C12-16-001
PR12-16-001 update to Jefferson Lab PAC46
July 16 2018

BDX
Dark matter search in a Beam-Dump eXperiment (BDX) at Jefferson Lab
2018 update to PR12-16-001

M.Battaglieri, *A.Celentano, M.DeNapoli, R.DeVita, G.Krnjaic, E.Smith*

and the BDX Collaboration

Motivations

- The BDX Proposal (PR12-16-001) was presented to PAC44 in 2016
- BDX Proposal was *Conditionally approved - C2*
- In 2017 we agreed with PAC45 on the strategy to address PAC44 concerns
- In this update we report the studies that confirm on a more firm ground the original proposal results

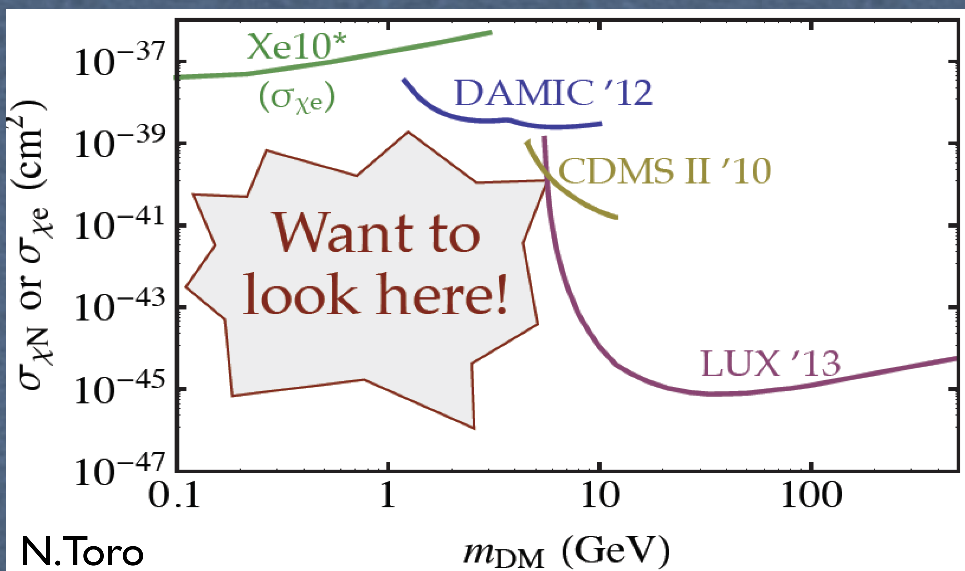
We believe all issues raised by PAC44/45 have been addressed aiming to obtain the full approval of PR12-16-001 (now *Conditionally Approved - C2*)

Layout

★ Summary of PR12-16-001- BDX proposal
★ Results of the beam-on background assessment (on-site measurement)
★ Neutrino background and reach optimization

Searching for (Light) Dark Matter

- Compelling astrophysical indications of DM existence but no prove of particle-behaviour
- An extensive experimental program based on WIMPS paradigm is searching for DM via nuclear recoil (Direct Detection)



- Negative results call for extending the DM hunting territory to unexplored regions

Dark/Hidden Sector
Light Dark Matter couples to SM with a new force

- Light Dark Matter (X) in 1-1000 MeV mass range where (traditional) Direct Detection is (almost) impossible
- High intensity beam makes accelerator-based DM search highly competitive

JLab is the world-leading facility for LDM search (HPS, APEX, DARK-LIGHT)

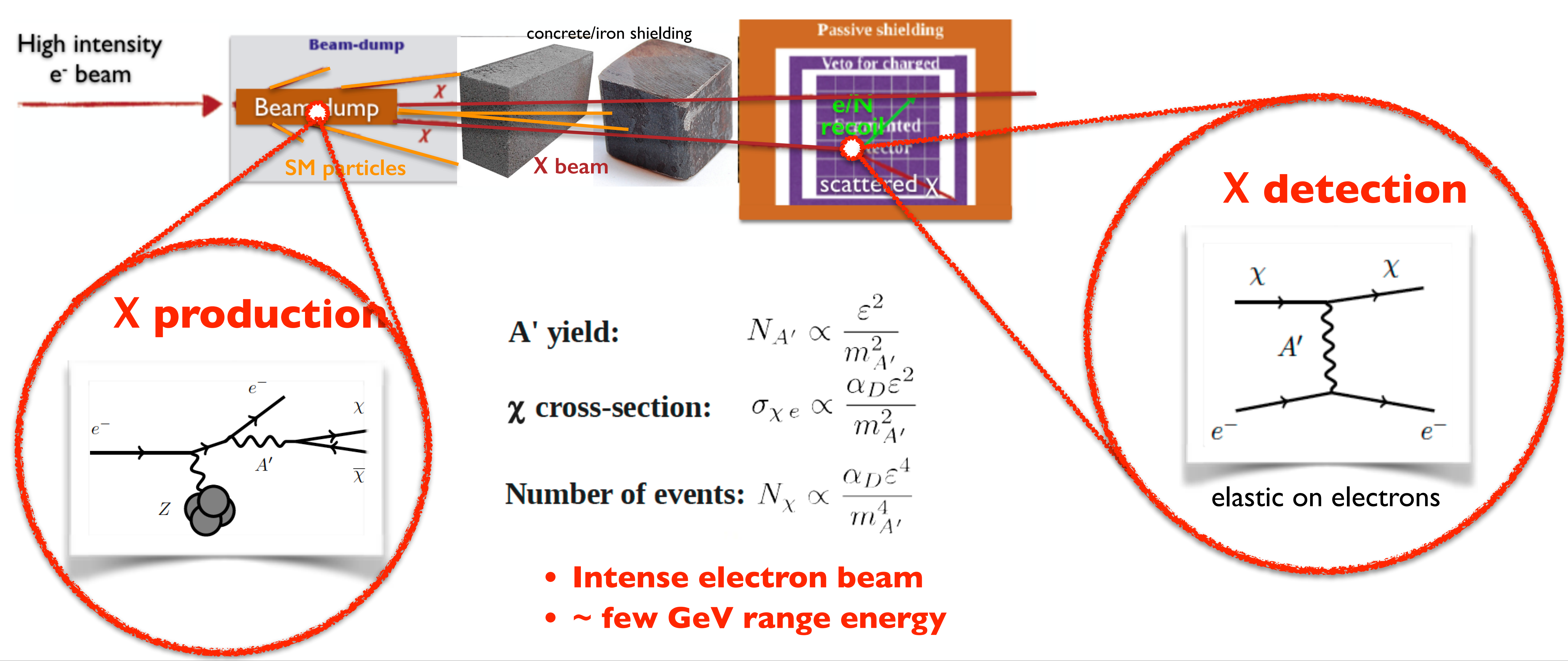
The BDX experiment

Two step process

I) An electron radiates an A' and the A' promptly decays to a χ (DM) pair

II) The χ (in-)elastically scatters on a e⁻/nucleon in the detector producing a visible recoil (GeV)

PhysRevD.88.114015 E.Izaguirre, G.Krnjaic, P.Schuster, N.Toro



A' yield: $N_{A'} \propto \frac{\varepsilon^2}{m_{A'}^2}$

χ cross-section: $\sigma_{\chi e} \propto \frac{\alpha_D \varepsilon^2}{m_{A'}^2}$

Number of events: $N_\chi \propto \frac{\alpha_D \varepsilon^4}{m_{A'}^4}$

- **Intense electron beam**
- **~ few GeV range energy**

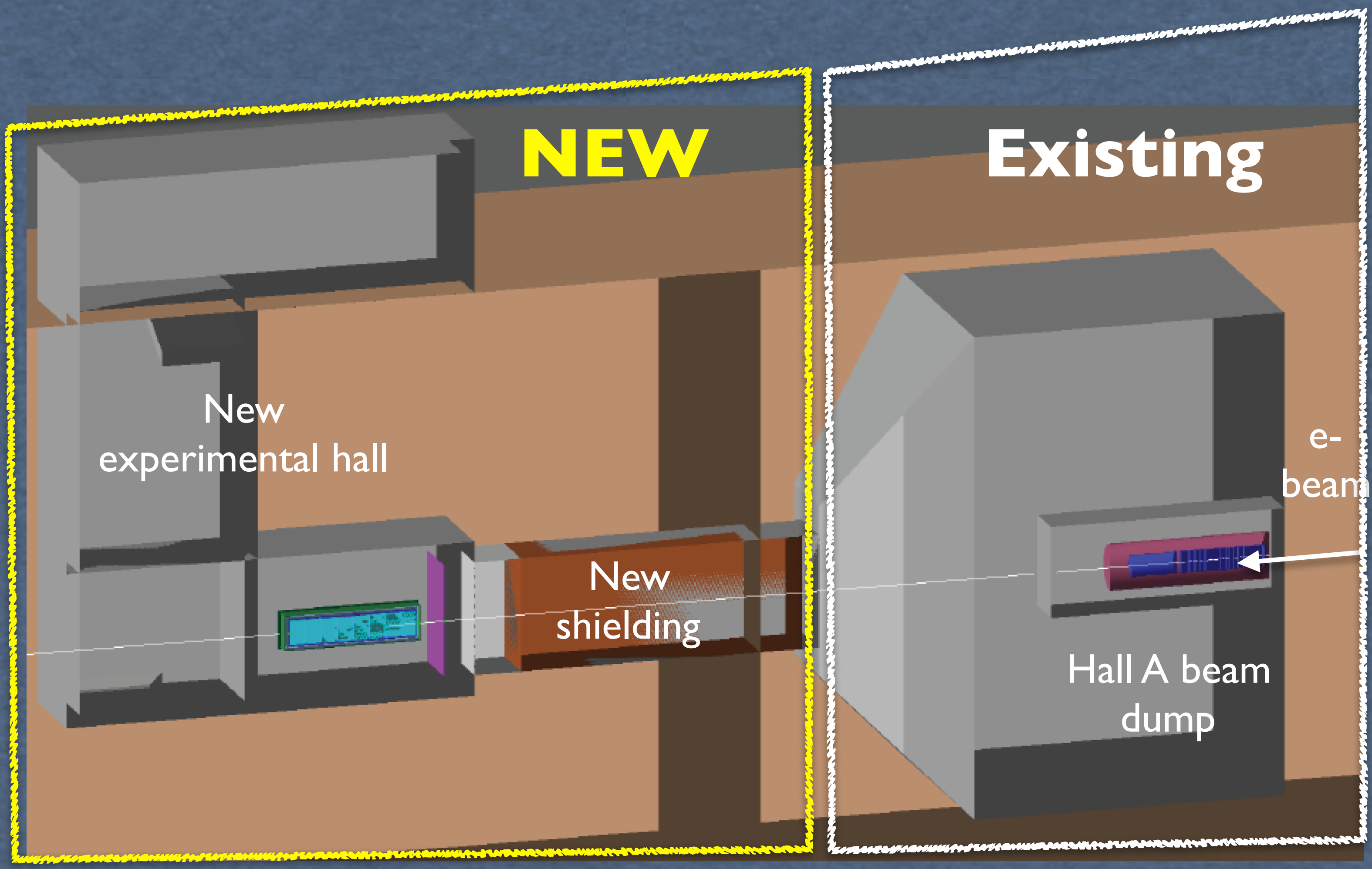
Experimental signature in the detector:

X-electron → EM shower ~GeV energy

BDX at JLab

★ High energy beam available: 11 GeV
★ The highest available electron beam current: ~65 uA
★ The highest integrated charge: 10^{22} EOT (41 weeks)

★ BDX detector located downstream of Hall-A beam dump
★ New underground experimental hall



The BDX detector

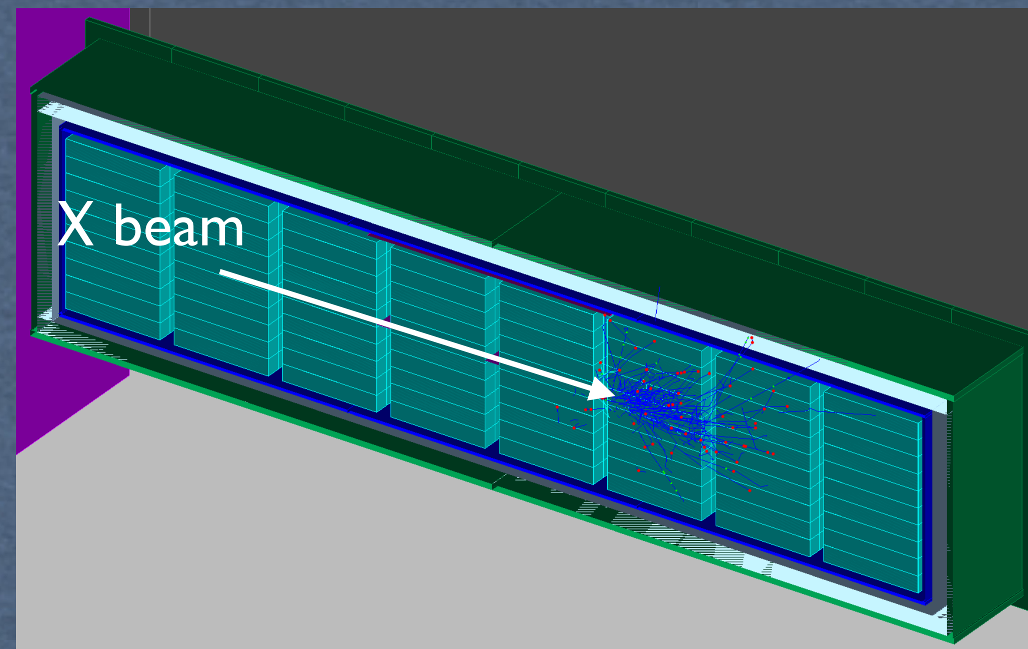
Detecting the X

E.M. Calorimeter

A **homogeneous crystal**-based detector combines all necessary requirements

Modular EM calorimeter

- 8 modules 10x10 crystals each
- 800 CsI(Tl) crystals (from BaBar EMCal)
- 6x6 mm^2 Hamamatsu SiPM readout
- 50 x 55 x 295 cm^3



Rejecting the bg

- Cosmic
- Beam-on

Two active veto layers

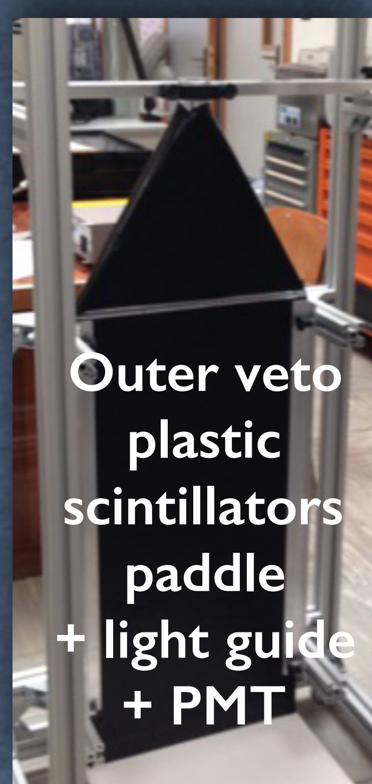
Plastic scintillator +WLS with SiPM and PMT readout

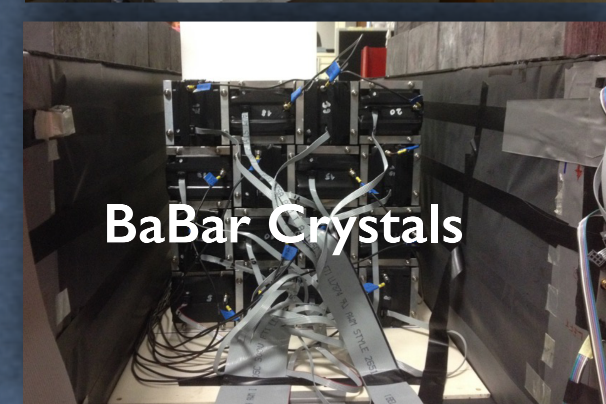
- Outer Veto: 2cm thick
- Inner Veto: 1 cm thick
- Lead Vault: 5cm thick

BDX detector technology validated with:

BDX-Proto

- EM Cal
  - 4x4 CsI(Tl) crystals
  - 6x6 mm^2 SiPM
- Outer Veto
- Lead vault
- Inner Veto

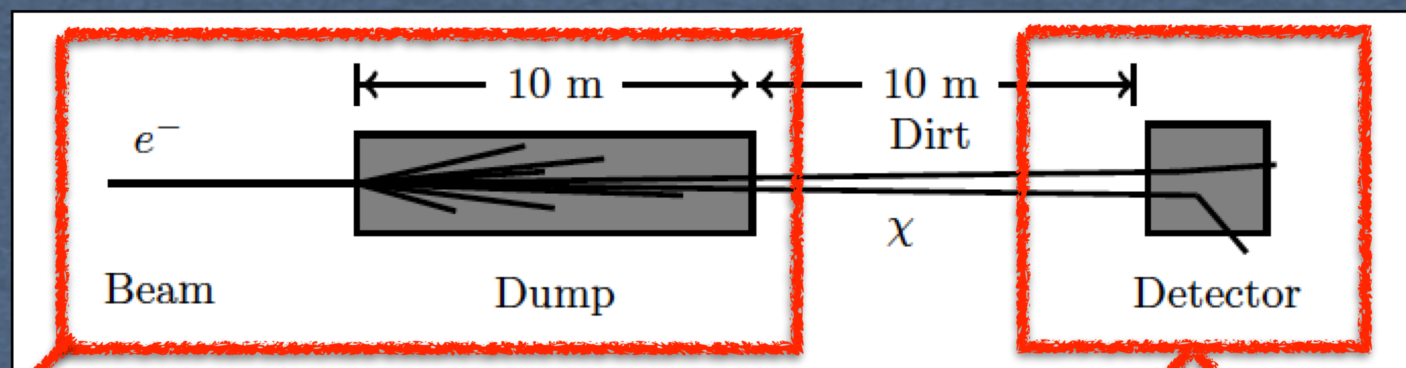




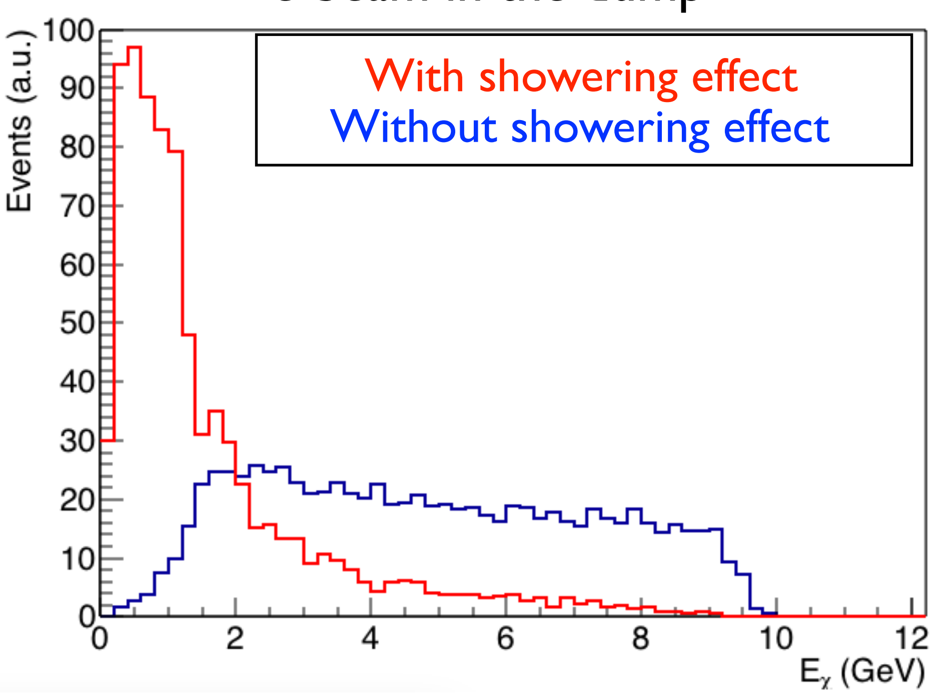
Presented to PAC44

X production and detection

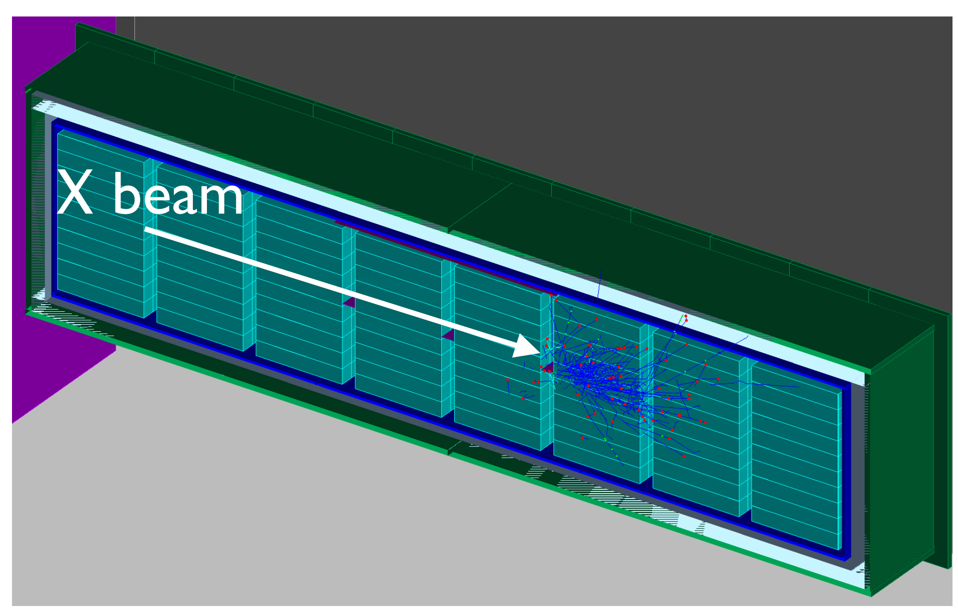
- Detailed simulations using ad-hoc MC code to describe the A' production, decay (A' →χ χ) and interaction in the BDX detector (X-e)
- Detailed description of Hall-A beam dump (production) and BDX detector (detection) using GEANT4



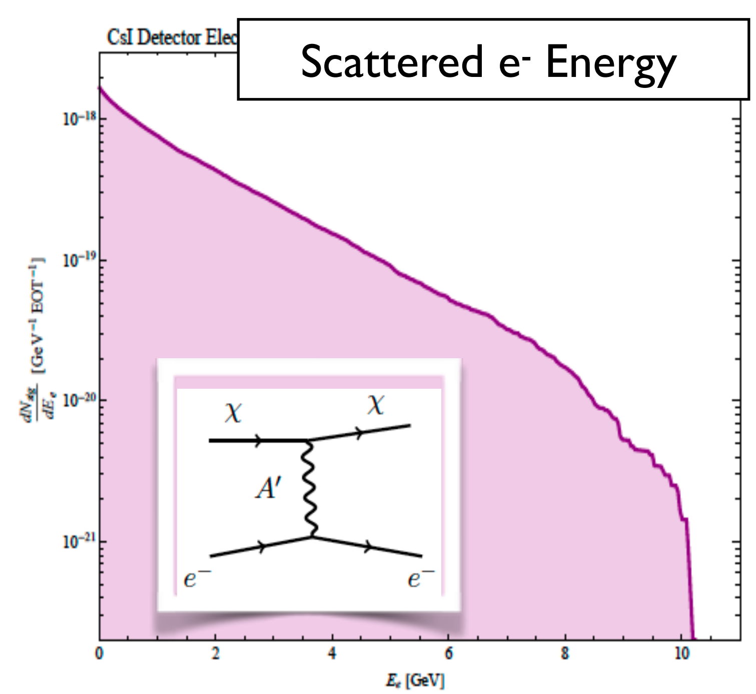
X energy spectrum generated by 11 GeV e-beam in the dump



χ-e interaction producing an em shower in the detector



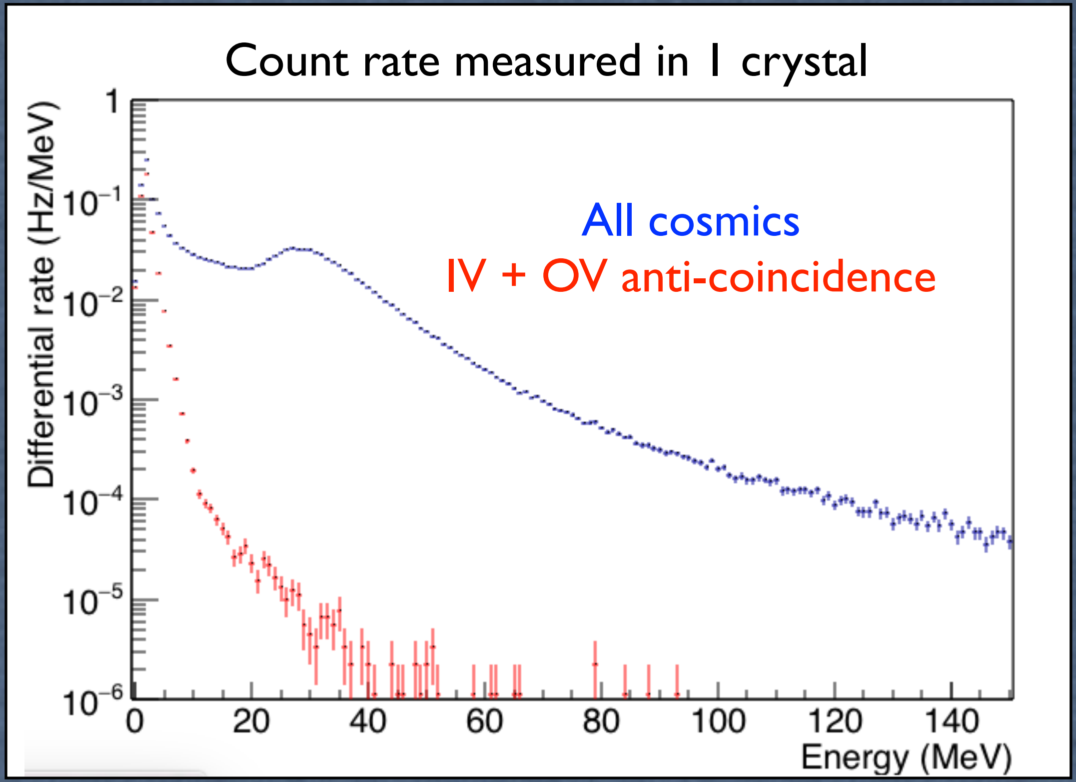
Elastic on electrons



Background

Cosmic

★ Cosmic background measured with the BDX detector prototype in CT



Expected cosmic bg counts in BDX lifetime < 2 counts

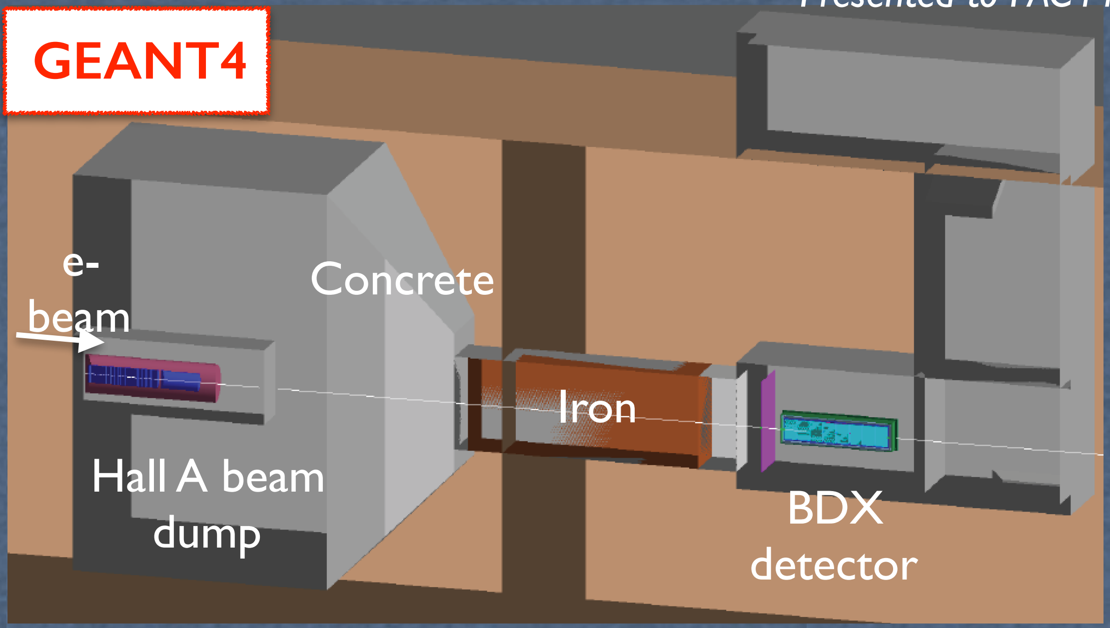
Beam-related

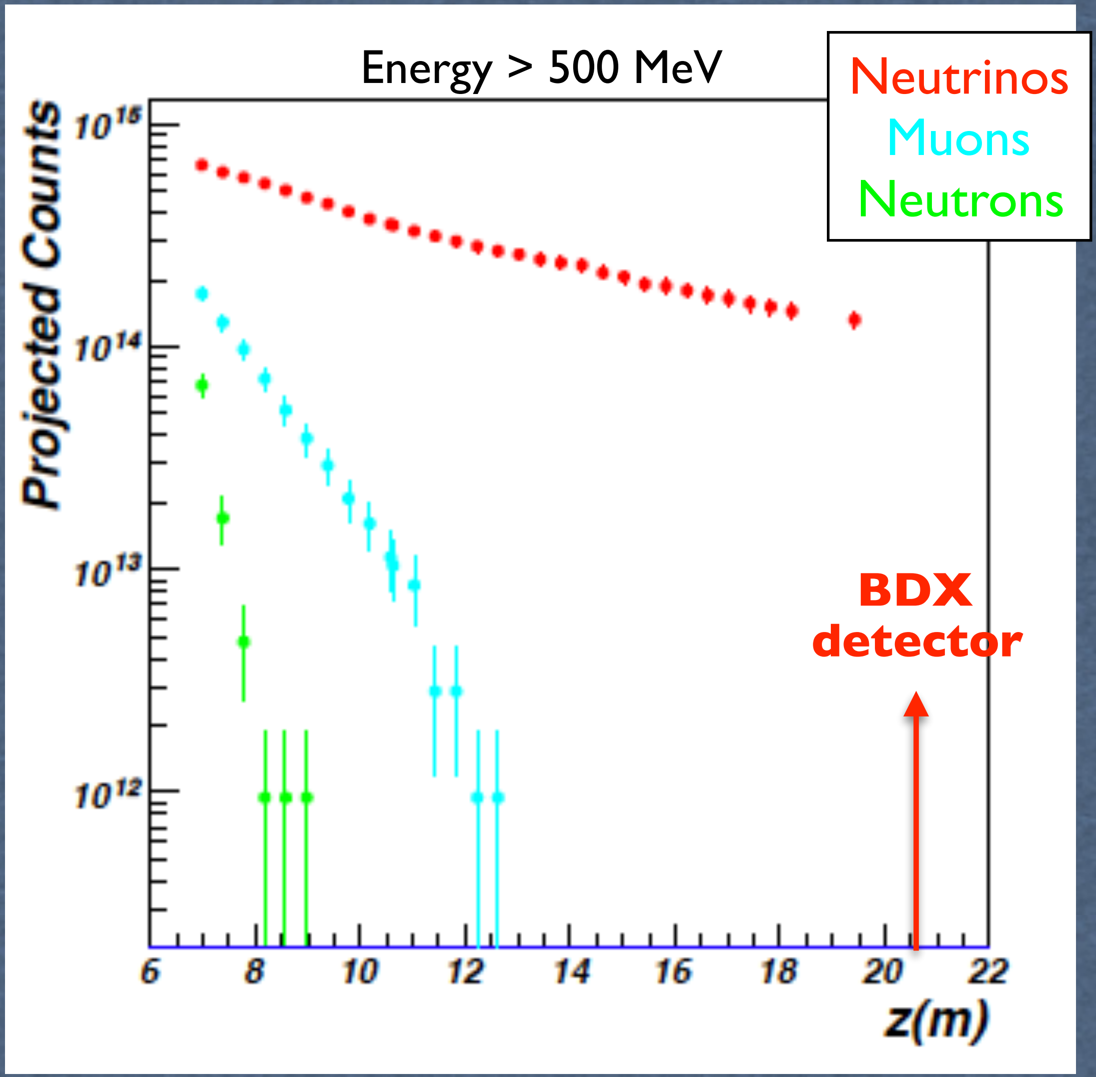
Bg estimated using GEANT4, tracking particles with $E>E_{Thr}$

★ Muons are ranged out by the iron shielding

★ Non-negligible contribution of high energy neutrino interacting in the detector by CC: $\nu + N \rightarrow X + e^-$

Expected beam-related counts in BDX lifetime ~ 10 counts





BDX expected reach

Beam time request

- 10^{22} EOT (65 uA for 285 days)
- BDX can run parasitically to any Hall-A E_{beam}>10 GeV experiments (e.g. Moeller)

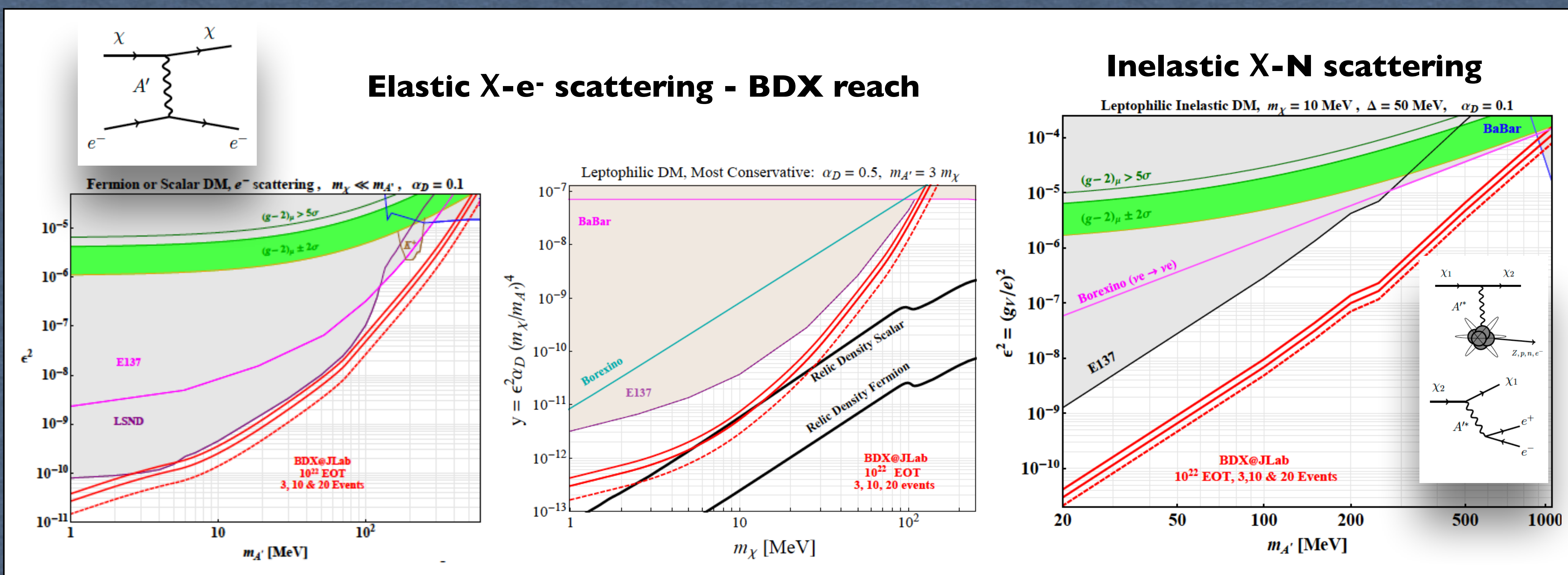
Beam-related background

Energy threshold	N_ν (285 days)
300 MeV	~10 counts

Cosmic background

Energy threshold	$\sqrt{Bg}$ (285 days)
300 MeV	<2 counts

BDX sensitivity is 10-100 times better than existing limits on LDM



Beam-related background

BDX presented in July 2016 to JLab PAC44 receiving a C2 - Conditionally Approval
The main concern expressed on BDX experiment in the PAC44 report

From PAC44 Report introduction:
… and the beam dump experiment was "C2" Conditionally Approved because **we would like to see them carry out some onsite measurements of the neutron flux when the accelerator is running**.

From PAC44 report:
While simulations are an essential tool in understanding background conditions, they are not sufficient to design an experiment. The BDX collaboration is therefore encouraged to think more about **benchmarking their simulations with measurements on site**.

In July 2017 we proposed to PAC45 to address beam-related background concerns

★ by **measuring the muon flux** in the current Hall-A dump configuration (in coordination with the Lab)
- to **validate MC** and demonstrate [CsI(Tl) crystal + SiPM]$_{EMCal}$ & [Plastic scintillator + WLS +SiPM]$_{Veto}$ works in a **high low-energy background** (neutron)

★ by **running high-statistic MC simulations** with GEANT4 and FLUKA (in coll. with JLab RadCon Group)
- to **compare results** obtained in the two frameworks, **increase the sim statistics** and understand irreducible **neutrino background**

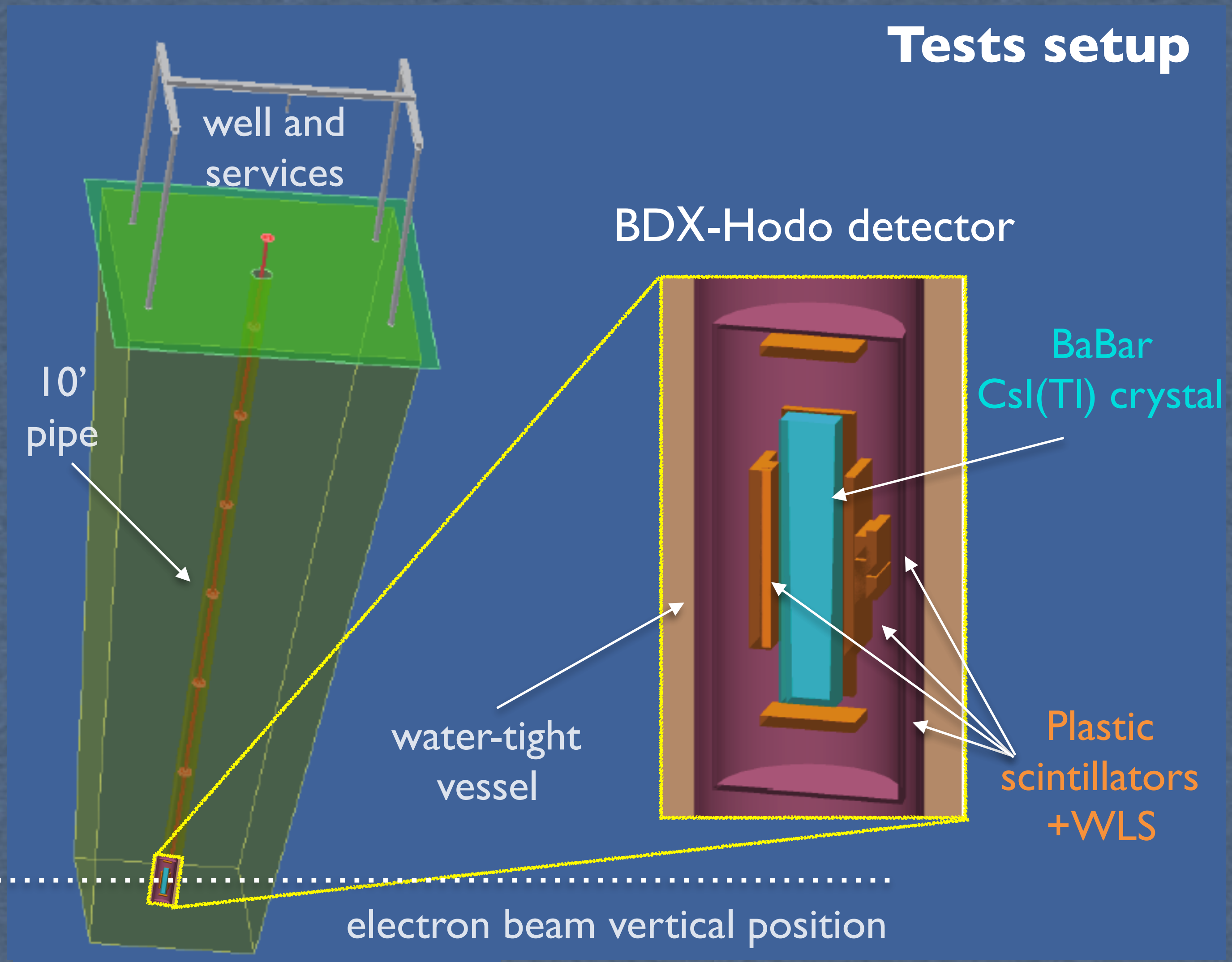
★ by developing a **systematic procedure for optimizing** the configuration of the detector
- to provide a **realistic** and **flexible** evaluation of BDX reach

From Pac 45 report:
Summary: The collaboration should continue working with JLab **to carry out the proposed tests**, **towards achieving full approval at a subsequent PAC.**

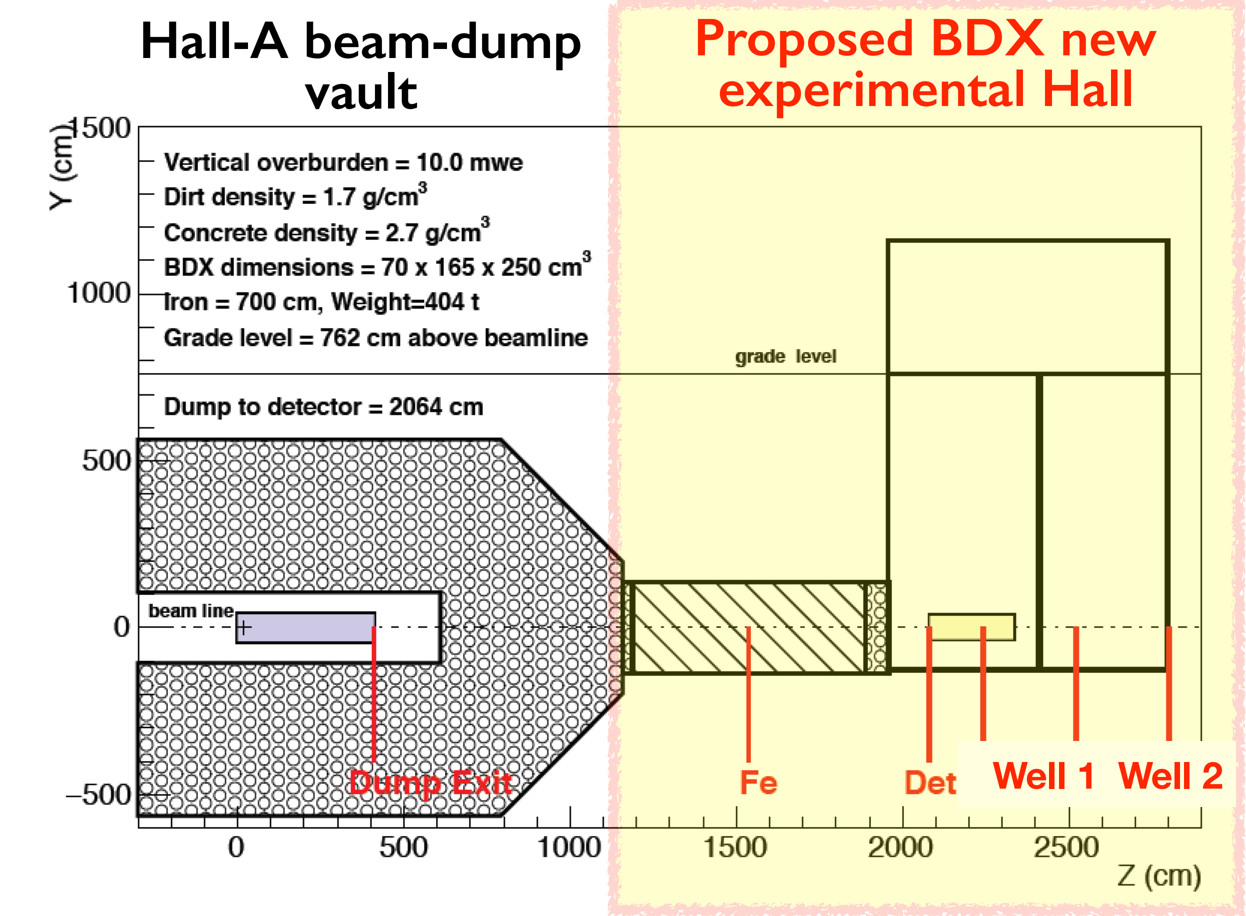
Test proposed to PAC45 to measure the beam-on background

Measurement campaign to characterize the flux of high-energy μ produced in the Hall-A beam dump

- Pipe downstream of Hall-A beam-dump at BDX location
- Insert a CsI(Tl) crystal surrounded by plastic scintillators
- Same detector technology proposed for BDX detector
- Measure μ flux when 11-GeV beam is on



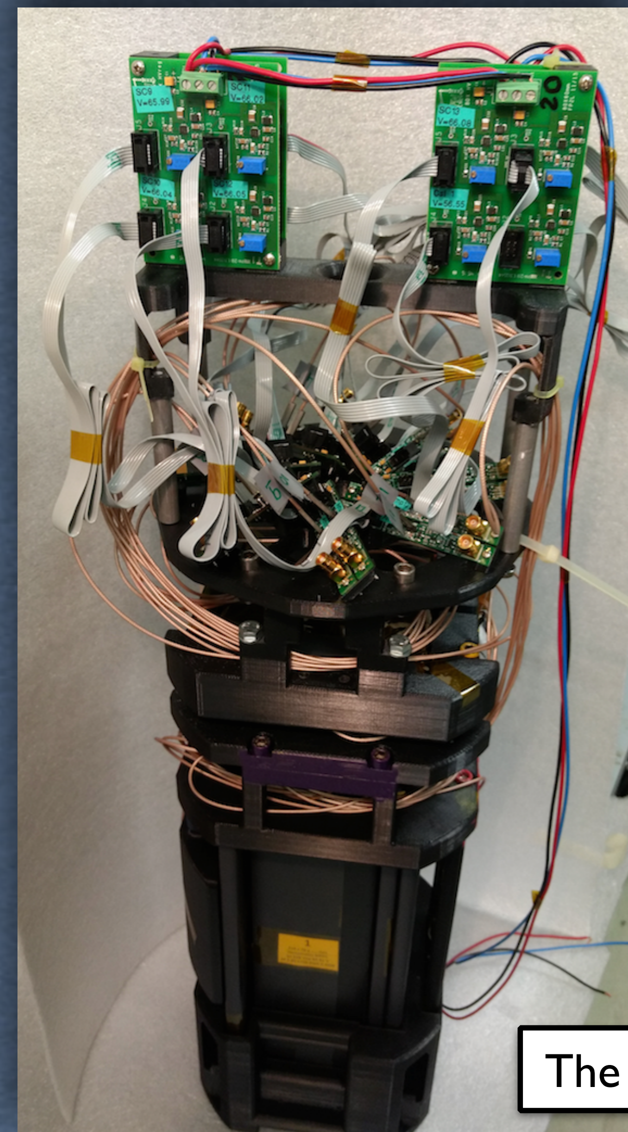
Downstream of the Hall-A beam dump - TODAY -



BDX-Hodo tests at JLab

Two wells


The tent

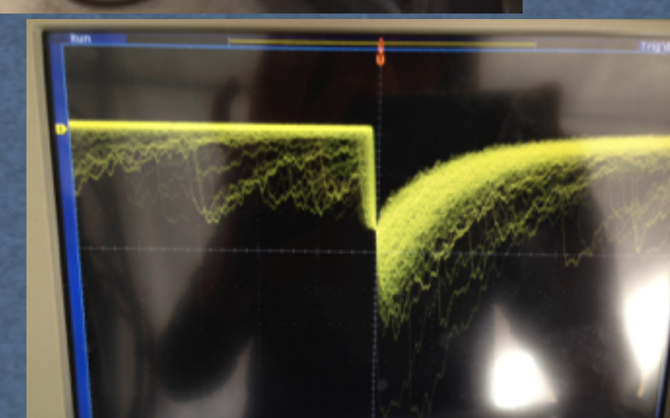

The BDX-Hodo


BDX-Hodo in the tent

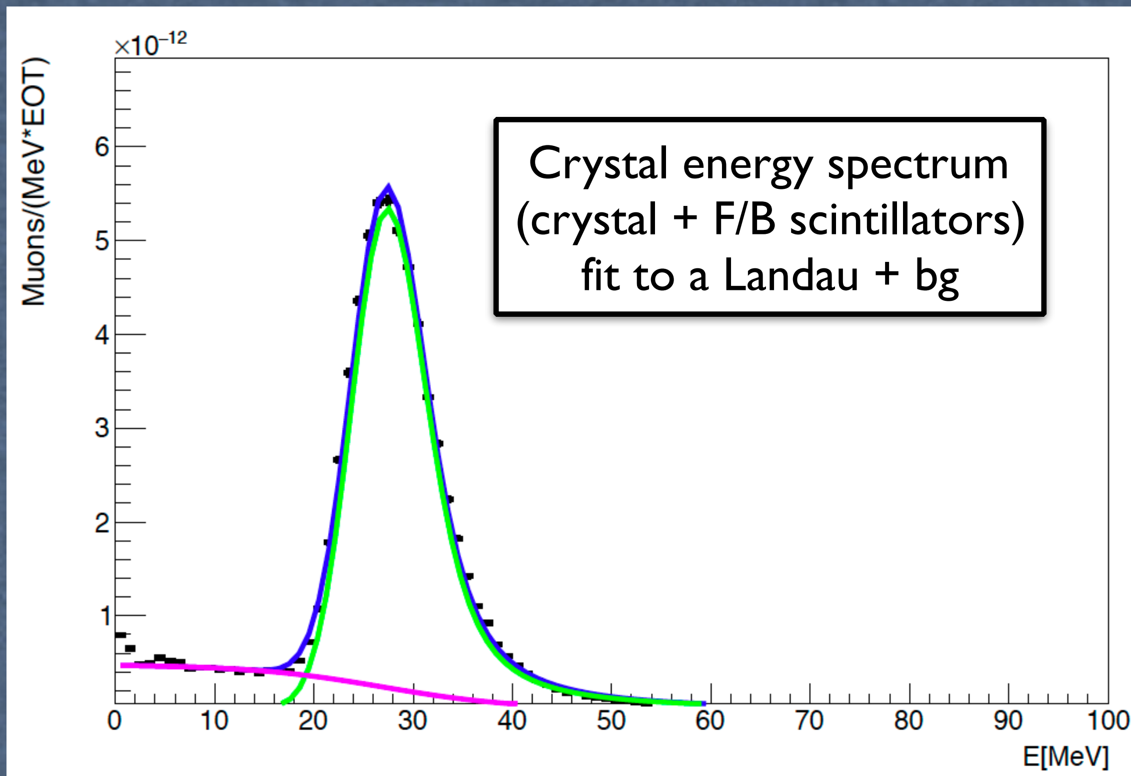

The BDX-Hodo lowered in well 1

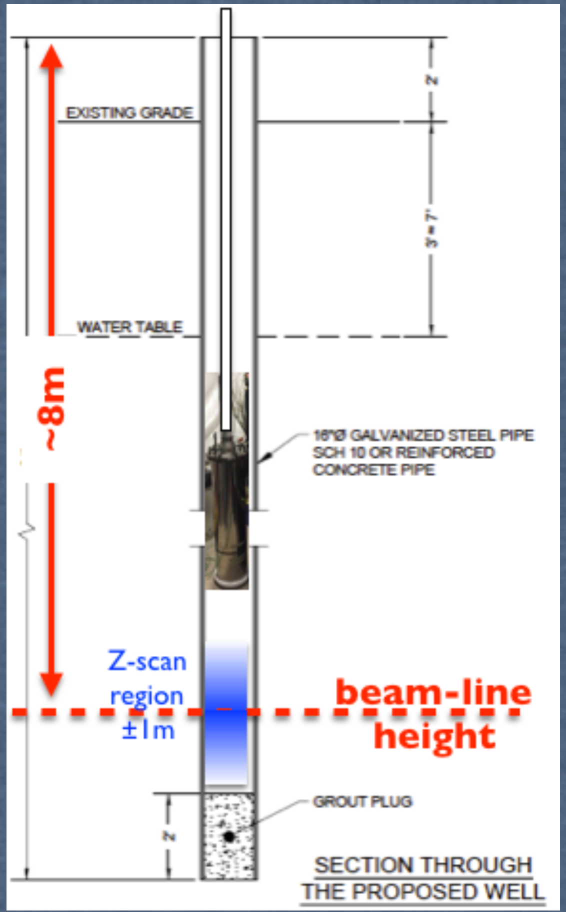
- Run: from Feb 22nd to May 2nd 2018
- Hall-A beam parameters
  - I_{Beam} ~ 22uA
  - E_{Beam} = 10.6 GeV
  - Diffuser: ON

\+ 1 week taken in Well II with E_{beam}=4 .3 GeV


The first muon signal on the scope

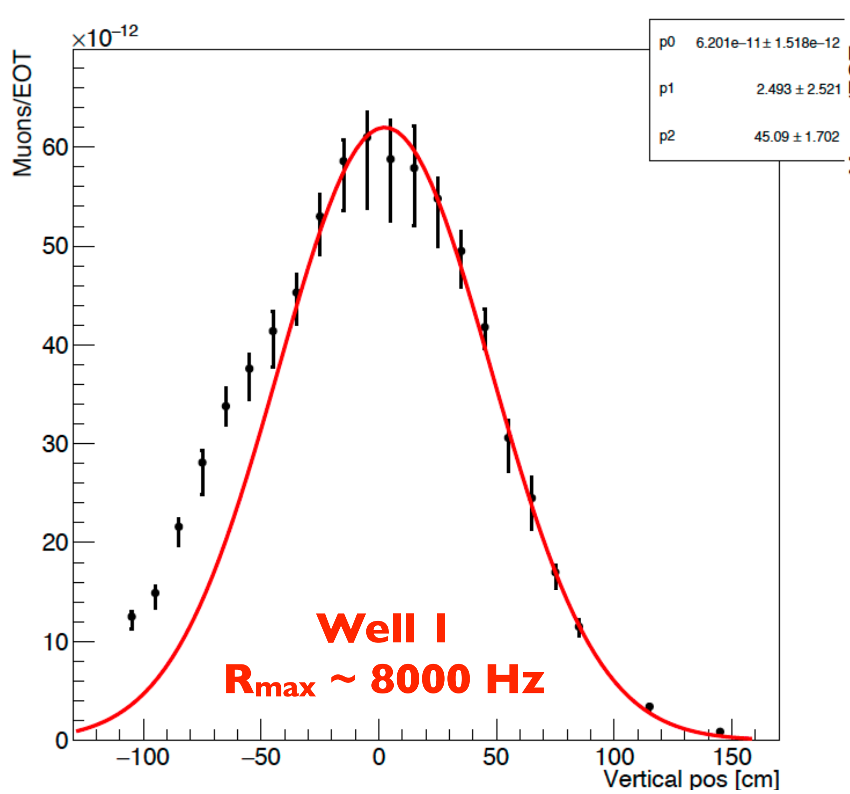
Results

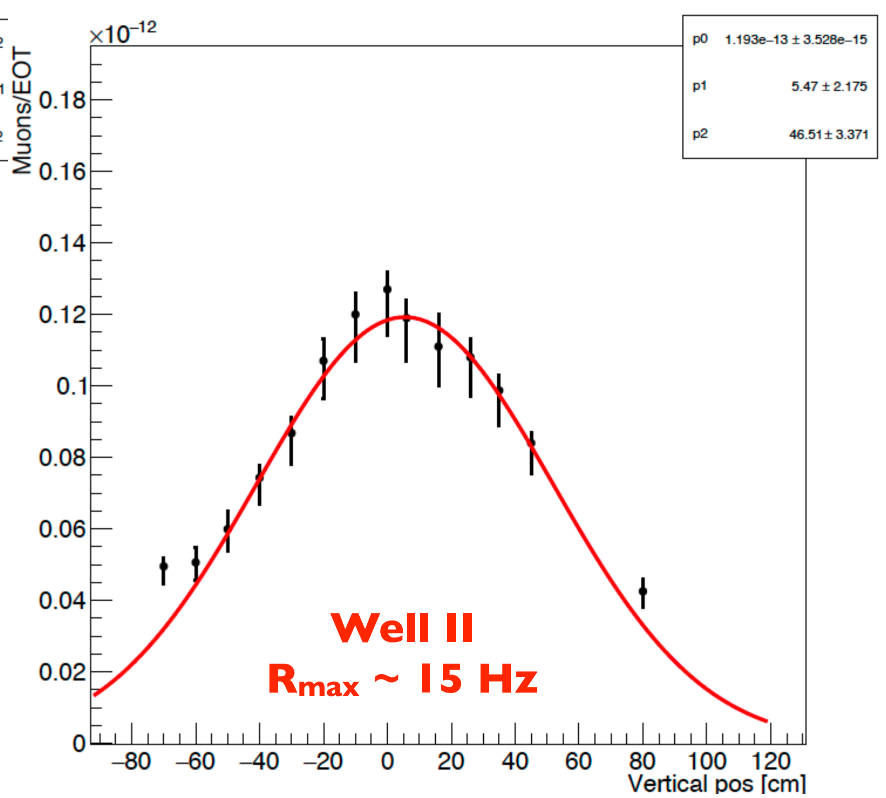


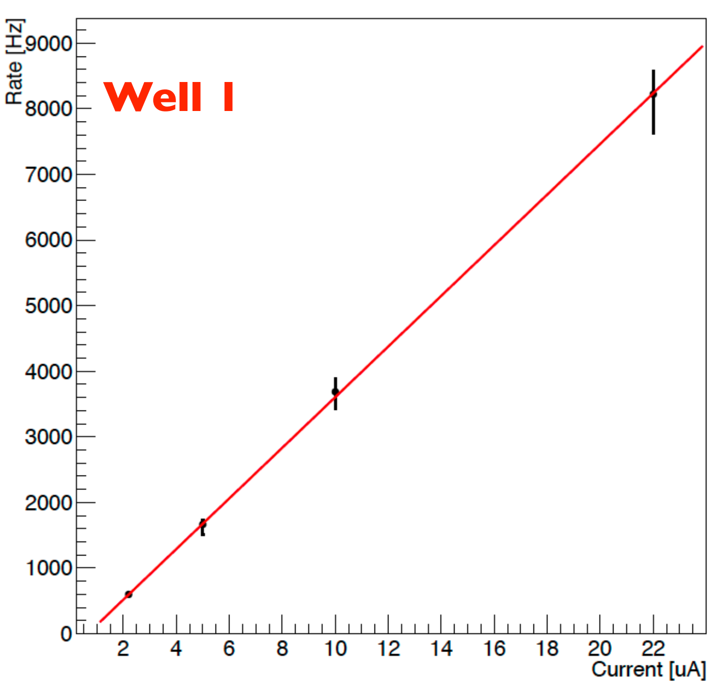


- ★ Measured rate ($h=0$, $I_{beam}=22\mu A$)
  - $R_{Well\ I}$ ~ 8000 Hz
  - $R_{Well\ II}$ ~ 15 Hz
- ★ Ratio of the two rates is ~500(!)
- ★ A gaussian fit to each rate profile results to the same width (σ~45cm)

NOTE: Max rate measured at δh=+10cm (Well I) and δh=+40cm (Well II) due probably to un-uniform dirt/concrete density



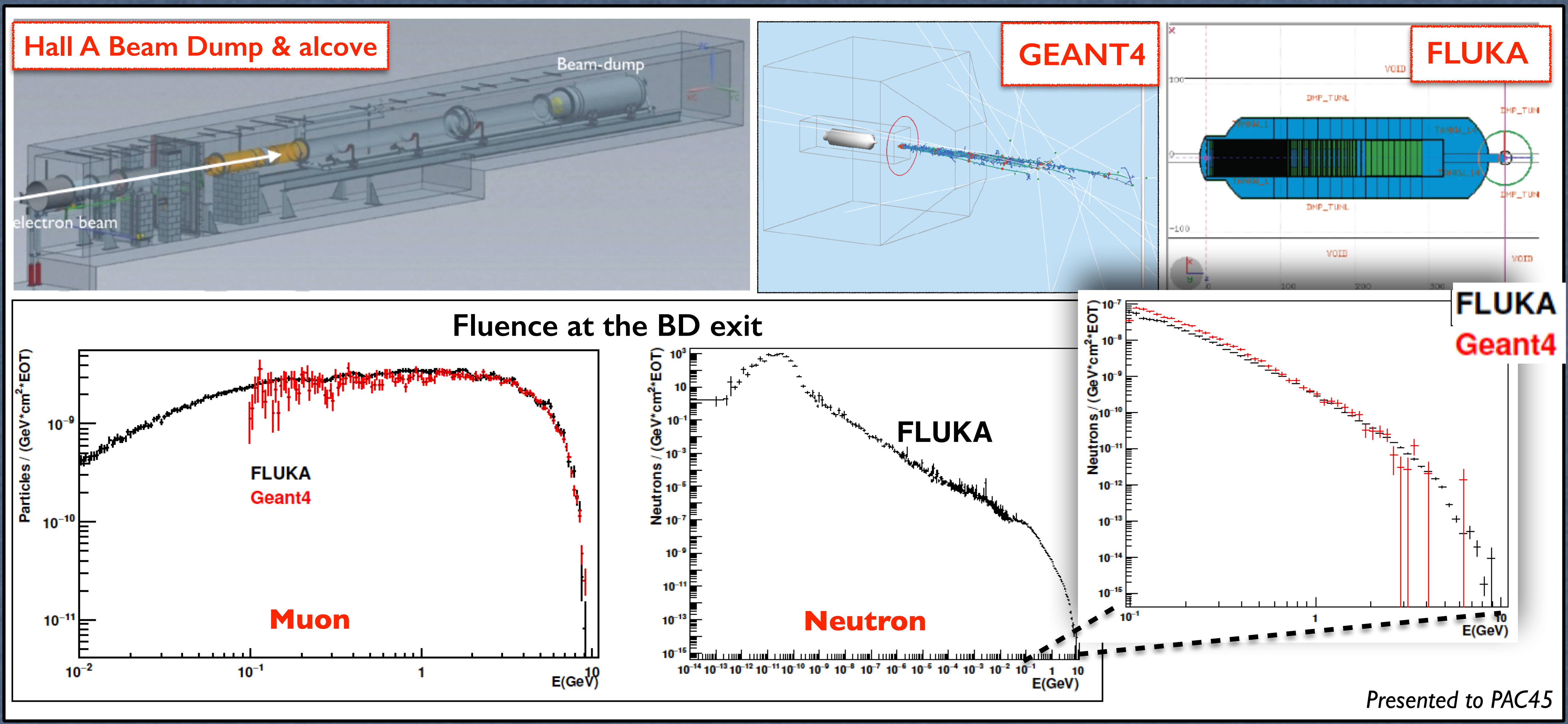




Muon rate scales linearly with I_{beam}

MC Simulations @ beam-dump (BD) location

- Hall-A beam-dump geometry/materials implemented in FLUKA (with JLab RadCon Group)
  - FLUKA biasing: xsecs enhancement, 'leading particle', importance sampling, threshold T>100 MeV
  - GEANT: detailed and realistic descriptions of the detector active volume response



- High-energy muon production in the BD dominated by the $\gamma \rightarrow \mu^+\mu^-$ process
- Good consistency between G4 and FLUKA for μ and high energy neutrons (T_n>100 MeV) in the BD

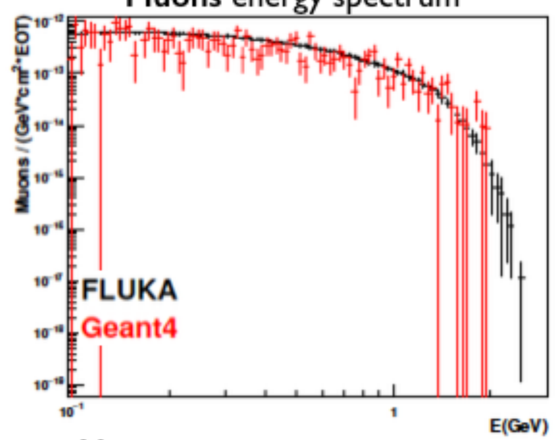
MC Simulations @ well's positions

Energy/flux at Well I position

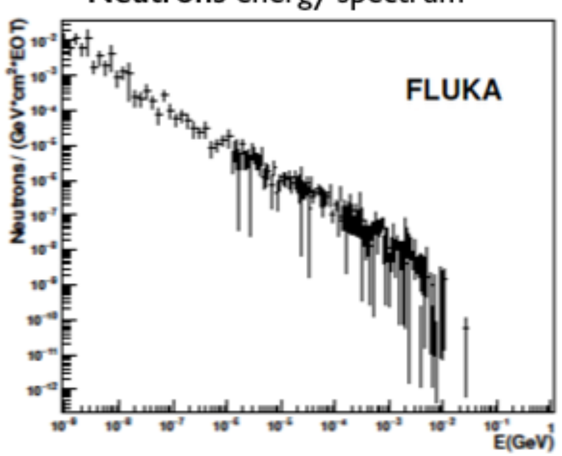
Presented to PAC45

Expected μ and n energy spectra in location B (d = 25.2m, beam height)

Muons energy spectrum

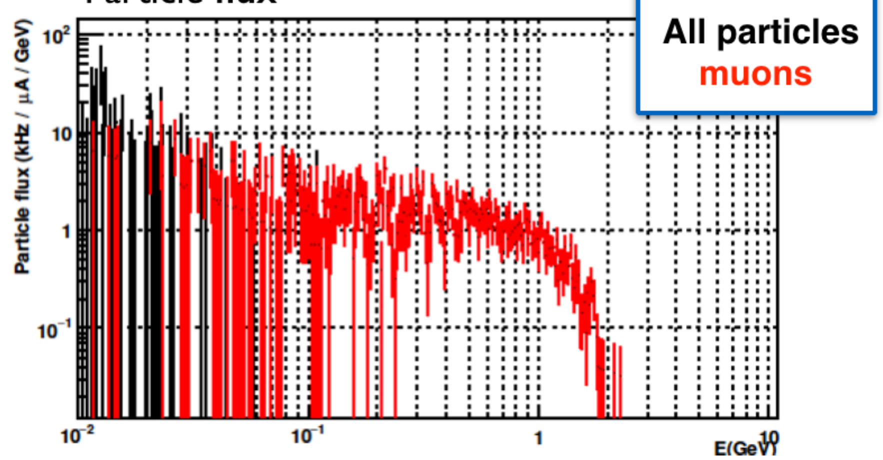


Neutrons energy spectrum

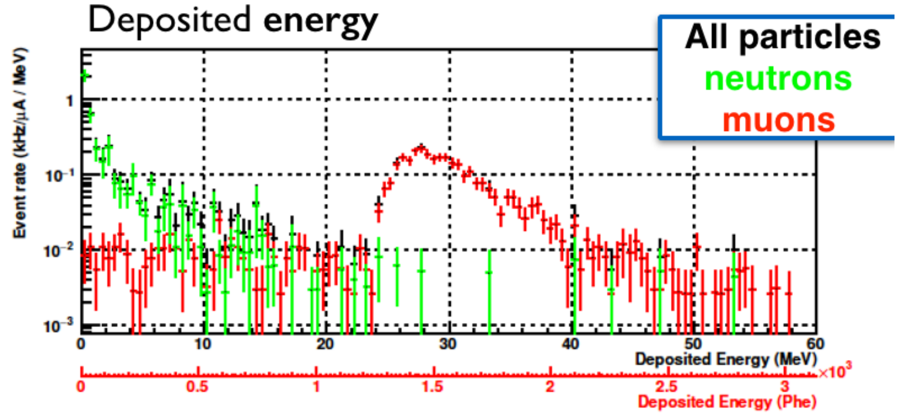


Expected particle flux and energy deposition in the CsI(Tl) crystal (FLUKA) in location B

Particle flux

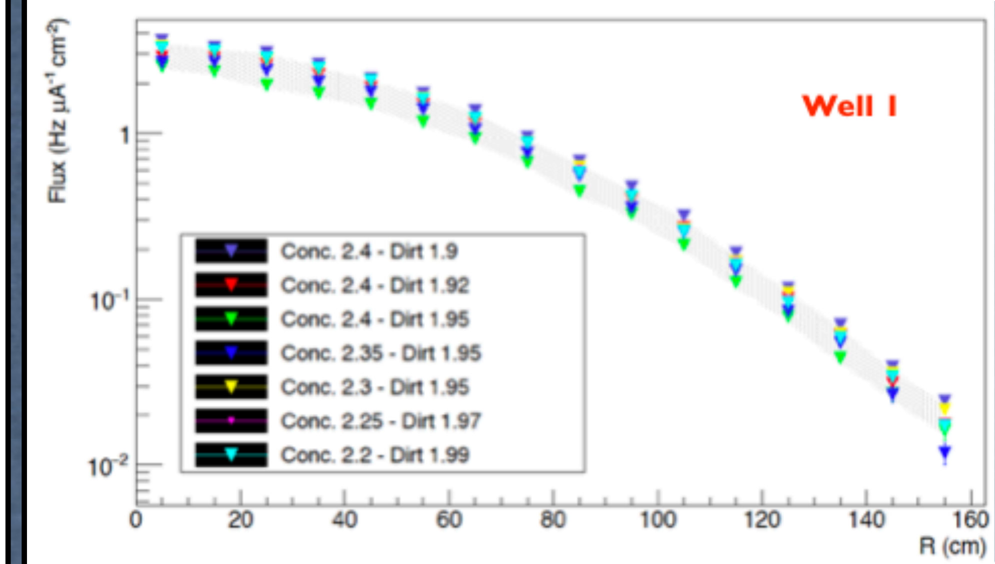


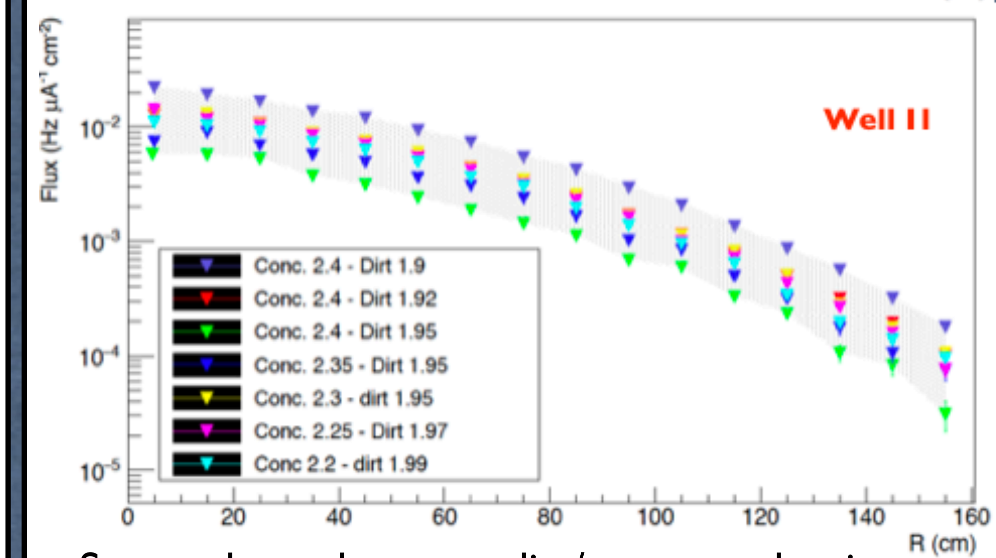
Deposited energy



- Only muons and neutrons reach the area of interest
- Rate from cosmic muons negligible and measurable
- Expected rates: ~10 kHz in Well I and ~500 Hz in Well II

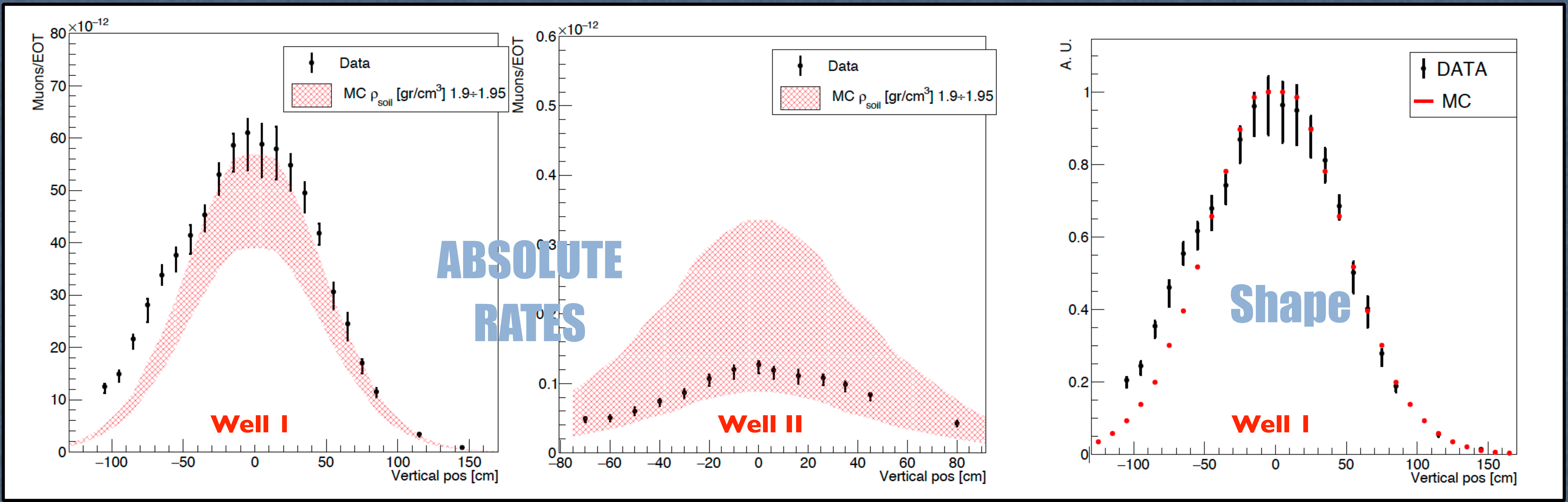
μ rate dependence on ρ_{dirt}





- Strong dependence on dirt/concrete density
- Measured ρ_{dirt} (2 samples): 1.93 g/cm³ 1.95 g/cm³
- For a **5% ρ_{dirt}** variation simulations predicts a rate variation of **30% in Well I** and **x2 in Well II**

Data/Sim comparison



★ **Absolute rates** for data and simulations in agreement within the density-related uncertainty band

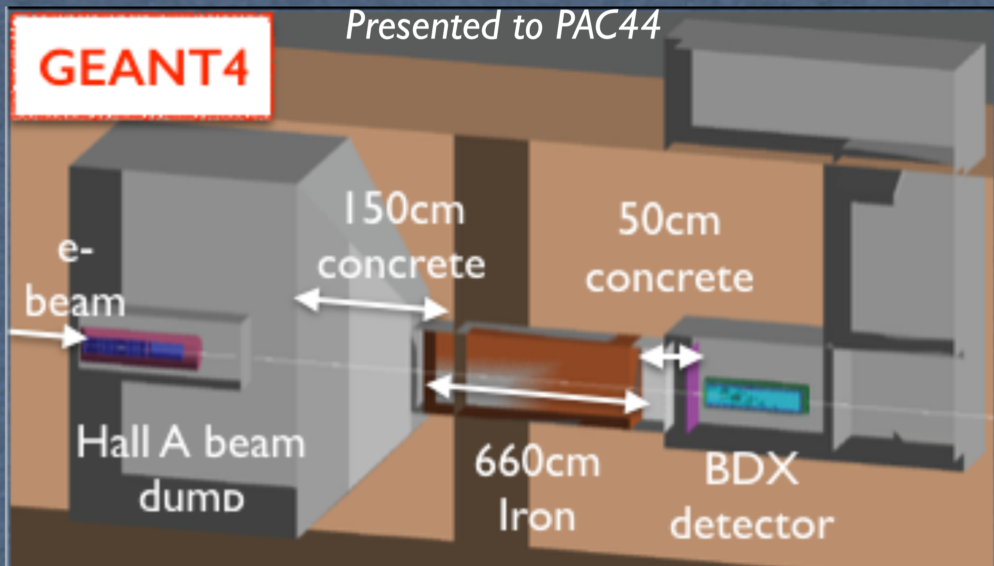
★ The **shape** of rates sampled at different heights is well reproduced by simulations (gaussian with the same σ)

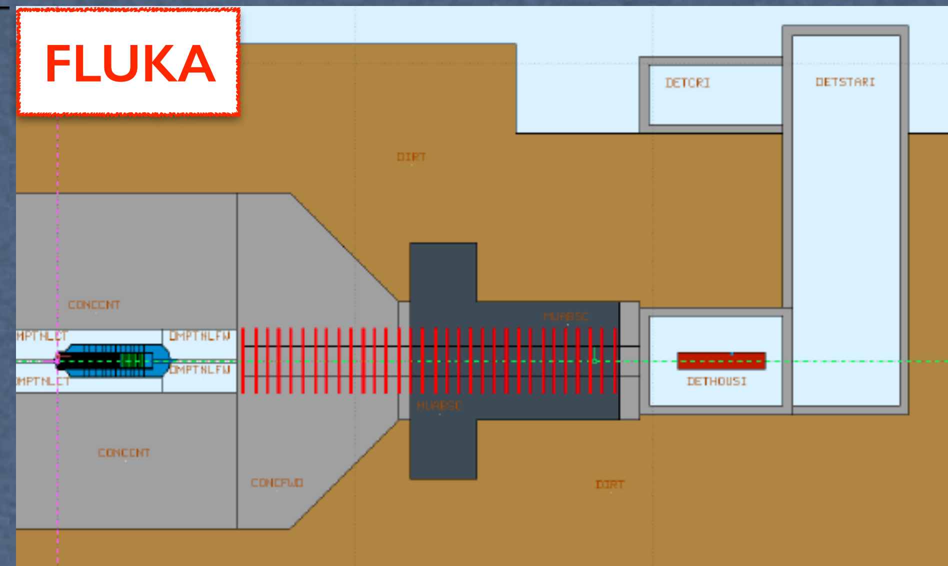
Good agreement between data and simulations prove:

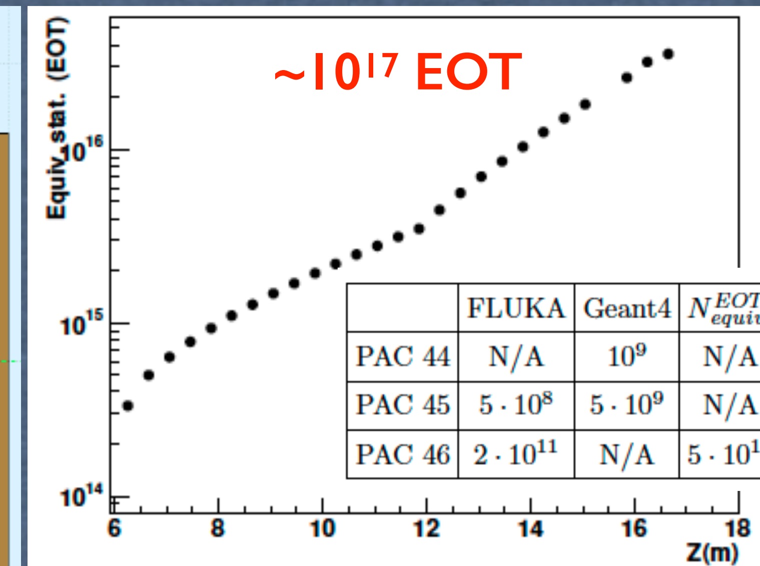
✳ **the BDX simulation framework is reliable**

✳ **no significant contribution from neutron bg (high energy n and/or pile-up effects)**

High statistics MC sim the BDX set-up





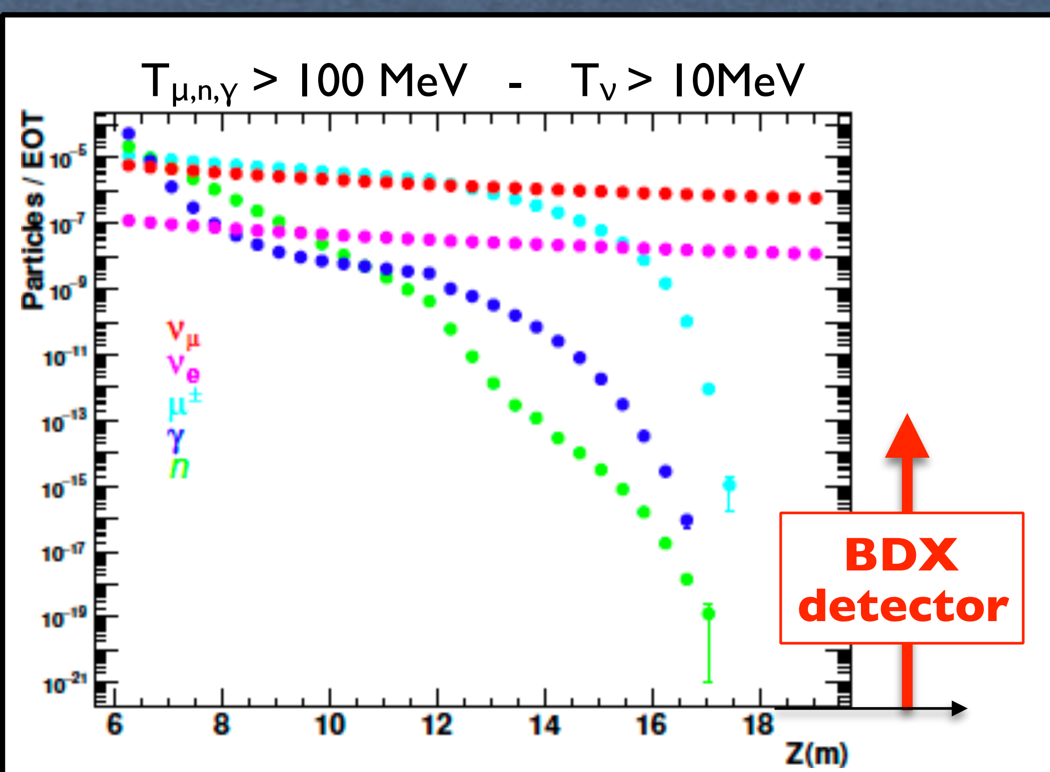


	FLUKA	Geant4	$N^{EOT}_{equiv.}$
PAC 44	N/A	10^9	N/A
PAC 45	$5 \cdot 10^8$	$5 \cdot 10^9$	N/A
PAC 46	$2 \cdot 10^{11}$	N/A	$5 \cdot 10^{17}$

★ Particles produced in the BD by the 11 GeV beam are tracked to BDX detector location

- 6.6m iron shield (+2m concrete) to stop high energy muons
- different shielding configuration tested

★ High statistics simulations: 300 cores x 3 months simulating ~10^{17} EOT equivalent at BDX detector location



★ No n and γ with E>100 MeV are found at the detector location

★ **Muons**

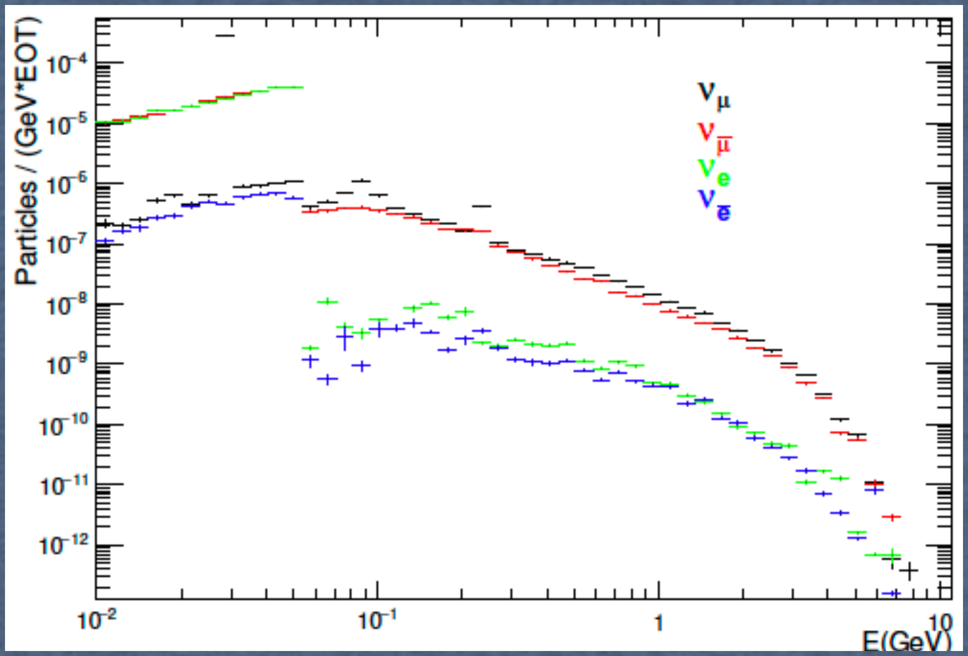
- All forward-going muons are ranged out
- Large angle μs may enter in BDX volume (R~0.02 Hz)
- They are rejected by combination of veto and threshold
- Shielding configuration leading to 0 bg events found
- An optimized shielding will be defined at the time of the new experimental Hall design

MC Simulations: neutrino background

★ **Neutrino**

- $\pi \to \mu\, \nu_\mu$ $\mu \to e\, \nu_\mu\, \nu_e$
- Mainly low energy (<60 MeV) from decay at rest
- Some ν produced in HadShower and boosted to BDX detector

➡ Non-negligible contribution of high energy ν interacting in the BDX detector



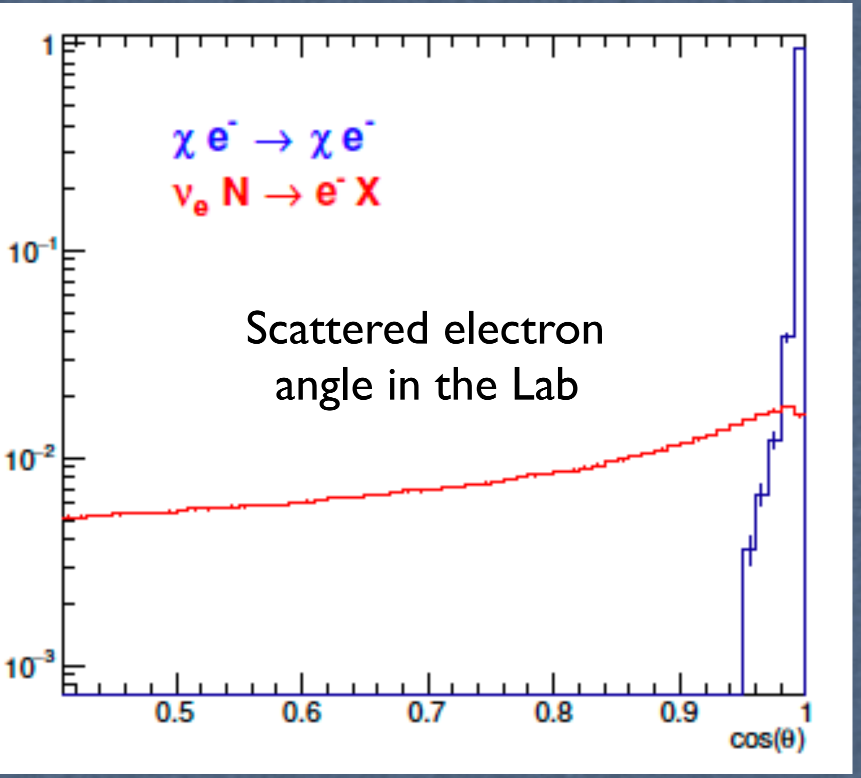
- FLUKA to generate and propagate ν (1.5x ν flux obtained by G4)
- FLUKA NUNDIS/NUNRES to simulate ν interaction with CsI(Tl) BDX crystals
- G4 to simulate the detector response to ν-CsI(Tl) interaction products

NC
$\nu_\mu + N \to \nu_\mu\, X$: all rejected by the det. threshold (limited energy transfer to N)
$\nu_e + N \to \nu_e\, X$: all rejected by the det. threshold (limited energy transfer to N)

CC
$\nu_\mu + N \to X + \mu$: all rejected by identifying the scattered muon
$\nu_{e-} + N \to X + e^-$: the largest contribution to over-tresh. hits in BDX

Different scattered e^- angle for signal and bg:
- $X_{DM} + e^- \to X_{DM} + e^-$:forward peaked for
- $\nu_{e-} + N \to X + e^-$:spread over all angles

➡ neutrino BG can be identified and suppressed!



New High-stats FLUKA simulations confirm results presented in BDX proposal to PAC44

- ✳ BDX only limited by the ν *irreducible* bg
- ✳ Expected beam-related bg counts ~5 events

Detector/detection optimization and BDX reach

A realistic reach evaluation requires:

- a sound statistical framework for upper-limit evaluation in ε (coupling) vs. M_X parameter space
- a simultaneous analysis of signal (N_{SG}) and background (N_{BG}) counts when varying the detector set-up (efficiency) and detection cuts

90%CL sensitivity
$N_{SG}(\varepsilon, M_X) = 2.3 + 1.5 \sqrt{N_{BG}}$
N_{SG} = Signal counts
N_{BG} = BG counts

✳ **Signal**

- Custom MC code + GEANT4 for detector response

✳ **Background**

- Cosmic BG counts: measured (and extrapolated)
- Neutrino BG counts: from FLUKA simulations

Optimization

★ **Detector set-up**

- Active volume = 800x 5x5x30 cm3 CsI(Tl) crystals
- Three different configurations: nominal (presented to PAC44), lead arrangement, segmentation

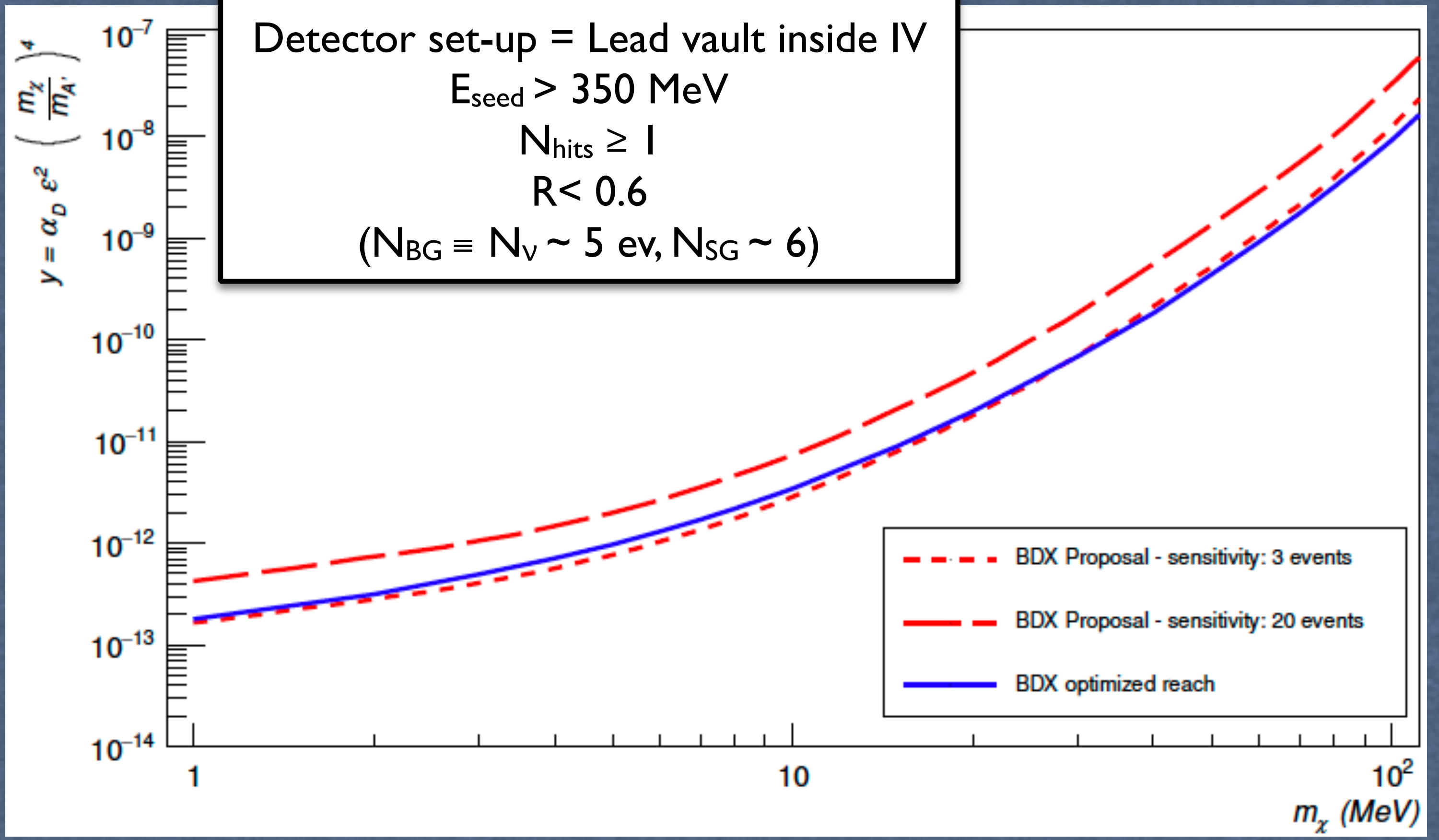
★ **Detection cuts**

- E_{seed}, E_{module}, N_{hits} , R (shower transverse dimension)

Detector and detection optimization based on a solid statistical analysis confirm the BDX reach presented in BDX proposal to PAC44

Optimized configuration

Detector set-up = Lead vault inside IV
$E_{seed} > 350$ MeV
$N_{hits} \geq 1$
R< 0.6
($N_{BG} \equiv N_\nu \sim 5$ ev, $N_{SG} \sim 6$)



See: BDX 2018 update - Appendix A

Summary

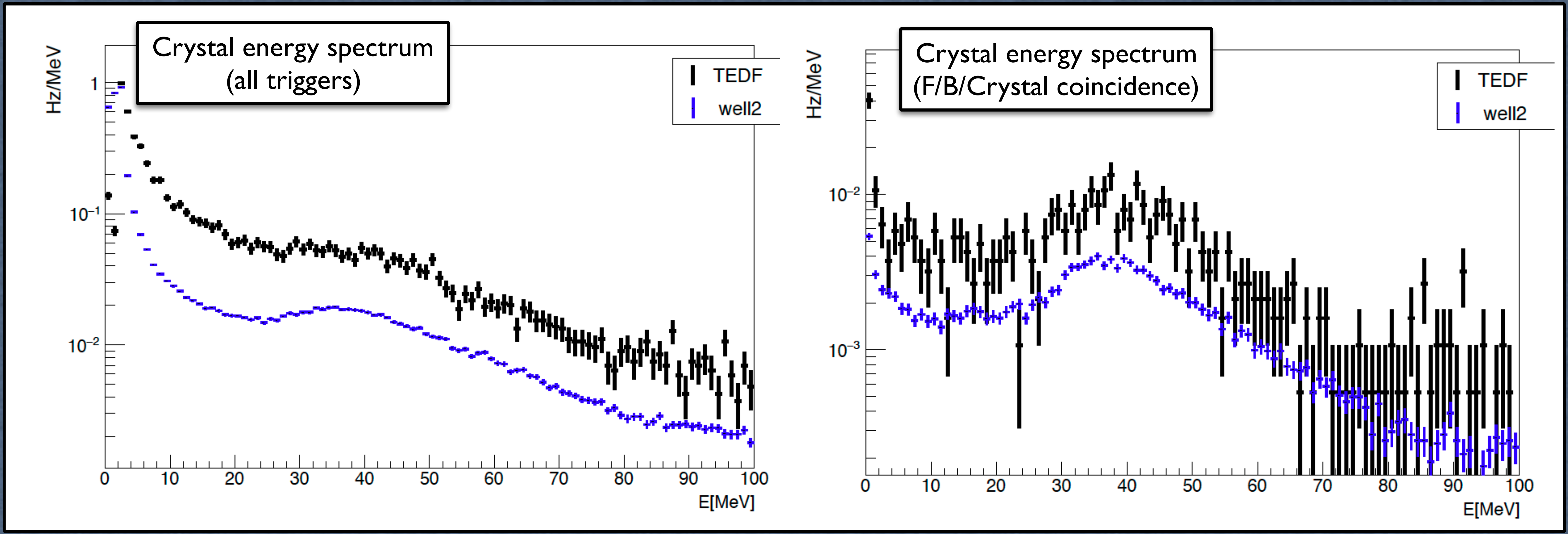
- ✳ The BDX physics case to asses the existence of Light Dark Matter remains valid and up-to-date
- ✳ Collecting 10^{22} EOT in 285 days of parasitic running (~4y-calendar) at 11 GeV the BDX experiment would be 10-100 times more sensitive than previous experiments
- ✳ We implemented two strategies for a more reliable beam-related background estimate:
  - high statistics simulations: *biasing* method in FLUKA, simulating ~10^{17} EOT (equivalent)
  - measurement on site when the accelerator is running
- ✳ Endorsed by PAC45 and supported by JLab we run the test in spring 2018 in the actual JLab configuration to assess the beam-on background (muon and neutron)
- ✳ Good agreement between data and simulations validated BDX MC framework and proved the BDX detector technology in a realistic condition (neutron bg)
- ✳ Using the BDX simulation framework we estimated neutrino (irreducible) background and optimised the detector-set-up/detection-cuts confirming what presented to PAC44
- ✳ The BDX Collaboration will be responsible to fund and build the detector/DAQ and will work with the lab to design the new facility
- ✳ With this update we believed we addressed the concern expressed by PAC44/PAC45 aiming to obtain the full approval of PR12-16-001 (now *Conditionally Approved - C2*)

Back up slides

Cosmic rays

★ BDX-Hodo has been calibrated measuring cosmic muons rates in Genova and at JLab (TEDF)
★ Rate in well 2:
- ~1 Hz (crystal trigger)
- ~0.1 Hz (F/B/Crystal)

★ Rates and reduction factor between TEDF and well, compatible with what obtained by GEANT4 simulations
★ No significant effect of cosmic muons on rates measured with beam-on (both wells)



Over-threshold background assessment

★ A significant fraction of BDX-Hodo data have been taken at E_{beam}=4.3 GeV (I_{beam} ~20μA)

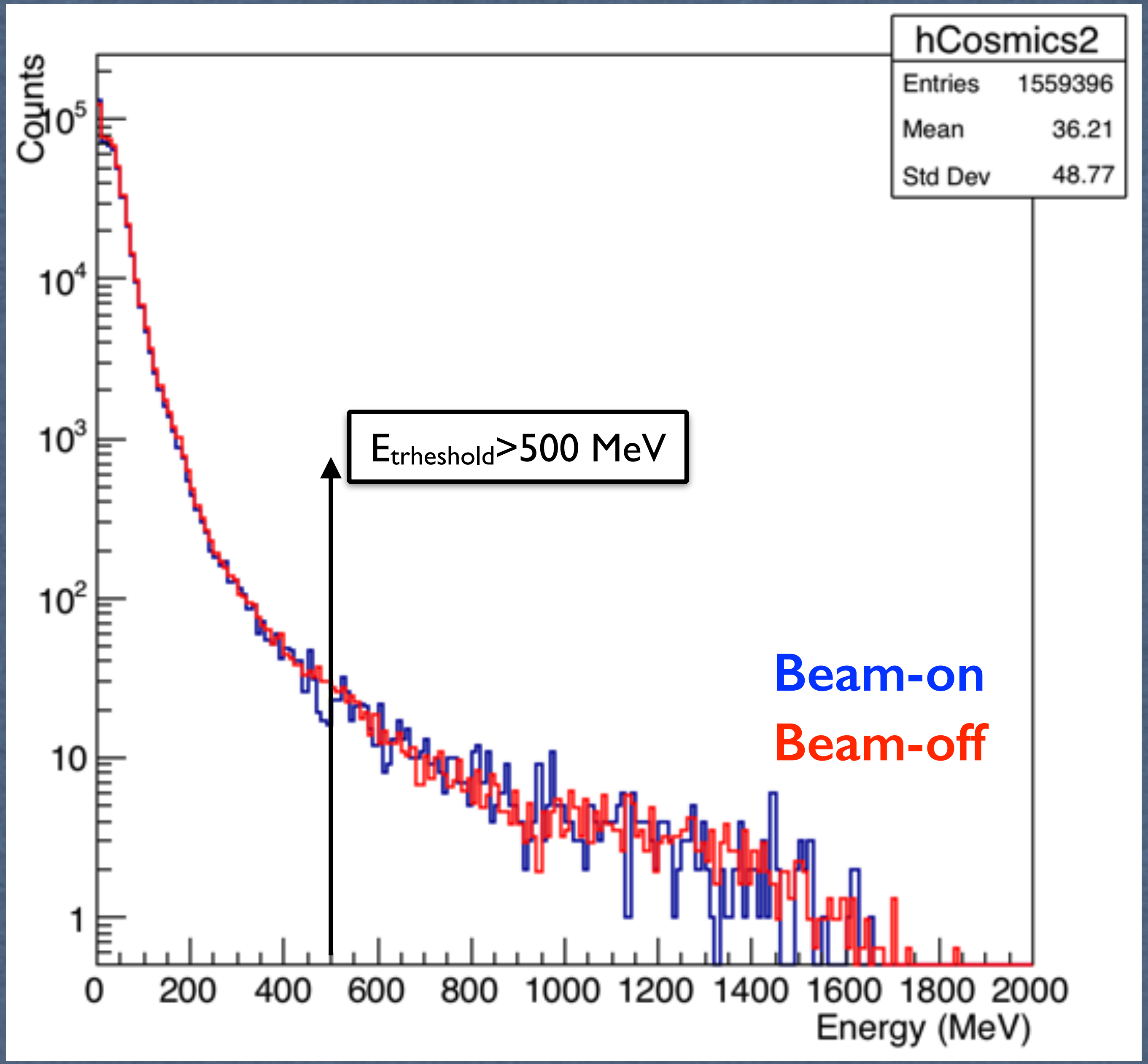
★ Good statistics with beam-off in the same experimental conditions

★ Statistics:

- beam-on = 6.5 days (7.7 10^{19} EOT)
- beam-off = 20 days

★ $E_{crystal}$>$E_{threshold}$ = E_{seed} = 500 MeV

★ No plastic scintillators (veto equivalent) used in the analysis (conservative)



✳For E>$E_{threshold}$ beam-on energy spectrum is compatible with beam-off (cosmic only)

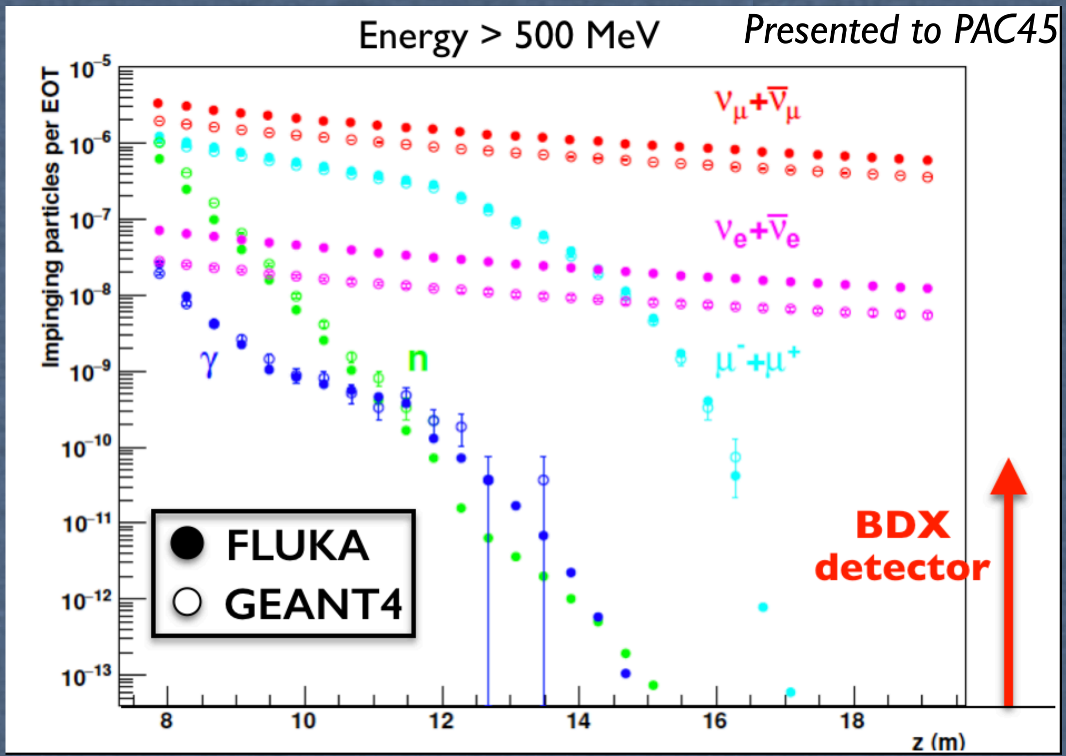
✳Tested on a significant fraction (~1%) of BDX EOT (difficult to simulate)

4.3 GeV data confirm simulations:
no beam-related bg observed when:
- SM particles are properly shielded
- the threshold energy is high enough

Neutrino background: production

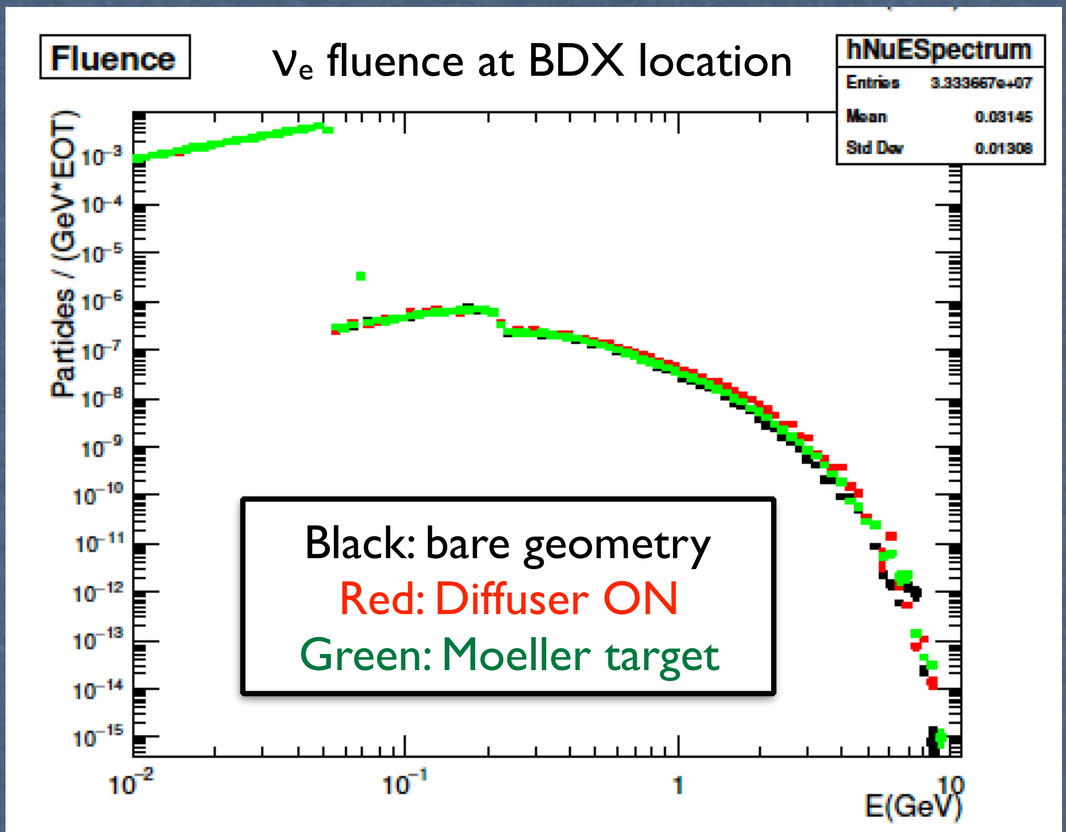
★ Neutrino production studied using FLUKA and GEANT4

★ Good agreement on high energy neutrino fluence at BDX detector location (within a factor of 2)



★ Different beam-line configurations tested:

- BeamDump 'bare' geometry
- Diffuser ON (50% r.l.)
- Moeller target (17% r.l.)



★ Fluence at the BDX detector location change at most by a factor of 2 (Diffuser ON) resulting in a 20% reduction of the BDX reach

See: BDX 2018 update - Appendix C

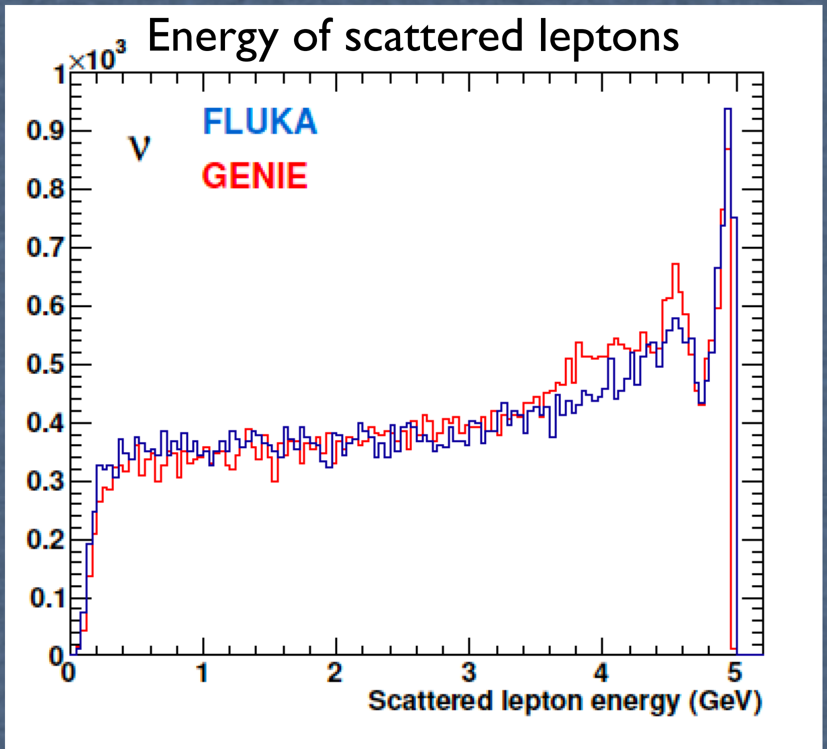
Neutrino background: interaction in BDX detector

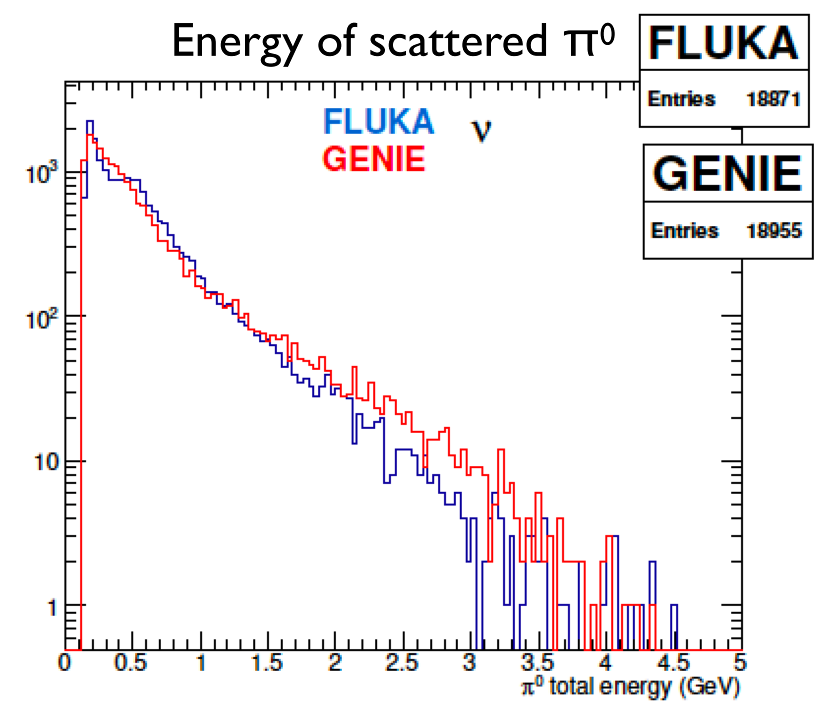
★ Neutrino interaction in BDX active volume simulated using NUNDIS and NUNRES routines (successfully used in ICARUS experiment)

★ Simulations validated by comparing FLUKA with GENIE codes for:

$\nu + {}^{137}Cs \rightarrow$ lepton + X

Observable	FLUKA	GENIE	Data
$\sigma(\nu)$	$5.3 \cdot 10^{-38} cm^2$	$5.2 \cdot 10^{-38} cm^2$	
$CC^{frac}(\nu)$	77%	75%	
$\sigma^{CC}(\nu)$	$4.1 \cdot 10^{-38} cm^2$	$3.9 \cdot 10^{-38} cm^2$	$4 \cdot 10^{-38} cm^2$
$\sigma(\overline{\nu})$	$2.2 \cdot 10^{-38} cm^2$	$2.1 \cdot 10^{-38} cm^2$	
$CC^{frac}(\overline{\nu})$	70%	70%	
$\sigma^{CC}(\overline{\nu})$	$1.6 \cdot 10^{-38} cm^2$	$1.5 \cdot 10^{-38} cm^2$	$1.6 \cdot 10^{-38} cm^2$

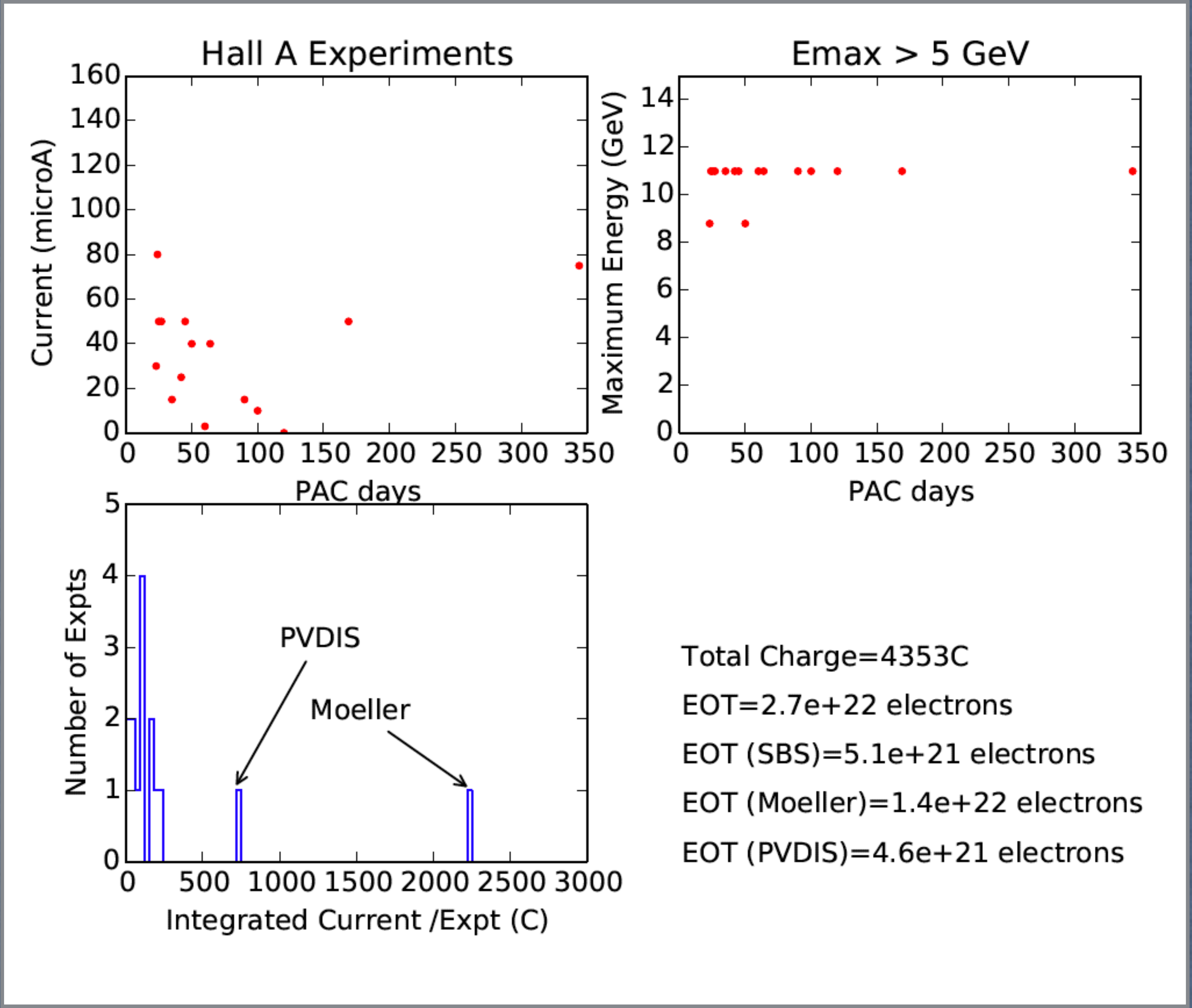




★ Good agreement between FLUKA and GENIE

See: BDX 2018 update - Appendix B

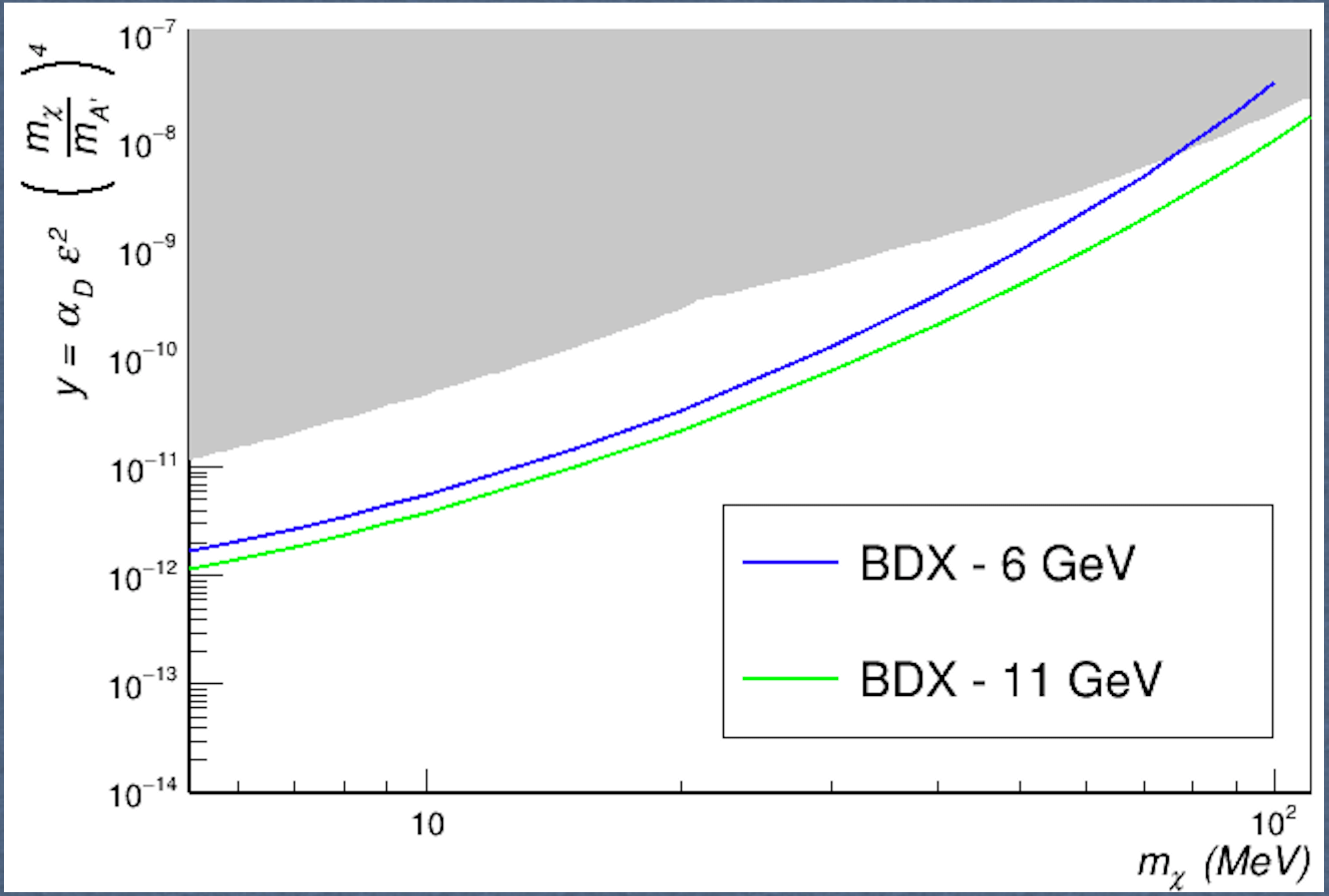
Hall A approved experiments



Total Charge = 4353 C
EOT = 2.7 10^{22} electrons

BDX beam-time request almost saturated by SBS, *Moeller* and *PVDIS (11GeV)* exps

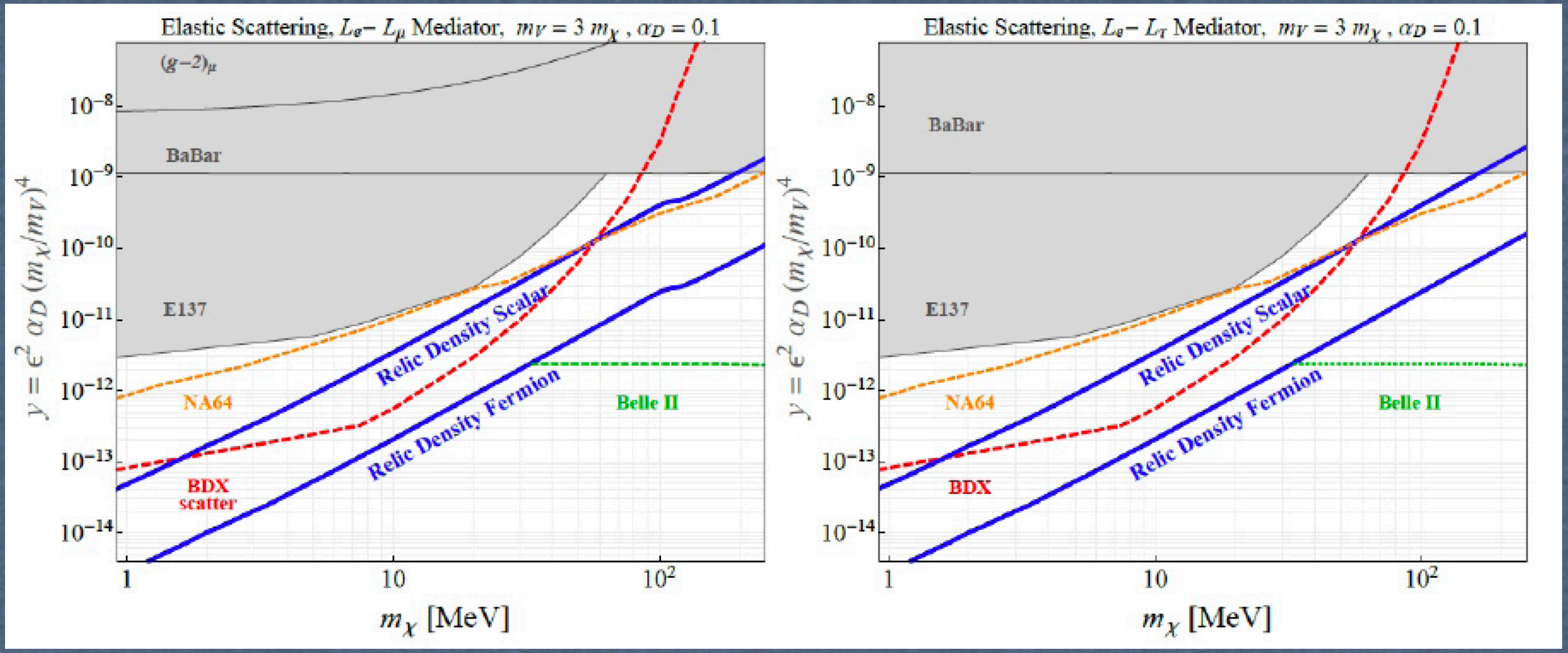
BDX reach at E_{beam} = 4 GeV



★ The reach at E_{beam}=4GeV has been derived in the same assumptions (time, NBG, NSG, thresholds, selesction cuts …) used at E_{beam}=10.6GeV

Theory update from PAC45

- **New models**
  - A more general formulation of SM/DM particle coupling to a 5th force with gauges a combination of SM quantum numbers (L=lepton number, B= baron number)



  - *Leptophillic* mediators particularly interesting: (L_e - L_μ) and (L_e - L_τ)
  - BDX experiment will cover a significant faction of the parameter space

- **BDX complementarity**
  - Proposed Direct Detection experiments will cover a similar parameter space but are insensitive to iDM
  - Accelerator-based searches are largely independent on the DM abundance and spin/velocity structure of the interaction relying solely on electron/baryon DM interaction
  - BDX search for DM scattering on atomic electrons, complementary to similar proton beam exps
  - BDX search for an observable particle scattering (vs. other missing momentum/energy exps)

Progress in LDM searches from PAC44

- ★ Growing word-wide (CERN, Mainz, LNF) and US (JLab, Fermilab SLAC, Cornell) interest for LDM searches
- ★ DOE-organized workshop in March 2017 at University of Maryland to identify new small projects for DM searches to complement the already approved program

U.S. Cosmic Visions: New Ideas in Dark Matter

23-25 March 2017 *Stamp Student Union, University of Maryland, College Park*
US/Eastern timezone

"To respond to the 2014 P5 report recommendations in the search for dark matter particles and maintaining a diversity of project scales in our program, **DOE Office of High Energy Physics (HEP) is interested in identifying new, small projects for dark matter searches in areas of parameter space (i.e. mass ranges or types of particles) not currently being (or on track to be) explored.** HEP is asking for community input in the spring 2017 timeframe in order to plan the program forward. Input is requested on the possibilities for small (the whole project is ~ $10 million or less) dark matter projects in unexplored parameter space. A community workshop, followed by a White Paper would be a good path to provide the input needed. We encourage you to collect information from the community, including theorists and experimentalists involved in non-accelerator and accelerator-based efforts."

US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

Marco Battaglieri (SAC co-chair),[1] Alberto Belloni (Coordinator),[2] Aaron Chou (WG2 Convener),[3] Priscilla Cushman (Coordinator),[4] Bertrand Echenard (WG3 Convener),[5] Rouven Essig (WG1 Convener),[6] Juan Estrada (WG1 Convener),[3] Jonathan L. Feng (WG4 Convener),[7] Brenna Flaugher (Coordinator),[3] Patrick J. Fox (WG4 Convener),[3] Peter Graham (WG2 Convener),[8] Carter Hall (Coordinator),[2] Roni Harnik (SAC member),[3] JoAnne Hewett (Coordinator),[9,8] Joseph Incandela (Coordinator),[10] Eder Izaguirre (WG3 Convener),[11] Daniel McKinsey (WG1 Convener),[12] Matthew Pyle (SAC member),[12] Natalie Roe (Coordinator),[13] Gray Rybka (SAC member),[14] Pierre Sikivie (SAC member),[15] Tim M.P. Tait (SAC member),[7] Natalia Toro (SAC co-chair),[9,16] Richard Van De Water (SAC member),[17] Neal Weiner (SAC member),[18] Kathryn Zurek (SAC member),[13,12] Eric Adelberger,[14] Andrei Afanasev,[19] Derbin Alexander,[20] James Alexander,[21] Vasile Cristian Antochi,[22] David Mark Asner,[23] Howard Baer,[24] Dipanwita Banerjee,[25] Elisabetta Baracchini,[26] Phillip Barbeau,[27] Joshua Barrow,[28] Noemie Bastidon,[29] James Battat,[30] Stephen Benson,[31] Asher Berlin,[9] Mark Bird,[32] Nikita Blinov,[9] Kimberly K. Boddy,[33] Mariangela Bondì,[34] Walter M. Bonivento,[35] Mark Boulay,[36] James Boyce,[37,31] Maxime Brodeur,[38] Leah Broussard,[39] Ranny Budnik,[40] Philip Bunting,[12] Marc Caffee,[41] Sabato Stefano Caiazza,[42] Sheldon Campbell,[7] Tongtong Cao,[43] Gianpaolo Carosi,[44] Massimo Carpinelli,[45,46] Gianluca Cavoto,[22] Andrea Celentano,[1] Jae Hyeok Chang,[6] Swapan Chattopadhyay,[3,47] Alvaro Chavarria,[48] Chien-Yi Chen,[49,16] Kenneth Clark,[50] John Clarke,[12] Owen Colegrove,[10] Jonathon Coleman,[51] David Cooke,[25] Robert Cooper,[52] Michael Crisler,[23,3] Paolo Crivelli,[25] Francesco D'Eramo,[53,54] Domenico D'Urso,[45,46] Eric Dahl,[29] William Dawson,[44] Marzio De Napoli,[34] Raffaella De Vita,[1] Patrick DeNiverville,[55] Stephen Derenzo,[13] Antonia Di Crescenzo,[56,57] Emanuele Di Marco,[58] Keith R. Dienes,[59,2] Milind Diwan,[11] Dongwi Handiipondola Dongwi,[43] Alex Drlica-Wagner,[3] Sebastian Ellis,[60] Anthony Chigbo Ezeribe,[61,62] Glennys Farrar,[18] Francesc Ferrer,[63] Enectali Figueroa-Feliciano,[64] Alessandra Filippi,[65] Giuliana Fiorillo,[66] Bartosz Fornal,[67] Arne Freyberger,[31] Claudia Frugiuele,[40] Cristian Galbiati,[68] Iftah Galon,[7] Susan Gardner,[69] Andrew Geraci,[70] Gilles Gerbier,[71] Mathew Graham,[9] Edda Gschwendtner,[72] Christopher Hearty,[73,74] Jaret Heise,[75] Reyco Henning,[76] Richard J. Hill,[16,3] David Hitlin,[5] Yonit Hochberg,[21,77] Jason Hogan,[8] Maurik Holtrop,[78] Ziqing Hong,[29] Todd Hossbach,[23] T. B. Humensky,[79] Philip Ilten,[80] Kent Irwin,[8,9] John Jaros,[9] Robert Johnson,[53] Matthew Jones,[41] Yonatan Kahn,[68] Narbe Kalantarians,[81] Manoj Kaplinghat,[7] Rakshya Khatiwada,[14] Simon Knapen,[13,12] Michael Kohl,[43,31] Chris Kouvaris,[82] Jonathan Kozaczuk,[83] Gordan Krnjaic,[3] Valery Kubarovsky,[31] Eric Kuflik,[21,77] Alexander Kusenko,[84,85] Rafael Lang,[41] Kyle Leach,[86] Tongyan Lin,[12,13] Mariangela Lisanti,[68] Jing Liu,[87] Kun Liu,[17] Ming Liu,[17] Dinesh Loomba,[88] Joseph Lykken,[3] Katherine Mack,[89] Jeremiah Mans,[4] Humphrey Maris,[90] Thomas Markiewicz,[9] Luca Marsicano,[1] C. J. Martoff,[91] Giovanni Mazzitelli,[26] Christopher McCabe,[92] Samuel D. McDermott,[6] Art McDonald,[71] Bryan McKinnon,[93] Dongming Mei,[87] Tom Melia,[13,85] Gerald A. Miller,[14] Kentaro Miuchi,[94] Sahara Mohammed Prem Nazeer,[43] Omar Moreno,[9] Vasiliy Morozov,[31] Frederic Mouton,[61] Holger Mueller,[12] Alexander Murphy,[95] Russell Neilson,[96] Tim

White paper on arXiv:1707.04591
Submitted to Phys.Rep.

- ★ The *white-paper* (signed by more than 200 researchers) will be used to evaluate the opportunity of DOE/NSF funding call for small (scale <$10M) project in the area to be launched soon
- ★ BDX has been included as a project in *LDM searches with accelerators* program

Costs

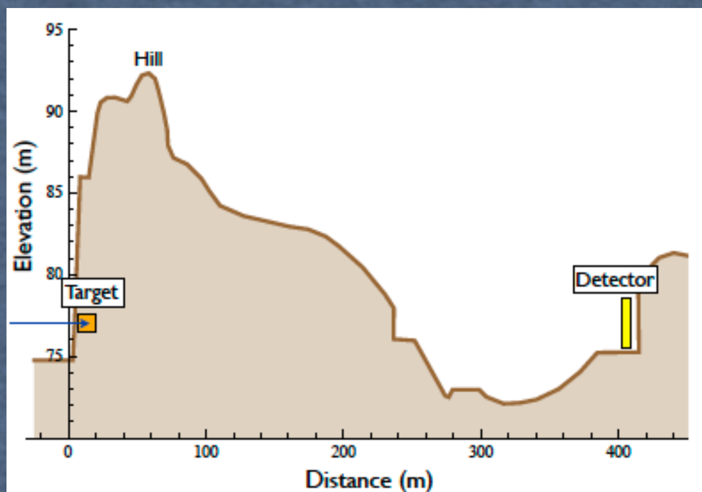
BDX detector	**~$0.9M**
Infrastructure at JLab	**~$1.8M**

Calorimeter					$145k
	CsI(Tl) crystals (BaBar)	~900	refurbishing, wrapping	$24k	
	(6x6) mm2 SiPM	~900	new procurement	$60k	
	Front-End RO and cables	~900ch	new procurement	$42k	
	Mechanical structure		design, procurement	$18k	
Inner Veto					$42k
	Plastic scintillator	~4 m^2, 8 paddles	new procurement	$30k	
	(3x3) mm^2 SiPM	~90	new procurement	$6k	
	mechanical structure		design, procurement	$6k	
Outer Veto					**$78k**
	Plastic scintillator	~12 m^2, 30 paddles	new procurement	$60k	
	PMT	28	refurbishing	$6k	
	mechanical structure		design, procurement	$12k	
DAQ					
	CAEN V1725	1000	procurement		**$600k**
Shielding	Lead bricks	~500	refurbishing		**$6k**

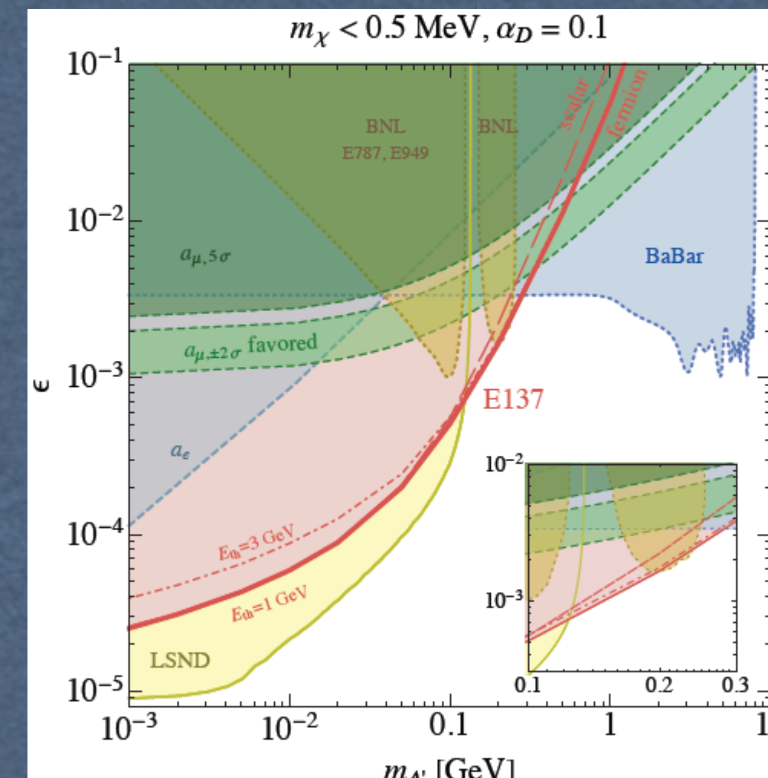
BDX detector costs will be entirely covered by the BDX Collaboration

A critical review of upper limits derived from old experiments

E137@SLAC (<1988)

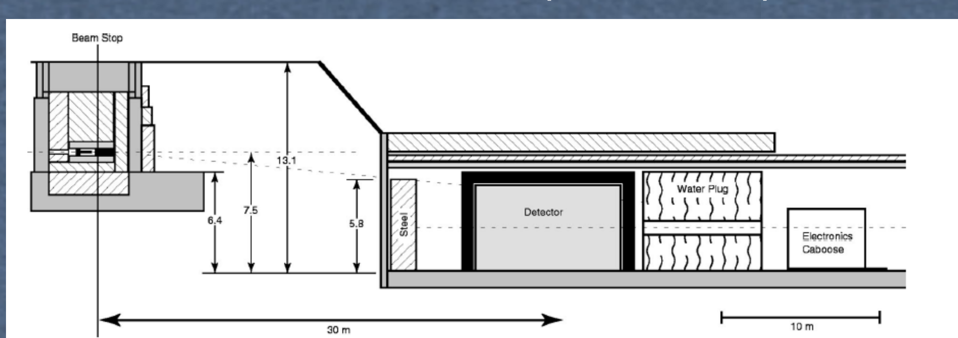


- SLAC electron beam: 20 GeV 2×10^{20} EOT
- Detector: 8 r.l. em calorimeter (hodo + converter + MWPC)
- Size: 1.5m x1.0 m at ~380m from the BD
- Cosmic bg suppressed by directionality and time coincidence
- Detection Threshold: 1-2 GeV
- 0 events detected

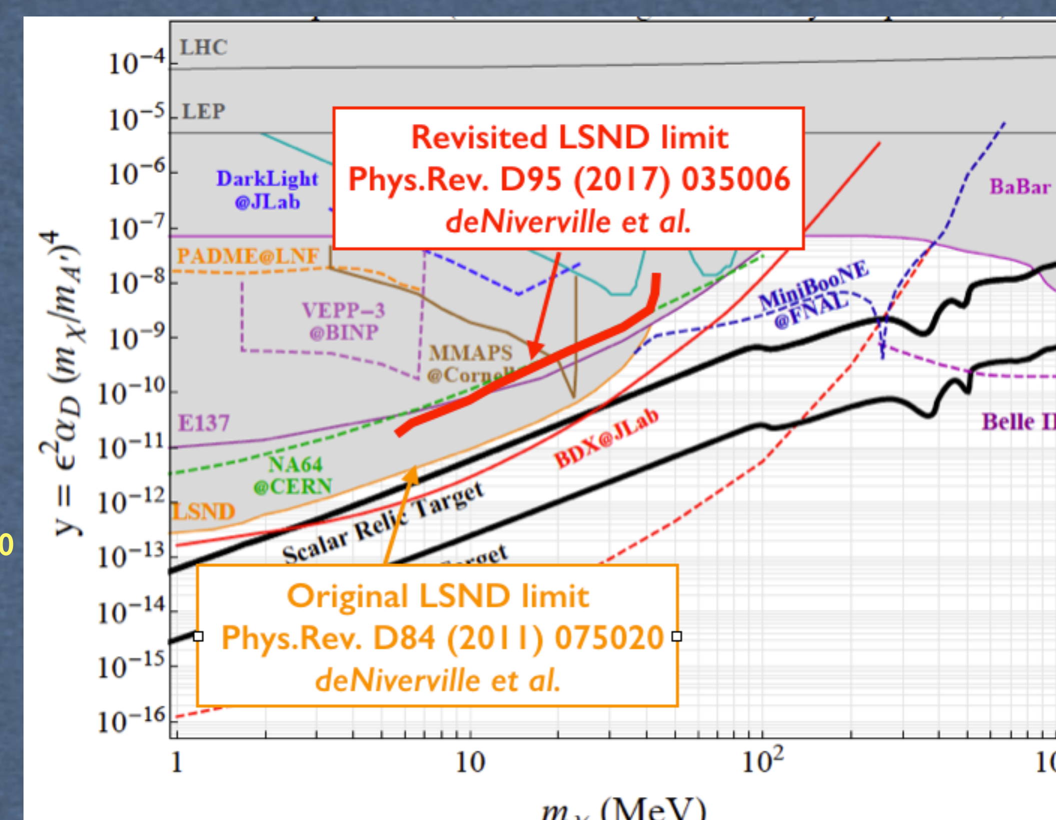


- Extracted upper limits suffer by poor knowledge of experimental details
- No e^- showering in the BD included: softer DM E spectrum and defocused DM beam
- Limits are overestimated by a factor ~3-4 (depending on the kinematics)

LSND@LosAlamos (1994/98)



- 800 MeV protons to LANSCE beam dump
- From $\pi^0 \to A'\gamma$ decay (and $A' \to XX$)



- Upper limits extracted in 2011 using a wrong π^+ spectrum to normalise π^0
- Recently recalculated, fund to be overestimated by a factor ~4-5

BDX is the first beam-dump experiment optimised for LDM searches

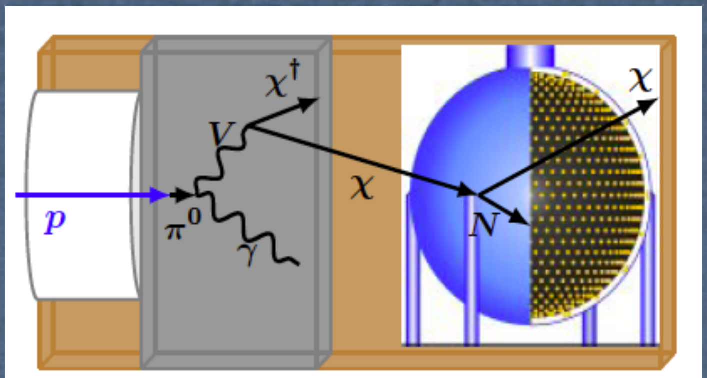
Presented to PAC45

New experimental results since PAC44

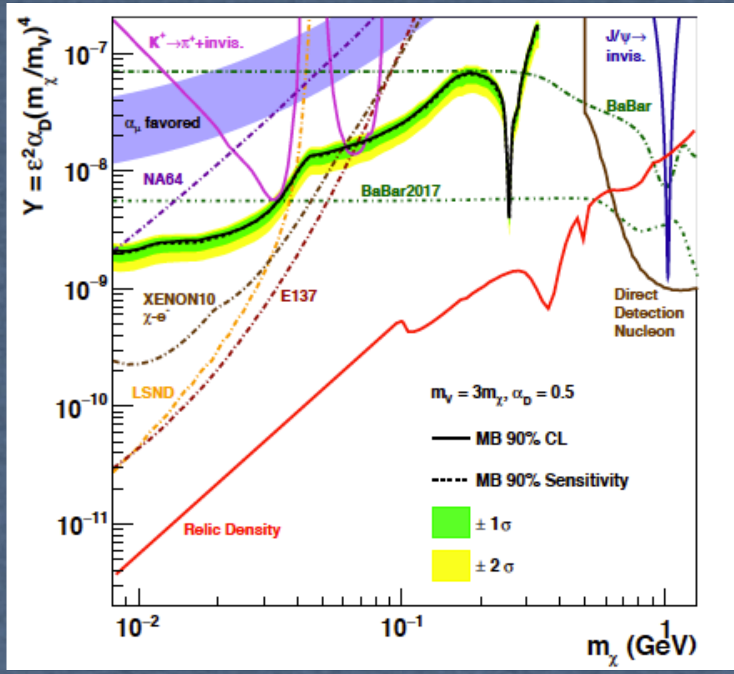
MiniBooNE@FERMILAB

PRL 118, 221803 (2017) PHYSICAL REVIEW LETTERS week ending 2 JUNE 2017

Dark Matter Search in a Proton Beam Dump with MiniBooNE



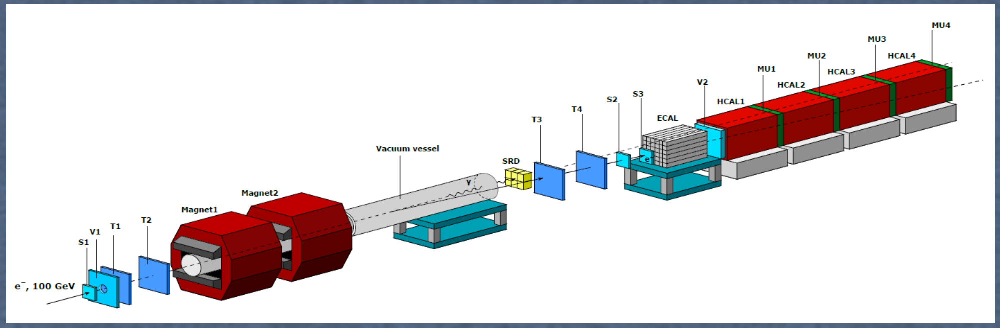
- BDX-like with an 8 GeV proton beam
- Cherenkov response of 12 m spherical detector with 800 tons mineral oil (CH2)
- Typical operation: 2×10^{20} protons on target (POT) per year



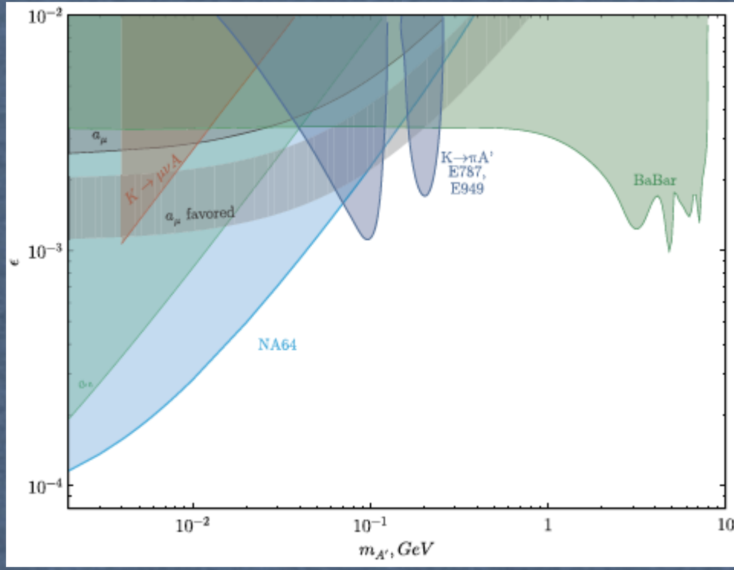
NA64@CERN

PRL 118, 011802 (2017) PHYSICAL REVIEW LETTERS week ending 6 JANUARY 2017

Search for Invisible Decays of Sub-GeV Dark Photons in Missing-Energy Events at the CERN SPS



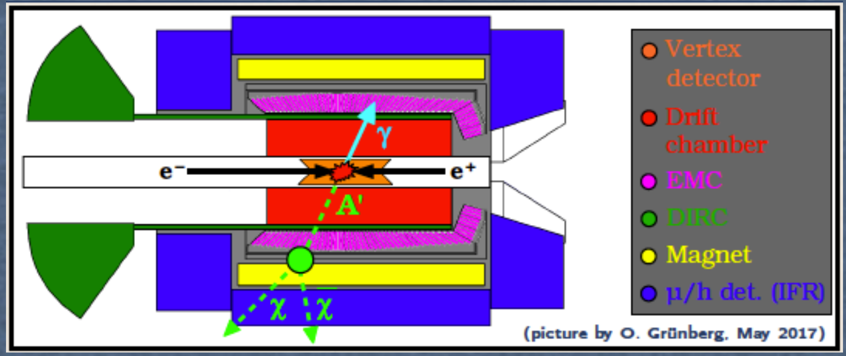
- Missing energy exp (e Z → e Z' A' with A' → invisible)
- 100 GeV SPS electron beam at SPS
- Active target (calorimeter)
- Exclusion plots based on 3×10^9 EOT



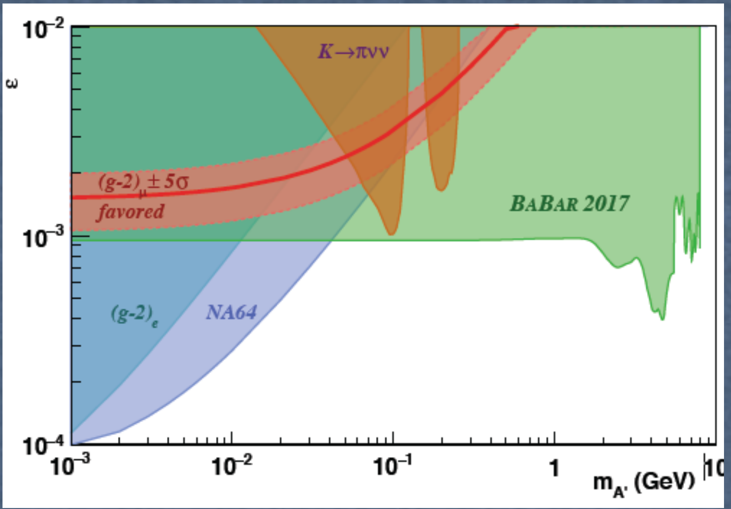
BaBar@SLAC

BABAR-PUB-17/001
SLAC-PUB-16923
arXiv:1702.03327v1 [hep-ex] 10 Feb 2017

Search for invisible decays of a dark photon produced in e^+e^- collisions at BABAR



- Missing mass exp (e- e+ → γ A' with A' → invisible)
- Mono-photon trigger
- Exclusion plots based on ~50 fb^{-1}



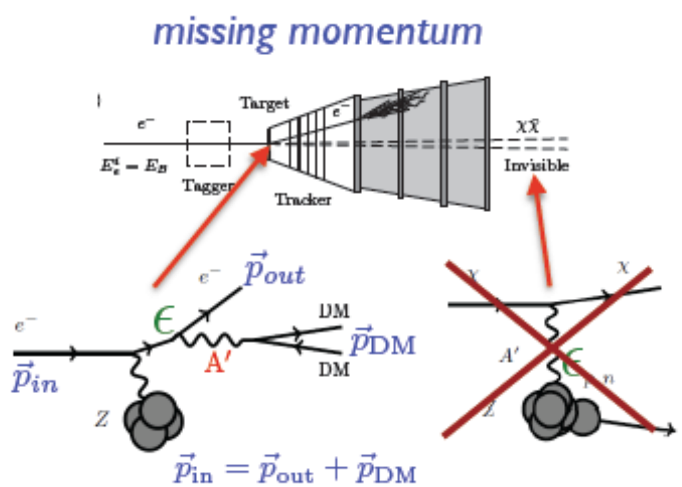
BDX & future experiments

LDMX@SLAC

Missing momentum experiments maximize sensitivity per luminosity using a challenging technique

LDMX

- If the experimental technique will be proved, Phase I (1e- / 25ns @ 4GeV) will be able to increase x10 BDX sensitivity
- When technical difficulties will be resolved Phase II (1e- / 1ns @ 8GeV) will gain another x40 in sensitivity



… but

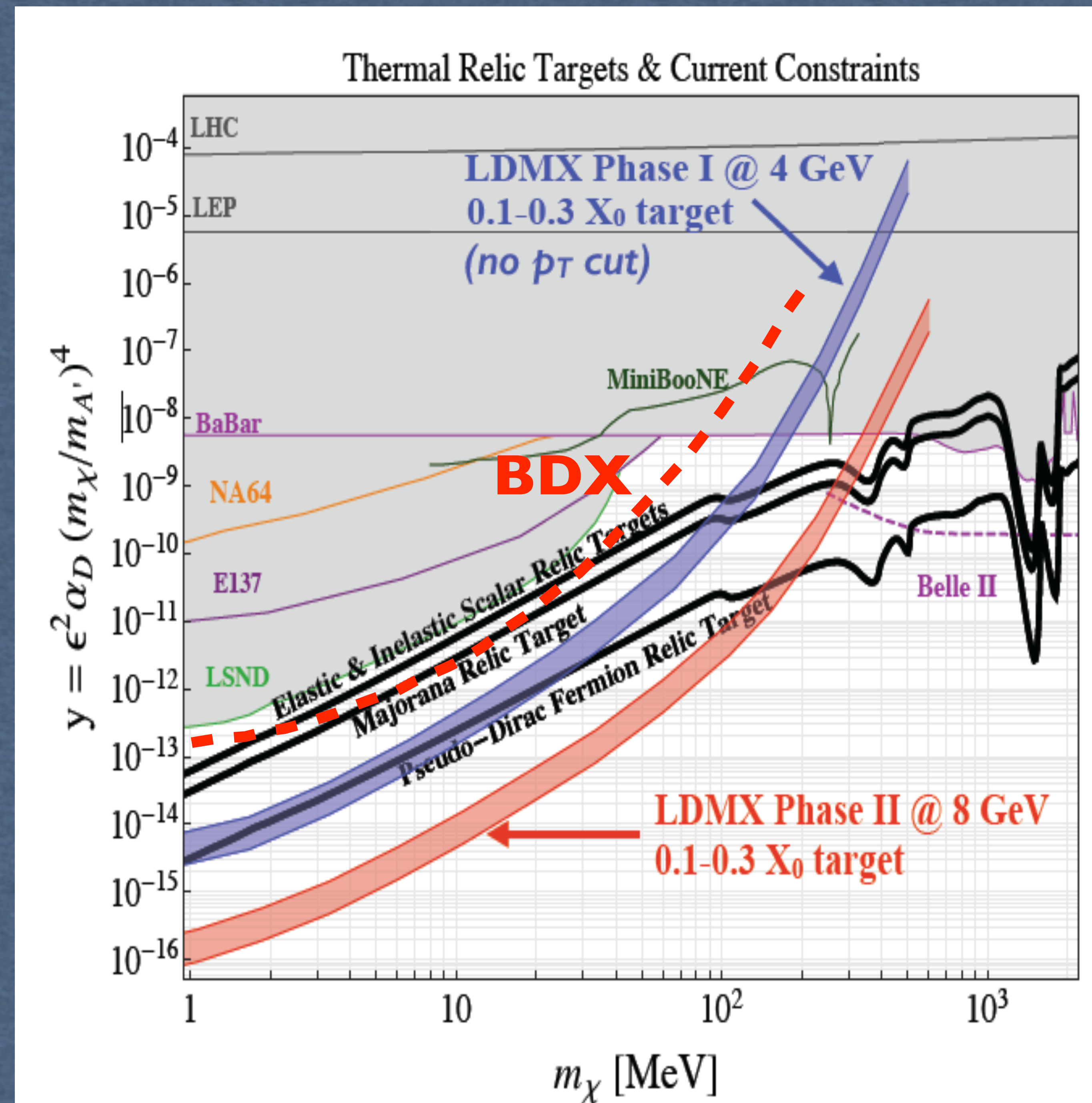
MissingMomentum vs BeamDump (*disappearance* vs *appearance*)

… **more sensitive** in the exclusion plots but **less reliable/convincing** in case of positive finding!

The two experimental approaches are complementary

★BDX will reach the ultimate sensitivity of beam dump experiments hitting the irreducible ν bg with a consolidated technology ready-to-go

★LDMX presents challenges that if/when overcome will lead the 2nd generation LDM searches experiments



High statistics MC simulations

★Simulation of full statistics (10^{22} EOT) not feasible because of computing resources limitation [GEANT4: 1y, 2000 cores→10^{11}-10^{12} EOT]

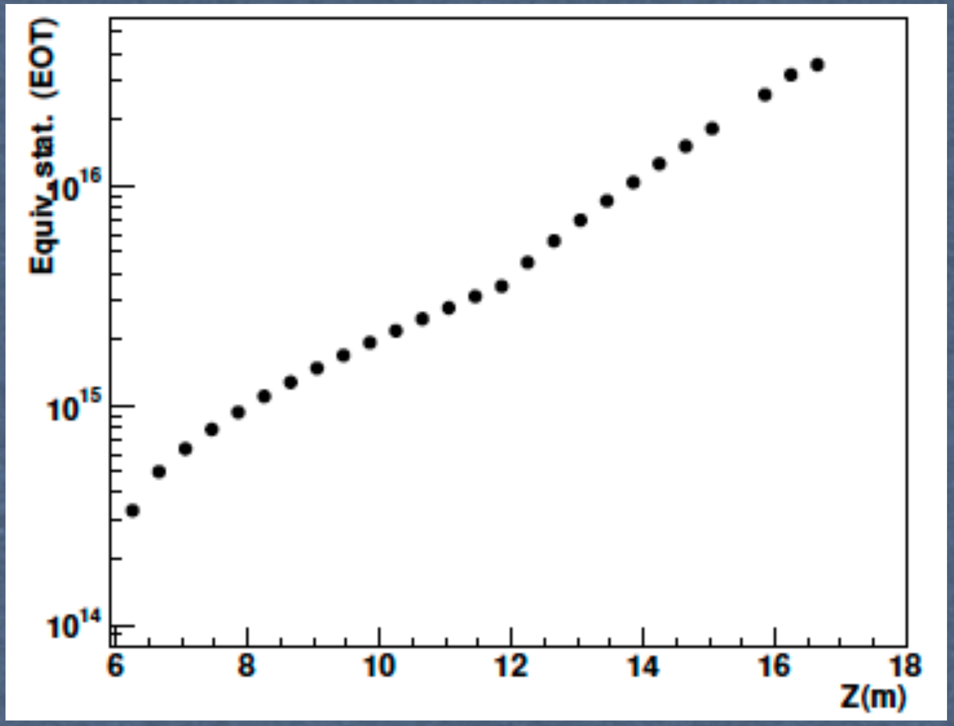
★FLUKA uses a tuned set of biasing weights to efficiently simulate low probability processes

- *Leading particle biasing* for e^+ e^- and γ
- *Region importance biasing* for hadrons and muons in the forward direction
- Photon inelastic cross section biased by a factor 10^2 and $\gamma \rightarrow \mu^+\mu^-$ biased by a factor 10^4
- Accurate treatment of low-energy neutron propagation and neutrino interaction

★Final bias configuration obtained after running multiple tests to optimize simulation parameters (discussed with JLab Radiation Control Group)

- For each parameters settings, score muons current across concrete and iron shielding
- Use a FOM defined as $\sigma^2 T$ (σ = FLUKA error, T = CPU time) to evaluate effect of parameters change

★**Equivalent number of primary particles (ENPP)** is the number of primary particles necessary to simulate in a full (unbiased) run to obtain the same statistical error



The BDX crystals

Requirements:
- High density
- High light yield
- Cost-affordable for a ~ m^3 detector volume
- Good timing (desirable)

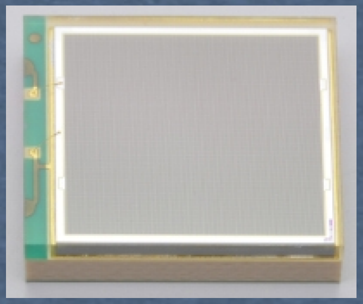
Possible options:

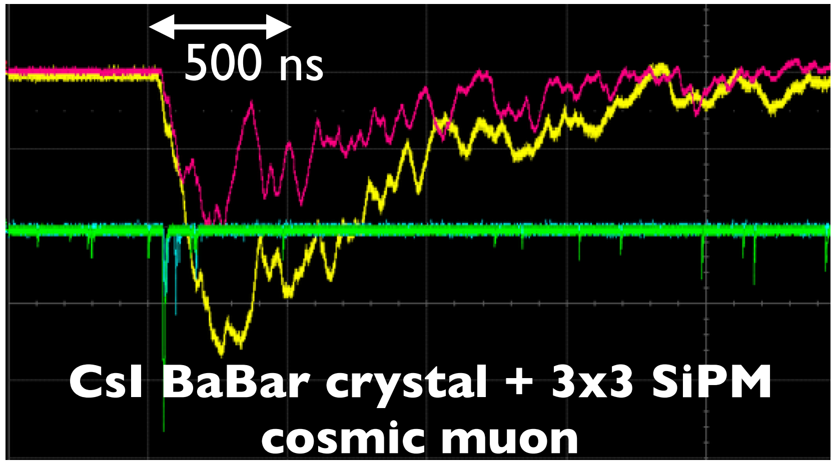
BaF2
CsI
BSO

A dedicated measurement campaign to characterise the crystal properties
- Light yield (with SiPM readout!)
- Intrinsic decay time / time resolution

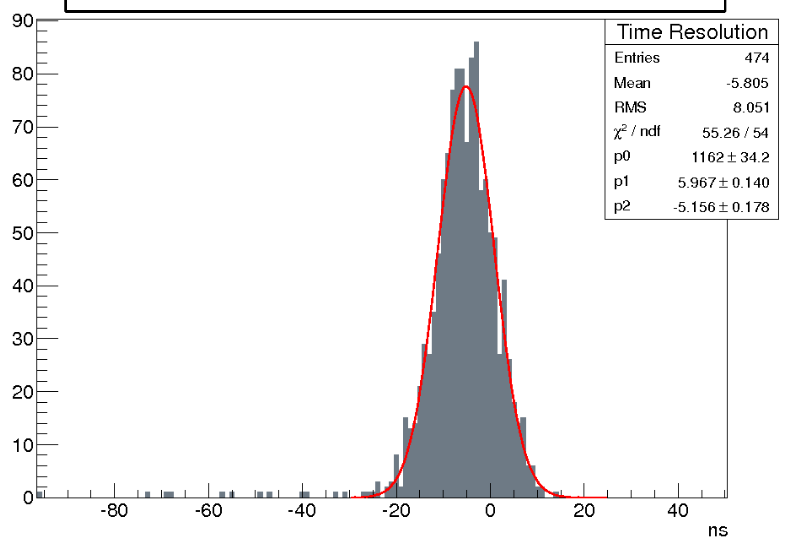
Parameter	Values
Radiation length	1.85 cm
Molière radius	3.8 cm
Density	4.53 g/cm^3
Light yield	50,000 γ/MeV
Light yield temp. coeff.	0.28%/°C
Peak emission λ_{max}	565 nm
Refractive index (λ_{max})	1.80
Signal decay time	680 ns (64%)
	3.34 µs (36%)

CsI(Tl) + SiPM readout





CsI BaBar crystal + 3x3 SiPM
Time resolution: σ = 6ns



Crystals are available from BABAR em calorimeter
- Size: (5x5)cm² front face, (6x6)cm² back face, 30cm length
- 820 crystals available from end cap
- Decay time: fast 900ns, slow 4000ns
- LY= 50k γ/MeV

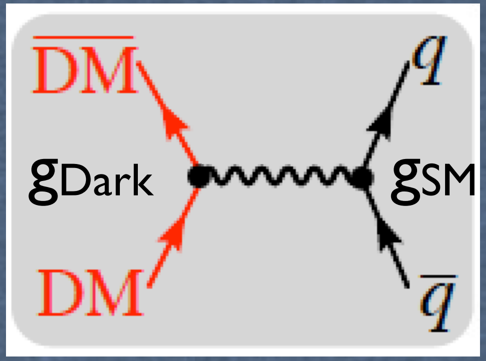
SiPM readout
- Size: (6x6) mm², 25µm, 57.6k cells, trenched, pde=25%
- SPE capability
- CsI(Tl): 40 pe/MeV
- Time resolution: ~5ns (MIPs)

★Due to the large LY signals at ~MeV level are detectable
★Despite a long scintillation time a few ns time coincidence is possible

Any guess about the DM mass and interaction?

★ (Obvious) first guess: DM interaction in the range of the weak force scale (WIMPS) with DM mass in the range of TeV

WIMPs paradigm is not the only option (keeping the DM thermal origin)



$\langle \sigma v \rangle \sim g^2_{Dark}\, g^2_{SM}\, M^2_{DM}/M^4_{mediator}$

Light Dark Matter

Light Dark Matter (<TeV) naturally introduces light mediators

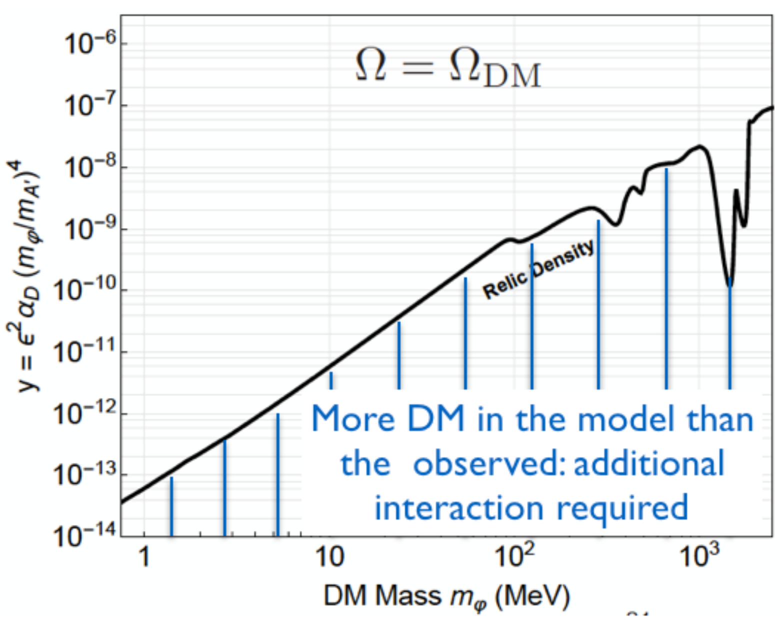
New interaction

★ Definition of [adimensional] variable $y \sim g^2_{Dark}\, g^2_{SM}\, (M_{DM}/M_{mediator})^4 \sim \langle \sigma v \rangle M^2_{DM}$

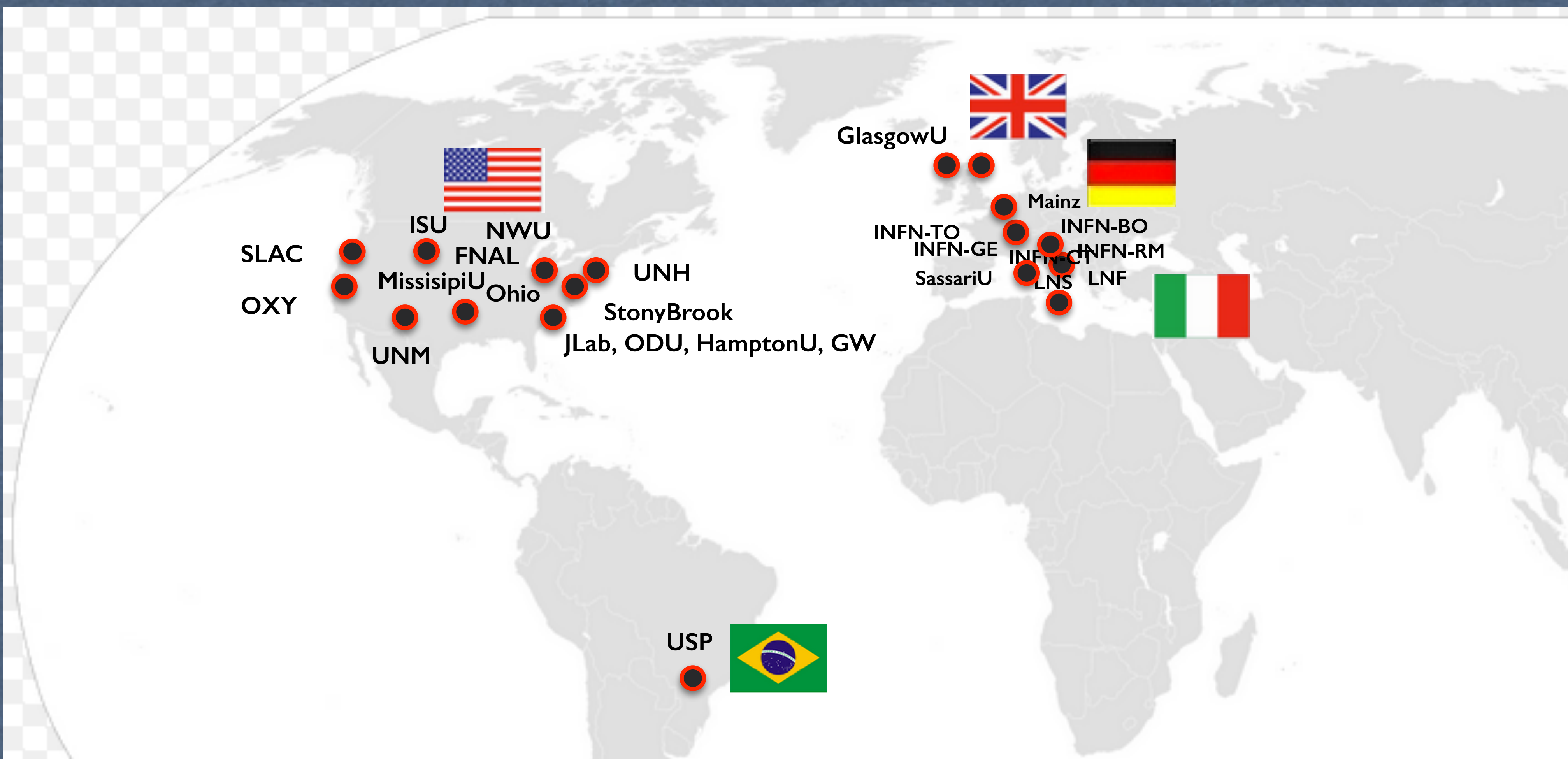
$$\langle \sigma v \rangle \propto \epsilon^2 \alpha_D \frac{m_\varphi^2}{m_{A'}^4} = \epsilon^2 \alpha_D \frac{m_\varphi^4}{m_{A'}^4} \frac{1}{m_\varphi^2} = \frac{y}{m_\varphi^2}$$

Computed for $m_{A'}/m_{\varphi/\chi} = 3$

But thermal target largely insensitive to this ratio



The BDX Collaboration



BDX Institutions

INFN-Italy: Genova, Catania, Roma, Bologna, Torino, LNS, LNF, Padova, Roma TV, SassariU, Ferrara, Bari, Lecce
Jefferson Lab
BNL
FNAL
Occidental College
University of New Mexico
SLAC
Ohio University
Stony Brook
Canisius College
University of New Hampshire
George Washington University
Missisipi Stae University
Hampton University
Old Dominio University
Northwestern University
Mainz University
Gulch
GlasgowU
IPN-Orsay

- More than 120 researchers signed the BDX proposal and this update
- Connection with groups involved in similar projects at SLAC, CERN, Mainz and LNF
- Core group working on different aspects: physics, detector, simulations
- Weekly meeting to check progresses and share information
- Wiki page to store documents and meetings minutes
- Organisation of dedicated workshops and satellite meetings at major venues
- R&D funds from INFN and grant requests submitted