Progress on the Production of Muon and Photon Beams for Applications in Muon-Ion Colliders

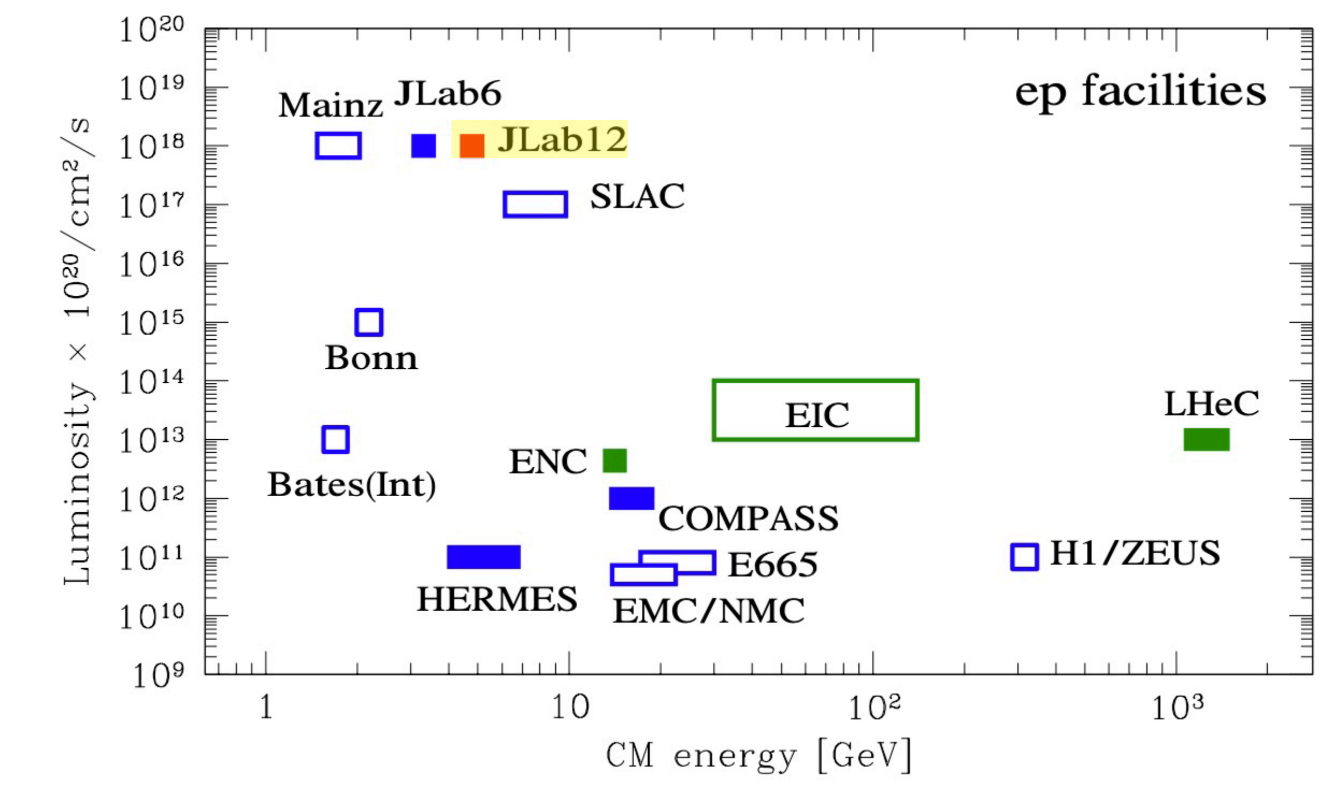
Tuesday Mar 26, 2024, 2:08 AM → 7:00 PM America/New_York

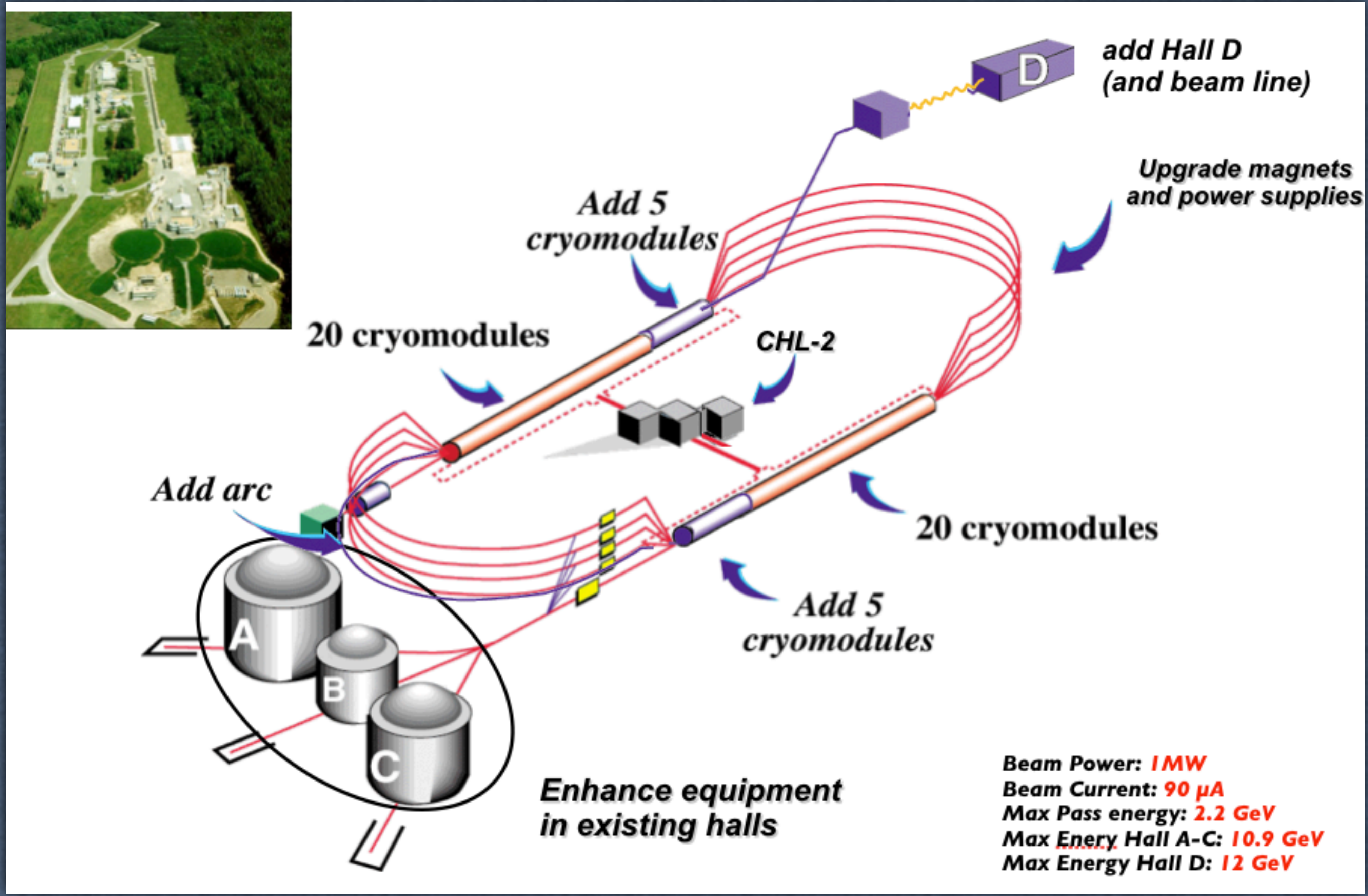
Secondary beams at high intensity lepton facilities

M.Battaglieri (INFN)

Based on https://www.mdpi.com/2410-390X/8/1/1/pdf

Jefferson Lab
The intensity frontier





✳Primary Beam: Electrons

✳ Beam Energy: 12 GeV

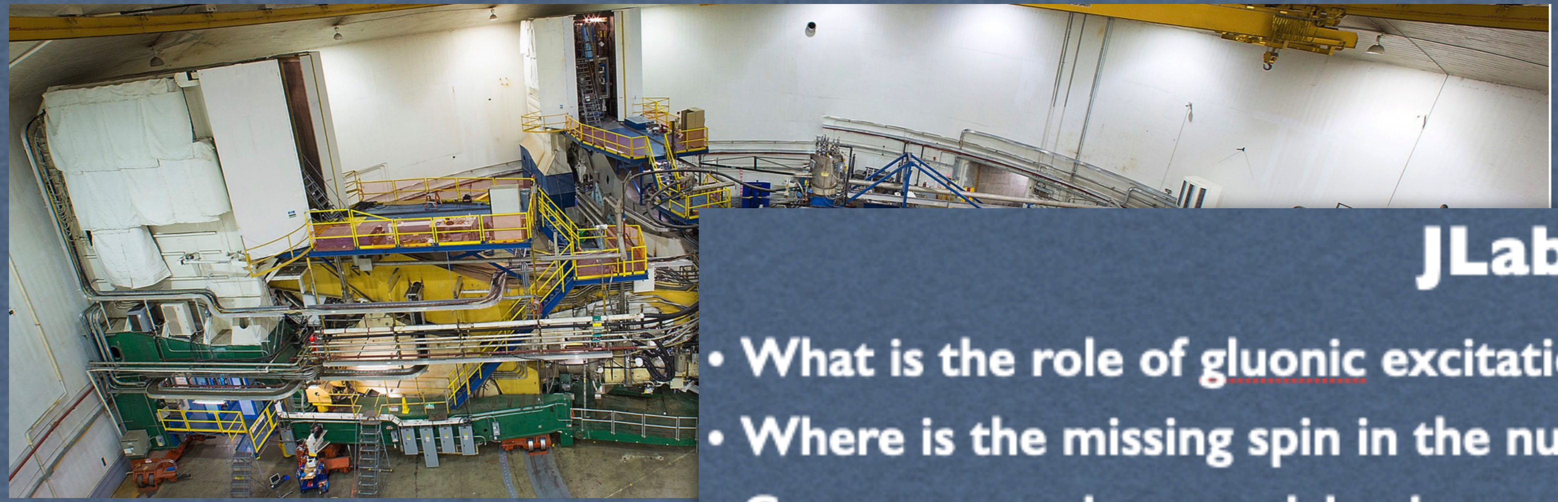
- $10 > \lambda > 0.1$ fm
- nucleon → quark transition
- baryon and meson excited states

✳100% Duty Factor (cw) Beam

- coincidence experiments
- Four simultaneous beams
- Independent E and I

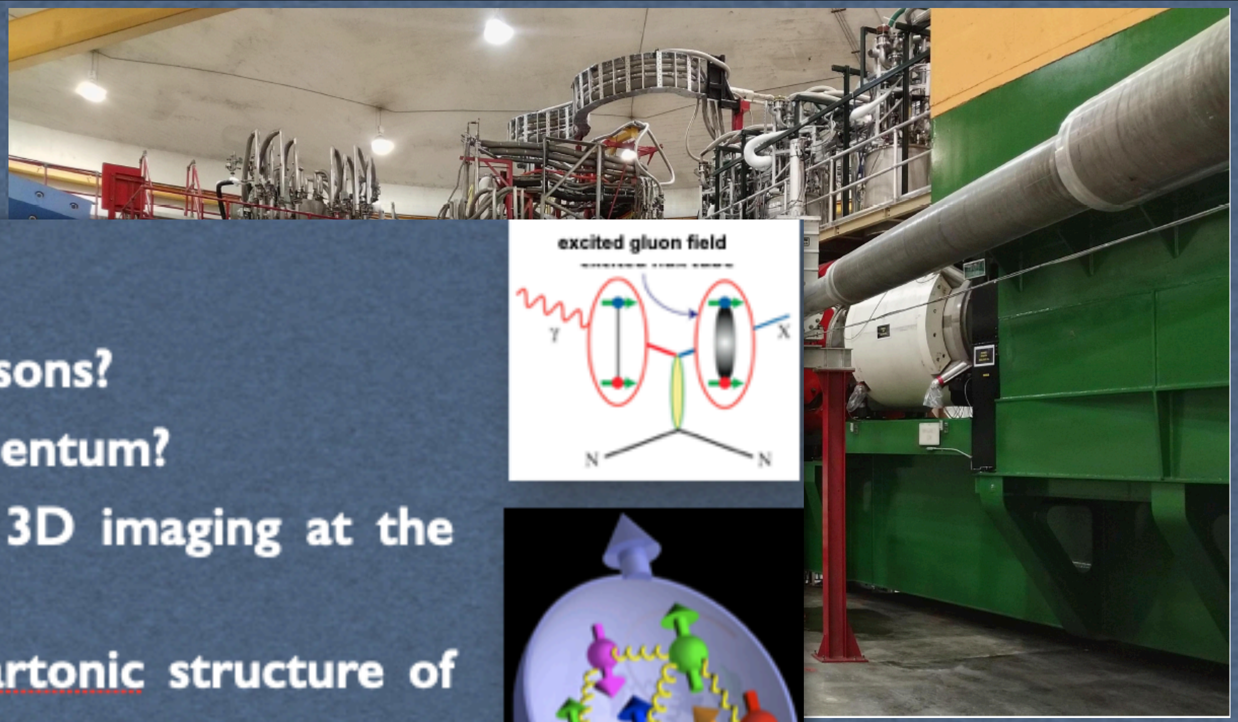
✳ Polarization

- spin degrees of freedom
- weak neutral currents



Hall A

Hall C



JLab Scientific mission

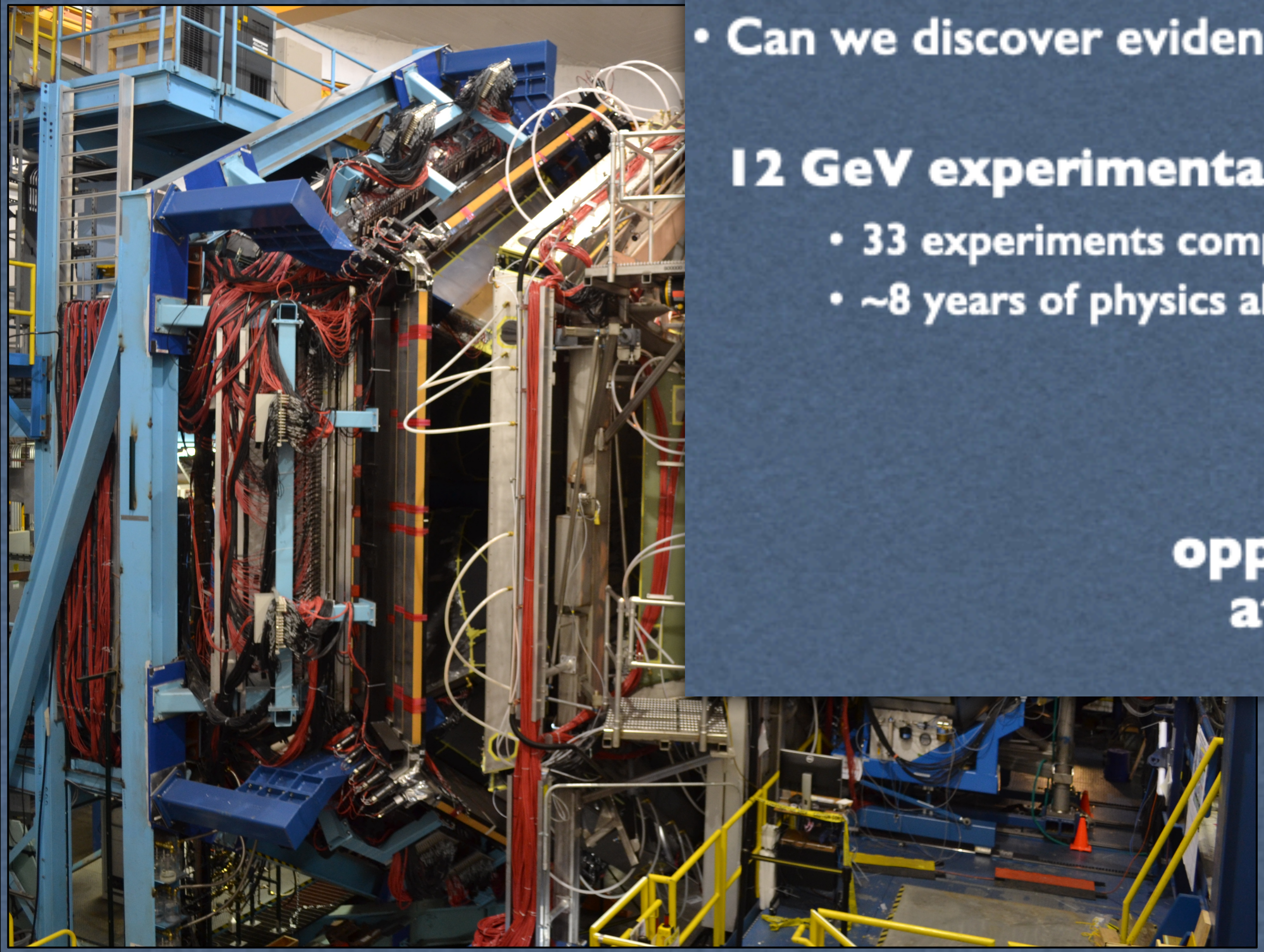
- What is the role of gluonic excitations in the spectroscopy of light mesons?
- Where is the missing spin in the nucleon? Role of orbital angular momentum?
- Can we reveal a novel landscape of nucleon substructure through 3D imaging at the femtometer scale?
- What is the relation between short-range N-N correlations, the partonic structure of nuclei, and the nature of the nuclear force?
- Can we discover evidence for physics beyond the standard model of particle physics?

12 GeV experimental program is in full swing

- 33 experiments completed out of 91 approved
- ~8 years of physics ahead (~30 weeks/year)

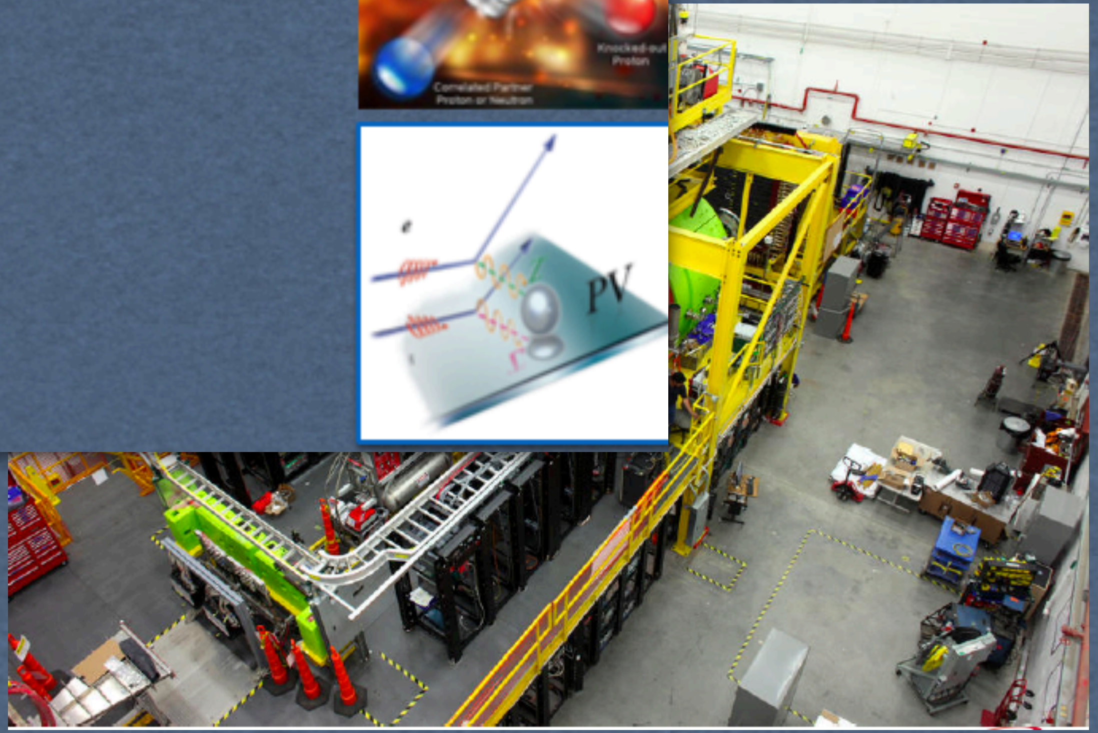
Future opportunities at CEBAF

- Higher Energy
- Higher luminosity
- Positron beam



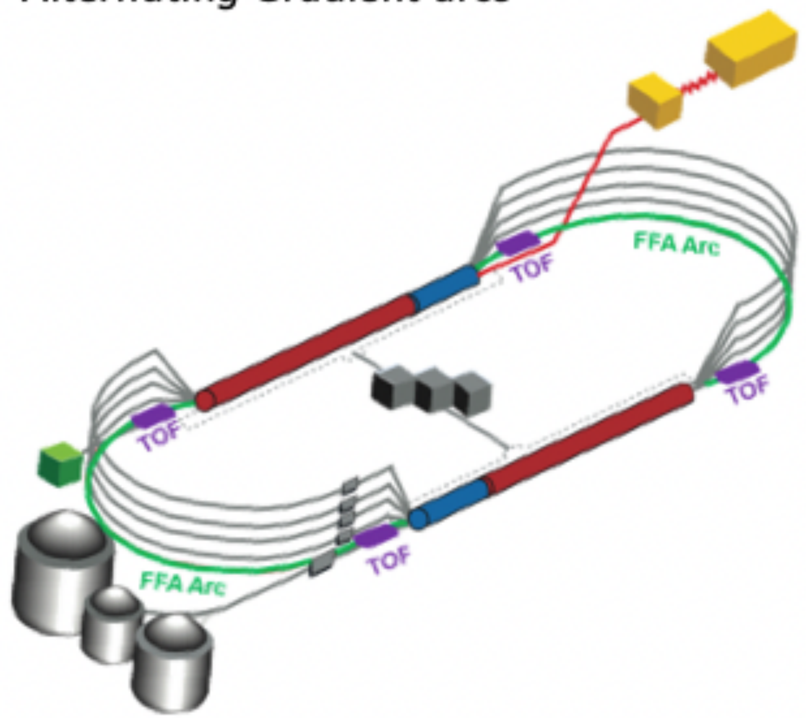
Hall B

Hall D



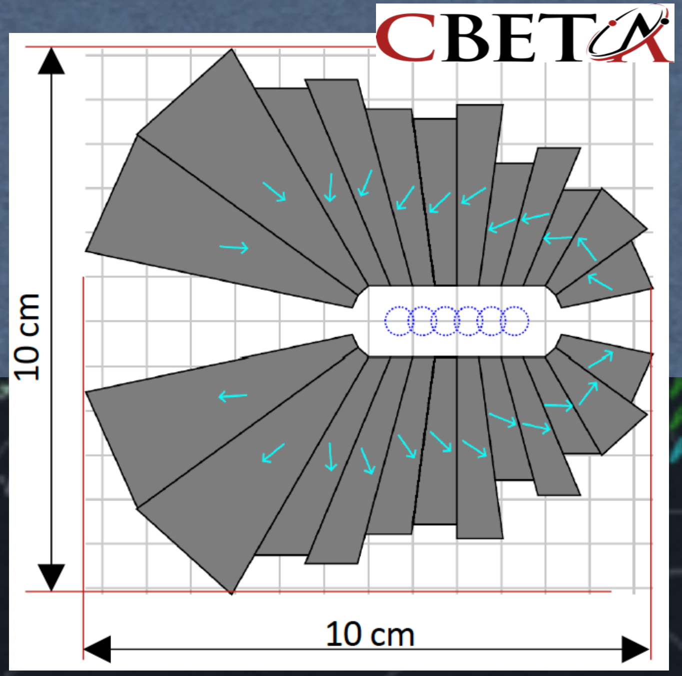
CEBAF @ 20+ GeV Infrastructures

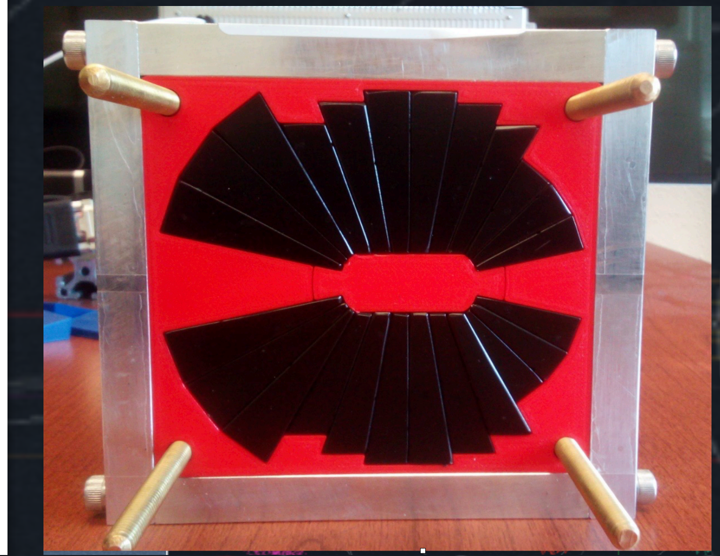
Cost-effective path to doubling CEBAF energy based on Fixed-Field Alternating Gradient arcs



- Starting with 12 GeV CEBAF
- NO new SRF
- NEW 650 MeV injector
- Remove the highest recirculation pass and replace them with **two FFA arcs** including TOF chicane
- Recirculate 4 + **6.5** times to get to **22 GeV**

Enabling Technology:
Novel permanent magnets





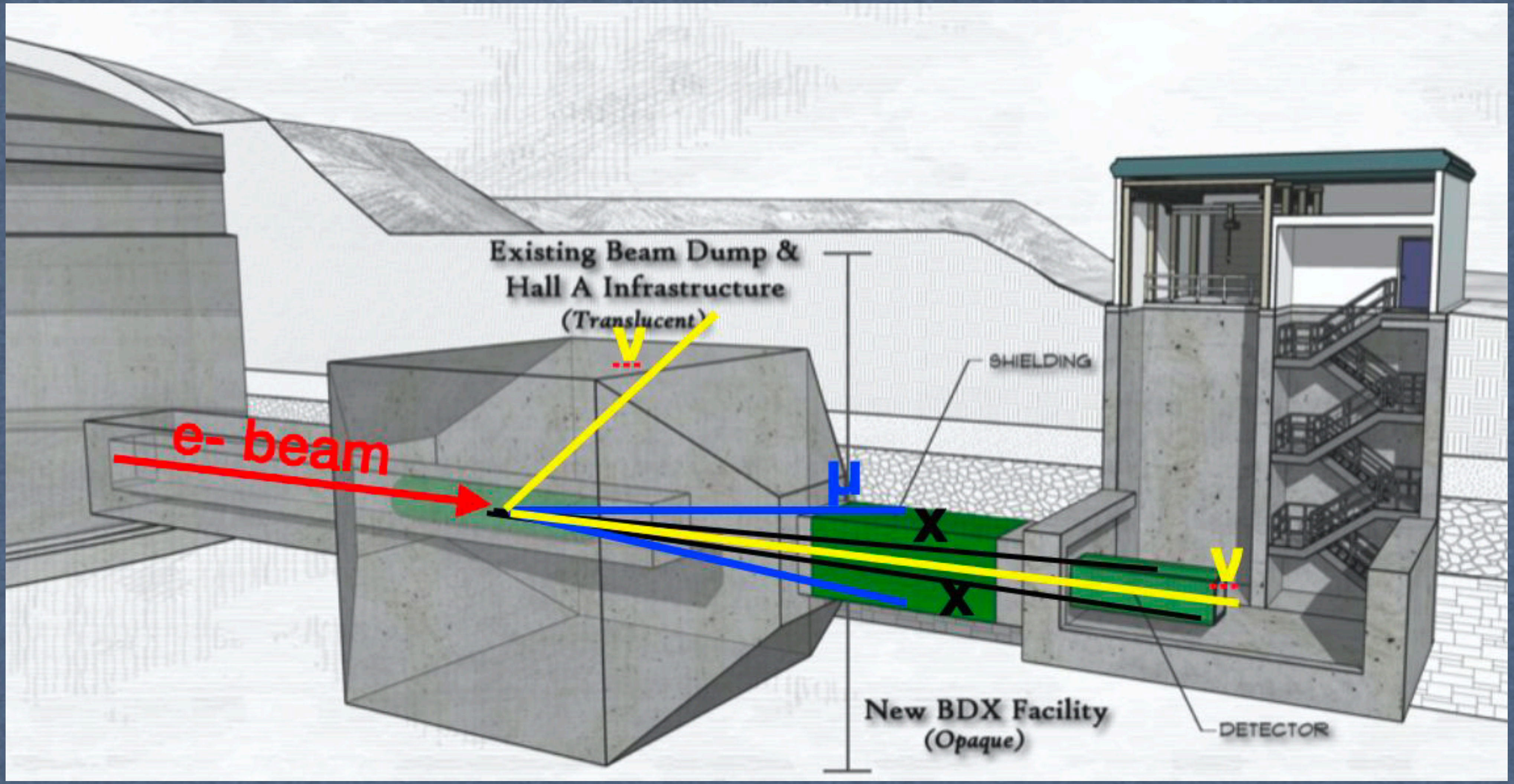
- FFA recirculation technique: multiple beam energies confined and recirculated in the same beam line
- No new SRF (1.1 GeV per LINAC), replace the highest recirculation passes with FFA arcs
- 11 passes to reach 22 GeV
- High energy beam delivered to Hall-D and Hall B suitable for an HS physics program
- **Hi-Lumi + Hi-E operations**

New physics perspectives at Jlab with secondary beams

- CEBAF provides a high-intensity 10 GeV (in future 20+ GeV) electron beam for extracted-beam experiments
- High-intensity secondary beams are produced in the dump(s) fully parasitically
- The machine can sustain up to ~MW power (100 uA @ 10 GeV, 200 uA @ 5 GeV)
- Hall-A routinely receives ~50-70 nA b@11 GeV, Hall-D 7-8 uA @ 12 GeV

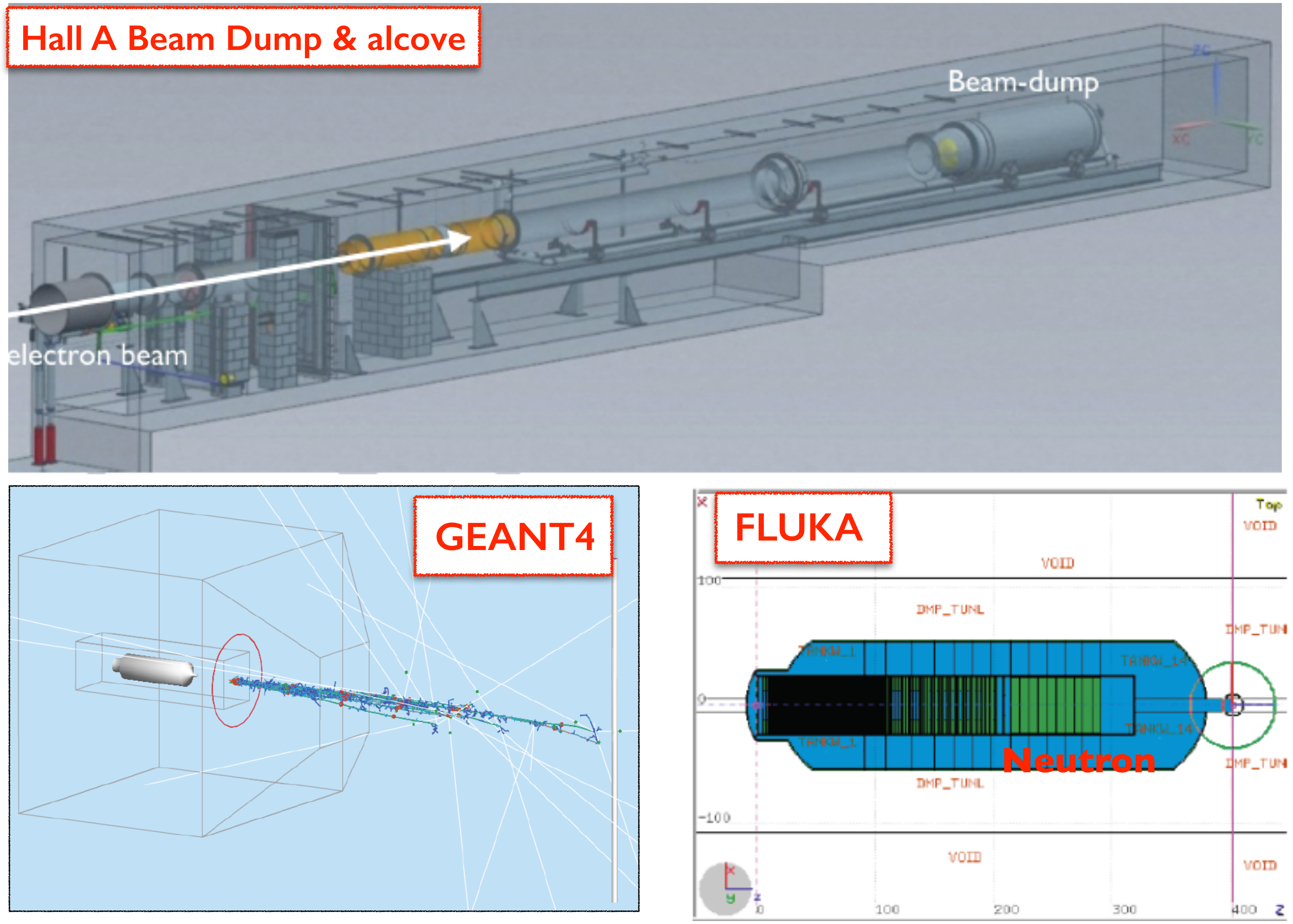
- High-intensity secondary beams:
  - Muon
  - Neutrino
  - Light Dark Matter (if it exists)

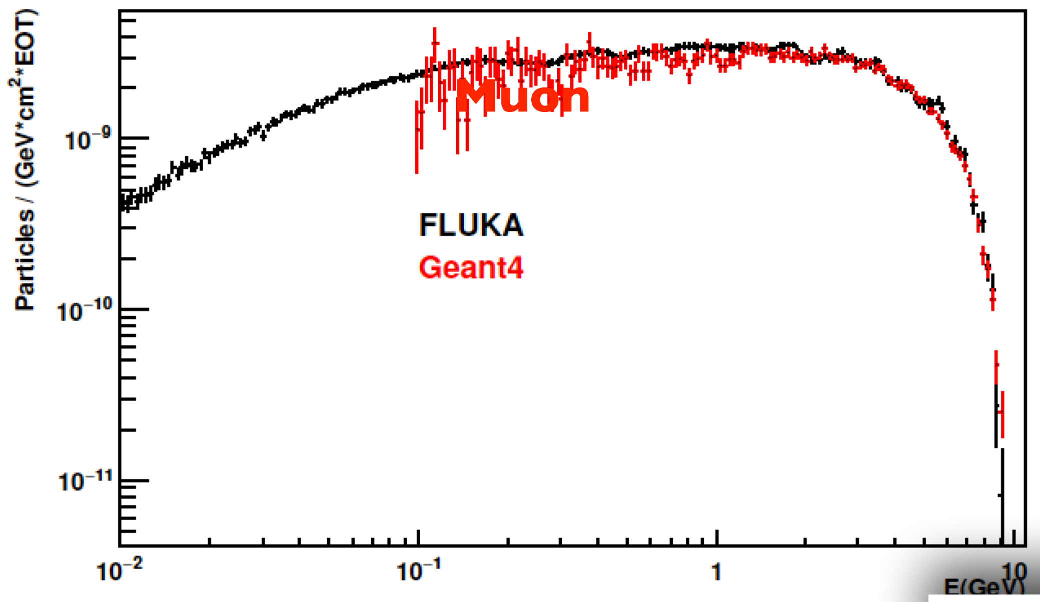
- A positron beam is expected in the near future as part of the 22 GeV upgrade of the machine



The simulation framework

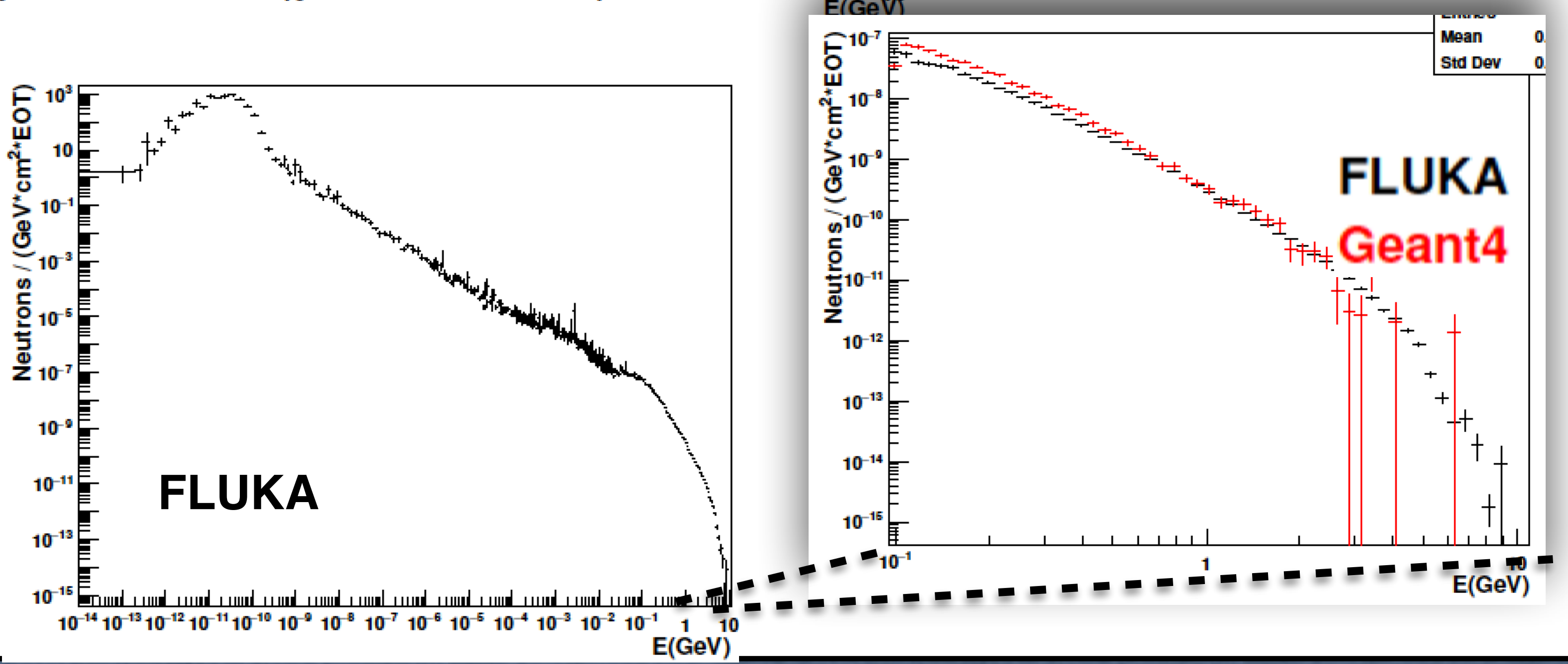
- Hall-A beam-dump geometry/materials implemented in FLUKA (with JLab RadCon Group)
  - FLUKA biasing: xsecs enhancement, 'leading particle', importance sampling, threshold T>100 MeV
  - GEANT: detailed and realistic descriptions of the detector active volume response





Fluence at the BD exit

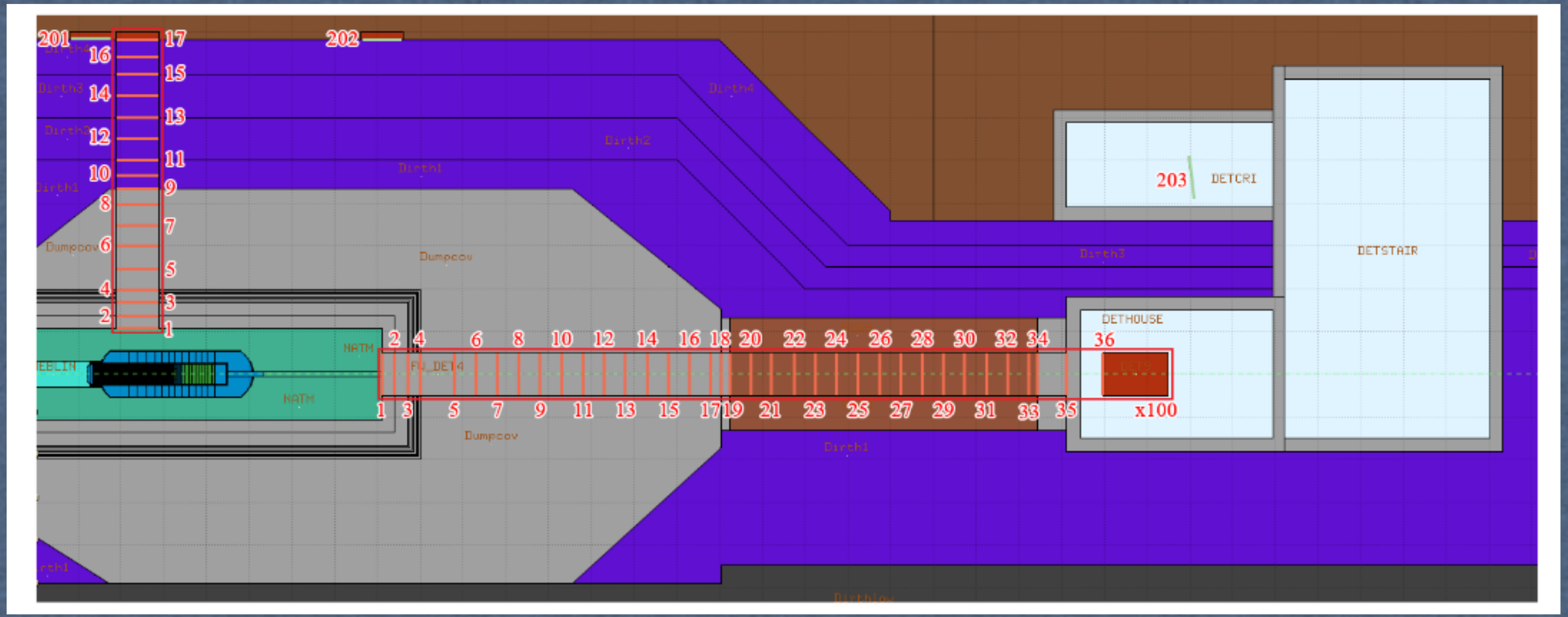
- Statistics equivalent to ~10^{22} Electron on Target (EOT)

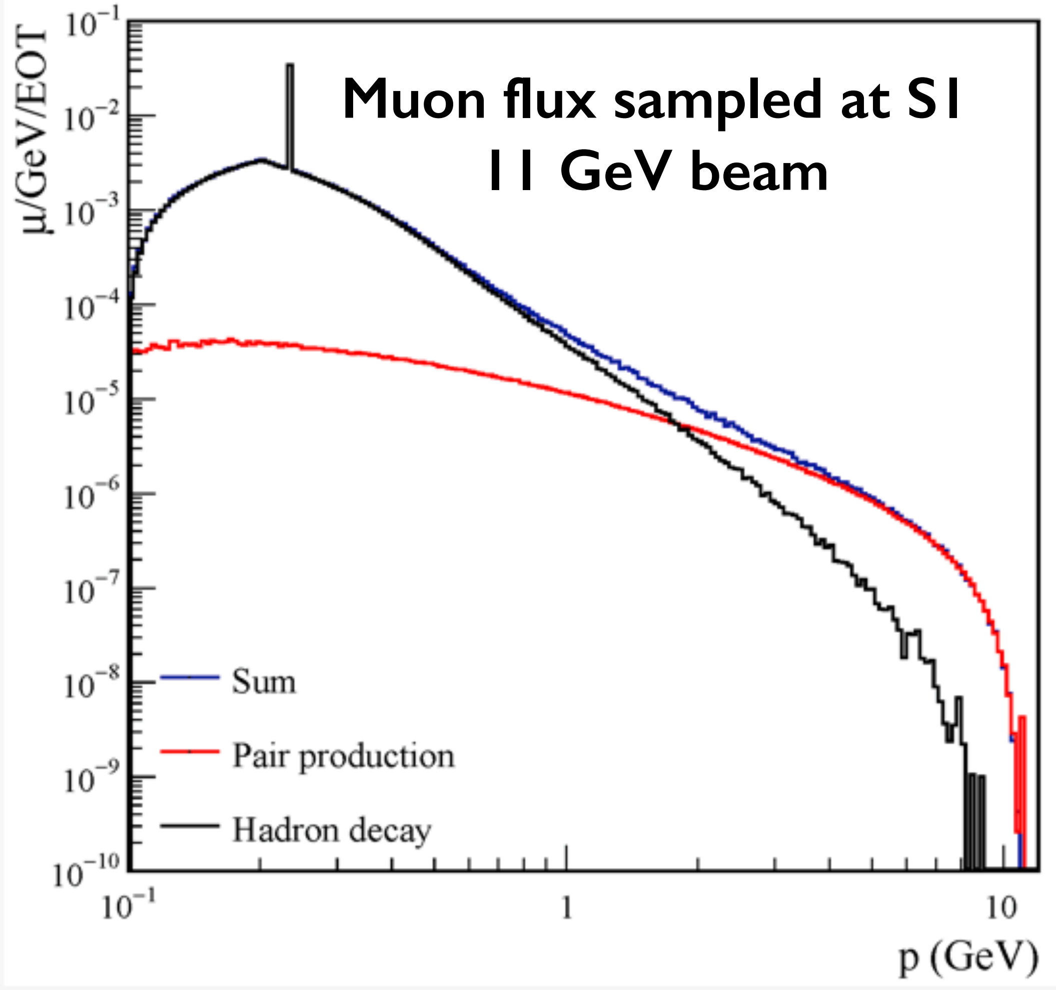


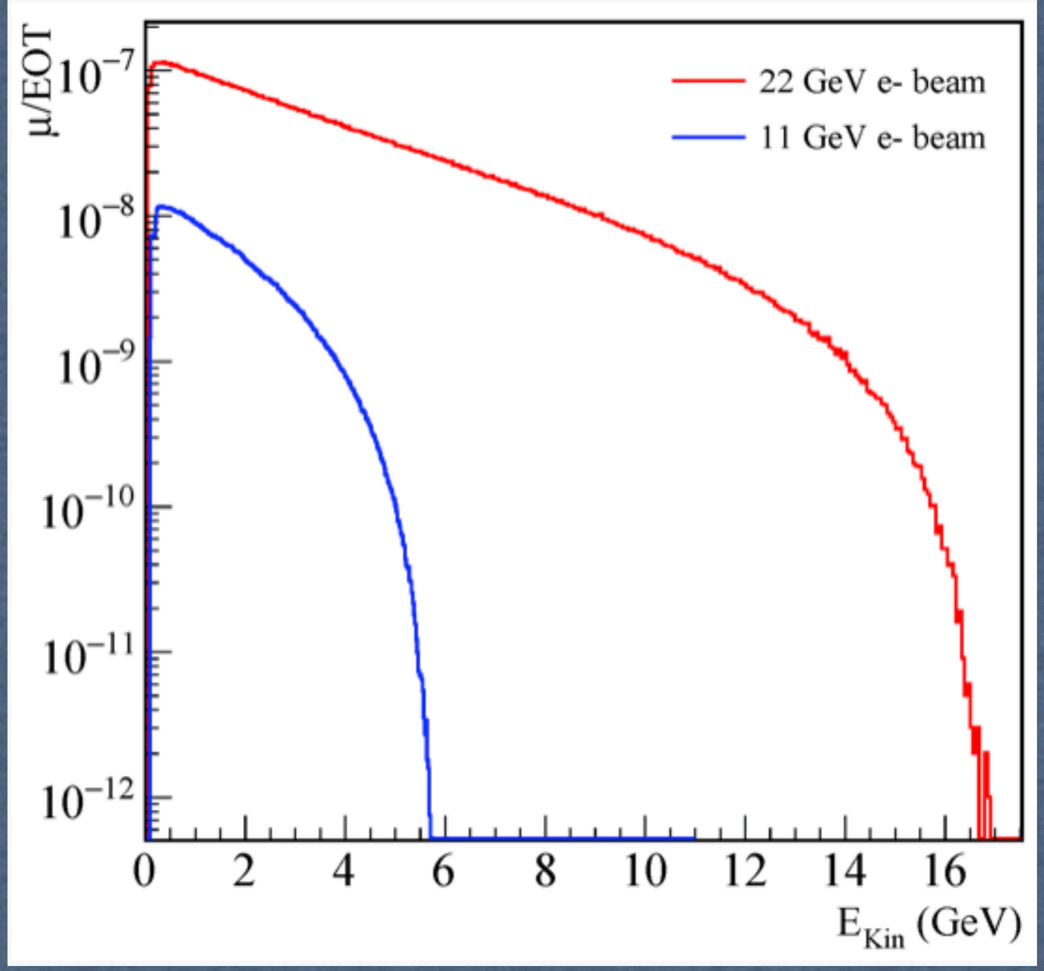
- Good consistency between G4 and FLUKA for μ and high energy neutrons (T_n>100 MeV) in the BD

Muon beam

- Muon flux estimated using FLUKA for 11 GeV and 22 GeV primary e- beam on Hall-A BD
- High-energy muon produced via two processes:
  - Photo-production of π and k and decay
  - Pair-production: γN -> μμN





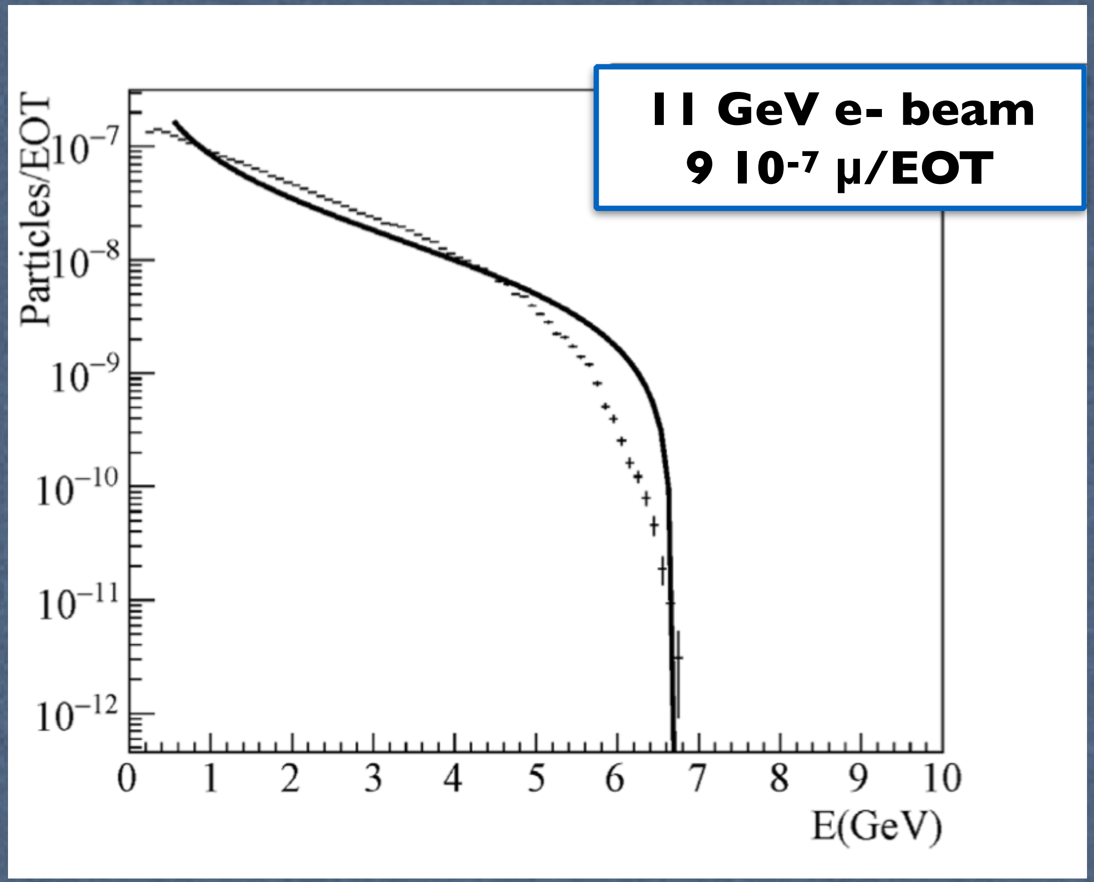


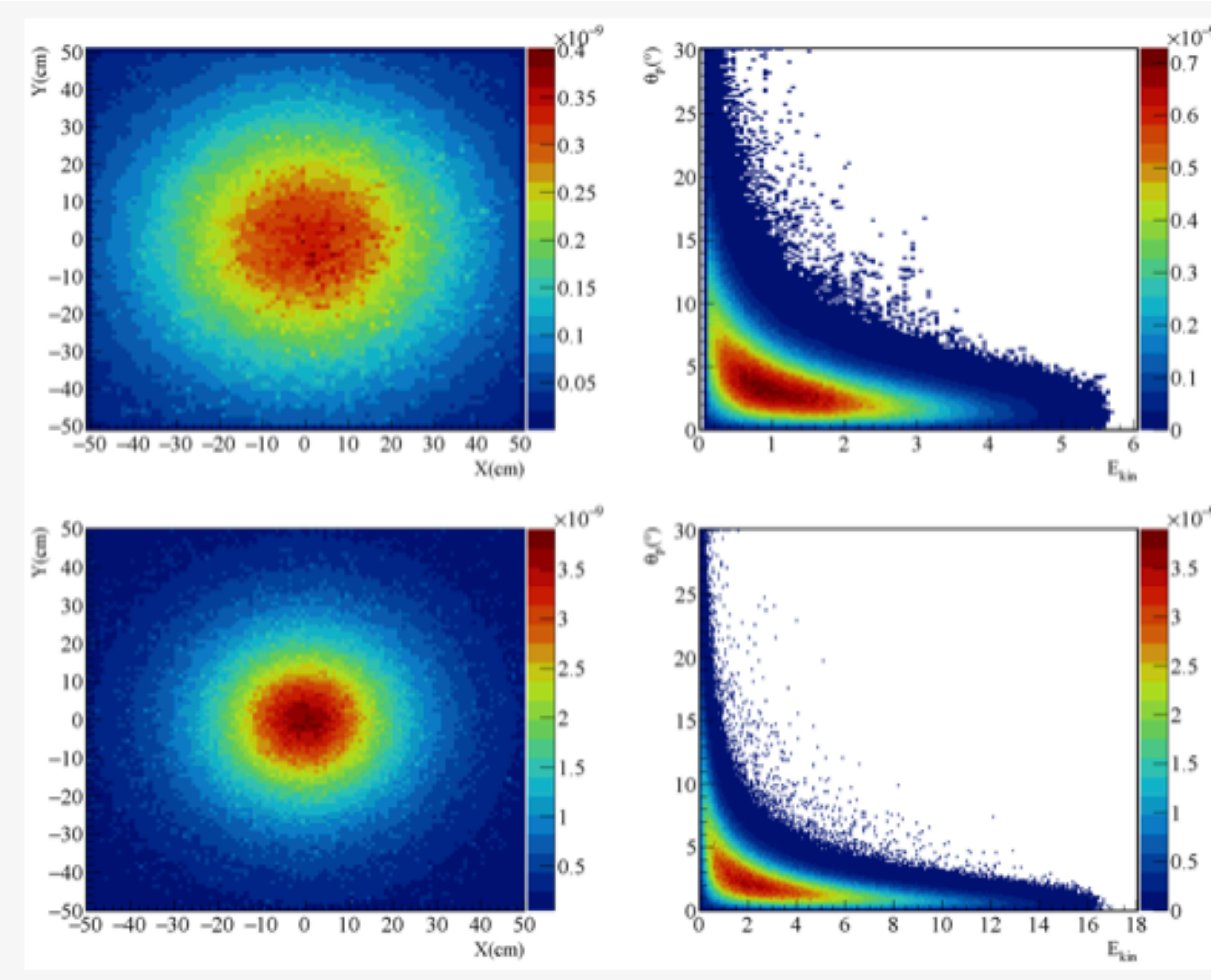
- Significant advantage at 22 GeV (higher muon flux and higher energy

The muon beam

- The flux increases with the energy of primary beam:
- Muon flux (11 GeV e- beam): 9 10^{-7} μ/EOT
  - Rate ~ 3 10^{8} μ/s
- Muon (22 GeV e- beam): 5.3 10^{-6} μ/EOT
  - Rate ~2 10^{9} μ/s
- CERN's M2 beamline (E_{μ}>100GeV - Rate ~2 10^{7})
- Muon flux profile: σ_x and σ_y ~ 20 cm

- Bremsstrahlung-like energy spectrum



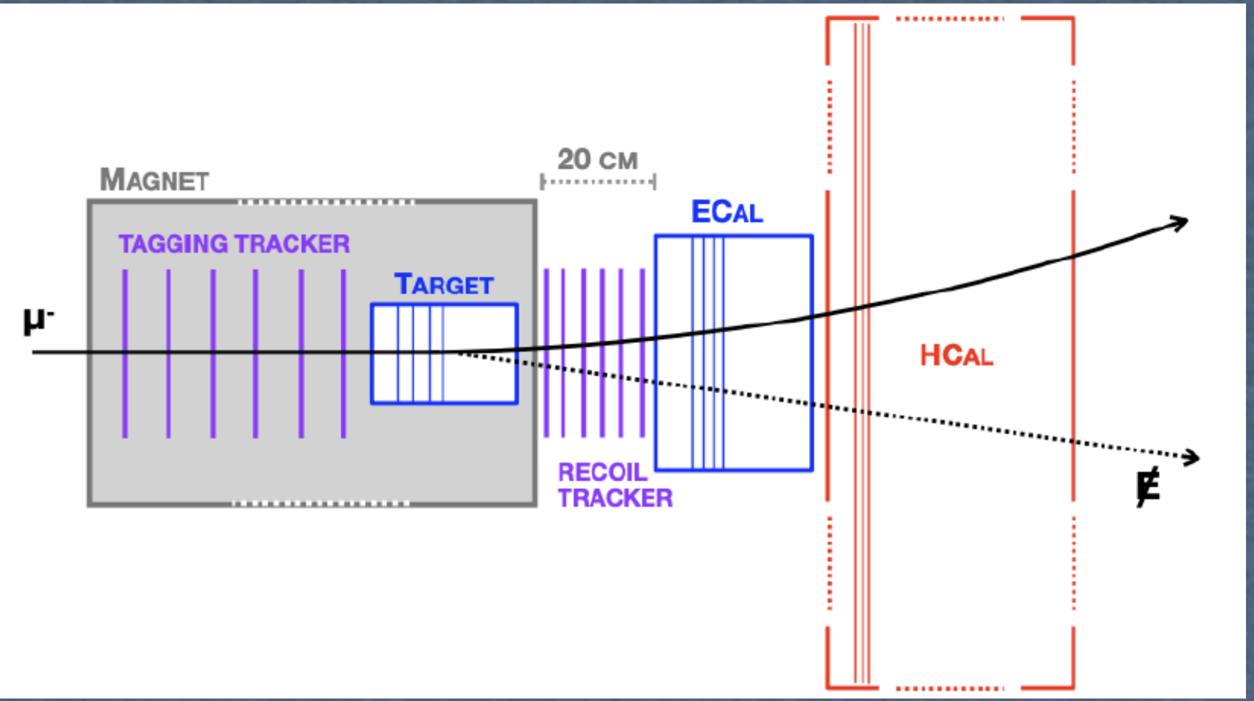


Beam Energy	Flux μ/EOT		σ_x (cm)	σ_y (cm)
	100 × 100 cm^2	25 × 25 cm^2		
11 GeV	9.8×10^{-7}	1.5×10^{-7}	24.6	25.1
22 GeV	7.6×10^{-6}	1.9×10^{-6}	20.9	20.9

Probing muon-philic forces with secondary muon beam

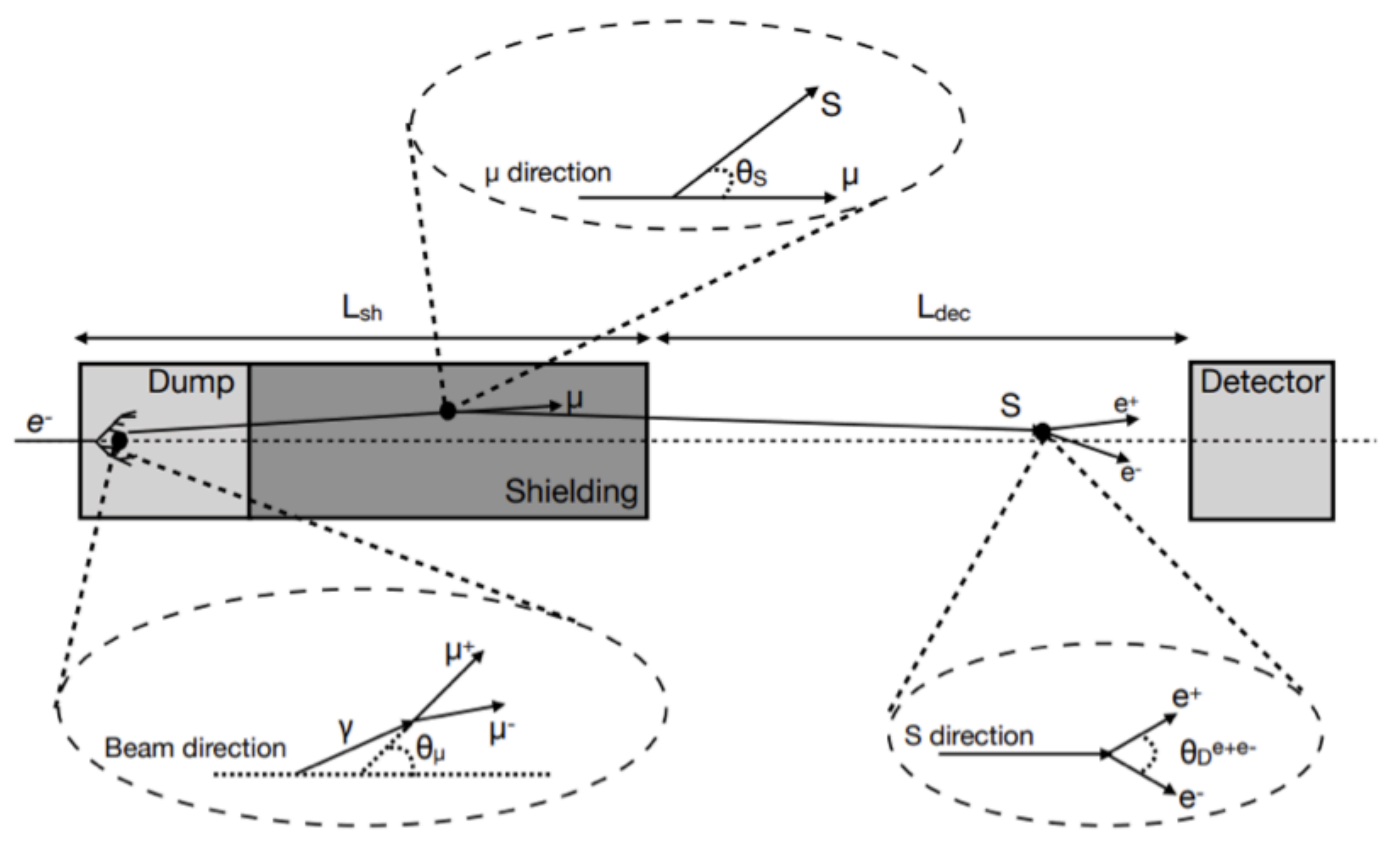
μ³BDX @ JLab

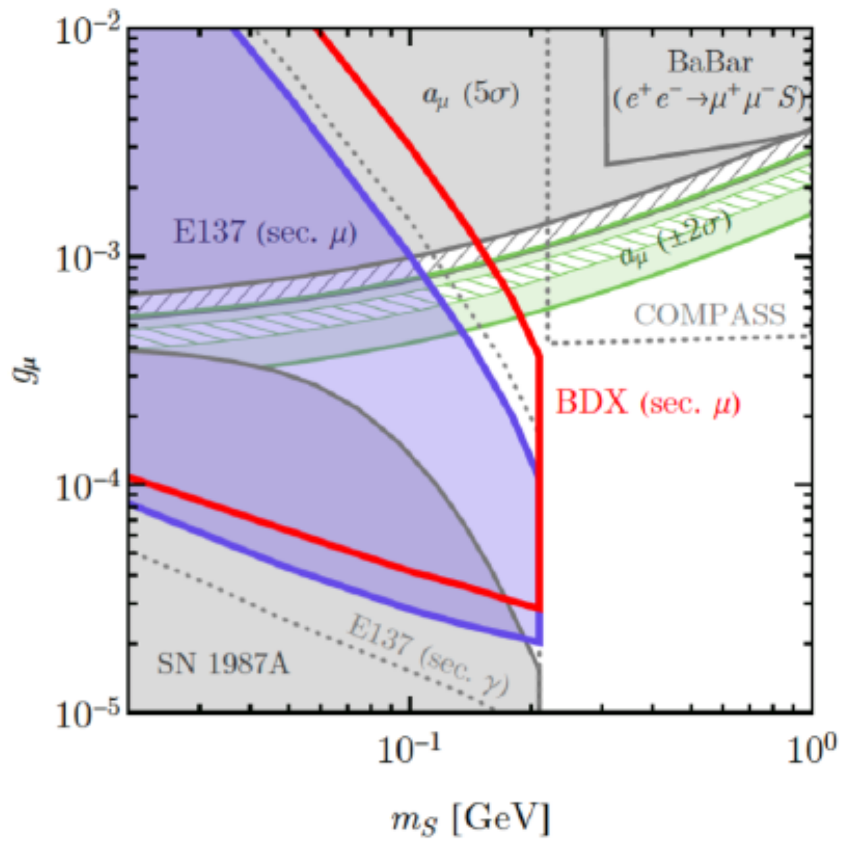
- Fixed-target, missing-momentum experiment to probe invisibly decaying particles
- BSM Light gauge boson couples predominantly to muon and or tau
- Scalar or vector mediator of a new force
- Its existence would be a viable explanation of g-2 anomaly
- This experiment is similar to M³ experiment proposed at FERMILAB



μBDX @ JLab

- Muon beam dump experiment to probe the visible decay into e+e-(γγ)
- Same infrastructure requested by BDX

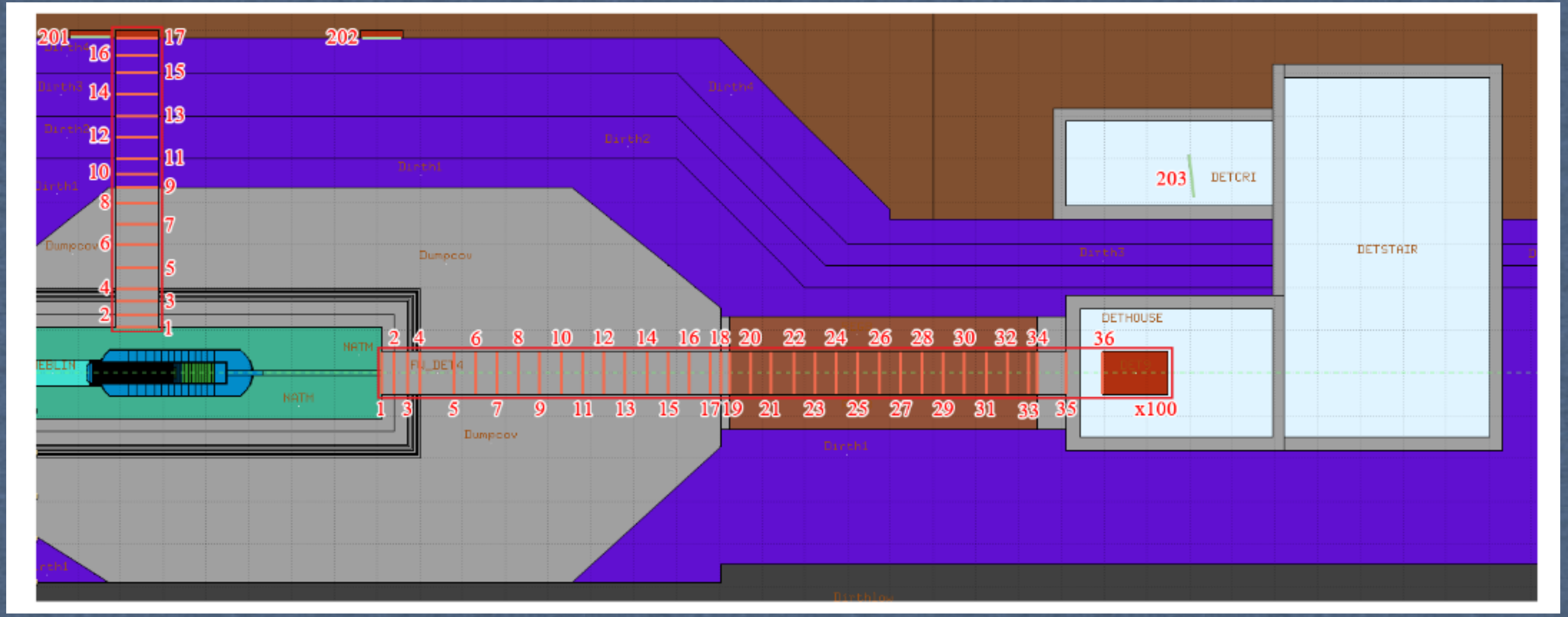


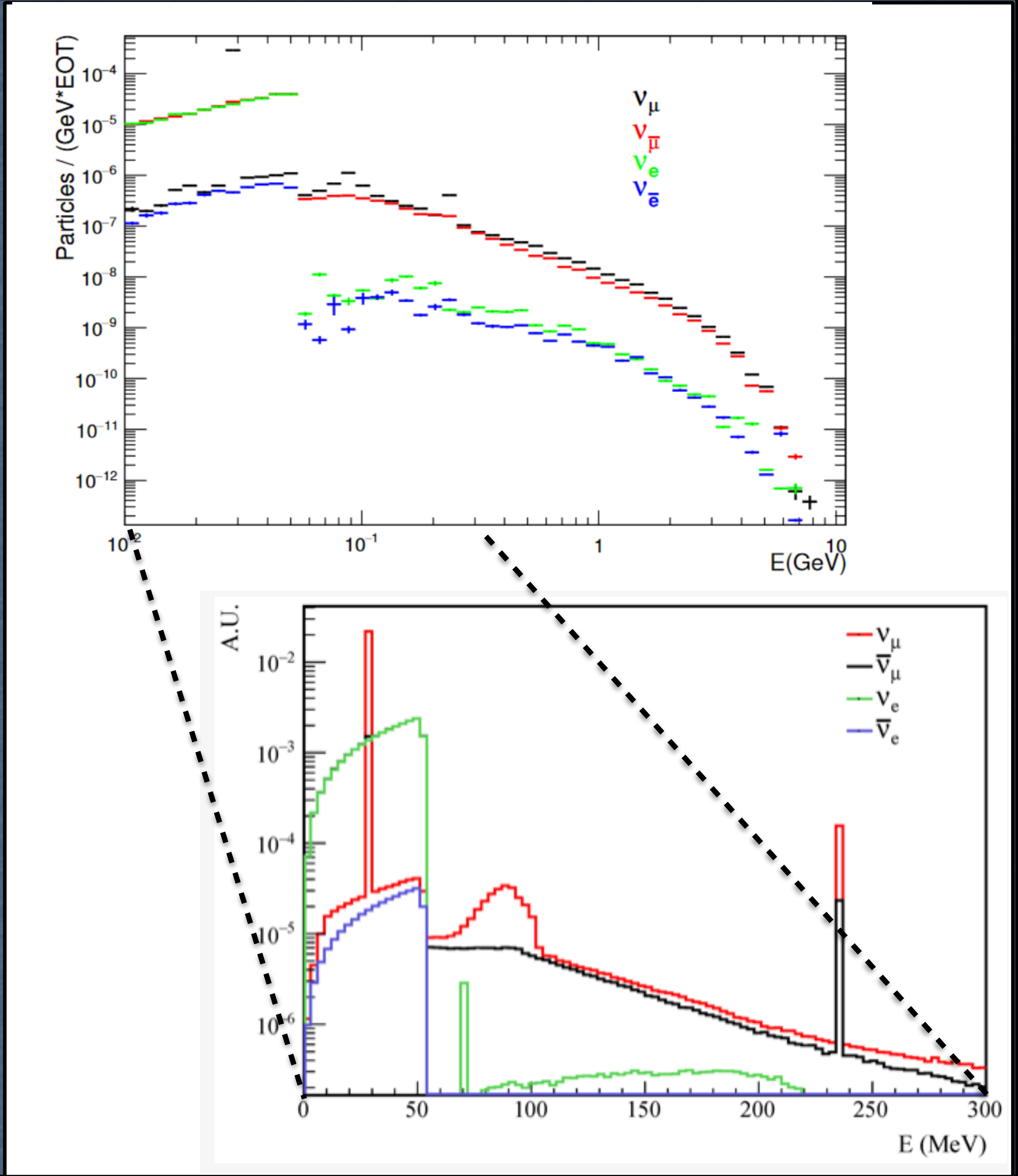


L. Marsicano et al., PRD 98, 115022 (2018)

Neutrino beam

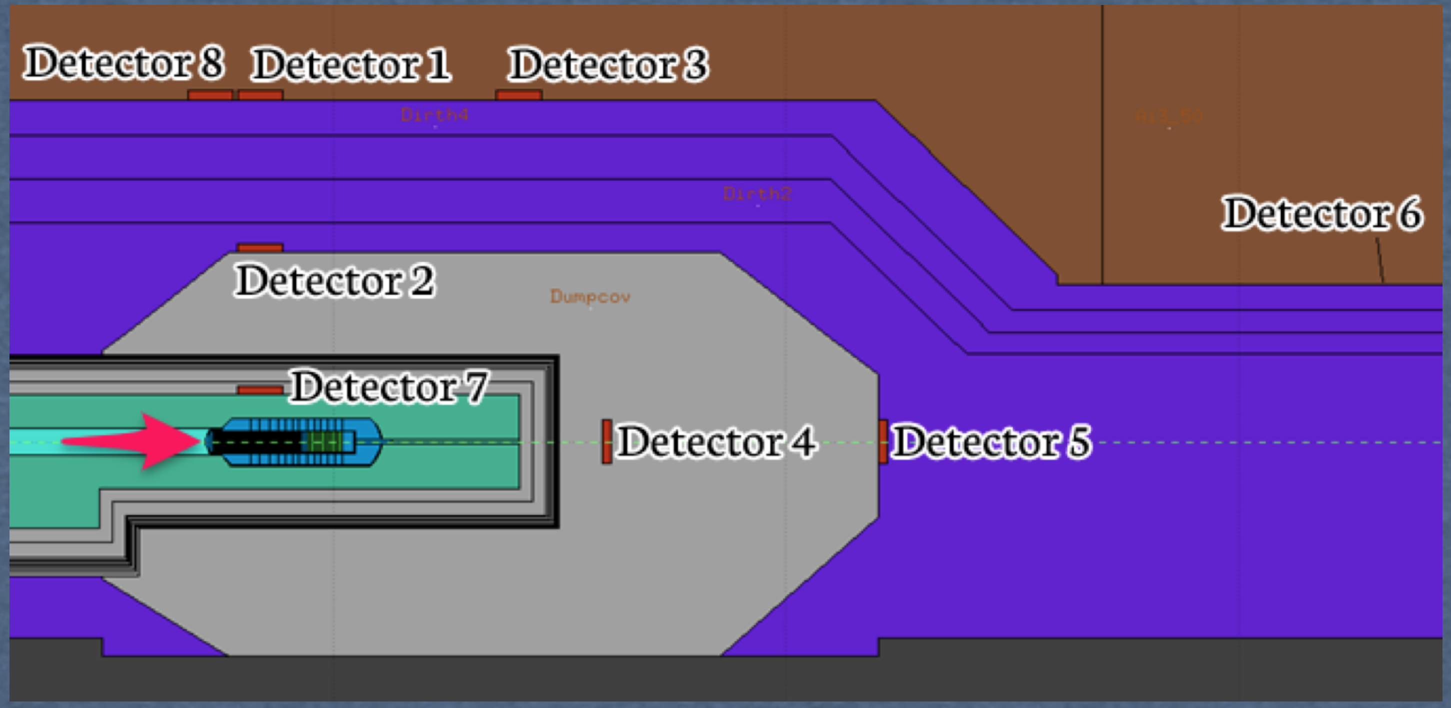
- Neutrino flux estimated using FLUKA for 11 GeV and 22 GeV primary e- beam on Hall-A BD
- Low energy νs due pion and muon decay at rest
  - π decay produces a prompt 28.5 MeV ν_μ along with a μ which subsequently decays producing a ν_e and a $\bar{\nu}_\mu$
  - Weak angular dependence
- High-energy ν from in-flight pion and muon decay

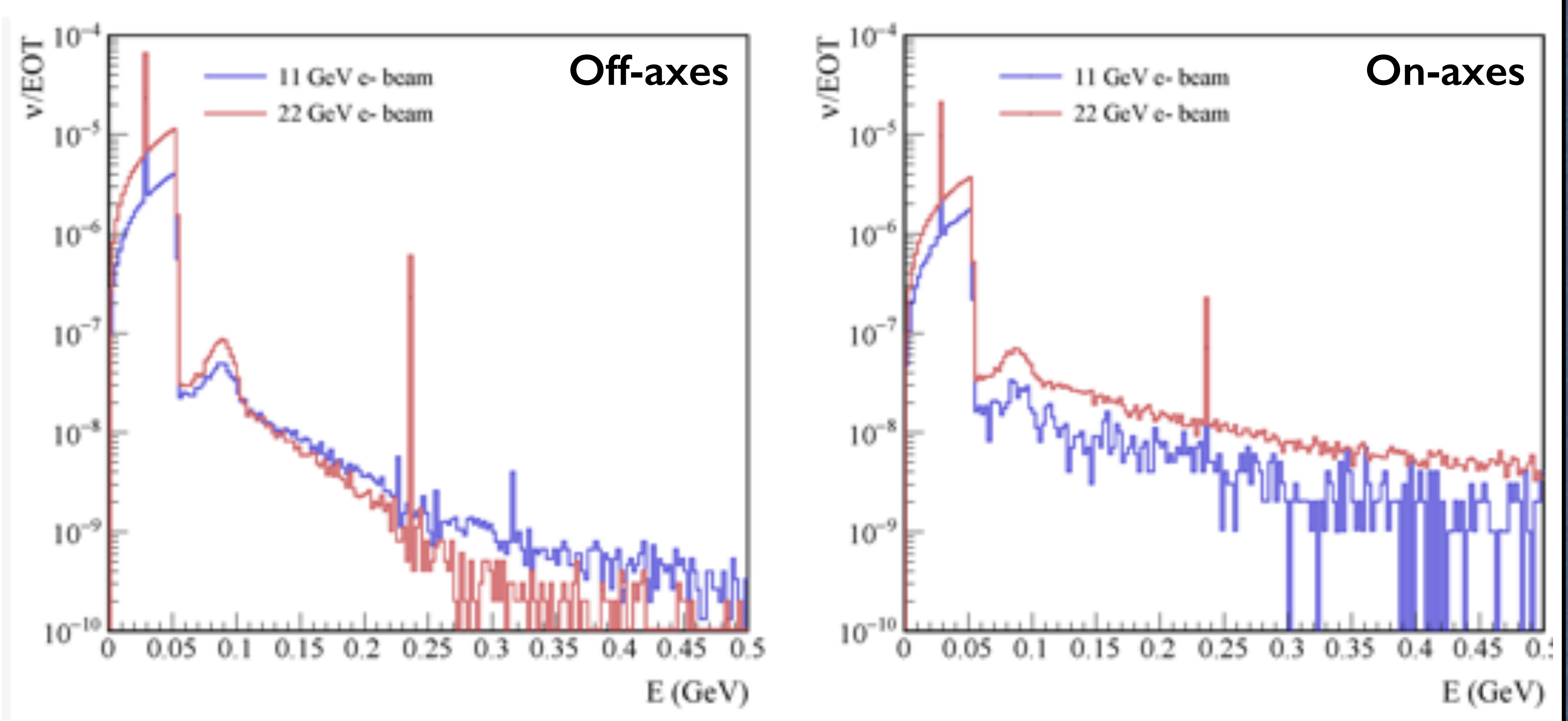




Neutrino beam

- Neutrino flux estimated using FLUKA for 11 GeV and 22 GeV primary e- beam on Hall-A BD
- Flux scored on a plane downstream Hall-A beam dump (D5):
  - 11 GeV e- beam: $3\ 10^{17}$ ν/m^2/year (1 year corresponding to 10^{22} EOT)
  - 22 GeV e- beam: $9\ 10^{17}$ ν/m^2/year (1 year corresponding to 10^{22} EOT)
- Decay-At-Rest (DAR) energy spectrum





Beam Energy	Off-Axis Flux [ν/EOT/m^2]	On-Axis Flux [ν/EOT/m^2]
11 GeV	6.7×10^{-5}	2.9×10^{-5}
22 GeV	1.9×10^{-4}	6.3×10^{-5}

νBDX @ JLab

Detecting CEvNS at JLab

CEvNS (Coherent Elastic nu-Nucleus Scattering)

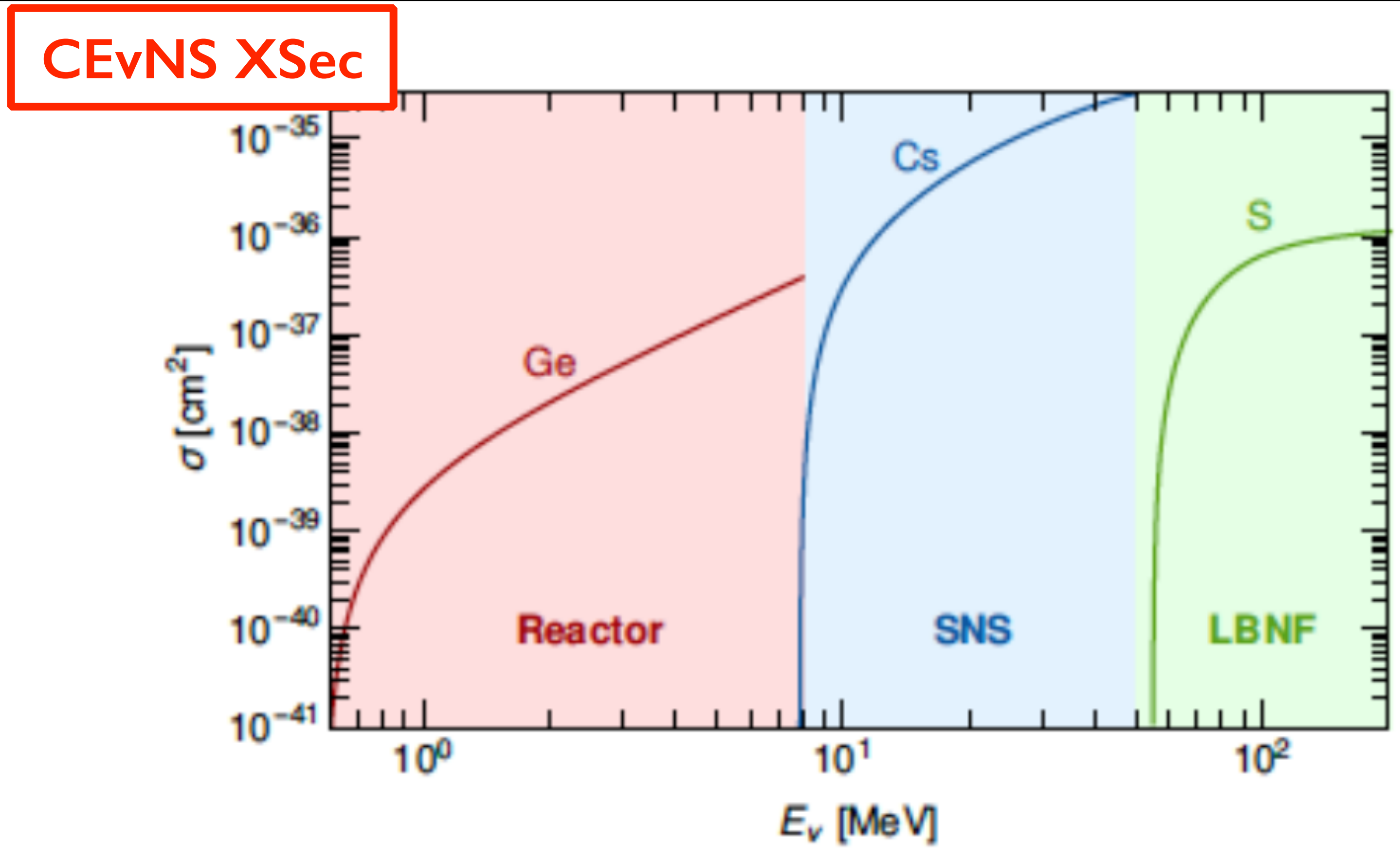
- Low-energy neutrinos (<100 MeV) coherent scatter on nucleus
- Cross-section scales as N^2
- The largest xsec for E_ν < 100 MeV
- First detected in 2017 on CsI by COHERENT (~134 events)
- Low recoil energy due to kinematics O(10 keV)

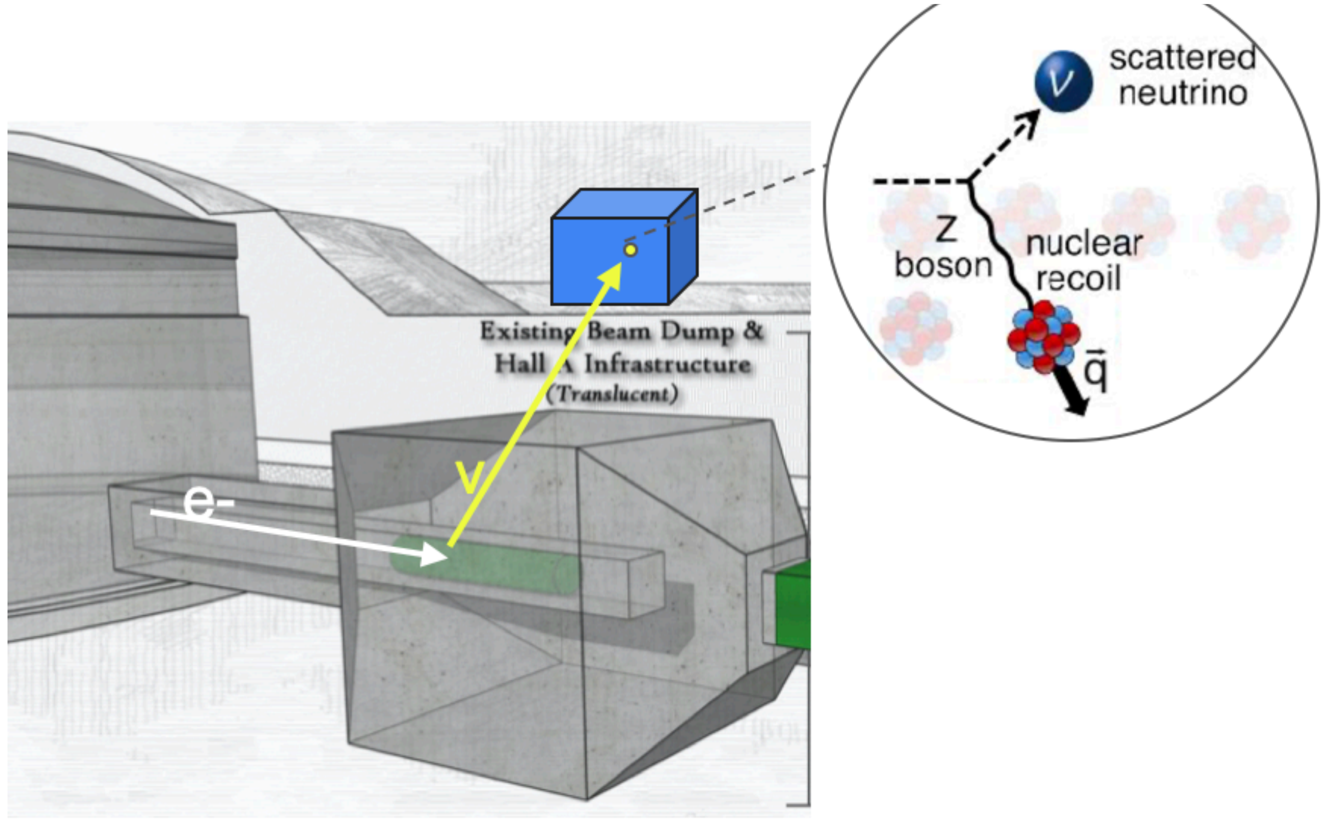
Why interesting?

- weak parameters -> mixing angle
- nuclear properties -> neutrons distribution radius
- sterile neutrino
- neutrino magnetic moment
- non standard interaction mediated by exotic particles

Requirements

- High-intense ν-flux
- ν-flux energy range: few MeV - few 100 MeV
- detector sensitive to small energy deposition
- small background





vBDX @ JLab

Detecting CEvNS at JLab

Neutrino beam

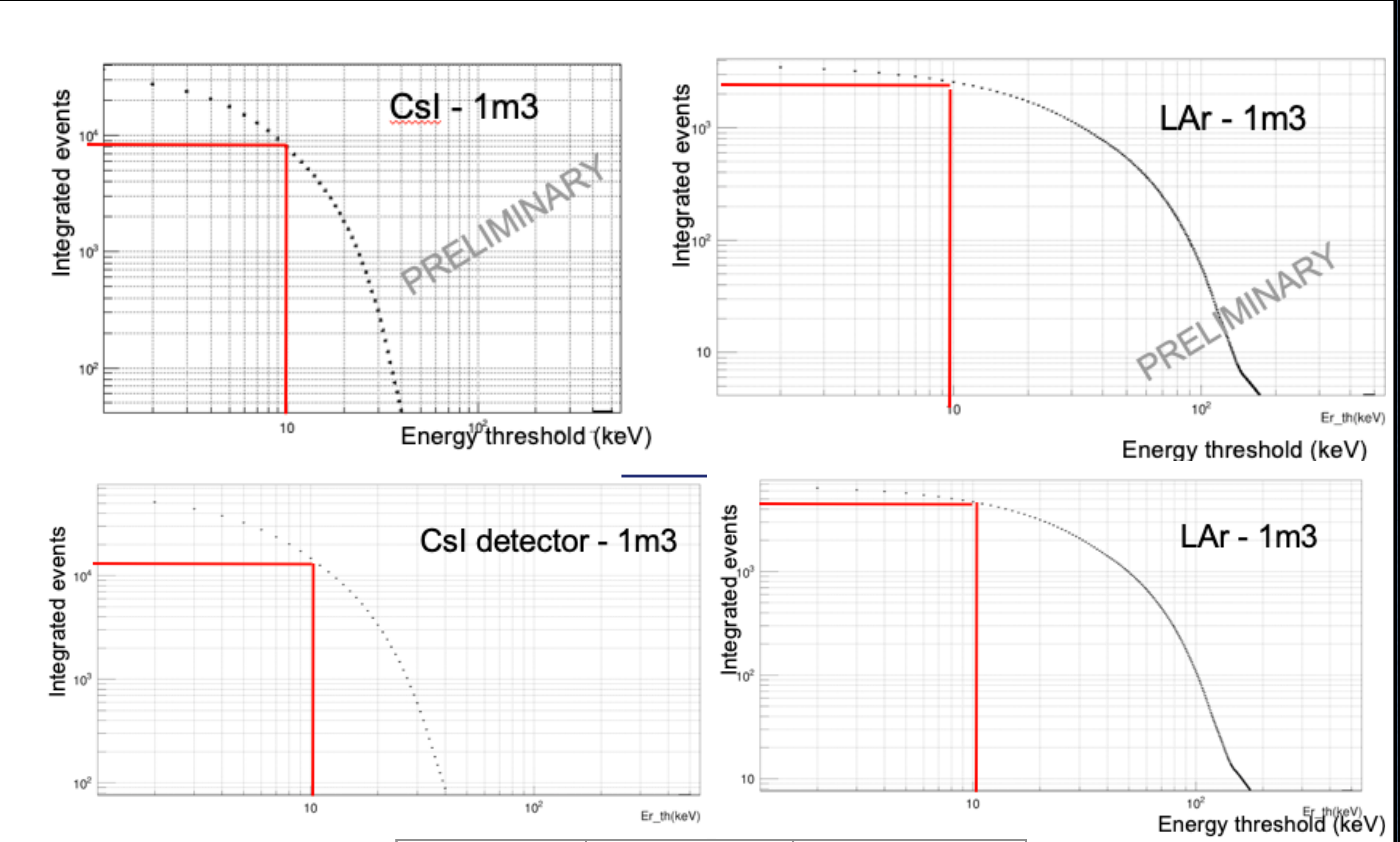
- Produced by the interaction between e- beam and Hall A dump
- DAR energy spectrum: 10MeV - 300 MeV
- 11 GeV e- beam : ~10^{18} v/m^2 at ~10 m above the dump for 10^{22} EOT
- 22 GeV e- beam: ~2 10^{18} v/m^2 at ~10 m above the dump for 10^{22} EOT

The detector

- 10m above the dump
- Two detection technologies under study:
  - CsI
  - LAr-TPC
- Veto system: active (plastic …) and passive (lead, water, borate silicone and/or cadmium sheet layers…)

The detector

- The beam-related background: neutron
- beam-unrelated background: cosmic, radioactive detector contamination, environmental radioactivity
- Background studies ongoing using MC simulation
  - In situ bg assessment to validate MC framework



Detector	e- @ 10 GeV v flux: 1E8 v/m^2/year	e- @ 20 GeV v flux: 2E8 v/m^2/year
CsI ($1m^3$) [thr : 10 keV]	8000	~15000
LAr ($1m^3$) [thr: 10 keV]	2500	~4500

vBDX @ JLab

Detecting CEvNS at JLab

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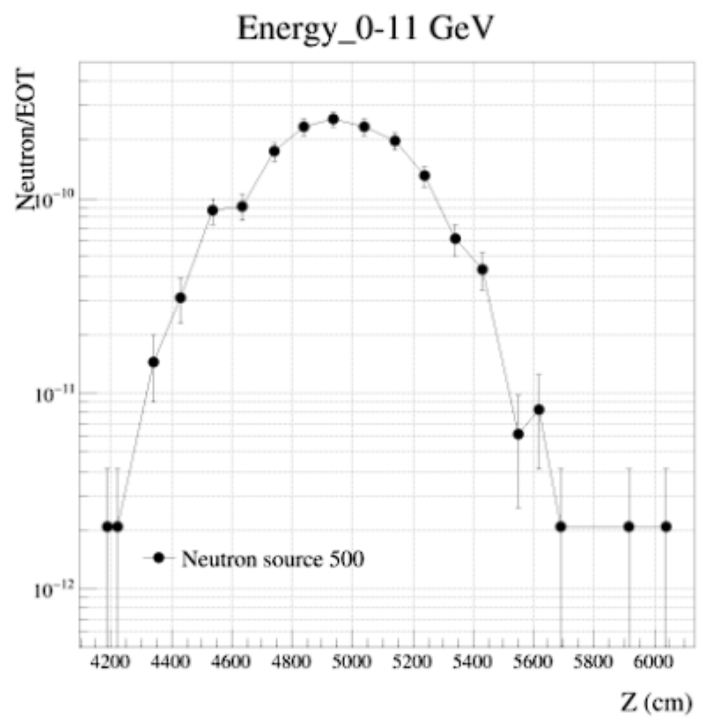
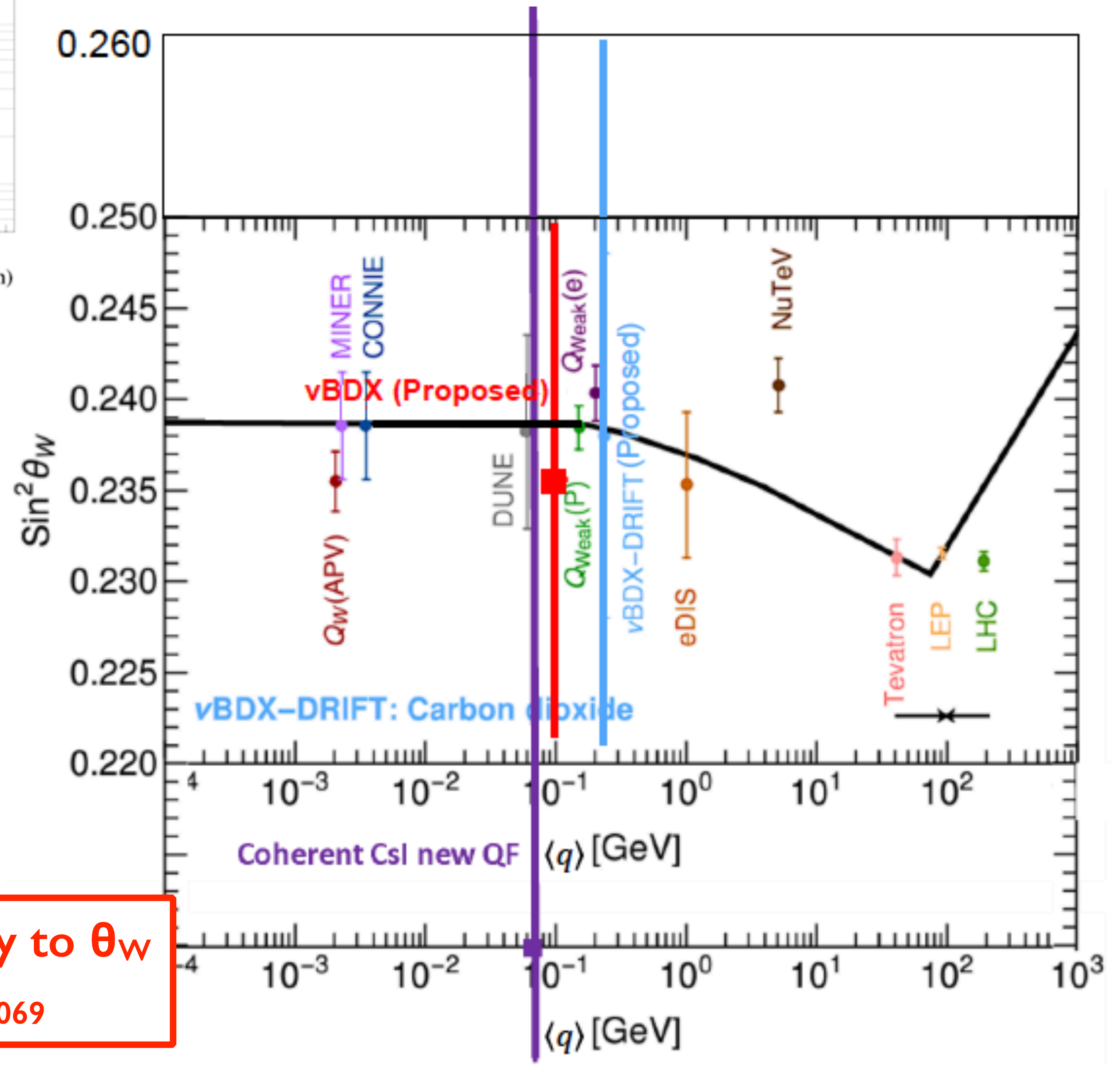


- Neutron background (beam-related and cosmics) included in vBDX reach

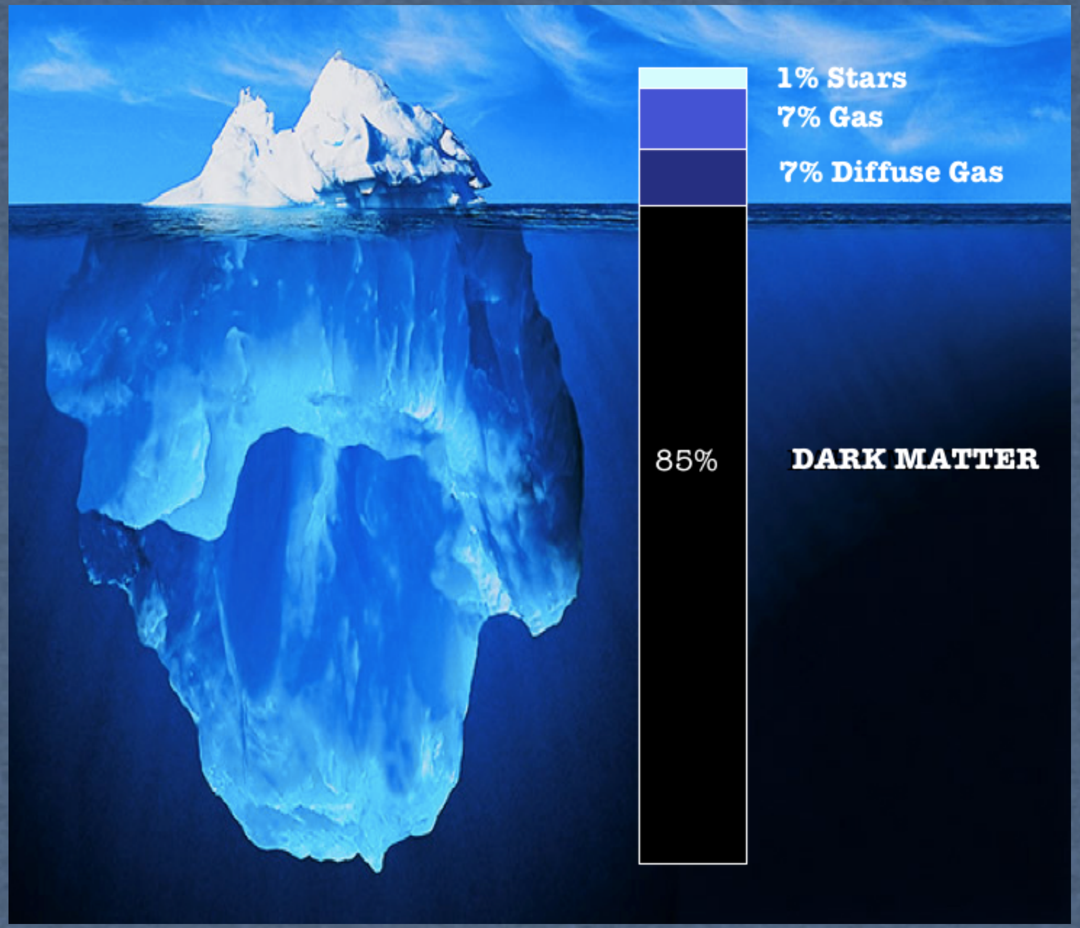


Projected vBDX sensitivity to θ_W
$\sin^2\theta_W = 0.209^{+0.072}_{-0.069}$

Dark Matter (DM) vs Baryonic Matter (BM)

Compelling astrophysical indications about DM existence

★ How much DM w.r.t. BM?



★ Does DM participate to non-gravitational interactions?
★ Is DM a new particle?

★ Constraint on DM mass and interactions

- should be '*dark*' (no em interaction)
- should weakly interact with SM particles
- should provide the correct relic abundance
- should be compatible with CMB power spectrum

… assuming that the gravity is not modified and DM undergoes to other interactions

★ We can use what we know about standard model particles to build a DM theory

Use the SM as an example: $SM = U(1)_{EM} \times SU(2)_{Weak} \times SU(3)_{Strong}$

Particles, interactions and symmetries

Known particles & new force-carriers

Particles:
quarks, leptons

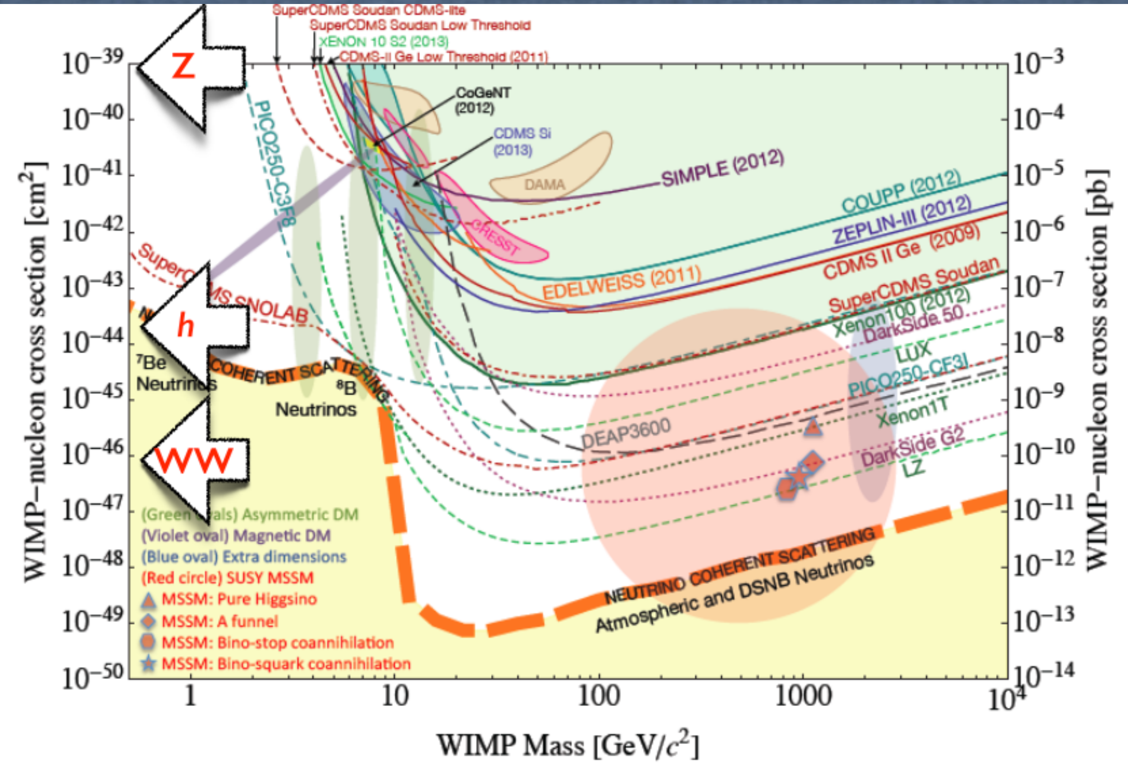
Force-carriers:
gluons, γ, W, Z, graviton (?), Higgs, ...

Two options:

★ New matter interacting trough the same forces
★ New matter interacting through new forces

Exploring the WIMP's option

★ Experimental limits



Slow-moving cosmological weakly interacting massive particles

- DM detection by measuring the (heavy) nucleus recoil
- Constraints on the interaction strength from the DM Direct Detection limits
  - Scattering through Z boson ($\sigma \sim 10^{-39}$cm^2): ruled out
  - Approaching limits for scattering through the Higgs ($\sigma \sim 10^{-45}$cm^2)
  - Close to irreducible neutrino background

✳ No signal observed in Direct Detection

✳ Experiments have (almost) no sensitivity to (light) DM (<1 GeV)

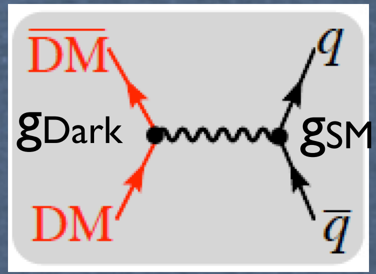
Direct Detection

1 MeV — 1 GeV — Mz — 10 TeV

WIMPs

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

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



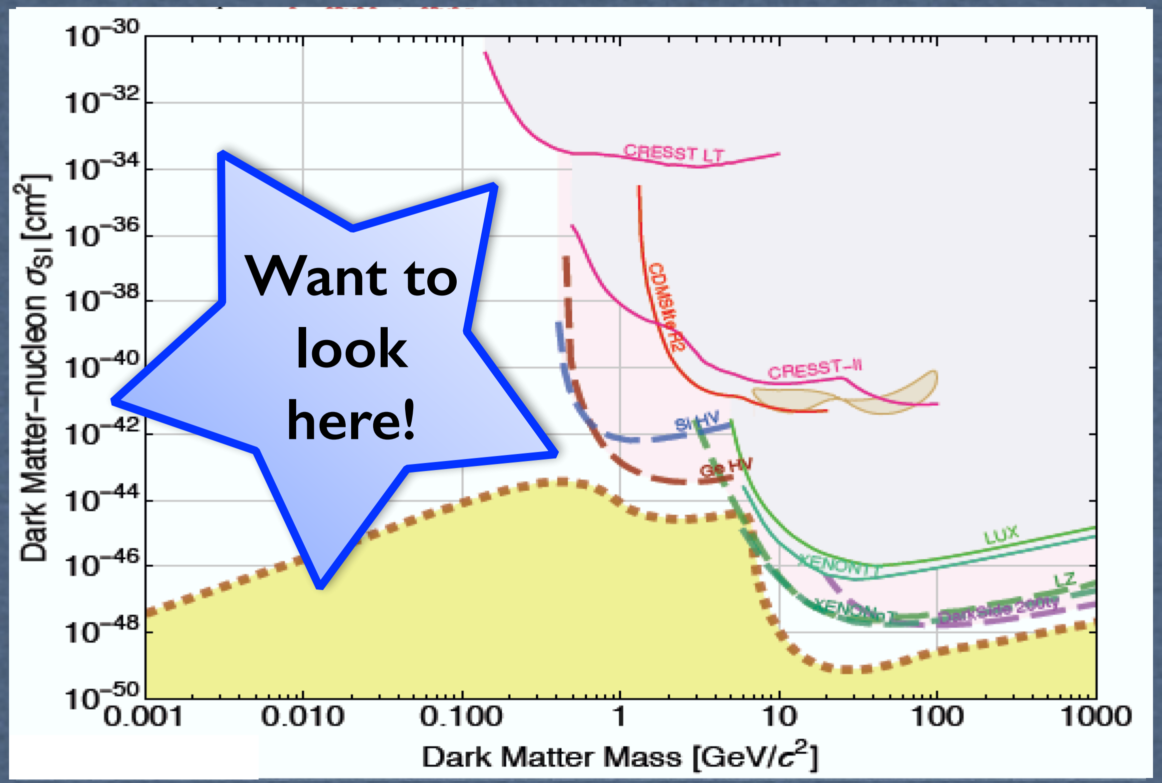
Light Dark Matter

Light Dark Matter (<TeV) naturally introduces light mediators

New interaction

Light Dark Matter

★ Experimental limits



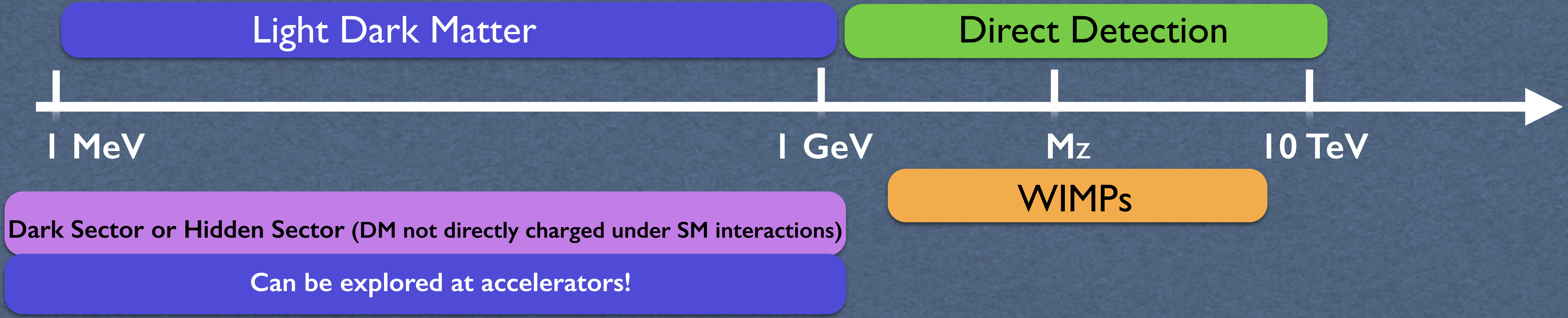
Light Dark Matter with a (almost) weak interaction (new force!)

- Direct Detection is difficult
  - Low mass elastic scattering on heavy nuclei produces small recoil
  - eV-range recoil requires a different detection technology
  - Directionality may help to go behind existing limits at large masses

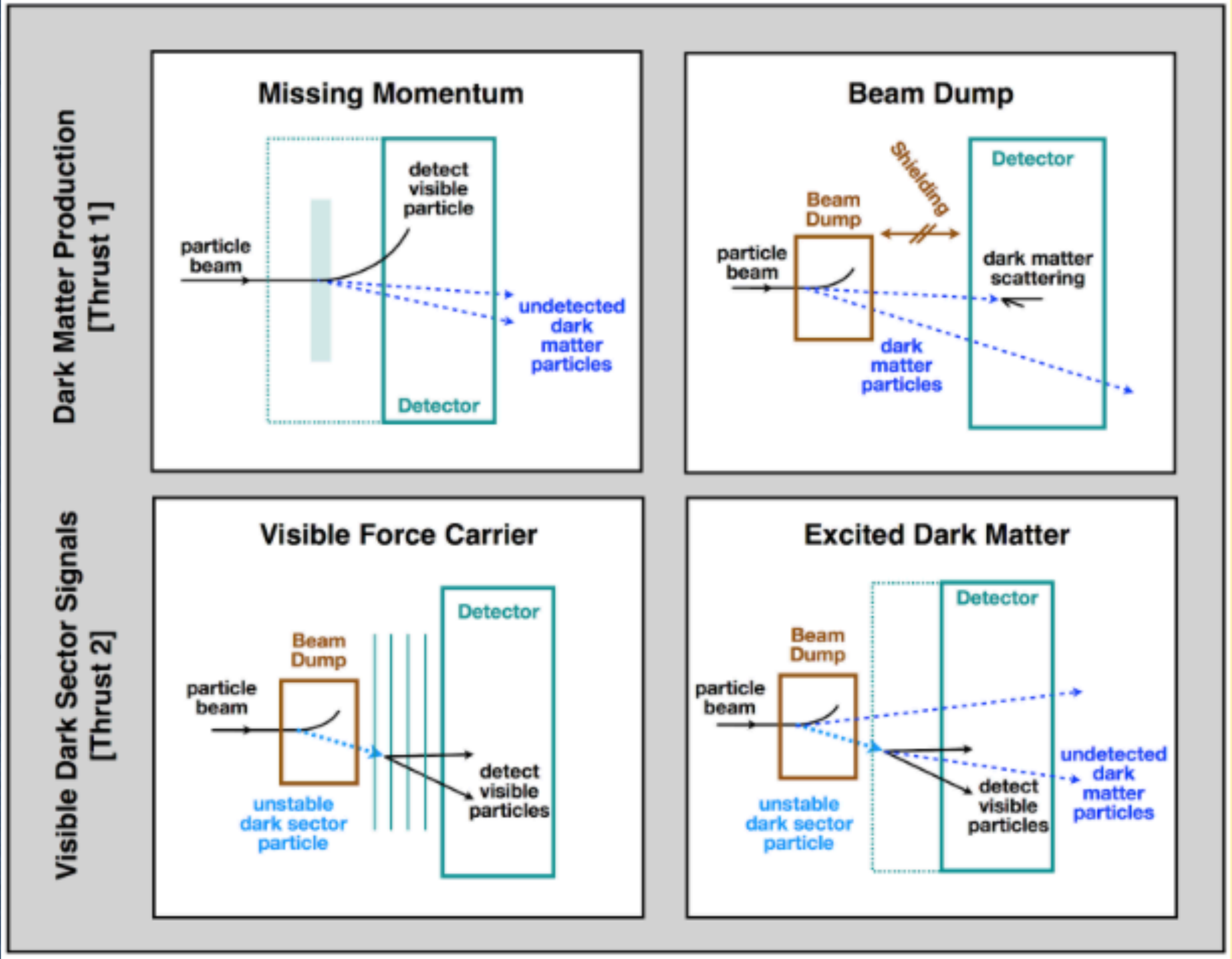
Accelerators-based DM search

covers an unexplored mass region extending the reach outside the classical DM hunting territory

- **High intensity**
- **Moderate energy**



Experimental techniques



Fixed target vs. collider

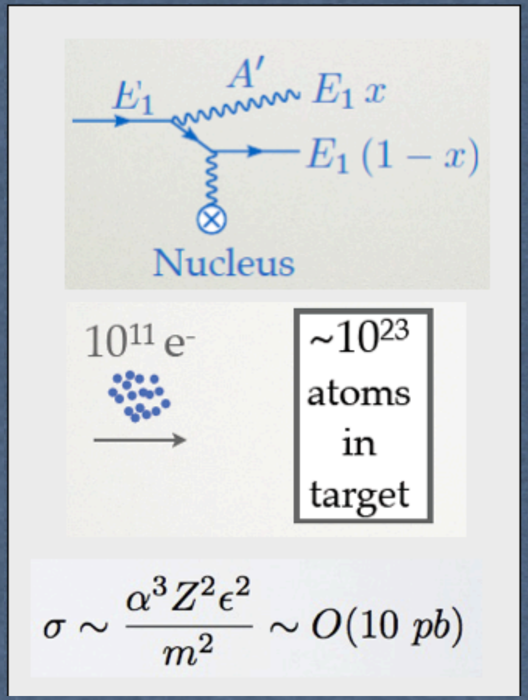
Fixed Target

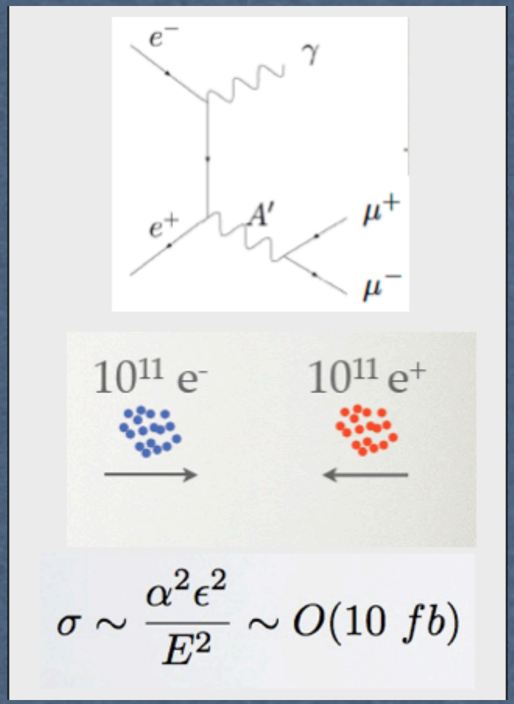
e+e- colliders

Process

Luminosity

Cross-Section





- high backgrounds
- limited A' mass

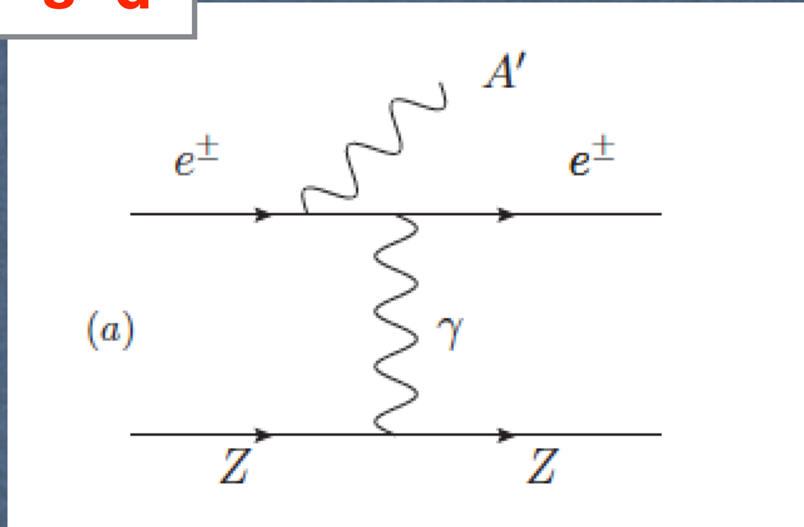
- low backgrounds
- higher A' mass

✶ $1/M_{A'}$ .vs. $1/E_{beam}$

✶ Coherent scattering from Nucleus (~Z^2)

A' Production mechanisms - $e^{\pm}$

~ $\varepsilon^2 \alpha^3$



The Weizsacker-Williams approximation (*A'-strahlung*)

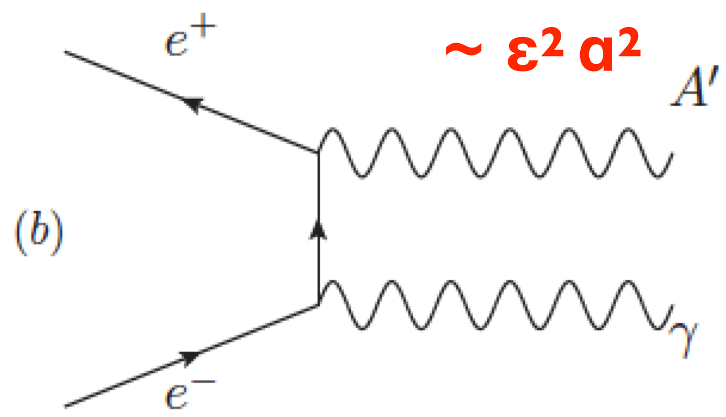
- The first tree-level mechanism proposed

L. Marsicano et al. Phys. Rev. Lett., 121(4) 041802, 2018
L. Marsicano et al. Phys. Rev. D, 98 (1) 015031, 2018

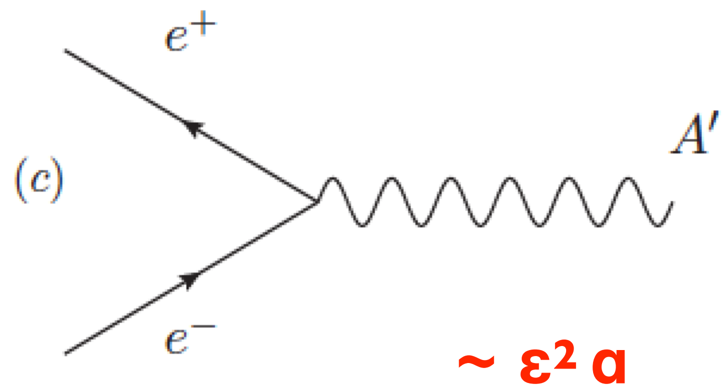
A' Production - resonant/non-resonant production

- Specific for positron annihilation
- A beam dump is a copious source of positrons
- Positrons in the EM shower may have any energy in the range of 0 - E_{beam}

~ $\varepsilon^2 \alpha^2$



- **NON-RESONANT annihilation**



~ $\varepsilon^2 \alpha$

- **RESONANT annihilation**

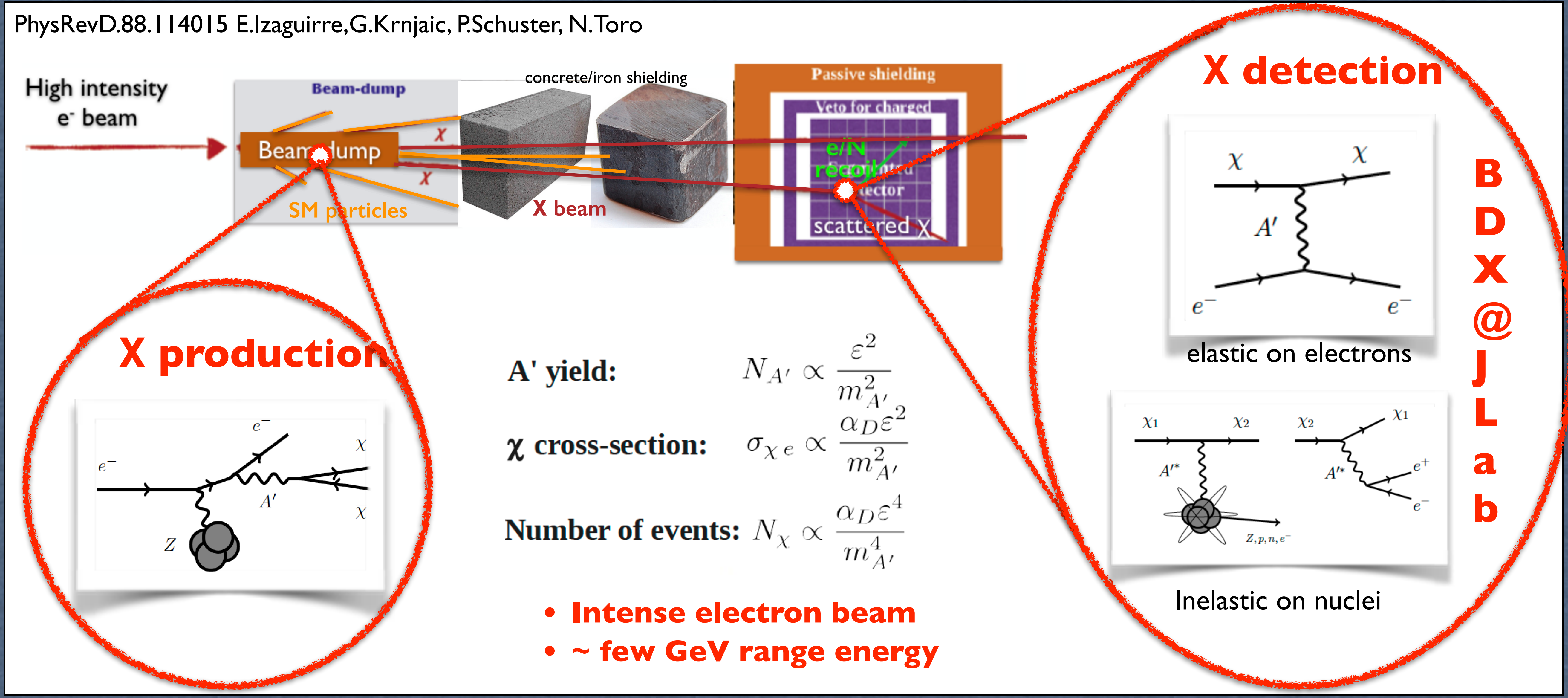
$$\sigma_r = \sigma_{\rm peak} \frac{\Gamma^2_{A'}/4}{(\sqrt{s} - m_{A'})^2 + \Gamma^2_{A'}/4},$$

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)



Experimental signature in the detector: **X-electron → EM shower ~GeV energy**

BDX @ JLab

★ JLab Hall-A offers the best condition for the BDX experiment
- A high energy beam: 11 GeV
- The highest available electron beam current: ~65 uA
- The highest integrated charge: 10^{22} EOT (41 weeks)

★ Fully parasitic wrt Hall-A physics program

★ Drilled shaft downstream of Hall-A BD

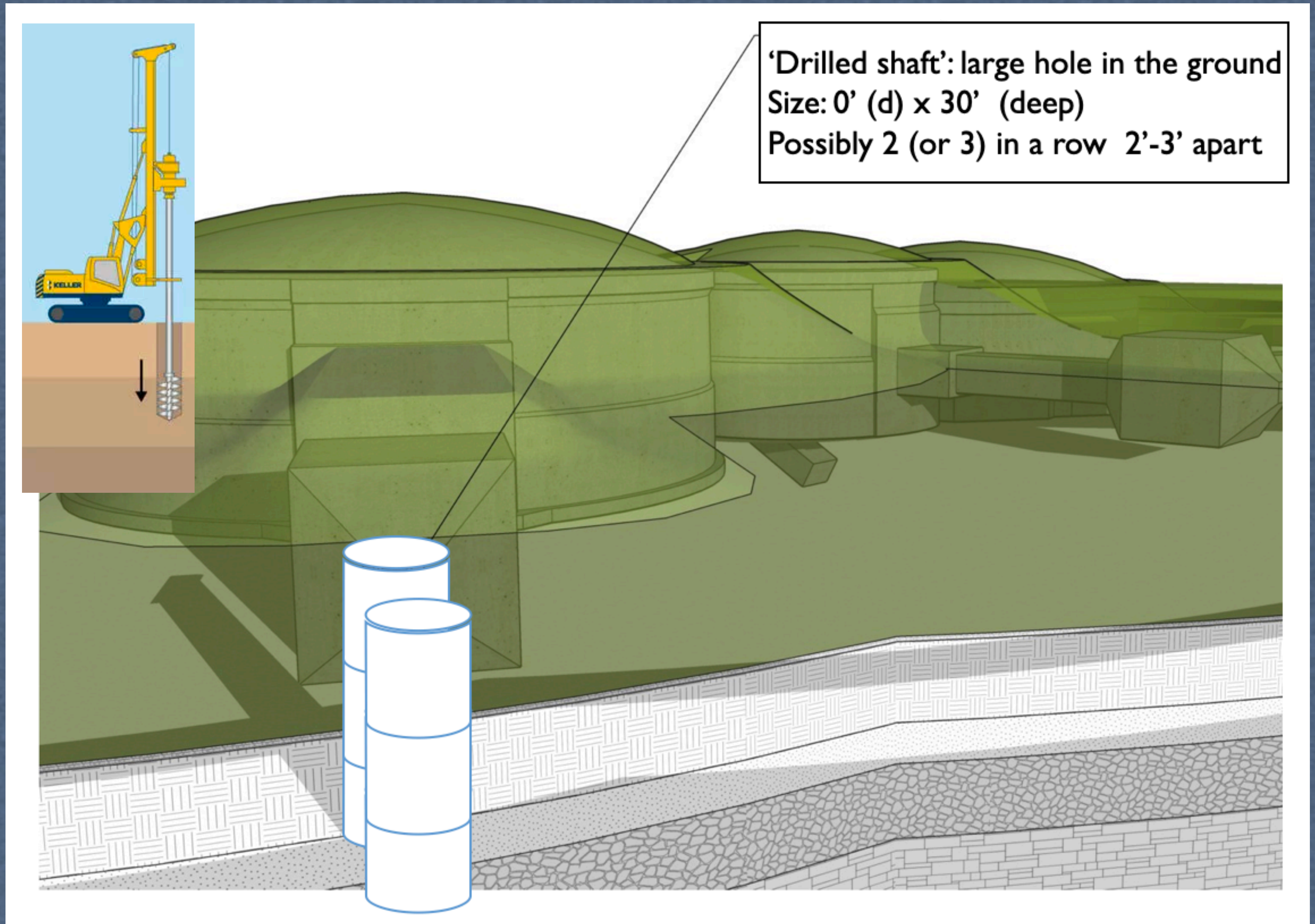
★ Approved by JLab PAC-46 in July 2018 with maximum scientific rate (A) and waiting for scheduling

★ Expected to run in parallel to the Moeller experiment (2026-2029)

★ Presented, discussed, and included in SNOWMASS-21 report (RF6-RF0)

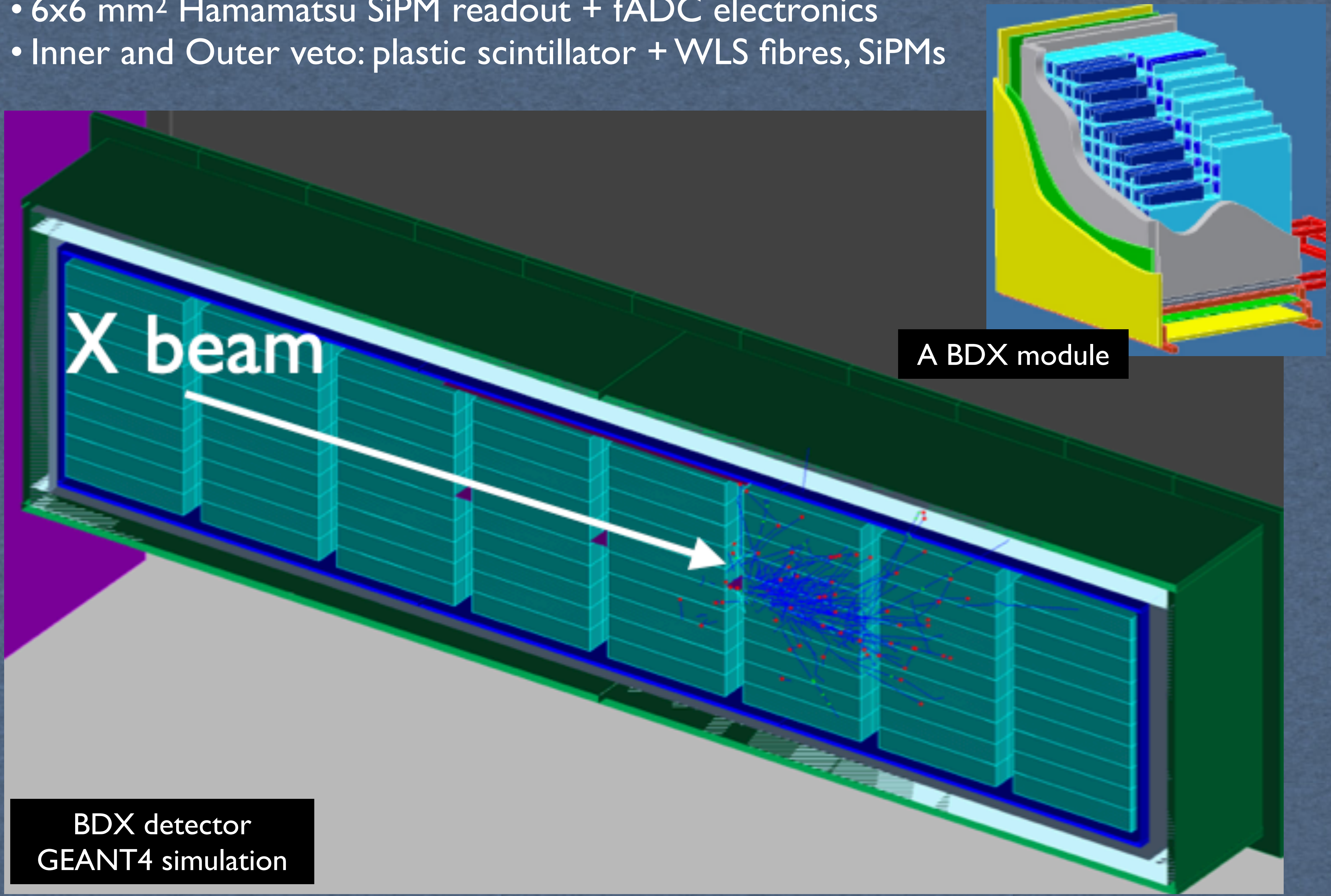
★ BDX would take advantage of the future 11 GeV positron beam and 20+ GeV upgrade

★ BDX Collaboration: more than 100 researchers from 18 institutions (US, Italy, Germany, UK, Korea) signed the BDX proposal



The BDX detector

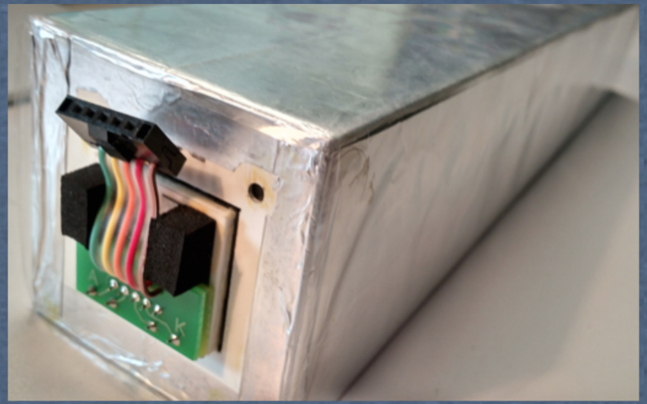
- Modular design
- 8 modules each having 10x10 crystals
- 800 CsI(Tl) crystals
- 6x6 mm^2 Hamamatsu SiPM readout + fADC electronics
- Inner and Outer veto: plastic scintillator + WLS fibres, SiPMs

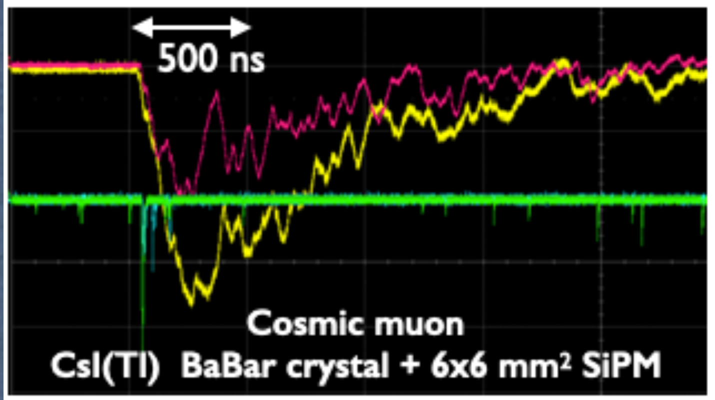


BDX detector
GEANT4 simulation

A BDX module

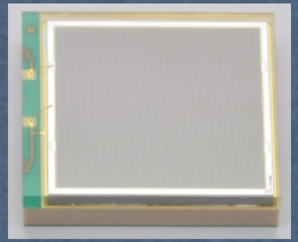
E.M. Calorimeter





Crystals available from BABAR em calorimeter

- Size: (5x5)cm^2 front face, (6x6)cm^2 back face, 30cm length
- 820 crystals available from end cap
- Decay time: fast 900ns, slow 4000ns
- LY= 50k γ/MeV



SiPM readout

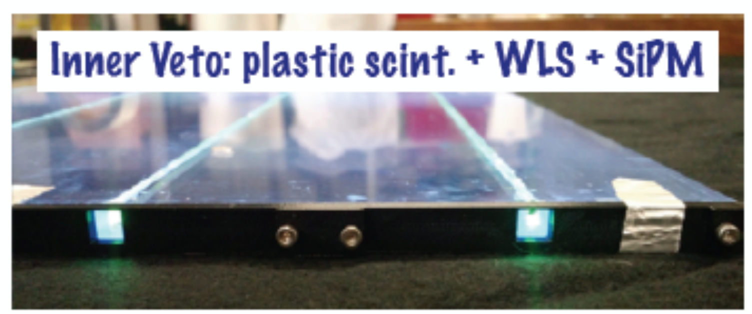
- Size: 6x6 mm^2, 25μm, 57.6k cells, trenched, pde=25%
- SPE capability
- CsI(Tl): 40 pe/MeV
- Time resolution: ~6ns (MIPs)

M.Bondi et al. NIM.A, 867:148–153, 2017

Veto

Inner/Outer veto:

- 1cm (clear) plastic scintillator + WLS fibers
- 3x3 SiPM readout
- LY= 15-50 pe/MIP



BDX sensitivity

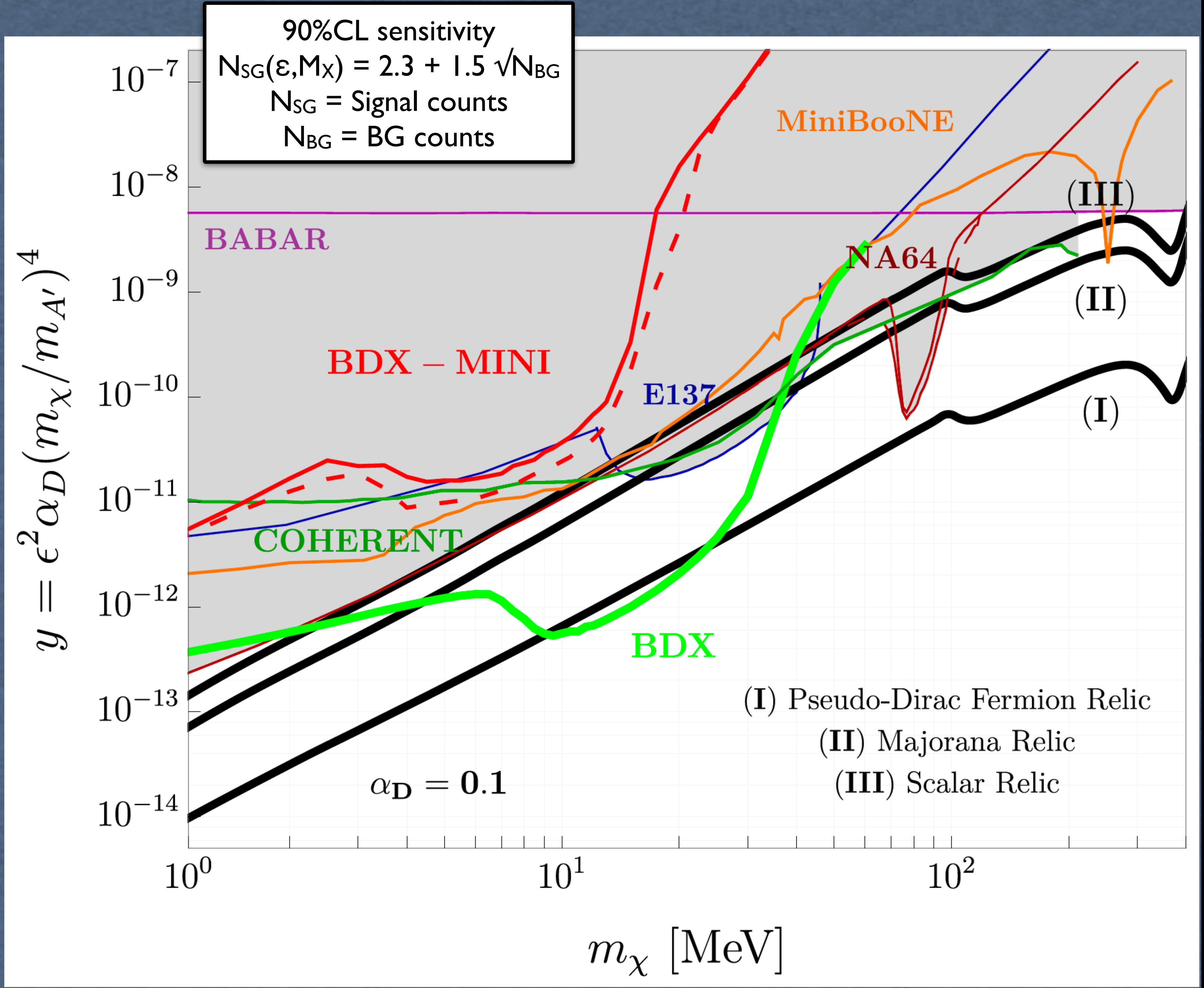
Beam time request (parasitic to Hall-A ops)

- 10^{22} EOT (65 uA for 285 days)
- BDX can run parasitically with 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	√ Bg (285 days)
300 MeV	<2 counts

- Calculation includes resonant positron annihilation
- Sensitivity to inelastic LDM is not shown



The sensitivity of BDX exceeds more than 10x the existing limits on LDM production
Such tight exclusions will set limits on LDM mechanisms or render an important null result

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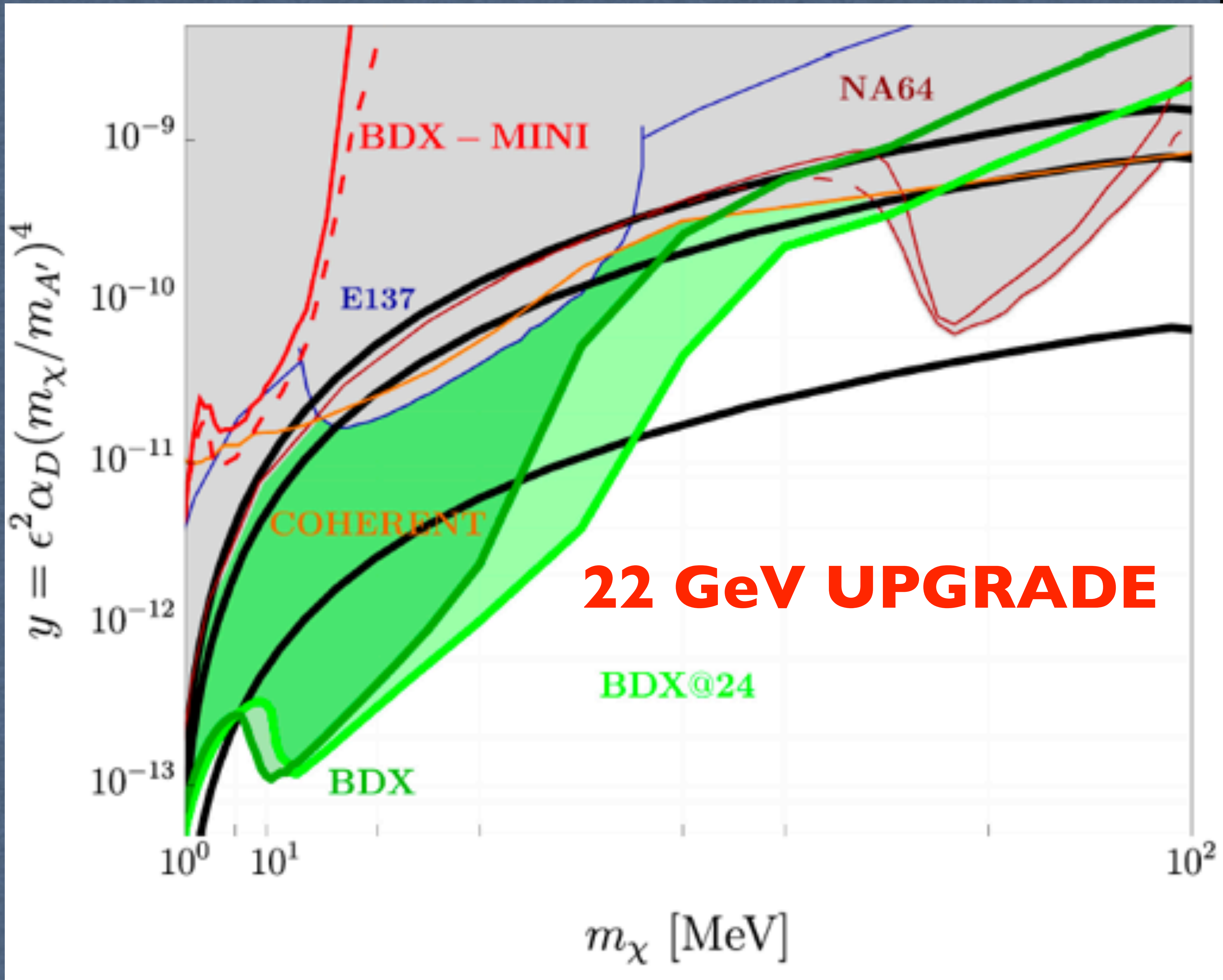

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Conclusions

- High-intensity electron beams are a precious source of secondary beams:
- The high intensity (~100uA), medium energy (~10 GeV) CEBAF electron beam at Jefferson lab is ideal for producing secondary beams
  - Light Dark Matter (if it exists)
  - Neutrinos
  - Muons
  - (positrons)
- Realistic simulations performed with FLUKA and GEANT4
  - Muon beam: Bremsstrahlung-like energy spectrum, (100 MeV - 5 GeV), $\sim 10^{-6}$ μ/EOT
  - Neutrino beam: DAR energy spectrum , (0 - 50 MeV), $3\ 10^{17}$ ν/m^2/year
  - LDM: best beam around the world for a beam-dump experiment
- The 22 GeV upgrade of CEBAF will provide even better secondary beams (in particular muons)
- Secondary beams offer new opportunities to complement hadron physics at lepton-beam facilities fully parasitically