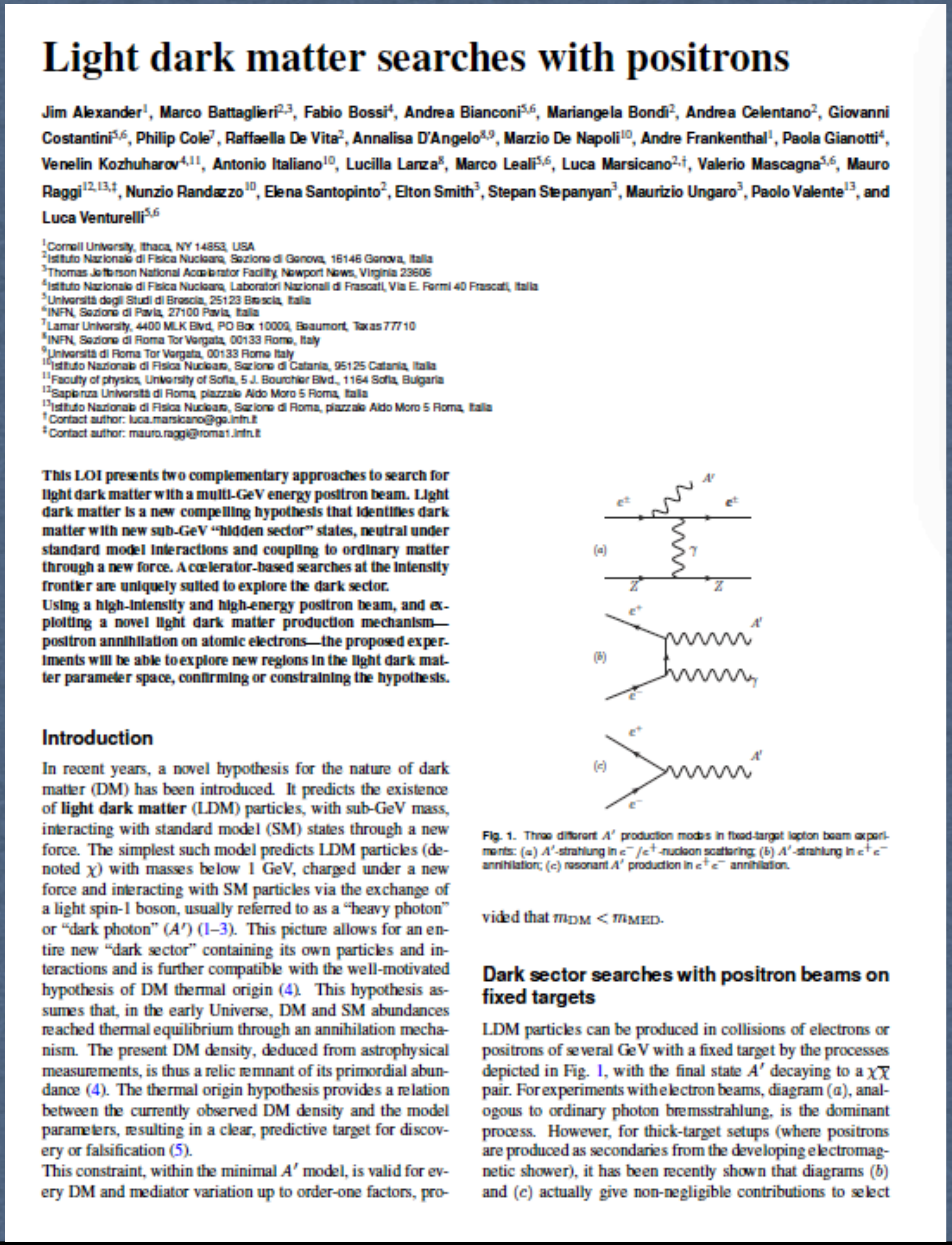
Light dark matter searches with positrons

Jim Alexander[1], Marco Battaglieri[2,3], Fabio Bossi[4], Andrea Bianconi[5,6], Mariangela Bondi[2], Andrea Celentano[2], Giovanni Costantini[5,6], Philip Cole[7], Raffaella De Vita[2], Annalisa D'Angelo[8,9], Marzio De Napoli[10], Andre Frankenthal[1], Paola Gianotti[4], Venelin Kozhuharov[4,11], Antonio Italiano[10], Lucilla Lanza[8], Marco Leali[5,6], Luca Marsicano[2,†], Valerio Mascagna[5,6], Mauro Raggi[12,13,‡], Nunzio Randazzo[10], Elena Santopinto[2], Elton Smith[3], Stepan Stepanyan[3], Maurizio Ungaro[3], Paolo Valente[13], and Luca Venturelli[5,6]

[1]Cornell University, Ithaca, NY 14853, USA
[2]Istituto Nazionale di Fisica Nucleare, Sezione di Genova, 16146 Genova, Italia
[3]Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606
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[7]Lamar University, 4400 MLK Blvd, PO Box 10009, Beaumont, Texas 77710
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[‡]Contact author: mauro.raggi@roma1.infn.it

This LOI presents two complementary approaches to search for light dark matter with a multi-GeV energy positron beam. Light dark matter is a new compelling hypothesis that identifies dark matter with new sub-GeV "hidden sector" states, neutral under standard model interactions and coupling to ordinary matter through a new force. Accelerator-based searches at the intensity frontier are uniquely suited to explore the dark sector.
Using a high-intensity and high-energy positron beam, and exploiting a novel light dark matter production mechanism—positron annihilation on atomic electrons—the proposed experiments will be able to explore new regions in the light dark matter parameter space, confirming or constraining the hypothesis.

Introduction

In recent years, a novel hypothesis for the nature of dark matter (DM) has been introduced. It predicts the existence of **light dark matter** (LDM) particles, with sub-GeV mass, interacting with standard model (SM) states through a new force. The simplest such model predicts LDM particles (denoted χ) with masses below 1 GeV, charged under a new force and interacting with SM particles via the exchange of a light spin-1 boson, usually referred to as a "heavy photon" or "dark photon" (A') (1–3). This picture allows for an entire new "dark sector" containing its own particles and interactions and is further compatible with the well-motivated hypothesis of DM thermal origin (4). This hypothesis assumes that, in the early Universe, DM and SM abundances reached thermal equilibrium through an annihilation mechanism. The present DM density, deduced from astrophysical measurements, is thus a relic remnant of its primordial abundance (4). The thermal origin hypothesis provides a relation between the currently observed DM density and the model parameters, resulting in a clear, predictive target for discovery or falsification (5).
This constraint, within the minimal A' model, is valid for every DM and mediator variation up to order-one factors, provided that $m_{DM} < m_{MED}$.

Fig. 1. Three different A' production modes in fixed-target lepton beam experiments: (a) A'-strahlung in e^-/e^+-nucleon scattering; (b) A'-strahlung in e^+e^- annihilation; (c) resonant A' production in e^+e^- annihilation.

Dark sector searches with positron beams on fixed targets

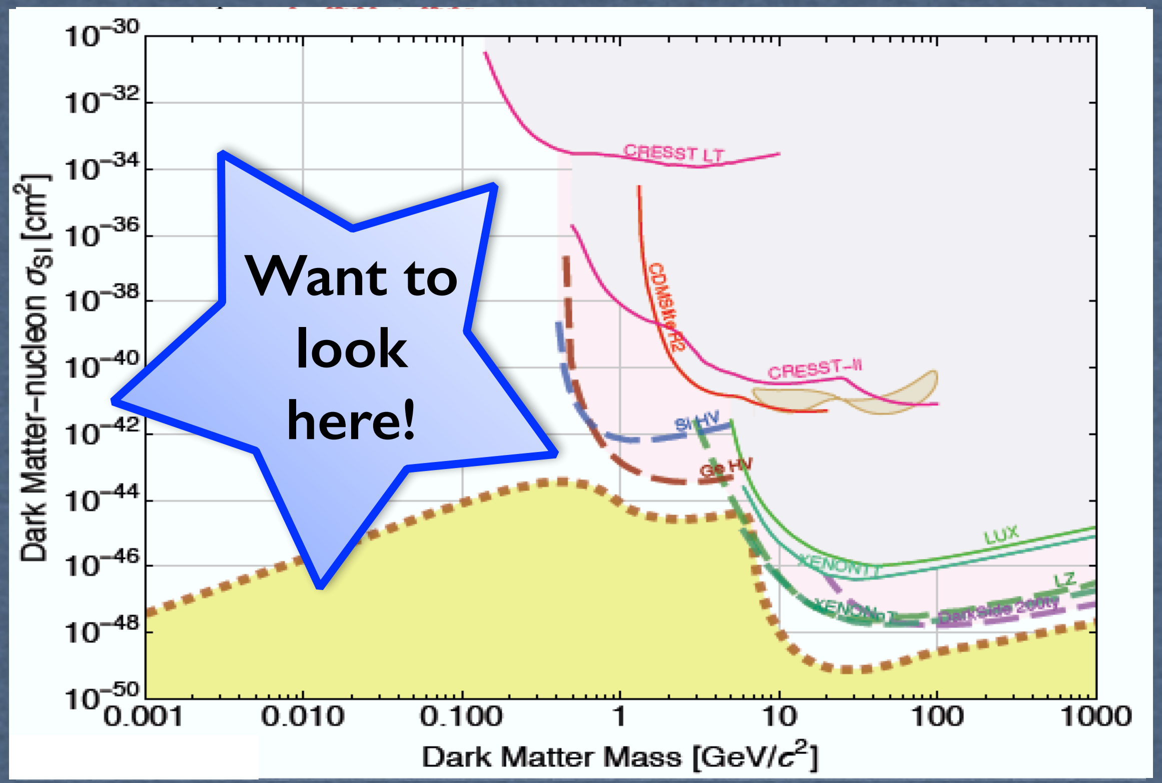
LDM particles can be produced in collisions of electrons or positrons of several GeV with a fixed target by the processes depicted in Fig. 1, with the final state A' decaying to a $\chi\bar{\chi}$ pair. For experiments with electron beams, diagram (a), analogous to ordinary photon bremsstrahlung, is the dominant process. However, for thick-target setups (where positrons are produced as secondaries from the developing electromagnetic shower), it has been recently shown that diagrams (b) and (c) actually give non-negligible contributions to select

Light Dark Matter searches with positrons

M.Battaglieri
INFN
(on behalf of JPOS-LDM)

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**

Light Dark Matter | Direct Detection

1 MeV — 1 GeV — Mz — 10 TeV

WIMPs

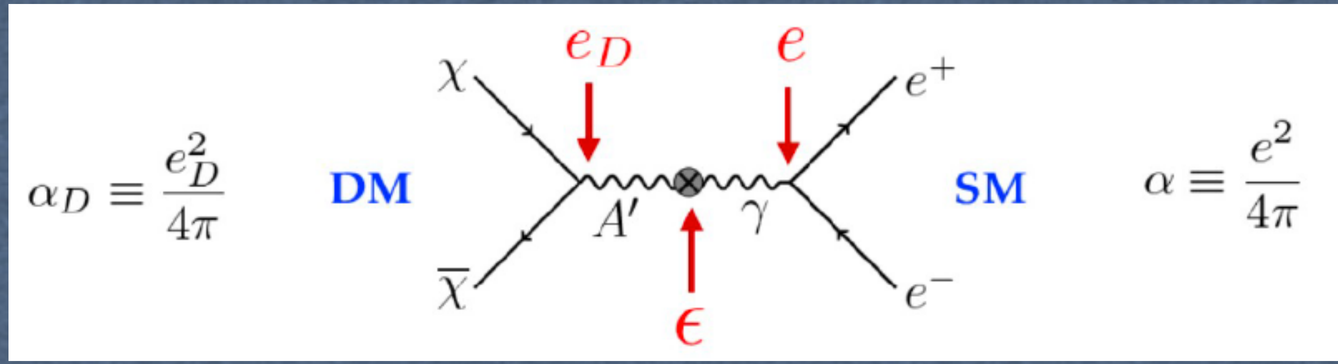
Dark Sector or Hidden Sector (DM not directly charged under SM interactions)

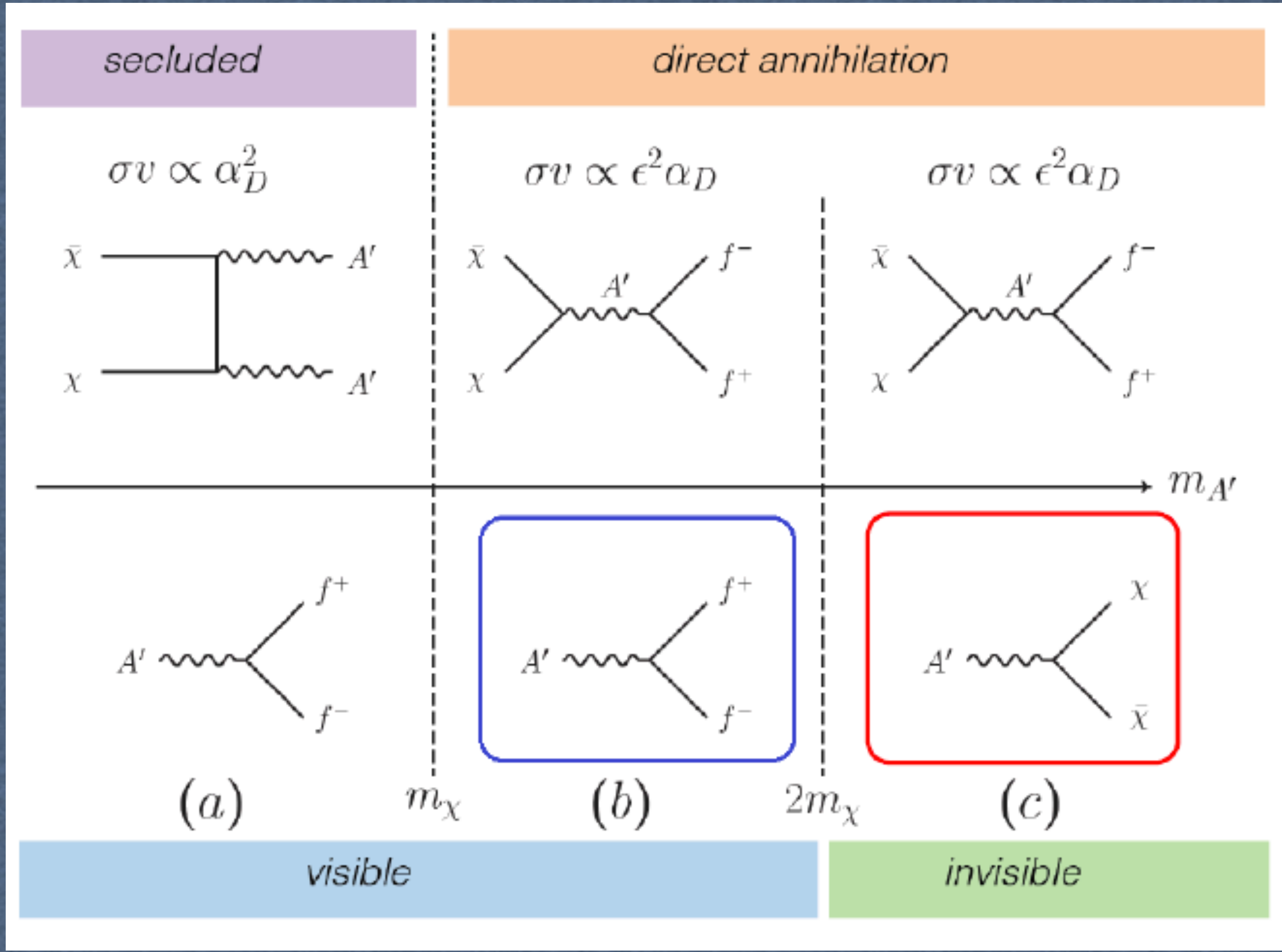
Can be explored at accelerators!

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

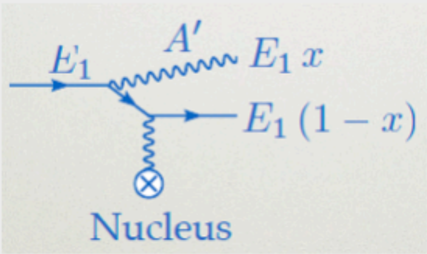
- **Secluded**: no constraints by cosmology for accelerator based experiments. Any ε allowed
- **Visible decay**: final state contains SM particles
- **Invisible decay**: A' decays to Dark Sector invisible particles

Light Dark Matter @ JLab

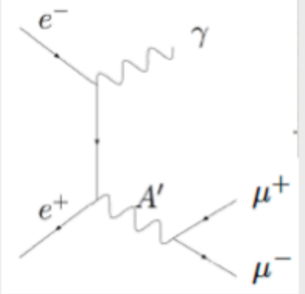
Fixed target vs. collider

Process

Fixed Target

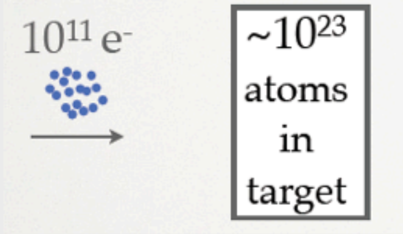


e+e- colliders

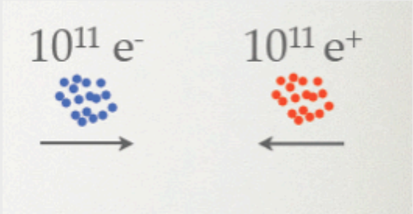


Luminosity

Fixed Target



e+e- colliders



Cross-Section

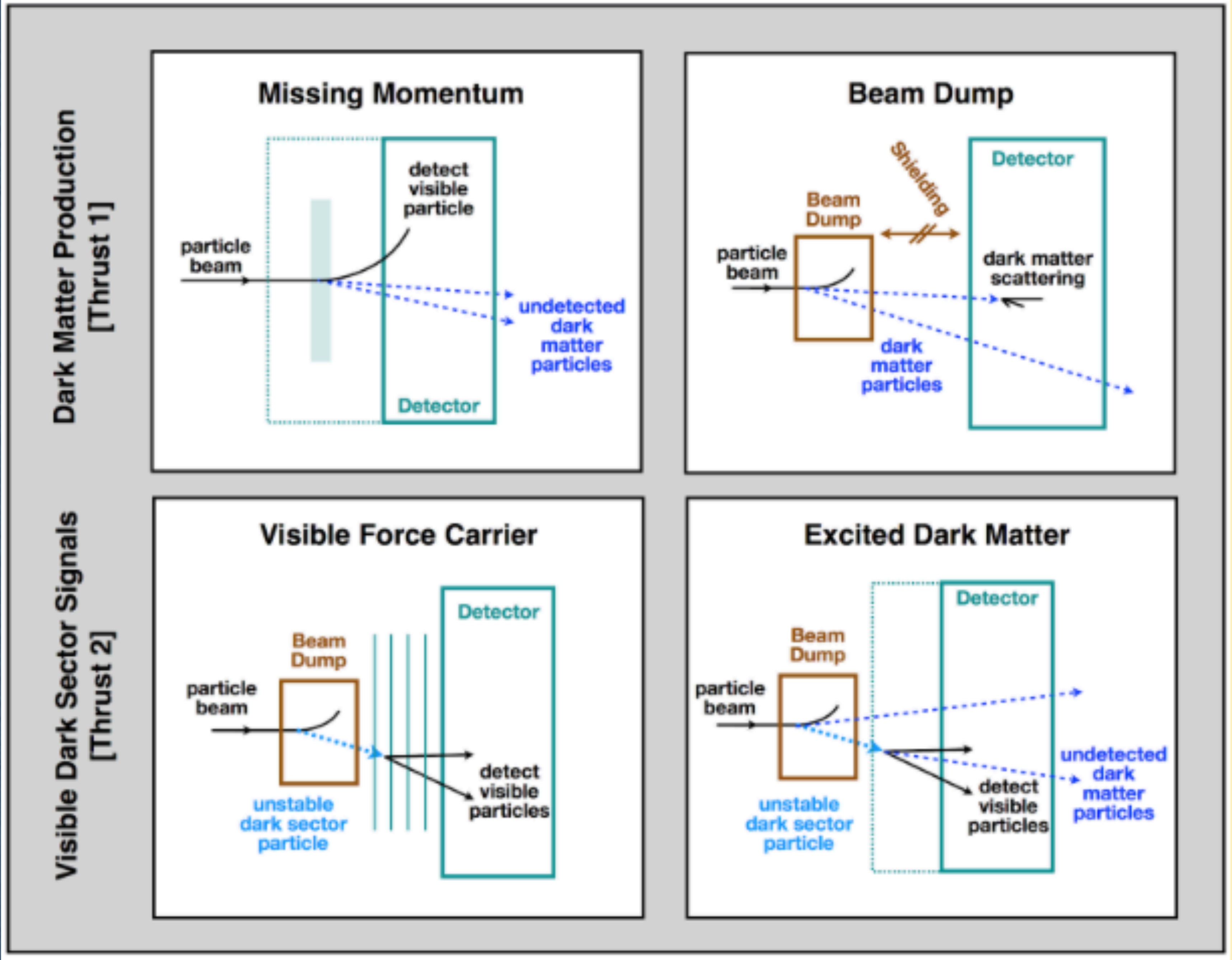
Fixed Target: $\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$

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

Fixed Target:
- high backgrounds
- limited A' mass

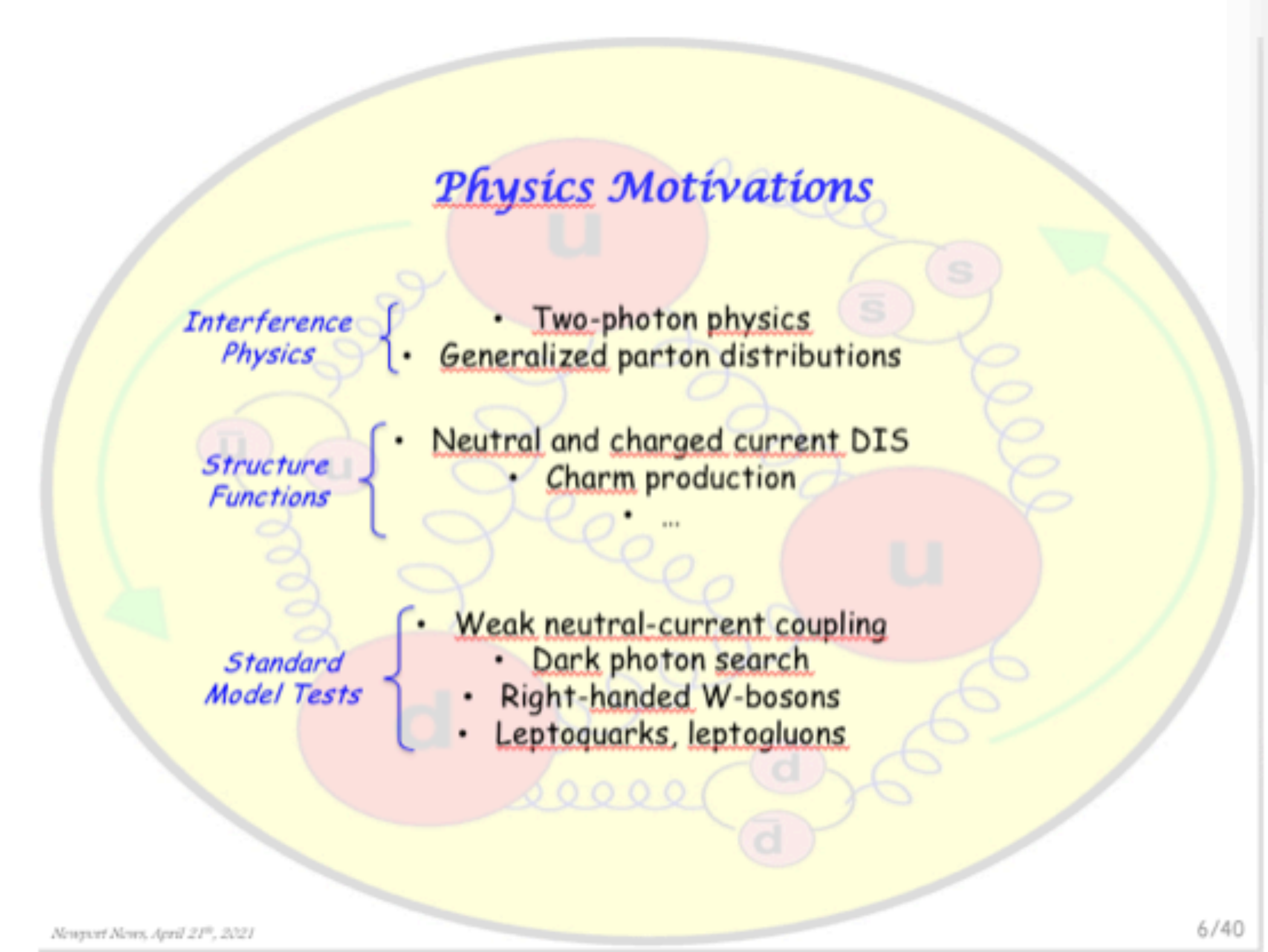
e+e- colliders:
- low backgrounds
- higher A' mass

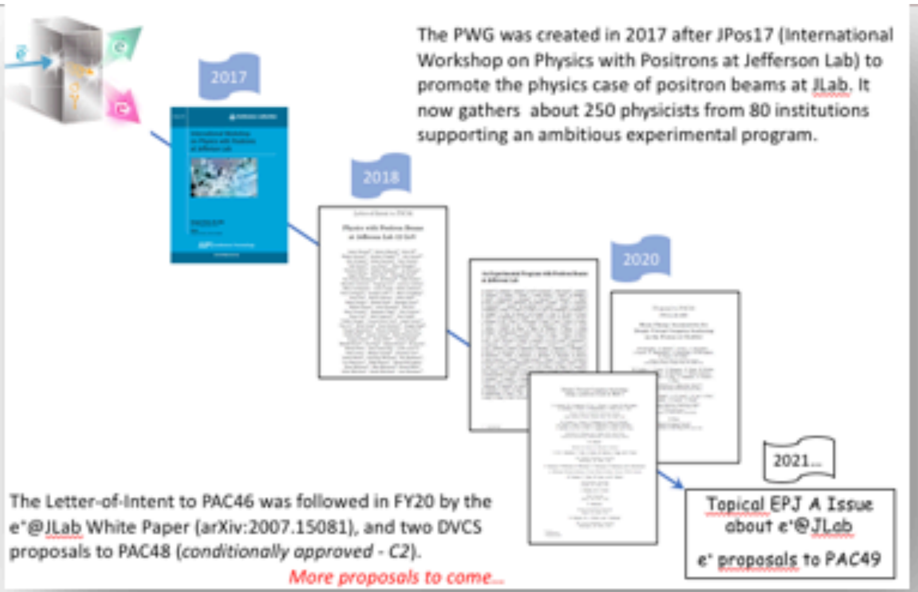
✶ $1/M_{A'}$ .vs. $1/E_{beam}$
✶ Coherent scattering from Nucleus (~Z^2)

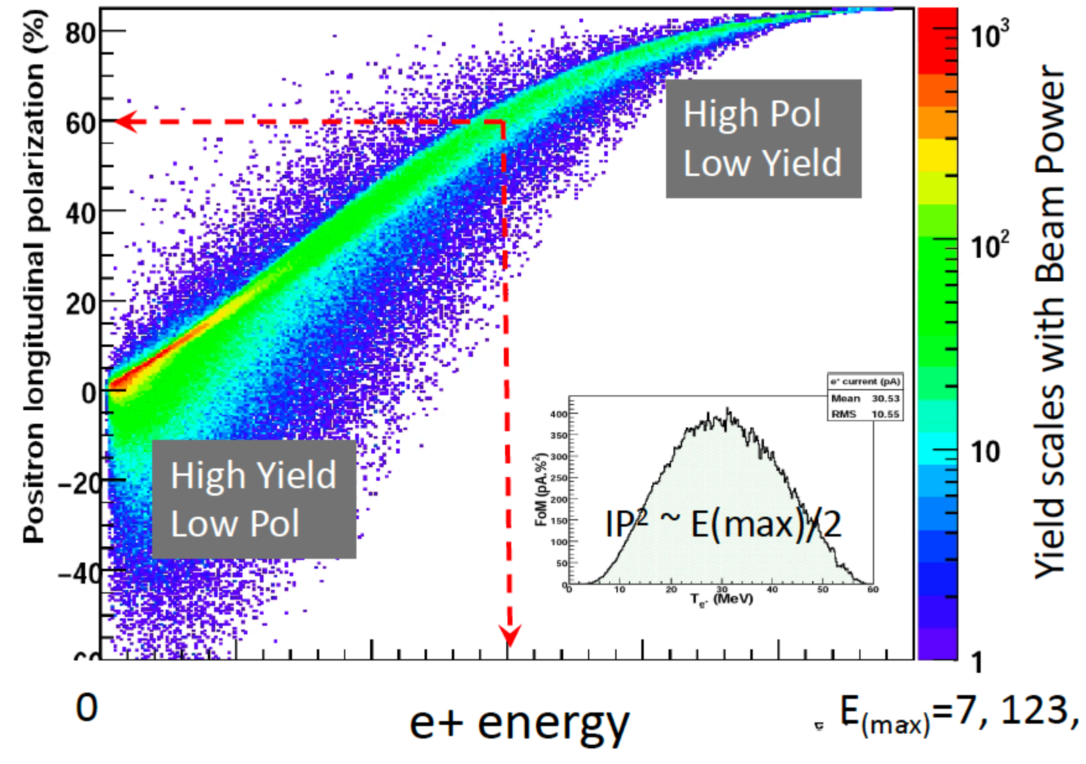


JLAB positron beam

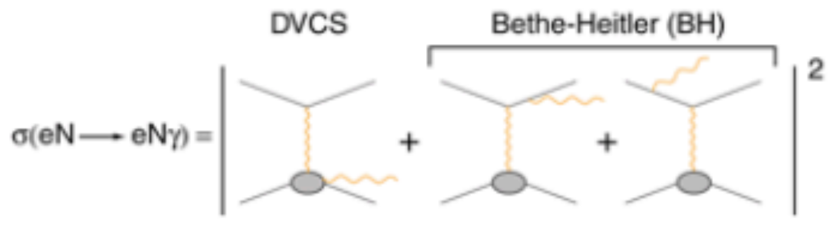
- Positron beam of high energy (up to 11 GeV), high current (I_{e+}~0.5-1uA), high polarisation (P_{e+}~60%)







Nucleon tomography and dynamics



The comparison of lepton beams of opposite charges allows to uniquely disentangle the different components of the cross section and offers an unambiguous access to the distribution of forces inside the nucleon.

The experimental determination of GPDs require a large set of observables involving unpolarized and polarized lepton beams together with unpolarized and polarized targets.

- DVCS on the proton with NPS in Hall C intends to measure cross sections with unpolarized e$^+$ beam. *Contact person: C. Muñoz Camacho*
- DVCS on the proton with CLAS12 intends to measure unpolarized and polarized beam charge asymmetries. *Contact person: E. Voutier*

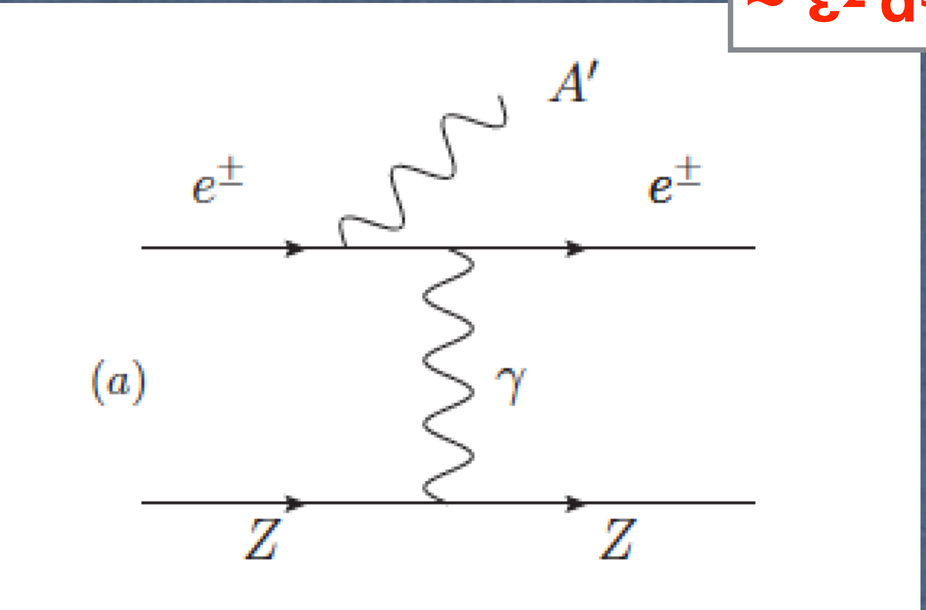
Proposal #	Hall	Detector	p (GeV/c)	I (μA)	P (%)	Beam Nature	Beam Time (d)	PAC Result
PR12-20-012	C	NPS & HMS	6.6	5	None	e$^+$	77	C2
			8.8					
			10.6					
PR12-20-009	B	CLAS12	2.2	0.045	60	e$^-$	48	C2
			10.6			e$^+$	52	

More proposals to come to PAC49.

From JLab PAC48 Report:
"The Committee sees great physics potential in a positron program. We encourage a vigorous effort to explore the technical feasibility of providing positron beams, and we are looking forward to receiving further proposals in this area. Clearly, it is difficult at the present stage to predict the characteristics of positron beams that will be achievable."

A’ Production mechanisms - $e^{\pm}$

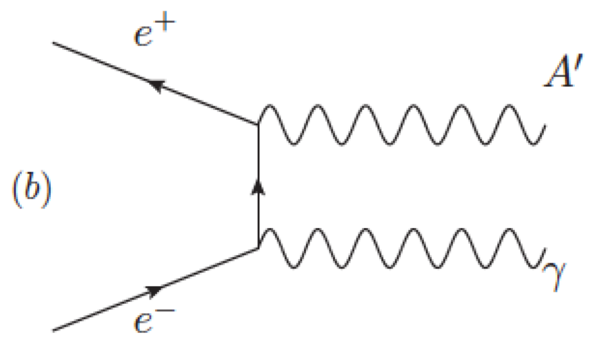
$\sim \varepsilon^2 \alpha^3$



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

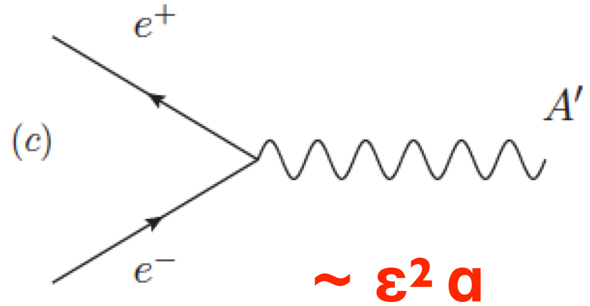
- The incoming electron ‘see’ a fast-moving cloud of effective photons to scatter from
- Photons are almost on-shell (low Q2) → transverse photons ~ $e^- \gamma_{Real}$ scattering
- Same treatment as the regular *bremstrahlung*
- Regularisations occurs in the case of interest $M_{A'} >> M_{e-}$
- Effective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

A’ Production - positrons



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

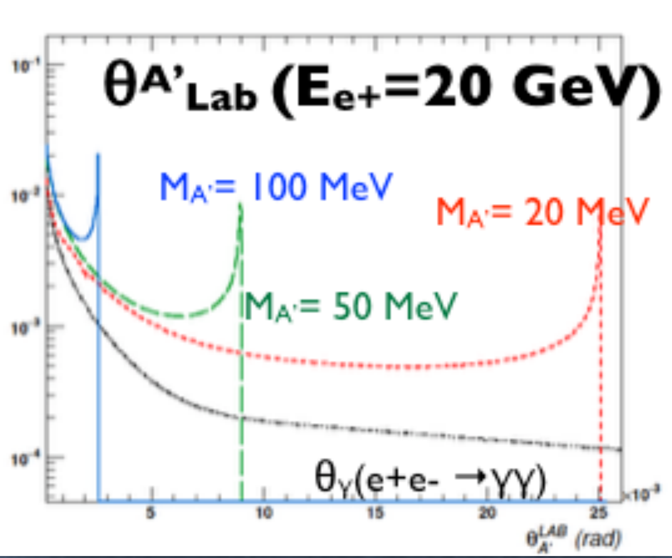
- **NON-RESONANT annihilation**
  - **A’ along (e^+e^-) direction**
- **Two-body process**
- **A’ forward-peaked along e^+ direction**
- $\mathbf{E_{A'} = E_R = m^2_{A'}/2m_e}$

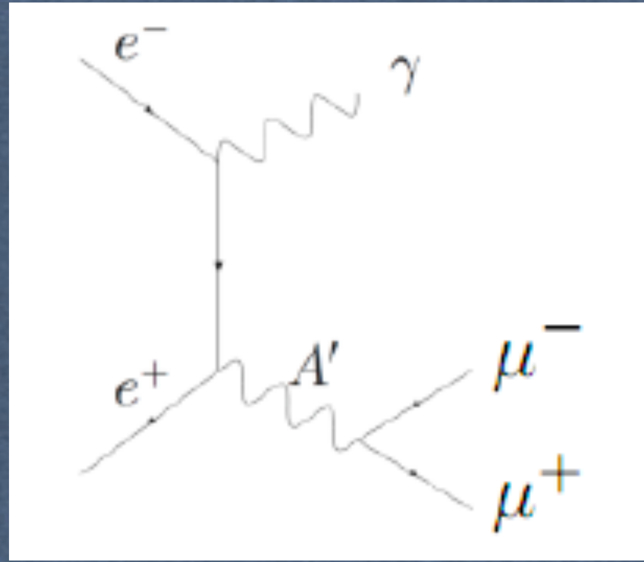


$\sim \varepsilon^2 \alpha$

- **RESONANT annihilation**

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



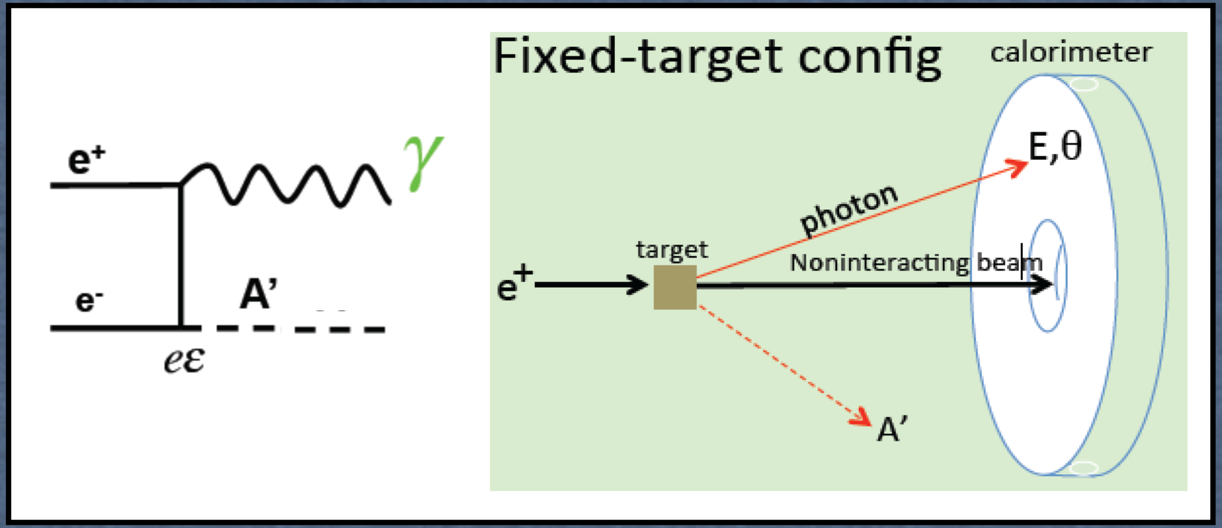


- Known and used
- Collider (missing mass experiments)
- Thin target experiments (visible decay)

$e^+e^- \to \gamma' \gamma \to \mu\mu \gamma$

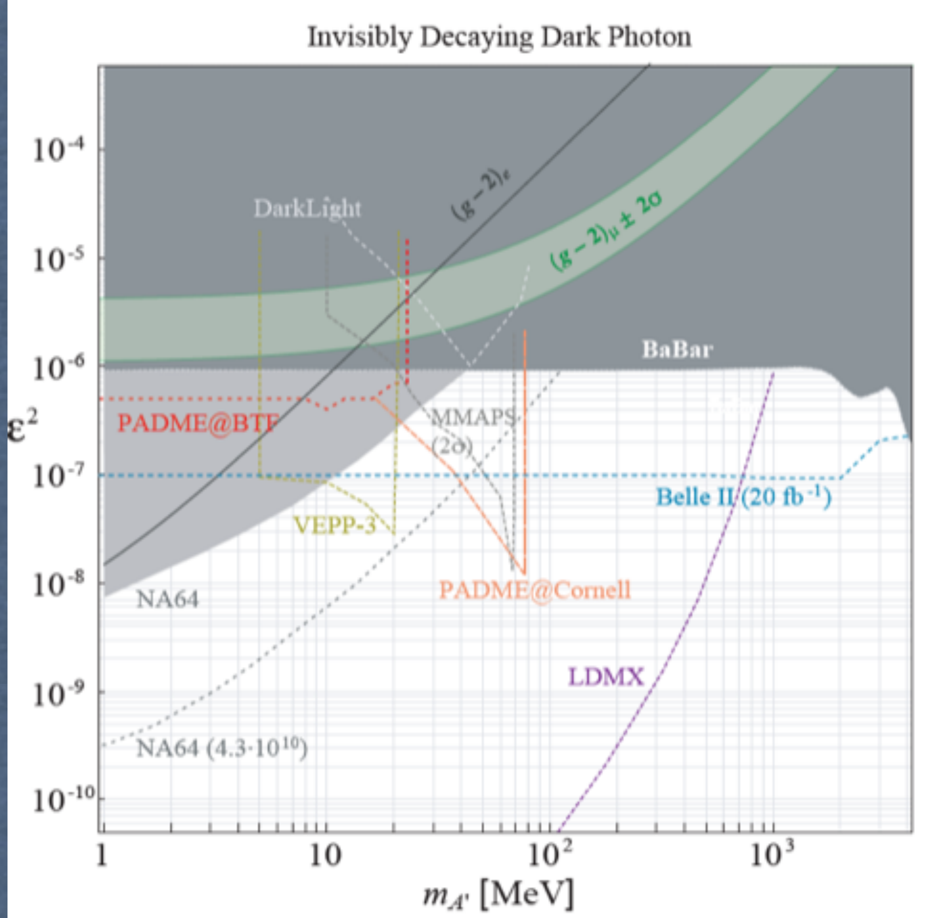
➜ BABAR, BELLE, KLOE, CLEO

e^+ annihilation on fixed (thin) target
invisible



Missing mass search:
- Independent of A' decay mechanism
- Bump hunt (monophoton@collider)
- Need a positron beam

- Limited $M_{A'}$ accessible
  - 1 GeV beam: $M_{A'}$ < 31 MeV
  - 5 GeV beam: $M_{A'}$ < 71 MeV



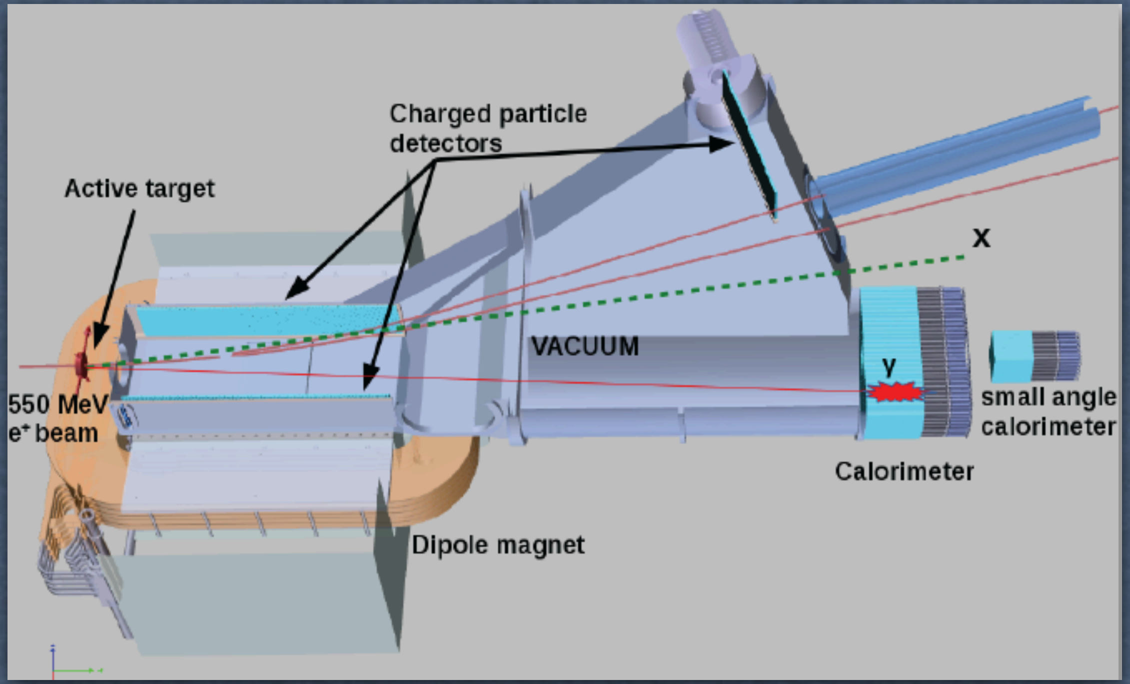
VEPP3
- E_{e+} = 500 MeV
- EOT ~ 10^{15} - 10^{16} year^{-1}

LNF
- E_{e+} = 550 MeV
- EOT ~ 10^{13} - 10^{14} year^{-1}

Cornell
- E_{e-} = 5.3 GeV
- EOT ~ 10^{17} - 10^{18} year^{-1}

JLab (future)
- E_{e-} = 11 GeV
- EOT ~ 10^{18} - 10^{19} year^{-1}

PADME @ LNF
- Beam: e+ from LNF LINAC, 550MeV, multiplicity ~ 20k e+/bunch, bunch 250 ns, frequency 49 Hz.
- Diamond active **target** 100 μm thickness: position, size and intensity of incoming beam
- Dipole **magnet** of 0.45 T to deflect charged particles out calorimeter
- Plastic scintillators **veto** system + high energy e+ veto to detect charged particles bent by magnet
- Electromagnetic calorimeter (**ECAL**) composed of 616 BGO crystals
- Small angle calorimeter **(SAC)** composed of 25 PbF2 crystals
- Already collected 5 10^{12} POT (expected 10^{13} POT)
- Next runs focused on X17

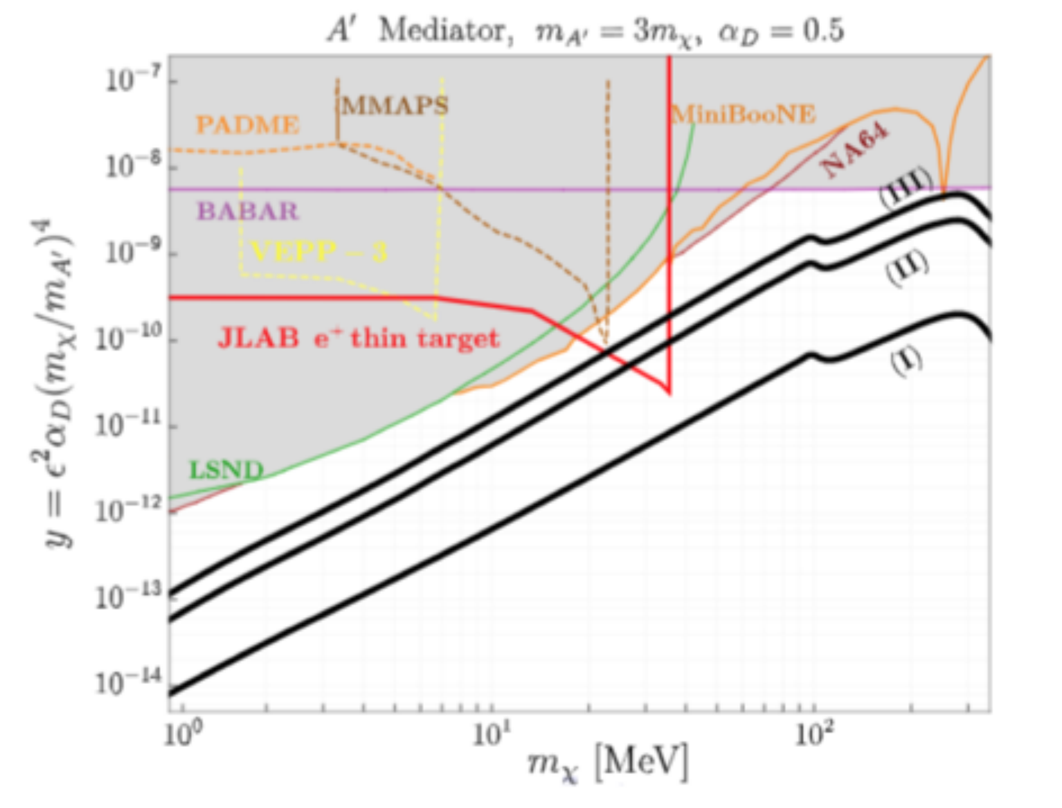


JPOS@JLAB

e^+ annihilation on fixed (thin) target
invisible

- Reusable PADME components: target, calorimeter and veto
- New DAQ suitable for a CW beam is necessary

- Main limitation: limited energy in the CM ~ sqrt(E_{beam})
- High energy positron beams are not (yet) available
- The highest energy at JLab (~11 GeV) Max $M_{A'}$ ~ 106 MeV



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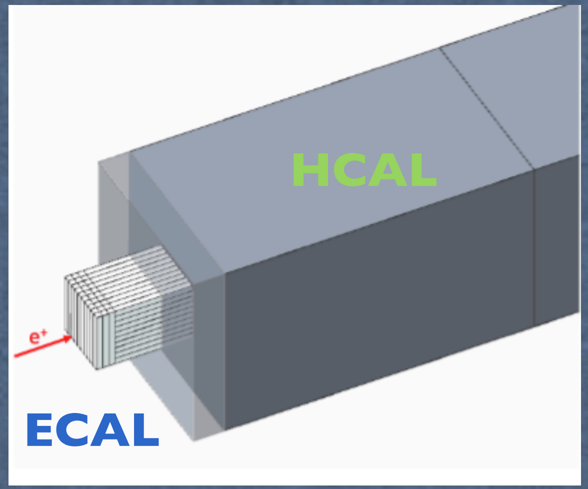
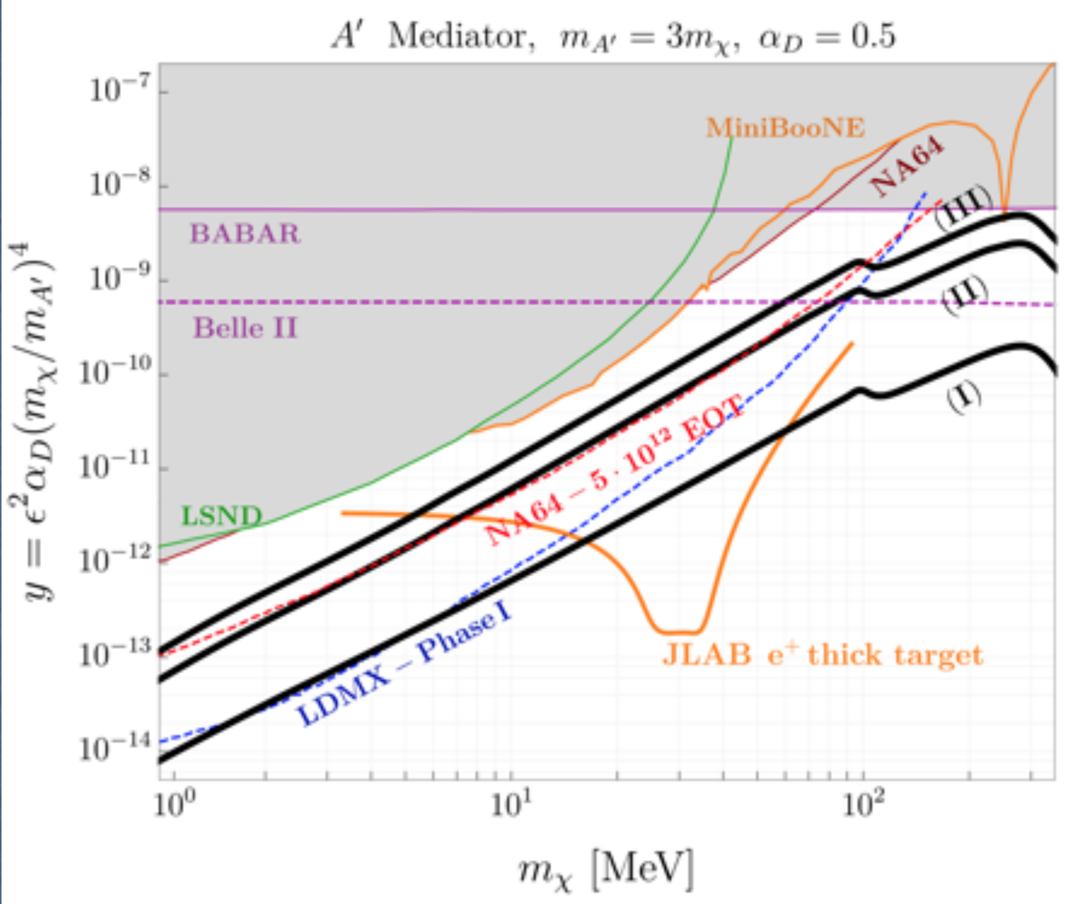


- *Active* beam-dump experiment (*á la* NA64 but with positron!)
- Clear signal (peak!) due to the annihilation: $M_{A'}$ = Sqrt(2 m_e E_{miss})
- Missing energy exp (e+ Z → e+ Z' A' with A' → invisible)
- 11 e+ beam, low current
- Active target (calorimeter)
- Exclusion plots based on 10^{13} POT
-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



PADME@JLAB

Snowmass 2021

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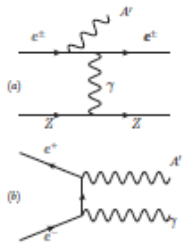

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PADME@JLAB

Reusable PADME components:
- Target - PADME carbon target can be installed at CEBAF
- Calorimeter - PADME Ecal meets all requirements of the experiment (energy resolution, angular resolution, size)
- Veto System - technology and front-end electronics from PADME veto can be reused

New equipment:
- DAQ system - suitable for a CW beam

- Main limitation: limited energy in the CM ~ sqrt(E_{beam})
- High energy positron beams are not (yet) available
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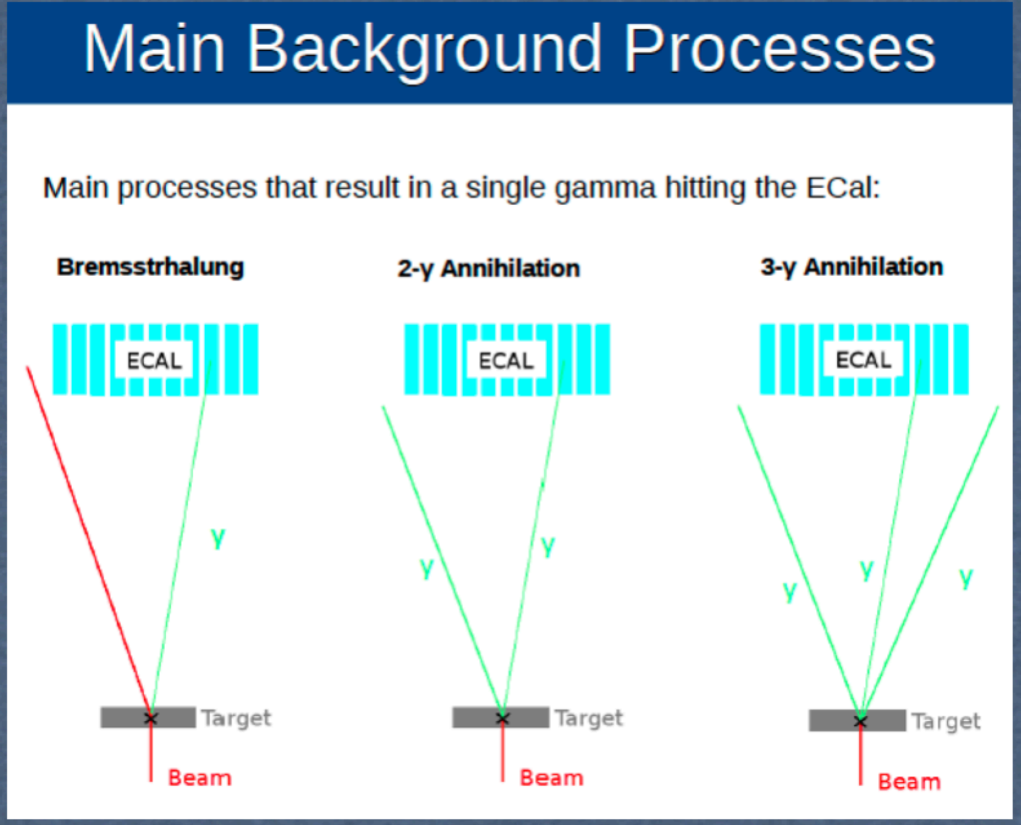
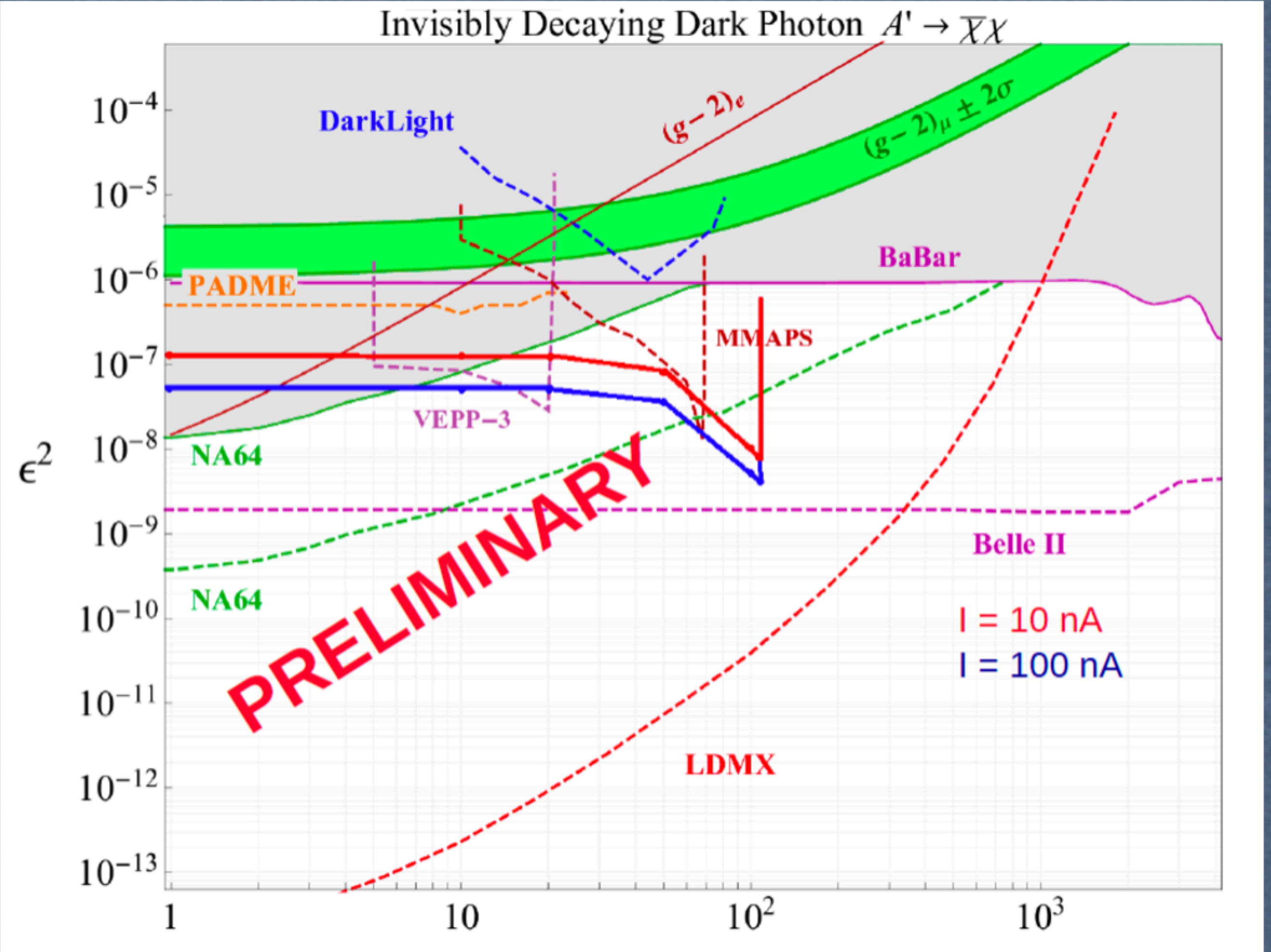
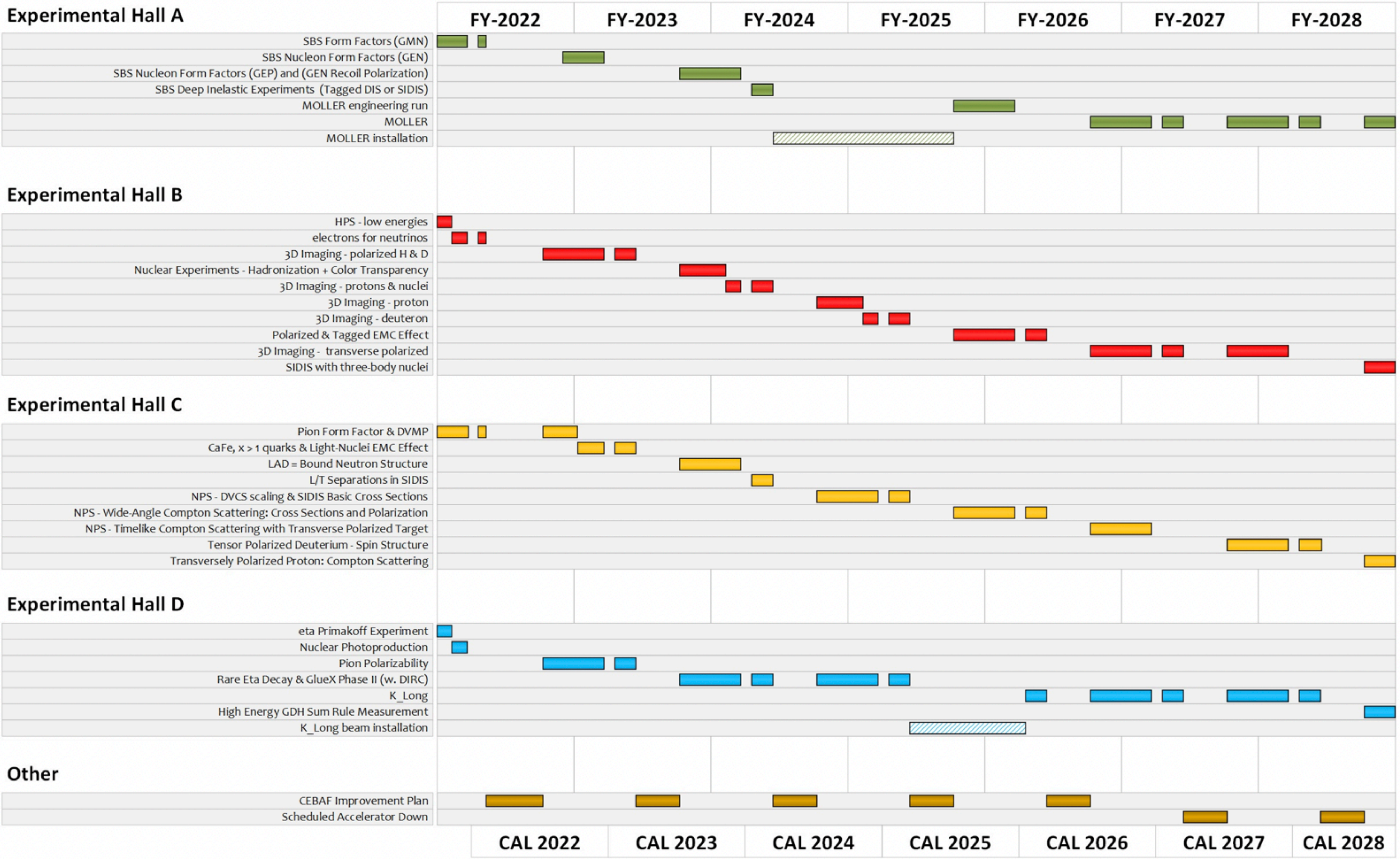




L.Marsicano, M.Raggi

EXTENDED EXPERIMENTAL SCHEDULE – *PLANNING AHEAD*



199 completed experiments to-date (21 full; 23 partial in 12 GeV era)

57.3 experiments remaining

~8 years at ~30 weeks/year (after PAC50)

CLAS Collaboration Meeting *D.Dean CLAS Coll. Meeting Nov 2022* 5

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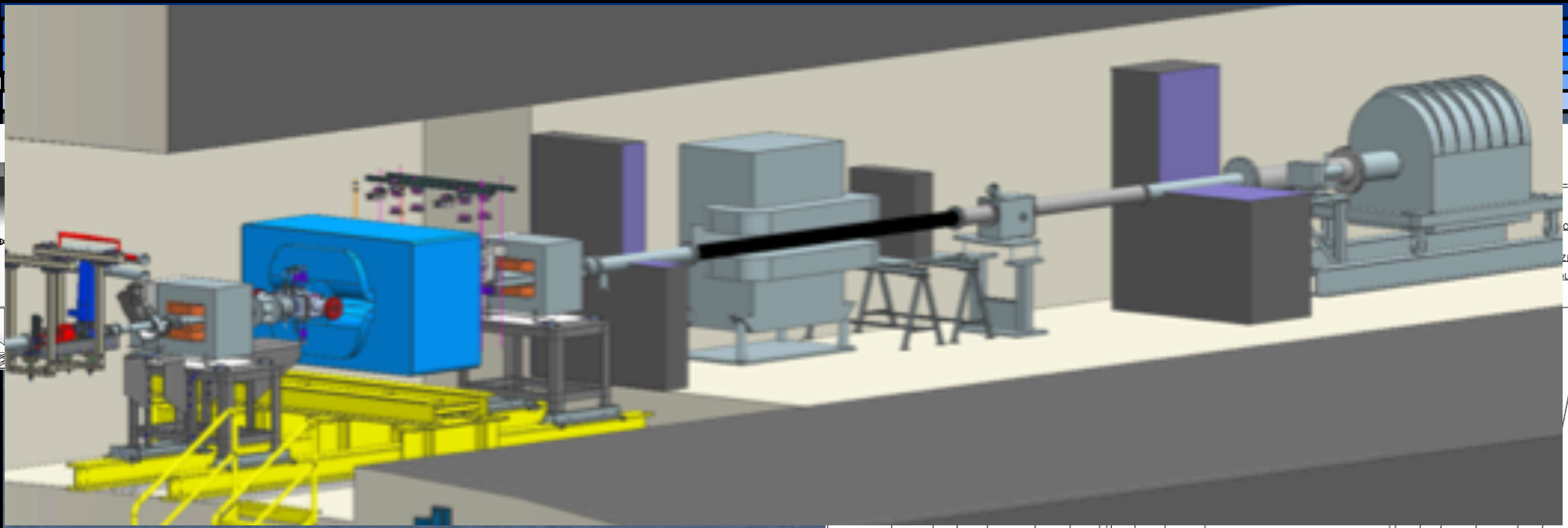
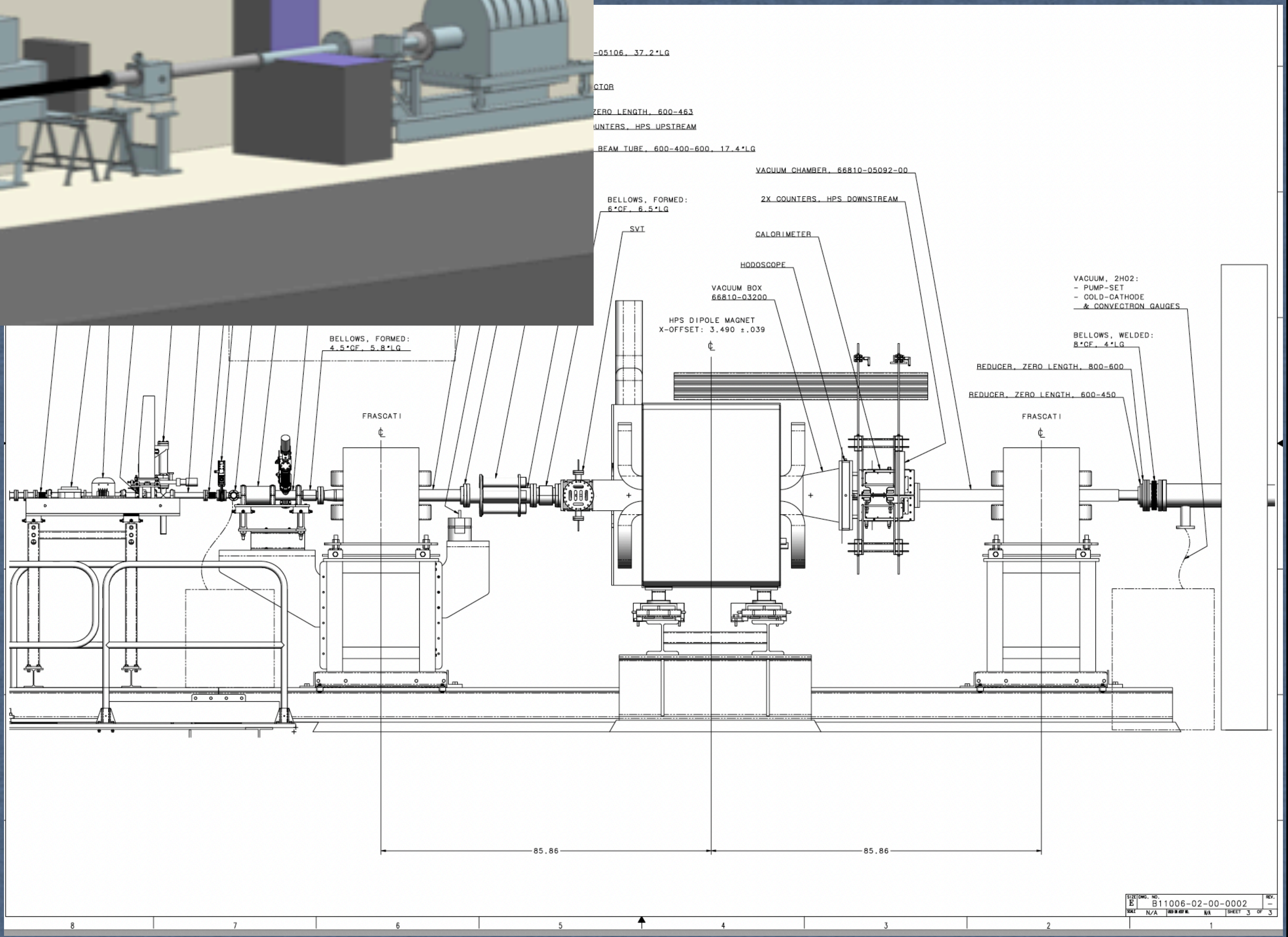
Jefferson Lab





Under study: JPOS-ThinTarget@Hall-B

- The first interaction with PADME Group is currently committed to concluding data analysis focusing on X17
- LOI for PAC51 due by end of May '23 (PAC meeting ~July '23) may be too early