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

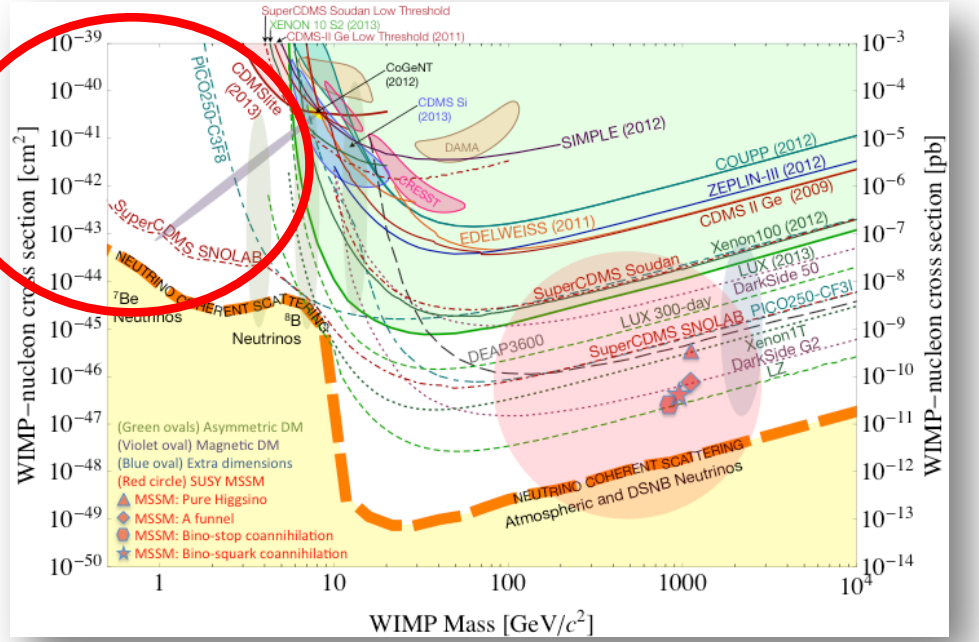
Ming Liu, Sho Uemura, Kun Liu (LANL),
Paul Reimer (ANL), Stefania Gori (Th., UCSC)

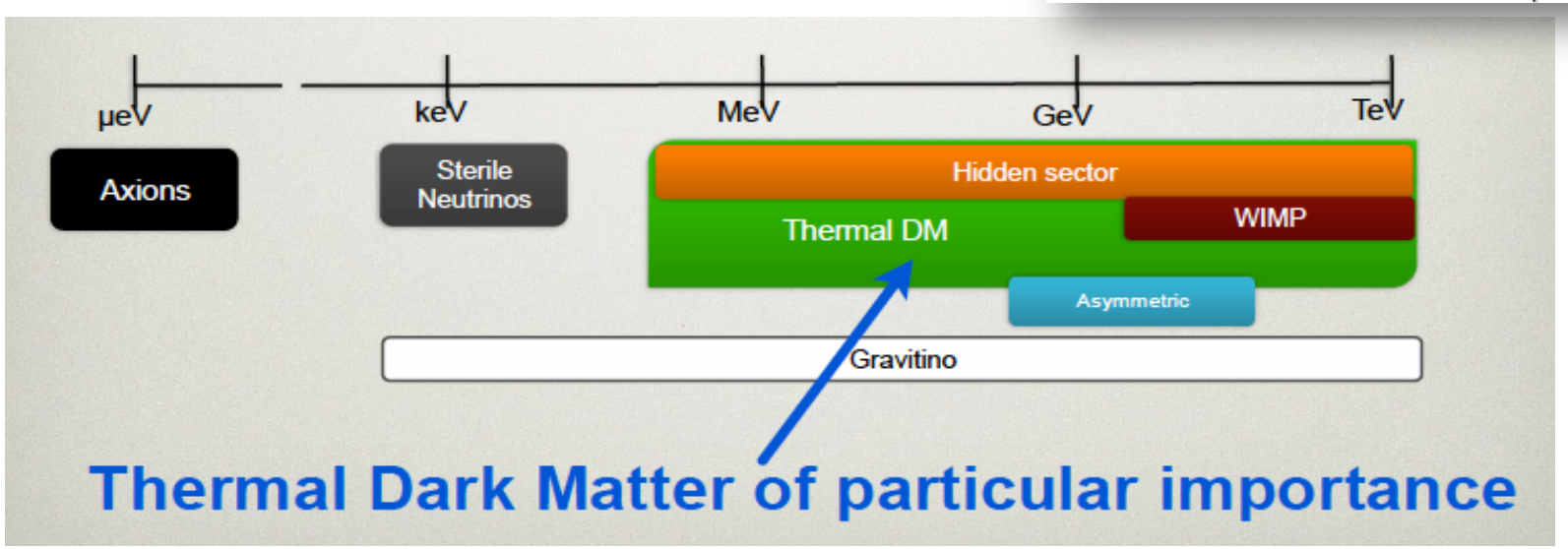
4/17/2019

Fermilab Precision Science WG - 2nd Planning Meeting for June 14 2019 Retreat
https://indico.fnal.gov/event/20512/

Dark Sector Physics @SeaQuest

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



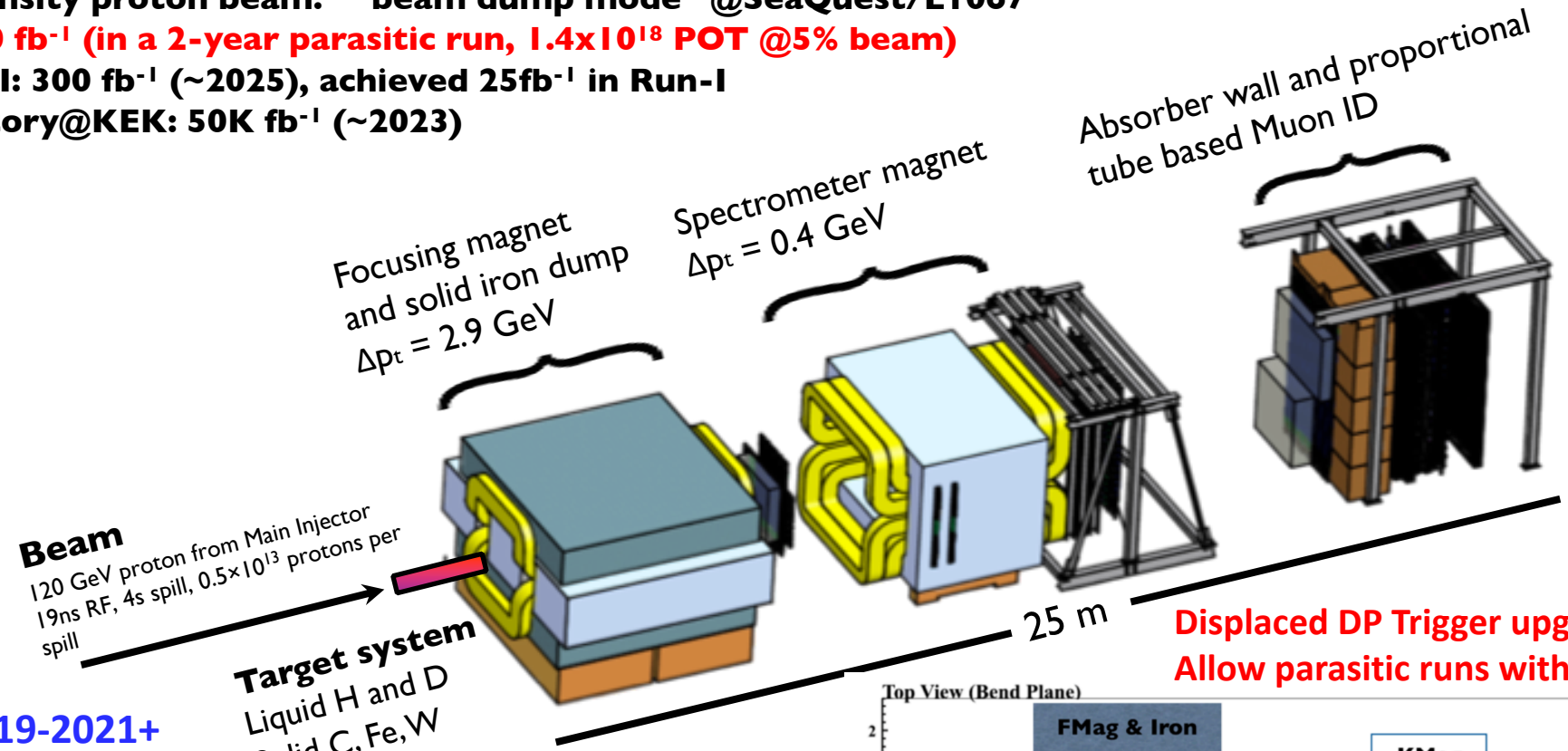


Schuster et al (2017)

SeaQuest Spectrometer at Fermilab

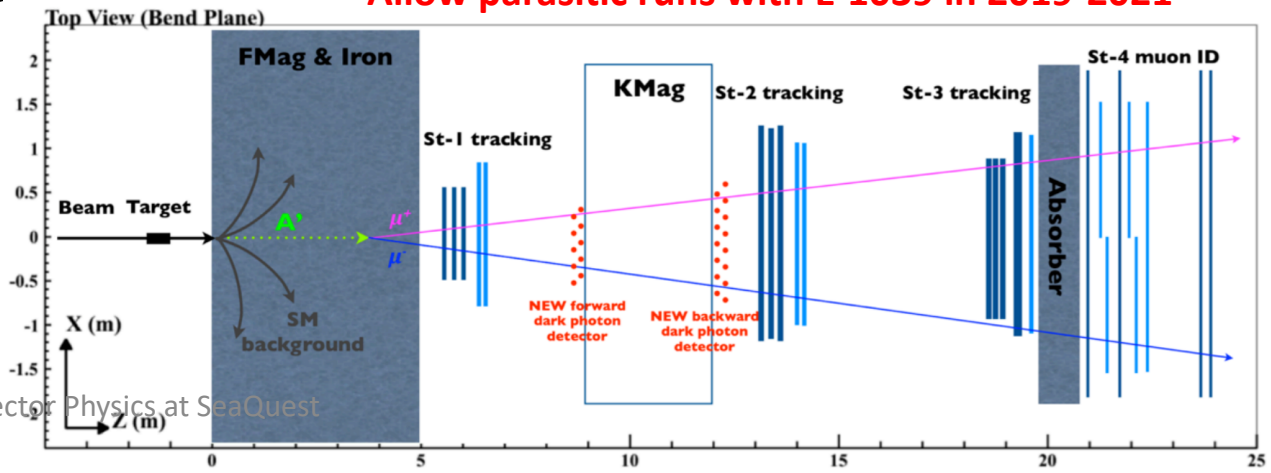
High intensity proton beam: "beam dump mode" @SeaQuest/E1067

- **35,000 fb^{-1} (in a 2-year parasitic run, 1.4x10^{18} POT @5% beam)**
- **LHC-II: 300 fb^{-1} (~2025), achieved 25fb^{-1} in Run-I**
- **B-factory@KEK: 50K fb^{-1} (~2023)**



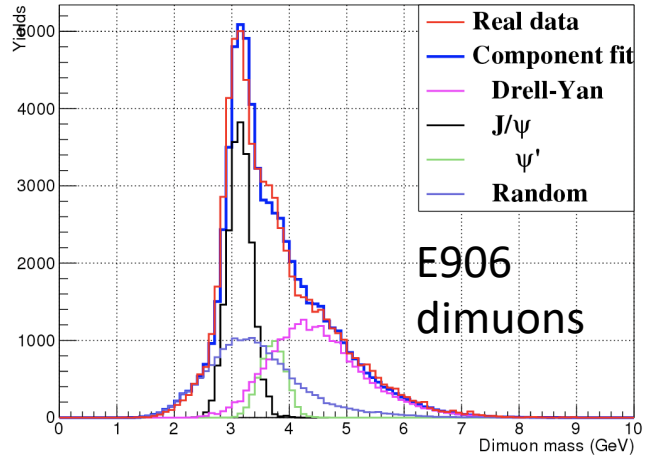
Displaced DP Trigger upgrade completed in 2017;
Allow parasitic runs with E-1039 in 2019-2021

E-1039: 2019-2021+
Polarized NH3 Target



- Beam dump mode: p+Fe collisions! Target ~ 10%λ_I
- Parasitic run with other fixed target experiments, E906/E1039

Status of SeaQuest Experiments



- E906 fixed target experiment: 2012 – 2017
  - H, D, C, Fe, W targets
  - High mass Drell-Yan, mass > 4GeV

- E1039 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: ~ June 2019
  - Physics data taking for two years: ~10/2019 - 7/2021+ (or longer)
  - POT: 1.4 x 10^18

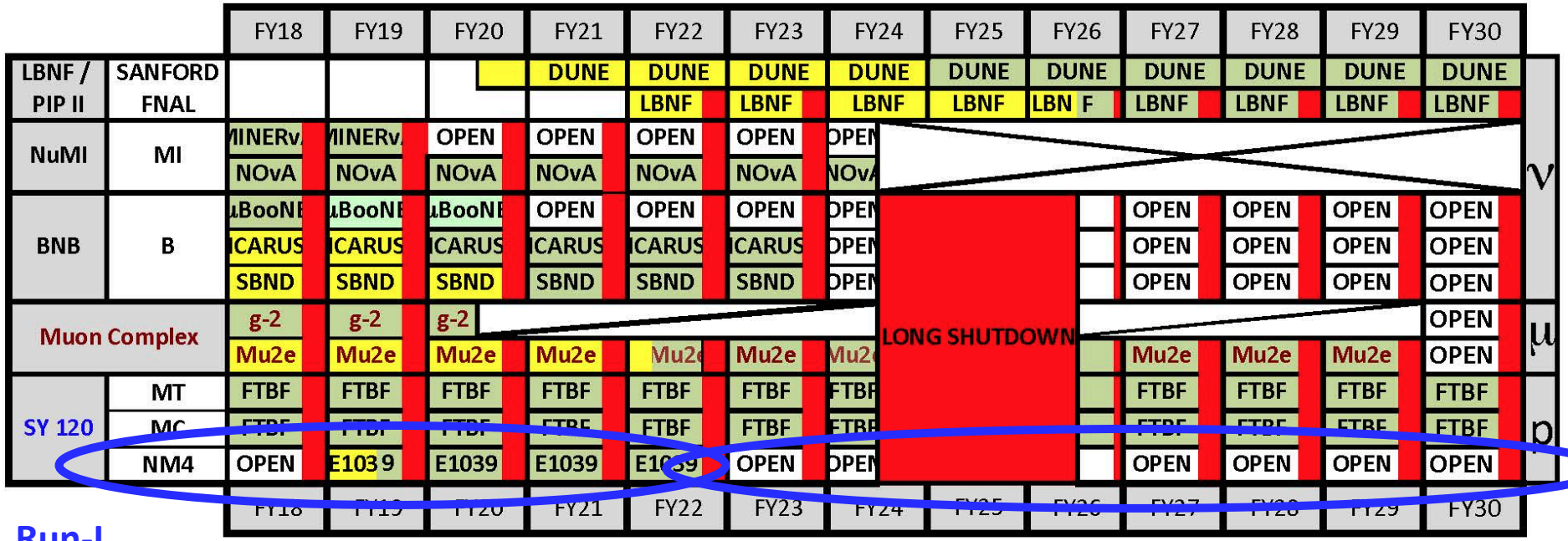
Parasitic E1067 Dark Photon program approved in 2015

- **Parasitic run to search for dark photon/Higgs/ALP etc.**
  - **E906, E1039, dimuon channel**
  - **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**

Fermilab Long Range Plan: 04/2018

Fermilab Program Planning 5-April-18

LONG-RANGE PLAN



Dark sector physics program: Run-I, II

Run-I 2019-2021+

Run-II: 2022 - 2030

Construction / commissioning | Run | Subject to PAC review | Shutdown

Capability ended | Capability unavailable

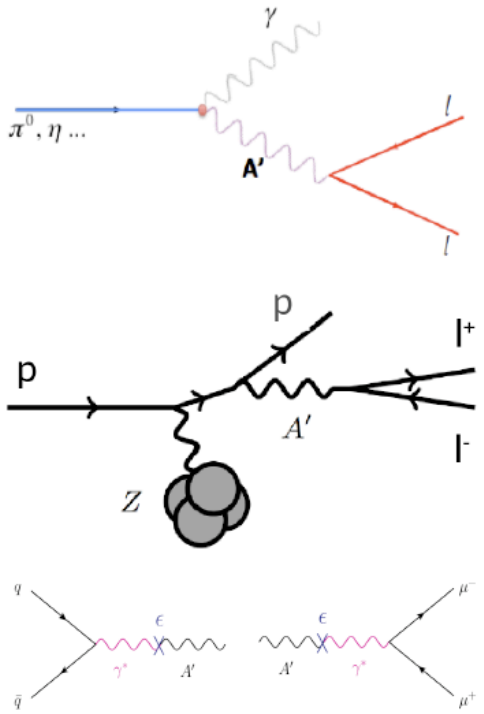
NOTES:
1. Mu2e estimates 4 year running starts mid-FY22 after 18 months commissioning. Assume, with contingency, 5.5 years data taking.
2. DUNE: 1st 10kT detector module commissioned in FY24. Runs without beam FY25 to mid-FY26.
3. NOvA runs as long as possible [in the spirit of PAC Nov 2017].
4. Assume 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].

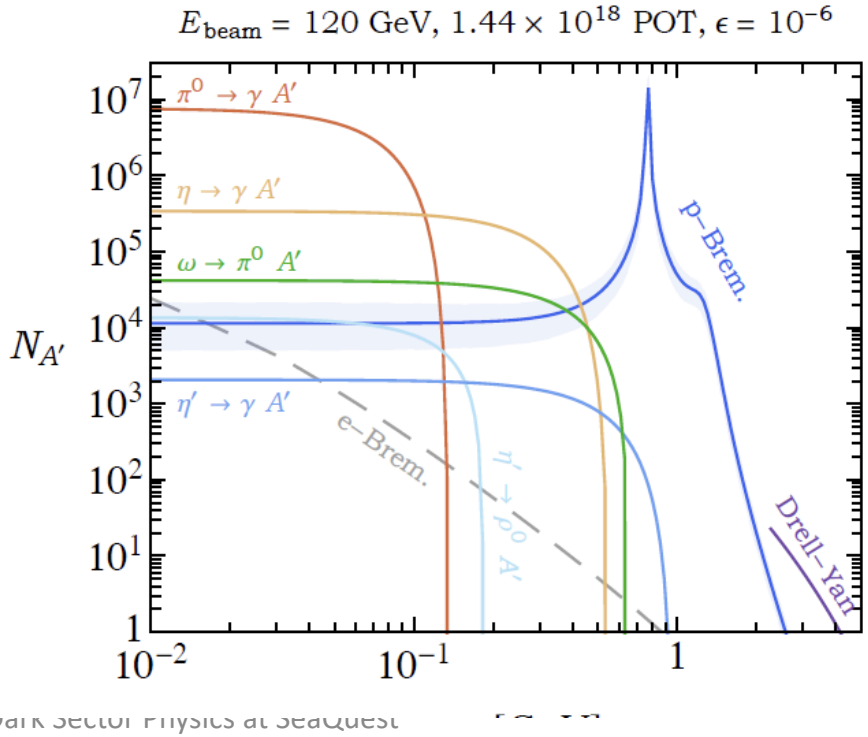
Dark Sector Physics – Dark Photon as an Example

Production and signatures at SeaQuest

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

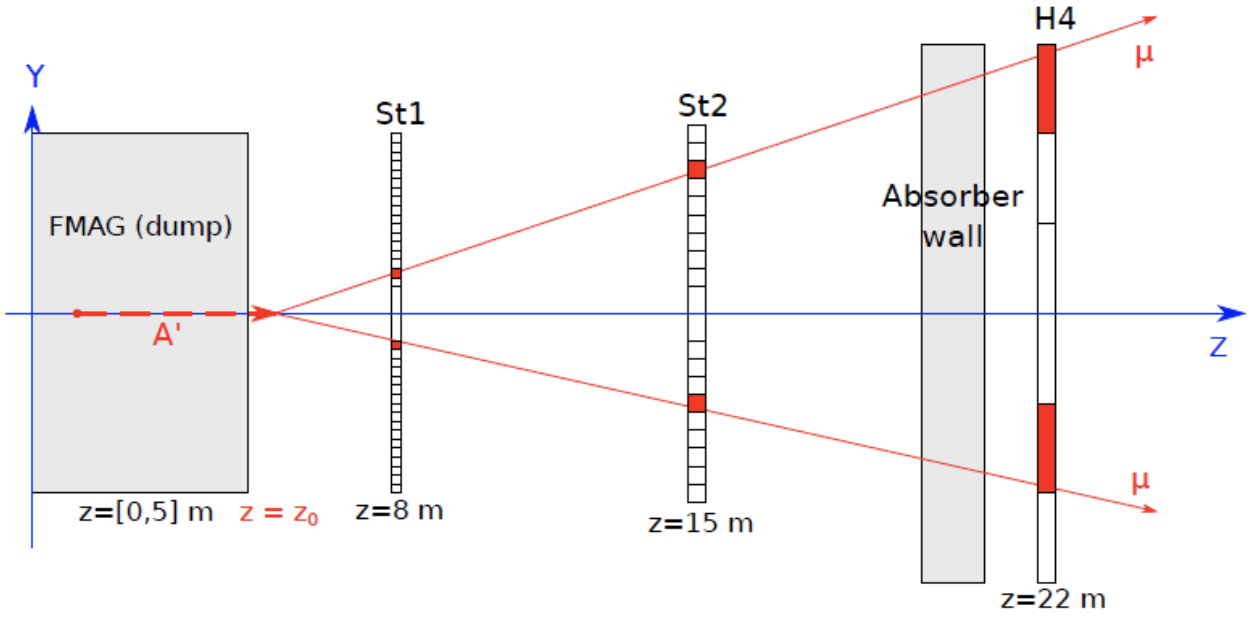
Mass range:
~1MeV - 10GeV





Dark Photon Detection @SeaQuest

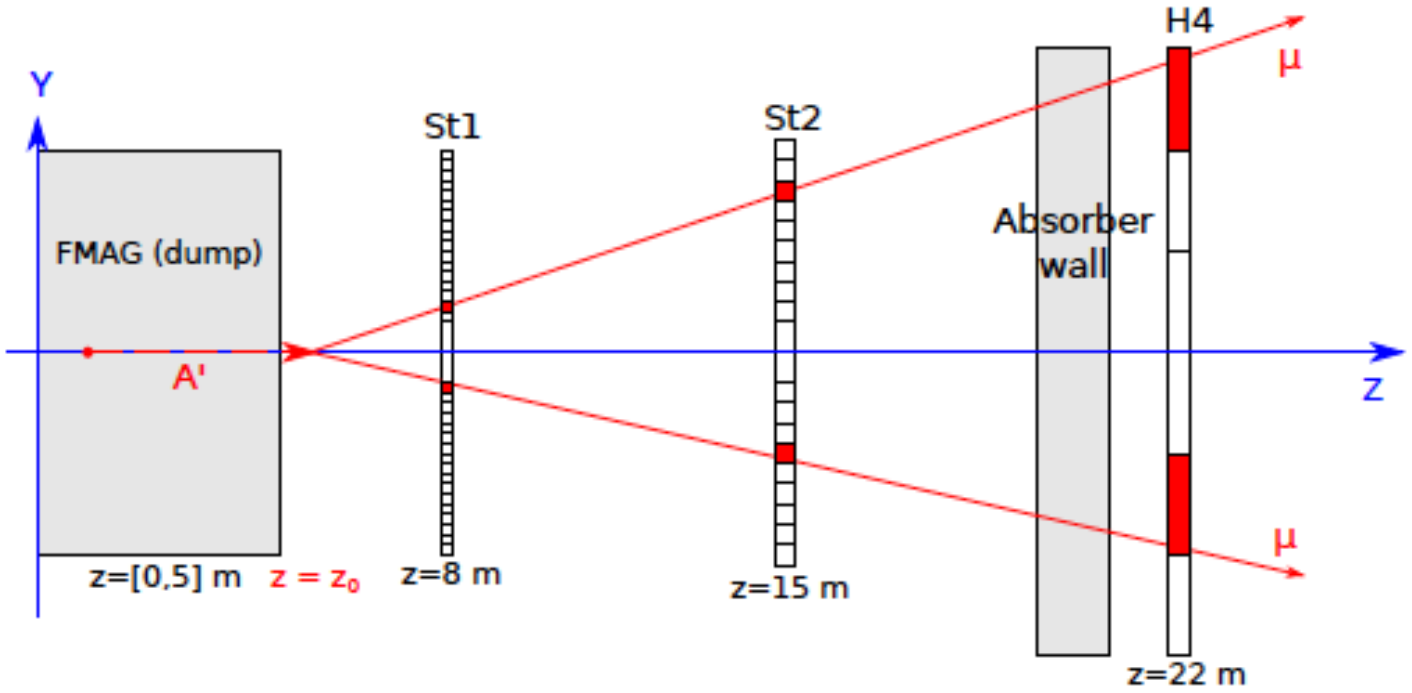
- Dimuons in main SeaQuest dataset
  - Bump-hunt at high mass (ongoing effort)
- Dimuon displaced-vertex trigger
  - Commissioned 2017, physics data soon
- Dielectron trigger
  - EMCal for electron PID (in planning)



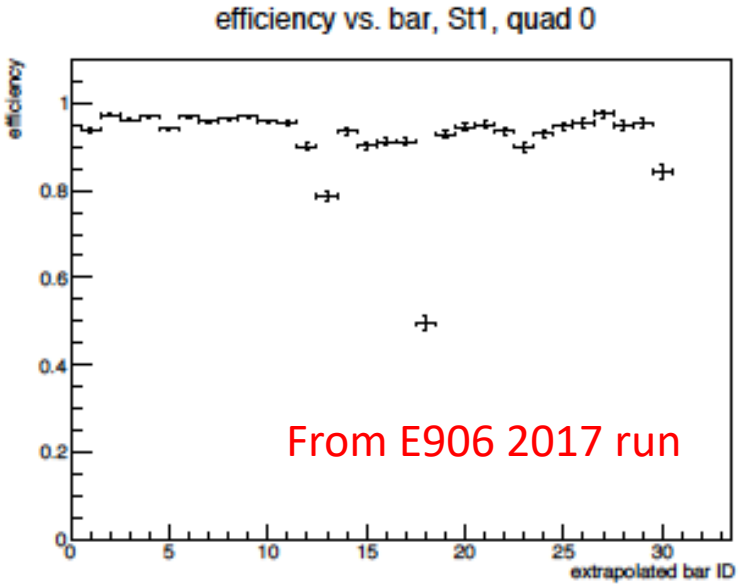
Displaced Dark Photon Trigger Detectors Commissioned

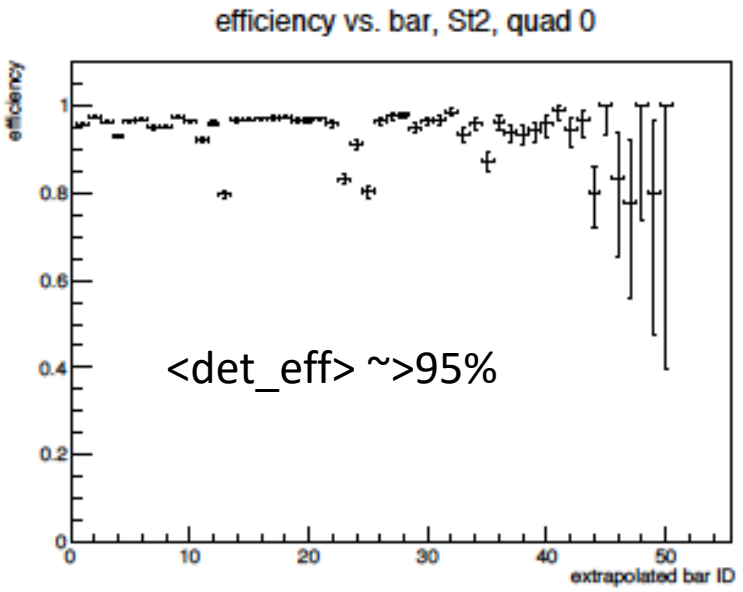
-Detector and trigger system installed and commissioned during the last SeaQuest/E906 run in 2017

- Physics analysis in progress
- Bad channels all fixed in 2018



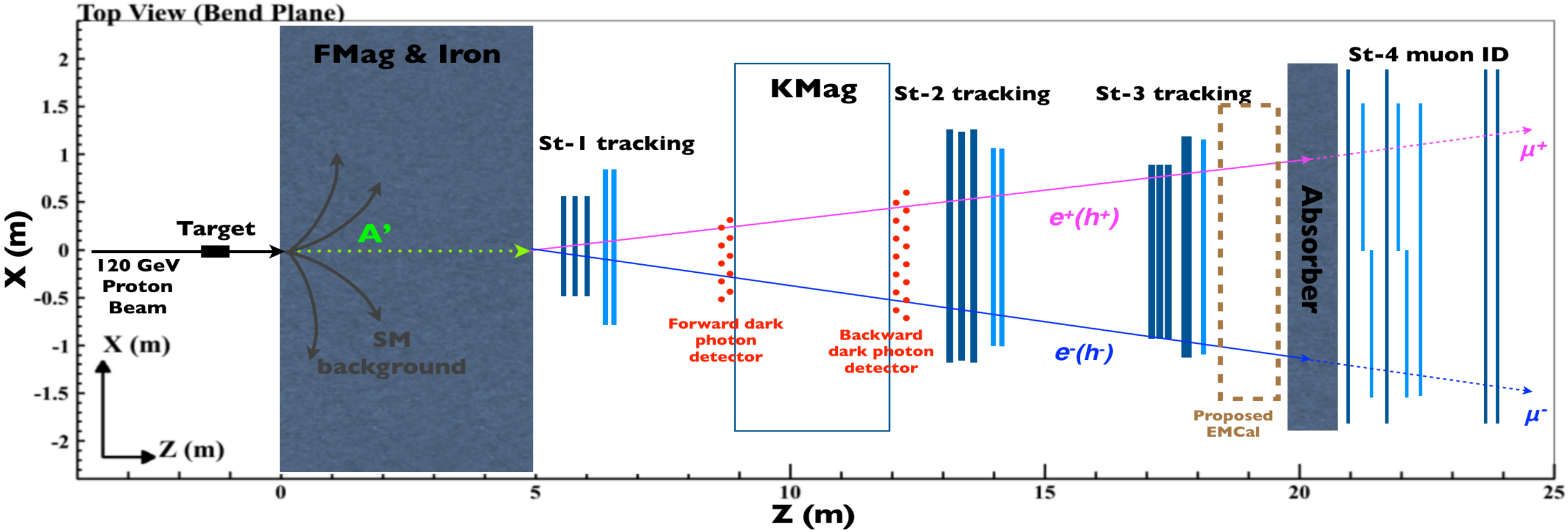
Schematic of displaced dimuon trigger





Near Term Upgrade Plan - EMCal Upgrade in 2021

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

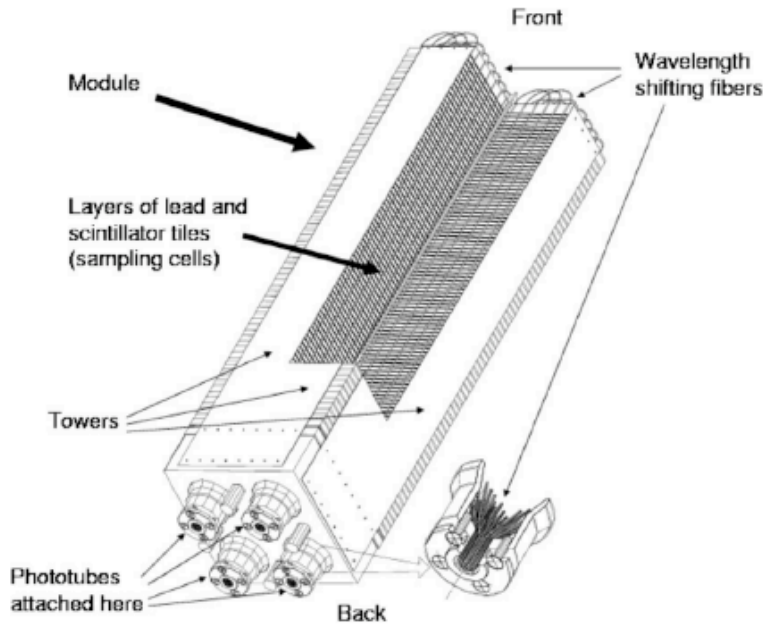


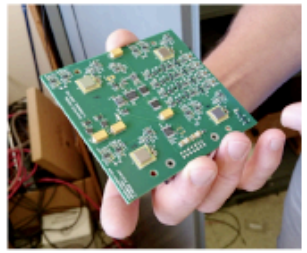
- Signal mostly from beam dump;
- Other parasitic targets operation possible

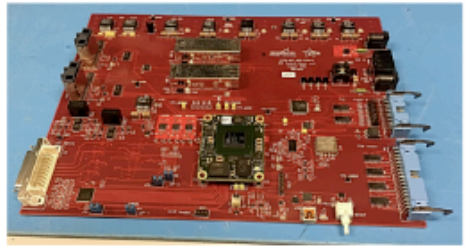
EMCal Upgrade Status

- 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 this week (STAR forward upgrade R&D)
- available for SeaQest







EMCal Upgrade Plans

- 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

A Letter of Intent to Search for Dark Sectors with the EMCal Upgrade of the SeaQuest Experiment at Fermilab*

A. Berlin[1], A. Durum[2], R. Gilman[10], S. Gori[3], Y. Goto[4,5], Y. Kwon[9], K. Liu[6], M. X. Liu[6], P. McGaughey[6], P. Reimer[7], S. Sawada[8], P. Schuster[1], C. da Silva[6], A. Tkatchev[6], N. Toro[1], S. Uemura[6], and R. Van De Water[6]

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June 28, 2018

Abstract

In 2017, the parasitic dark sector physics search experiment SeaQuest/E1067 successfully installed and commissioned a new displaced dark photon di-muon trigger along with 10-fold improvement in SeaQuest DAQ bandwidth during the last run of the SeaQuest/E906 experiment. This upgrade allows the SeaQuest experiment to search for dark photons (and, more in general, for new displaced dark particles decaying into muons) in the mass range from 200 MeV to about 10 GeV, in a parasitic operation mode with the E906 and the upcoming E1039 experiments. Given the recent stage-II approval of the E1039 polarized fixed target experiment and the success of the dark photon trigger upgrade, we propose to further expand the dark sector physics program to particles with a mass below 200 MeV (di-muon mass limit) down to about 1 MeV, a two orders of magnitude improvement. This will be achieved via adding a new electromagnetic calorimeter (EMCal), recycled from the PHENIX experiment at BNL, before the station-4 muon identification absorber for electron identification. With this EMCal upgrade, SeaQuest will have an unprecedented discovery reach for a large set of New Physics models predicting resonant and non-resonant electron signatures. Leveraging the existing SeaQuest experiment, we will be able to carry out a very broad dark sector physics program, first parasitically with the E1039 polarized fixed target experiment at Fermilab in 2019-2021, and second with a dedicated experiment after the EMCal upgrade. These two phases of the experiment will produce world best and most timely searches for uncharted models with new dark particles in the mass range from about 1 MeV to 10 GeV.

*Contacts : Ming Liu, Paul Reimer, Sho Uemura, and Kun Liu (experiment), Stefania Gori (theory)

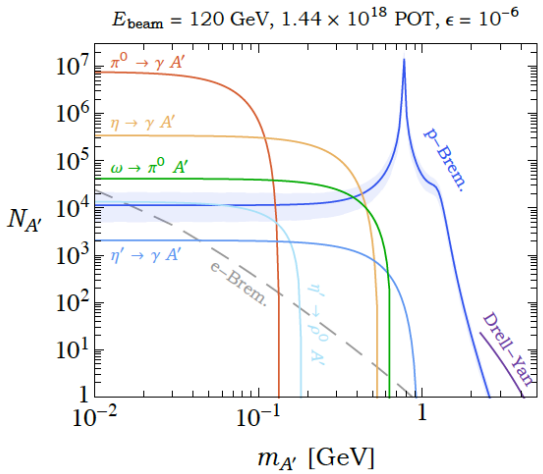
Money Plots (I)
- to include all other experimental searches up to year ~2025+

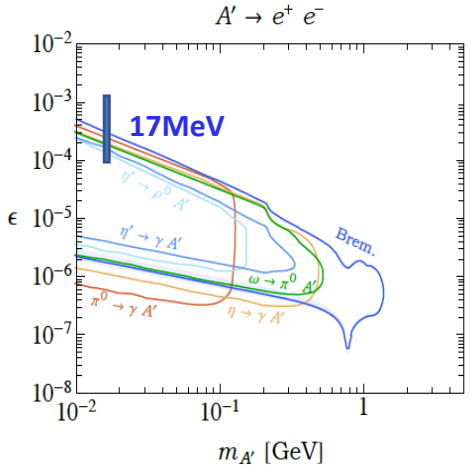
Phase space covered by SeaQuest:
2019 ~2021 – dimuon channel (POT = 10^18)
2022-2024 – add di-electron (POT = 10^18)
2026 – 2030+ --- all channels (POT > 10^19)

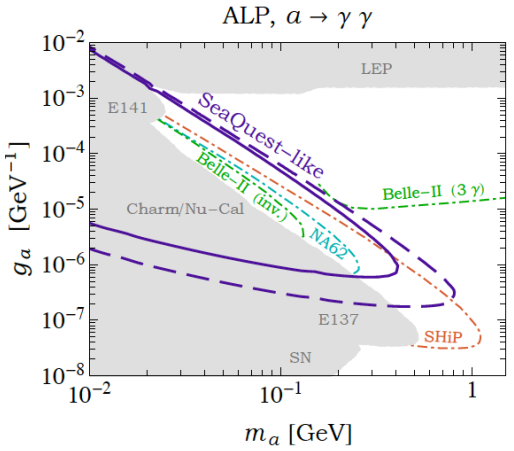
SeaQuest dark photon coverage:

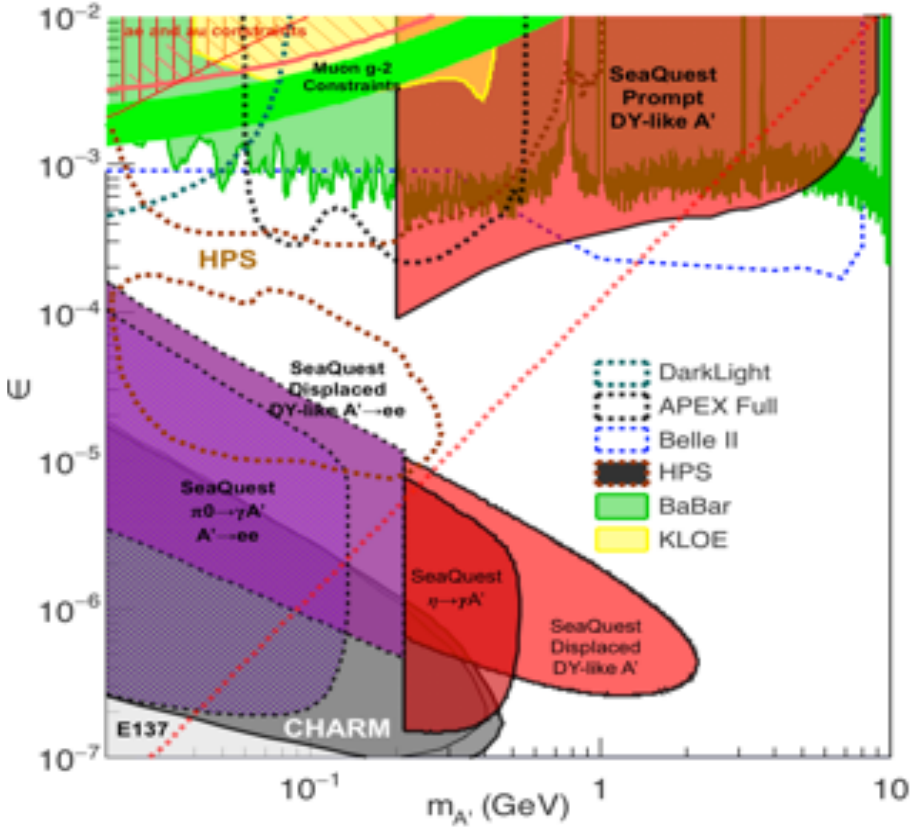
- Dimuons (current capability)
- Di-electrons (w/ EMCal upgrade)

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



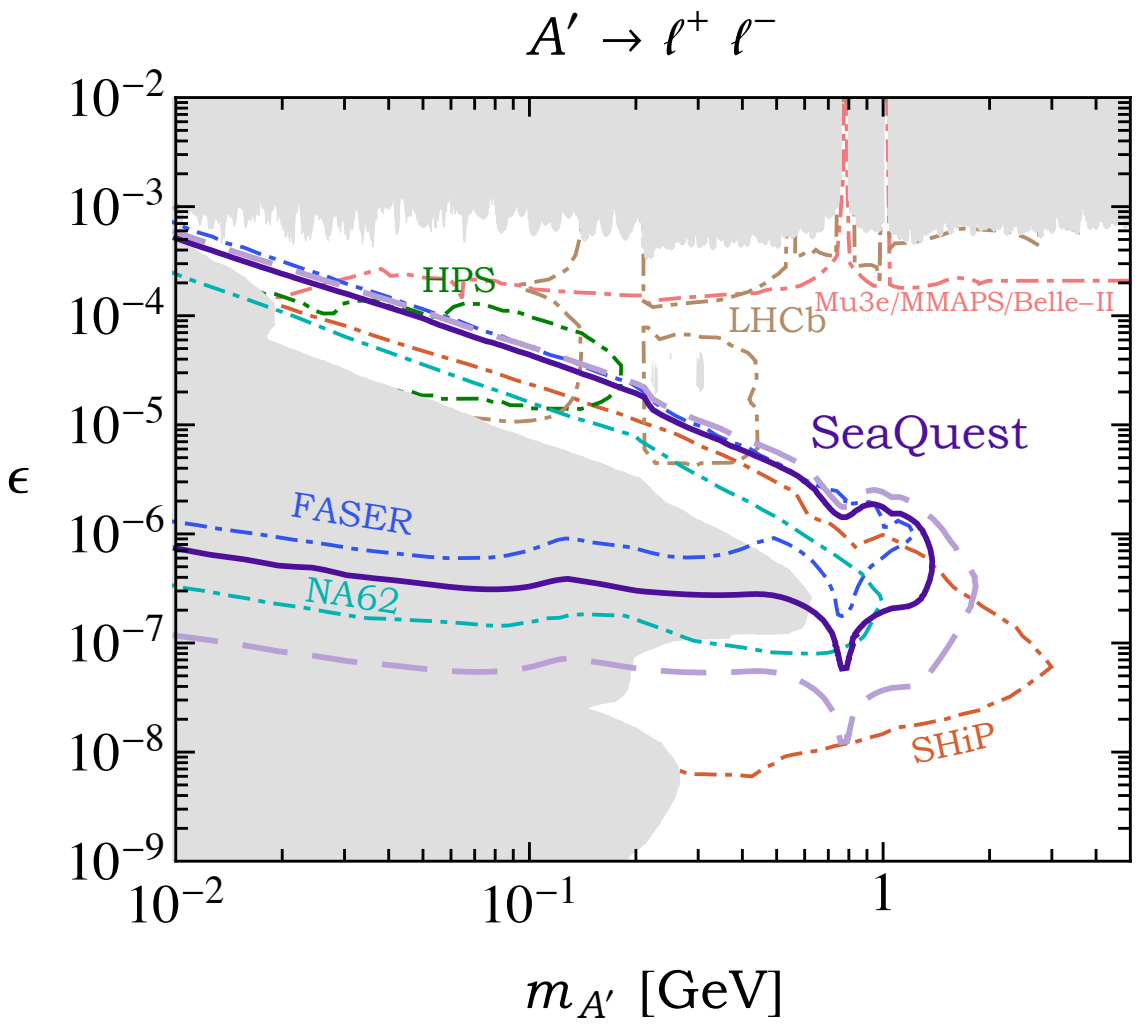


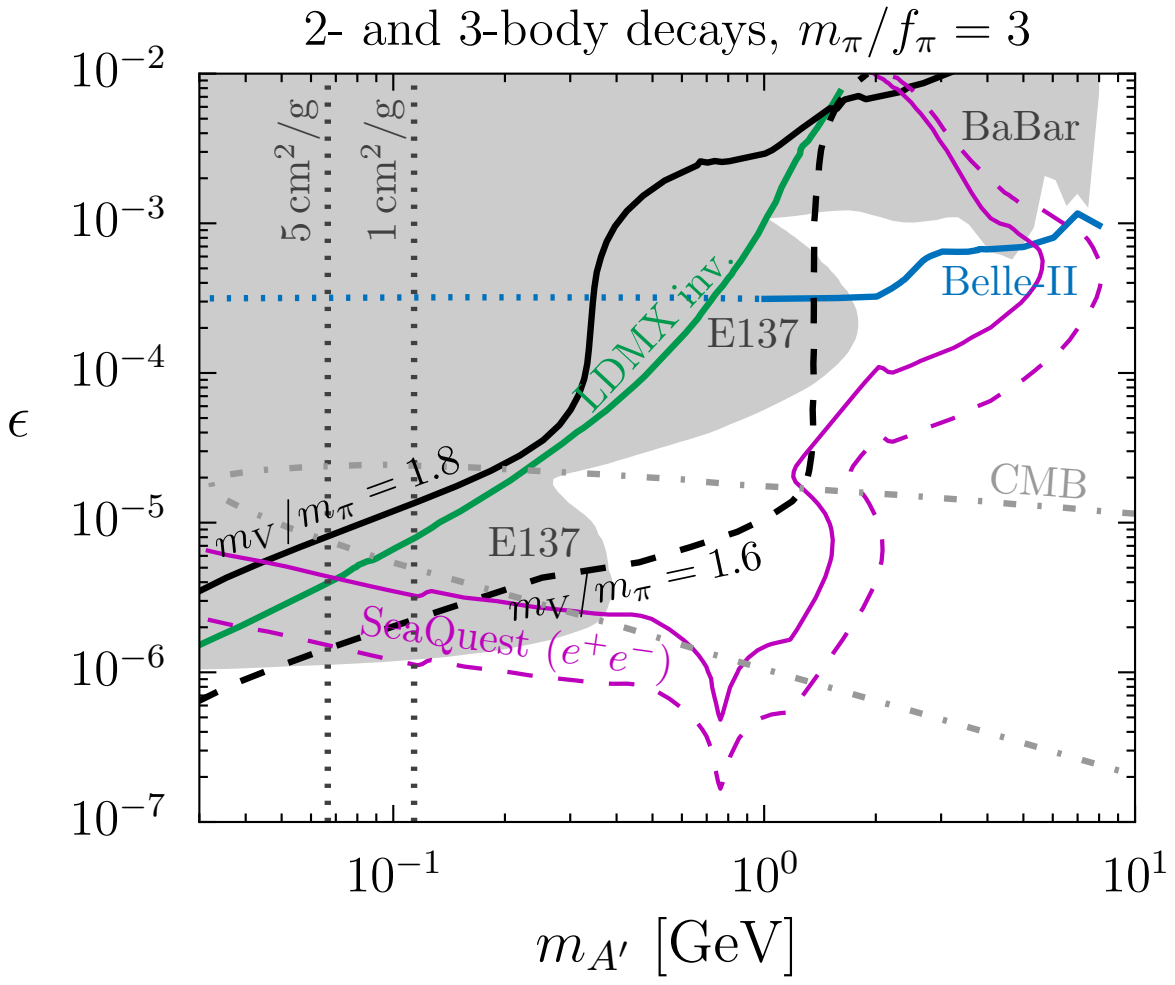




arXiv:1804.00661, Berlin, Gori, Schuster and Toro;
1801.05805, Berlin, Blinov, Gori, Schuster and Toro

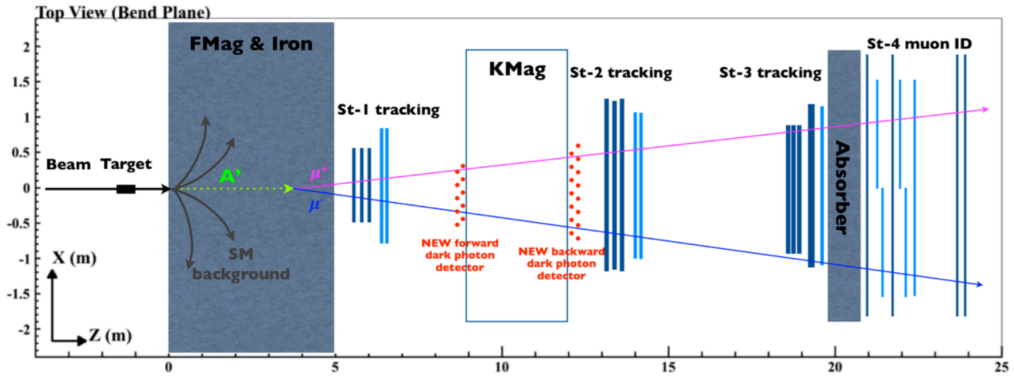
Money Plots (II) - with all Future Projections



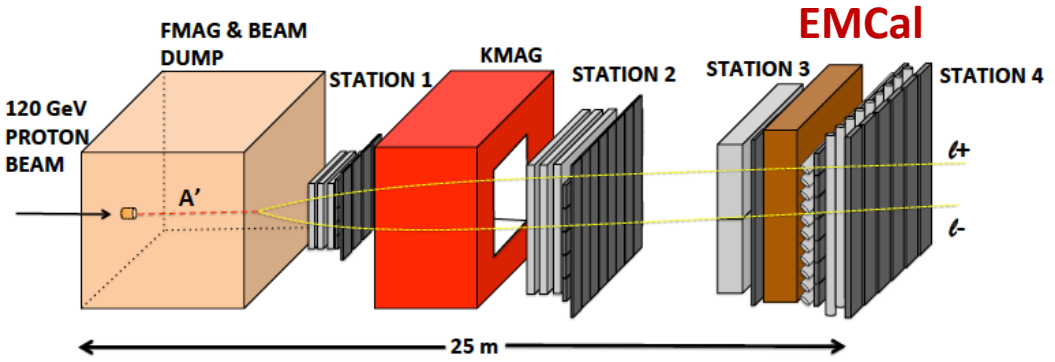


Long Term Prospects of Dark Sector Physics Program at SeaQuest

- 2019-2021: Parasitic Dark Sector physics program with E1039
  - **Attract and build up HEP groups in SeaQuest**
    - 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 SeaQuest 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
  - POT = 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}~10^{20}
  - Carry out an extensive (SHiP-like) HEP experimental program at NM4
  - Possible NP parasitic physics program under discussion (~US EIC physics era)

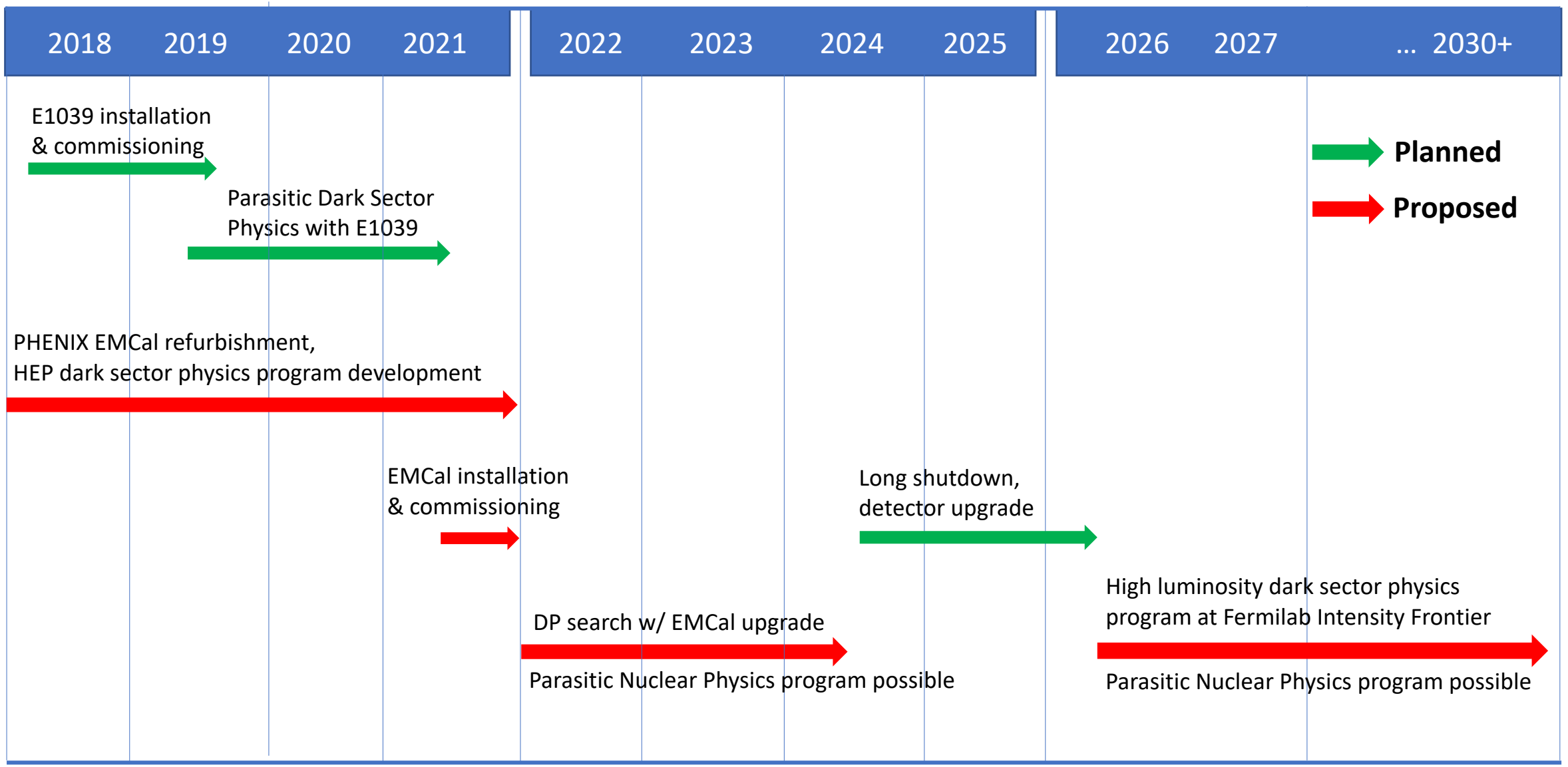


SeaQuest in 2017 with displaced dark photon trigger



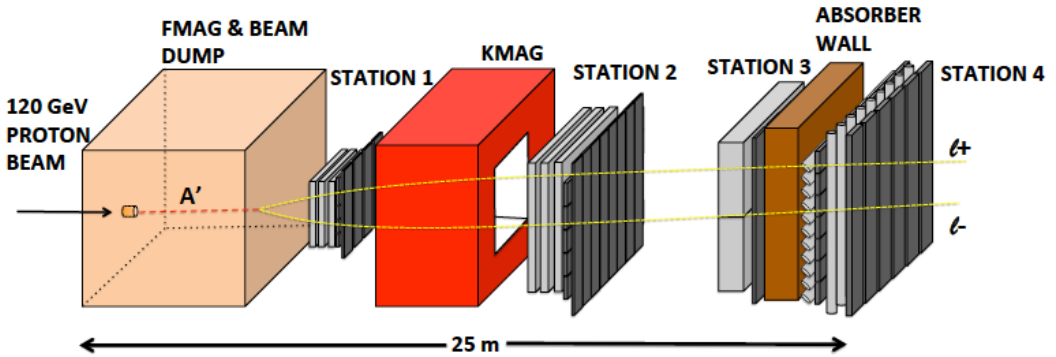
SeaQuest in 2021+ with EMCal upgrade

Schedule @SeaQuest



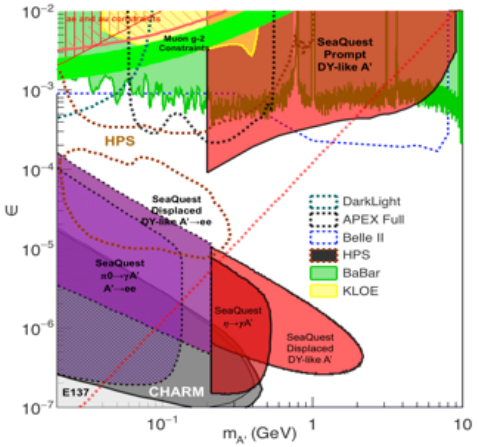
Summary and Outlook

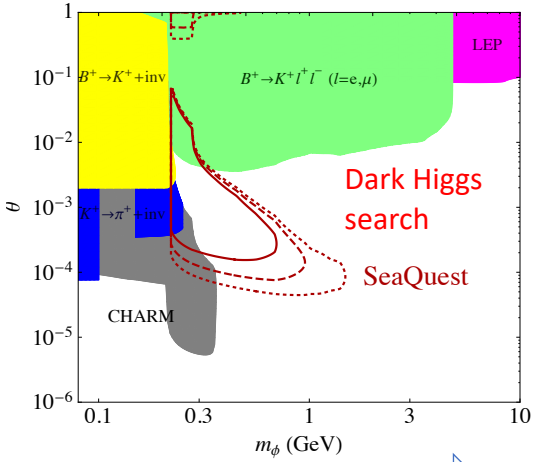
- ***Phase-I***
  - ***Great discovery potential!***
  - ***A new vertex trigger & DAQ++***
  - ***Early parasitic data taking 2019-2021+***
  - ***POT 1.4 x10^{18} or more***

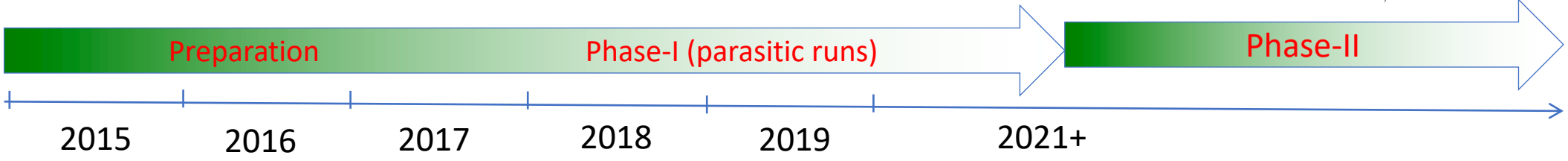


SeaQuest in 2021+ with EMCal upgrade

- ***Phase-II: beyond E1039, 2021+***
  - ***Possible detector upgrade later, add electron, photon and hadron capability***
  - ***A new dedicated dark matter program at Intensity Frontier!***





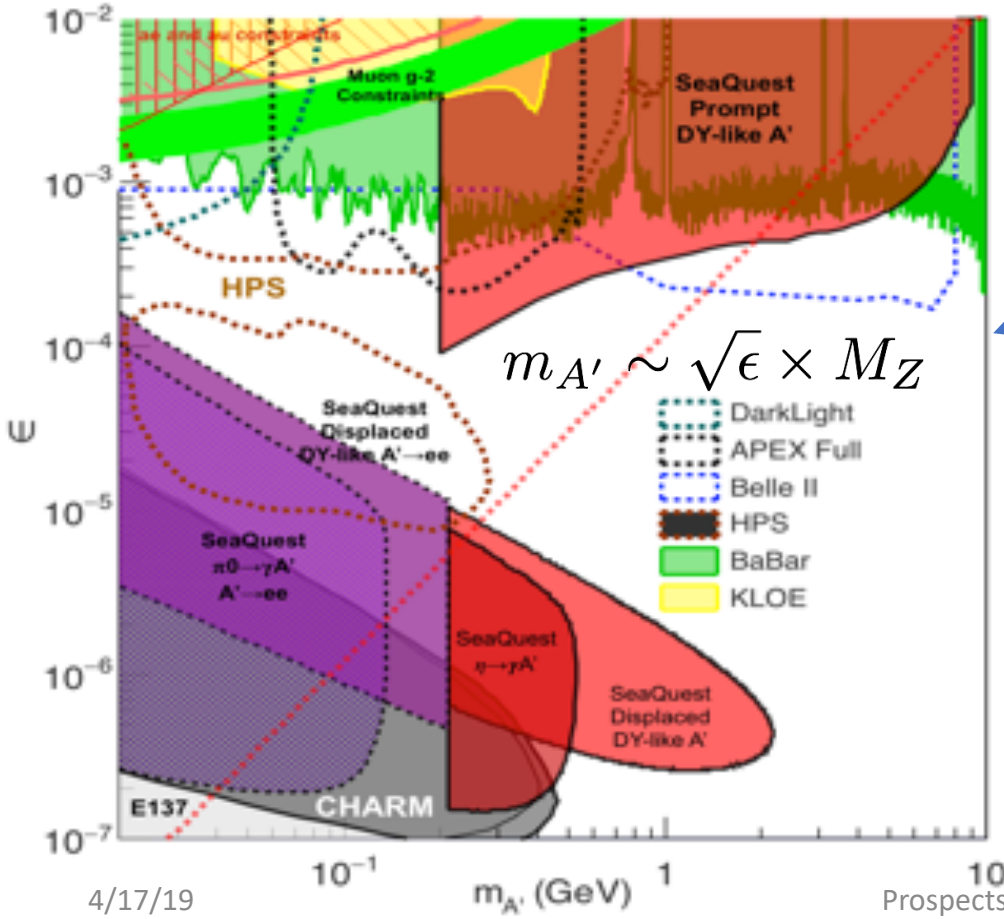


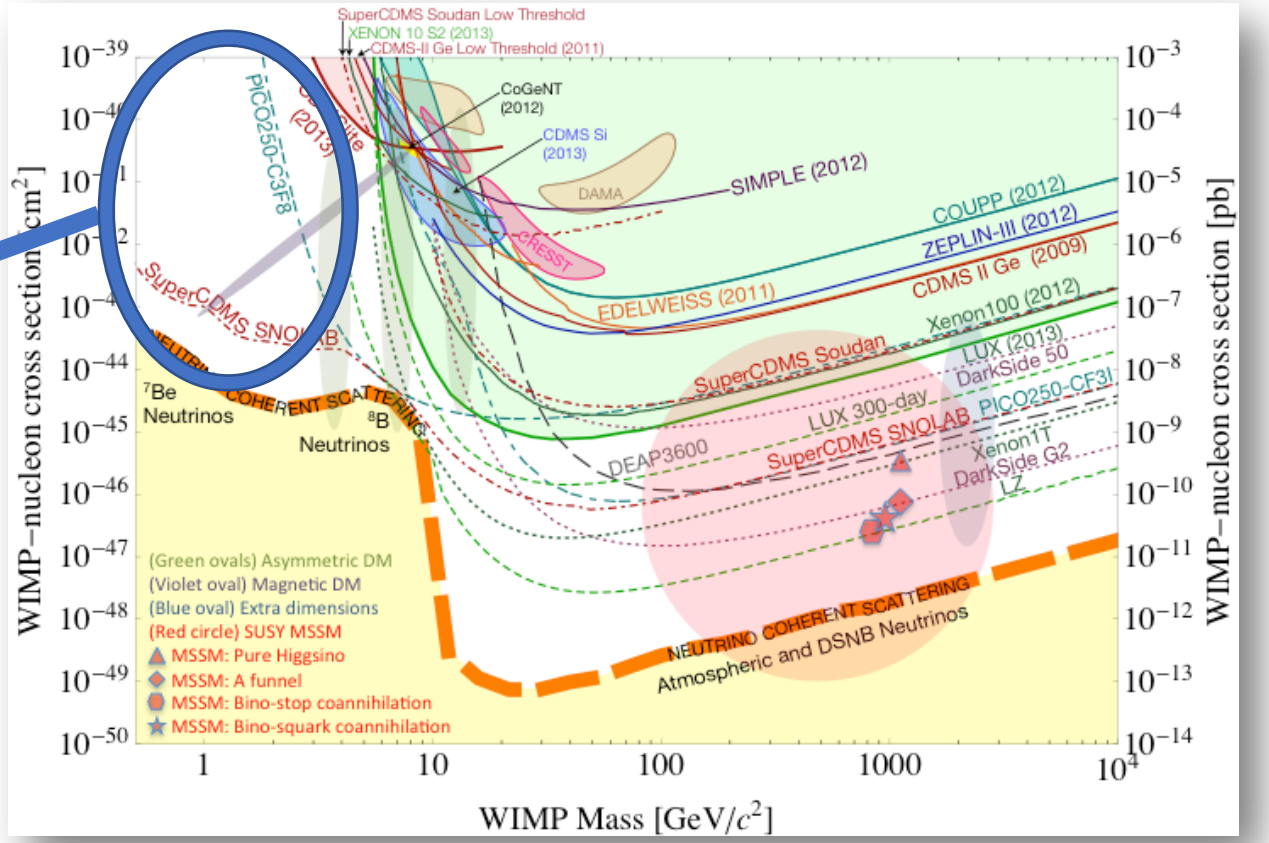
Supporting Slides

Dark Photon/Higgs Search at Beam Dump Experiments @SeaQuest

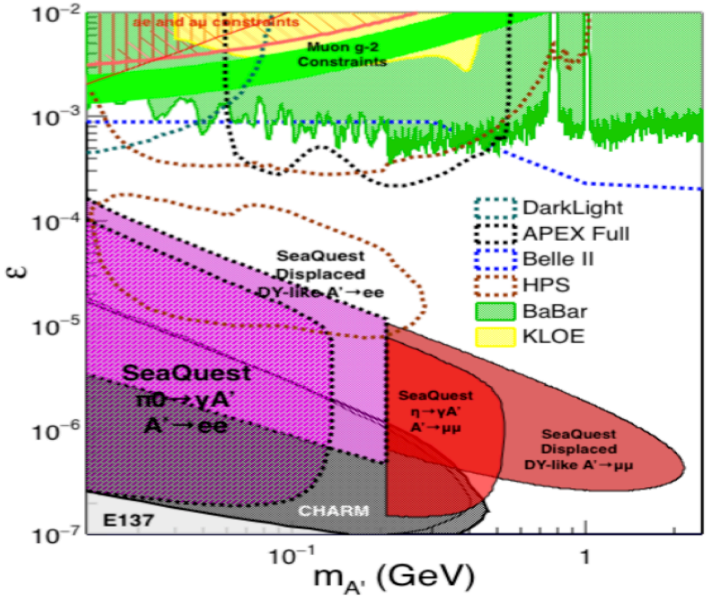
SeaQuest search for **low mass dark particles**:
mass ~ 1 MeV – 10GeV

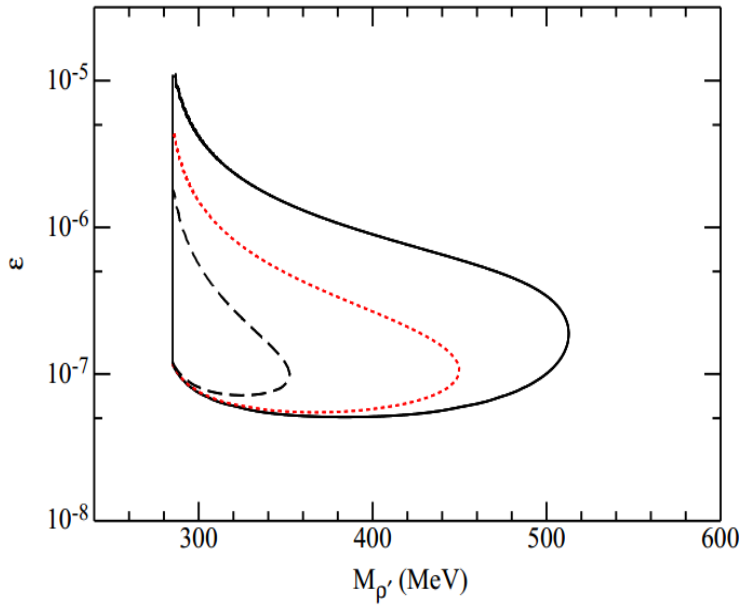
- WIMP search – mass >~ 10GeV,
- Needs low mass coverage, mass < 10GeV





Physics goals and recent 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

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

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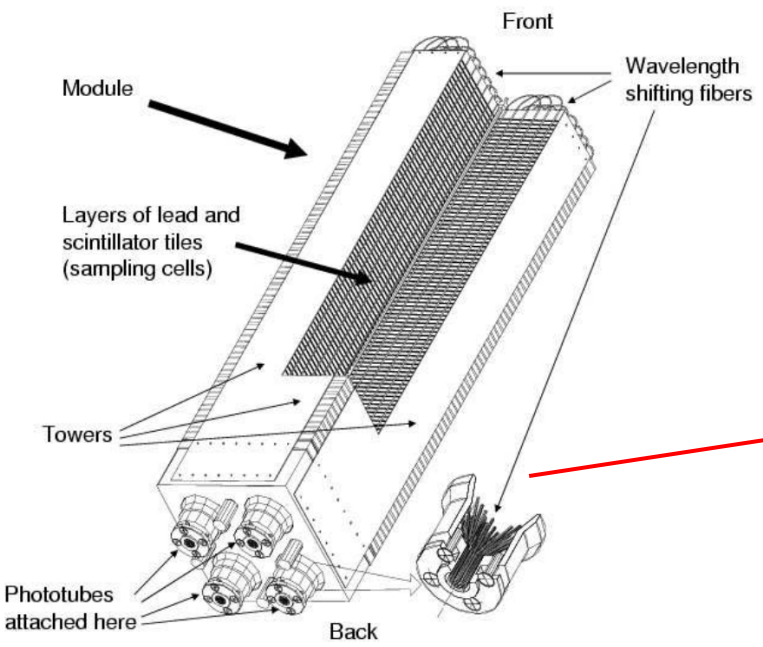
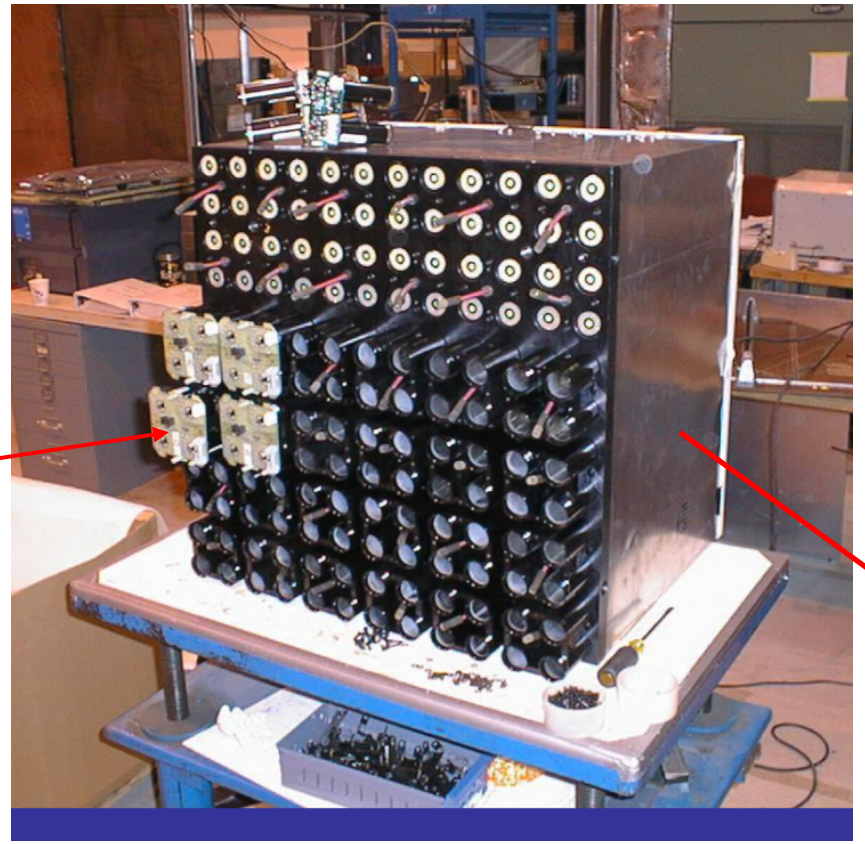
Details of PHENIX EMCal

(we get 2 best sectors)



- Shashlik-type Pb scintilator
- 1 tower is 5.52*5.52*33 cm^3
- 4 towers make a module

Total # of readout channels if gang 4-"PMTs":
36 x 3 x 6 = 648 (2592)



- 6x6 modules make a super module
- 3x6 supermodules make a sector
- 1 sector covers 2x4 m^2, weights about 22t(std)