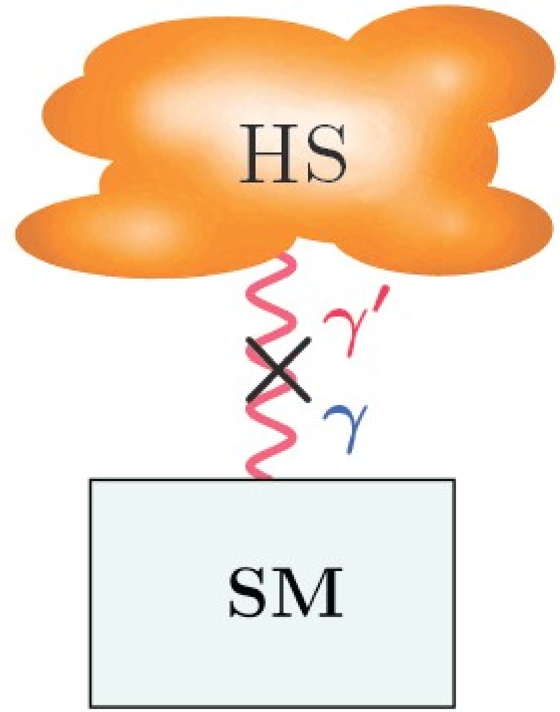
The BDX experiment at Jefferson Laboratory

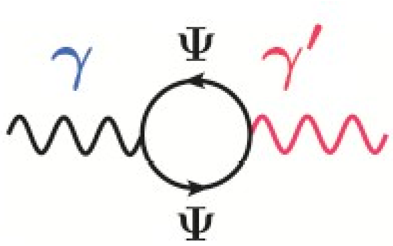
A. Celentano

INFN Genova

Dark Photons



- Consider an additional U(1) hidden symmetry in nature: this leads to a kinetic mixing between the photon and the new gauge boson A'

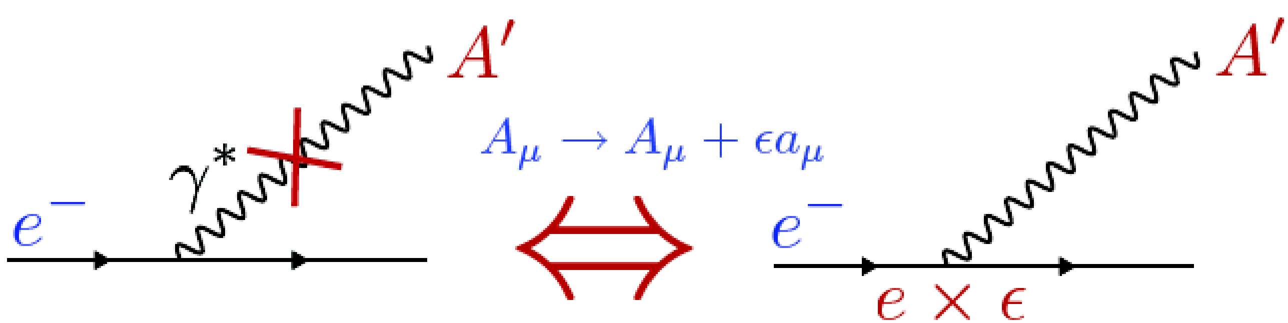


Ψ is a huge mass scale particle (M~1EeV) coupling to both SM and HS

- General hypothesis to incorporate new physics in the SM: the A' acts as a “portal” between the SM and the new sector

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \frac{\varepsilon}{2} F'_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + m_A^2 A'^{\mu} A'_{\mu}$$

- Under A' interaction, ordinary charged matter acquires a new charge **εe:**



New interaction term:

$$\varepsilon A'_{\mu} J^{\mu}_{EM}$$

Boldom, Phys. Lett. B166, 1986

Dark photons and dark matter

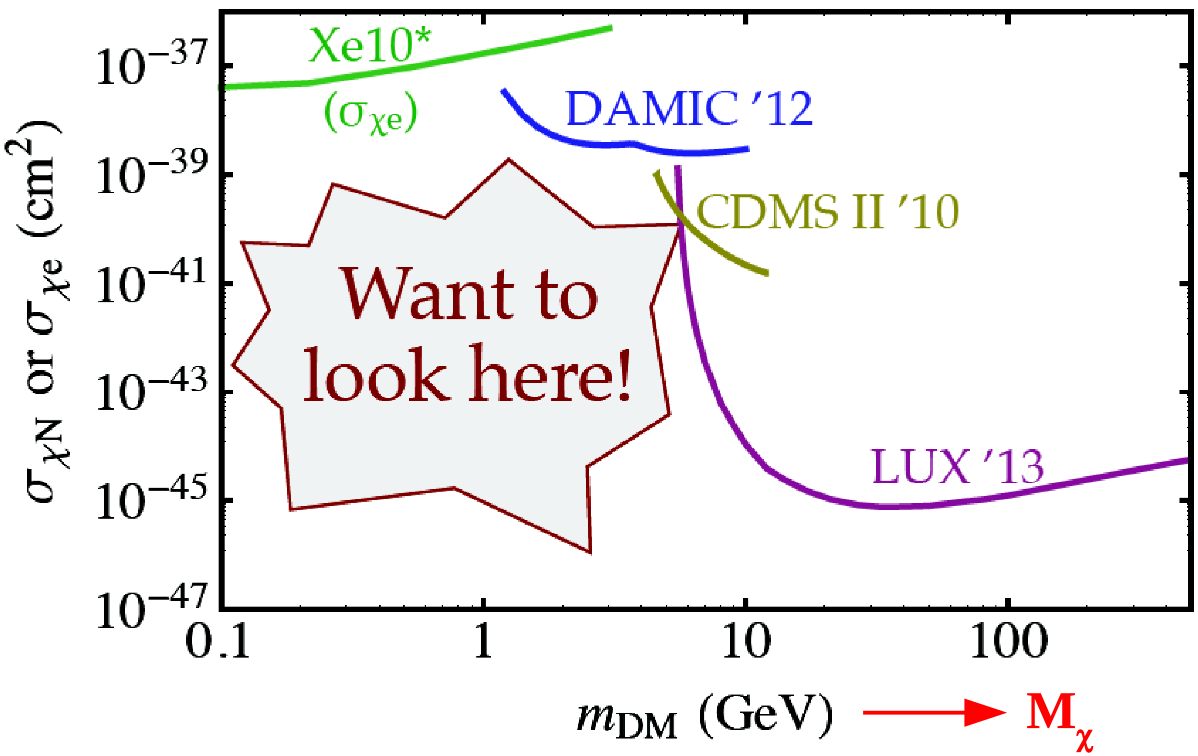
Most of the dark matter searches so far focused on WIMPS:

- High mass (10 GeV – 1 TeV)
- Low cross-sections for interaction with SM matter (10^{-15} µbarn)

Dark photons with ~ GeV mass coupled to DM would permit to explore DM existence in the mass region:

10 MeV – 1 GeV

Complementary search to explore another region in the parameter space M_{DM}, g_D



Important!

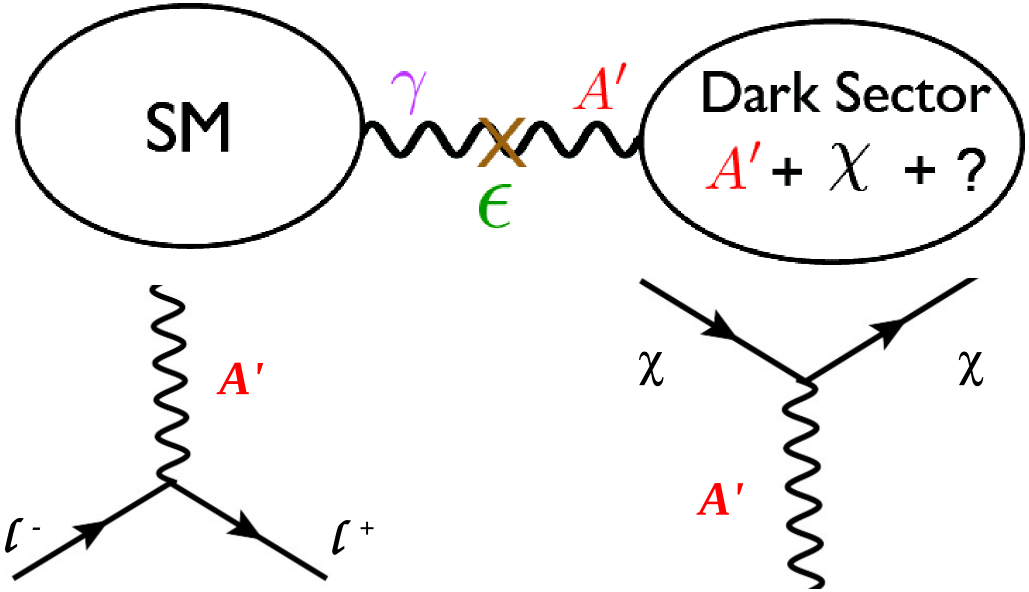
Testing the idea of dark sectors requires a collection of searches sensitive to all possible A' decays, visible & invisible.

Dark photons and dark sector

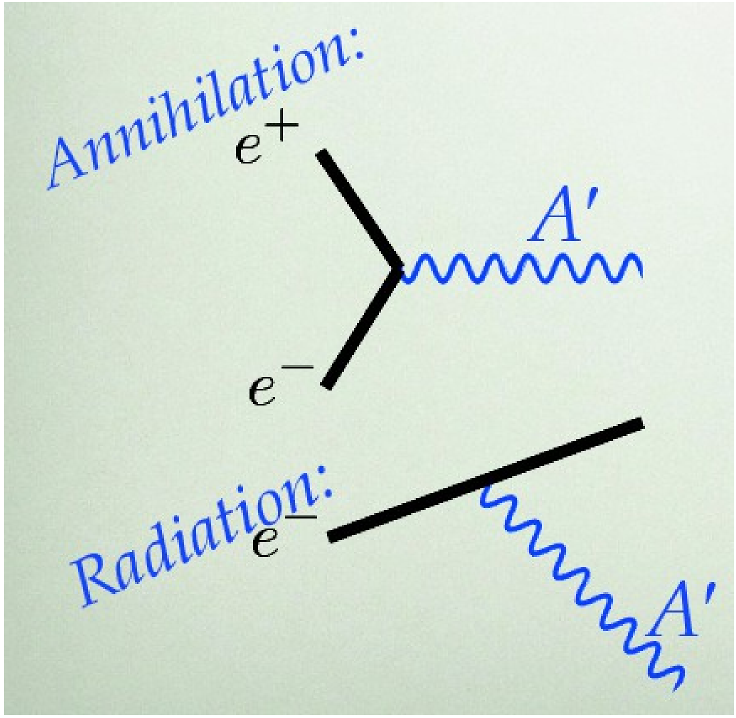
A simple model:

- A' interacts with γ trough kinetic mixing
- Dark sector particle χ interacts with A'

4 parameters: $M_{A'},\ M_{\chi},\ \varepsilon,\ g_d$

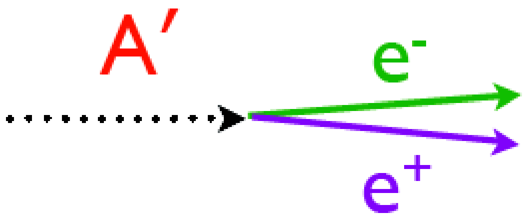


A' production: $\sigma \propto \varepsilon^2$



A' decay:

Visible **First scenario**



$\Gamma \propto \varepsilon^2$

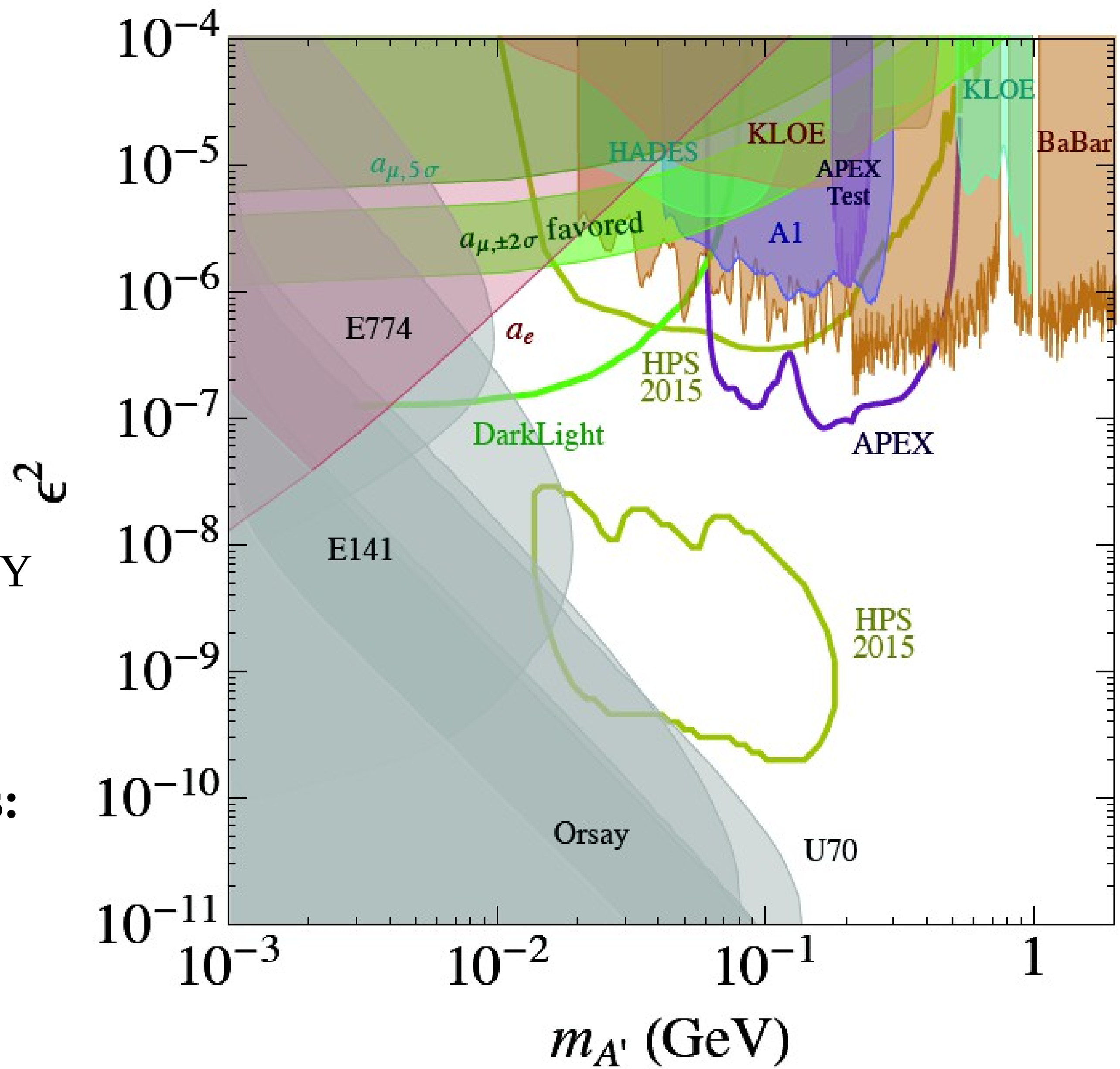
- Minimal scenario
- Decay suppressed by small mixing ε
- Valid for any M_χ value

HPS, APEX, DarkLight (JLab)
A1 (Mainz)
Babar, Kloe, NA48/2, ...

A' current searches and constrains

Any γ-rich environment is suitable for A' searches.

- Fixed target with e⁻ beam
  - JLab, Mainz
- Fixed target with p beam
  - Fermilab
- Annihilation
  - BABAR, BELLE, KLOE
- Meson decay
  - KLOE, BES-3, WASA-COSY



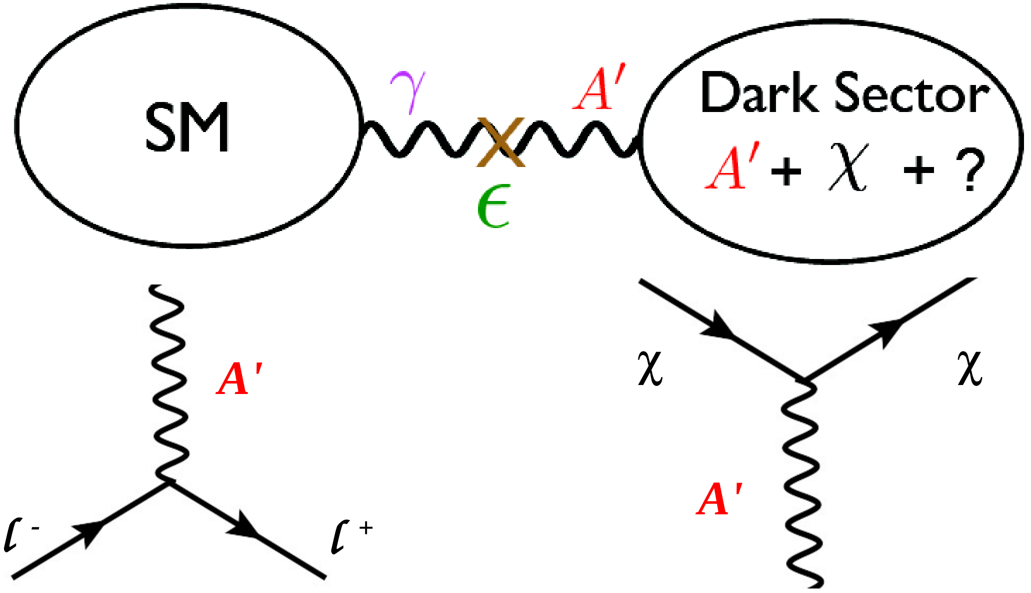
So far, no positive A' evidences: limits in the parameters space

Dark photons and dark matter

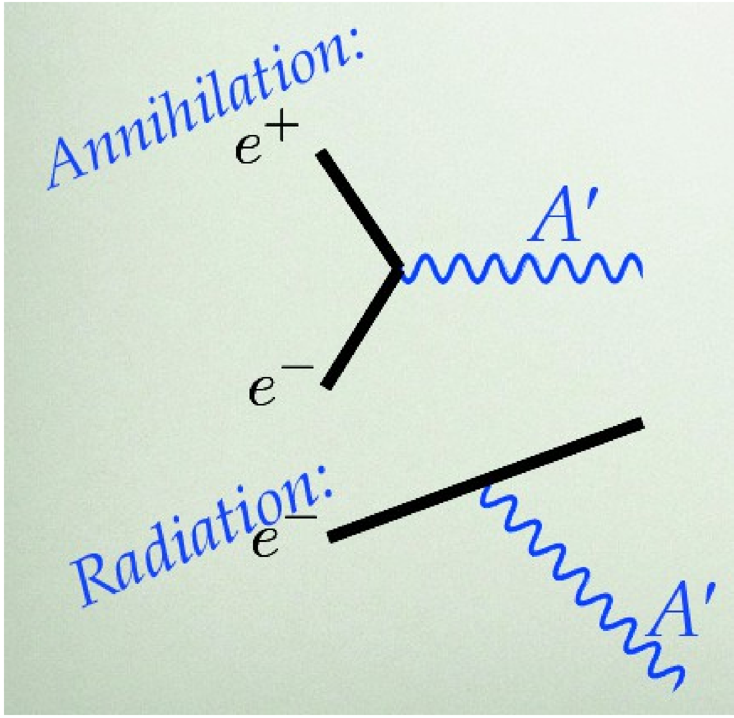
The simplest model:

- A' interacts with γ trough kinetic mixing
- DM χ interacts with A'

4 parameters: $M_{A'},\ M_\chi,\ \varepsilon,\ g_d$



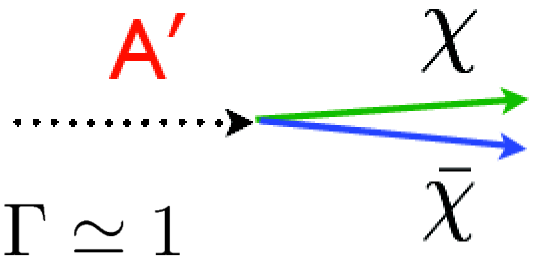
A' production: $\sigma \propto \varepsilon^2$



A' decay:

Invisible

Second scenario



$\Gamma \simeq 1$

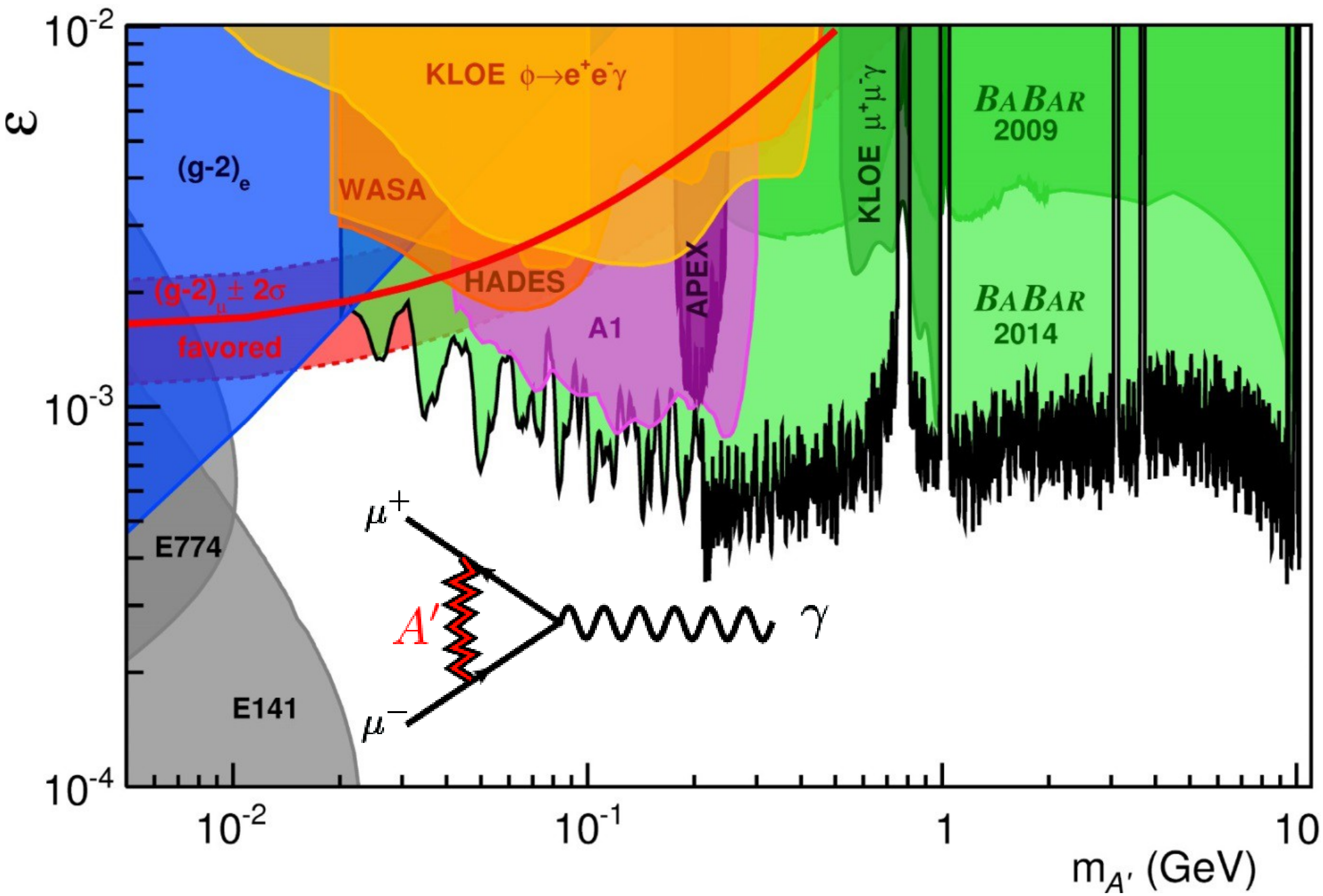
- **Only if $M_\chi < M_{A'} / 2$**
- Not ε-supressed
- If present, is the preferred A' decay mode
- **If present, visible decays are ε^2 suppressed**

BDX experiment at JLab
(LOI submitted to JLab PAC 42)

Dark photons invisible decay: g-2

- Muon g-2 anomaly: "traditional" motivation for A' search
  - New results (Babar, Kloe) seem to exclude the g-2 motivated region in the $\varepsilon - M_A$ plane
  - **This conclusion is model-dependent: if invisible decay is included, limits do not hold!**

Muon g-2 anomaly has to be investigated considering visible AND invisible decay modes



[arXiv:1406.2980]

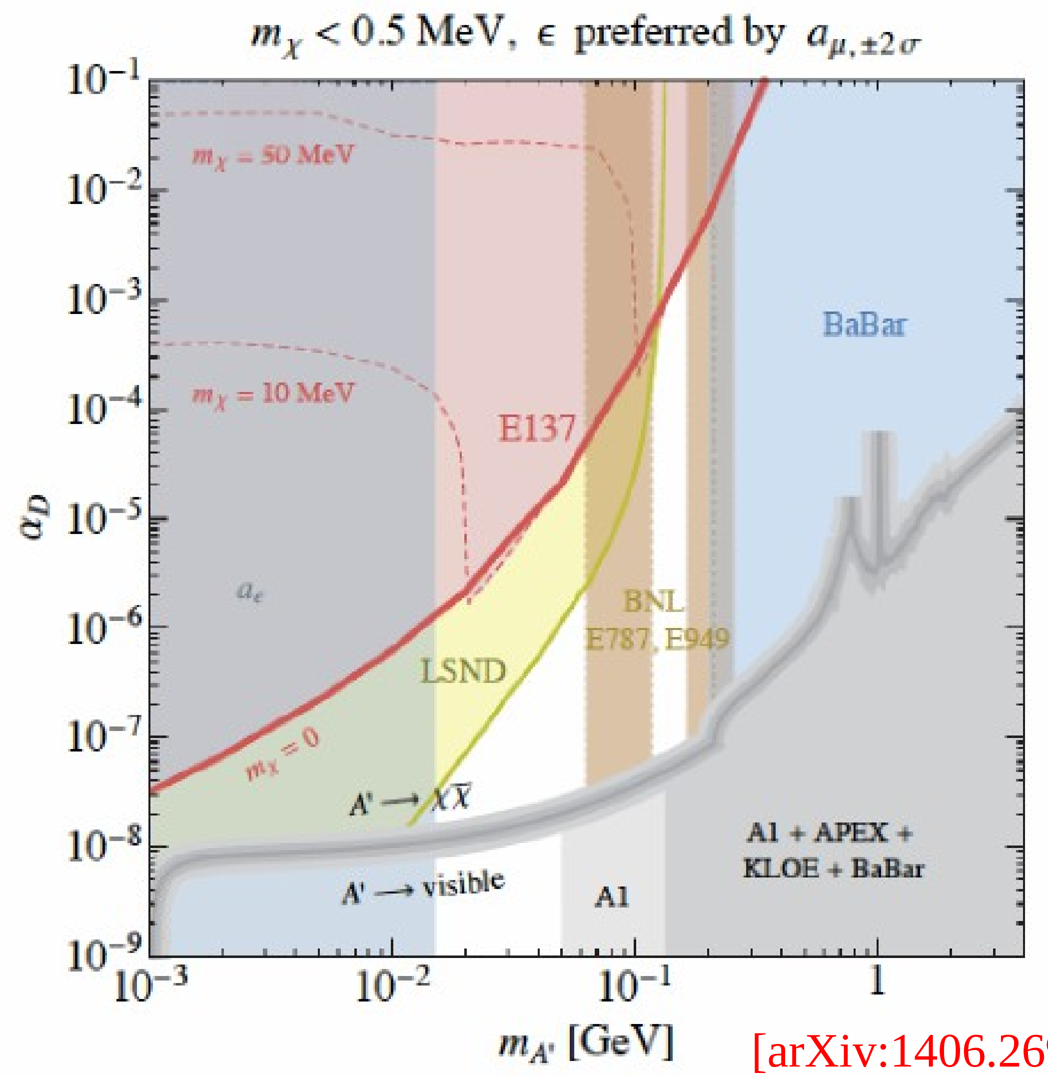
Dark photons invisible decay: g-2

- Muon g-2 anomaly: "traditional" motivation for A' search
  - New results (Babar, Kloe) seem to exclude the g-2 motivated region in the $\varepsilon - M_A$ plane
  - **This conclusion is model-dependent: if invisible decay is included, limits do not hold!**

Muon g-2 anomaly has to be investigated considering visible AND invisible decay modes

"New" approach:

- For a given M_A, fix ε to explain g-2
- Exclusion plot: $\alpha_D - M_A$ plane
- Depending on $\varepsilon(M_A)$ and α_D decay can be visible or invisible
  - Use both searches to constrain g-2

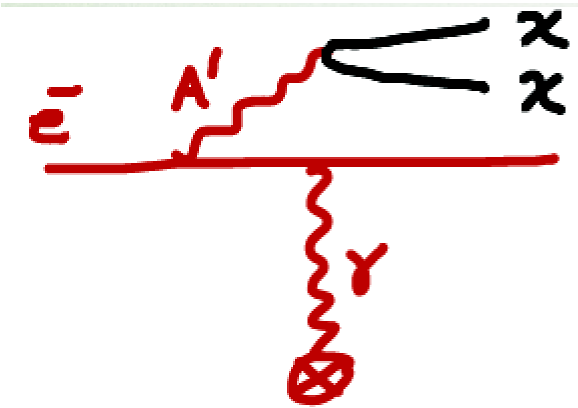


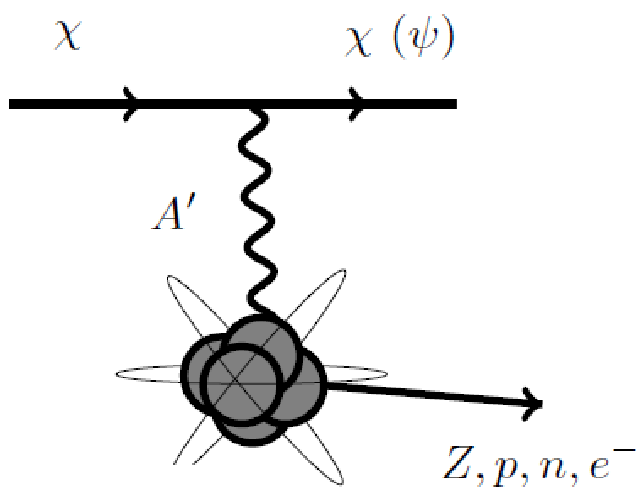
[arXiv:1406.2698]

Beam dump experiments for dark matter searches

Two-Step Detection Process:

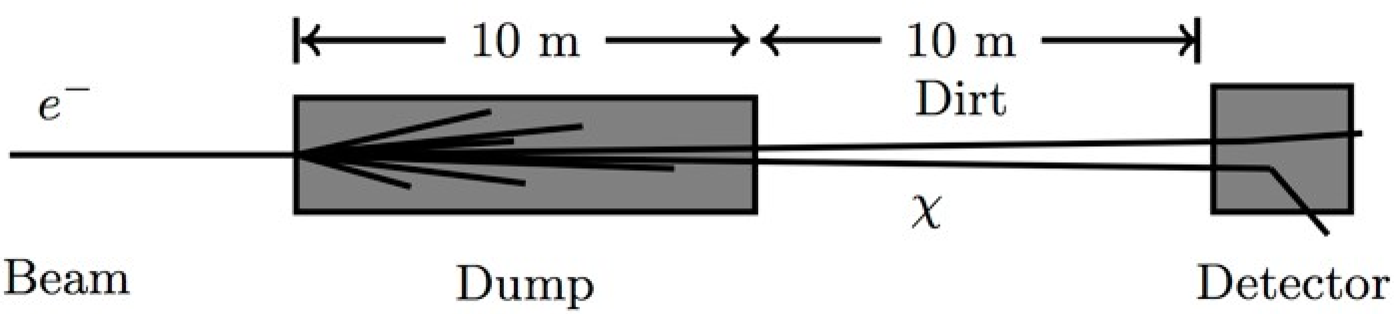
- **Fixed-target:** A' produced in the dump, decays promptly to invisible χ
- **Detector:** Neutral-current scattering of χ trough A' exchange, detect recoil. Different signals depending on the interaction (e^- scattering, coherent nuclear, quasi-elastic,..)





Background sources:

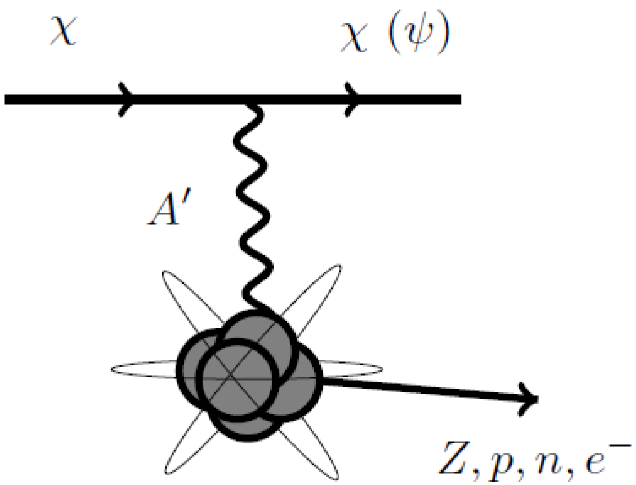
- **Beam-related:** mainly neutrinos, provided the dump is thick enough to shield other particles.
- **Cosmogenic:** mainly neutrons. Can shield or veto.



χ detection

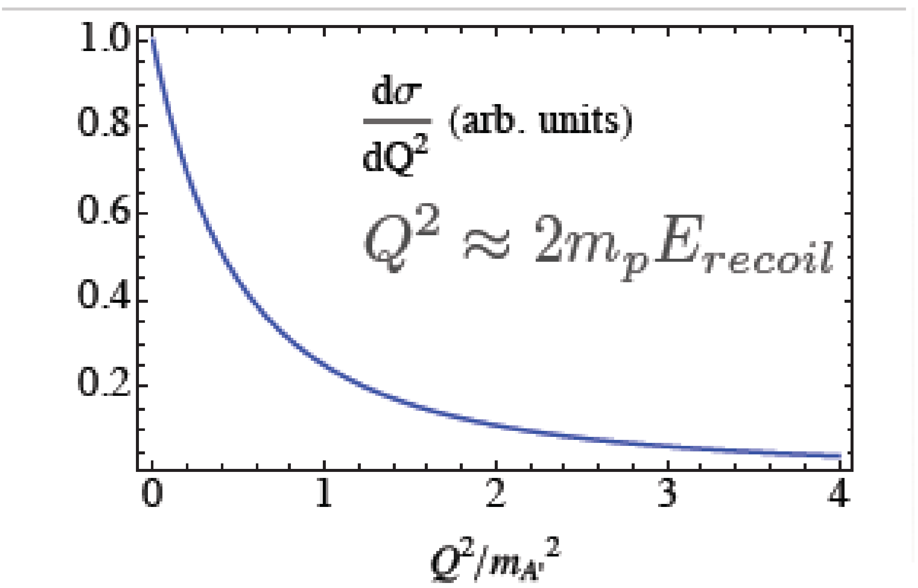
1) Elastic scattering on nucleon

The χ scatters elastically on a nucleon (p) in the detector producing a visible recoil (~ MeV)



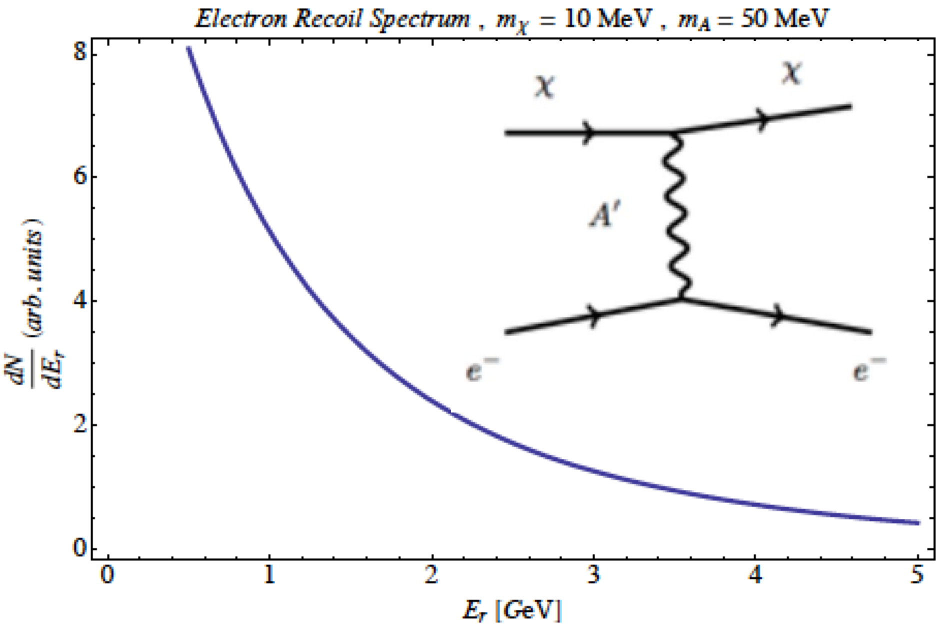
Experimental requirements:

- Sensitivity to ~MeV nucleon recoil (low detection thresholds)
- Low energy backgrounds rejection capability



χ detection

2) Elastic scattering on electrons

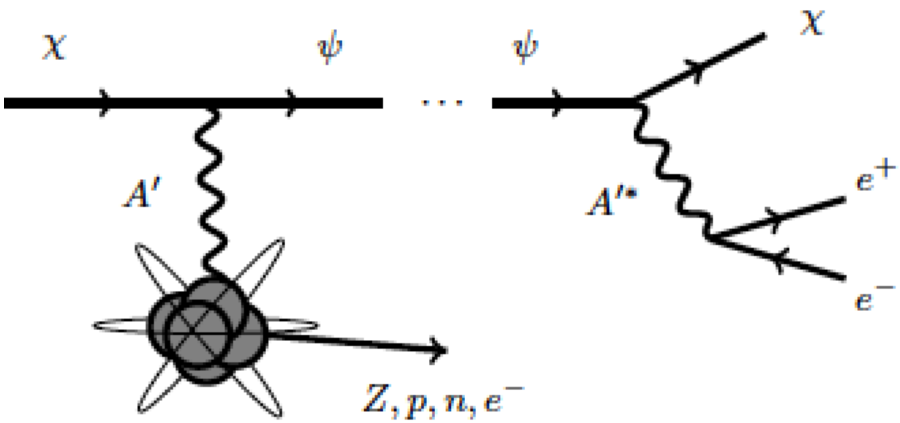


The χ scatters elastically on an electron in the detector producing a well visible recoil (~ GeV)

Experimental requirements:

- Sensitivity to ~GeV electrons (EM showers)
  → Easy background rejection

3) Inelastic scattering



The χ scatters inelastically on a nucleon / electron, producing a ψ that decays promptly to χ e^+ e^-

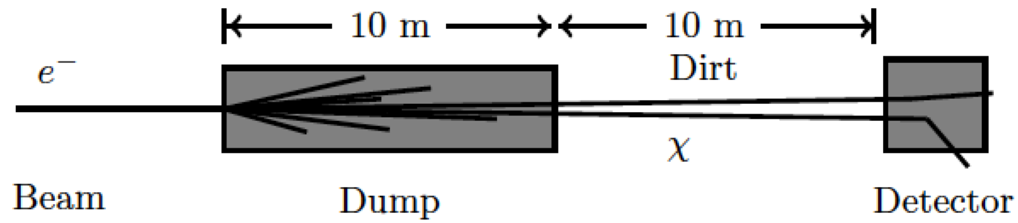
Experimental requirements:

- Sensitivity to ~100 MeV nucleon recoil
- Sensitivity to ~GeV electrons (EM showers)

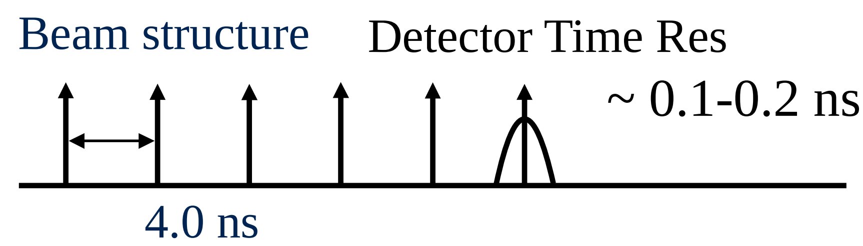
  → Easy background rejection

Experimental technique

Detect χ interaction in a detector placed behind the beam-dump of an high intensity (~ 100 μA) Hall



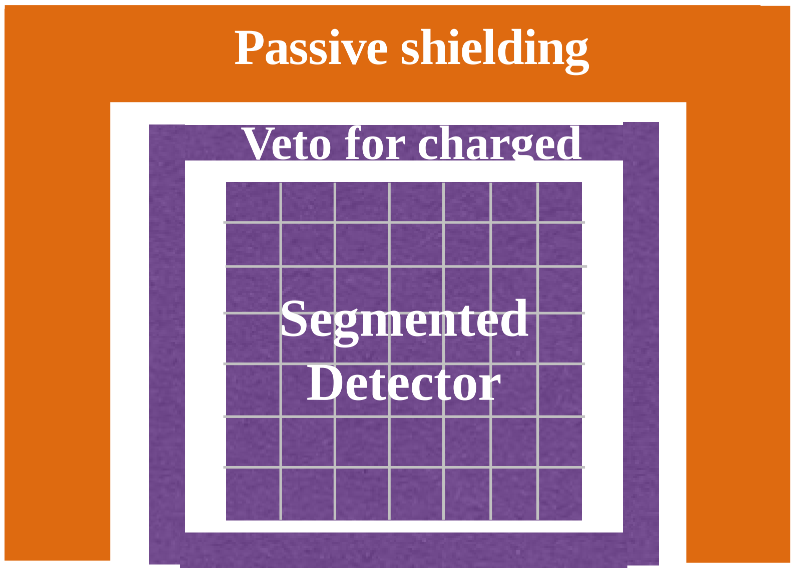
Make a tight coincidence with the primary e- beam to reject cosmogenic (beam-uncorrelated) backgrounds



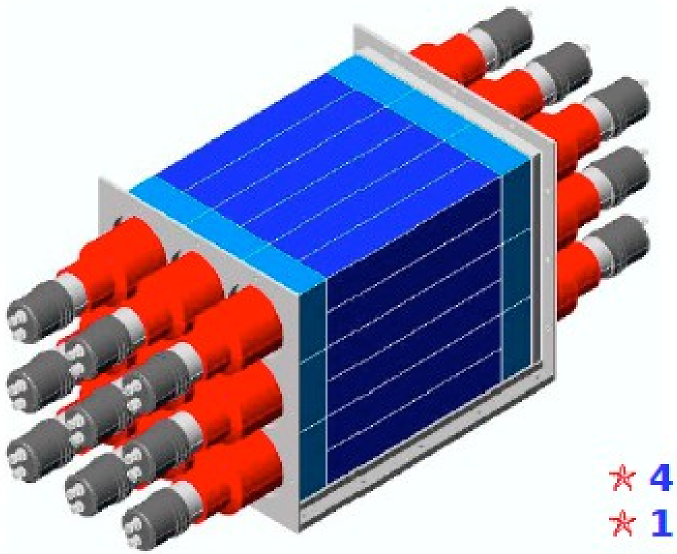
Detector requirements

- Good time resolution to reject beam-uncorrelated background
- Segmentation
- Active veto
- Passive shielding
- Low threshold for nucleon recoil detection (~MeV)
- EM showers detection capability

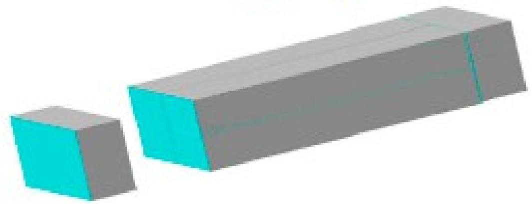
→ 1 m^3 segmented plastic scintillator + lead foils

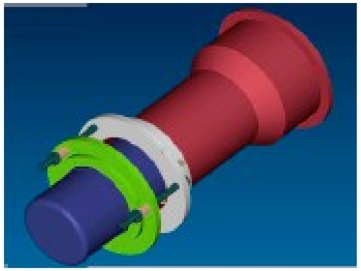


Full detector prototype: CORMORINO



CORMORINO
scale $(1:3)^3$ ~3% m^3

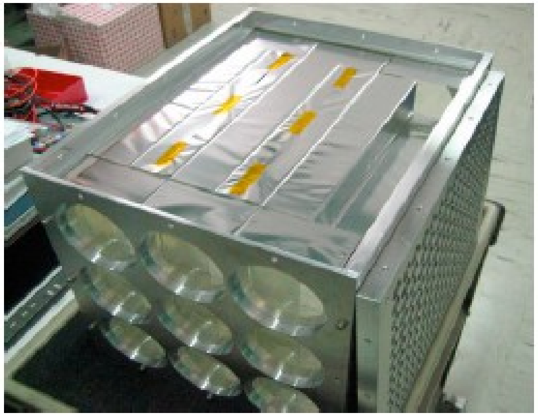


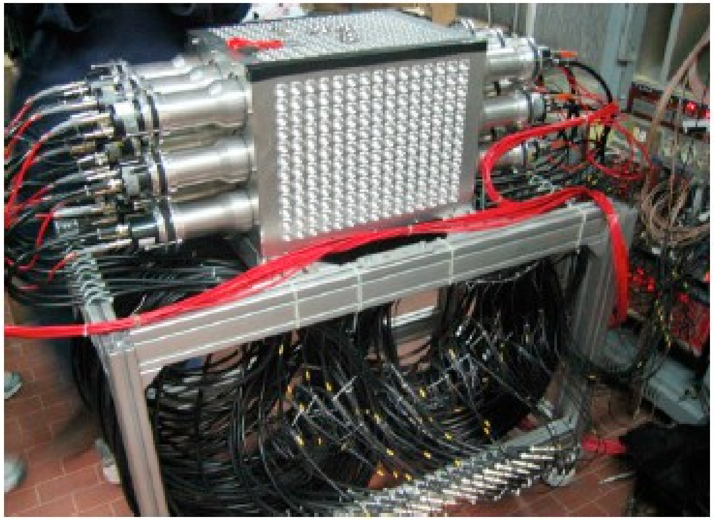


Prototype cell
- 4 30x5x5 cm^3 NE110 bars
- 1 5x10x10 cm^3 NE110 block
- 12.5 μm Gd foils wrapping

- Light read-out: 18 Photonis XP2312 3" PMTs

- Size: 40 x 30 x 30 cm^3



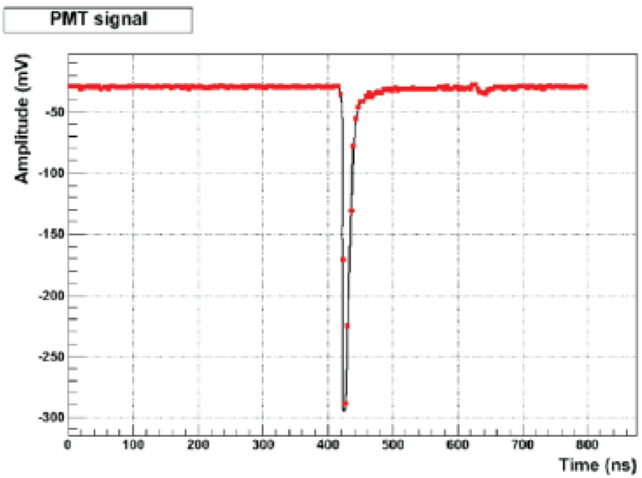


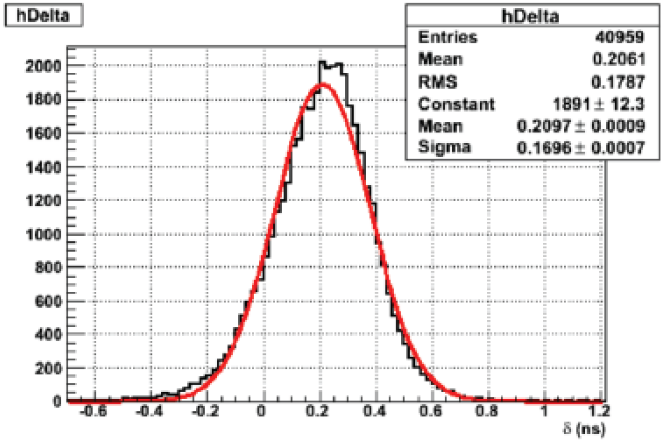
CORMORINO is a full working prototype of the full-scale detector.

- Validate detector design
- Measure background rates and validate MC simulations
  - Scale MC results to full detector

Full detector prototype: CORMORINO

First CORMORINO test with cosmic rays + FADC-based DAQ



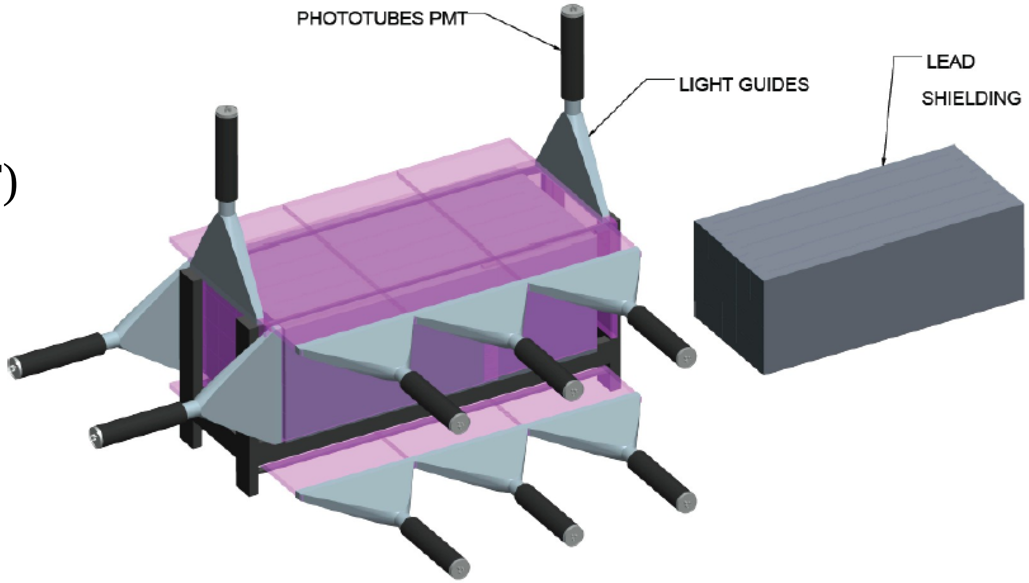


Time resolution:

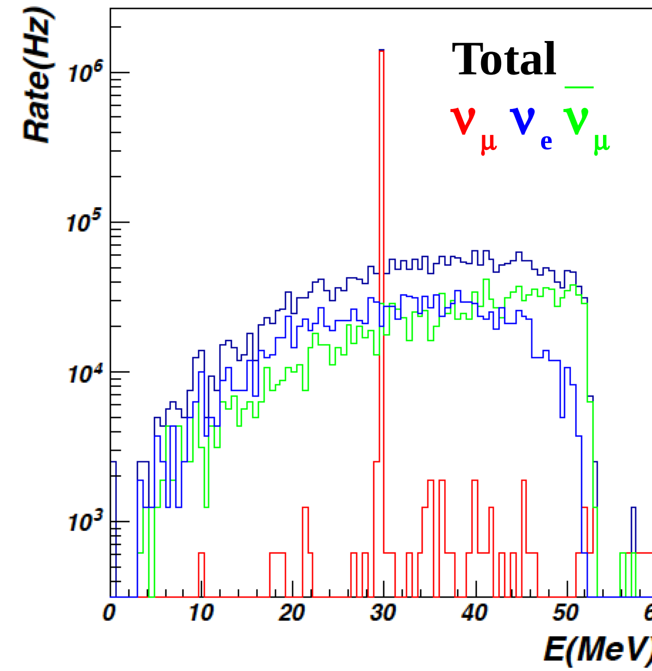
σ_T ~ 110 ps / MIP

CORMORINO preparation for background measure campaign:

- Add active veto (plastic scintillator + PMT)
- Add passive shielding (5cm lead)
- Optional: add a second VETO between detector and shield



CORMORINO simulation: backgrounds



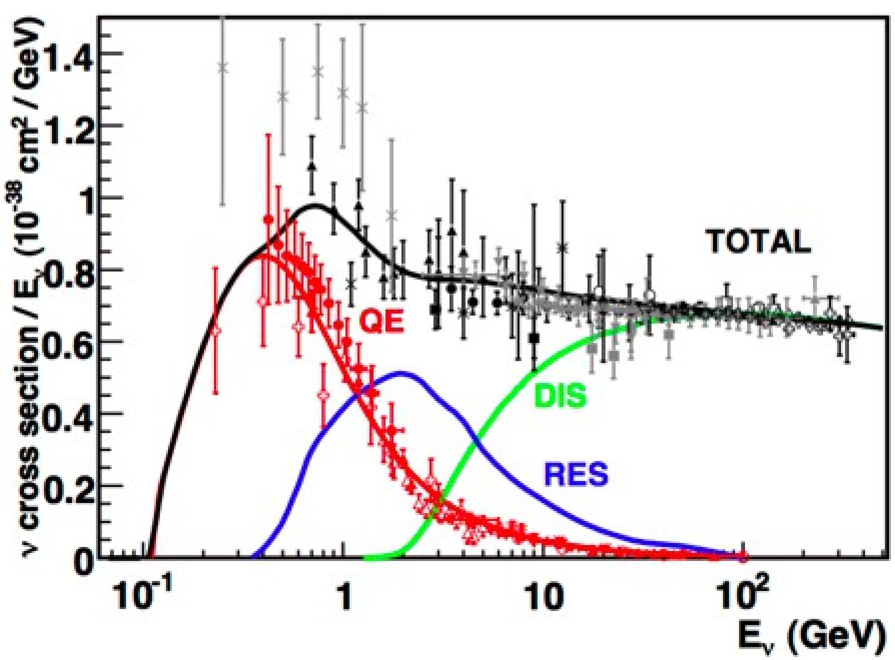
Beam-related backgrounds

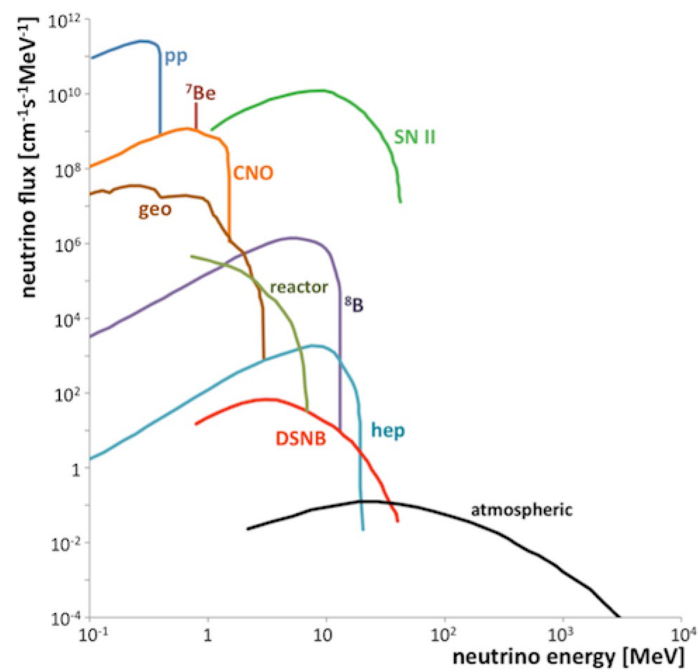
- Simulated 1.6 10^9 EOT
- Only neutrinos pass the beam dump and cross the detector
- **Rate is negligible**

Beam-unrelated backgrounds

1) Cosmic neutrinos

- Considering flux, interaction cross-sections, and thresholds the number of detected cosmic neutrinos is negligible



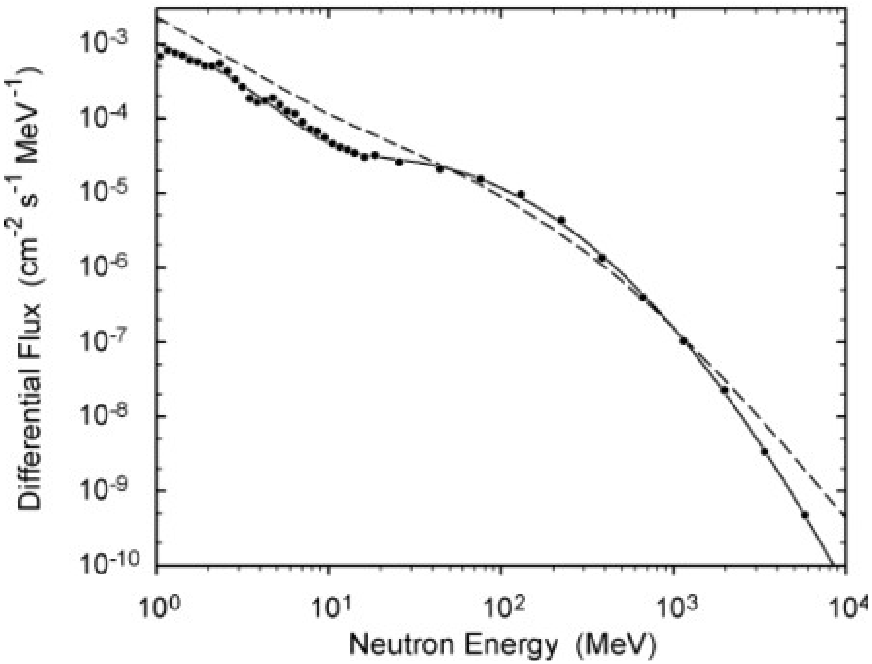


CORMORINO simulation: backgrounds

Beam-unrelated backgrounds

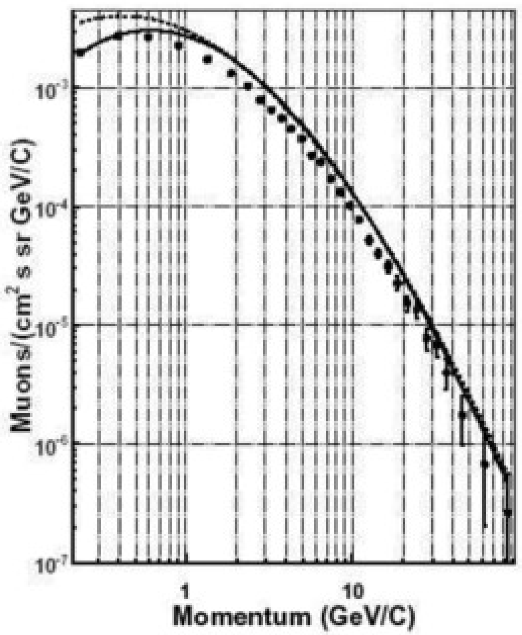
2) Cosmic neutrons

- High-energy neutrons can penetrate the shielding and interact inside the detector, mimicking a x-N interaction
- 1 m iron shield + detection threshold introduce an energy cut-off on the primary spectrum ~ 50 MeV



3) Cosmic muons: different background contributions

- Crossing muons producing a fake signal for VETO inefficiency
- Muons decaying inside the detector not rejected for VETO inefficiency
- Muons decaying inside the lead shield not rejected for VETO inefficiency
- Muons decaying between iron and veto
  - The γ from the rare decay $\mu \rightarrow e^- \nu \nu \gamma$ could by-pass the veto and interact in the detector
  - Rate is negligible



CORMORINO simulation: rates

CORMORINO background rates from MC simulation

For comparison, also the expected signal rate for two theoretical χ-N elastic scattering scenarios is shown.

- Two detection thresholds:
  1 MeV / 10 MeV
- Beam-related background is not an issue
- Cosmogenic backgrounds are dominant

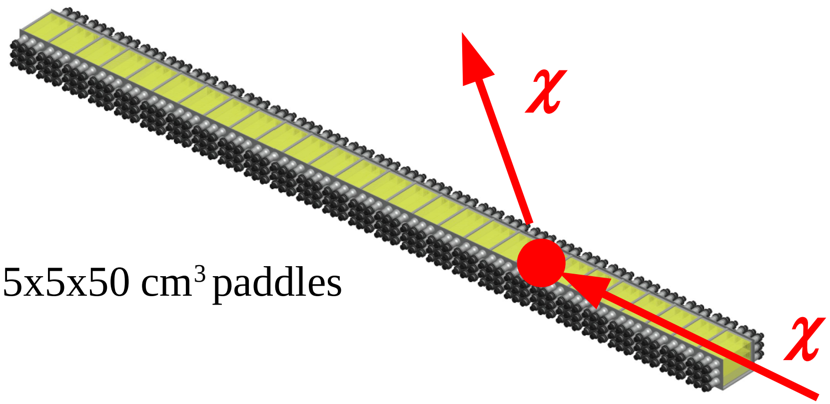
	Rate $_{Thr=1MeV}$ (Hz/μA))	Rate $_{Thr=10MeV}$ (Hz/μA))
χ detection - S.I	$1.0\ 10^{-5}$	$1.2\ 10^{-6}$
χ detection - S.II	$2.0\ 10^{-7}$	$0.7\ 10^{-7}$
B-rel ν	$2.0\ 10^{-9}$	$2.0\ 10^{-10}$
B-rel neutron	0	0

	Rate $_{Thr=1MeV}$ (Hz)	Rate $_{Thr=10MeV}$ (Hz)
B-unrel ν	$2.0\ 10^{-6}$	$2.0\ 10^{-7}$
B-unrel neutron	$2.7\ 10^{-3}$	$0.6\ 10^{-3}$
Crossing muons	$3.3\ 10^{-3}$	$3.5\ 10^{-3}$
Captured μ^+	$1.4\ 10^{-3}$	$2.4\ 10^{-3}$
Decaying μ^- (CORM)	$2.9\ 10^{-3}$	$4.8\ 10^{-3}$
Stopped μ in lead	$7.0\ 10^{-3}$	$4.3\ 10^{-3}$
μ^- rare decay	$2.0\ 10^{-5}$	$8.0\ 10^{-6}$
Total Beam-unrelated bg	$1.7\ 10^{-2}$	$1.5\ 10^{-2}$

These results will be validated by a dedicated measurement campaign (Autumn 2014)

Full BDX experiment

BDX detector size: 30x CORMORINO



- Exploiting the χ forward kinematics the front size is the same as CORMORINO (~50x50 cm^2)
- Each optical channel (L/R PMTs) is made by a 3x3 matrix of 5x5x50 cm^3 paddles
- CORMORINO-like module: 3x3 optical channels, 0.1 m^3
  - 20 modules, 360 PMTs
  - **Factor 30x in counts**
- Each scintillator bar is interleaved with 1mm lead foil to increase the EM radiation length

BDX accumulated charge: 10^{22} EOT

- Beam current: 100 μA (Hall-A / Hall – C option)
- Accelerator availability: 50%
- Run time: 1 calendar year

BDX improvements under study:

- Better time resolution for cosmogenic backgrounds rejection
- VETO design to reduce inefficiency (5% in current estimates)
- PID (liquid scintillator?)

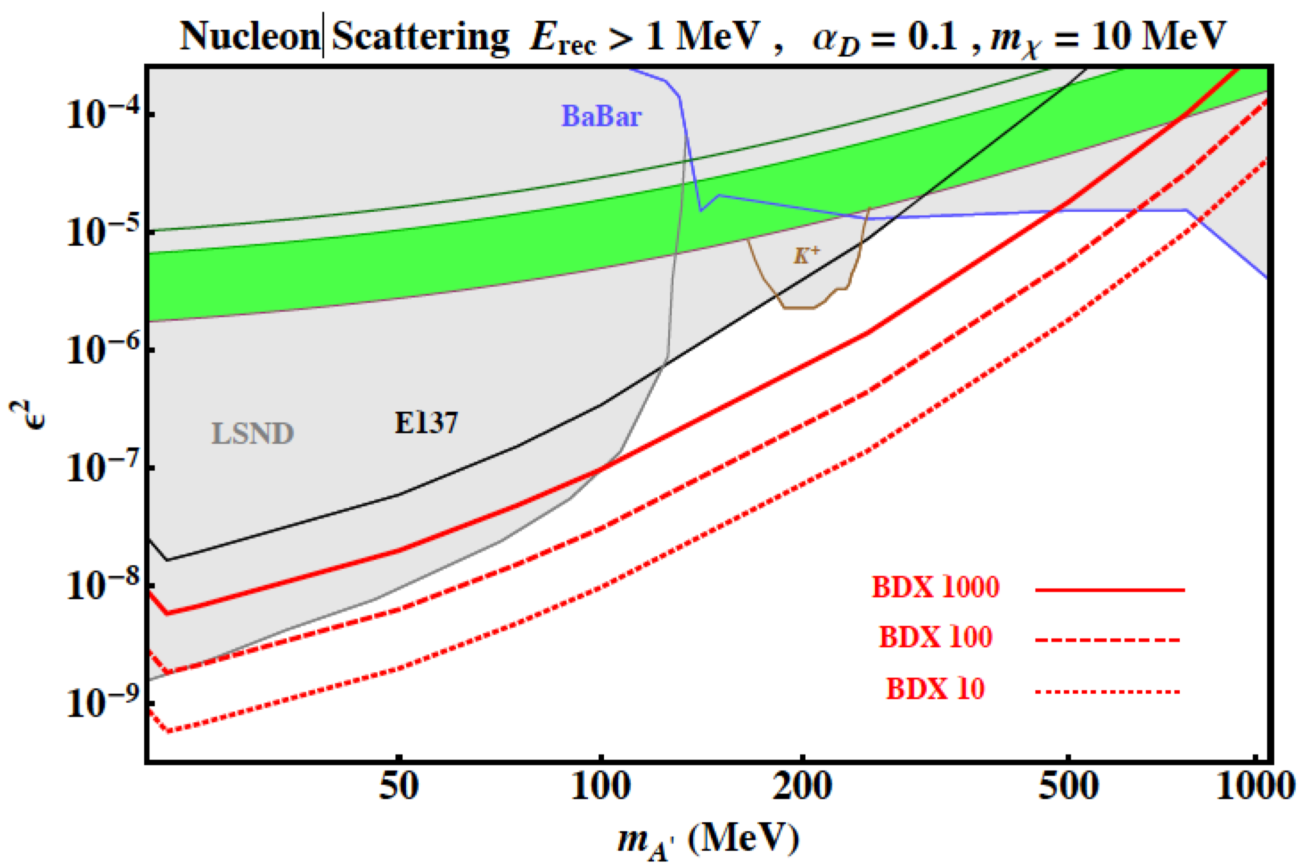
  ...

Full BDX experiment: reach

Elastic χ - p scattering BDX reach

- Reach is limited by background rate

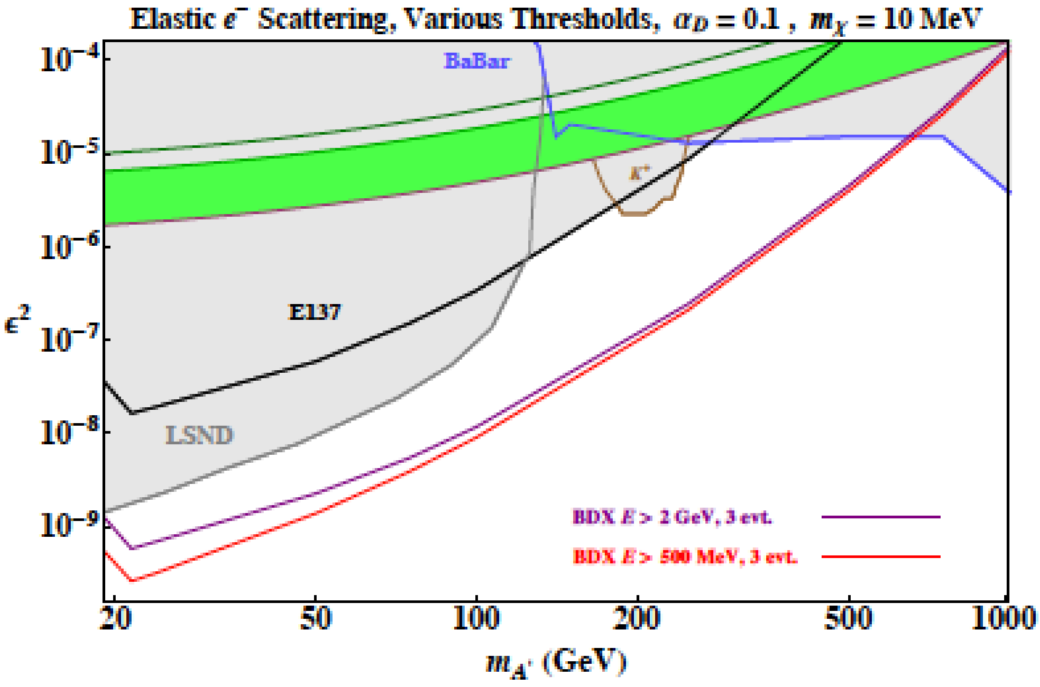
	Counts $_{Thr=1\text{MeV}}$	Counts $_{Thr=10\text{MeV}}$
χ detection - S.I	$0.5\ 10^6 \pm 700$	$5.7\ 10^4 \pm 240$
χ detection - S.II	$1.0\ 10^4 \pm 100$	$3.3\ 10^3 \pm 60$
Beam-rel bg	100 ± 10	10 ± 3
Beam-unrel bg	$1.6\ 10^6 \pm 1300$	$1.4\ 10^6 \pm 1200$

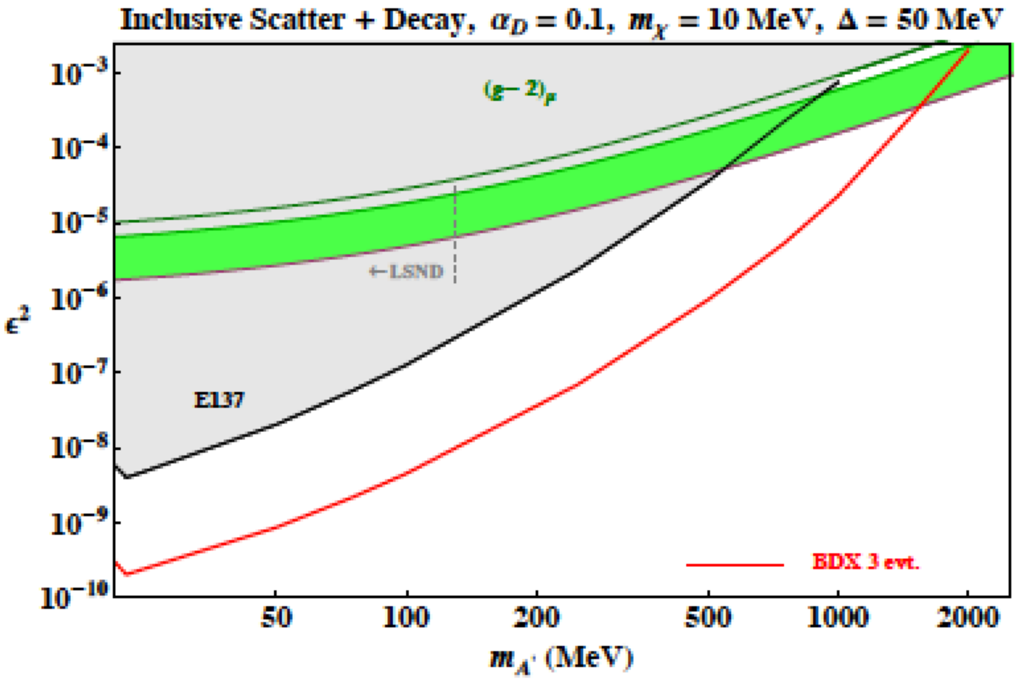


Full BDX experiment: reach

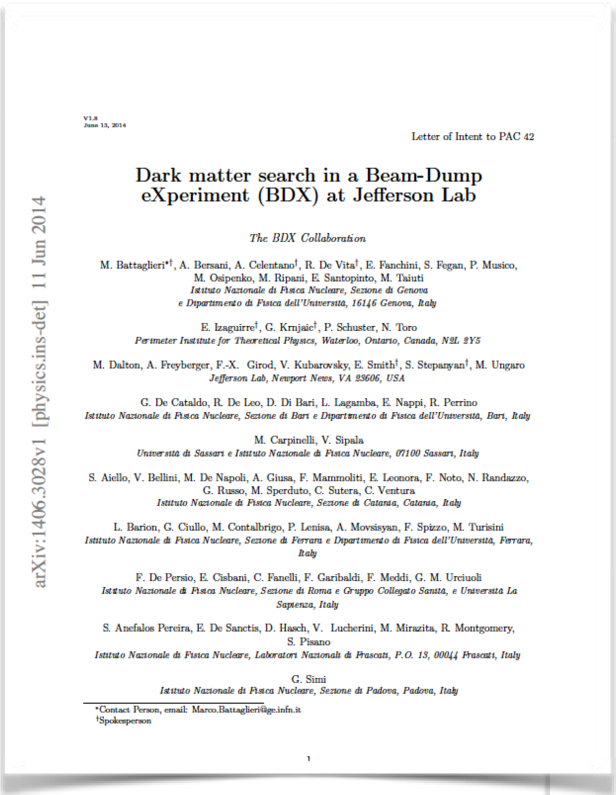
Elastic χ - e⁻ scattering and inelastic scattering BDX reach

- (almost) background-free search
- Reach is limited by the signal rate





Full BDX experiment: work plan



V1.8
June 13, 2014

Letter of Intent to PAC 42

arXiv:1406.3028v1 [physics.ins-det] 11 Jun 2014

Dark matter search in a Beam-Dump eXperiment (BDX) at Jefferson Lab

The BDX Collaboration

M. Battaglieri*†, A. Bersani, A. Celentano†, R. De Vita†, E. Fanchini, S. Fegan, P. Musico, M. Osipenko, M. Ripani, E. Santopinto, M. Taiuti
Istituto Nazionale di Fisica Nucleare, Sezione di Genova e Dipartimento di Fisica dell'Università, 16146 Genova, Italy

E. Izaguirre†, G. Krnjaic†, P. Schuster, N. Toro
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada, N2L 2Y5

M. Dalton, A. Freyberger, F.-X. Girod, V. Kubarovsky, E. Smith†, S. Stepanyan†, M. Ungaro
Jefferson Lab, Newport News, VA 23606, USA

G. De Cataldo, R. De Leo, D. Di Bari, L. Lagamba, E. Nappi, R. Perrino
Istituto Nazionale di Fisica Nucleare, Sezione di Bari e Dipartimento di Fisica dell'Università, Bari, Italy

M. Carpinelli, V. Sipala
Università di Sassari e Istituto Nazionale di Fisica Nucleare, 07100 Sassari, Italy

S. Aiello, V. Bellini, M. De Napoli, A. Giusa, F. Mammoliti, E. Leonora, F. Noto, N. Randazzo, G. Russo, M. Sperduto, C. Sutera, C. Ventura
Istituto Nazionale di Fisica Nucleare, Sezione di Catania, Catania, Italy

L. Barion, G. Ciullo, M. Contalbrigo, P. Lenisa, A. Movsisyan, F. Spizzo, M. Turisini
Istituto Nazionale di Fisica Nucleare, Sezione di Ferrara e Dipartimento di Fisica dell'Università, Ferrara, Italy

F. De Persio, E. Cisbani, C. Fanelli, F. Garibaldi, F. Meddi, G. M. Urciuoli
Istituto Nazionale di Fisica Nucleare, Sezione di Roma e Gruppo Collegato Sanità, e Università La Sapienza, Italy

S. Anefalos Pereira, E. De Sanctis, D. Hasch, V. Lucherini, M. Mirazita, R. Montgomery, S. Pisano
Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati, P.O. 13, 00044 Frascati, Italy

G. Simi
Istituto Nazionale di Fisica Nucleare, Sezione di Padova, Padova, Italy

*Contact Person, email: Marco.Battaglieri@ge.infn.it
†Spokesperson

1

A. D'Angelo, L. Colaneri L. Lanza, A. Rizzo, C. Schaerf, I. Zonta
Istituto Nazionale di Fisica Nucleare, Sezione di Roma-TorVergata e Dipartimento di Fisica dell'Università, Roma, Italy

D. Calvo, A. Filippi
Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Torino, Italy

M.Holtrop, R. Peremuzyan
University of New Hampshire, Durham NH 03824, USA

D. Glazier, D. Ireland, B. McKinnon, D. Sokhan
University of Glasgow, Glasgow G12 8QQ, United Kingdom

A. Afanasev, B. Briscoe
The George Washington University, Washington, D.C., 20052

N. Kalantarians
Department of Physics, Hampton University, Hampton VA 23668, USA

L. El Fassi, L. Weinstein
Old Dominion University, Department of Physics, Norfolk VA 23529, USA

P. Beltrame, A. Murphy, D. Watts, L. Zana
Edinburgh University, Edinburgh EH9 3JZ, United Kingdom

K. Hicks
Ohio University, Department of Physics, Athens, OH 45701, USA

Abstract

MeV-GeV dark matter (DM) is theoretically well motivated but remarkably unexplored. This Letter of Intent presents the MeV-GeV DM discovery potential for a 1 m^3 segmented plastic scintillator detector placed downstream of the beam-dump at one of the high intensity JLab experimental Halls, receiving up to 10^{22} electrons-on-target (EOT) in a one-year period. This experiment (Beam-Dump eXperiment or BDX) is sensitive to DM-nucleon elastic scattering at the level of a thousand counts per year, with very low threshold recoil energies ($\sim$1 MeV), and limited only by reducible cosmogenic backgrounds. Sensitivity to DM-electron elastic scattering and/or inelastic DM would be below 10 counts per year after requiring all electromagnetic showers in the detector to exceed a few-hundred MeV, which dramatically reduces or altogether eliminates all backgrounds. Detailed Monte Carlo simulations are in progress to finalize the detector design and experimental set up. An existing 0.036 m^3 prototype based on the same technology will be used to validate simulations with background rate estimates, driving the necessary R&D towards an optimized detector. The final detector design and experimental set up will be presented in a full proposal to be submitted to the next JLab PAC. A fully realized experiment would be sensitive to large regions of DM parameter space, exceeding the discovery potential of existing and planned experiments by two orders of magnitude in the MeV-GeV DM mass range.

2

A significant interested for BDX LOI

- The Letter of Intent is only the first step in the (long) way to run the experiment

ToDo list (very partial)

- Measure cosmogenic bg rate with CORMORINO
- Define the full detector design
- Look for detector financing
- Prepare the full proposal for '15 July PAC
- Set full simulations
- Build the detector
- Prepare the JLab beam-dump
- Install the detector

- BDX LOI submitted to PAC42
- BDX LOI published **http://arxiv.org/abs/1406.3028**
- Spokespersons:
  - M.Battaglieri, A.Celentano, R. De Vita, E.Izaguirre, G.Krnjaic, E.Smith, S.Stepanyan

- **Run the experiment !!!!**

BDX@LNF

χ production and detection

- 1.5 GeV electron beam
- 7 10^{19} EOT/year
- 1 year run (50% efficiency)
- Repetition rate: 50 Hz, (0.7A in 10 ns bunch)
- **Negligible cosmogenic BG with timing cut**
- Expected ~20 counts in 1m^3 plastic scintillator detector (1 MeV threshold)
- **Significant sensitivity to low mass (A'/χ) region**

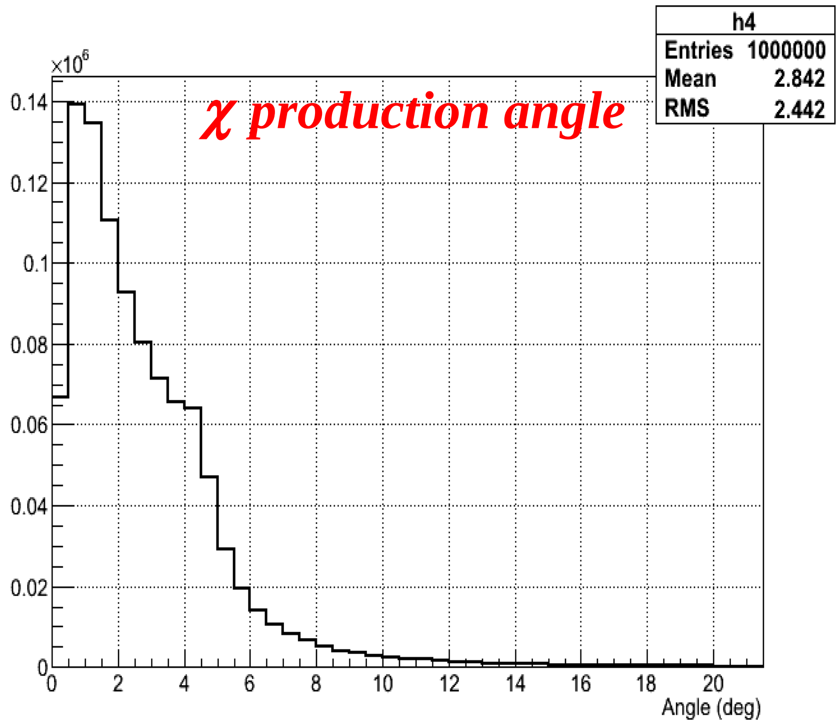
Parameters:

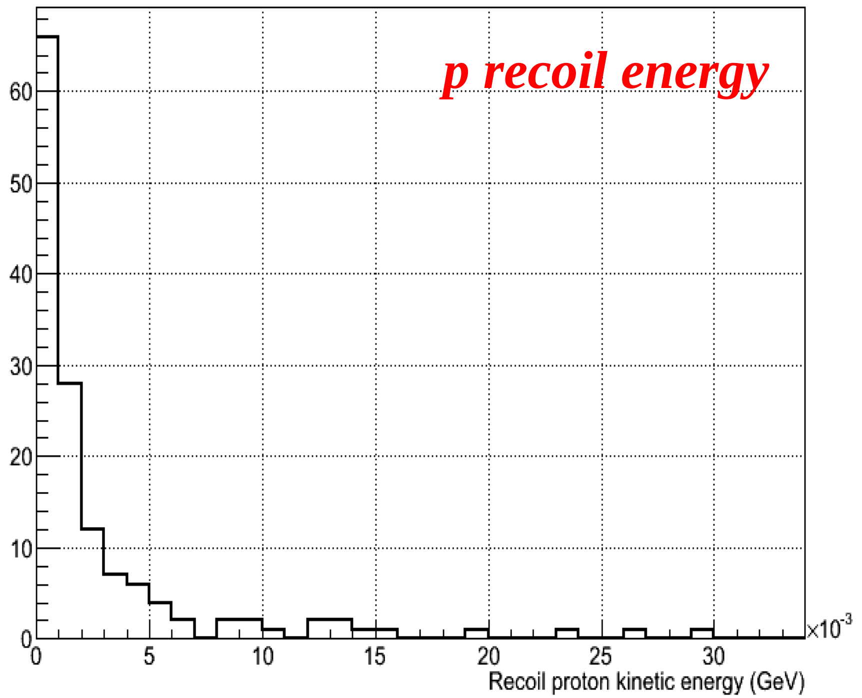
M_A' = 50 MeV

M_Chi = 10 MeV

Alpha_dark = 0.1

Epsilon = 10^{-3}





Very preliminary study of a very interesting experimental opportunity.

Conclusions

- **The dark sector may be more complex than originally expected**
  - Extensive search for low mass DM
  - Natural extension of the heavy photon model to include light DM via invisible A' decay

- **Beam Dump eXperiment at JLab: search for light DM particles in the 10 – 1000 MeV range**
  - High intensity e- beam for 1 year (10^{22} EOT), 1 m3-size plastic scintillator detector
  - Sensitivity to different χ interactions:
    - χ-N scattering
    - χ-e scattering
    - Inelastic
  - BDX would extend the exclusion region and can put an end to the possible A' role in the muon g-2 anomaly

- **Cosmogenic backgrounds are the main issue (at least for χ-N scattering)**
  - These will be measured with a small-scale prototype of the full detector

- **Current status:**
  - LOI submitted to PAC42, waiting for response
  - Full proposal in preparation

Back up

MiniBooNE

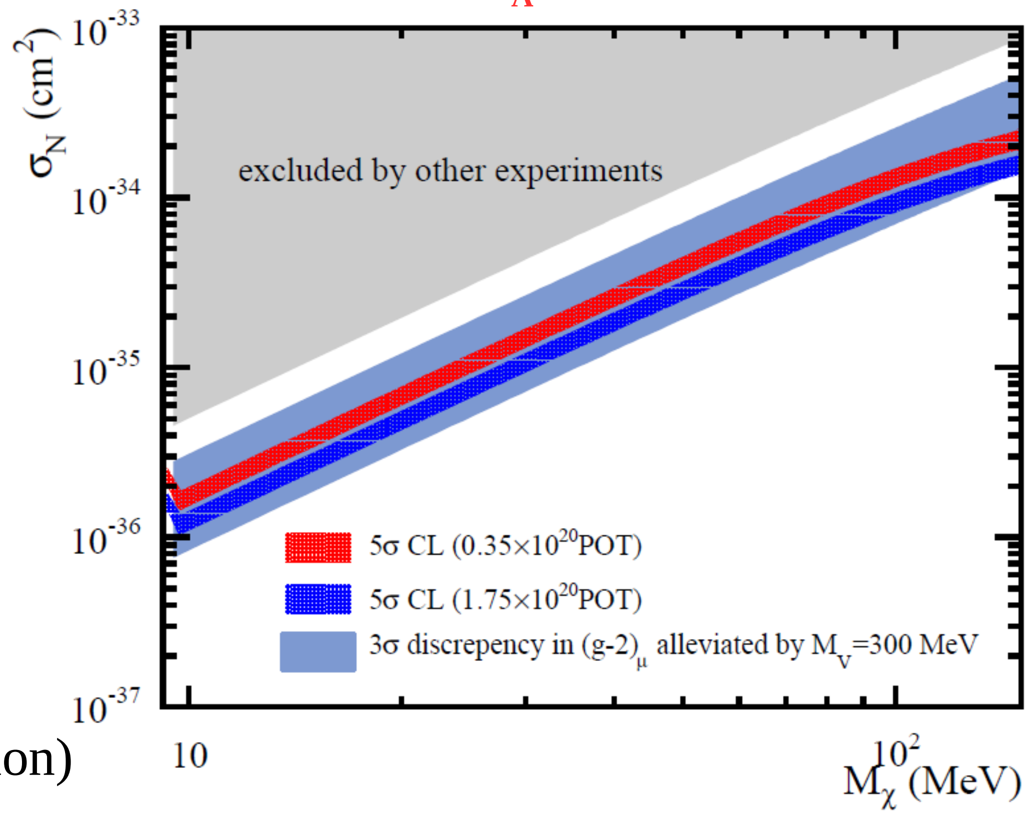
MiniBooNE DM search:

- 8 GeV protons on a 50m beam dump
- Detector ~ 500 m after the beam dump
  - 800 t mineral oil, 1280 PMTs

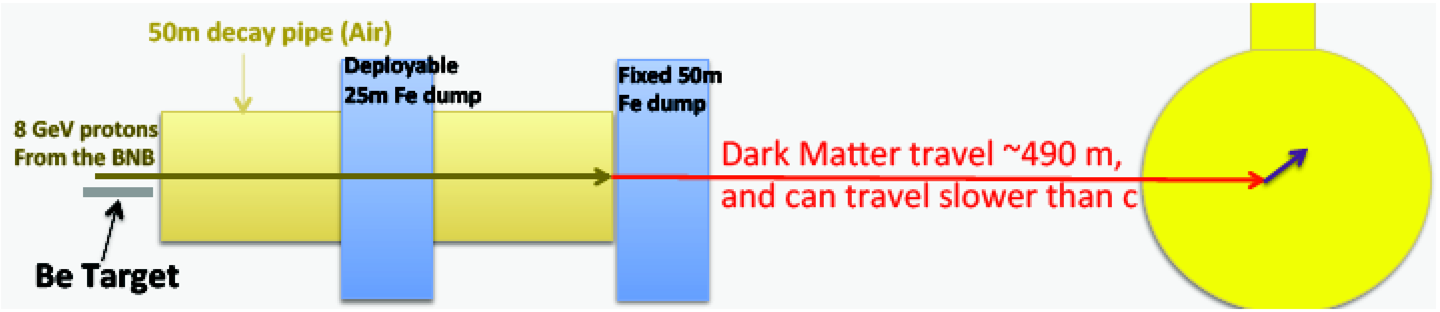
MiniBooNE test run (2013):

- 0.4 10^{20} protons on target
- "Off-axis" configuration to reduce ν background (reduction factor ~ 42)
- Selection cuts for DM events:
  - Timing (χ can travel slower than c)
  - Energy (different χ–ν energy deposition)

Preliminary, $M_{A'}$=300 MeV, α'=0.1

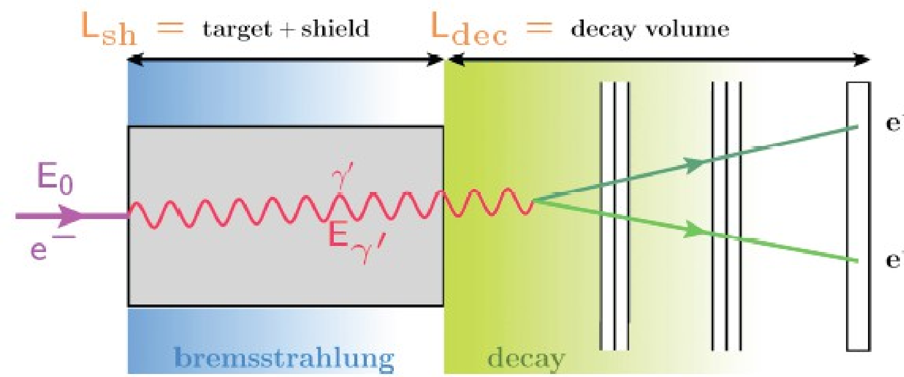


MiniBooNE 2014 proposal: 2 10^{20} PoT



First generation fixed target experiments: beam dump

Beam dump experiments for A' search:



- e^- beam incident on thick target
- A' is produce in a process similar to ordinary Bremsstrahlung
- A', emitted forward at small angle, carries most of the beam energy and decays before the detector
- Decay products are measured in the detector

$$\gamma c\tau \approx 1\ \mathrm{mm}\,(\gamma/10)\,(10^{-8}\alpha/\alpha')$$
$$\times\,(100\ \mathrm{MeV}/m_{A'})$$