

Status of Dark Photon/Higgs Search Trigger/DAQ Upgrade

Kun Liu and Ming Liu

Los Alamos

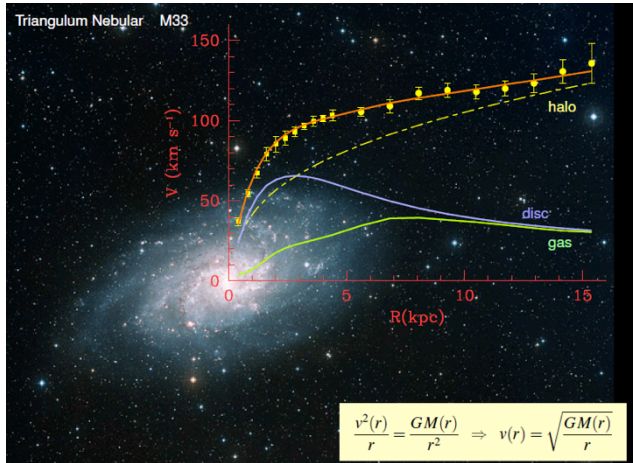
With Grass, Dave C., Xinkun et. al.

Outline

- Physics of dark sectors
 - Mass: MeV $\sim$ GeV
- Detector upgrade
 - Displaced dimuon trigger
 - DAQ improvement
- New opportunity
 - EMCal from PHENIX, available this fall
 - electron/hadron ID @SeaQuest!
- Possible schedules and tasks
 - DAQ, Trigger work during this summer shutdown
 - Be ready for data taking in 2017 with E906
 - PHENIX EMcal installation?

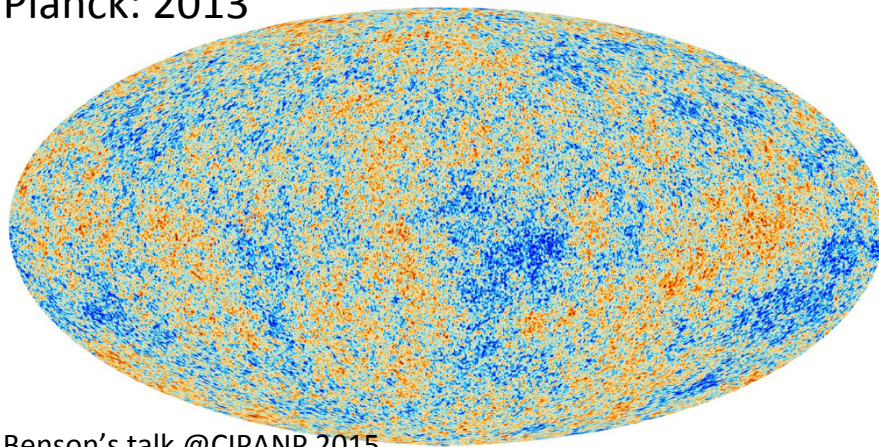
Dark Matter?

Galaxies' rotation curve



F. Zwicky, ApJ 86 (1937) 217, V. Rubin et al, ApJ 238 (1980) 471

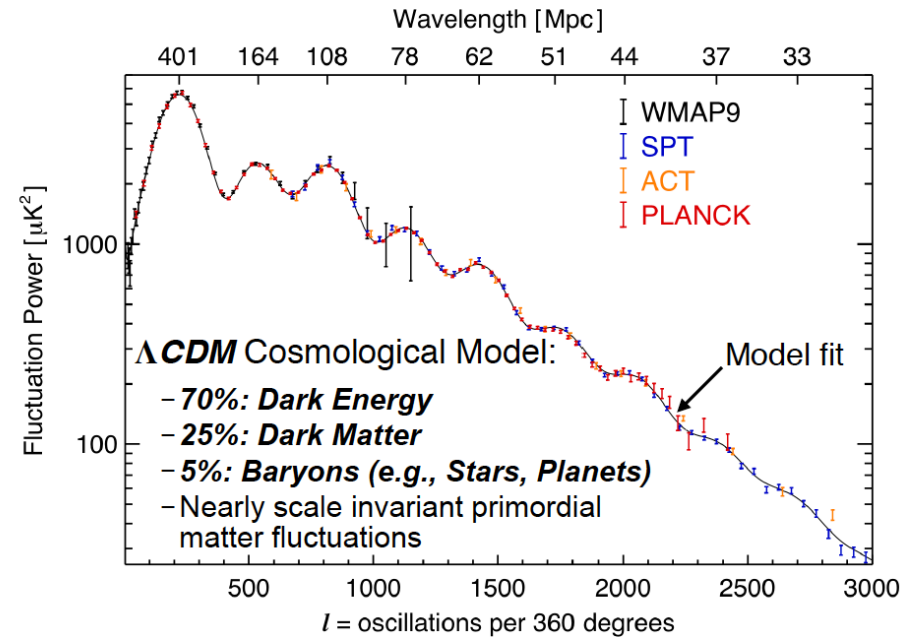
30 μ K RMS fluctuations on 3 K background
Planck: 2013



Benson's talk @CIPANP 2015

6/12/16

Gravitational lensing (Hubble 2007)



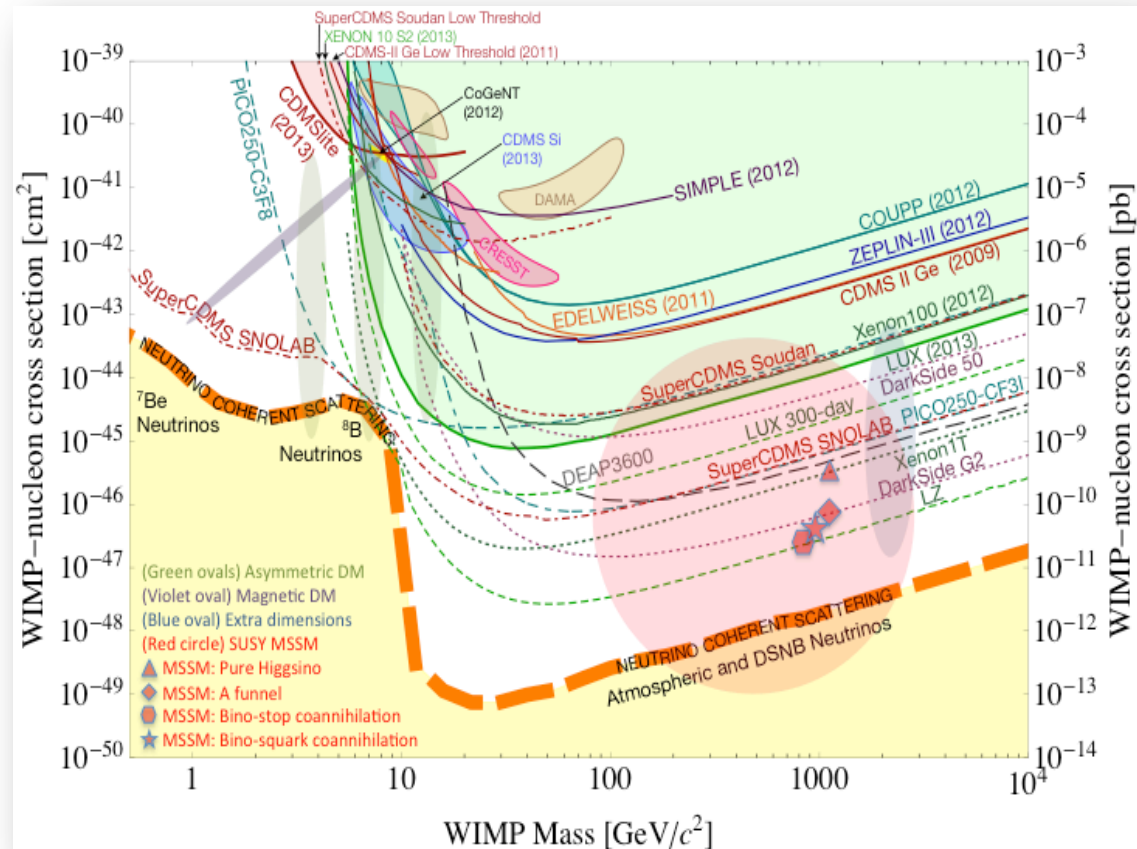
Dark photon/Higgs Search @SeaQuest

No Luck so far in Direct Search for WIMP

Montgomery's talk at CIPANP2015
 "a vision of nuclear and particle physics"

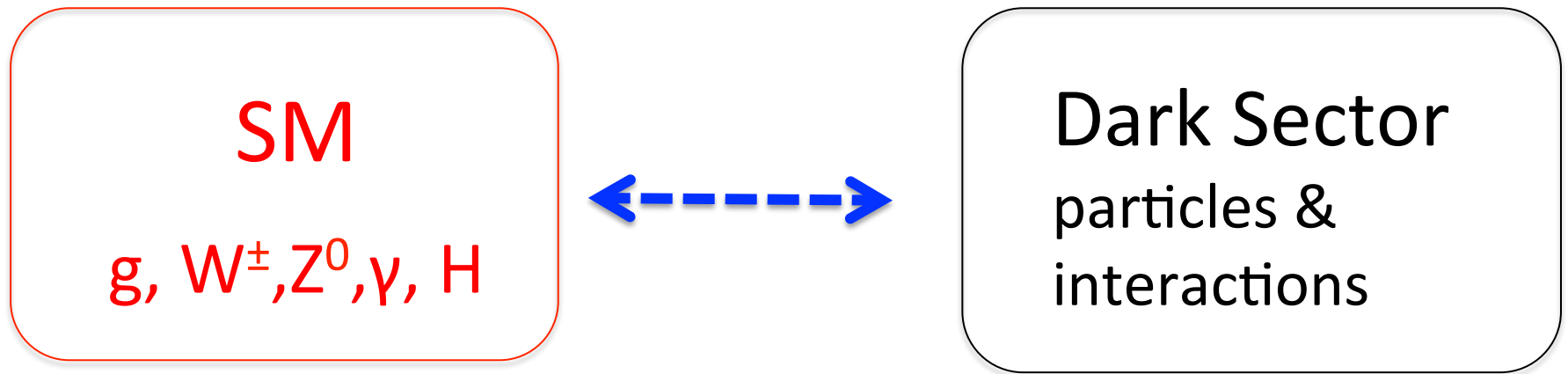
- WIMP being excluded?
 - Recent anomalies observed by satellite and terrestrial experiments have motivated dark matter models introducing a new **"dark sector"**
 - There are "portals" between the dark sector and the SM.
 - "vector portal": dark photon
 - "scalar portal": dark Higgs
 - ...
- "Sub-GeV" low mass weakly-interacting dark particles become very interesting!**
 Mass: $O(\text{MeV} \sim \text{GeV})$
- In particular, high-intensity colliders (B-factories) and fixed target experiments (Fermilab, JLab, LHC etc.) offer an ideal environment to probe these new ideas.

- Imaginable space for these experiments is rapidly disappearing
 - the "natural" theory space is also disappearing.
 - I like to think that Dark Matter is on solid ground, maybe not!!!



Portals to a Dark Sectors?

- SM symmetries limit the allowed couplings
 - scalar, vector, tensor interactions etc.

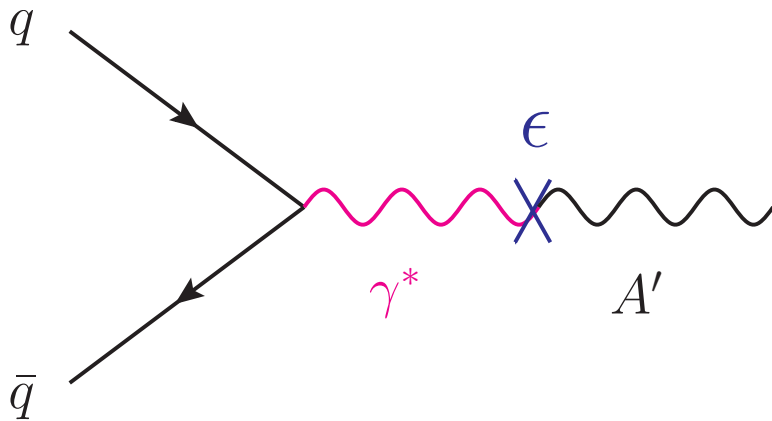


E-1067/SeaQuest: Dark photon (vector) and Dark Higgs (scalar) Portals

Dark Photons and Dark Higgs Productions in p+Fe Collisions at Fermilab

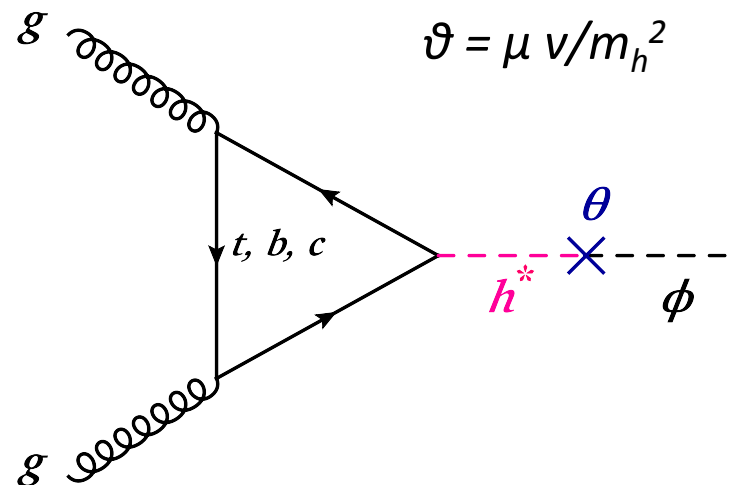
Photon portal: “vector”

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



Higgs portal: “scalar”

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



Letter of Intent for a Direct Search for Dark Photon and Dark Higgs Particles with the SeaQuest Spectrometer in Beam Dump Mode

Co-Spokespersons: Ming X. Liu (LANL) and Paul E. Reimer (ANL)

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R.-S. Guo, G. Wang
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LOI submitted to Fermilab PAC
on May 20, 2015

A joint experimental and theoretical collaboration
(most E906/E1039 + new members, ~60)

Phase-I: (parasitic runs)

1. Addition of a new displaced dimuon trigger to tag long-lived downstream decayed dark photons (dark Higgs).
2. Parasitic data taking with E1039 in 2017-2019;
 - A short dedicated run (up to ~1 month) if needed.
3. POT 1.44×10^{18}

Phase-II: (upgrade)

1. Dedicated runs later with EMC/HCAL upgrades, $e^{+/-}$ and $h^{+/-}$ capabilities.
2. Cover the full parameter phase space allowed by beam energy and luminosity
3. POT: $>> 1.4 \times 10^{18}$

Phase-II request will be presented to PAC at a later time.

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

NEW EXPERIMENT! E-1067

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

LANL LDRD support:

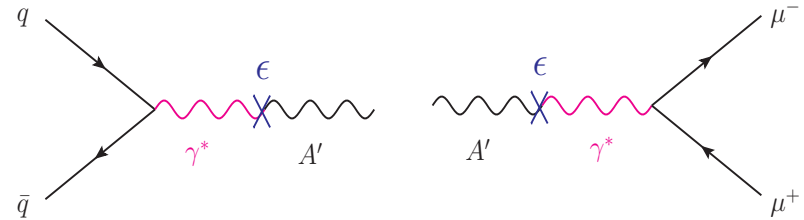
- FY16-17-18
- \$1M to implement the trigger upgrade and theory development

Goals:

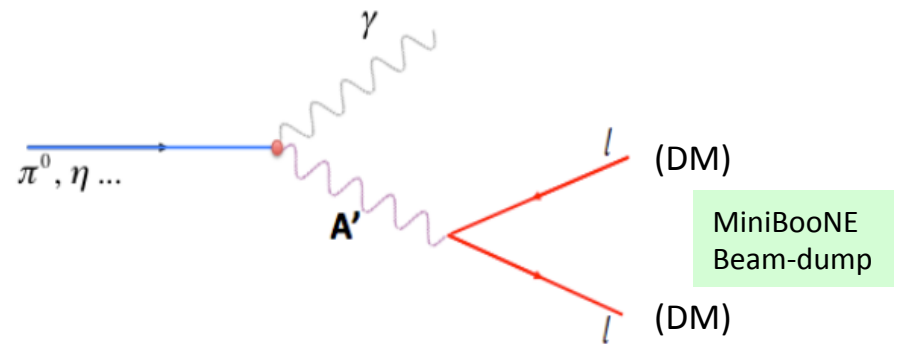
- Trigger installed, 2017
- Physics run, 2017-18
- Preliminary results 2018!

Dark Photon Detection in Dimuon Decay Channel

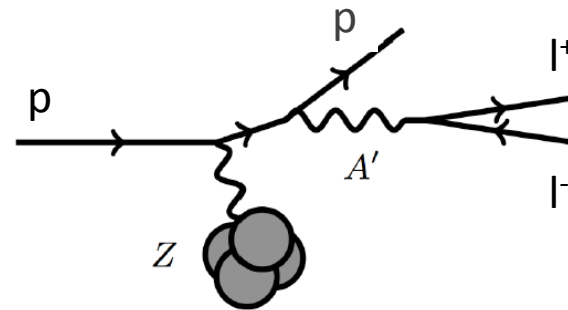
1. Drell-Yan like



2. $\pi^0, \eta, \dots$ decay



3. Bremsstrahlung

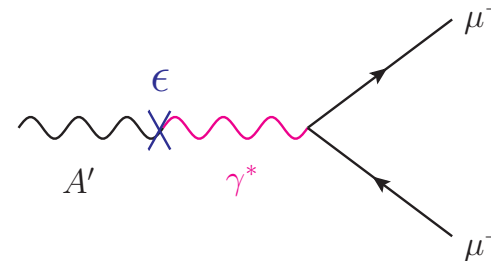


Dark Photon Decay Modes

“Minimal” Decay:

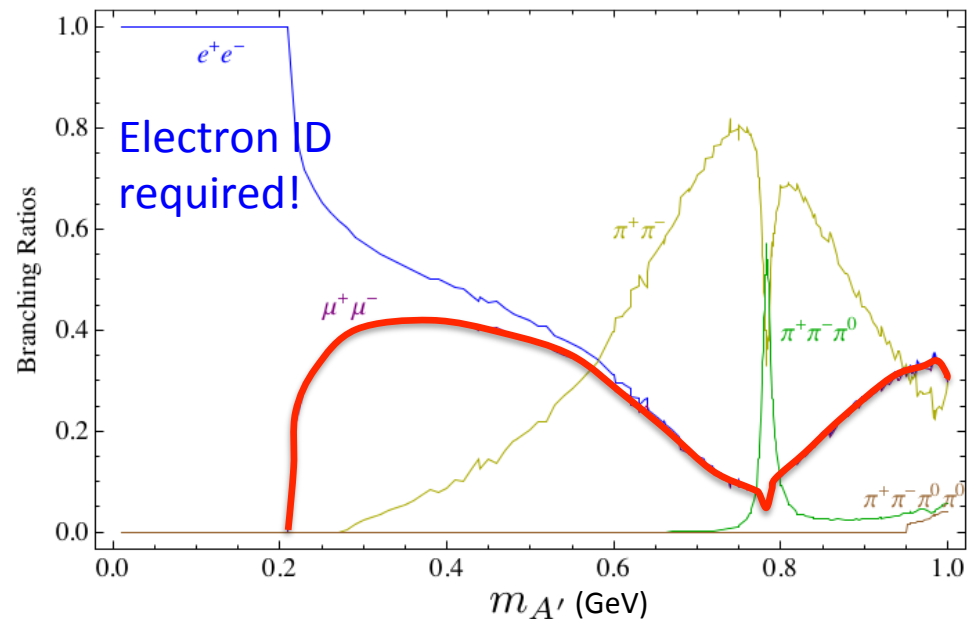
- Dark photon is the lightest in the dark sector;
 - SM final state particles only

Long proper decay length: $L_0 \sim O(1m)$



$$\Gamma(A' \rightarrow f + \bar{f}) = C \frac{\epsilon^2 m_{A'}}{3} e_f^2 \alpha_{\text{em}} \left(1 + \frac{2m_f^2}{m_{A'}^2} \right) \sqrt{1 - \frac{4m_f^2}{m_{A'}^2}},$$

D. Curtin, et al, arXiv: 1312.4992



$$L_0 \sim \frac{1}{\epsilon^2 \times m_{A'}}$$

“General” Decay:

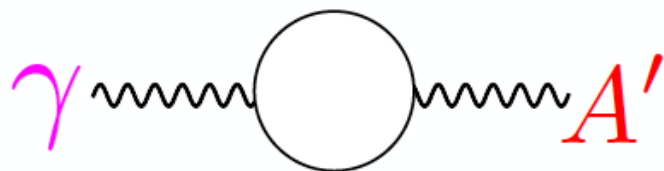
- Decay into other dark particles, dominant channel if allowed
 - Dark $\rightarrow$ Dark
 - Dark $\rightarrow$ SM particles

Expectations from GUT

- After EWSB, there is a coupling ϵ between the dark photon and the photon (also the Z, less important at low energies).
- Theoretical prejudice for a mass scale

e.g. Arkani-Hamed & Weiner;
Cheung, Ruderman, Wang, Yavin;
Morrissey, Poland, Zurek;
Essig, Schuster, Toro;

$$m_{A'} \sim \sqrt{\epsilon} m_{EW} \sim (\text{MeV} - \text{GeV})$$



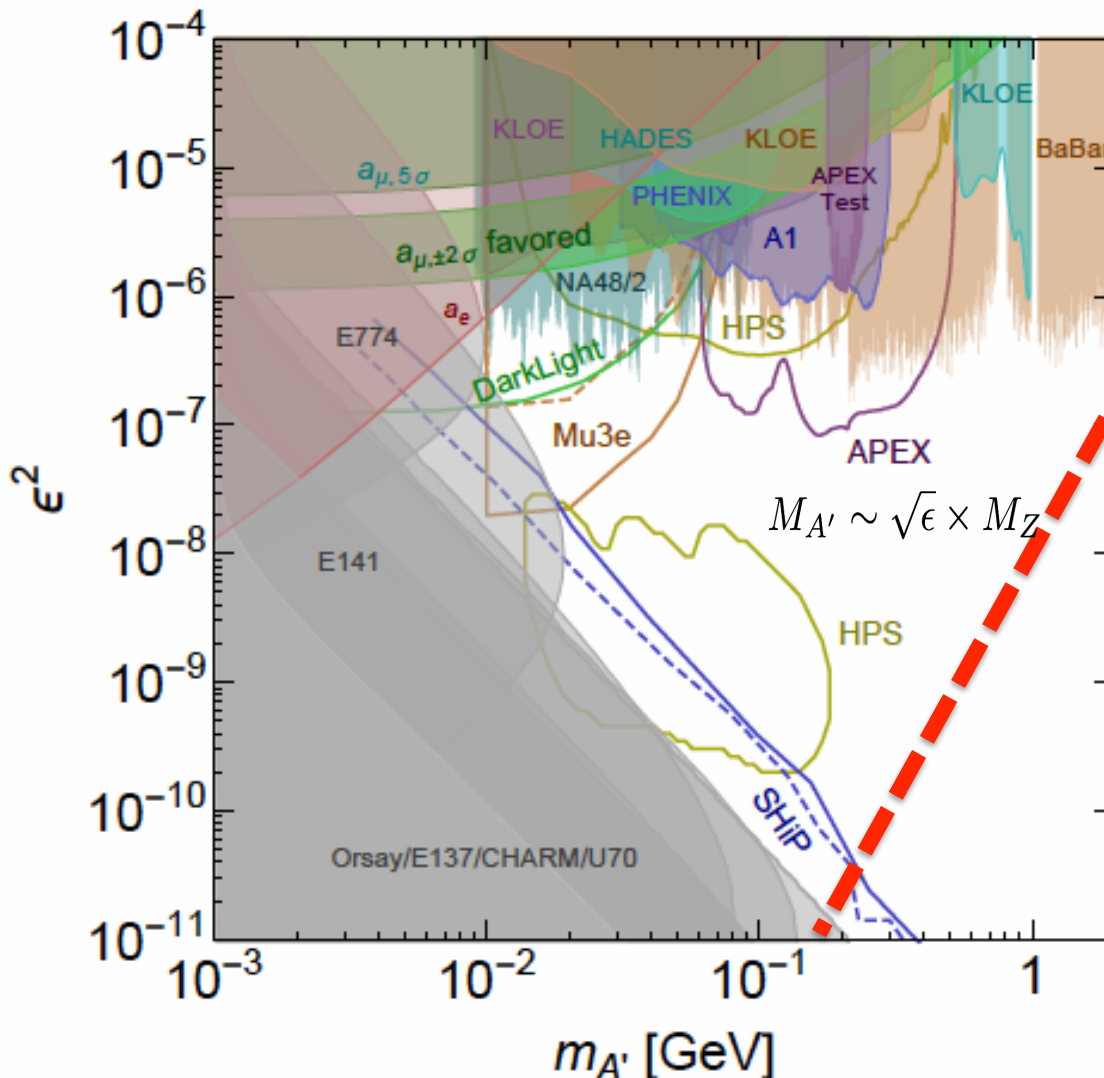
$$\epsilon \sim \frac{g_Y g_D}{16\pi^2} \ln \left(\frac{M}{M'} \right)$$

$$\sim 10^{-3} - 10^{-1}$$



$$\epsilon \sim 10^{-5} - 10^{-3}$$

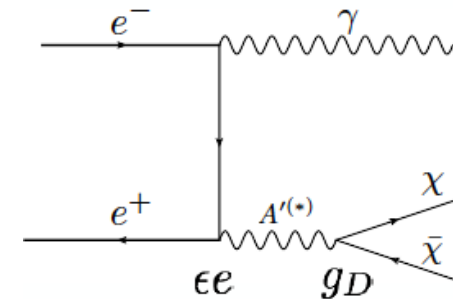
Dark Photon Current and Future Limits



- Several new results in recent years and more to come

Muon (g-2) region disfavored

- for A' directly decay into SM;
- but allowed with some “invisible modes”

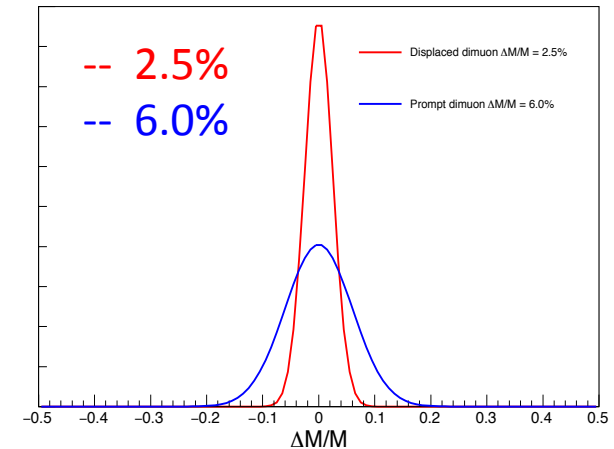


- New experimental proposals

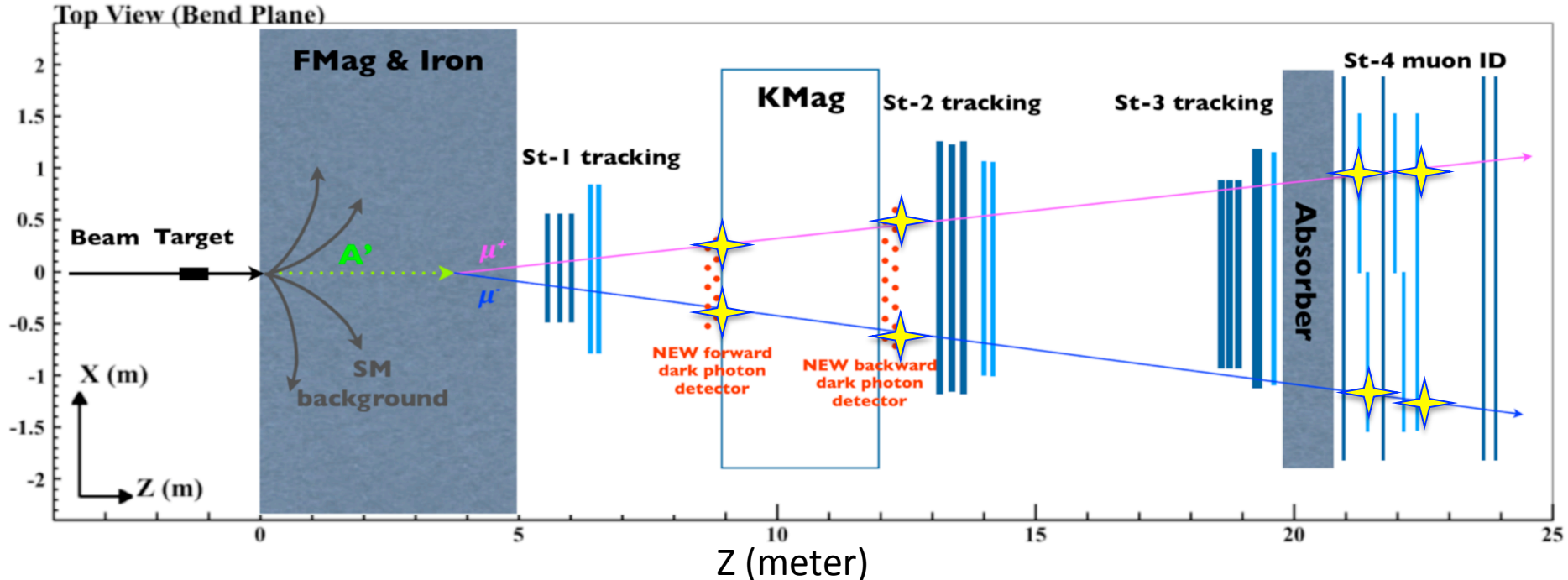
Fermilab E-1067 beam dump,
SHiP at CERN

Detector Upgrades and Expected Signals

- **Dark photon trigger upgrade**
 1. Add a fine-granularity scintillating strip based 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
 3. Mostly from beam dump (target $\sim 10\% \lambda_i$)
- **Beam time**
 1. Run parasitically with E906/E1039 (2017-2019)
 2. Possible dedicated runs later with upgraded ($e^{+/-}$, $h^{+/-}$)



Dimuon mass resolution



A New High-Granularity Displayed Dimuon Vertex Trigger

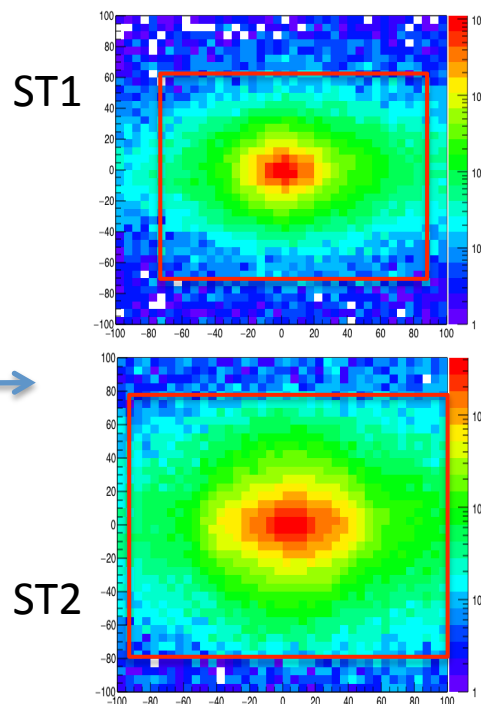
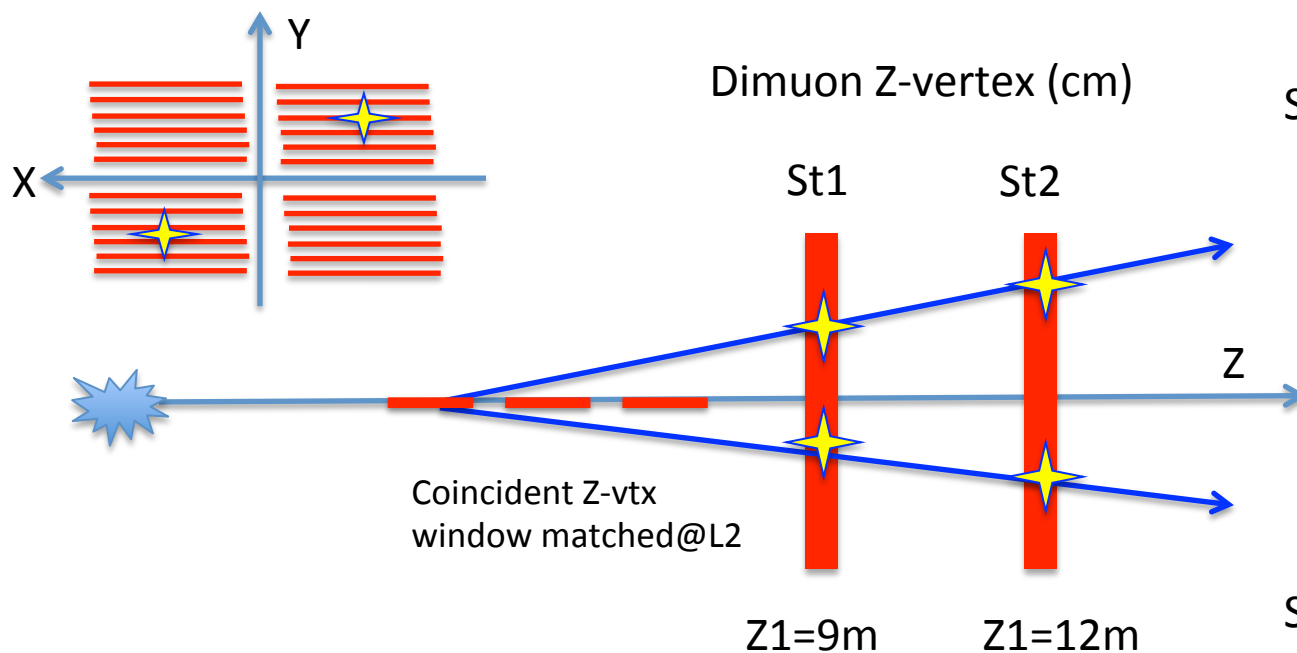
High rejection power, very low rate, $\ll 1$ kHz (current E906 DAQ limit)

Y-Plane (non-bending) Trigger:

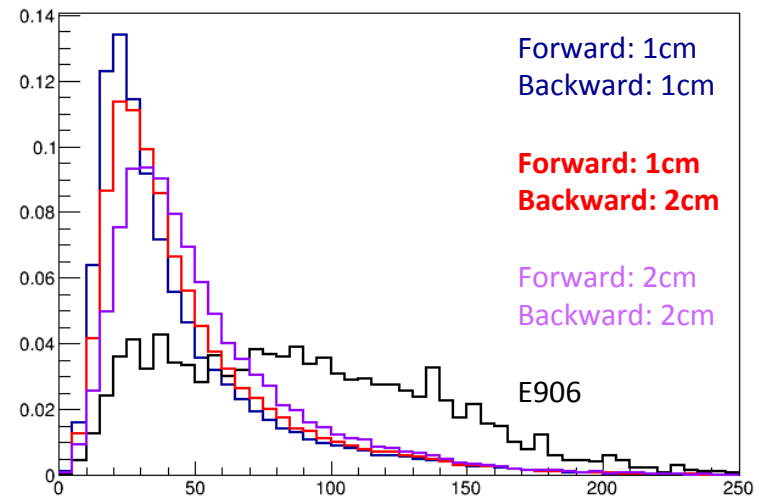
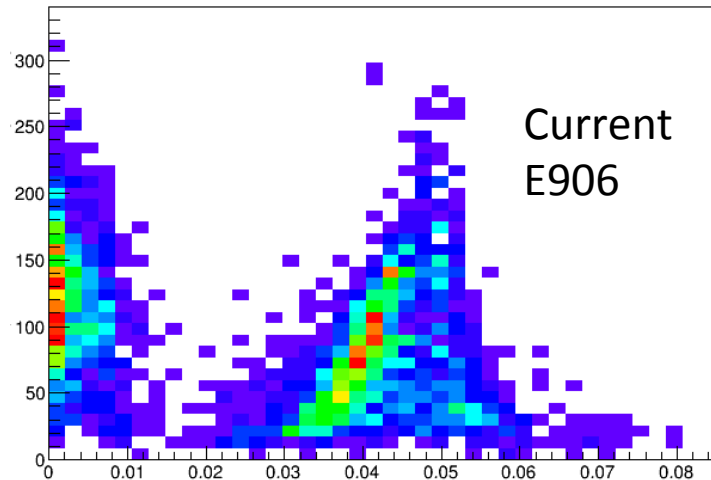
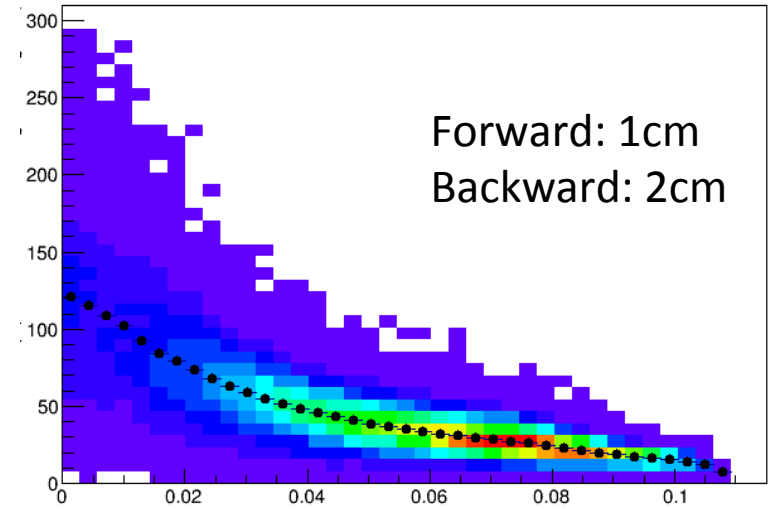
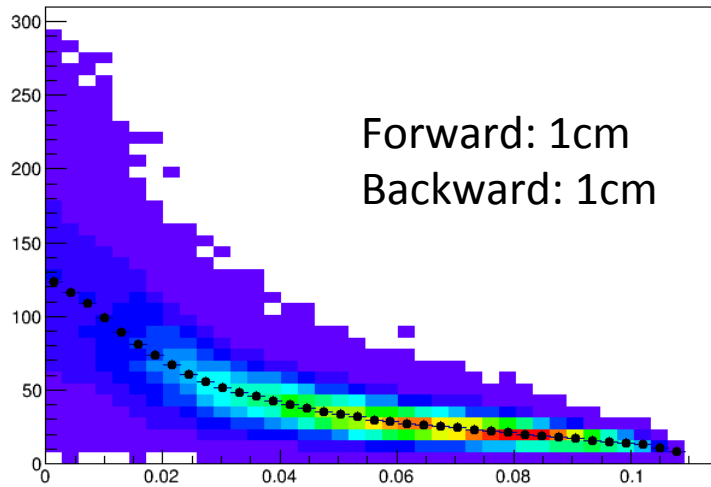
- A quadrant panel: 80cm x 72cm (100cm x 72cm @ ST-2)
 - ST1: 1cm x 1cm x 80 cm scintillating strips, SiPM readout
 - ST2: 2cm x 2 cm x 100 cm strips
- Straight line projection, 30cm Z-vertex resolution
- Displaced z-vertex, mostly low mass < 3 GeV

Y-channels per quadrant:

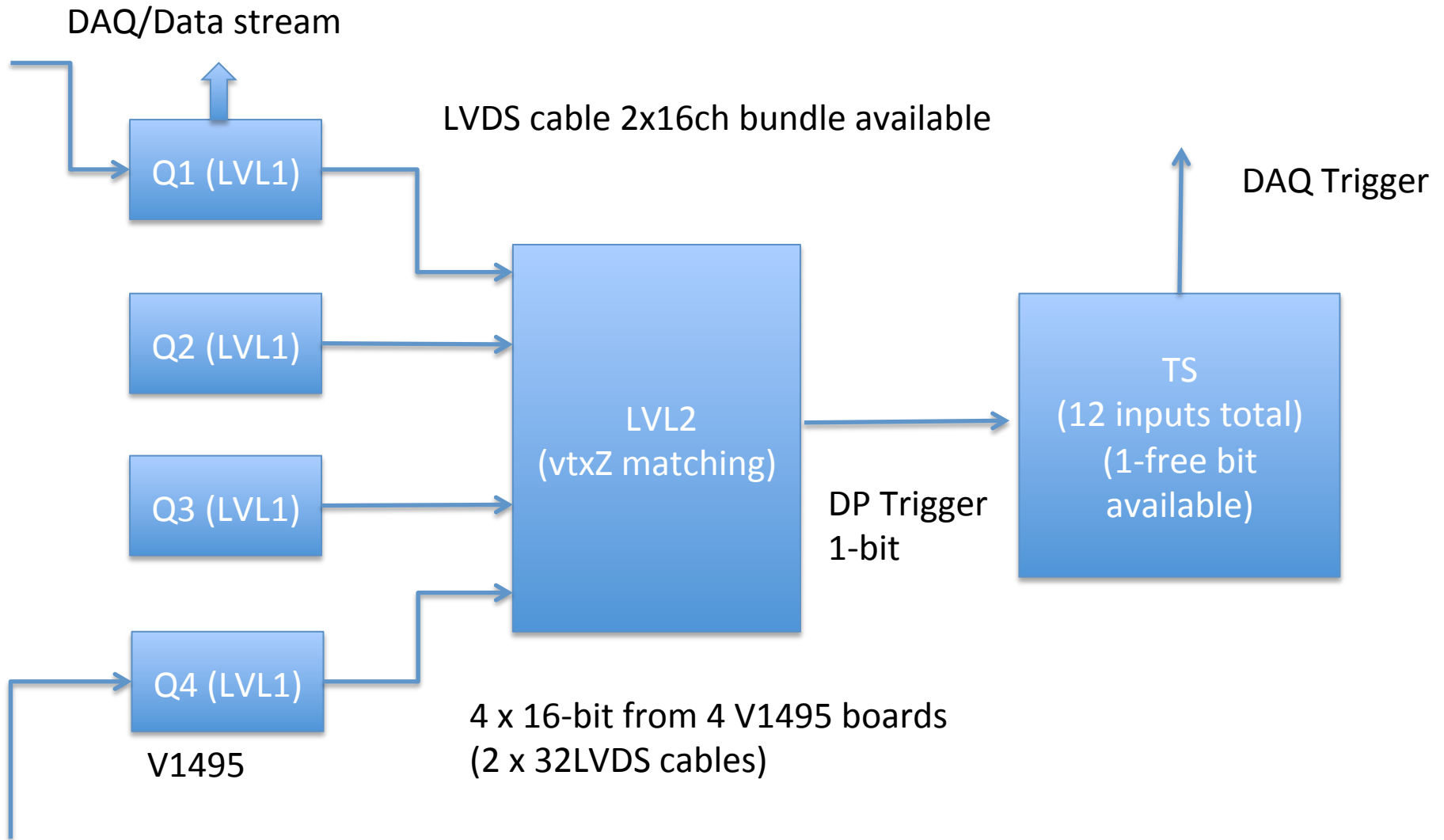
- 1x V1495
- $72(\text{St1}) + 72(\text{St2}) + 8 \times 2 (\text{St4-Y1,2}) = 116$
- $96 + 64 = 160$ inputs possible
($2\text{NIM} = \text{RFCLK} + \text{ComSTOP}$)
- $72 \times 4 \times 2 = 576$ SiPMs needed (600)



Single Muon Z-Vertex Resolutions



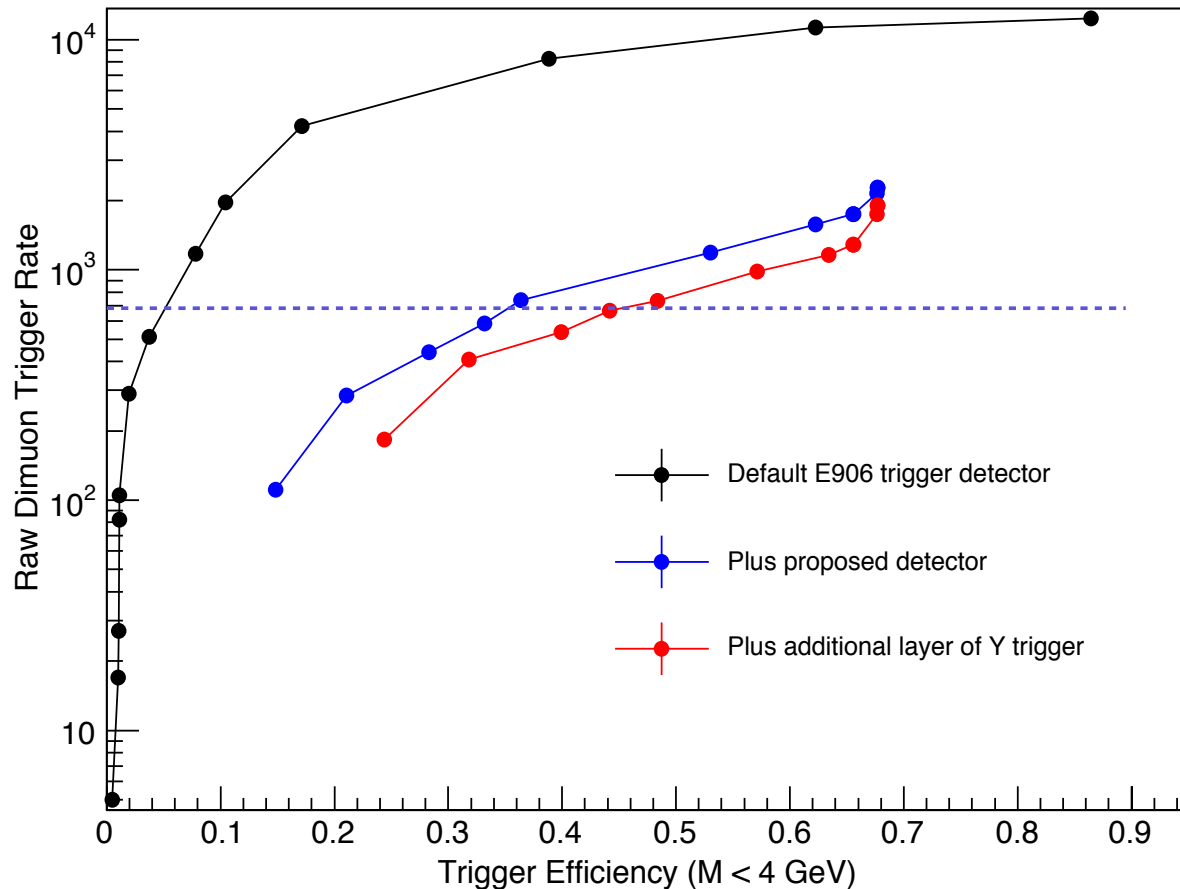
Displaced Dark Photon Trigger



Q1: $72(ST1') + 72(ST2') + 2 \times 8(ST4 - Y1/2) = 160$, FANOUT ST4 Hodo (or EMCal Cluster)

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)
- Current E906 DAQ 1kHz, can be improved to ~10kHz with small cost
- 100+kHz possible in the future (reprogramming trigger firmware etc.)

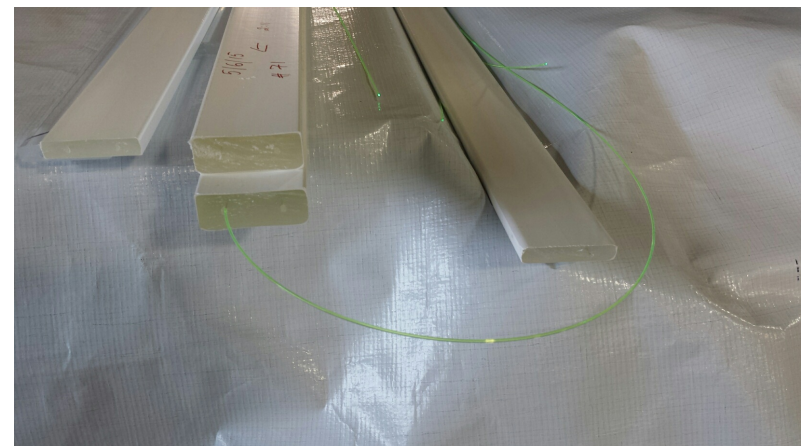
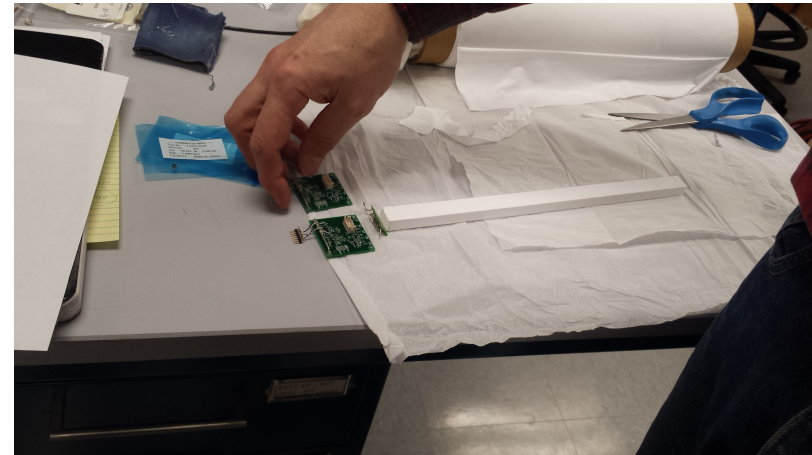


Parasitic mode: use up to ~10% DAQ bandwidth

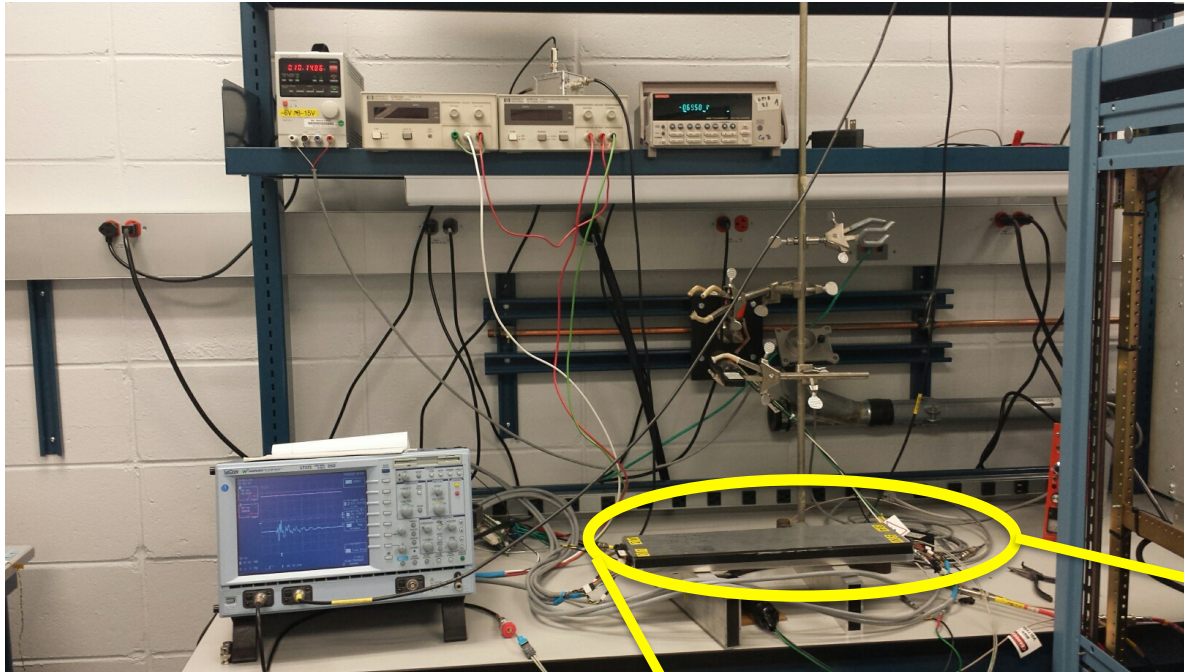
Expected (Prompt) Low mass dimuon trigger performance

Trigger Scintillator Options

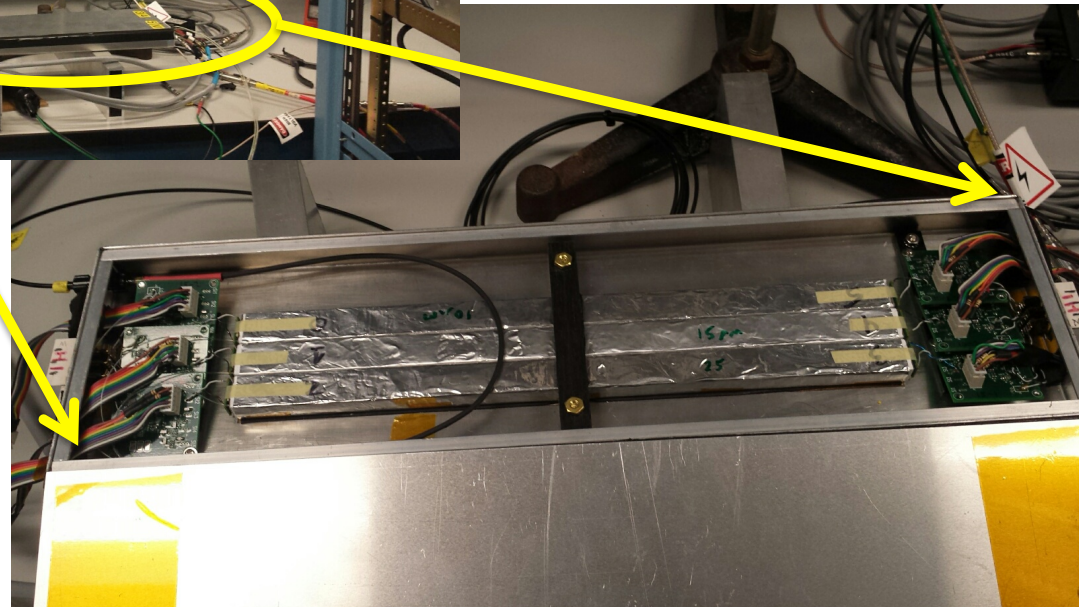
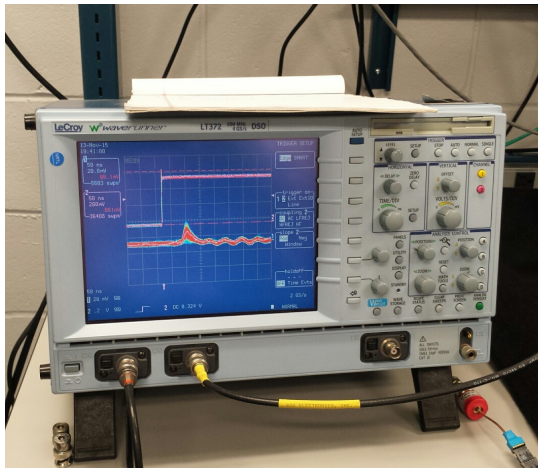
- High quality scintillator bars
 - 1x1x50cm
 - sPHENIX EMCal SiPM readout
 - Expensive, ~\$100/ch.
- Fermilab extruded scintillators + WLSF
 - 1x1cm
 - 2x2cm
 - SiPM readout
 - Low cost, ~\$10/ch



Trigger Prototype R&D (I)



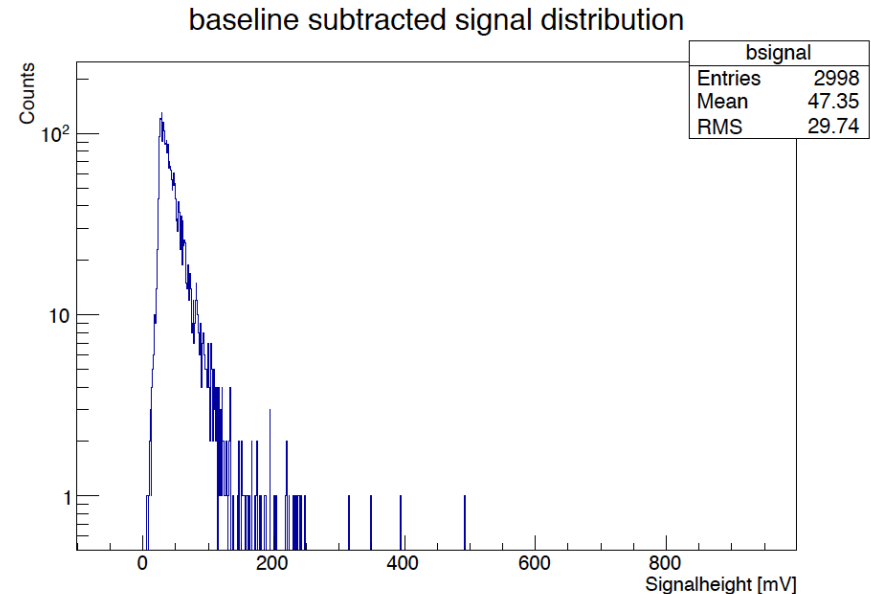
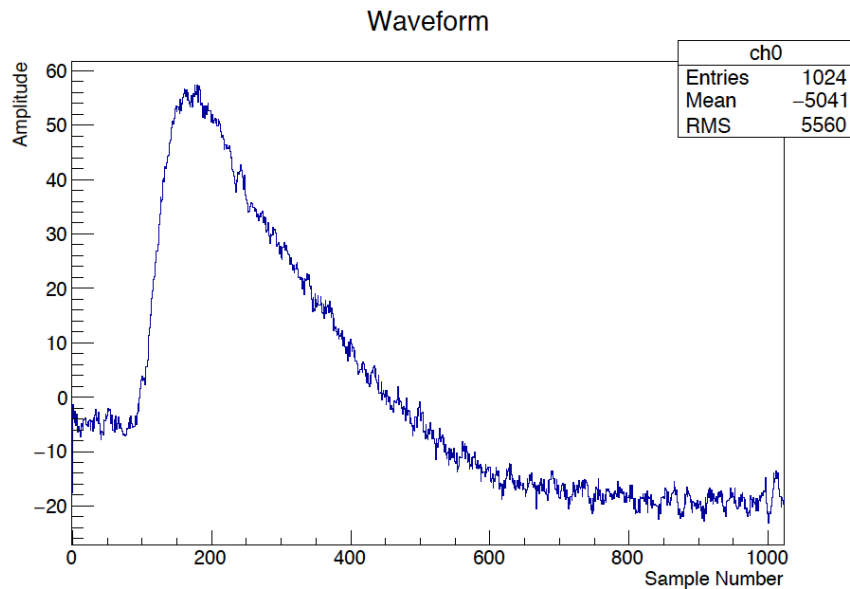
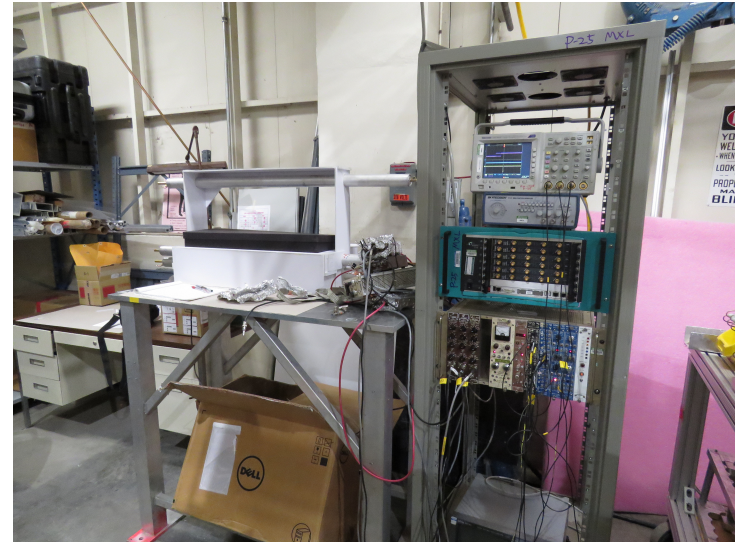
- 10mm x 10mm x 500 mm
- Scintillators + SiPM readout
- Cosmic rays
- Fast $< \sim 10\text{ns}$ rising time



Trigger Prototype R&D (II)

- Fermilab extruded scintillators + WLSF
- SiPM readout
- Excellent S/B!
- **Default option now!**

2 x 2 x 50 cm + 1mmD WLSF
+ SiPM readout

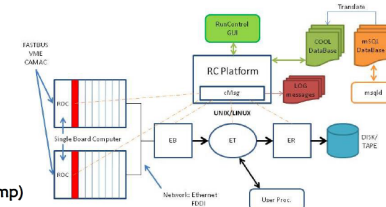


DAQ and Trigger Upgrade R&D Tasks

- Improve the DAQ bandwidth
 - Xinkun, Kun, Grass, Dave C. et al
- Trigger upgrade
 - Build scintillator based displaced dimuon trigger detectors
 - Mechanical assembly and support structure
 - Readout integration
 - Develop trigger firmware for displaced vertex
 - V1495
 - Can use more help
- A Standalone DAQ – a sandbox
 - DAQ improvement
 - Trigger algorithm development (Byron Roe, Daniel Morton, Kun et al)
 - Trigger firmware and DAQ integration (?, LANL?)
 - Can use more help

LANL machine build-up

- ✓ Install Scientific Linux Fermi 6.7
- ✓ Setup rsh connections
- ✓ Install CODA 2.6.1
- ✓ Setup the CODA database
- ✓ Add Trigger Supervisor SIS3610
- ✓ Start with Run Control
- ✓ Offline data monitoring (xceedmp)



A Standalone DAQ for Trigger Development

- PC/Linux: Jlab CODA, Ethernet Readout
- CPU MVME5500: old VxWork (Jlab)
- “TS” SIS3200
- TDC-II
- V1495 pulse generator
- V1495 L1 Trigger “development brd”
- Windows PC: Altara FPGA programming

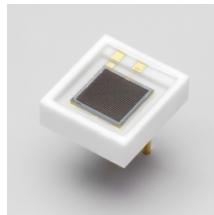


- CNTRL
- SIS3200, as TS
- TDC-II (x)
- TDC-II (x)
- V1495, trigger inputs
at least 4
- V1495 as trigger
pattern emulator

Hardware in hand/Ordered

Scintillator trigger

- WLSF: Y-11 (200)
 - 1 mm D, 1,000m
 - 1.5 mm D, 1,000m
- Extruded scintillators
 - Quote, in progress
- SiPMs
 - 3x3mm, 600 ordered
 - S13360-3050CS
 - Gain $\sim 1.7 \times 10^6$
- Mechanical support
 - 80-20 Al frames
 - Safety review



Readout & DAQ integration

- VMEs
 - 1 VME crate + Linux CPU
 - 1 Linux computer
- New V1495 boards
 - 2 V1495
 - 6 daughter cards
 - Splitting Y-cables (12)
- E906 spares
 - V1495, 4(LVL-0)+2
 - Daughter cards, #?
- preAMPs+LVDS
 - Fermilab ones
 - sPHENIX

Progress in Theory and Simulations

- Active theoretical collaboration

- LANL (Kang, Vitev, Cirigliano, Gupta, Graesser et al)
- SLAC (Toro, Schuster, Gori et al)
- Caltech (Zhang, An et al)
- SBU (Zhong, Essig)

- cross check dark photon and dark Higgs signals

- Long-lived decays
- Bump search from “prompt” productions
- SM backgrounds

- Physics and detector simulations

- New root-based event GEANT4 package (Kun, DavidK)

- New trigger optimization (LANL, U. Michigan)

- Study the impacts of parasitic runs with E906/E1039

- Detector and trigger optimization
- Improve polarized dimuon/DY signals
- Improve reference single muon spin asymmetry signals from target/dump

Search Mode (1): Long-lived Dark Photons

Reconstructed dimuons with downstream Z-vertex:

$$3m < Z\text{-vertex} < 6m$$

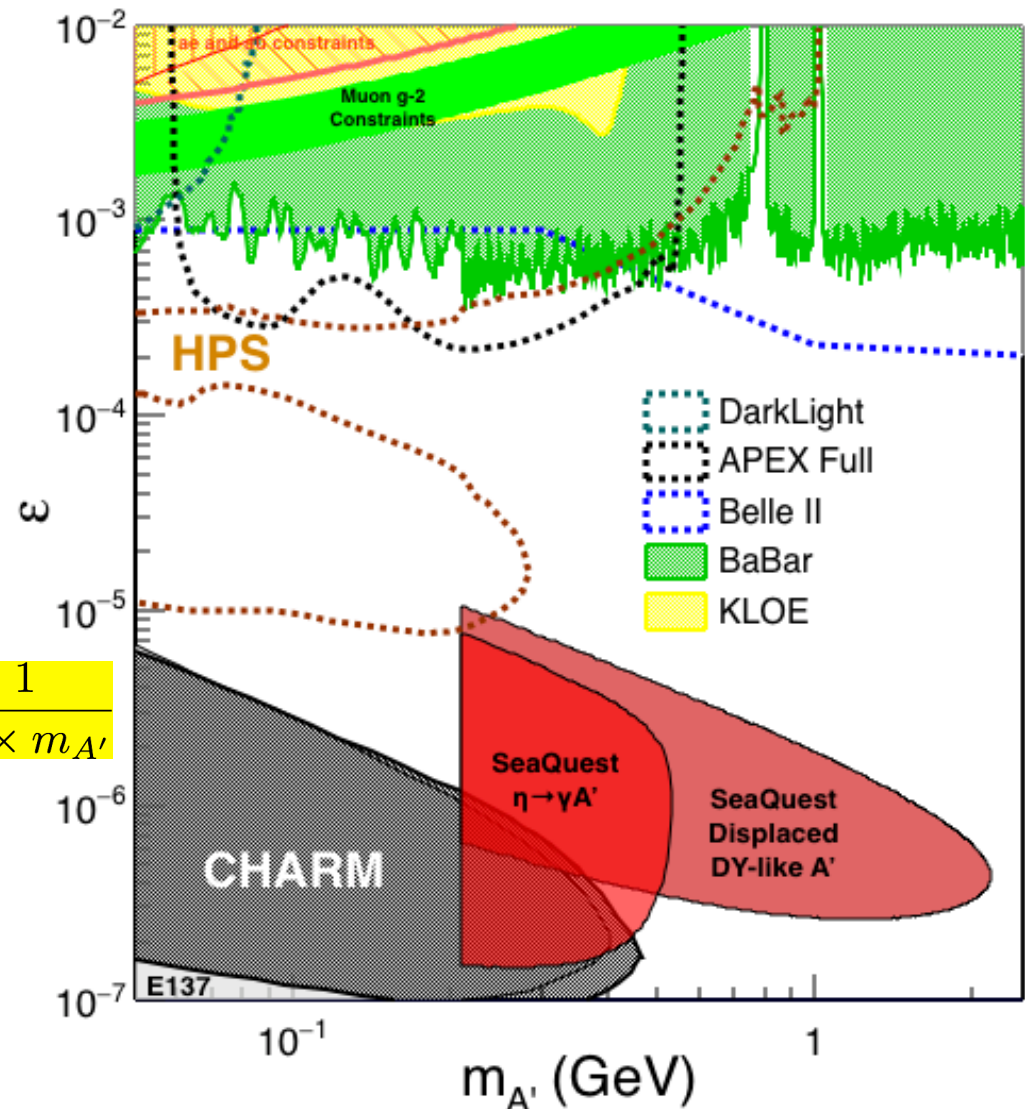
- Very low trigger rate, $\ll 1\text{kHz}$
- Almost SM background free
- Dimuon mass peak

- 5×10^{12} ppp (current E906)
- 200 days

1.4×10^{18} POT (recorded) $L_0 \sim \frac{1}{\epsilon^2 \times m_{A'}}$

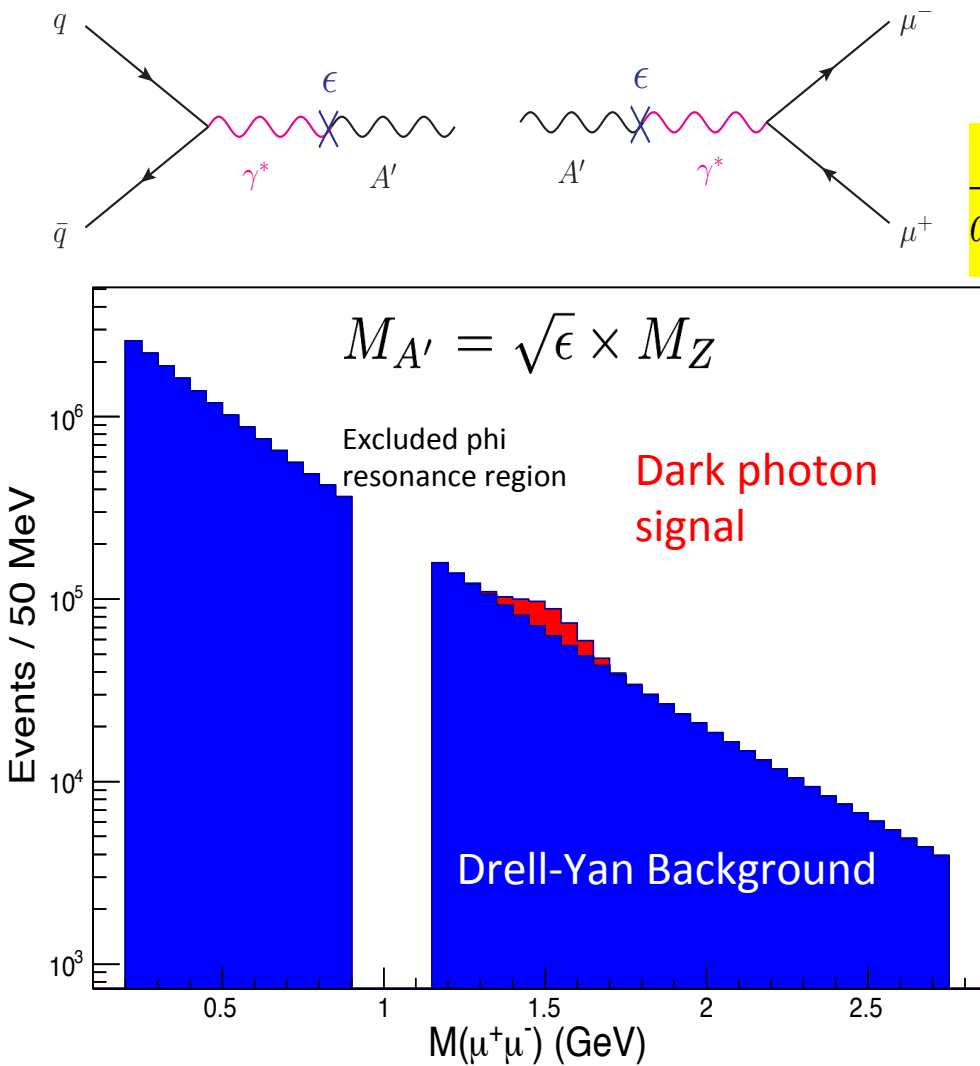
- 4 events contours (2-sigma)
- 2-sigma (95%) exclusion plots

Excellent coverage of uncharted region!



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

Z-vertx < 3m



Expected Drell-Yan like signal and backgrounds:

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

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

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

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

*Work in progress ...,
Understaning BG ...*

Summary: Dark Photon Sensitivity

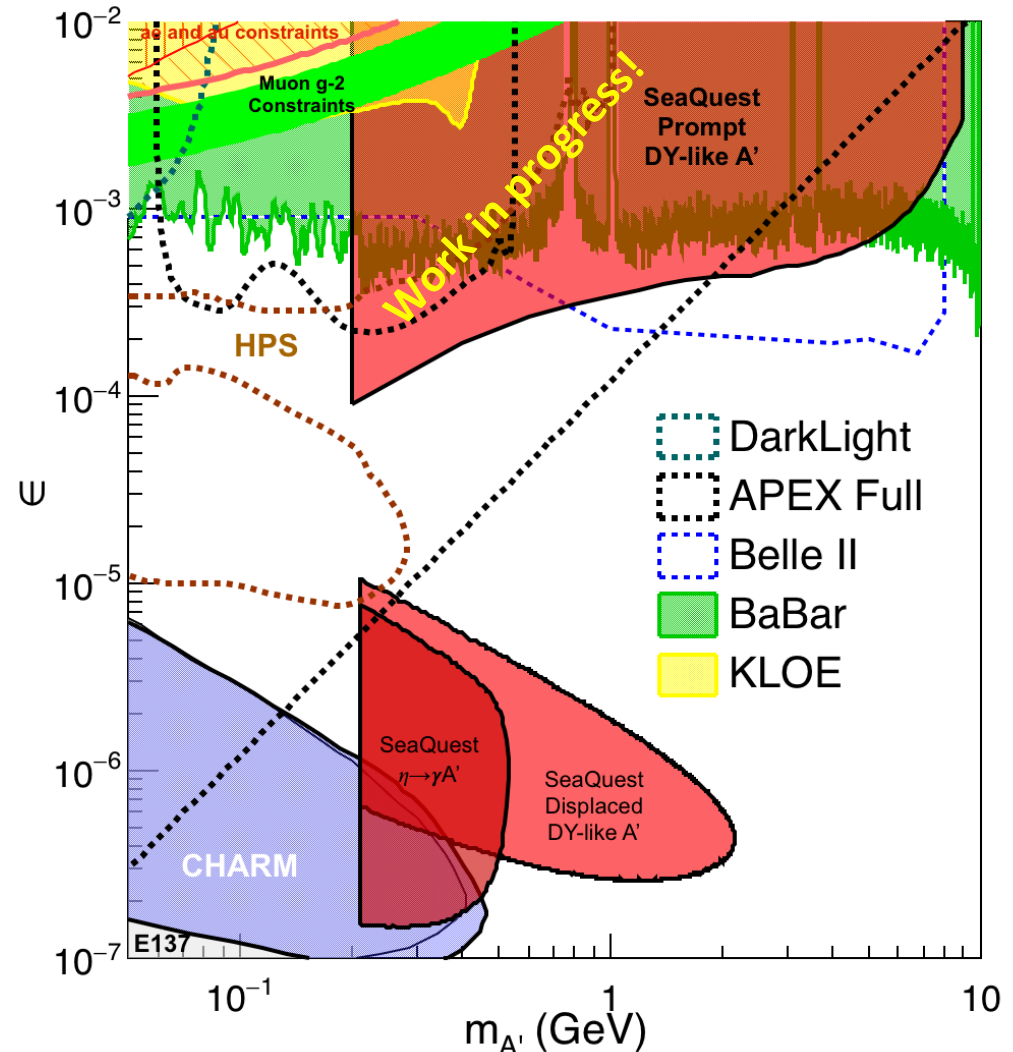
(parasitic run w/ E906/1039)

Signals considered:

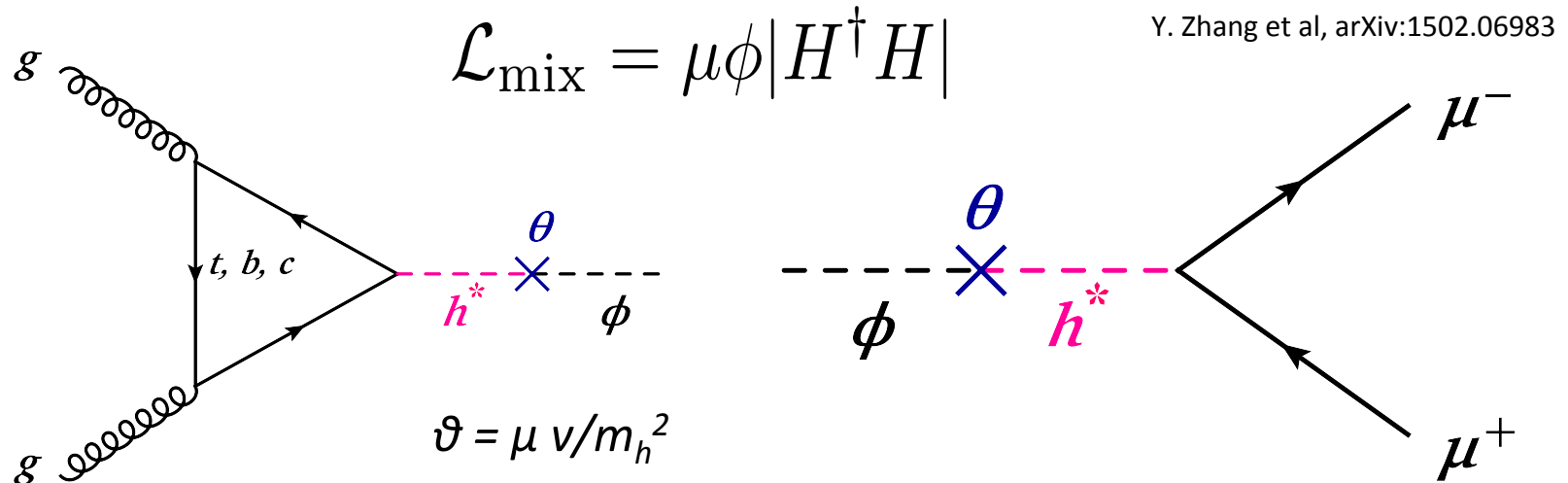
- Drell-Yan like
- Eta decays
- Bremsstrahlung

Covers a wide range of unexplored parameter phase space

- **Displaced dimuons**
 - Minimal SM background
- **Prompt dimuons**
 - Excellent coverage over BELLE-II projection
 - Possible dedicated runs later to fully restore mass < 3GeV (Phase-II)
- **Phase-II with upgrades**
 - Access below 200MeV with di-electrons (add EMCal)



Dark Higgs Search at E-1067



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

Phase-I:

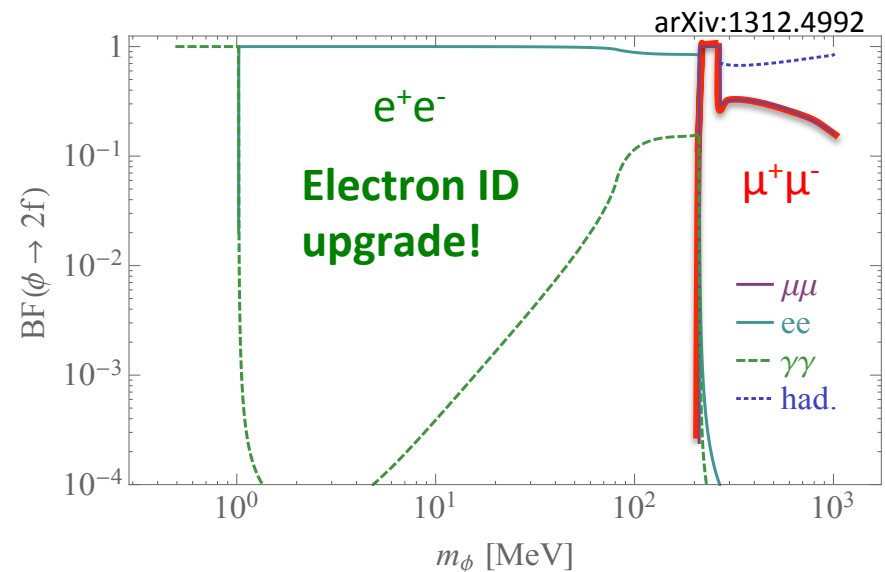
High-mass: $\mu^+\mu^-$ and hadrons

Advantage of using hadron beams
with muon probes over electrons

Phase-II:

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

High-mass: hadrons, (5x)

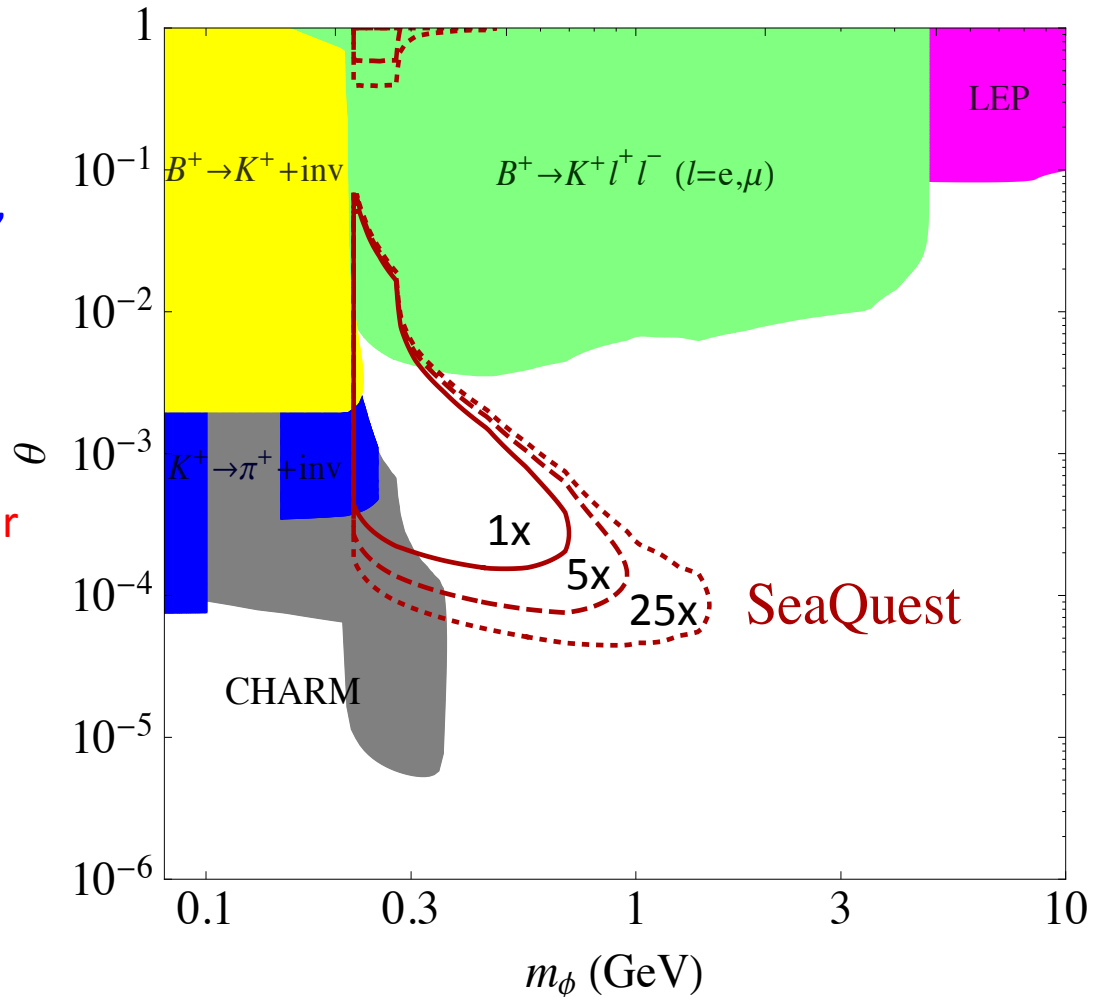


E-1067 Dark Higgs Sensitivity

POT: 1.4×10^{18} (Phase-I)

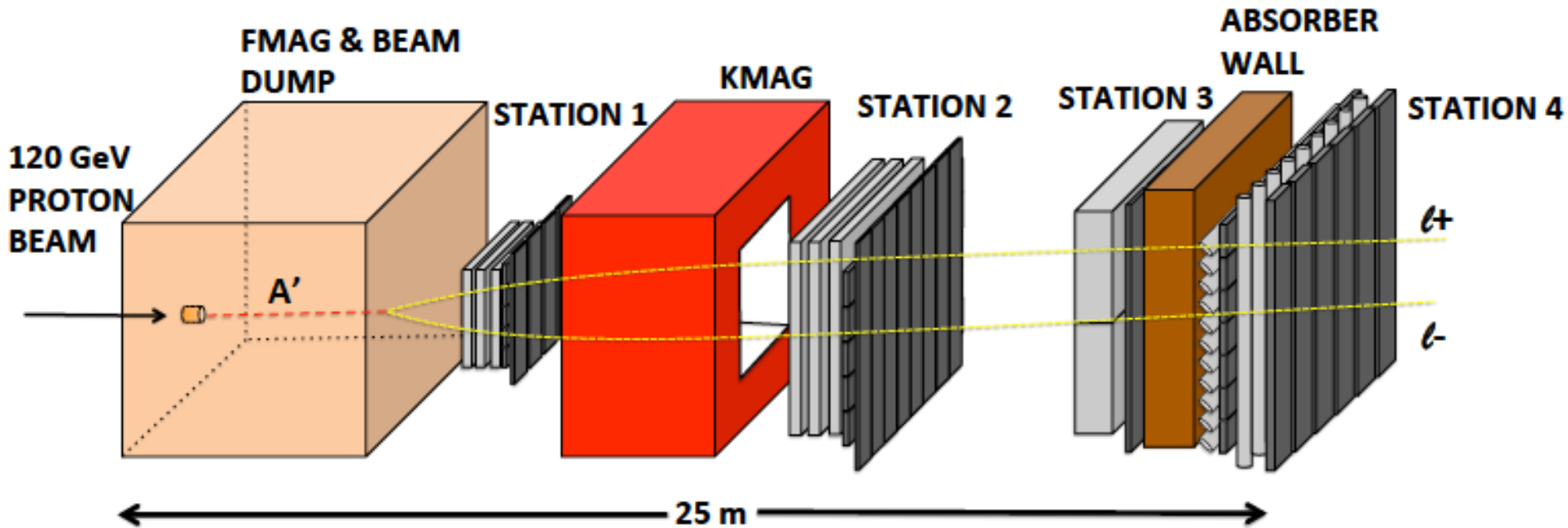
Y. Zhang (2015)

- 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
- Phase-II
 - Dedicated high luminosity runs optimized for low mass acceptance, $\text{mass} < 3 \text{ GeV}$



E-1067 Future Upgrade: Phase-II

2020 ~ 2025+ ?



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

Add tracking close to "target" to improve mass resolution

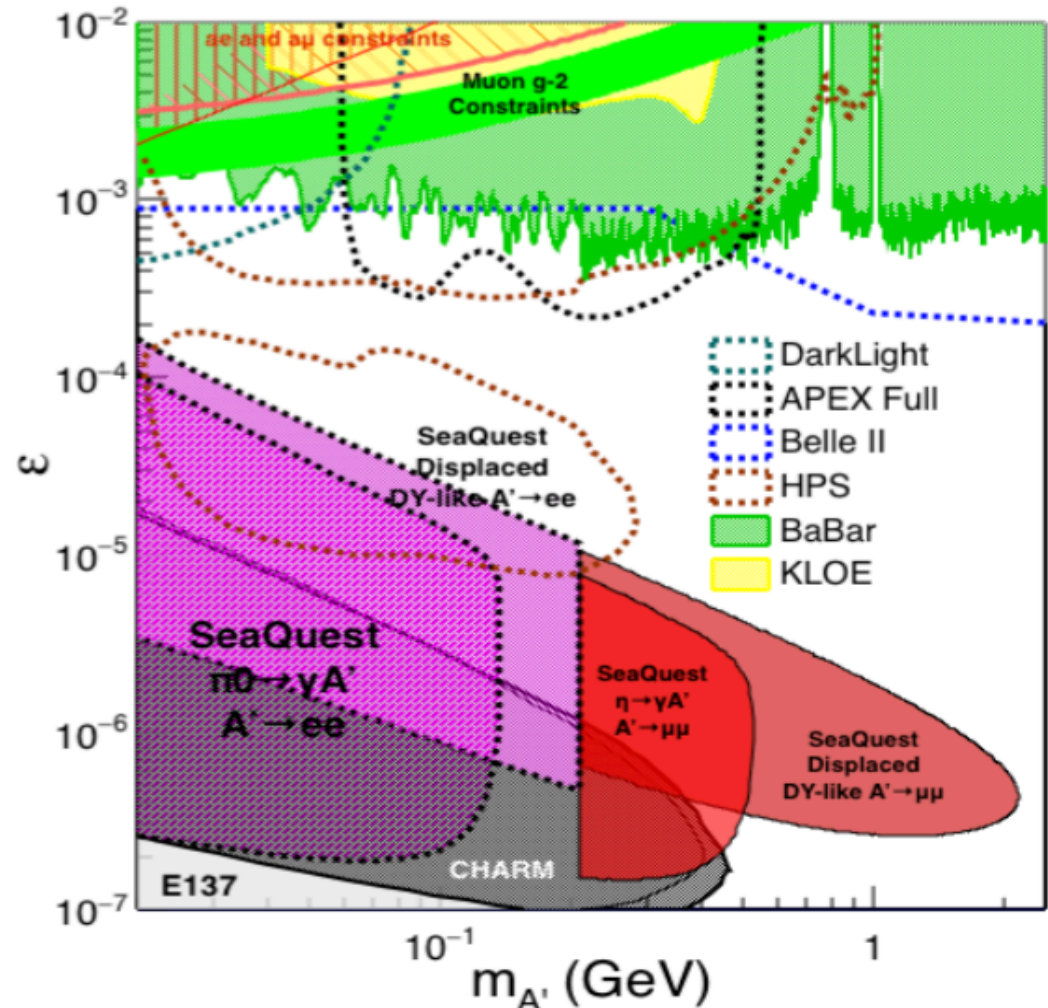
Add EMCal + Hcal, PID?
 $e^{+/-}, h^{+/-}, \pi^{+/-}$

Phase-II: Displaced Dark Photons

with future detector “EMCal/HCal” upgrades

Projection: POT 1.4 x 10¹⁸

- Detector upgrades
 - EMCal: $e^{+/-}$
 - HCal: $\pi^{+/-}$
 - Recycle from other experiments, PHENIX/RHIC etc
- DAQ upgrade
 - 100+ kHz
- Timeline of dedicated runs
 - 2020+
- Detector configuration
 - Access low mass region with optimized Fmag setting



EMCal from PHENIX/RHIC: this Year!

- 2 EMCal sectors are available from PHENIX experiment at RHIC, ~Sept/Oct 2016

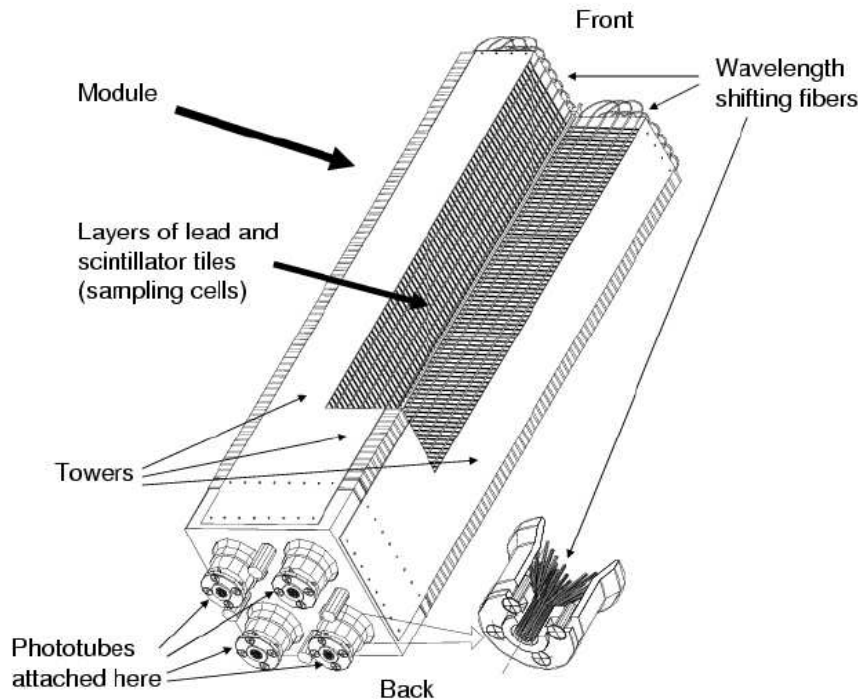
- $dE/E = 8.1\%/\sqrt{E} + 2.1\%$
- $dT < 200$ ps
- *Excellent e/π separation*

– A sector:

- 2m x 4m, 18 (3x6)super modules
- Super module = 36 modules
- Module = 4 towers
- 36 x 4 x 18 = 2592 channels
- Could gang 2x2 (or 3x3) into one ADC/TDC readout

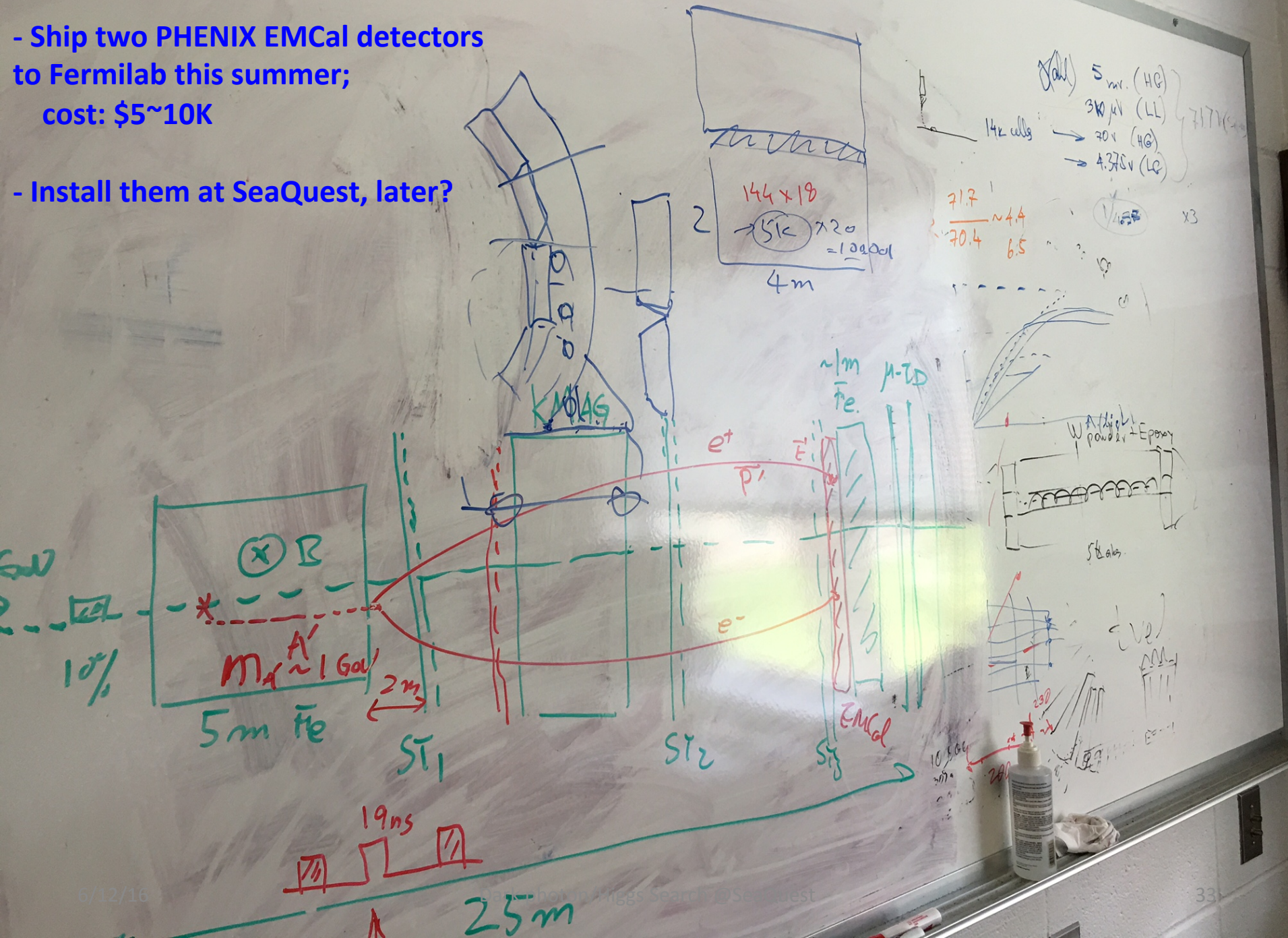
Individual Pb-Scintillator Calorimeter Tower Parameters

Parameter	Value
Lateral Segmentation	$5.535 \times 5.535 \text{ cm}^2$
Active Sampling Cells	66
Scintillator	Polystyrene (1.5% PT / 0.01% POPOP), 0.4 cm
Absorber	Pb, 0.15 cm
Cell Thickness	0.56 cm (0.277 X_0)
Active Depth	37.5 cm
Radiation Length	18
Nuclear Interaction Length	0.85
WLS Fiber	BCF-99-29a, 0.1 cm
WLS Fibers per Tower	36
PMT Type	FEU115M, MELS, Russia, 3.0 cm
Photocathode	Sb-K-Na-Cs
Luminous Sensitivity	$\geq 80 \mu\text{a/lm}$
Rise Time (20%–80%)	≤ 5 ns

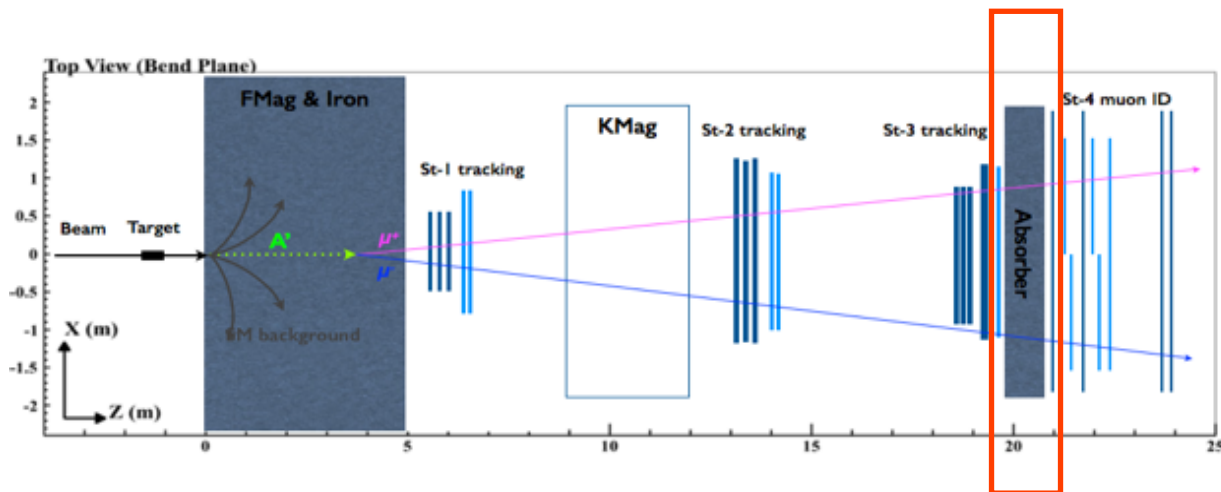


- Ship two PHENIX EMCal detectors
to Fermilab this summer;
cost: \$5~10K

- Install them at SeaQuest, later?



Two Possible Configurations and Their Impacts



Two configurations:

Option I: use EMCal to replace the absorber

Option II: insert EMCal between H3 and absorber (will need to slightly adjust station-3 position)

Test MC samples (for each scenario):

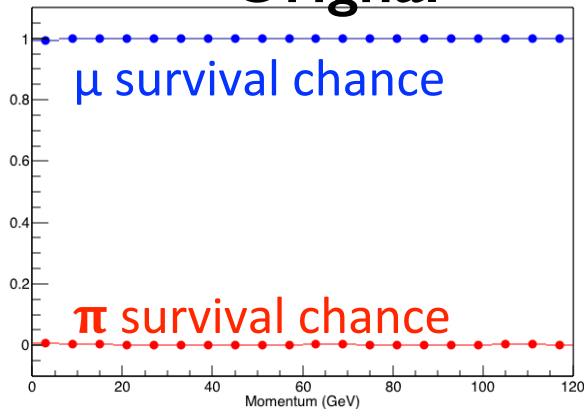
- 500k single $\pi/\mu/e$ tracks with $5 \text{ GeV} < P < 115 \text{ GeV}$
- 1M high mass ($M > 4 \text{ GeV}$) target DY pairs
- $2\text{E}10$ inclusive pp collisions (see, *MC simulation talk by David K.*)

Potential impacts on our primary physics goal:

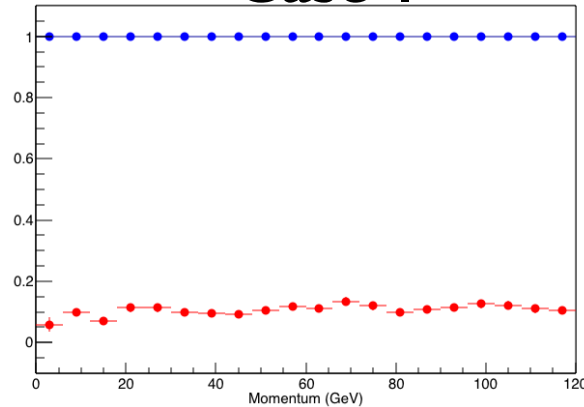
- Muon identification power
- Acceptance? (*MC shows no impact*)
- Occupancy in station-4 and thus our raw trigger rate
- Data volume and DAQ deadtime?

μ/π separation: case 1 vs. case 2 vs. original

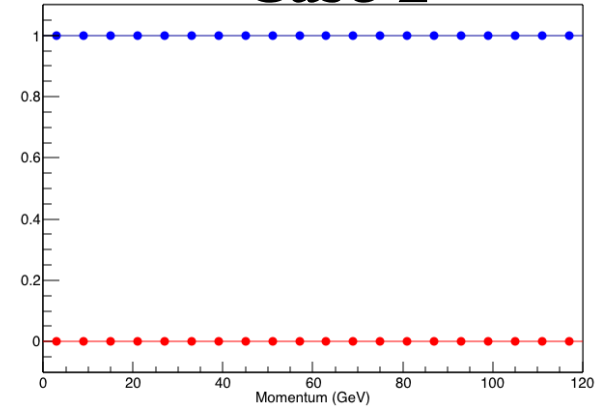
Original



Case 1



Case 2

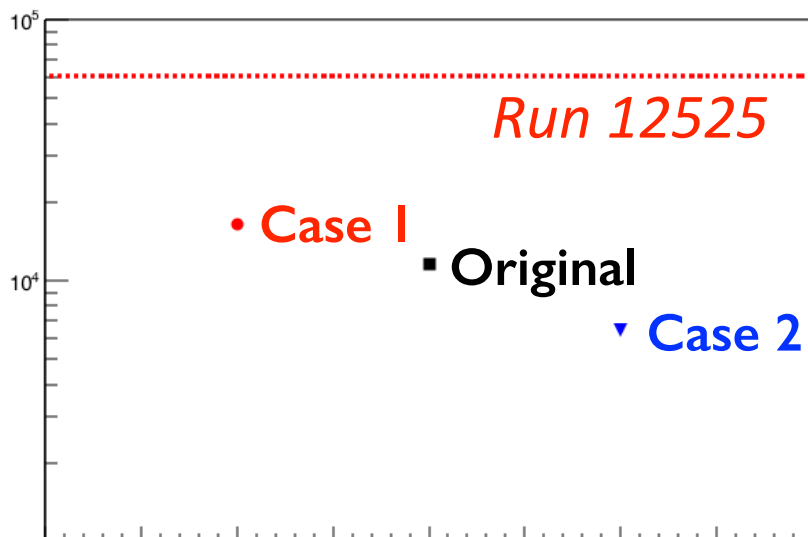


- For μ survival chance (or μ -ID efficiency), all 3 cases are very close to 100%
- For π survival chance (or π contamination):
 - original design is around 0.5%
 - case 1 is around 10%
 - case 2 is around 0.1%

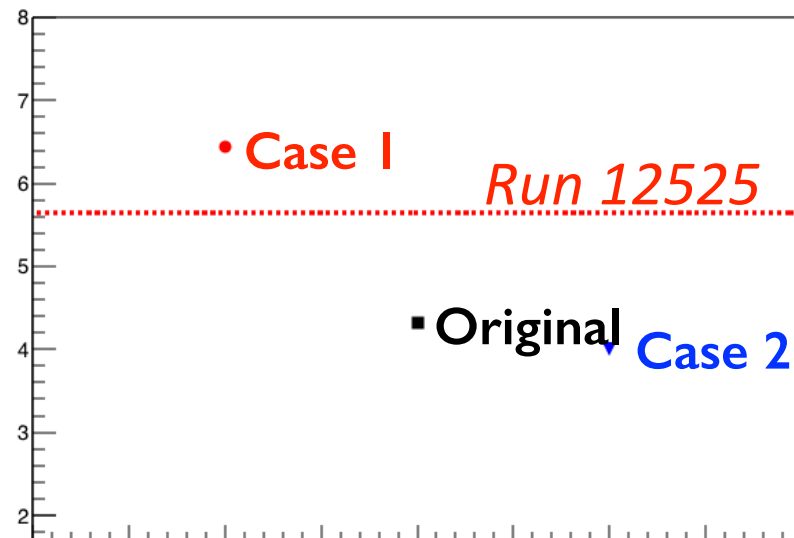
μ identification favors case 2

Station-4 occupancy: case 1 vs. case 2 vs. original

Avg. RawMATRIX1 per spill



Avg. H4T occupancy per MATRIX1 event



- In terms of both raw trigger rate and station-4 occupancy, case 2 works much better than case 1
- By adding EMCal between station-3 and absorber (case 2), we could also slightly improve w.r.t our current design

Station-4 occupancy and raw trigger rate favors case 2

Extra DAQ requirements: case 1/2 vs. original

If fully instrumented, 2 sectors of EMCal add 5184 channels to our DAQ:

- $5184/64 = 81$ new TDCs
- $81/7 = 12$ new VME crates (includes 12 new ROCs and trigger interface cards)
- data volume per event will be increased by $\sim 5\%$ (based on simulation)

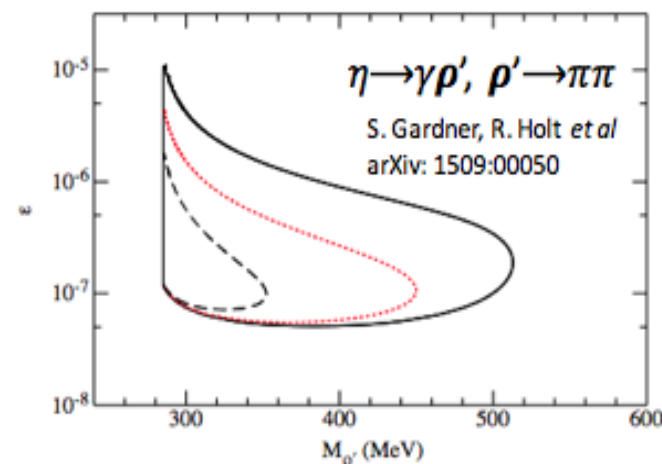
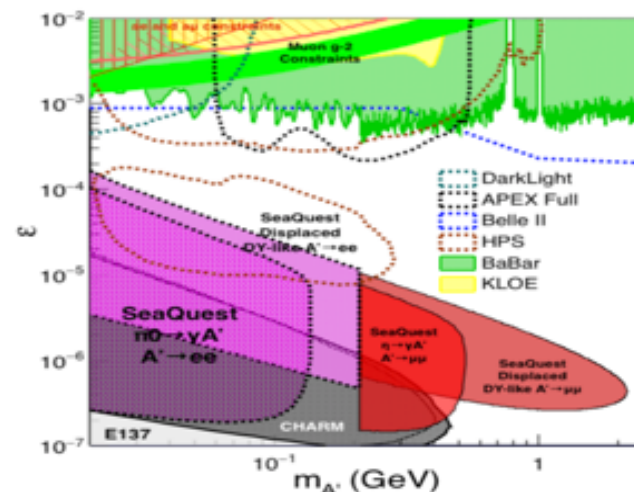
If 4 towers are ganged together, total number of channels reduced by a factor of 4:

- $1296/64 = 21$ new TDCs
- $21/7 = 3$ new VME crates (includes 3 new ROCs and trigger interface cards)
- data volume per event will be increased by $\sim 3\%$

Adding EMCal requires significant amount of extra electronics; but adds very little deadtime, this is good!

Summary: EMCal Upgrade

- 2 sectors (4×4 m² coverage) PHENIX EMCal will be available after this summer almost for free (not including shipping and instrumentation)
- With EMCal installed, we will be able to access:
 - dark photon from π^0 decay
 - dark ρ decays to $\pi\pi$
 - enhanced dark higgs sensitivity
- Two different scenarios of including EMCal have been studied via MC, and it poses little impact to our primary physics goal
- Potential bonus of better background rejection on trigger level (studies underway).

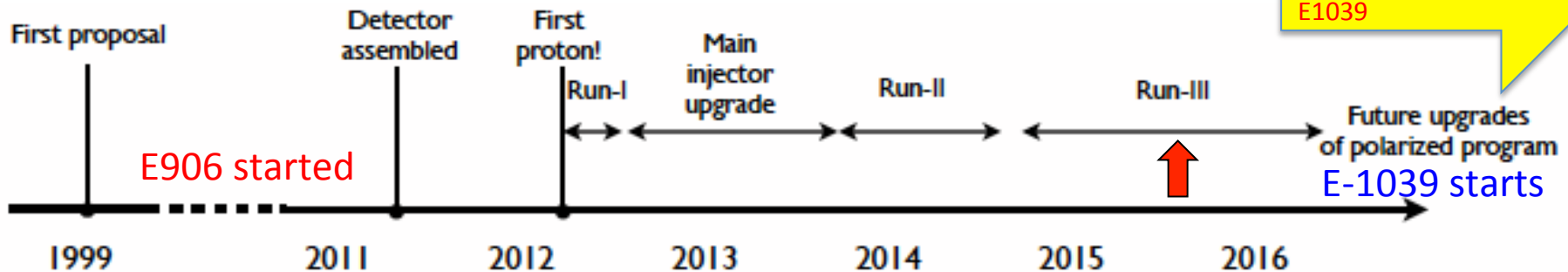


Schedules of SeaQuest Experiments

- E-906 complete data taking in summer 2017
 - Summer shutdown 8/1-11/6, 2016
- **E-1067 Timeline – Dark photon/Higgs Search!**
 - Phase-I (Parasitic run) with E906/E1039: 2017-2019
 - (Phase-II: detector upgrades and dedicated runs)
- E-1039 will replace current E906 targets with a polarized NH_3 target.
 - No change to E906 spectrometer setup
 - New target located about 3.5m upstream of the beam-dump, $\sim 6\% \lambda_1$.
 - Target/trigger installation: 2016 - 2017
 - Data taking: 2017 – 2019
- E-1027 polarized Main Injector (future)

A lot of upgrade tasks can be achieved this summer before next run!

- DAQ upgrade
- Trigger upgrade
- (EMCal)

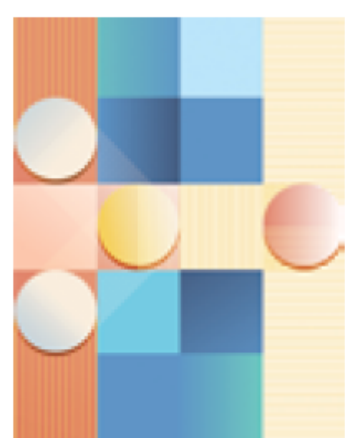
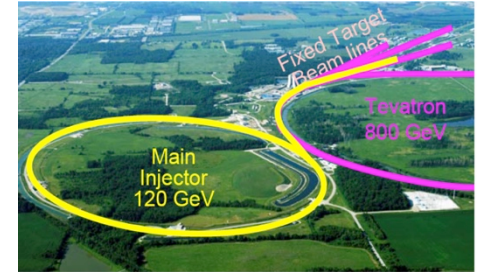


backup

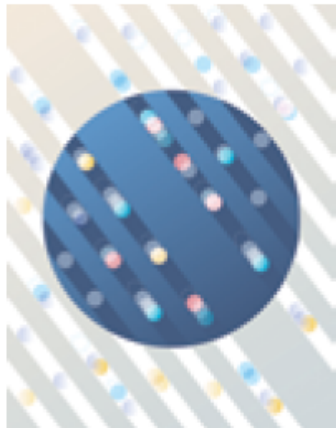
2014 US P-5 Report

Five intertwined scientific Drivers were distilled from the results of a yearlong community-wide study:

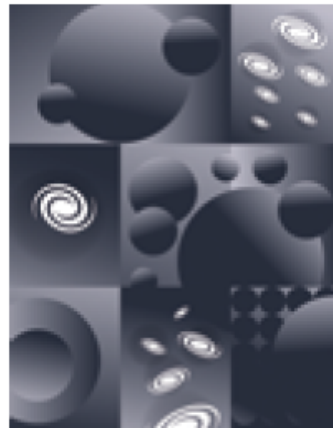
- Use the Higgs boson as a new tool for discovery 😊
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter 😊
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles 😊



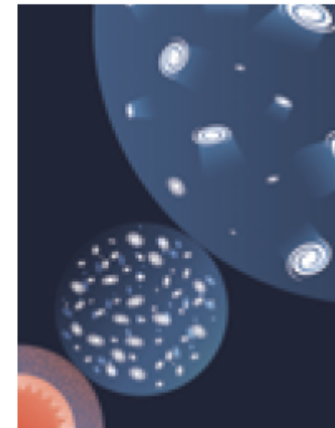
Higgs boson



Neutrino mass



Dark matter



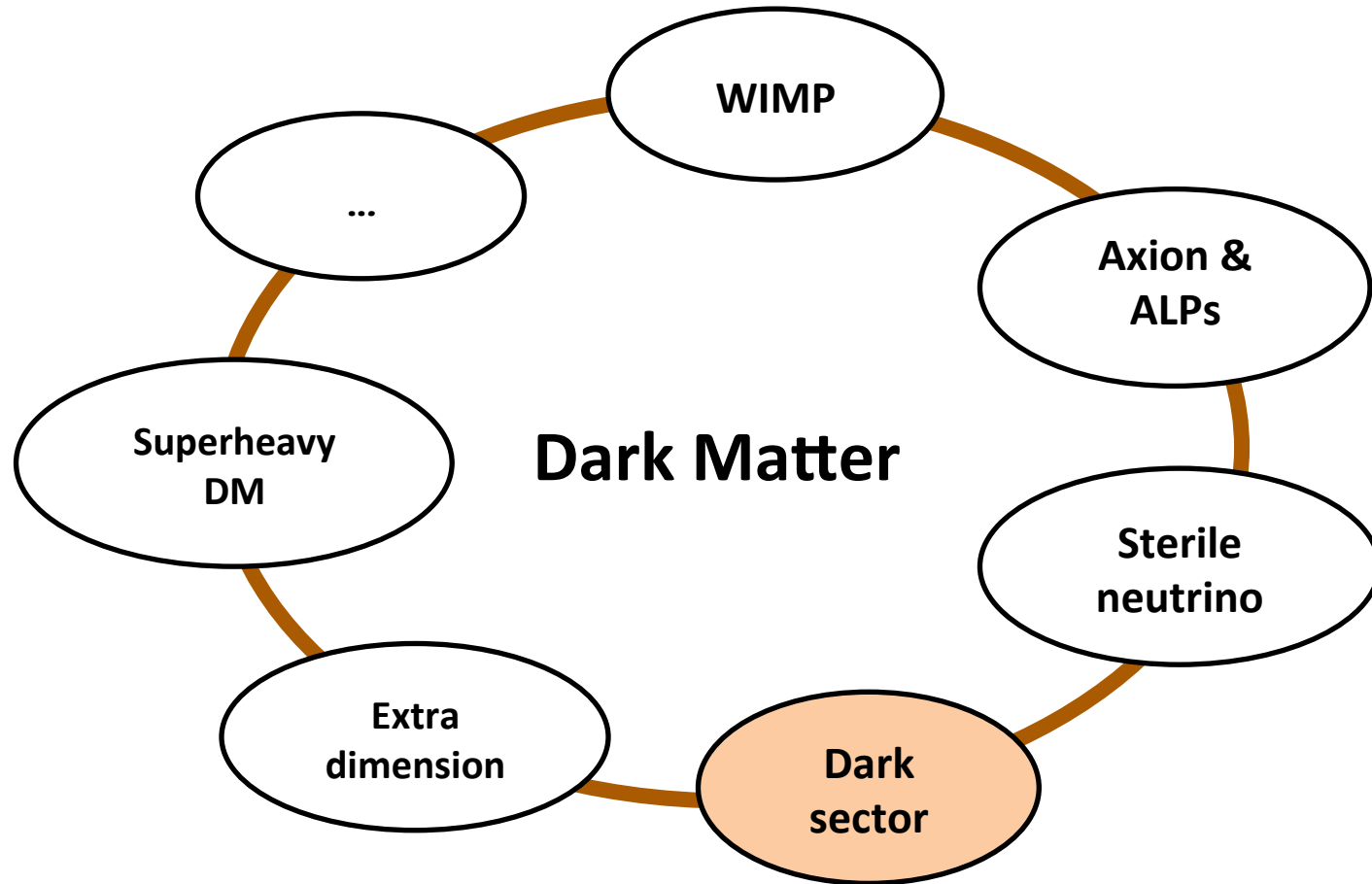
Cosmic acceleration



Explore the unknown

Great Opportunities at the Fermilab Intensity Frontier!!!

What is Dark Matter?



Recent results from the LHC and direct detection experiments “challenge” the traditional WIMP paradigm and motivate the exploration of new ideas.

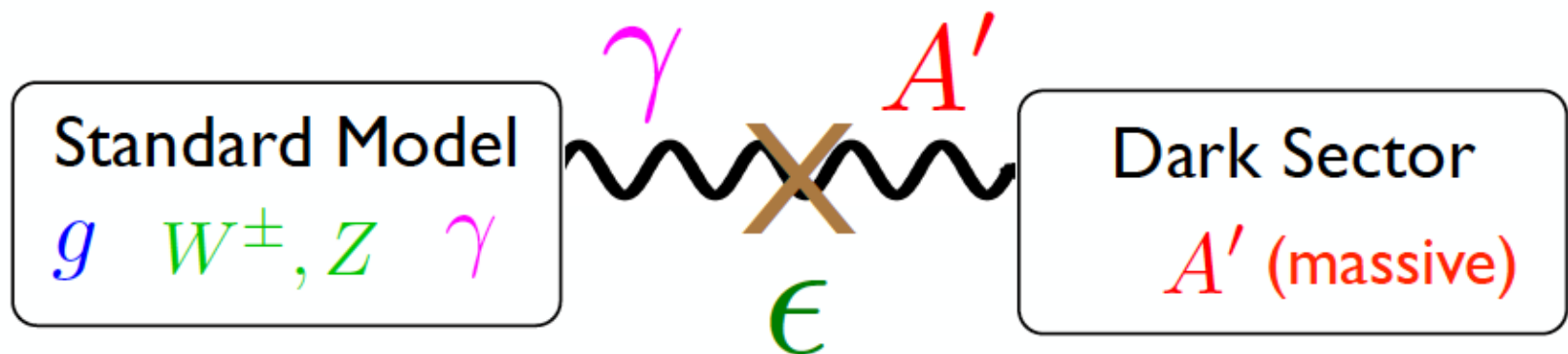
Vector Portal and Dark Photon

A simplest model of dark sector

- An extra $U(1)_X$, kinetic mixing
- Not suppressed by mass scale

Holdom
Galison, Manohar

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times \mathbf{U(1)}_X \quad \Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

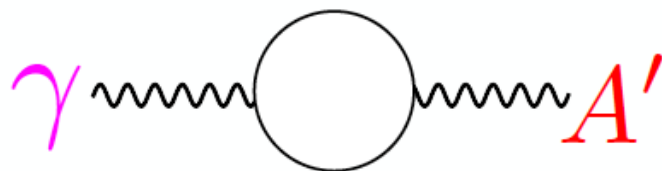


Expectations from GUT

- After EWSB, there is a coupling ϵ between the dark photon and the photon (also the Z, less important at low energies).
- Theoretical prejudice for a mass scale

$$m_{A'} \sim \sqrt{\epsilon} m_{EW} \sim (\text{MeV} - \text{GeV})$$

e.g. Arkani-Hamed & Weiner;
Cheung, Ruderman, Wang, Yavin;
Morrissey, Poland, Zurek;
Essig, Schuster, Toro;



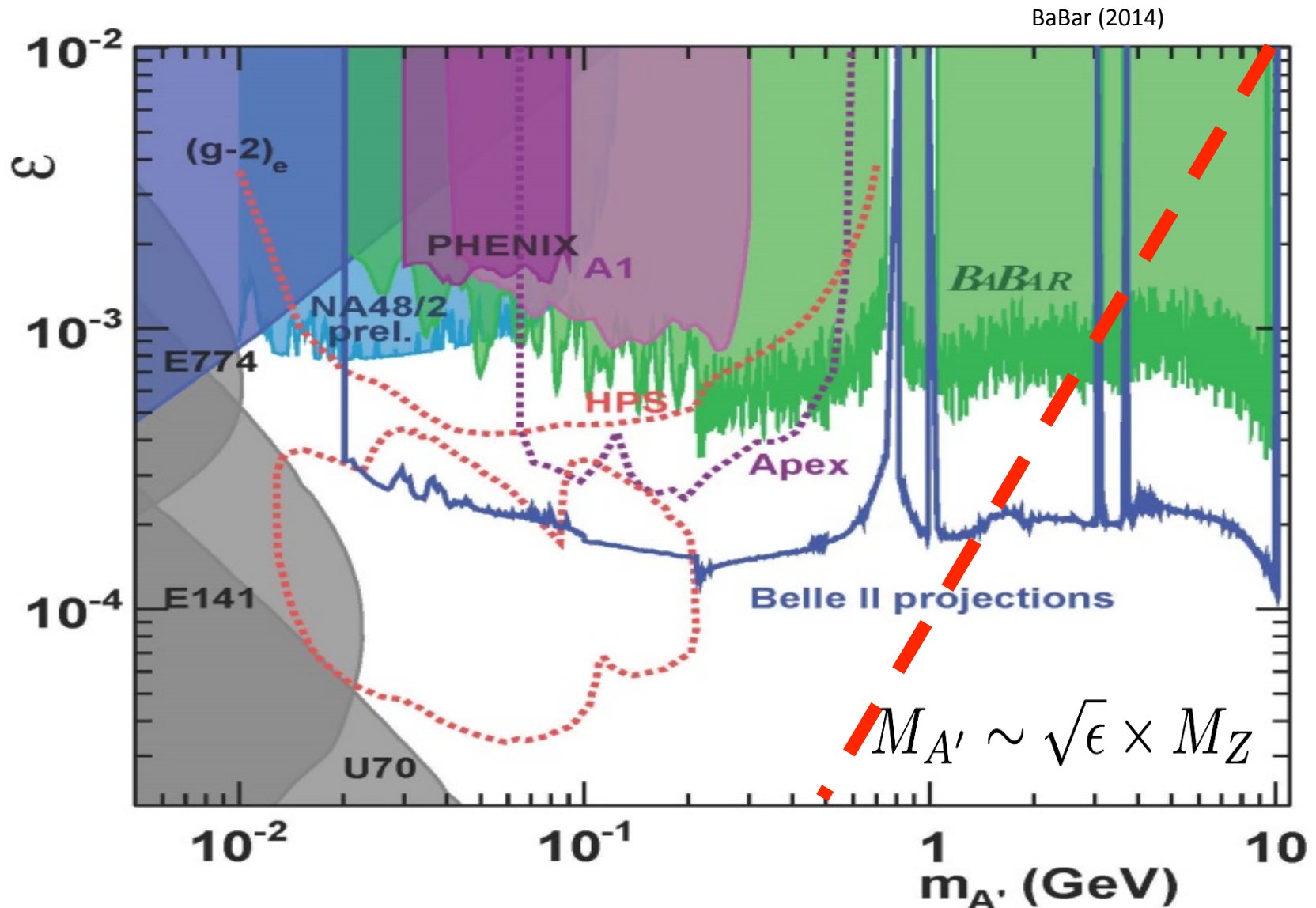
$$\epsilon \sim \frac{g_Y g_D}{16\pi^2} \ln \left(\frac{M}{M'} \right)$$

$$\sim 10^{-3} - 10^{-1}$$



$$\epsilon \sim 10^{-5} - 10^{-3}$$

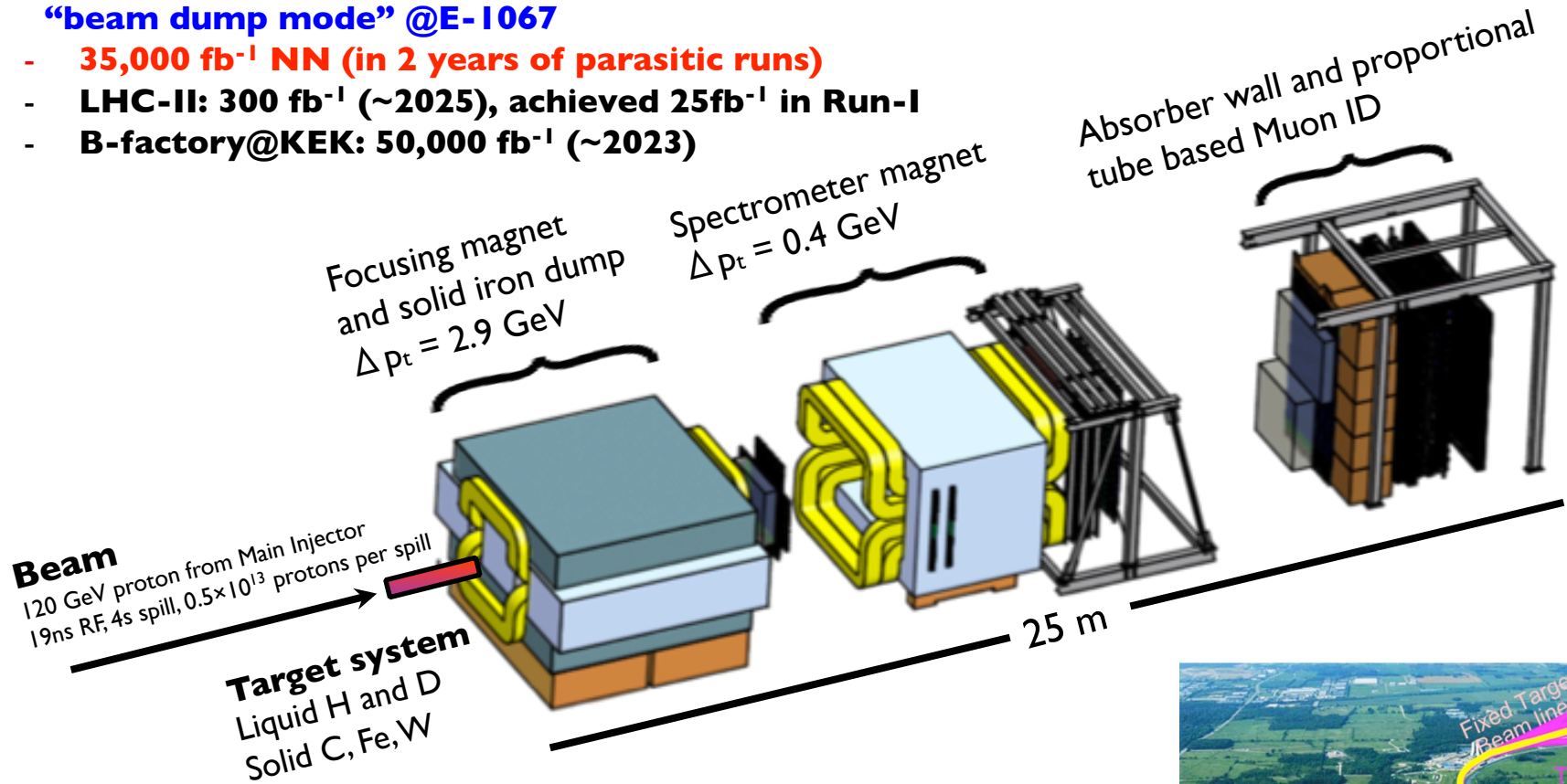
Current Limits on Dark Photon Search



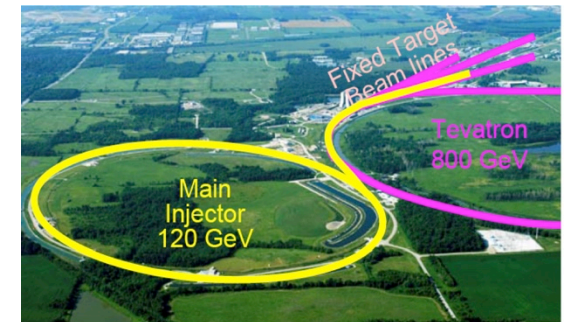
Intensity Frontier at Fermilab: 120 GeV Beam

**World's highest intensity high energy proton beam:
"beam dump mode" @E-1067**

- **35,000 fb⁻¹ NN (in 2 years of parasitic runs)**
- **LHC-II: 300 fb⁻¹ (~2025), achieved 25fb⁻¹ in Run-I**
- **B-factory@KEK: 50,000 fb⁻¹ (~2023)**



- Capture most beam in beam dump mode: p+Fe collisions!
- Parasitic run mode possible with other experiments, E906/E1039



A New High-Granularity Displayed Dimuon Vertex Trigger

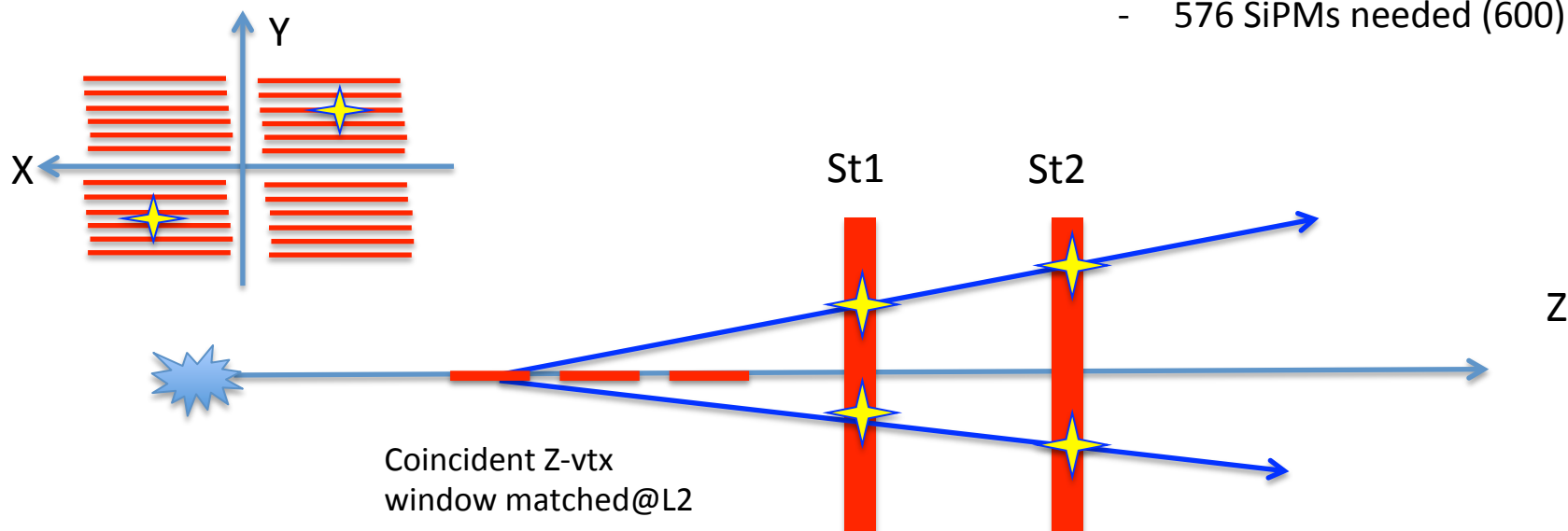
High rejection power, very low rate, $\ll 1$ kHz (E906 DAQ limit)

Y-Plane Trigger:

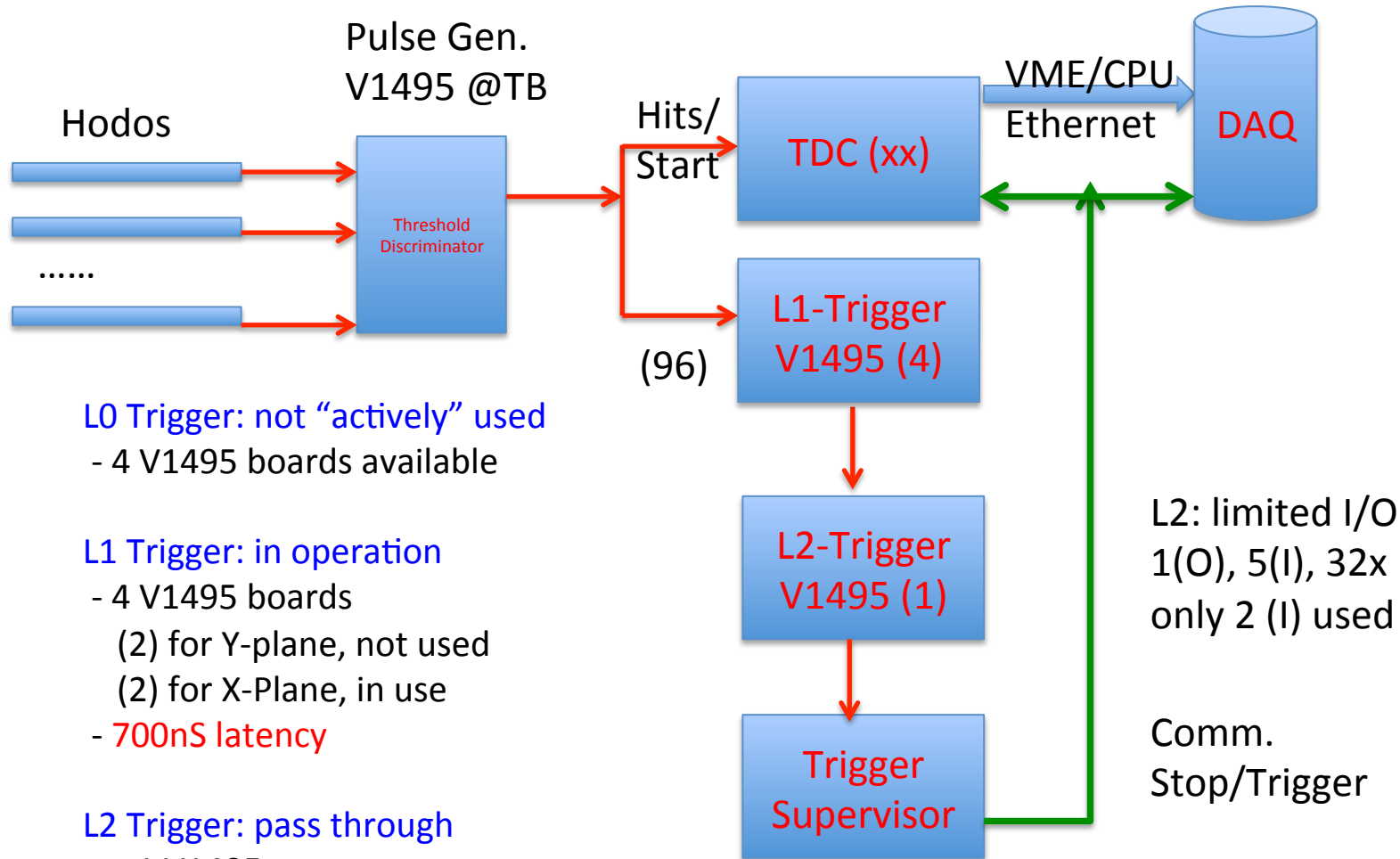
- A quadrant panel: 50cm x 50cm, 1cm thick
 - 1cm x 1cm x 50 cm scintillating strips, SiPM readout
- Straight line projection, 30cm Z-vertex resolution
- Displaced z-vertex, mostly low mass $< 3\text{GeV}$
- Coincident with St-4 Hodos(muons), or EMCal($e^{\pm}$)

Y-channels per quadrant:

- 1x V1495
- $50(\text{St1}) + 50(\text{St2}) + 8 \times 2 (\text{St4-Y1,2}) = 116$
- $96 + 64 = 160$ inputs possible
 - $72 + 72 + 16 = 160$ (possible)
 - (2NIM=RFCLK+ComSTOP)
- Bigger one?!, 72 channel per Q/station
 - 576 SiPMs needed (600)



Current E906 Trigger & DAQ System



L0 Trigger: not “actively” used
- 4 V1495 boards available

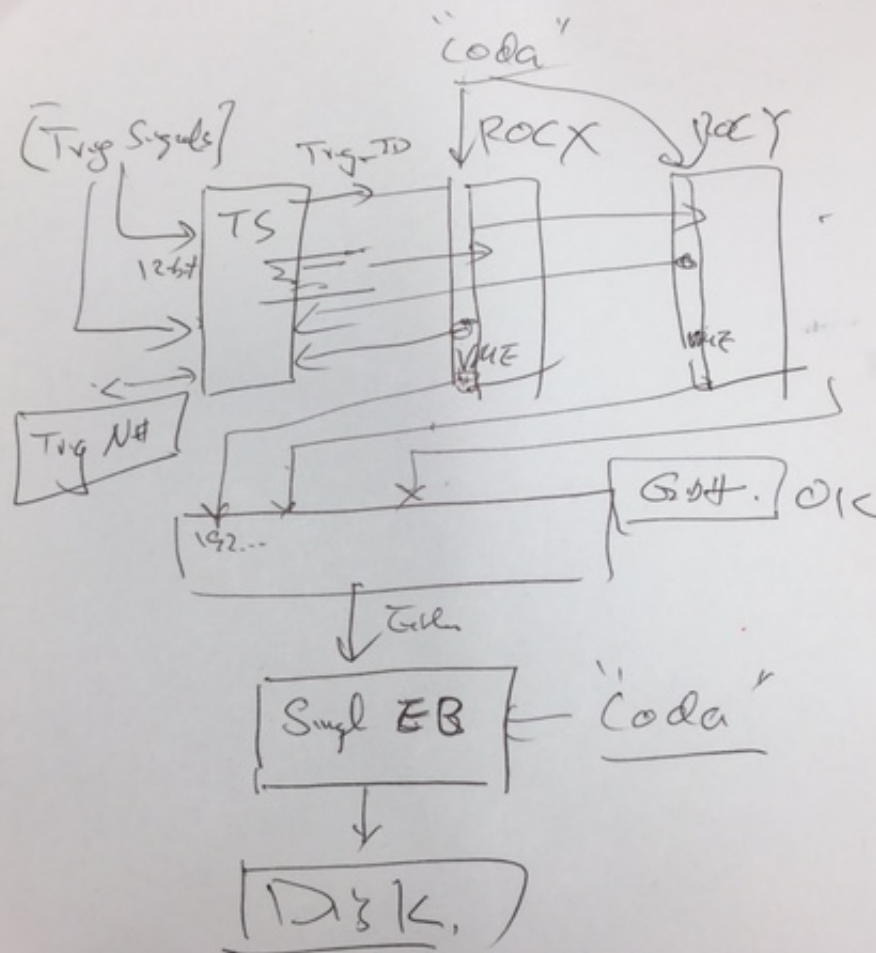
L1 Trigger: in operation
- 4 V1495 boards
 (2) for Y-plane, not used
 (2) for X-Plane, in use
- 700nS latency

L2 Trigger: pass through
- 1 V1495
- Could do simple look-up

TS: Trigger Supervisor

L2: limited I/O
1(O), 5(I), 32x
only 2 (I) used

Comm.
Stop/Trigger

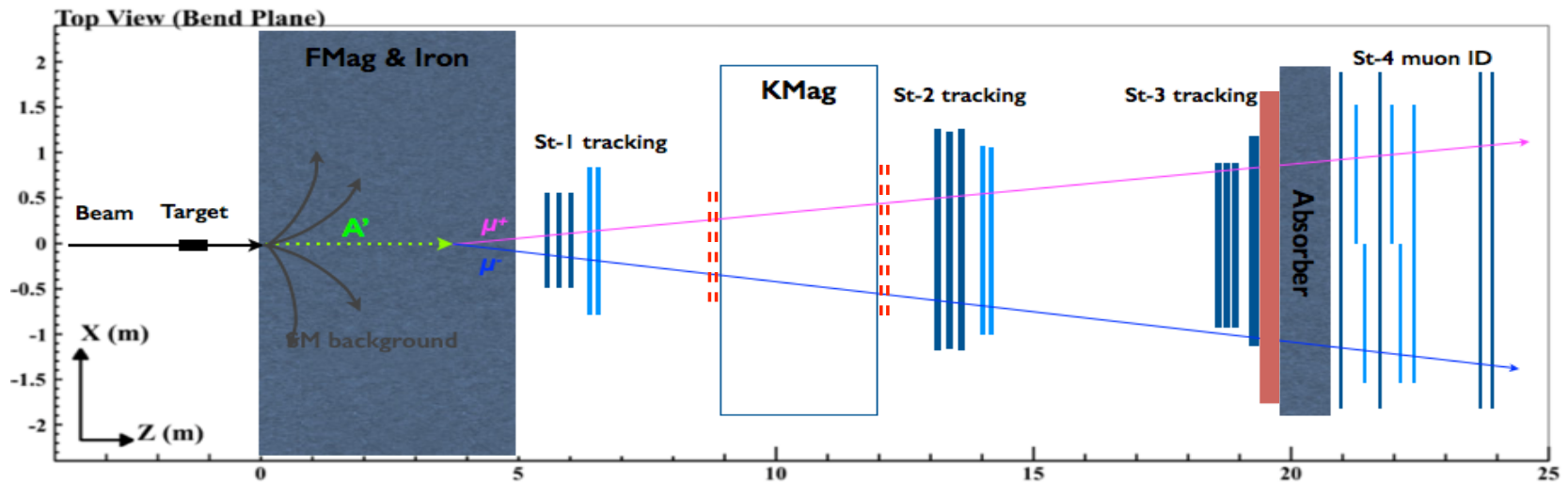


2 Altara FPGA Chips: Cyclone-V

Trigger lookup table



Future E1067 Upgrades



Fine-pitched vertex trigger

- Efficiently trigger on the dilepton pairs generated from downstream while suppressing the background rate
- Significantly enlarge the fiducial region from $\sim 2\text{m}$ to $\sim 6\text{m}$
- Supported by LANL LDRD

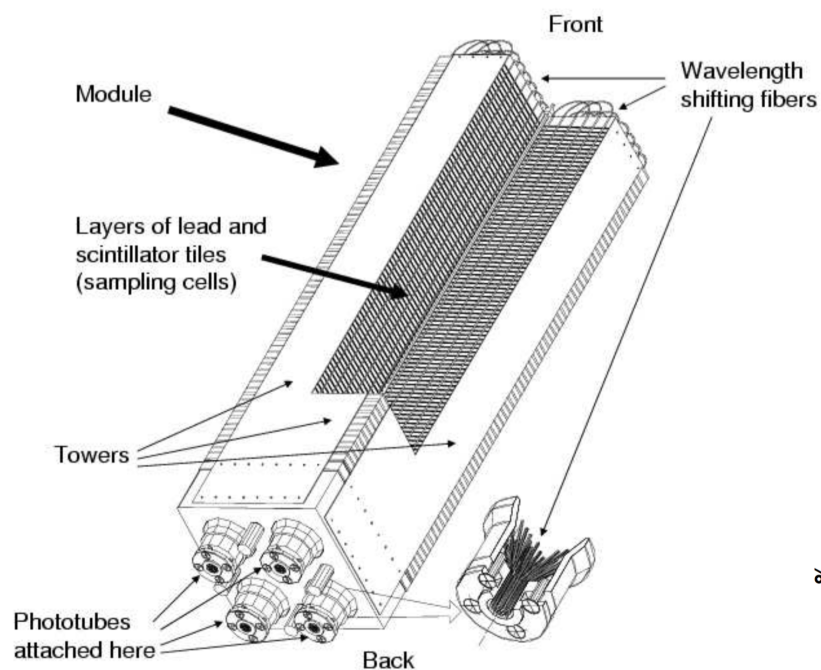
EMCal/HCal

- Add $e^{+/-}$ and $\pi^{+/-}$ capabilities to SeaQuest spectrometer
- Extend the physics reach to A' from π^0 decay, dark ρ , and hadronic decay mode for heavier A'
- Re-commission the existing detectors (EMCal from PHENIX being considered)

***Modest upgrades with significantly increased physics reach.
Data taking expected to start in summer 2017!***

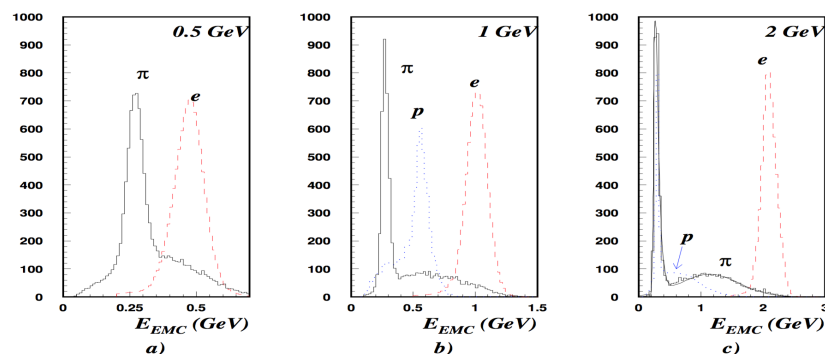
PHENIX EMCa1

2 sectors available in this summer!

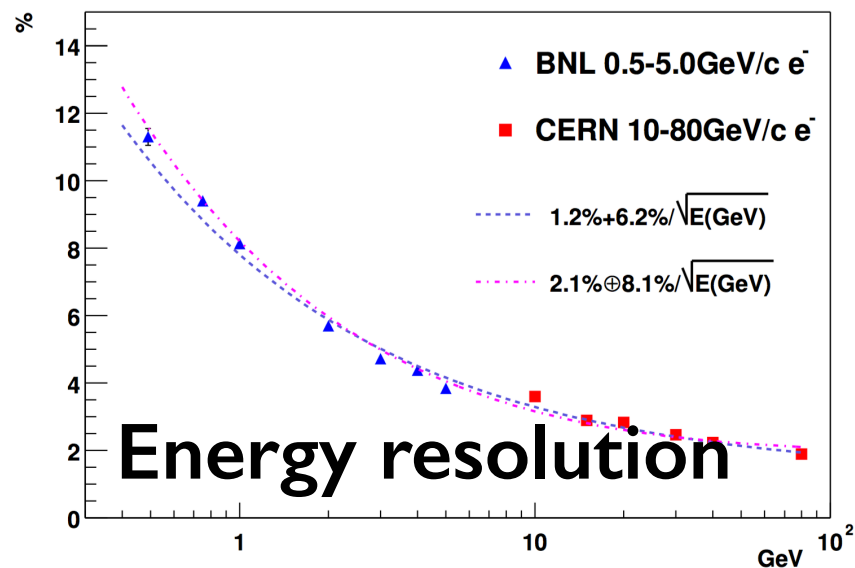


Key specs:

- Tower size: $5.525 \times 5.535 \text{ cm}^2$
- Number of towers per sector: 72×36
- Active sampling cells: 66
 - Scintillator: Polystyrene, 0.4 cm
 - Absorber: Pb, 0.15 cm
- Active depth: 37.5 cm
- Radiation Length: 18
- Nuclear Int. Length: 0.85

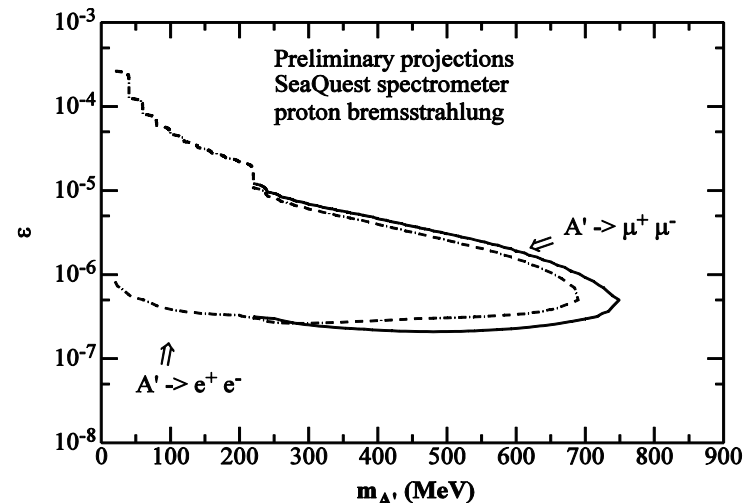
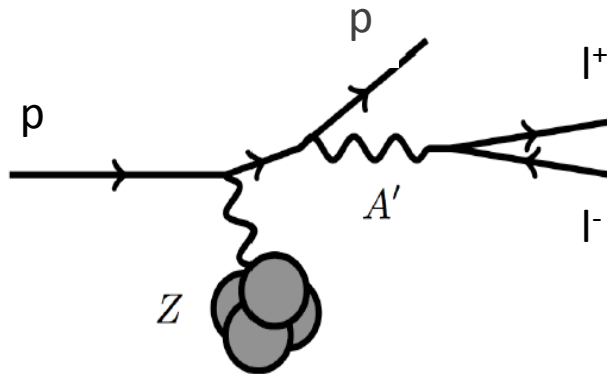
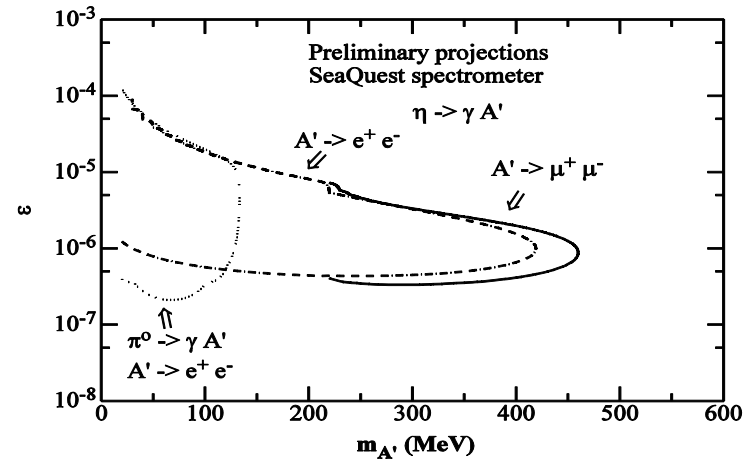
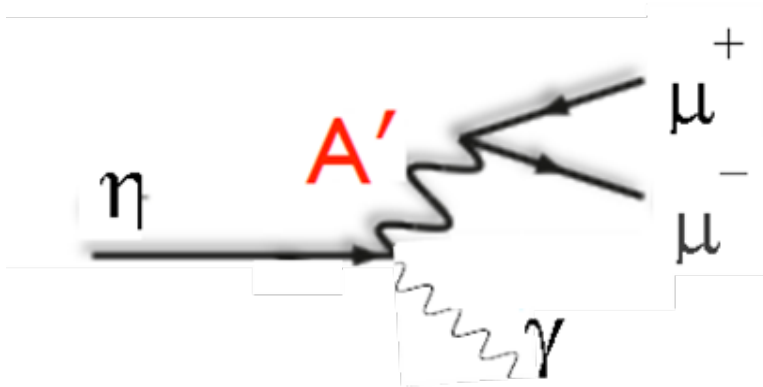


π/e separation



Phase-II: Access Low Mass Region with e^+e^- with future detector upgrades

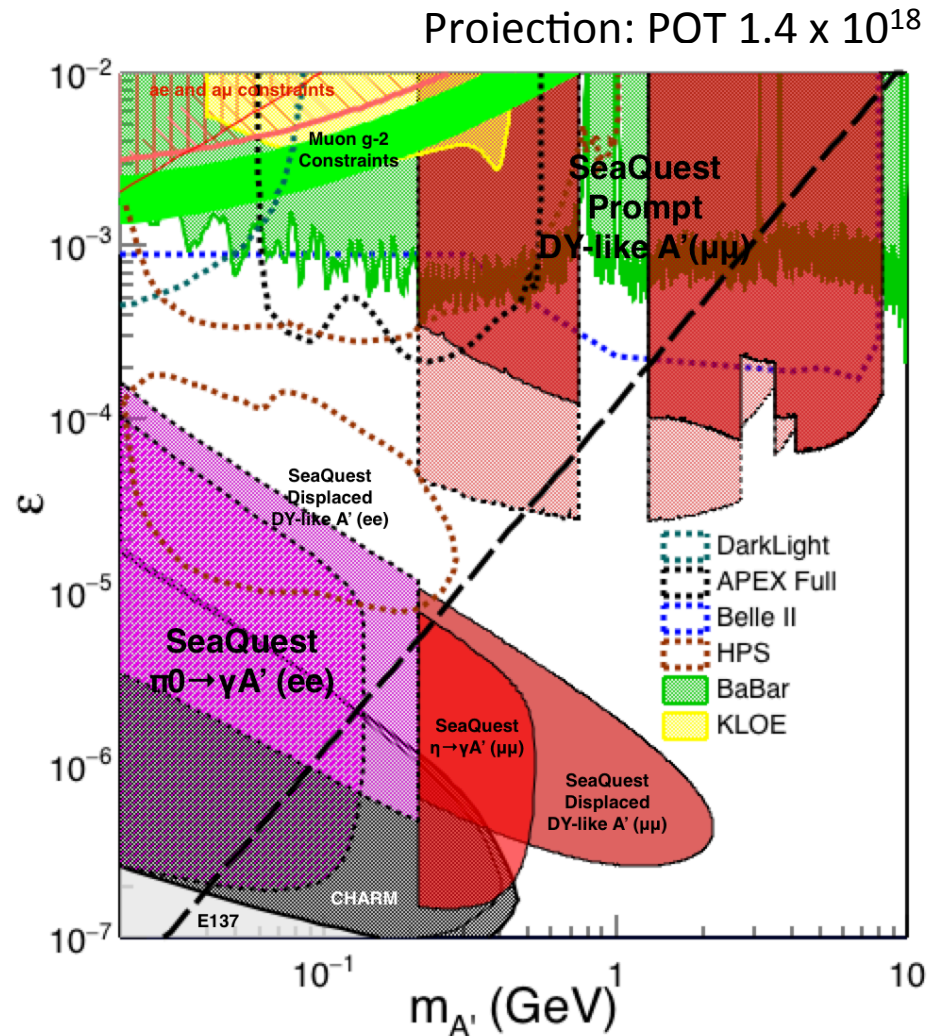
S. Gardner, R. Holt et al



Phase-II: Full Coverage

with future detector “EMCal/HCal” upgrades

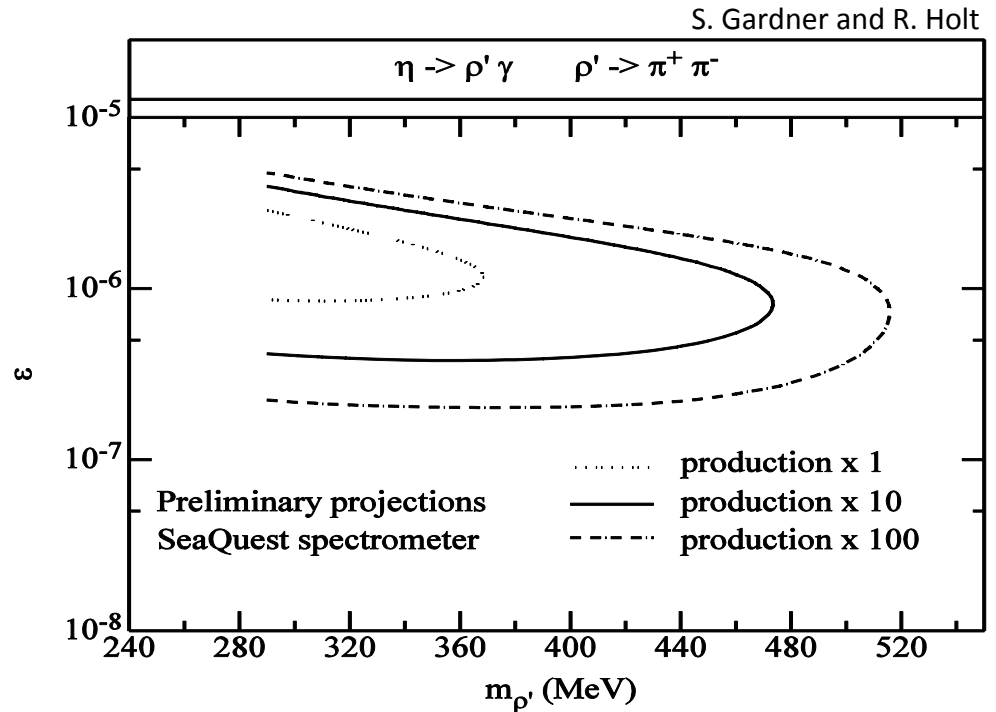
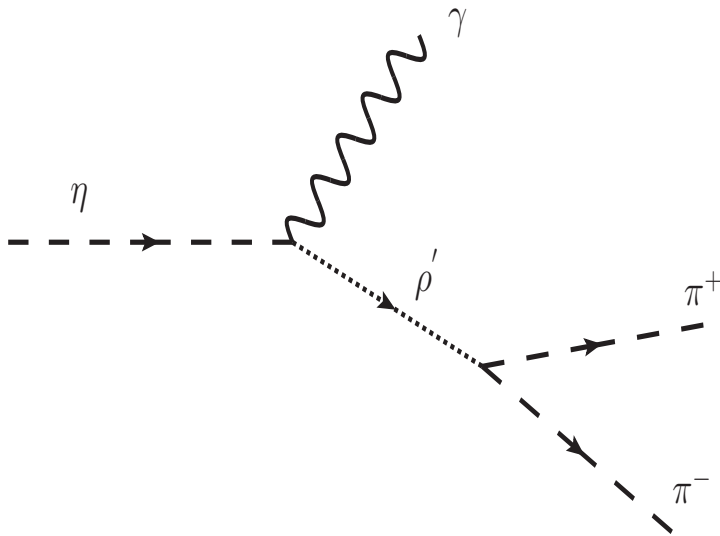
- **Detector upgrades**
 - EMCal: $e^{\pm}$
 - HCal: $\pi^{\pm}$
 - Recycle from other experiments, RHIC/JLab etc.
- **DAQ upgrade**
 - 100 kHz
- **Timeline of dedicated runs**
 - 2019+
- **Detector configuration**
 - Access low mass region with optimized Fmag setting



Phase-II: Probe Non Abelian Dark Sector

with future detector “HCal” upgrades

non-Abelian dark sector process



[Note: Batell, Pospelov, and Ritz, PRD 80 (2009) 095024 for a review re fixed target expts.]

Here we consider a non-Abelian (gluon) portal

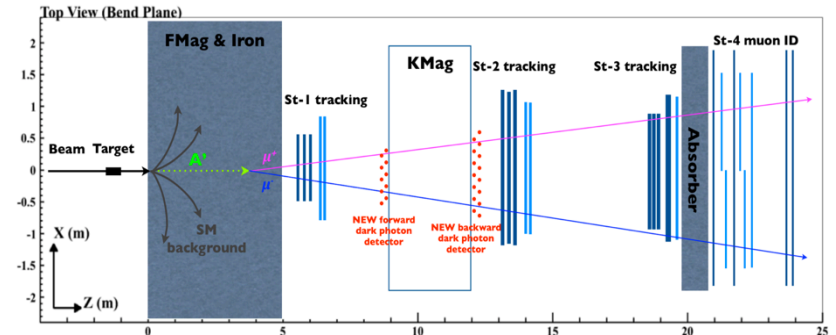
[Baumgart et al., JHEP 0904, 014 (2009); Gardner and He, PRD 87 (2013) 116012]

The “shining through walls” design – unique to Seaquest – makes this possible ,
to yield, e.g., via a “minimal” decay....

Summary and Outlook

• Phase-I

- *Great discovery potential!*
- *Add a new displayed vertex trigger*
- *Early parasitic data taking 2017-2019+*
 - *A short dedicated run up to ~1 month if needed*
- *POT 1.4×10^{18}*



• Phase-II

- *Possible detector upgrade later, add electrons and hadrons*
- *A new dedicated dark matter program at Intensity Frontier!*

