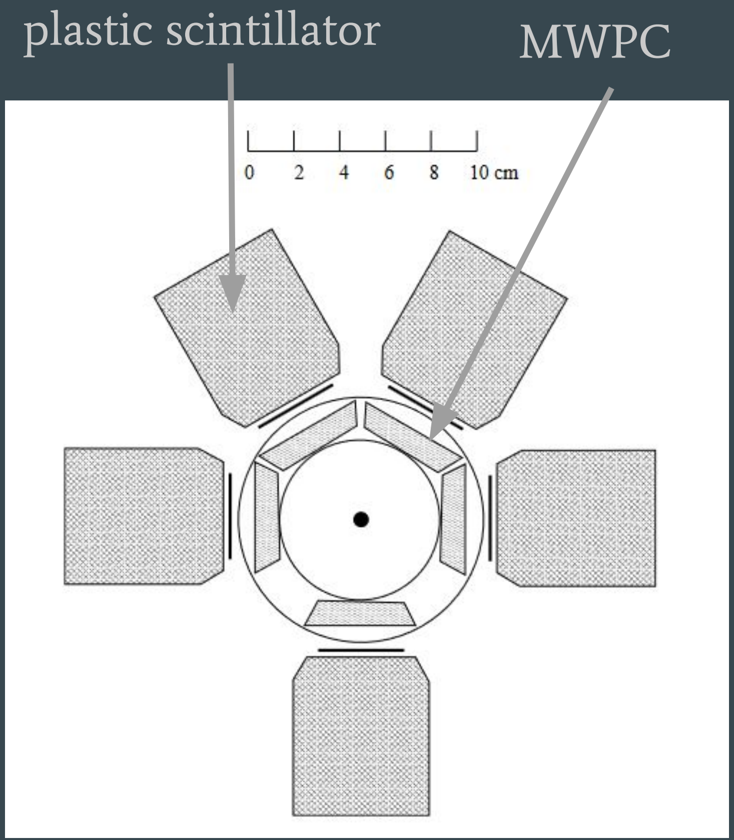
Parenthesis: the ATOMKI experiment

- ATOMKI experiment: measurement of the angular correlation between e+e- pairs produced by *internal pair conversion* in the de-excitation of $^{8}Be^{*}$ nuclei

- $^{8}Be^{*}$ nuclei produced hitting a ^{7}Li target with a ~1 MeV proton beam

- Pair spectrometer detector composed of "telescopes": Multi Wire Proportional Chambers (MWPC) for impinging position definition and plastic scintillator for energy measurement



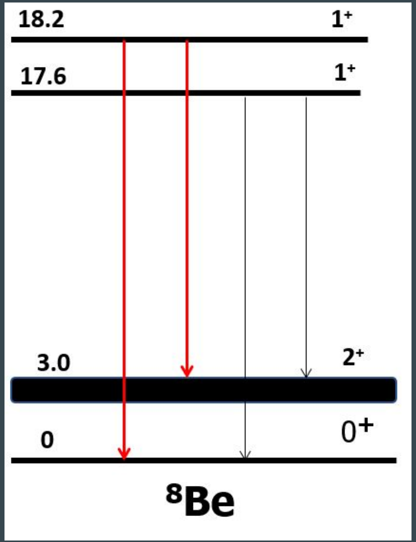
arXiv:1504.01527v1

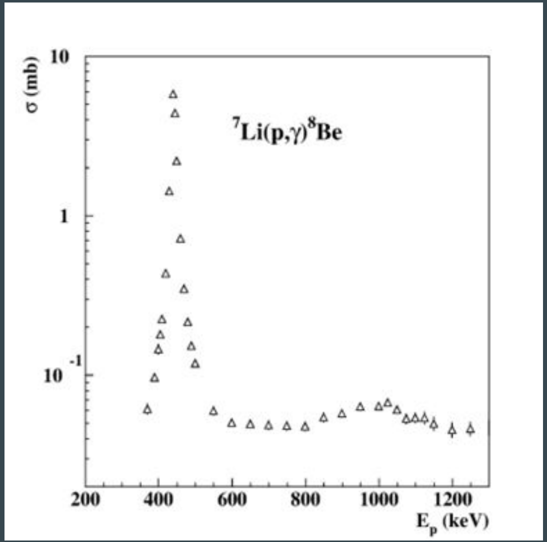
^{8}Be* transitions

ATOMKI: study of the M1 transitions from excited ^{8}Be* states

Internal pair conversion: the photon emitted due to the de-excitation converts in a e+e- pair in the nucleus

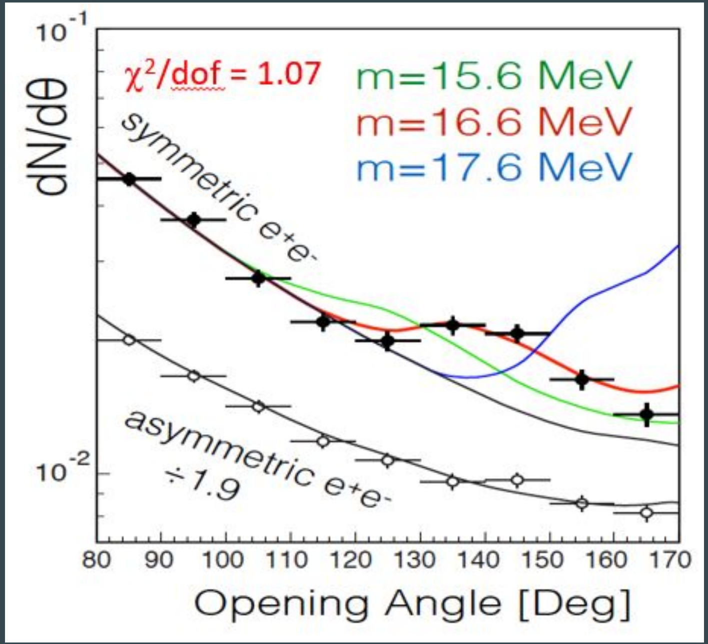
Excited states (18.2 MeV, 17.6 MeV) obtained with 1030 keV and 441 keV proton beams



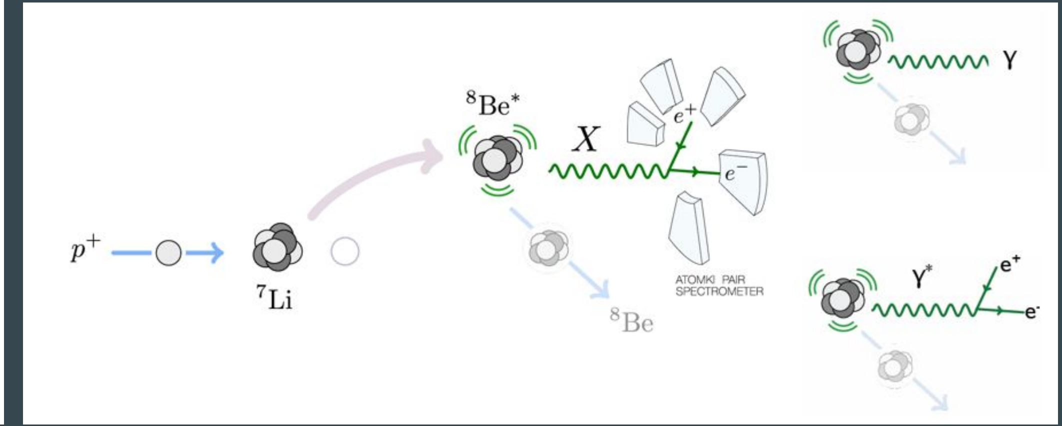


New physics hints?

❖ ATOMKI anomaly: observed unexpected peak in the e+e- opening angle distribution!

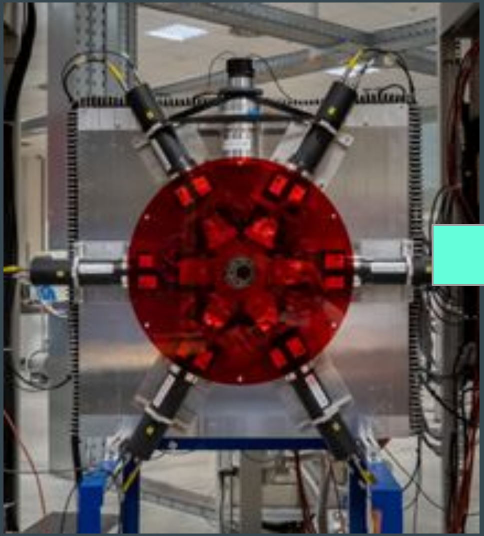


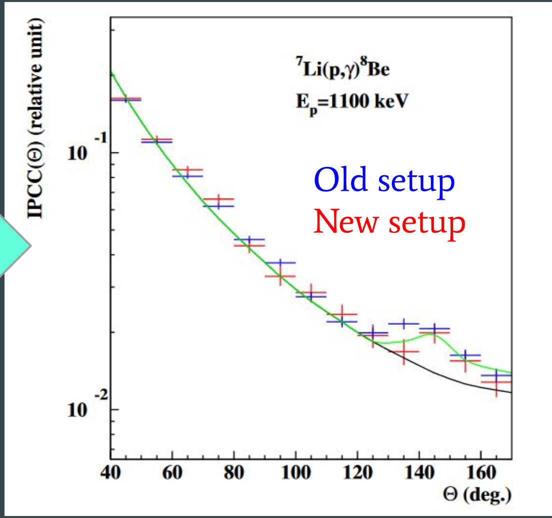
Possible explanation: new short lived particle with mass ~17 MeV (X17) decaying to e+e- pairs

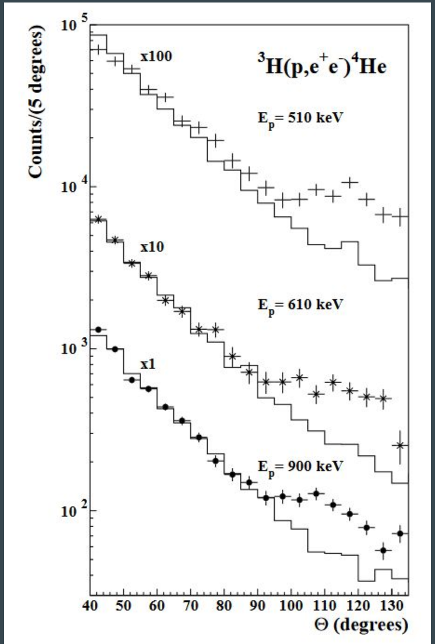


Additional studies:

- Same anomaly observed with a new experimental setup and on excited He nuclei



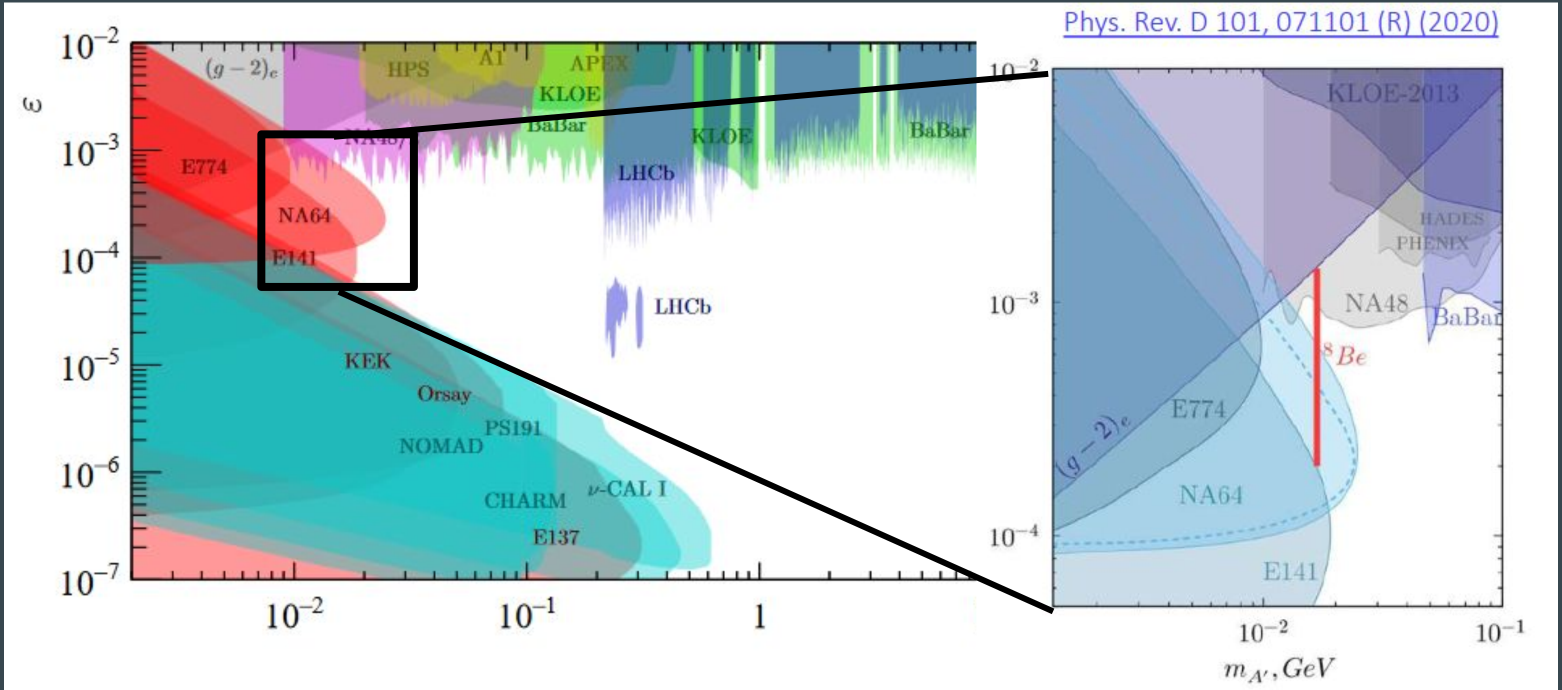




arXiv:2104.10075v1, J. Phys.: Conf. Ser. 1056 012028

May it be a dark photon??

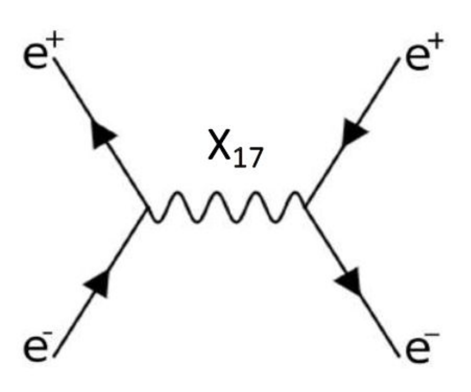
- There is still some free parameter space compatible with a Dark Photon explanation of the ATOMKI anomaly



Resonant A' production

❖ Idea: X17 production via e+e- **resonant annihilation** on thin target at the exact beam energy such that:

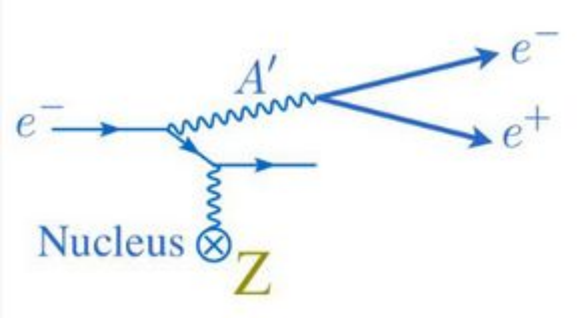
$$\sqrt{s} = \sqrt{2m_e E_{beam}} = m_{X17} = 17\ MeV$$



❖ **Resonant annihilation:**

- ➢ Better α_{EM} scaling than the A'-strahlung
- ➢ Large cross section in a very narrow range of sqrt(s)
- ➢ Ideal to search for a candidate with known mass!

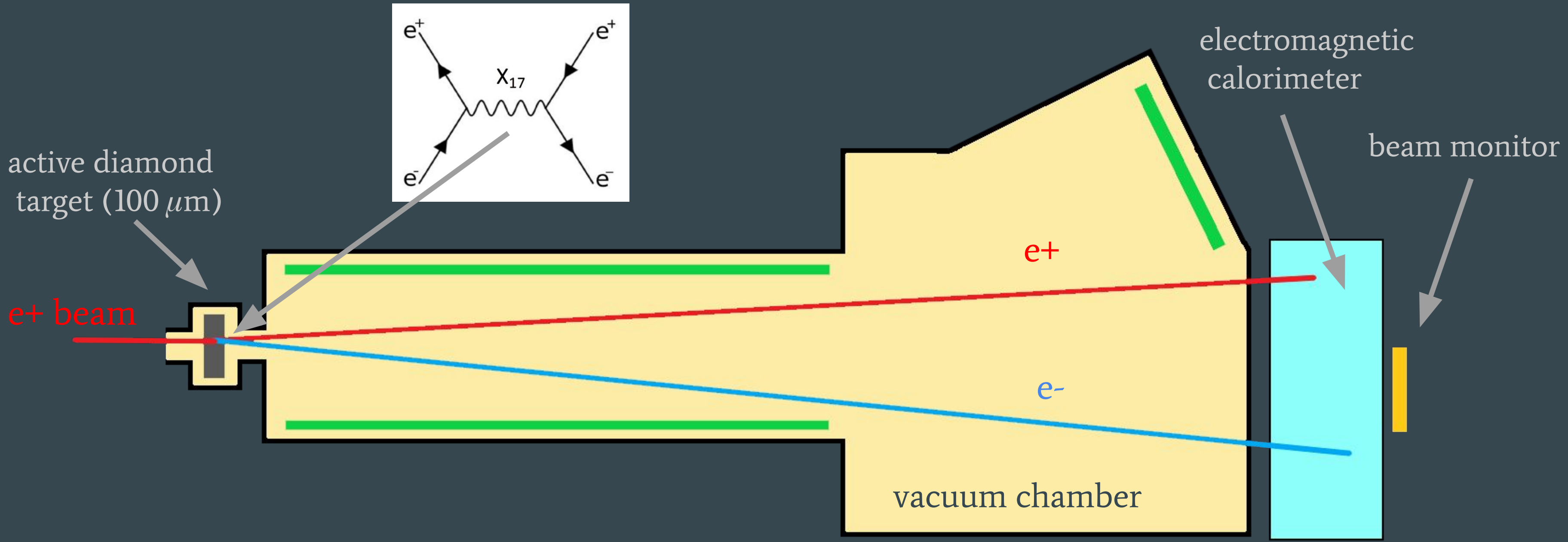
$$\sigma_r = \sigma_{\text{peak}} \frac{\Gamma_{A'}^2/4}{(\sqrt{s} - m_{A'})^2 + \Gamma_{A'}^2/4}\ , \quad \sigma_{\text{peak}} = 12\pi/m_{A'}^2$$



Need a positron beam with energy: $E_{resonant} = \frac{m_{X17}^2}{2m_e} \simeq 390\ MeV$

The PADME experiment at LNS

- PADME: search for X17 via resonant annihilation, performing a “scan” in beam energy around the resonance value



arXiv:2209.09261v2

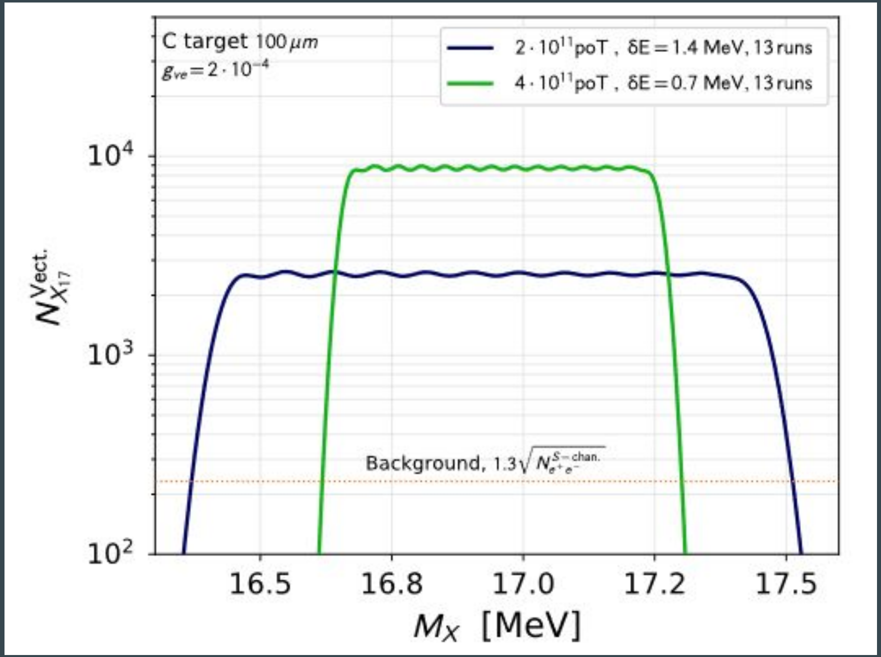
The PADME detector

arXiv:2405.07203

The Heavy Photon Search (HPS) Experiment

- Given the narrow width of the X17/*A'* , the resonant production yield depends critically on the beam energy

  → by performing several measurements varying the energy of the beam in small steps, it is possible to observe the rate increase of the e+e- pairs impinging on the ECAL, when the beam energy comes close to the resonance



- The overall increase in e+e- rate at the resonance is of order ~1% or less
  - ➢ It is critical to monitor the stability of the beam

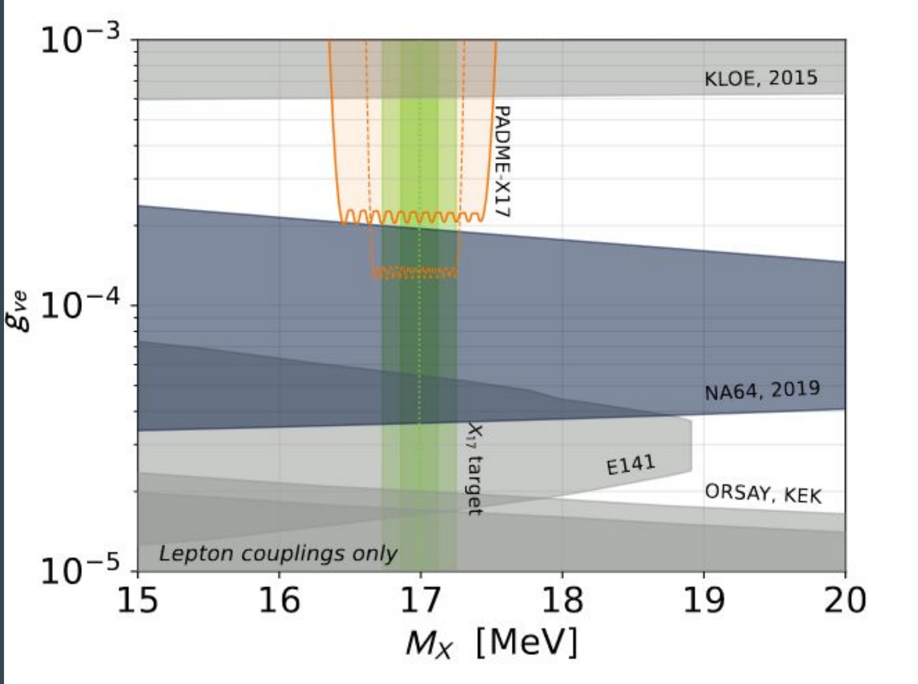
arXiv:2209.09261v2

PADME projected sensitivity

- Two scenarios considered:

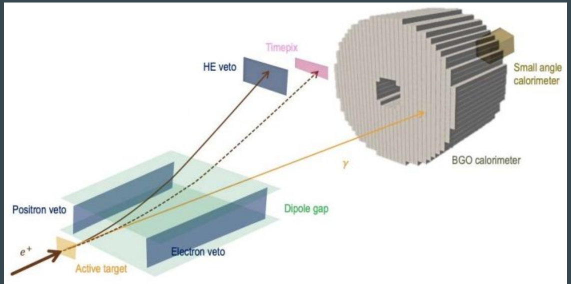
  Conservative: $2 \cdot 10^{11}$ total PoT, a 0.5% beam spread, a broad energy range [265, 297] MeV, an energy scan with 12 bins

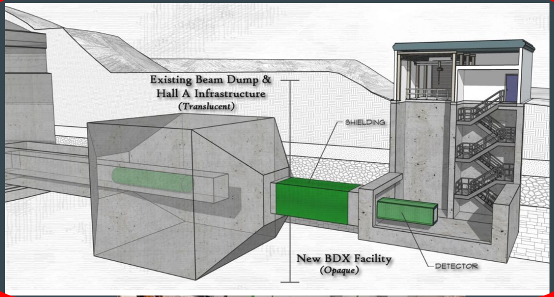
  Aggressive: 4×10^{11} total PoT on target, a 0.25% beam spread, a narrow energy range [273, 291] MeV, and an energy scan with 14 bins.

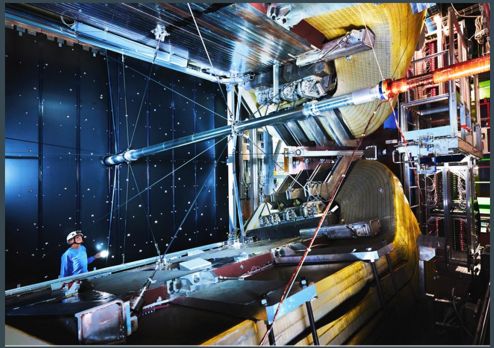


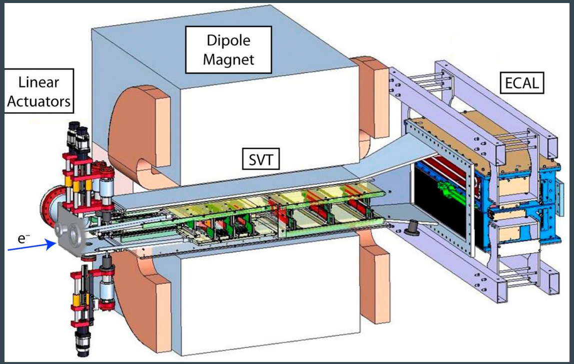
arXiv:2209.09261v2

Light DM searches at accelerators - thin targets



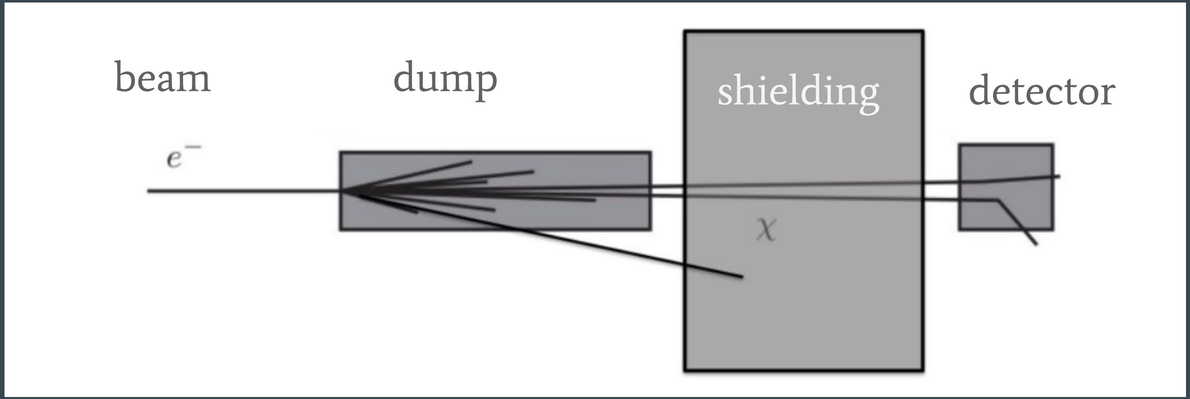






Beam dump experiments

- General concept:
  - high intensity particle beam impinging on a thick-target, the *beam dump*
  - LDM particles produced by the interaction of the beam in the dump (radiative processes, SM particles decays...)
  - Detector located O(10-100 m) downstream
  - Passive/active shielding usually placed between the dump and the detector
  - Search LDM scattering/decays within the detector

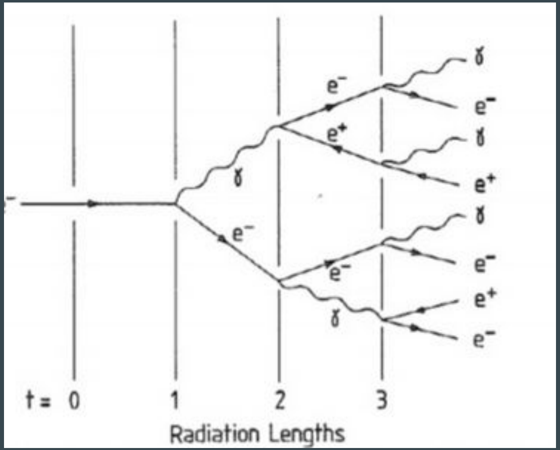


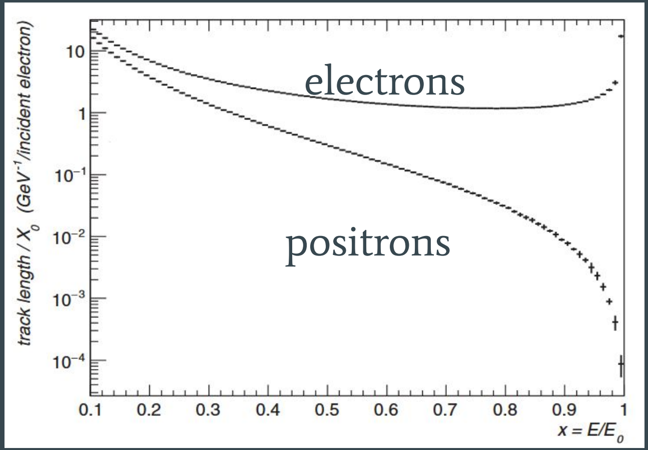
Several variations:

- Beam: typical e^-,p; energy ~10-100 GeV
- decay volume?
- distances, shielding

A' production in electron beam-dump experiments

In electron beam-dump experiments, the beam impinging on the target gives rise to an electromagnetic shower → large number of secondary e^+,e^- but also muons are produced



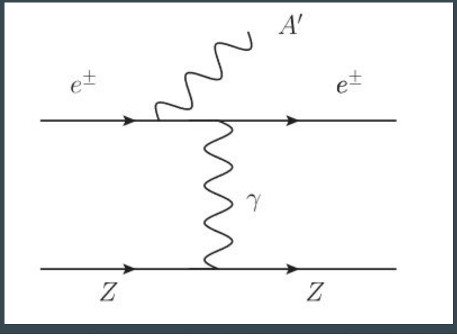


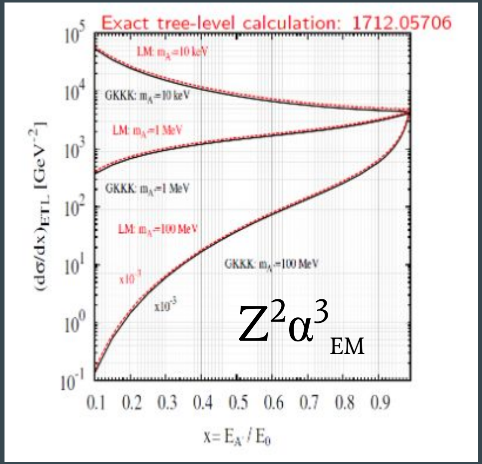
Introduce the *differential track length* $\frac{dT}{dE}(x)$: the average path of particles with energy in the *(E, E+dE)* range

Secondary particles can improve significantly the A' yield in beam-dump experiments

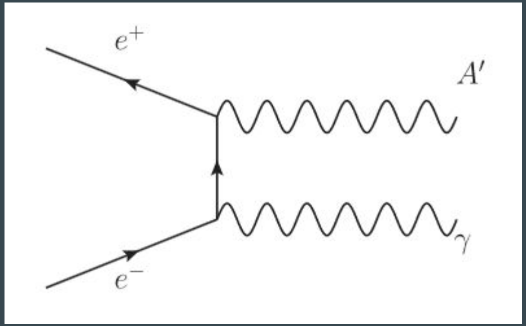
A' production processes with e^+ and e^-

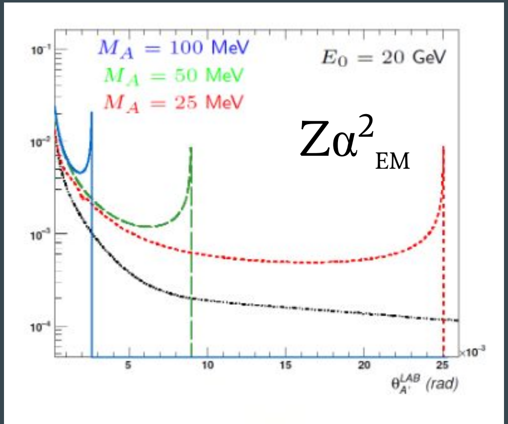
A'-strahlung



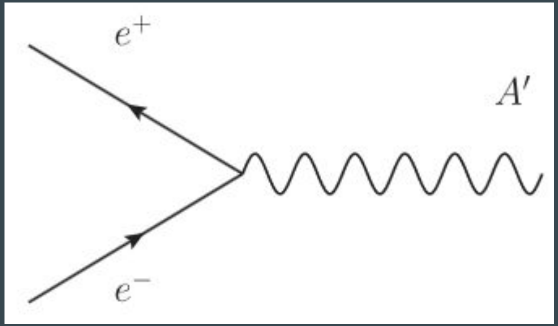


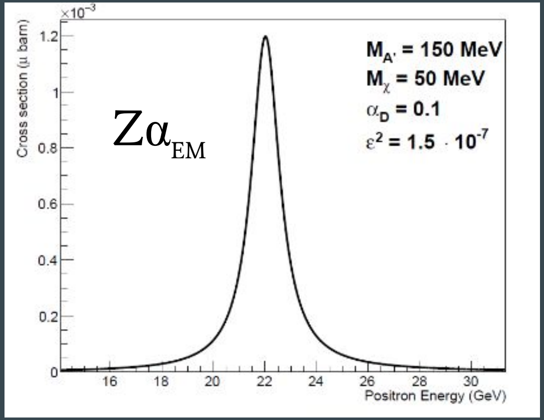
Annihilation



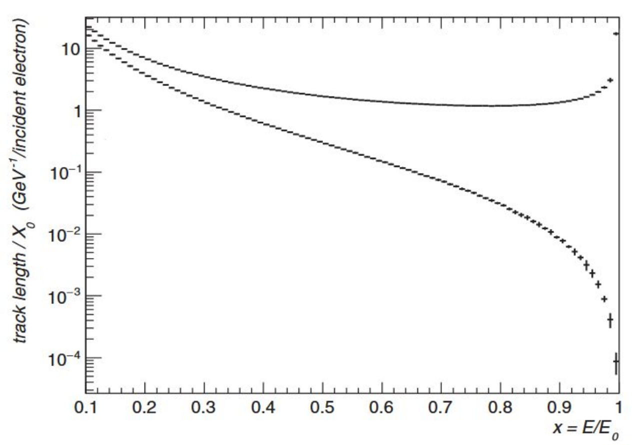


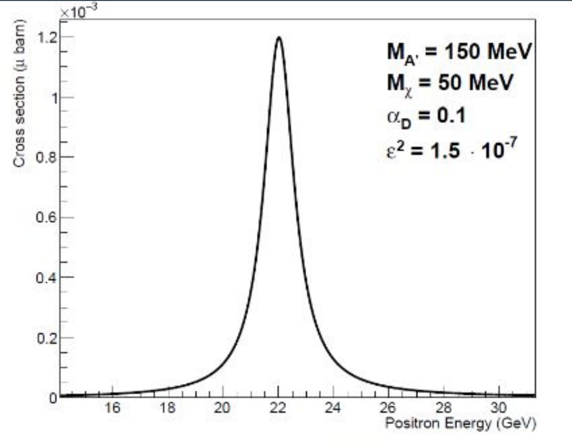
Resonant annihilation





Resonant annihilation “scan” at beam-dumps experiments



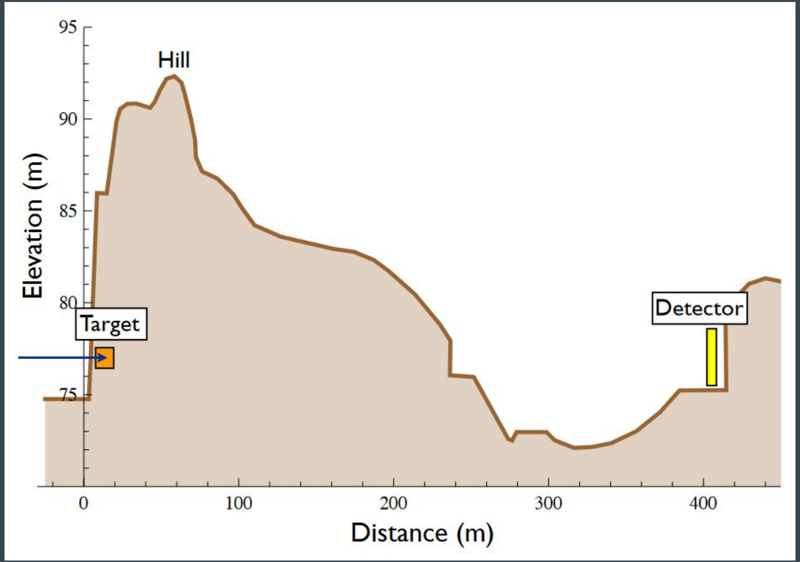


$$N_{A'} = \frac{N_A}{A} Z \rho \int_{E_{min}}^{E_0} \frac{dT_{e+}}{dE}(E) \sigma_r(E) dE$$

The E137 experiment

ALPs search experiment, results re-interpreted as LDM search.

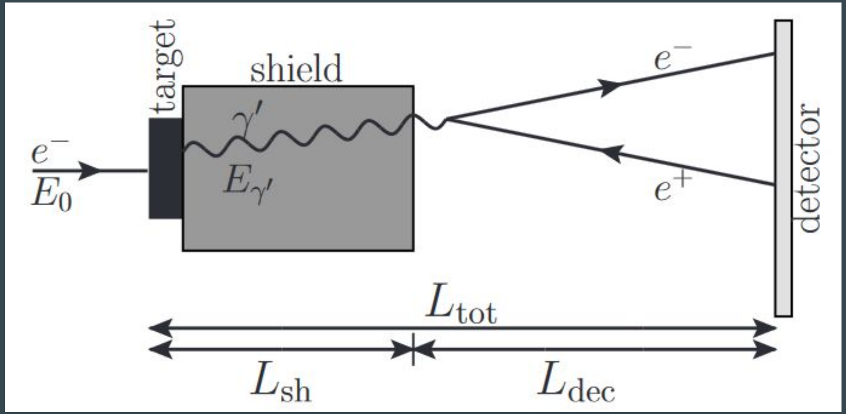
- **Beam:** 20 GeV e^- beam, 2×10^{20} EOT
- **Target** : Water-filled Al beam dump
- **Shielding:** 179 m of ground (hill)
- **Decay volume:** ~150 m (air)
- **Detector:** $8 - X_0$ EM calorimeter + MWPC

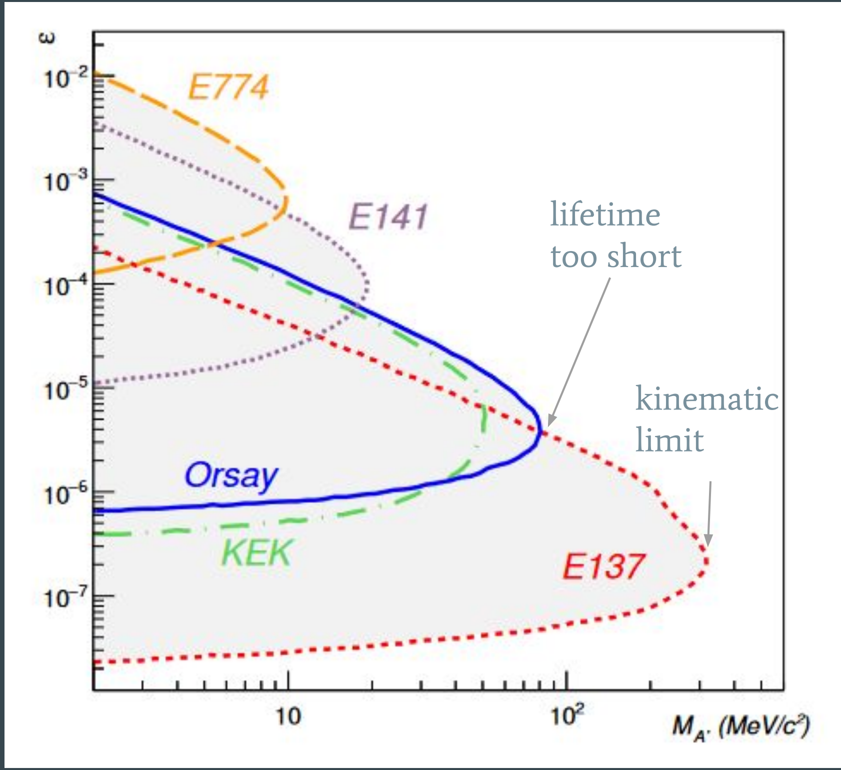


No ALP-compatible signal (deposited energy larger than 1 GEV, pointing towards the dump) observed during operation; results re-interpreted both in the visible and invisible decay scenario

E137 - Visible re-analysis

- The large collected charge allows E137 to explore coupling down to $\sim\varepsilon^{-8}$
- Limitation at higher coupling values comes from the limited *A'* lifetime (decay occurs in the shielding)



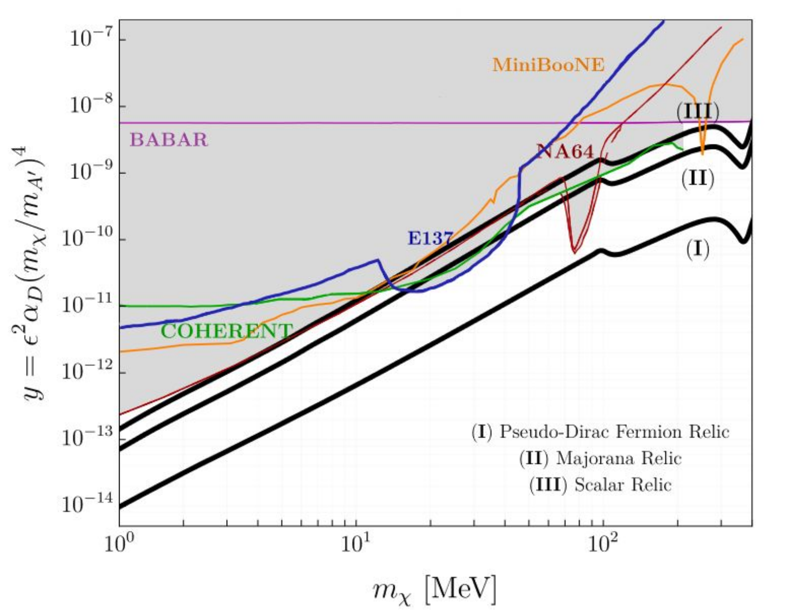


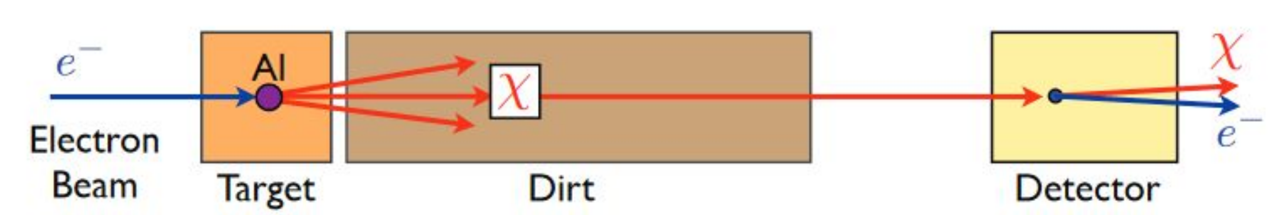
1209.6083

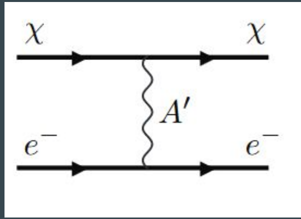
E137 - Invisible re-analysis

- E137 results recast in the LDM scenario
- Flux of LDM particles from decay of *A'* produced in the target (*A'*-strahlung, annihilation)
- Signal: Elastic LDM-electron scattering in the detector -> EM shower

$$\frac{d\sigma_{\chi e}}{dE_R} = 4\pi\alpha\alpha_D\varepsilon^2 m_e \frac{4m_e m_\chi^2 E_R + [m_\chi^2 + m_e(E - E_R)]^2}{(m_{A'}^2 + 2m_e E_R)^2(m_\chi^2 + 2m_e E)^2}$$





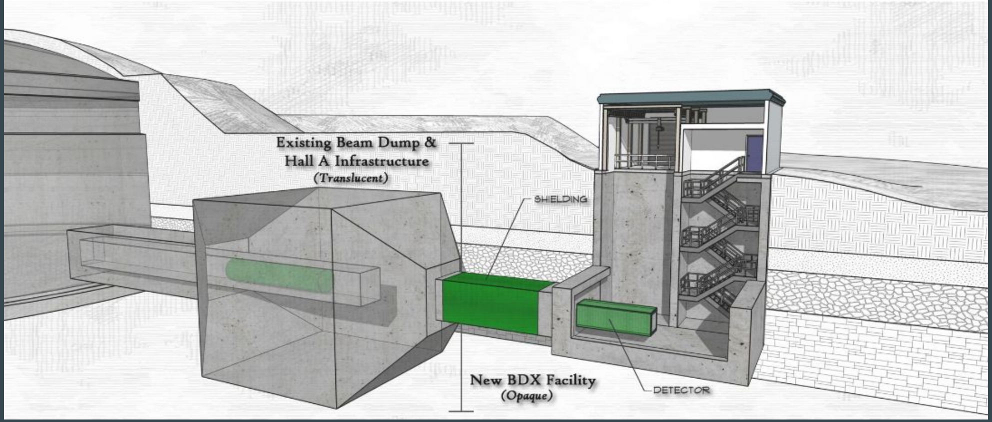


arXiv:1406.2698v2

The Beam Dump eXperiment (BDX)

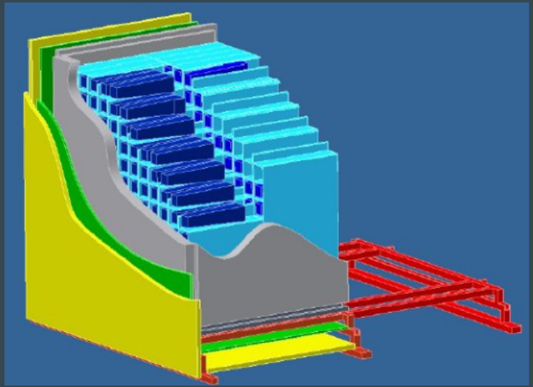
Modern beam-dump experiment proposed at JLab: 11 GeV e– beam, Al/H2O beam-dump - optimized for invisible searches

- ❖ Detector installed O(20 m) behind Hall-A beam -dump, in a new experimental hall
- ❖ Passive shielding layer between beam dump and detector to reduce SM beam-related background
- ❖ Sizable overburden ('10 m water-equivalent) to reduce cosmogenic background



Detector Design:

- ❖ EM calorimeter: CsI(Tl) crystals+SiPM readout (active volume ~0.5 m^3)
- ❖ Dual active-veto layer Passive lead layer surrounding the calorimeter

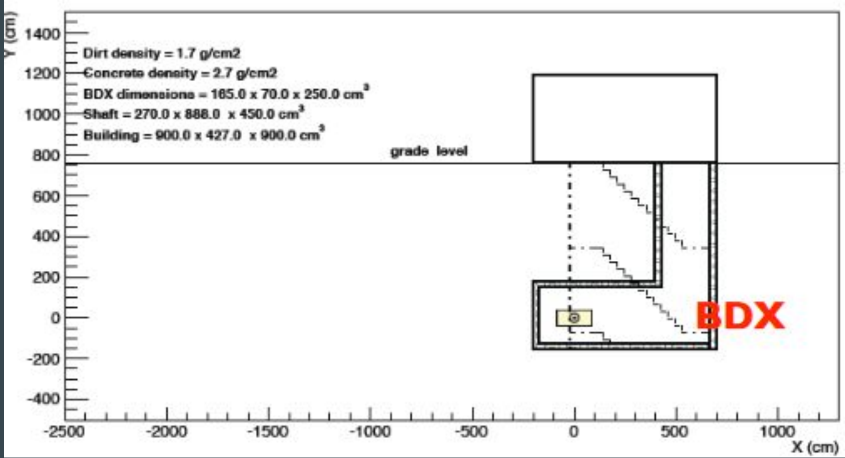


arXiv:1607.01390

BDX at JLab

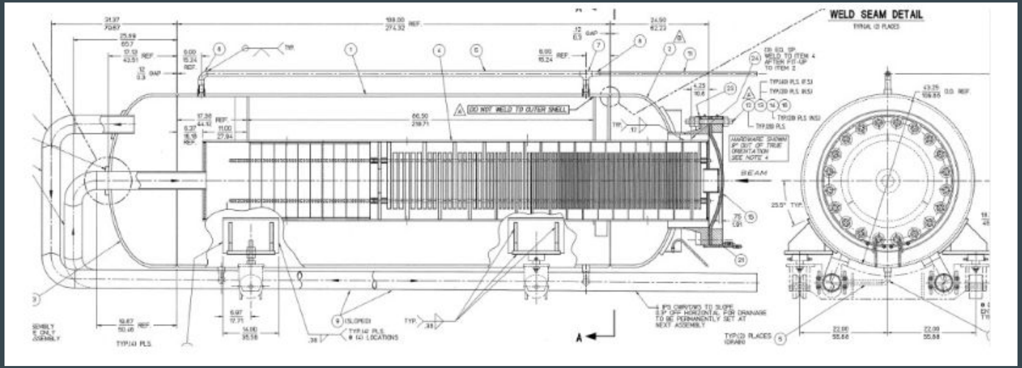
JLab offers the best condition for BDX:

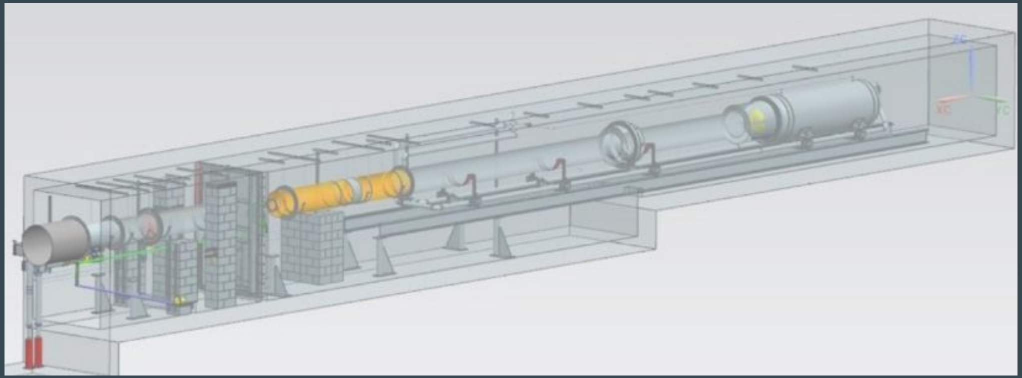
- ➢ Medium energy beam (11 GeV)
- ➢ High electron beam current (65 µA)
  - ■ possible to acquire a statistics of 10^{22} electrons on target in less than 1 year of beam time
- ➢ Possibility to run parasitically to other experiments running in Hall-A (Moeller)



The Hall A beam-dump

- The beam-dump is made of a set of ~80 Al disks, ~40 cm in diameter of increasing thickness (from 1 cm to 2 cm)
- An Al cylinder 50 cm in diameter and 2 m thick follows the disks
- Both the disks and the cylinder are cooled by circulating water
- The beam dump is enclosed in 4- 5 m thick concrete bunker to increase radiation shielding

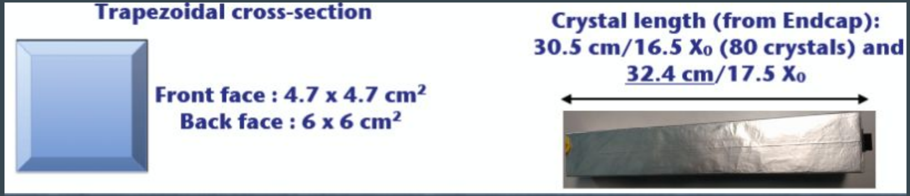




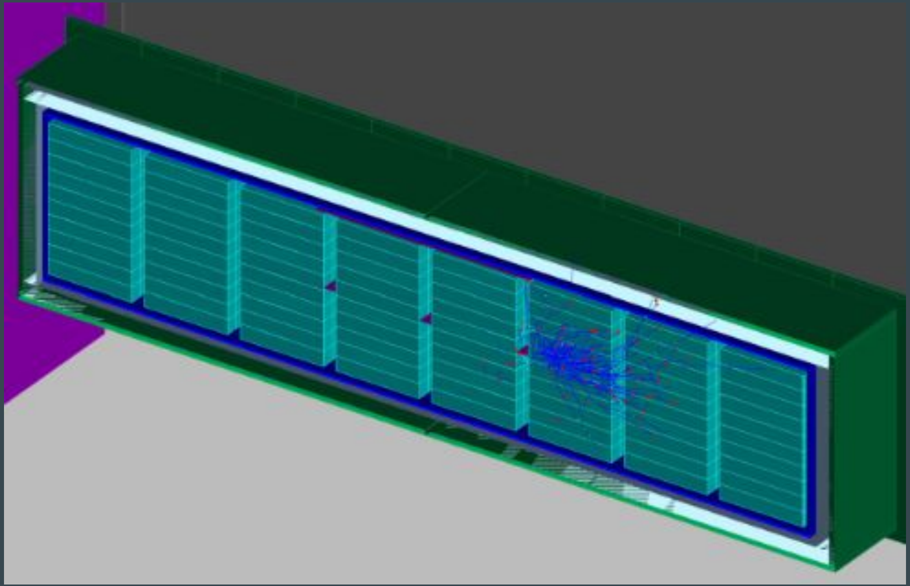
The BDX detector

possibility: re-use BaBar Crystals?

BDX detector: state-of-the-art CsI(Tl) EM calorimeter



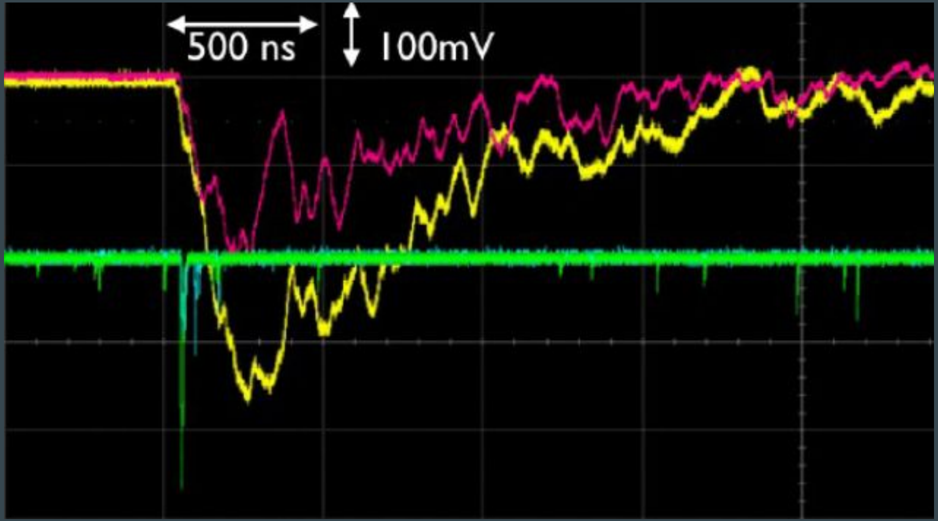
- ❖ **Detector design:**
  - ➢ 800 CsI(Tl) crystals, total interaction volume 0.5 m3
  - ➢ 5 cm thick lead shielding
  - ➢ Dual active-veto layer (IV and OV), made of plastic scintillator counters with SiPM readout
- ❖ **Calorimeter arrangement:**
  - ➢ module: 10x10 crystals, 30-cm long; front face: 50x50 cm2
  - ➢ modules: interaction length 2.6 m
- ❖ **Signal:**
  - ➢ EM-shower, (threshold: 300 MeV), anticoincidence with IV and OV
  - ➢ Efficiency: O(50%) – dominated by EM shower splash-back to veto counters



CsI(TI) crystals

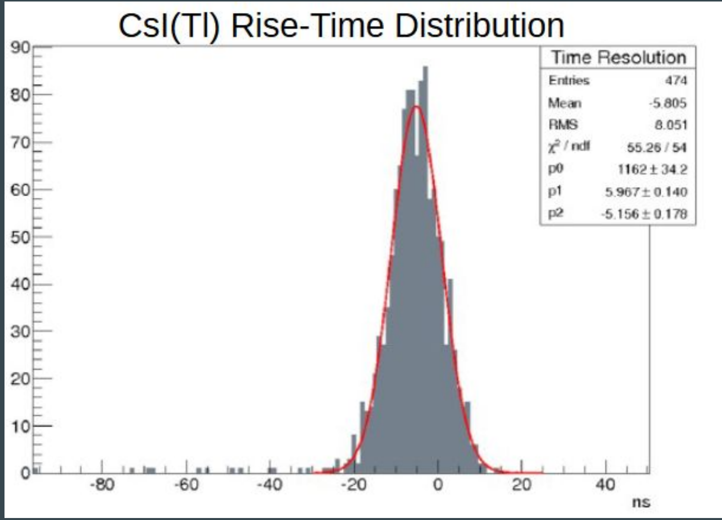
Optimal material choice for BDX:

- ❖ high light yield
- ❖ Reasonable density
- ❖ Fast enough rise time (order 5 ns time resolution with SiPM readout)



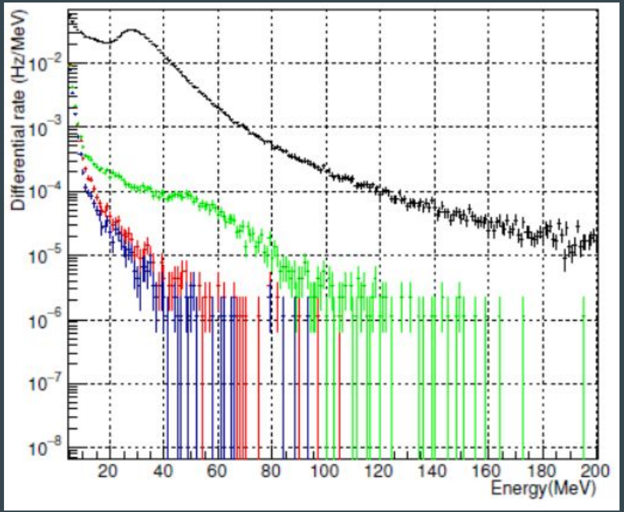
CsI(Tl) properties

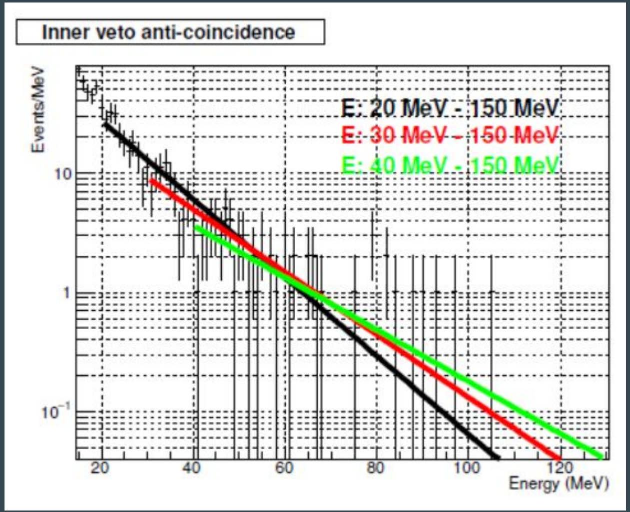
Parameter	Values
Radiation length	1.85 cm
Molière radius	3.8 cm
Density	4.53 g/cm^3
Light yield	50, 000 γ/MeV
Light yield temp. coeff.	0.28%/°C
Peak emission λ_{max}	565 nm
Refractive index (λ_{max})	1.80
Signal decay time	680 ns (64%)
	3.34 μs (36%)



Cosmogenic backgrounds

- Cosmic rays and cosmic ray-induced particles can produce a background for an experiment such as BDX, if they cross the veto system undetected and deposit ~300 MeV energy
- This background was evaluated by an ancillary measurement performed with a small prototype detector: *BDX proto*, whose results have been scaled to the full BDX dimensions



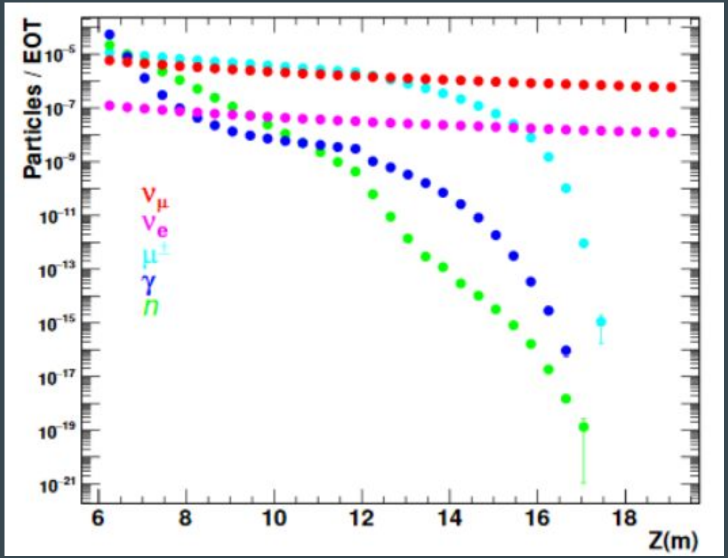


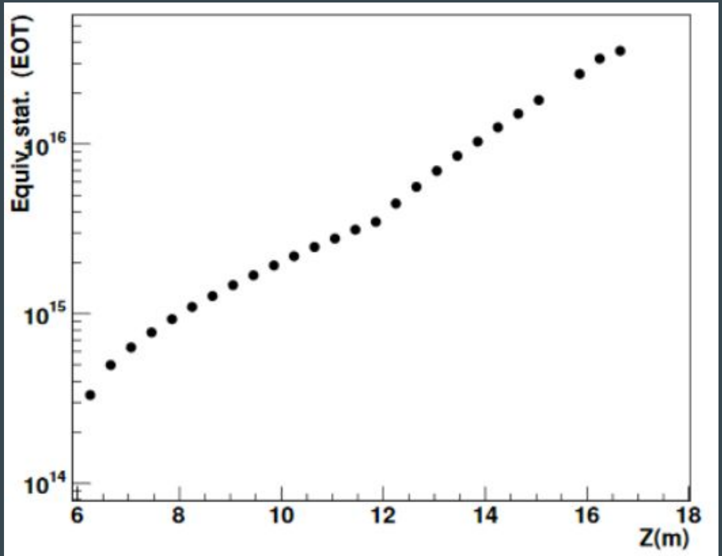
Energy threshold	Extrapolated rate
200 MeV	$(3.6 \pm 1.5) \cdot 10^{-8}$ Hz
250 MeV	$(2.9 \pm 1.3) \cdot 10^{-9}$ Hz
300 MeV	$(2.4 \pm 1.1) \cdot 10^{-10}$ Hz
350 MeV	$(1.9 \pm 0.9) \cdot 10^{-12}$ Hz

0 cosmic background events expected with an energy threshold over 350 MeV

Beam related Backgrounds

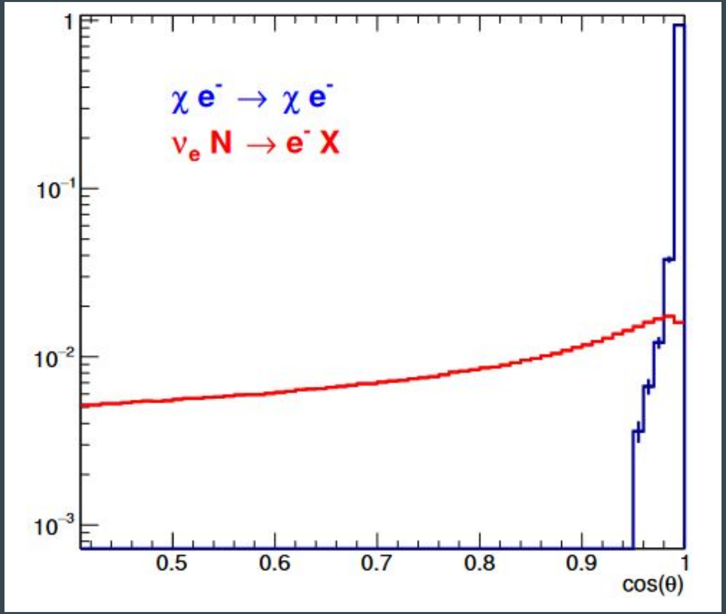
- ❖ Penetrating SM particles produced in the dump (muons, neutrons, neutrinos) can hit the detector mimicking the LDM signal
- ❖ This background can be evaluated only with simulations
- ❖ The large charge collected by BDX (1022) EOT makes impossible to simulate the whole experiment -> Biasing

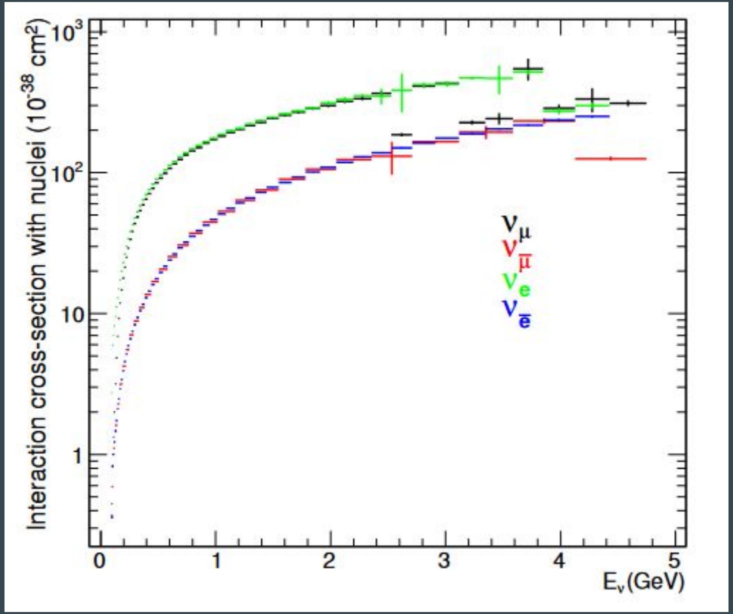




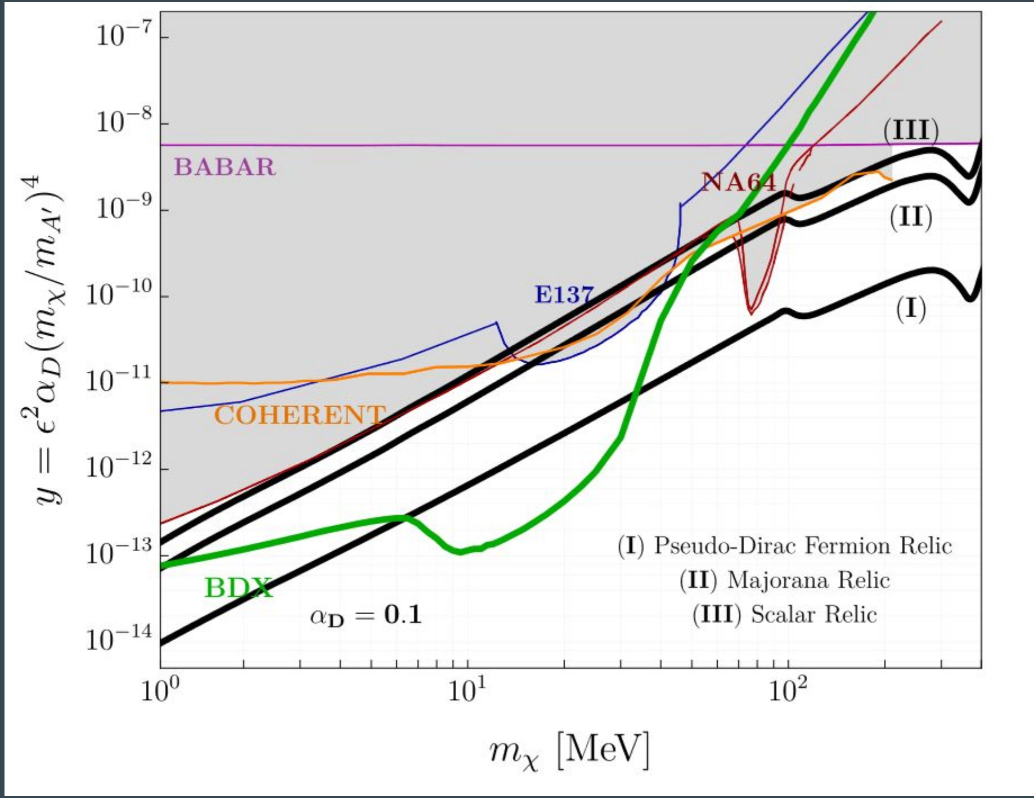
Neutrino induced background

- Not negligible neutrino flux impinges on the BDX detector
- Most dangerous reaction: electron neutrino CC $\nu_e N \rightarrow e\,\chi$ resulting in high energy e scattered within the detector
- Possible mitigation exploiting difference in kinematics between CC and signal
- Expected ~5 neutrino background events in the whole data taking

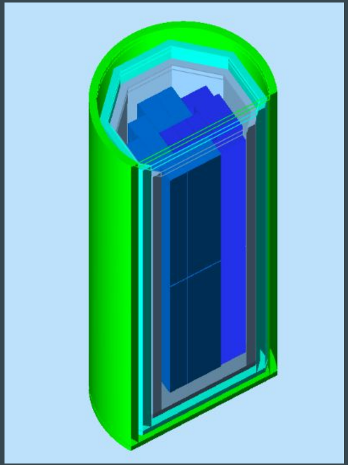




BDX projected sensitivity

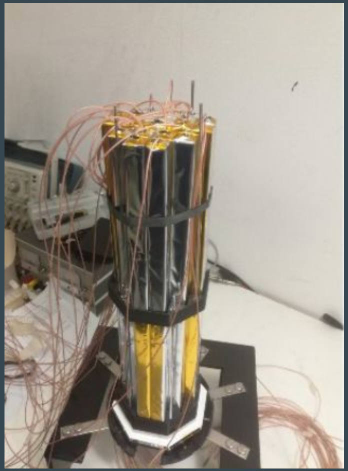


BDX - mini

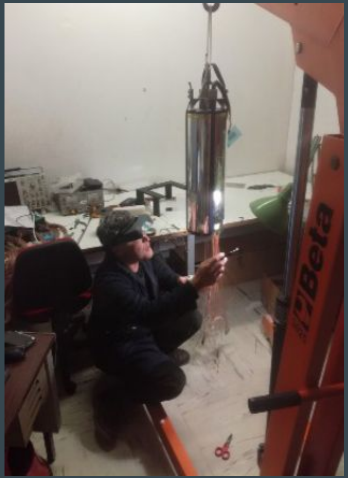


Small scale demonstrator for technical design validation:

- 0.15% of BDX active volume (44 $PbWO_4$ crystals, 4 dm^3), SiPM readout
- High efficiency hermetic multi layer veto (2 active vetoes + passive tungsten innermost layer)

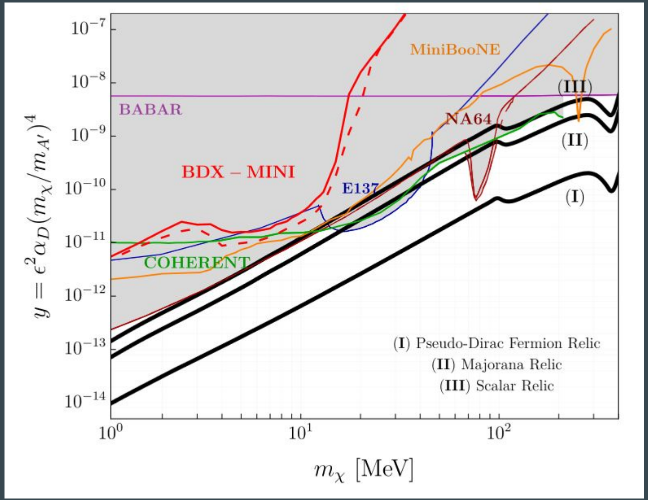


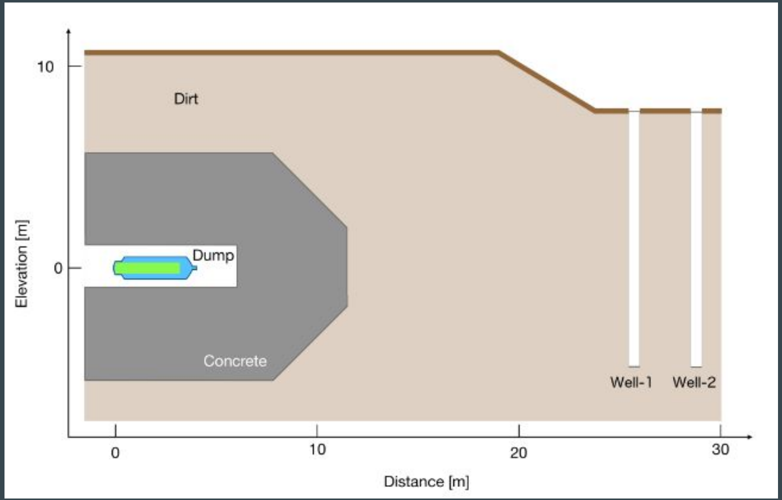




BDXmini- Measurement

❖ Experimental setup:
  ➢ 2.2 GeV, 150μA beam impinging on hall A
  ➢ Detector installed in a well 25 m downstream
  ➢ 20 % of BDX total charge collected (2×10^{21} EOT)

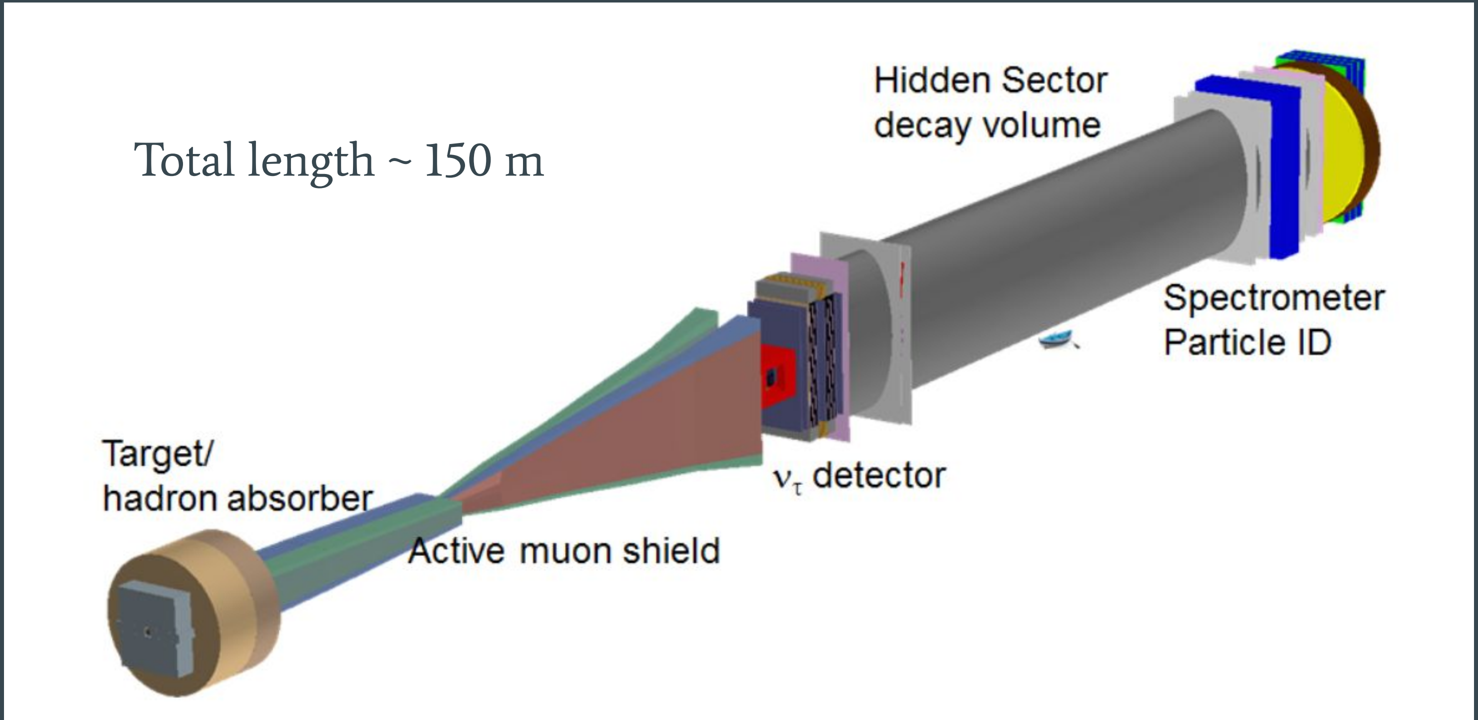




arXiv:2208.01387v1

The SHiP experiment

SHiP (Search for Hidden Particles) proton beam-dump experiment searching for dark sector particles at CERN SPS



arXiv:1504.04956

The SHiP

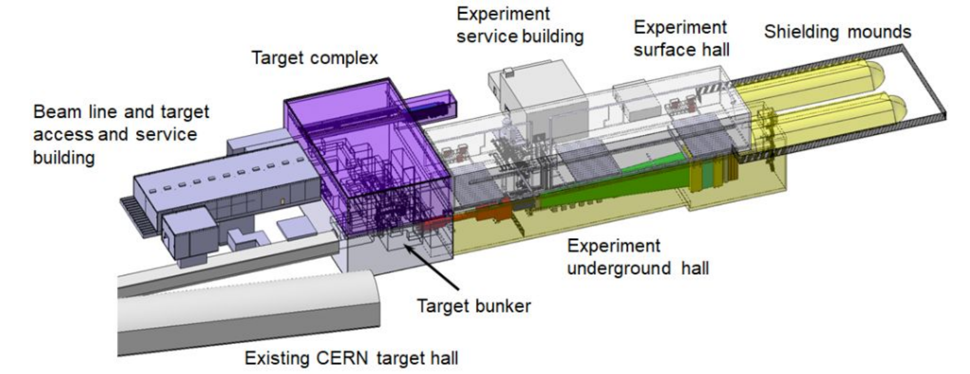
Optimized for the exploration of a broad BSM physics target

Models	Final states
Neutrino portal, SUSY neutralino	$\ell^{\pm}\pi^{\mp}, \ell^{\pm}K^{\mp}, \ell^{\pm}\rho^{\mp}, \quad \rho^{\pm} \to \pi^{\pm}\pi^{0}$
Vector, scalar, axion portals, SUSY sgoldstino	$\ell^{+}\ell^{-}$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^{+}\pi^{-}, K^{+}K^{-}$
Neutrino portal ,SUSY neutralino, axino	$\ell^{+}\ell^{-}\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^{0}\pi^{0}$

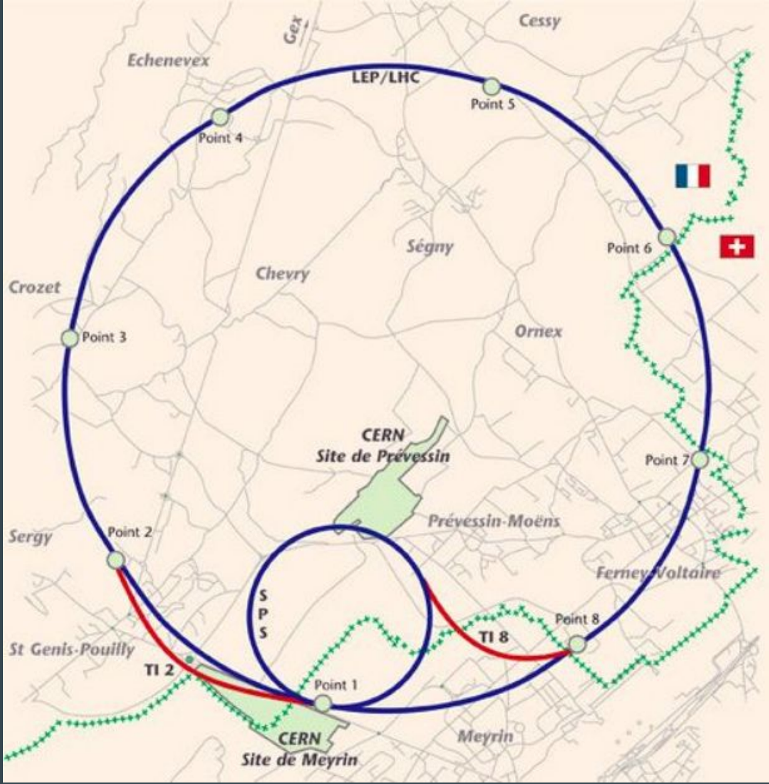
(invisible)

CERN Super Proton Synchrotron

- SHiP will make use of the SPS proton beam
  - Energy: 400 GeV
  - $2 \cdot 10^{13}$ proton per spill of 7.2 s
  - average power during extraction: 2.56 MW
- Total accumulated statistics: $5 \cdot 10^{20}$ POT



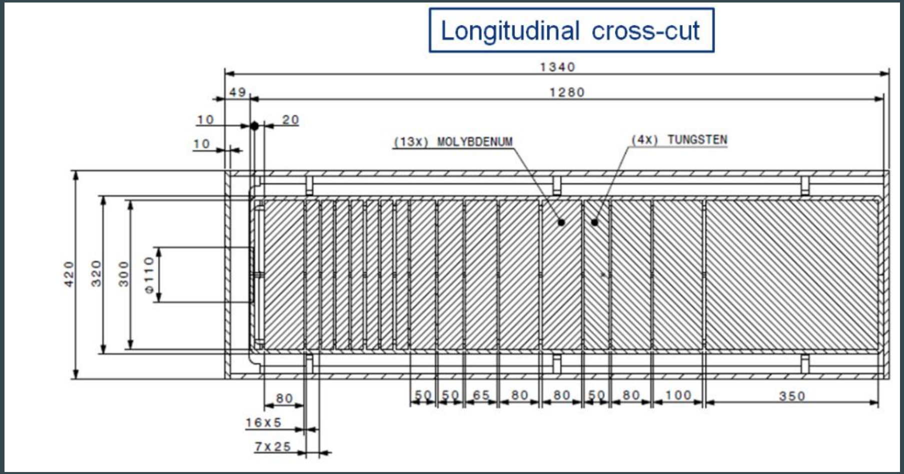
arXiv:1504.04956



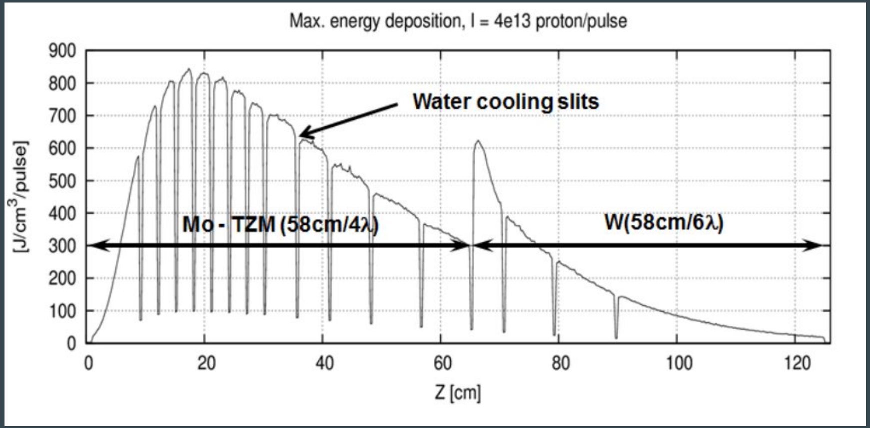
https://www.flickr.com/photos/arselectronica/5679905067

The SHiP target

- 10 nuclear interaction length long production target (~ 120 cm)
- High-Z target, composed of TZM (molybdenum/tungsten alloy) and pure W
- 30x30 cm^2, segmented target
- 58 cm TZM (13 layers) + 58 cm W (4 layers)



Energy deposition per SPS spill



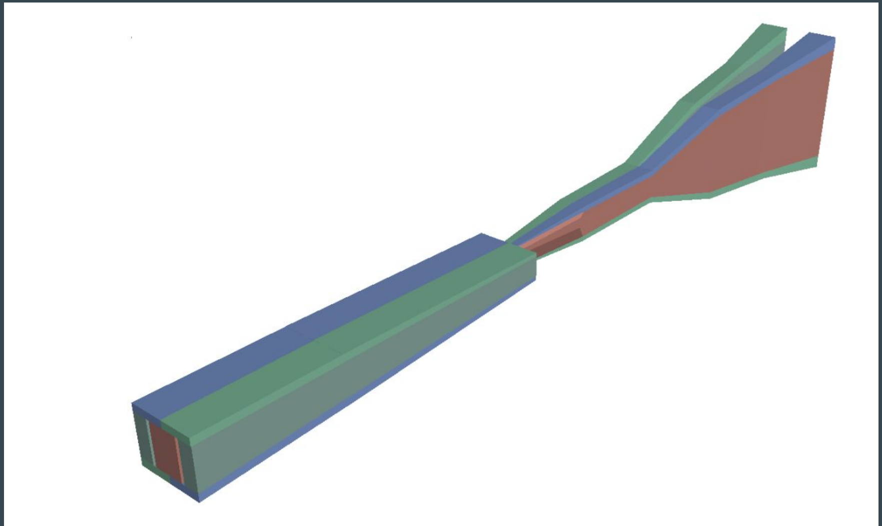
arXiv:1504.04956

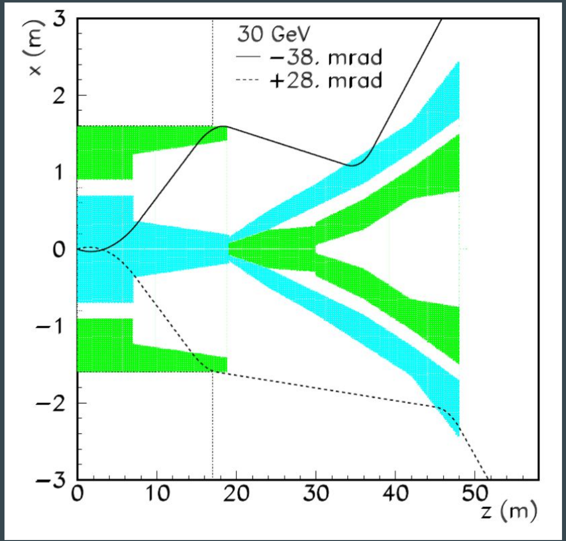
The muon shield

- ❖ Given the energy scale of the muons produced in the target, it is impossible to stop them with passive materials (production rate $5 \cdot 10^3$ muons/ spill)

→ magnetic shield based only on magnetic sweeping

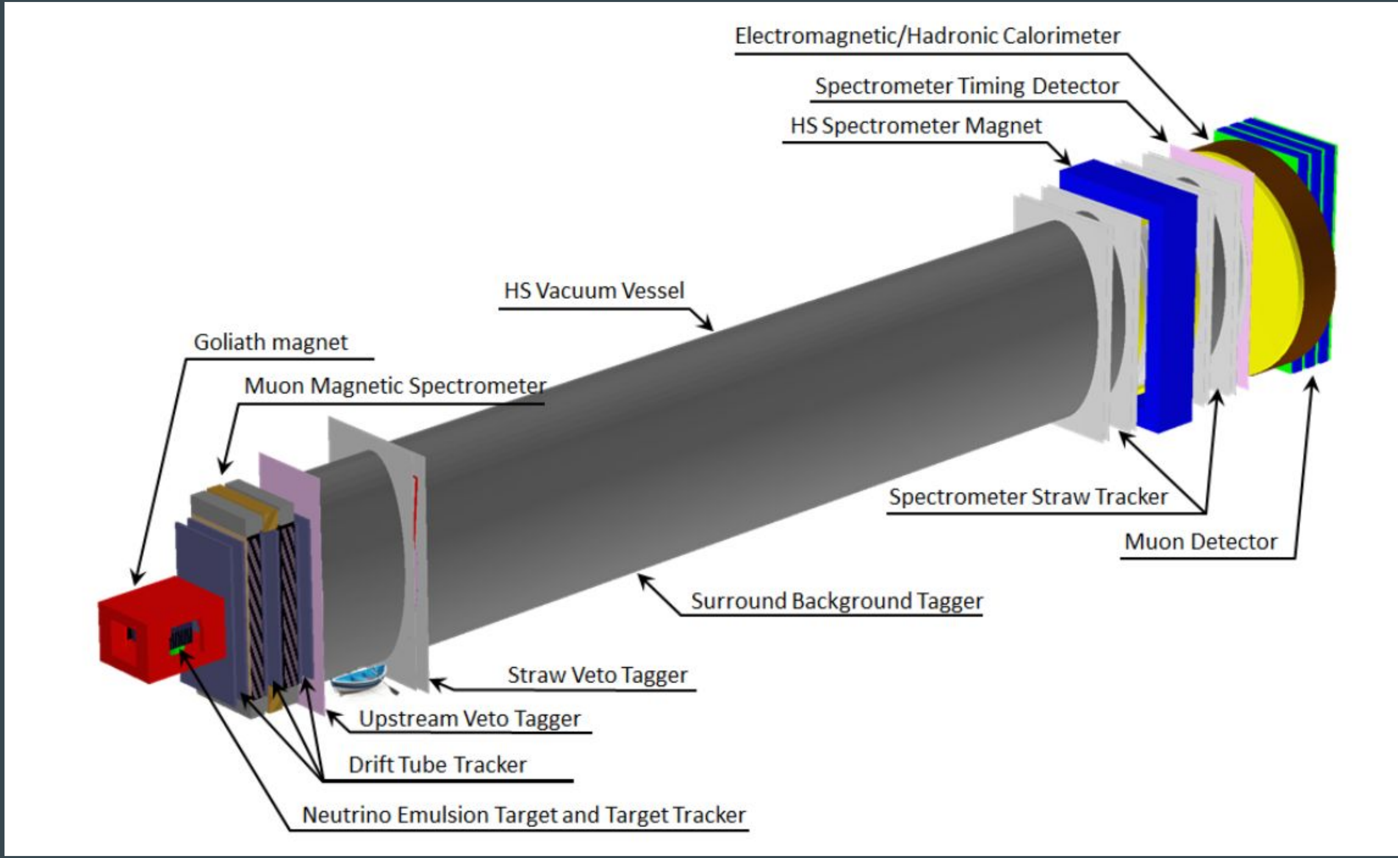
- ❖ Residual flux on detectors: $7 \cdot 10^3$ muons/ spill (negligible)
- ❖ Shield dimensions: 28 m length , 2800 tons weight



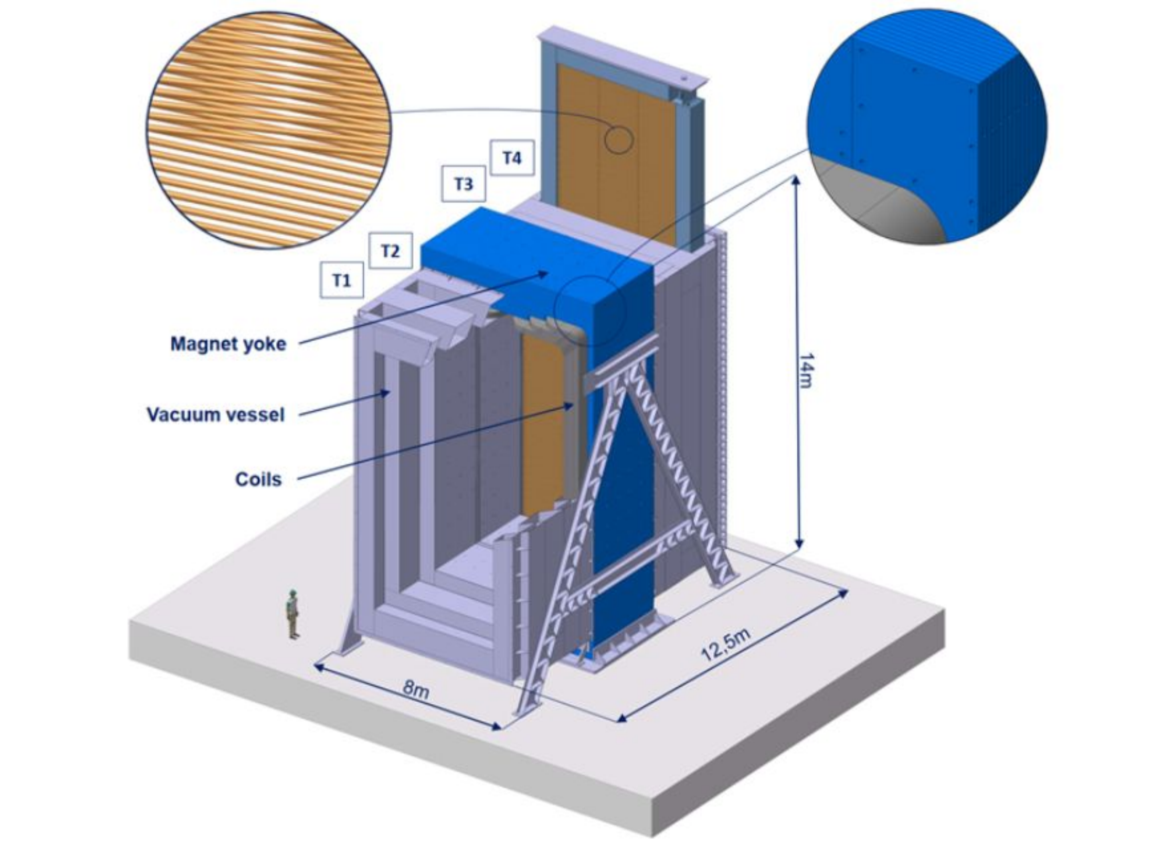


arXiv:1504.04956

The SHiP detector



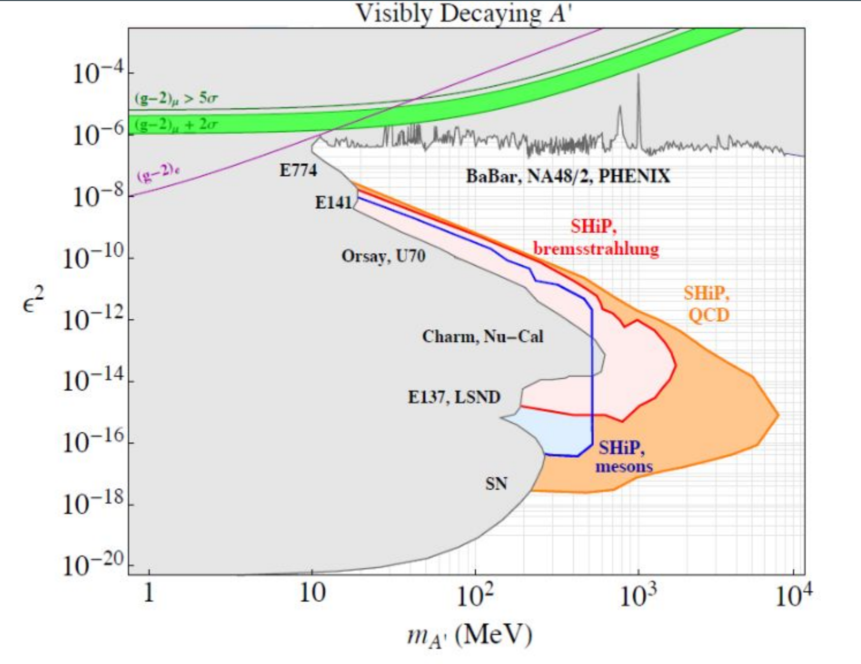
The SHiP spectrometer scale

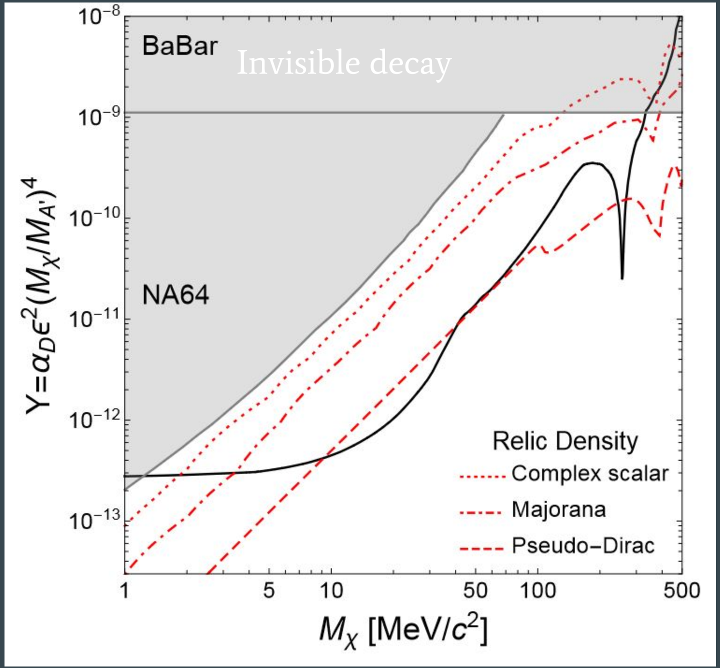


arXiv:2112.01487

Expected SHiP sensitivity to *A'*-mediated LDM scenarios

- $5 \cdot 10^{20}$ POT in 5 years of operation
- A' production via several processes: radiative, Drell Yan, meson decays





arXiv:2010.11057, arXiv:2011.05115