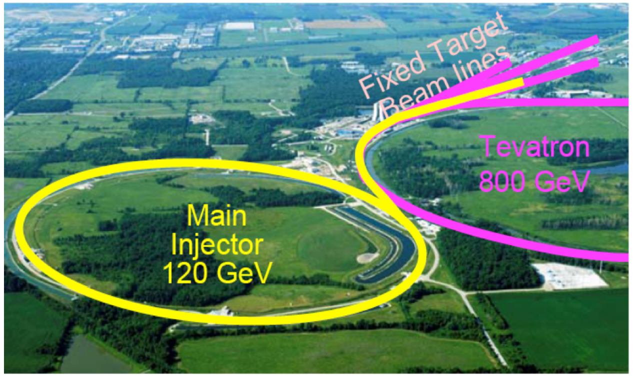
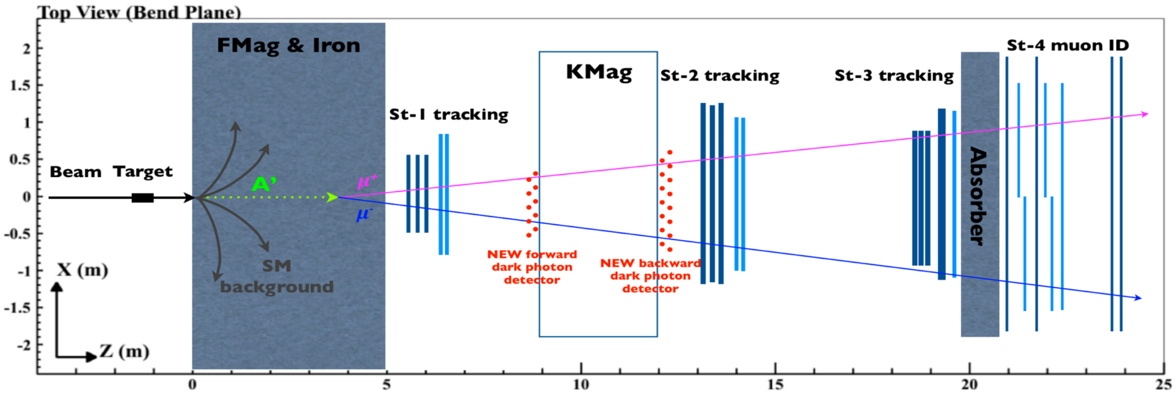
A Direct Search for Dark Photon and Dark Higgs Particles with the SeaQuest Spectrometer in Beam Dump Mode at Fermilab

Ming X. Liu (Los Alamos) and Paul E. Reimer (Argonne)

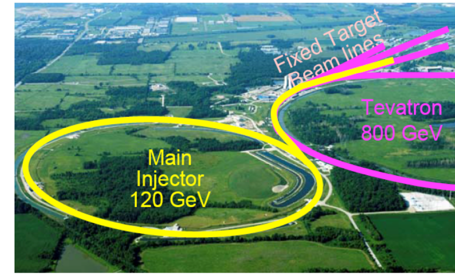
P-1067 Collaboration



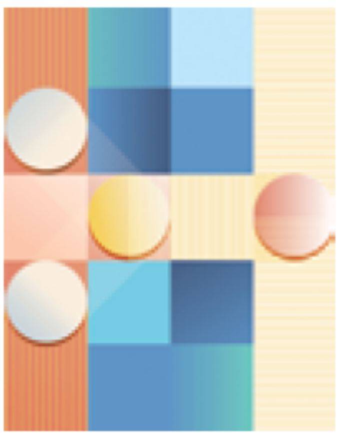


2014 US P-5 Report

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



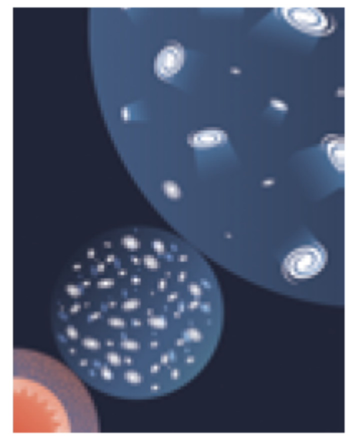
- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles



Higgs boson

Neutrino mass

Dark matter



Cosmic acceleration

Explore the unknown

Great Opportunities at the Fermilab Intensity Frontier!!!

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:

M. S. Daugherity, L. D. Isenhower, R. S. Towell, T. S. Watson
Abilene Christian University, Abilene, TX 79699
J. Arrington, D. Geesaman, K. Hafidi, R. J. Holt, P. E. Reimer, B. G. Tice
Argonne National Laboratory, Argonne, IL 60439
J. Huang
Brookhaven National Laboratory, Upton, NY 11973
Y. Zhang
Caltech, Pasadena, CA 91125
E. Kinney, P.-J. Lin
University of Colorado, Boulder, CO 80309
C. Brown, D. Christian, J.-Y. Wu
Fermi National Accelerator Laboratory, Batavia IL 60510
B. Dannowitz, M. Diefenthaler, B. Kerns, N. Makins, R. E. McClellan, J.-C. Peng,
University of Illinois, Urbana, IL 61081
W.-C. Chang, S.-Y. Wang
Institute of Physics, Academia Sinica, Taiwan
S. Sawada
KEK, Tsukuba, Ibaraki 305-0801, Japan
S. Gardner ,W. Korsch
University of Kentucky, Lexington, KY 40506
T. Bhattacharya, M. Brooks, V. Cirigliano, C. da Silva, M. Graesser, R. Gupta, X.
Kang, A. Klein, D. Kleinjan, K. Liu, M. Liu, M. McCumber, P. McGaughey, M. S
Ivan Vitev, R. G. Van de Water, H. van Hecke, H. Xing
Los Alamos National Laboratory, Los Alamos, NM 87545
E. Beise, Y.-C. Chen
University of Maryland, College Park, MD 20742
C. Aidala, W. Lorenzon, R. Raymond, J. G. Rubin
University of Michigan, Ann Arbor, MI 48109-1040
K. P. Adhikari, J. A. Dunne, D. Dutta, L. El Fassi
Mississippi State University, Mississippi State, MS 39762
T. Badman, E. Long, K. Slifer, R. Zielinski
University of New Hampshire, Durham, NH 03824
D. Fields
University of New Mexico, Albuquerque, NM 87131
S. Pate, V. Papavassiliou, X.R. Wang
New Mexico State University, Las Cruses, NM 88003
R.-S. Guo, G. Wang
National Kaohsiung Normal University, Taiwan

LOI submitted to Fermilab PAC on May 20, 2015

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

Phase-I: (focus of this presentation)

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}

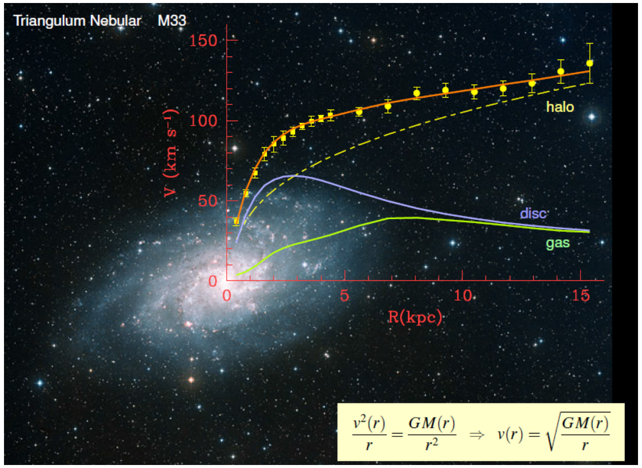
Phase-II:

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}

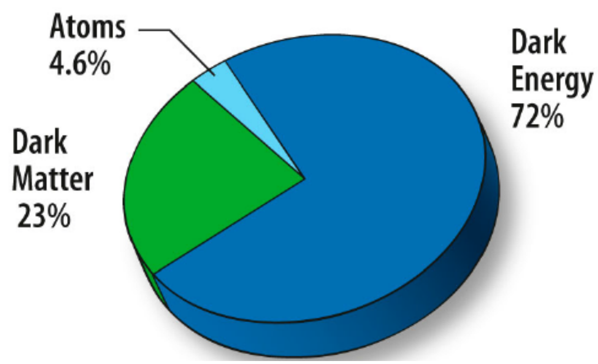
Phase-II request will be presented to PAC at a later time.

Dark Matter?

Galaxies' rotation curve



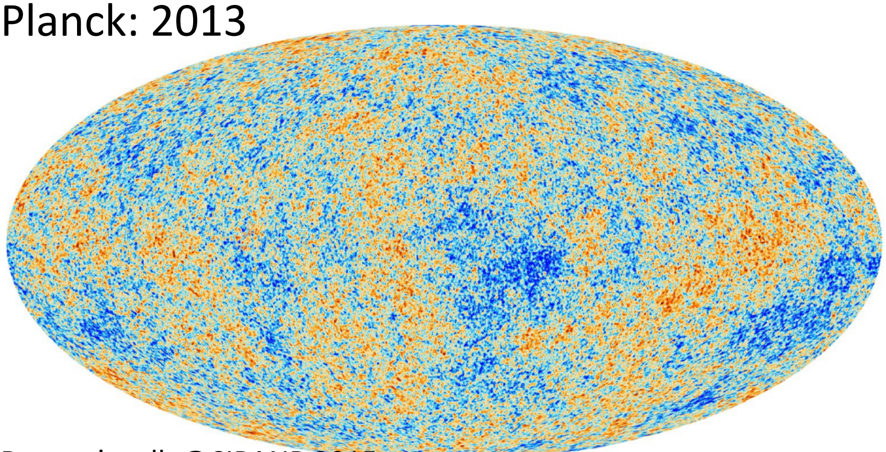
F. Zwicky, ApJ 86 (1937) 217, V. Rubin et al, ApJ 238 (1980) 471



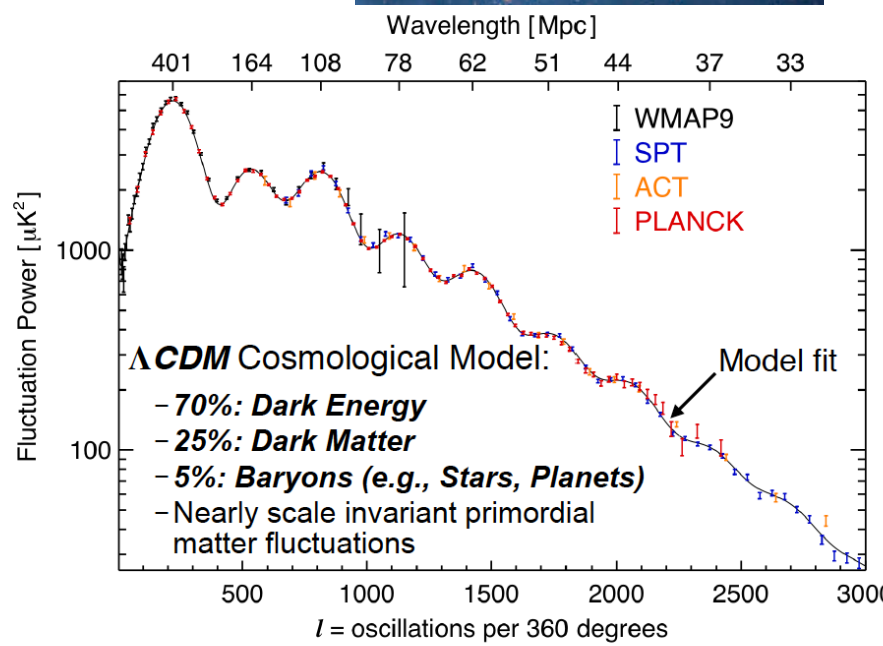
Gravitational lensing (Hubble 2007)

30μK RMS fluctuations on 3 K background

Planck: 2013



Benson's talk @CIPANP 2015



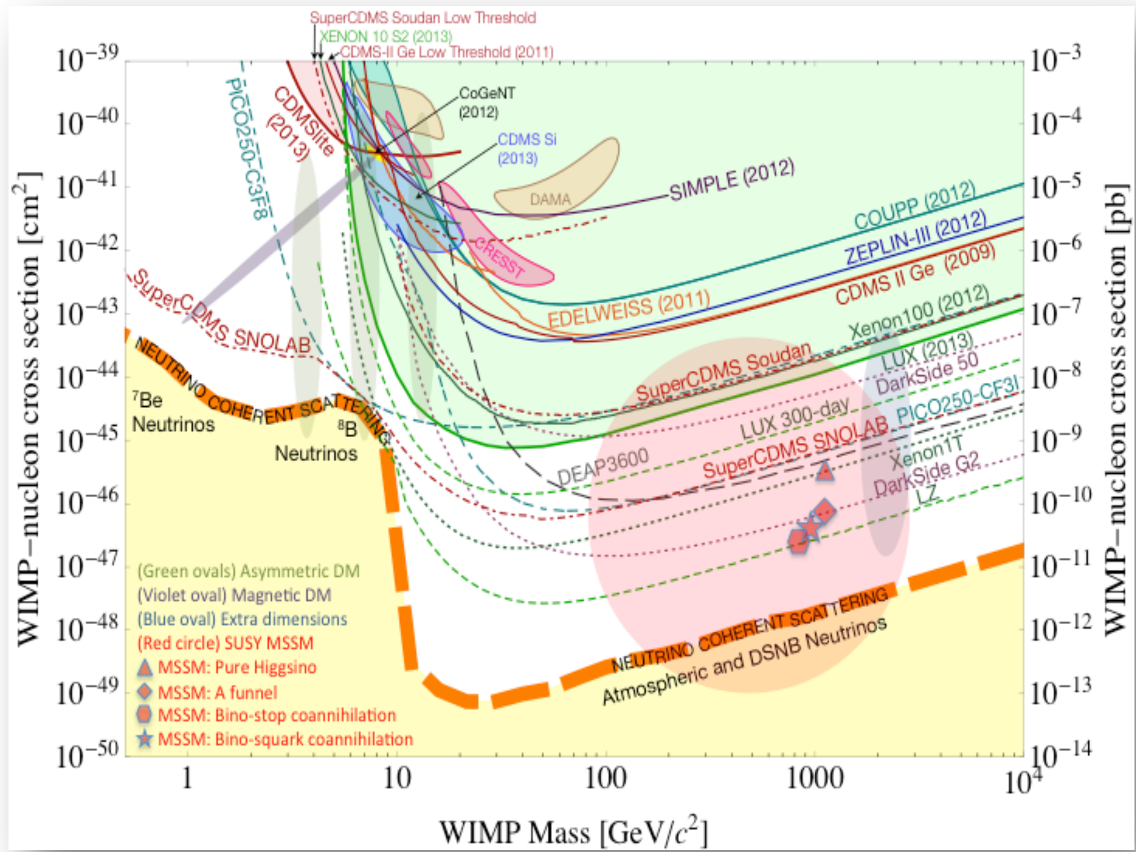
What Are the Dark Particles?

- WIMP being excluded?

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

- Recent anomalies observed by satellite and terrestrial experiments have motivated dark matter models introducing a new dark sector

- 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!!!



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

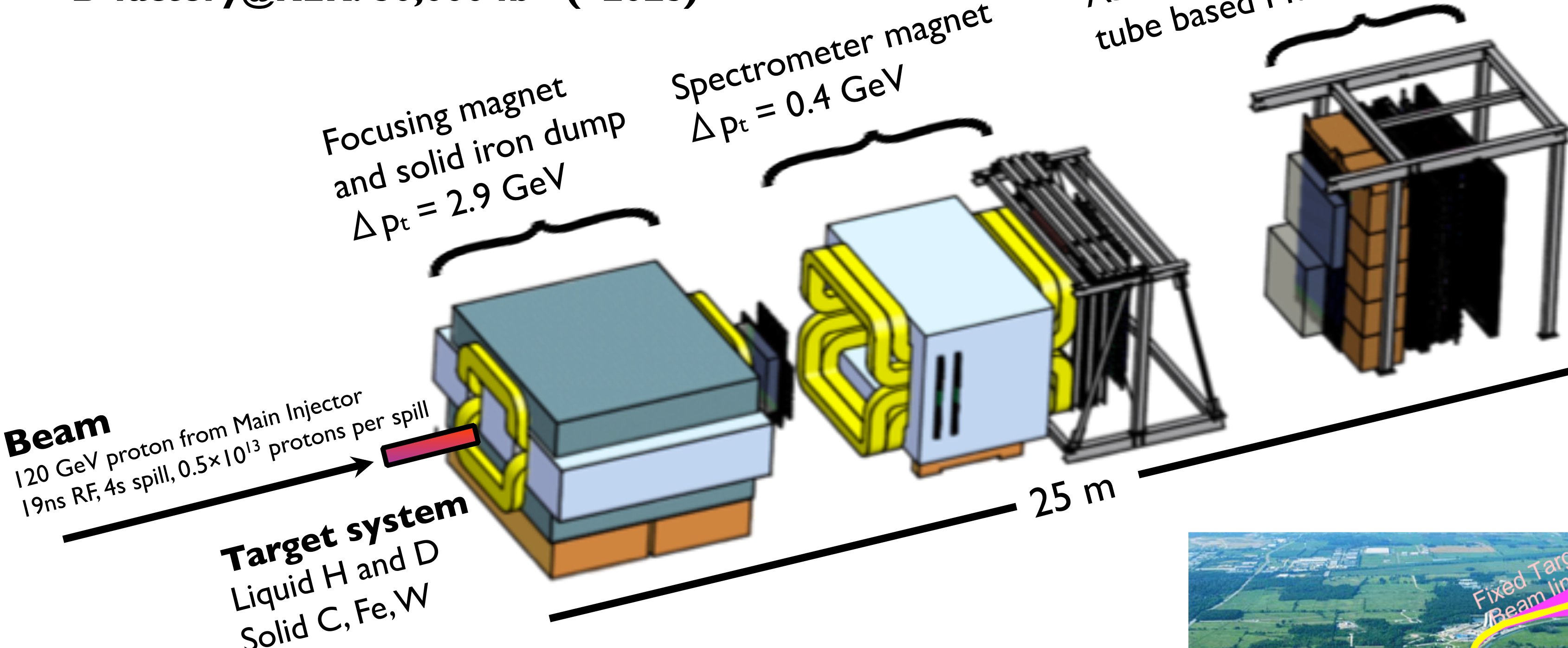
Mass: *O(MeV ~ GeV)*

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

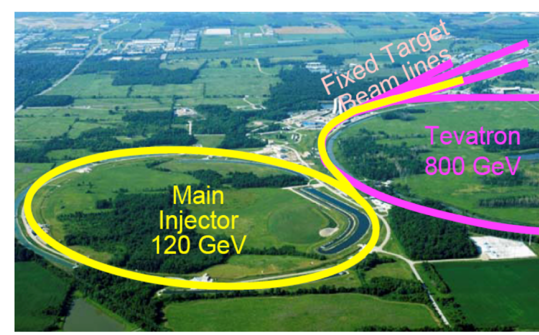
Intensity Frontier at Fermilab: 120 GeV Beam

World's highest intensity high energy proton beam:
"beam dump mode" @SeaQuest/E906

- **35,000 fb^{-1} (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)**

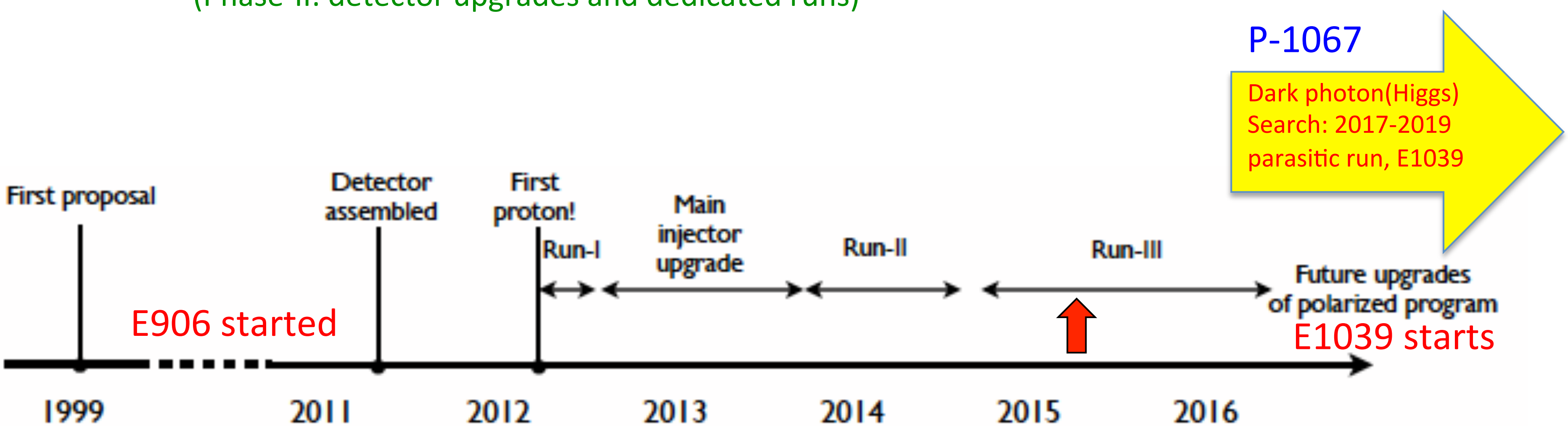


- Capture most beam in beam dump mode: p+Fe collisions!
- Parasitic run mode possible with other experiments, E1039/E1027



Schedule of SeaQuest Experiments

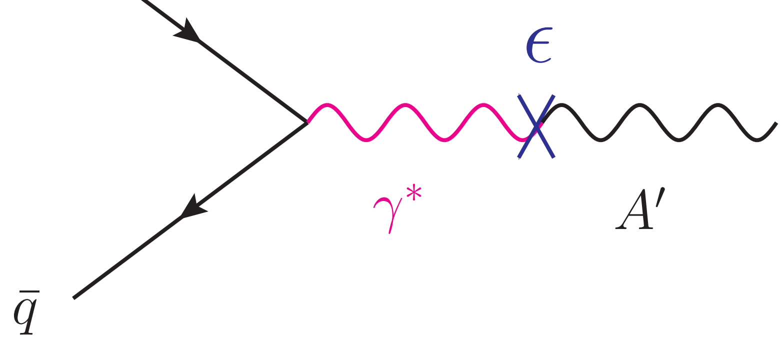
- E906 complete data taking in summer 2016
  - E906 targets are located ~1.3m upstream of the beam-dump
- E1039 will replace current E906 targets with a polarized NH_3 target.
  - No change to E906 spectrometer setup
  - New target located about 3.5m upstream of the beam-dump
- E1039 Timeline
  - Target/trigger installation: 2016 - 2017
  - Data taking: 2017 – 2019
- P1067 Timeline
  - Phase-I (Parasitic run) with E1039: 2017-2019
  - (Phase-II: detector upgrades and dedicated runs)



Direct Productions of Dark Photons and Dark Higgs in p+Fe at Fermilab

Photon portal: "vector"

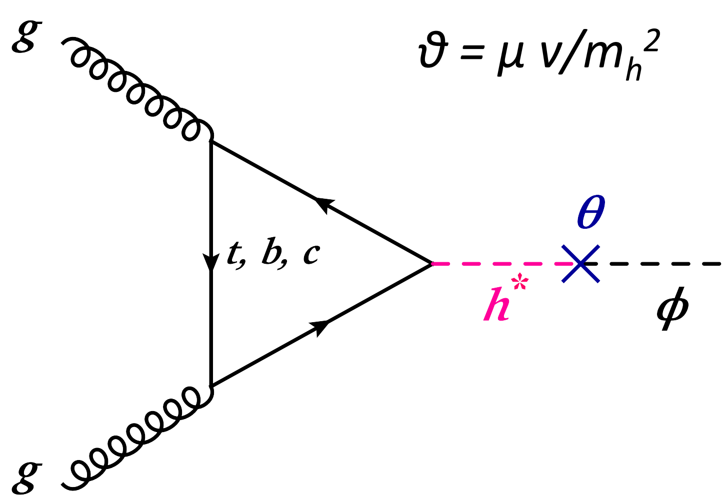
$$\mathcal{L}_{\mathrm{mix}} = \frac{\epsilon}{2} F_{\mu\nu}^{\mathrm{QED}} F_{\mathrm{Dark}}^{\mu\nu}$$



Higgs portal: "scalar"

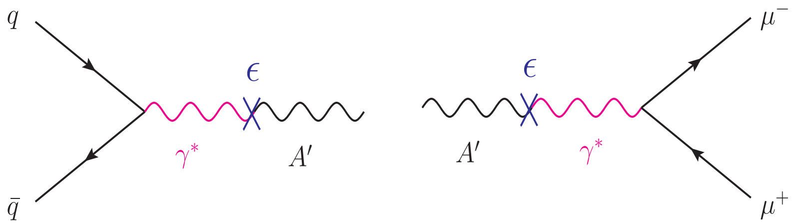
$$\mathcal{L}_{\mathrm{mix}} = \mu\phi |H^\dagger H|$$

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

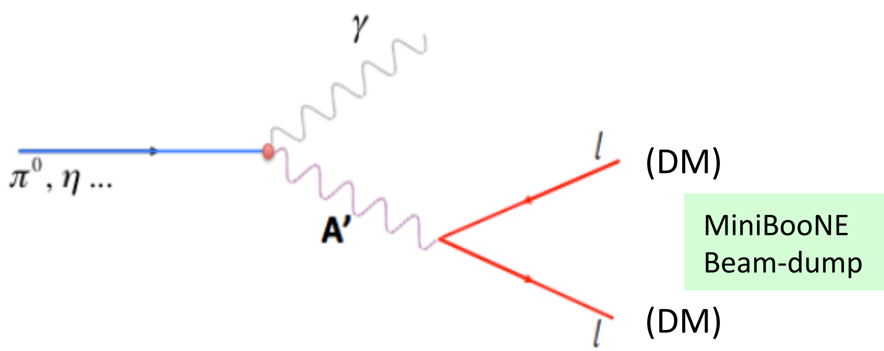


Dark Photon Search in Dimuon Channel at SeaQuest in Beam Dump Mode (p+Fe)

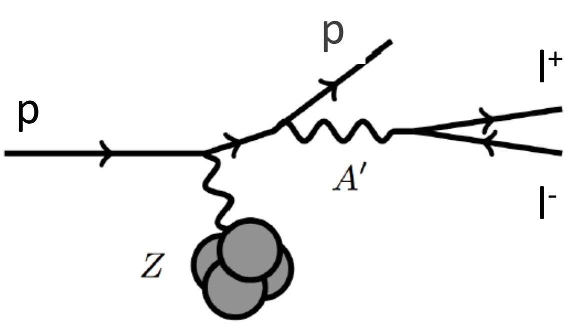
1. Drell-Yan like



2. π^0, η, … decay



3. Bremsstrahlung



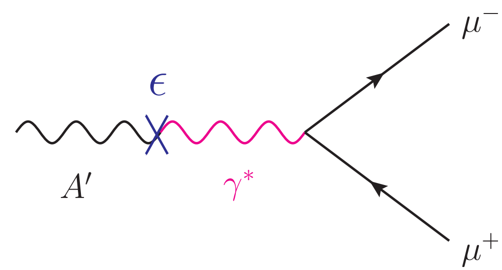
Dark Photon Decay Modes

"Minimal" Decay:

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

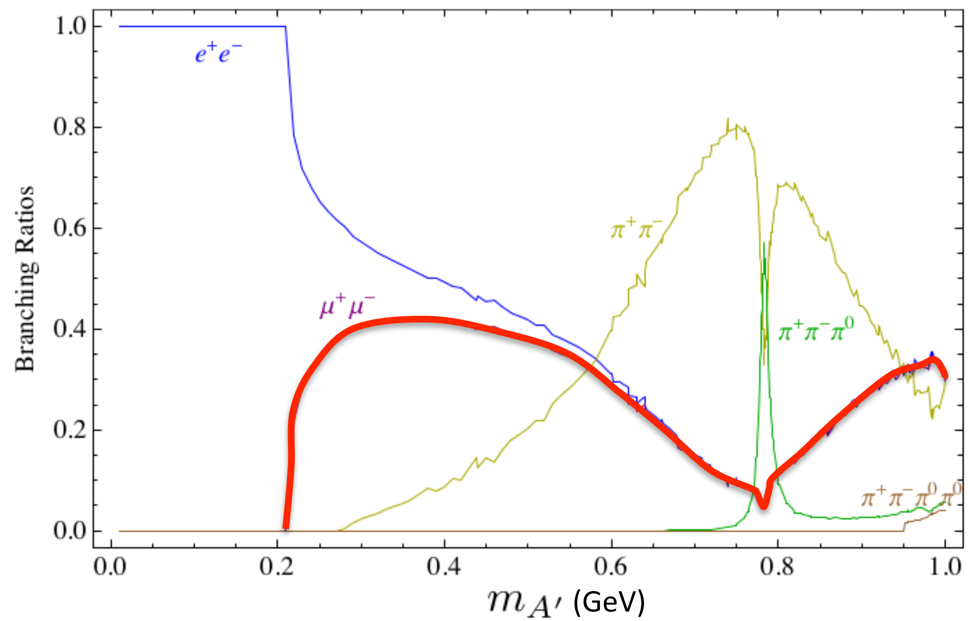
Long proper decay length: L_0 ~ *O(1m)*

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



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

D. Curtin, et al, arXiv: 1312.4992

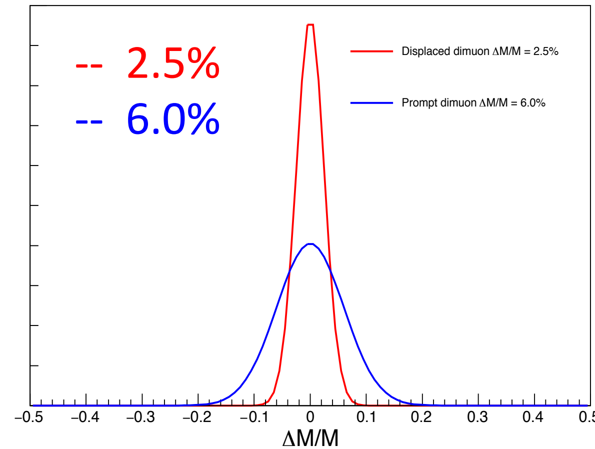


"General" Decay:

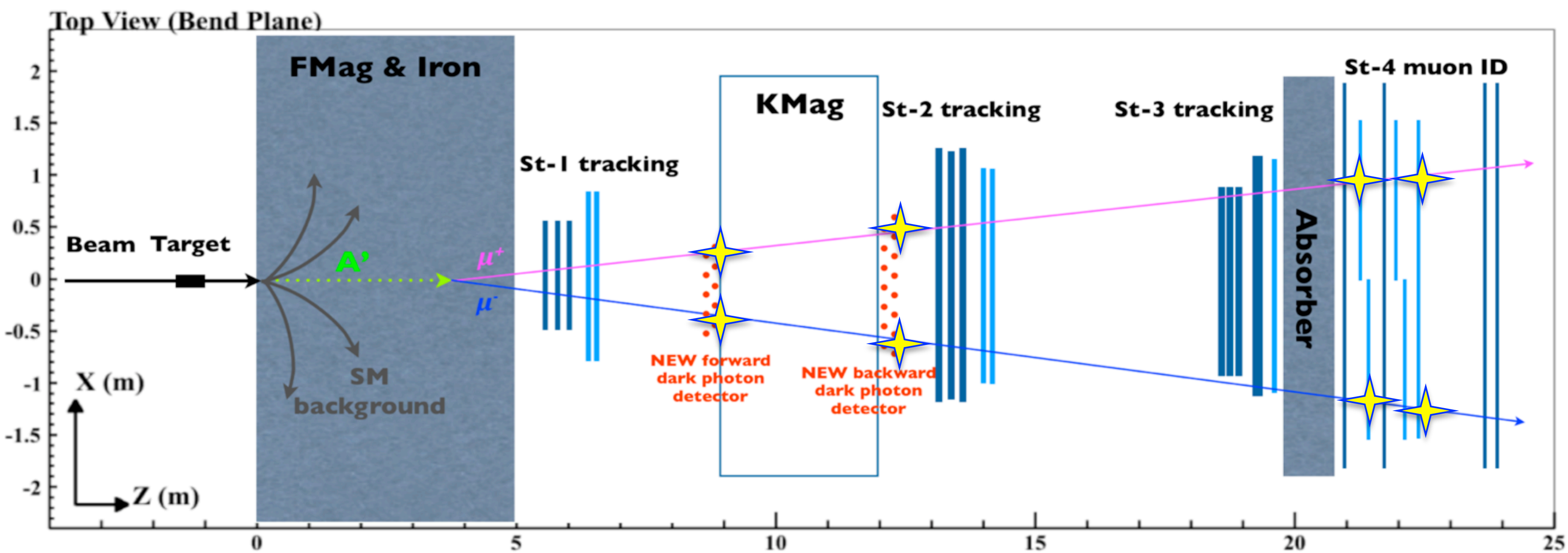
- Decay into other dark particles, dominant channel if allowed
  1. Dark -> Dark
  2. Dark -> SM particles

Proposed Experimental Measurements

- 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
- Beam time
  1. Run parasitically with E1039 (2017-2019)
  2. Possible dedicated runs later with upgraded ($e^{+/-}$, $h^{+/-}$)



Dimuon mass resolution



Z (meter)

A New High-Granularity Displayed Dimuon Vertex Trigger

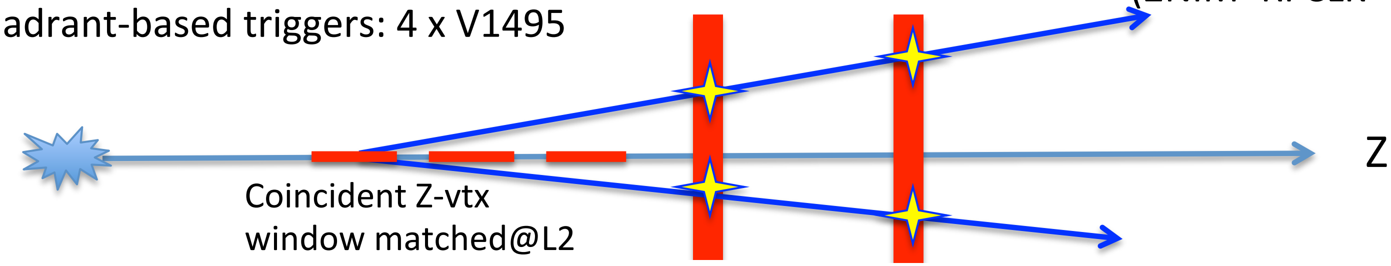
High rejection power, very low rate, << 1 kHz(E906 DAQ limit)

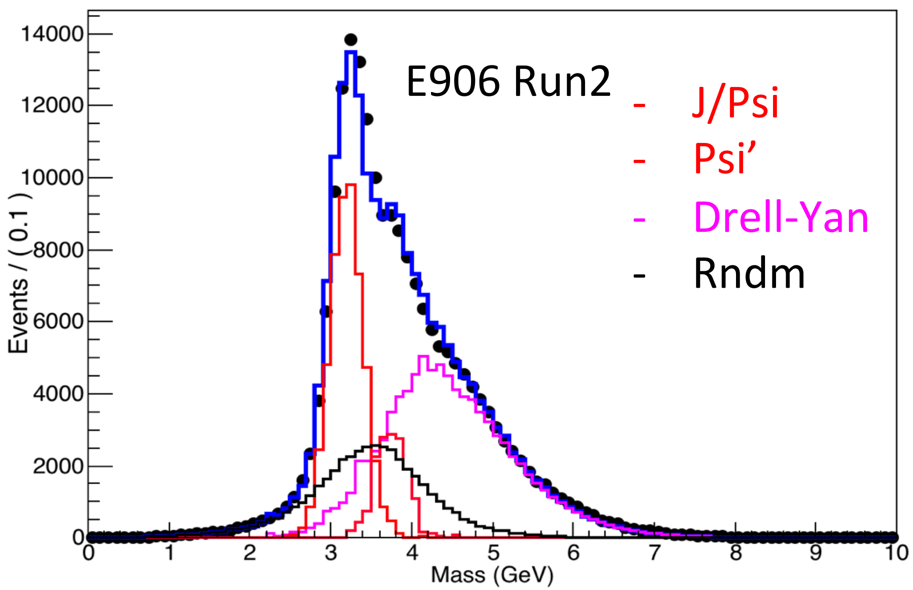
Y-Plane Trigger:

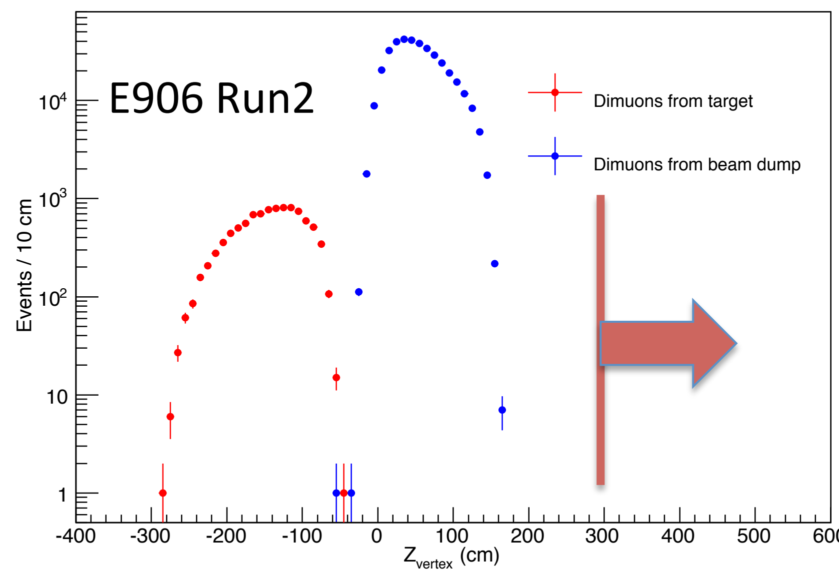
- A quadrant panel: 40 x 40 cm^2, 1cm thinck
  - 40 x 1cm x 40 cm scintillating strips, SiPM readout
- Straight line projection, 30cm Z-vertex resolution
- Displaced z-vertex, mostly low mass < 3GeV
- Coincident with St-4 Hodos(muons)
- Quadrant-based triggers: 4 x V1495

Y-channels per quadrant:

- 1x V1495
- 40(St1) + 40(St2) + 8x2 (St4-Y1,2) = 96
- 96+64 = 160 possible
  - 72+72+16 = 160 (possible)
  - (2NIM=RFCLK+ComSTOP)







Dimuon Z-vertex (cm)

Search Mode (1): Long-lived Dark Photons

Reconstructed dimuons with downstream Z-vertex:

3m < Z-vertex < 6m

- Very low trigger rate, << 1kHz
- SM background free
- Dimuon mass peak

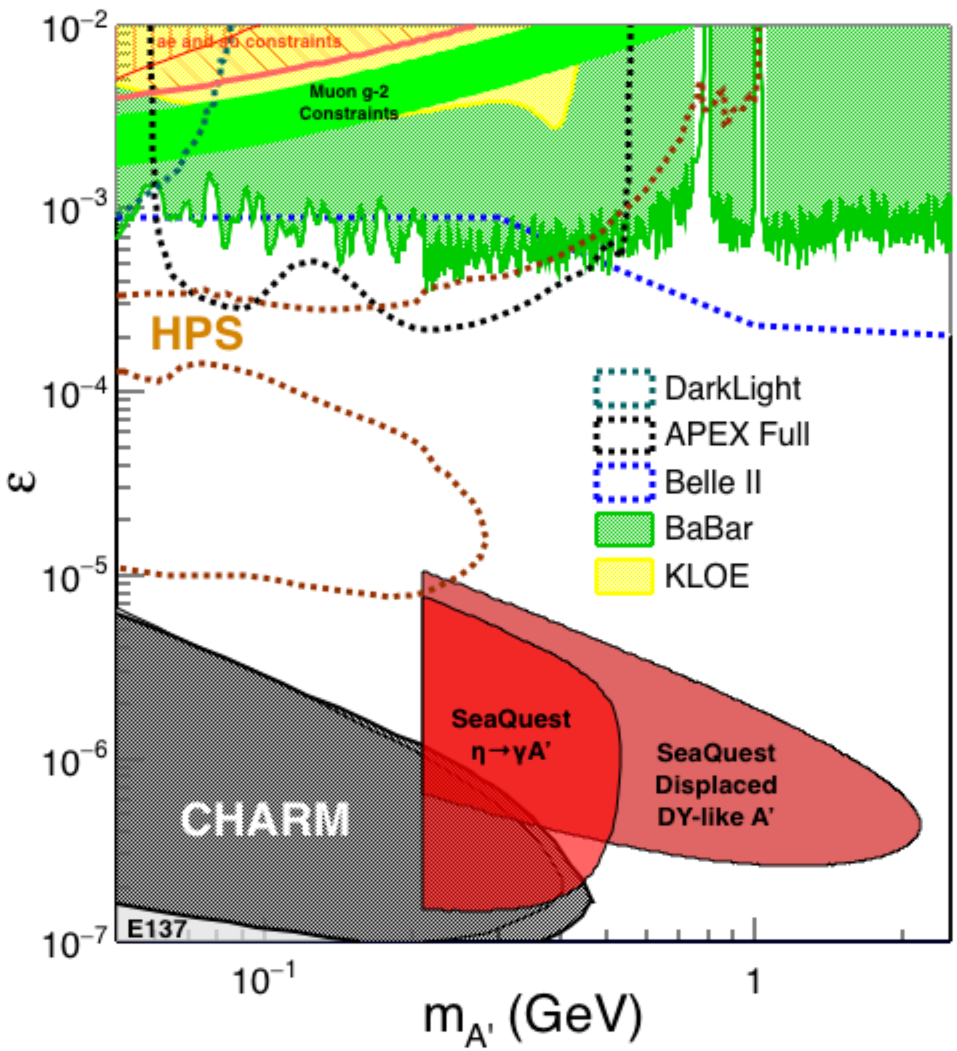
- 5×10^{12} ppp (current E906)
- 200 days

1.4×10^{18} POT (recorded)

- 4 events contours (2-sigma)

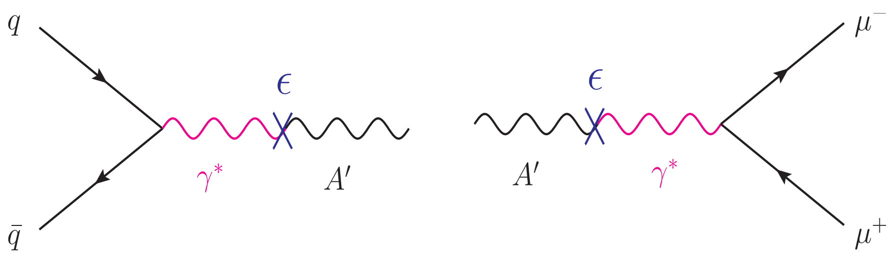
2-sigma (95%) exclusion plots

Excellent coverage of uncharted region!



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

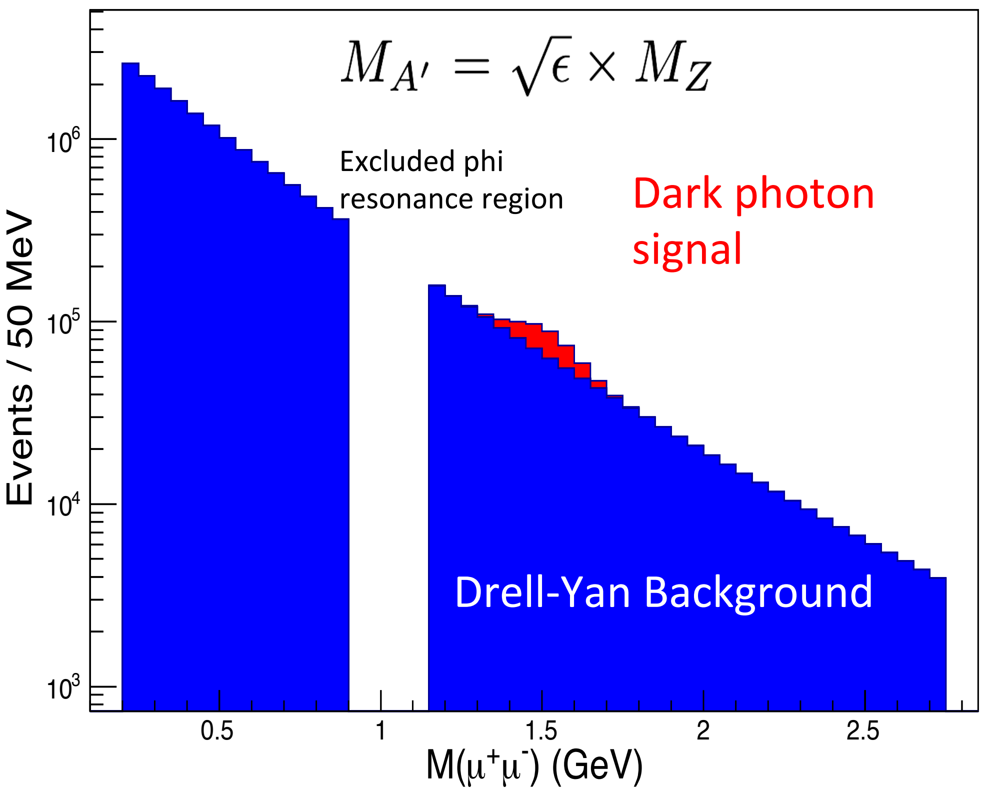
Z-vertx < 3m



Expected Drell-Yan like signal and backgrounds:

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

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



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

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

Work in progress
Further optimization possible

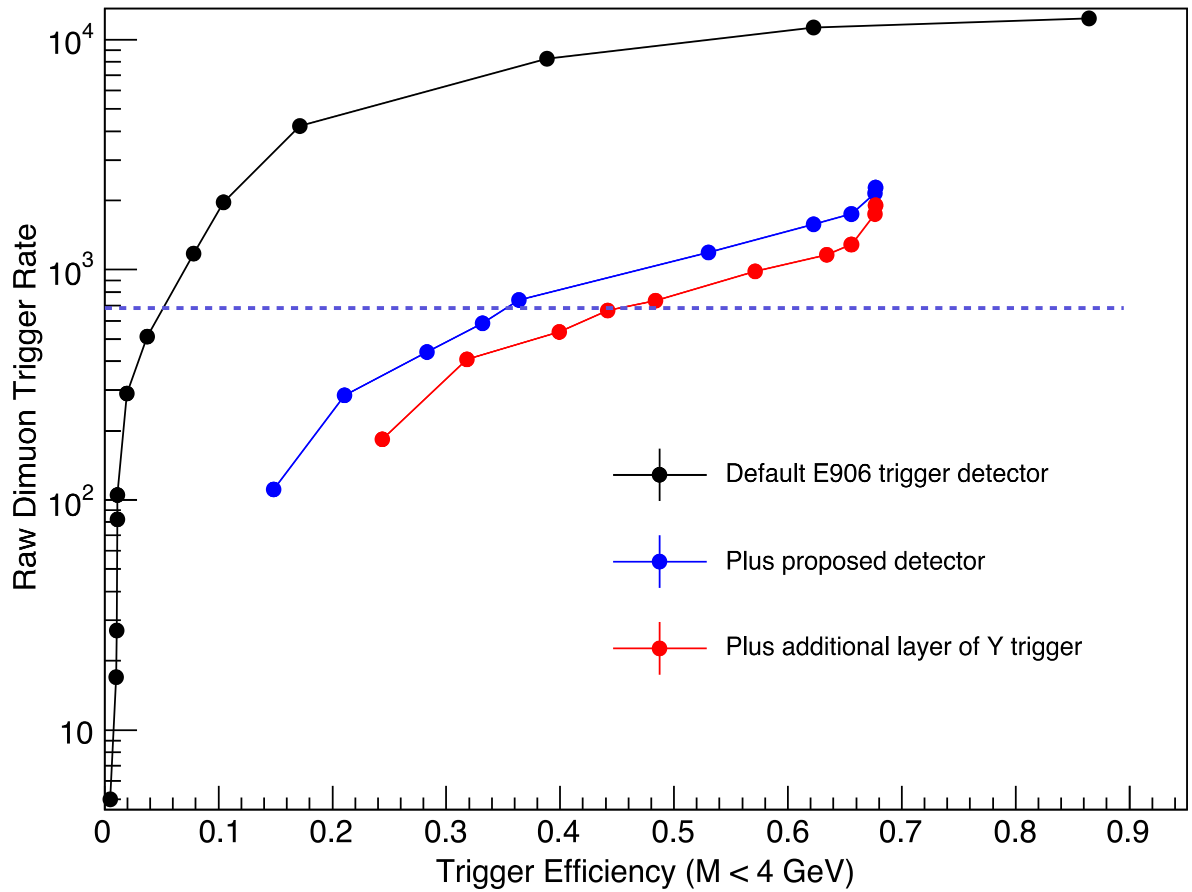
Low Mass Prompt Dimuon Trigger Rate Study

- 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

- 200kHz possible in the future (reprograming trigger firmware etc.)

Parasitic mode: use up to ~10% DAQ bandwidth



(Prompt)Low mass dimuon trigger efficiency

Dark Photon Sensitivity: Summary

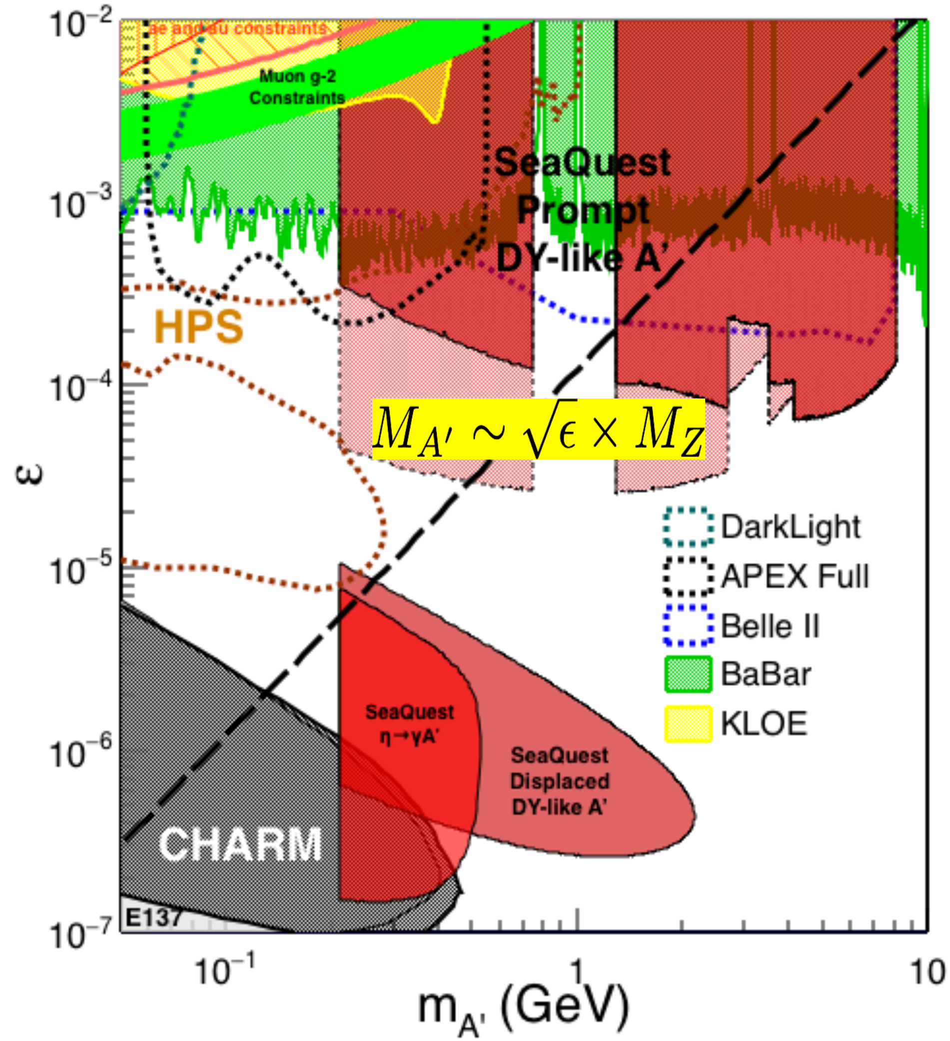
POT:1.4x10^{18} (parasitic w/ E1039)

Signals considered:

- Drell-Yan like
- Eta decays
- Bremsstralung

Covers a wide range of unexplored parameter phase space

- Displaced dimuons
  - Minimal SM background
- Prompt dimuons
  - 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)

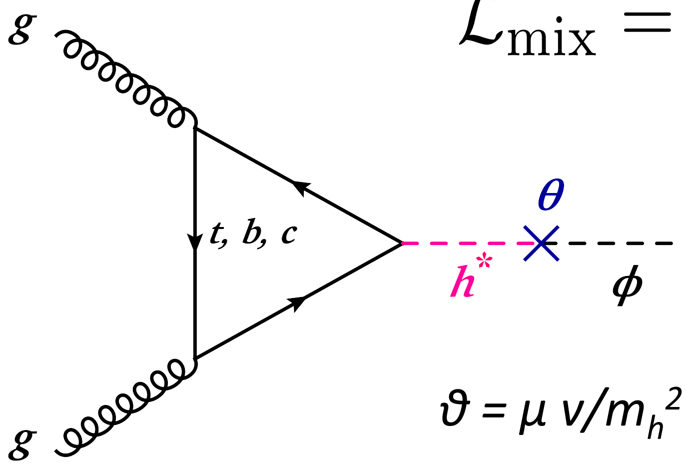


(2017?)
(2016?)
(~2023)

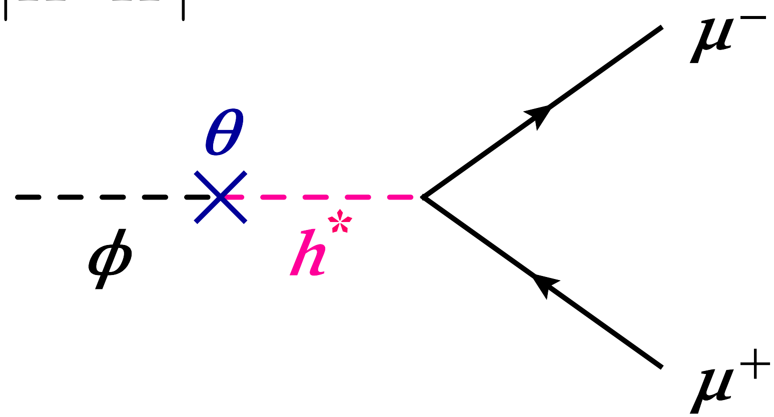
Dark Higgs Search at SeaQuest

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

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:

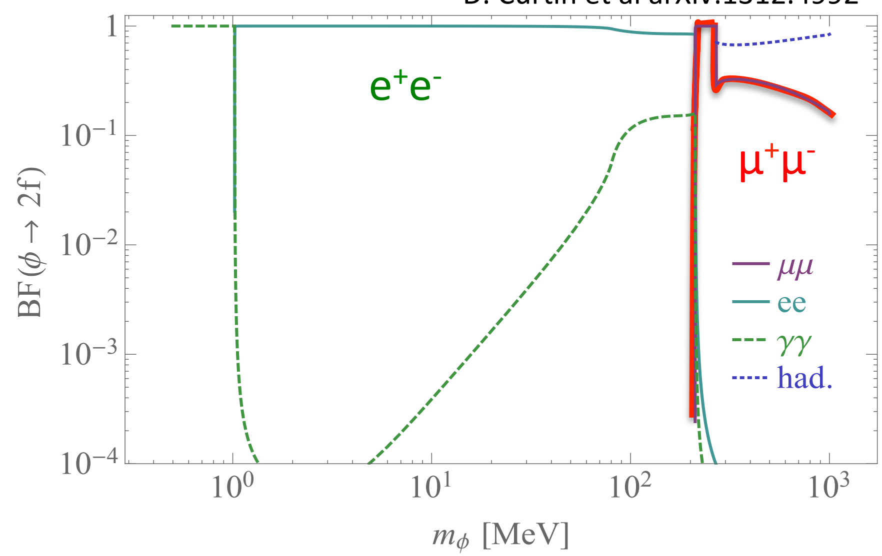
High-mass: $\mu^+\mu^-$ and hadrons

Advantage of using hadron beams with muon probes over electrons

Phase-II:

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

D. Curtin et al arXiv:1312.4992

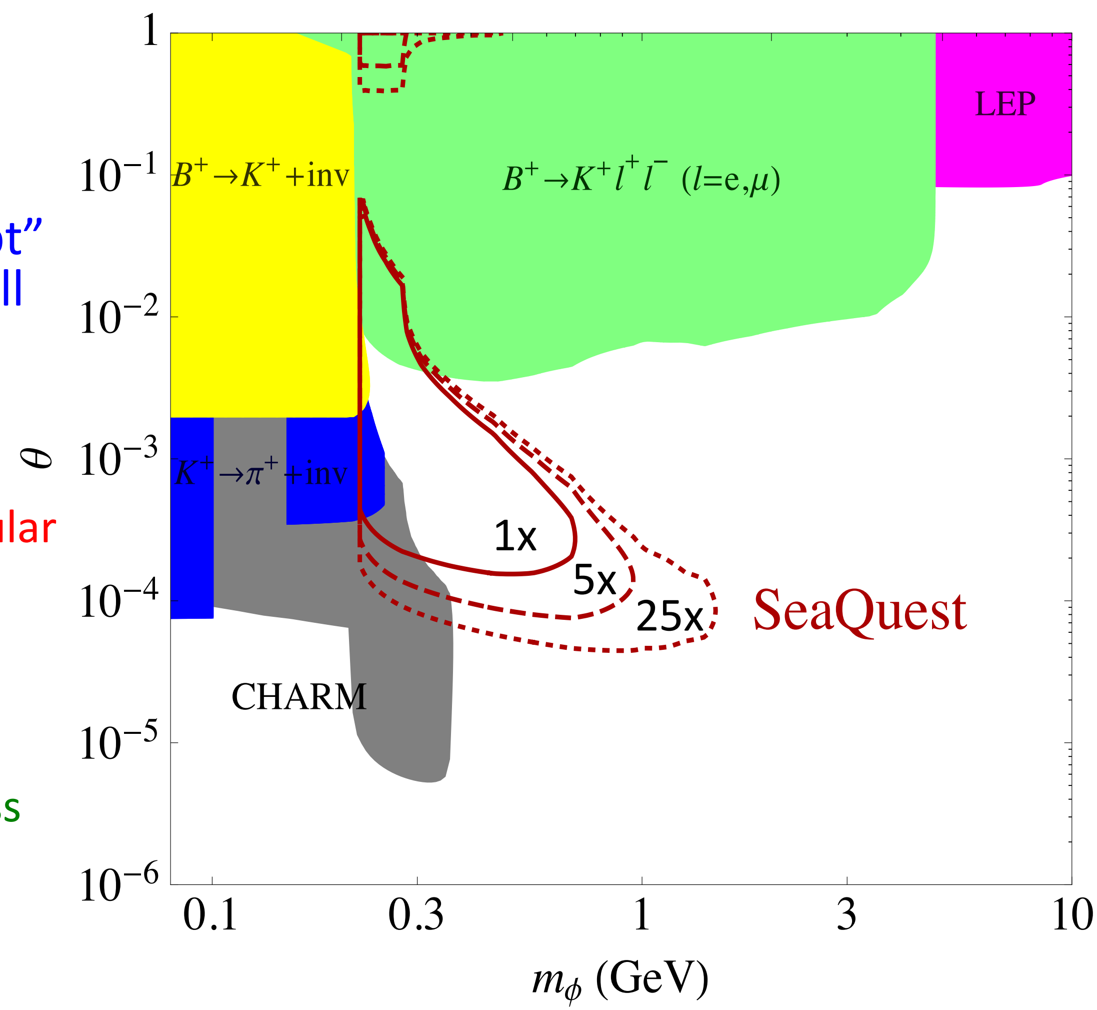


SeaQuest Dark Higgs Sensitivity

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)



Scope and Compatibility

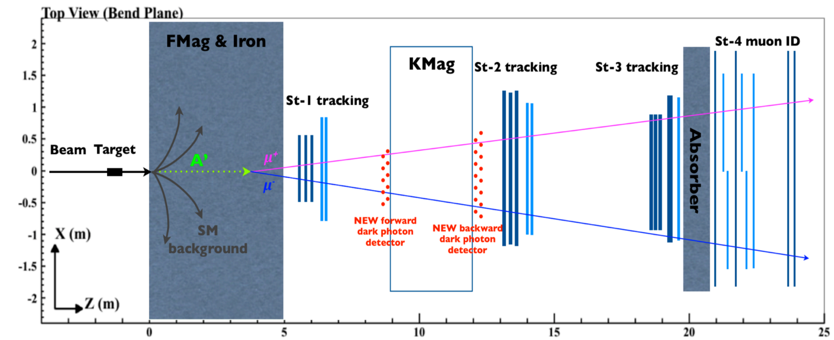
- Preparation work: 2016 – 2017
  - Displaced vertex dimuon trigger upgrade (LANL LDRD? $100K)
    - Add a new trigger bit
    - No change to existing trigger matrix
  - Possible upgrade of DAQ bandwidth under consideration (external $$)
    - 1kHz (E906) -> 10+ kHz
  - Commissioning with cosmic rays

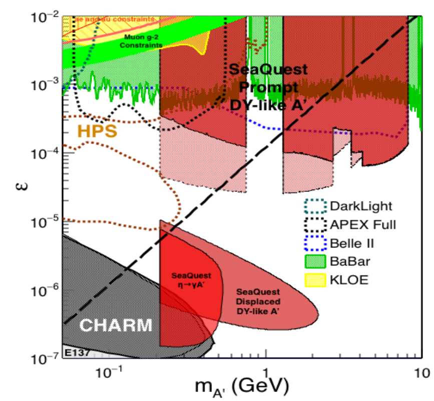
- Parasitic runs w/ E1039: 2017 – 2019
  - Displaced vertex dimuon trigger upgrade
  - Use up to ~10% DAQ bandwidth
  - Achieve 1.44 x10^{18} POT

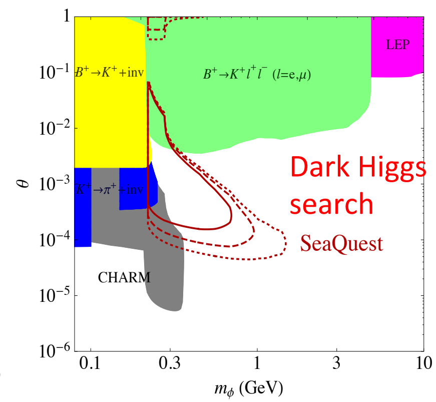
- Possible parasitic runs w/ E1027 and/or dedicated runs later with upgrades: 2019+
  - High luminosity goals:
    - POT >> 1.4x10^{18}
  - DAQ
    - 10 – 100 kHz capability
  - EMCAL/HCAL/PID
    - Electrons
    - charged hadrons
  - Fully cover the accessible phase space
    - Low mass “prompt photon” region, M < 3 GeV
  - Possible parasitic runs with other proposals

Summary and Outlook

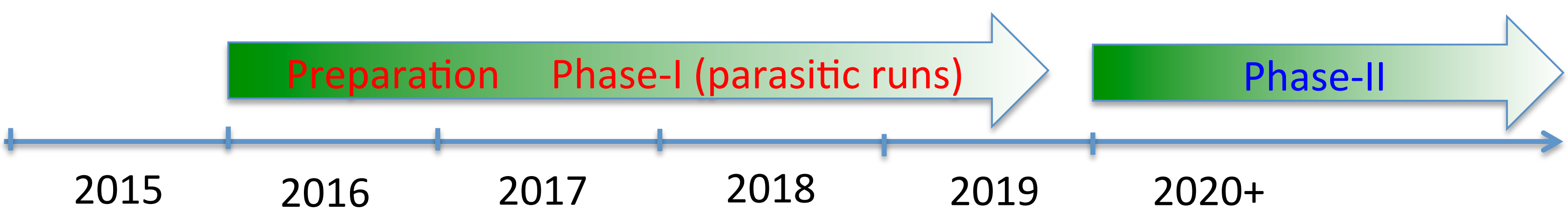
- ***Phase-I (this LOI)***
  - ***Great discovery potential!***
  - ***Add a new displayed vertex trigger***
  - ***Early parasitic data taking 2017-2019+***
    - ***A short dedicated run up to ~1 month if needed***
  - ***POT 1.4 x10^{18}***







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



Backup slides

Work in Progress Sensitivity Study

2-year parasitic run and more

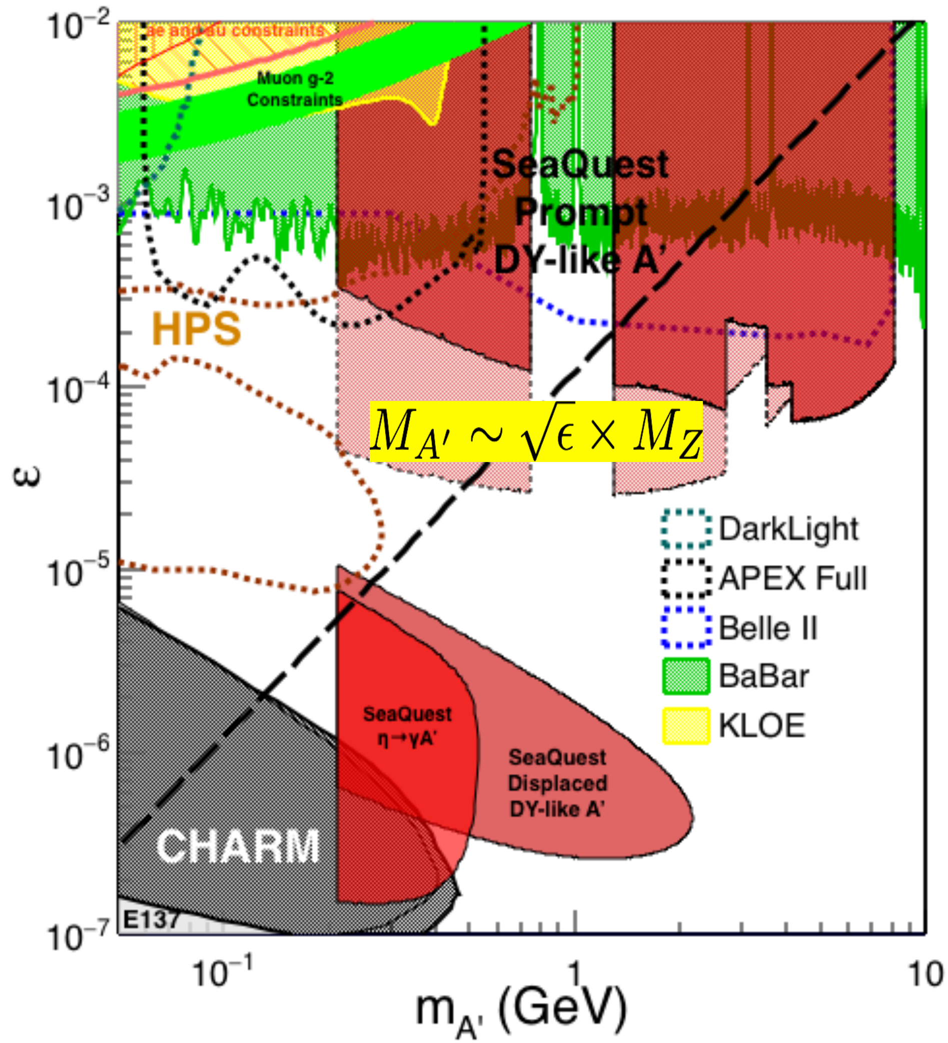
With 10kHz DAQ bandwidth,
the accepted low mass "prompt" dimuons, M<3GeV, are statistically limited by DAQ throughput and detector acceptance (assuming only uses 10% DAQ).

100kHz DAQ bandwidth is needed to fully cover the phase space (assuming 10% usage of DAQ bandwidth) and dedicated dark photon run.

In the first two-year parasitic runs with E1039, our focus is on 1)the displaced dimuons for low mass; 2)prompt high mass dimuons M> 3GeV.

We can still cover more phase space than what BELLE-II can achieve in ~2023.

Full coverage of low mass (M<3GeV) can be achieved later through dedicated runs with much improved DAQ bandwidth after E1039.

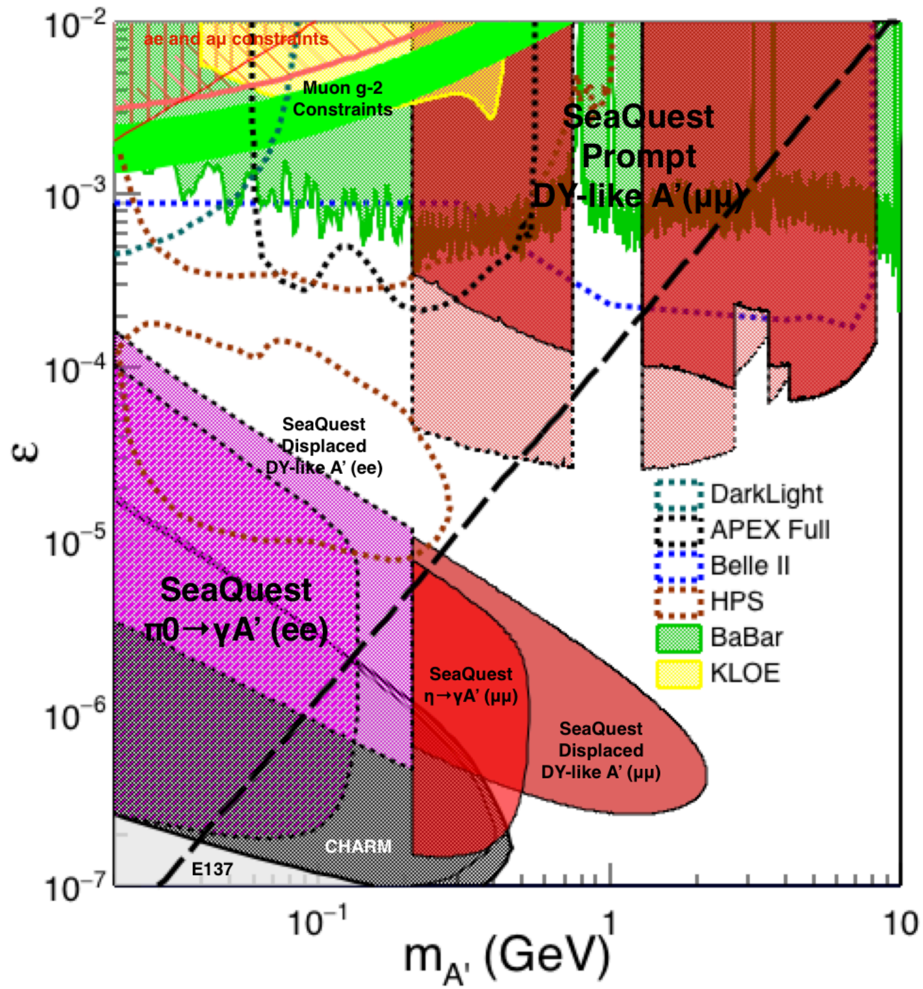


Phase-II: Full Coverage

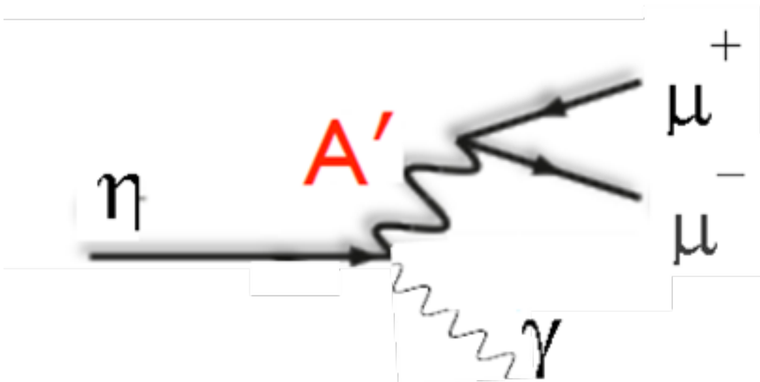
with future detector “EMCal/HCal” upgrades

Projection: POT 1.4 x 10^{18}

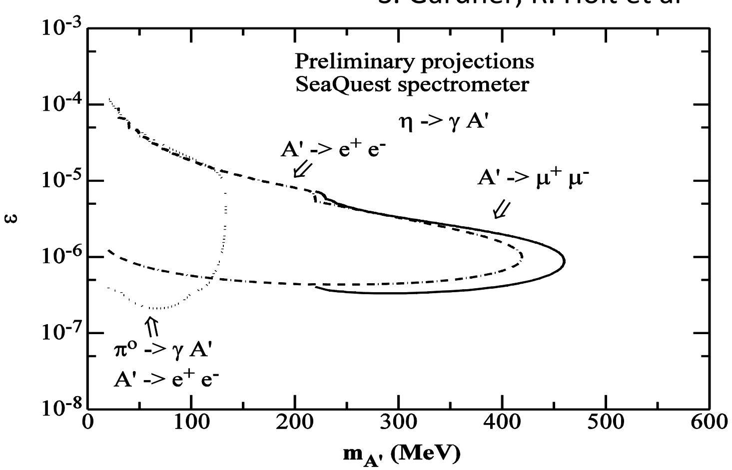
- Detector upgrades
  - EMCal: $e^{+/-}$
  - HCal: $\pi^{+/-}$
  - Recycle from other experiments, RHIC/JLab etc.
- DAQ upgrade
  - 100 kHz
- Timeline of dedicated runs
  - 2019+
- Detector configuration
  - Access low mass region with optimized Fmag settting

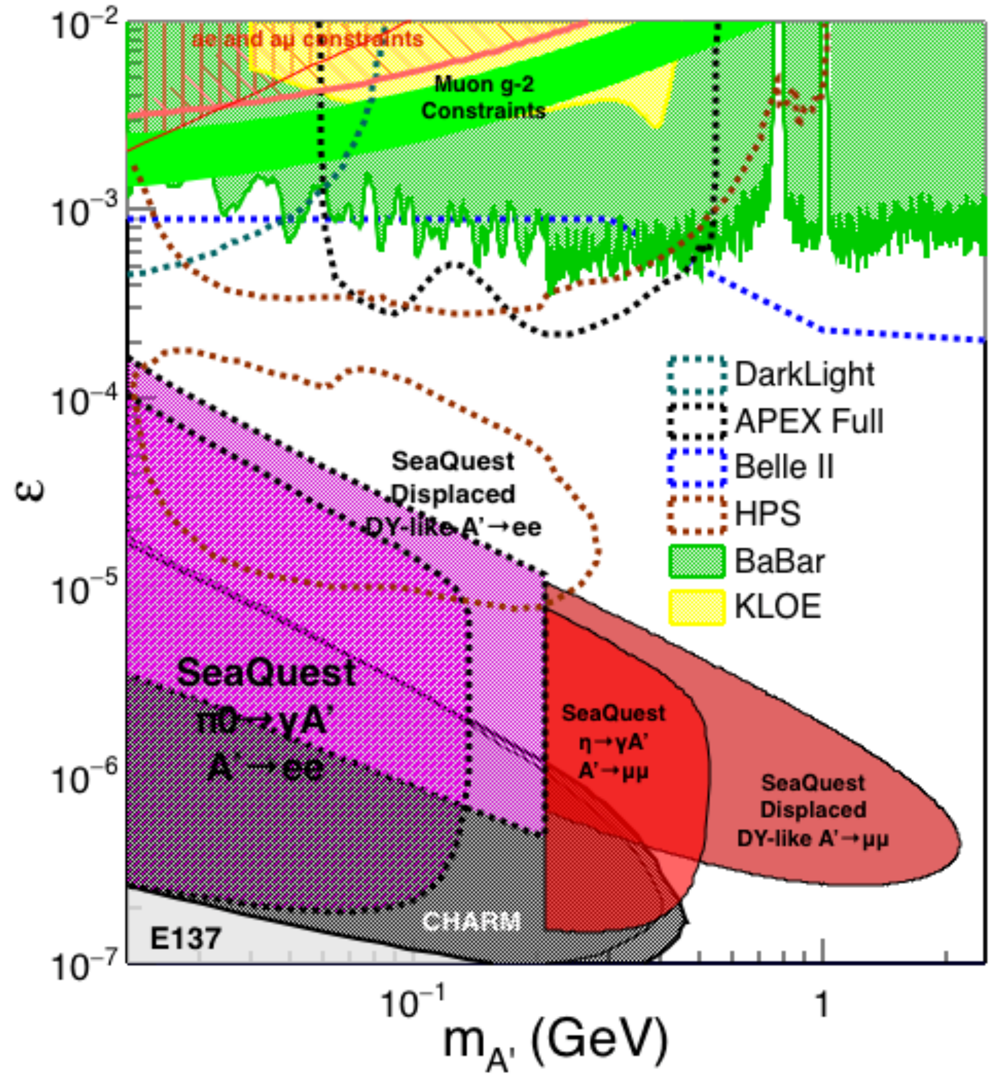


Phase-II: Access Low Mass Region with e^+e^-
with future detector "EMCal" upgrades



S. Gardner, R. Holt et al

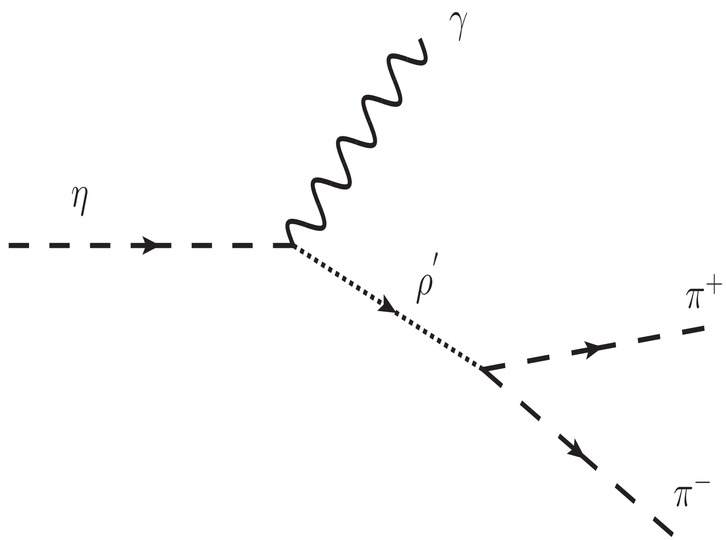




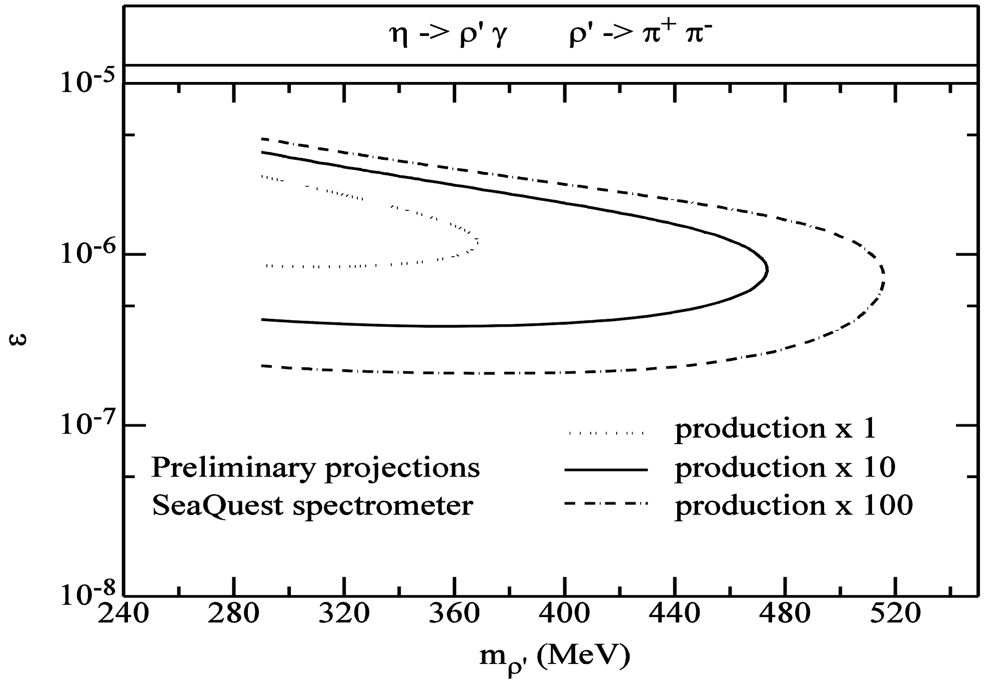
Non Abelian Dark Sector

with future detector "HCal" upgrades

non-Abelian dark sector process



S. Gardner and R. Holt

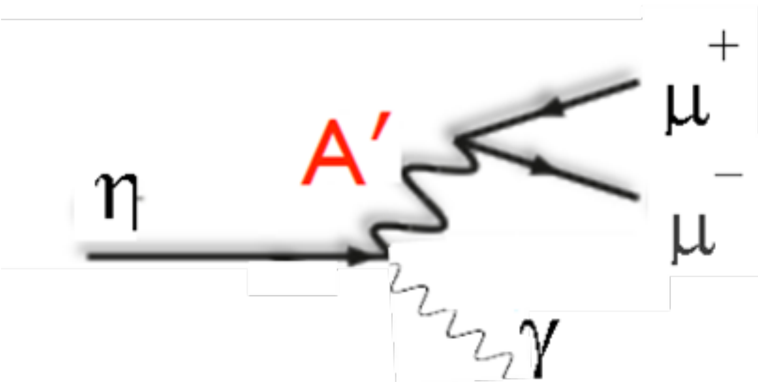


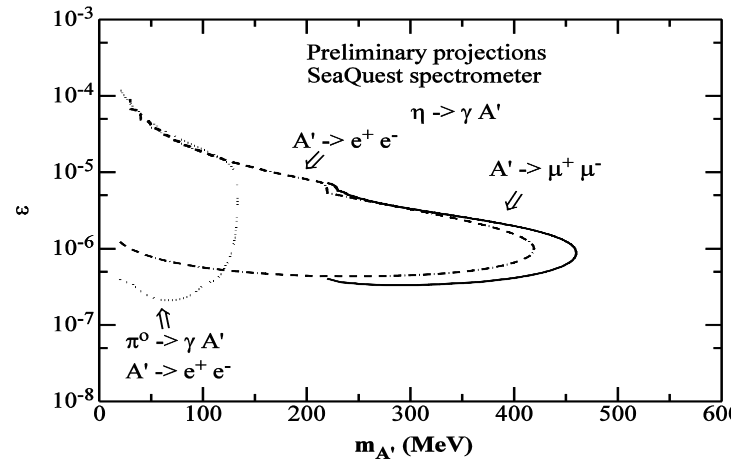
[Note: Batell, Pospelov, and Ritz, PRD 80 (2009) 095024 for a review re fixed target expts.]
Here we consider a non-Abelian (gluon) portal
[Baumgart et al., JHEP 0904, 014 (2009); Gardner and He, PRD 87 (2013) 116012]
The "shining through walls" design – unique to Seaquest – makes this possible ,
to yield, e.g., via a "minimal" decay….

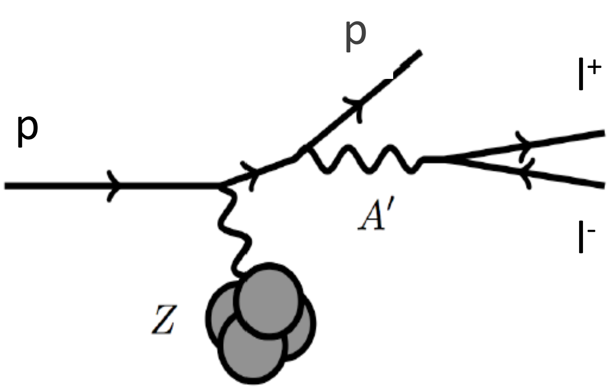
Phase-II: Access Low Mass Region with e^+e^-

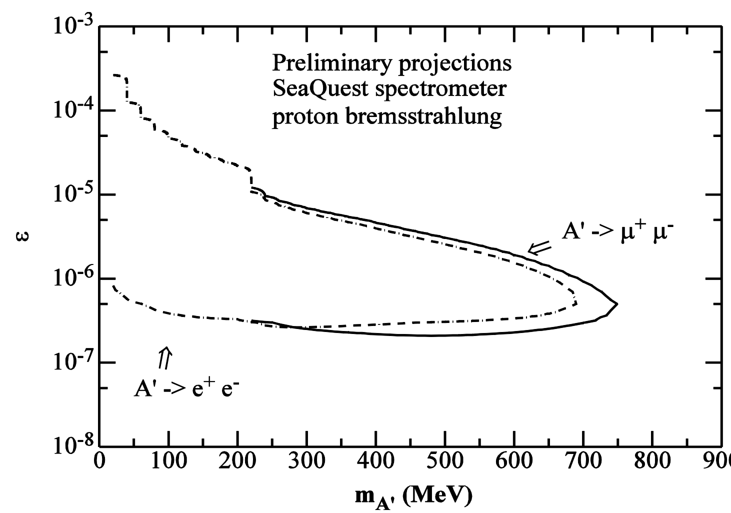
with future detector upgrades

S. Gardner, R. Holt et al

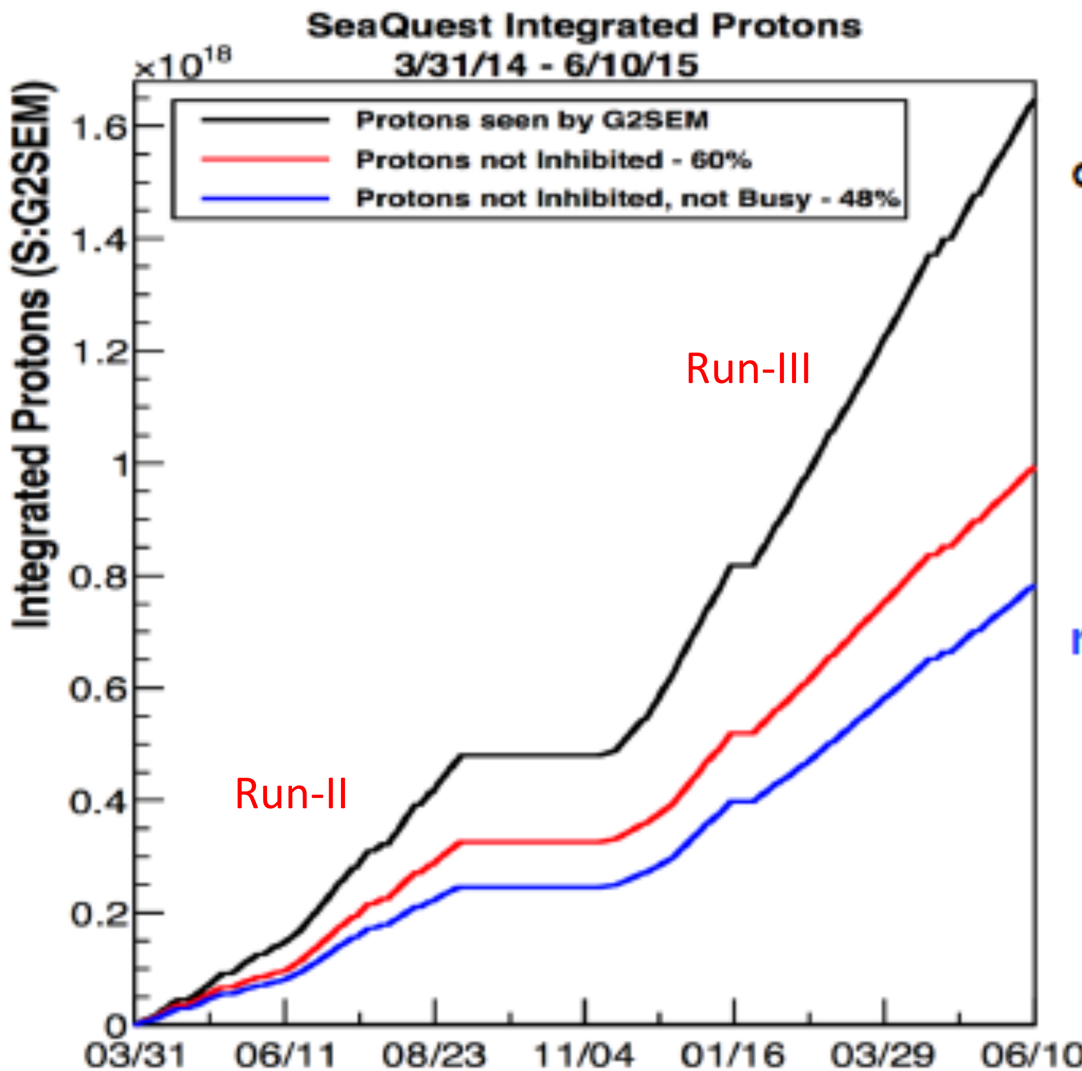








E906 Run-II and III Performance

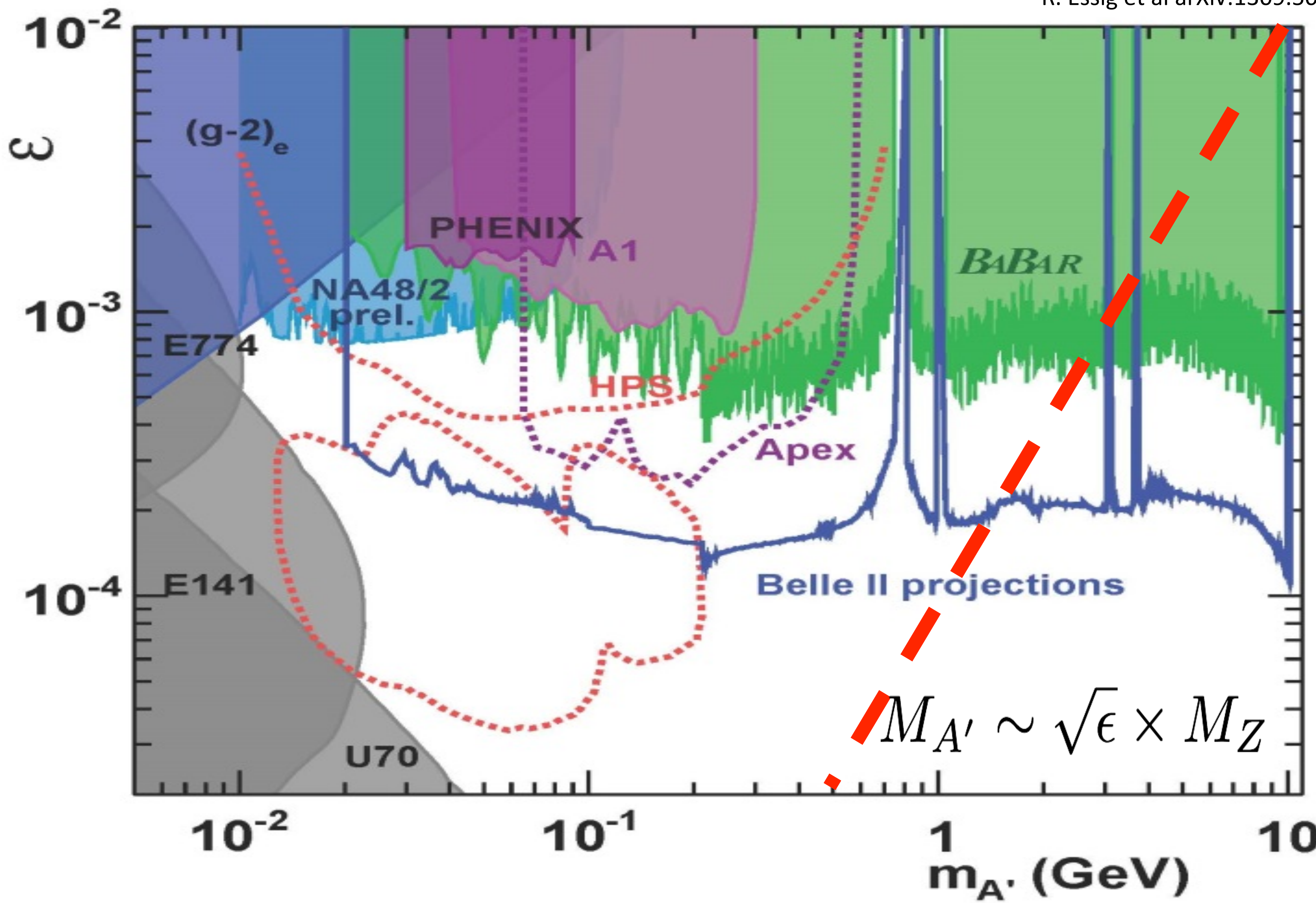


1.6E18 protons delivered

0.7E18 protons recorded

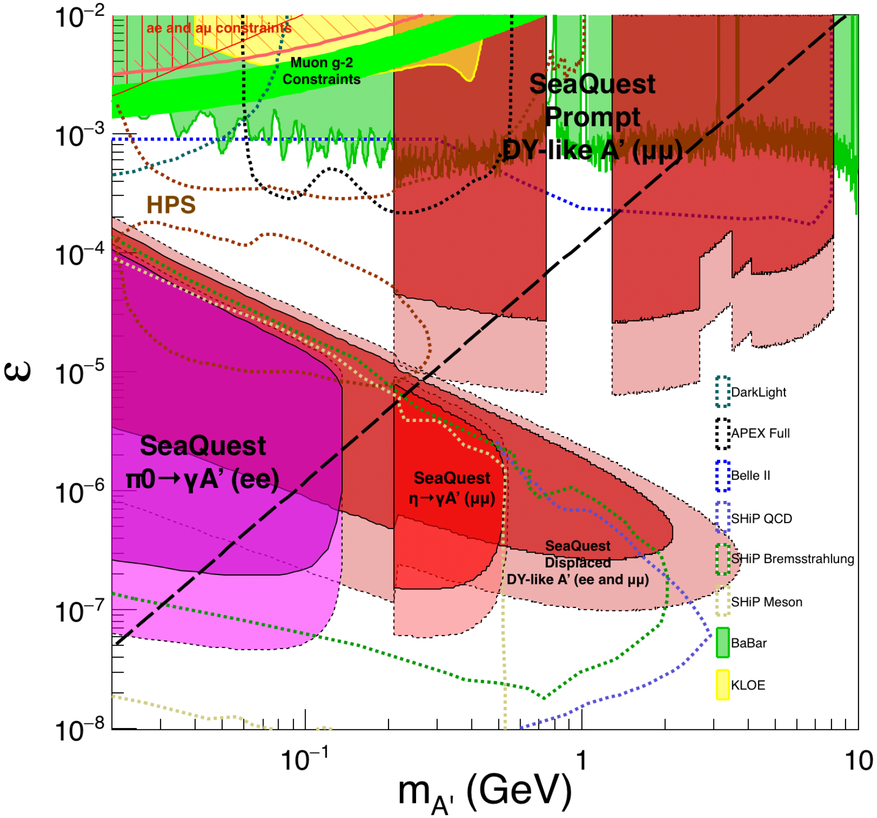
Current Limits on Dark Photon Search

R. Essig et al arXiv:1309.5084

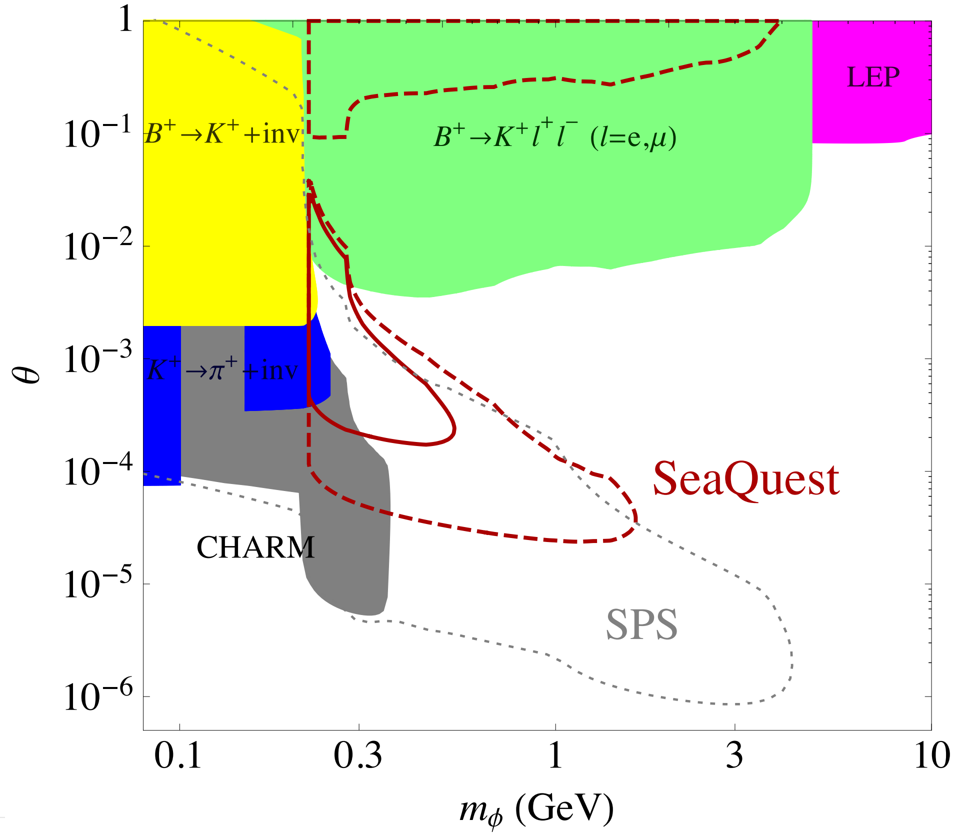


Comparison with SHiP Proposal

120 GeV@FNAL: 2017 -2019
1.4x10^{18} POT, future dedicated runs



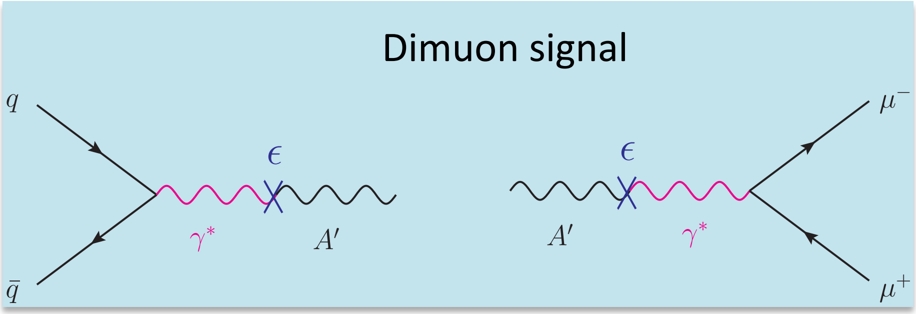
400 GeV@SPS: 2025 -2030
4x10^{20} POT

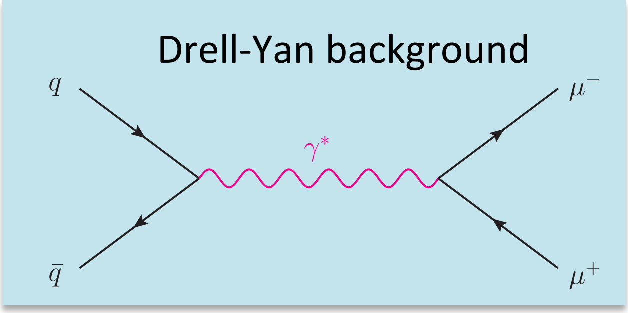


Integrated theory efforts

Signal: detailed calculation for dark photon (dark Higgs) 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

How important are dark photons in current models of new physics ?

- 2014 US High-Energy Physics Report (P5)
  - Top 5 science drivers:
    "Identify the New Physics of Dark Matter"
  - Dark photons
    "one of the key search area for physics beyond the SM"
    One of the two most important portals to "dark sector":
    - *Vector coupling, kinetic mixing*
    - (scalar coupling, dark Higgs)
- On-going and/or proposed experimental programs in all major accelerator facilities in the world!
  - World wide competitions!

Ongoing A' Searches

- KLOE-2@DAϕNE($\phi \rightarrow \phi A'$ followed by $A' \rightarrow e^+e^-$)
- HADES@GSI (p+p, p+^{93}Nb, p+^{40}Ar, ^{84}K+^{35}Cl production: π^0,η, Δ decay followed by $A' \rightarrow e^+e^-$)
- BaBar@SLAC ($e^+e^- \rightarrow \Upsilon \rightarrow \gamma A'$ with $A' \rightarrow \mu\mu$)
- WASA@COSY (π^0 decay)
- PHENIX@RHIC (π^0 decay)
- A1@MAMI (e on ^{181}Ta)
- ATLAS and CMS @LHC
- SeaQuest @ FNAL
- milliQ@SLAC: invisible search
- APEX@JLab (e on ^{181}Ta)
- HPS@JLab (e on ^{184}W)
- DarkLight @ JLab ERL (e-p elastic scattering below π threshold)

Courtesy: R. Milner(MIT) at the Fundamental Interactions Town Meeting, Chicago, Sept. 28-29, 2014

The P5 report recommends a prioritized and time-ordered list of experiments to address the five science Drivers optimally. These opportunities are at the small, medium, and large investment scales that, together, produce a continuous flow of major scientific results throughout a twenty-year timeframe.

- Large projects, in time order, include the Muon g-2 and Muon-to-electron Conversion (Mu2e) experiments at Fermilab, strong collaboration in the high-luminosity upgrades to the Large Hadron Collider (HL-LHC), and a U.S.-hosted Long Baseline Neutrino Facility (LBNF) that receives the world's highest intensity neutrino beam from an improved accelerator complex (PIP-II) at Fermilab.

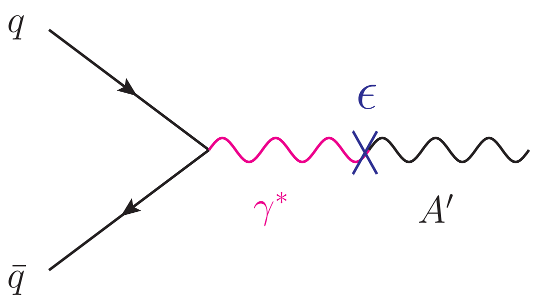
- U.S. involvement in a Japanese-hosted International Linear Collider (ILC), should it proceed, with stronger participation in more favorable budget scenarios.

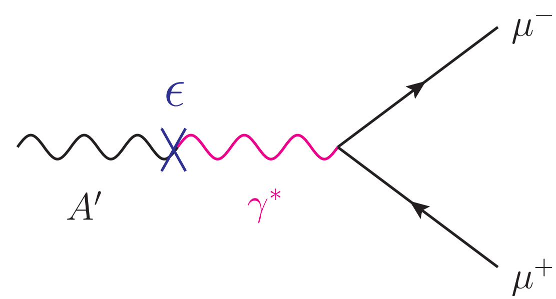
- Areas with clear U.S. leadership in which investments in medium- and small-scale experiments have great promise for near-term discovery include dark matter direct detection, the Large Synoptic Survey Telescope (LSST), the Dark Energy Spectroscopic Instrument (DESI), cosmic microwave background (CMB) experiments, short-baseline neutrino experiments, and a portfolio of small projects.

- Specific investments in particle accelerator, instrumentation, and computing research and development are required to support the program and to ensure the long-term productivity of the field.

Probe-1: Drell-Yan Like

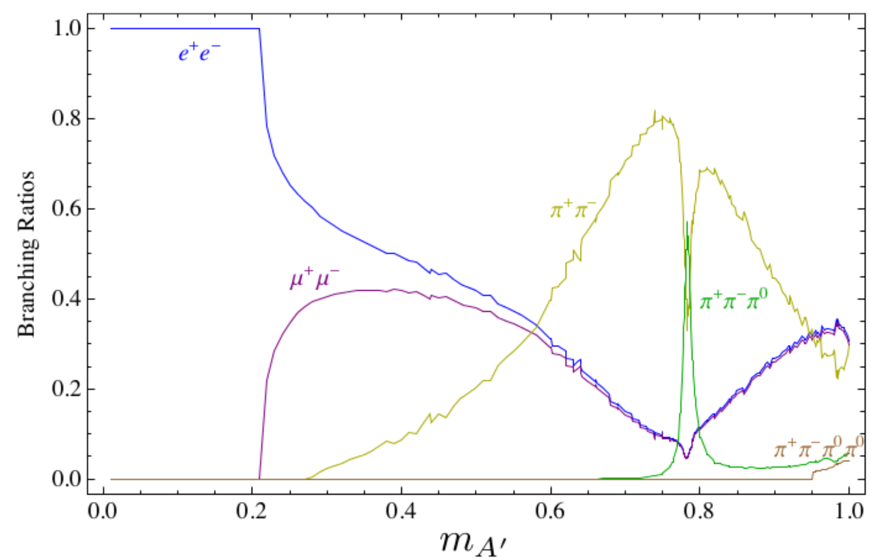
sensitive to both prompt and long-lived decay





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

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

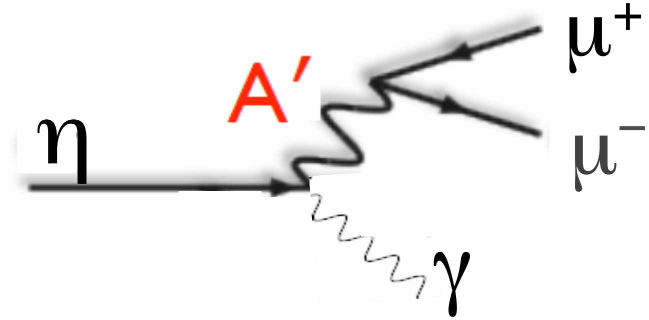


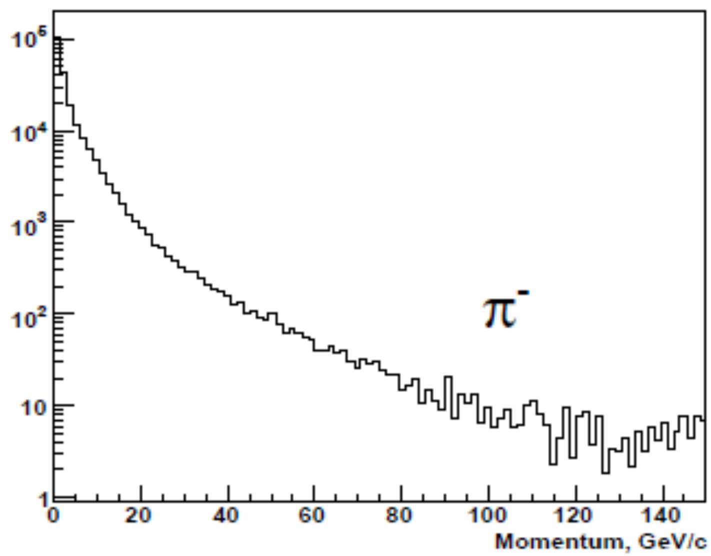
Probe-2: η Meson Production at 120 GeV

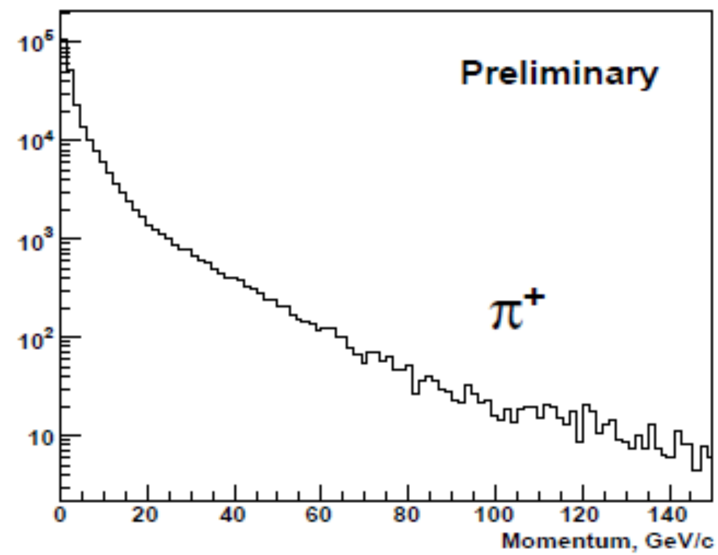
σ = 2.2 b for all charged particle production
Assume that π's represent 90% of charged particles,

$$\sigma_{\pi^\circ} = \frac{1}{2}(\sigma_{\pi^+} + \sigma_{\pi^-})$$

and η production is ~1/10 of this value.





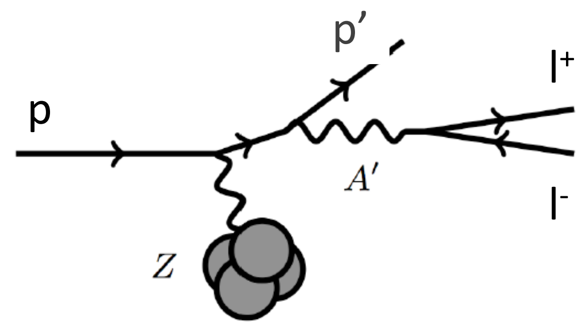


S. Mahajan, R. Raja, arXiv:1311.2258; FNAL E907, MIPP

Probe-3: Proton Bremsstrahlung

Generalized Fermi-Williams-Weizsacker approximation

J. Blumlein, J.Brunner, PLB **731** (2014) 320



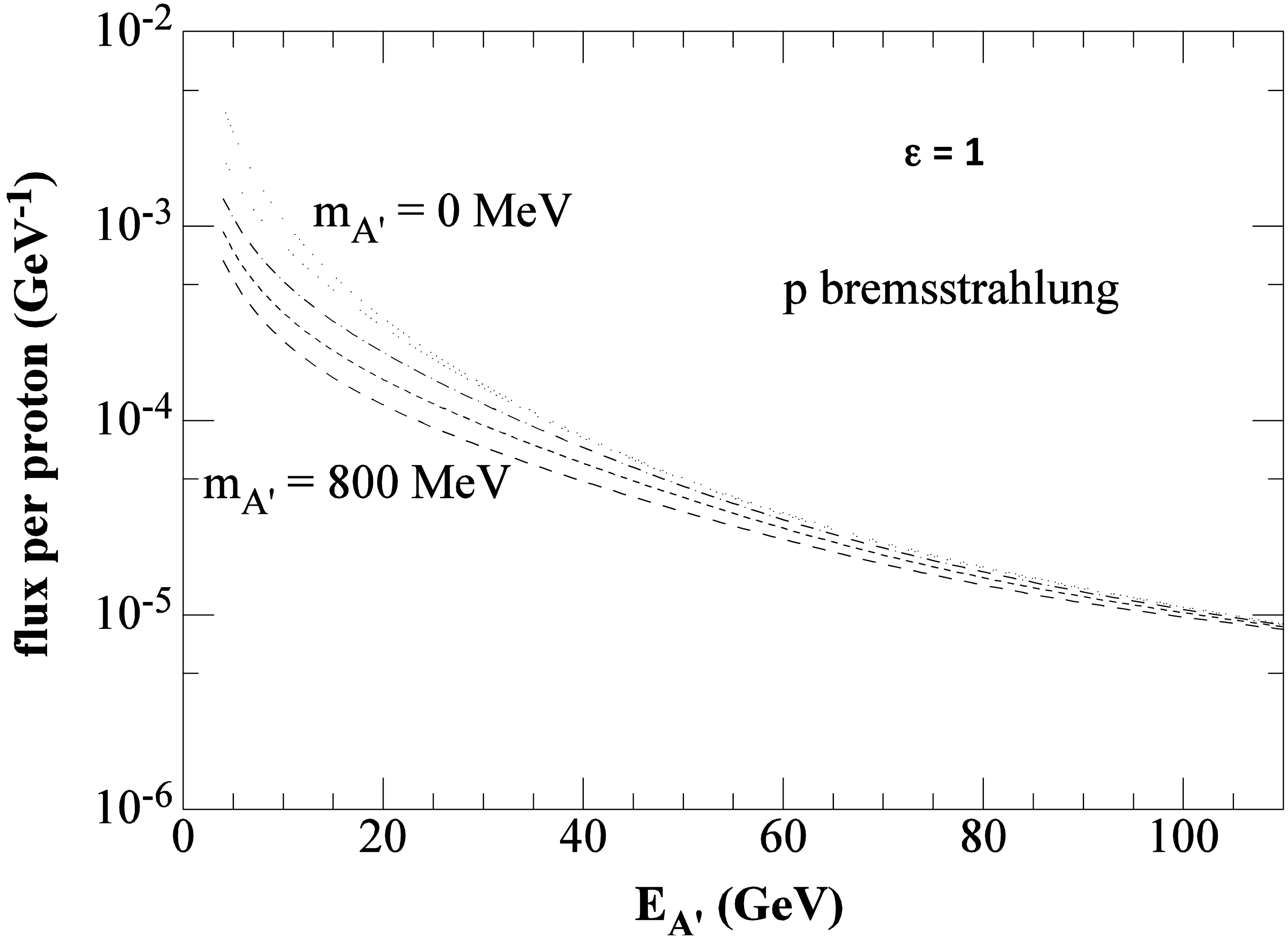
γ + p -> A' + p'

$$w_{ba}(z,p_\perp^2)dz\,dp_\perp^2 = \frac{\alpha'}{2\pi}\left\{\frac{1+(1-z)^2}{z} - 2z(1-z)\left[\frac{2M^2+m_{\gamma'}^2}{H} - z^2\frac{2M^4}{H^2}\right] + 2z(1-z)[1+(1-z)^2]\frac{M^2m_{\gamma'}^2}{H^2} + 2z(1-z)^2\frac{m_{\gamma'}^4}{H^2}\right\}\frac{dz\,dp_\perp^2}{H}$$

$$\frac{dN}{dE_{\gamma'}} = \frac{1}{E_p}\frac{\sigma_{pA}(s')}{\sigma_{pA}(s)}\int_0^{p_{\perp,\max}^2} w_{ba}(z,p_\perp^2)dp_\perp^2,$$

$z = (E_p - E_p')/E_p$; $s = 2ME_p$; $s' = 2M(E_p - E_{A'})$

Proton Bremsstralung Flux

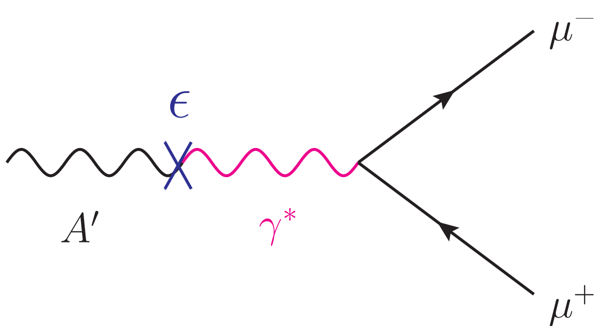


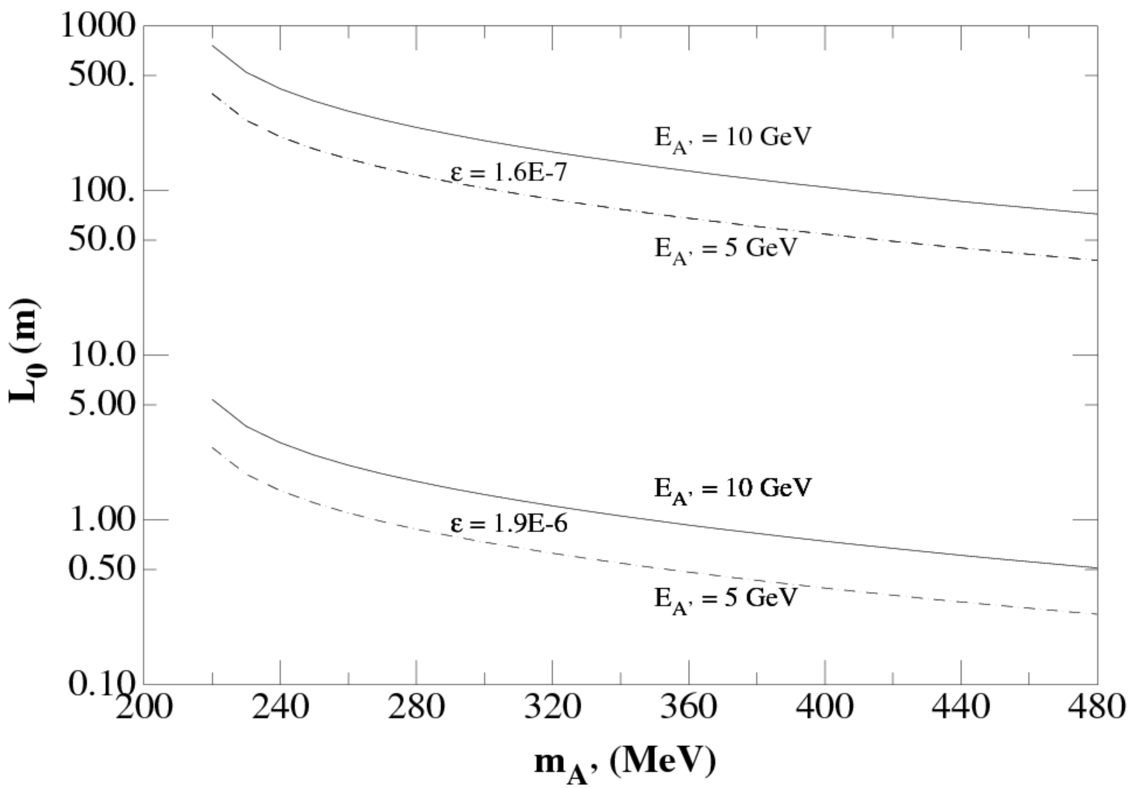
Dark Photon Decay Modes

“Minimal” Decay:

- Dark photon is the lightest in the dark sector;
- SM final state particles only
- Same mixing parameter
  - Long proper decay length, ~O(1m)

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

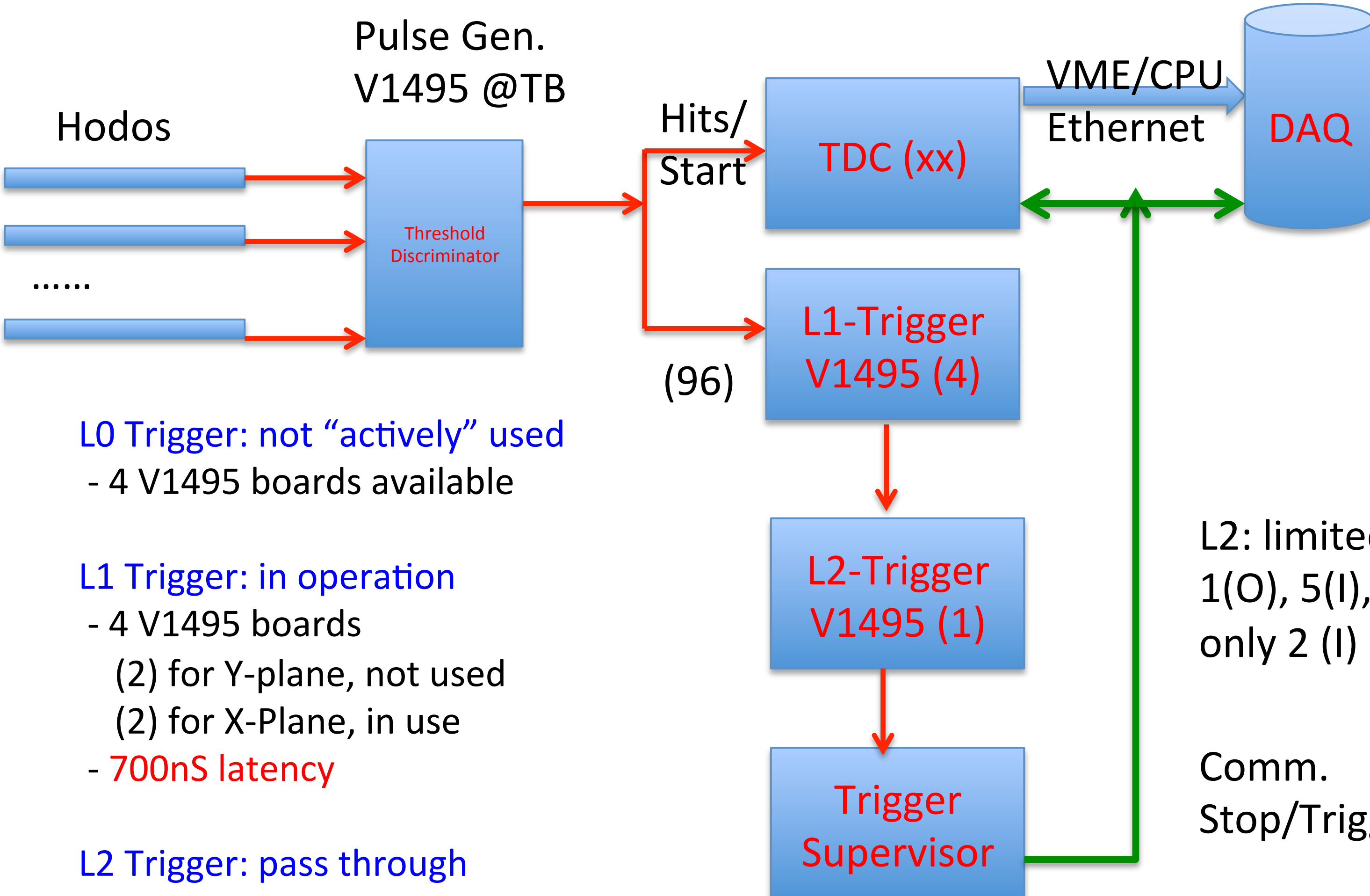




Toward Improving E906 DAQ Bandwidth

- Working with E906 DAQ group to improve DAQ bandwidth from 1kHz to 10kHz(or more)
  - TDC board FPGA reprogramming
    - Taiwan group
    - Fermilab engineer
  - Two options considered:
    1. Directly readout each TDC with Ethernet instead of reading serially through VME backplane
       - ~10kHz possible
    2. Store all raw data in onboard RAM chips (already built in on Taiwan TDC boards, but not used yet!) during the 4-sec spill and read them out during the remaining 56-sec.
       - ~200kHz possible

E906 Trigger & DAQ System



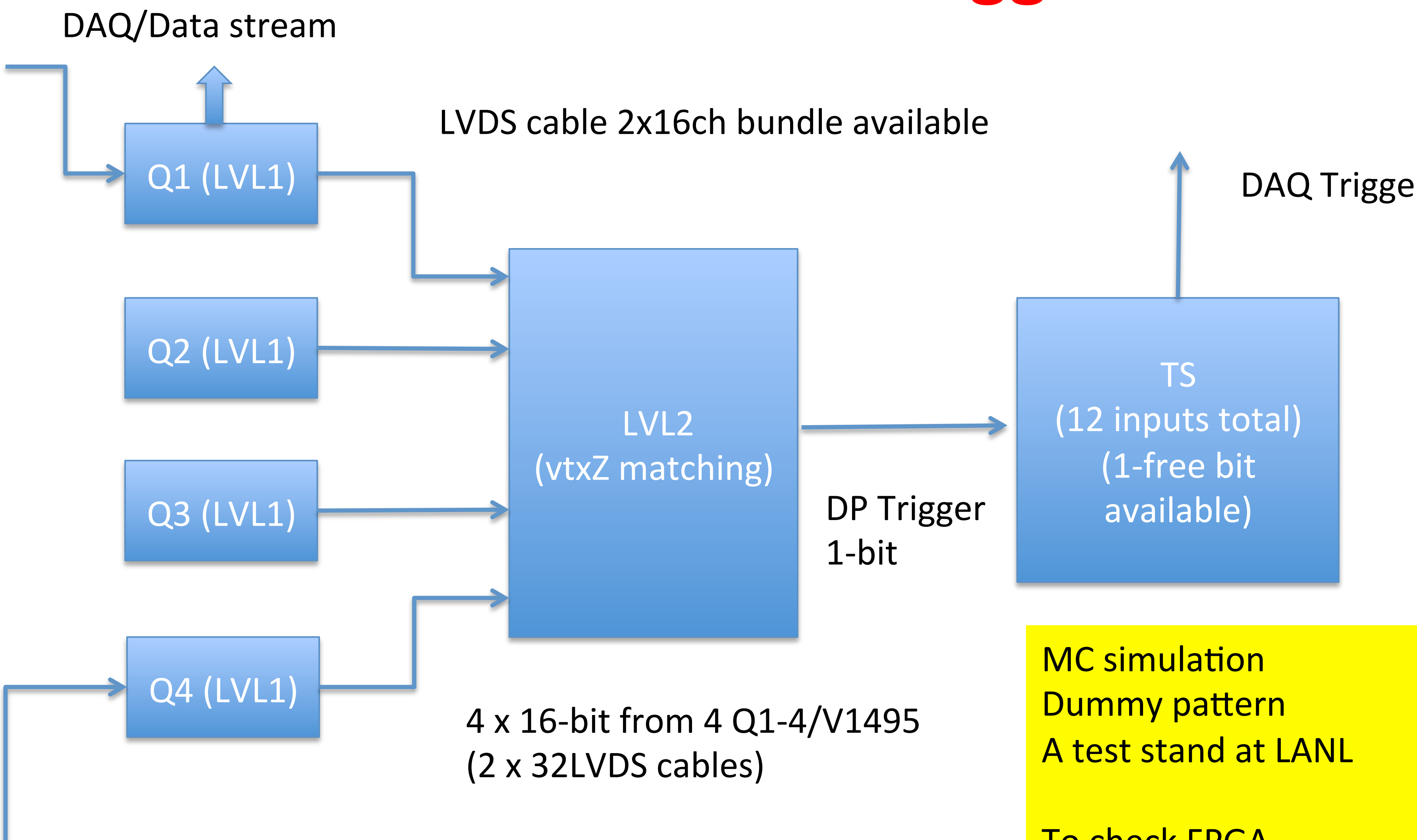
L0 Trigger: not "actively" used
- 4 V1495 boards available

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

Dark Photon Q-Trigger



Q1: 40(ST1’) + 40 (ST2’) + 2x8(ST4-Y1/2) = 96, FANOUT ST4

Upto 72(ST1) + 72 (ST2) + 2x8(ST4Y1/2) = 160

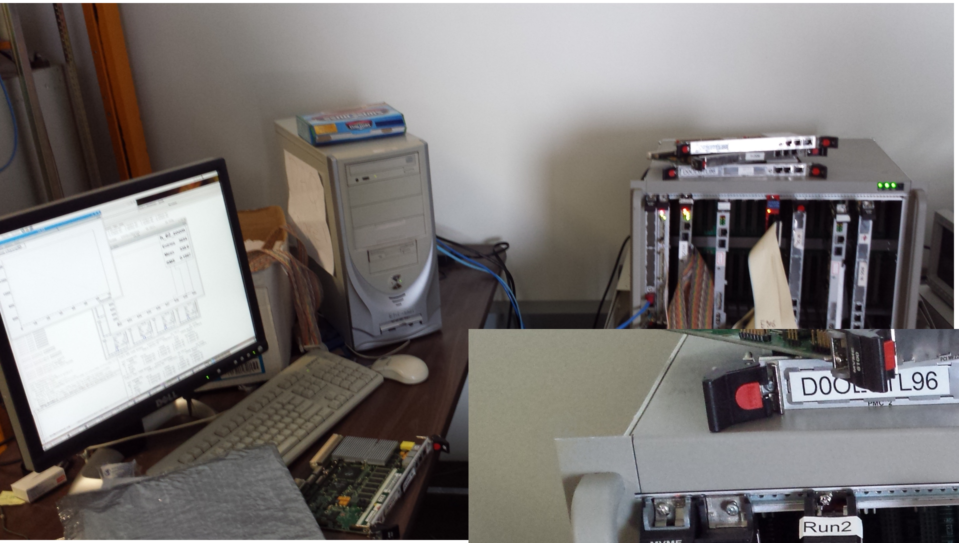
MC simulation
Dummy pattern
A test stand at LANL

To check FPGA
- Logic
- Timing

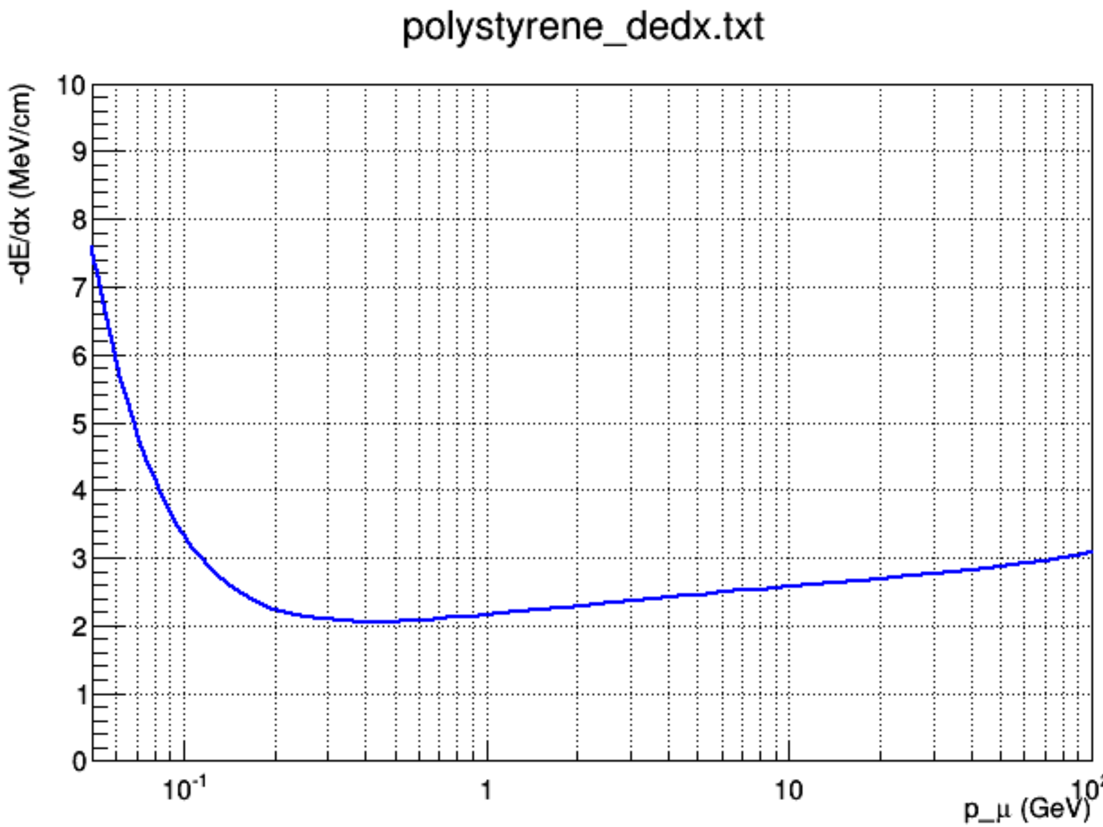
E906 DAQ Test Stand

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

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



Plastic Scintillator dE/dx and Particle Identification



- Using polystyrene as example (same as FNAL scintillator factory)
- Muon dE/dx = 2.41 MeV/cm @ 4 GeV, and 2.69 MeV/cm @ 20 GeV
  - 11.5% difference
- For 4 GeV Kaon vs 20 GeV muon it's an even bigger difference, 26.5%

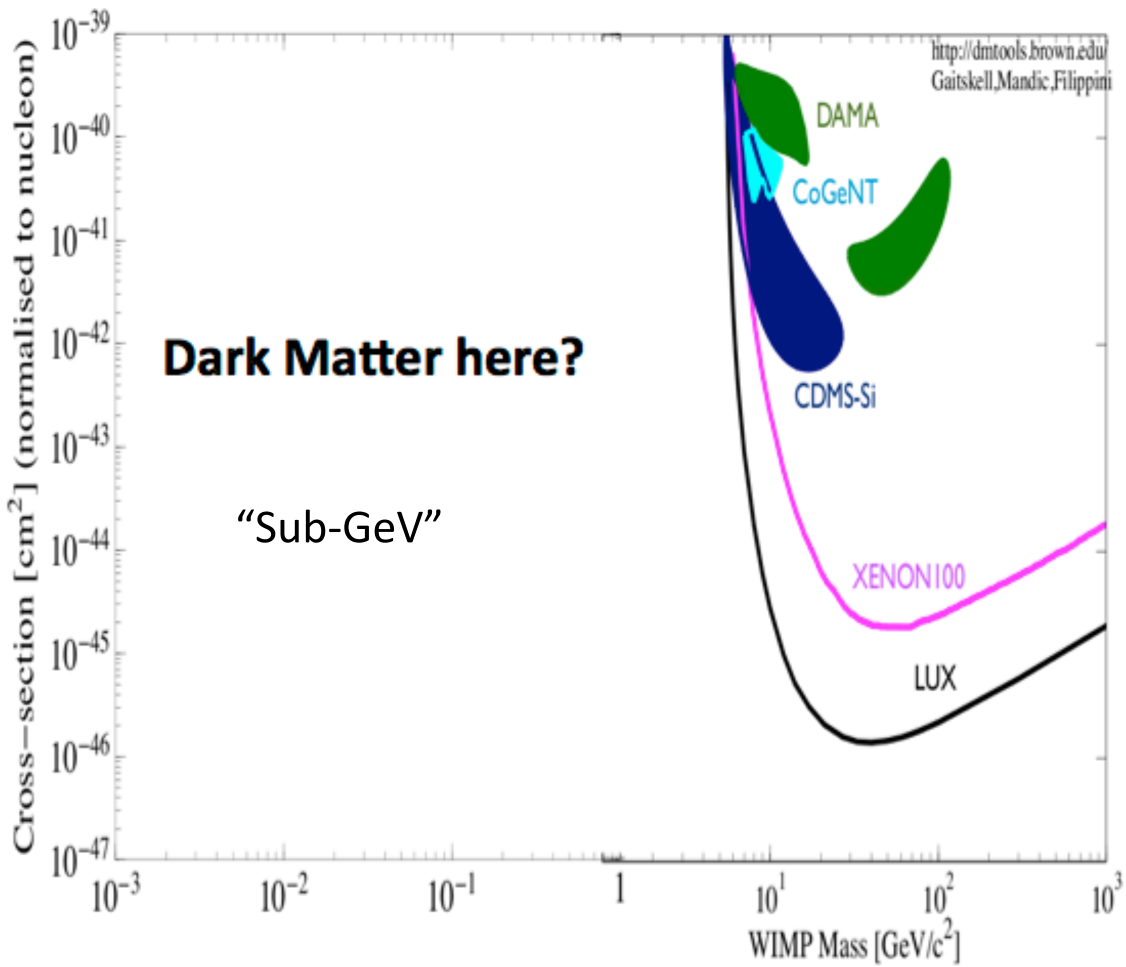
Minimal Thickness for Light Yields

- For thickness = 1.0cm, P > 5GeV
  - dE/dx = 2.5MeV/cm
  - Light yield = 2.5MeV / 100eV ~ 25K photons
  - SiPM Eff = 20%
  - Scintillating strip light collection Eff = 10%
  - Total "light yield" = 25K x 20% x 10% = 500 >>1

- Required light output
  - Photon detecting eff > 99%

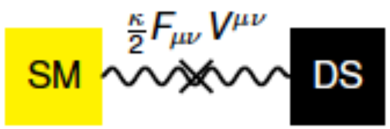
MiniBooNE Dark Matter Search

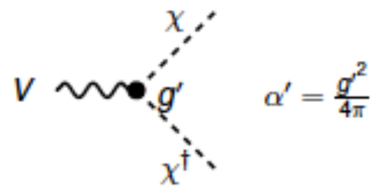
- Invisible decay mode, search for "sub-GeV" particles



Benchmark Theory

- Extension of dark photon theory
- Dark mediator (V) and a dark matter particle (χ)
- 4 free parameters: $m_V,\ m_\chi,\ \kappa,\ \alpha'$



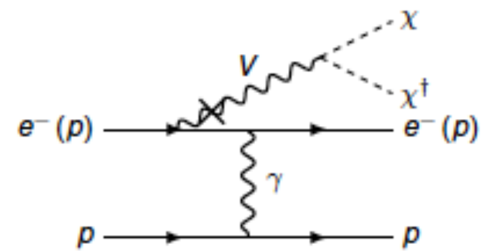


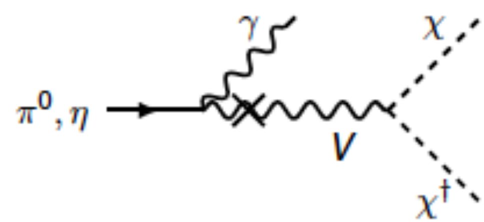
- Not constrained to Lee-Weinberg Bound
- Decay Modes

Visible: Condition: $m_V < 2m_\chi$
Mode: $V \to \ell^-\ell^+\,(\gamma\gamma)$

Invisible: Condition: $m_V > 2m_\chi$
Mode: $V \to \chi\chi^\dagger$

Production mechanisms



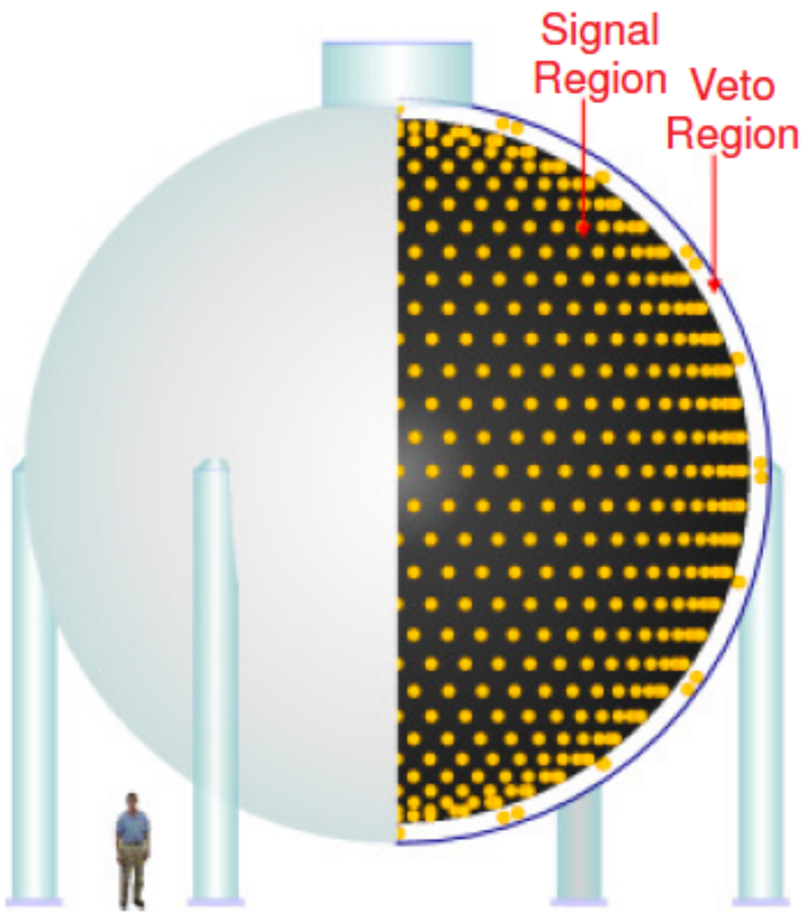


Beam Dump/Fixed Target Experiments

Experiment	Location	approx. Date	Amount of Beam	Beam Energy (GeV)	Target Mat.	Ref.
Electron Beams			**(10^{20} EOT)**			
E137	SLAC	1980-1982	1.87	20	Al	[1–3]
E141	SLAC	1986	2×10^{-5}	9	W	[2, 4]
KEK-PF	KEK	1986	1.67×10^{-3}	2.5	Fe,PB,Plastic	[5]
LAL 86/25	Orsay	1986	$\sim 9.6 \times 10^{-5}$	1.5	W	[6]
E774	Fermilab	1991	0.52×10^{-10}	275	W	[2, 7]
A1	MAMI	2011	$90\,\mu A * t$	0.855	Ta	[8]
APEX	JLAB	2011	$150\,\mu A * t$	2.260	Ta	[9]
Proton Beams			**(10^{20} POT)**			
CHARM	CERN	1983	0.024	400	Cu	[10]
PS191	CERN	1984	0.086	19.2	Be	[11, 12]
E605	Fermilab	1986	4×10^{-7}	800	Cu	[13]
SINDRUM	SIN,PSI					
ν-Cal I	IHEP Serpukhov	1989	0.0171	70	Fe	[14–16]
LSND	LANSCE	1994-1995 1996-1998	813 882	0.798	H20, Cu W,Cu	[17]
NOMAD	CERN	1996-1998	0.41	450	Be	[12, 18]
WASA	COSY	2010		0.550	LH2	[19]
HADES	GSI	2011	$0.32\,pA * t$	3.5	LH2,No,Ar+KCl	[20]
		2003-2008	6.27		Be	[21]
MiniBooNE	Fermilab	2005-2012	11.3	8.9	Be	[22]
		2013-2014	1.86		Steel	[23]

- DarkLight and Heavy Photon Search have been aproved to run at JLab.

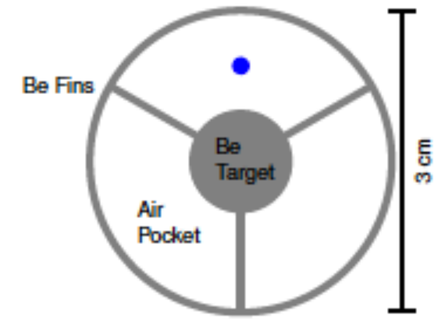
MiniBooNE Detector

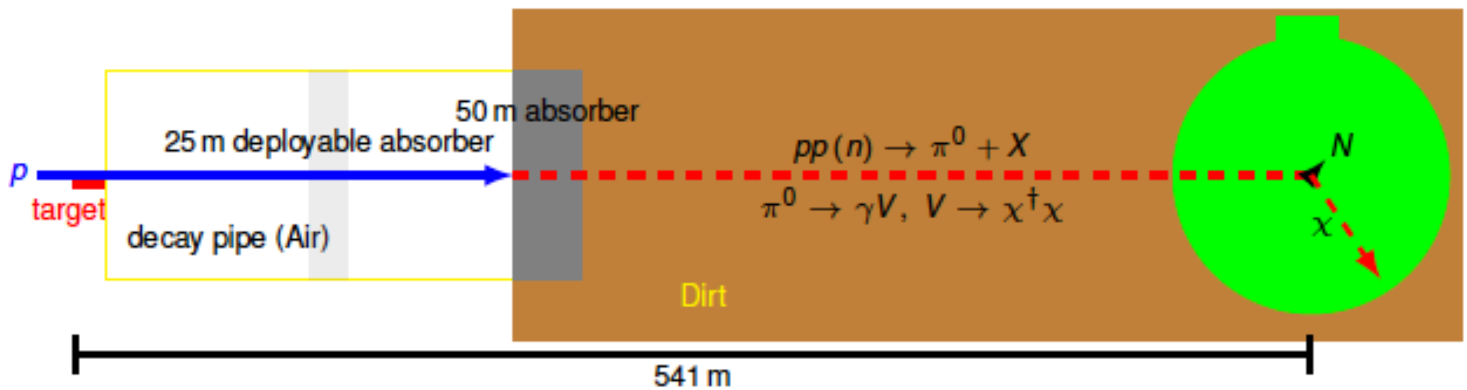


- 800 tons of mineral oil acting as a Cherenkov/scintillator detector.
- 1280 inner and 240 veto PMTs.
- Running for 10 years
  - ν mode: 6.5×10^{20} POT
  - $\overline{\nu}$ mode: 11.3×10^{20} POT
- ***The detector is well understood***
- Ran 10 months 2013-2014
  - off-target mode: 1.86×10^{20} POT

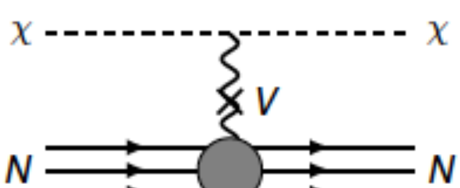
Beam Dump Mode

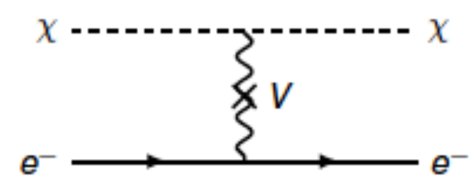
8 GeV protons hit steel beamstop 50 m downstream





Interactions in detector





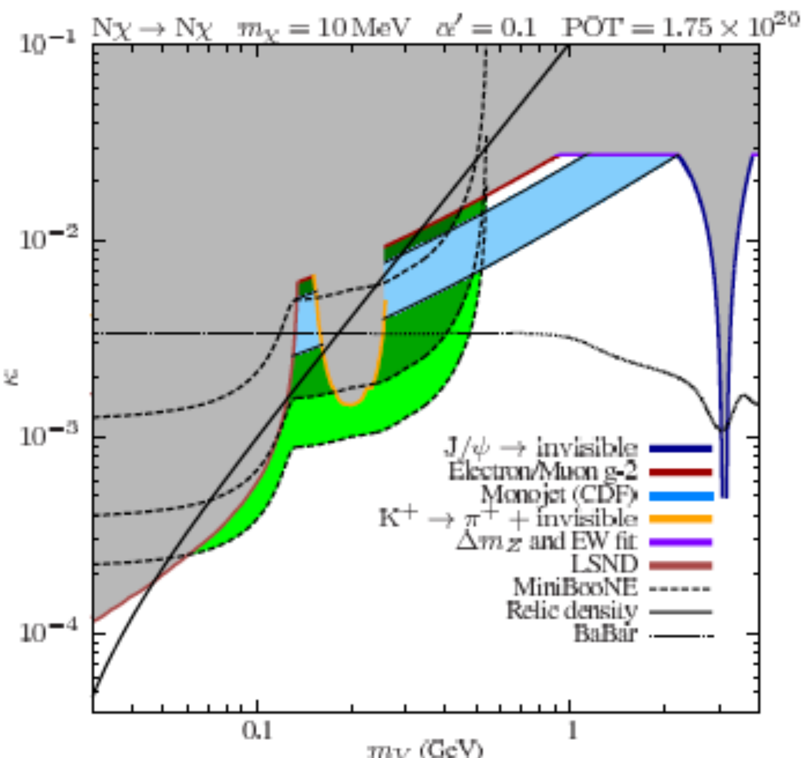
- Similar to ν neutral current elastic scattering (NCel)

Theoretical Predictions for MiniBooNE

κ vs. m_V

- Theory group from U. Victoria is working on C++ dark matter generator
- Dashed lines predict CL for 1, 10 and 1000 signal events

N-DM Interaction



e-DM Interaction