

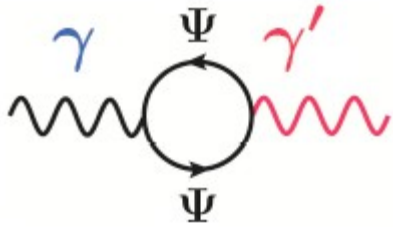
# *Dark matter searches at Jefferson Laboratory*

*A. Celentano*

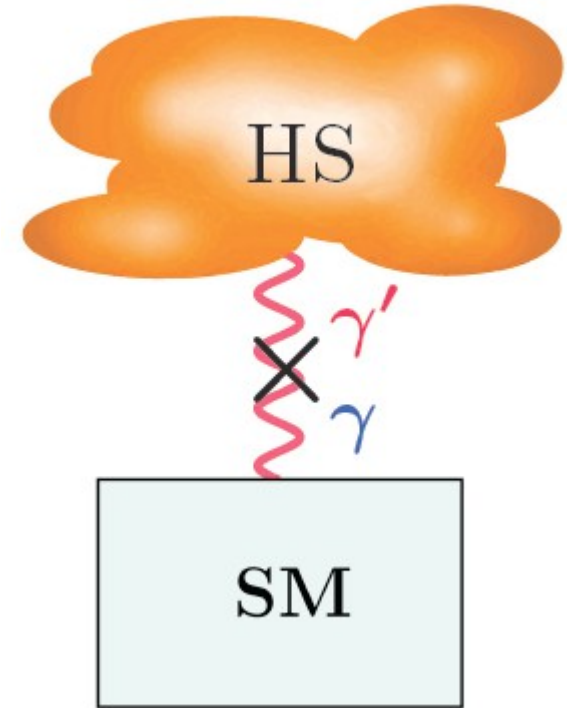
*INFN Genova*

# 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  $A'$



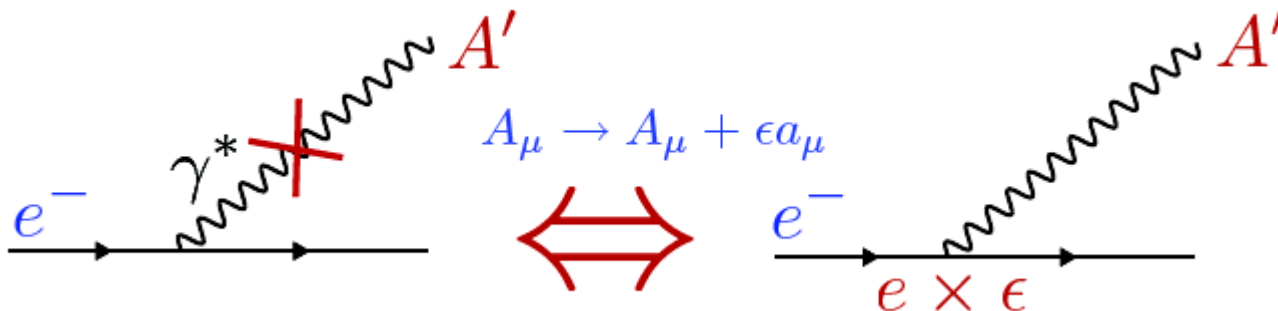
$\Psi$  is a huge mass scale particle ( $M \sim 1 \text{ EeV}$ ) coupling to both SM and HS



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

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

- Under  $A'$  interaction, ordinary charged matter acquires a new charge  $\epsilon e$ :

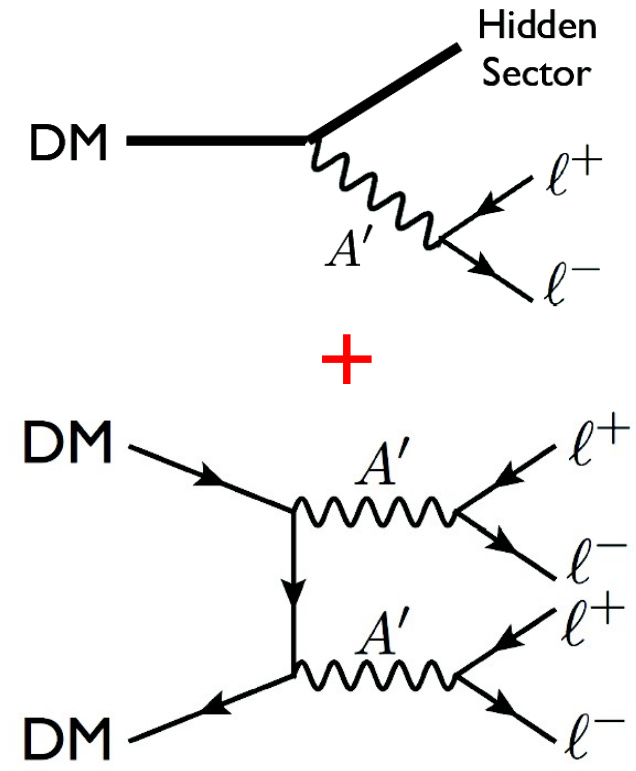
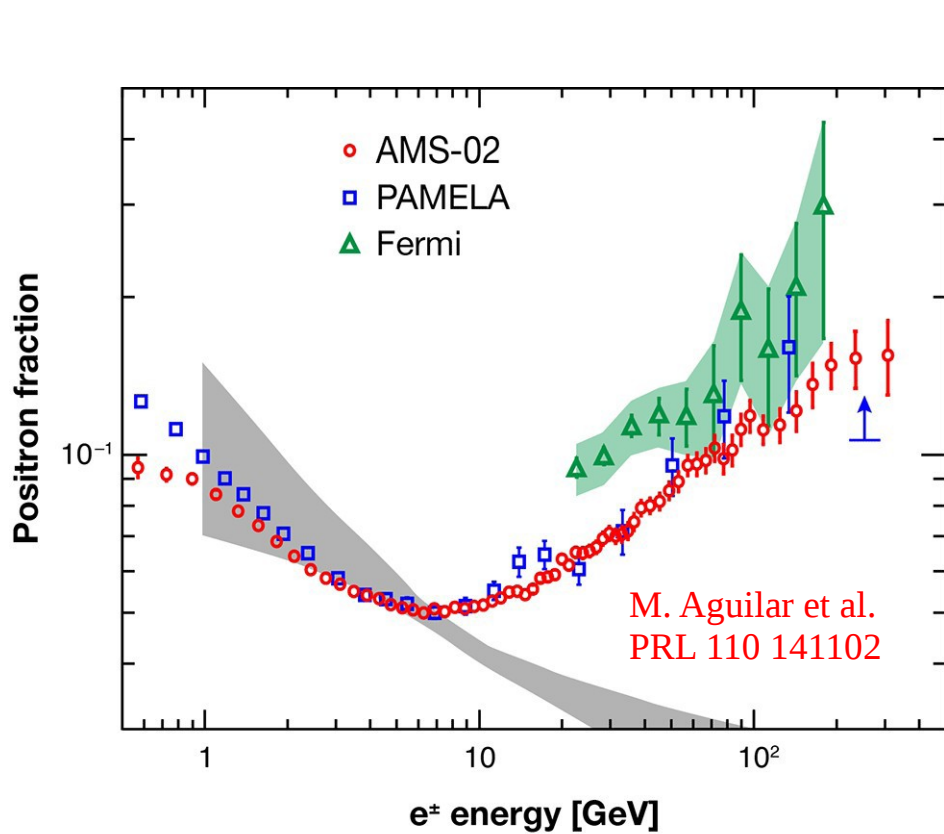


**New interaction term:**

$$\epsilon A'_\mu J_{EM}^\mu$$

# *A'* existence indications

- The measured excess in positron fraction (AMS, FERMI, PAMELA) can be explained by dark matter decaying or annihilating in  $A'$ , which in turns decays to  $e^+ e^-$
- $A'$  can explain muon anomalous magnetic momentum ( $> 3 \sigma$  deviation experiment-SM)



**These indications point to the same region in the  $A'$  parameter space:**

$$\epsilon \sim 10^{-2} - 10^{-5}$$

$$M_{A'} \sim \text{MeV} - \text{GeV}$$



**This region can be explored with particles experiments at accelerators!**

# Dark photons and dark matter

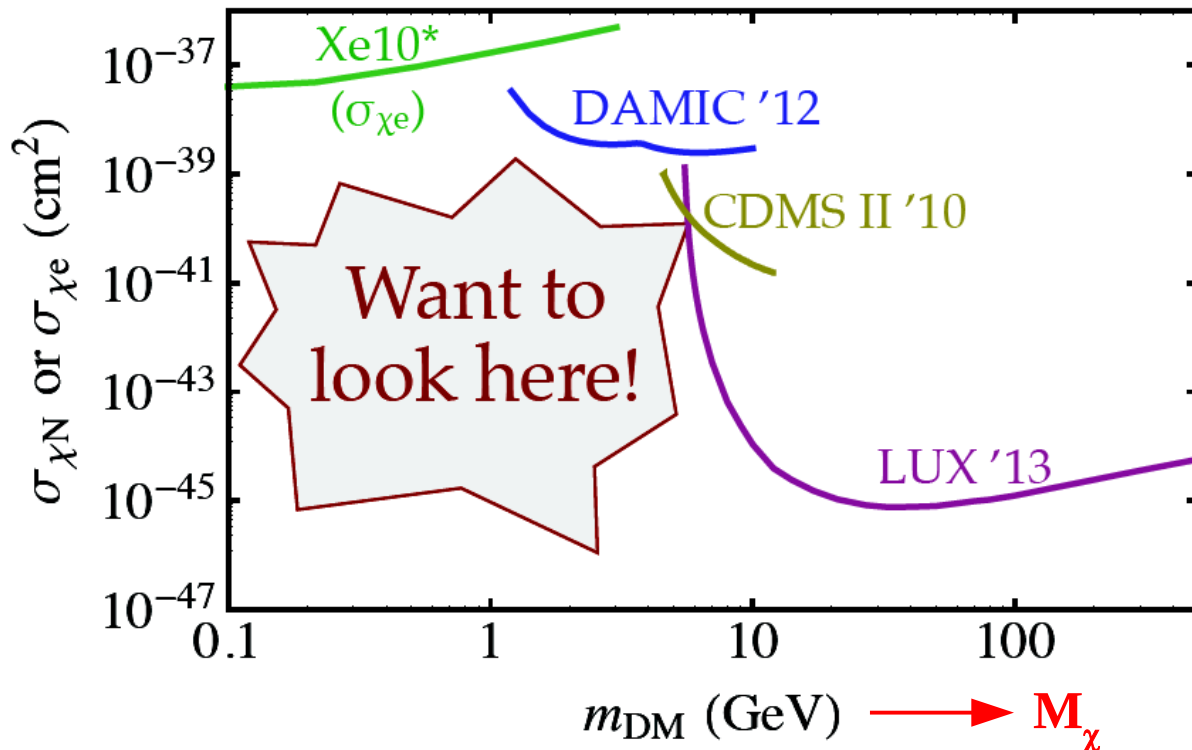
Most of the dark matter searches so far focused on WIMPS:

- High mass (10 GeV – 1 TeV)
- Low cross-sections for interaction with SM matter ( $10^{-15}$   $\mu\text{barn}$ )

Dark photons with  $\sim$  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  $M_{\text{DM}}, g_{\text{D}}$



**Important!**

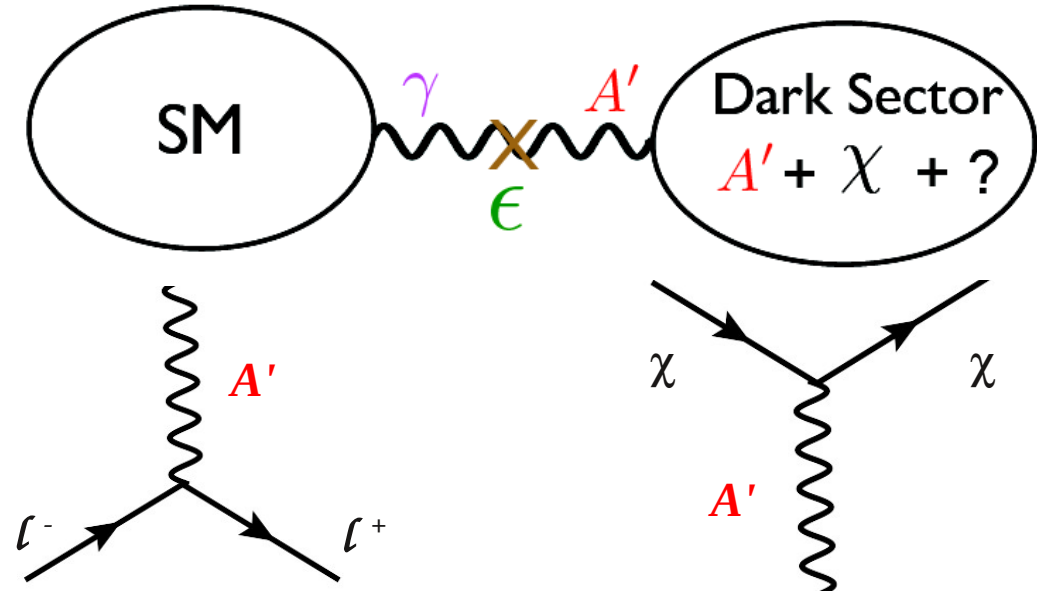
Testing the idea of dark sectors requires a collection of searches sensitive to all possible  $A'$  decays, visible & invisible.

# Dark photons and dark sector

## A simple model:

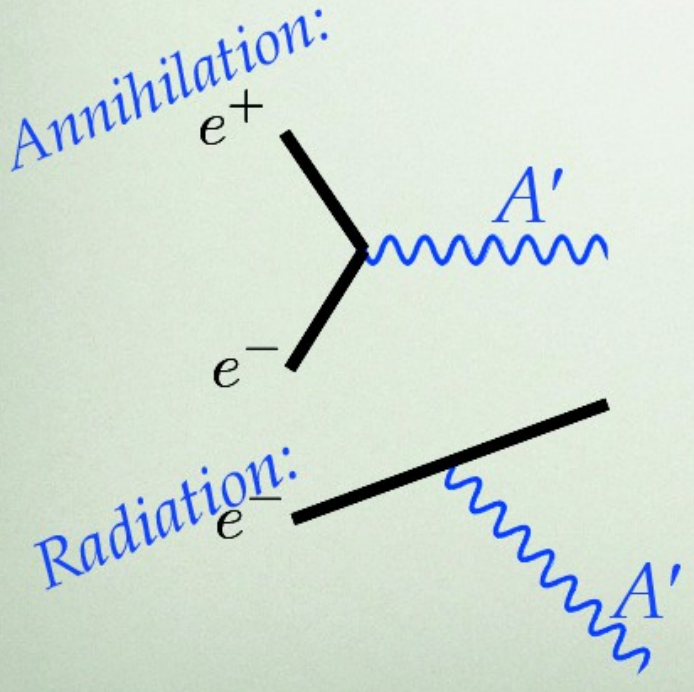
- $A'$  interacts with  $\gamma$  through kinetic mixing
- Dark sector particle  $\chi$  interacts with  $A'$

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



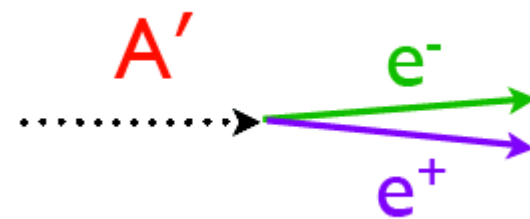
$A'$  production:  $\sigma \propto \epsilon^2$

$A'$  decay:



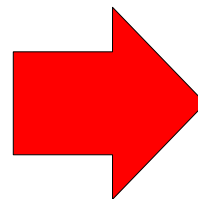
Visible

First scenario



$$\Gamma \propto \epsilon^2$$

- Minimal scenario
- Decay suppressed by small mixing  $\epsilon$
- Valid for any  $M_\chi$  value



HPS experiment at JLab  
(approved, expected to run in 2014 - 2015)

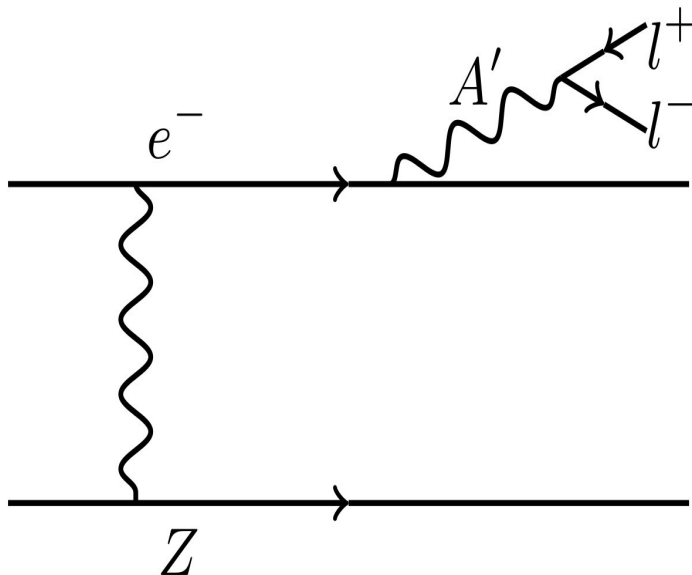
# $A'$ searches in particle physics

Any  $\gamma$ -rich environment is suitable for  $A'$  searches.

Fixed target with  $e^-$  beam:  $e^- N \rightarrow e^- N A' \rightarrow e^- N l^+ l^-$

- JLab, Mainz
- Fixed target with p beam:  $p N \rightarrow p N A' \rightarrow p N l^+ l^-$ 
  - Fermilab
- Annihilation:  $e^- e^+ \rightarrow A' \gamma \rightarrow l^+ l^- \gamma$ 
  - BABAR, BELLE, KLOE
- Meson decay:  $\pi^0, \eta, \eta', \rho, \omega, \phi \rightarrow A' \gamma \rightarrow l^+ l^- \gamma$ 
  - KLOE, BES-, WASA-COSY

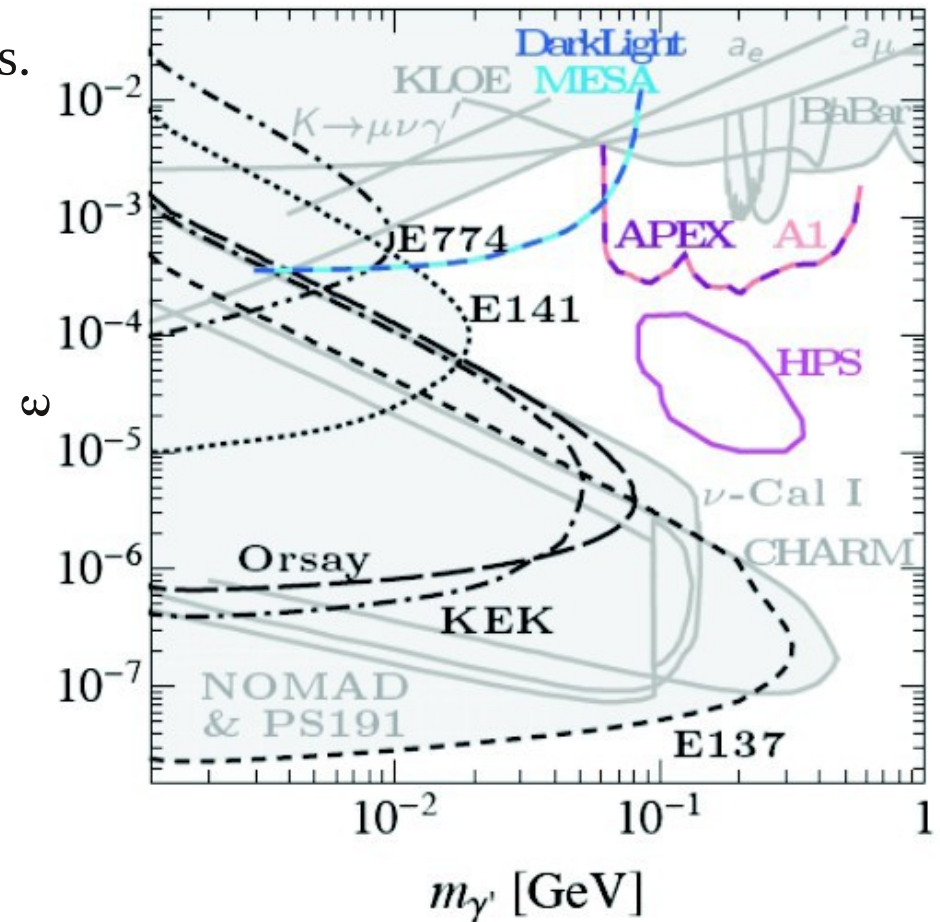
**Fixed-target experiments:**



- $A'$ -strahlung on a nuclear target

- Detect  $A'$  decay products

- Very high cross-section:  $\sigma \simeq \frac{\alpha^3 Z^2 \epsilon^2}{M^2} \simeq O(pb)$





# The HPS experiment at JLab

## The HPS experiment at Jlab:

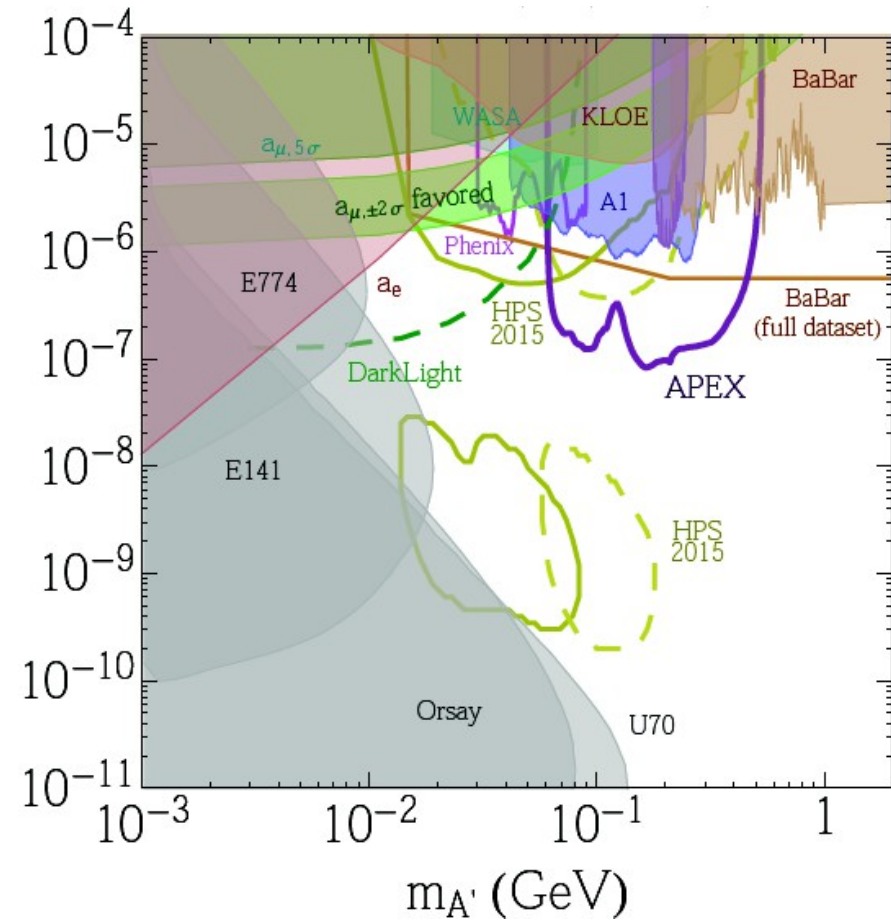
- Searches for  $A'$  in a fixed tungsten-target setup with an  $e^-$  beam.
- Employs both resonance search and detached vertexing techniques
- Uses a high-rate, high-acceptance, high-resolution detector.

**JLAB officially approved experiment.**  
**Data taking starts in December 2014**

## Experimental reach: $2\sigma$ contours

- Continuous contour: planned for 2014-2015
  - 1 week @ 1.1 GeV, 50 nA
  - 2 weeks @ 2.2 GeV, 250 nA
- Dashed contour: still being discussed
  - 2 weeks @ 4.4 GeV, 350 nA

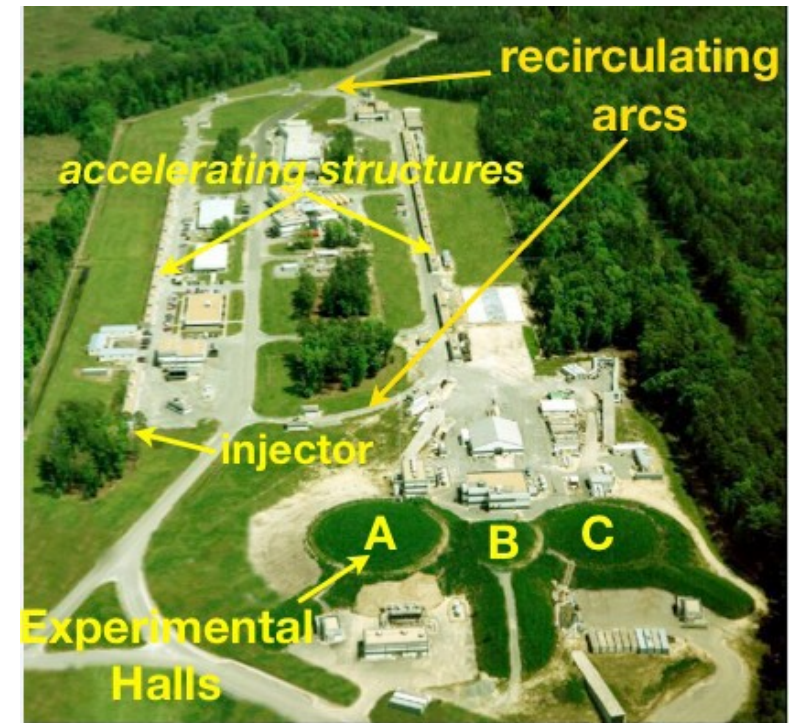
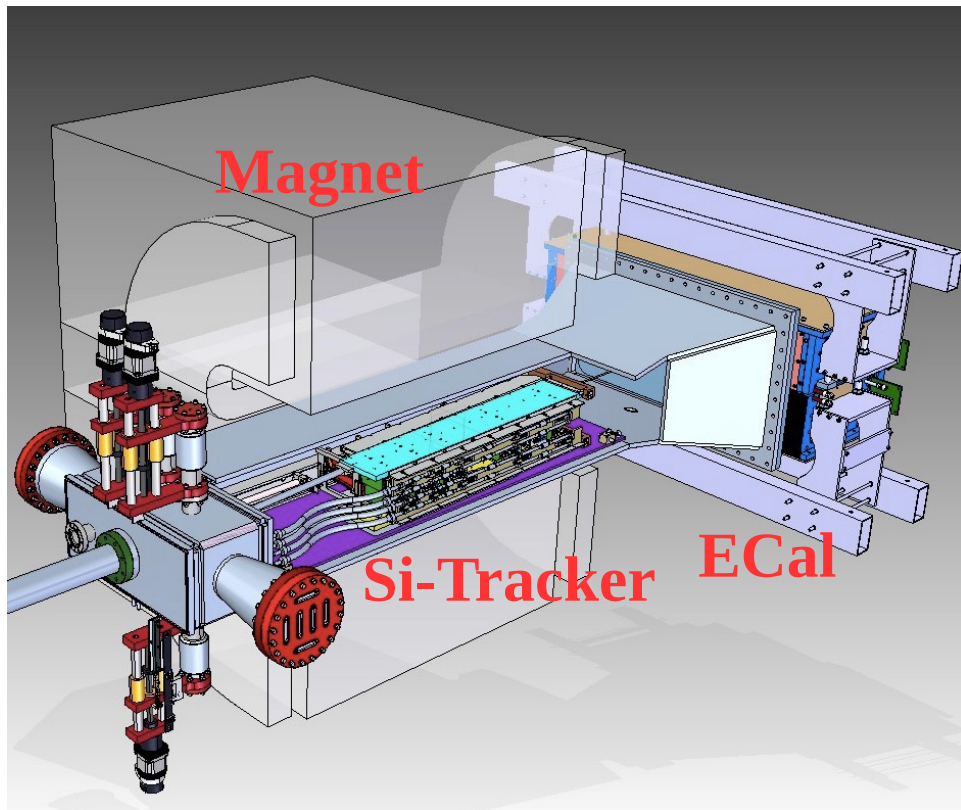
**Within few years HPS will explore a unique region in the  $A'$  parameter space.**



# The HPS experiment at JLab

HPS will run in the Hall B of Jefferson Laboratory  
(Newport News, Virginia)

- Electron beam with tunable energy (2.2 GeV per pass, up to 11 GeV, 12 GeV in Hall-D)
- Continuous beam, 4ns bunches
- $I_{\text{beam}} < 800 \text{ nA @ Hall B}$
- $I_{\text{beam}} < 100 \mu\text{A @ Hall A, C}$



HPS detector:

- Thin W target ( $\sim 10^{-3} X_0$ )
- Dipole magnet
- Si-tracker (5 layers w. axial/stereo modules)
  - Momentum analysis
  - Vertexing
- $\text{PbWO}_4$  calorimeter
  - Triggering



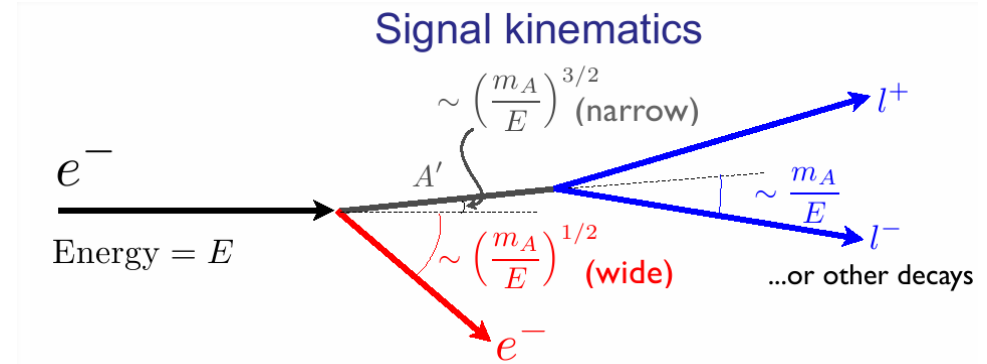
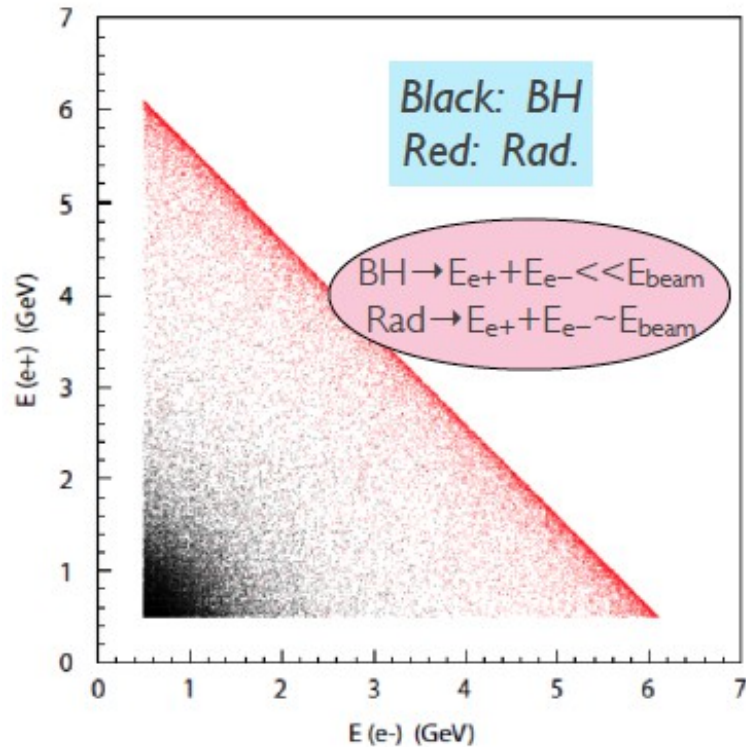
# The HPS experiment at JLab

## A' signal kinematic features:

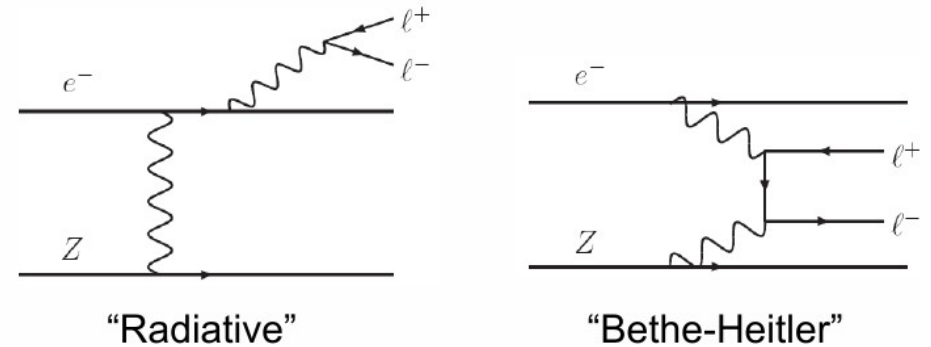
- Very forward A' emission angle,  $E_{A'} \sim E$
- Decay products opening angle  $\sim m_{A'}/E$
- Possible detached decay vertex

## Main background sources:

- Radiative  $l^+ l^-$  emission (irreducible)
- Bethe-Heitler processes (different kinematics)



## Trident backgrounds



## Signal searches:

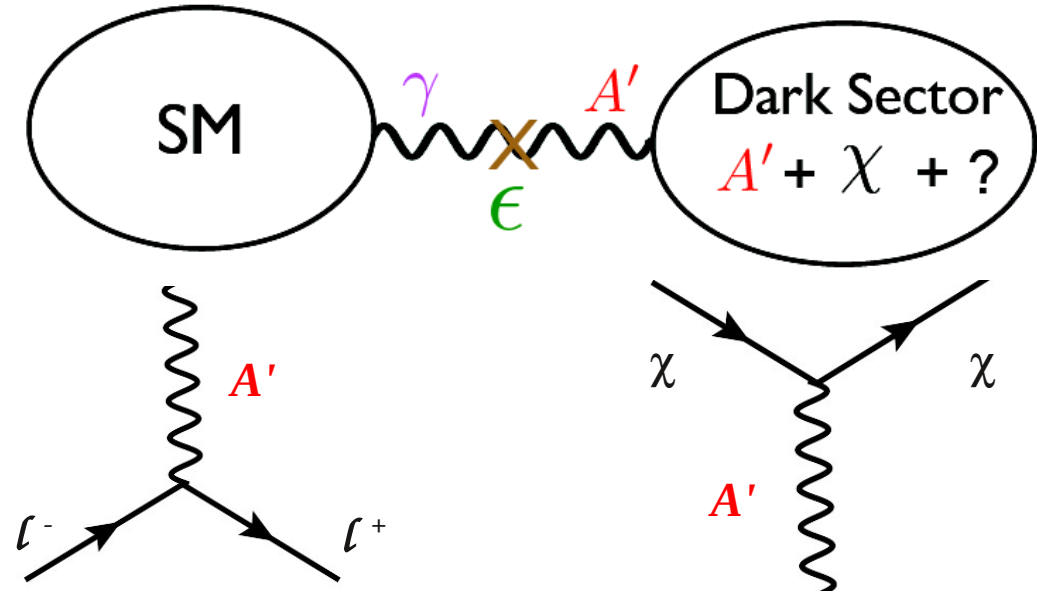
- "Bump hunting" in narrow invariant mass windows
- Detached vertexing

# Dark photons and dark matter

## The simplest model:

- $A'$  interacts with  $\gamma$  through kinetic mixing
- DM  $\chi$  interacts with  $A'$

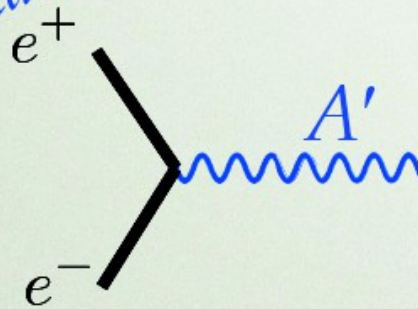
4 parameters:  $M_{A'}$ ,  $M_\chi$ ,  $\epsilon$ ,  $g_d$



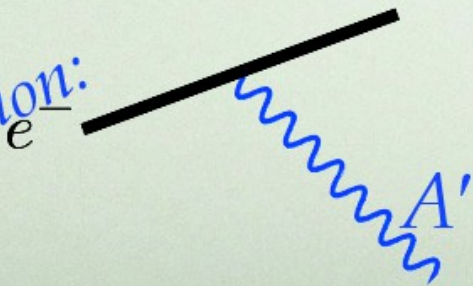
$A'$  production:  $\sigma \propto \epsilon^2$

$A'$  decay:

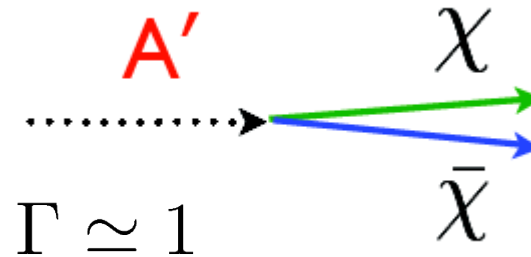
Annihilation:



Radiation:

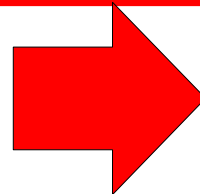


Invisible



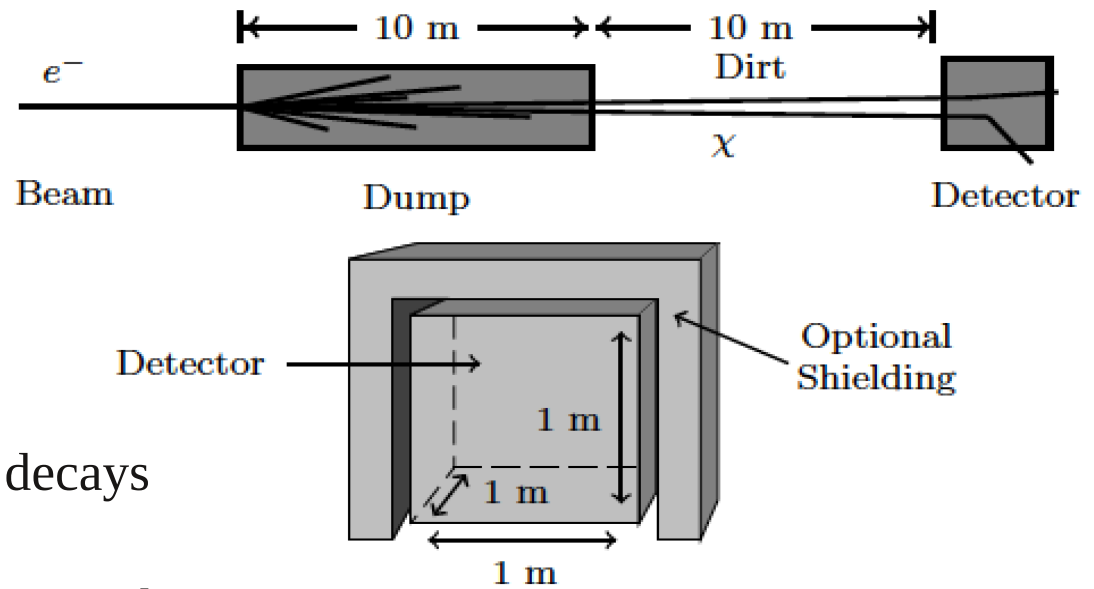
Second scenario

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



**BDX experiment at JLab**  
(LOI to be submitted to JLab PAC)

# *BDX: beam dump experiments for DM searches*

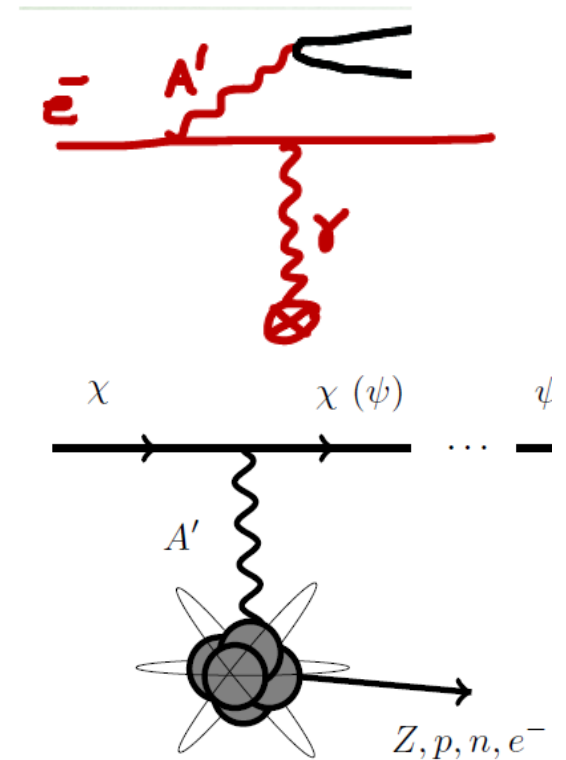


## Two-Step Detection Process:

- **Fixed-target:**  $A'$  produced in the dump, decays promptly to invisible  $\chi$
- **Detector:** Neutral-current scattering of  $\chi$  through  $A'$  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:** muons and neutrons. Can shield or veto

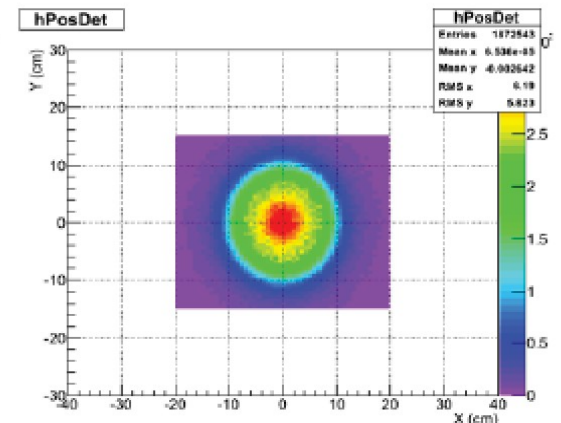
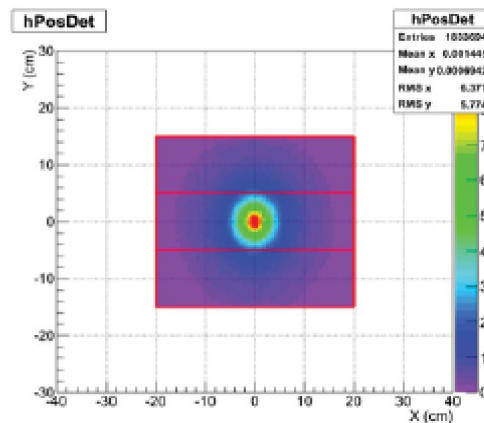
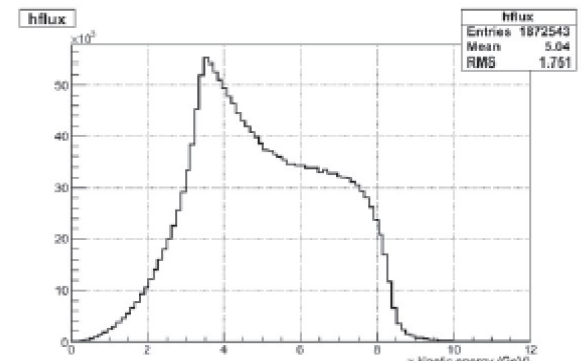
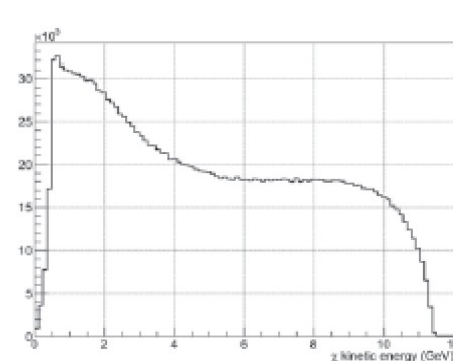
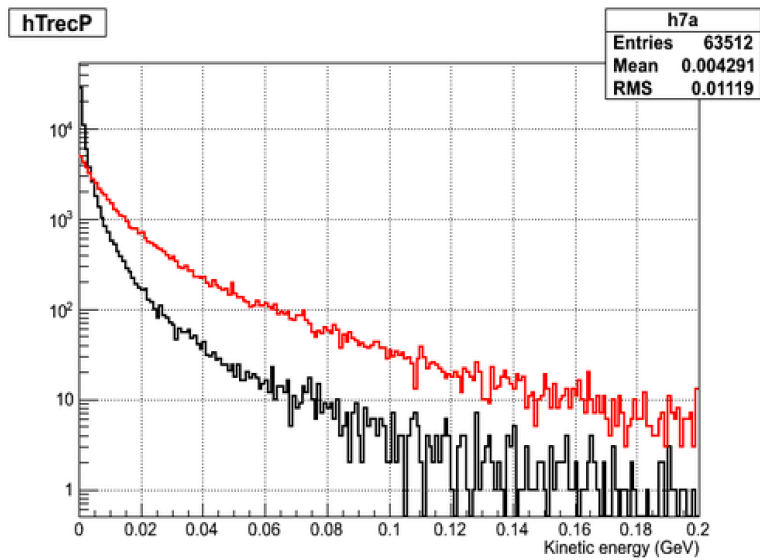


# BDX@JLab

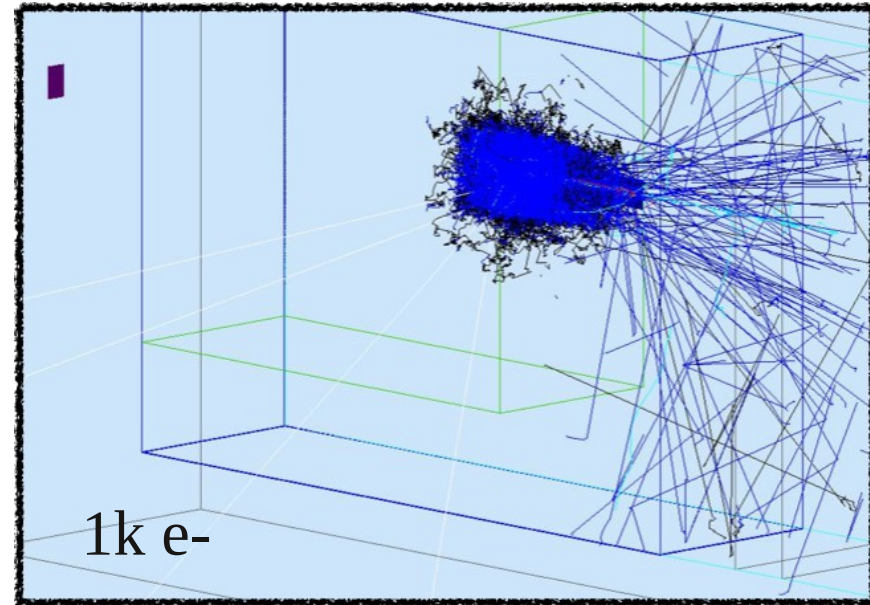
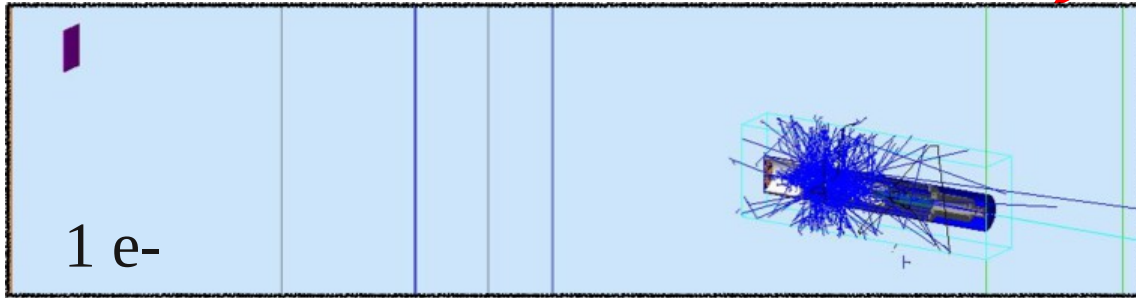
## $\chi$ production and detection

- Energy = 11 GeV
- CW beam (4ns spacing between bunches)
- Response studied as a function of the detection threshold (1 MeV and 10 MeV)
- Realistic simulation in GEANT4
  - Detector and beam-dump
  - Signal and background

	S.I	S.II
$M_\chi$	10 MeV	68 MeV
$M_{A'}$	50 MeV	150 MeV
$\epsilon$	$10^{-3}$	$10^{-3}$
$\alpha_{Dark}$	0.1	0.1
$N_\chi$ pairs produced per EOT	$3.4 \cdot 10^{-10}$	$3.4 \cdot 10^{-11}$
$\sigma_{\chi-p}$	1.4 nb	0.14 nb



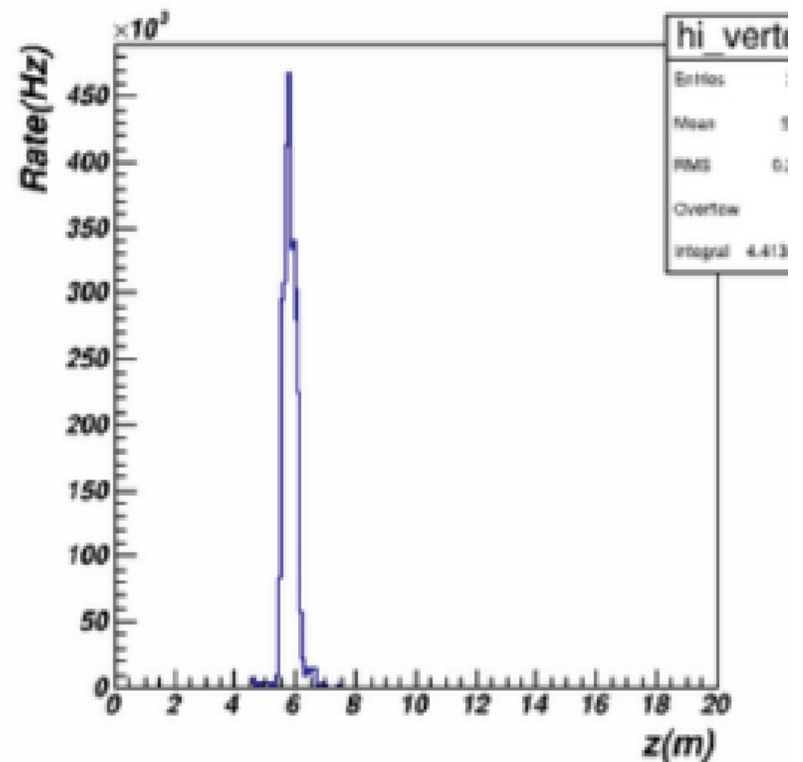
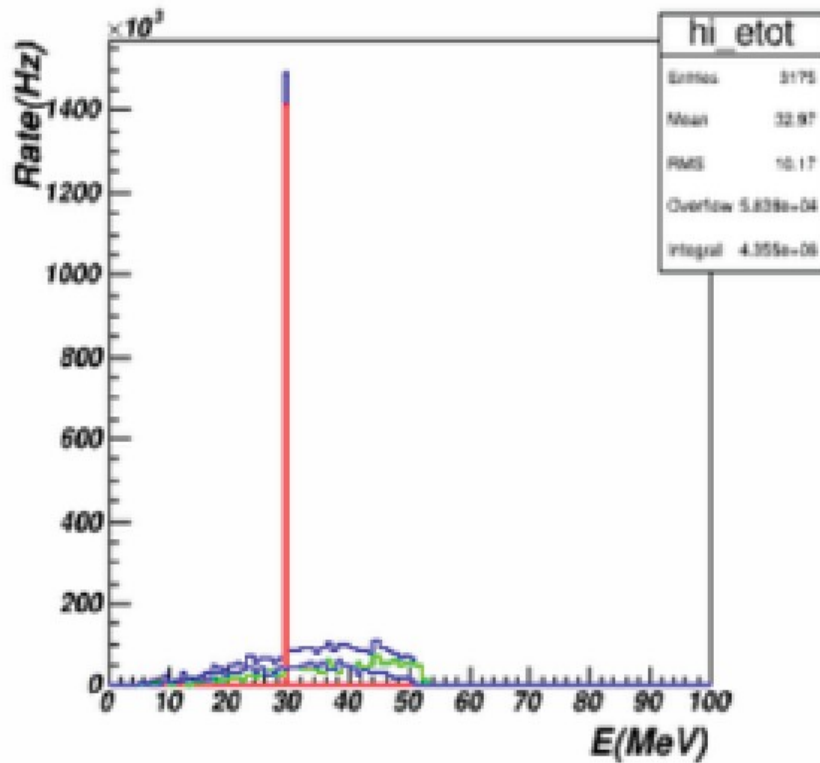
# BDX@JLab



## Beam related BG

- Only neutrino are produced
- No other particles (n and charged)

**Beam-related background is negligible**





# *BDX@JLab: background rates*

## Beam related BG

- Neutrinos
- Neutrons (<1 for 1s beam simulation)

## Beam unrelated BG

- Cosmic  $\mu$ 
  - Crossing
  - Captured/ decaying within the detector
  - Stopped in shielding
  - Rare  $\gamma$  decays
- Cosmic neutron
- Cosmic neutrinos

## BG reduction

- Time coincidence cut
- Directionality
- Particle id (e<sup>-</sup>/p separation)

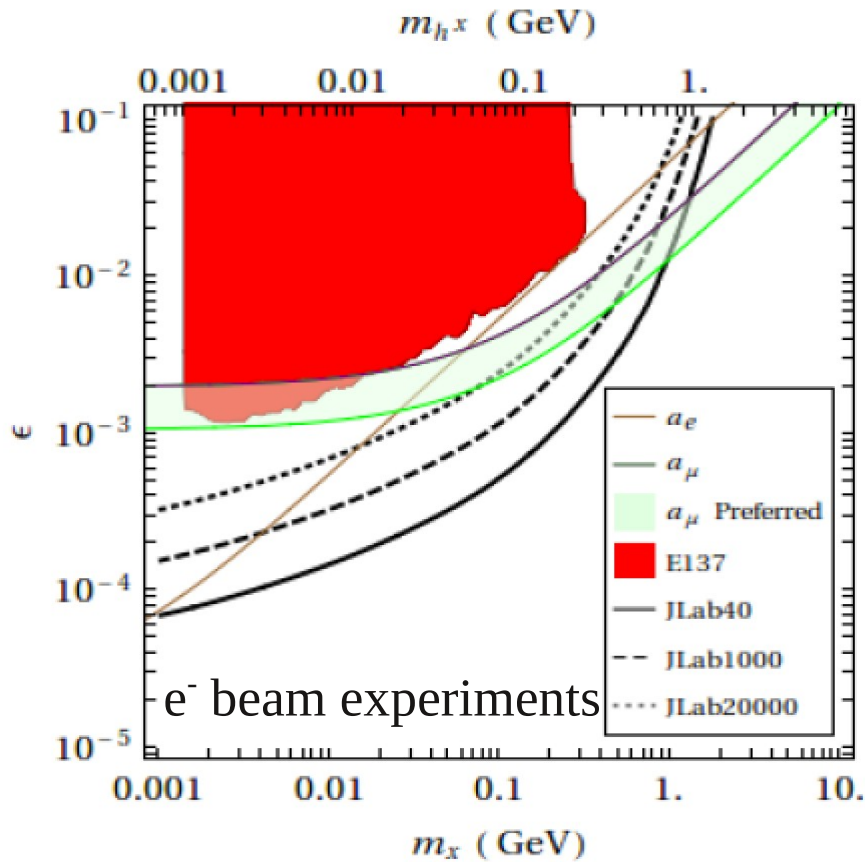
	Rate <sub>Thr=1MeV</sub> (Hz/ $\mu$ A))	Rate <sub>Thr=10MeV</sub> (Hz/ $\mu$ A))
$\chi$ detection - S.I	$1.0 \cdot 10^{-5}$	$1.2 \cdot 10^{-6}$
$\chi$ detection - S.II	$2.0 \cdot 10^{-7}$	$0.7 \cdot 10^{-7}$
B-rel $\nu$	$2.0 \cdot 10^{-9}$	$2.0 \cdot 10^{-10}$
B-rel neutron	0	0
	Rate <sub>Thr=1MeV</sub> (Hz)	Rate <sub>Thr=10MeV</sub> (Hz)
B-unrel $\nu$	$2.0 \cdot 10^{-6}$	$2.0 \cdot 10^{-7}$
B-unrel neutron	$2.7 \cdot 10^{-3}$	$0.6 \cdot 10^{-3}$
Crossing muons	$3.3 \cdot 10^{-3}$	$3.5 \cdot 10^{-3}$
Captured $\mu^+$	$1.4 \cdot 10^{-3}$	$2.4 \cdot 10^{-3}$
Decaying $\mu^-$ (CORM)	$2.9 \cdot 10^{-3}$	$4.8 \cdot 10^{-3}$
Stopped $\mu$ in lead	$7.0 \cdot 10^{-3}$	$4.3 \cdot 10^{-3}$
$\mu^-$ rare decay	$2.0 \cdot 10^{-5}$	$8.0 \cdot 10^{-6}$
Total Beam-unrelated bg	$1.7 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$

- Background sources are well-known and can be identified and/or reduced
- A full measure campaign of beam-unrelated BG is planned, using a detector prototype

# BDX@JLab: reach

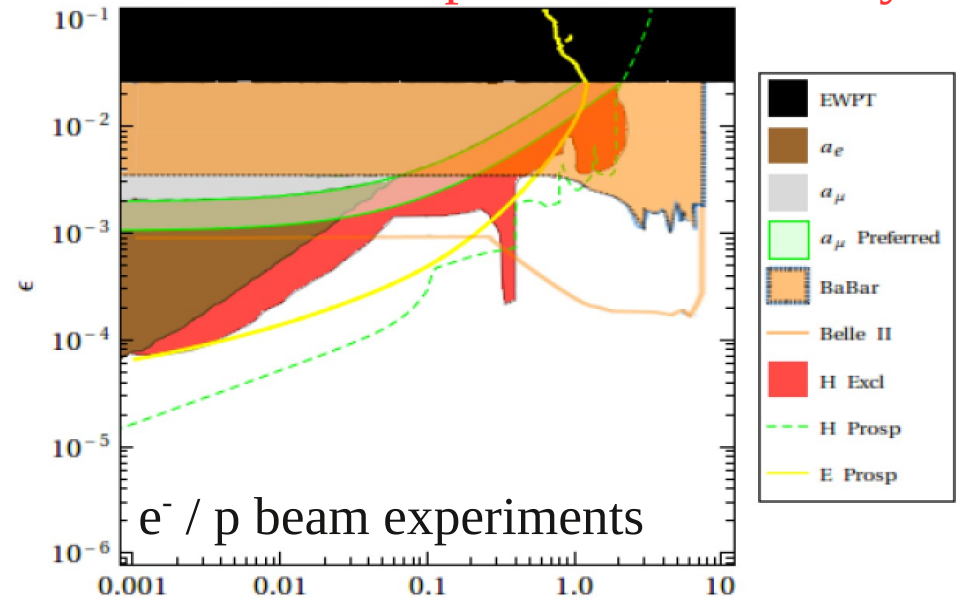
## BDX@JLab

- 1m<sup>3</sup> plastic scintillator detector
- 1 MeVee threshold
- I<sub>e</sub> = 100 μA (Hall-A beam-dump)
- 1y run (50% run efficiency) = 10<sup>22</sup> EOT



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

Model-independent background estimate.  
Determines the experiment sensitivity

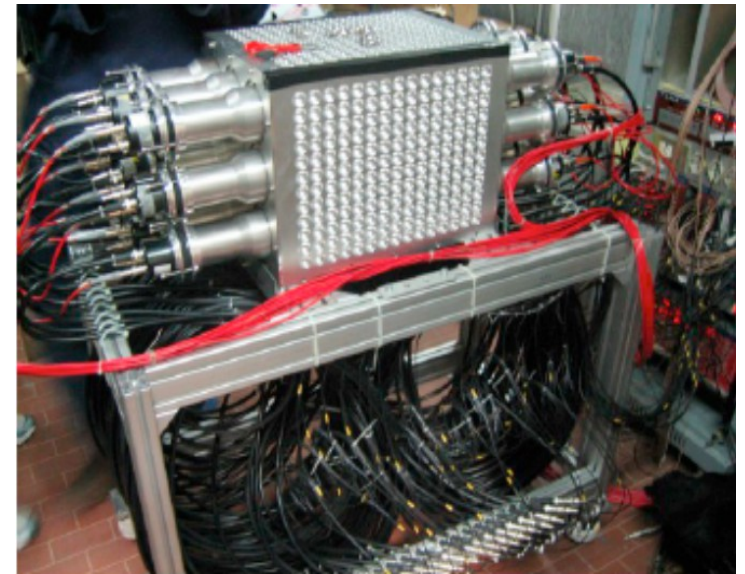
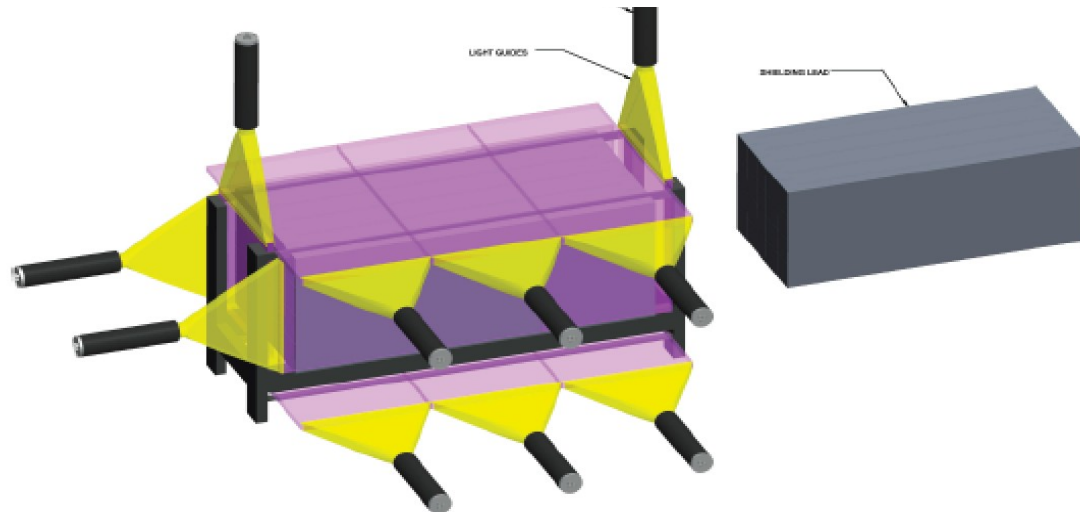
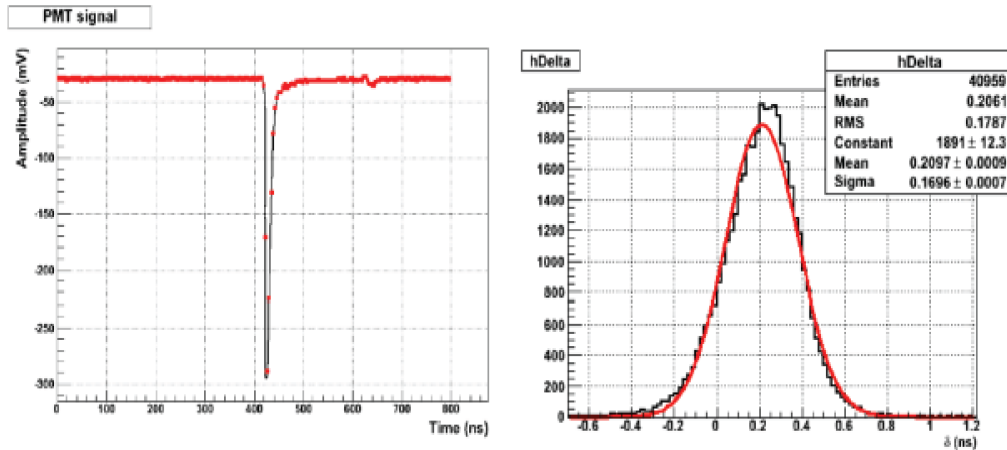
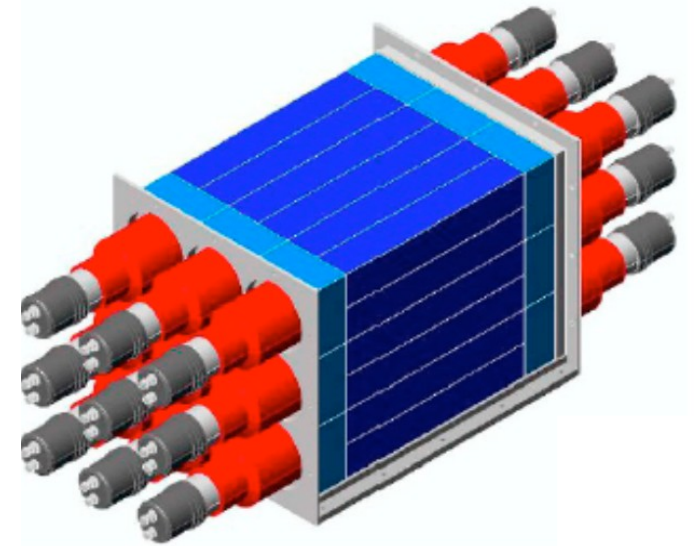


Letter of Intent (LOI) to be presented to JLab Program Advisory Committee PAC42  
Full proposal to the next JLAB PAC meeting

# BDX R&D

## CORMORINO: detector prototype

- Plastic scintillator-based detector,  $40 \times 30 \times 30 \text{ cm}^3$
- $3 \times 3$  matrix of 40 cm bars, read at both ends by fast PMT
- FADC-based fast DAQ
- Veto and shield design in progress
- **Validation of simulations for cosmogenic BG**





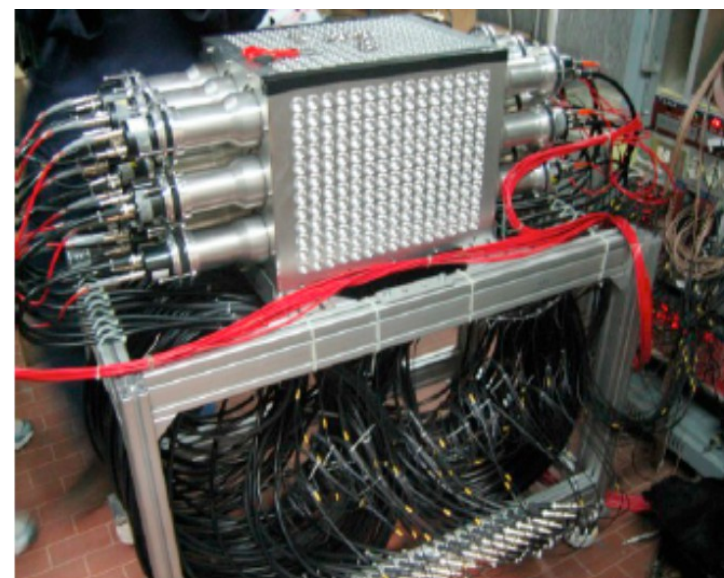
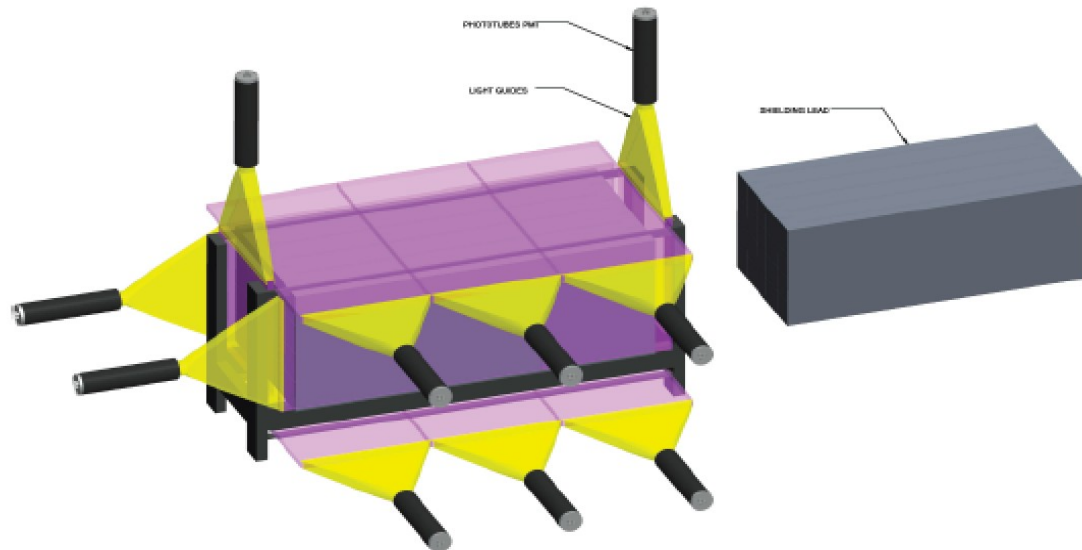
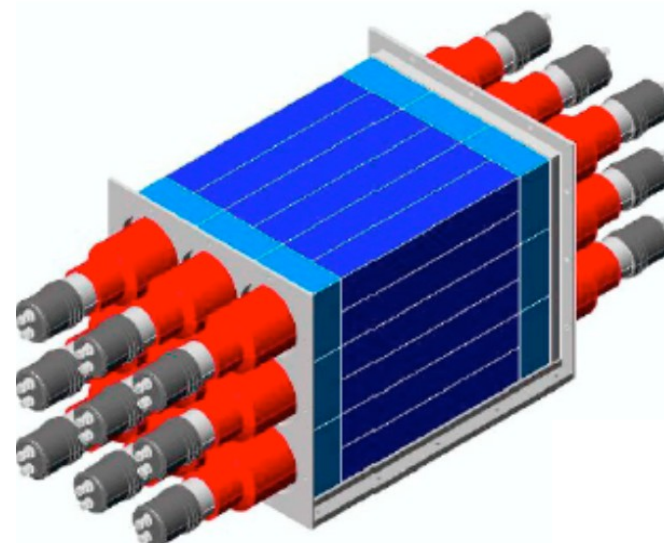
# *BDX R&D*

## **CORMORINO: detector prototype**

- Plastic scintillator-based detector, 40 x 30 x 30 cm<sup>3</sup>
- 3x3 matrix of 40 cm bars, read at both ends by fast PMT
- FADC-based fast DAQ
- Veto and shield design in progress
- **Validation of simulations for cosmogenic BG**

## **R & D for improvements:**

- Liquid scintillator (PID)
- SiPMs instead of PMTs
- Extrude plastic with fibers readout



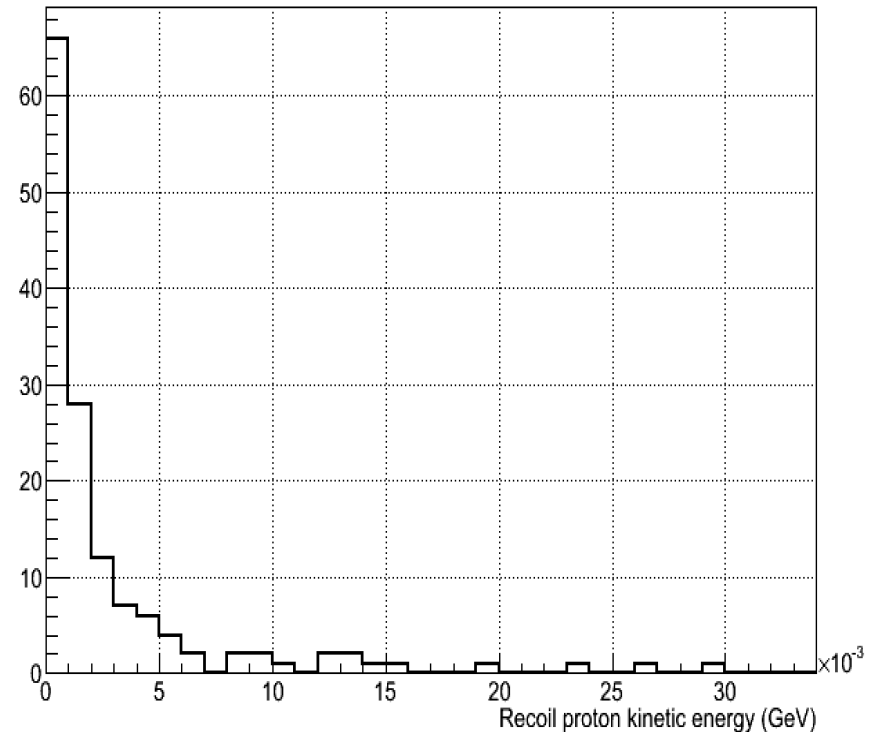
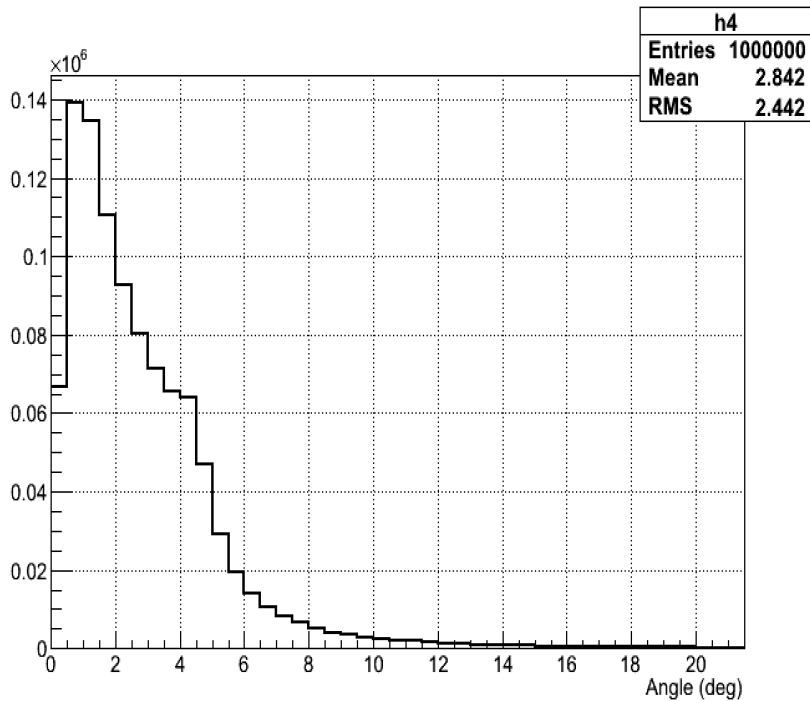
# *BDX@LNF*

## $\chi$ production and detection

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

### Parameters:

$M_{A'} = 50$  MeV  
 $M_{\chi} = 10$  MeV  
 $\text{Alpha}_{\text{dark}} = 0.1$   
 $\text{Epsilon} = 10^{-3}$



**Very preliminary study. Results look very promising and should be investigated further.**



# Conclusions

If there is an additional U(1) hidden symmetry in nature, ordinary photons would interact with the new gauge boson  $A'$  through kinetic mixing.

**The  $A'$  acts as a “portal” between SM and a new, hidden sector (DM?).**

The simplest model foresees 4 parameters:  $M_{A'}$ ,  $\epsilon$ ,  $M_\chi$ ,  $g_d$

- **“Minimal” scenario:** if  $M_{A'} < 2 M_\chi$ , then the  $A'$  decays only to SM particles.
- $A'$  is measured through the SM decay products. Only  $M_{A'}$ ,  $\epsilon$  are relevant.
- **HPS @ JLAB: Approved experiment, 2014-2015 foreseen run.**
  - “Bump-hunting” and detached vertexing techniques
  - Explore a **new region** in the parameters space. Results expected within few years.
- **“Evolved” scenario:** if  $M_{A'} > 2 M_\chi$ , then the  $A'$  decays invisible to  $\chi\chi$ 
  - Detector placed behind a beam dump to shield all SM particles (except  $\nu$ ).
  - $\chi$  detected through the  $A'$ -mediated interaction in the detector: elastic recoil on protons.
  - **BDX experiment @ JLAB. LoI currently being proposed to JLab PAC42**
    - 1 m<sup>3</sup> plastic scintillator detector placed behind the Hall-A beam dump.
    - Beam related and un-related backgrounds evaluated through MC simulations.
    - Cosmogenic backgrounds will be measured using a detector small-scale prototype.
    - **Experiment sensitivity evaluated to be  $\sim 3000$  events for a 6-month run with  $10^{22}$  EOT.**

Back up

# MiniBooNE

## MiniBooNE DM search:

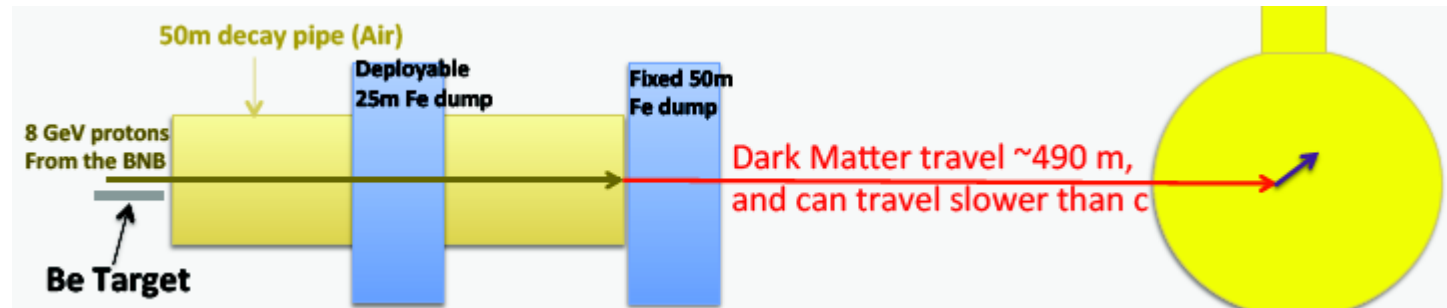
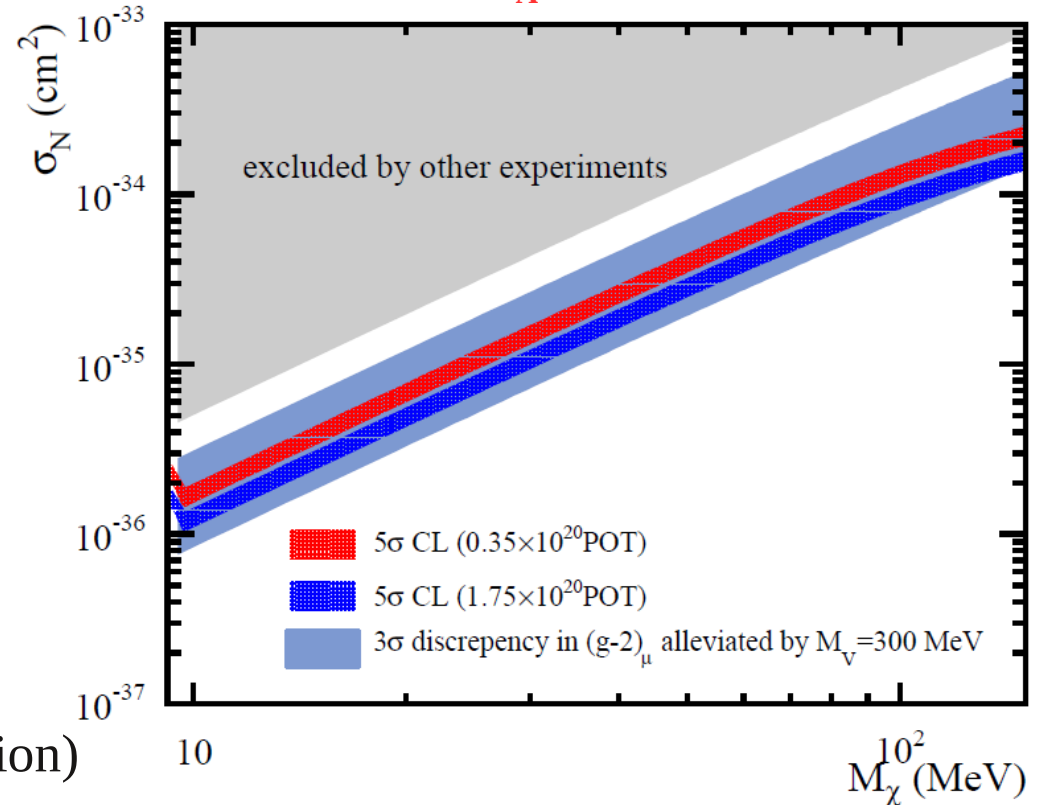
- 8 GeV protons on a 50m beam dump
- Detector ~ 500 m after the beam dump
  - 800 t mineral oil, 1280 PMTs

## MiniBooNE test run (2013):

- $0.4 \times 10^{20}$  protons on target
- “Off-axis” configuration to reduce  $\nu$  background (reduction factor  $\sim 42$ )
- Selection cuts for DM events:
  - Timing ( $\chi$  can travel slower than  $c$ )
  - Energy (different  $\chi$ - $\nu$  energy deposition)

## MiniBooNE 2014 proposal: $2 \times 10^{20}$ PoT

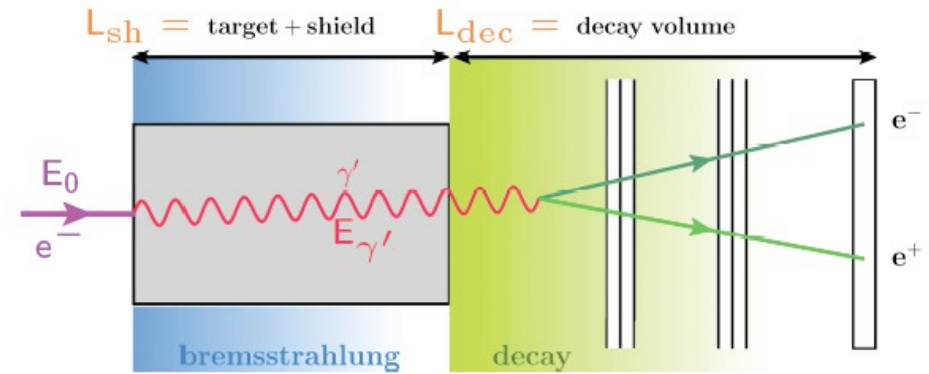
Preliminary,  $M_{A'} = 300$  MeV,  $\alpha' = 0.1$



# First generation fixed target experiments: beam dump

## Beam dump experiments for $A'$ search:

- $e^-$  beam incident on thick target
- $A'$  is produced 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



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

