

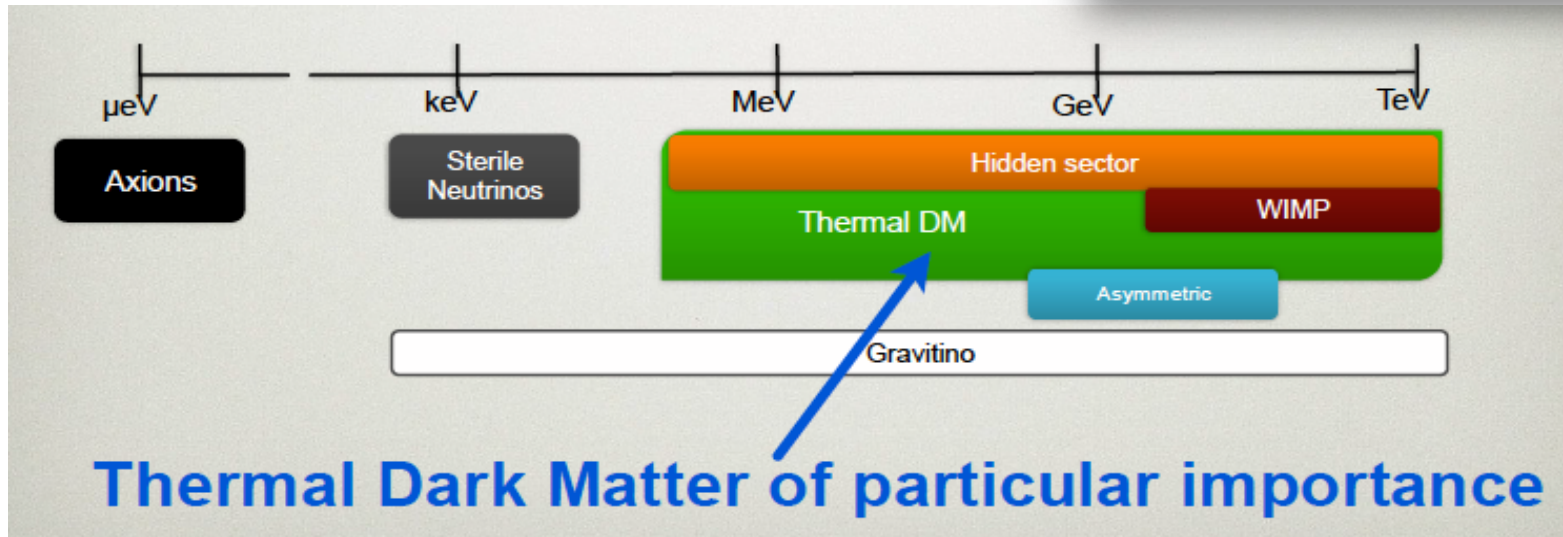
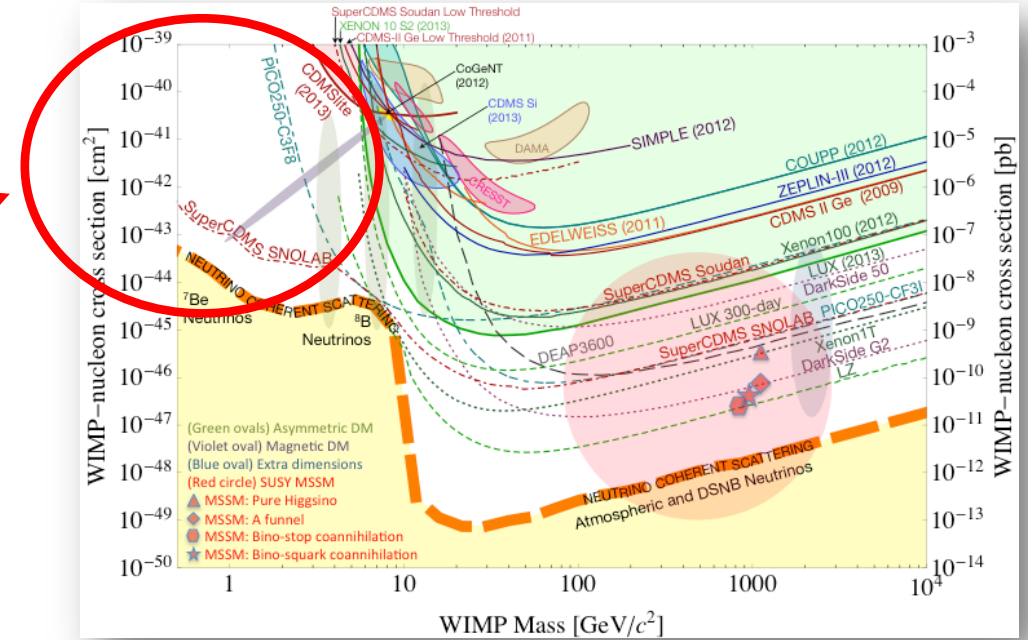
Prospects of the Dark Sector Physics Search at the Fermilab Intensity Frontier

Ming Liu, P-25
6/20/2019

LANL Dark Matter Physics Program Development Workshop

Dark Sector Physics @DarkQuest

Current and near future high-intensity colliders and fixed target experiments offer an ideal environment to probe dark sector physics in mass range: MeV - GeV



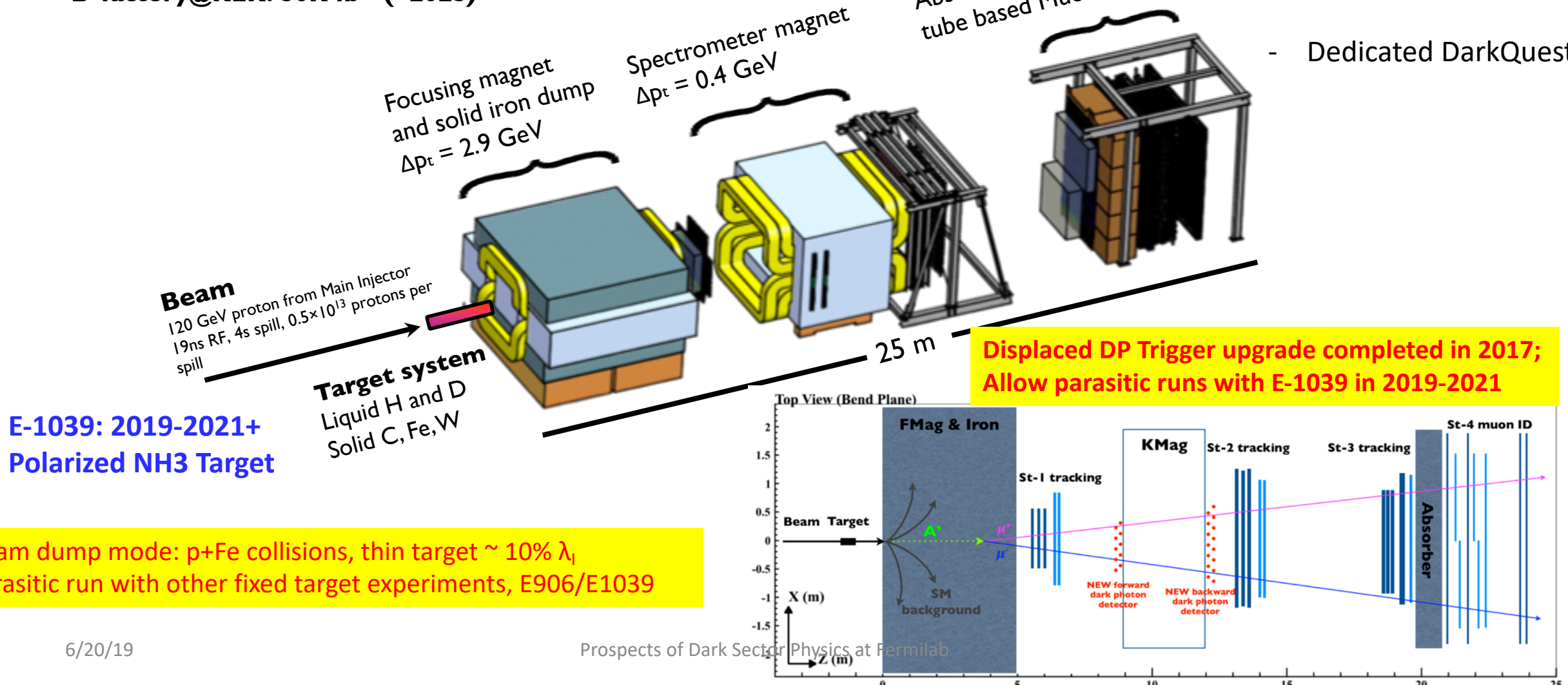
Schuster et al.
(2017)

DarkQuest Spectrometer at Fermilab

High intensity proton beam: “beam dump mode” @SeaQuest/E1067

- **35,000 fb⁻¹ (in a 2-year parasitic run, 1.4×10^{18} POT @5% beam)**
- **LHC-II: 300 fb⁻¹ (~2025), achieved 25fb⁻¹ in Run-I**
- **B-factory@KEK: 50K fb⁻¹ (~2023)**

- E906/SeaQuest
- E1039/SpinQuest (E1067/parasitic)
- Dedicated DarkQuest



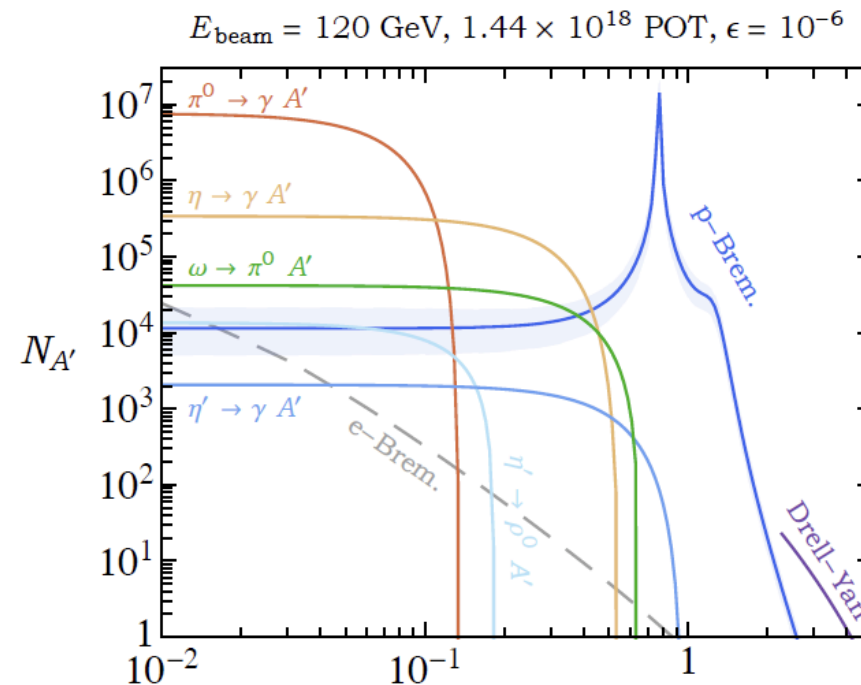
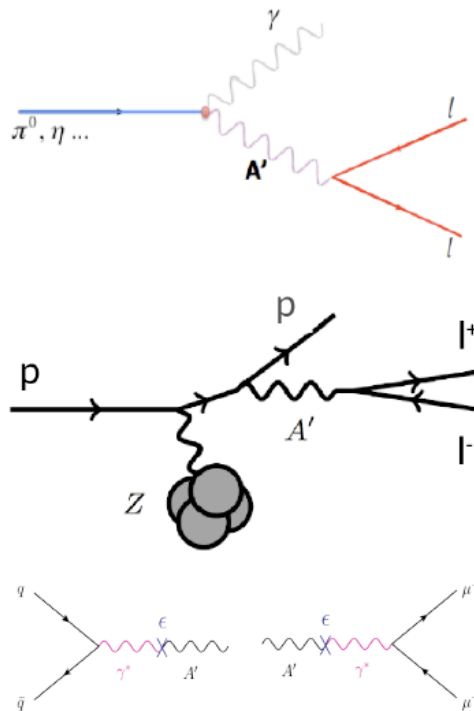
Dark Sector Physics – Dark Photon as an Example

Production and signatures at SeaQuest

- Three dominant production mechanisms: meson decay, proton bremsstrahlung, Drell-Yan
- Prompt $A' \rightarrow \mu^+ \mu^-$: bump-hunt
- Displaced $A' \rightarrow \mu^+ \mu^-$: background suppressed by vertexing
- Displaced $A' \rightarrow e^+ e^-$: background absorbed in dump

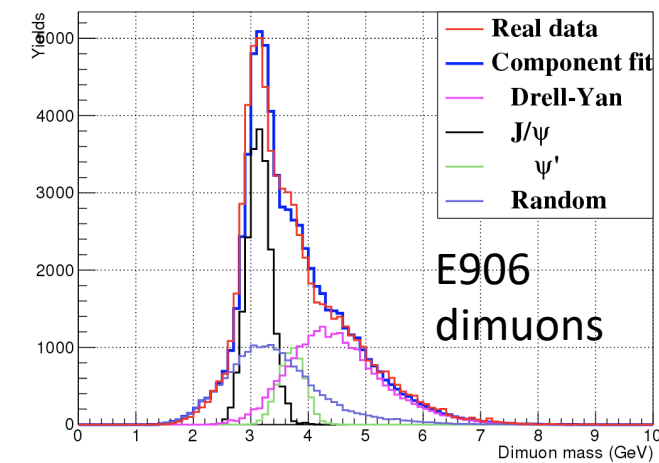
Mass range:
~1MeV - 10GeV

Visible mode



Status of Our Experiments

- E906/SeaQuest fixed target experiment: 2012 – 2017
 - H, D, C, Fe, W targets
 - High mass Drell-Yan, mass > 4GeV
- E1039/SpinQuest polarized proton (NH3) fixed target experiment: 2018 - 2021
 - Approved by DOE HP/HEP and Fermilab, May 2018
 - Install polarized NH3 target by summer 2019
 - Polarized target commissioning run: ~ Fall 2019
 - Physics data taking for two years: ~10/2019 - 7/2021+ (or longer)
 - Proton On Target: 1.4×10^{18}



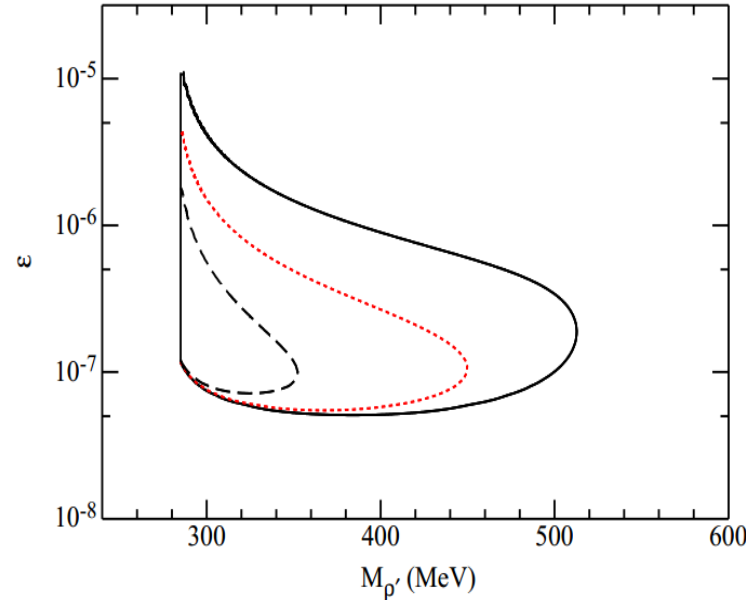
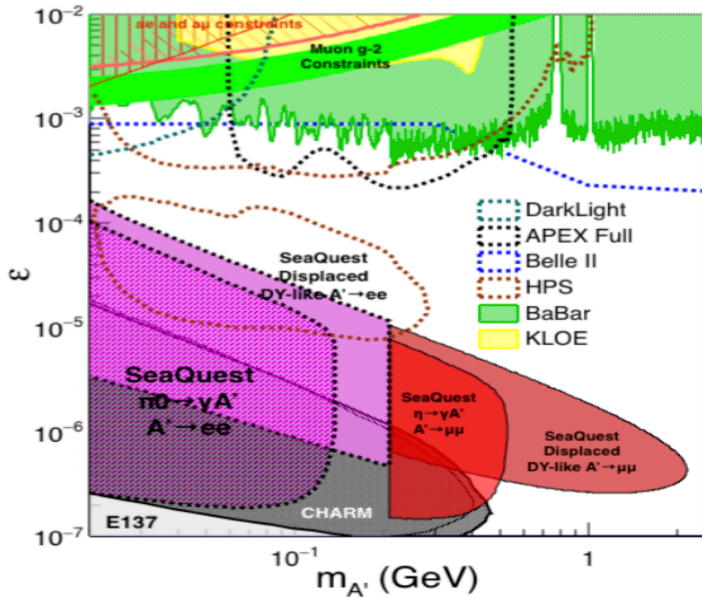
Parasitic E1067/DarkQuest Dark Photon search program approved in 2015

- Parasitic run to search for dark photon/Higgs/ALP etc.
 - E906, E1039, **dimuon channel (mass > 200MeV)**
 - Displaced dimuon dark photon trigger upgrade completed in 2017
- Propose dedicated dark sector physics beyond E1039, 2022+ ~
 - Additional detector upgrade possible → **muons**, **electrons**, **photons**, **hadrons**

LANL LDRD/ER (2016-2018)

- Developed physics program
- Built and installed displaced dark photon trigger

Recent Activities and Accomplishments



- LOI of dark matter search in dimuon channel was presented to PAC in June 2015. Obtained very positive feedbacks.
- A phase-II of EMCAL and possibly HCal upgrade was also mentioned. PAC suggested we submit a new proposal based on the results obtained from the phase-I study
- The detector proposed in the phase-I was successfully installed and accumulated one week worth of data before E906 shuts down in July 2017
- We will continue to take the dimuon data parasitically with E1039/SpinQuest

6/20/19

Prospects of Dark Sector Physics at Fermilab



Nigel S. Lockyer
Directorate
TEL 630.840.3211
Lockyer@fnal.gov

July 15, 2015

Ming Liu
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dear Ming,

Thank you very much for your presentation: "P-1067 LOI: Direct Search for Dark Photon and Dark Higgs" at the June meeting of the Fermilab Physics Advisory Committee (PAC). The Committee explicitly mentioned its appreciation of the carefully prepared presentations for this meeting.

Future initiatives were an important topic at the meeting. Excerpts on your LOI from the PAC report are attached. As you can see, the committee "... recognizes the exciting opportunity brought by P1067 to search directly for a dark photon and dark Higgs in high-energy proton-nucleus collisions using existing SeaQuest Spectrometer." The PAC noted that in the LOI the collaboration requests approval for inclusion of the new elements in the detector needed to make a dark sector trigger, and approval of parasitic data collection during E-1039 running. The committee "... believes that P-1067 offers exciting physics prospects and recommends the Laboratory to grant these modest requests." The PAC also suggests "A proposal for a dedicated experiment, or a parasitic experiment with electron and hadron calorimeters, should be based on the results obtained with this first phase."

I accept the PAC recommendations, and wish you good luck in implementing a dark sector trigger.

Sincerely,

Nigel S. Lockyer
Director of Fermilab

cc: D. Bortoletto
G. Bock
P. Reimer
J. Shank

S. Geer
P. McBride
D. Geesaman

J. Lykken
T. Meyer
A. Stone

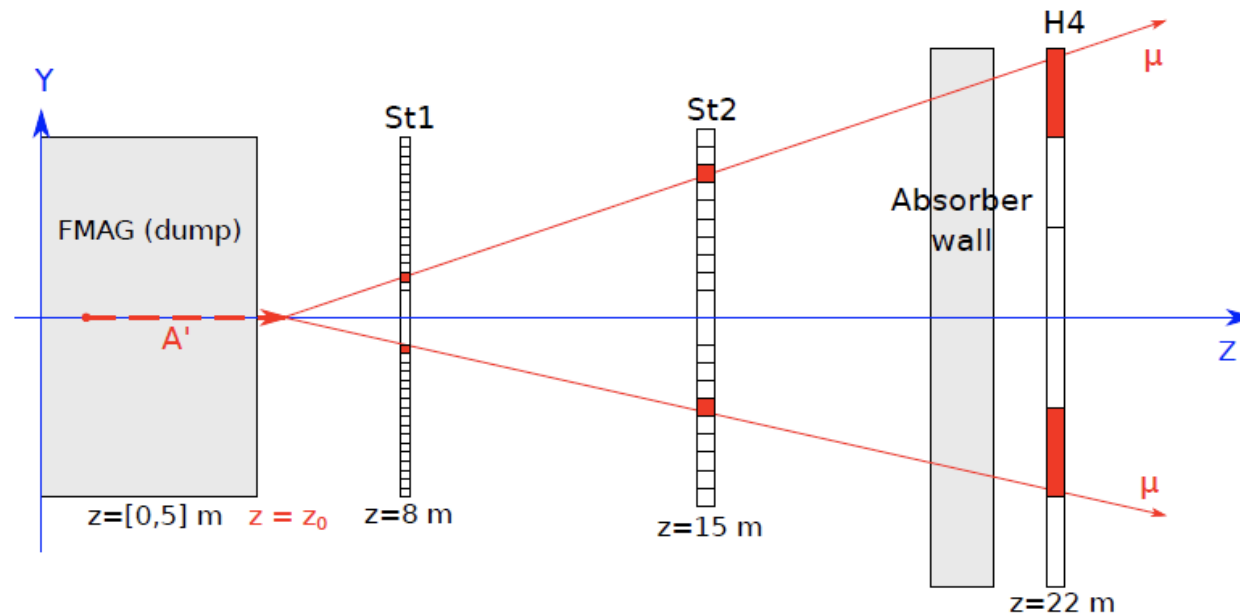
Fermi National Accelerator Laboratory / Kirk and Pine Street / P.O. Box 500 / Batavia, IL 60510 / 630.840.3000 / www.fnal.gov / fermilab@fnal.gov
Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Dark Photon Detection @E906/SeaQuest

LANL LDRD/ER (2016-2018)

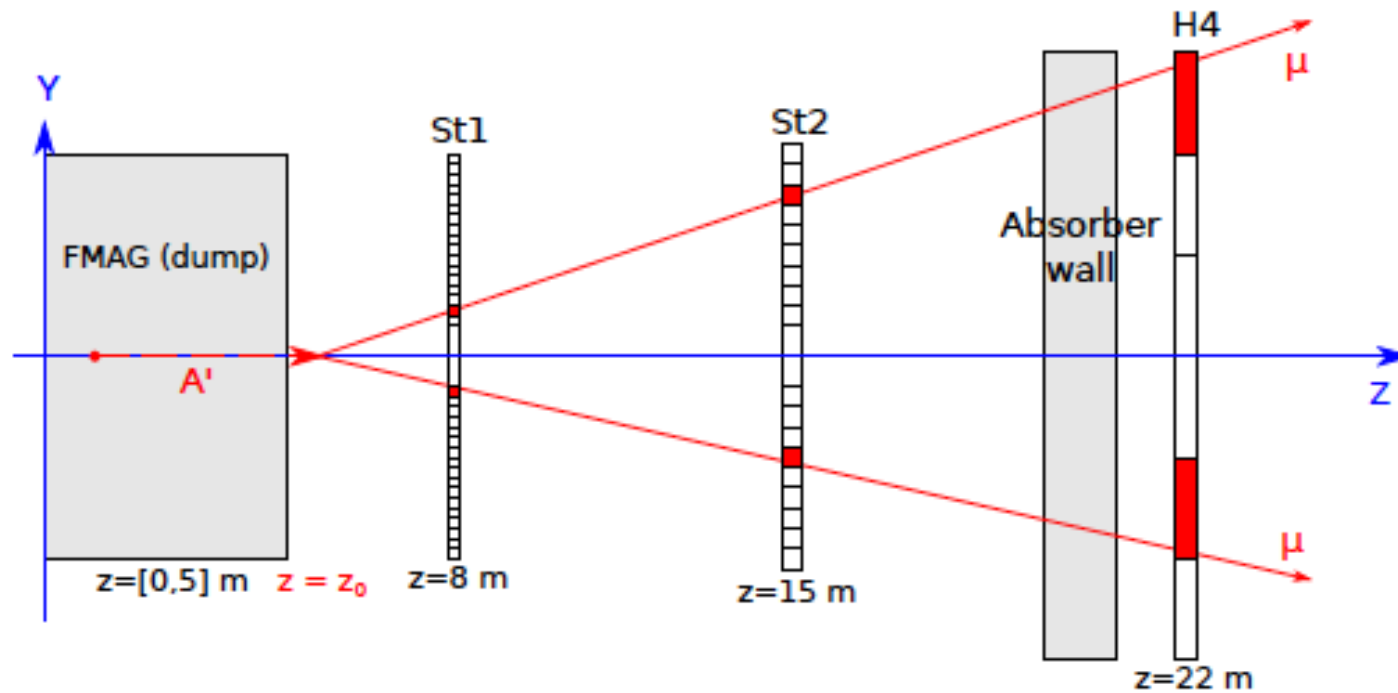
- Developed physics program
- Built and installed displaced dark photon trigger

- Dimuons in main SeaQuest dataset
 - ▶ Bump-hunt at high mass (ongoing effort)
- Dimuon displaced-vertex trigger
 - ▶ Commissioned 2017
- Dielectron trigger
 - ▶ EMCal for electron PID (in planning)

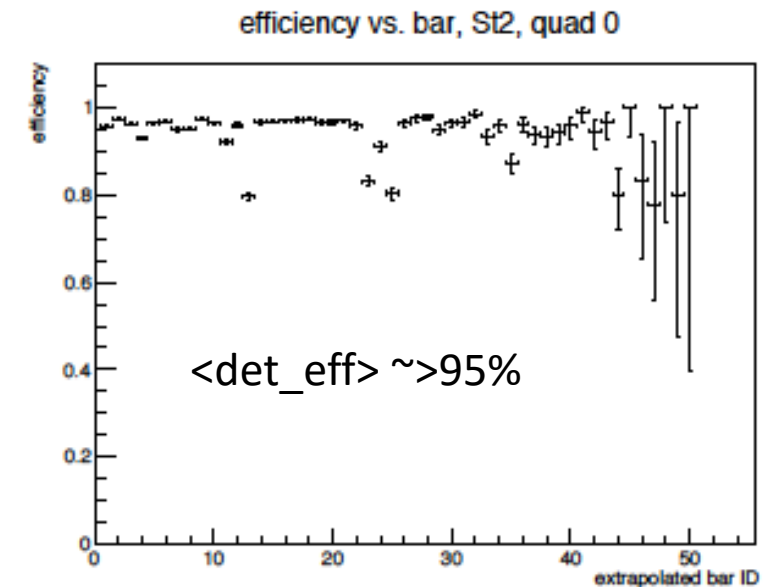
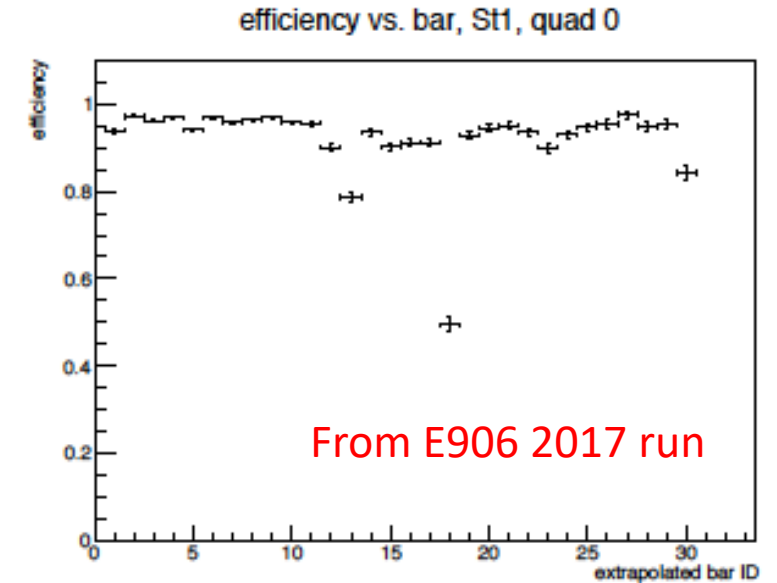


Displaced Dark Photon Trigger Detectors Commissioned

- Detector and trigger system installed and commissioned during the last SeaQuest/E906 run in 2017
- Physics analysis in progress
- Bad channels all fixed in 2018



Schematic of displaced dimuon trigger



Opportunity: Fermilab Long Range Plan 04/2018

Fermilab Program Planning 5-April-18

LONG-RANGE PLAN

		FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30
LBNF / PIP II	SANFORD FNAL				DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE
						LBNF	LBNF	LBNF	LBNF	LBN F	LBNF	LBNF	LBNF	LBNF
NuMI	MI	MINERv	MINERv	OPEN	OPEN	OPEN	OPEN	OPEN	LONG SHUTDOWN					
		NOvA	NOvA	NOvA	NOvA	NOvA	NOvA	NOvA						
BNB	B	MicroBooNE	MicroBooNE	MicroBooNE	OPEN	OPEN	OPEN	OPEN	LONG SHUTDOWN					
		CARUS	CARUS	CARUS	CARUS	CARUS	CARUS	OPEN						
		SBND	SBND	SBND	SBND	SBND	SBND	OPEN						
Muon Complex		g-2	g-2	g-2	LONG SHUTDOWN						LONG SHUTDOWN			
		Mu2e	Mu2e	Mu2e										
SY 120	MT	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	LONG SHUTDOWN					
	MC	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF						
	NM4	OPEN	E1039	E1039	E1039	E1039	OPEN	OPEN						
		FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30

Dark sector physics program:
Run-I, II

Run-I
2019-2021+

	Construction / commissioning		Run		Subject to PAC review		Shutdown
	Capability ended		Capability unavailable				

Run-II:
2022 - 2030

- NOTES:
1. Mu2e estimates 4 year running starts mid-FY22 after 18 months commissioning. Assume, with contingency, 5.5 years data taking.
 2. DUNE: 1st 10kT detector module commissioned in FY24. Runs without beam FY25 to mid-FY26.
 3. NOvA runs as long as possible [in the spirit of PAC Nov 2017].
 4. Assume NuMI in nubar mode through FY19 - facilitates 12E20 POT for MINERvA [PAC Nov 2017]. Assumption may need revision.
 5. Assume g-2 completed before Mu2e commissioning start mid-FY20. Very tight. Needs scrutiny.
 6. Assume E1039 fully approved & commissioned by mid-FY19.
Experiment estimates 2 yrs run. Add 1 yr contingency. [Stage 1 approval PAC June 2013, update July 2017]
 7. FY19 and FY20 MicroBooNE running subject to future PAC review [PAC July 2017].

Our Fermilab DarkQuest Physics DOE-HEP Proposal

- Track #1 calls for 1 to 2 years of effort to pursue planning activities that culminate in a design report and execution plan for carrying out the small project. Track #1 proposals are limited to 2 years of funding.
- **PRD #1: Create and detect dark matter particles and associated forces below the proton mass, leveraging DOE accelerators that produce beams of energetic particles.** The interactions of energetic particles recreate the conditions of dark matter
- **Our submitted proposal: a 2-year program**
 - Year-1 (2020):
 - R&D on EMCal readout, calibration and background measurements in SeaQuest
 - Year-2 (2021):
 - Complete R&D on EMCal readout integration into SeaQuest;
 - Produce a design report and execution plan;

DOE-HEP Proposal Title: Search for Dark Sectors with the DarkQuest Experiment at Fermilab

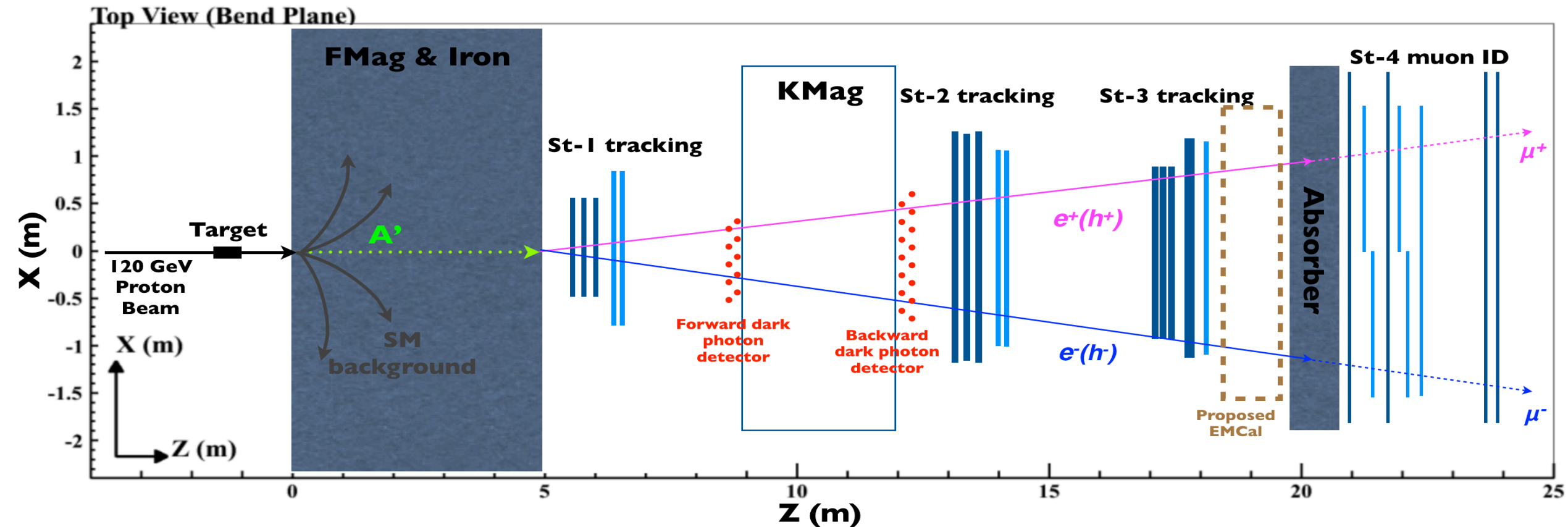
- Fermilab – PI
 - LANL, co-PI
- LANL initiated, in collaboration with FNAL
- In addition, NP-supported Fermilab E906/SeaQuest and E1039/SpinQuest collaborations
- Several new HEP institutions
 - FNAL
 - SLAC
 - MIT
 - BU
 - JHU
 - Univ. Pitt
 - UCSC

Table 3: Consortium Proposal Budget Summary Information

	Names	Institution	BY1	BY2	Total
Lead PI	Nhan Tran	FNAL	\$152.4k	\$97.9k	\$250.4k
co-PI	Ming Liu	LANL	\$124.8k	\$137.3k	\$261.1k
co-PI	Tim Nelson	SLAC	\$177.2k	\$126.3k	\$303.5k
co-PI	Stefania Gori	UCSC	\$25.6k	\$18.8k	\$44.4k
co-PI	Philip Harris	MIT	\$0k	\$62.8k	\$62.8k
co-PI	David Sperka	BU	\$20.2k	\$45.5k	\$65.7k
co-PI	Petar Maksimovic	JHU	\$36.0k	\$25.5k	\$61.5k
co-PI	Brian Batell	Pitt	\$20.3k	\$10.5k	\$30.8k
	university pass through	FNAL	-	-	\$15.9k
				Total	\$1,093.5k

DarkQuest EMCal Upgrade Proposal

An EMCal detector recycled from PHENIX at RHIC: 2m x 4 m

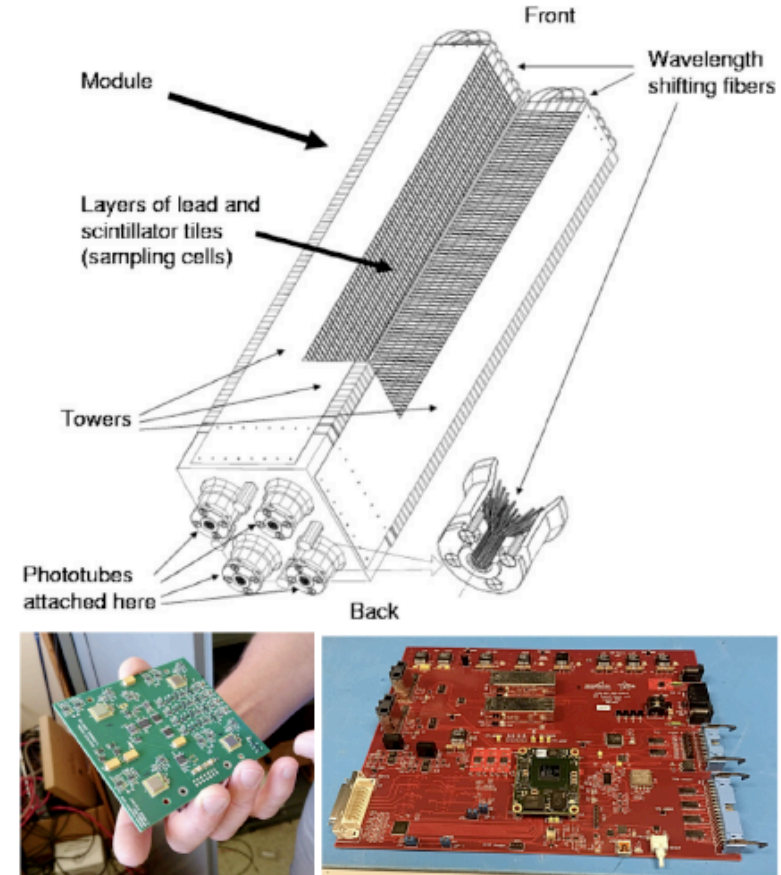


- Signal mostly from FMag (beam dump)
- Other parasitic targets operation possible (NP programs)

EMCal Upgrade Status

- The two best sectors have been transferred (on paper) to LANL
- We have the full PHENIX readout system; investigating whether it can be directly reused for SeaQuest
 - ▶ Time structure (10 MHz vs. 53 MHz) is the main concern, but pileup is negligible
 - ▶ Alternative: STAR is developing an SiPM-based readout system with the same modules
- We have a set of EMCal modules, with the full electronics chain, at LANL

4 x 4 EMCal modules being tested @FTBF
in May 2019 (STAR forward upgrade R&D)
- available for DarkQest



Money Plots (I)

- to include all other experimental searches up to year $\sim 2025+$

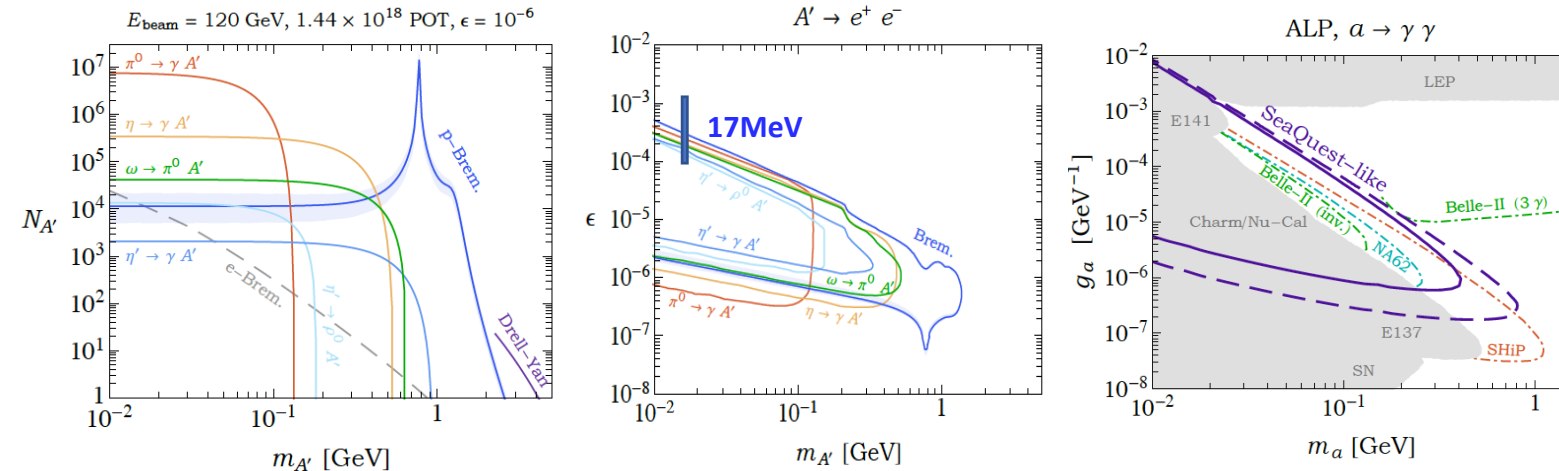
Phase space covered by DarkQuest:

2019 - 2021 : dimuon channel (POT = 10^{18})

2022 - 2024 : add di-electron (POT = 10^{18})

2026 - 2030+ : all channels (POT > 10^{19})

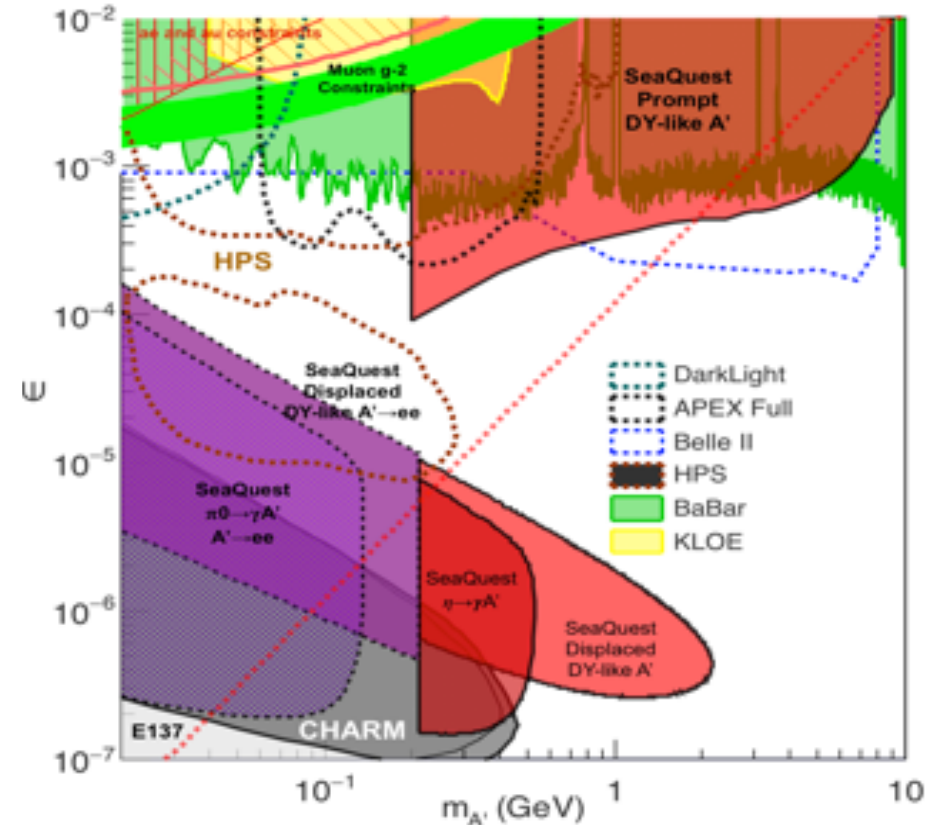
Detailed DarkQuest coverage in various production channels with di-electrons and di-photons



arXiv:1804.00661, Berlin, Gori, Schuster and Toro;
1801.05805, Berlin, Blinov, Gori, Schuster and Toro

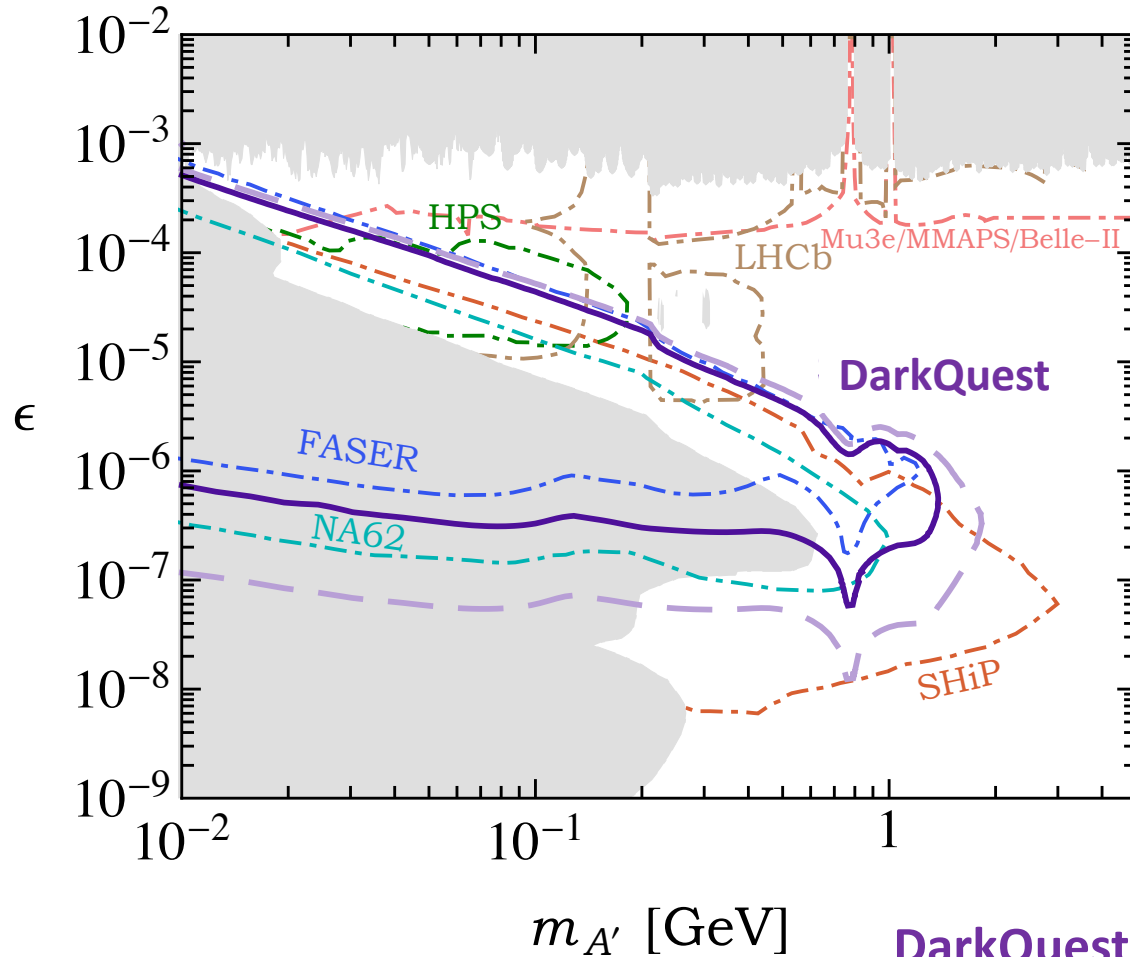
DarkQuest dark photon coverage:

- Dimuons (current capability)
- Di-electrons (w/ EMCal upgrade)

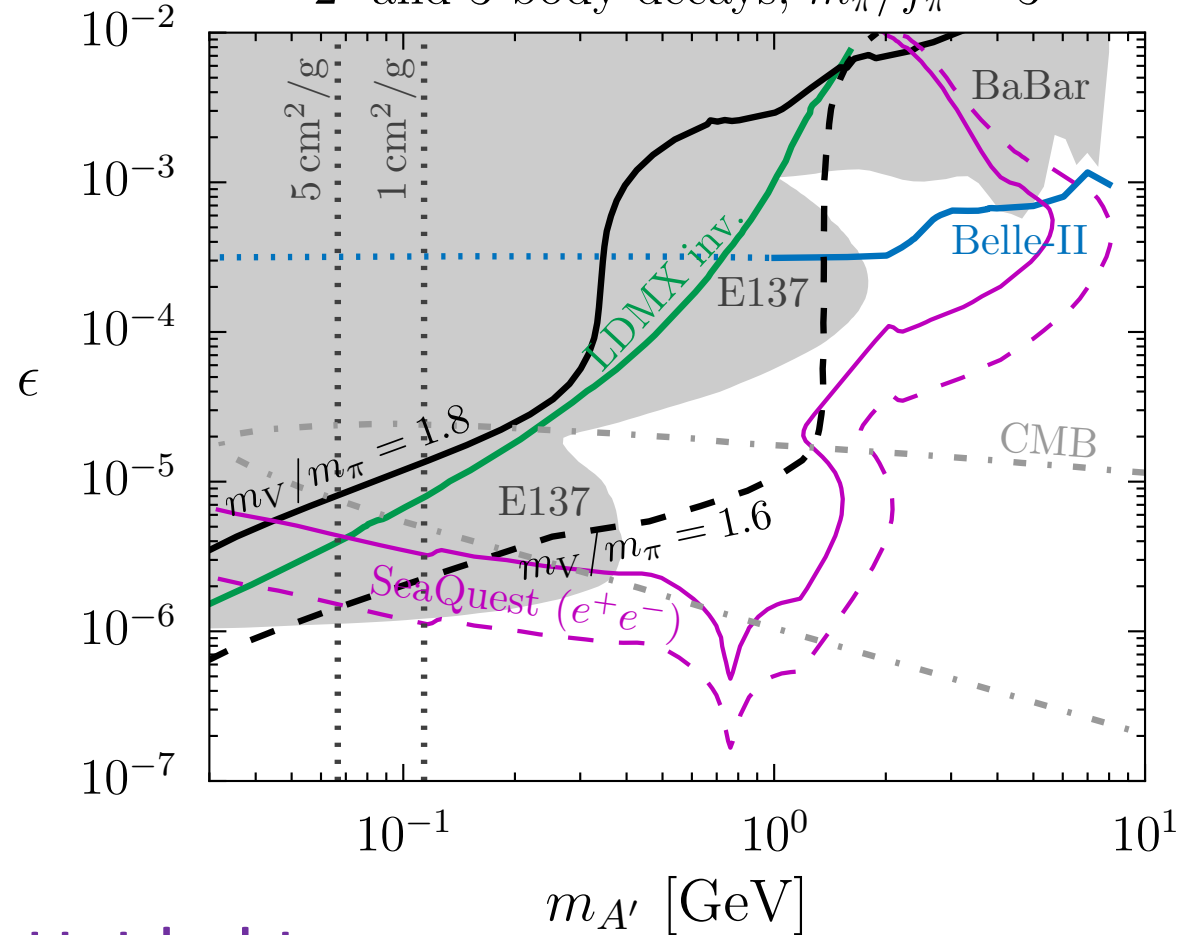


Money Plots (II) - with Future Projections

$$A' \rightarrow \ell^+ \ell^-$$

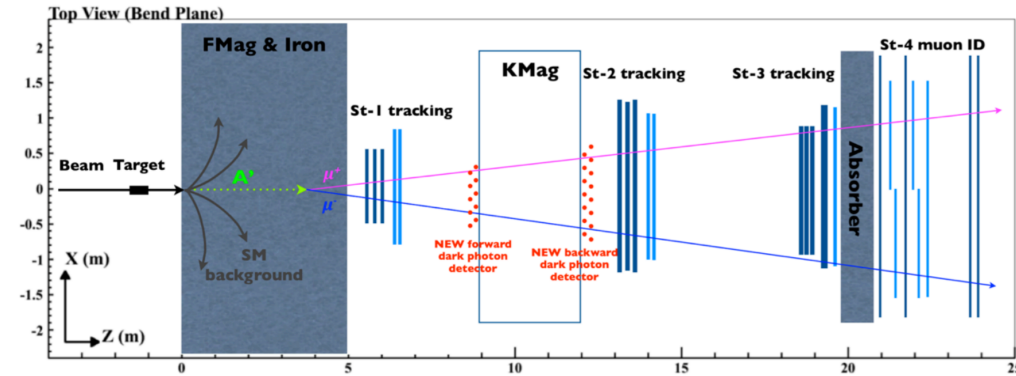


$$2\text{- and }3\text{-body decays, } m_\pi/f_\pi = 3$$

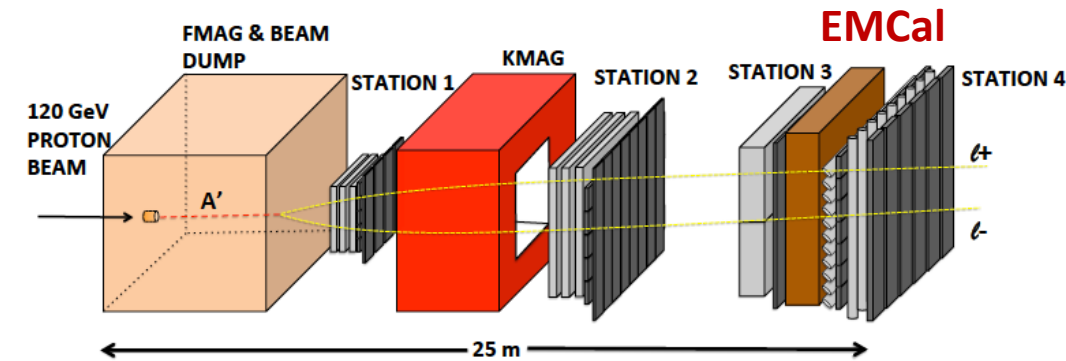


Long Term Prospects of Dark Sector Physics Program at DarkQuest

- **2019-2021: Parasitic Dark Sector physics program with E1039**
 - **Attract and build up HEP groups in DarkQuest**
 - Carry out DP physics program with dimuons: dark photon, dark Higgs etc.
 - EMCal refurbishment and preparation for integration at Fermilab, 2018-2021
 - **New HEP members develop DarkQuest detector expertise for the future experiment operation and data analysis**
 - Also help E1039 operation and maintenance of spectrometer and DAQ
 - **Transition into HEP DP program after E1039**
 - Develop new proposals, seek HEP DOE/NSF and other external fund
 - Parasitic data taking with E1039 for DP search, further explore new opportunities
 - Develop online/offline analysis, study DAQ and triggers capability for future DP experiment
 - Background study, test small prototype in SeaQuest, w/ minimal impact on E1039
- **E1039 2-year data taking: summer 2019 – summer 2021**
- **2022-2024: first dedicated dark sector physics run @NM4**
 - Install EMCal for electron and hadrons ID, explore new phase space below dimuon mass (200MeV)
 - Further develop dark sector physics program
 - Possible NP parasitic physics program under discussion
 - Protons On Target = a few 10^{18}
- **2024-2025: major detector upgrade during the long shutdown**
 - Upgrade tracking chambers
 - Add di-photon capability with preshower detectors
 - Add tracking station-0 near target, more shielding
 - Possible PID with TOF etc
 - And more
- **2026-2030+: high luminosity dark sector physics program**
 - Full physics program with upgrade detectors, POT = $10^{19} \sim 10^{20}$
 - Carry out an extensive (SHiP-like) HEP experimental program at NM4
 - Possible NP parasitic physics program under discussion (US EIC physics era)



SeaQuest in 2017 with displaced dark photon trigger

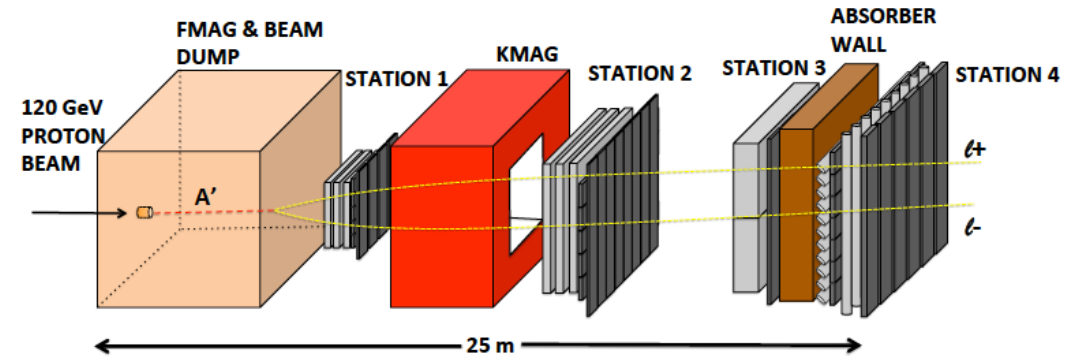


DarkQuest in 2021+ with EMCal upgrade

DarkQuest: Summary and Outlook

• Phase-I

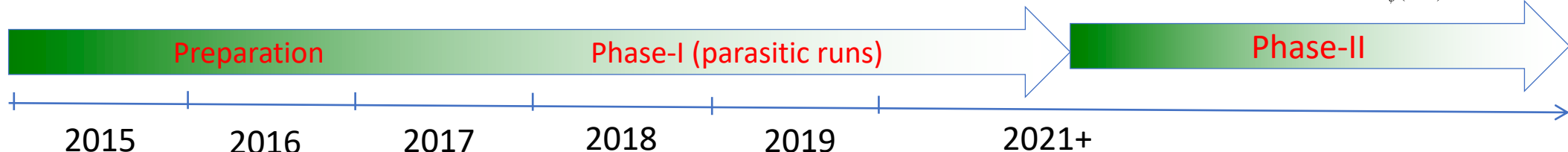
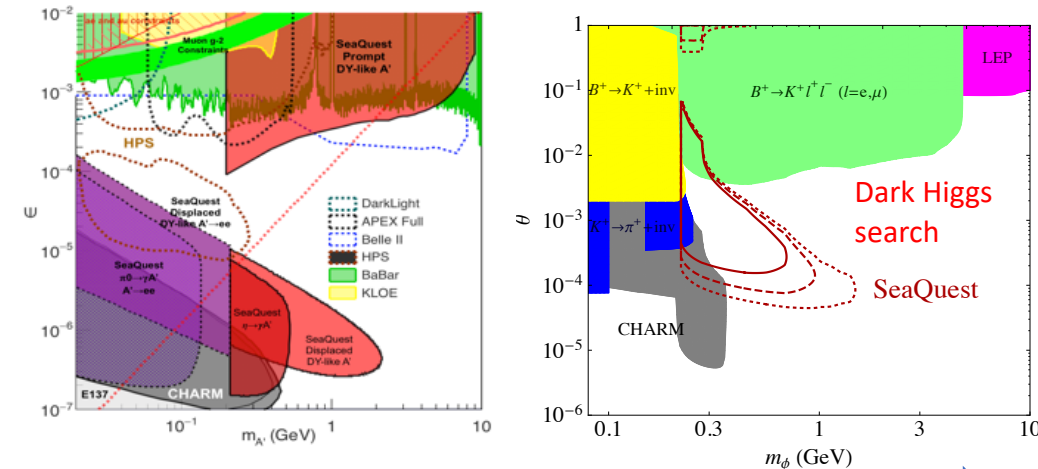
- *Great discovery potential!*
- *A new vertex trigger & DAQ++*
- *Early parasitic data taking 2019-2021+*
- *POT 1.4×10^{18} or more*



SeaQuest in 2021+ with EMCal upgrade

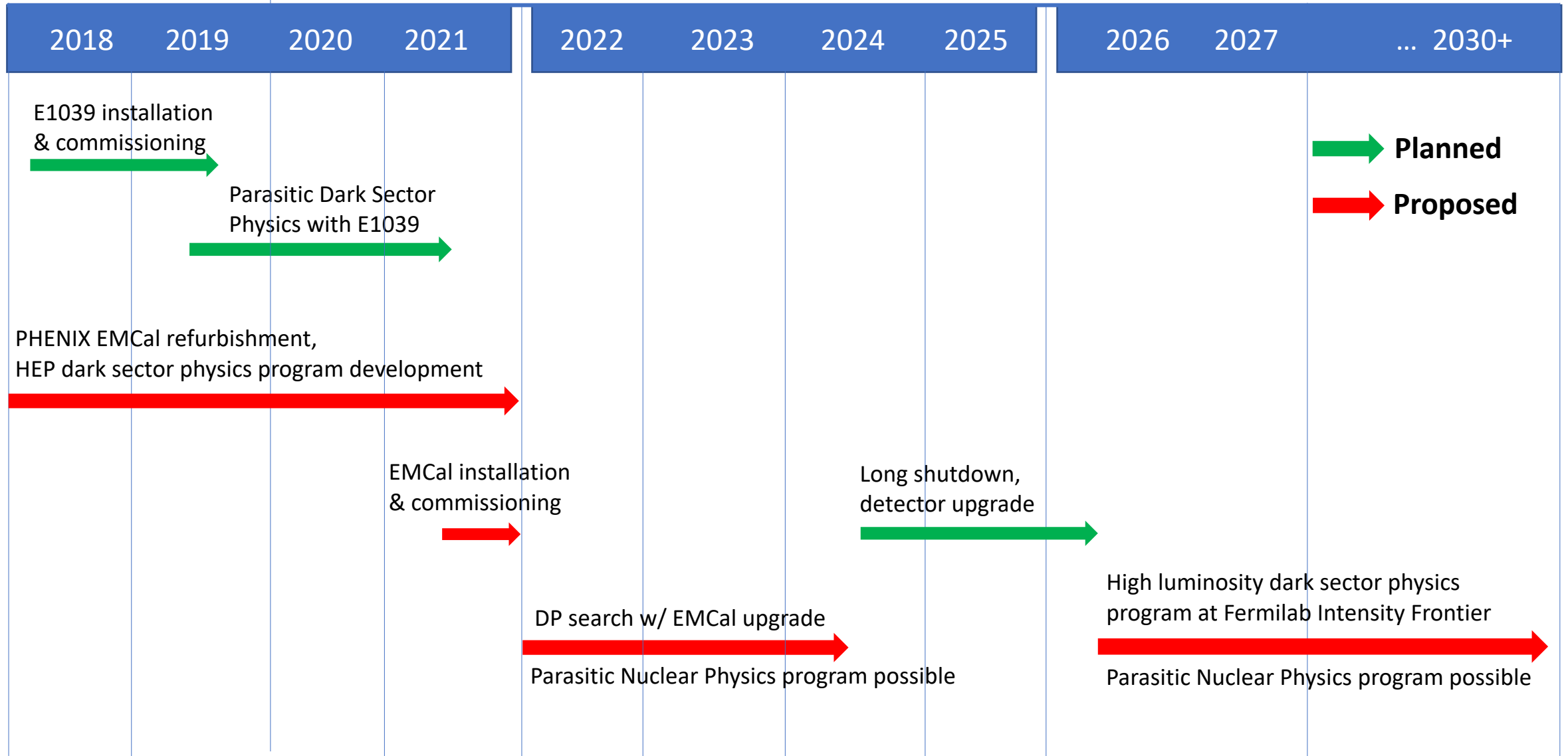
• Phase-II: beyond E1039, 2021+

- *Possible detector upgrade later, add electron, photon and hadron capability*
- *A new dedicated dark matter program at Intensity Frontier!*



Supporting Slides

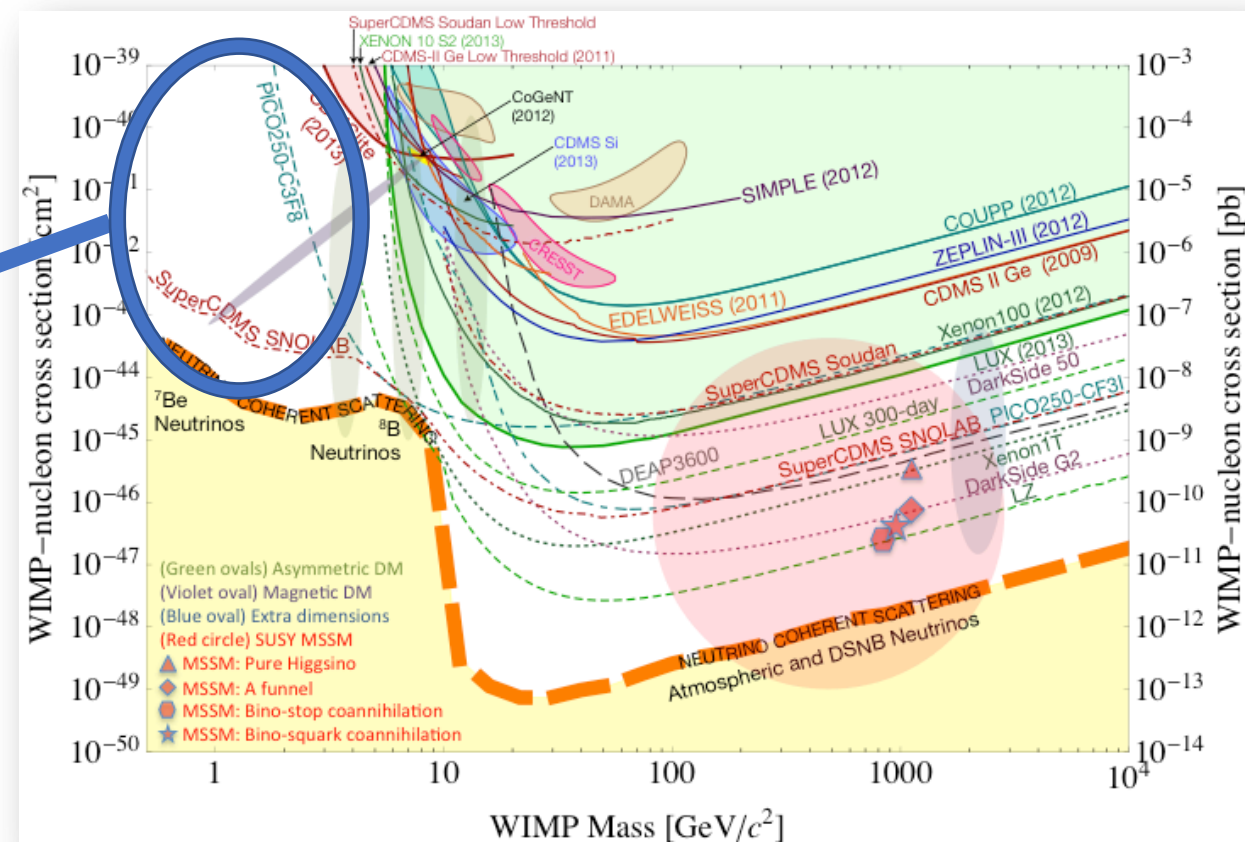
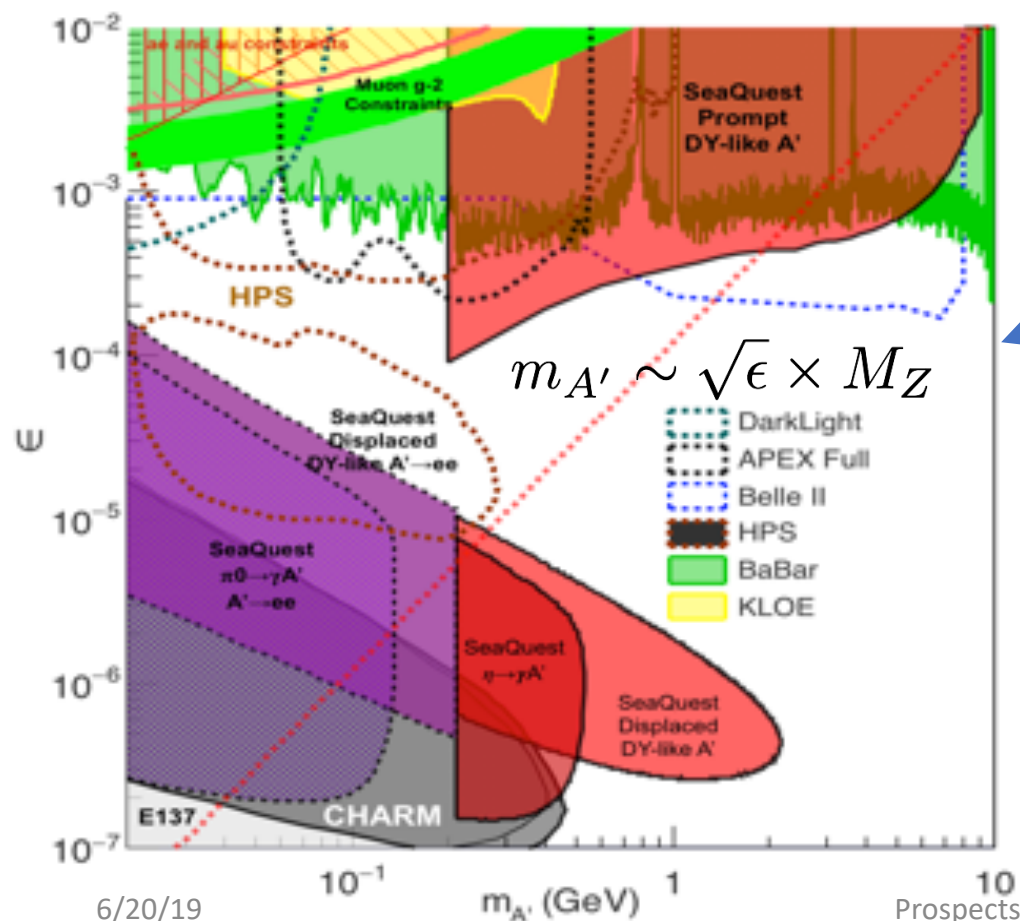
Schedule @DarkQuest



Dark Photon/Higgs Search at Beam Dump Experiments @DarkQuest

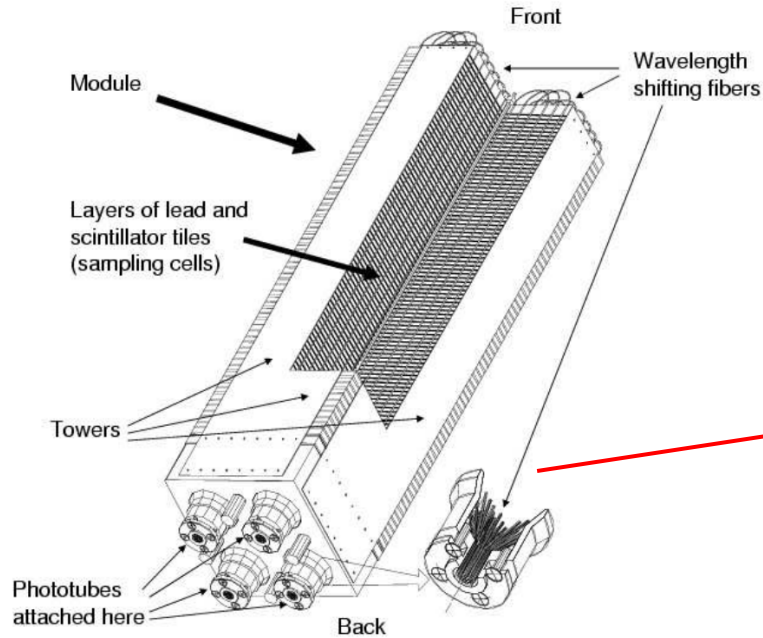
DarkQuest search for low mass dark particles:
mass ~ 1 MeV – 10GeV

- WIMP search – mass $> \sim 10$ GeV,
- Needs low mass coverage, mass < 10 GeV



Details of PHENIX EMCal

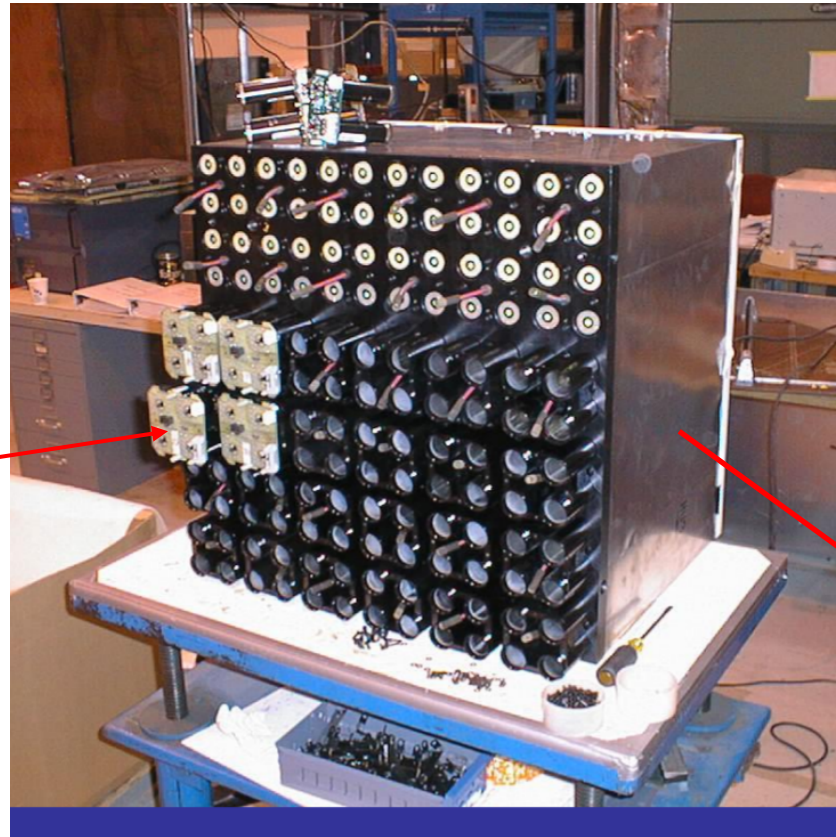
(we get 2 best sectors)



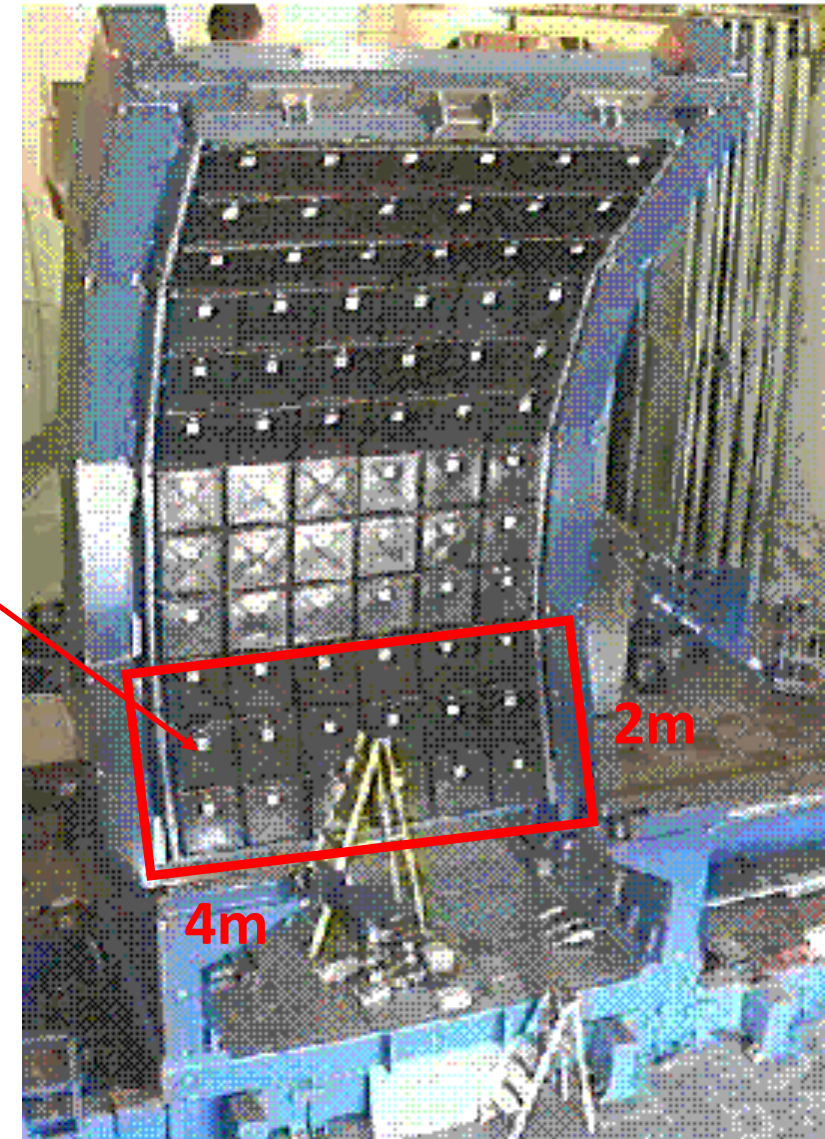
- Shashlik-type Pb scintillator
- 1 tower is $5.52 \times 5.52 \times 33 \text{ cm}^3$
- 4 towers make a module

Total # of readout channels if
gang 4-”PMTs”:

$$36 \times 3 \times 6 = 648 \text{ (2592)}$$



- 6x6 modules make a super module
- 3x6 supermodules make a sector
- 1 sector covers $2 \times 4 \text{ m}^2$, weights about 22 tons



EMCal Upgrade Plans

Submitted DOE HEP Proposal, 5/2019

Title: Search for Dark Sectors with the DarkQuest Experiment at Fermilab

Sponsoring Institution:	Fermi National Accelerator Laboratory
Street Address/City/State/Zip:	P.O. Box 500, Batavia, IL 60510
Principal Investigator:	Nhan Tran
Position Title of PI:	Wilson Fellow
Telephone Number of PI:	630-840-2575
Email of PI:	ntran@fnal.gov
Administrative Point of Contact:	Hema Ramamoorthi
Administrative POC telephone:	630-840-6723
Administrative POC email:	hema@fnal.gov
Funding Opportunity FOA Number:	LAB 19-2112
DOE/SC Program Office:	High Energy Physics (HEP)
DOE/SC Program Office Technical Contact:	Dr. Kathleen Turner
PAMS Letter of Intent:	LOI-0000025691
Research Track and PRD Area:	Track #1, PRD#1

- Install a small number of modules in SeaQuest to measure background rates
- Develop MC to understand our efficiency for triggering on electrons
- Brainstorm additional dark sector searches possible at SeaQuest, possibly with additional hardware or spectrometer reconfiguration
- Work on a letter of intent, gather HEP collaborators