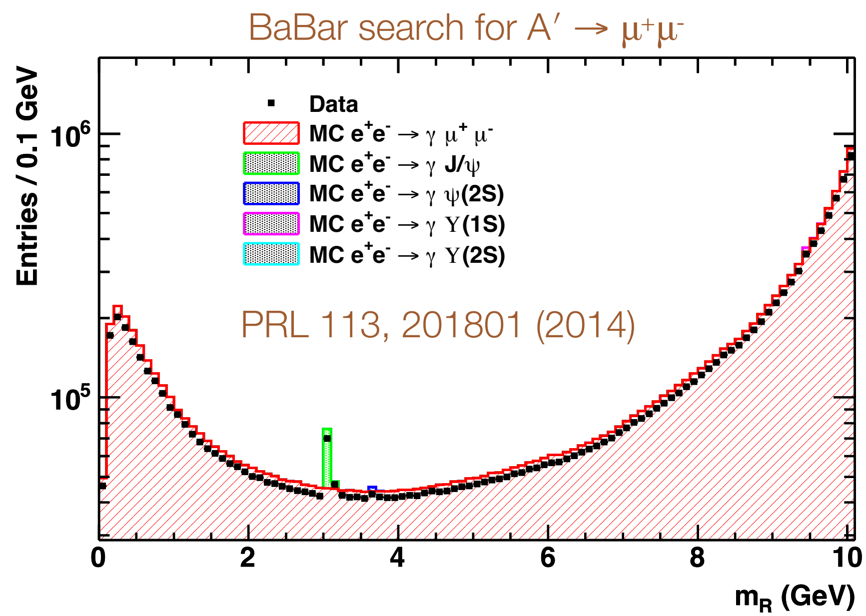
Belle II projection, 20 fb^{-1}
KEK-2018-27,
arXiv:1808.10567 [hep-ex]



If astronomical dark matter is due to the dark sector, parameters will lie along one of these lines. Derived from E. Izaguirre, G. Krnjaic, P. Schuster, N. Toro, Phys. Rev. Lett. 115, 251301 (2015)

Search for a dark photon decaying to leptonic final states





- Final state is photon plus lepton pair. Large SM backgrounds, particularly in electron final state.
- Muon final state is dominant above threshold due to lower backgrounds.

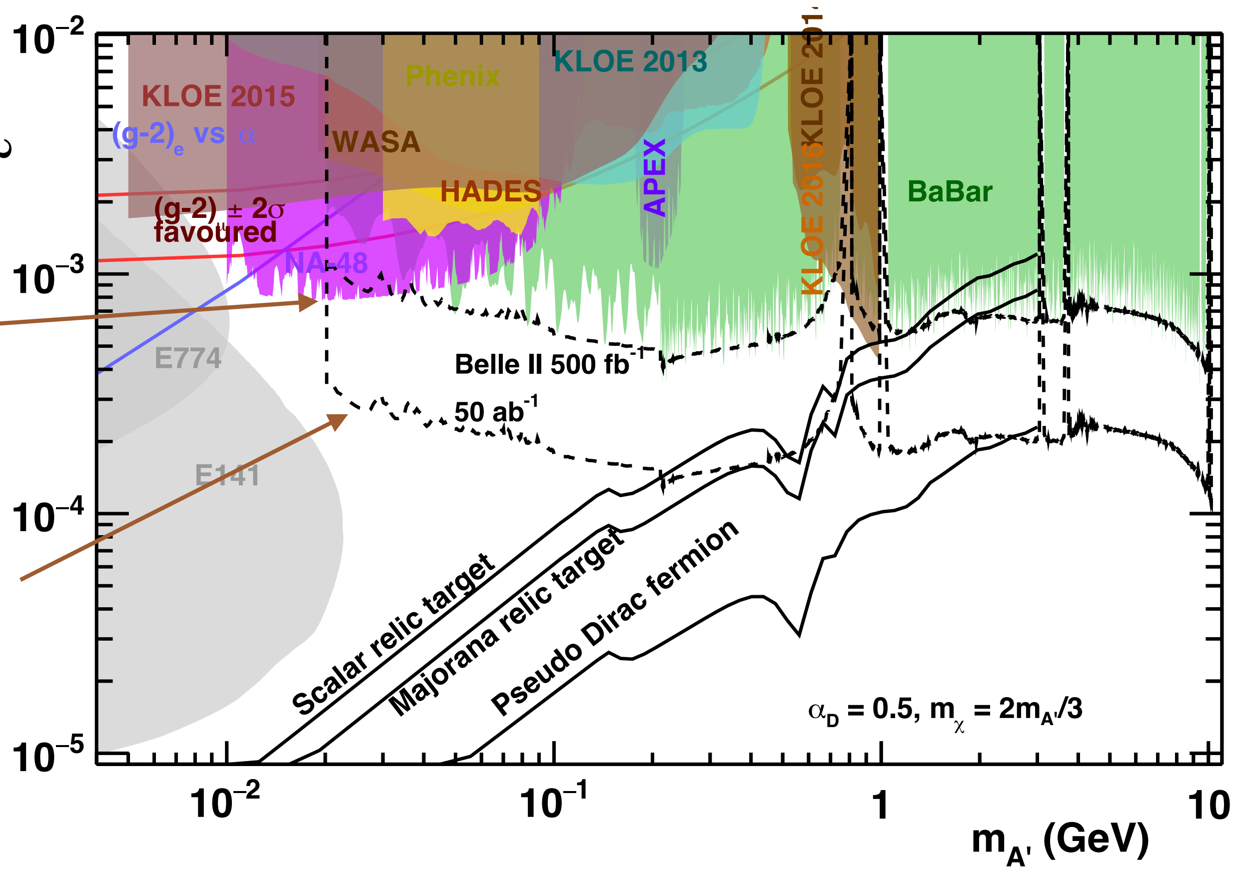
Projected Belle II sensitivity for prompt dark photon decays to leptons

- No real analysis yet; projected limits scaled from BaBar, assuming twice as good mass resolution.

Upper limit on ε scales as luminosity $L^{0.25}$

BaBar did not go below 20 MeV/c^2 due to backgrounds from photon conversions

lifetime is non-negligible here; next slide



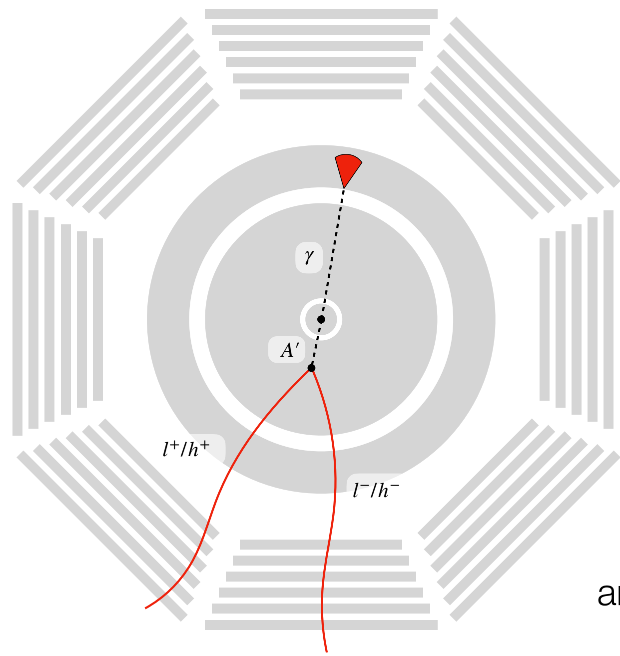
BaBar collab., PRL 113, 201801 (2014), 514 fb-1

Belle II sensitivity to long-lived dark photons decaying to two charged particles

- Prompt analysis has very large standard model backgrounds. However, these all have zero lifetime.

- Small dark photon mixing ε
  ⇒ non-negligible lifetime.
  i.e., displaced vertex.

- Small ε also means small production cross section
  ⇒ need high luminosity.

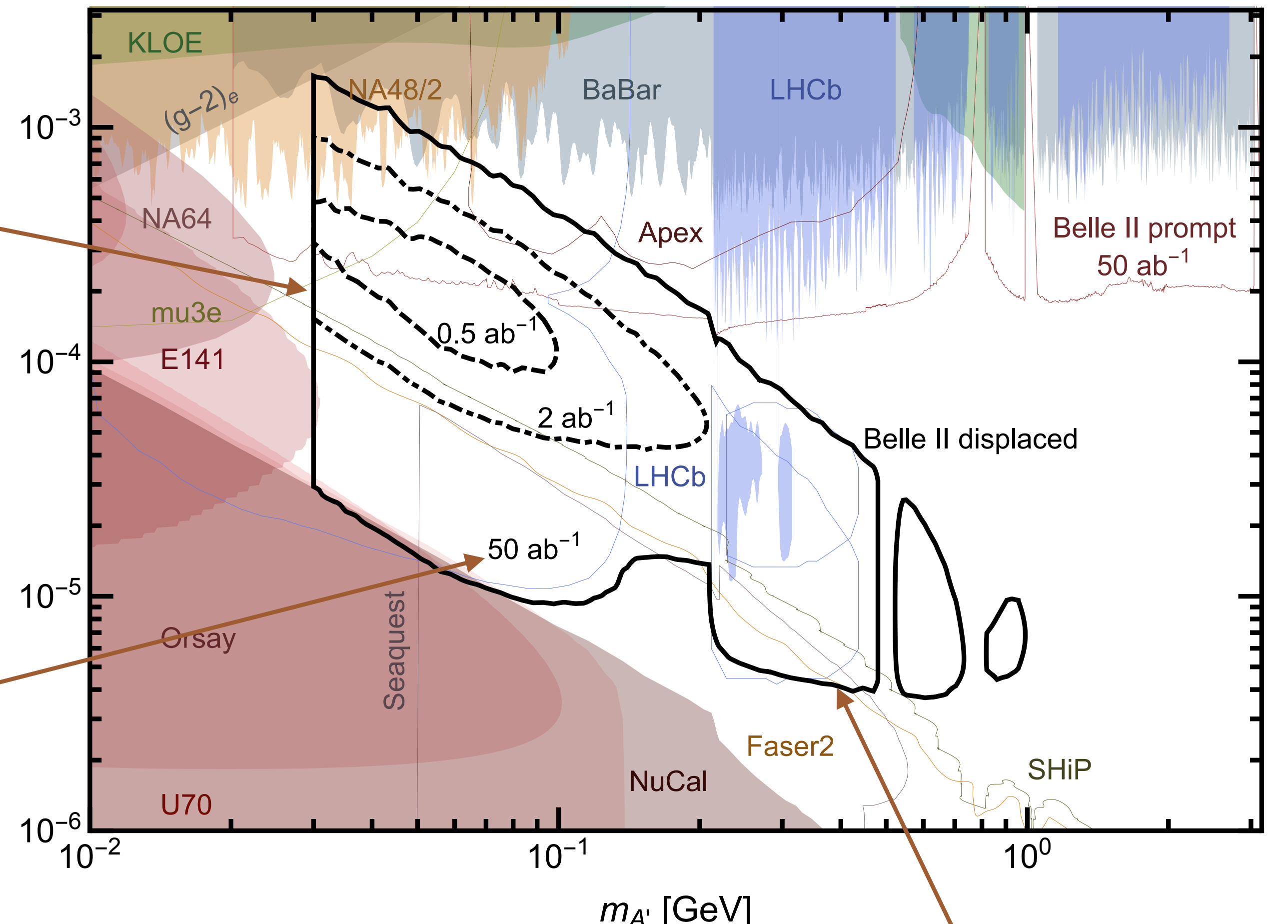


arXiv 2202.03452

Belle II sensitivity to visible dark photon decays including displaced vertices

30 MeV/c² cut to reject photon conversions.

Assumes 10 e^+e^- and 0 $\mu^+\mu^-$ background in 50 ab^{-1}



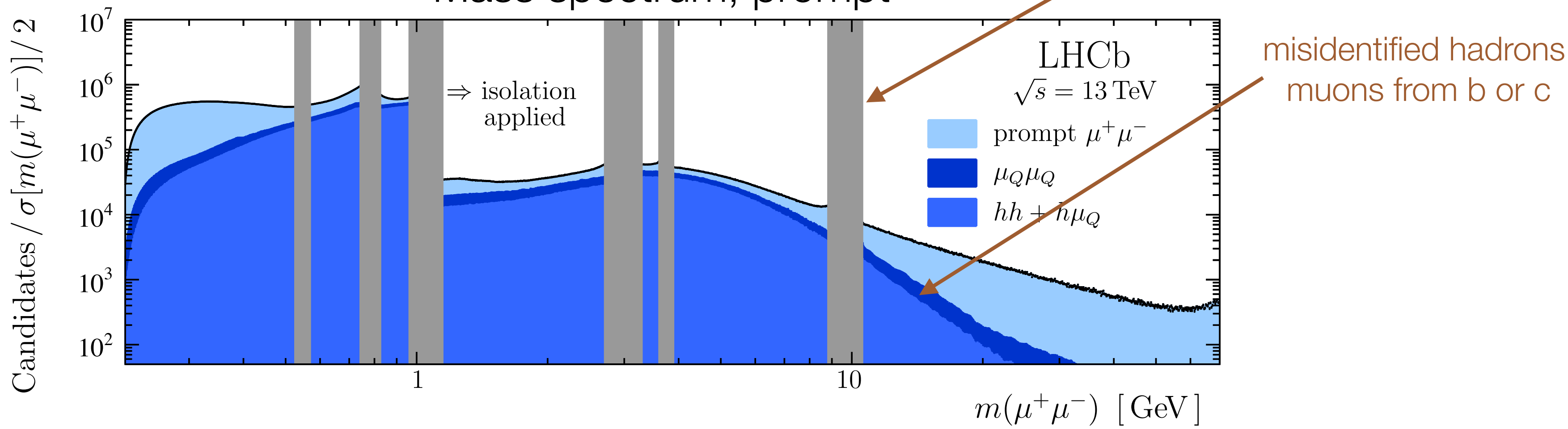
~1 $\mu^+\mu^-$ signal per ab^{-1}

T. Ferber, C. Garcia-Cely, and K. Schmidt-Hoberg, *Belle II sensitivity to long–lived dark photons*, arXiv 2202.03452

LHCb — forward spectrometer at the LHC

- LHCb has previously published a dark photon search in the $\mu^+\mu^-$ final state, prompt and displaced.
  - Drell-Yan production $q\bar{q} \rightarrow A'$;
  - meson decay, especially $\pi^0/\eta \rightarrow \gamma A'$.

Mass spectrum, prompt



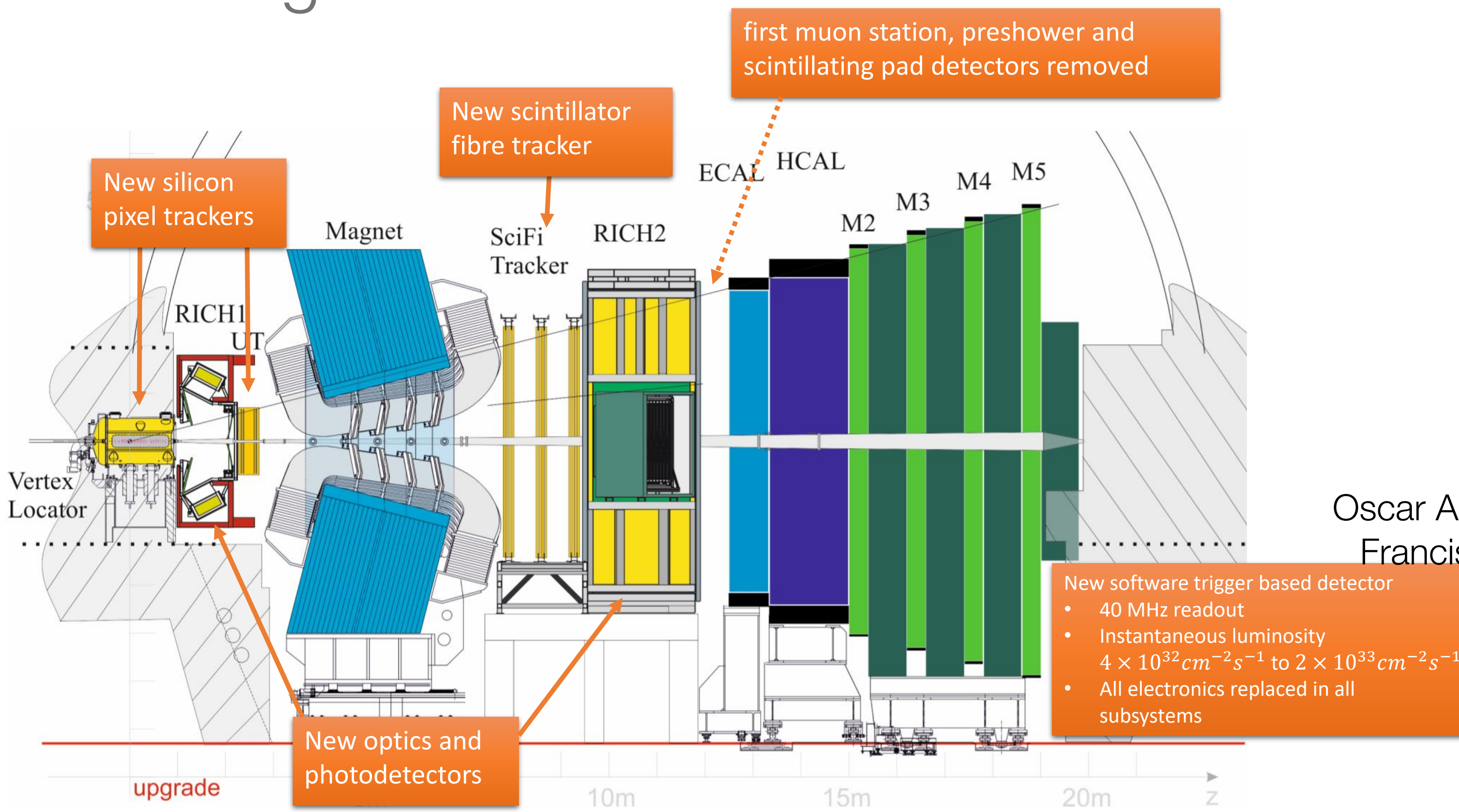
LHCb collaboration, *Search for A′ → $\mu^+\mu^-$ decays*, Phys. Rev. Lett. 124, 041801 (2020).

- Non-negligible displaced backgrounds: γ conversions to $\mu^+\mu^-$; b decays to two muons; mis-identified K_S decays.

- Displaced limits are unique; prompt limits are world-best for some masses.

LHCb outlook — Upgrade I

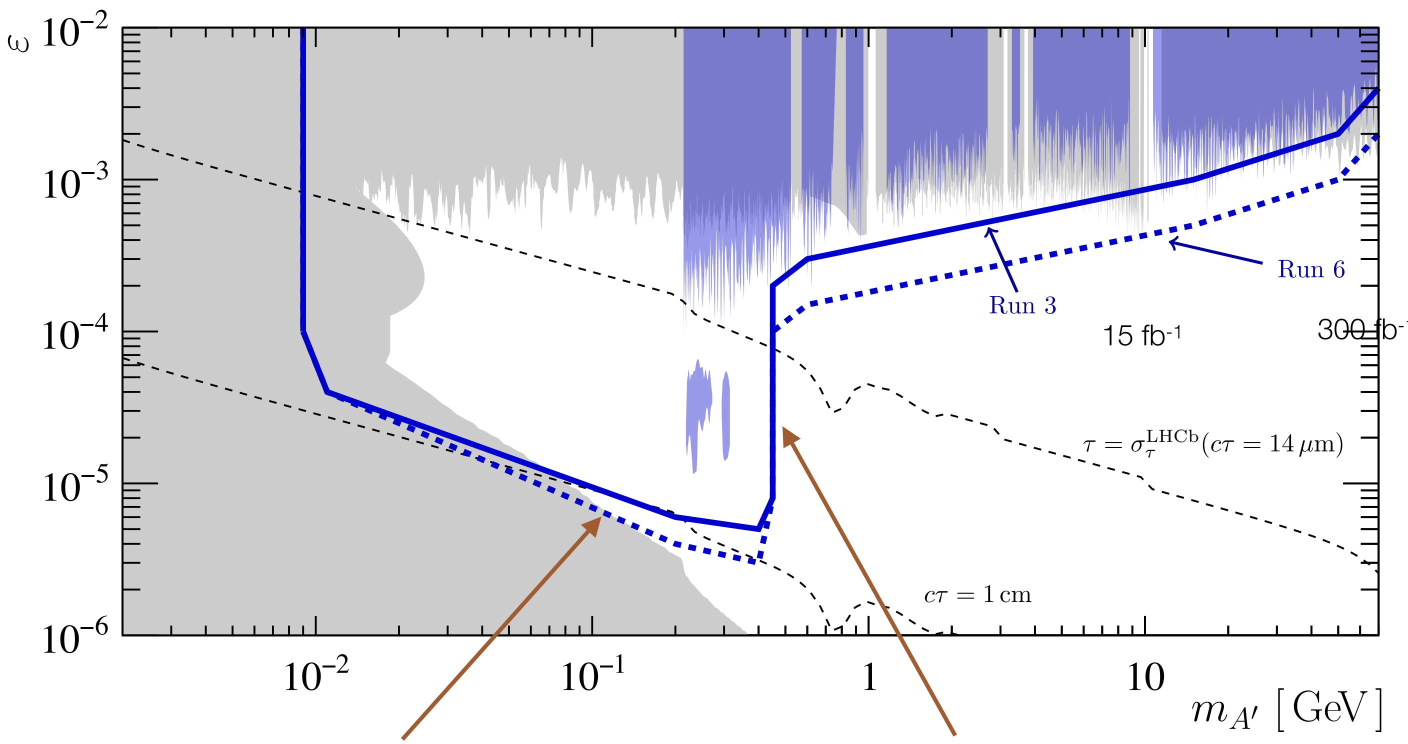
- About to start Run 3 with a significantly upgraded detector, including triggerless readout of every LHC beam crossing.



Oscar Augusto de Aguiar Francisco, LHCC 148

- New trigger will enable the inclusive e^+e^- sample to be recorded, in addition to $\mu^+\mu^-$.

- Will cover wide range of parameter space above 10 MeV/c^2 over the next several years.

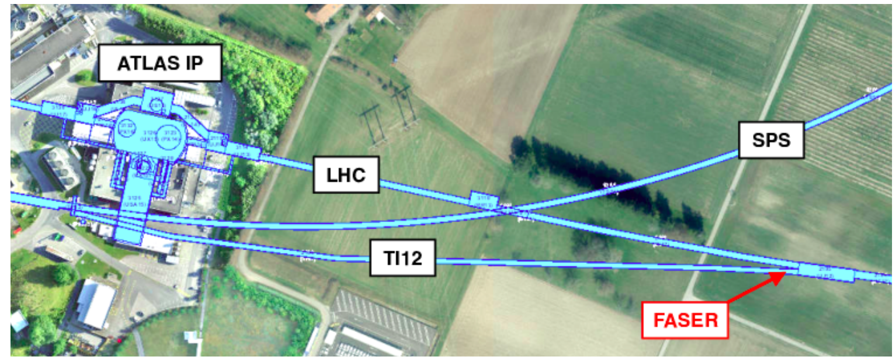


Size of the VELO silicon tracker sets a lifetime limit

K_S veto and η mass

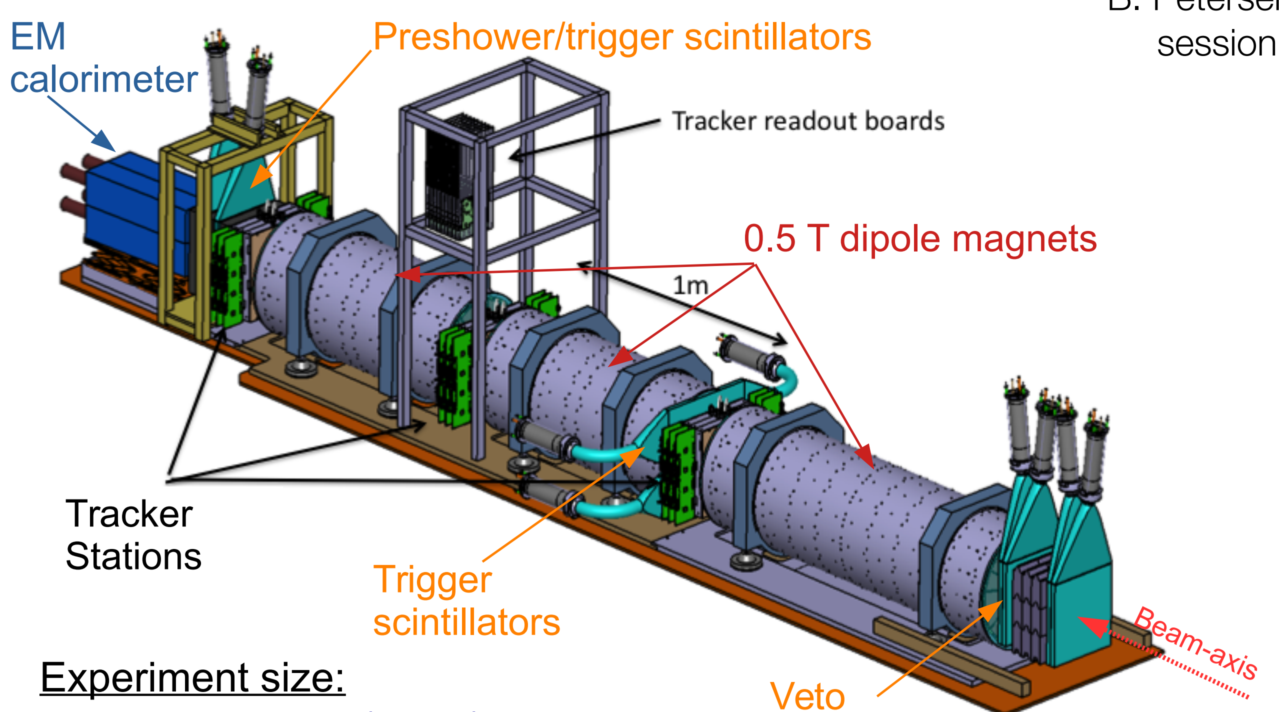
FASER — long-lived and feebly interacting particles at the LHC

- Located 500 m downstream of ATLAS, on the collision axis. 100 m of rock/concrete.



B. Petersen, open LHCC session, Nov 2019

- Low p_t.



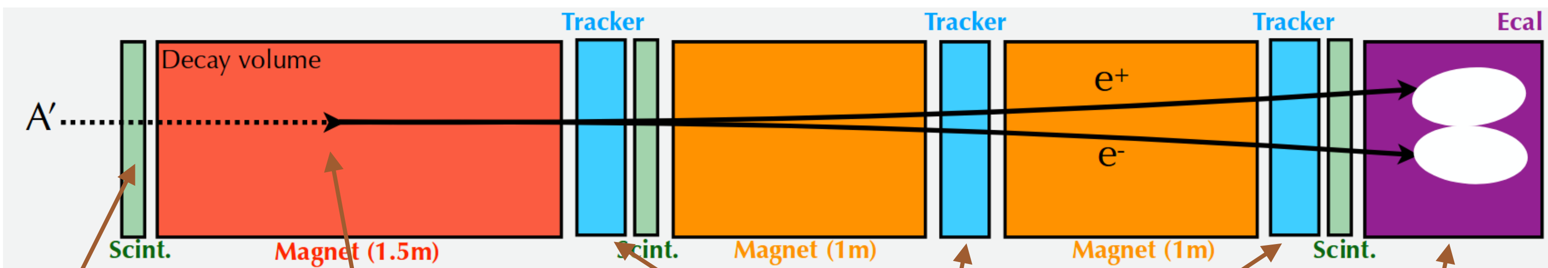
Detector privately funded by Simons Foundation

Experiment size:

- 20 cm aperture ($\eta>9.1$)

Dark photons in FASER

- Predominantly produced by $\pi^0/\eta \rightarrow \gamma A'$; detected in e^+e^- final state.



nothing in veto counters (reject muons)

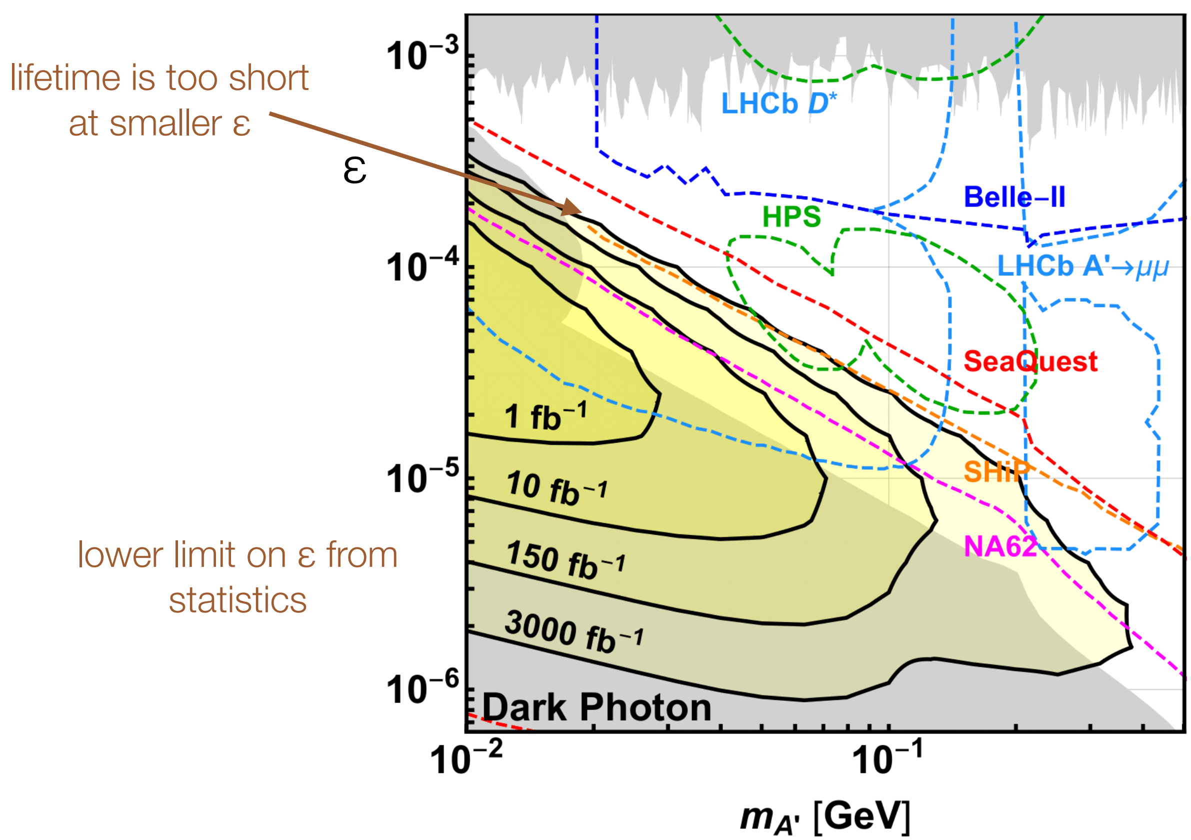
dark photo decays in decay volume

electrons trajectories from 3 tracking stations

electrons energies from calorimeter

FASER outlook

- Will start collecting data this summer. Should collect 250 fb^{-1} by end of Run 3 (end of 2025).

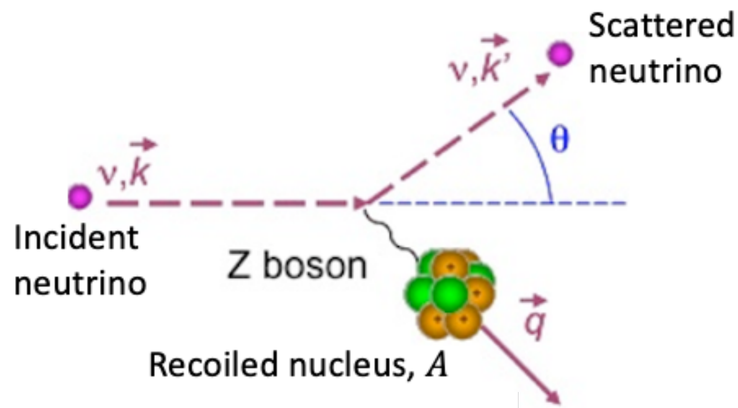


B. Petersen, open LHCC session, Nov 2019

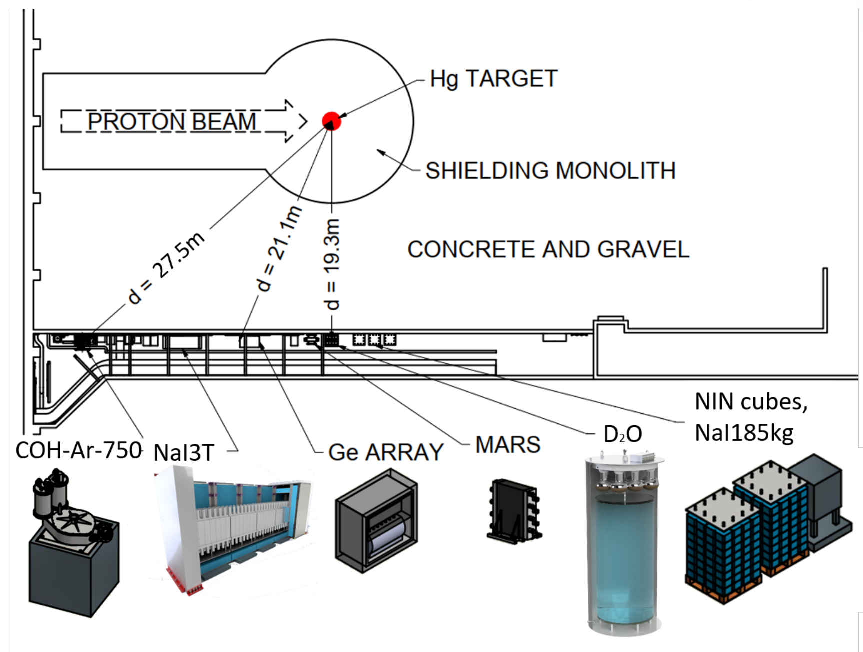
see also *FASER's physics reach for long-lived particles*, Phys. Rev. D 99, 095011 (2019).

COHERENT — studying coherent elastic neutrino-nucleus scattering (CEvNS) at the Oakridge SNS

- Spallation neutron source is also an excellent source of ν from the decay of stopped π^+.



- COHERENT has made the first observation of CEvNS using CsI and LAr.

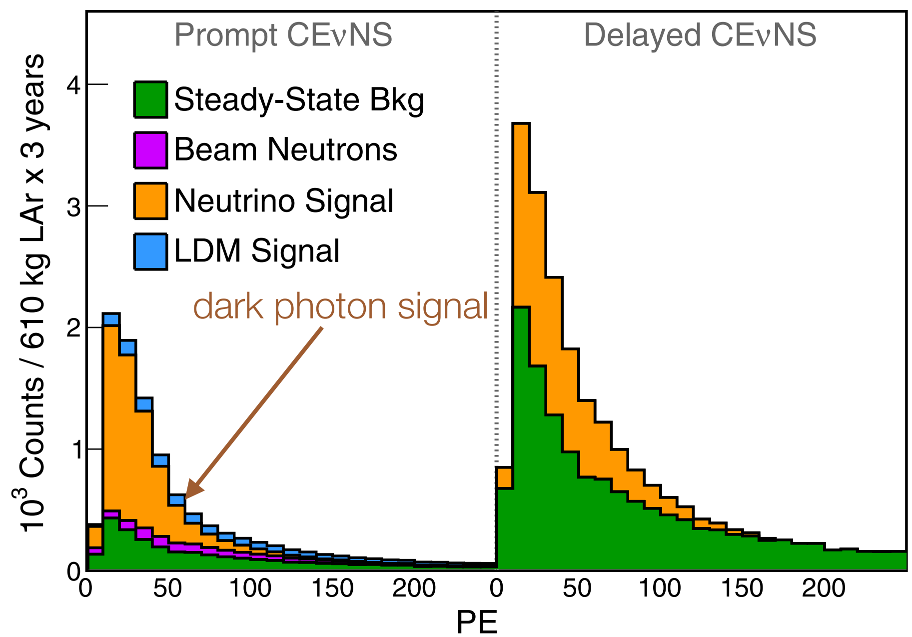


The COHERENT Experimental Program, 2204.04575, 2022.

Dark photons at COHERENT

- Dark photons are produced in the decay of π^0 and η mesons, and in the nuclear absorption of π^-.
- Will also produce CEvNS, but with different time structure than ν signal.

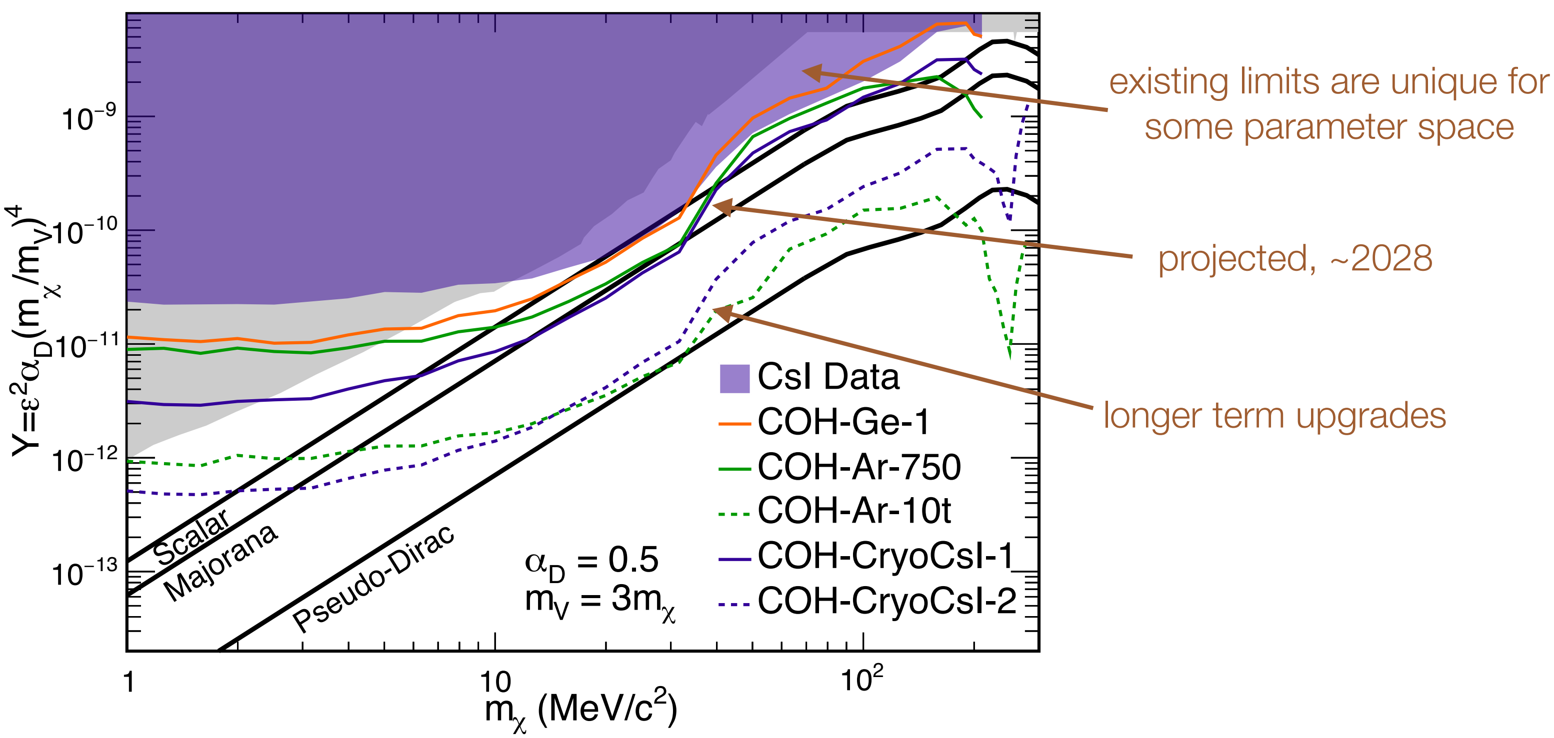
dark photons and ν_μ from π^+ decay arrive promptly



ν_e and $\bar{\nu}_\mu$ from μ^+ decay are delayed by muon lifetime

Outlook for COHERENT

- New detectors online ~now through 2025. 3 years running.

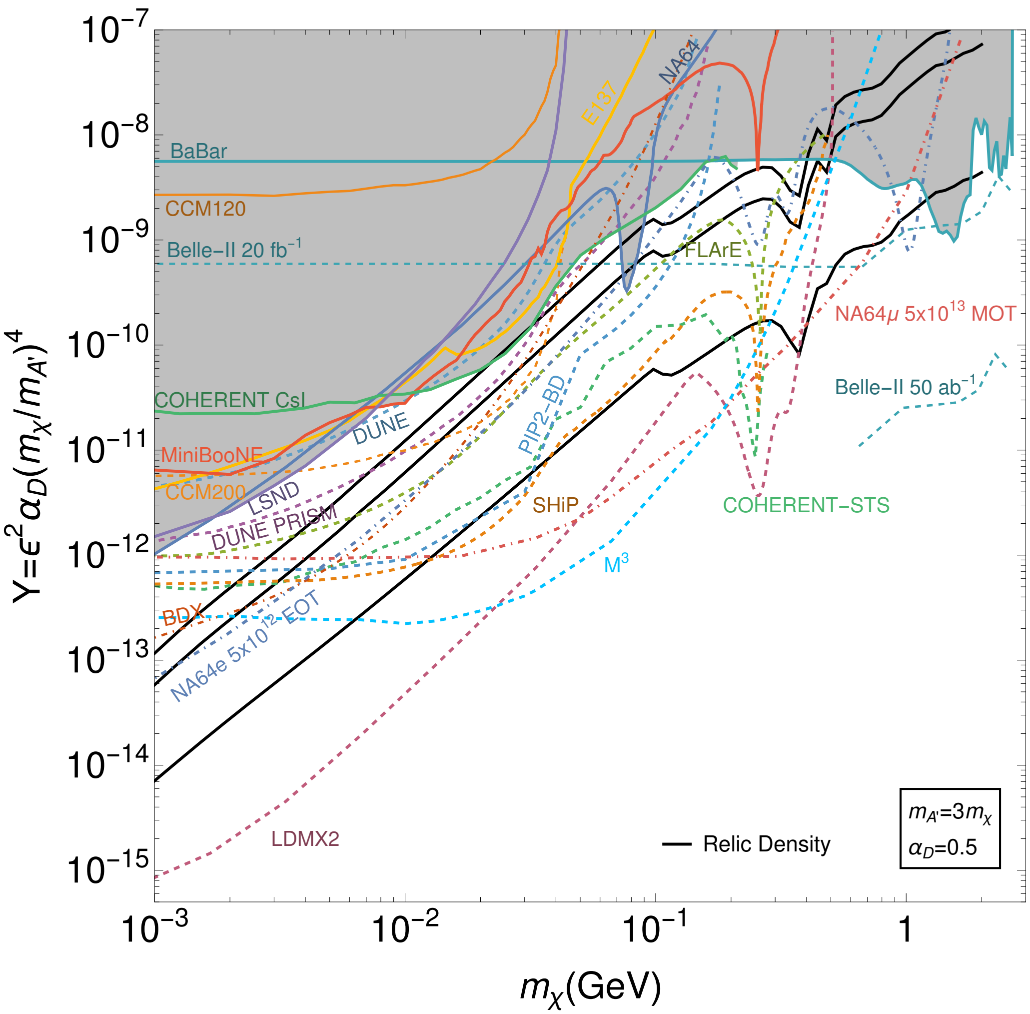


Summary

- Searches for dark photons aim to shed light on a possible dark sector that would explain dark matter.
- Wide range of experimental approaches, including a number of dedicated experiments.
- Results have started to approach regions of parameter space that would explain the observed relic density of dark matter.
- I did not discuss the large number of proposed projects.

Summary of invisible dark photon projections

G. Krnjaic and N. Toro, *Dark Matter Production at Intensity-Frontier Experiments*; Snowmass RF6 summary white paper "Big idea 1" (to appear on arXiv).



Summary of visible dark photon projections

B. Batell, N. Blinov, C. Hearty, and R. McGehee, *Exploring Dark Sector Portals with High Intensity Experiments*, Snowmass RF6 summary white paper “Big idea 2” (to appear on arXiv).