FY17 Highlights of Dark Photon Search at Fermilab

Ming Liu, P-25 Dark Photon/Higgs Search @Fermilab LDRD/ER Team

- Overview, 20' Ming
- Theory Highlights, 10' Kang & Vincenzo
- Experimental Highlights, 35' Sho & Kun

SeaQuest at the Intensity Frontier at Fermilab

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

- 35,000 fb⁻¹ (in a 2-year parasitic run, 1.4x10¹⁸ POT @5% beam)
- LHC-II: 300 fb⁻¹ (~2025), achieved 25fb⁻¹ in Run-I





Goals and Scope of the Project (from Proposal)



FY2015	FY2016	FY2017	FY2018
Experiment	Dark photon trigger	Pol. Drell-Yan E1039	
	development & test Trigger cons installation,	truction, Parasitic data taking v	vith E1039
	Exp. optimization commissioni	ning	Physics data analysis, first results
Theory			· · · · · · · · · · · · · · · · · · ·
	Dark photon cross section at LO and NLO	QCD rusummation to all order	
	Experimental sensitivity study	-	Data interpretation, first results

People Involved

- Experimental efforts (P-25): ~8 staff + 8 PD/Students + 2 Engineer/Tech
 - Ming Liu, Kun Liu(PD, Staff), Sho Uemura (PD, 11/2016-), Grass Wang(PD, 7-9/2016), Pat McGaughey, Hubert van Hecke, Andi Klein, Cesar da Silva, Matt Durham, Sanghoon Lim(PD), Shaun Newman(P-21, Mechanical Engineer), Xinkun Chu (Student, graduated 5/2017), Xuan Li (PD), Marie Boer (PD), Dave Kleinjan(PD), Alex Wickes(Student), Jeff Bacon, Richard Van de Water
- 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 growing ...



A New High-Granularity Displayed 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, $\sigma_z \sim 30$ cm
- Displaced z-vertex, mostly low mass < 3GeV

A' μ^+





Achievements in the 1st Year (FY16)

- Completed trigger detector R&D and technology down selection
 - Extruded scintillators, produced at Fermilab
 - WLSF, procured from Kuraray, Japan
 - SiPM readout in strong magnetic field, procured from Hamamatsu, Japan
- Completed preliminary design of the mechanical frame
 - 80-20 Al frame selected
 - Assembled 4 (50%) 80-20 box-frames at LANL
- Redesigned DAQ readout with a new architecture
 - Take advantage of the beam spill structure: 4sec/60sec
 - Preliminary new DAQ firmware developed and tested
- Down selected trigger electronics
 - CAEN V1495 logic boards for LVL-1 & LVL2
- Developed a new GEANT detector simulation package
 - Preliminary physics study
- Completed LO and NLO calculations
 - Provided Drell-Yan and Dark Photon event inputs for simulations









Major Tasks and Accomplishments in FY17

Goals

• Complete DAQ Upgrade

Complete trigger detector construction

• Trigger detector installation and commissioning

• Take data with E1039(E906)

QCD resummation

Accomplishments

- Successfully commissioned the new DAQ and integrated the dark-photon trigger system
 - DAQ bandwidth improved by ~10
 - A new displaced dimuon trigger electronics & firmware
- Designed and built full trigger detectors at LANL
 - Extruded scintillators + WLSF + SiPMs, 520-channel
 - 80-20 Al box frames + global supporting structures
 - Station-1:
 - 4 quadrants, 80x80cm^2 each, 320 channels
 - Station-2:
 - 4 quadrants, 100 x 100 cm² each, 200 channels
 - Optical calibration system
 - LV/HV power distribution and control boards
- Installed and commissioned trigger detectors @Fermilab
 - Timing resolution: < 1.5 nS (collision rate ~ 19nS)
 - Track hit eff. > 96% (from cosmic)
- Took production data parasitically with E906
 - Detector calibration, performance and initial search
- Completed DY & DP QCD resummation to all order
 - Inputs to physics simulations

Very Successful Team Work!











Completed modules, 8 of them in total!

Station-1: 80 x 80 cm², 80 channels



Station-2: 100 x 100 cm², 50 channels



Optical Calibration, LV/HV Power Distribution and Controls Systems



All designed, built and tested at LANL





Trigger, DAQ R&D and Cosmic Test @LANL

- 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
 - V1495 trigger logic + TDC read out
 - E906 upgraded DAQ and firmware

Timing resolution, < 1.5nS (19nS RF)

Detector eff. > 96%





bar_times[0]:bar_times[1] {bar_pattern==127}



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10/17/17

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

- Eight trigger detector modules
- Electronics and Power supplies





Trigger Detector Systems Installed and Commissioned @FNAL Took Production Data with E906!



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Publications and Presentations

• Papers:

- Dark Sector Community Report, 2016, arXiv:1608.08632
- US DOE Cosmic Vision Whitepaper, 2017, arXiv:1707.04591
- An invited review paper on SeaQues/E1067, Mod. Phys. Lett. A, 2017, Vol. 32, Issue 10
- A phenomenology paper in preparation

• Presentations:

- BNL Dark Sector Physics Workshop, 10/2016
- DOE Cosmic Vision Workshop, 3/2017
- Fermilab PAC discussion, 7/2017
- APS/DNP, 10/2017
- HPS Mini-Symposium, 10/2017, SLAC
- Light Dark World International Forum, 10/2017, Pittsburgh

Being recognized in the community as an important new player:

- Our dark photon program highlighted at opening plenary talk, BNL Dark Interactions 2016
- Invited talk at HPS mini-Symposium 2017
- Invited plenary talk at Light Dark World 2017



Impacts of this LDRD

• Two ECR Proposals

- A new LHCb forward tracking upgrade based on the detector technology developed here (funded, LANL/ECR FY17-19, Cesar da Silva)
- A new search for low mass dark matter in di-electron channel (a new proposal, FY18-20, Kun Liu)
- Provided important hardware trainings for postdocs and young staff
 - Refresh skills after many years of mostly data analyses and simulations
- Development of a possible new HEP program of high P-5 impact
 - A new dark sector physics program at Fermilab Intensity Frontier
- Visibility of LANL's scientific R&D to the outside world
 - 4 papers, 4 invited talks

Experimental Challenges: Plan vs Reality

	FY2015	FY2016		FY2	017	FY2018	
	Experiment	Dark photon trigger development & test Exp. optimization Trigger cons installation, commission	+ -,	Pol. Drell-Yan E1039			
			Trigger con installation	rigger construction, Parasitic data taking v stallation, ommissioning	Parasitic data taking v	vith E1039	
			commission		Physics data ana	sis, first results	
	SeaQuest Reality:	E906	5 operatior	n contin	ued to 7/2017	E1039 target installation by 5/2018	E1039 commissioning & data taking 5/2018 – 9/2018
Mu	Much larger R&D: DAQ, detector, readout & control				rigger detector constructior tion, commissioning and da	ı, ta	LDRD data taking w/ E1039, 5/2018
 electronics changed and delayed, unavailable, cost increased Took Plan-B, redesigned everything from scratch, much larger R&D 			sed R&D	taking;	offline data analysis	5/3	3/2018

- Collaborated with Fermilab to reduce readout cost

SeaQuest schedule changes:

- E1039 installation delayed by ~1.5 year
- E906 continued data taking till 7/2017
- No dedicated installation time, 2-month delay

Tasks and Schedule	Planned for FY17	Achieved in FY17	Status in FY18
Trigger & DAQ upgrade completed	March 2017	April 2017	ready for beam
Data taking with E1039/E906	May 2017	June 2017, parasitic w/ E906	Ready for beam w/ E1039

Plan for FY18 and Beyond

• FY18:

- Analyze FY17 data
 - Study detector performance and realistic projection
 - Complete physics analysis package
- Take more data with E1039
 - E1039 target installation: 11/2017 5/2018
 - E0139 commissioning & data taking run: 5/4/2018 9/2018
 - Analyze FY18 data
- Produce preliminary search results with full theoretical inputs

• Beyond FY18

- Parasitic data taking with E1030 for two years: FY2019 FY2020
- Much improved measurements, reaching the original sensitivity goal
- Possible EMCal upgrade with a new proposal
 - Low mass dark photon search below 200MeV, with di-electrons

Beyond FY18 – Long Term Prospects

Low Mass Dark Photons in di-electron Channel with EMCal upgrade

• Detector upgrades

- EMCal: e^{+/-}
- EMCal recycled from PHENIX/RHIC
- Data taking w/ E1039, 2019 2020
- Timeline of dedicated runs
 - After E1039 completion: 2020+ ~ 2025
 - SHiP/CERN starts ~2025
- Detector configuration optimization
 - Access low mass region with optimized FMag settting etc.





Summary and Outlook

• FY17

- Successfully completed Trigger and DAQ Upgrade
- Successfully took data with E906
- Ready for full data taking with E1039

• FY18

- Take more data with E1039 in FY18
- Data analysis and first preliminary search results

Fermilab dark sector physics program:

- Phase-I (2017-2020)
 - Great discovery potential!
 - Parasitic data taking with E906/E1039, 2017-2020
 - *POT 1.4 x10¹⁸ or more*
 - Possible detector upgrade, add electron and hadron capability
- Phase-II (2020-2025+)
 - A new dedicated dark sector physics program at Intensity Frontier!





backup

A target Drell-Yan event



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



E1067

10/17/17

Developing a long term program at Fermilab

• New ideas

- Low mass region with di-electroncs
- QCD-like Dark Sector physics
- EMCal upgrade (recycled from PHENIX)
- Dedicated accelerator based beam-dump dark sector physics program
 - Dark photon
 - Dark Higgs
 - Dark "QCD" mesons
 - Complete major program by 2025, when SHiP@CERN is on line

Phase-I Expectation: Dark Photons (parasitic run w/ E1039)

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)
- **Phase-II with upgrades** Access below 200MeV with di-electrons (add EMCal)



Projected Dark Higgs Sensitivity POT:1.4x10¹⁸ (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, mass<3GeV



10/17/17

EMCal from PHENIX/RHIC

• 2 EMCal sectors are available from PHENIX experiment at RHIC, ~April of 2018

- 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



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



E-1067 Future Upgrade: Phase-II 2020 ~ 2025+



A Great Opportunity Dark Photons and Dark Higgs Search at SeaQuest



Dark Photon Detection in Dilepton Channel

1. Drell-Yan like



1. π⁰, η, ... decay

1. Bremsstrahlung

Dark Higgs

