BDX-Mini data analysis

Marco Spreafico

On behalf of BDX Collaboration

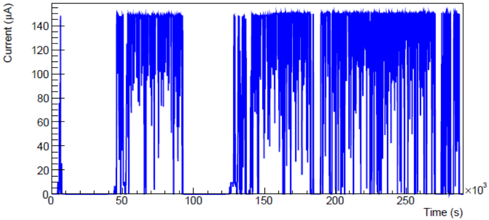
11 - 17 - 2021

BDX-Mini measurement

Measurement took place in spring-summer 2020

$\rightarrow$ collected $\sim 3 \times 10^{21}$ EOT (30% BDX)

- $\rightarrow$ used 2.176 GeV beam
- $\rightarrow$ beam current up to 150 μA
- $\rightarrow$ beam-on and beam-of measurements alternate
  - $\rightarrow$ *beam on time* $\sim$ 50%
  - $\rightarrow$ beam-off data for cosmic background study



$\rightarrow$ special 10 GeV-beam run for calibration purpose

Data Analysis

Blind analysis:

→ all studies performed using MC and beam-off data

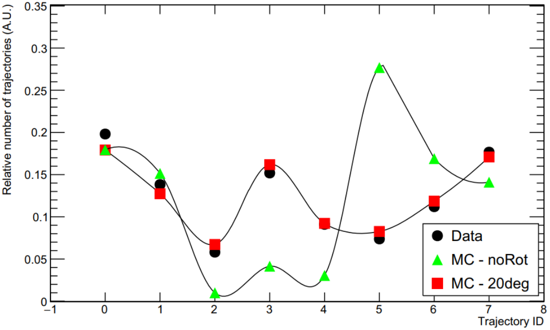
Analysis steps:

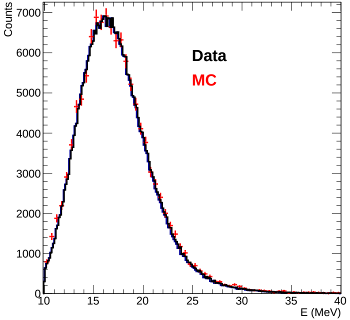
1. ECal calibration
2. detector response stability
   → ECal calibration stability and veto response stability studied with cosmic muons
3. background study
   → cosmic background rejected requiring anti-coincidence with the veto
   → neutrino background simulated with MC (same as BDX) → negligible
4. sensitivity optimization
   → maximizing signal and minimizing background
5. *unblinding*
   → selection cuts applied to beam-on data

1) ECal calibration

ECal calibrated using muons produced by 10 GeV beam

- calibration constants evaluated comparing data to MC
- we found out that the detector was rotated ($\sim 20^\circ$)





Data Analysis

Blind analysis:

→ all studies performed using MC and beam-off data

Analysis steps:

1. ECal calibration
2. detector response stability
   → ECal calibration stability and veto response stability studied with cosmic muons
3. background study
   → cosmic background rejected requiring anti-coincidence with the veto
   → neutrino background simulated with MC (same as BDX) → negligible
4. sensitivity optimization
   → maximizing signal and minimizing background
5. *unblinding*
   → selection cuts applied to beam-on data

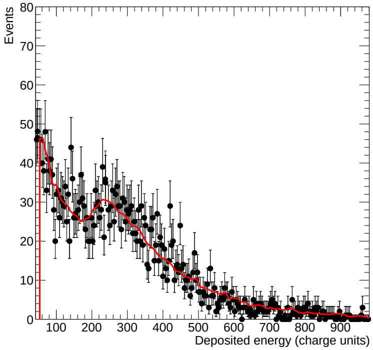
2.1) ECal calibration stability

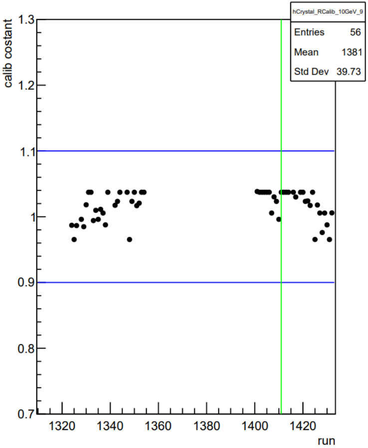
ECal calibration constants stability monitored using cosmic muons

→ Muon trajectories with a clear Landau peak are chosen

→ MC simulation used to perform a template fit of data

→ calibration constants stable within 10%

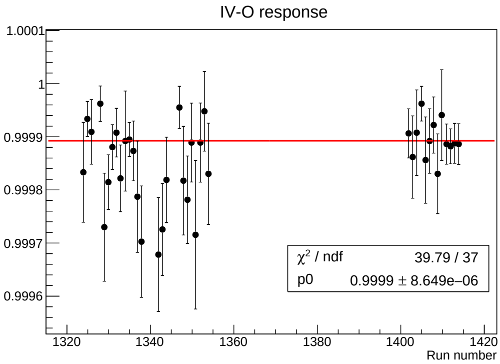




2) Veto response stability

Veto stability studied with cosmic muons ($\rightarrow$ only beam-off data used)

- $\rightarrow$ selected muons traversing the detector
- $\rightarrow$ measured response for each component (*caps*, IV-O, OV-C)
- $\rightarrow$ response stable within $\sim 1\%$



Data Analysis

Blind analysis:

→ all studies performed using MC and beam-off data

Analysis steps:

1. ECal calibration
2. detector response stability
   → ECal calibration stability and veto response stability studied with cosmic muons
3. background study
   → cosmic background rejected requiring anti-coincidence with the veto
   → neutrino background simulated with MC (same as BDX) → negligible
4. sensitivity optimization
   → maximizing signal and minimizing background
5. *unblinding*
   → selection cuts applied to beam-on data

3) Cosmic background study

Anti-coincidence with the veto used to reject most cosmic background events

$\rightarrow$ few events remain with energy in ECal and no activity in the veto

$\rightarrow$ main background

Number of cosmic background events in beam-on data evaluated from beam-off data

$\rightarrow$ measurement contain beam-on and beam-off data

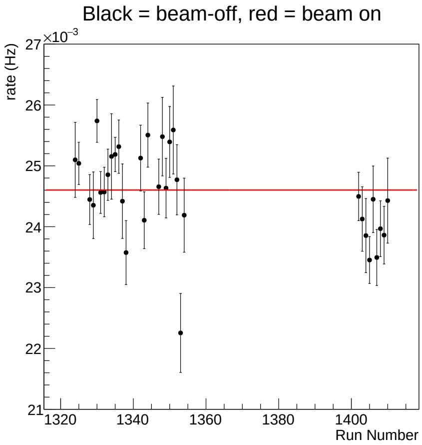
Problems:

- long term stability of the cosmic background
- short term stability (subsequent beam-on and beam-off measurements)

Cosmic background study

Long term cosmic background stability

- we studied vertical muons ($\Longrightarrow$ different topology with respect to DM)
- only beam-off data used

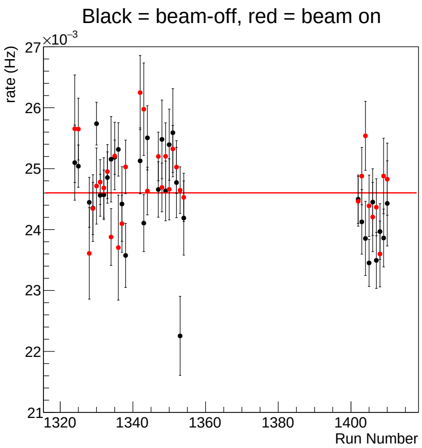


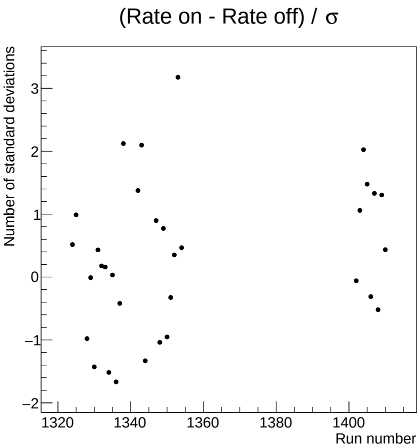
$\rightarrow$ there are non negligible fluctuations in the background

Cosmic background study

Short term cosmic background stability

- we used also beam on-data (vertical muons $\Longrightarrow$ different topology with respect to DM)





$\rightarrow$ cosmic background stable over short ($\sim$ min) periods of time

$\rightarrow$ fluctuations are negligible when considering all data together

Data Analysis

Blind analysis:

→ all studies performed using MC and beam-off data

Analysis steps:

1. ECal calibration
2. detector response stability
   → ECal calibration stability and veto response stability studied with cosmic muons
3. background study
   → cosmic background rejected requiring anti-coincidence with the veto
   → neutrino background simulated with MC (same as BDX) → negligible
4. sensitivity optimization
   → maximizing signal and minimizing background
5. *unblinding*
   → selection cuts applied to beam-on data

4) Sensitivity optimization

Upper limit on number of signal events evaluated with one sided test statistic:

$$q(S) = \begin{cases} -2\log\lambda(S) & S > \hat{S} \\ 0 \quad S < \hat{S} \end{cases} \qquad \lambda(S) = \frac{\mathscr{L}(S, \hat{\hat{B}})}{\mathscr{L}(\hat{S}, \hat{B})}$$

$$\mathscr{L}(n_{on}, n_{off}; S, B_c, B_\nu) = \mathrm{Pois}(n_{on}, \mu S + B_\nu + B_c)\mathrm{Pois}(n_{off}, \tau B_c)P(\mu; \mu_0 = 1, \sigma_\mu).$$

Upper limit on LDM parameters evaluated using MC simulations to evaluate $S(\epsilon)$

- $\mathrm{Pois}(n_{on}, \mu S + B_\nu + B_c)$: beam-on data $\rightarrow$ signal+background
- $\mathrm{Pois}(n_{off}, \tau B_c)$: beam-off data $\rightarrow$ only cosmic background
- $P(\mu; \mu_0 = 1, \sigma_\mu)$: includes MC simulations systematic uncertainties

4.1) Systematic uncertainties

$\mu =$ *signal scale*

$\rightarrow$ accounts for uncertainties in MC simulations used to relate S to ϵ

Systematic uncertainties considered:

ECal calibration	$\sigma_E/E = \pm\ 10\%\ (\pm\ 20\%)$	$\sigma_{E,\mu} = \pm 0.14$
Detector position	$\sigma_z = \pm\ 5$ cm	$\sigma_{z,\mu} = \pm 0.07$
Detector rotation	$\sigma_\theta = \pm\ 5^\circ$	$\sigma_{\theta,\mu} = \pm 0.025$
Veto threshold	$\sigma_{th}/Q_{th} = \pm\ 0.5$	$\sigma_{th,\mu} = \pm 0.06$
DM interaction	Requires different MC	$\sigma_{DM,\mu} = \pm 0.05$

$\Rightarrow$ total uncertainty:

$$\sigma_\mu = \sqrt{\sum_{sys} \sigma_{sys}^2} = 0.18$$

4.2) Sensitivity optimization

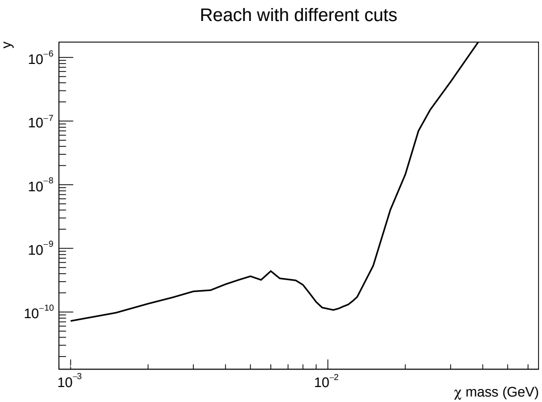
Idea: improve reach with respect to the 0 background condition

→ maximizing signal while minimizing background

→ reference = exclusion limit on y

→ optimization performed on events passing the anti-coincidence condition

→ study performed using MC and beam-off data



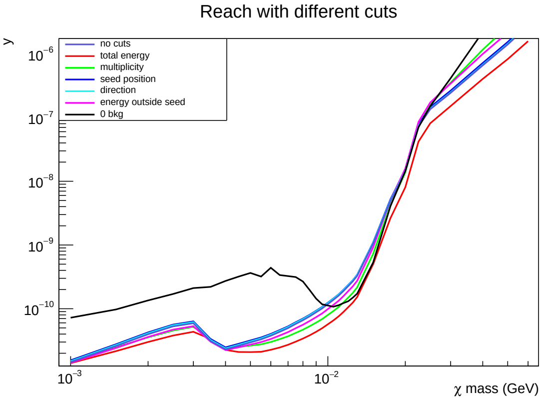
4.2) Sensitivity optimization

Idea: improve reach with respect to the 0 background condition

- → maximizing signal while minimizing background
- → reference = exclusion limit on y
- → optimization performed on events passing the anti-coincidence condition
  - → study performed using MC and beam-off data

Cuts tested:

- Total energy
- Hit multiplicity
- Most energetic hit position
- EM shower direction
- Energy outside seed



Maximum sensitivity achieved with cut on total energy
→ cuts used: **anti-coincidence with veto and** $E_{tot} > 50$ **MeV**

Data Analysis

Blind analysis:

→ all studies performed using MC and beam-off data

Analysis steps:

1. ECal calibration
2. detector response stability
   → ECal calibration stability and veto response stability studied with cosmic muons
3. background study
   → cosmic background rejected requiring anti-coincidence with the veto
   → neutrino background simulated with MC (same as BDX) → negligible
4. sensitivity optimization
   → maximizing signal and minimizing background
5. *unblinding*
   → selection cuts applied to beam-on data

5) Unblinding

Unblinding $\Longrightarrow$ number of beam-on events evaluated

- $R_{on} = (3.87 \pm 0.10)10^{-4}\mathrm{Hz}$
- $R_{off} = (3.86 \pm 0.10)10^{-4}\mathrm{Hz}$

$\Rightarrow$ no data excess

$\Rightarrow$ upper limit on y

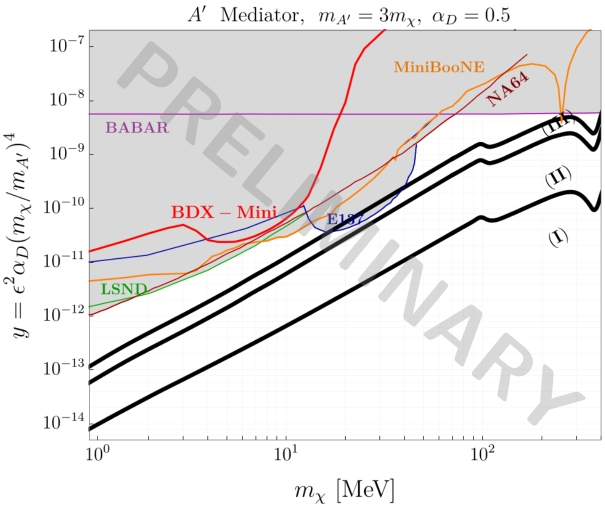
5) Unblinding

Unblinding $\Longrightarrow$ number of beam-on events evaluated

- $R_{on} = (3.87 \pm 0.10)10^{-4}\text{Hz}$
- $R_{off} = (3.86 \pm 0.10)10^{-4}\text{Hz}$

$\Rightarrow$ no data excess

$\Rightarrow$ upper limit on y



No new region excluded

$\rightarrow$ excellent sensitivity in the bump due to resonant A' production

$\rightarrow$ low sensitivity for higher masses

$\rightarrow$ exclusion curve touches NA64 exclusion limits

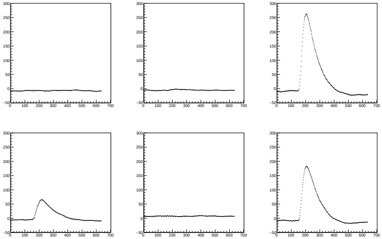
$\rightarrow$ reach similar to flagship experiments!

Conclusions

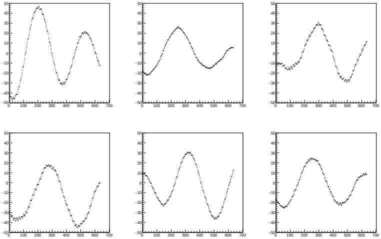
- BDX-Mini is the first modern beam-dump experiment optimized for LDM searches
- Data taking in spring-summer 2020
  - accumulated 3×10^{21} EOT in few months
- analysis optimized for LDM searches
  - $\rightarrow$ sensitivity optimization shows that the 0 background condition do not achieve the best reach
  - $\rightarrow$ a similar approach can be implemented in BDX analysis
- reach similar to flagship experiments (NA64, E137)

Backup Slides

Waveform analysis



(a) Example of signal event



(b) Example of noise

Filtering algorithm based on cross-correlation

- with sine function
- with signal functional form

→ 100% efficiency on training dataset