MENU 2023 - The 16th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon

15–20 Oct 2023
Europe/Berlin timezone

MENU 2023

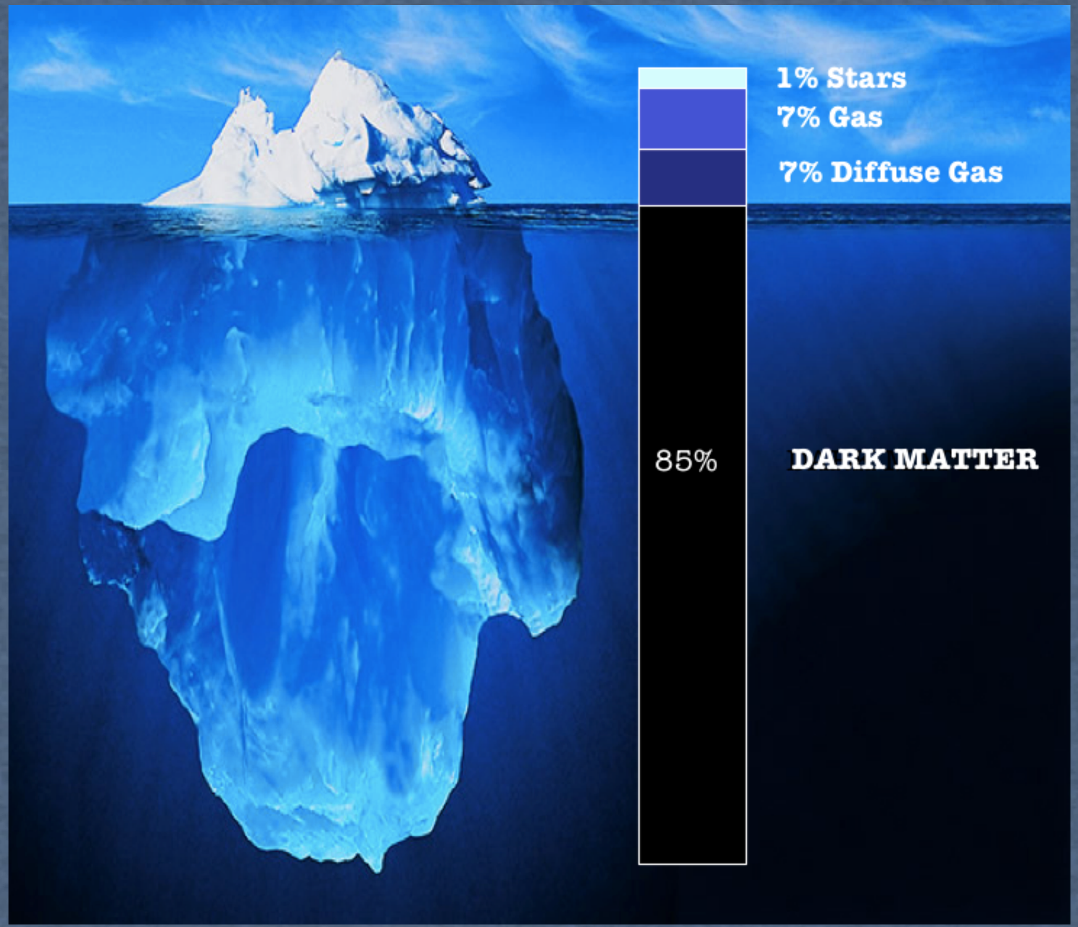
Dark Sector searches at the intensity frontier

M.Battaglieri (INFN)

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

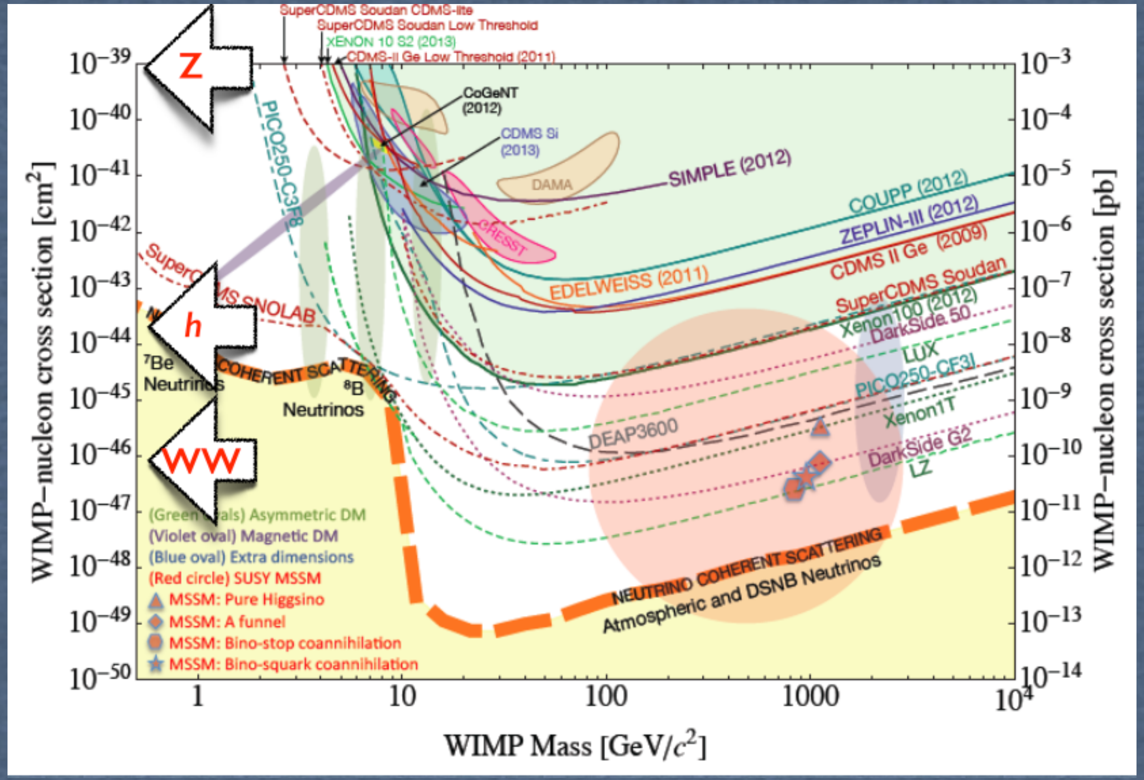
Force-carriers:
gluons, γ, W, Z, graviton (?), Higgs, ...

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)

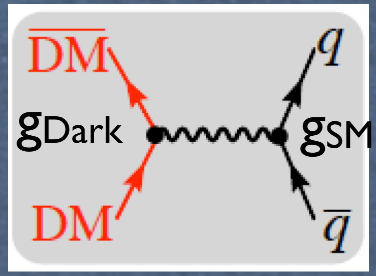
Direct Detection

1 MeV — 1 GeV — Mz — 10 TeV

WIMPs

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

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



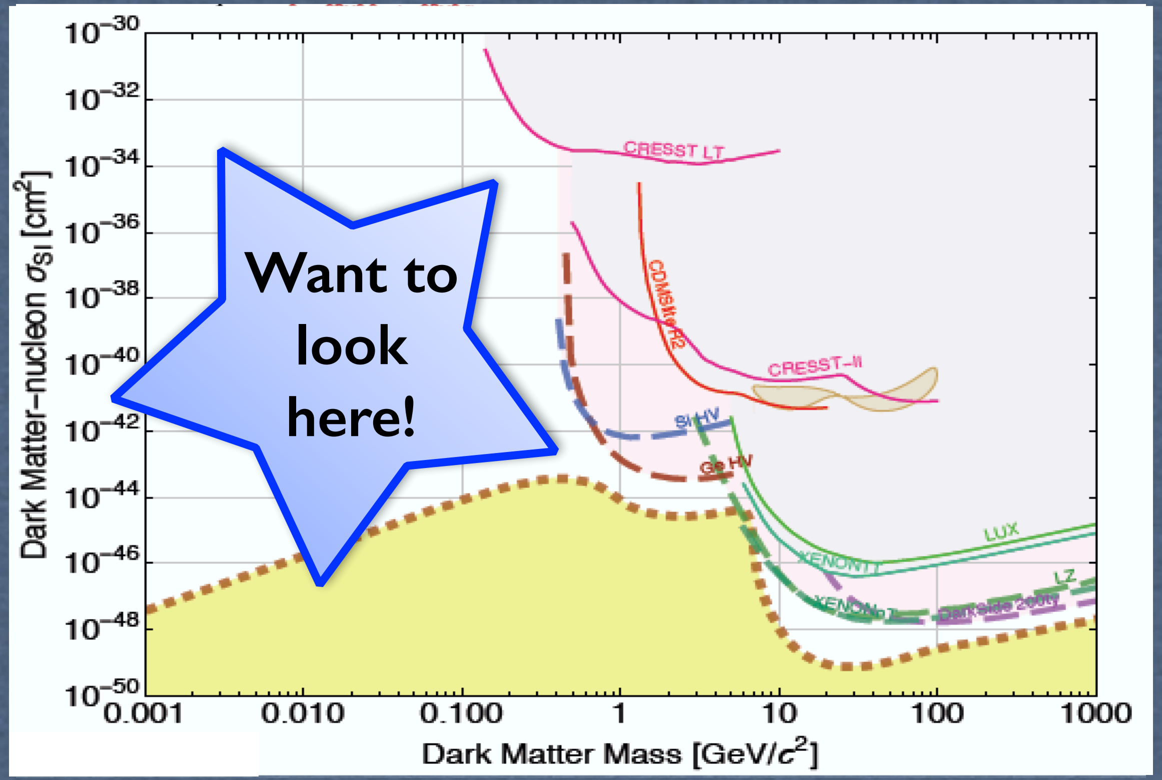
Light Dark Matter

Light Dark Matter (<TeV) naturally introduces light mediators

New interaction

Light Dark Matter

★ Experimental limits



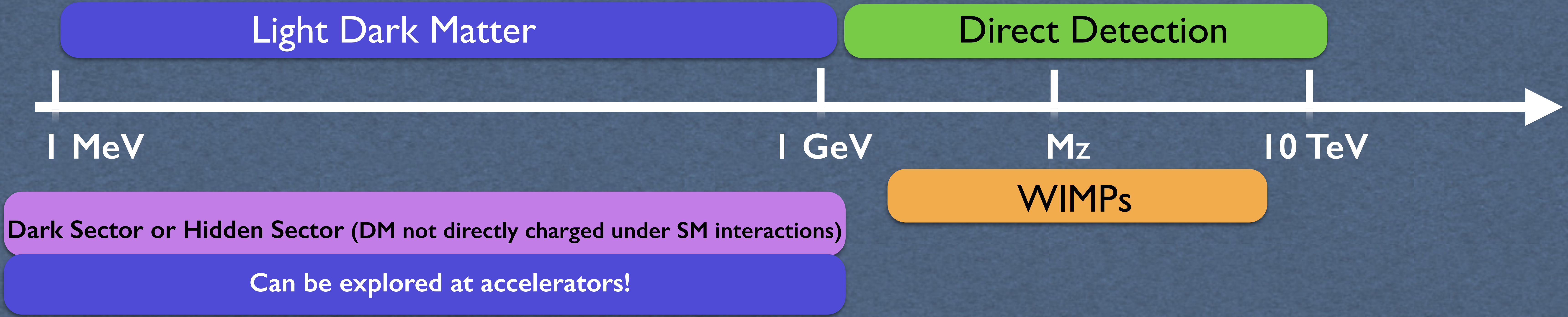
Light Dark Matter with a (almost) weak interaction (new force!)

- 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

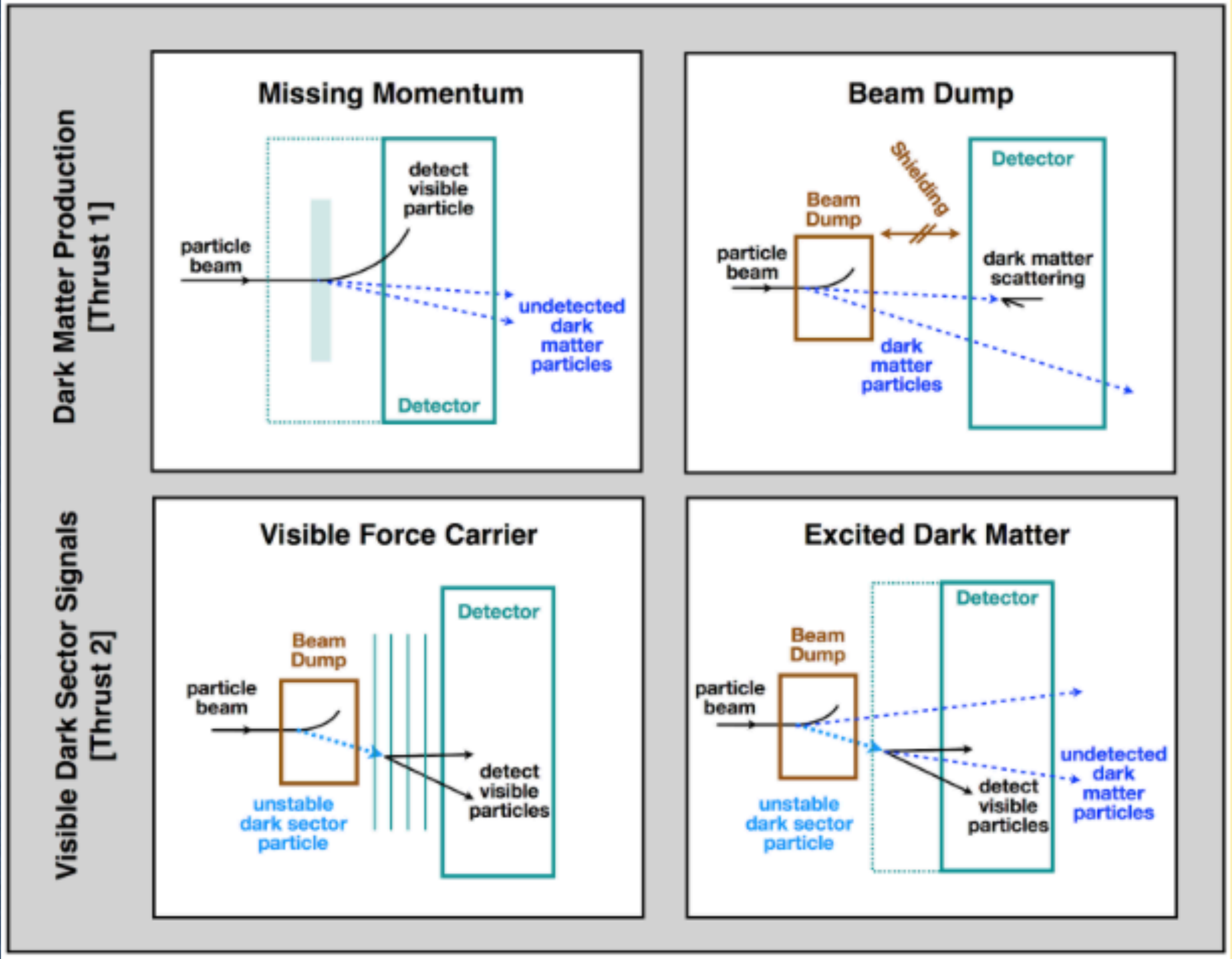
Accelerators-based DM search

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

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



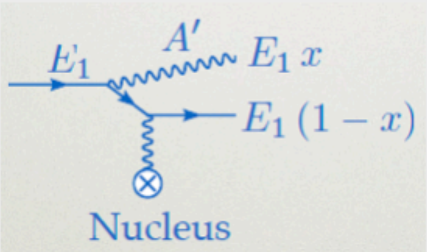
Experimental techniques



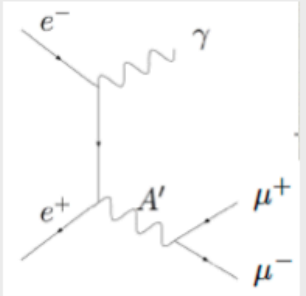
Fixed target vs. collider

Process

Fixed Target:



e+e- colliders:



Luminosity

Fixed Target: 10^{11} e- ; ~10^{23} atoms in target

e+e- colliders: 10^{11} e- ; 10^{11} e+

Cross-Section

Fixed Target: $\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$

e+e- colliders: $\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10\ fb)$

Fixed Target:
- high backgrounds
- limited A' mass

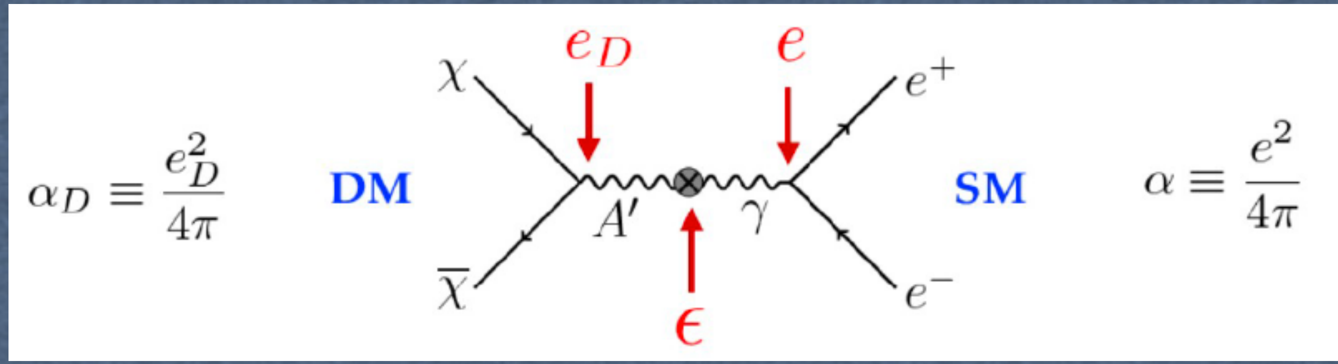
e+e- colliders:
- low backgrounds
- higher A' mass

✳ $1/M_{A'}$ .vs. $1/E_{beam}$
✳ Coherent scattering from Nucleus (~Z^2)

Dark Photon Signatures

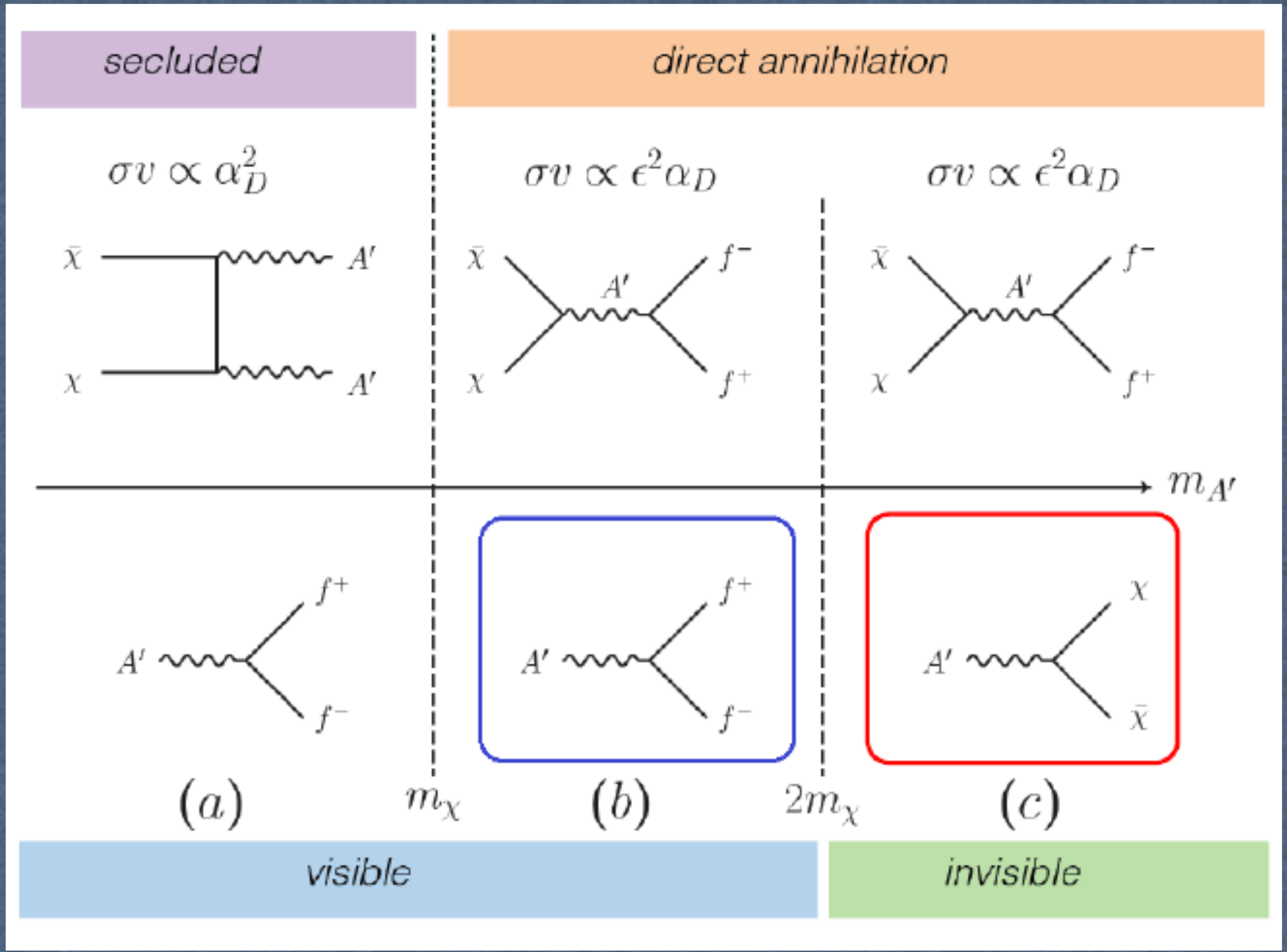
Vector mediated Light Dark Matter

- Vector-Portal: DM-SM interaction mediated by U(1) gauge-boson (dark photon or A’) couples to electric charge



A’ interaction scenarios

- **Secluded**: no constraints by cosmology for accelerator based experiments. Any ε allowed
- **Visible decay**: final state contains SM particles
- **Invisible decay**: A’ decays to Dark Sector invisible particles



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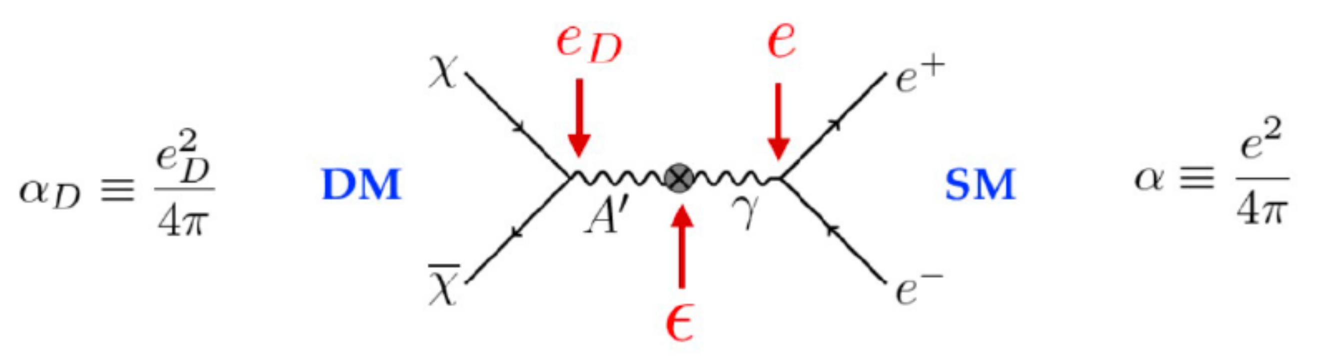

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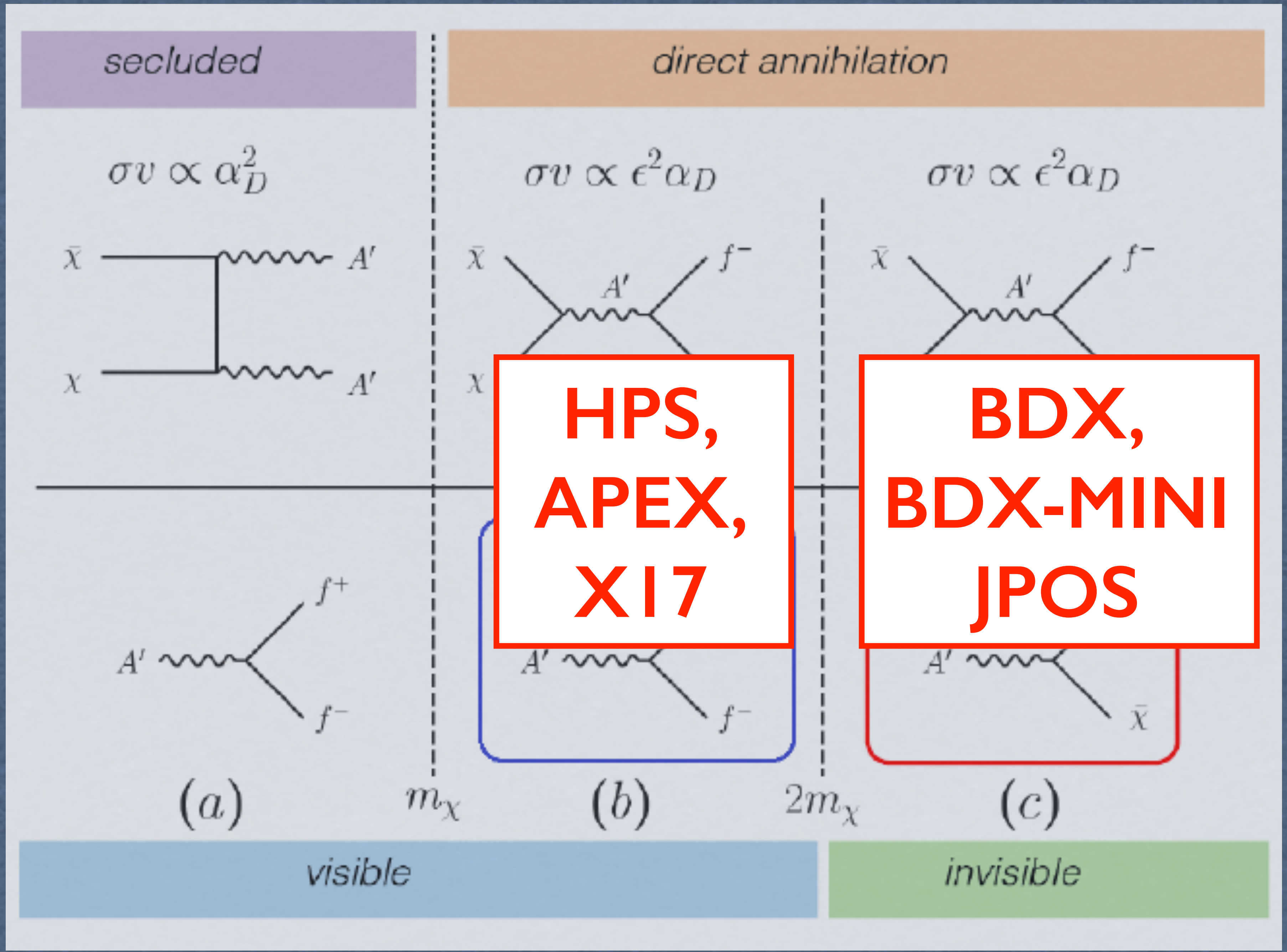
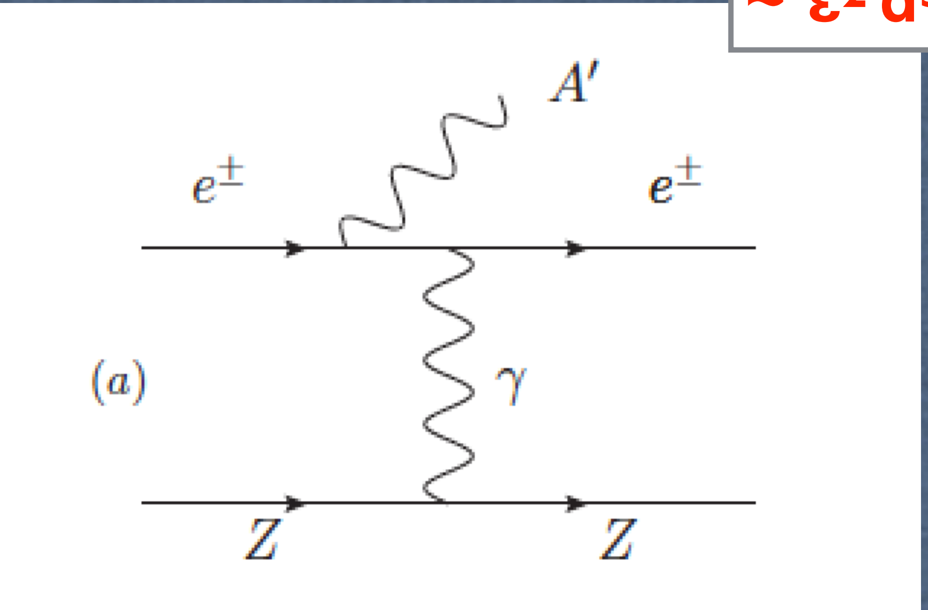


A' Production mechanisms - $e^{\pm}$

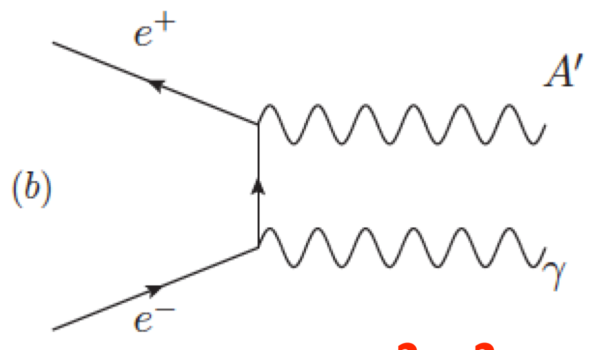
$\sim \varepsilon^2 \alpha^3$



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

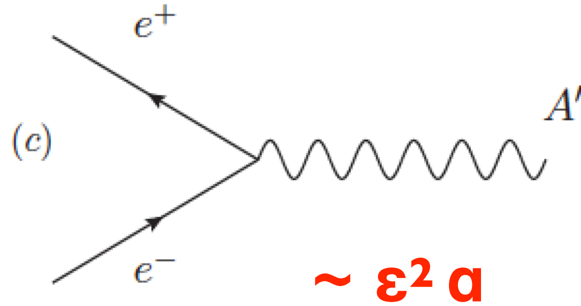
- The incoming electron 'see' a fast-moving cloud of effective photons to scatter from
- Photons are almost on-shell (low Q2) → transverse photons ~ $e^- \gamma_{Real}$ scattering
- Same treatment as the regular *bremstrahlung*
- Regularisations occurs in the case of interest $M_{A'} >> M_{e-}$
- Effective photon flux χ is critical, accounting for nuclear effect using FF

A' Production - positrons



$\sim \varepsilon^2 \alpha^2$

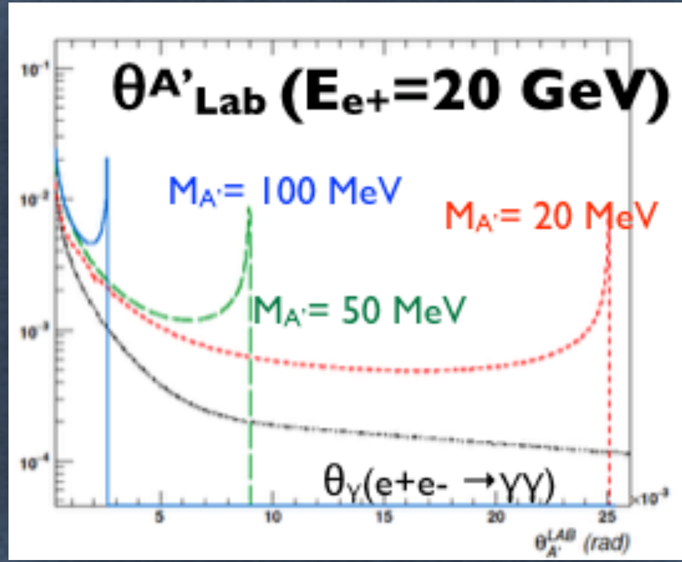
- **NON-RESONANT annihilation**
  - **A' along (e^+e^-) direction**
- **RESONANT annihilation**

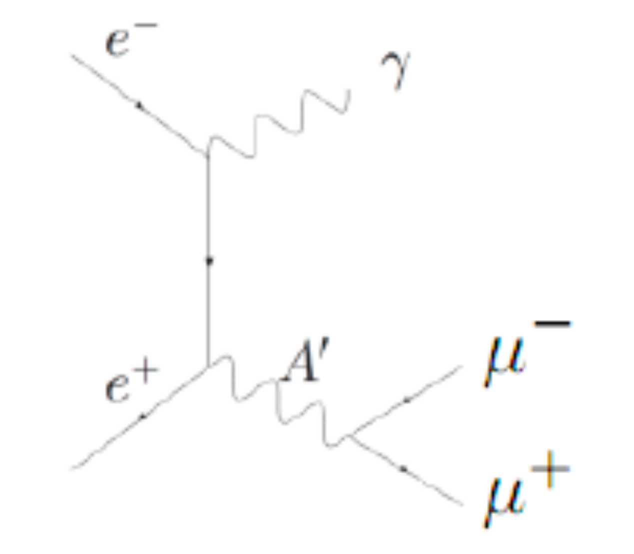


$\sim \varepsilon^2 \alpha$

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

- **Two-body process**
- **A' forward-peaked along e^+ direction**
- **$E_{A'} = E_R = m^2_{A'}/2m_e$**



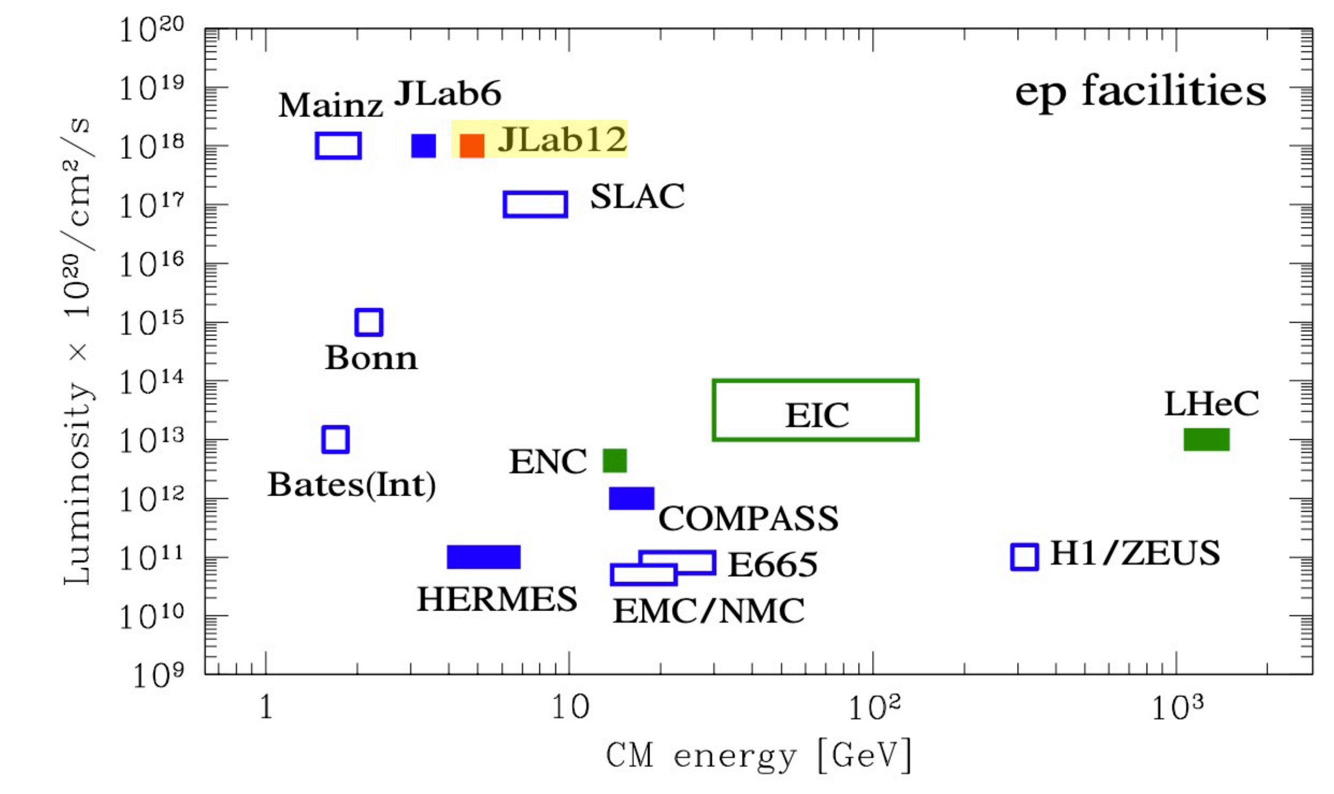


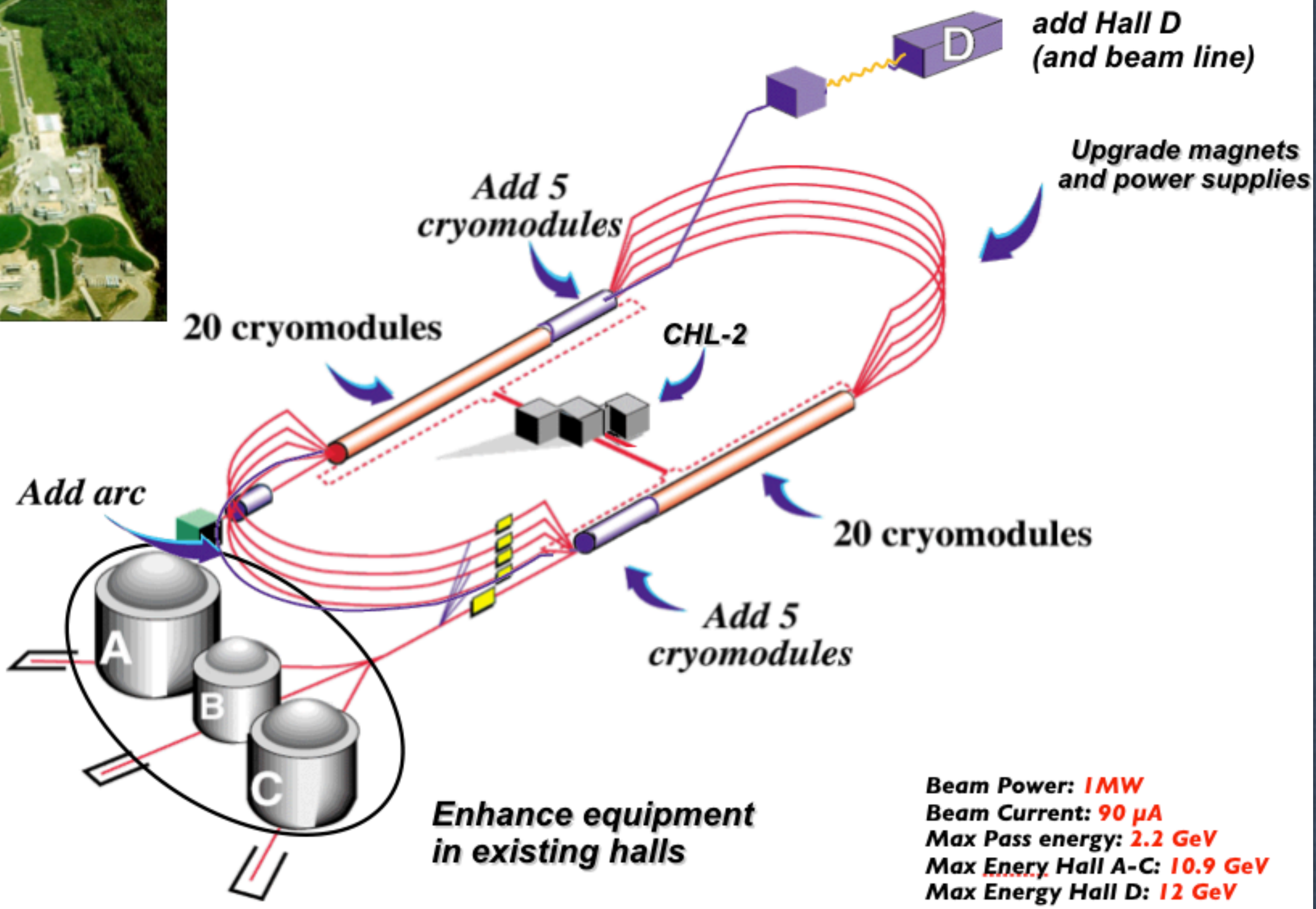
- Known and used
- Collider (missing mass experiments)
- Thin target experiments (visible decay)

D.Domenici talk!

$e^+e^- \to \gamma' \gamma \to \mu\mu\gamma$
→ BABAR, BELLE, KLOE, CLEO

Jefferson Lab
The intensity frontier





✳ Primary Beam: Electrons

✳ Beam Energy: 12 GeV

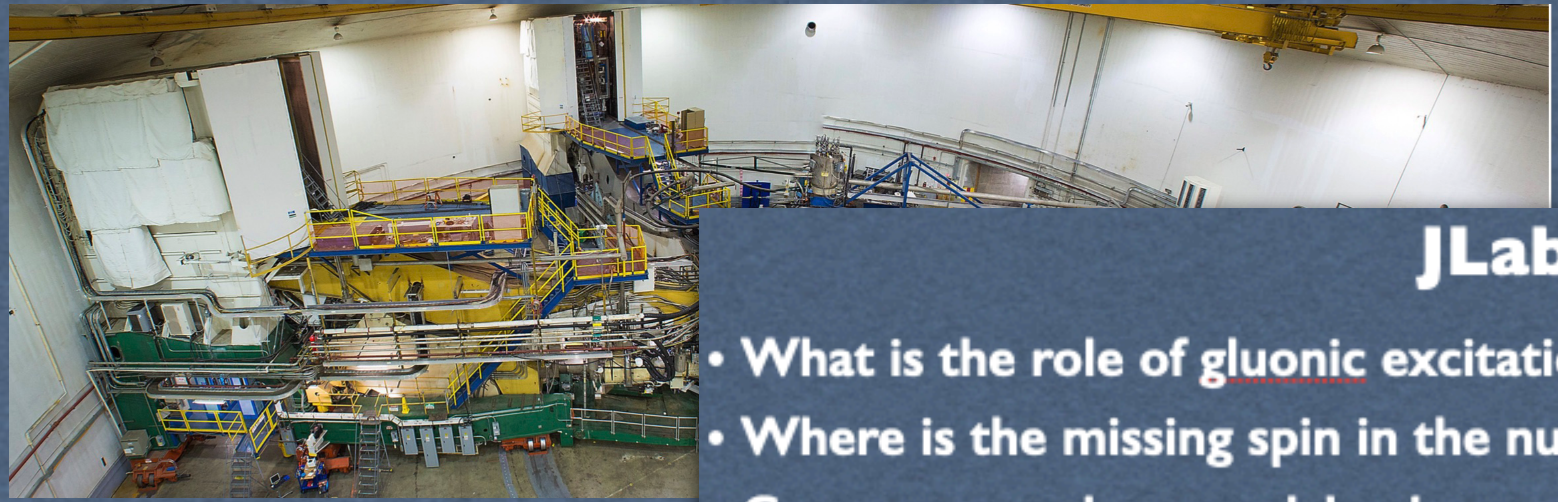
- $10 > \lambda > 0.1$ fm
- nucleon → quark transition
- baryon and meson excited states

✳ 100% Duty Factor (cw) Beam

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

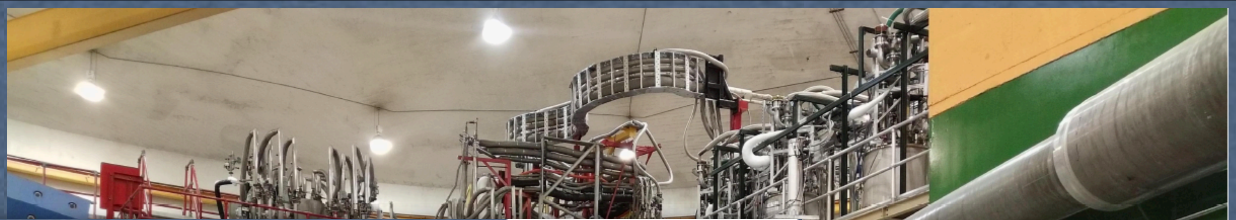
✳ Polarization

- spin degrees of freedom
- weak neutral currents



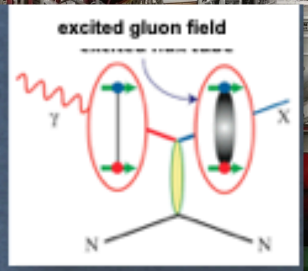
Hall A

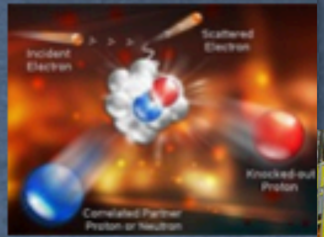
Hall C

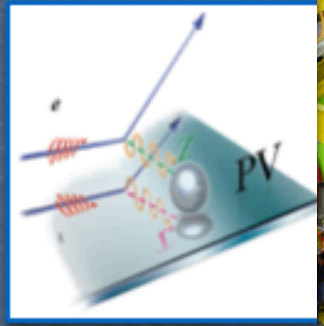


JLab Scientific mission

- 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?





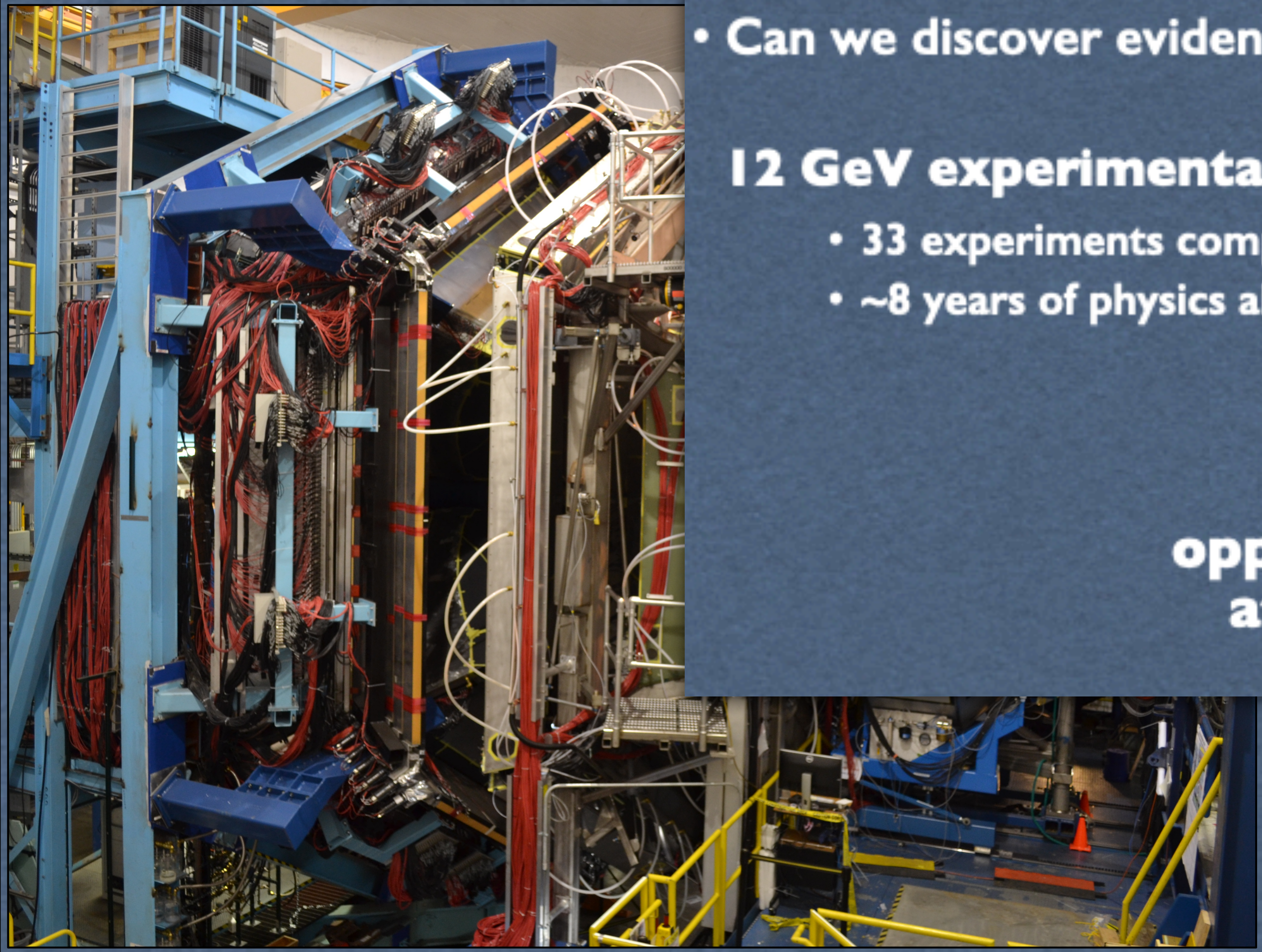


12 GeV experimental program is in full swing

- 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



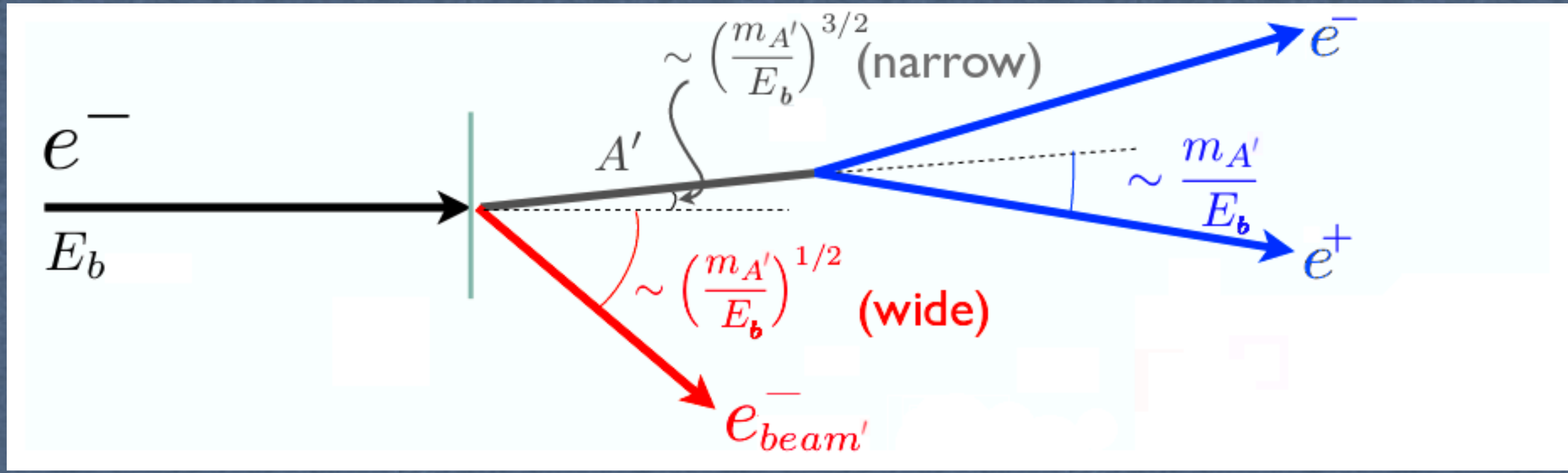
Hall B

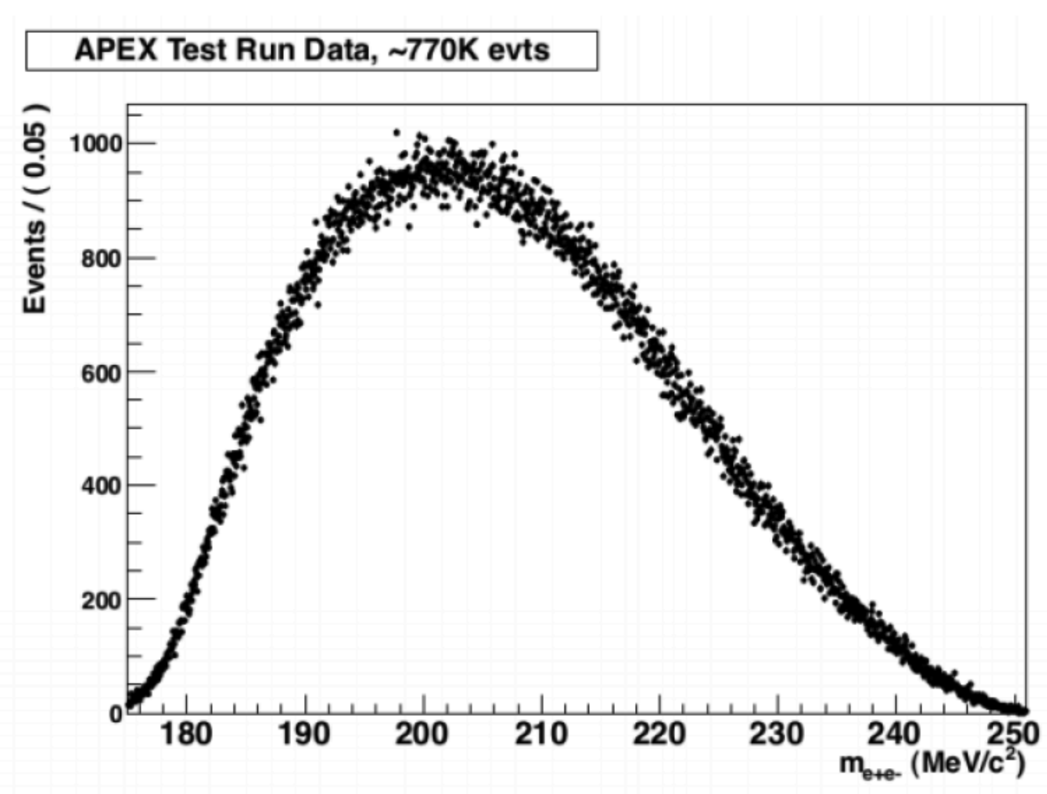
Hall D

APEX: A-Prime EXperiment

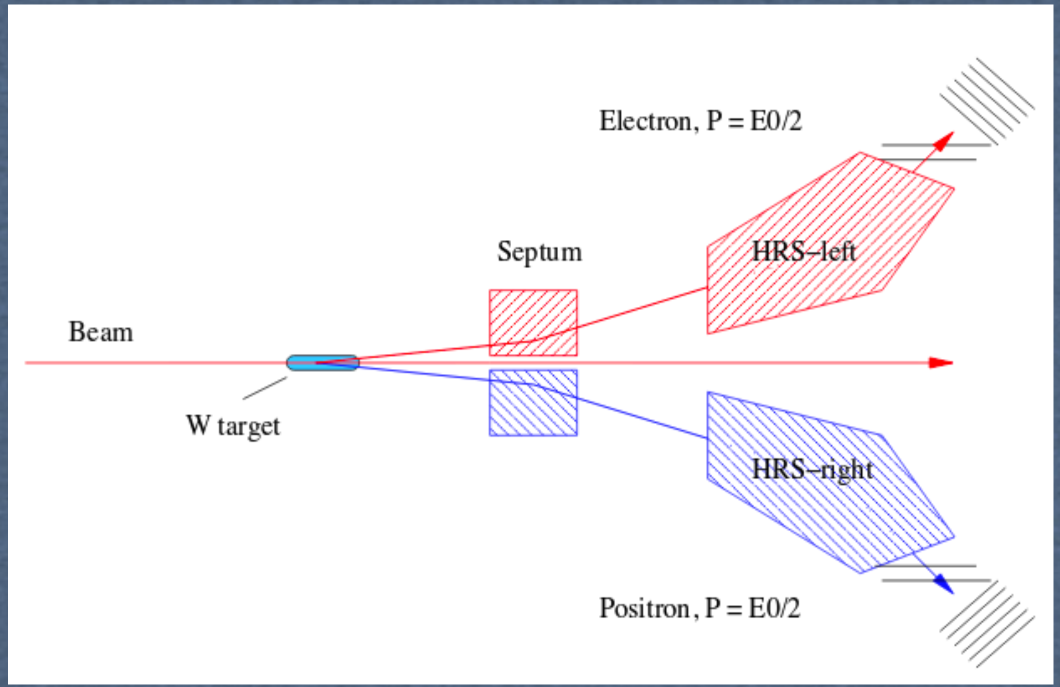
e- fixed target experiment installed in HALL A searching for dark photon visible decay

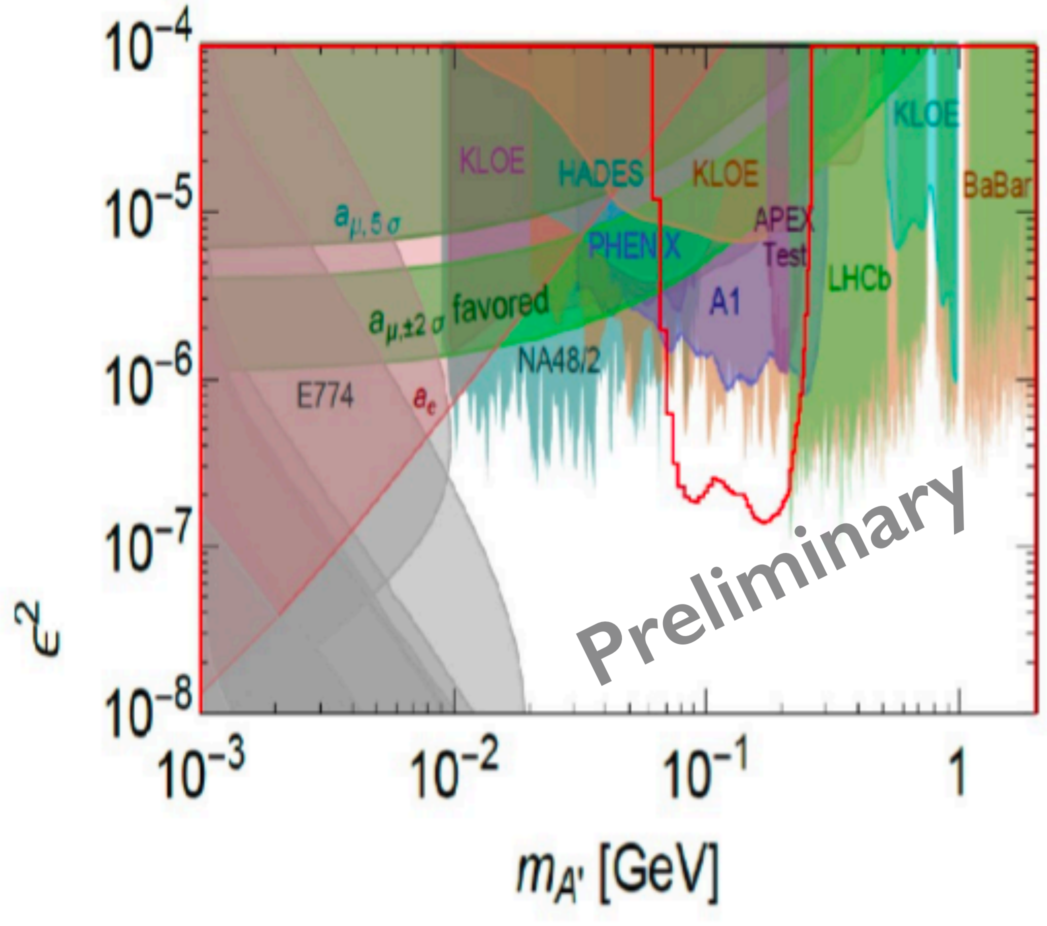
- Dark photon searched as a narrow resonance in e+e- mass over a smooth QED background





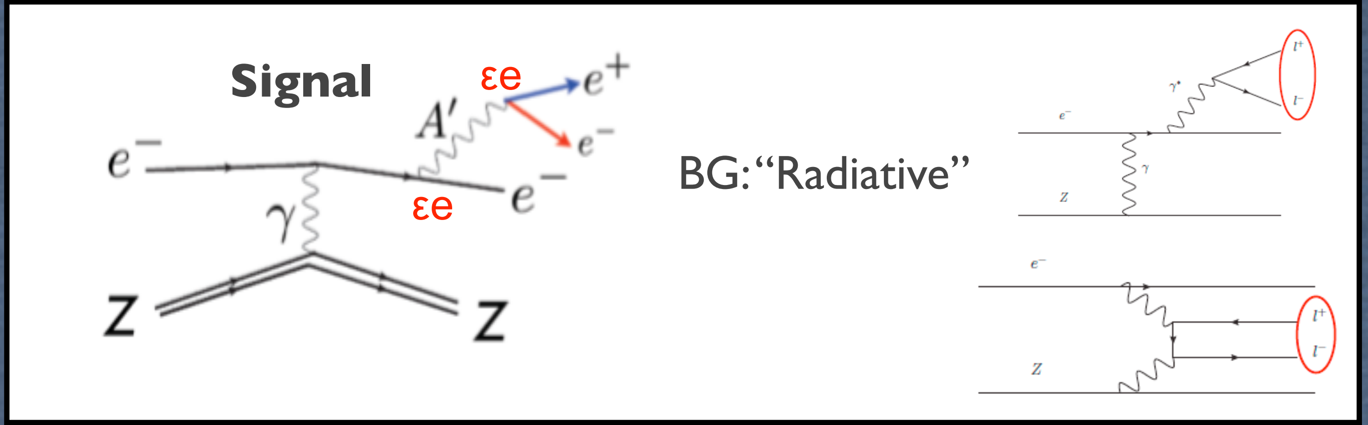
- Two High Resolution Spectrometers (HRSs) in coincidence to measure events with an e- in one arm and e+ in the other
- Standard HRS detector stack in both arms: Scintillators: S0 and S2(timing), VDC (tracking), Cherenkov and Calorimeters (PID)
- 2010 test run: E_b=2.2 GeV@150 uA on Ta foil
- Entire run in 2019: over 100x statistics

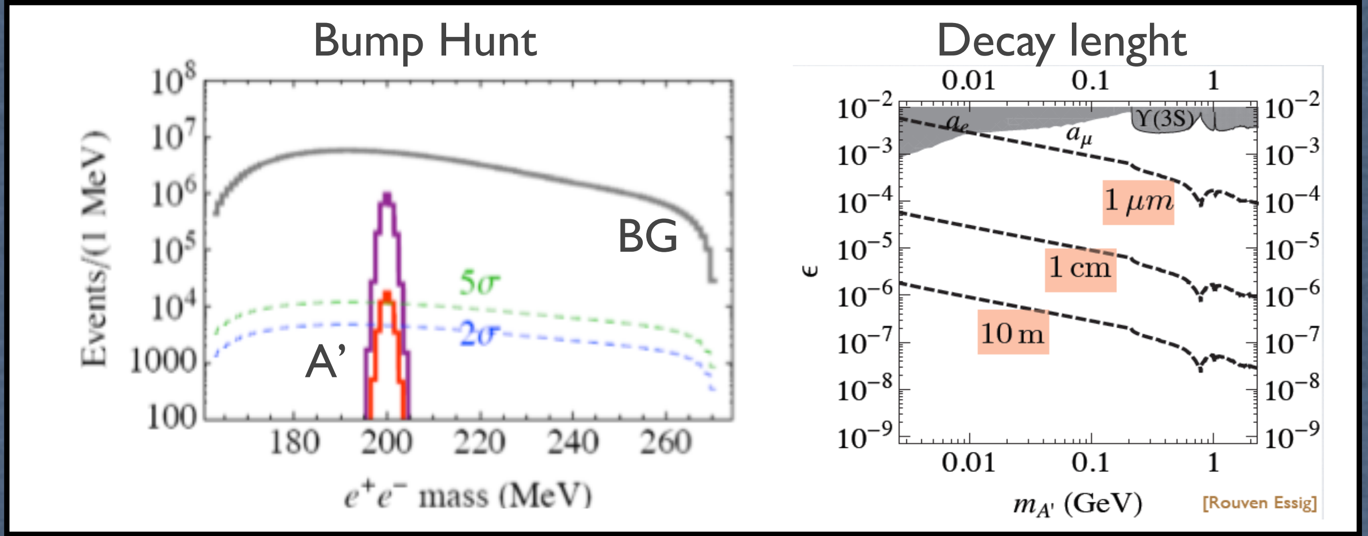




10.1103/PhysRevLett.107.191804

Heavy Photon Search @ JLab
visible decay





1) Bump Hunting (BH)

Narrow e+e-resonance over a QED background

➥ good mass resolution: $\sigma_{A'mass}$~1 MeV

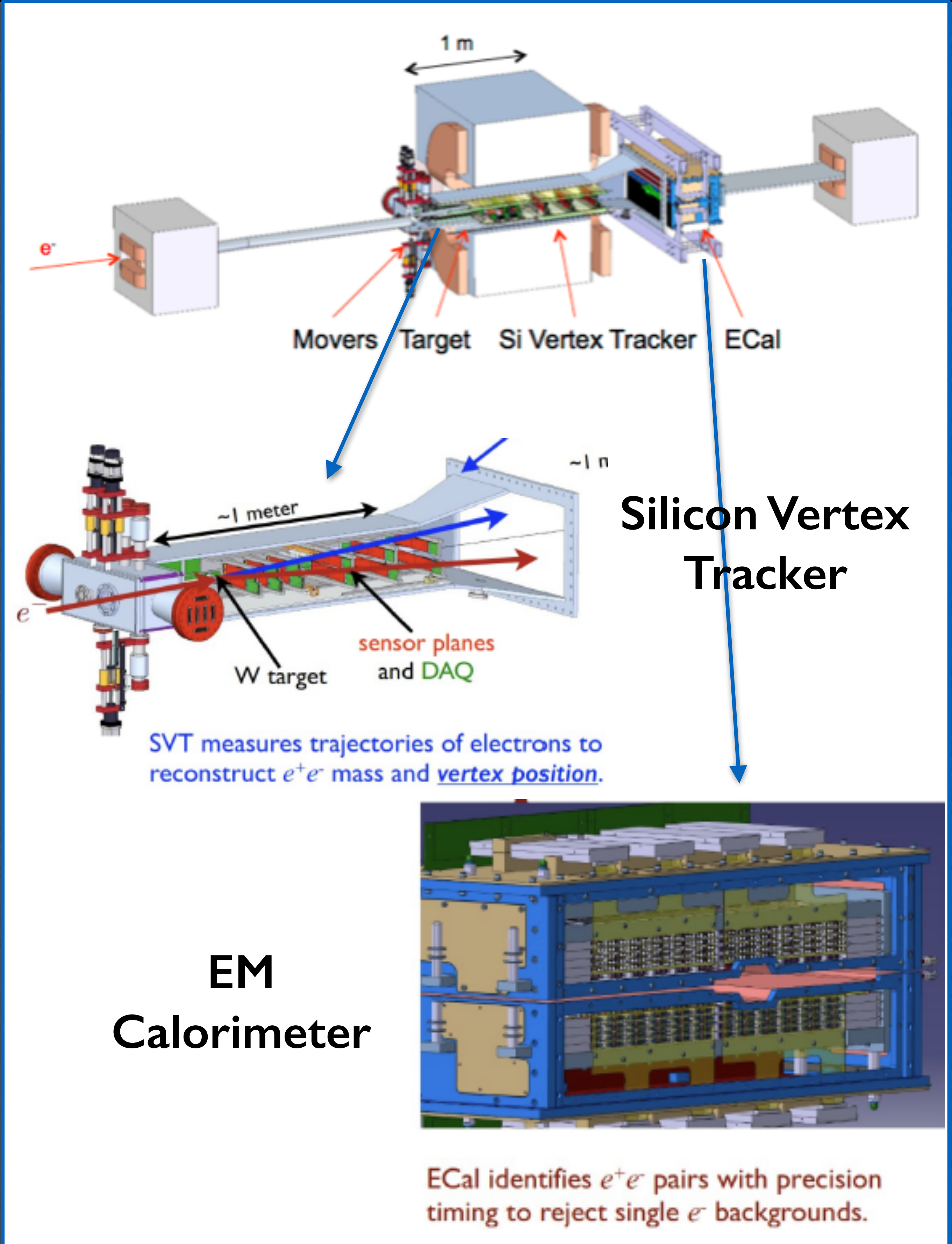
2) Secondary decay vertex (vertexing)

Detached vertex from few mm to tens cm

➥ good spacial resolution: σ_{vertex}~1mm

Heavy photon signatures in HPS

BH + Vertexing = enhanced experimental reach



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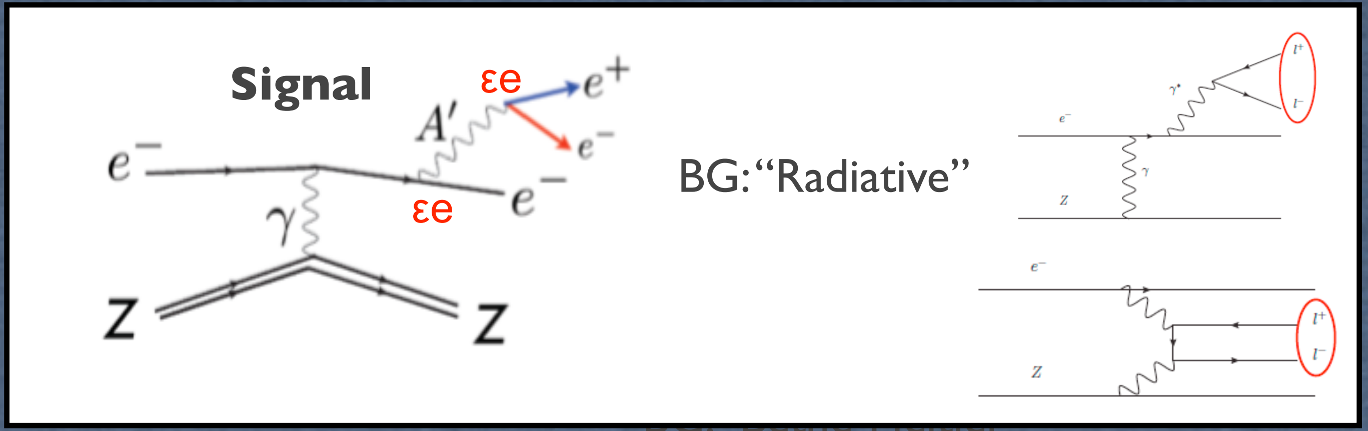

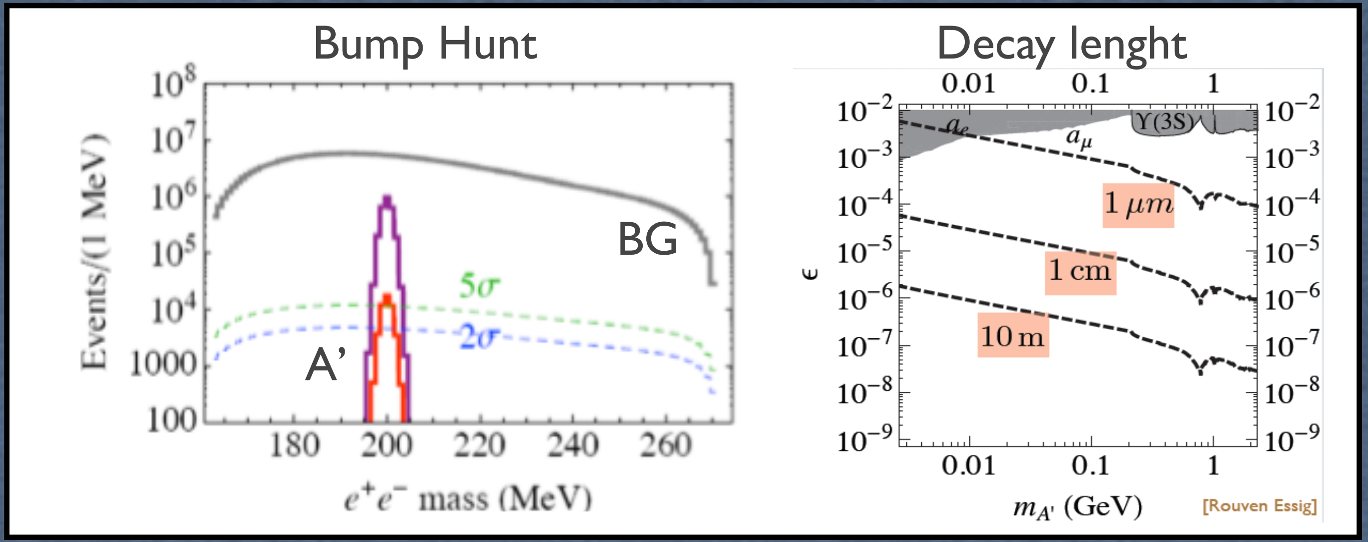

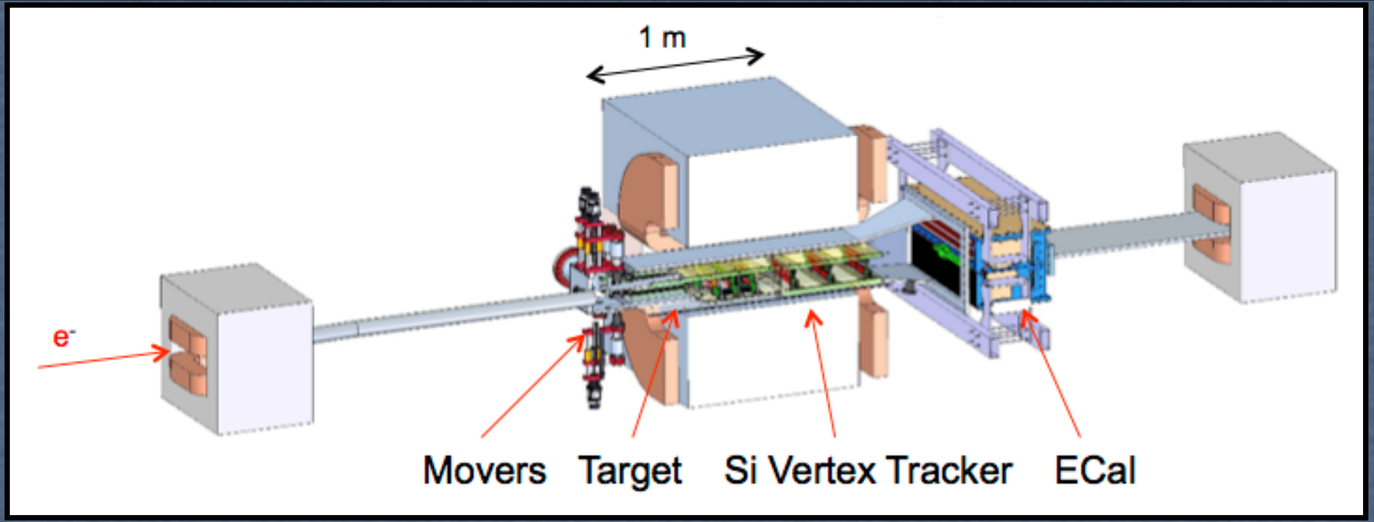

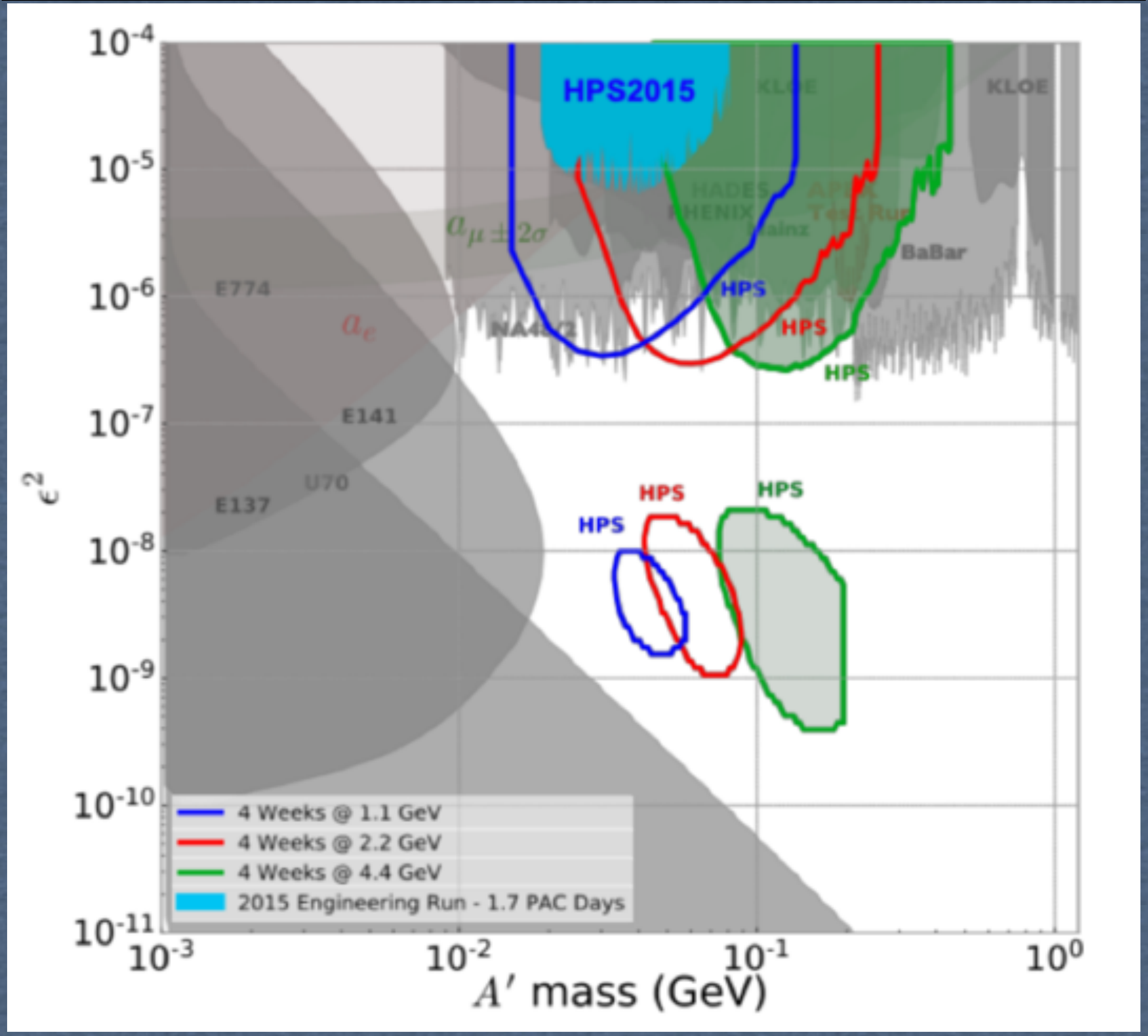

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Heavy photon signatures in HPS

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X17 search at JLab

- Search for the X17 in e+e- invariant mass
- Presented to JLab PAC 49 in Aug 21 and granted a C2 approval

Search for Hidden Sector New Particles in the 3 – 60 MeV Mass Range

Proposal submitted to JLab PAC49

- New (hidden) particle in MeV-scale mass range in forward electroproduction reactions from a heavy A solid target.

$$e^- + Ta \rightarrow e' + \gamma^* + Ta \rightarrow e' + X + Ta',$$

$$X \rightarrow e^+e^- \quad \text{(with tracking)}$$

$$\text{or } X \rightarrow \gamma\gamma \quad \text{(without tracking)}$$

Mass range: [3 ÷ 60] MeV

- Target: Tantalum ($_{73}Ta^{181}$) film, thickness: 1 μm, 2.5×10^{-4} r.l.
  density: 16.69 g/cm^3
  N(Ta) = $0.56\times10^{+19}$ atoms/cm^2

Experimental method:

✓ "bump hunting" in the invariant mass spectrum over the beam background.

✓ direct detection of decay particles (e^+e^-) and scattered e-

Detection criteria:

- scattered electron is in the PbWO$_4$ acceptance with E_e = [30MeV to 0.7xE_{beam}];
- decay e- and e+ are in the PbWO$_4$ within energy: [0.03 – 0.8xE_{beam}]
- Target to PbWO4 distance L=7.5 m beam energy optimized for E_e = 2.2 GeV and 3.3 GeV

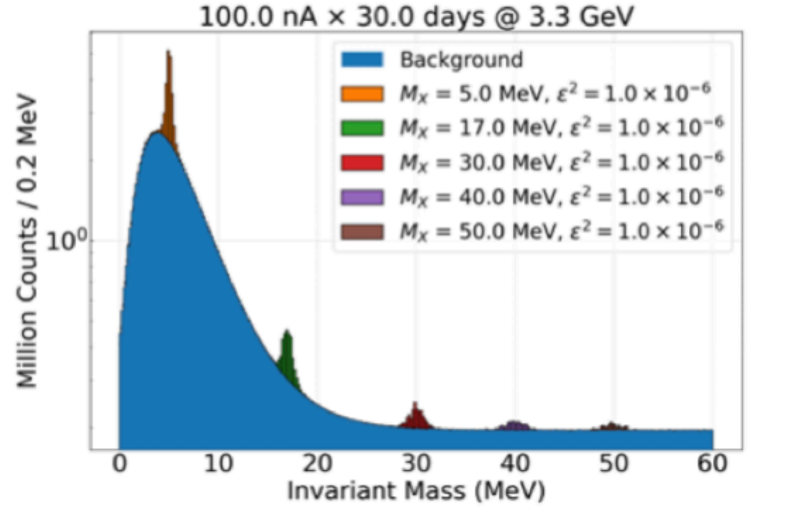
Beam time request

	Time [days]
Setup checkout, tests and calibration	4.0
Production at 2.2 GeV @ 50 nA	20.0
Production at 3.3 GeV @ 100 nA	30.0
Energy change	0.5
No target background sampling at 2.2 & 3.3 GeV	5.5
Total	60.0

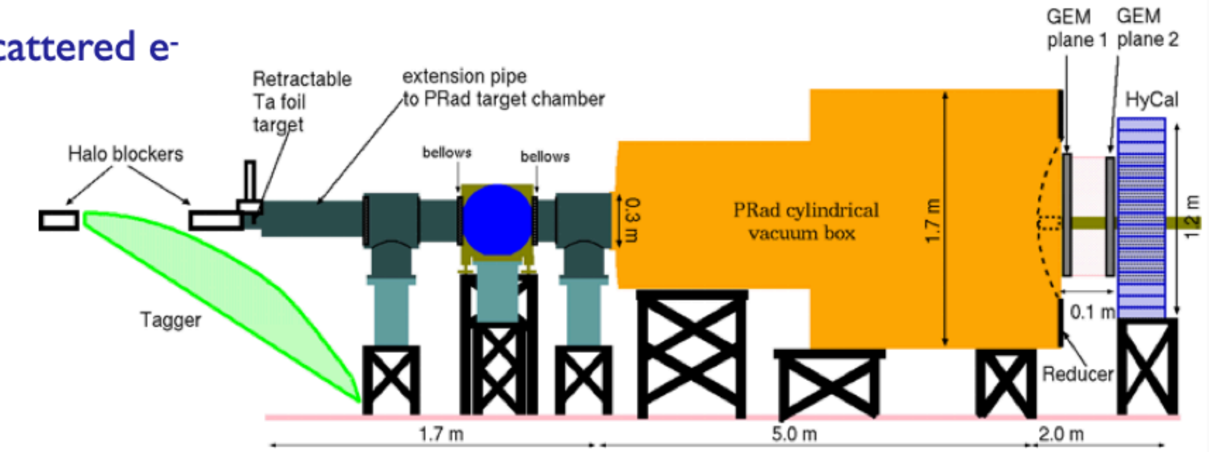
Search sensitivity

m_X MeV	σ_{m_X} MeV	Background Counts	Signal Counts (5.0 Significance)	Lowest ϵ^2	lowest ϵ^2
30 days of 3.3 GeV at 100 nA					combined with signal from 20 days at 2.2 GeV
5.0	0.263	22.02M	23.48k	6.86E-09	5.94E-09
17.0	0.467	3.60M	9.50k	9.83E-09	8.51E-09
30.0	0.692	3.06M	8.76k	2.60E-08	2.25E-08
40.0	0.938	4.08M	10.11k	5.71E-08	4.94E-08
50.0	1.009	4.38M	10.48k	8.37E-08	7.24E-08

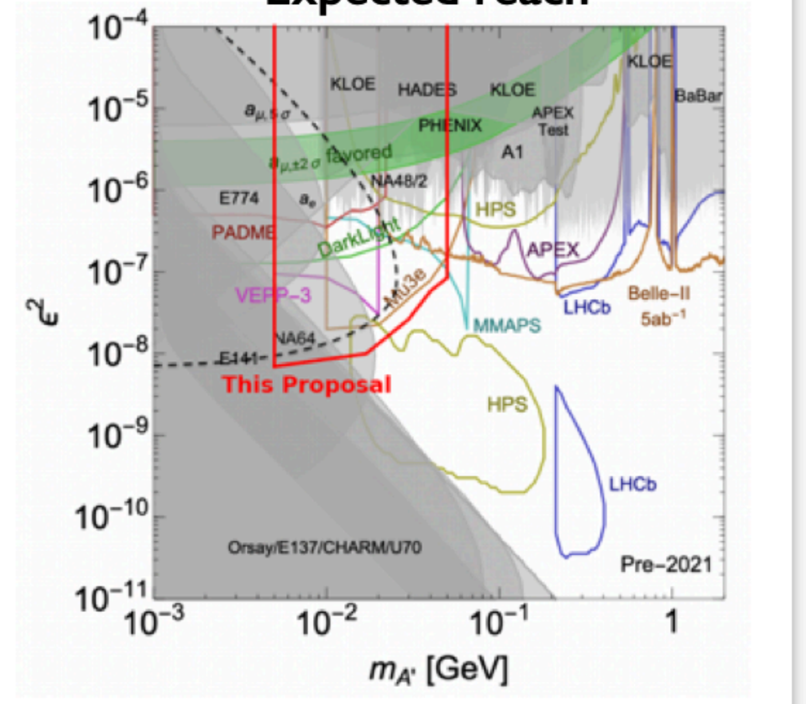
Sensitivity Example for $\epsilon^2 = 10^{-6}$



Experimental Setup (Side View)



Expected reach



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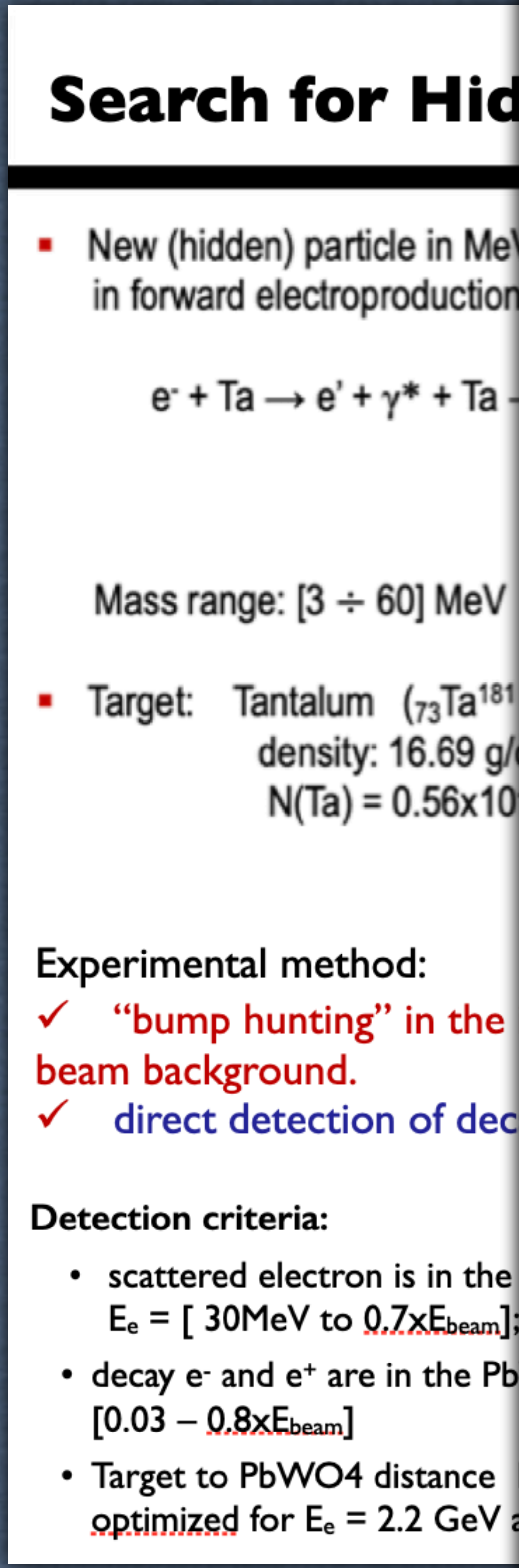
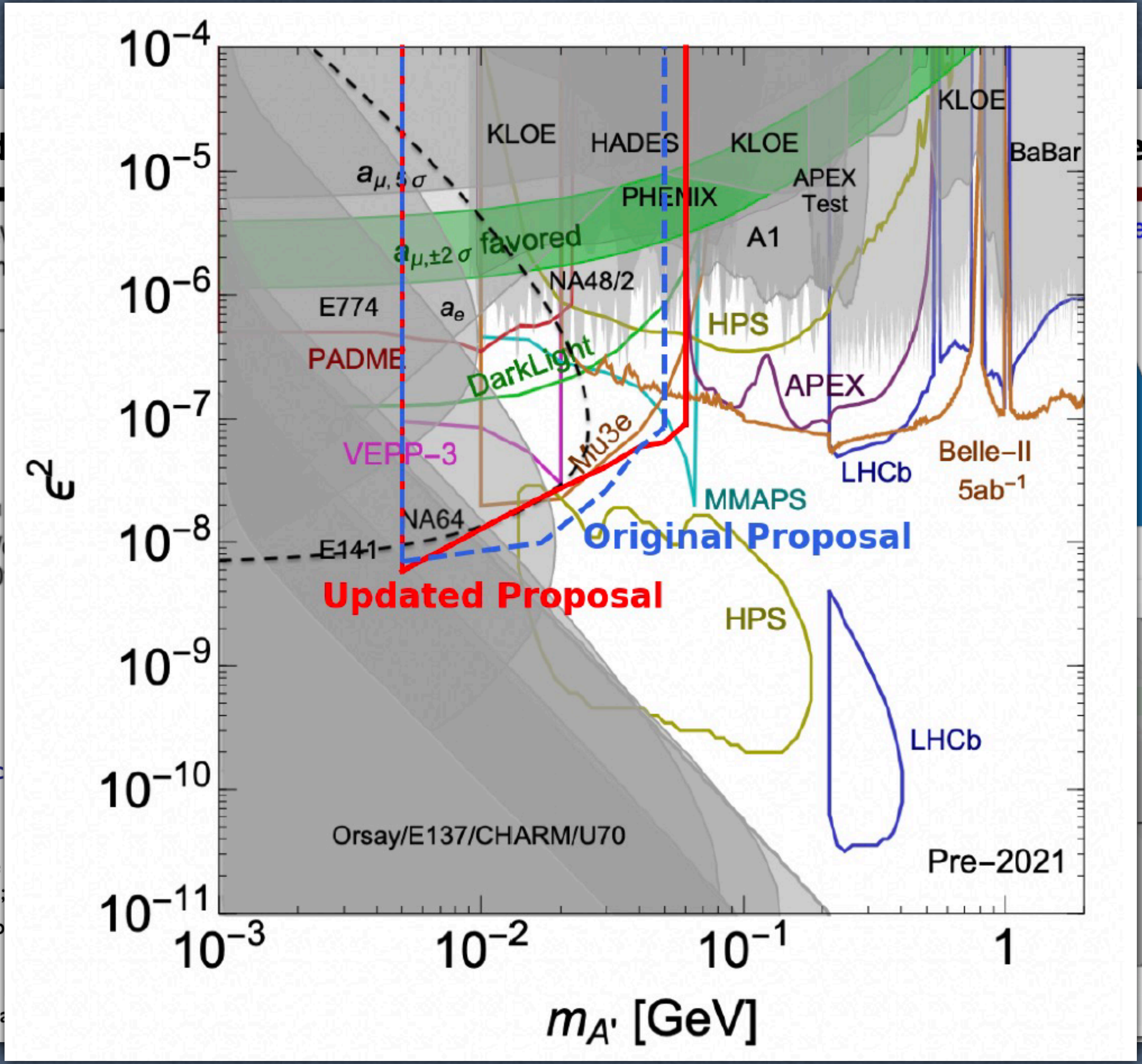
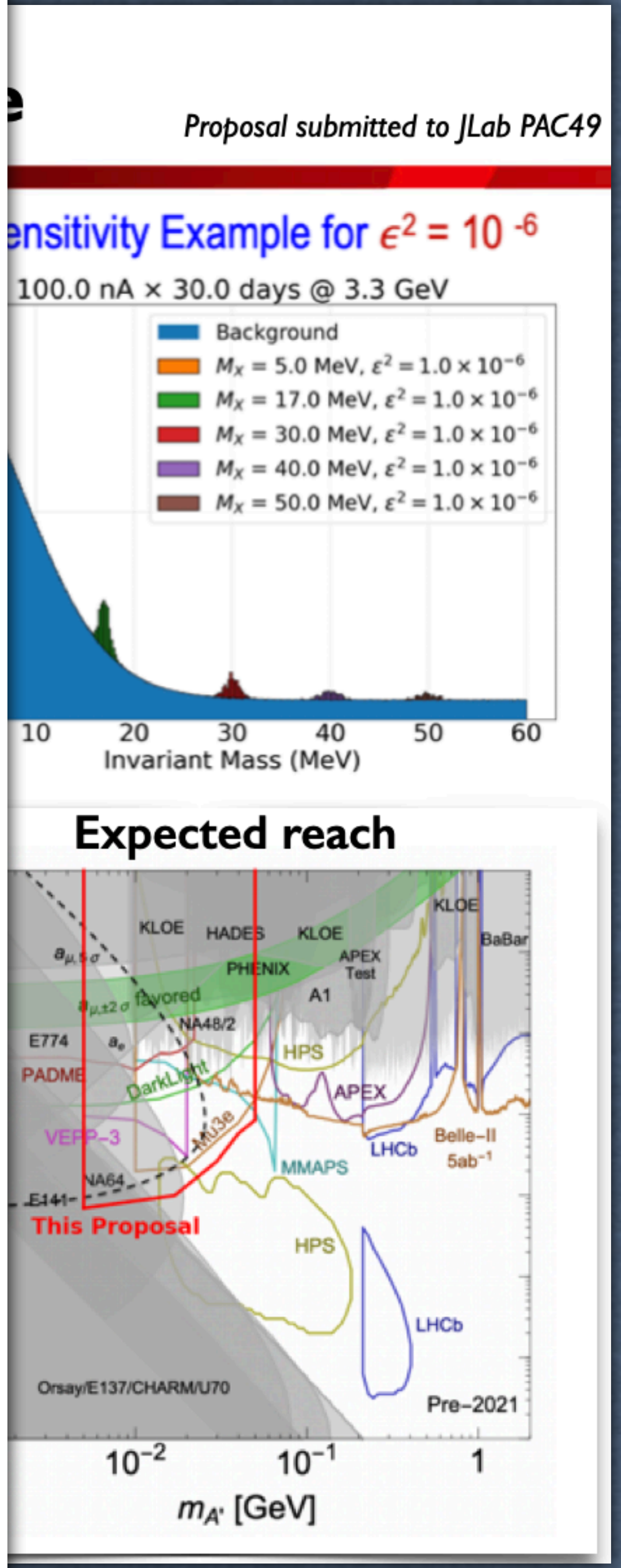
- Search for the X17 in e+e- invariant mass
- Presented to JLab PAC 49 in Aug 21 and granted a C2 approval
- Presented to JLab PAC 50 in Aug 2022 and granted A rate (full approval)
- To be scheduled





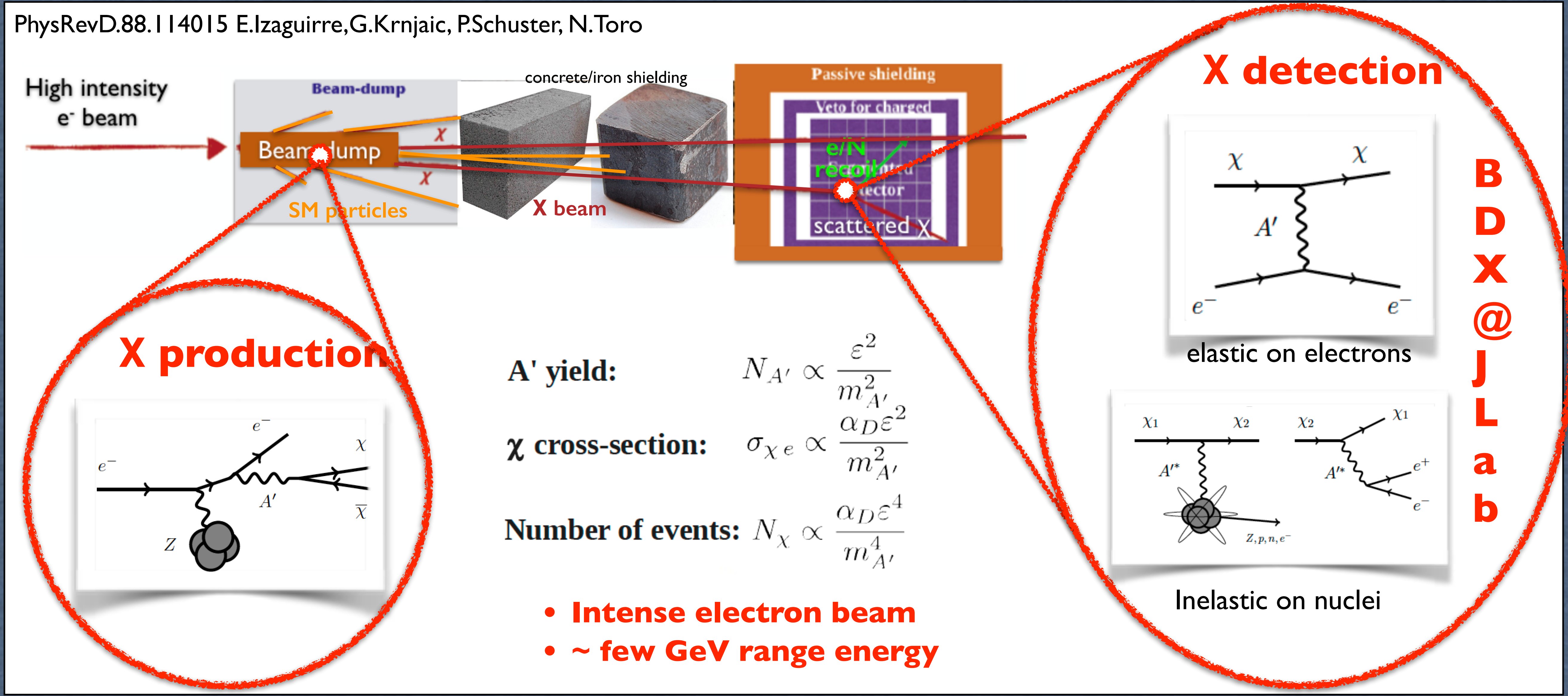


The BDX experiment

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)

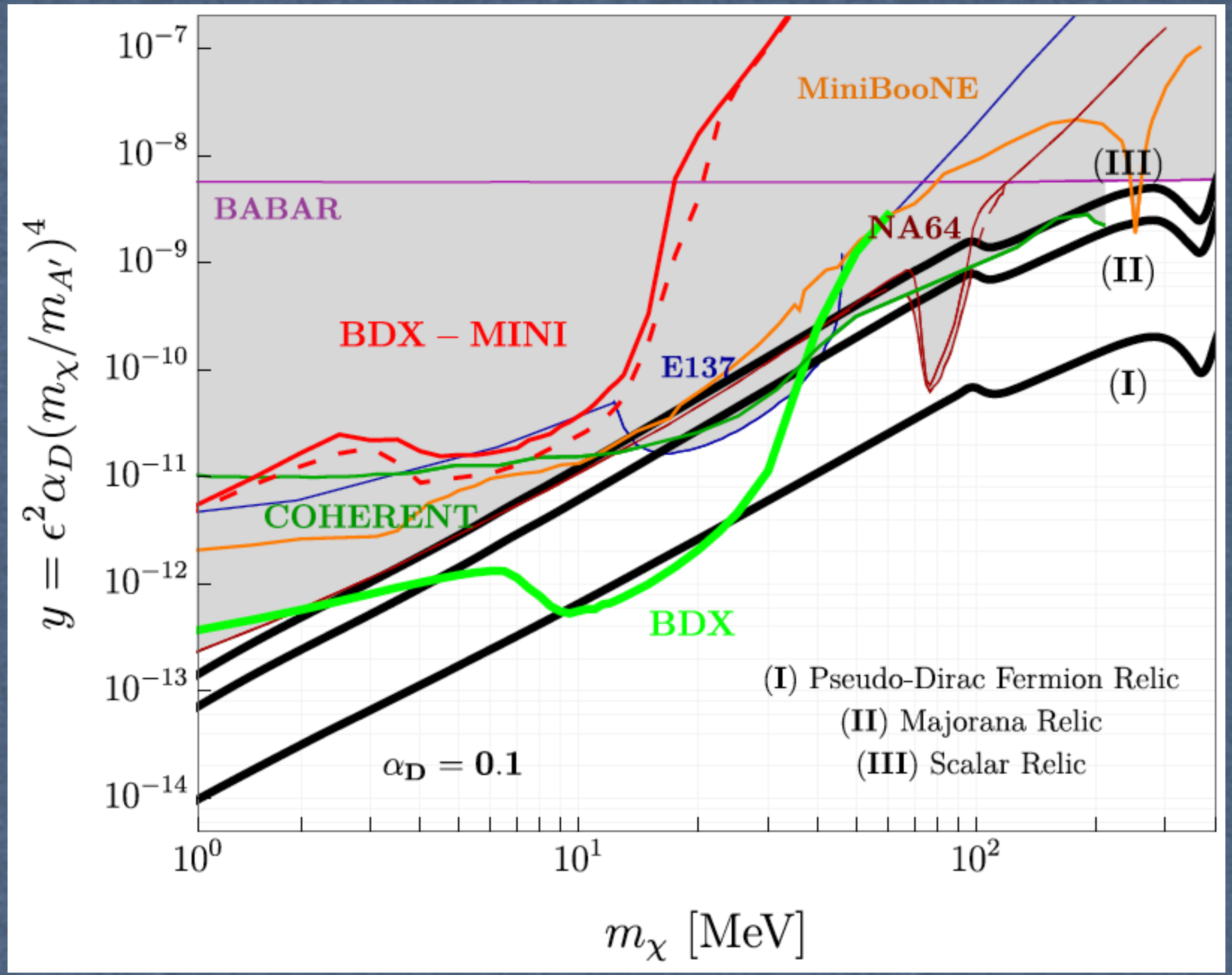


Experimental signature in the detector: **X-electron → EM shower ~GeV energy**

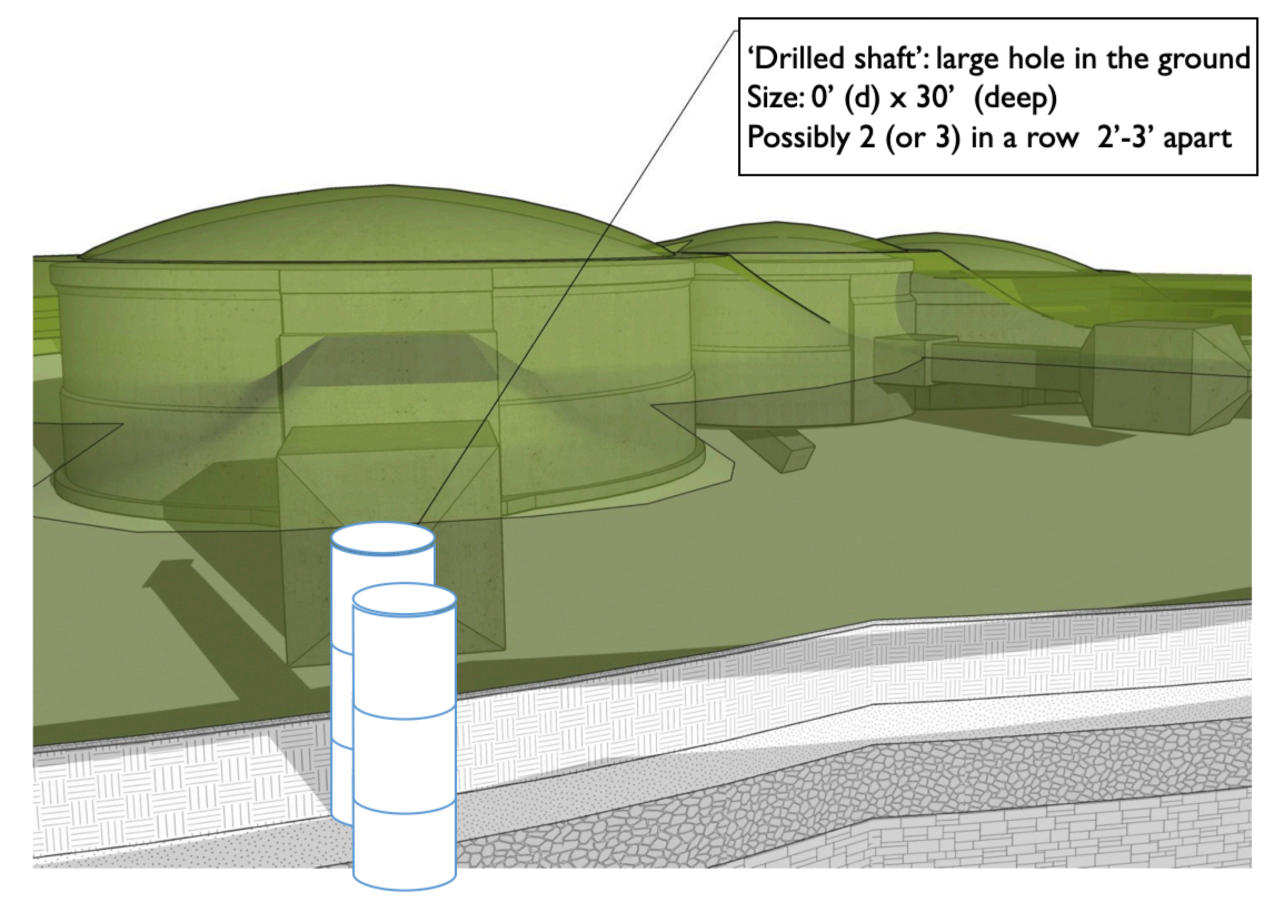
BDX @ JLab

Approved by JLab 2018 PAC with max rate (A)

Waiting to be scheduled

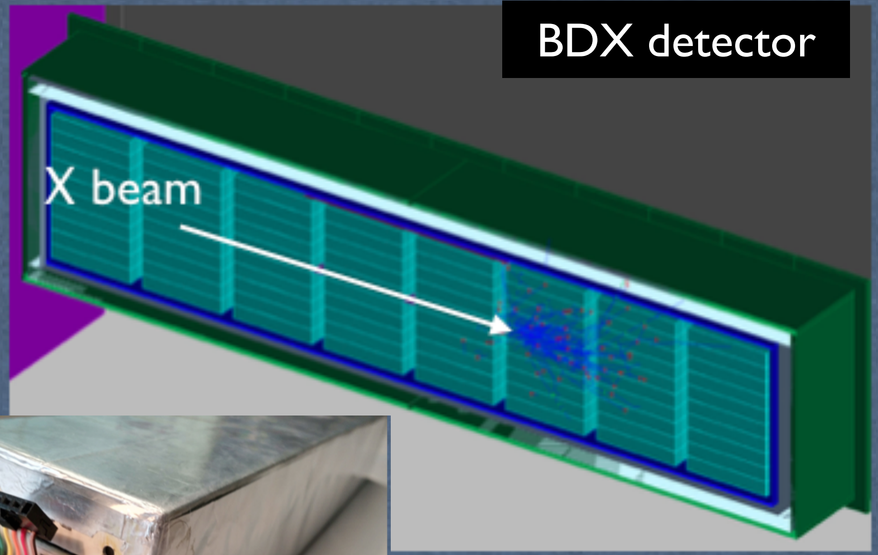


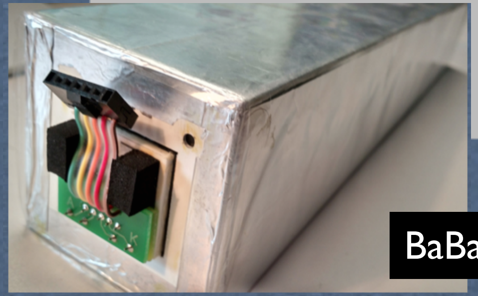
- High energy beam available: 11 GeV
- The highest available electron beam current: ~65 uA
- The highest integrated charge: 10^{22} EOT (41 weeks)
- Drilled shaft downstream of Hall-A BD
- BDX detector (recycling BaBar CsI and/or PANDA PbWO4 crystals)
- Expected to run in parallel to the Moeller experiment (2026-2029)



BDX detector:
EMCalorimeter + Veto

- 8 modules 10x10 crystals each
- 800 CsI(Tl) crystals (BaBar)
- Negotiating with PANDA to loan ~3k ECal PbWO crystals
- 6x6 mm² Hamamatsu SiPM
- Plastic scintillator + WLS fibres

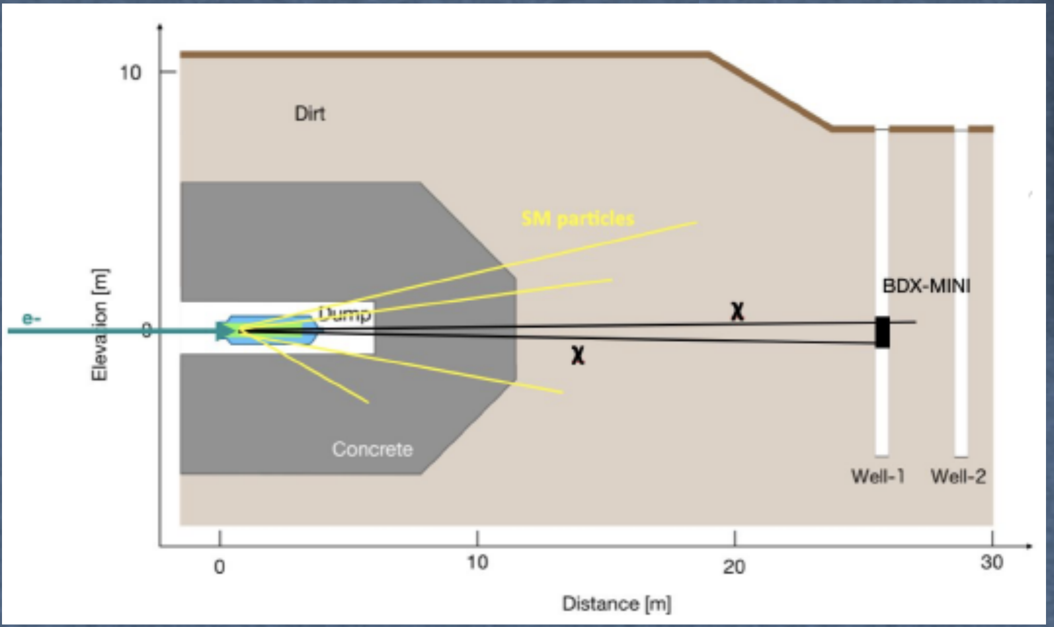




Accumulating 10^{22} EOT in ~2y BDX sensitivity is 10-100 times better than existing limits on LDM

BDX-MINI @JLab

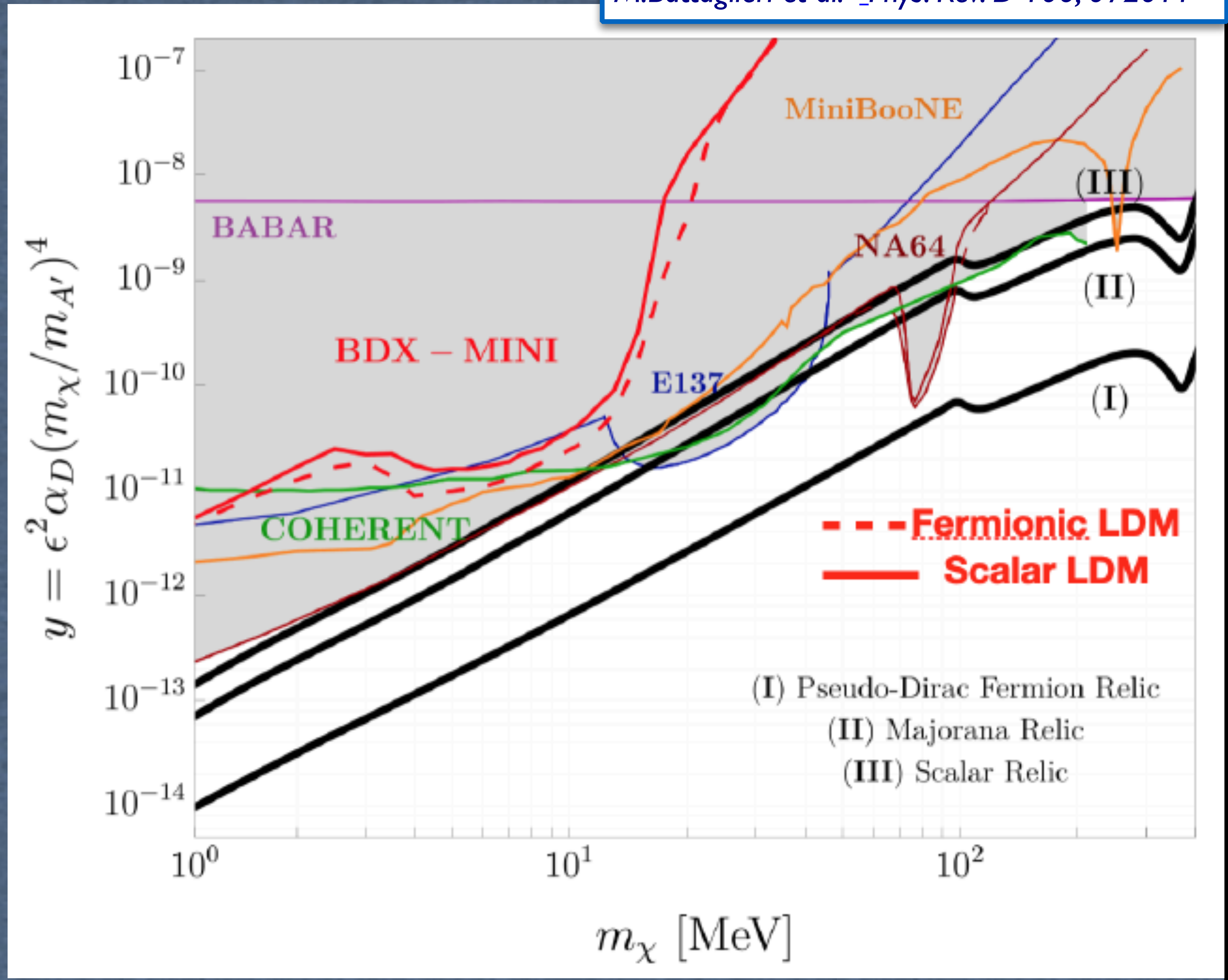
BDX-MINI: pilot experiment to prove the validity and feasibility of the BDX experiment



- Installed in March 2019
- Run form Dec 2019 to Aug 2020
- Collected 4e21 EOT (40% BDX!) in ~4 months (+ cosmics)
- Good detector performance with high duty factor

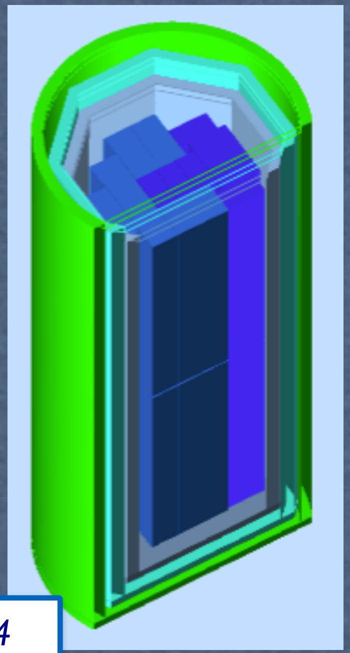
- Two wells dug for bg muon tests
- E_{beam}=2.2 GeV, no muons
- Limited reach but first physics result!

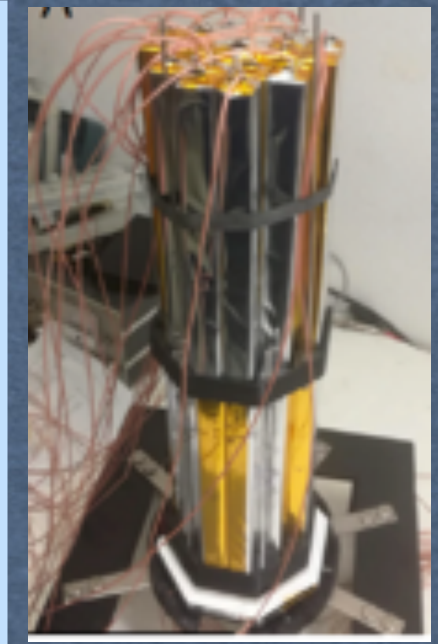
M.Battaglieri et al. _Phys. Rev. D 106, 072011

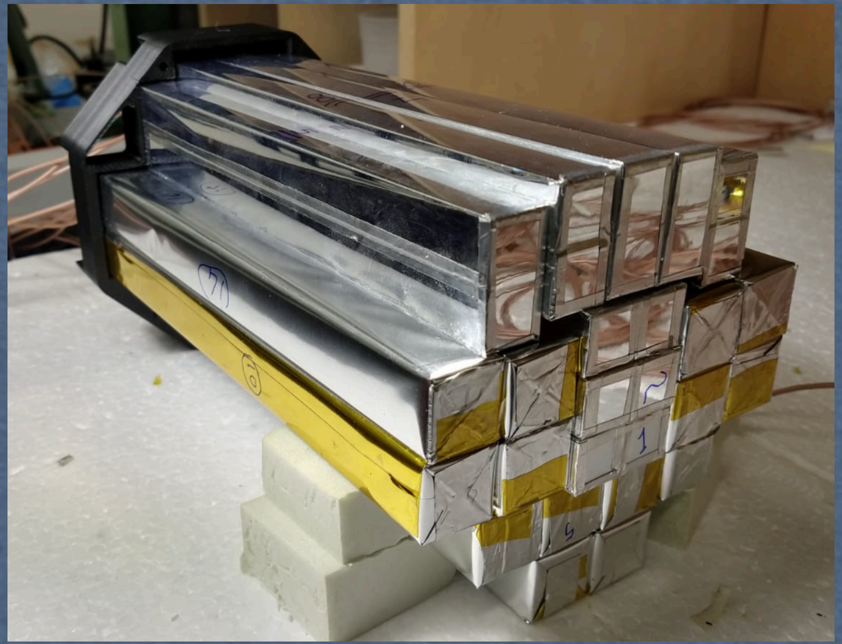


- 44 PbWO4 PANDA/FT-Cal crystals (~1% BDX active volume)
- 6x6 mm2 SiPM readout
- 2 active plastic scintillator vetos: cylindrical and octagonal (8 sipm each) + 2x lids + Passive W shielding

M.Battaglieri et al. EPJC (2021) 81: 164





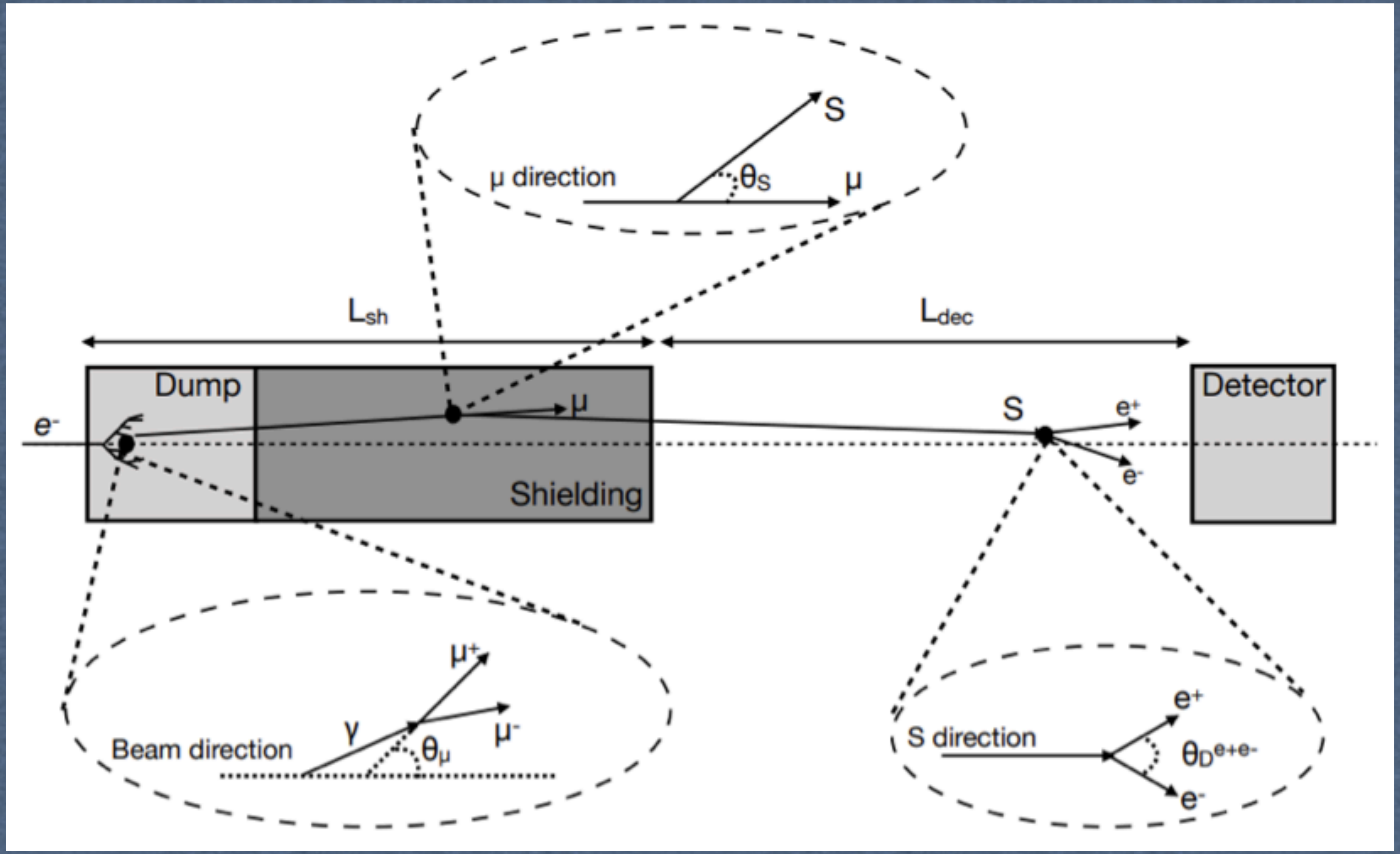


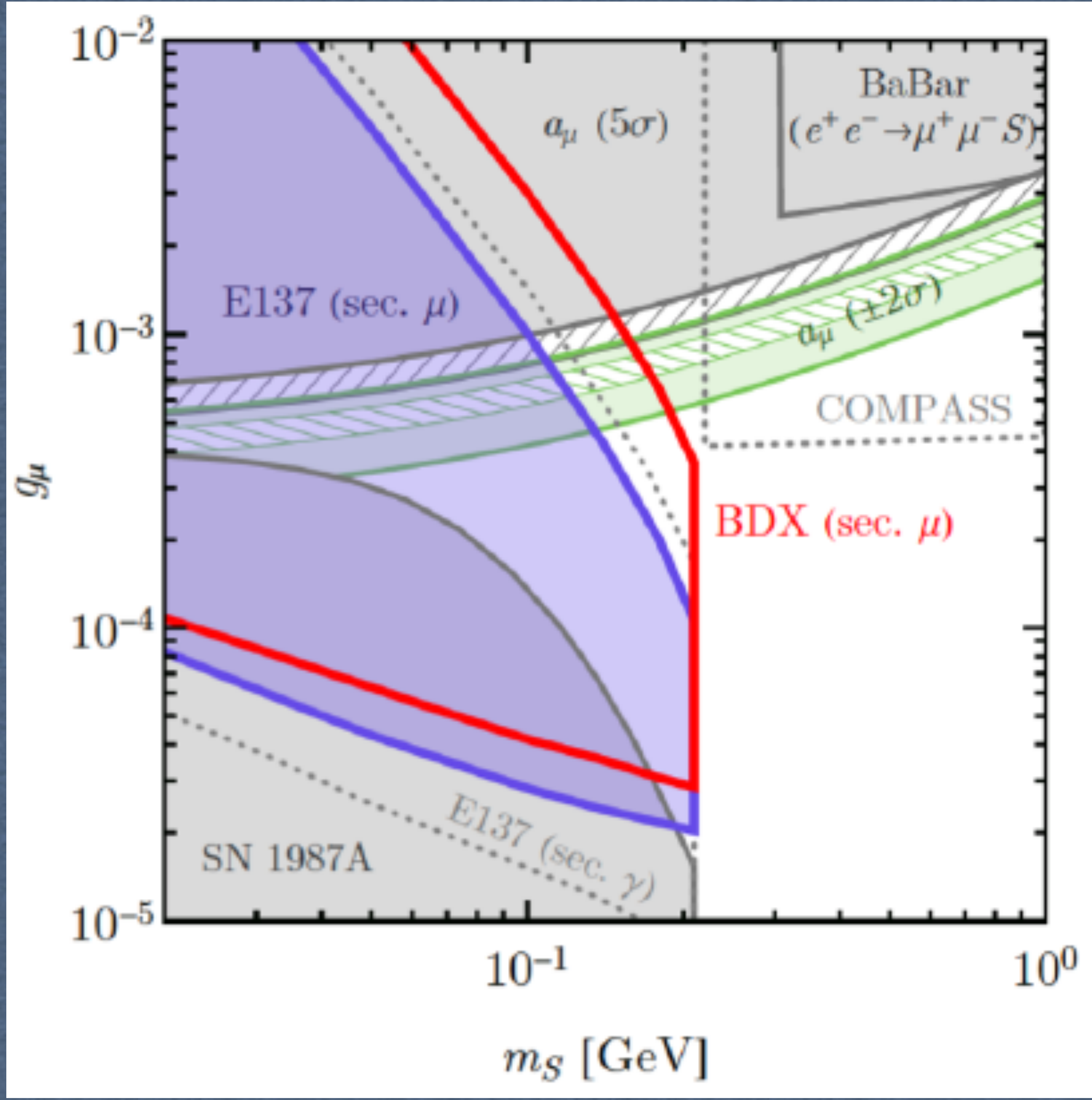
- Data-taking completed, analysis completed
- Results provide exclusion limits similar to the best existing experimnts (E137, NA64, BaBar, …)

μBDX @ JLab

Probing muon-philic forces with secondary muon beam

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





- A sizable flux of high energy muons produced in the dump by the e- beam:
  - 11 GeV (22 GeV) e- hitting Hall-A beam dump: 3 10^8 μ/s (~2 10^9 μ/s)
  - Use the secondary muon beam to produce exotic particles (g-2 anomaly)

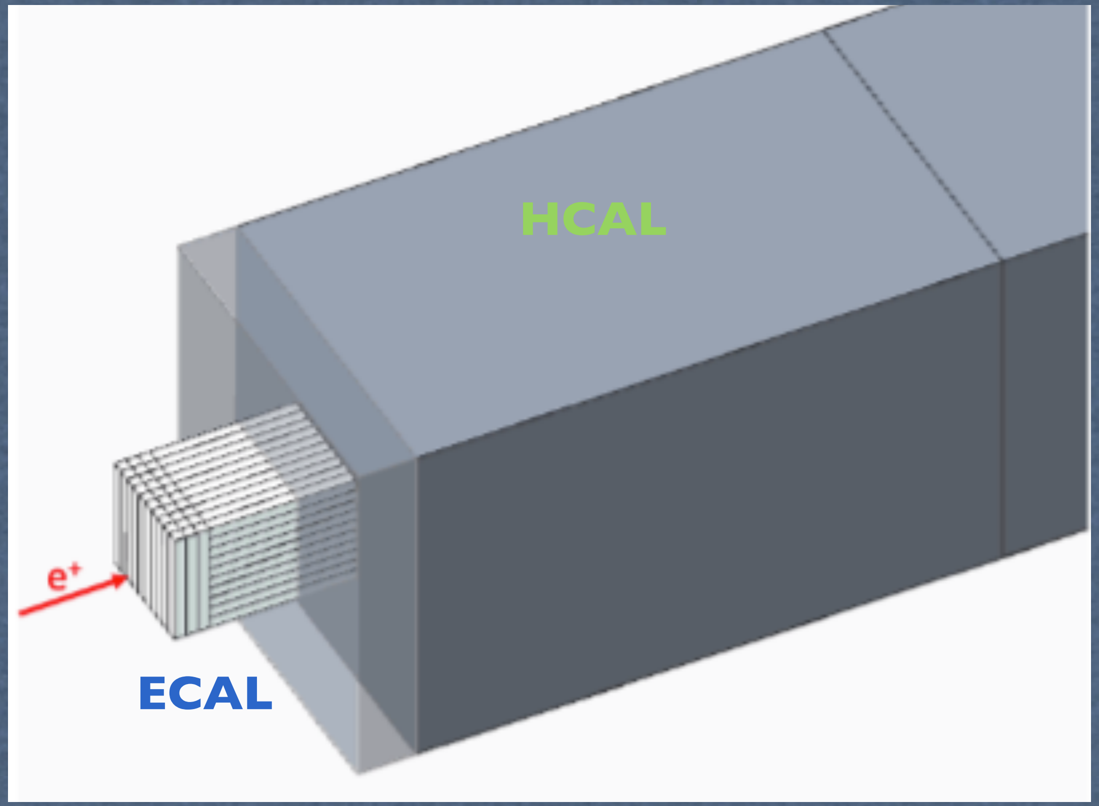
L. Marsicano et al., PRD 98, 115022 (2018)

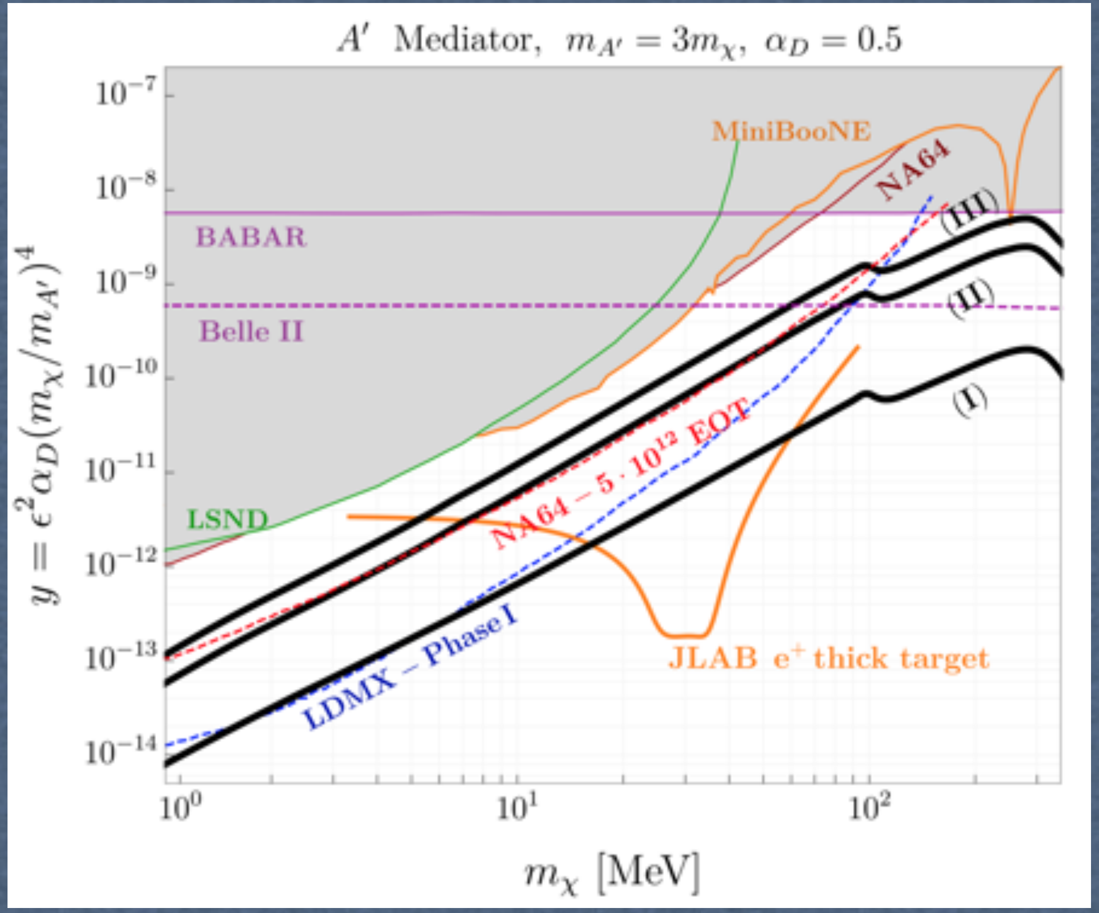
Future: JPOS@JLAB

e^+ annihilation on fixed (thick) target

invisible

- Missing energy experiment with a positron beam
- *Active* beam-dump experiment (*á la* NA64 but with positron!)
- Clear signal (peak!) due to the annihilation: $M_{A'} = \mathrm{Sqrt}(2\, m_e\, E_{miss})$
- Missing energy exp (e+ Z → e+ Z' A' with A' → invisible)
- 11 GeV e+ beam, low current
- Active target (calorimeter)
- Exclusion plots based on 10^{13} POT
- Detector: ECAL to measure e+ and an HCAL as a veto

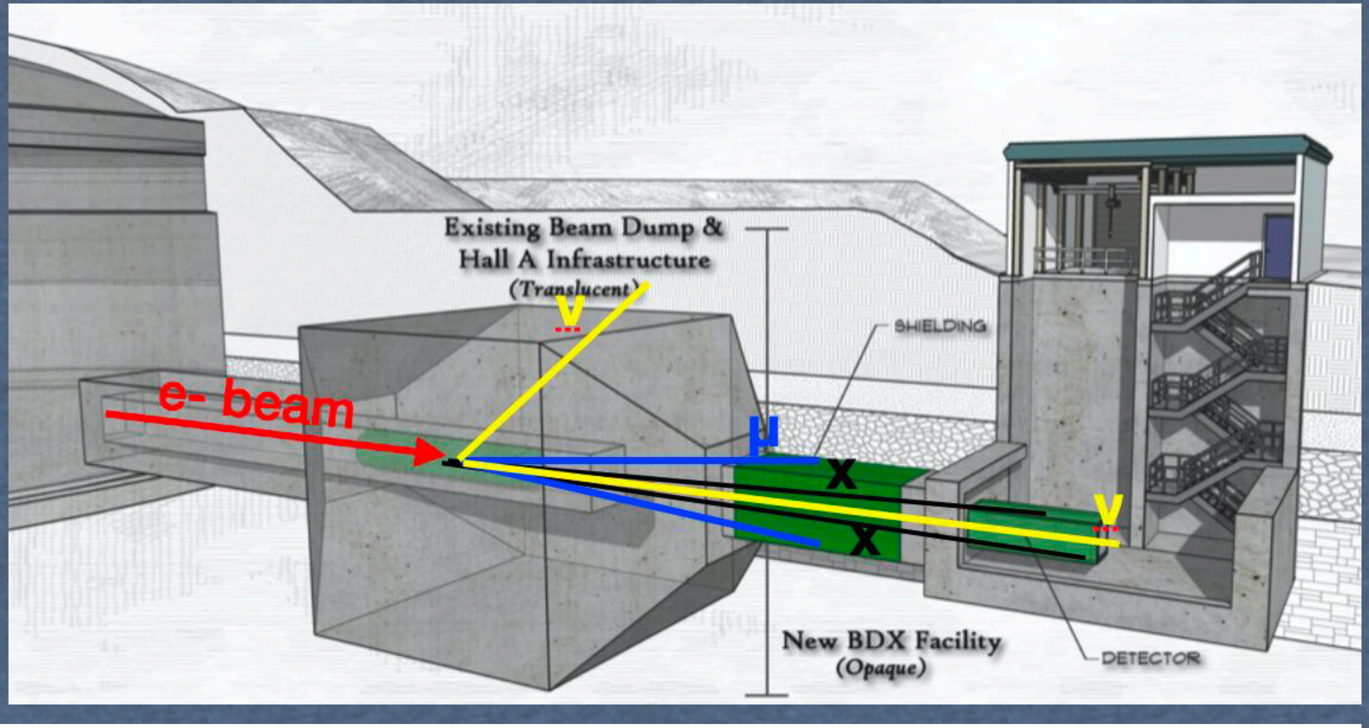




E.Voutier talk!

M. Battaglieri et al., Eur. Phys. J. A 57, 253 (2021)

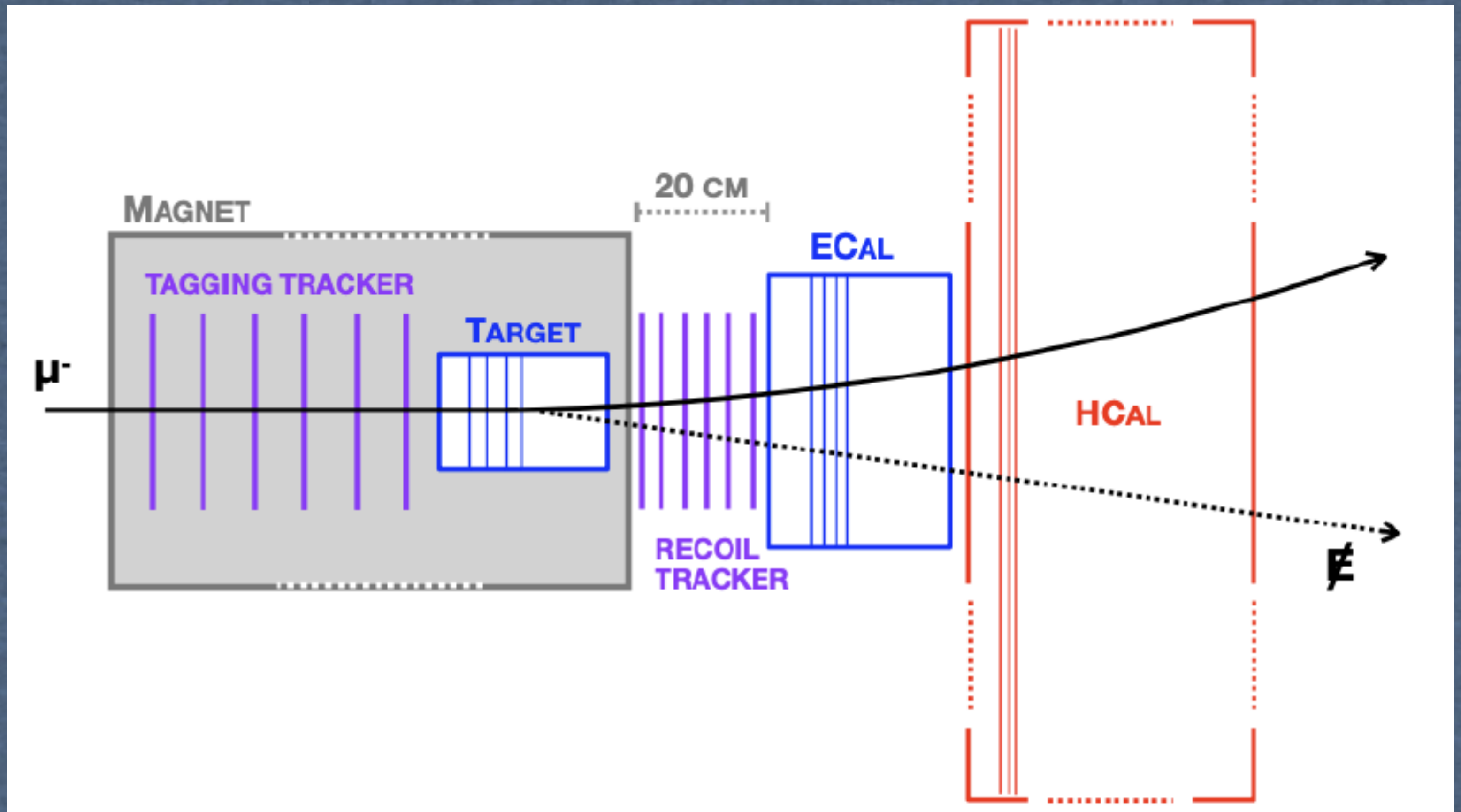
New physics perspectives at Jlab with secondary beams



- CEBAF-JLAB provides the highest intensity 10 GeV electron beam in the word
- High-intensity secondary beams are produced in the dump
  - LDM (if it exists)
  - Muon
  - Neutrino

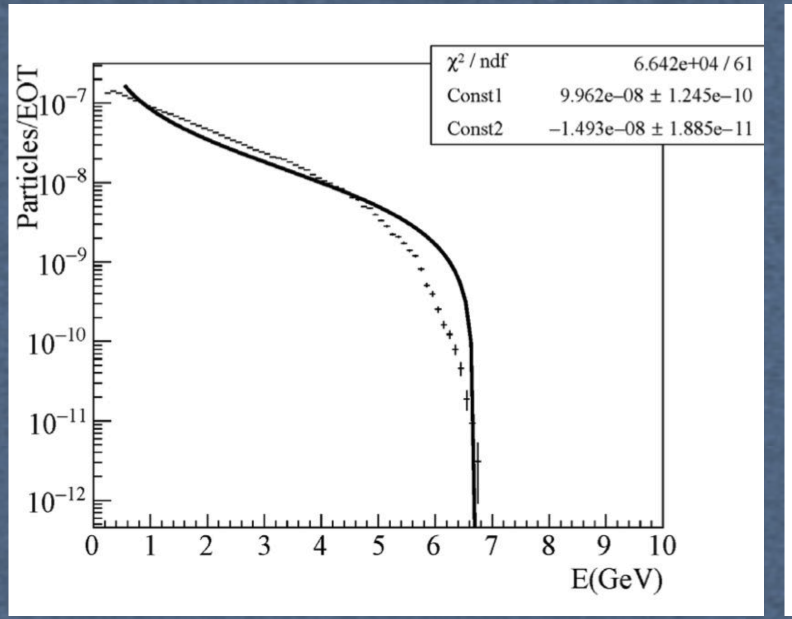
μ^3BDX @ JLab

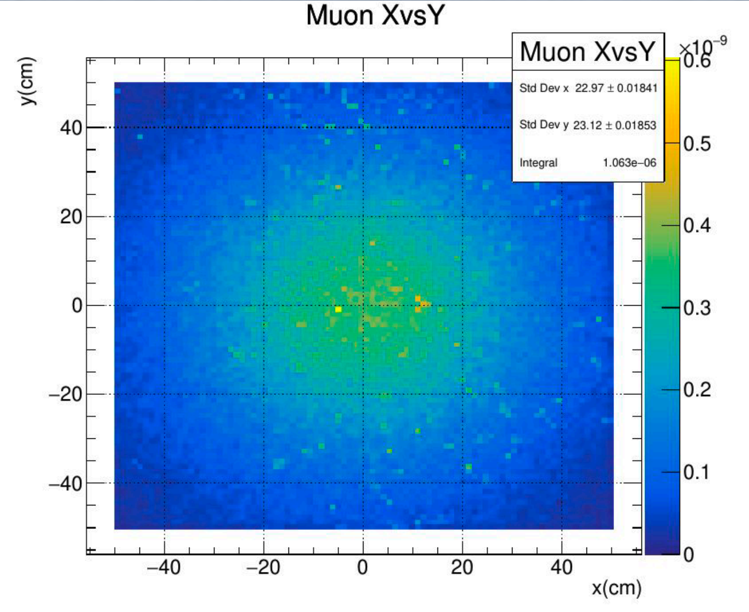
Probing muon-philic forces with secondary muon beam



Muon beam

- muons are mainly produced by Bethe-Heitler radiative process
- high-intensity beam (up 10^8 μ/s)
- Bremsstrahlung-like E spectrum, focused and compact muon beam





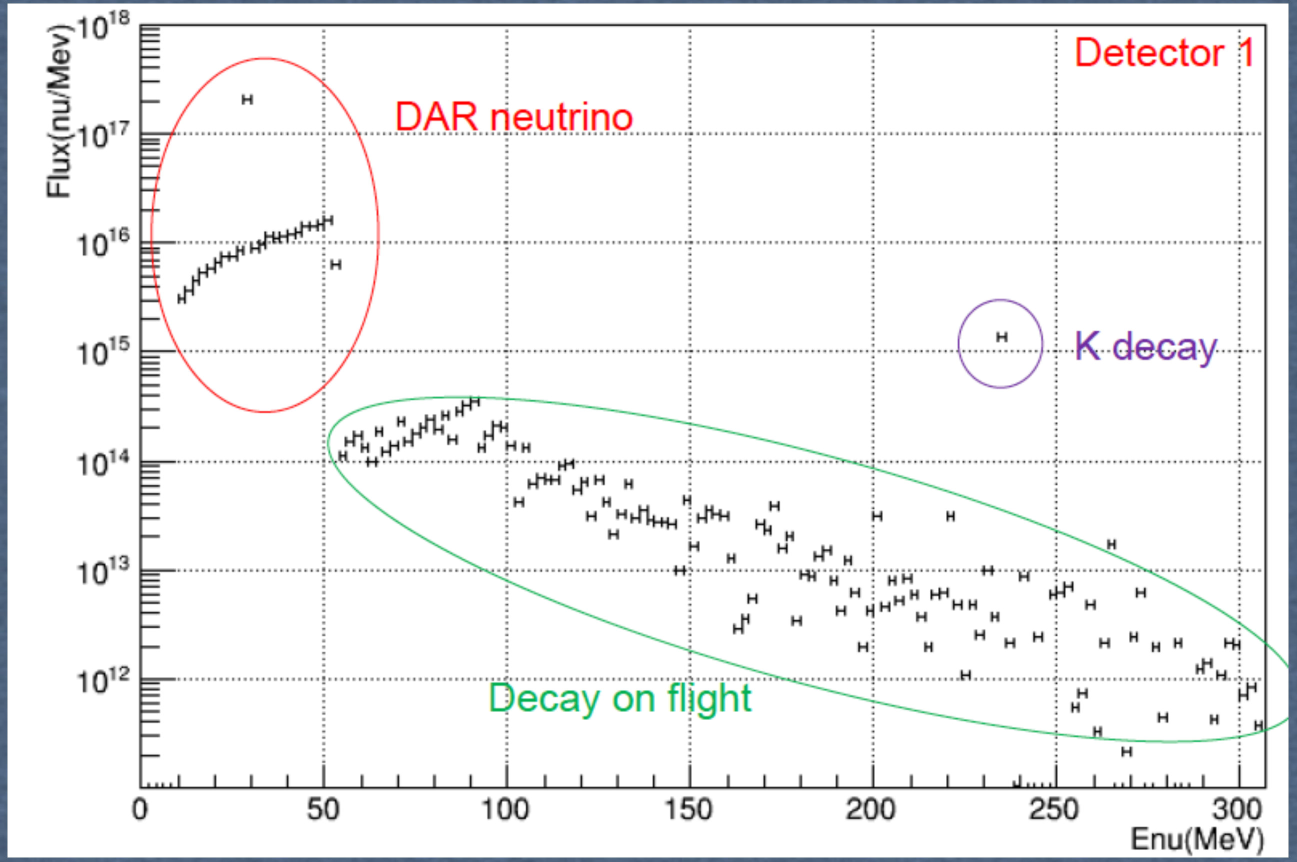
Fixed-target, missing-momentum experiment to probe invisibly decaying particles (similar to M^3 proposed at Fermilab)

νBDX @ JLab

Detecting CEvNS at JLab

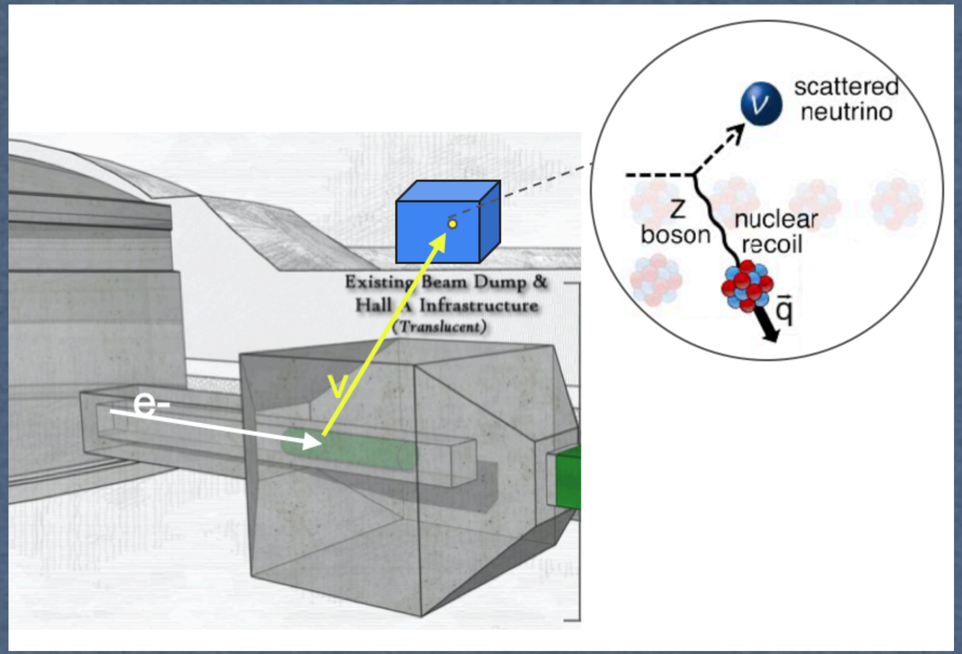
Neutrino beam

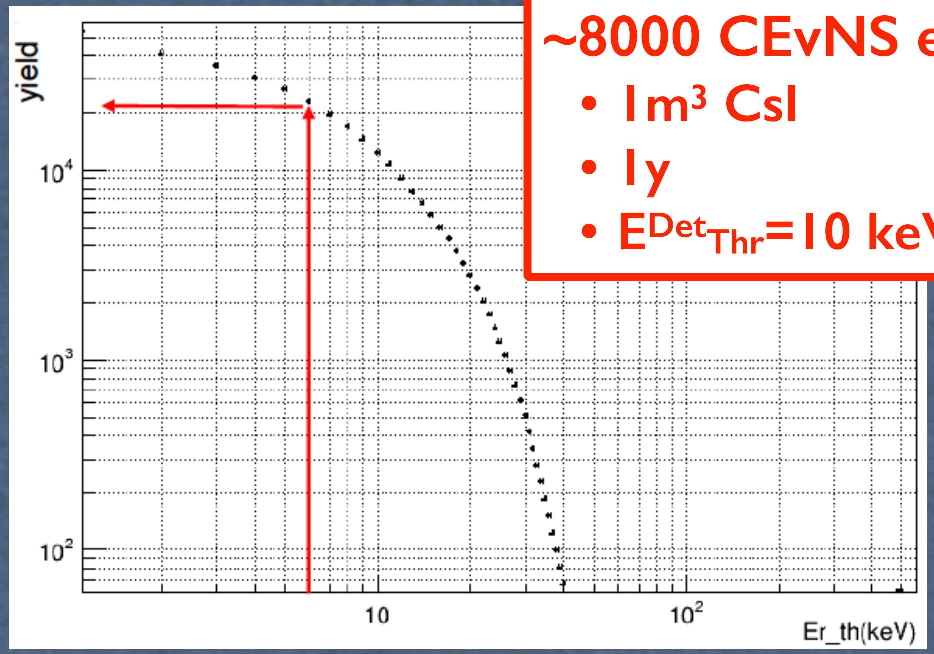
- Mainly produced by π and μ decays (3ν)
- high-intensity beam (up 10^{18} ν/y/m2)
- Decay-At-Rest energy spectrum(off-axis)



CEvNS (Coherent Elastic nu-Nucleus Scattering)

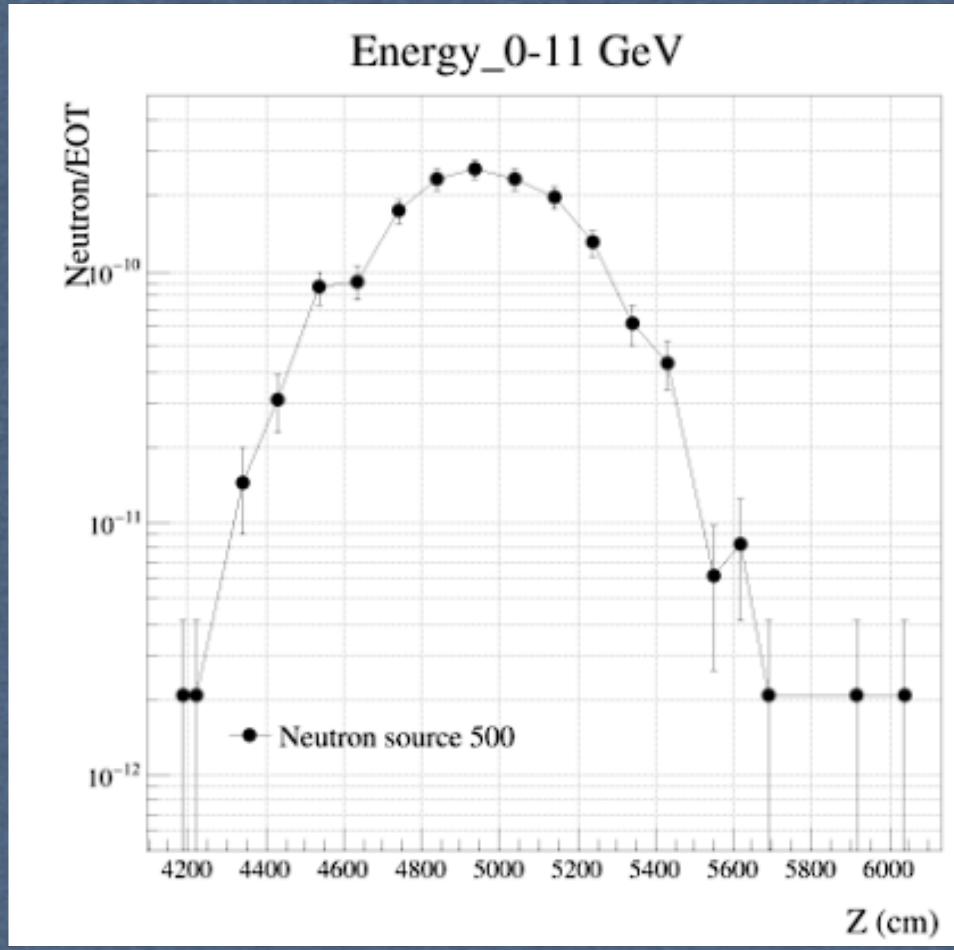
- Low-energy neutrinos (<100 MeV) coherent scatter on nucleus
- Cross-section scales as N^2
- The largest xsec for E_ν < 100 MeV
- First detected in 2017 on CsI by COHERENT (~134 events)
- Low recoil energy due to kinematics O(10 keV)



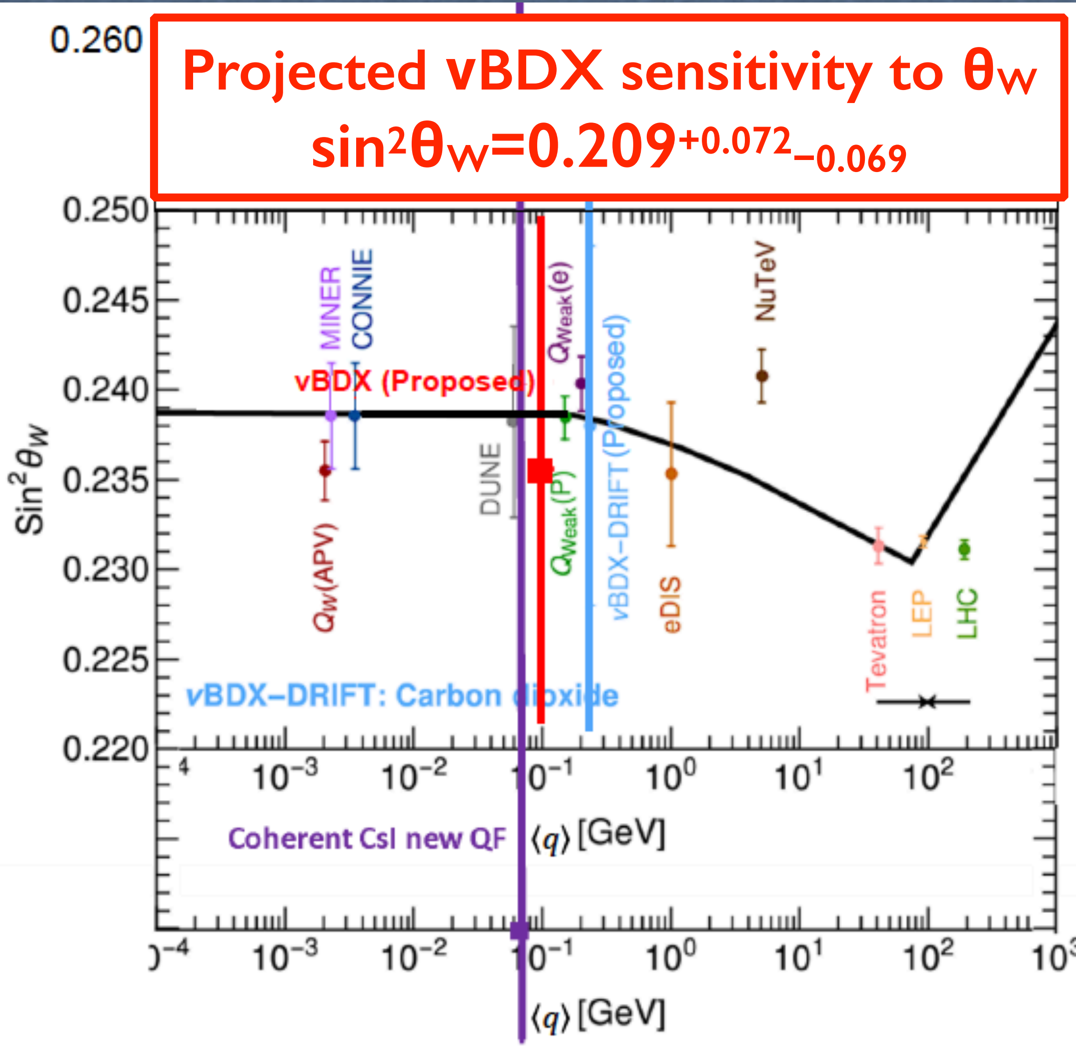


~8000 CEvNS events

- 1m³ CsI
- 1y
- E^{Det}_{Thr}=10 keV



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



Projected νBDX sensitivity to θ_W

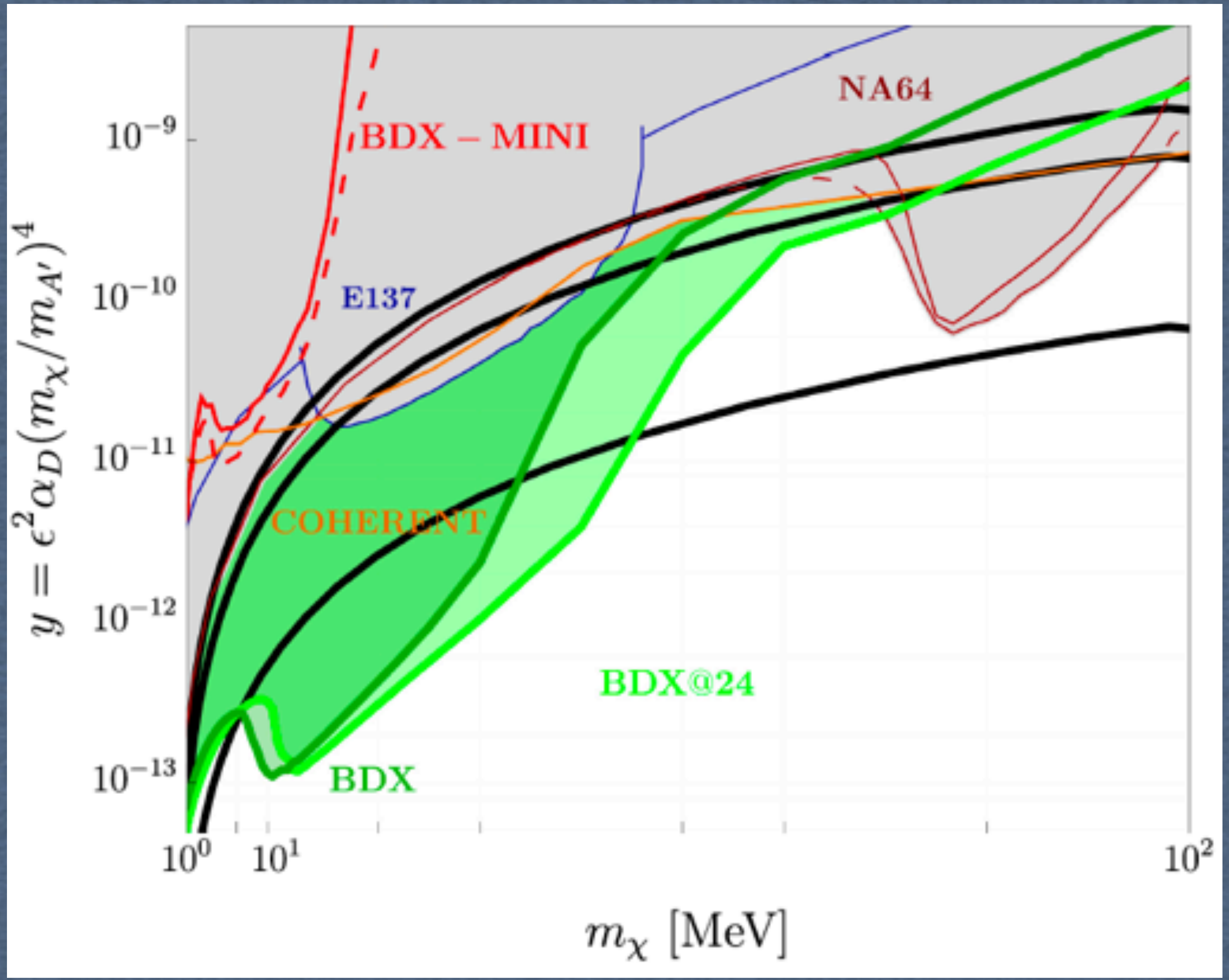
$\sin^2\theta_W = 0.209^{+0.072}_{-0.069}$

Opportunities with 20+ GeV CEBAF: BSM physics

Beyond hadronic physics with secondary beams at 24 GeV

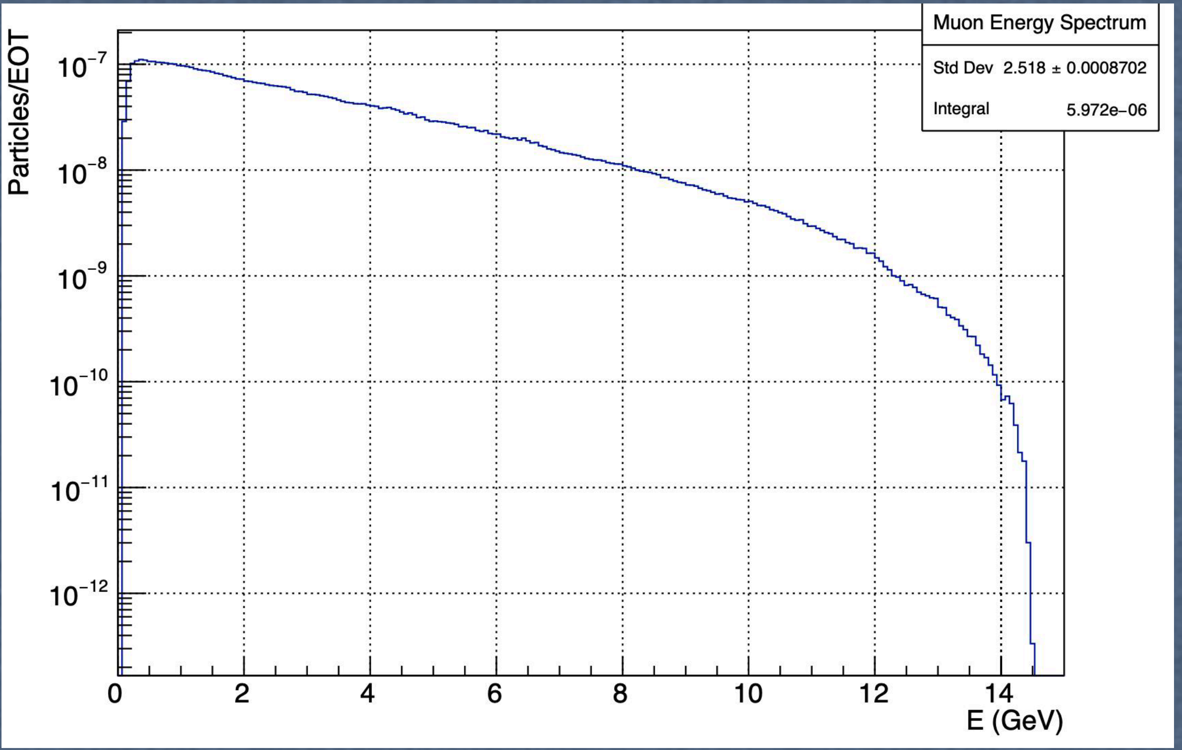
Searching for Light Dark Matter in BDX

- Extension of the current LDM searches at 24 GeV
- Unique sensitivity to LDM scenarios (inelastic LDM)
- Complementarity to the current program



Muon beam

- More focused beam, up to 10^{10} μ/s with energy up to 14 GeV
- Flux larger than CERN's M2 beam line (Eμ>100GeV ~2×10^7 μ/s)



Neutrino beam

- up to 2×10^{18} nu/year/m3, with Decay-At-Rest Energy spectrum

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

Conclusions

- ✳ The existence of Dark Matter is a compelling reason to investigate new forces and matter over a broad range of mass
- ✳ Accelerator-based (Light)DM search provides a unique feature of distinguishing DM signal from any other cosmic anomalies or effects
- ✳ An extensive program to explore the Dark Sector making use of the high-intensity ~10GeV electron beam available at Jefferson Lab is in full swing
- ✳ A new generation of dedicated and optimized experiments at high-intensity frontier will test the relic (light) dark matter scenario
- ✳ A high-intensity positron beam available in the near future at Jefferson Lab will optimize LDM searches via annihilation
- ✳ Other high-intensity muon and neutrino secondary beams will complement the current program
- ✳ Discovery or decisive tests of the simplest scenarios will possible in the next 5-10 years!