Today's Presentations

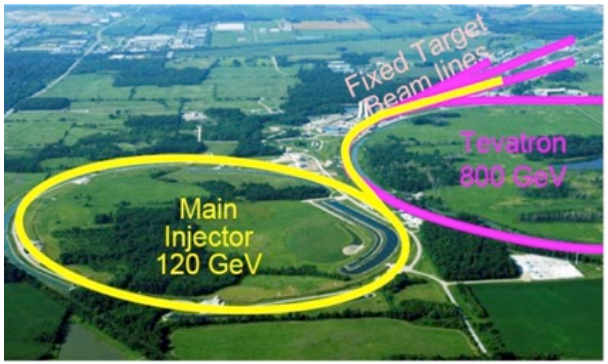
- Overview and Plan, 40+10' – Ming Liu (PI)
- Theoretical progress, 20+10' – Zhongbo Kang(T-2, co-PI)
- Experimental highlights, 20+10' – Kun Liu (P-25, co-PI)
- Open Q&As

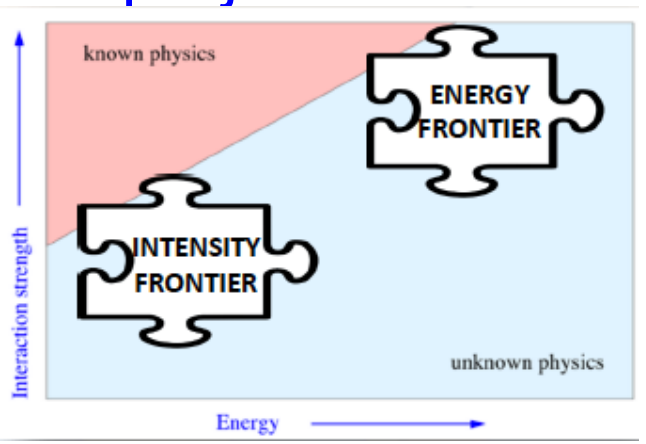
Direct Search for Low-Mass Dark Photons at Fermilab Intensity Frontier

Ming Liu (PI), Zhongbo Kang(co-PI, T-2), Kun Liu (co-PI), Hubert van Hecke, Sanghoon Lim, Pat McGaughey, Richard Van De Water, Xinkun Chu, Vincenzo Cirigliano(T-2)

LDRD/ER 20160081

A joint experimental and theoretical project

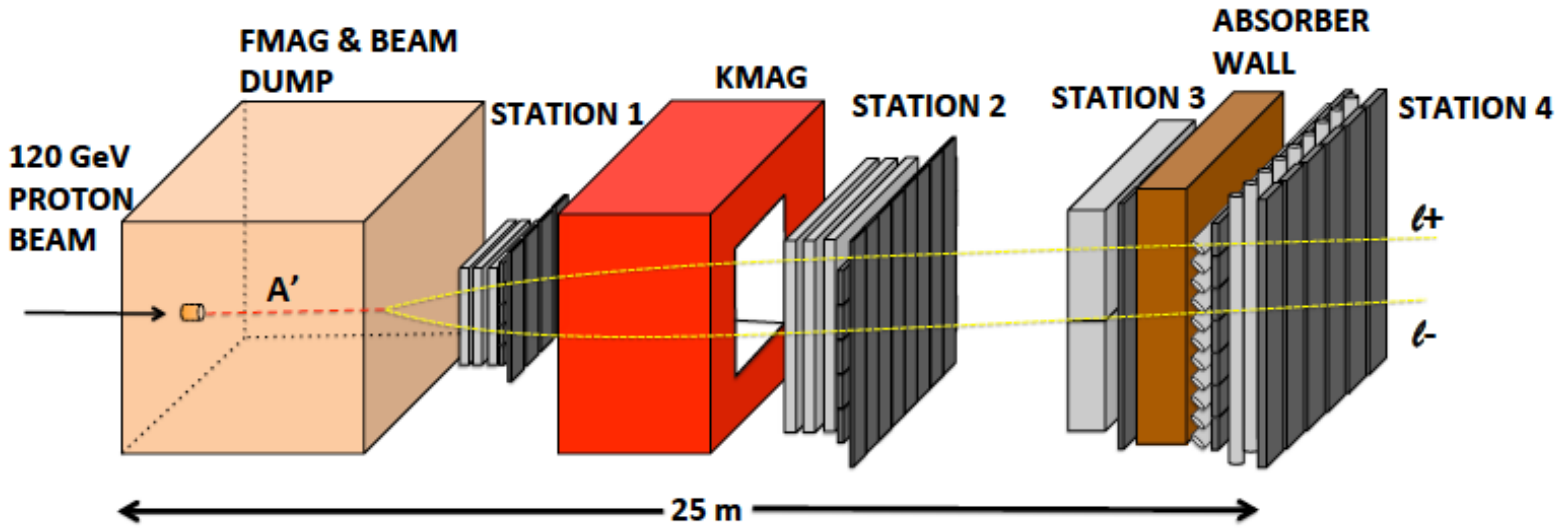




Goal of the LDRD/ER Project

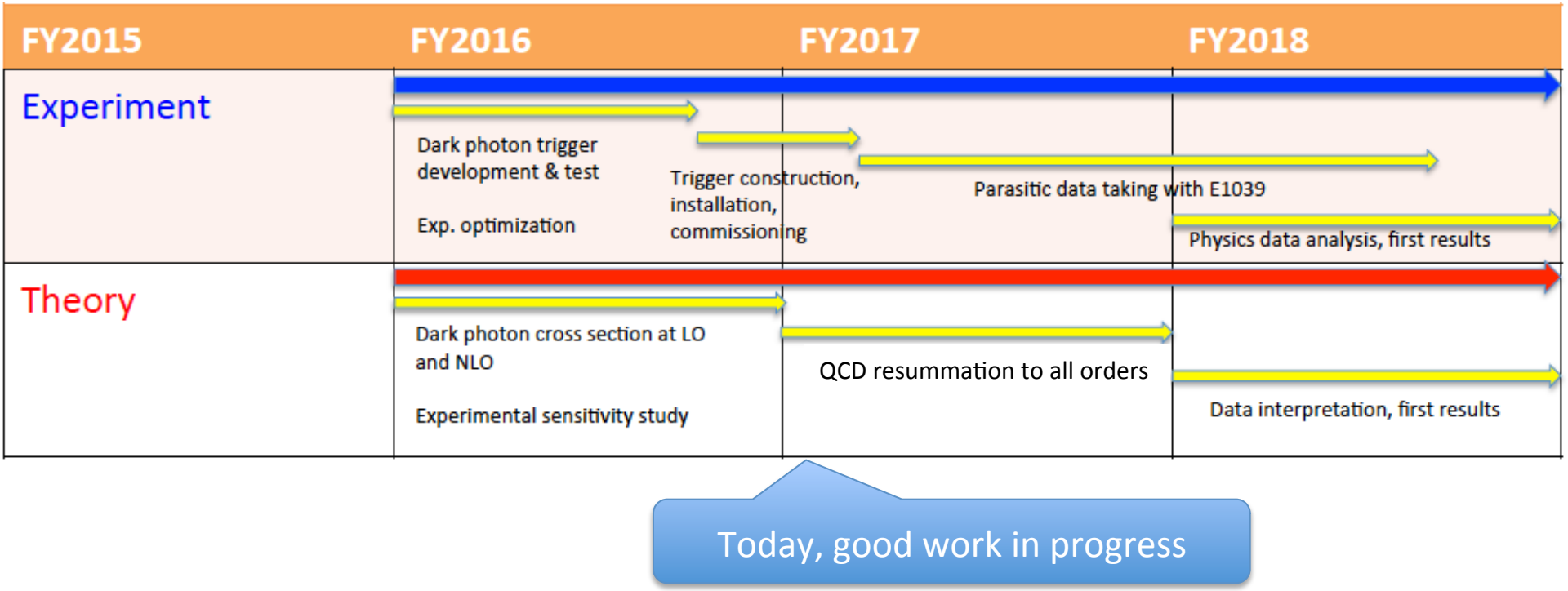
Direct search of dark photon production in the beam-dump mode using SeaQuest/ E-1067 dimuon spectrometer at Fermilab Main Injector High Intensity Frontier

- Experimental measurements
- Theoretical study of sensitivity



LDRD Tasks & Schedules

FY16: Accomplished all milestones and more!



Proposed LDRD/ER Budget: 350K/year

Date: 14-APR-2015 02.15.47 PM Los Alamos National Laboratory Pricing and Estimating Detail Report by CE#, FY, Org, Resource... ---------- &Cost Est ID Cost Est Number:20160081ER Cost Est Description:SEARCH FOR

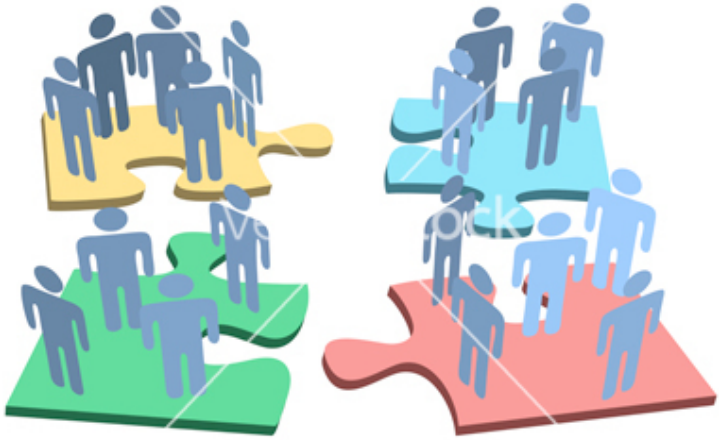
Cost Estimate ID:12841	Cost Est Number:20160081ER	Cost Est Description:SEARCH FOR LOW MASS DARK PHOTONS IN HIGH ENERGY P+A COLLISIONS AT FERMILAB	Originator Z No:167255	Originator Name:Liu, Ming Xiong	Start Date:01-OCT-2015	End Date:30-SEP-2018	Creation Date:24-MAR-2015	FY:2015

Year	Org Code	Resource Name	FTE	Hours	Base Cost	Site Burden	Prog Support	NMGRT Burden	LDRD Burden	S S Burden	G A Burden	Fee Burden	DOE FAC	Total Burden	Total Cost
2016	3R050A	Liu, Kun	0.50	912.50	50,687	8,237	0	0	0	0	5,450	0	0	13,687	64,375
		Liu, Ming Xiong	0.25	432.50	55,978	49,401	0	0	0	0	9,748	0	0	59,148	115,127
		Materials	0.00	0.00	60,000	0	0	0	0	0	5,550	0	0	5,550	65,550
		Van De Water, Richard G	0.05	86.50	12,284	10,840	0	0	0	0	2,139	0	0	12,979	25,263
	3R050A		**0.80**	**1431.50**	**178,949**	**68,478**	**0**	**0**	**0**	**0**	**22,887**	**0**	**0**	**91,365**	**270,314**
	3W200A	Cirigliano, Vincenzo	0.10	173.00	22,391	19,760	0	0	0	0	3,899	0	0	23,659	46,051
		Kang, Zhongbo	0.15	273.75	22,362	3,634	0	0	0	0	2,405	0	0	6,039	28,401
		Travel	0.00	0.00	4,500	0	0	0	0	0	416	0	0	416	4,916
	3W200A		**0.25**	**446.75**	**49,254**	**23,394**	**0**	**0**	**0**	**0**	**6,720**	**0**	**0**	**30,114**	**79,368**
2016			**1.05**	**1878.25**	**228,203**	**91,872**	**0**	**0**	**0**	**0**	**29,607**	**0**	**0**	**121,479**	**349,682**
2017	3R050A	Liu, Kun	0.50	912.50	52,208	8,484	0	0	0	0	5,614	0	0	14,098	66,306
		Liu, Ming Xiong	0.25	432.50	57,658	50,883	0	0	0	0	10,040	0	0	60,923	118,581
		Materials	0.00	0.00	50,000	0	0	0	0	0	4,625	0	0	4,625	54,625
		Van De Water, Richard G	0.05	86.50	12,652	11,165	0	0	0	0	2,203	0	0	13,369	26,021
	3R050A		**0.80**	**1431.50**	**172,518**	**70,532**	**0**	**0**	**0**	**0**	**22,482**	**0**	**0**	**93,014**	**265,532**
	3W200A	Cirigliano, Vincenzo	0.10	173.00	23,063	20,353	0	0	0	0	4,016	0	0	24,369	47,432
		Kang, Zhongbo	0.15	273.75	23,033	3,743	0	0	0	0	2,477	0	0	6,220	29,253
		Travel	0.00	0.00	7,000	0	0	0	0	0	648	0	0	648	7,648
	3W200A		**0.25**	**446.75**	**53,096**	**24,096**	**0**	**0**	**0**	**0**	**7,140**	**0**	**0**	**31,236**	**84,333**
2017			**1.05**	**1878.25**	**225,614**	**94,628**	**0**	**0**	**0**	**0**	**29,622**	**0**	**0**	**124,251**	**349,865**
2018	3R050A	Liu, Kun	0.50	912.50	53,774	8,738	0	0	0	0	5,782	0	0	14,521	68,295
		Liu, Ming Xiong	0.30	519.00	71,265	62,891	0	0	0	0	12,409	0	0	75,301	146,566
		Materials	0.00	0.00	7,500	0	0	0	0	0	694	0	0	694	8,194
		Van De Water, Richard G	0.05	86.50	13,032	11,500	0	0	0	0	2,269	0	0	13,770	26,801
	3R050A		**0.85**	**1518.00**	**145,571**	**83,130**	**0**	**0**	**0**	**0**	**21,155**	**0**	**0**	**104,285**	**249,856**
	3W200A	Cirigliano, Vincenzo	0.10	173.00	23,755	20,964	0	0	0	0	4,136	0	0	25,100	48,855
		Kang, Zhongbo	0.20	365.00	31,632	5,140	0	0	0	0	3,401	0	0	8,542	40,174
		Travel	0.00	0.00	10,000	0	0	0	0	0	925	0	0	925	10,925
	3W200A		**0.30**	**538.00**	**65,387**	**26,104**	**0**	**0**	**0**	**0**	**8,463**	**0**	**0**	**34,567**	**99,954**
2018			**1.15**	**2056.00**	**210,958**	**109,234**	**0**	**0**	**0**	**0**	**29,618**	**0**	**0**	**138,852**	**349,810**
Grand Total			**3.25**	**5812.50**	**664,776**	**295,735**	**0**	**0**	**0**	**0**	**88,847**	**0**	**0**	**384,581**	**1,049,357**

More people get involved later at various R&D and construction stages:
Hubert, Sanghoon(PD), David(PD), Xinkun (Student) et al.

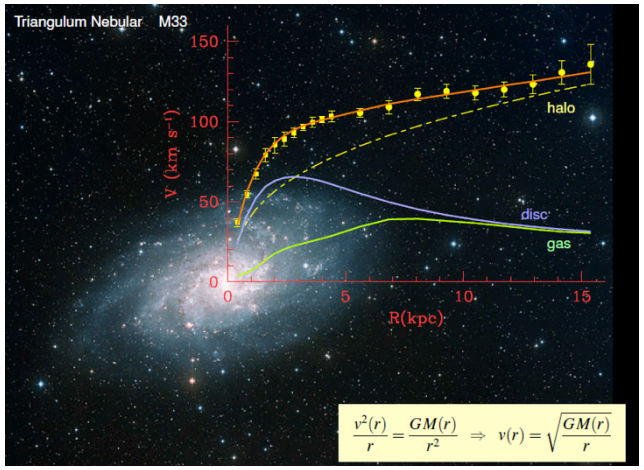
People Involved

- Experimental efforts (P-25)
  - Ming Liu, Kun Liu(PD, Staff), Pat McGaughey, Hubert van Hecke, Sanghoon Lim(PD), Richard Van de Water, Grass Wang(PD), Xinkun Chu (Student)
- Theoretical effort (T-2)
  - Zhongbo Kang
  - Vincenzo Cirigliano
- External collaborators
  - Fermilab/SeaQuest
  - BNL/sPHENIX
  - SLAC/N. Toro, P. Schuster
  - Caltech/Y. Zhang
  - Univ. Cincinnati/S. Gori
  - And more…

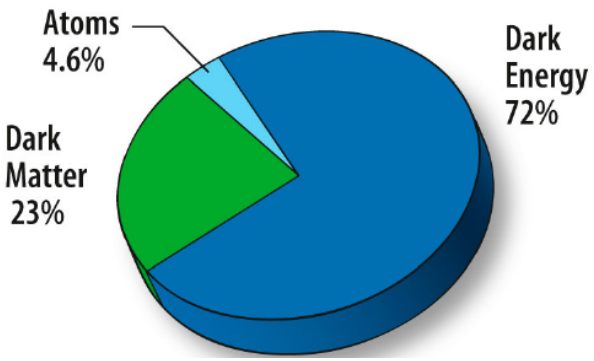


Dark Matter?

Galaxies' rotation curve



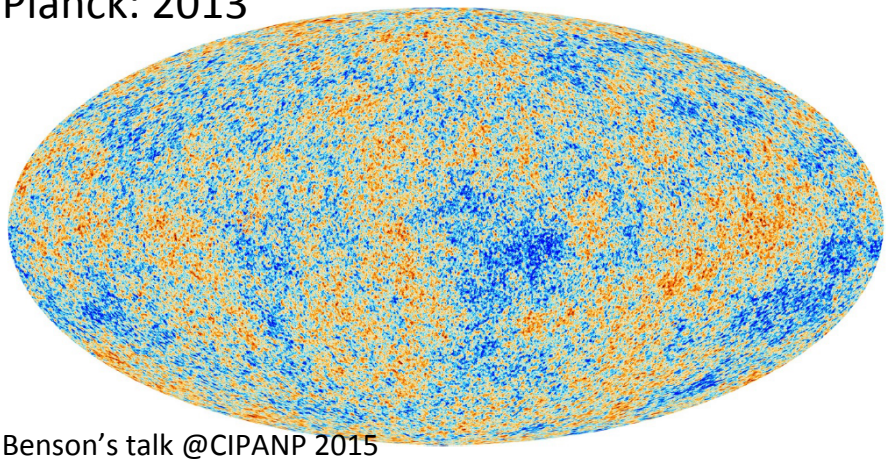
F. Zwicky, ApJ 86 (1937) 217, V. Rubin et al, ApJ 238 (1980) 471



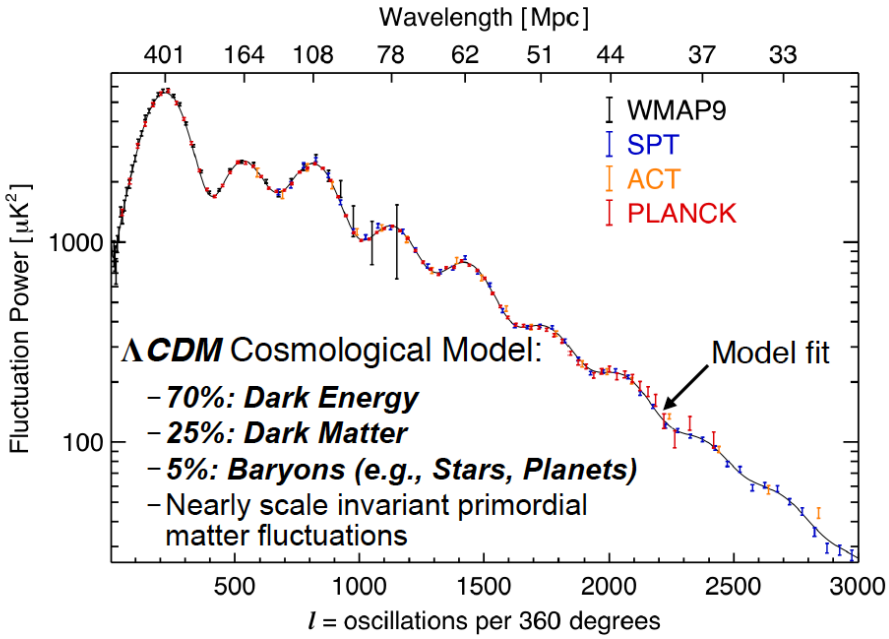
Gravitational lensing (Hubble 2007)

30μK RMS fluctuations on 3 K background

Planck: 2013



Benson's talk @CIPANP 2015



Why Light Dark Matter?

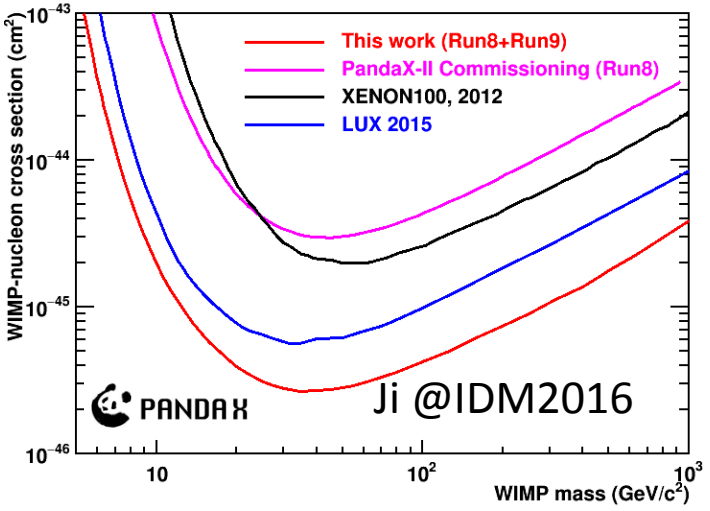
- WIMPs (Weekly Interacting Massive Particles) being excluded?

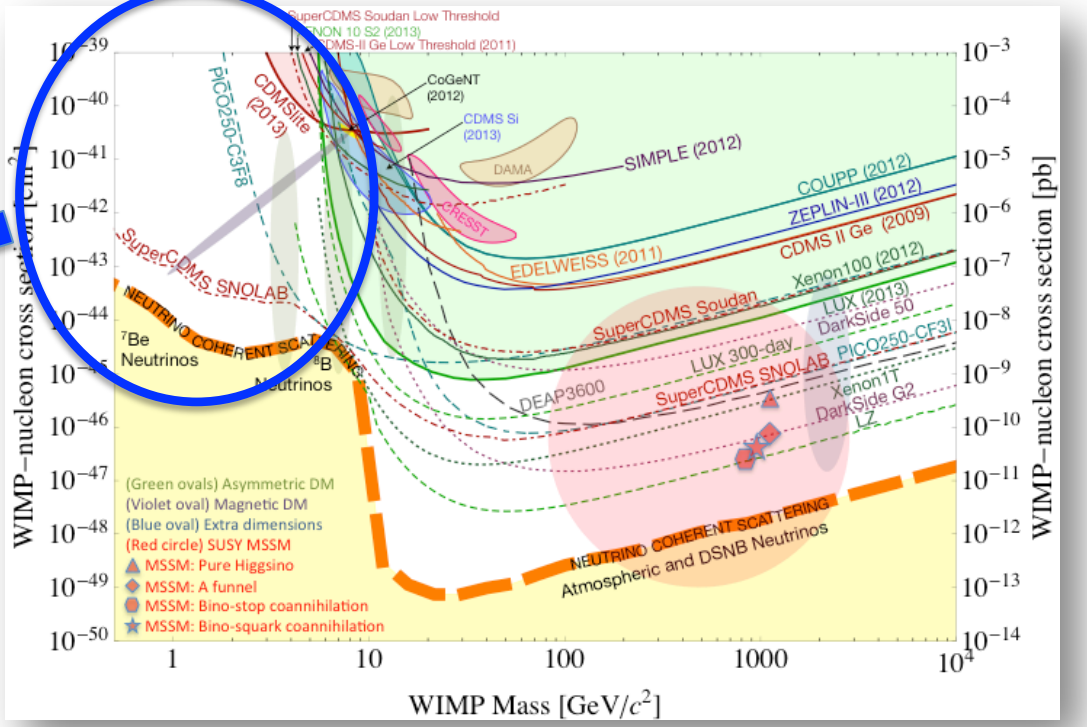
- Recent anomalies observed by satellite and terrestrial experiments suggest a new **"dark sector"**
  - "Portals" to the SM
    - **"vector portal": dark photon**
    - **"scalar portal": dark Higgs**
    - **"neutrino portal" and more …**

"Sub-GeV" low mass weakly-interacting dark particles become very interesting!

Mass: *O(MeV ~ GeV)*

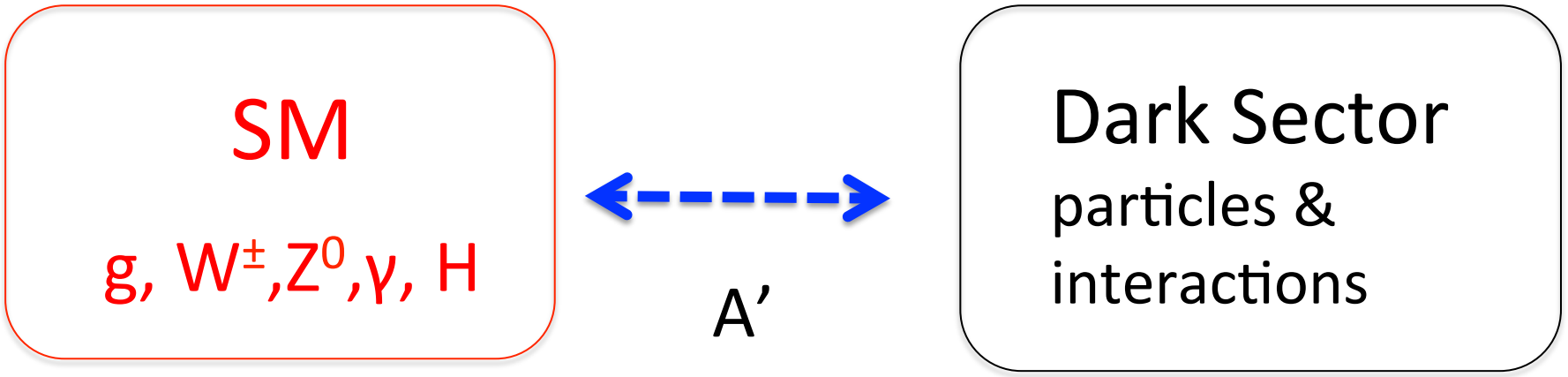
- High-intensity colliders (B-factories) and fixed target experiments (Fermilab, JLab, LHC etc.) offer an ideal environment to probe these new ideas.





Portals to a Dark Sector?

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



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

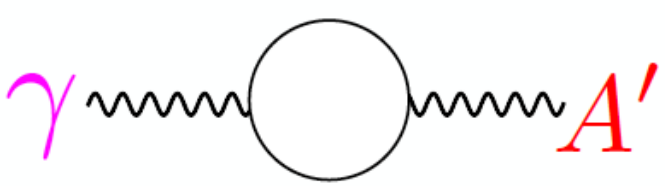
Expected Coupling Strength from GUT

- 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

$m_{A'} \sim \sqrt{\varepsilon}\, m_{EW} \sim$ (MeV – GeV)

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



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

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

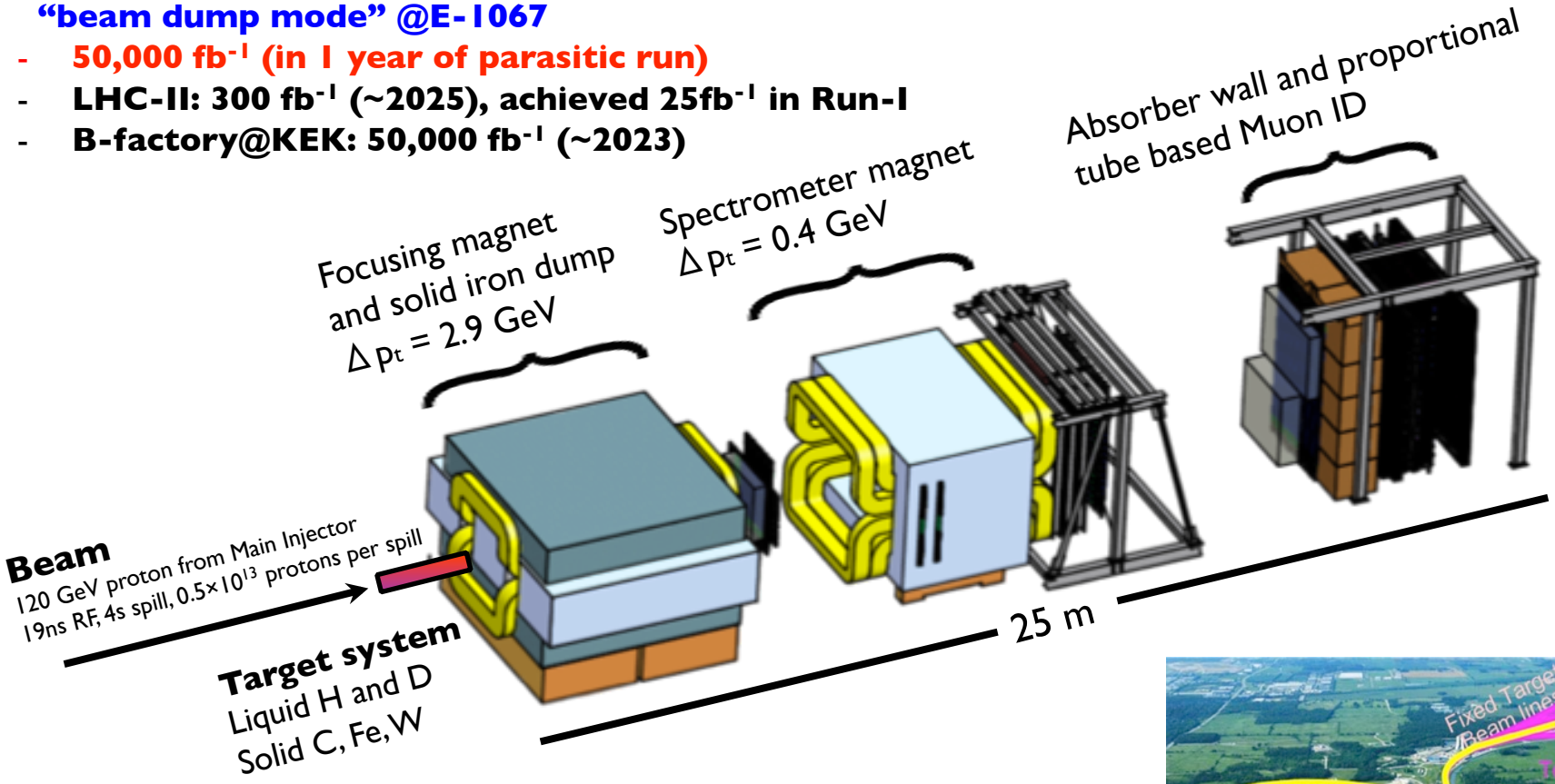
$$\epsilon \sim 10^{-5} - 10^{-3}$$

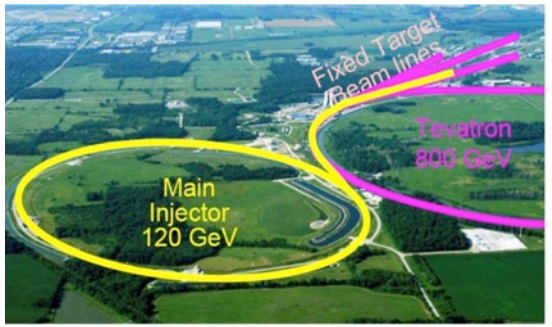
Weakly interacting → small cross section →high intensity beam to create them

Intensity Frontier at Fermilab: 120 GeV Beam

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

- **50,000 fb^{-1} (in 1 year of parasitic run)**
- **LHC-II: 300 fb^{-1} (~2025), achieved 25fb^{-1} in Run-I**
- **B-factory@KEK: 50,000 fb^{-1} (~2023)**





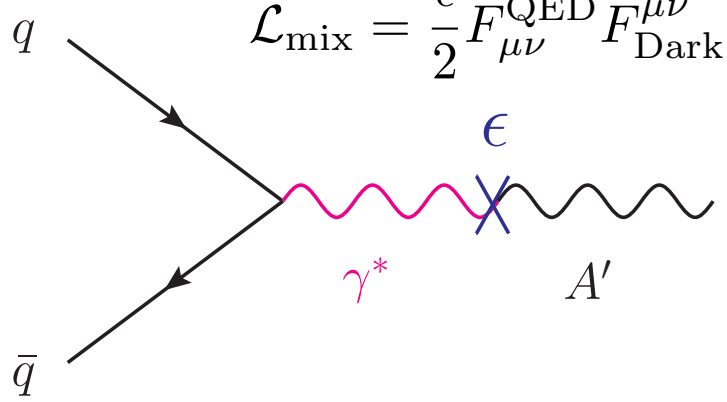
- Capture most beam in beam dump mode: p+Fe collisions!
- Parasitic run mode possible with other experiments, E906/E1039

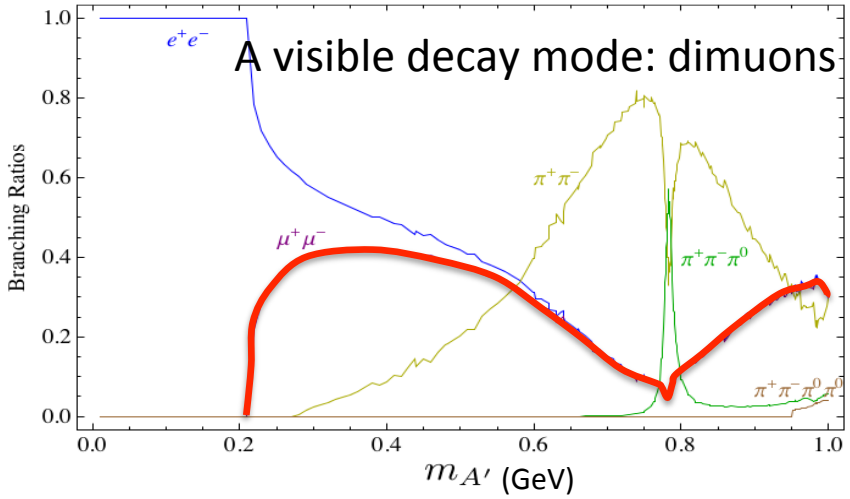
Dark Photon Production and Decay in p+Fe (Beam-dump) at Fermilab

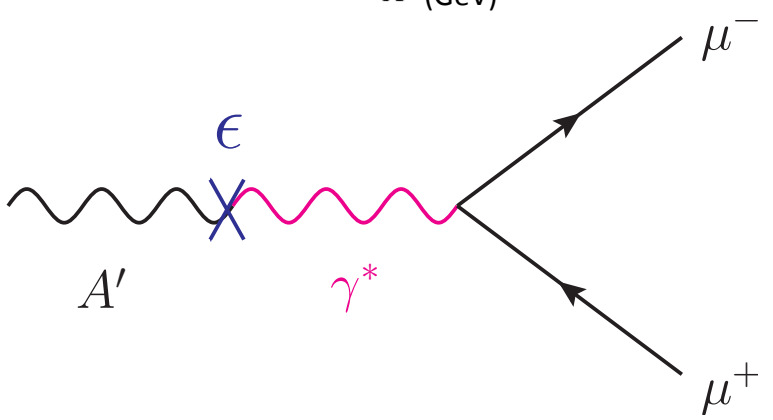
Photon portal: "vector"

Fermilab(on-going)
SHiP/CERN(in preparation)
J-Lab12(on-going)
KEK B-factory(on-going)
and many more …

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

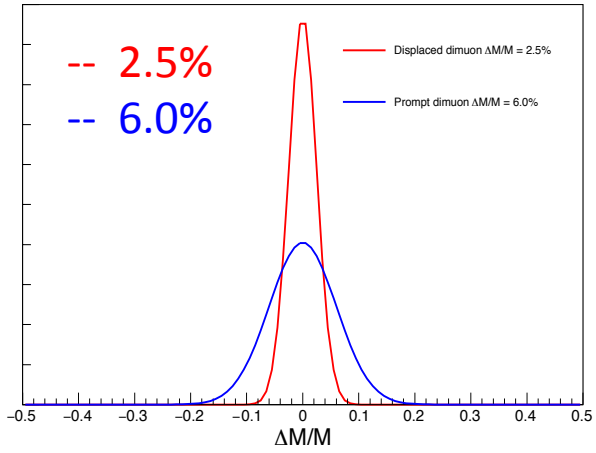






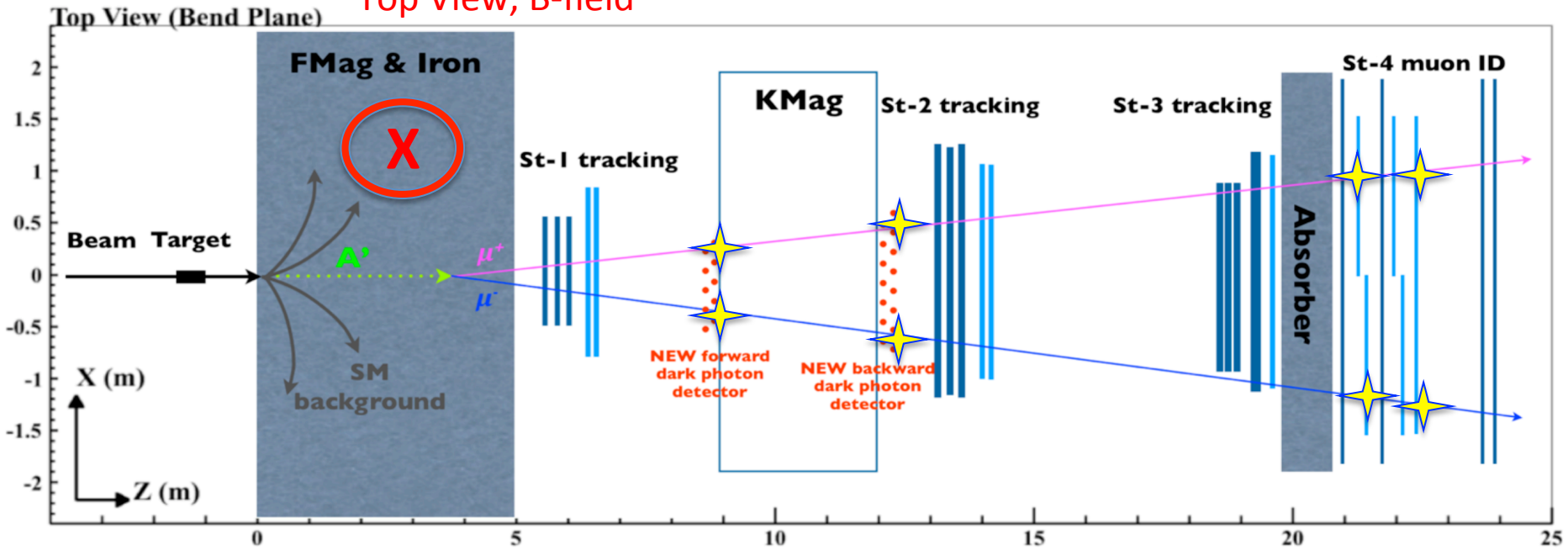
Our Approach and Expected Signals

- Dark photon displaced vertex trigger upgrade
- Unique signals
  1. Displaced dimuon decay vertex for long-lived particles
  2. Invariant mass peak in dimuon mass spectrum
- Beam time
  1. Run parasitically with E906/E1039 (2017-2019)
  2. Possible dedicated runs later with upgraded ($e^{+/-}$, $h^{+/-}$)



Dimuon mass resolution

Top View, B-field

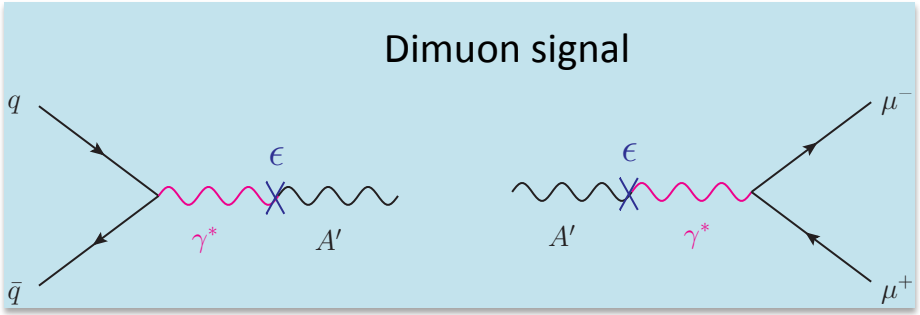


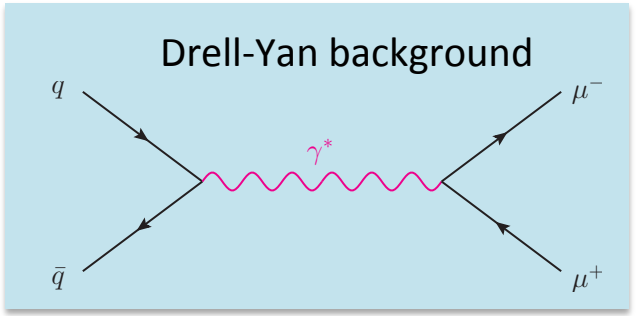
Kang's talk

Integrated Theory Effort

Signal: detailed calculation for dark photon cross section

- To provide expected dimuon signal from dark photon decay as function of decay length L and model parameters (ε, $m_{A'}$), theory team will
  - Compute Dark photon production cross section at both LO and NLO
  - Derive the branching ratio of dark photon to dimuon
  - Theory team: expertise in perturbative QCD and effective field theory for resummation

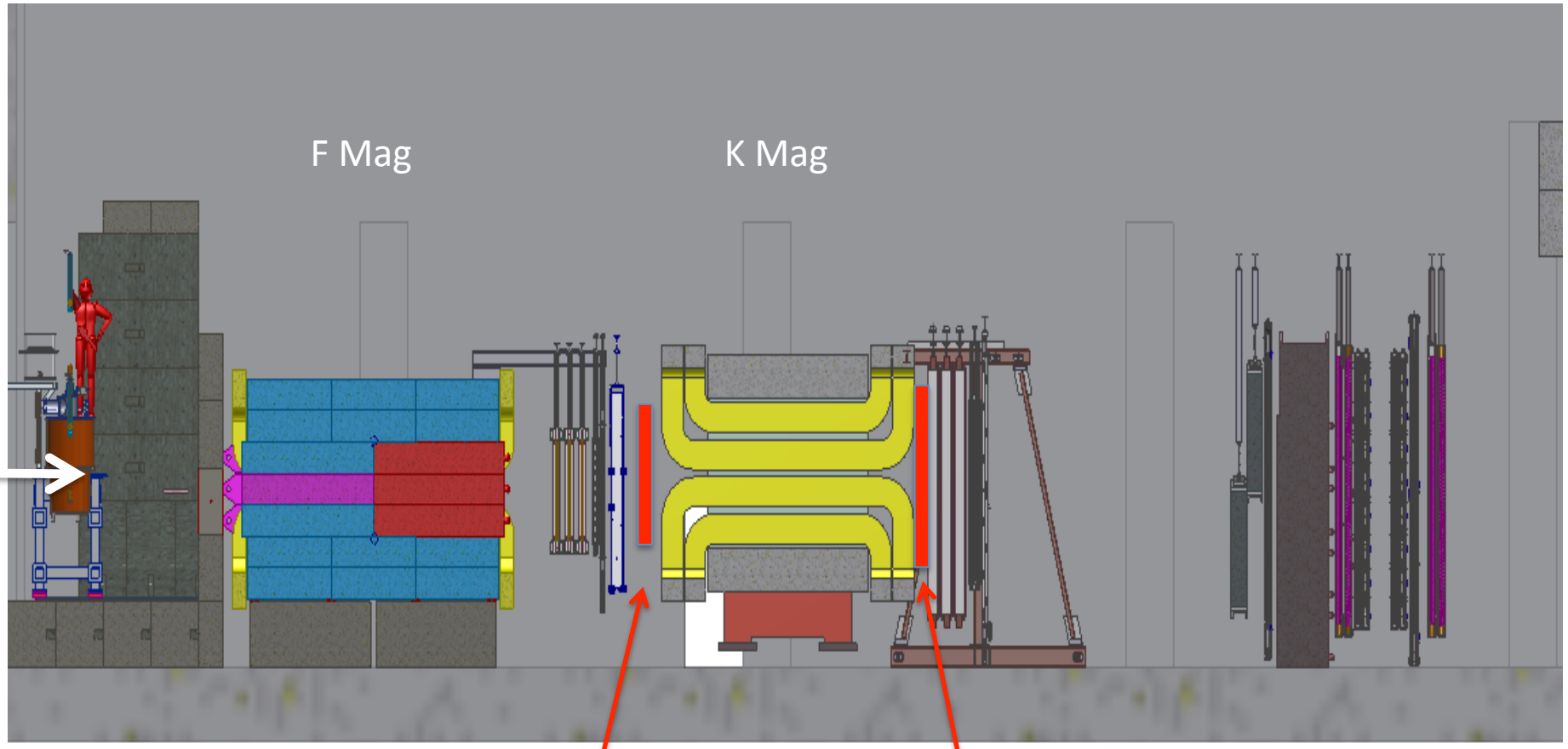




Background: detailed calculation for Drell-Yan cross section

- Main background is DY dimon production: reliable computation of the cross section is essential to calculate our experimental sensitivity to (ε, $m_{A'}$), and understand implication of dark photon search
  - We have a NLO DY code that works well in the required energy range
  - Calculations will be performed in the necessary energy and kinematic regions

Side View of the Proposed Experimental Setup



LDRD: 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

A New High-Granularity Displayed Dimuon Vertex Trigger

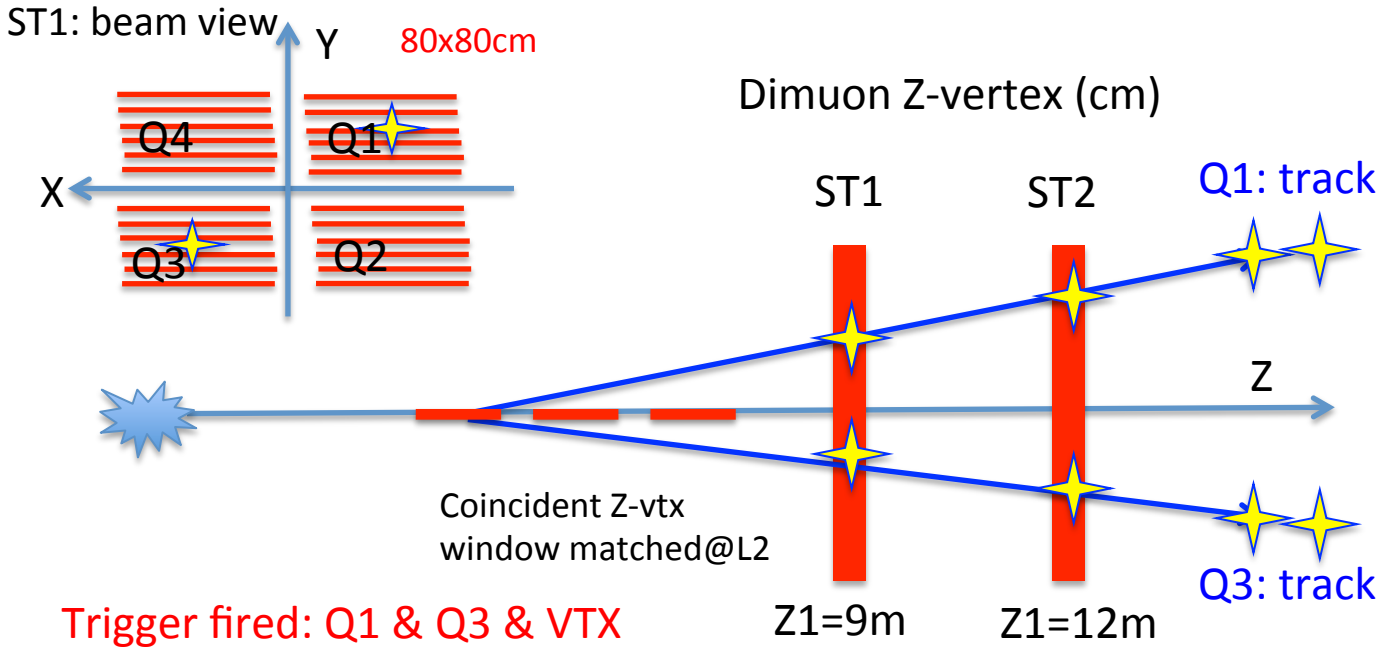
High rejection power, low rate, << 1 kHz(current E906 DAQ limit)

Y-Plane (non-bending) Trigger:

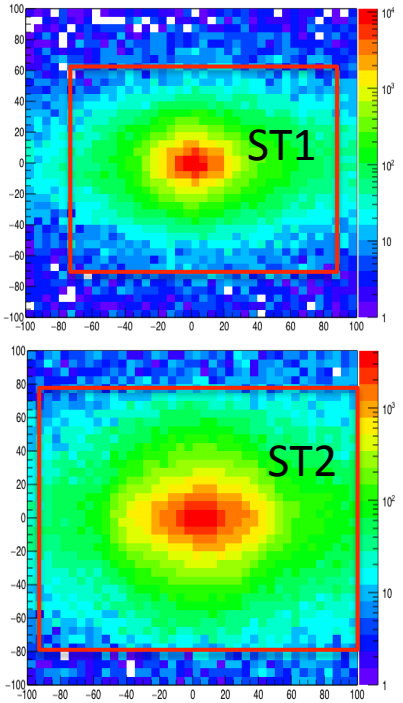
- A quadrant panel: 80cm x 80cm (100cmx100cm @ST-2)
  - ST1: 1cm x 1cm x 80 cm scintillating strips, SiPM readout
  - ST2: 2cm x 2 cm x 100 cm strips
- Straight line projection, σ_Z ~30cm
- Displaced z-vertex, mostly low mass < 3GeV

Y-channels per quadrant:

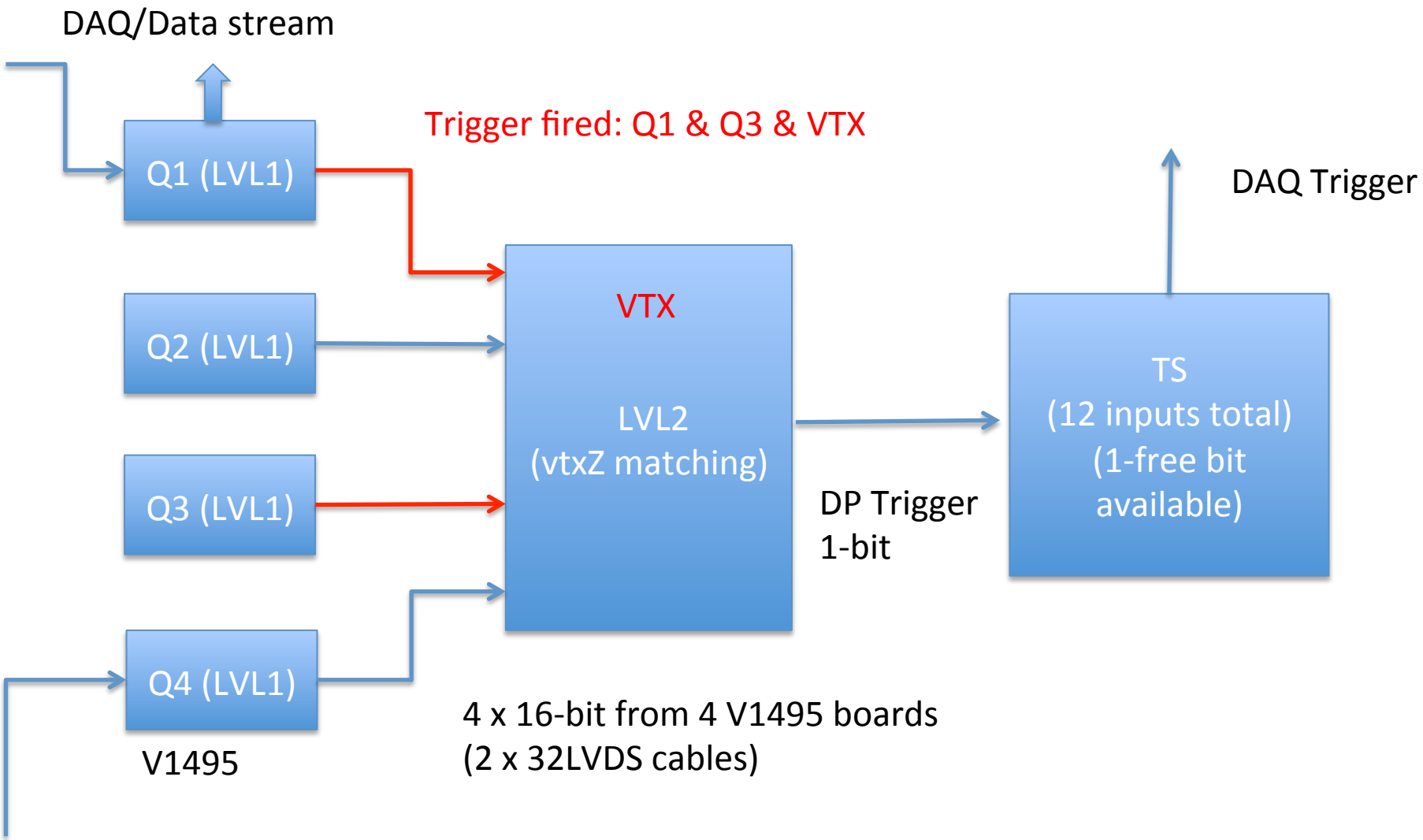
- 1x V1495
- 80(St1) + 50(St2) + 8x2 (St4-Y1,2) = 146
- 96+64 = 160 inputs possible
  (2NIM=RFCLK+ComSTOP)



Trigger fired: Q1 & Q3 & VTX



Displaced Dark Photon Trigger Logic



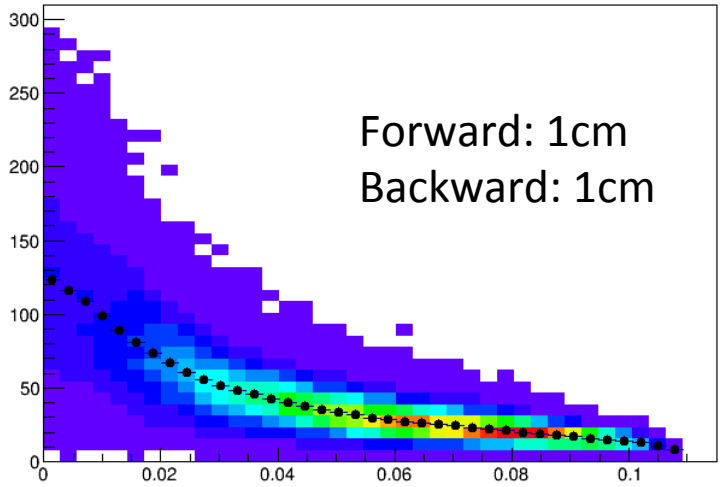
Per quadrant $Q_{(1\text{-}4)}$: 80(ST1) + 50 (ST2) + 2x8(ST4-Y1/2) = 146, FANOUT ST4 Hodo

Scintillator Size Optimization

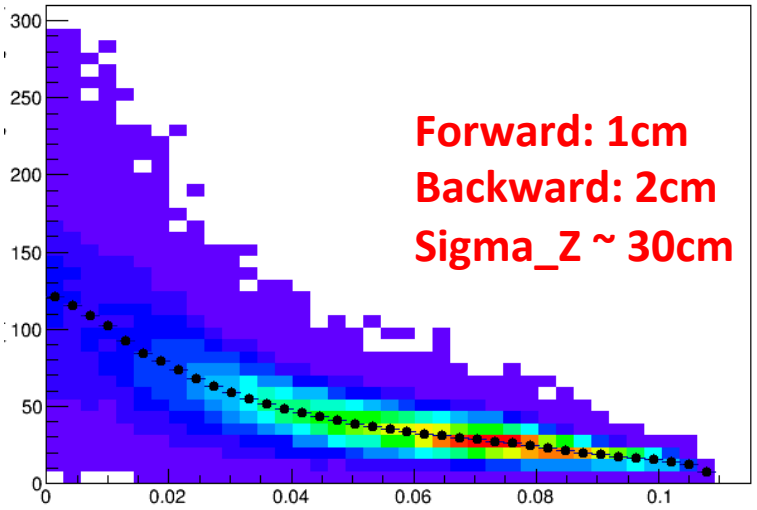
Single Muon Z-Vertex Resolution

Kun's talk
-DPSim package

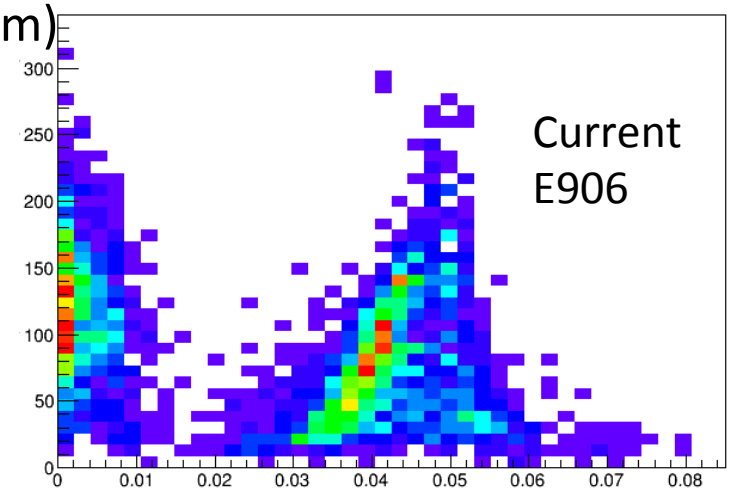
σ_Z (cm)

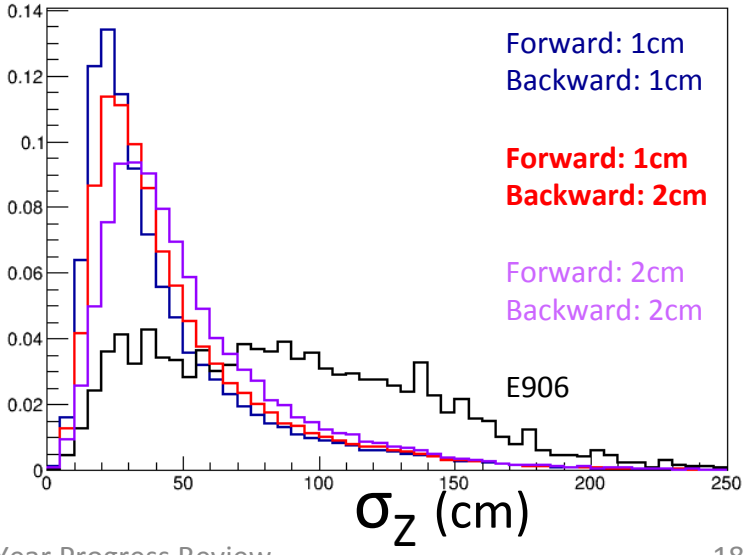


σ_Z (cm)



σ_Z (cm)





Low Mass Prompt Dimuon Trigger Rate Study

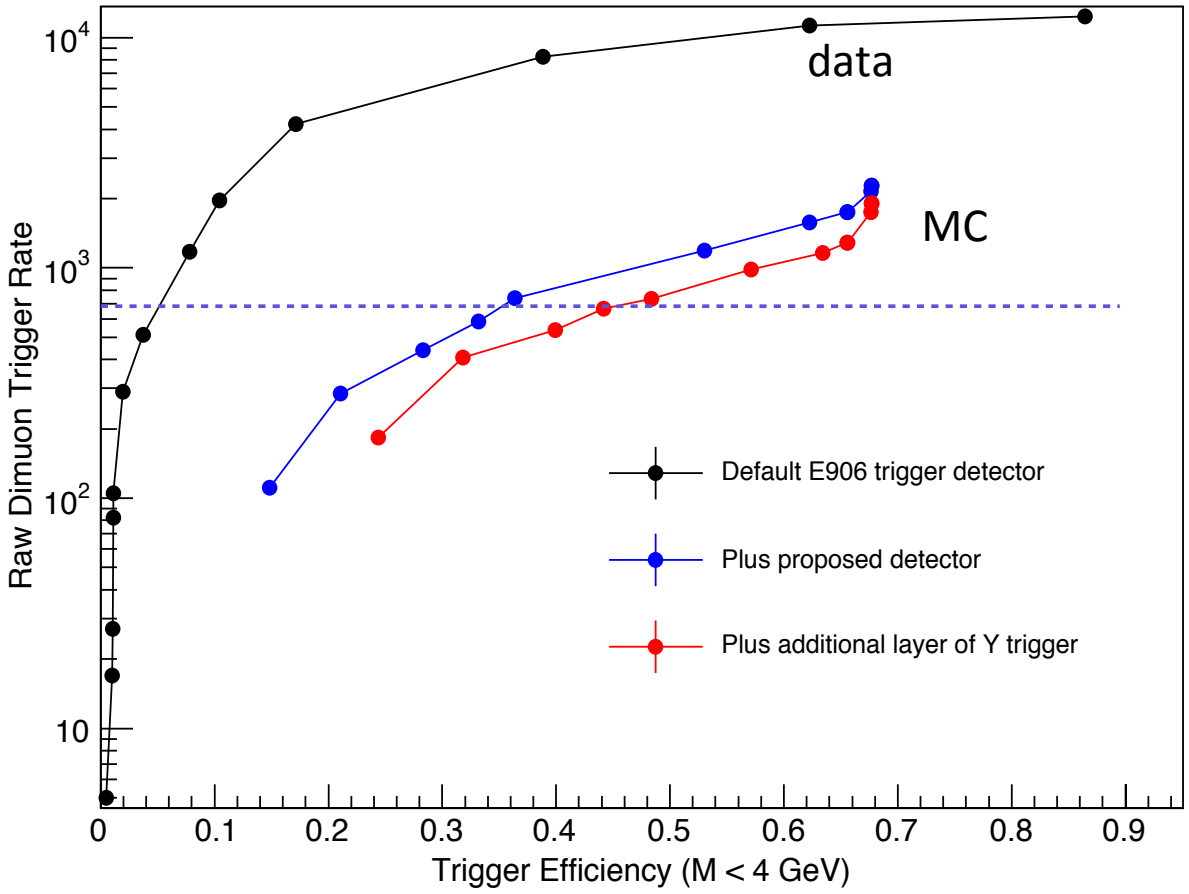
- Current E906 setup
- Proposed 2-layer trigger upgrade (10x improvement)
- Additional Y-trigger after ST-3 absorber, and also using existing E906 X-Plane trigger (additional ~2x improvement)

- Current E906 DAQ 1kHz, can be improved to ~10+kHz with small cost

Kun's talk
- DPSim & DAQ

- 15+kHz possible for next run (reprogramming trigger firmware etc.)

Parasitic mode: use up to ~10% DAQ bandwidth



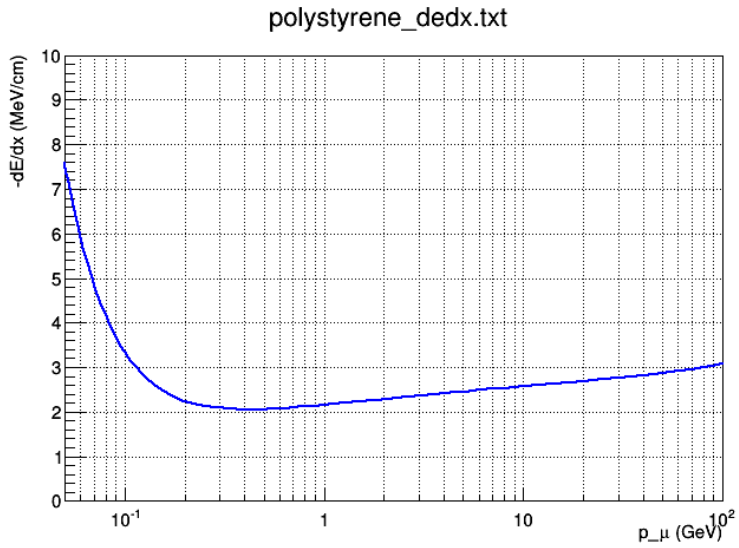
Expected (Prompt) Low mass dimuon trigger performance

Trigger Detector R&D

Scintillator Thickness and Light Yield

- For thickness = 1.0cm, P > 5GeV
  - dE/dx = 2.5MeV/cm
  - Light yield = 2.5MeV / 100eV ~ 25K photons
  - SiPM Eff = 30%
  - Scintillator/WLSF light collection Eff estimated ~O(1%)
  - Total "PE" = 25K x 30% x 1% = 75 >>1

- Required light output
  - MIP detecting eff > 95%

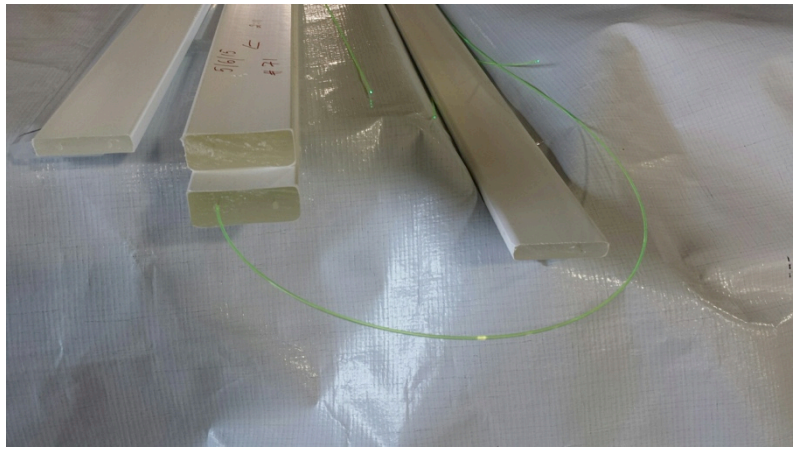


- Using polystyrene as example (same as FNAL scintillator)
- Muon dE/dx = 2.41 MeV/cm @ 4 GeV, and 2.69 MeV/cm @ 20 GeV

Selection of Trigger Scintillator

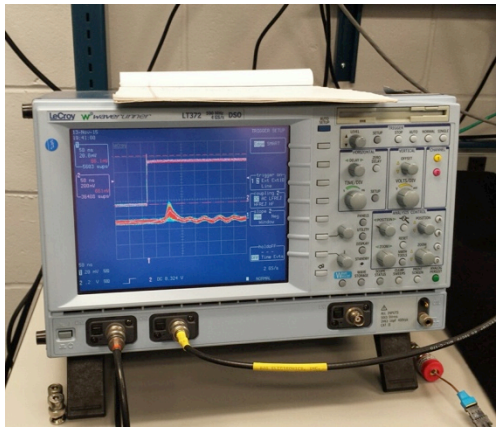
- High quality scintillator bars
  - 1x1x50cm
  - Directly coupled SiPM readout
  - Expensive, ~$100/ch.
  - Original plan

- Fermilab extruded scintillator + WLSF for light detection
  - 1x1cm
  - 2x2cm
  - SiPM readout
  - Low cost, ~$10/ch
  - Final choice!



Trigger Detector R&D (I)

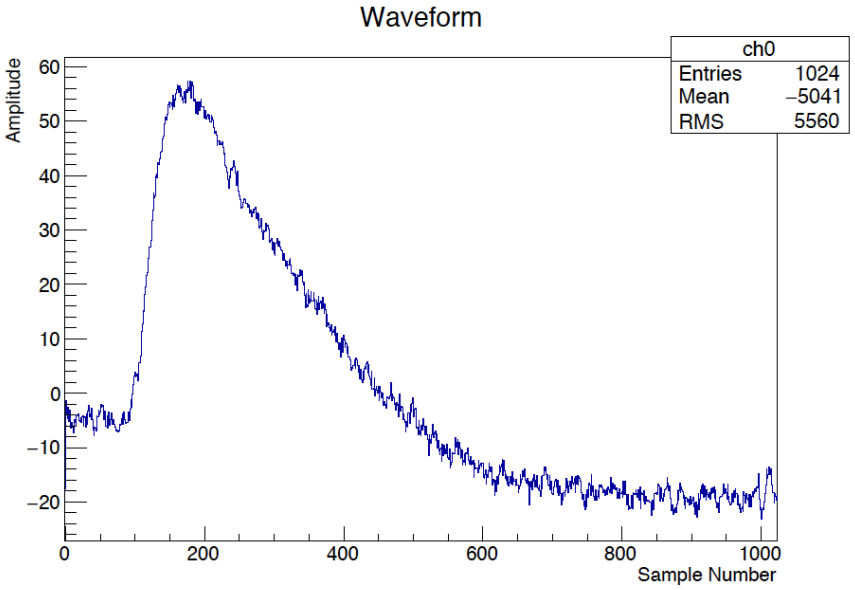
- Scintillator directly coupled to SiPMs
  - Preamps developed by sPHENIX group at BNL
  - Clear MIP signal observed
  - But with long tail … 30nS



Trigger Detector Prototype R&D (II)

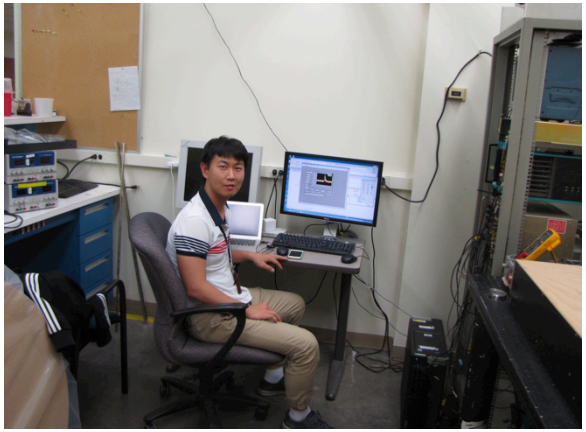
- Fermilab extruded scintillator + WLSF
- SiPM readout
- Excellent S/B!
- Default option now!

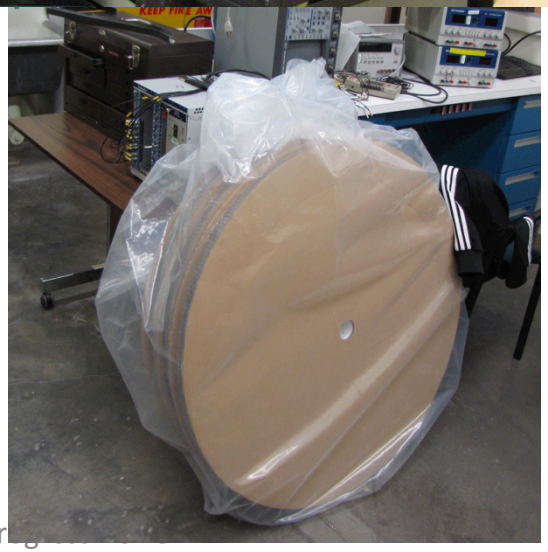
2 x 2 x 50 cm + 1mmD WLSF
+ SiPM readout



Trigger R&D Lab - C114

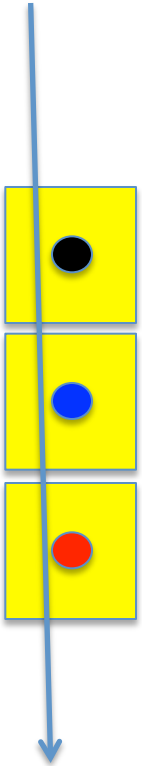
a good training ground for postdocs on detector hardware skills





Light Collection Efficiency vs # of WLSF

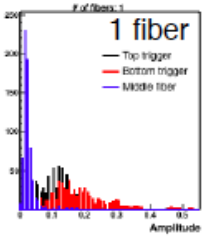
Scan # of fibers

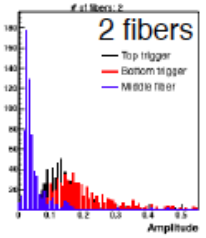


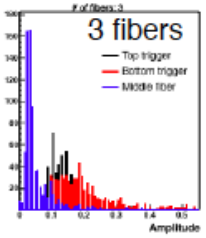
Cosmic ray

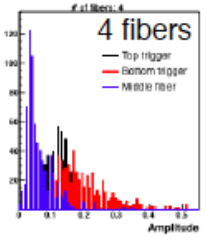
- Amplitude distribution

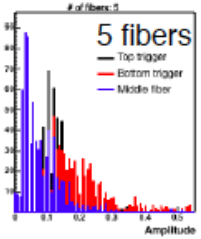
Top (7 fibers)
Middle (1-7 fiber)
Bottom (7 fibers)

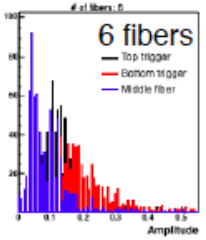








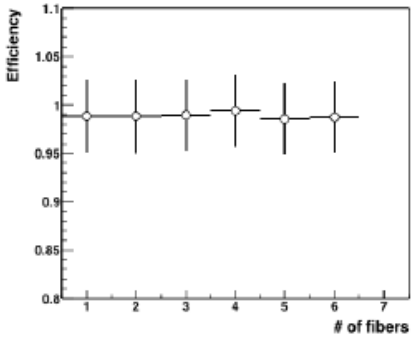




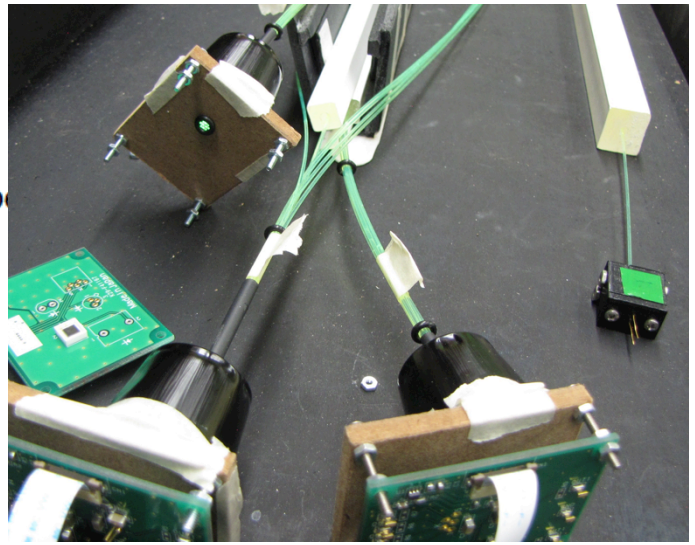
mean of amplitude distribution getting larger with increasing # of fibers

Hole:
- d~ 2.8mm
- up to 7 1mm fibers

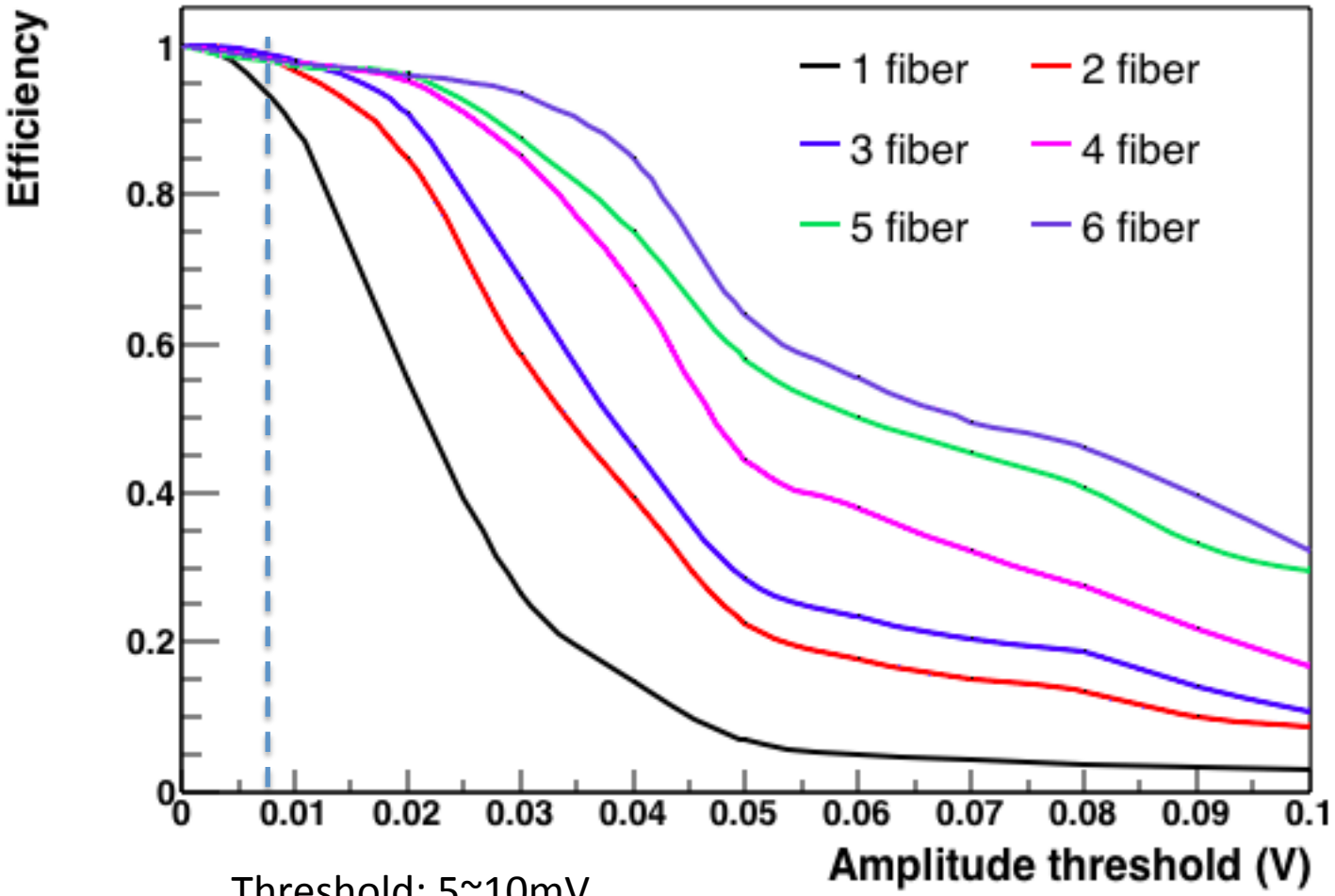
- Efficiency



Single fib



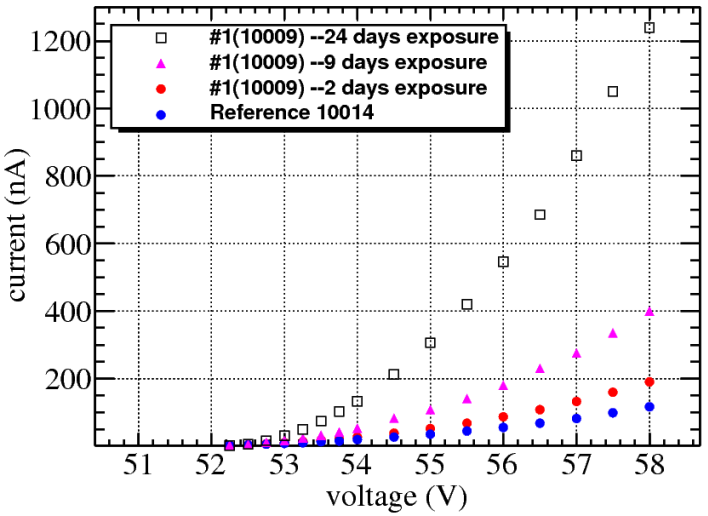
Scintillator-based Trigger Efficiency



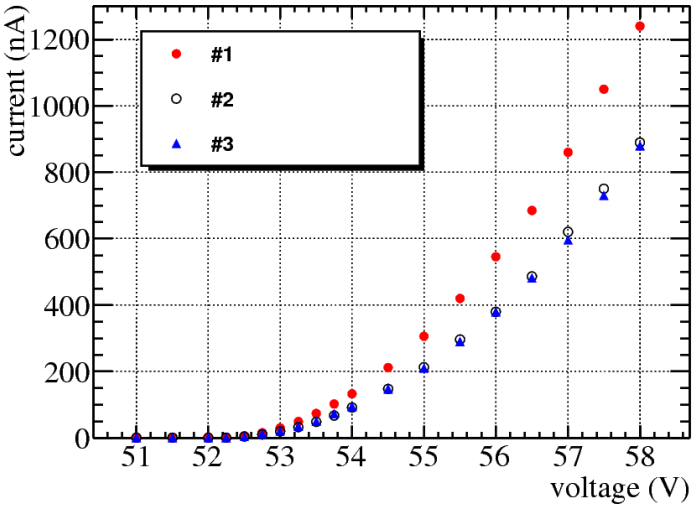
Threshold: 5~10mV

Eff > 98% (w/ 2+ WLSF)

SiPM Irradiation Study at LANSCE and Fermilab



2,9,24 days

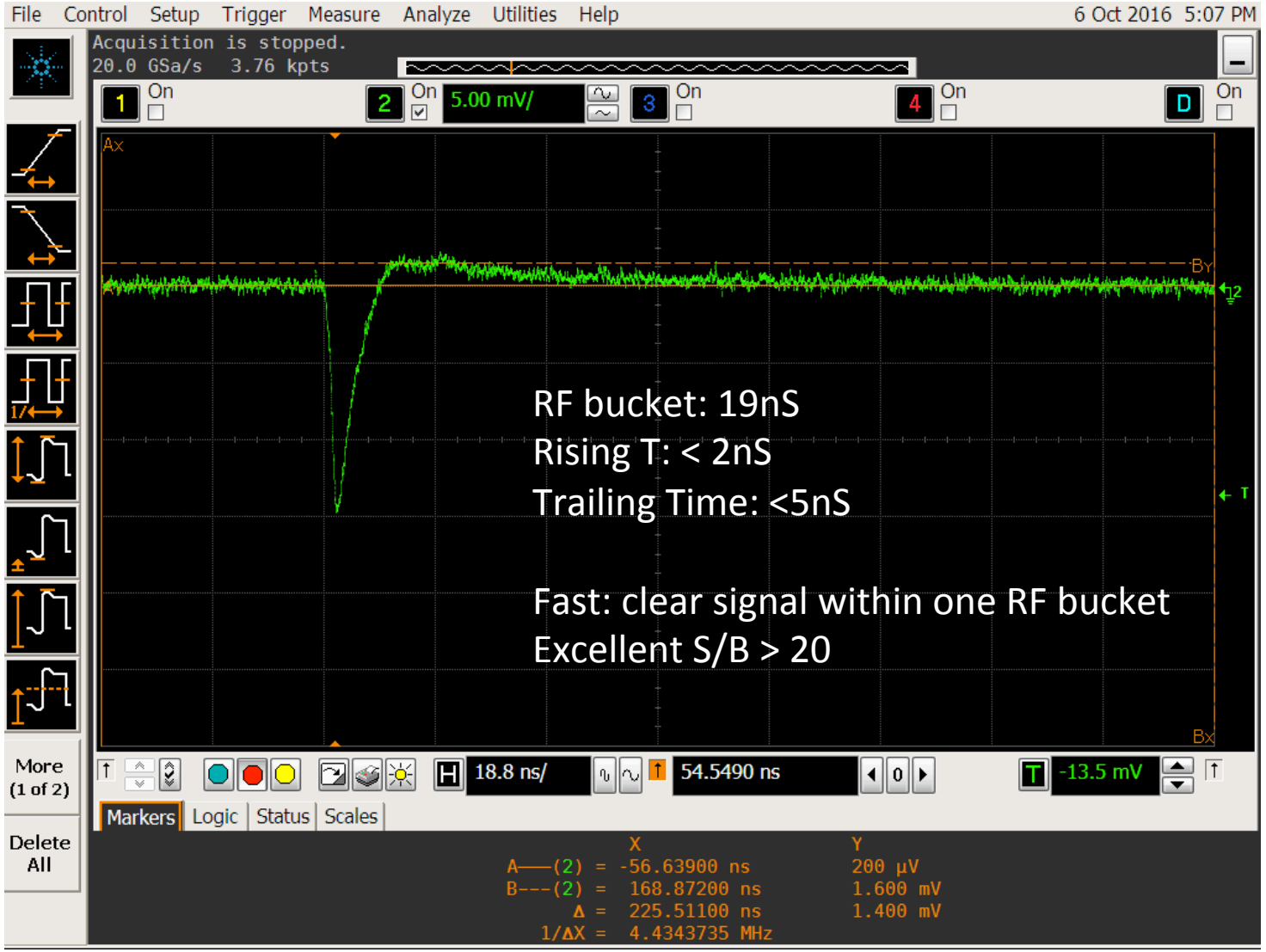


24 days

Y-position dependence

SiPM Readout R&D with Fermilab preamps

Scope Capture of MIP signal



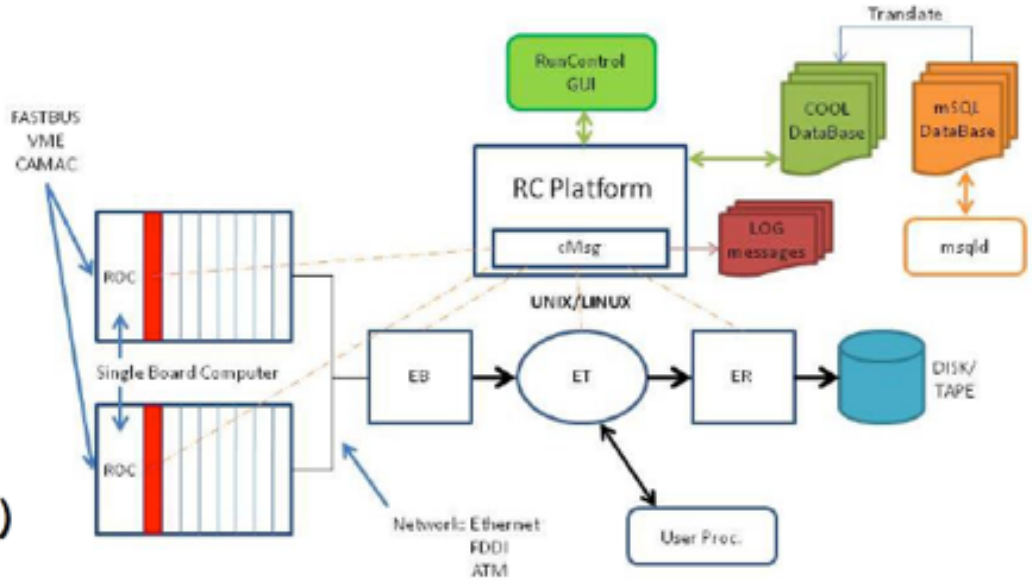
4 Mechanical Box Frames Assembled

Work in progress:

- 4 more box frames
- System integration
- Fermilab safety review

LANL Standalone DAQ/Trigger Upgrade

- ✓ 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 (xcefdmp)



- Test new DAQ readout scheme
- Trigger algorithm development
- Trigger firmware and system integration
- Online monitoring

DAQ new readout R&D:
Proof of principle achieved!
Expected improvement ~15x

Kun's talk

Detector Upgrade Status: Summary

Trigger detector

- WLSF: Y-11 (200)
  - 1 mm D, 1,000m
  - 1.5 mm D, 1,000m
- Extruded scintillator
  - Produced at Fermilab
- SiPMs
  - 3x3mm, 600
  - S13360-3050CS
  - Gain ~ 1.7 x 10^6
- Mechanical support
  - 80/20 Al frame
  - Assembly 50%
  - System integration
  - Safety review

Readout & DAQ integration

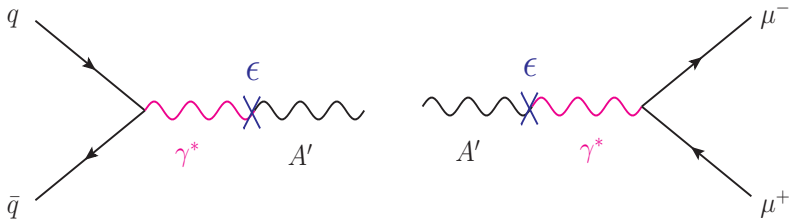
- VME and Control
  - 1 VME crate + Linux CPU
  - 1 Linux computer
- New V1495 boards
  - 4 V1495
  - 12 daughter cards
  - Splitting Y-cables (12x2)
- E906 spares
  - V1495, 4(LVL-0)+2
  - Daughter cards, #?
- DAQ upgrade
  - Expected x15+ improvement
- Preamp+LVDS digital board
  - Fermilab stamp-peramp

Dark Photon Physics Simulation and Sensitivity Study

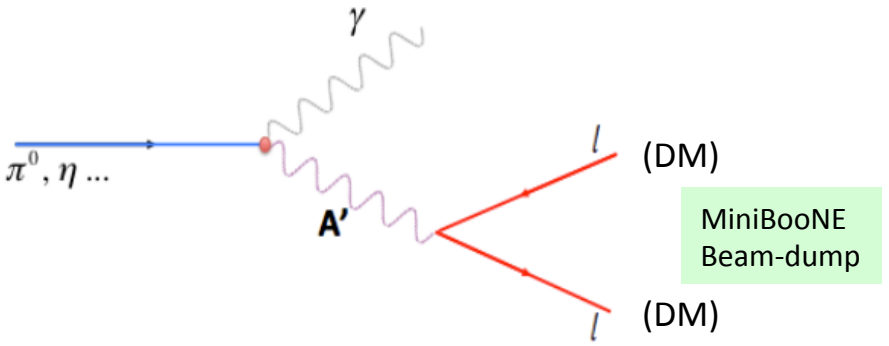
- A new MC simulation package developed
- Updated theoretical model calculations
  - Production channels
  - Decay channels
  - Collaboration with other leading theorists

Dark Photon Detection in Dimuon Decay Channel

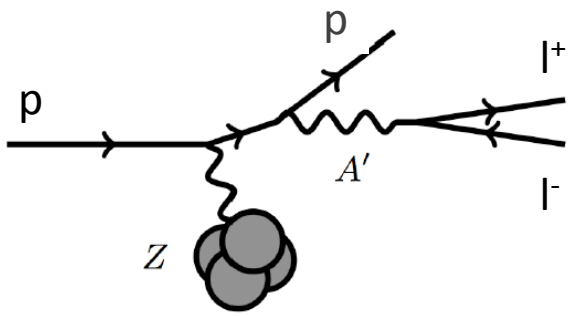
1. Drell-Yan like



2. π^0, η, … decay



3. Bremsstrahlung



Preliminary Results: Dark Photon Sensitivity

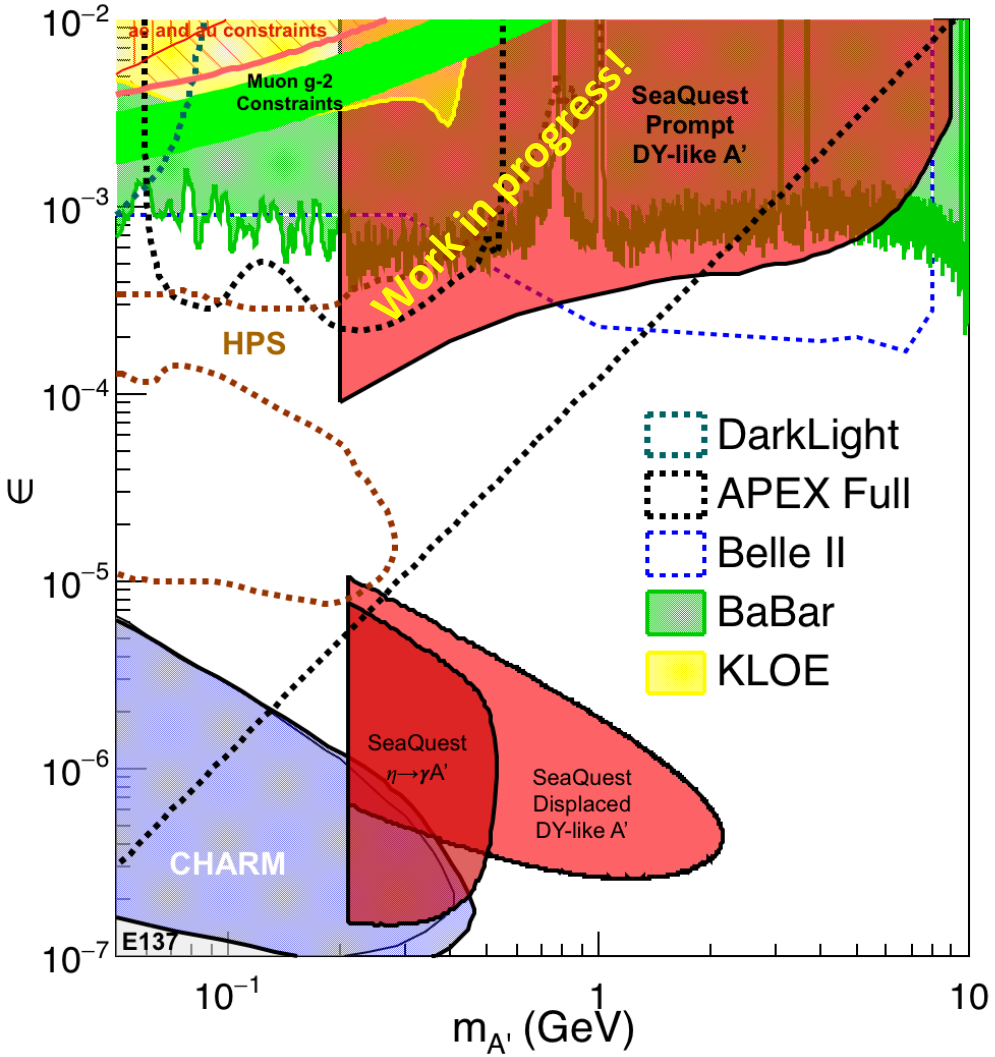
(parasitic run w/ E906/1039)

Signals considered:

- Drell-Yan like
- Eta decays
- Bremsstralung

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)



FY16: Scientific Impact to the Community

SLAC Dark Sectors Workshop: 4/28-30, 2016
- Community Report arXiv:1608.08632

1st report of Fermilab dark photon program to the community
- Kun, Ming, Richard

BNL Dark Interactions: 10/4-7, 2016

Our Fermilab dark photon/Higgs program highlighted at opening plenary talk
- Two talks, by Arun, Ming

Publications and Presentations

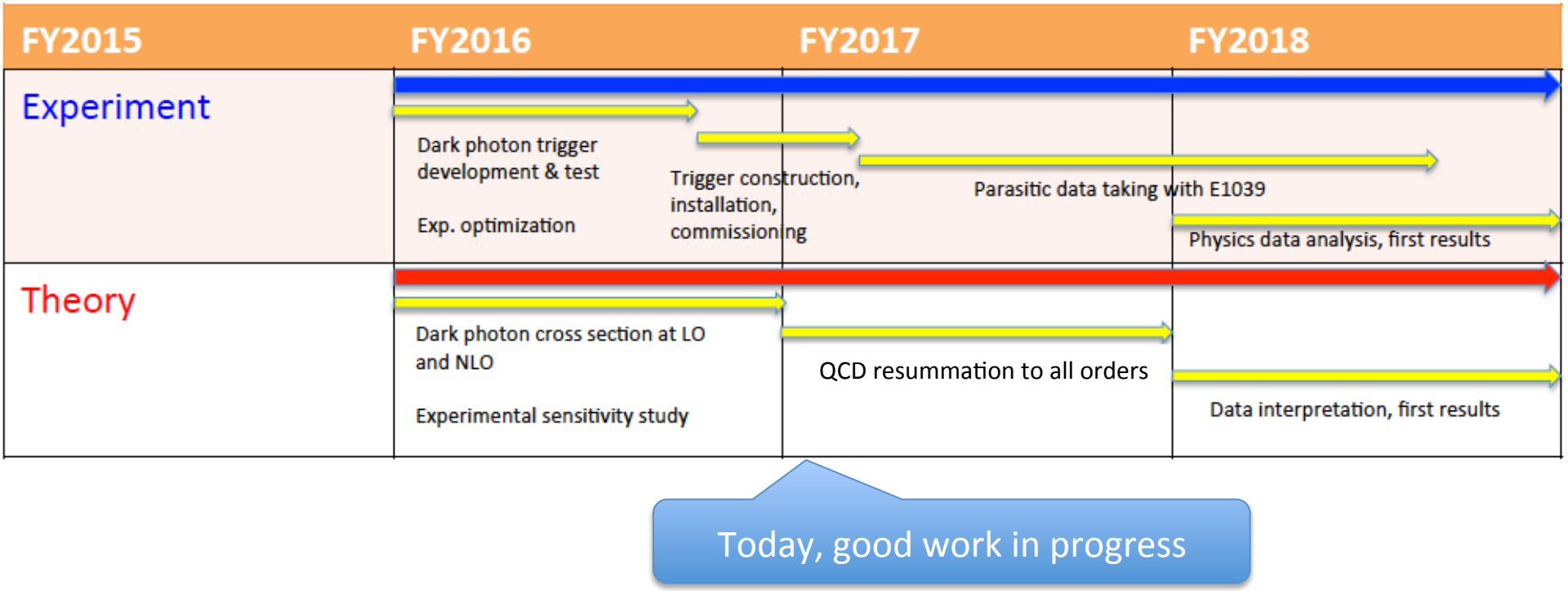
- SLAC Dark Sectors Physics Workshop, April, 2016
  - Kun, Richard and Ming
  - Community report whitepaper (arXiv:1608:08632)
- BNL Dark Interaction Workshop, October, 2016
  - Arun (SeaQuest student), Ming
- Invited seminar at Caltech, November, 2015
  - Ming
- Invited seminar at MIT, ~early 2017
  - Ming
- Invited review paper for Modern Physics Letters A (MPLA, World Scientific)
  - Ming, in progress
- In preparation of a paper on updated sensitivity with latest calculations/simulations
  - LDRD team + external collaborators (Toro et al.)

Summary of FY16 Progress

- Met all FY16 milestones, and more!
  - New MC simulation package and DAQ Upgrade
  - Trigger detector R&D and optimization
  - Trigger readout R&D
  - Mechanical support frames R&D
  - Major hardware purchases
  - Completed LO calculation and more
  - New ideas developed for the future
- Recognized by the community as an important experiment
- In good progress to meet FY-17 goals
  - Experimental
  - Theoretical

LDRD Tasks & Schedules

FY16: Accomplished all milestones and more!



Plan for FY17-FY18 and Beyond

FY-17

- Complete DAQ upgrade for next run
  - Early November
- Trigger detector installation and commissioning
  - By early 2017
- Parasitic data taking with E906
  - Till summer 2017

FY-18 and beyond

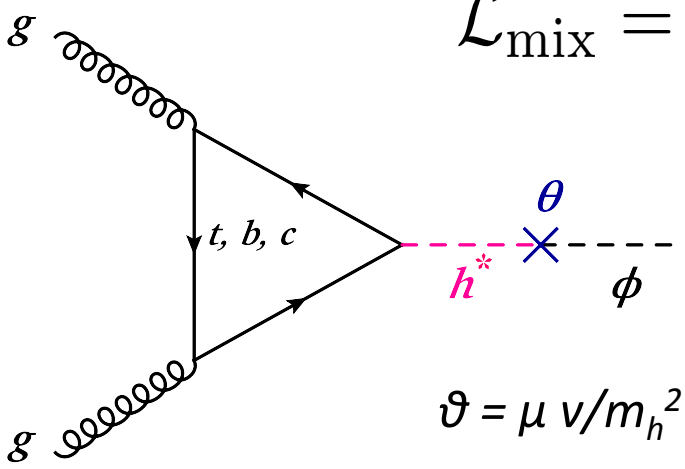
- Parasitic data taking with E1039 (polarized DY)
  - Two years, FY18-19
- Physics data analysis
  - FY17, 18 and 19 data sets
- Publications of preliminary results!
- Major discovery potential!

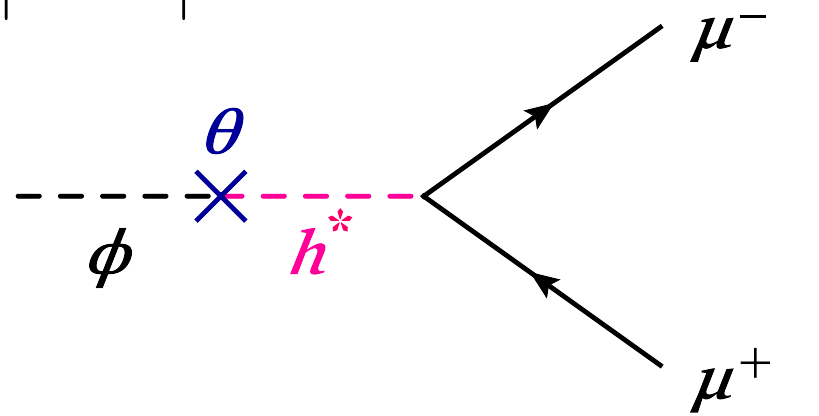
More New Ideas!

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

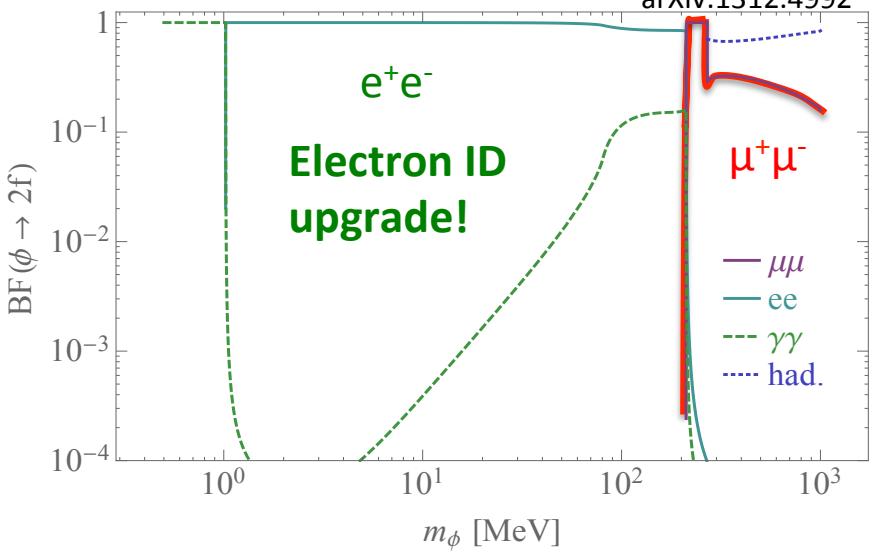
Advantage of using hadron beams with muon probes over electrons

Phase-II:

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

High-mass: hadrons, (5x)

arXiv:1312.4992

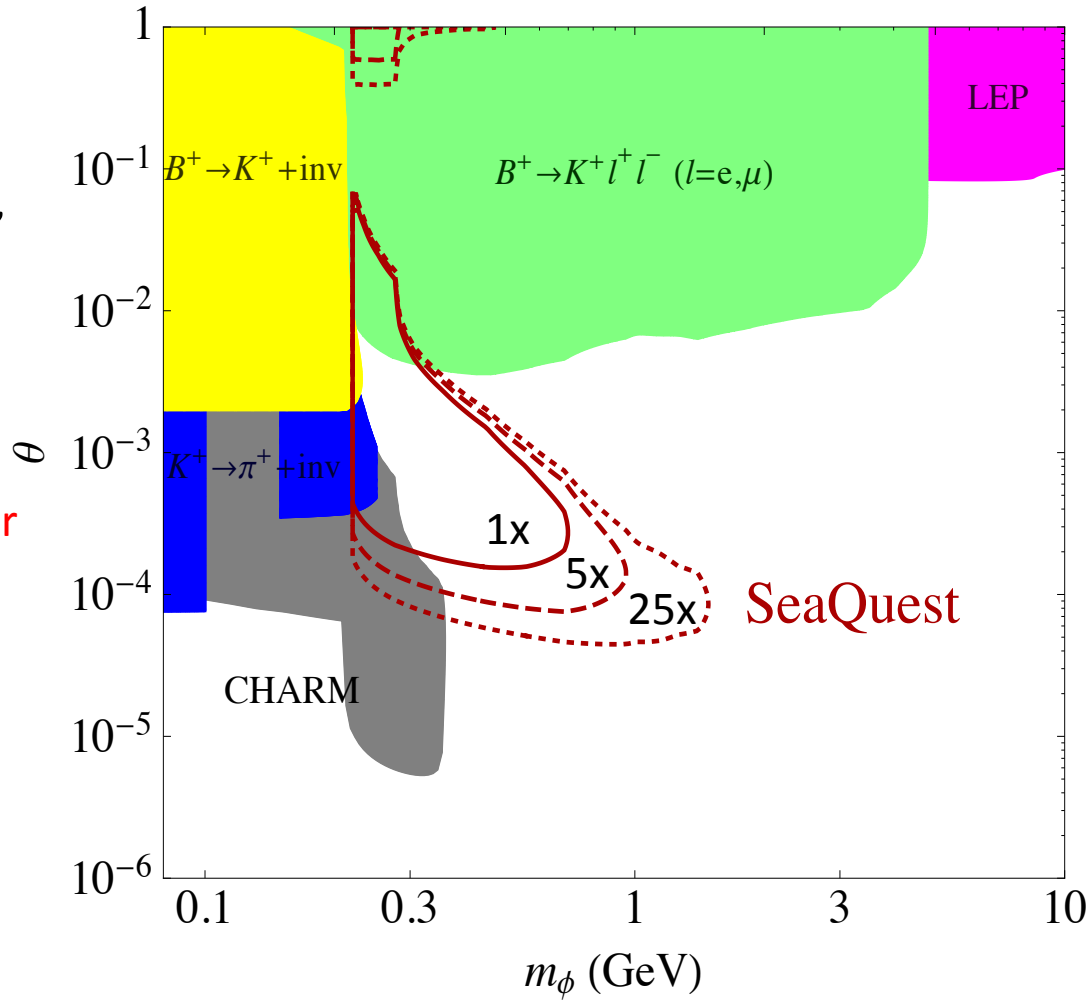


Projected Dark Higgs Sensitivity

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

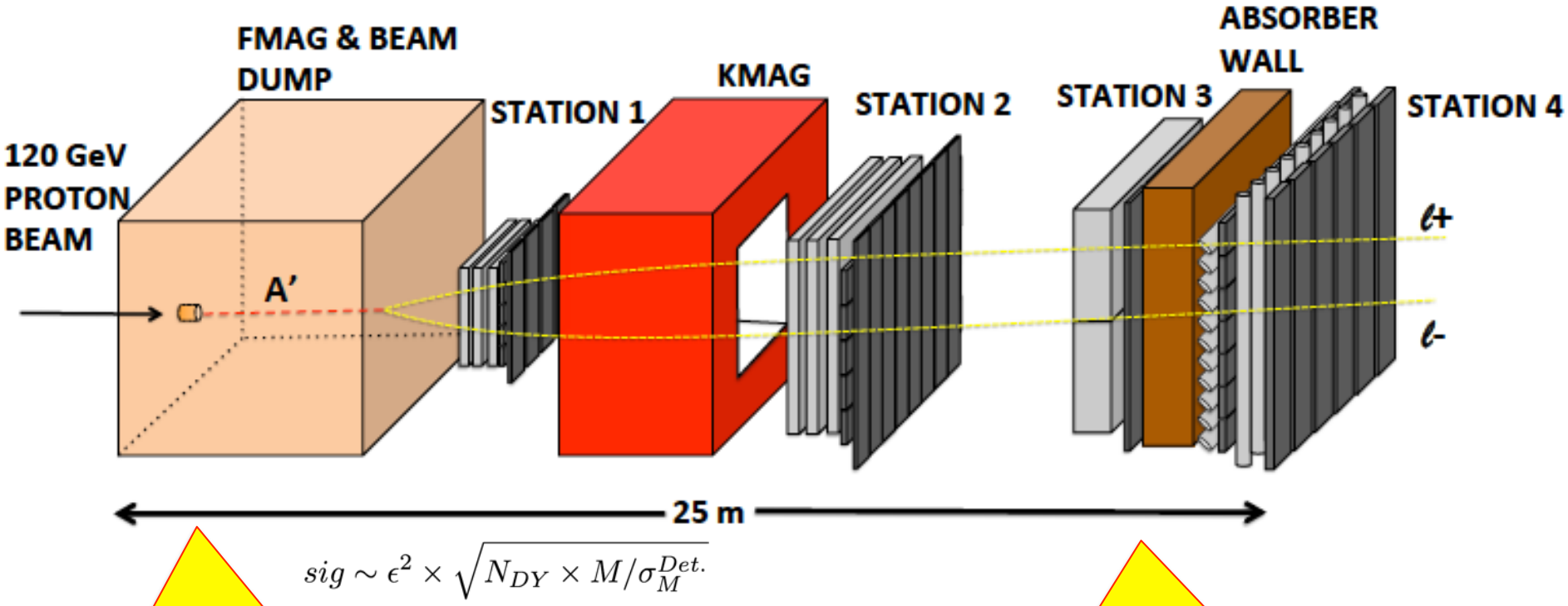
- Dimuons with downstream displaced decay vertices
- Limited sensitivity to "prompt" large mixing case due to small cross-section
- Dark Higgs or dark photons?
  - Dimuon kinematic and angular distributions
- Phase-II
  - Dedicated high luminosity runs optimized for low mass acceptance, mass<3GeV

Y. Zhang (2015)



E-1067 Future Upgrade: New Idea

2018 ~ 2025+



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

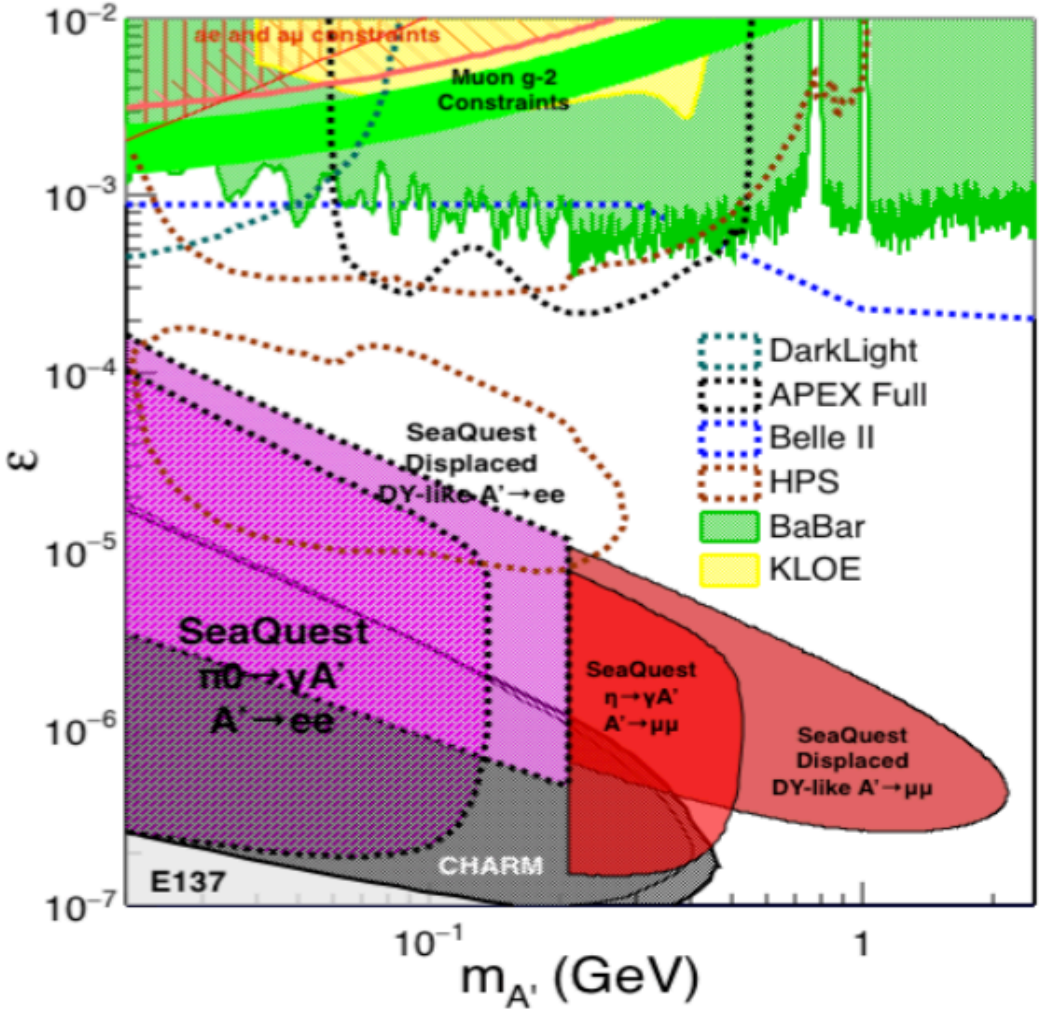
Add tracking detectors close to "target" to improve mass resolution

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
- DAQ upgrade
  - 100+ kHz
- Timeline of runs
  - 2018+
- Detector configuration
  - Access low mass region with optimized Fmag settting

Projection: POT 1.4 x 10^{18}

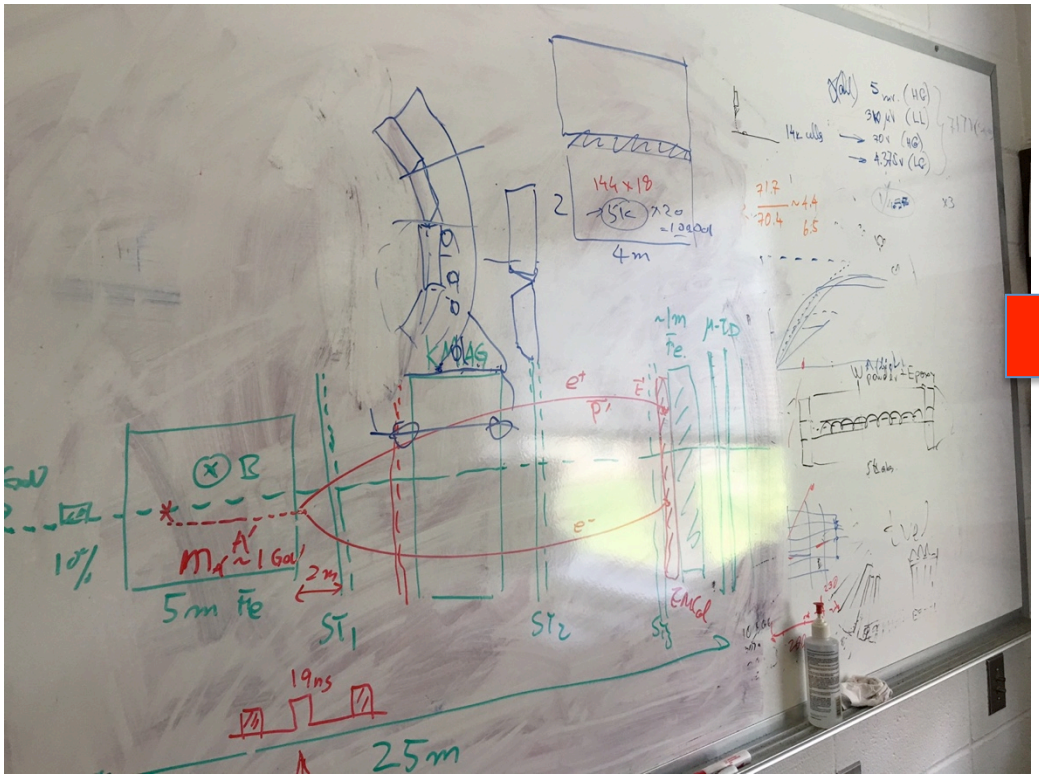


EMCal from PHENIX/RHIC

- 2 EMCal sectors are available from PHENIX experiment at RHIC, ~end of 2016
  - One 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

Available in summer 2017 for installation at Fermilab

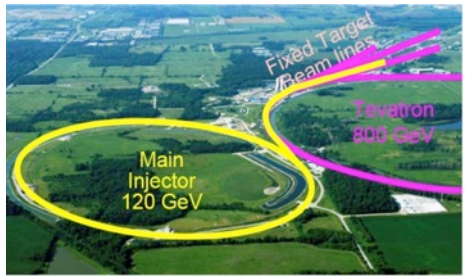
- *dE/E = 8.1%/sqrt(E) + 2.1%*
- *dT < 200 ps*
- *Excellent e/pi separation*

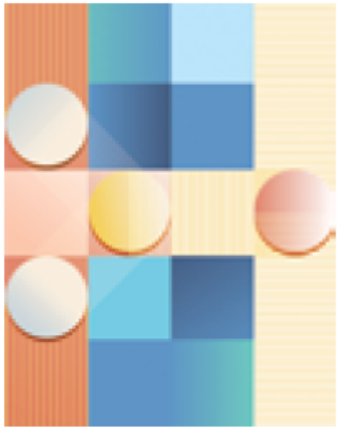


Impacts on the 2014 US P-5 Report

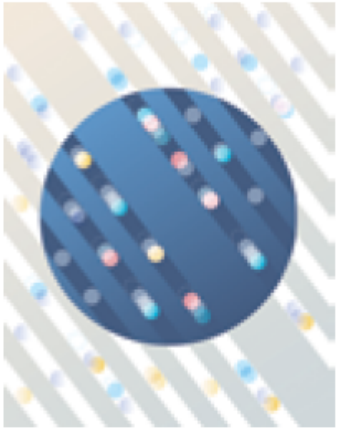
Five intertwined scientific Drivers were distilled from the results of a yearlong community-wide study:

- 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



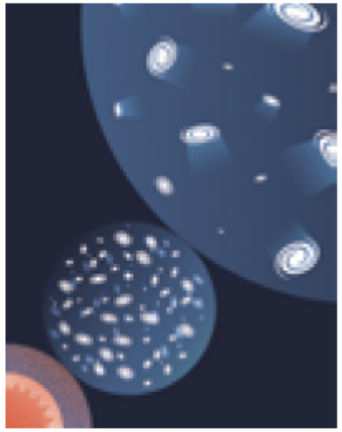


Higgs boson



Neutrino mass

Dark matter



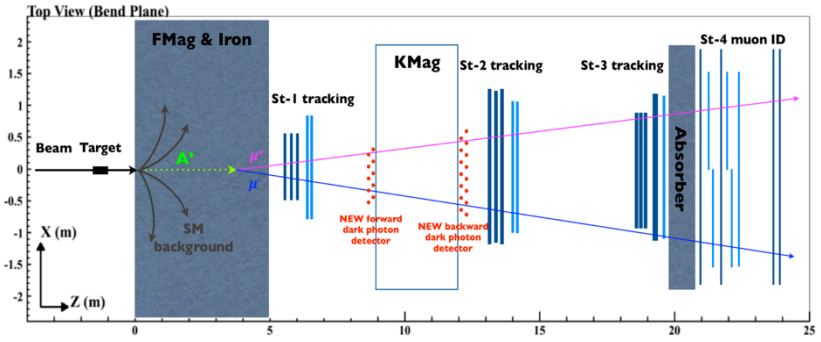
Cosmic acceleration

Explore the unknown

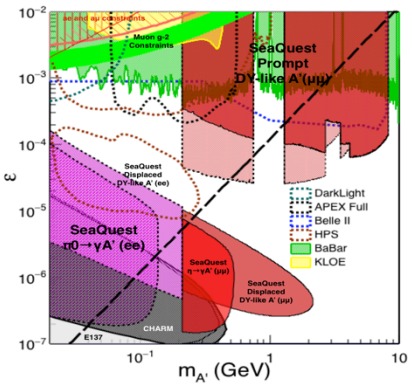
E1067/SeaQuest: Great Discovery Opportunities at the Fermilab Intensity Frontier!

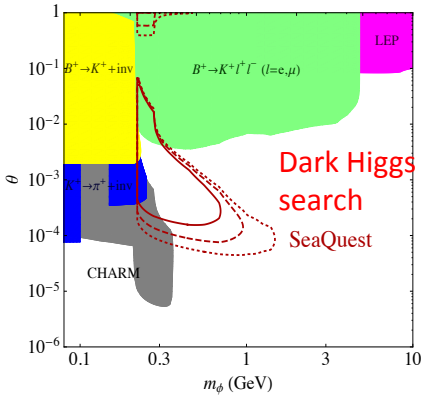
Outlook

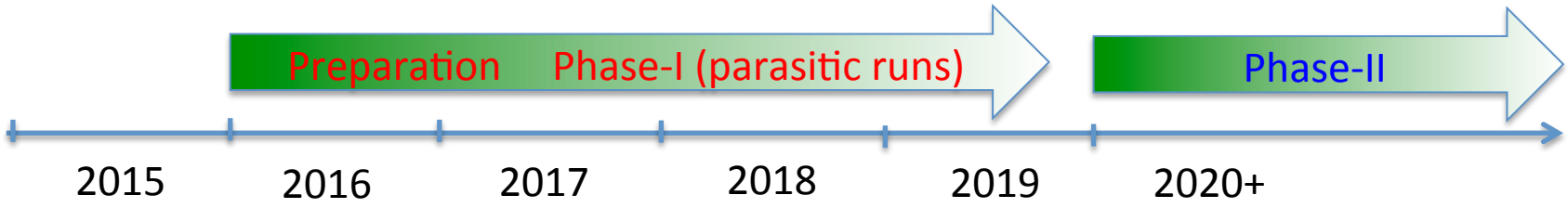
- ***Phase-I (LDRD) on track!***
  - ***Completed all FY16 milestones***
  - ***On track to meet FY17 milestones***
  - ***Great discovery potential!***
  - ***Early parasitic data taking 2017-2019+***
  - ***POT 1.4 x10^{18}***



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







Backup

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)

Collaboration:

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LOI submitted to Fermilab PAC
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 EMCal/HCal upgrades, $e^{+/-}$ and $h^{+/-}$ capabilities.
2. Cover the full parameter phase space allowed by beam energy and luminosity
3. POT: >> 1.4×10^{18}

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

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

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

NEW EXPERIMENT! E-1067

LANL LDRD support:

- FY16-17-18

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

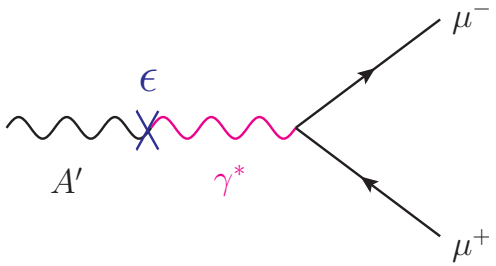
Goals:

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

Dark Photon Decay Modes

"Minimal" Decay:

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

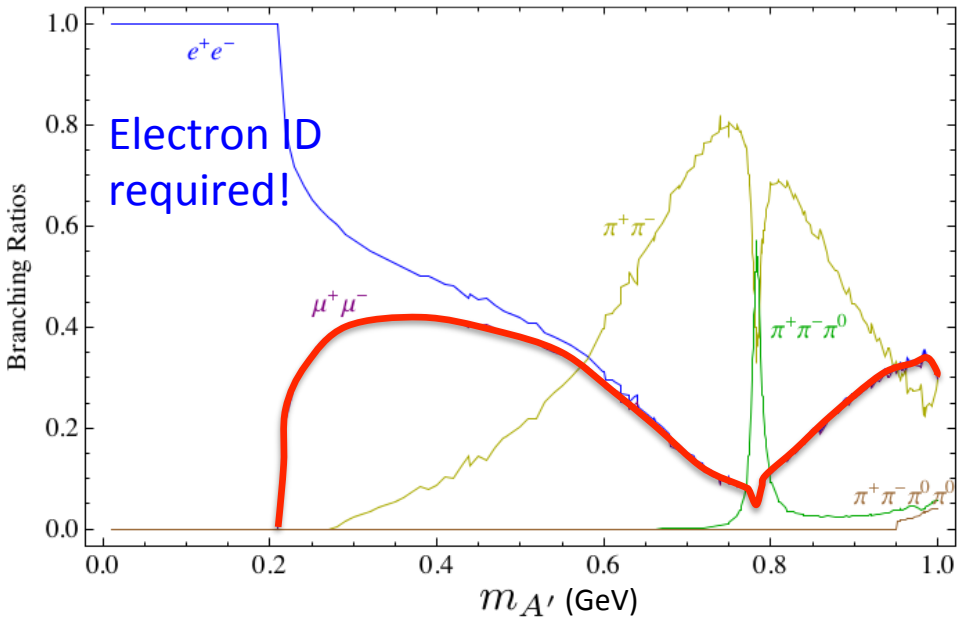


$$\Gamma(A' \to f + \bar{f}) = C\frac{\epsilon^2 m_{A'}}{3} e_f^2 \alpha_{\rm em} \left(1 + \frac{2m_f^2}{m_{A'}^2}\right) \sqrt{1 - \frac{4m_f^2}{m_{A'}^2}},$$

Long proper decay length: L_0 ~ *O(1m)*

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

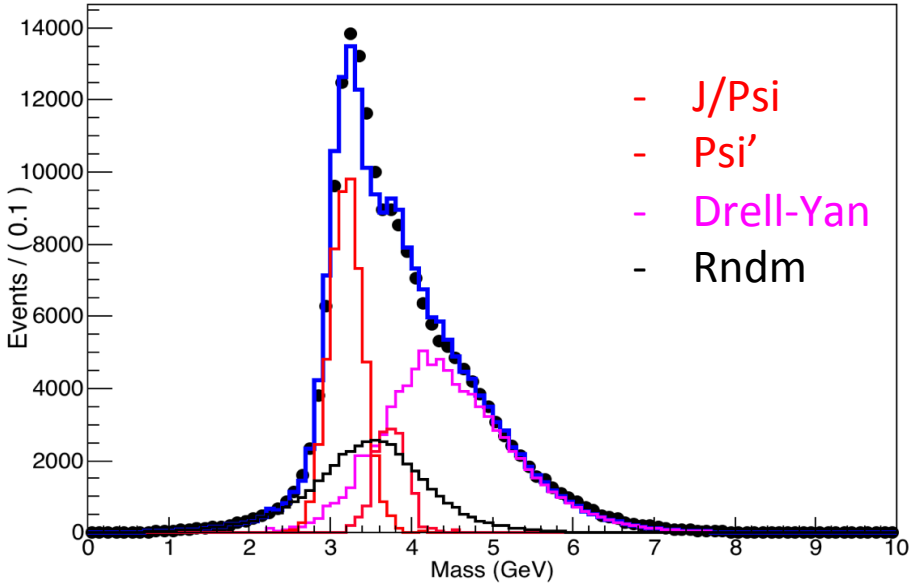
D. Curtin, et al, arXiv: 1312.4992

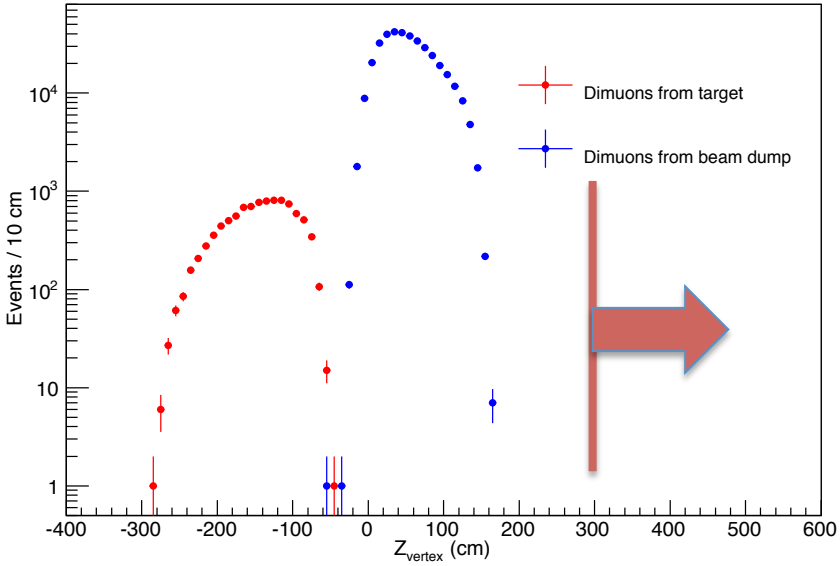


"General" Decay:

- Decay into other dark particles, dominant channel if allowed
  1. Dark -> Dark
  2. Dark -> SM particles

E906 Run 2 Data: Dimuon Invariant Mass and Reconstructed Z-Vertex





E906 Trigger and event selection optimized for high-mass dimuons, mass > 2.5GeV ;

Low-mass dimuons are rejected by trigger.

Dimuon event z-vtx distributions after target/dump separation;

No events observed beyond Z-vtx > 2m

Production Scintillator Bars

Production SIPMs etc.

- SiPMS, 600
- Cables
- Power supply

DAQ Upgrade

- Current E906 mode
  - Log event on every trigger
  - Store each event on disk at each trigger

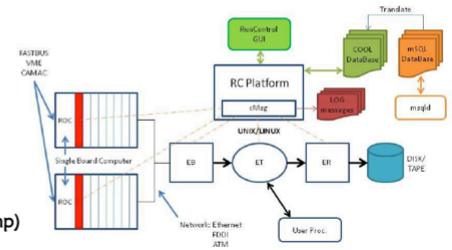
- New DAQ mode
  - Store event on buffer during the spill ~4 Sec
  - Send data to disk when no beam, ~56 Sec
  - Low dead time
  - High bandwidth

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 tr 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 (Byr Morton, Kun et al)
  - Trigger firmware and DAQ integrati
  - Can use more help

LANL machine build-up

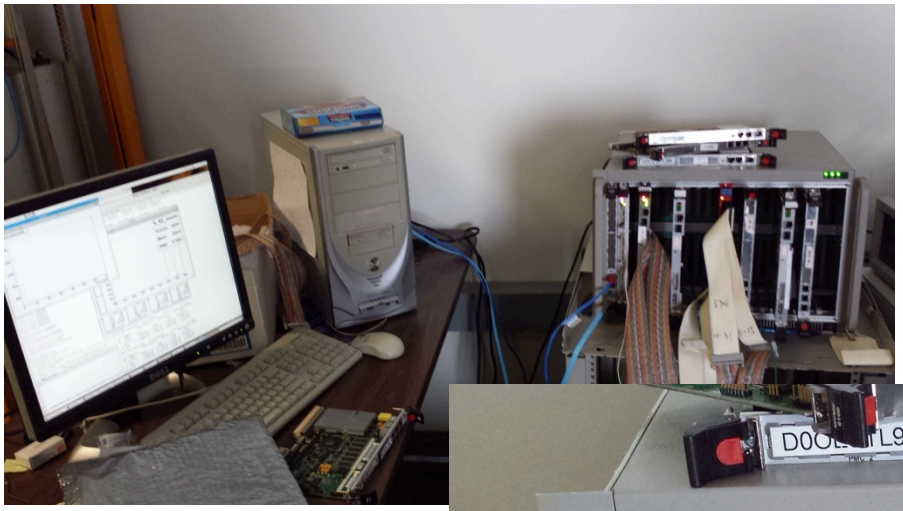
- ✓ Install Scientific Linux Fermi 6.7
- ✓ Setup rsh connections
- ✓ Install CODA 2.6.1
- ✓ Setup the CODA database
- ✓ Add Trigger Supervisor SIS3610
- ✓ Start with Run Control
- ✓ Offline data monitoring (xcefdmp)



A Standalone DAQ for Trigger Development

- PC/Linux: Jlab CODA, Ethernet Readout
- CPU MVME5500: old VxWork (Jlab)
- “TS” SIS3200
- TDC-II
- V1495 pulse generator

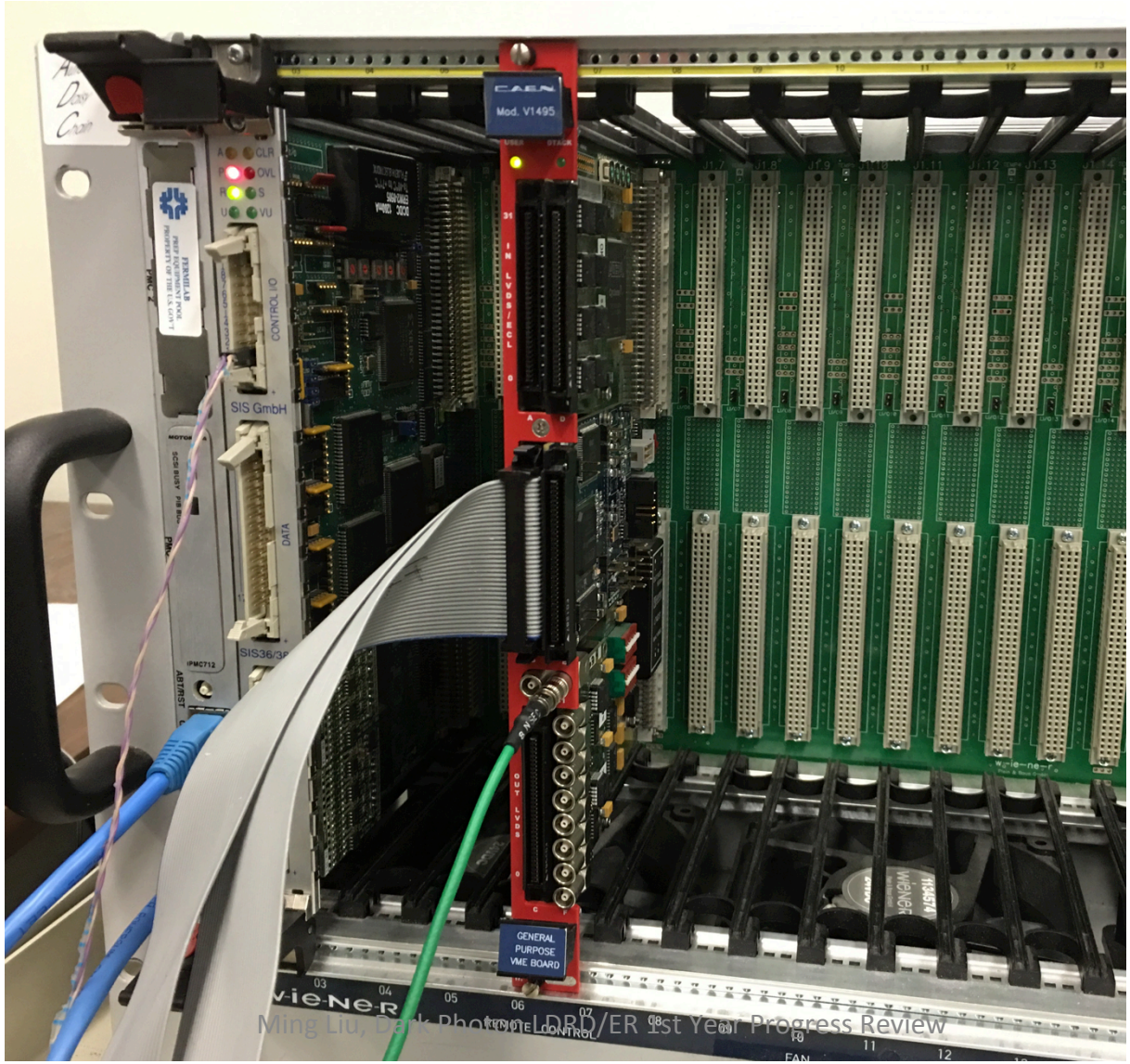
- V1495 L1 Trigger “development brd”
- Windows PC: Altara FPGA programing



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

DAQ and Trigger Test Stand at Fermilab

V1495 Trigger Logic Unit R&D

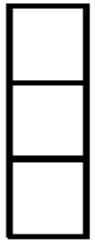


More on Scintillator+WLSF Efficiency Study

Scan single fiber efficiency

- Amplitude distribution

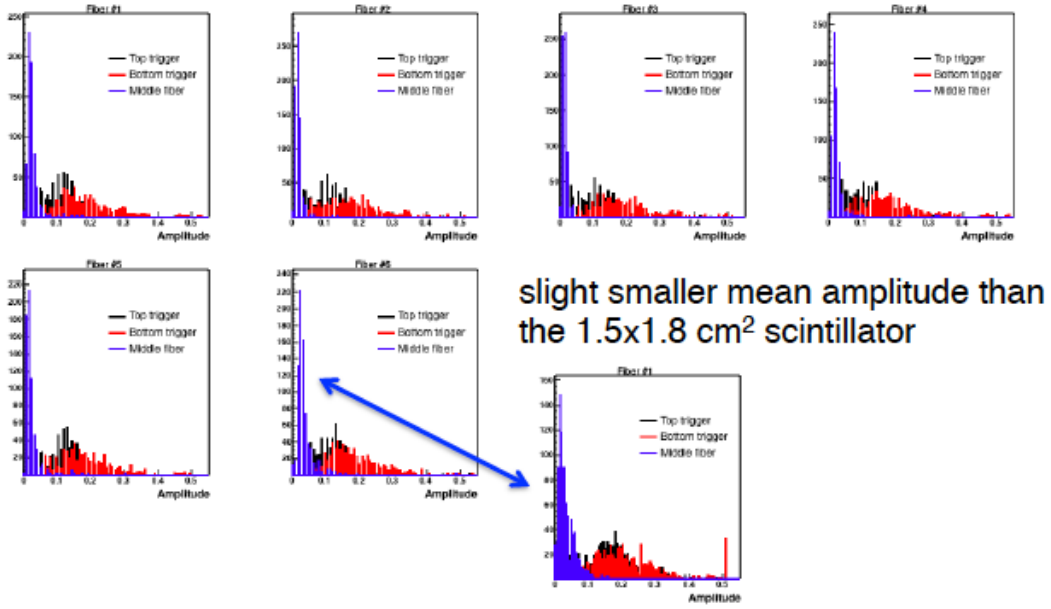
all scintillators are 1x1 cm^2



Top (7 fibers)

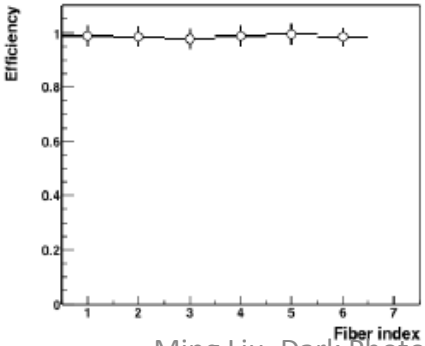
Middle (1 fiber)

Bottom (7 fibers)



slight smaller mean amplitude than the 1.5x1.8 cm^2 scintillator

- Efficiency



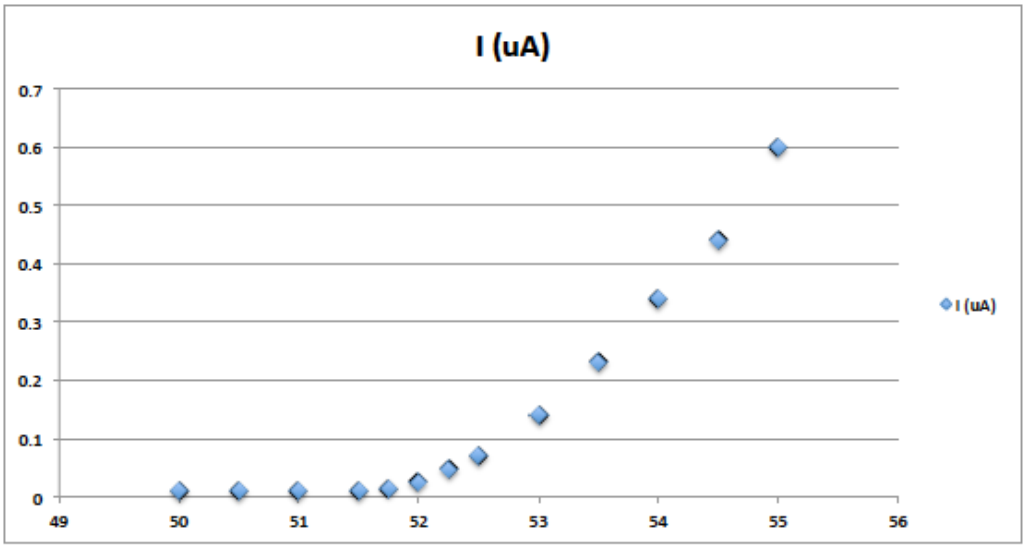
Before doing this test, I rechecked fiber connection to SiPM.

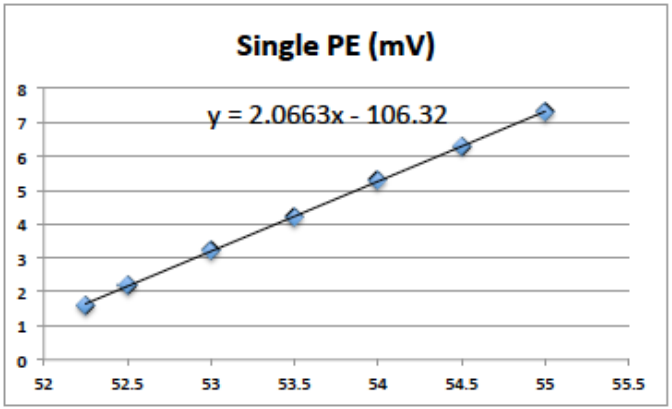
Efficiency looks pretty good

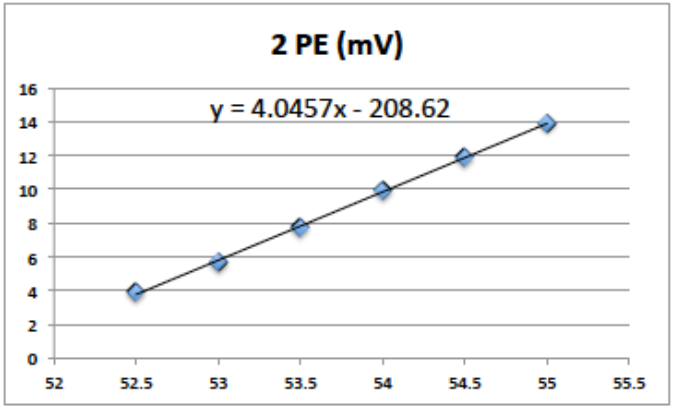
1

SiPM I-V and Gain

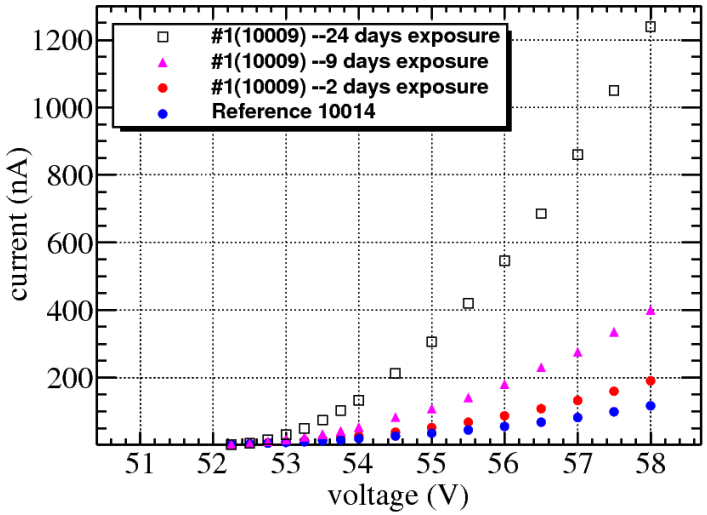
Vbias (V)	I (uA)	Single PE (mV)	2 PE (mV)
54.5	0.44	6.3	11.9
55	0.6	7.3	13.9
54	0.34	5.3	9.9
53.5	0.23	4.2	7.7
53	0.14	3.2	5.7
52.5	0.07	2.2	3.9
52	0.025		
51.5	0.01		
51	0.01		
50.5	0.01		
50	0.01		
52.25	0.047	1.6	
51.75	0.014		
V_BR(1)	51.45		
V_BR(2)	51.57		

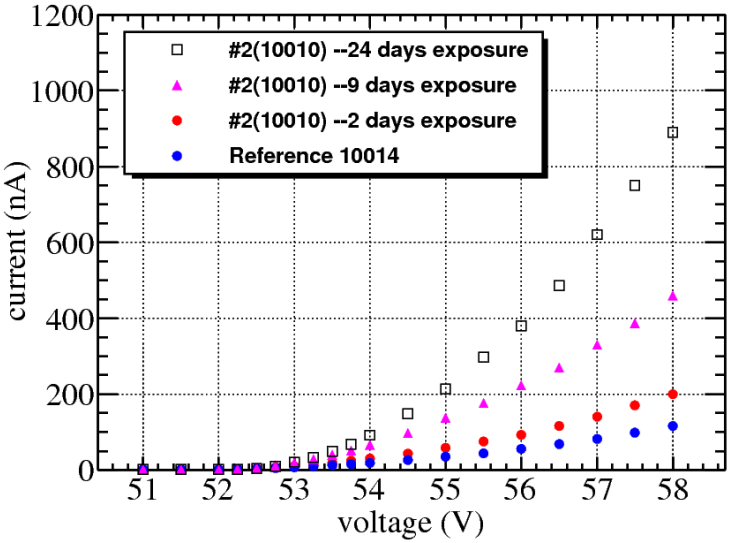






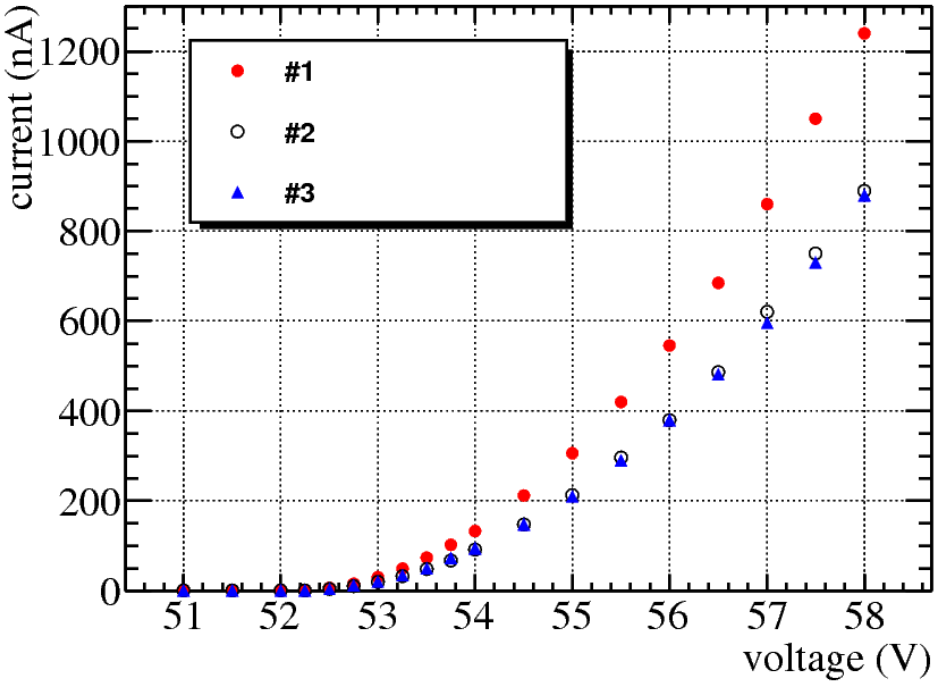
SiPM Radiation Damage Study at Fermilab



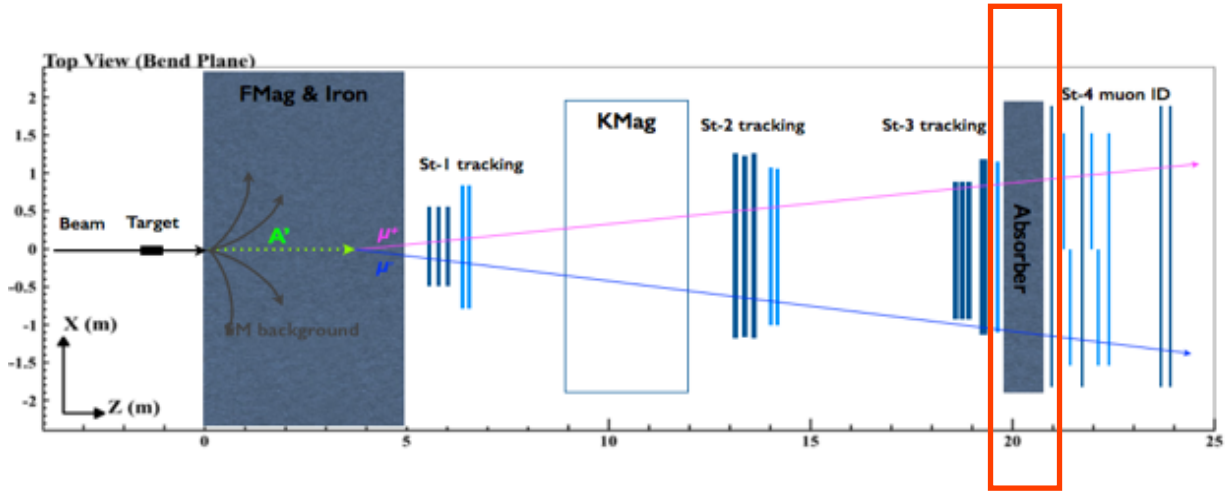


After 24 days exposure (~10% of total)
~100nA at 54V
~400nA at 56V
~1,000nA at 58V

~ observed no change in gain (<10%)



Two Possible Configurations and Their Impact



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 π/μ/e tracks with 5 GeV < *P* < 115 GeV
- 1M high mass (M > 4 GeV) target DY pairs
- 2E10 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?