Dark Photon/Higgs Search in the SeaQuest/E1067 Experiment at Fermilab

Ming Liu

Los Alamos National Lab

Light Dark World International Forum 2017

Pittsburgh, PA

Outline

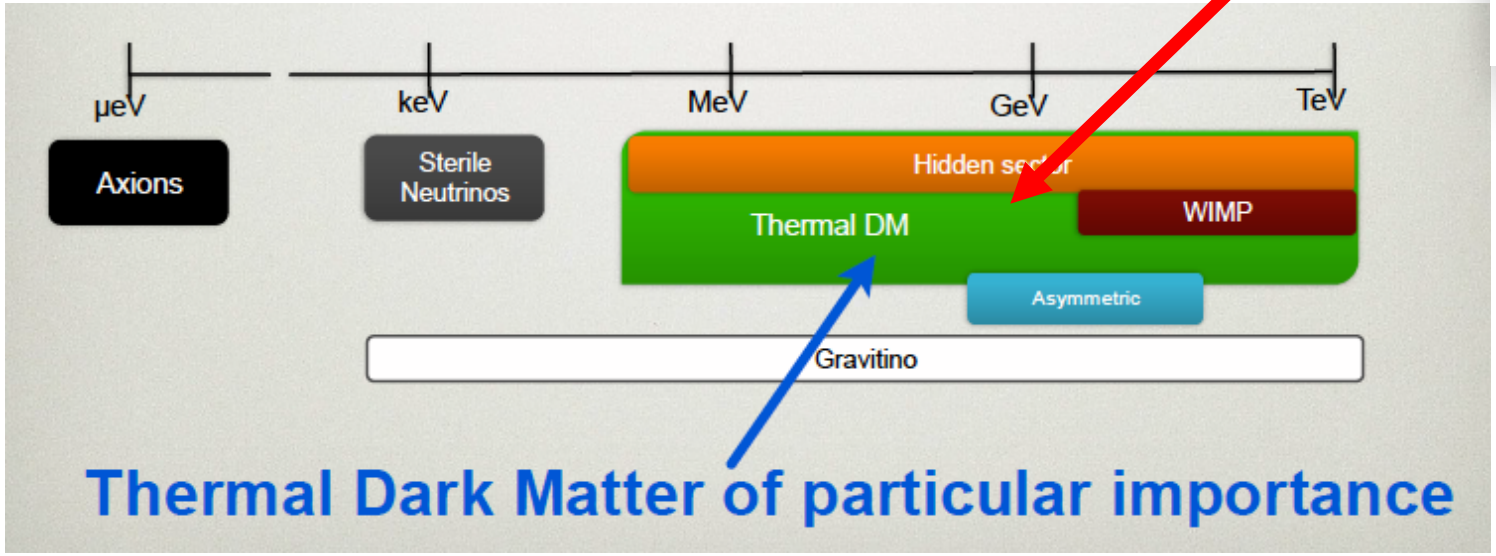
- Dark sector physics @SeaQuest/E1067
  - Experimental setup
- Detector upgrade @SeaQuest/E1067
  - Commissioning run in 2017
- Future plan and opportunity
  - Phase I: 2017 - 2020
    - Parasitic run with E1039(polarized Drell-Yan)
    - Electron/hadron ID w/ EMCal upgrade
  - Phase II: 2020 -2025+
    - Dedicated dark photon program @Fermilab

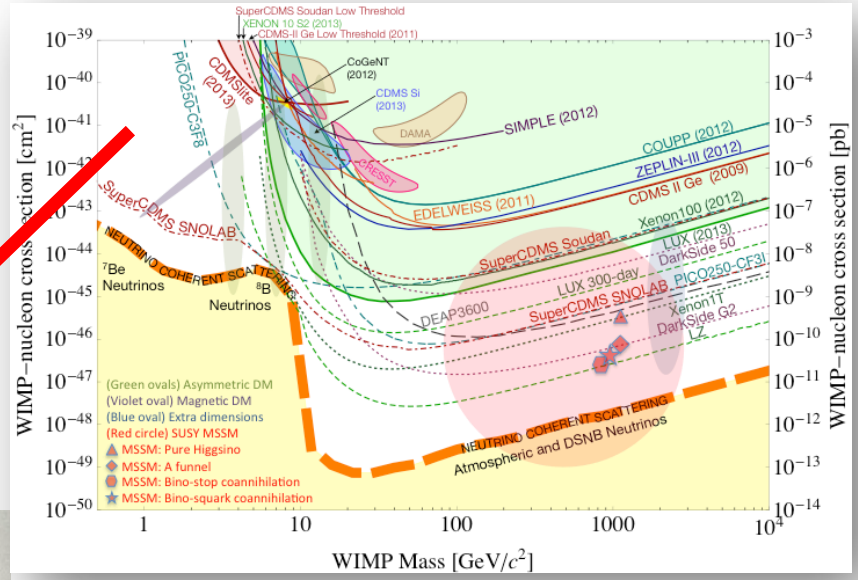
You inputs to further develop the program

Dark Sector Physics at Low Mass

Current and near future high-intensity colliders and fixed target experiments offer an ideal environment to probe dark sector physics, in O(MeV) ~ O(GeV), SeaQuest@Fermilab

P. Schuster et al.



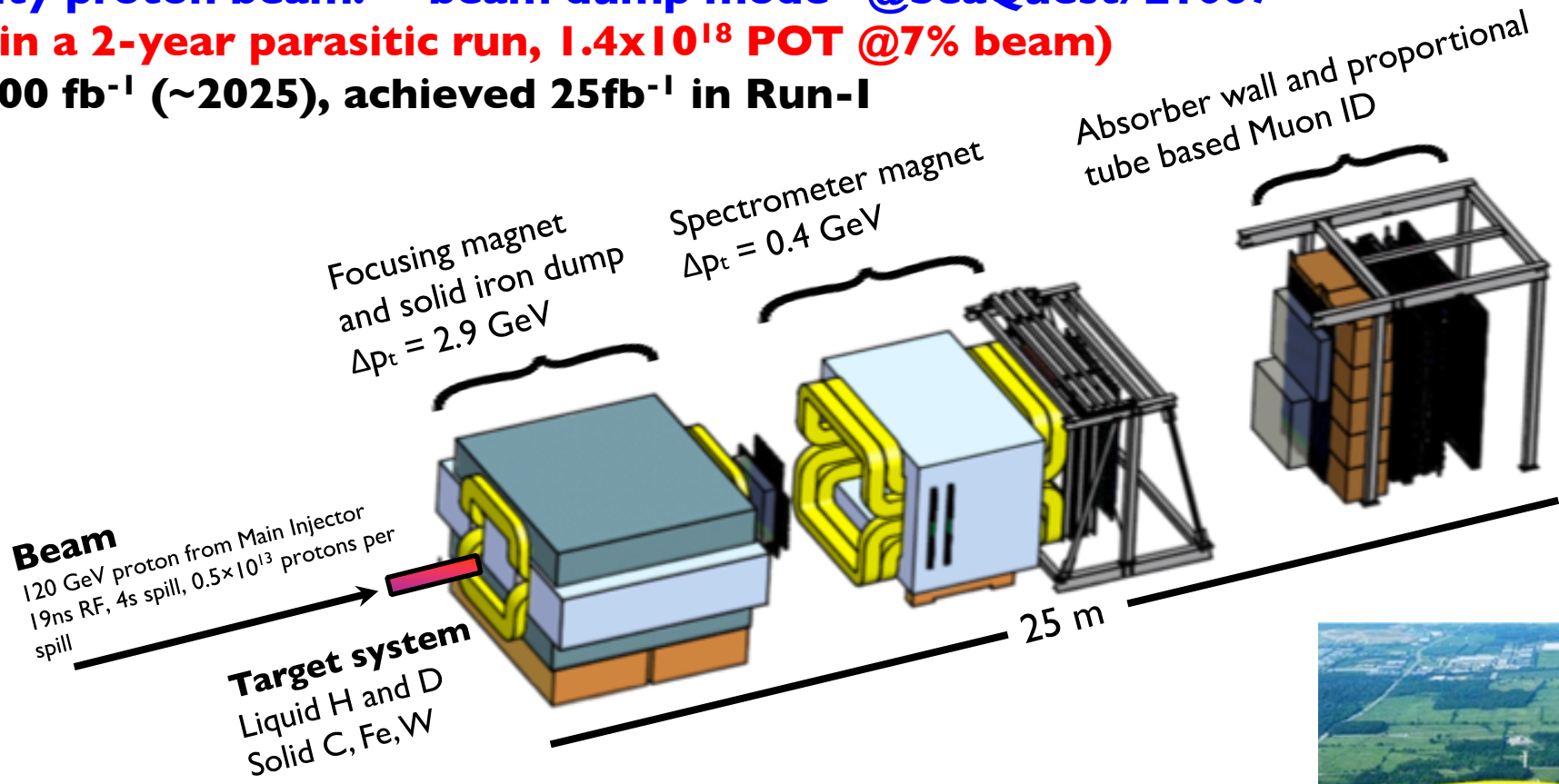


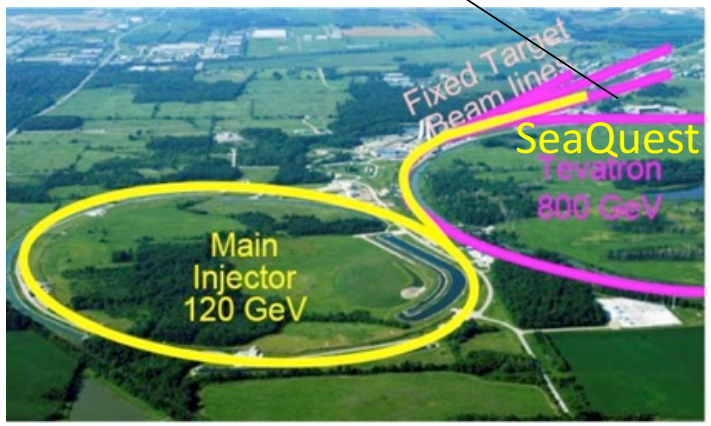
WIMP Search

SeaQuest Dimuon Experiment at the Intensity Frontier at Fermilab

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

- **35K fb^{-1} (in a 2-year parasitic run, 1.4x10^{18} POT @7% beam)**
- **LHC-II: 300 fb^{-1} (~2025), achieved 25fb^{-1} in Run-I**

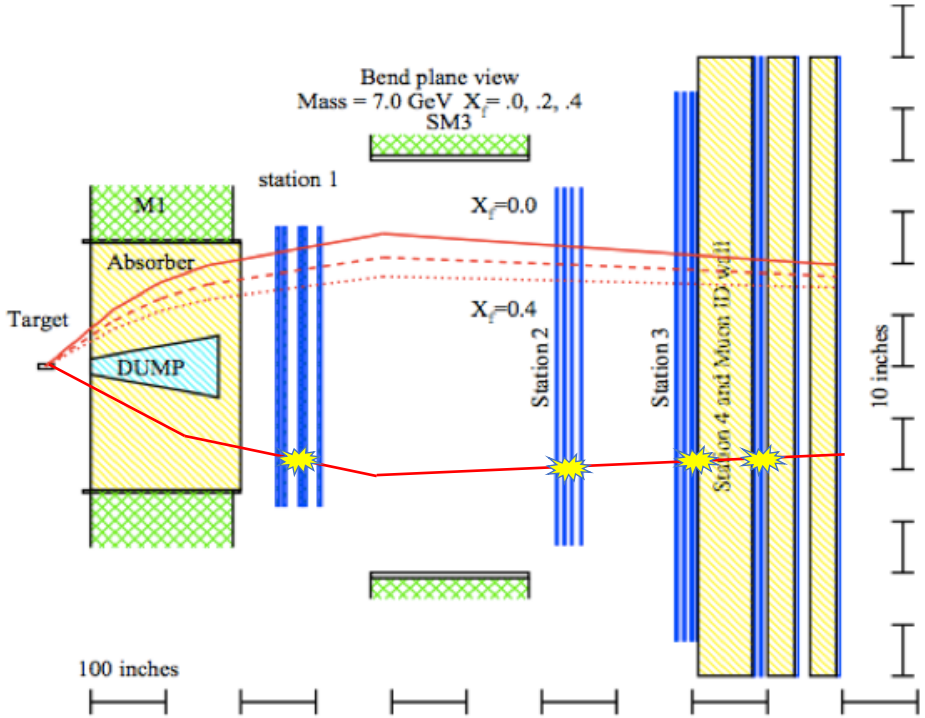


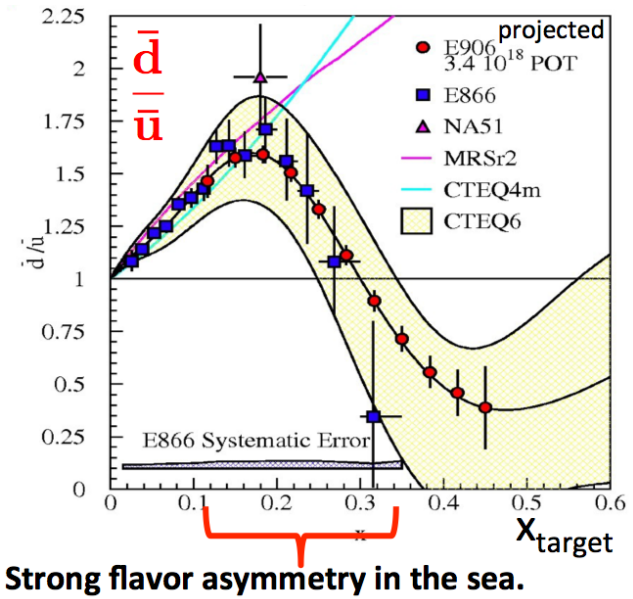


- Beam dump mode: p+Fe collisions! Target ~ 10%λ_I
- Parasitic run mode possible with other experiments, E906/E1039

SeaQuest: Nuclear Physics with Drell-Yan

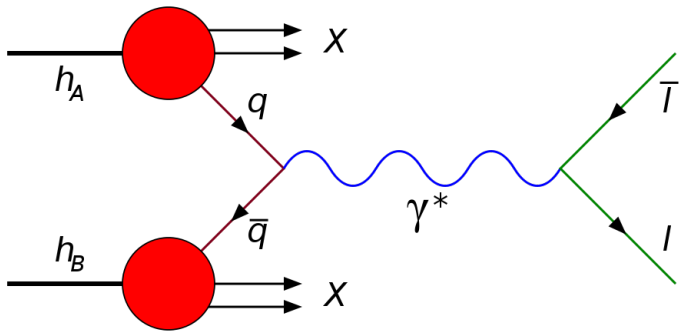
DOE/Nuclear Physics Programs: 2008-2017(E906), 2017-2020(E1039)

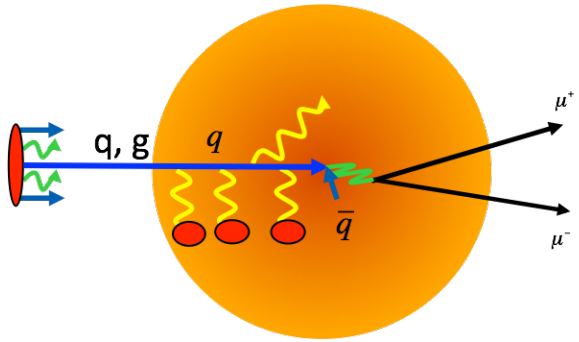




Strong flavor asymmetry in the sea.

High mass Drell-Yan:
4<M<8 GeV

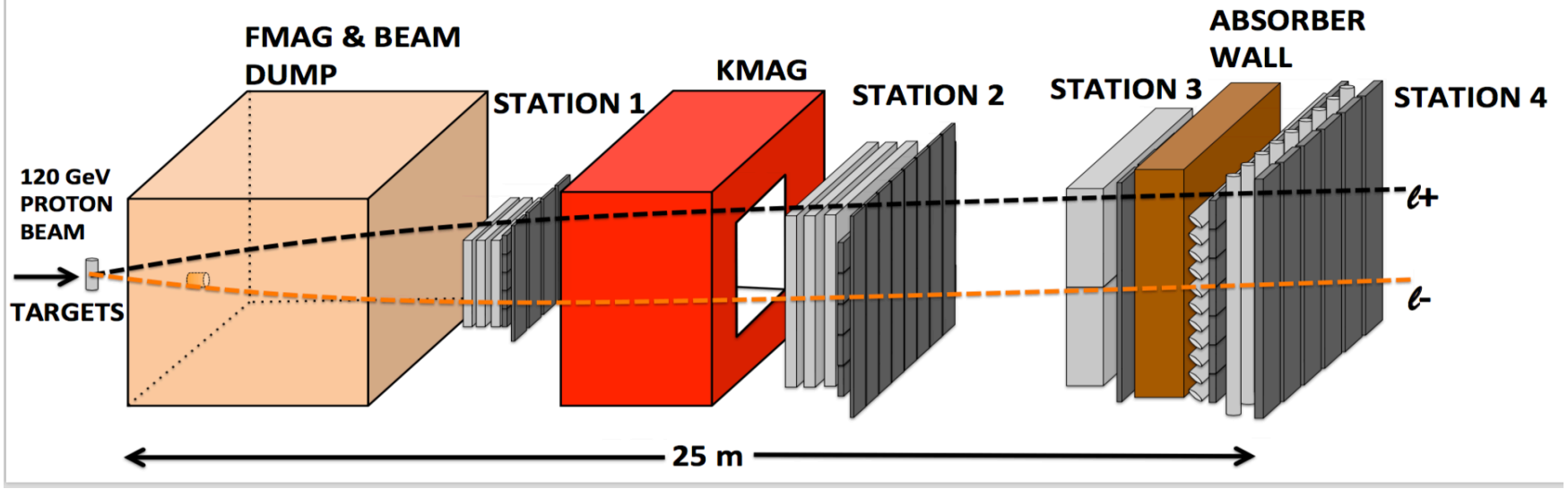




Quark Energy Loss dE/dx in p+A collisions

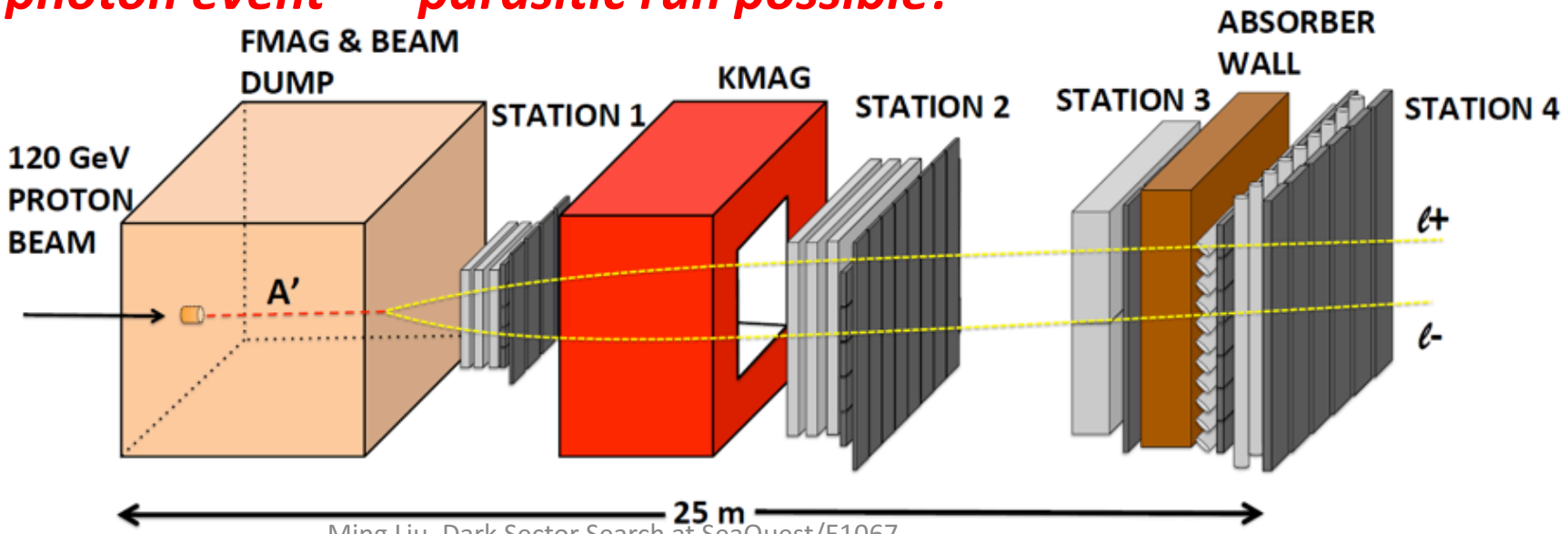
E906

A target Drell-Yan event



A beam-dump dark photon event --- parasitic run possible!

A new idea developed in ~2014

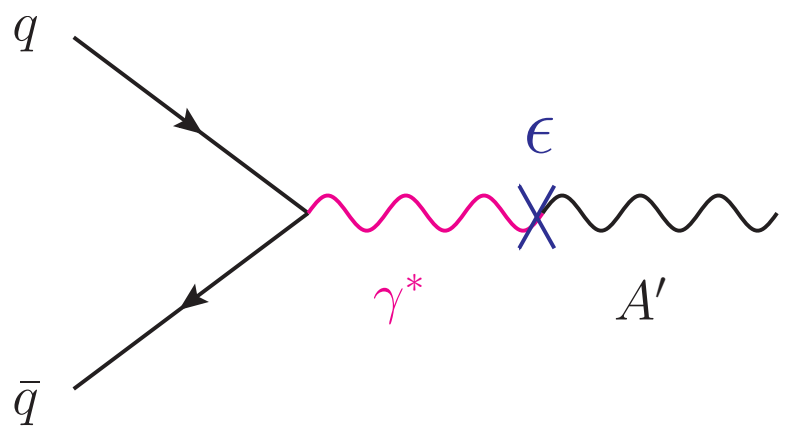


A Great Opportunity

Dark Photons and Dark Higgs Search at SeaQuest

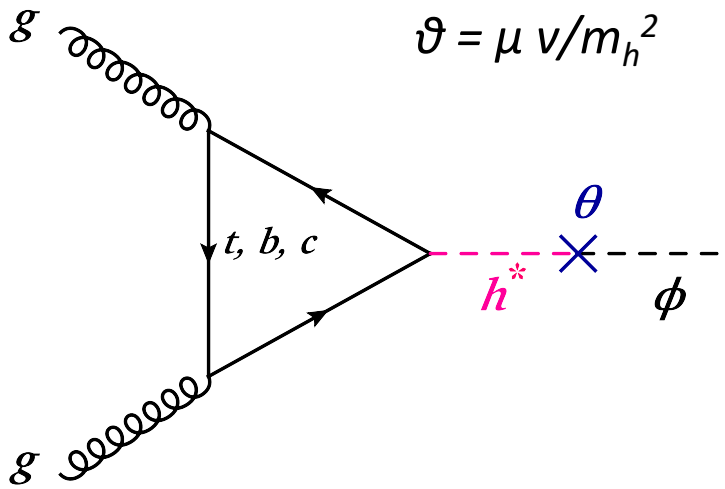
Photon portal: "vector"

$$\mathcal{L}_{\text{mix}} = \frac{\epsilon}{2} F^{\text{QED}}_{\mu\nu} F^{\mu\nu}_{\text{Dark}}$$



Higgs portal: "scalar"

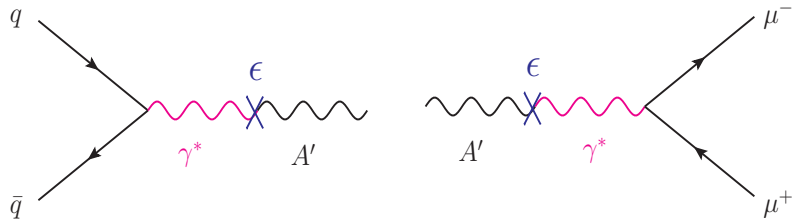
$$\mathcal{L}_{\text{mix}} = \mu\phi|H^\dagger H|$$



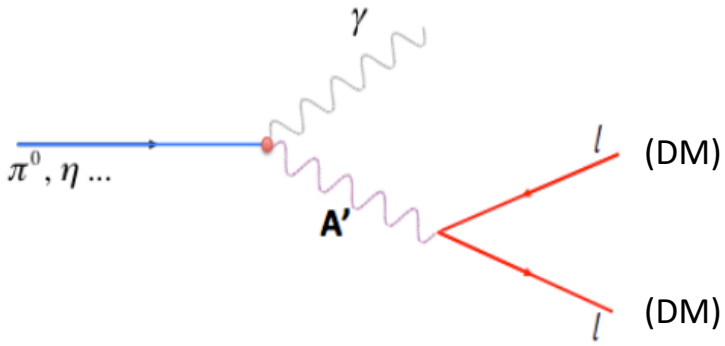
A great advantage for proton beam!

Dark Photon Detection in the Dilepton Channel

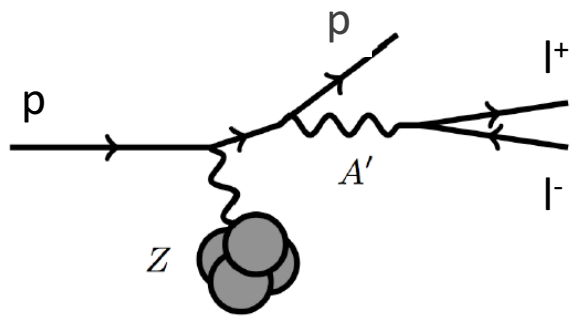
1. Drell-Yan like



2. π^0, η, … decay



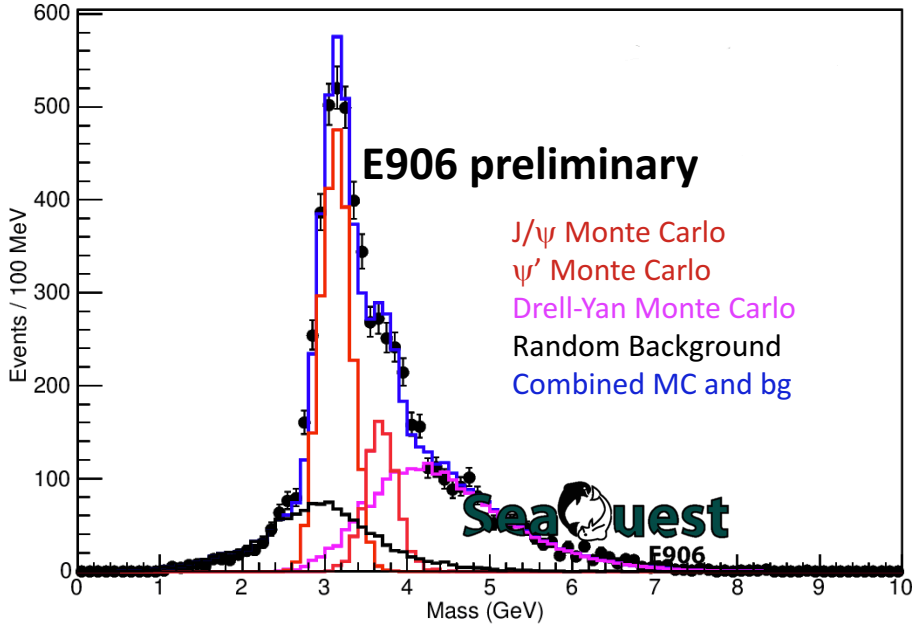
3. Bremsstrahlung



Upgrades Required for Dark Sector Search

Events collected in SeaQuest/E906

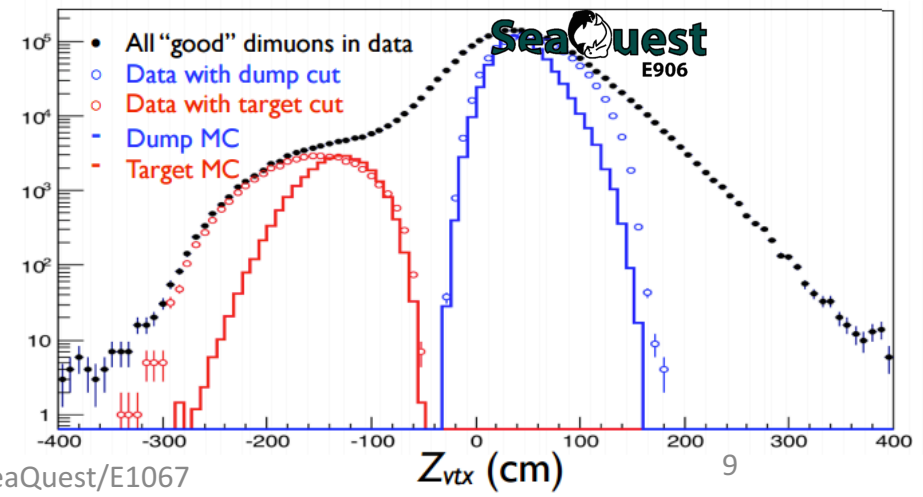
- Invariant mass spectrum from 2015 data
- Data agrees well with Monte Carlo (spectrometer works as expected)
- Data with Mass > 4.2 GeV are mostly dimuons coming from the Drell-Yan process



For Dark Photon Search:

1)DAQ upgrade required to collect low mass dimuons

2)Trigger upgrade for displaced/long-lived particles



Fermilab

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July 15, 2015

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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

A HEART-FULL ENDORSEMENT FROM FERMILAB DIRECTOR AND PAC JULY 15, 2015!

A NEW EXPERIMENT! SEAQUEST/E-1067

Generous LANL LDRD support:

- 2016-2018

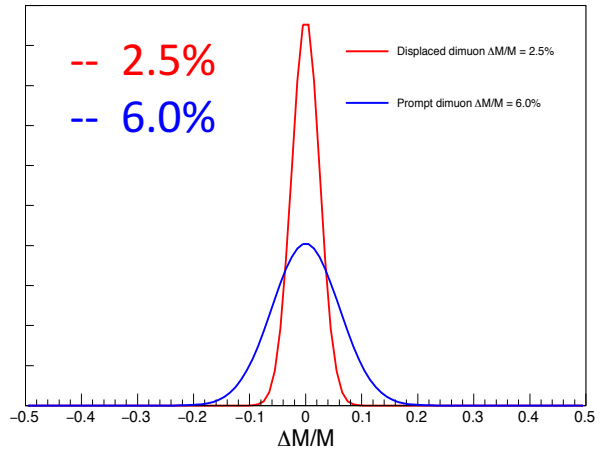
- $1M to implement the trigger/DAQ upgrade and theory development

Goals:

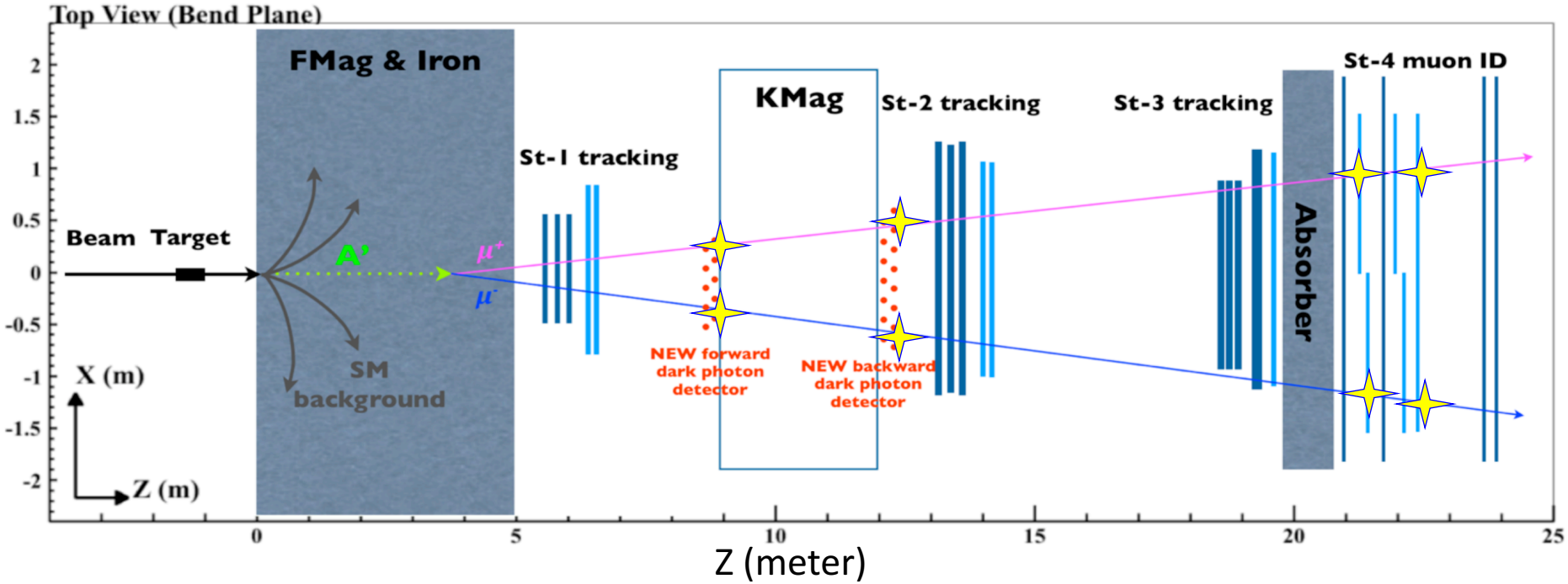
- *Trigger installed, 2017*
- *Physics run, 2017-20*
- *Preliminary results 2018!*

Detector Upgrades and Expected Signals

- Dark photon trigger upgrade
  1. A fine-granularity trigger/tracking to tag dimuons from the same decay Z-vertex
  2. A new trigger for events with displaced down-stream dimuons
- Unique signals
  1. Displaced dimuon decay vertex for long-lived particles
  2. Invariant mass peak in dimuon mass spectrum
- Planned beam time
  1. Run parasitically with E906/E1039 (2017-2020)
  2. Possible dedicated runs later with further upgrade ($e^{+/-}$, $h^{+/-}$)



Dimuon mass resolution

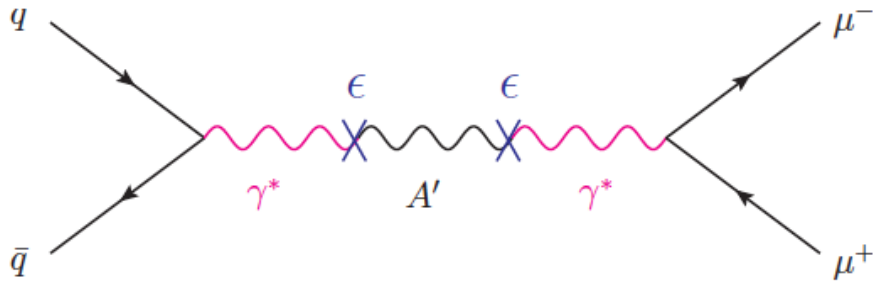


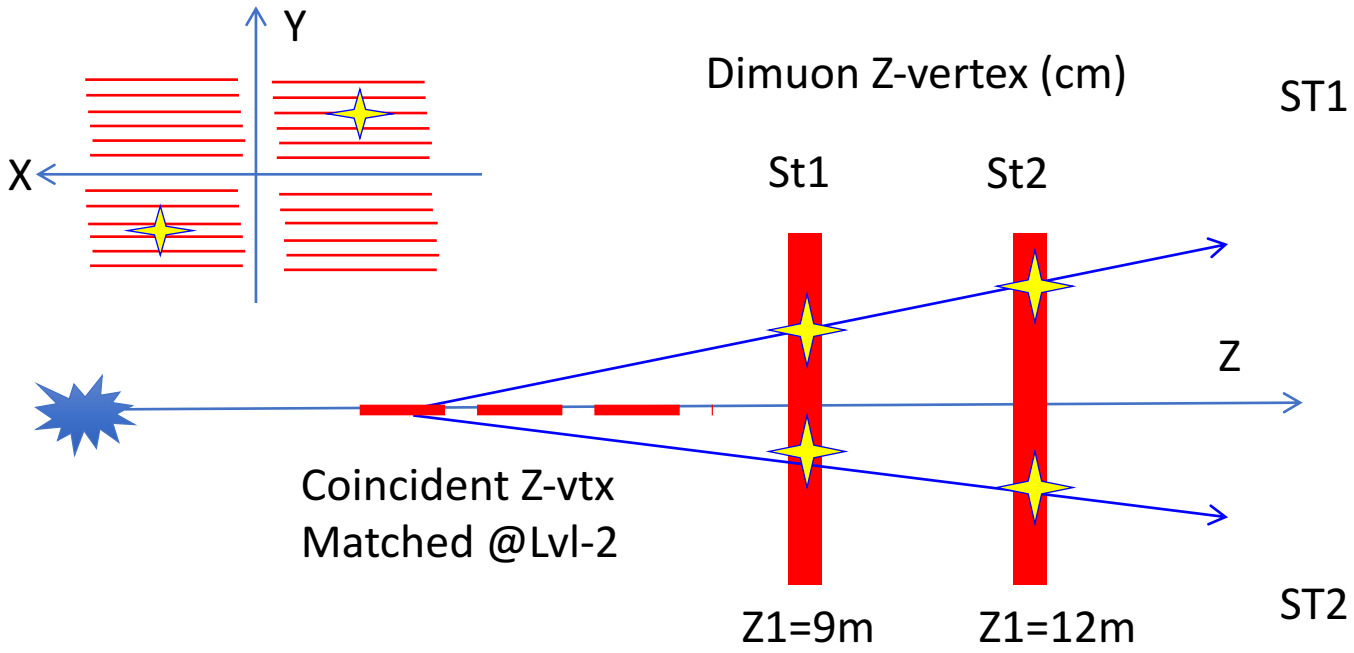
A New High-Granularity Displayed Dark Photon/Higgs Dimuon Vertex Trigger

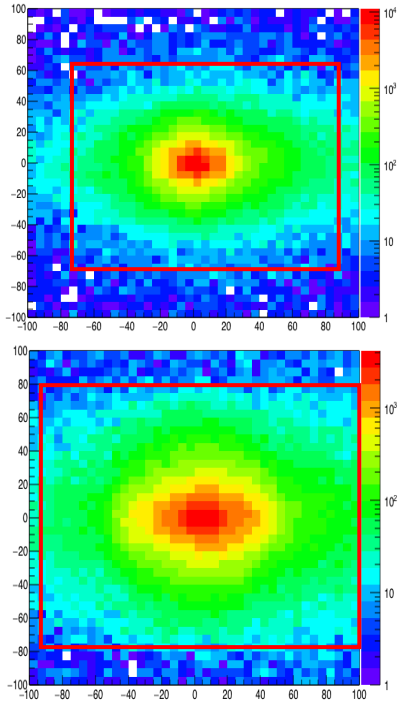
High rejection power, low rate, < 1 kHz (previous E906 DAQ limit)

Y-Plane (non-bending) Trigger:

- A quadrant panel: 80cm x 80cm (100cmx100cm @ST-2)
  - ST1: 1cm x 1cm x 80 cm scintillating strips, SiPM readout
  - ST2: 2cm x 2 cm x 100 cm strips
- Straight line projection, σ_Z ~30cm
- Displaced z-vertex, mostly low mass < 3GeV



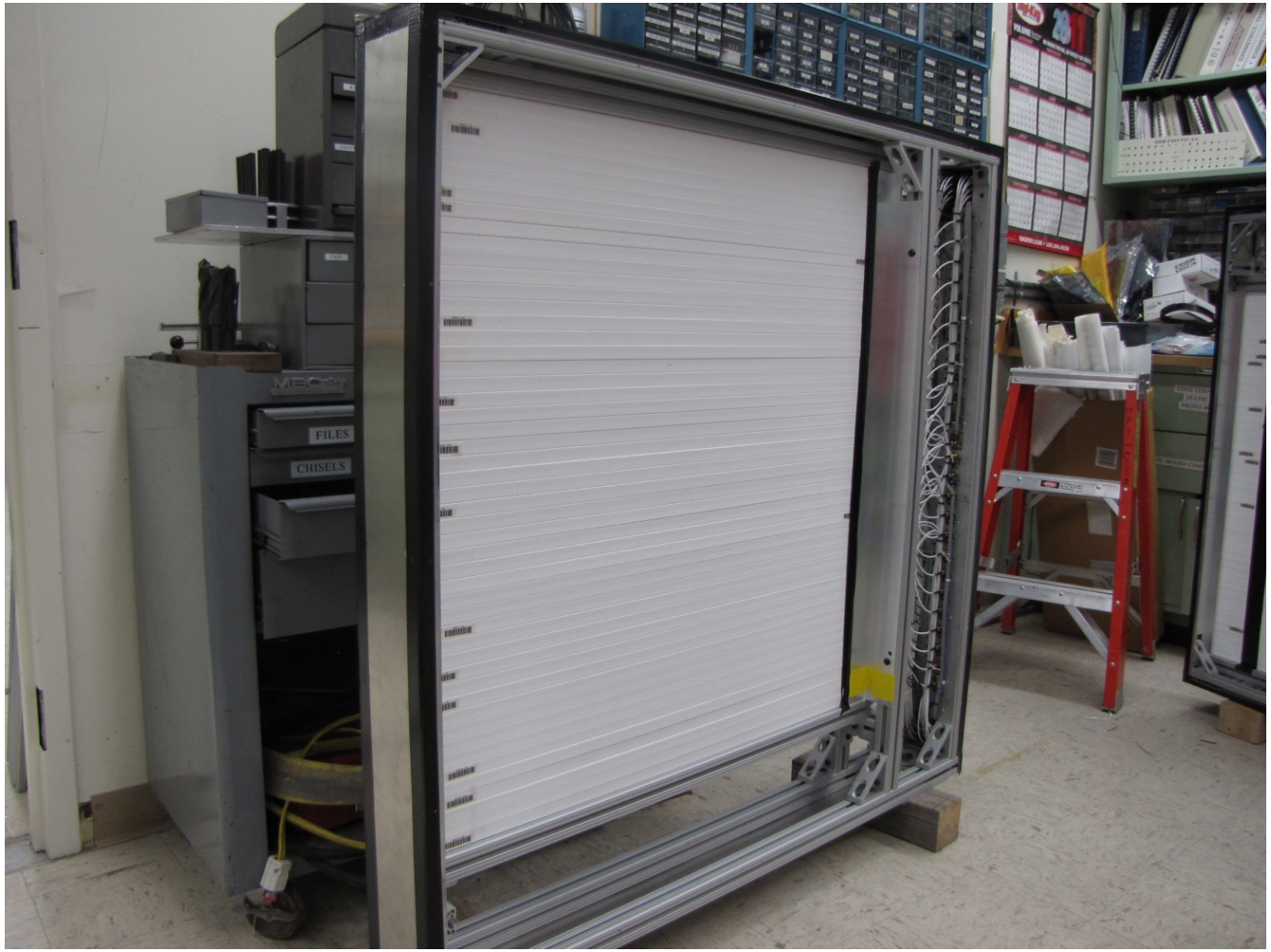




Completed modules, 8 of them in total

Station-1: 1cm scintillators, 80 x 80 cm^2,

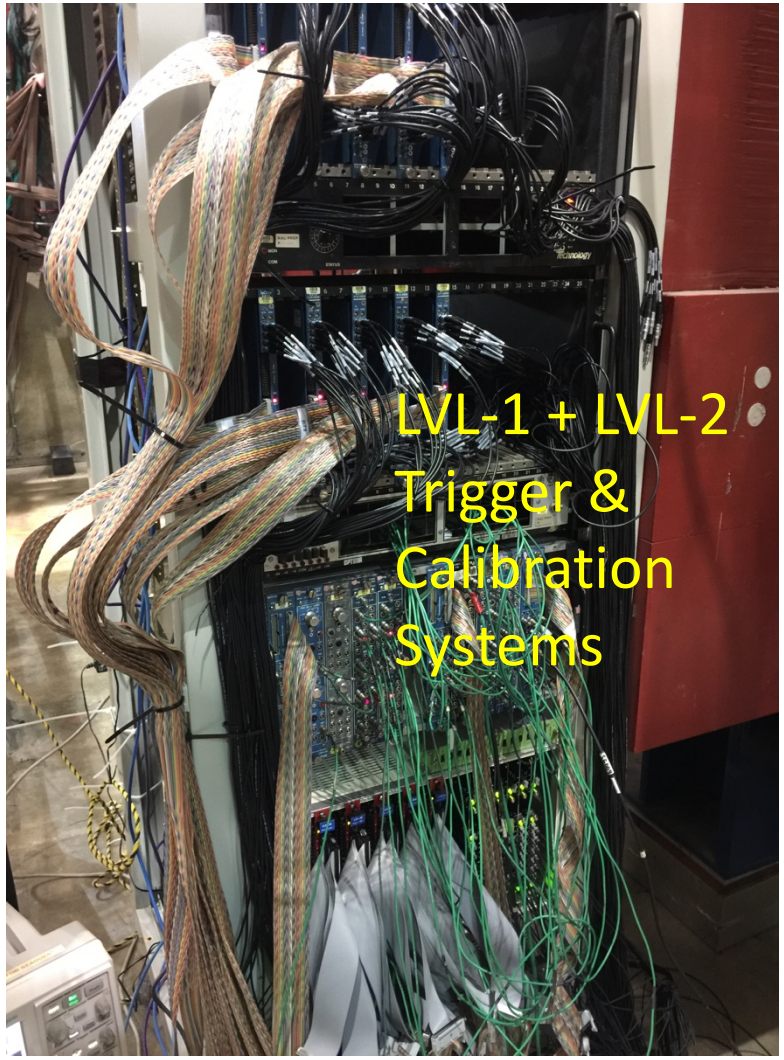
Station-2: 2cm scintillators, 100 x 100 cm^2

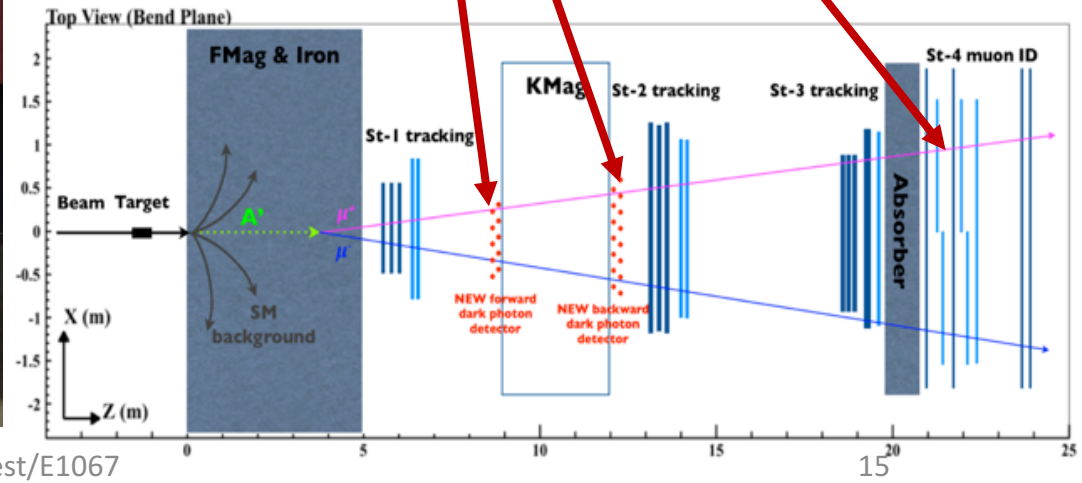


Trigger detectors shipped to Fermilab for installation 4/3/2017

Dark Photon/Higgs Trigger Upgrade Completed in Summer 2017

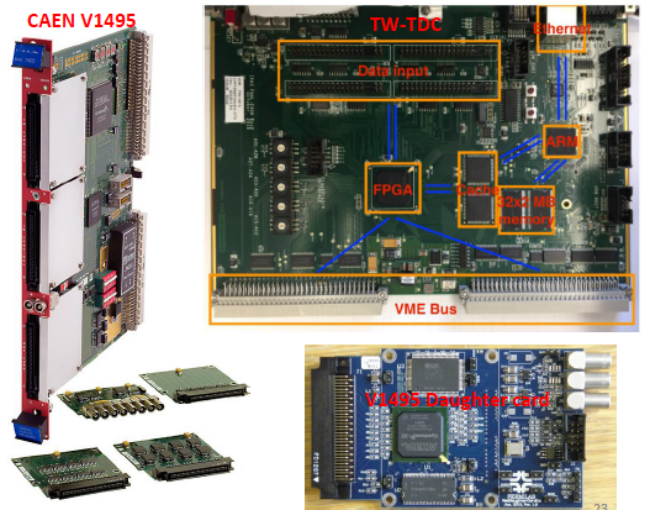
Successfully took 1-week of production data with E906!



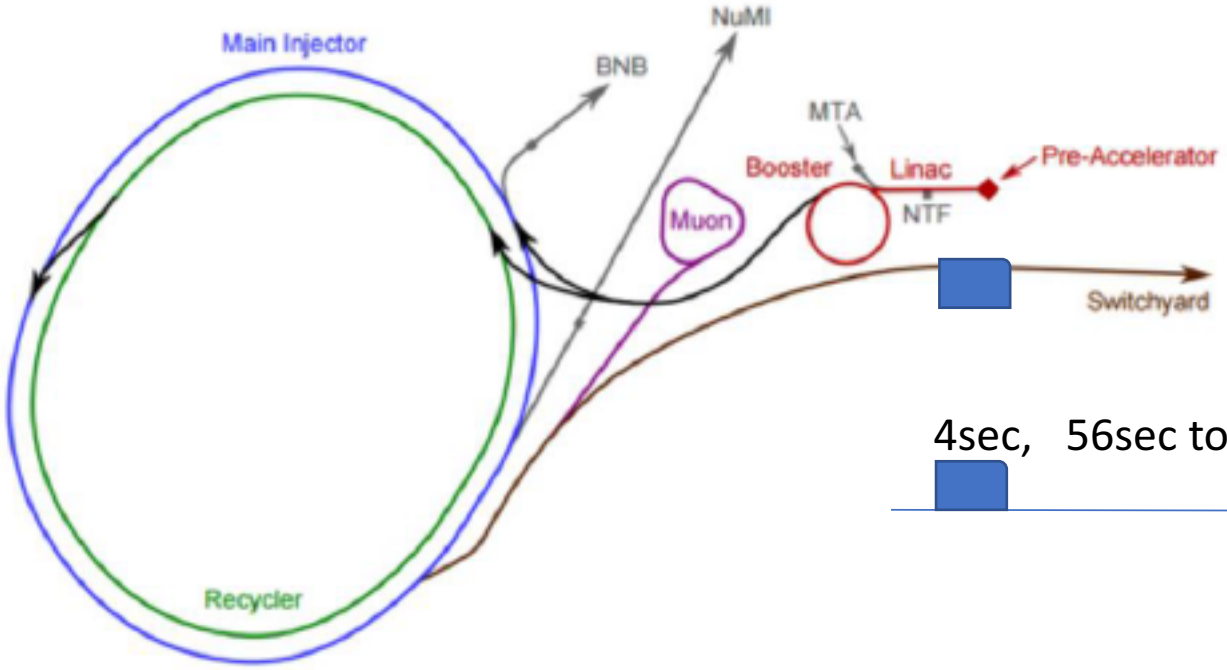


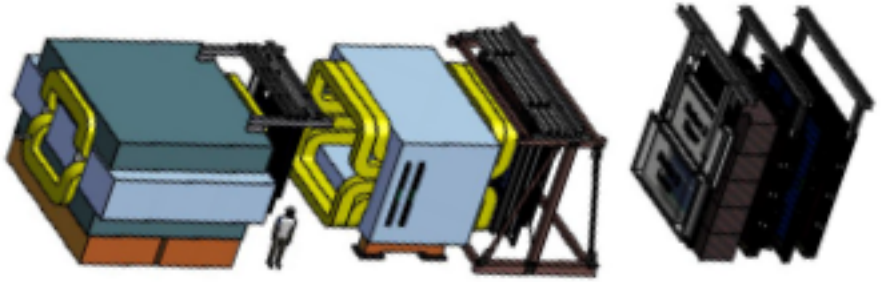
DAQ Upgrade Completed in Early 2017

- Take advantage of beam structure: 4 sec/ 60 sec.
- Locally store data during collisions
  - 10x DAQ improvement



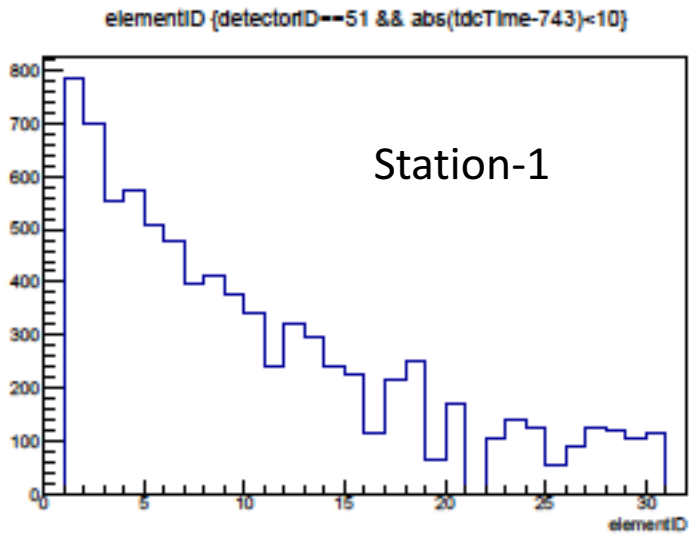
New DAQ boards

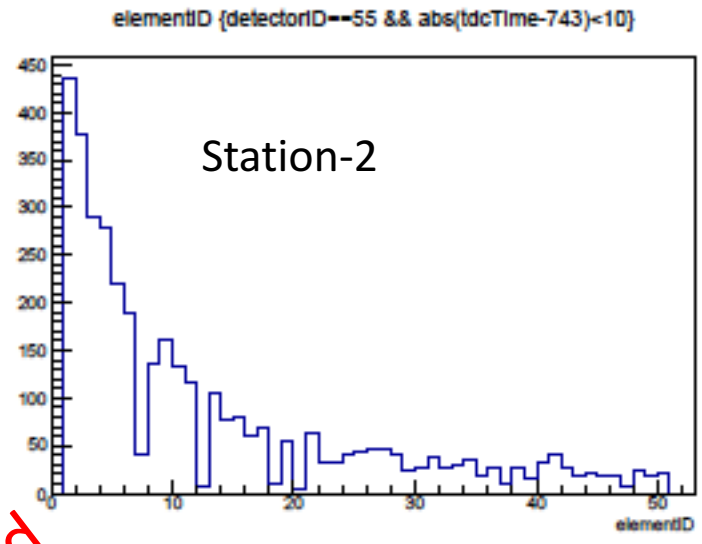




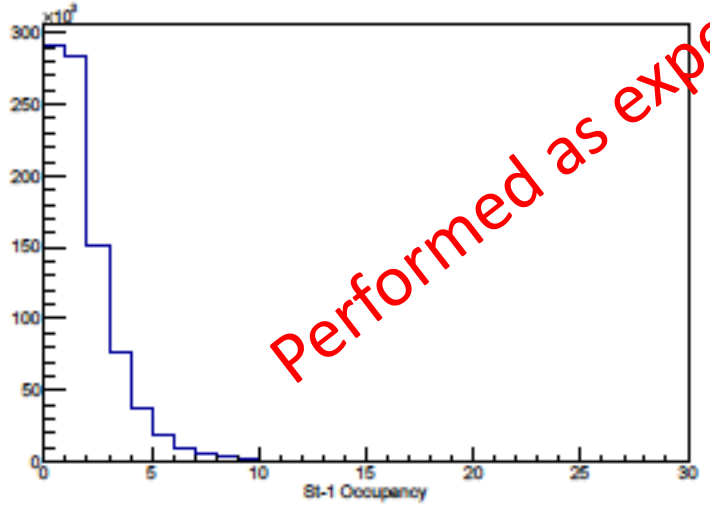
Trigger Detector Performance from 2017 Run

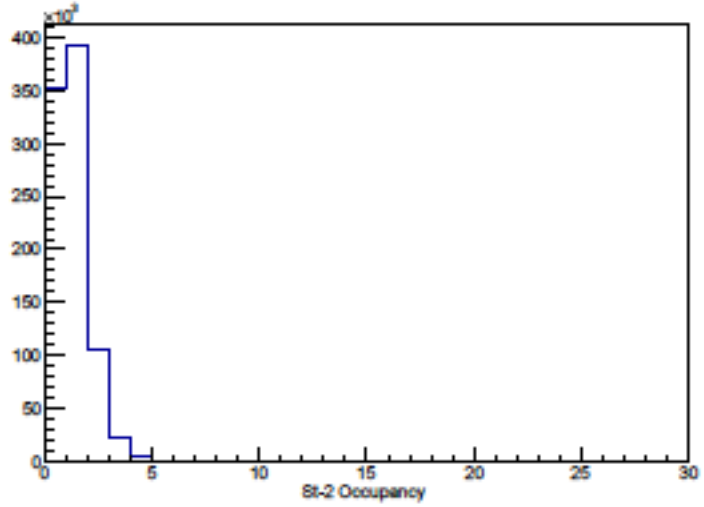
Hit rate vs Channel





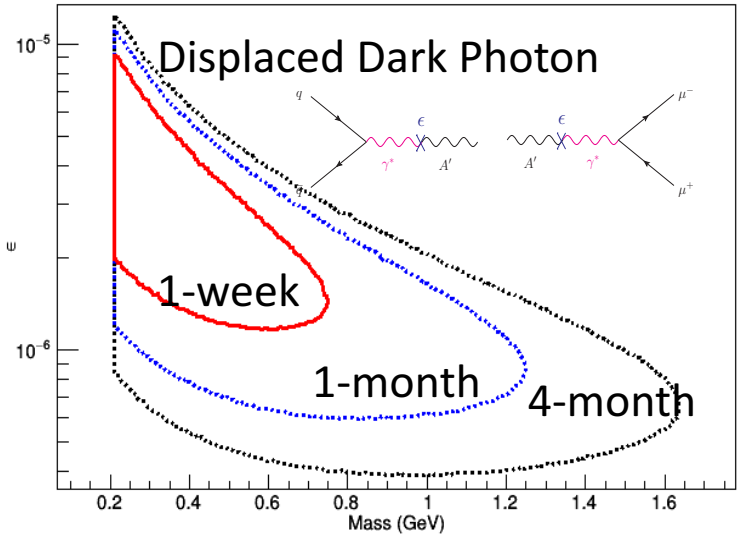
Hit occupancy

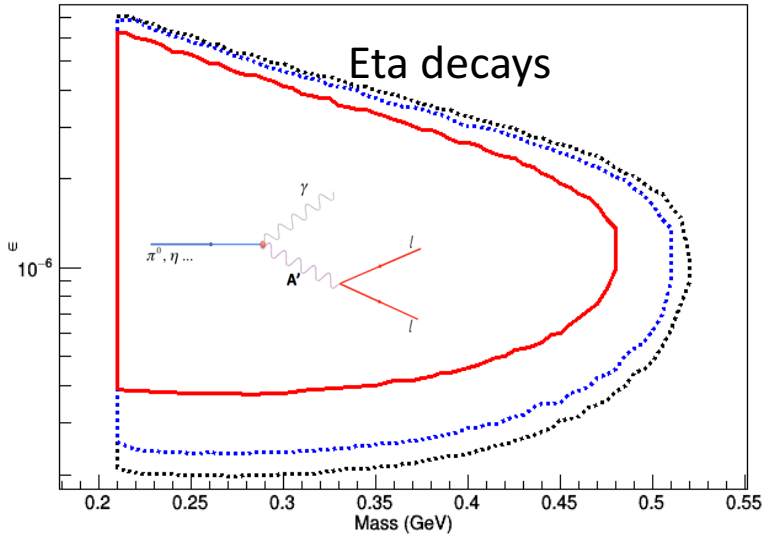


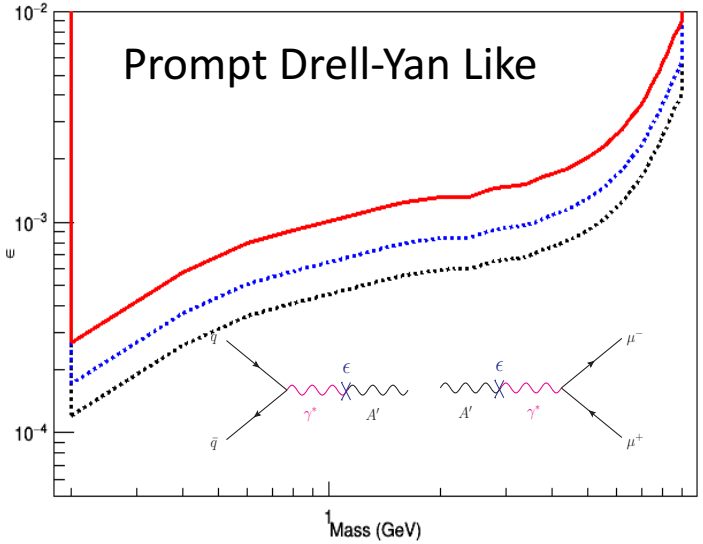


Performed as expected

Expectations from 2017 data … Preliminary results ~2018







Expectation from 2018 run:
The dashed black curve stands for 4 months of data, blue dashed curve stands for 1 month of data, and red curve shows 5 days of existing data.

Full Projections - Dark Photons
(parasitic run w/ E1039: 2018-2020)

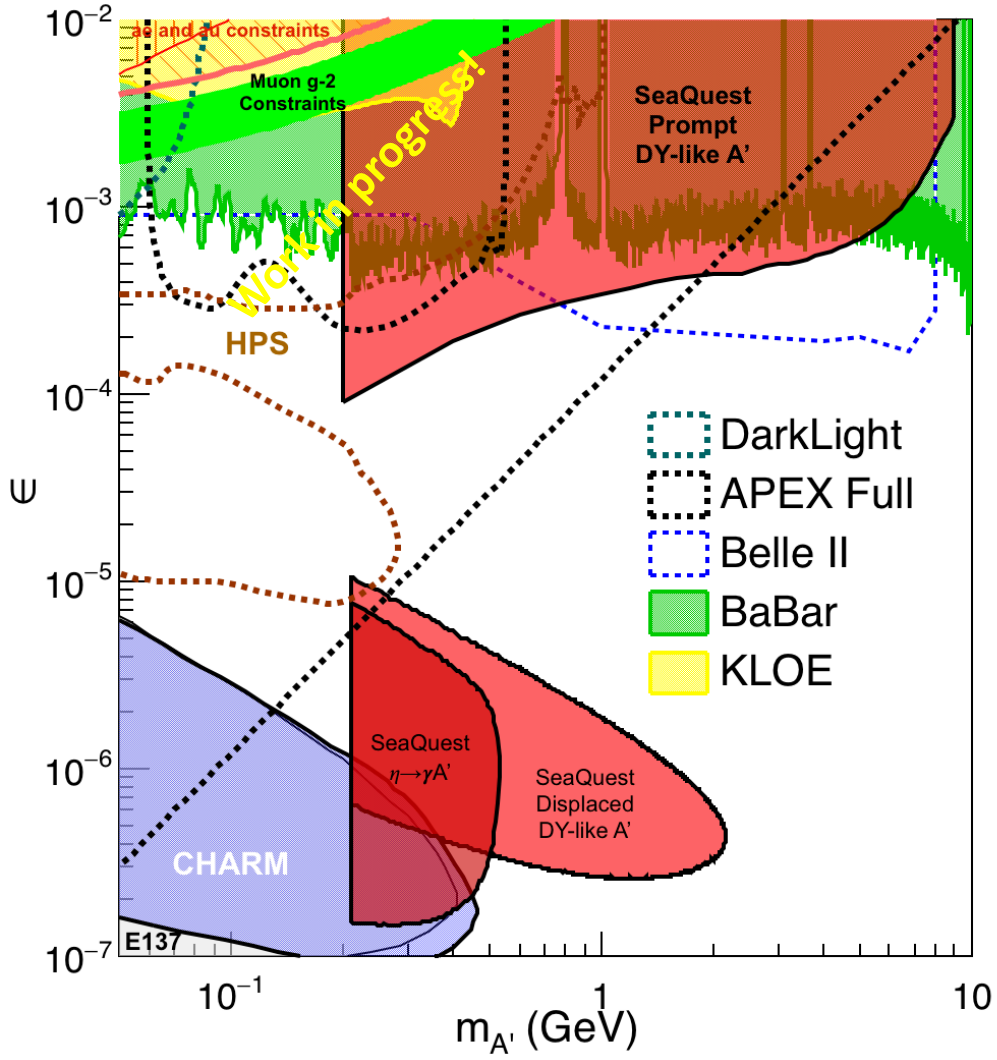
Signals considered:
- Drell-Yan like
- Eta decays
- Bremsstralung

Covers a wide range of unexplored parameter phase space

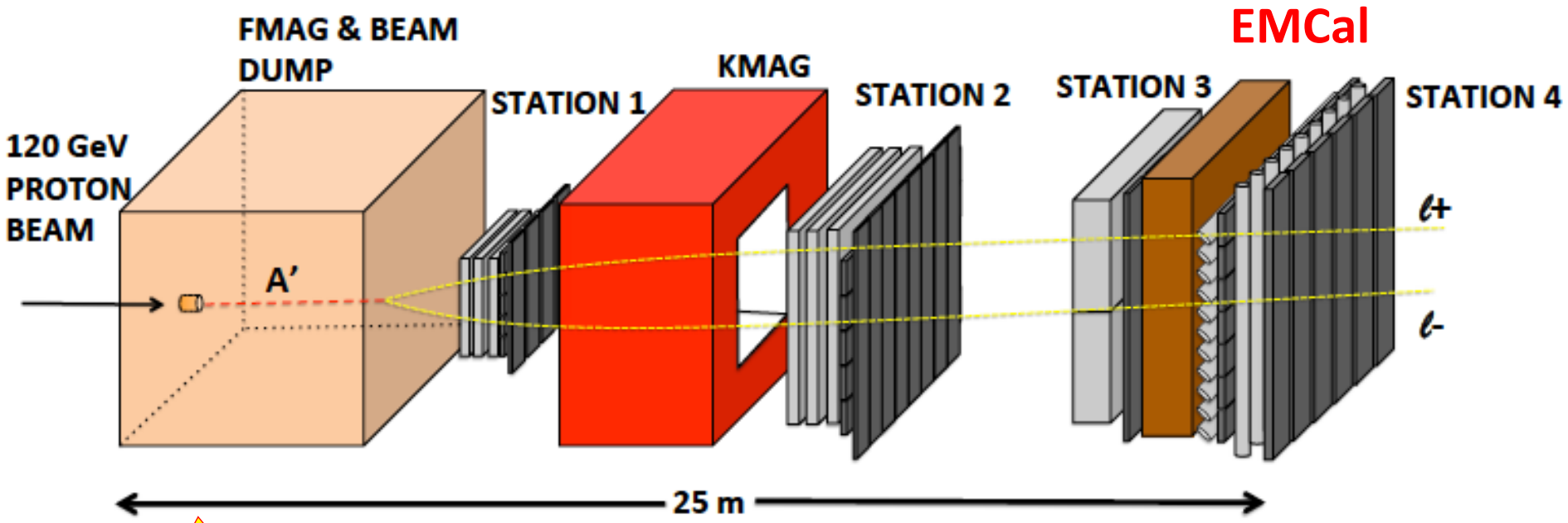
- Displaced dimuons
  - Minimal SM background
- Prompt dimuons
  - Good coverage
  - Possible dedicated runs later to fully restore mass < 3GeV (Phase-II)

Possible EMcal upgrade (a new proposal)

Access below 200MeV with di-electrons



SeaQuest/E-1067 Upgrade Opportunity



$$sig \sim \epsilon^2 \times \sqrt{N_{DY} \times M/\sigma_M^{Det.}}$$

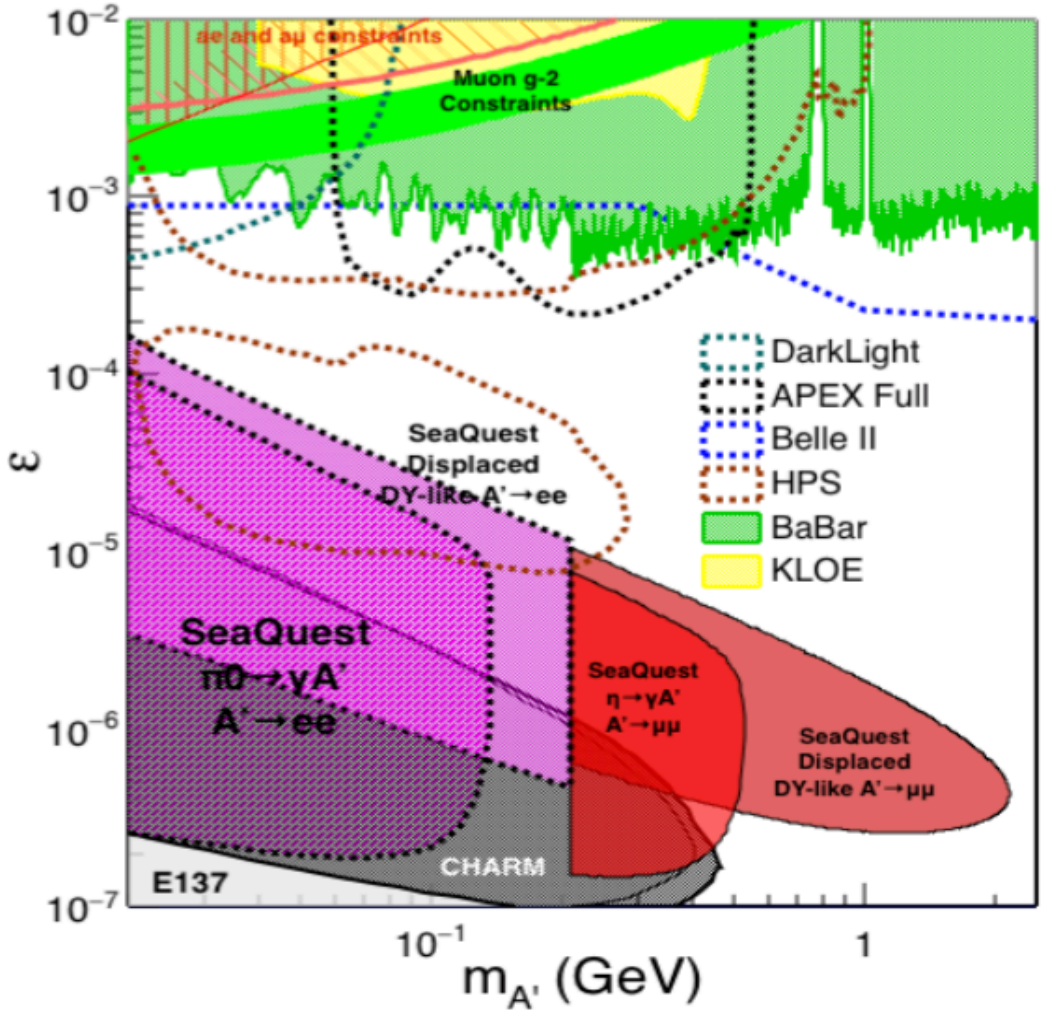
Add tracking detectors close to "target" to improve mass resolution

Add EMCal, PID
$e^{+/-}$, $h^{+/-}$, $\pi^{+/-}$

Displaced Low Mass Dark Photons
with EMCal upgrades

- Detector upgrades
  - EMCal: $e^{+/-}$
  - HCal: $\pi^{+/-}$
  - Recycle from other experiments, PHENIX/RHIC etc.
- Timeline of dedicated runs
  - 2020+
- Detector configuration
  - Access low mass region with optimized FMag settting

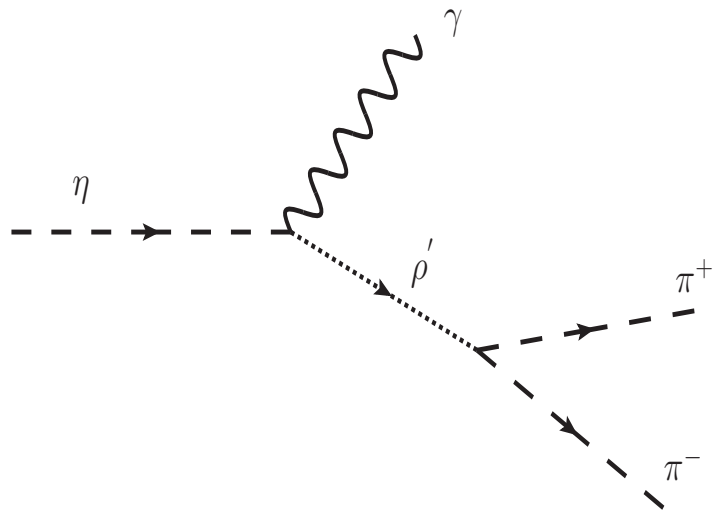
Projection: POT 1.4 x 10^{18}

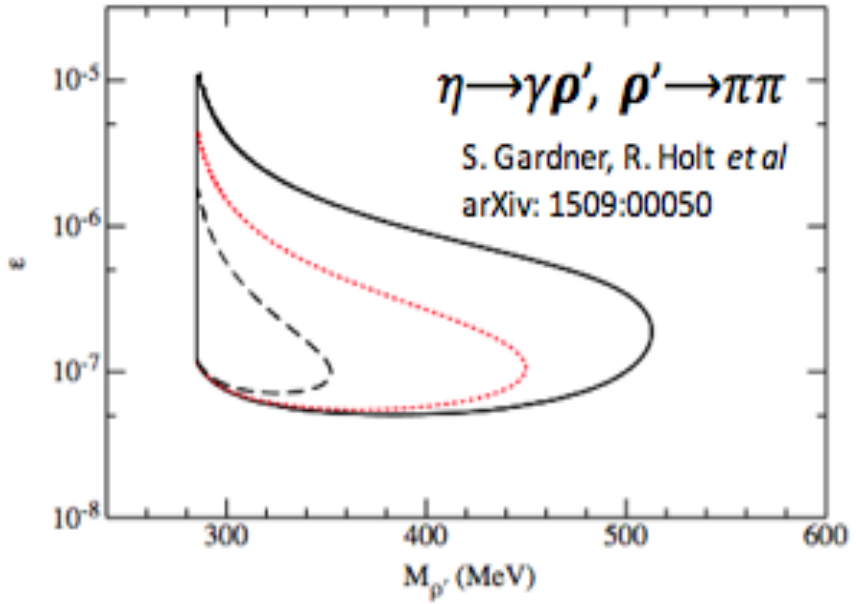


EMCal Upgrade: More Physics

- EMCal opens up:
  - dark ρ decays to $\pi\pi$
  - enhanced dark higgs sensitivity
  - SIMP, "dark QCD-like" etc.

- Potential bonus of better background rejection on trigger level (studies underway).

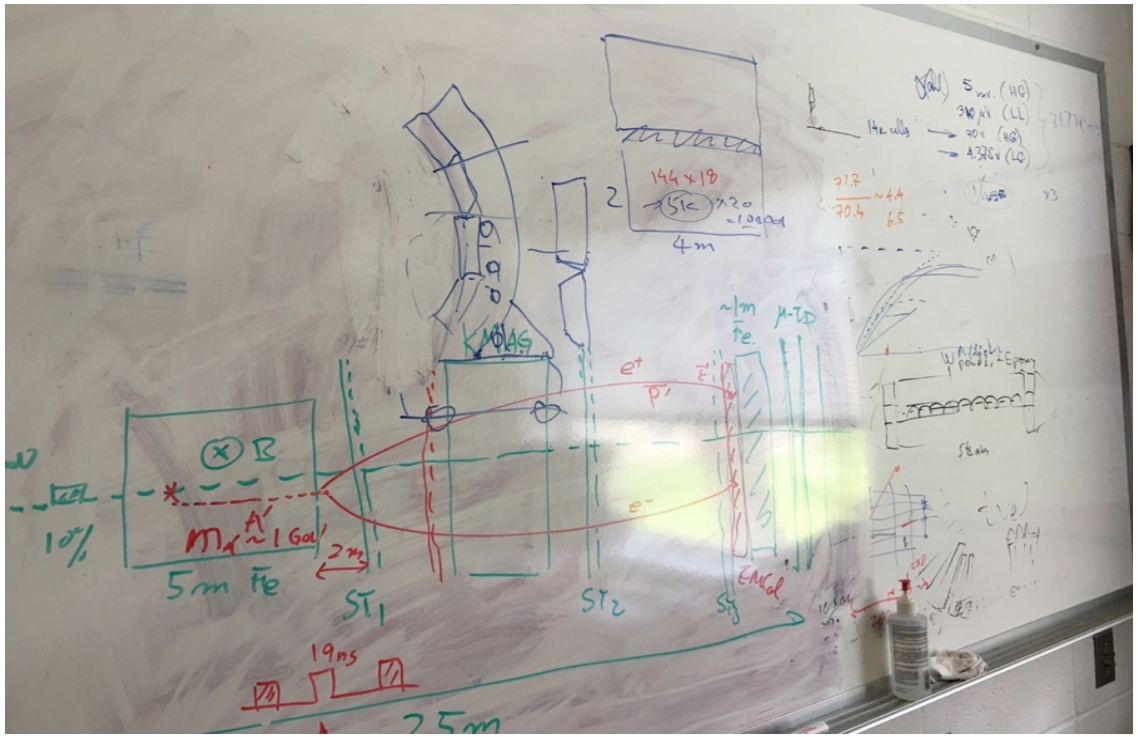




EMCal Identified & DOE Approved!

- Two EMCal sectors are available from PHENIX experiment at RHIC, ~April of 2018

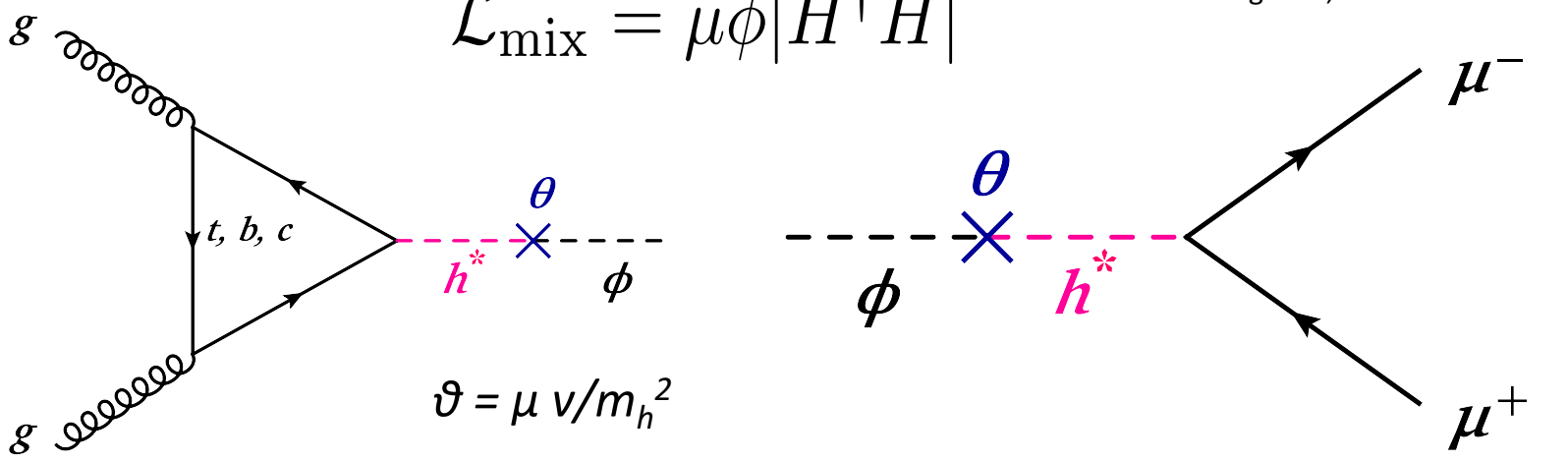
- dE/E = 8.1%/sqrt(E) + 2.1%
- dT < 200 ps
- Excellent e/pi separation



Dark Higgs!

$$\mathcal{L}_{\rm mix} = \mu\phi|H^\dagger H|$$

Y. Zhang et al, arXiv:1502.06983



$\vartheta = \mu\, v/m_h^2$

$$\sigma(p+p\to\phi+X) = \int_0^1 \frac{dx}{x} g(x) g\left(m_\phi^2/(xs)\right) \frac{\alpha_s^2 G_F m_\phi^2}{288\sqrt{2}\pi s}$$

Phase-I:

High-mass: $\mu^+\mu^-$ and hadrons

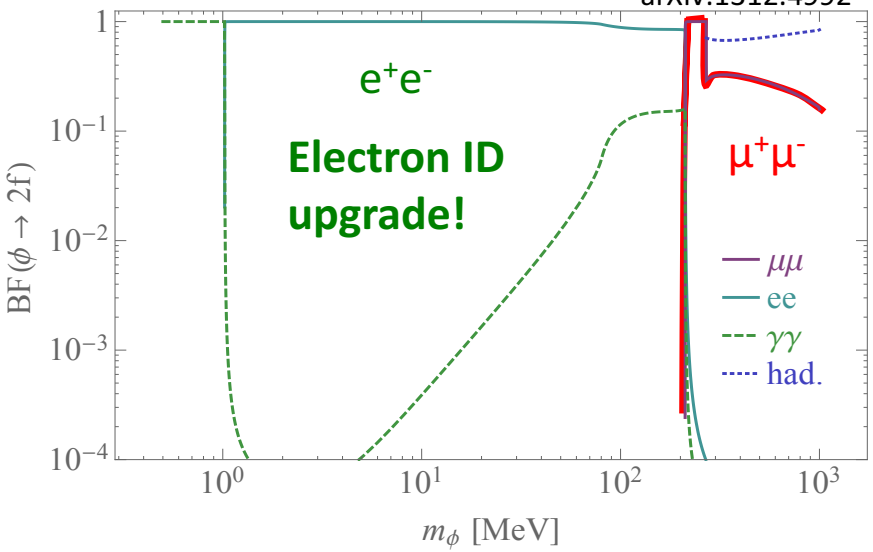
Advantage of using hadron beams with muon probes over electrons

Phase-II:

Low-mass: e^+e^-, <200MeV possible

High-mass: hadrons, (5x)

arXiv:1312.4992

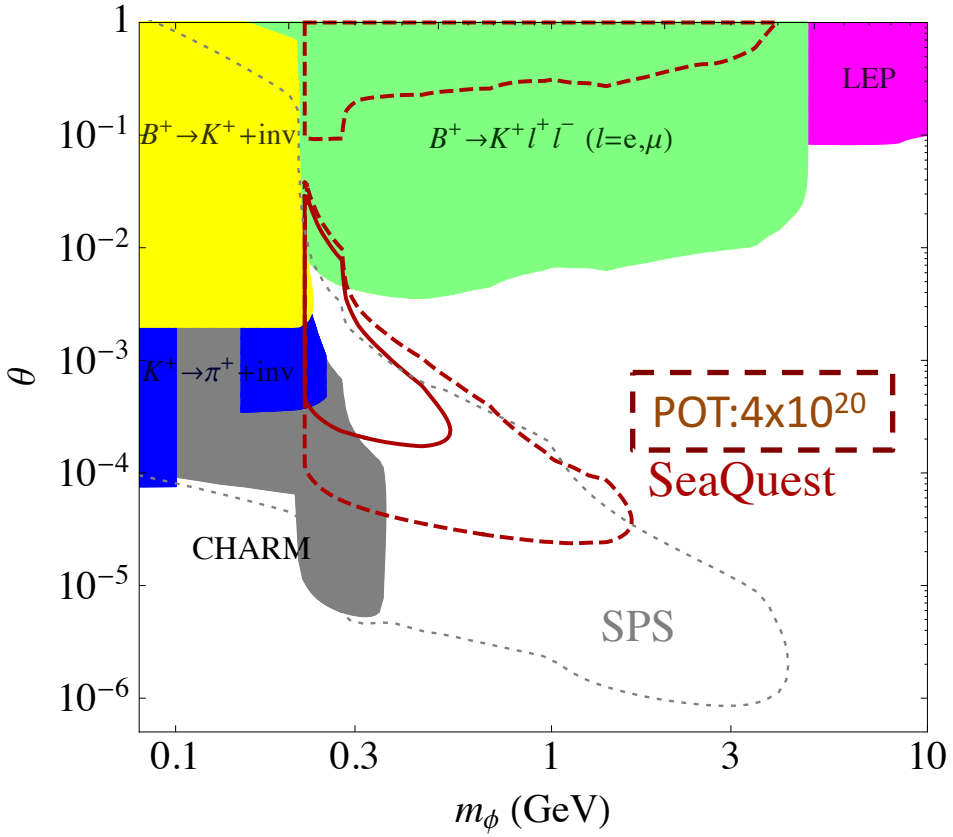


Projected Dark Higgs Sensitivity

POT:1.4x10^{18} (Phase-I)

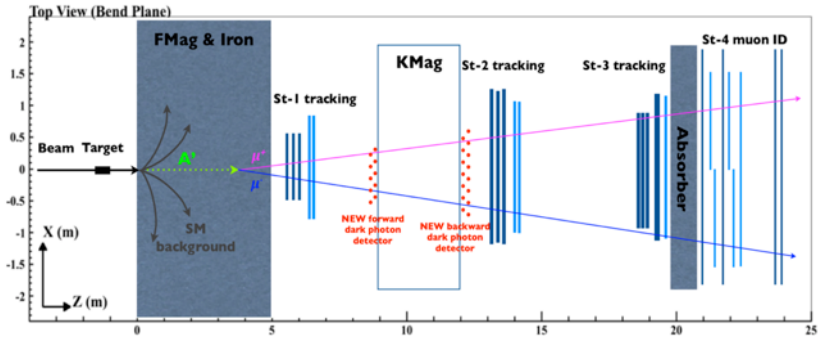
- Dimuons with downstream displaced decay vertices
- Limited sensitivity to “prompt” large mixing case due to small cross-section
- Dark Higgs or dark photons?
  - Dimuon kinematic and angular distributions

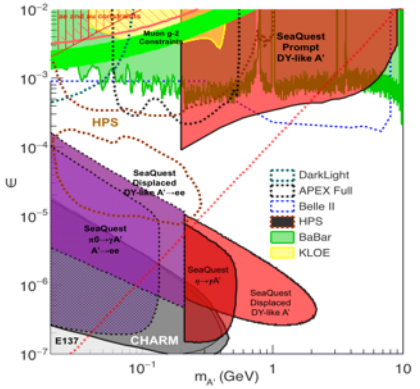
Y. Zhang (2015)

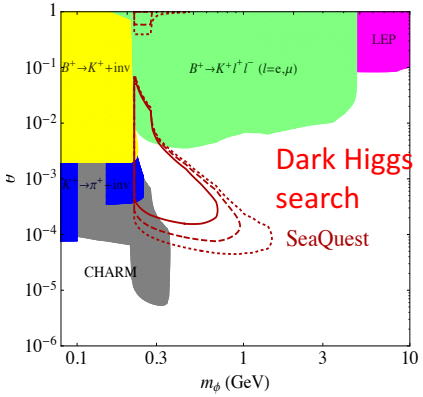


SeaQuest/E1067 Summary and Outlook

- **2017**
  - **Successfully completed Trigger and DAQ Upgrade**
  - **Successfully took production data parasitically with E906**
  - **Data analysis in progress**
  - **Ready for full data taking with E1039**
- **2018**
  - **Take more data parasitically with Polarized Drell-Yan experiment E1039**
  - **First preliminary search results**

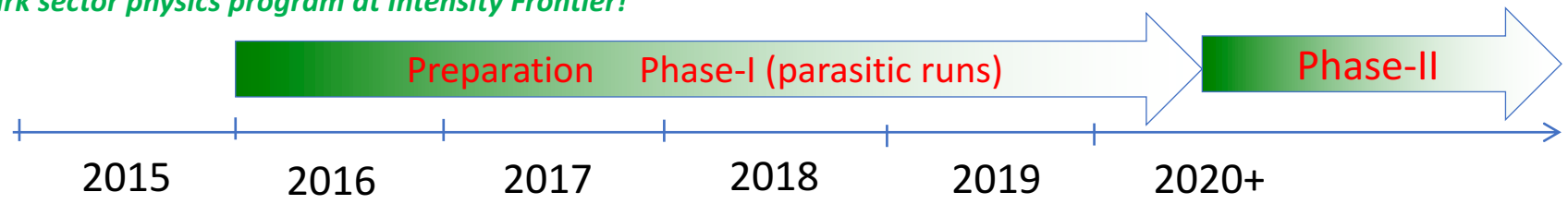






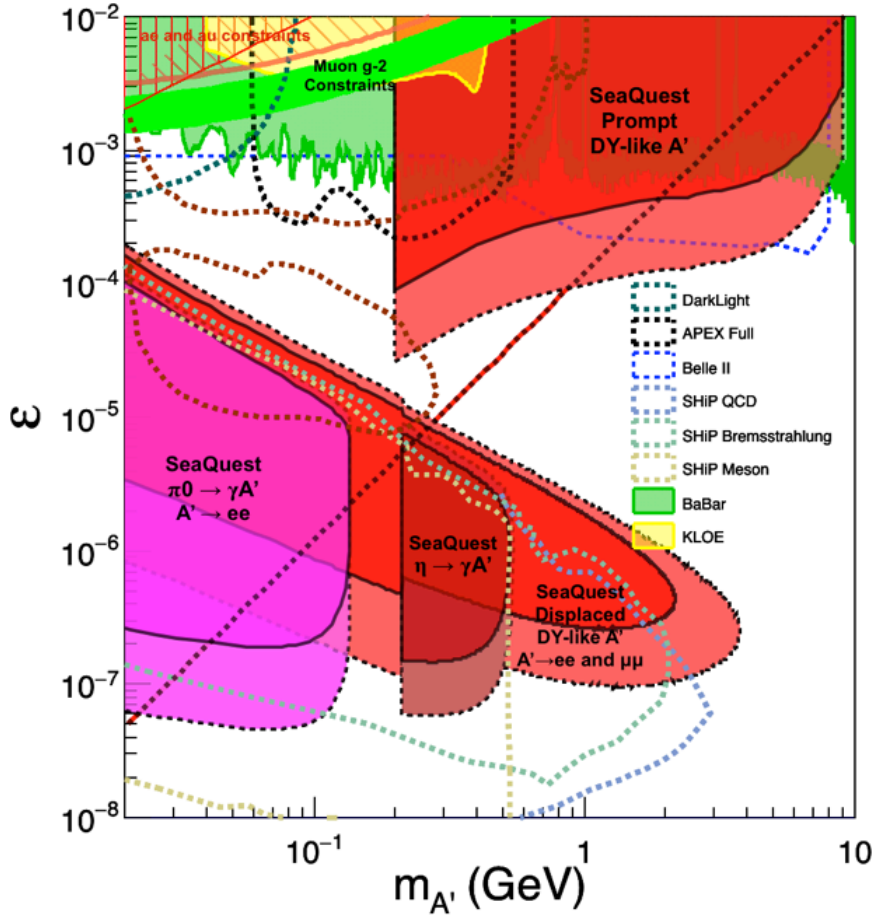
Fermilab dark sector physics program @Seaquest/E1067:

- ***Phase-I (2017-2020)***
  - ***Great discovery potential!***
  - ***Parasitic data taking with E906/E1039, 2017-2020***
  - ***POT 1.4 x10^{18} or more***
  - ***Possible detector upgrade, add electron and hadron capability***
- ***Phase-II (2020-2025+)***
  - ***A dedicated dark sector physics program at Intensity Frontier!***

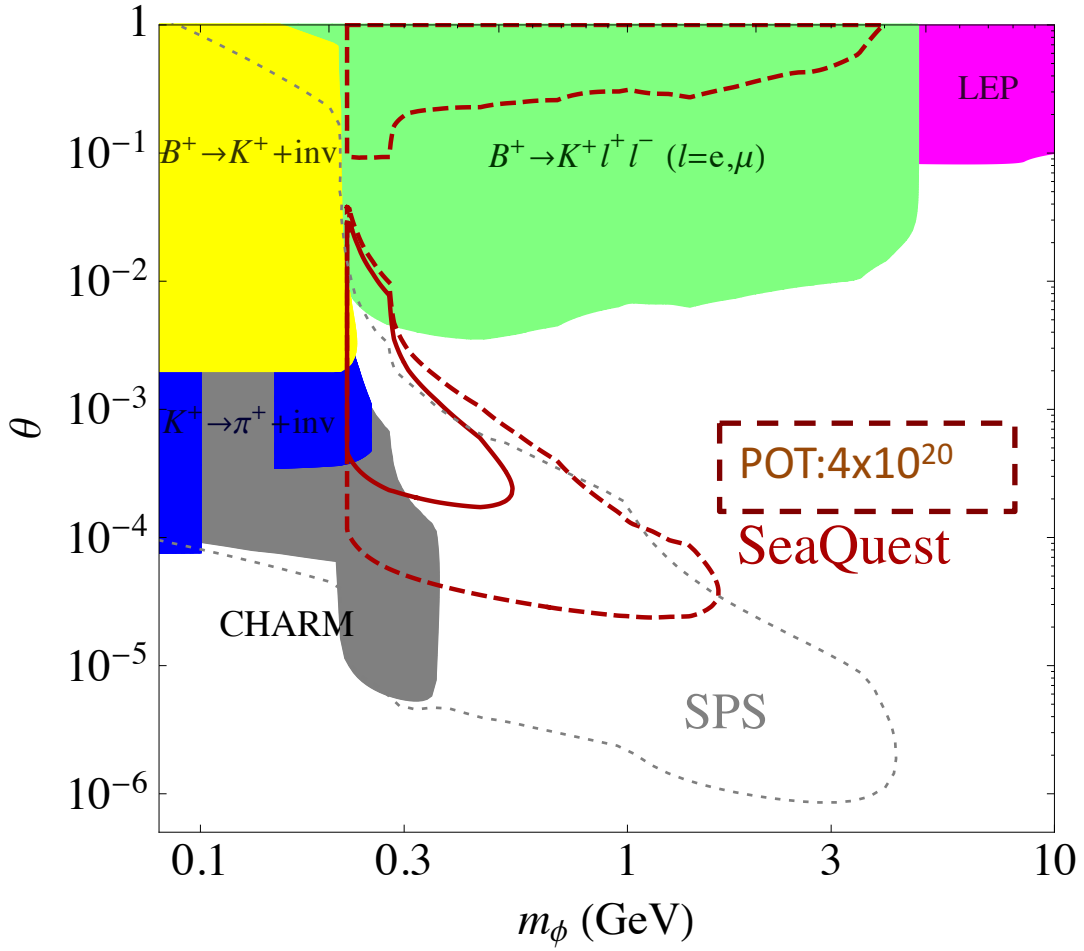


Comparison with SHiP Proposal

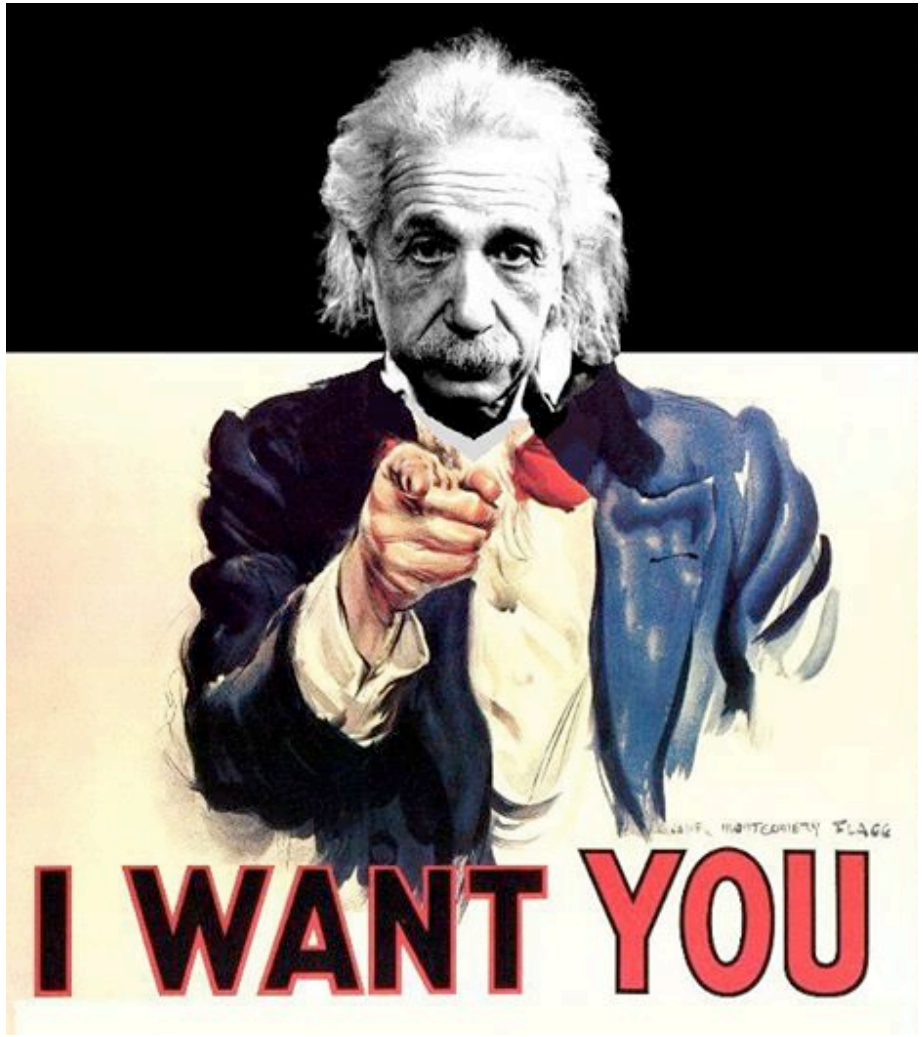
120 GeV@FNAL: 2018 -2020
1.4x10^{18} POT or more, future dedicated runs
Phase-II: 2020-2025+, POT: 4x10^{20}



400 GeV@SPS: 2025 -2030
4x10^{20} POT



Come to Join Us!



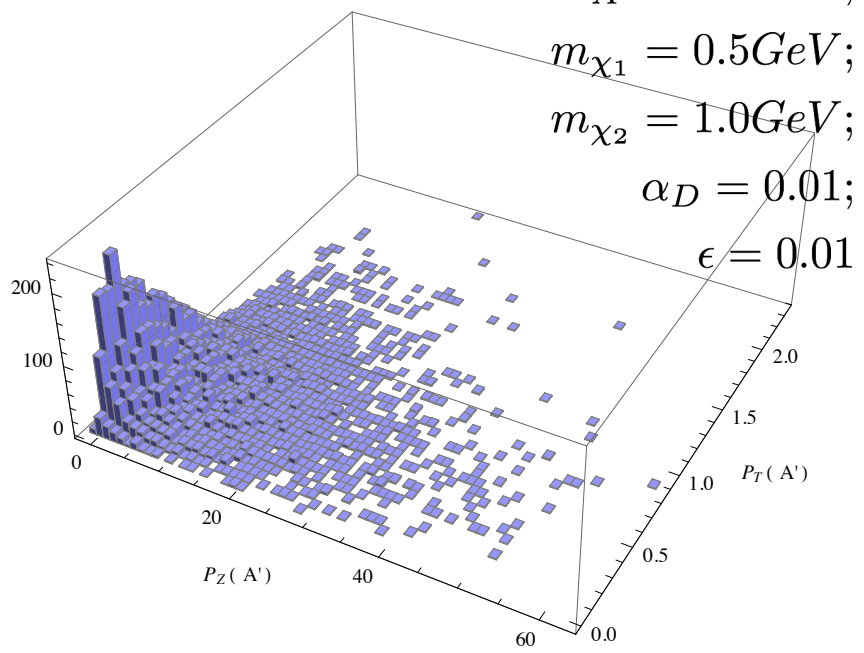
backup

Beyond Exclusive Channels

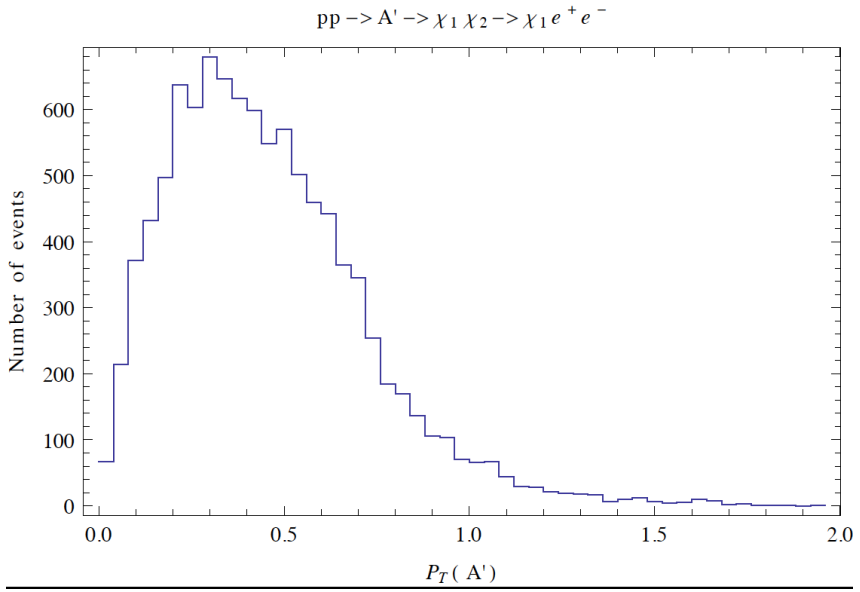
possible missing pT measurements being explored

$$pp \rightarrow A' \rightarrow \chi_1 \chi_2 \rightarrow \chi_1 e^+ e^-$$

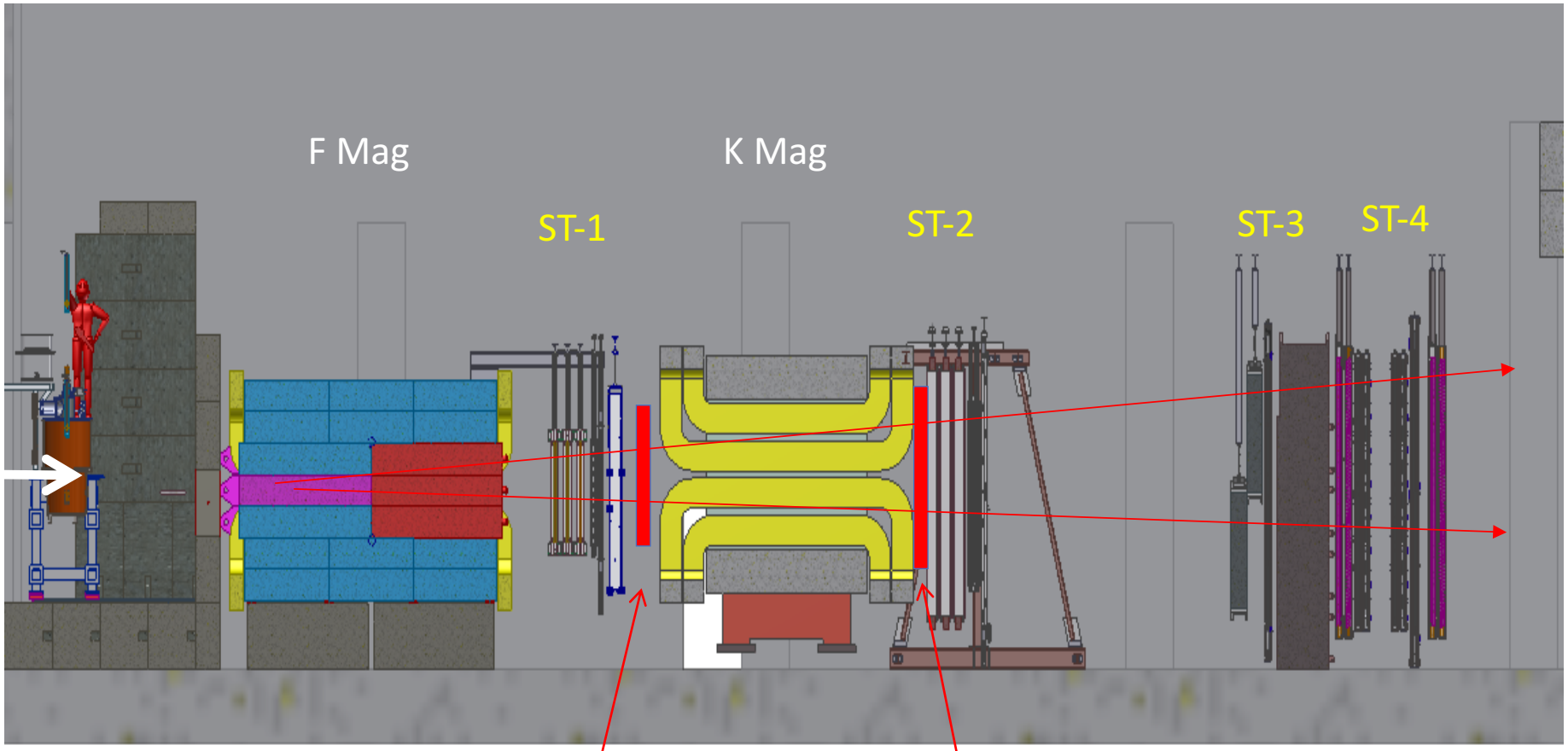
$$m_{A'} = 0.1GeV;$$
$$m_{\chi_1} = 0.5GeV;$$
$$m_{\chi_2} = 1.0GeV;$$
$$\alpha_D = 0.01;$$
$$\epsilon = 0.01$$



Chien-Yi Chen, 2017



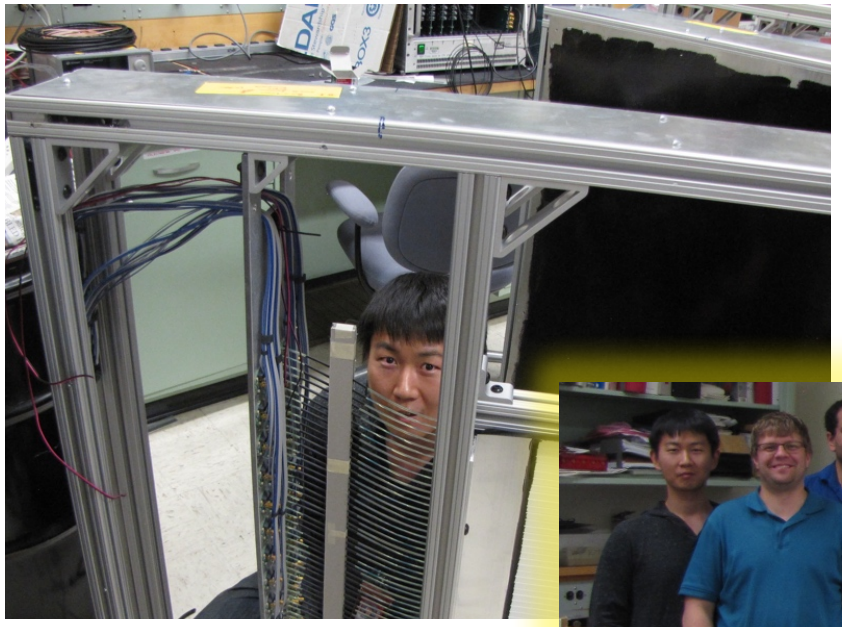
Side View of the Upgraded SeaQuest Experiment



St-1 trigger plane, 160 x 160 cm
Made of 4 1cm x 1cm x 80cm
scintillator planes

St-2 trigger plane, 200 cm x 200 cm
Made of 4 2cm x 2cm x 100cm
scintillator planes

Very Successful Team Work!

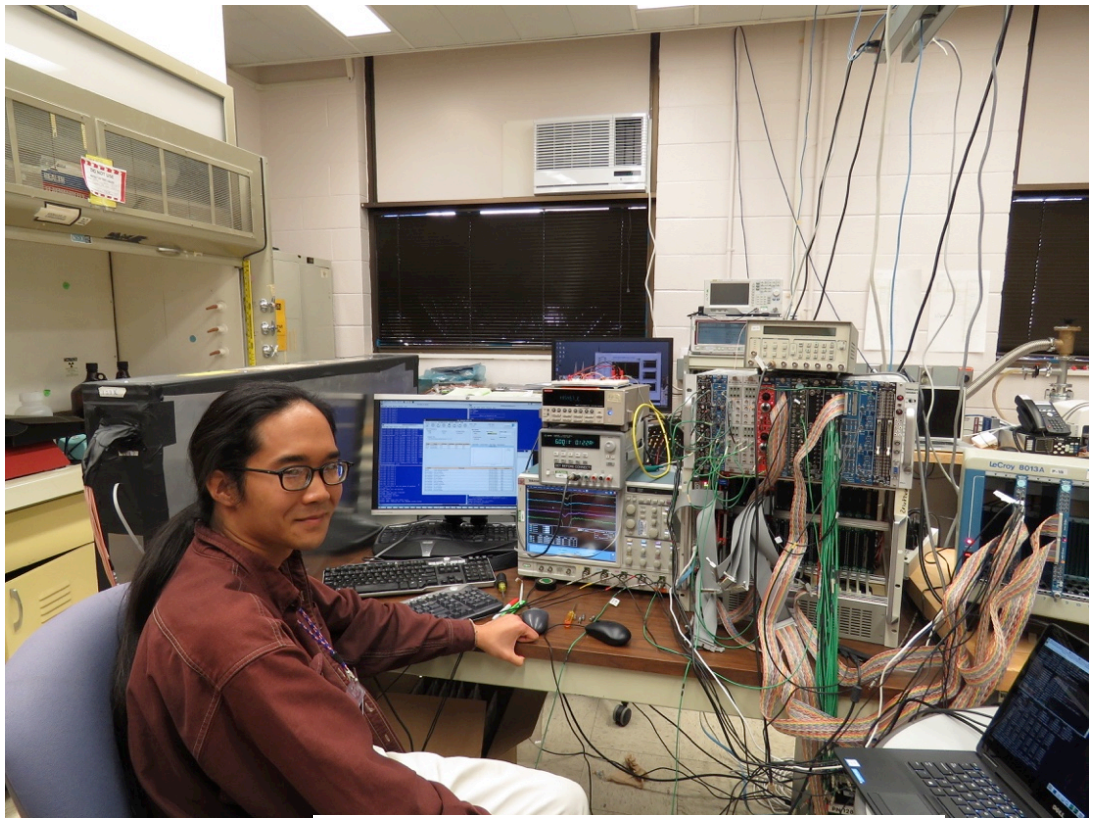


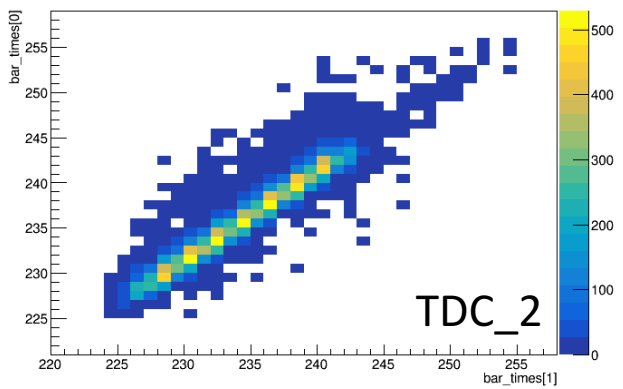
Trigger, DAQ R&D and Final Cosmic Test @LANL in 2017

- Trigger & DAQ hardware and firmware designed and tested at LANL, in collaboration with Fermilab Engineers
- Readout from a full module for cosmic test
  - Full SiPM readout and Trigger
  - E906 upgraded DAQ and firmware

Timing resolution, < 1.5nS (19nS RF)

Detector eff. > 96%



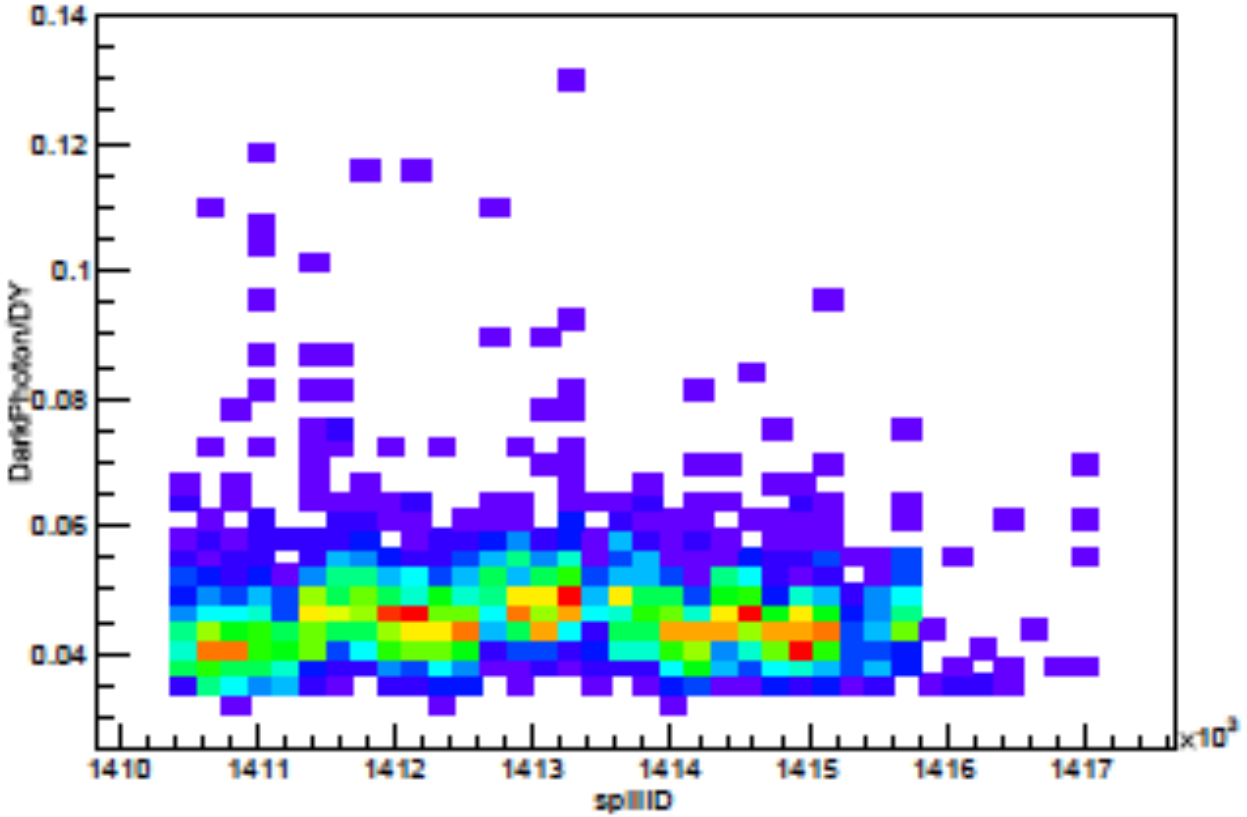


All Trigger Detectors Designed and Built at LANL, Truck loaded to Fermilab on 4/3/2017

- Eight trigger detector modules
- Electronics and Power supplies

New trigger rate: ~5%DAQ

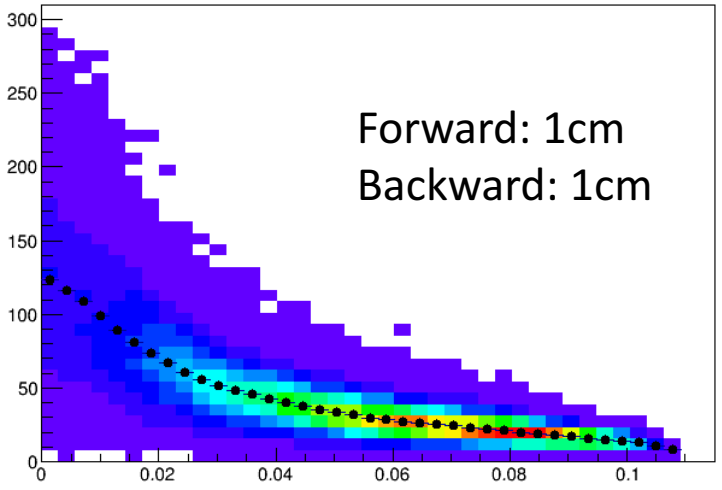
Parasitic run OK!

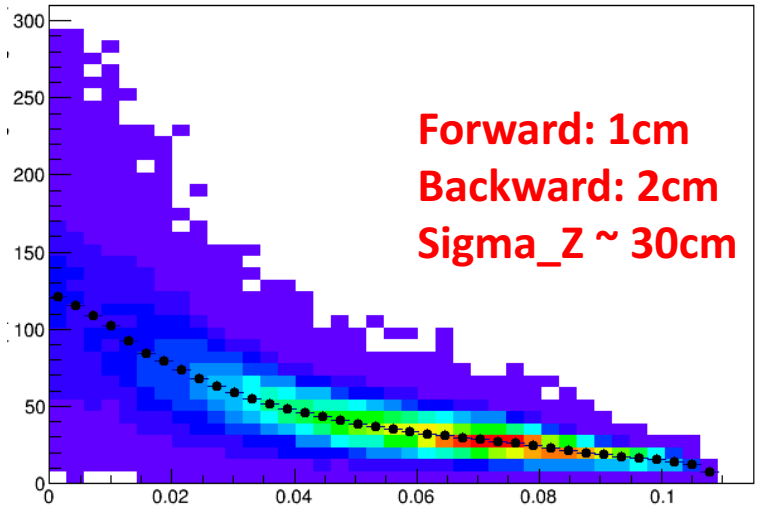


Trigger Scintillator Size Optimization

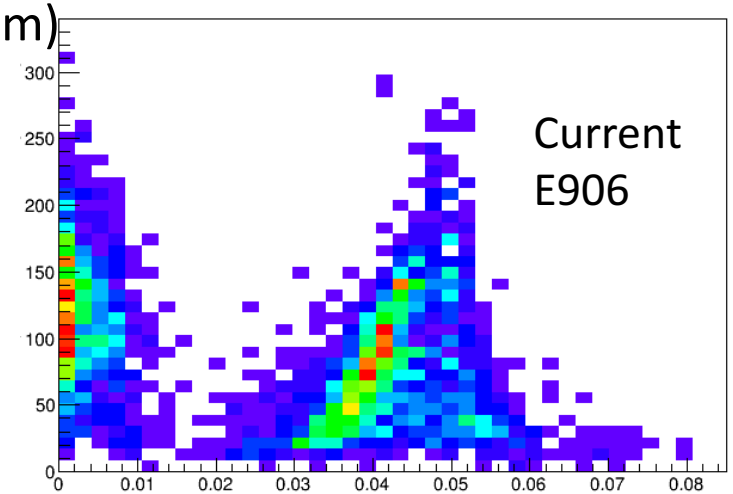
Single Muon Z-Vertex Resolution

σ_Z (cm)

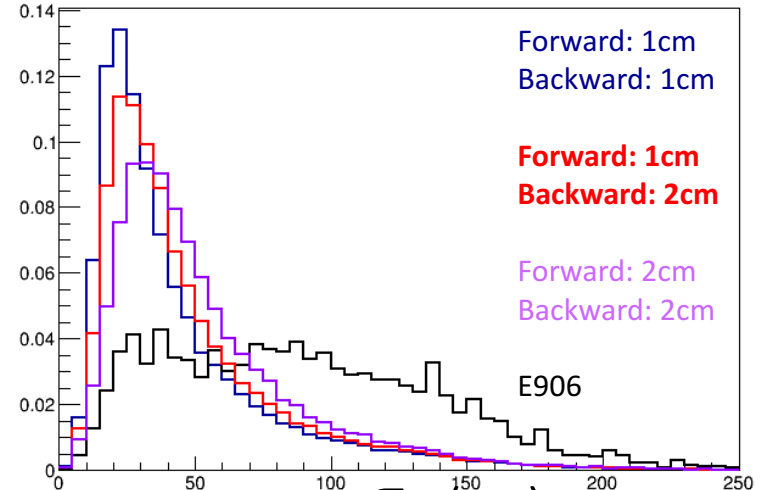




σ_Z (cm)



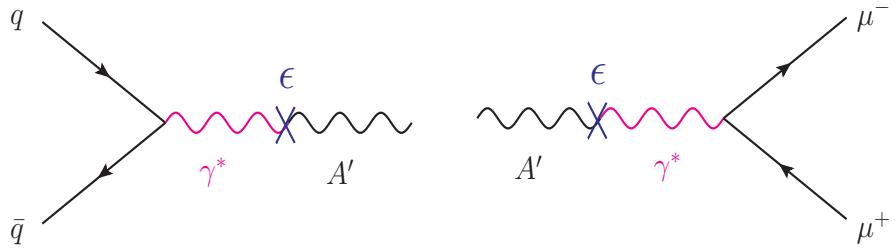
Open. Angl.



σ_Z (cm)

Search Mode (2): “Prompt” Dark Photons vs Drell-Yan

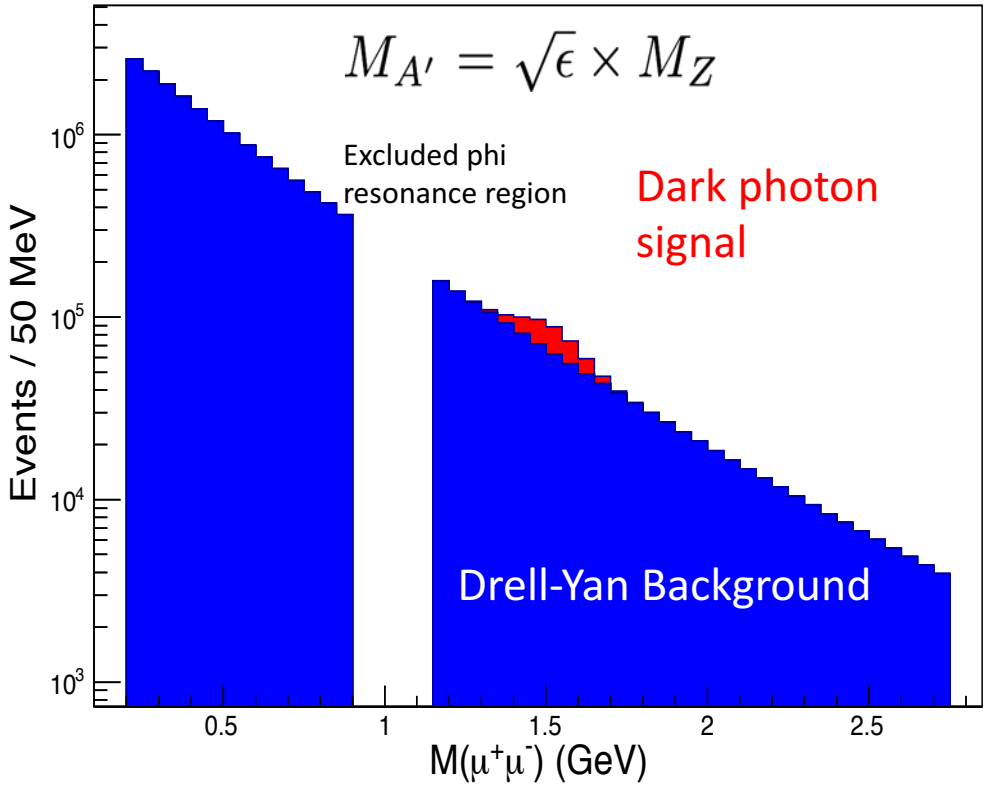
Bump hunt at Z-vertx < 3m



Expected Drell-Yan like signal and backgrounds:

$$\frac{d\sigma}{dx_F}(p+p\to A'+X)=\sigma_0^{A'}\sum_q e_q^2 q(x_1)\bar{q}(x_2)\frac{x_1x_2}{x_1+x_2}$$

$$\sigma_0^{A'}=\frac{4\pi^2\alpha_{em}\epsilon^2}{N_c m_{A'}^2},\quad x_1=\frac{x_F+\sqrt{x_F^2+4m_{A'}^2/s}}{2},\quad x_2=\frac{-x_F+\sqrt{x_F^2+4m_{A'}^2/s}}{2},$$



$$sig = S/\sqrt{(S+B)}$$

$$sig \sim \epsilon^2 \times \sqrt{N_{DY}\times M/\sigma_M^{Det.}}$$

Work in progress:

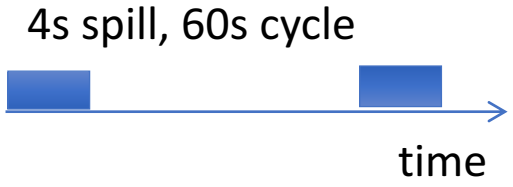
- optimization …,

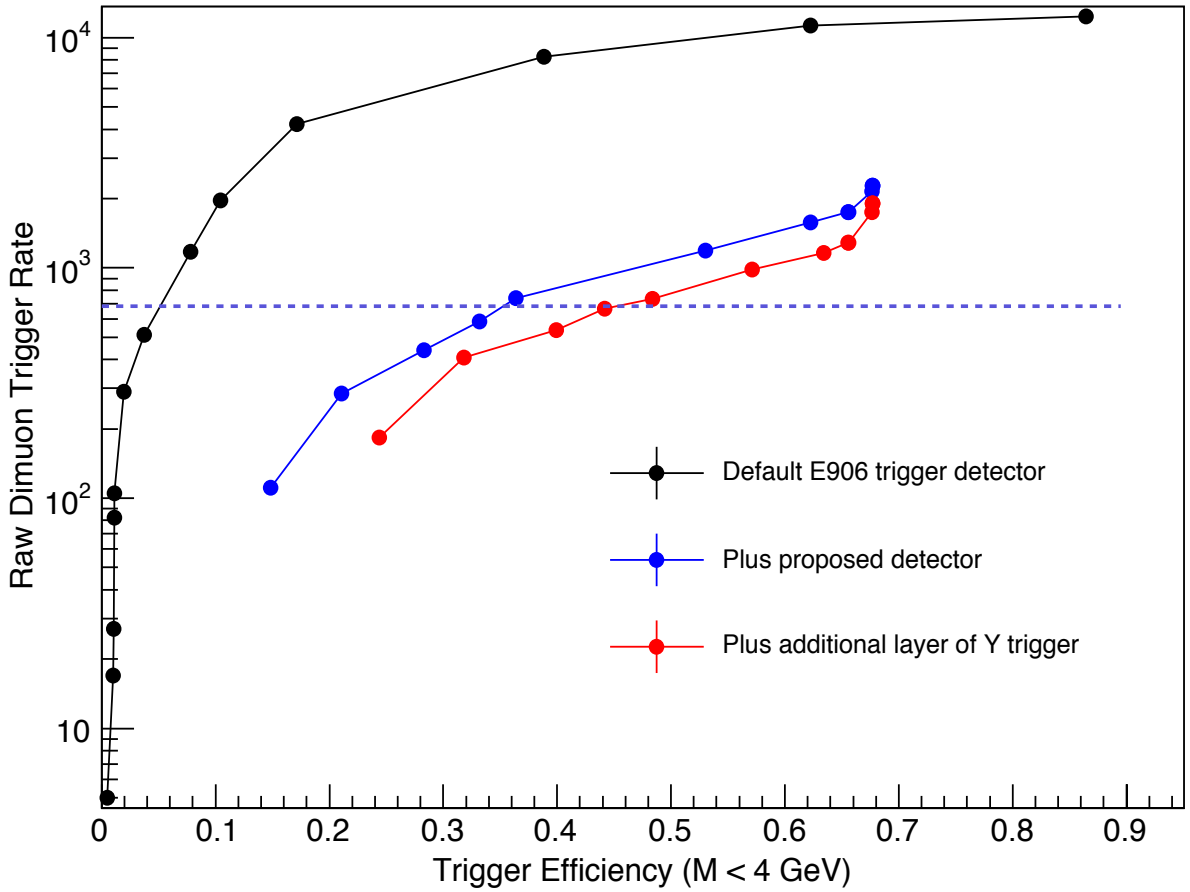
- understand BG …

Low Mass Prompt Dimuon Trigger Rate Study

- Current E906 setup
- Proposed 2-layer trigger upgrade (10x improvement)
- Additional Y-trigger after ST-3 absorber, and also using existing E906 X-Plane trigger (additional ~2x improvement)

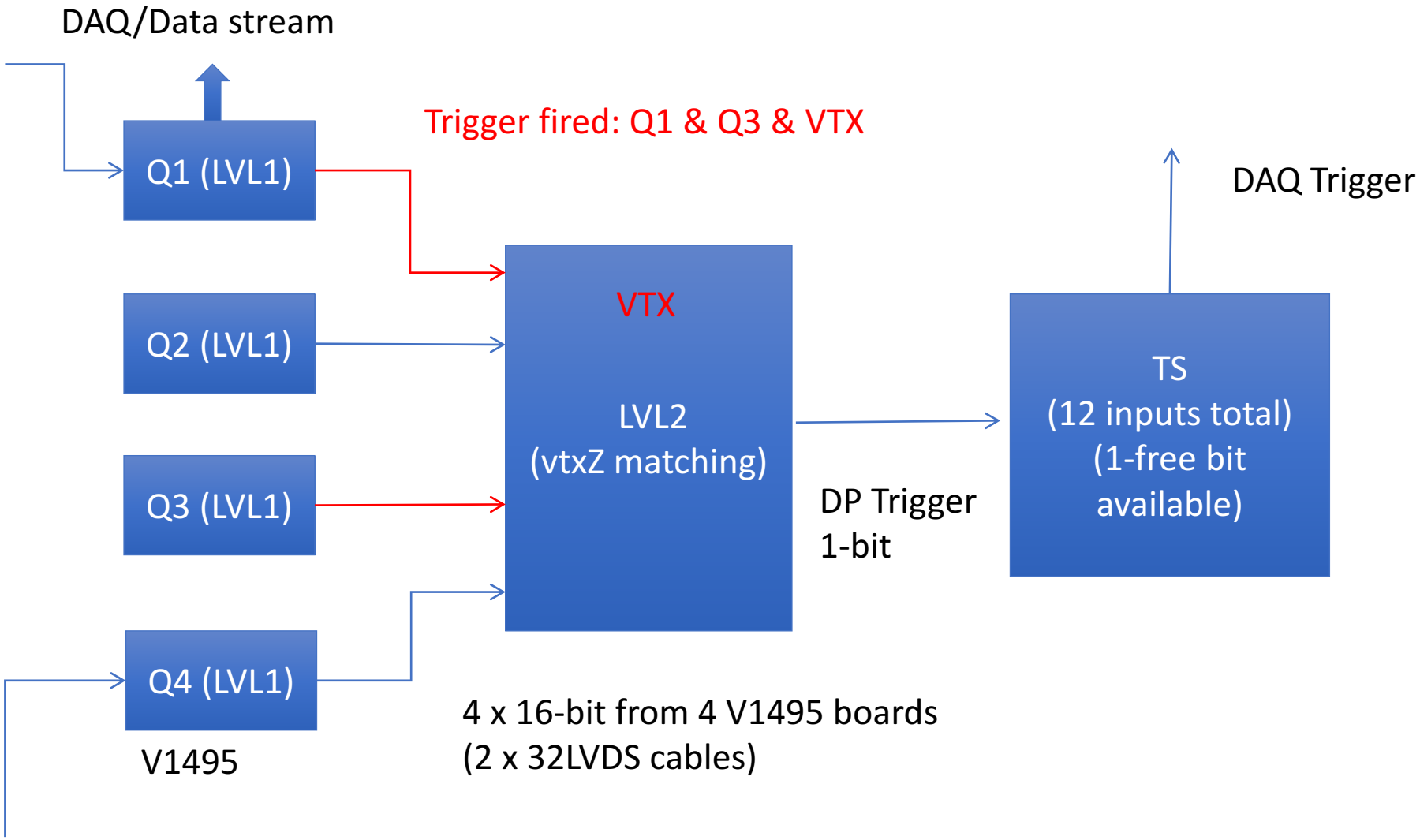
- DAQ upgrade completed
  - Previous E906 DAQ 1kHz
  - Now 10+ kHz
  - Can take all dark photon events of interest





Expected (Prompt) Low mass dimuon trigger performance

Displaced Dark Photon Trigger Logic



Per quadrant $Q_{(1\text{-}4)}$: 80(ST1) + 50 (ST2) + 2x8(ST4-Y1/2) = 146, FANOUT ST4 Hodo