PAC charge

LOI: Direct Search for Dark Photon & Dark Higgs Particles with the SeaQuest Spectrometer in Beam (P-1067)

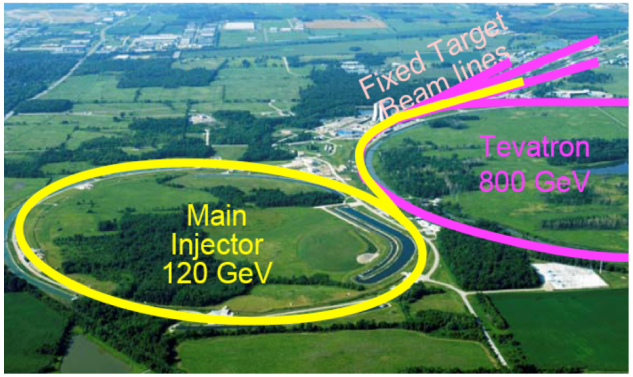
- We ask the PAC to comment on whether the science goals are compelling, the scope and appropriateness of the support requested, and the compatibility of this new initiative with the previously proposed SeaQuest running with a polarized target.

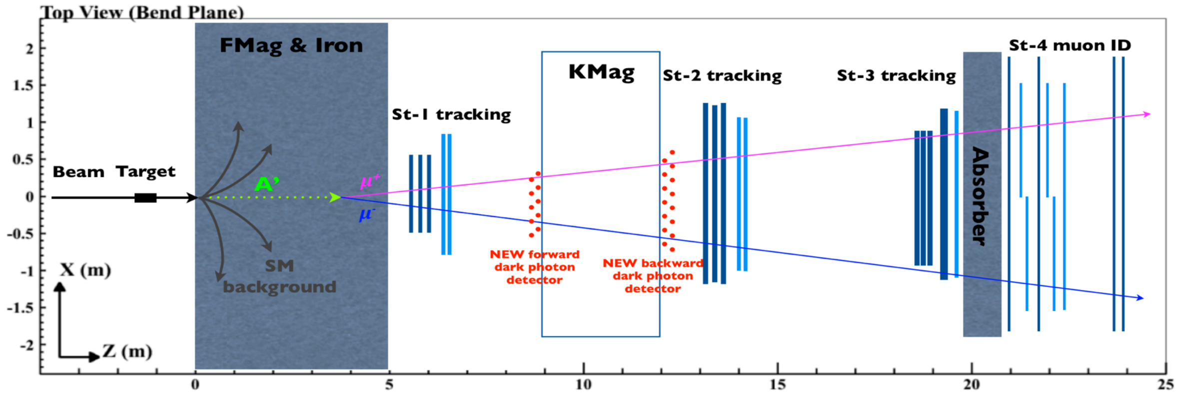
- **20’+10’ for PAC presentations 6/22**
  - **Science goals, Ming ~15’**
  - **Scope and compatibility, Paul ~5’**

A Direct Search for Dark Photon and Dark Higgs Particles with the SeaQuest Spectrometer in Beam Dump Mode at Fermilab (P-1067)

Ming X. Liu

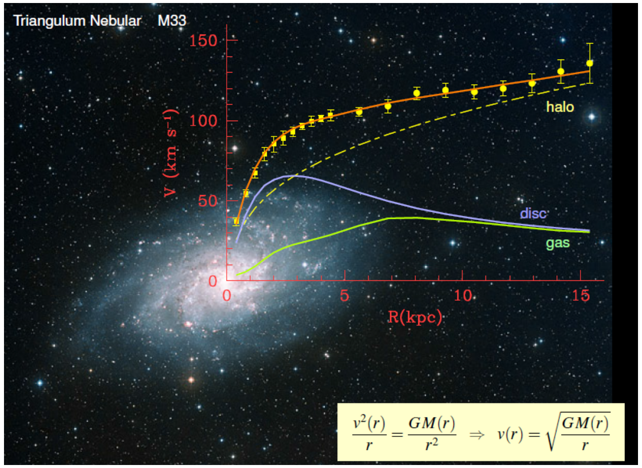
Los Alamos National Laboratory



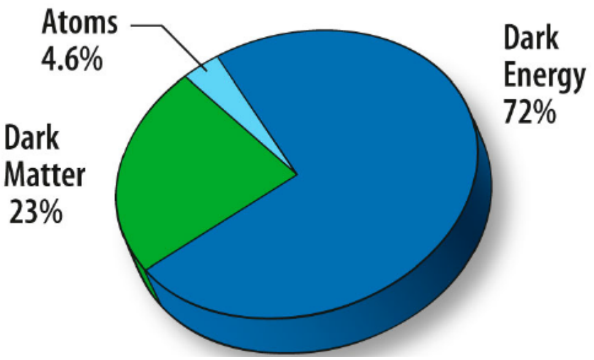


Hints of Dark Matter?

Galaxies' rotation curve



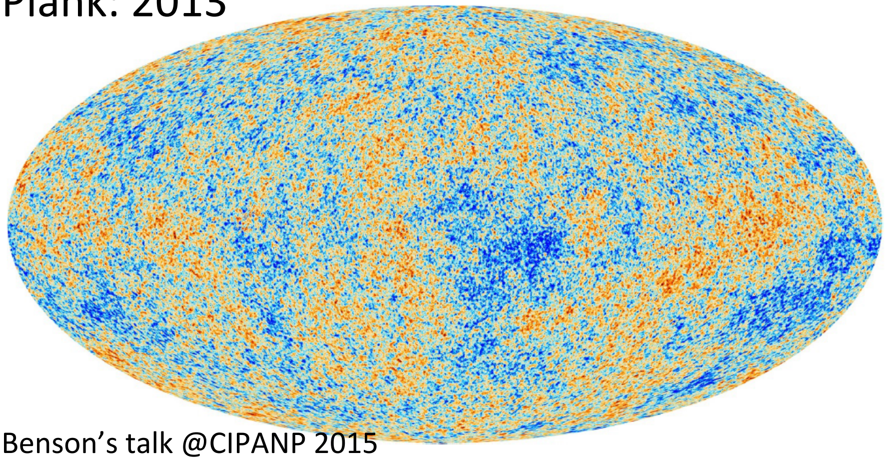
F. Zwicky, ApJ 86 (1937) 217, V. Rubin et al, ApJ 238 (1980) 471

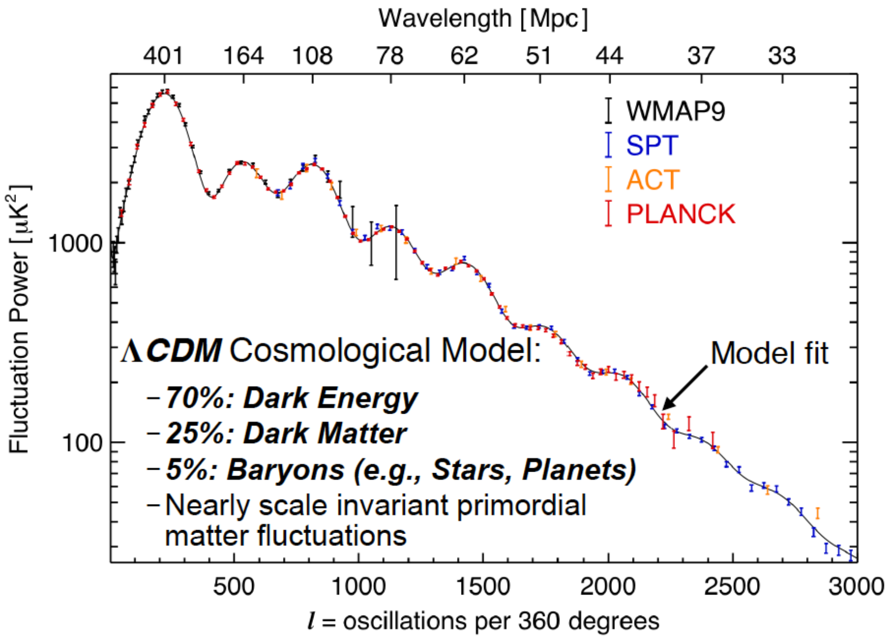


Gravitational lensing (Hubble 2007)

30μK RMS fluctuations on 3 K background

Plank: 2013

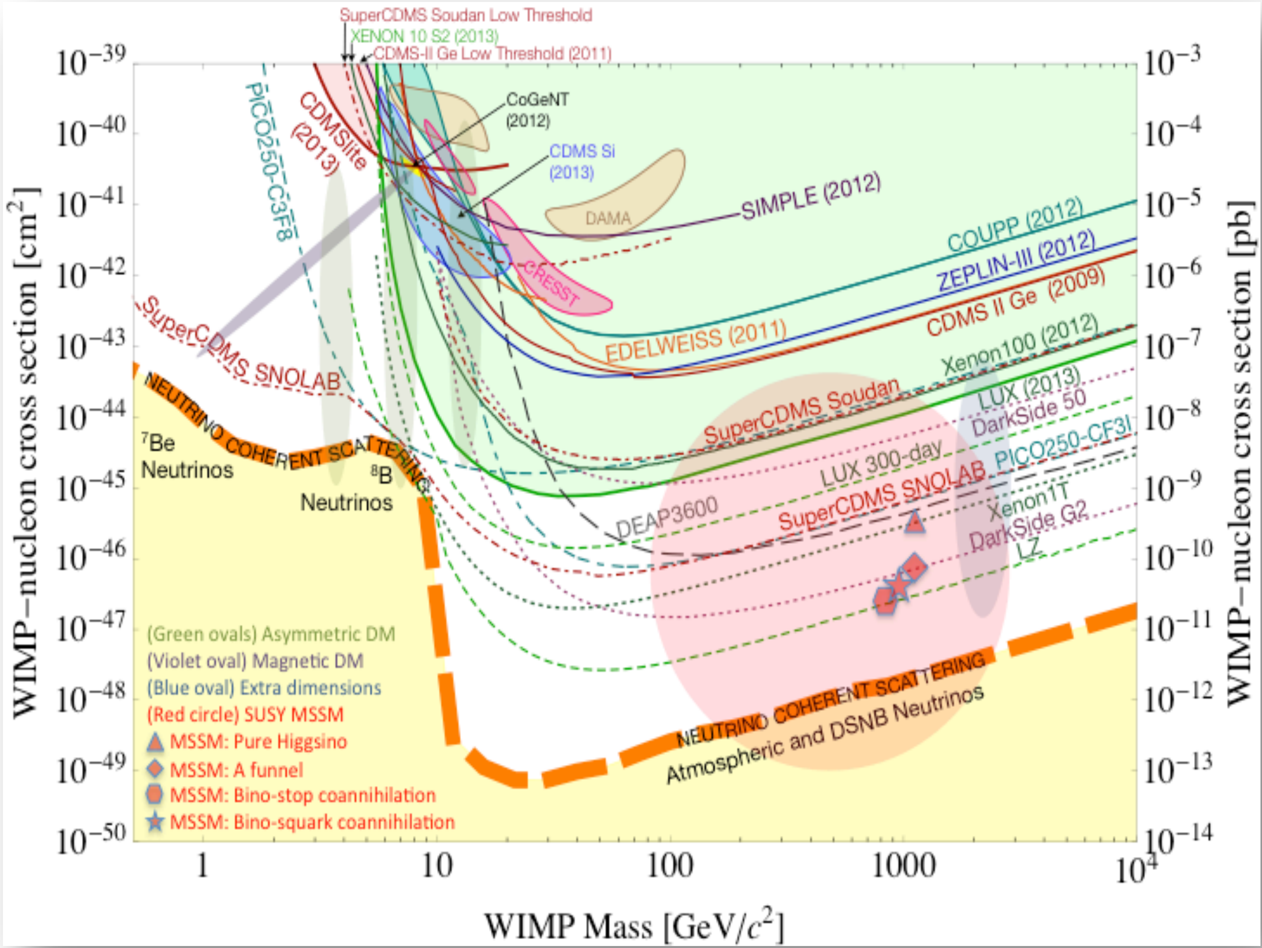




Benson's talk @CIPANP 2015

High Mass WIMP ?

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



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!!!

Low Mass Dark Particles?

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

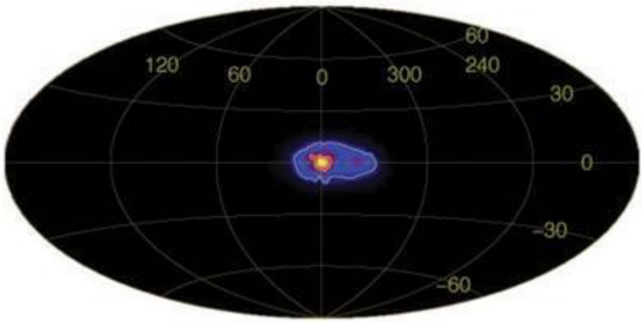
Low mass weakly-interacting "dark particles" become very interesting!

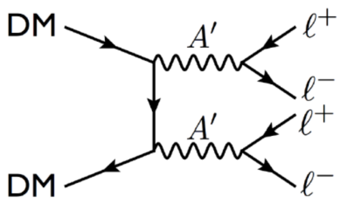
Mass: *O(MeV ~ GeV)*

- There are "portals" between the dark sector and the SM.
  - **"vector coupling": dark photon**
  - **"scalar coupling": dark Higgs**
  - **…**
  - **could be within experimental reach**

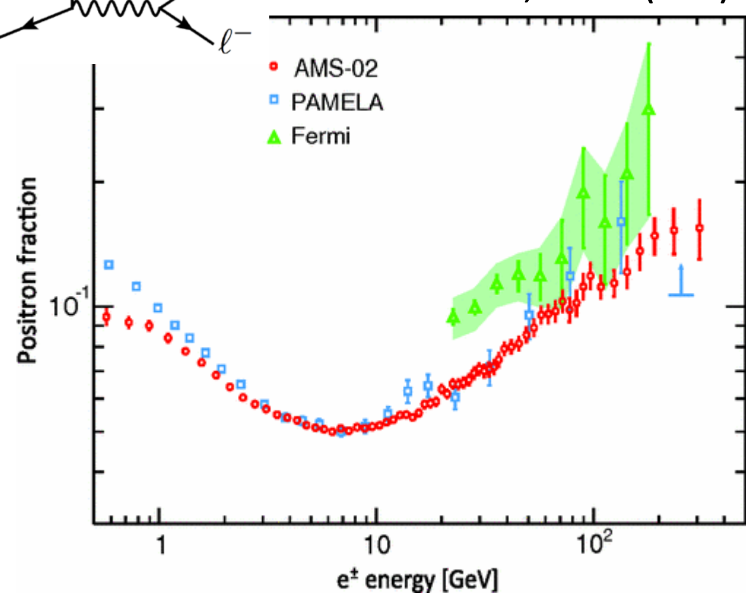
- In particular, low-energy and high-intensity colliders (B-factories) and fixed target experiments (Jlab, Fermilab, LHC) offer an ideal environment to probe these new ideas.

511 keV gamma ray excess from galactic center(INTEGRAL)





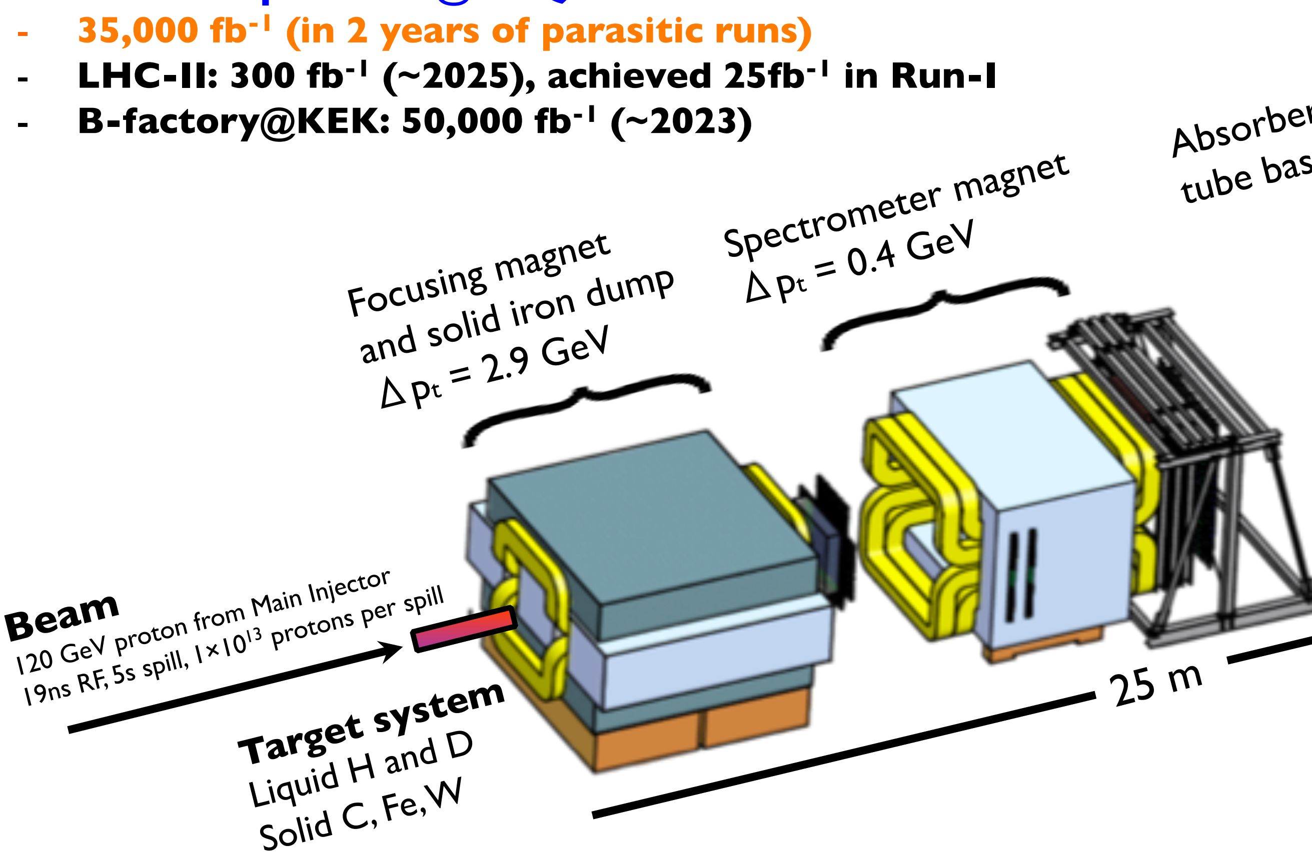
PLR 110, 141102 (2013)

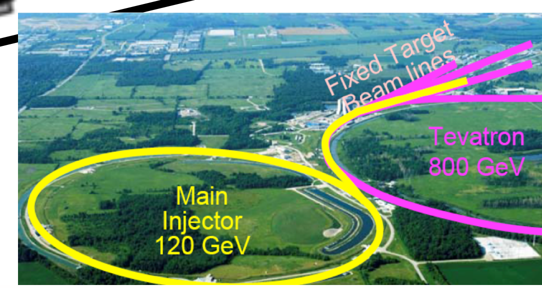


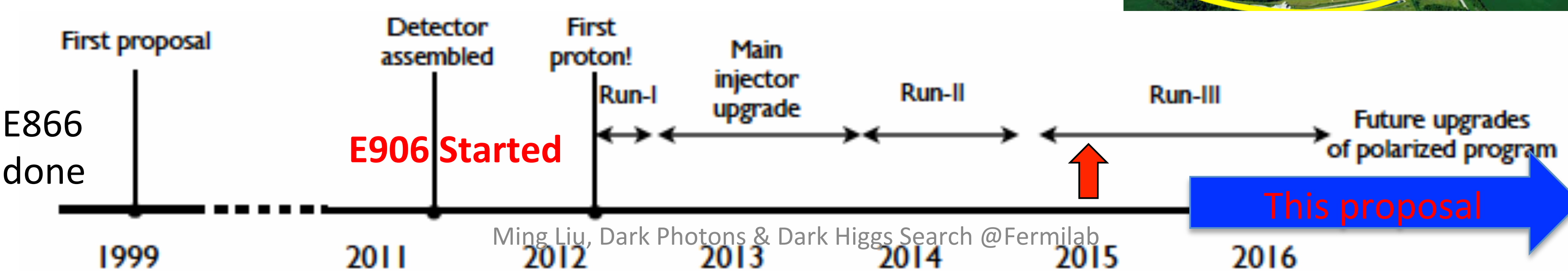
Intensity Frontier at Fermilab: 120 GeV Beam

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)**





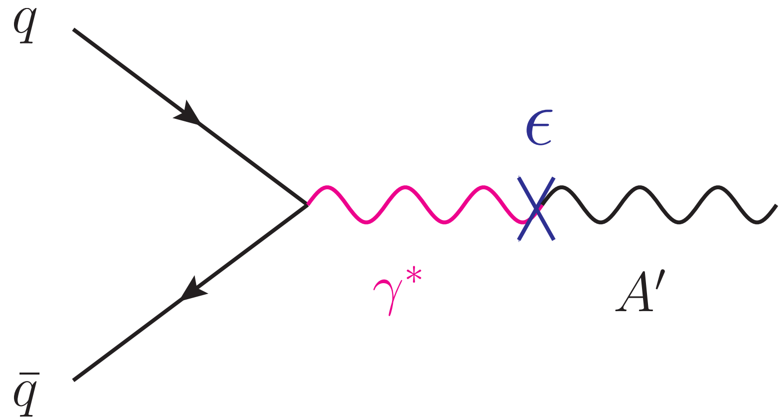


Direct Production of Dark Photons and Dark Higgs in p+Fe at Fermilab

- Weakly interacting dark photon(Higgs)

Photon Portal:

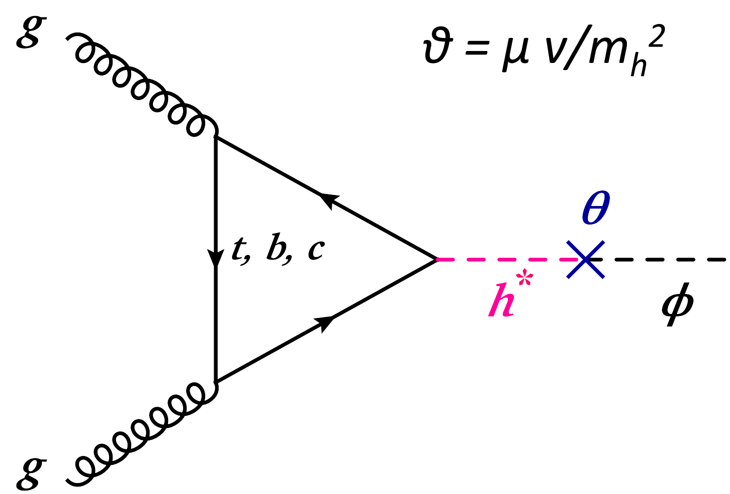
$$\mathcal{L}_{\rm mix} = \frac{\epsilon}{2} F^{\rm QED}_{\mu\nu} F^{\mu\nu}_{\rm Dark}$$



Higgs Portal:

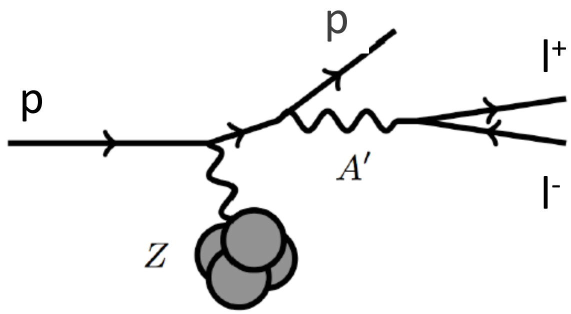
$$\mathcal{L}_{\rm mix} = \mu\phi|H^\dagger H|$$

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

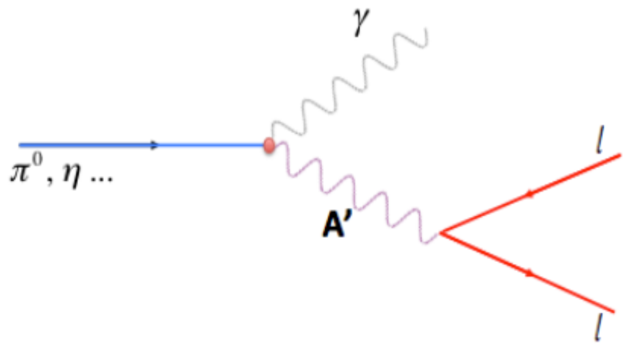


Dark Photon Search in Dimuon Channel at SeaQuest in Beam Dump Mode (p+Fe)

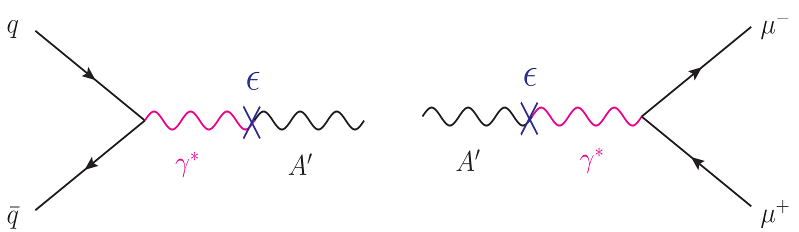
1. Bremsstrahlung



2. π^0, η, … decay



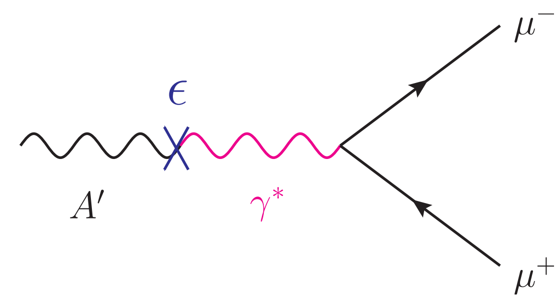
3. Drell-Yan like



Dark Photon Decay Modes

“Minimal” Decay:

- Dark photon is the lightest in the dark sector;
- SM final state particles only
- Same mixing parameter
  - Decay is ε^2 suppressed
  - Very small decay width

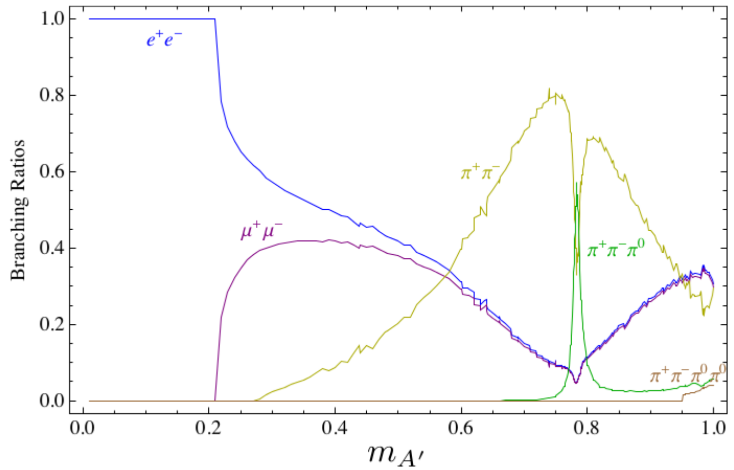


$$\Gamma \sim \epsilon^2 \times m_{A'}$$

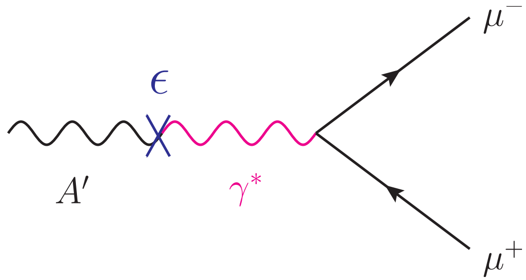
“General” Decay:

- Decay into other dark particles, dominant channel if allowed

1. Dark -> dark
2. Dark -> SM particles



Long-lived Dark Photons



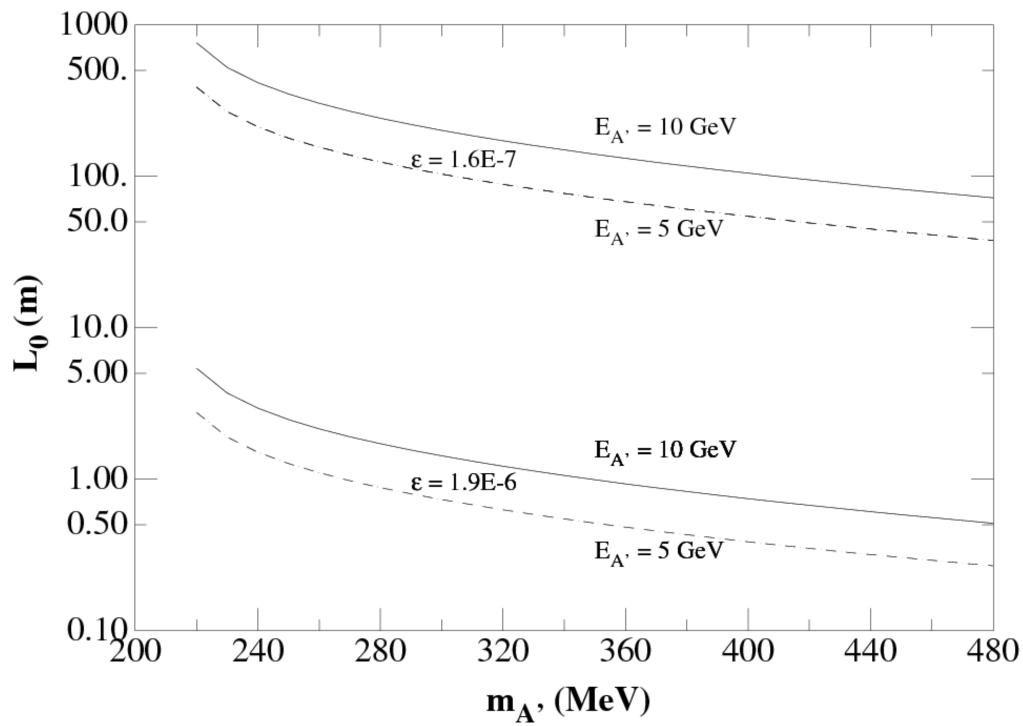
$$\Gamma(A' \to f + \bar{f}) = C\frac{\epsilon^2 m_{A'}}{3} e_f^2 \alpha_{\rm em} \left(1 + \frac{2m_f^2}{m_{A'}^2}\right)\sqrt{1 - \frac{4m_f^2}{m_{A'}^2}},$$

Decay is ε^2 suppressed, a sharp mass peak in mass spectrum:

$$\frac{\Gamma}{m_{A'}} \sim \epsilon^2$$

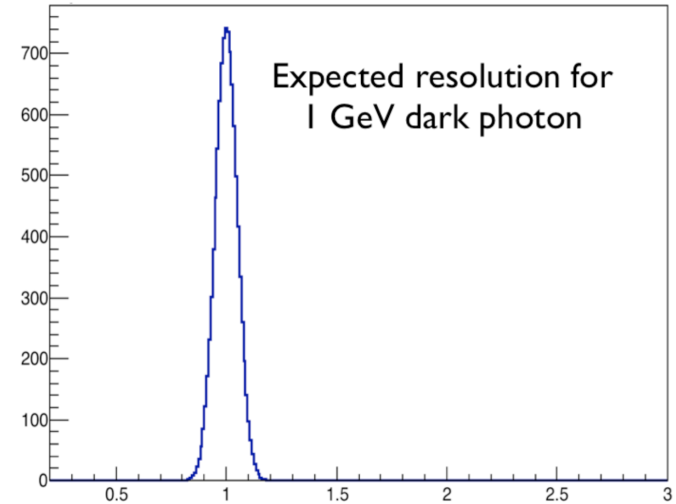
Long decay length:

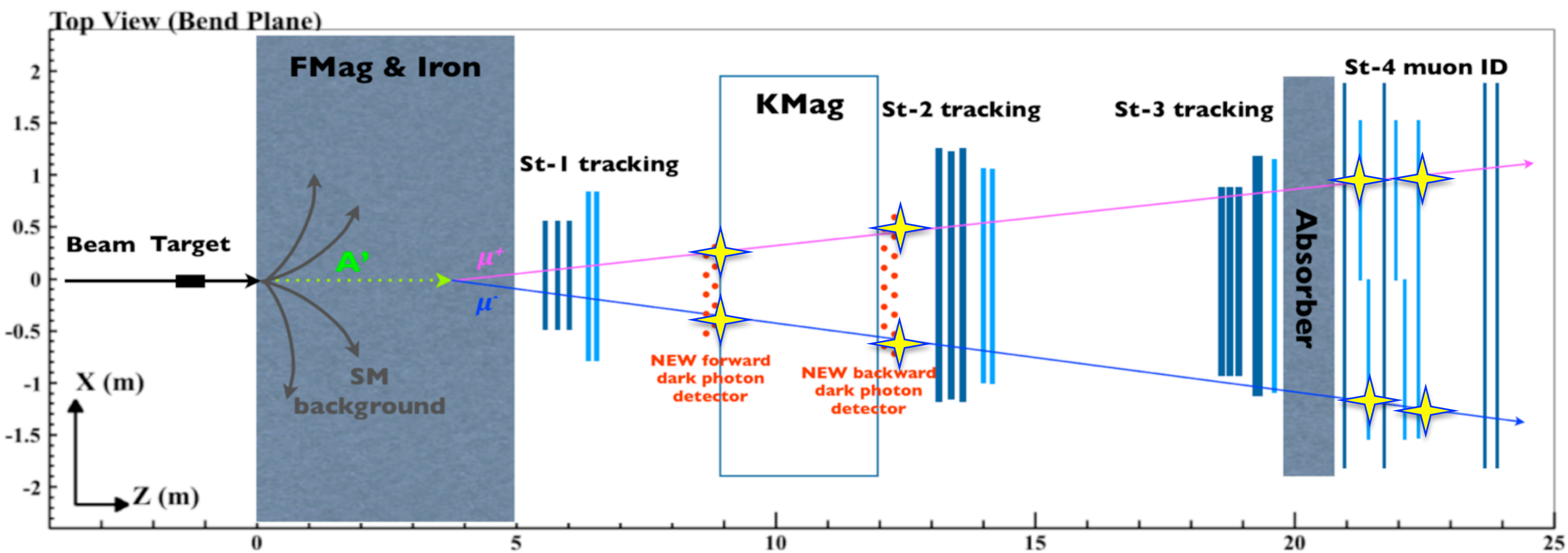
$$L_0 \sim \frac{1}{\epsilon^2 \times m_{A'}}$$



Proposed Experimental Measurements

- Unique signals
  - Invariant mass peak in dimuon mass spectrum
  - Displaced dimuon decay vertex for long-lived particle
- Beam time
  - Run parasitically with E906/E1039 (2017-2019)
  - Possible more beam time later
- Dark photon trigger upgrade
  - low mass dimuons (0.2 - 3)GeV
  - Displaced dimuon vertex trigger





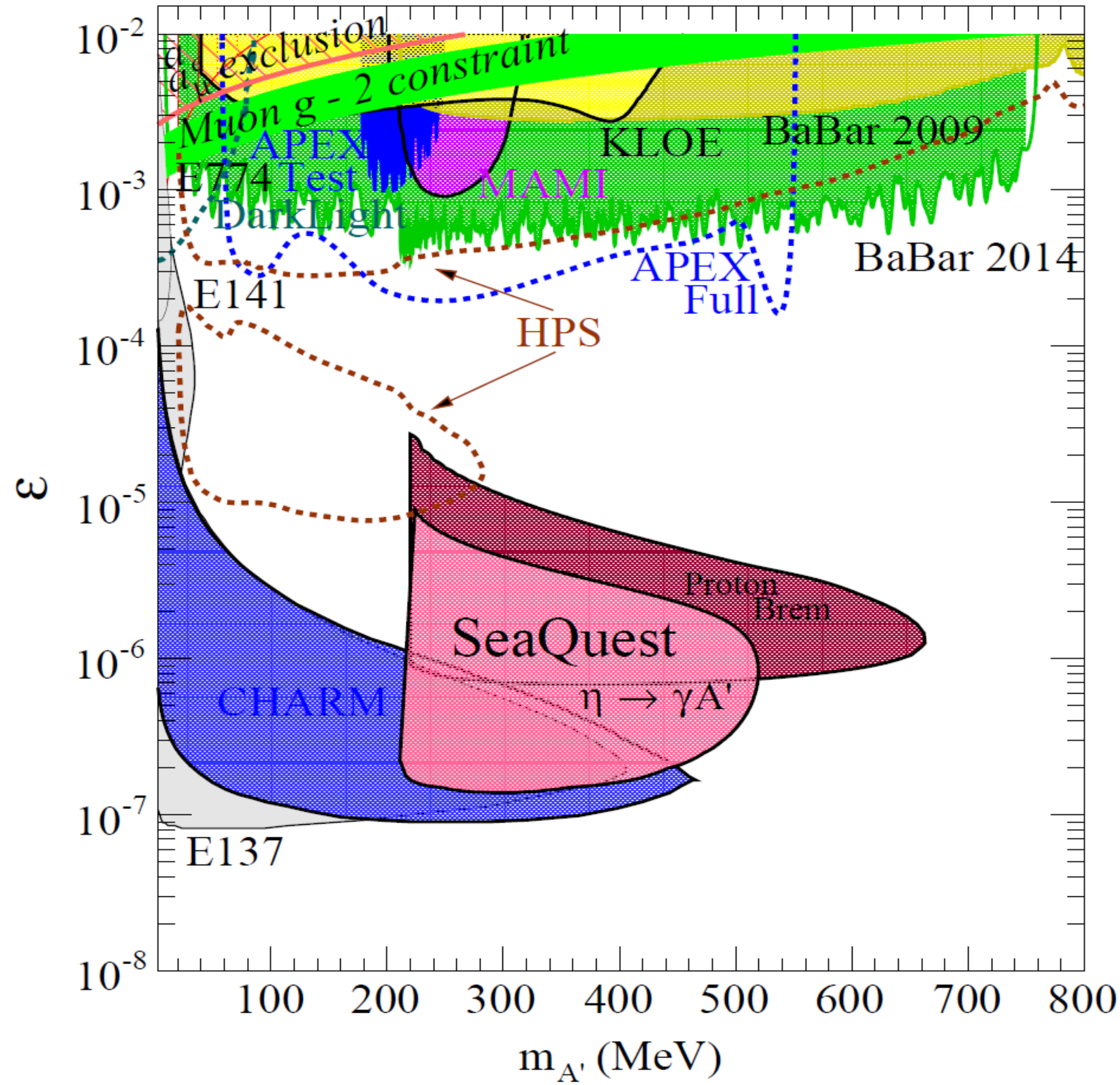
Sensitivity (I): Long-lived Dark Photon

Required reconstructed dimuon decay Z-vtx: >6.0m out side of the F-Mag

2E12 ppp
100% efficiency
200 days
10 event contours

~ 1.4 x 10^{18} POT

Plot credit: A. Tadepalli

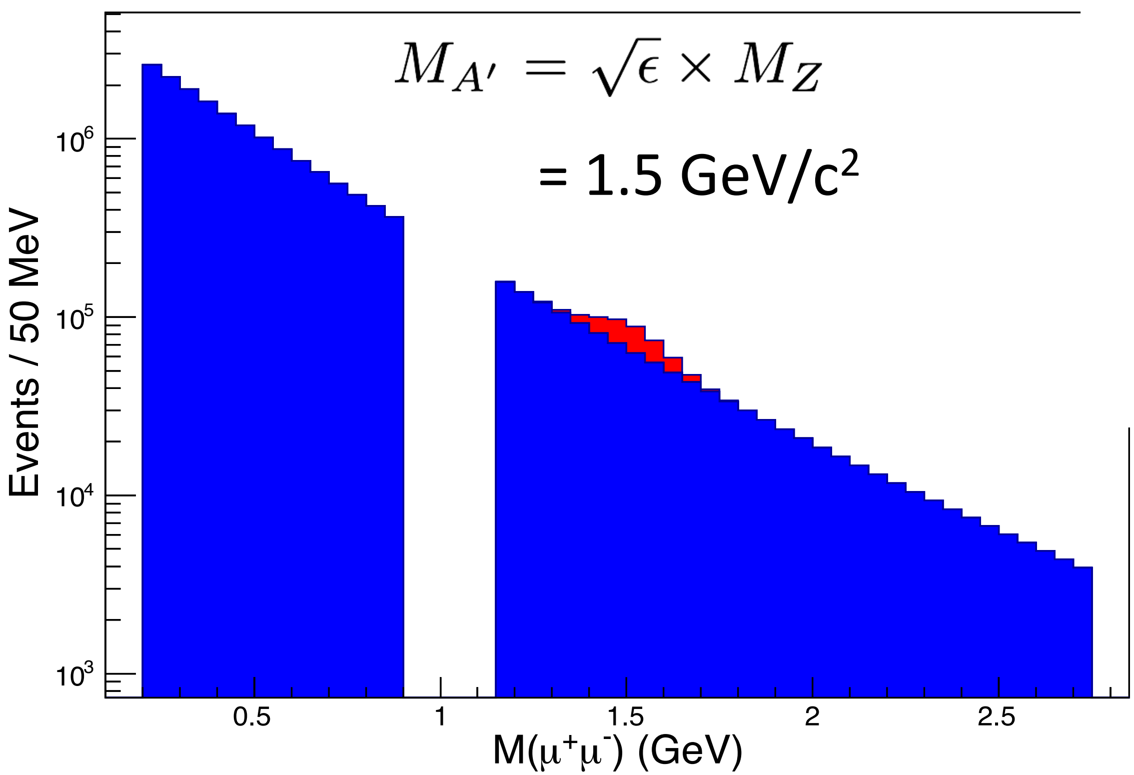


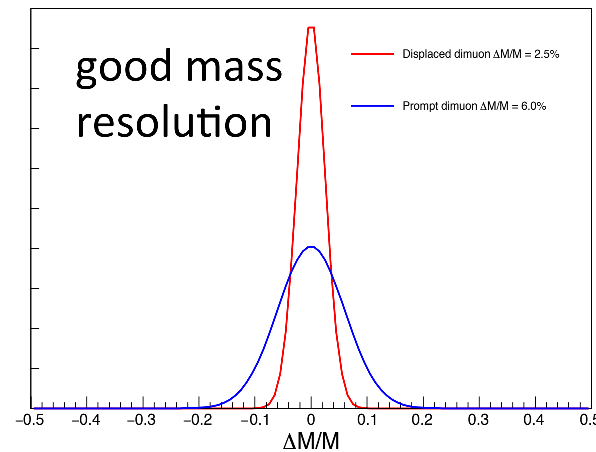
Sensitivity (II): "Prompt" Dark Photons

With projected POT: 1.4 x10^{18}

$$sig = S/\sqrt(S+B) = 20$$

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





Drell-Yan: NLO

SeaQuest Dark Photon Sensitivity

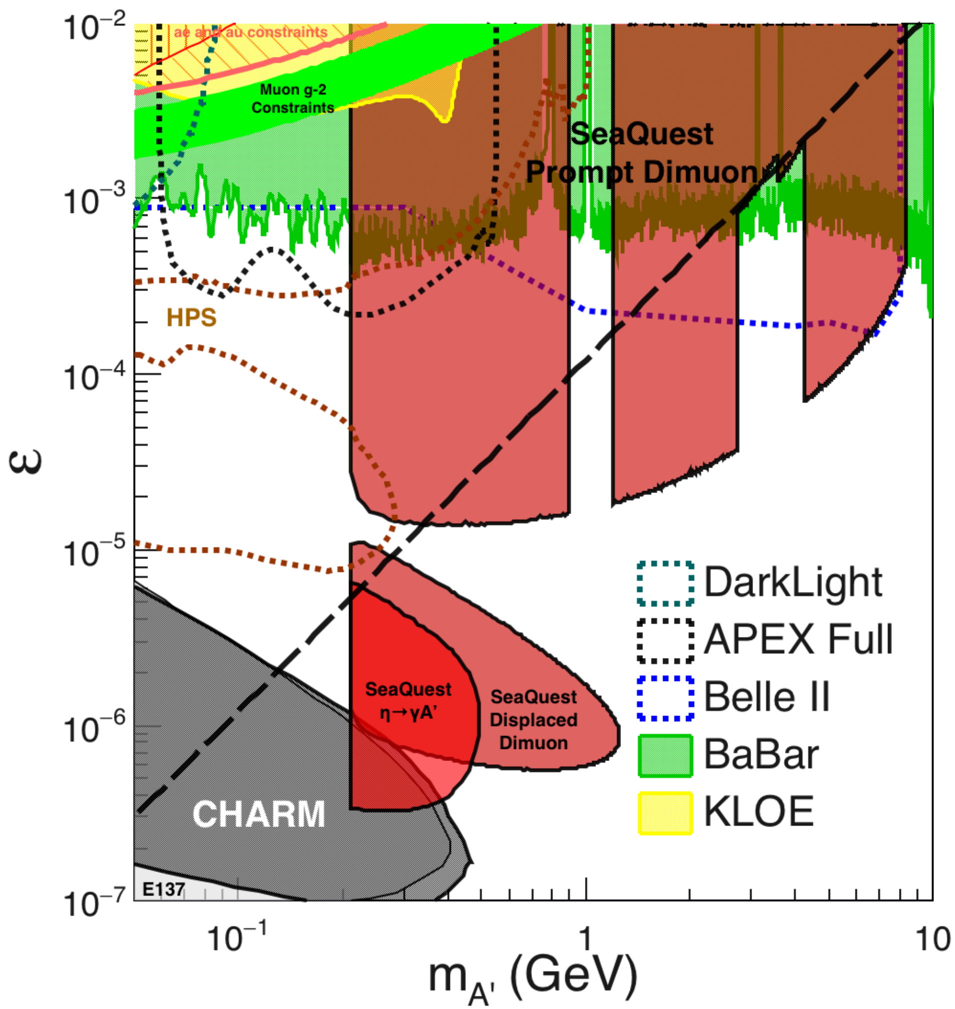
POT:1.4x10^{18} (parasitic w/ E1039)

From signals:
- Drell-Yan like
- Eta decays
- Bremsstralung

Covers a wide range of phase space

- Prompt dimuons
- Displaced dimuons

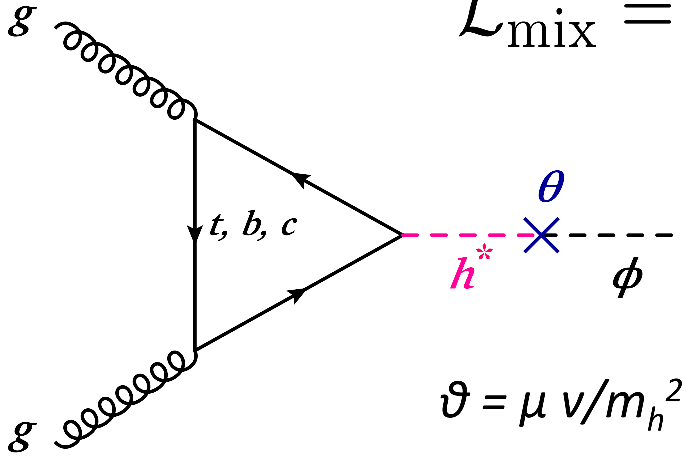
Plot credit: K. Liu



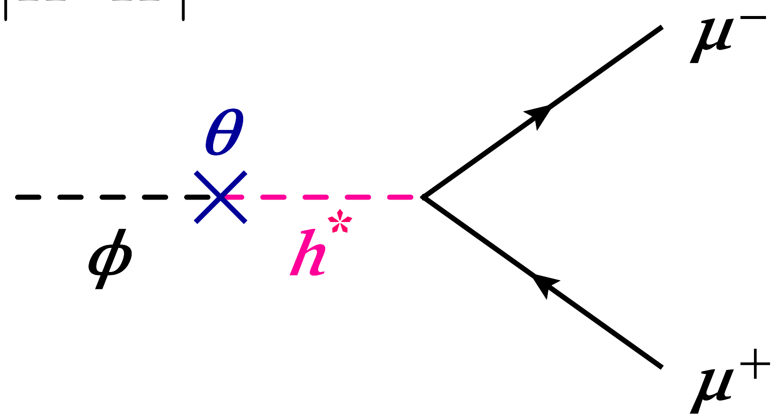
Dark Higgs Search at SeaQuest

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

Y. Zhang et al, arXiv:1502.06983

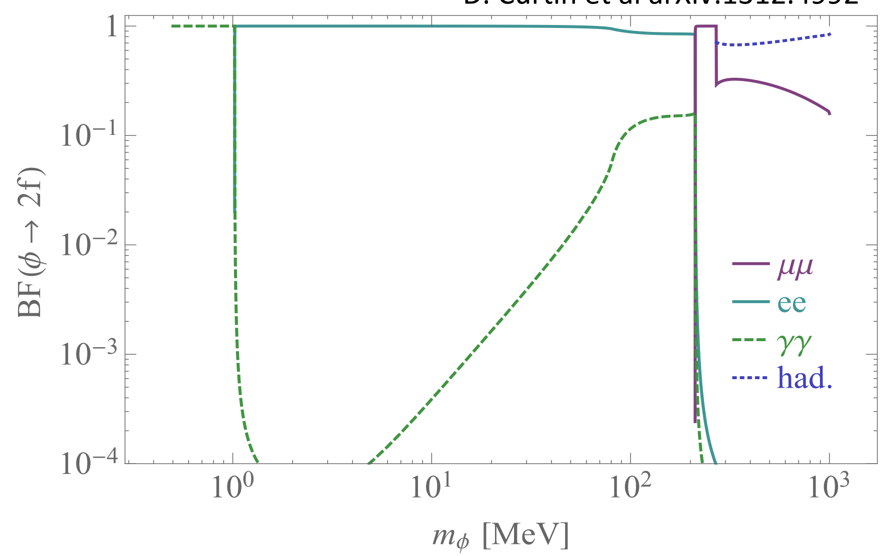


$\vartheta = \mu\, v/m_h^2$



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

D. Curtin et al arXiv:1312.4992



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

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

Advantage of using hadron beams with muon probes over electrons

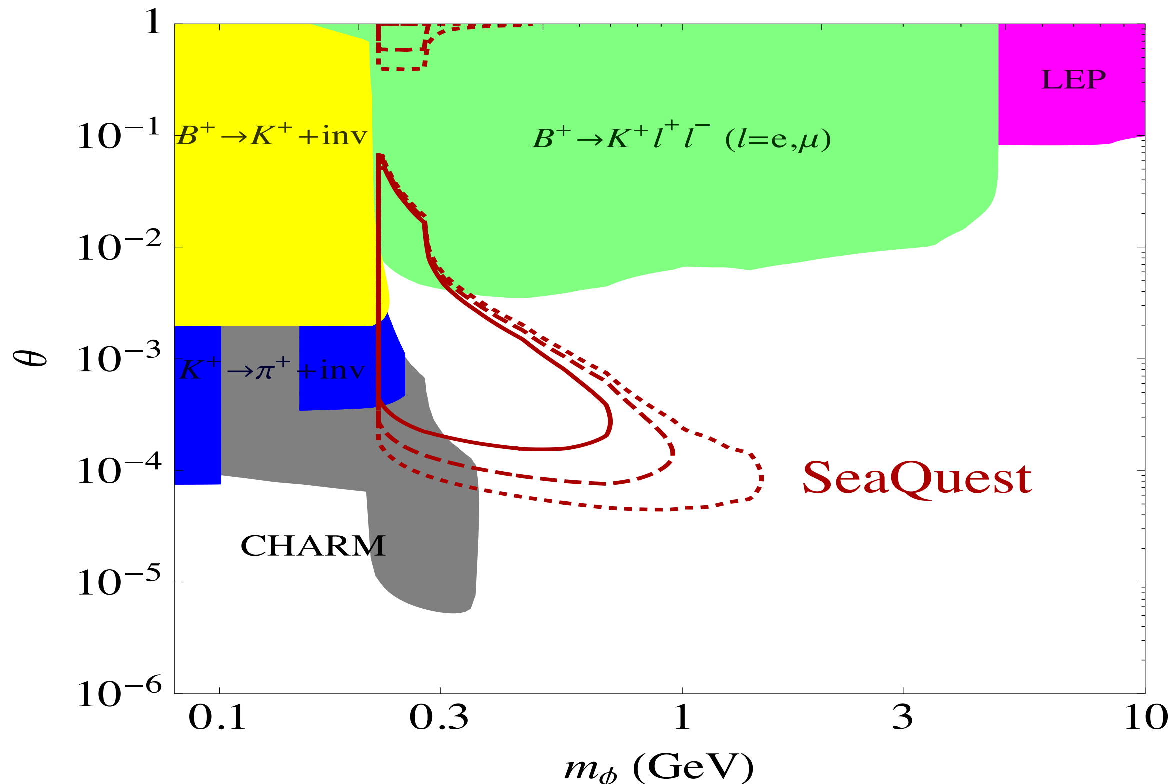
SeaQuest Dark Higgs Sensitivity

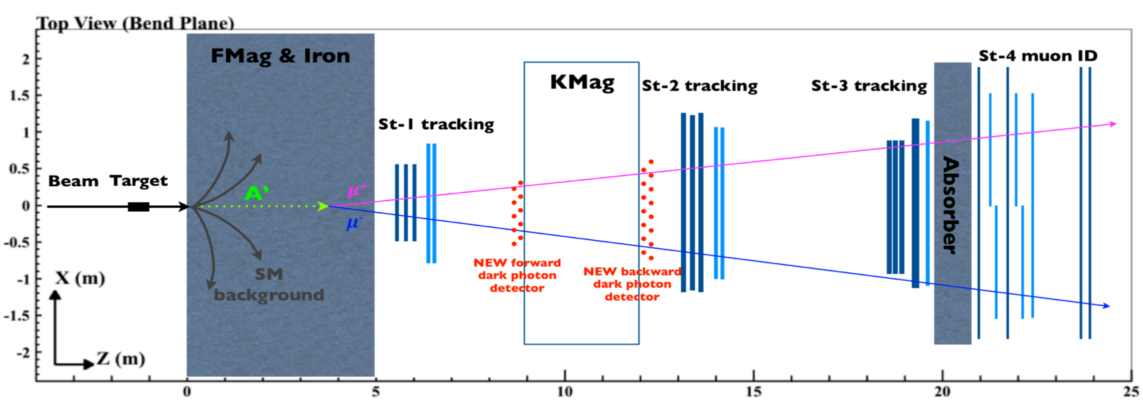
POT:1.4×10^{18}, 5x, 25x

Y. Zhang (2015)

Tagged by displaced dimuon Z-vtx > 2 m;

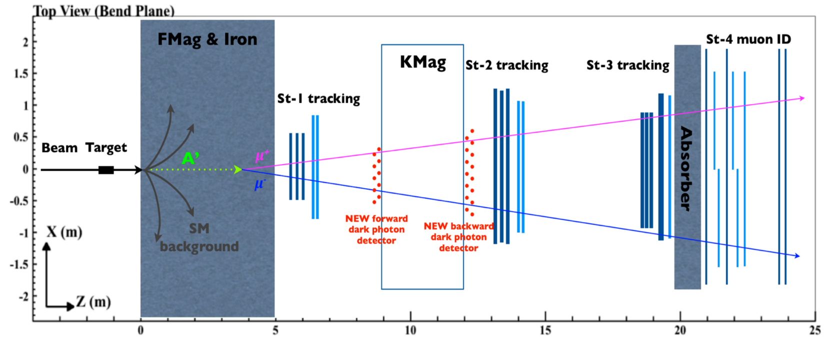
Low sensitivity for large mixing paramater due to small cross-section

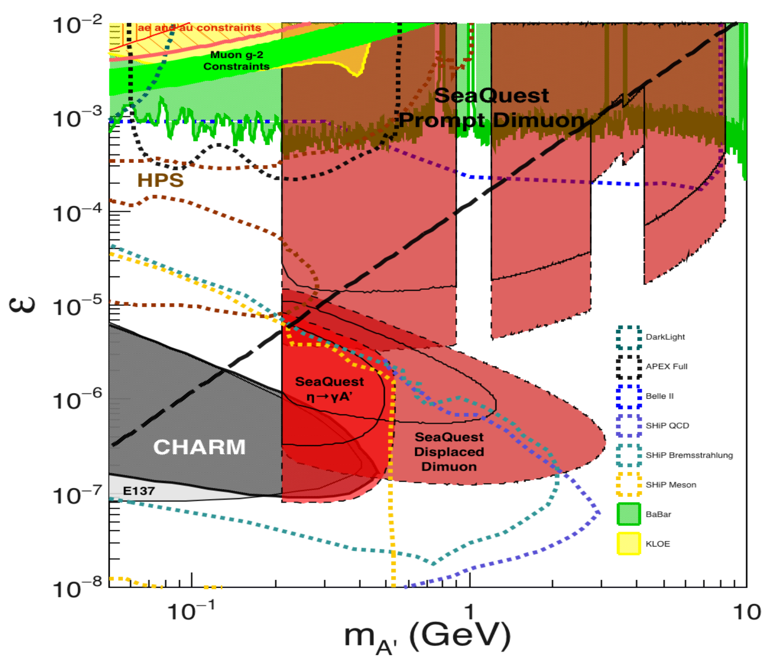


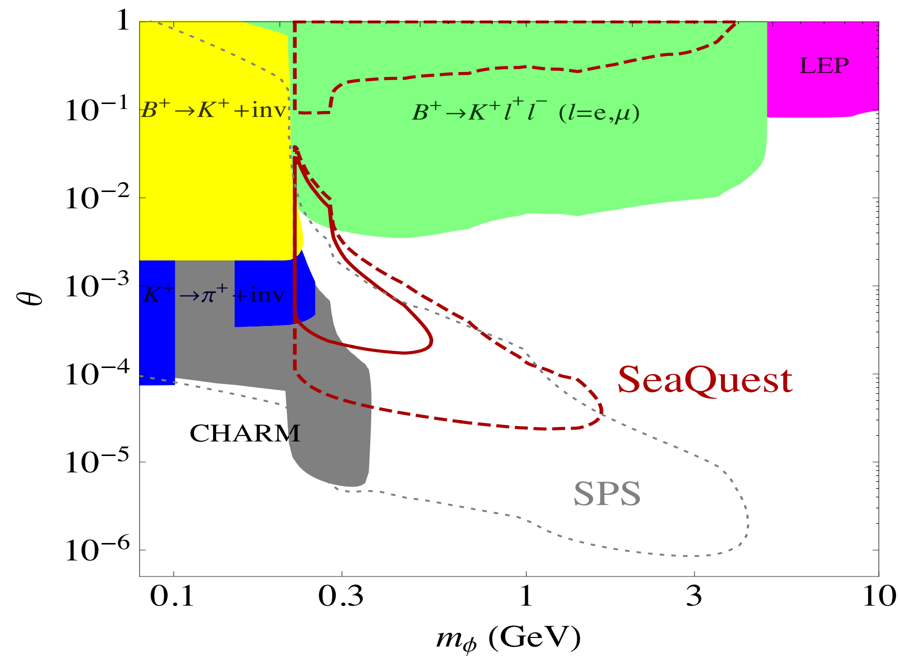


Summary and Outlook

- *Great discovery potential!*
- *Early parasitic data taking 2017-2019+*
- *Possible upgrade later, a new dedicated dark matter program at Intensity Frontier!*







Scope and Compatibility

- Preparation work: 10/2016 – 4/2017
  - Displaced vertex dimuon trigger upgrade (collaboration $$)
  - Possible upgrade of DAQ bandwidth under consideration (collaboration $$)

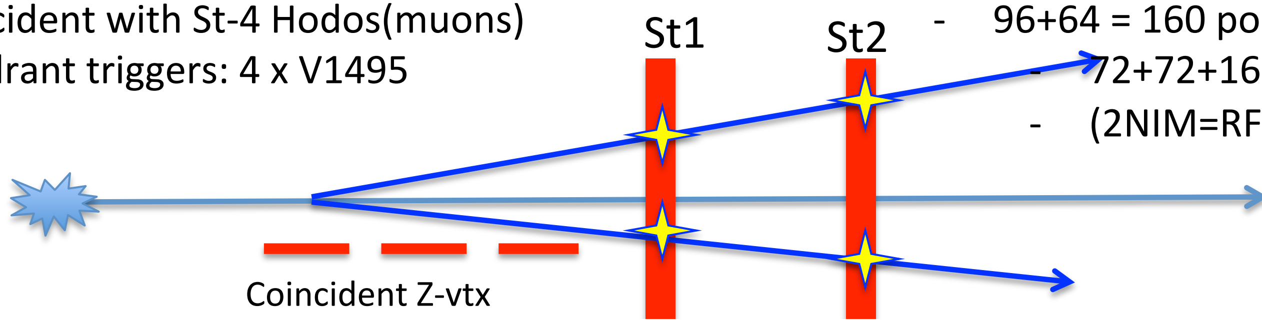
- Parasitic runs w/ E1039: 5/2017 – 5/2019
  - Displaced vertex dimuon trigger upgrade (external $$)
  - Use ~10% DAQ bandwidth, possible upgrade under consideration
  - Achieve 1.44 $\times 10^{18}$ POT

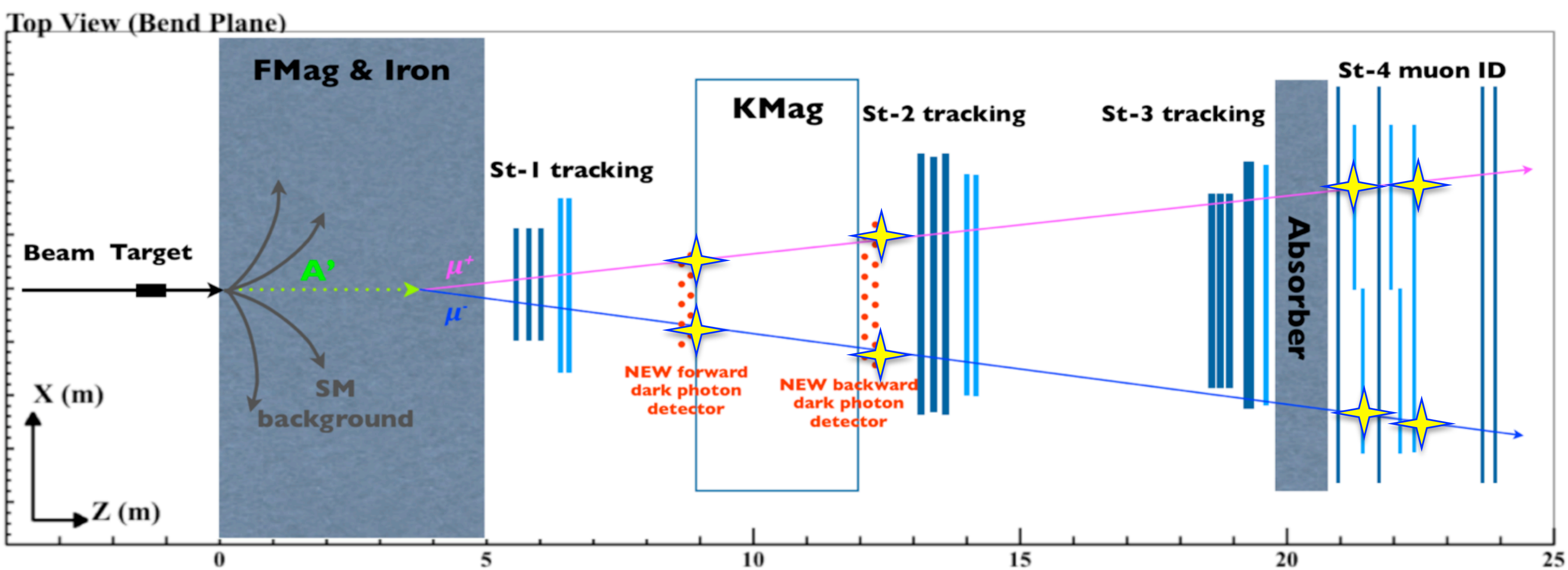
- Possible dedicated runs later with upgrades: 2019+
  - High luminosity goals:
    - POT >> 1.4×10^{18}
  - DAQ
    - 10 – 100 kHz capability
  - EMCAL/HCAL/PID
    - Electrons
    - charged hadrons

Dark Photon/Higgs Displayed Dimuon Vertex Trigger

Y-Plane Trigger:
- No mass cut
- Displaced z-vertex
  - Coincident with St-4 Hodos(muons)
  - Quadrant 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)



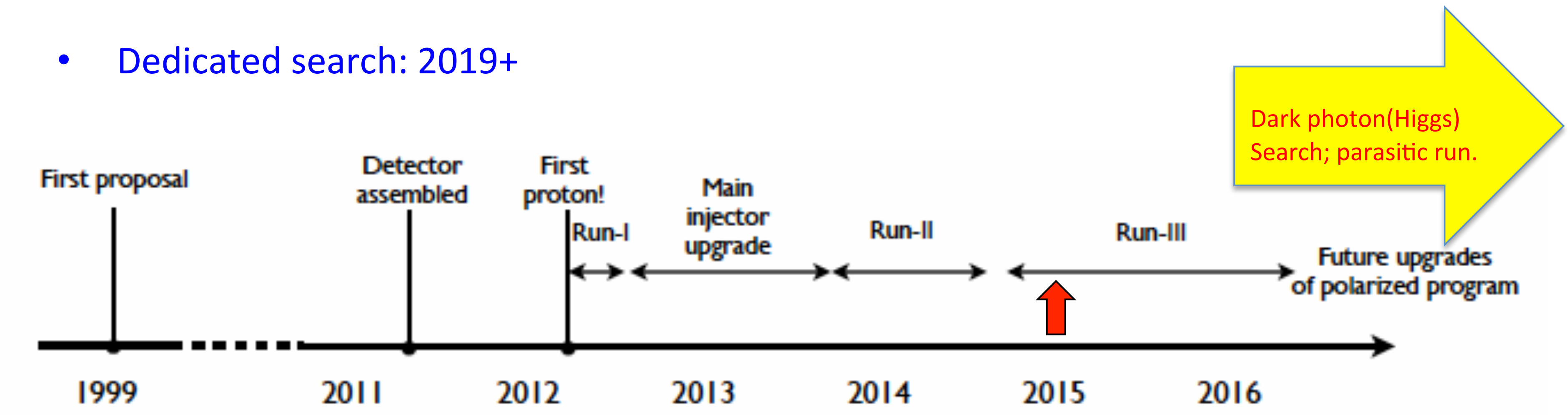


Schedule of SeaQuest Experiments

- E906: ~ 2017
  - Unpolarized fixed target Drell-Yan
  - dbar/ubar, and p+A
- E1039: 2017 ~ 2019
  - Polarized fixed target Drell-Yan
  - Parasitic run beam-dump mode
- E1027: ??
  - Polarized Main Injector Drell-Yan
- Dedicated search: 2019+

Dark photon and dark Higgs search:
Parasitic run: 2017 -2019

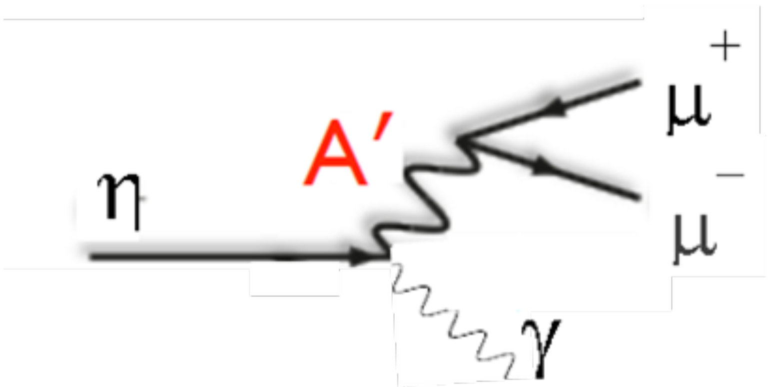
Future runs under consideration:
- detector upgrades
- DAQ upgrade

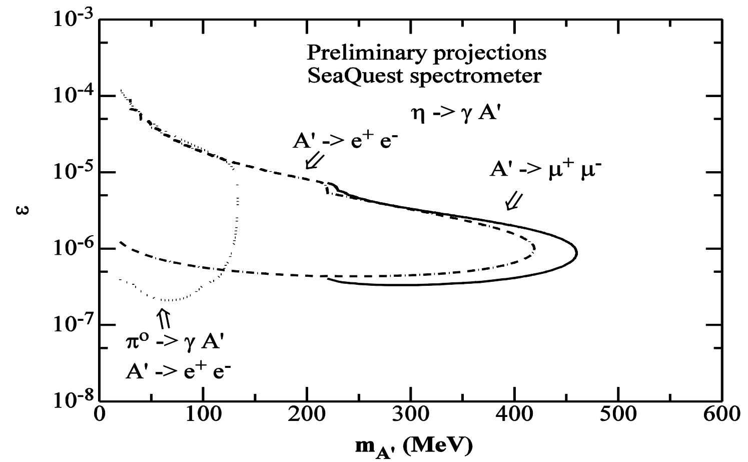


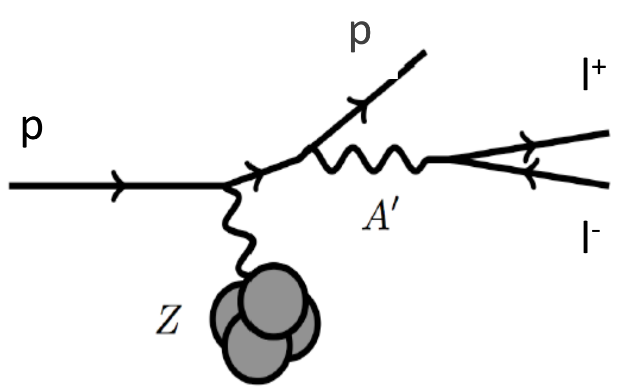
Access Low Mass Region with e^+e^-

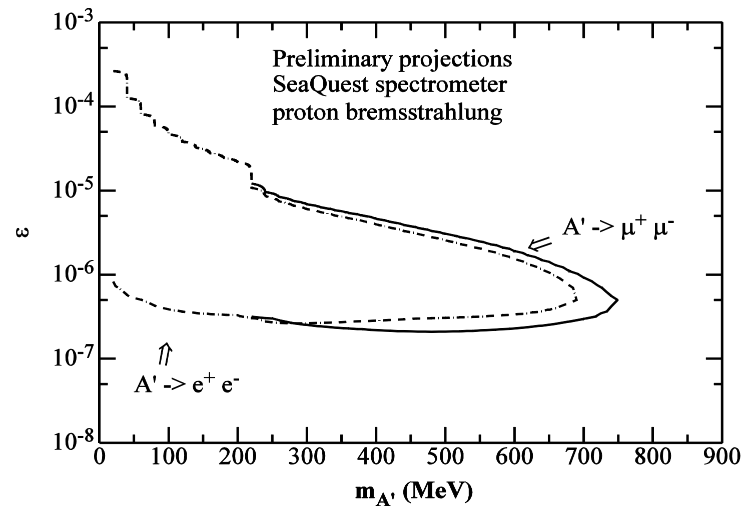
with future detector upgrades

S. Gardner, R. Holt et al





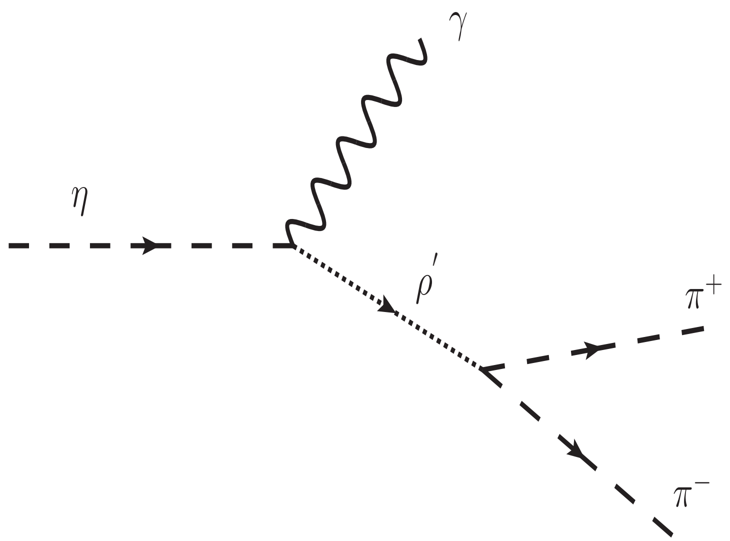


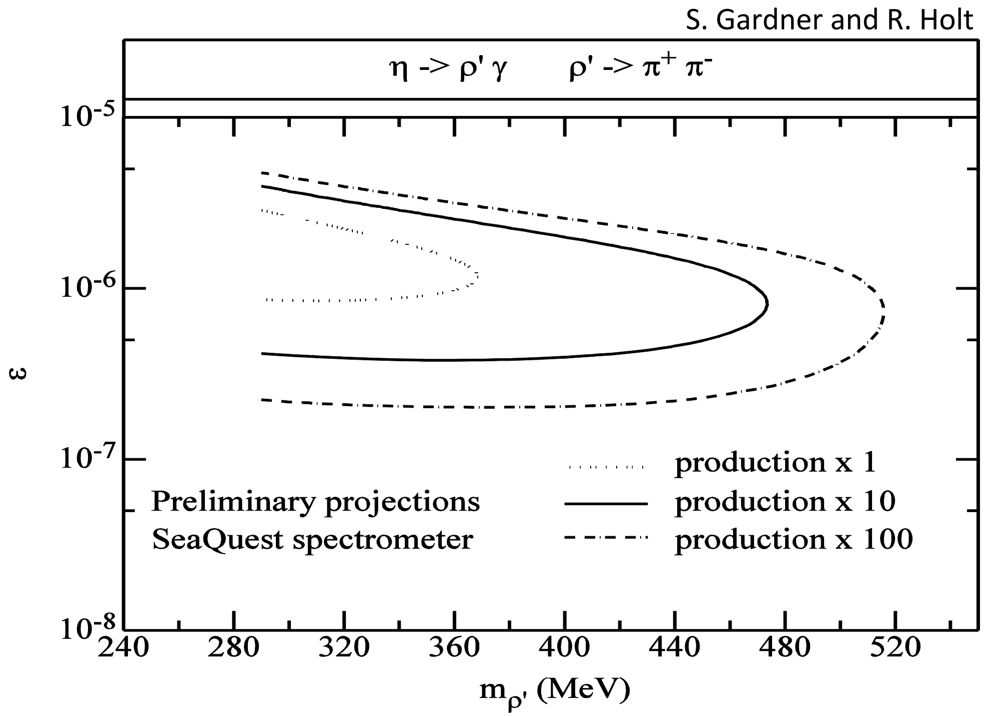


Non Abelian Dark Sector

with future detector upgrades

non-Abelian dark sector process





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

Here we consider a non-Abelian (gluon) portal

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

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

Backup

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

LOI submitted to Fermilab PAC on May 20, 2015

A joint experimental and theoretical collaboration

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

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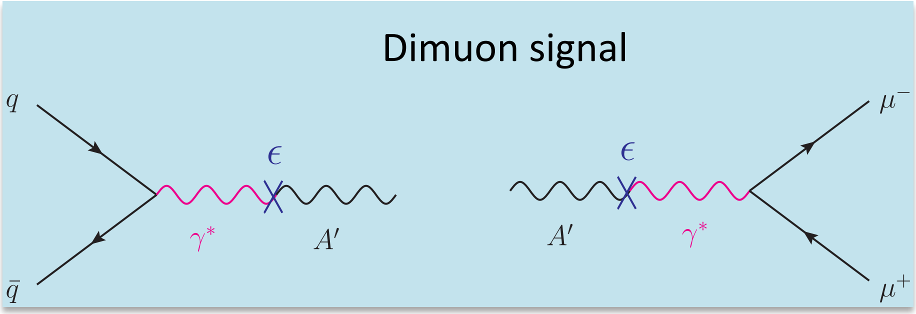
Abstract:

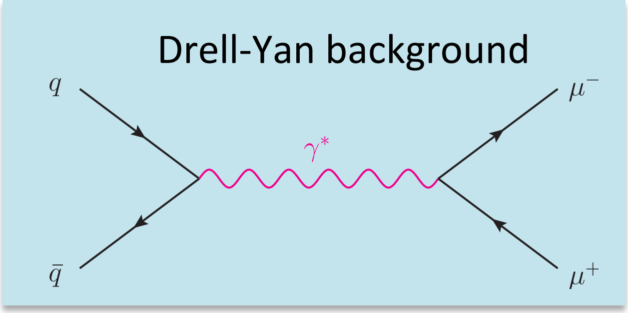
There is a worldwide race in the search for dark photons and dark Higgs particles. If dark photons (dark Higgs) were observed, they would revolutionize our understanding of the fundamental structures and interactions of our universe. There is a unique opportunity today at Fermilab to search directly for dark photon and dark Higgs production in a highly motivated parameter space in high-energy proton-nucleus collisions using the existing SeaQuest (E906/E1039/E1027) dimuom spectrometer. This search can be accomplished with parasitic data taking with the upcoming E1039 experiment. The resulting data would provide the world's best sensitivity to dark photon (dark Higgs) masses between 0.2 – 10 GeV/c^2 for the next decade. Only a relatively minor upgrade of the existing SeaQuest dimuon spectrometer and trigger system is required to improve the acceptance and reduce the trigger rate to an acceptable level.

Integrated theory efforts

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





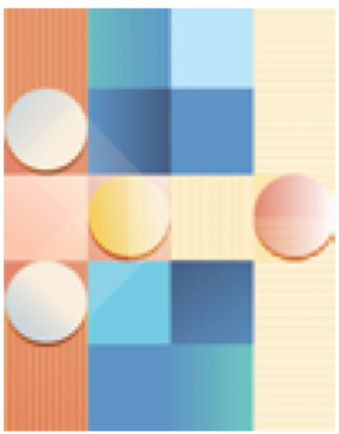
Background: detailed calculation for Drell-Yan cross section

- 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

2014 US P-5 Report

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

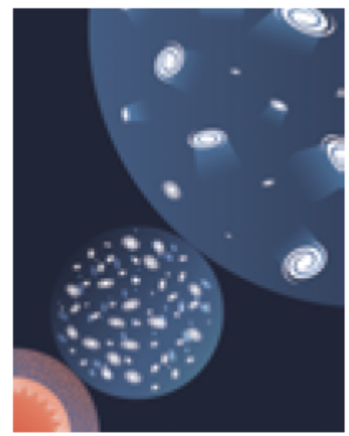
- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles



Higgs boson

Neutrino mass

Dark matter



Cosmic acceleration

Explore the unknown

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.

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*
    - (scaler coupling, dark Higgs)
- On-going and/or proposed experimental programs in all major accelerator facilities in the world!
  - World wide competitions!

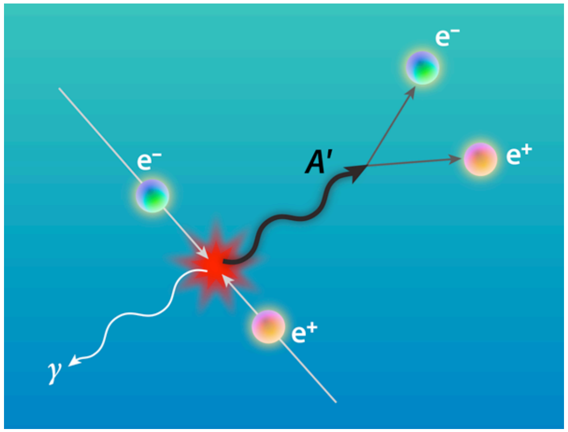
Ongoing A' Searches

- 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)

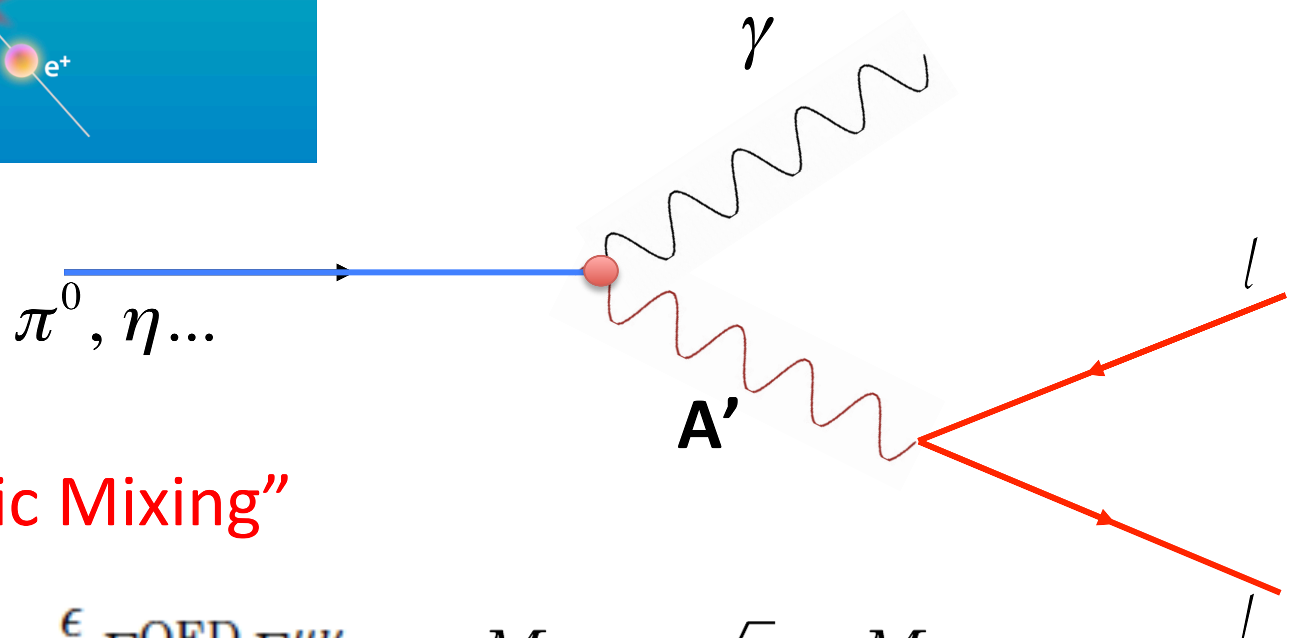
Courtesy: R. Milner(MIT) at the Fundamental Interactions Town Meeting, Chicago, Sept. 28-29, 2014

Current Accelerator Based Direct Search for Dark Photons

B-fatories, RHIC, LHC, Jlab, BES-III etc



B. Holdom, Phys. Lett. **B 166** (1986) 196
J. D. Bjorken et al, arXiv:0906.0580

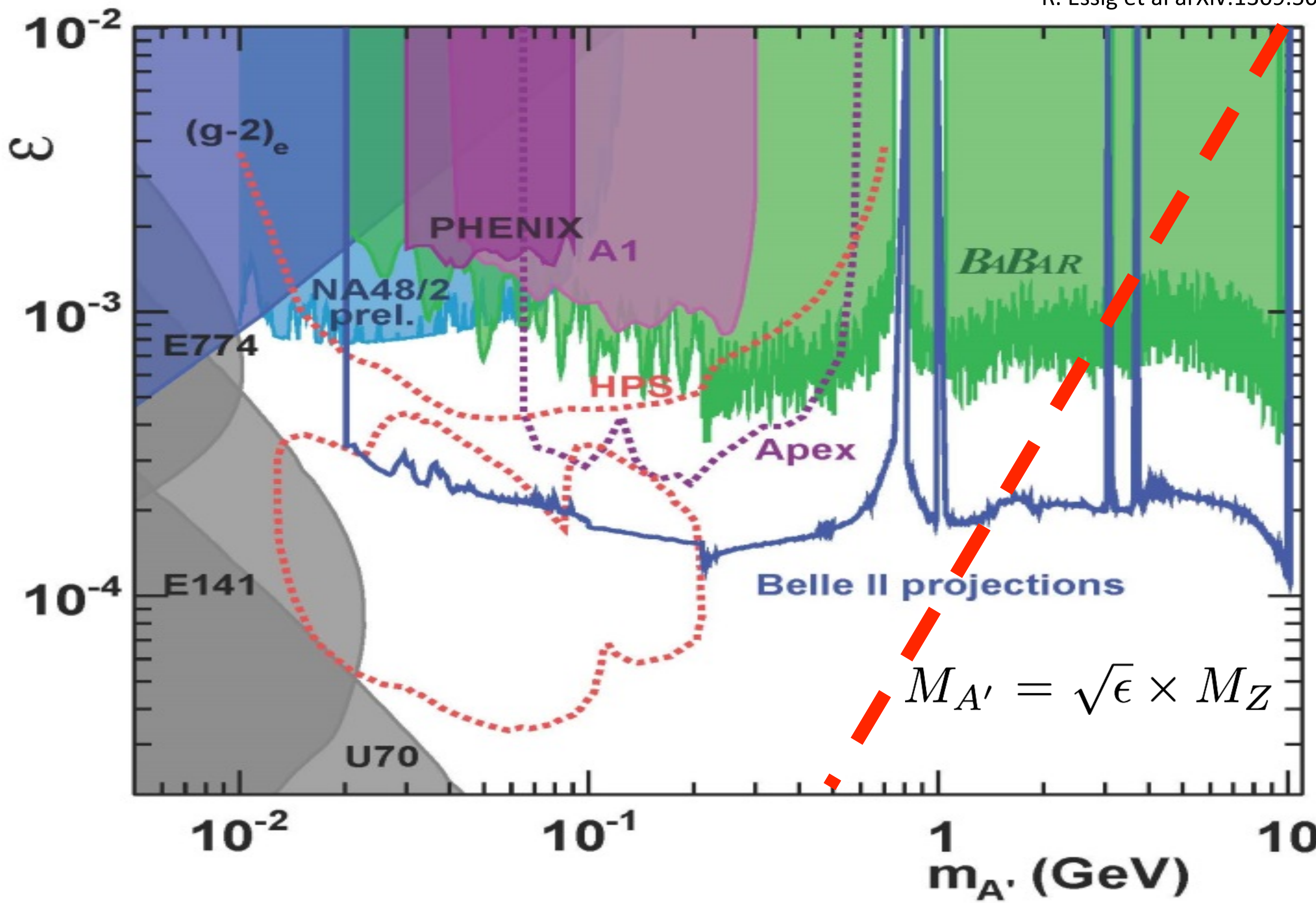


"Kinetic Mixing"

$$\mathcal{L}_{\rm mix} = -\frac{\epsilon}{2} F^{\rm QED}_{\mu\nu} F^{\mu\nu}_{\rm dark} \qquad M_{A'} \sim \sqrt{\epsilon} \times M_Z$$

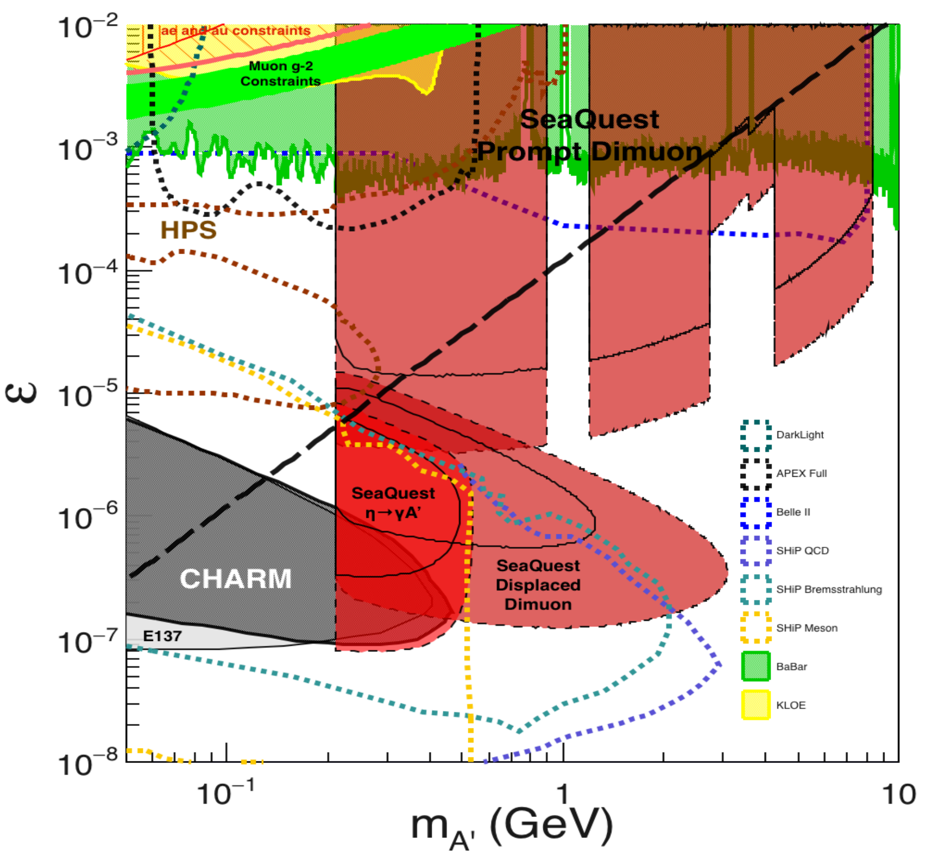
Current Limits on Dark Photon Search

R. Essig et al arXiv:1309.5084

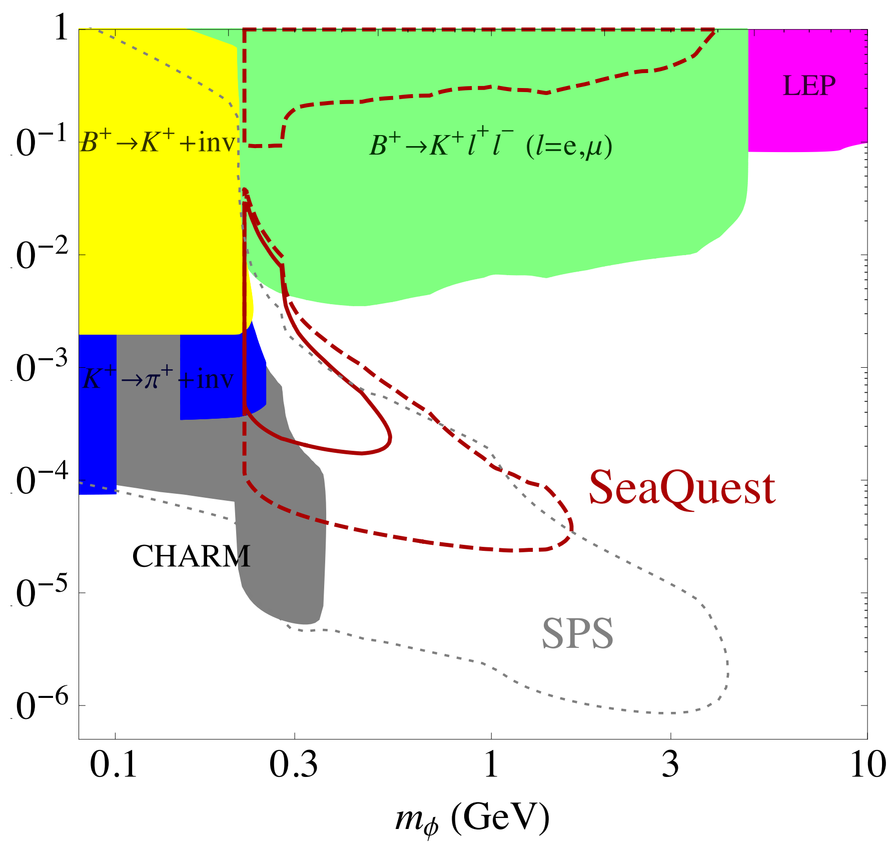


Comparison with SHiP Proposal

120 GeV@FNAL: 2017 -2019
1.4x10[18] POT, future runs possible

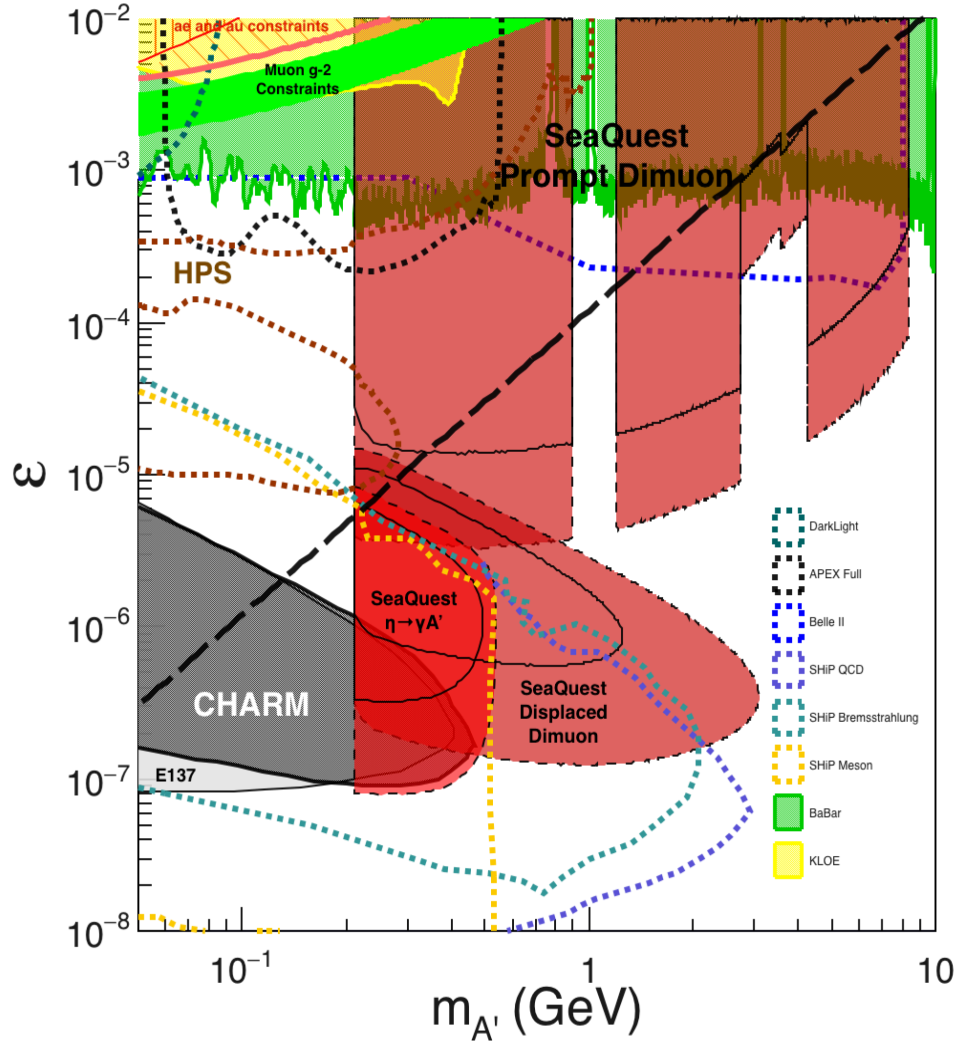


400 GeV@SPS: 2025 -2030
4x10[20] POT



How does the newly-proposed SHiP related to this proposal in terms of overlap in parameter space, timing, and scale?

- E906: a running experiment
  - Minor upgrade of the trigger and DAQ system, ~$100K
  - First parasitic runs w/ E1039, 2017-2019
  - Dedicated runs later, with upgraded detectors ($e^{+/-}$, $h^{+/-}$)
  - Lower beam energy (120GeV)
    - Pros:
      Access phase space of low mixing parameter as SM background is low
- SHiP: a proposal using SPS @CERN
  - Needs ~10 years to build the experiment, @$100M, (Search for Hidden Particles)
  - A new fixed target experiment for "dark sector"
  - Data taking, 2025 – 2030
  - Higher beam energy (400GeV)
    - Pros:
      Access to a large phase in the displaced decay mode
    - Cons:
      Not sensitive to phase space of low mixing parameters, due to much larger SM background than what E906 sees



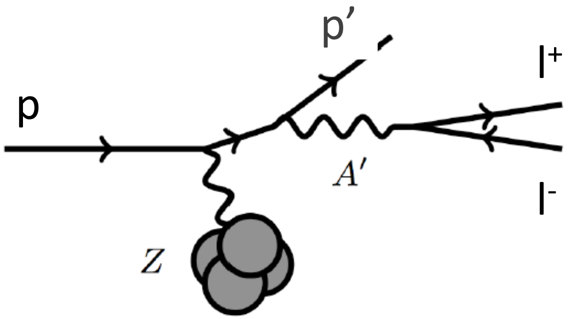
Probe-1: Proton Bremsstrahlung

R. Holt

Generalized Fermi-Williams-Weizsacker approximation

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

$\gamma + p \to A' + p'$



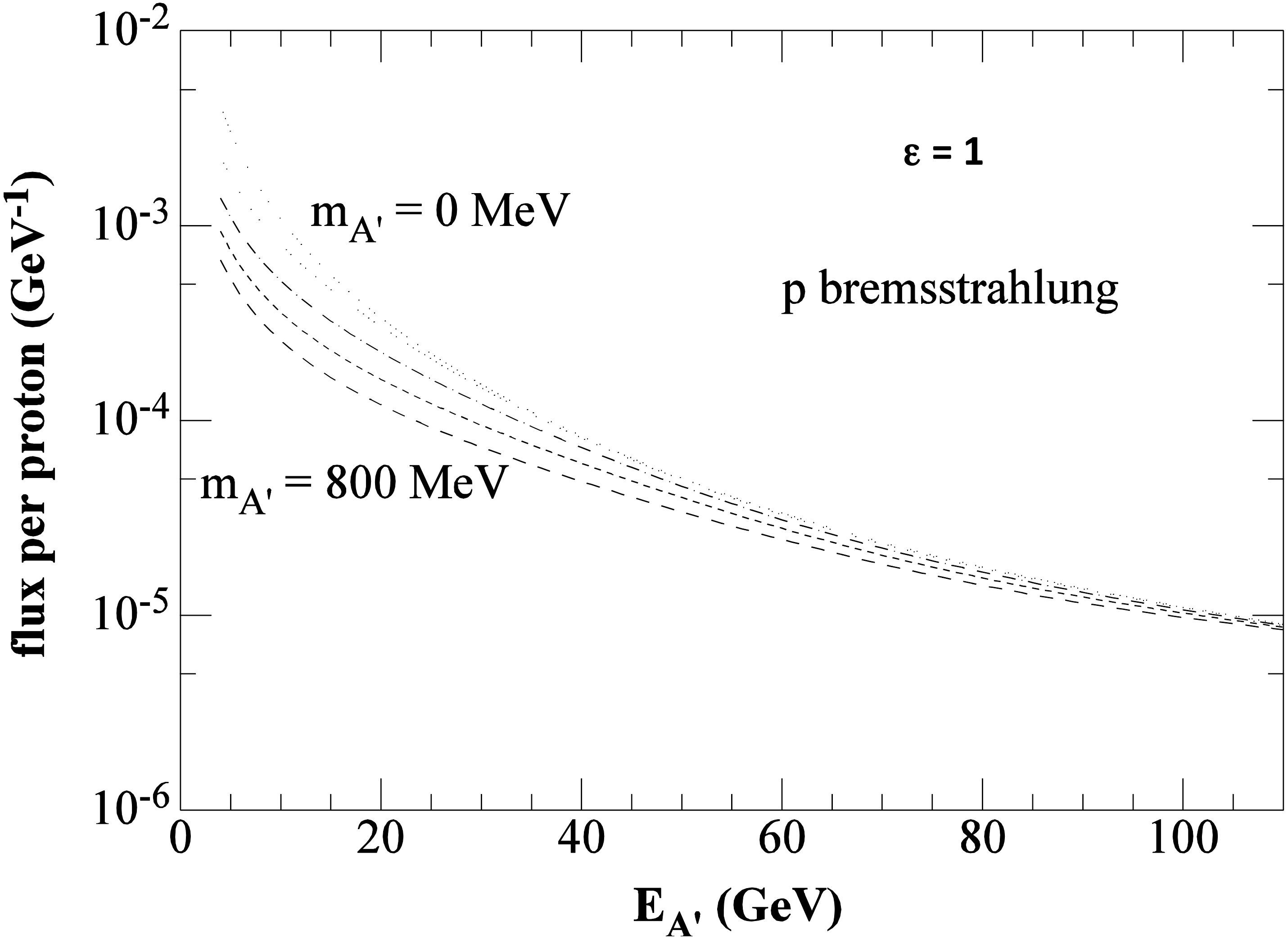
$$w_{ba}(z, p_\perp^2)dz\,dp_\perp^2 = \frac{\alpha'}{2\pi}\left\{\frac{1+(1-z)^2}{z} - 2z(1-z)\left[\frac{2M^2+m_{\gamma'}^2}{H} - z^2\frac{2M^4}{H^2}\right] + 2z(1-z)[1+(1-z)^2]\frac{M^2 m_{\gamma'}^2}{H^2} + 2z(1-z)^2\frac{m_{\gamma'}^4}{H^2}\right\}\frac{dz\,dp_\perp^2}{H}$$

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

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

Proton Bremsstralung Flux

R. Holt



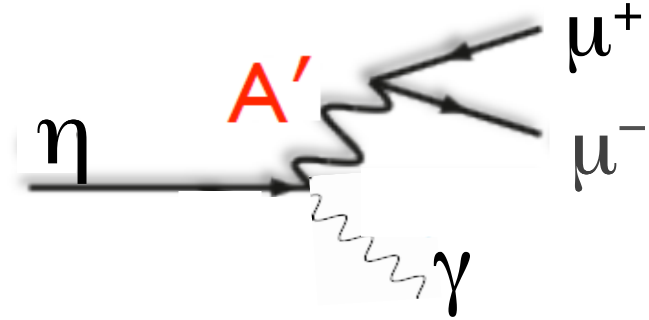
Probe-2: η Meson Production at 120 GeV

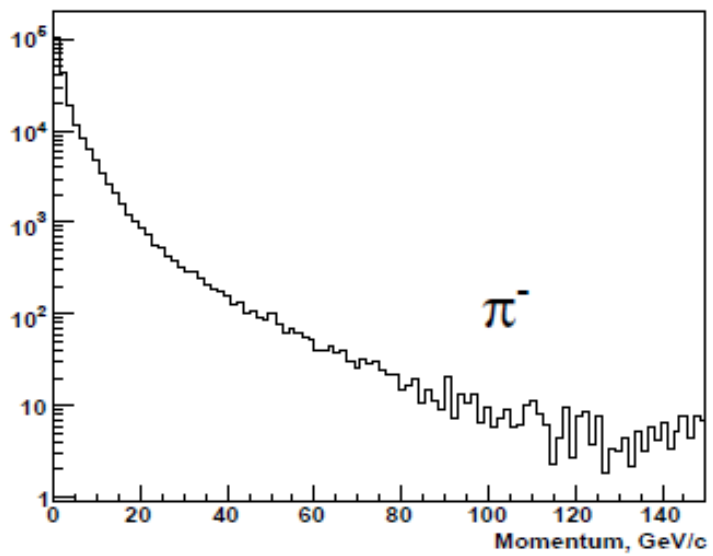
R. Holt

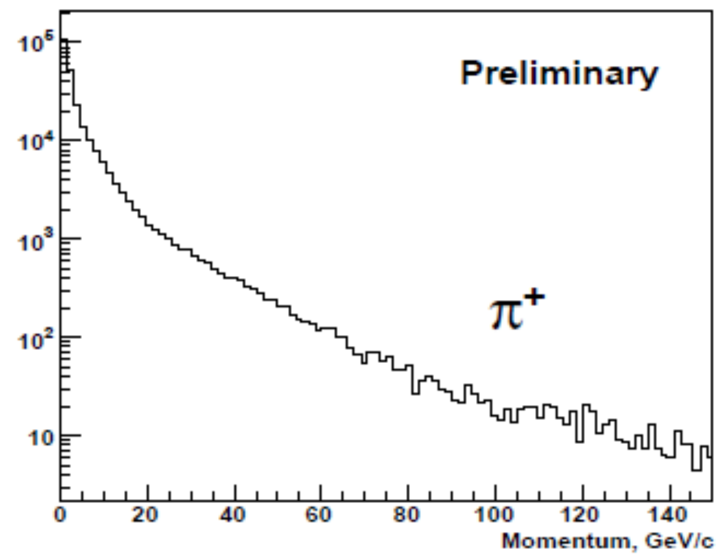
σ = 2.2 b for all charged particle production
Assume that π's represent 90% of charged particles,

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

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



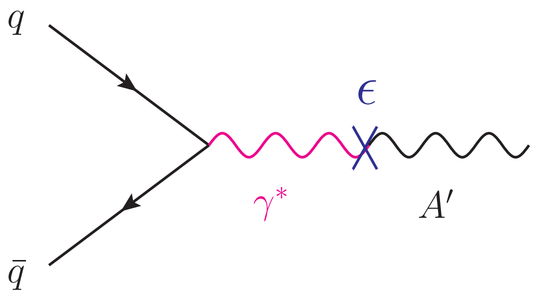


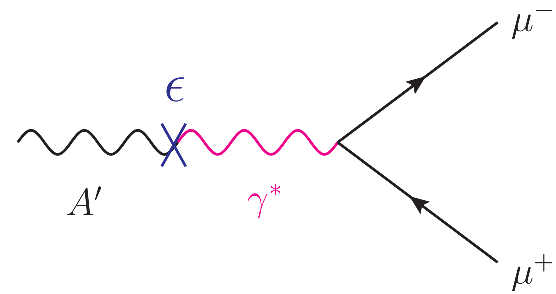


S. Mahajan, R. Raja, arXiv:1311.2258; FNAL E907, MIPP

Probe-3: Drell-Yan Like

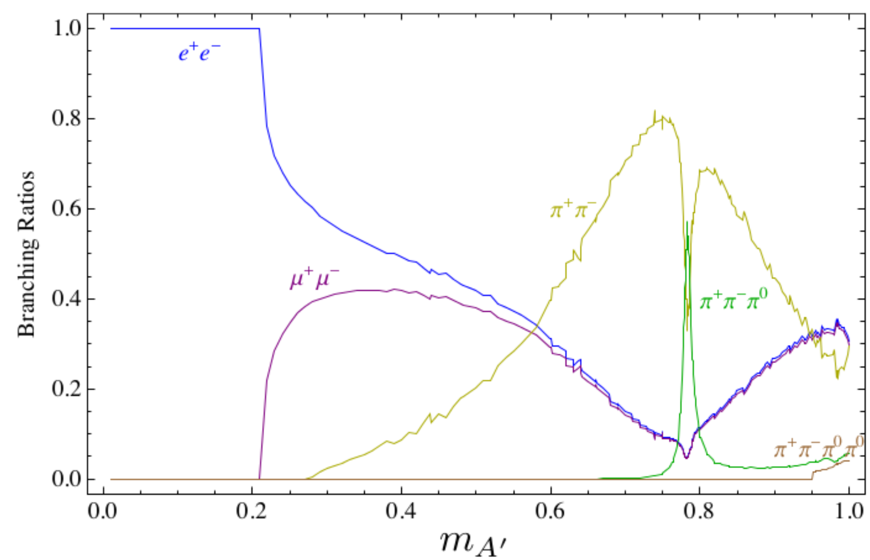
sensitive to both prompt and long-lived decay





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

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

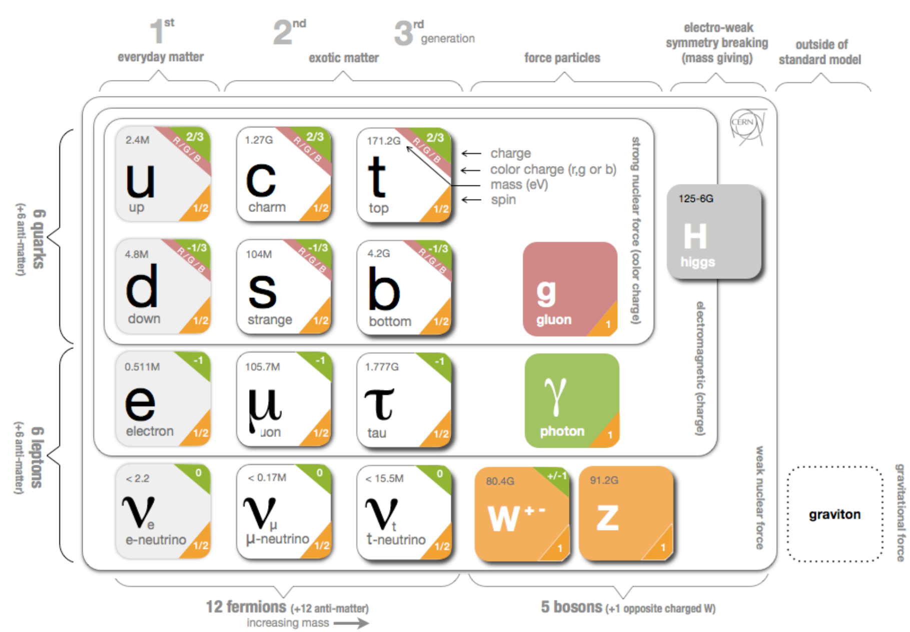


Higgs!

$$\mathcal{L} = -g_{Hff}\bar{f}fH + \frac{g_{HHH}}{6}H^3 + \frac{g_{HHHH}}{24}H^4 + \delta_V V_\mu V^\mu \left(g_{HVV}H + \frac{g_{HHVV}}{2}H^2\right)$$

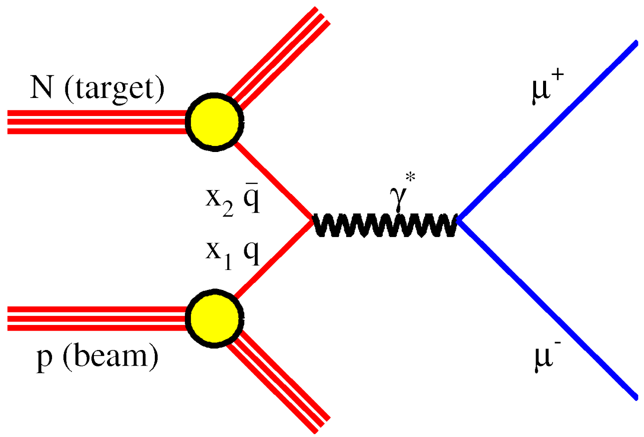
$$g_{Hf\bar{f}} = \frac{m_f}{v}, \quad g_{HVV} = \frac{2m_V^2}{v}, \quad g_{HHVV} = \frac{2m_V^2}{v^2}$$
$$g_{HHH} = \frac{3m_H^2}{v}, \quad g_{HHHH} = \frac{3m_H^2}{v^2}$$

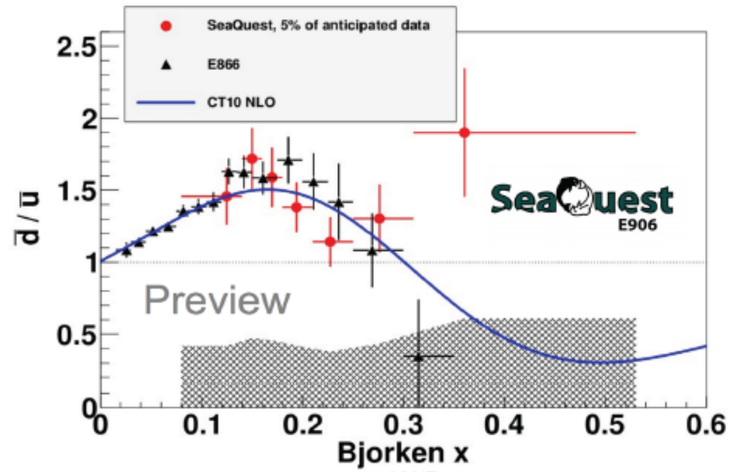
- The only scalar in the SM
- Couples strongly with mass
- High potential portal to dark sector

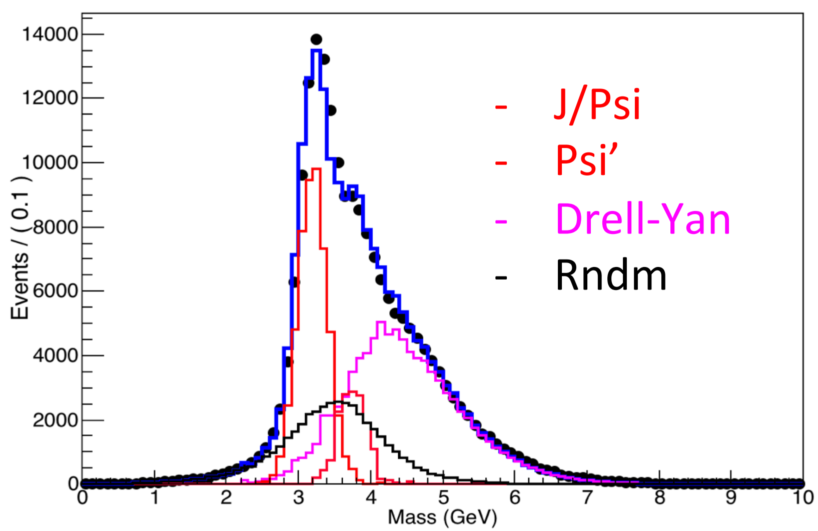


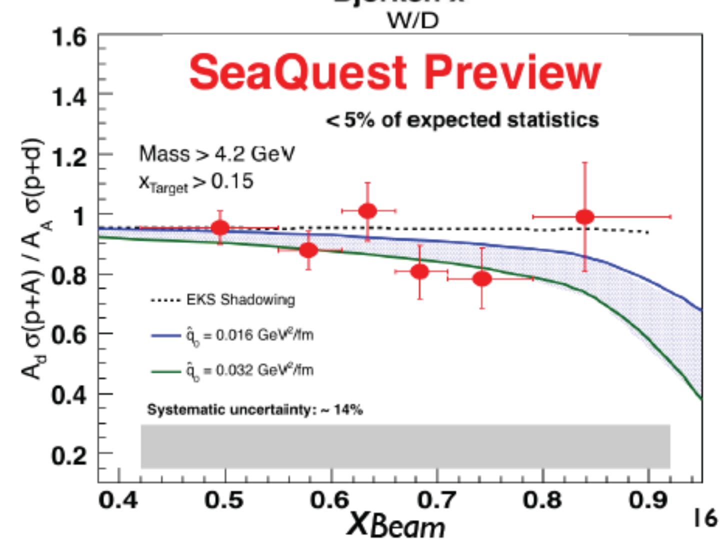
E906 Drell-Yan Measurements in p+A Collisions

Thin targets (10-20% λ_I): H, D, C, Fe, W

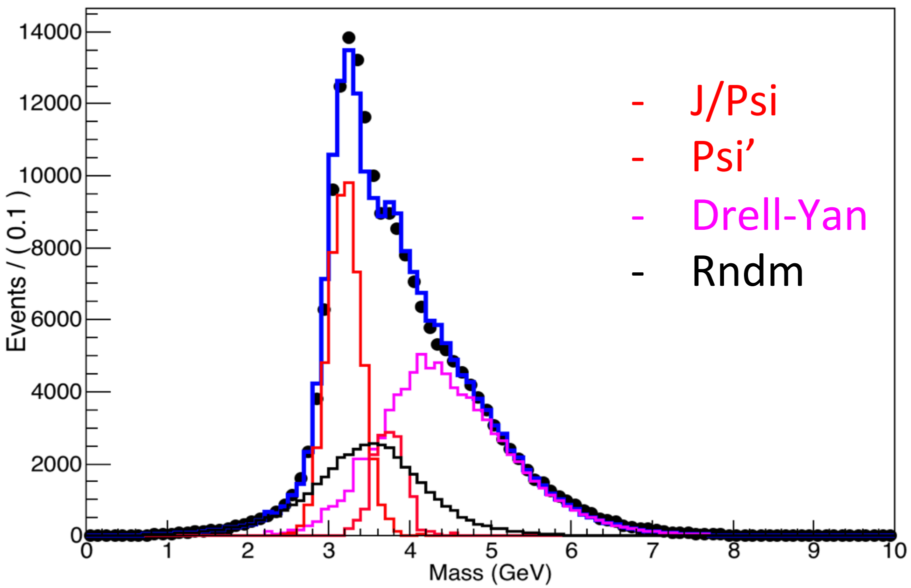


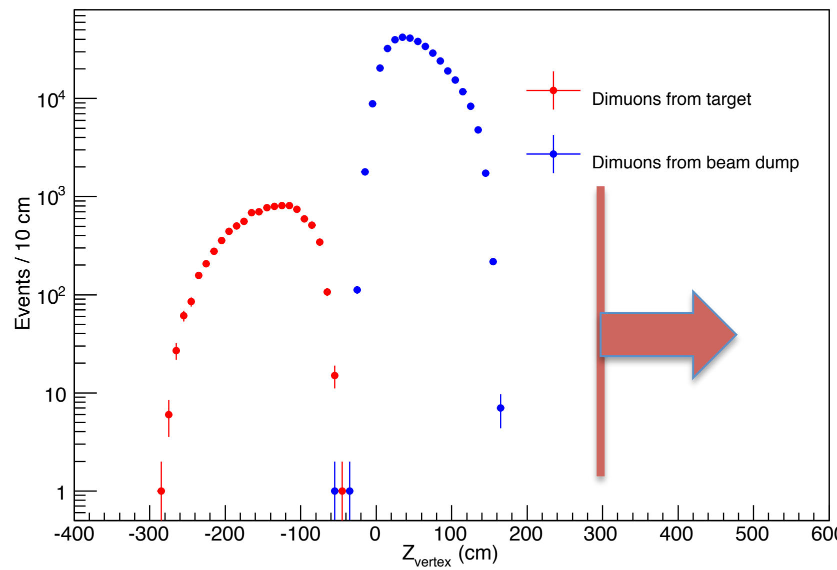






E906 Run 2 Data: Dimuon Invariant Mass and Reconstructed Z-Vertex





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

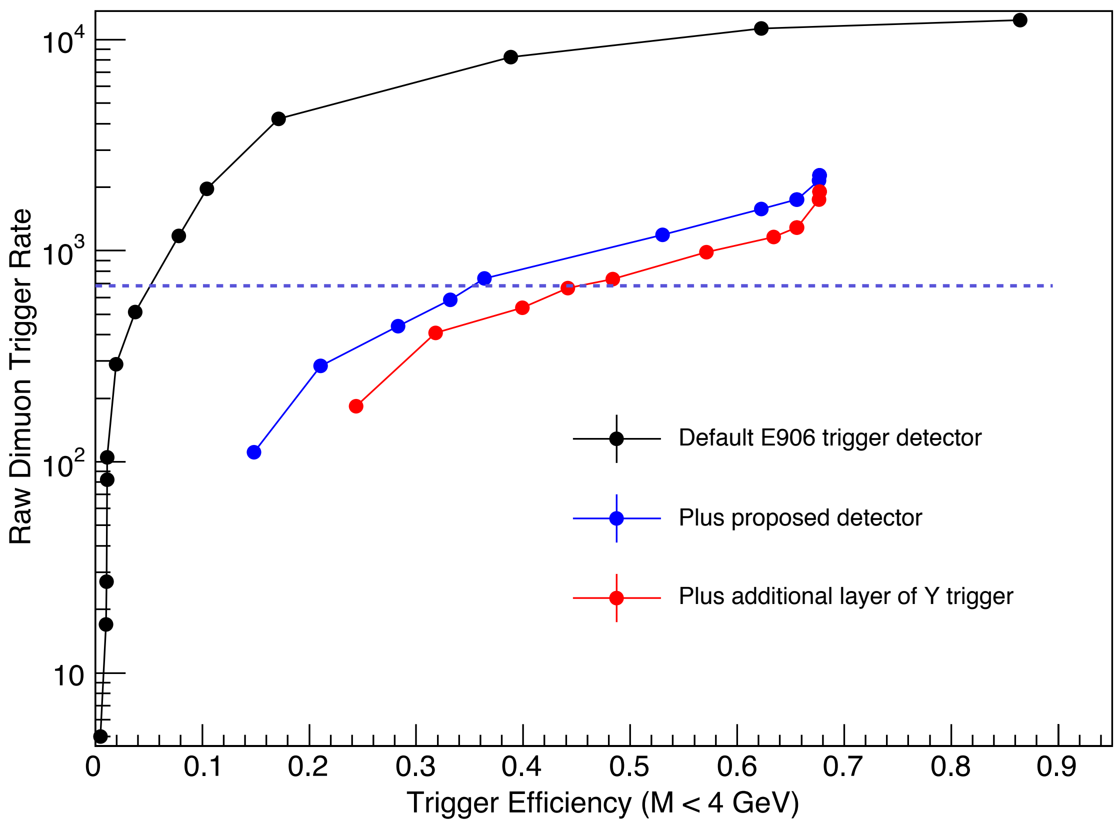
Low Mass Dimuon Trigger Rates Study

- Current E906 setup

- Proposed 2-layer trigger upgrade (10x improvement)

- Additional Y-trigger after ST-3 absorber, and also use E906 X-Plane trigger (additional ~2x improvement)

- Current E906 DAQ 1kHz, can be improved to 10kHz with small cost
- 200kHz possible (reprograming trigger firmware)



Work in Progress Sensitivity Study

2-year parasitic run

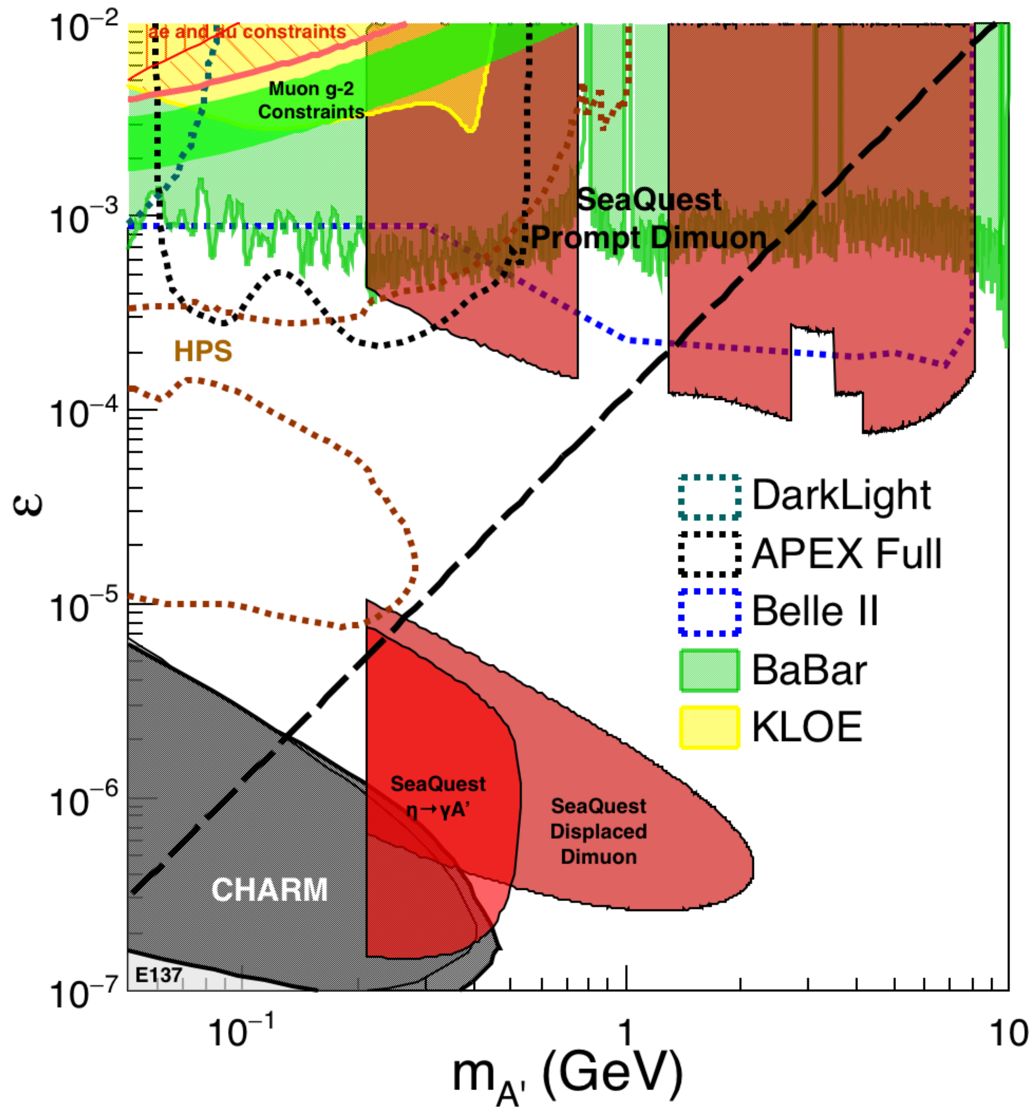
With 10kHz DAQ bandwidth,
the accepted low mass dimuons, M<3GeV, are statistically limited by DAQ throughput and detector acceptance (assuming only uses 10% DAQ).

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.

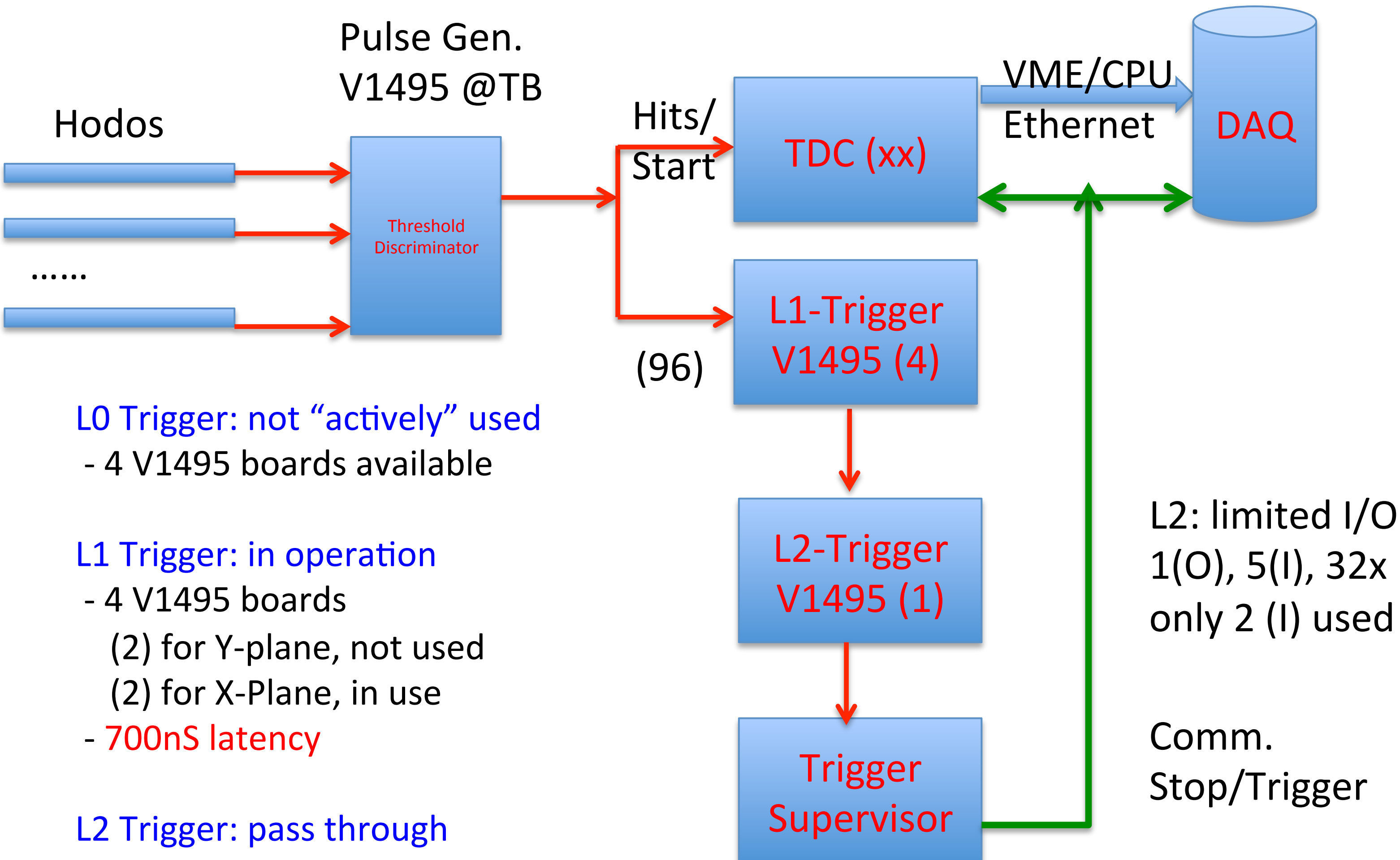
Full coverage of low mass (M<3GeV) can be achieved later through dedicated runs with much improved DAQ bandwidth after E1039.



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



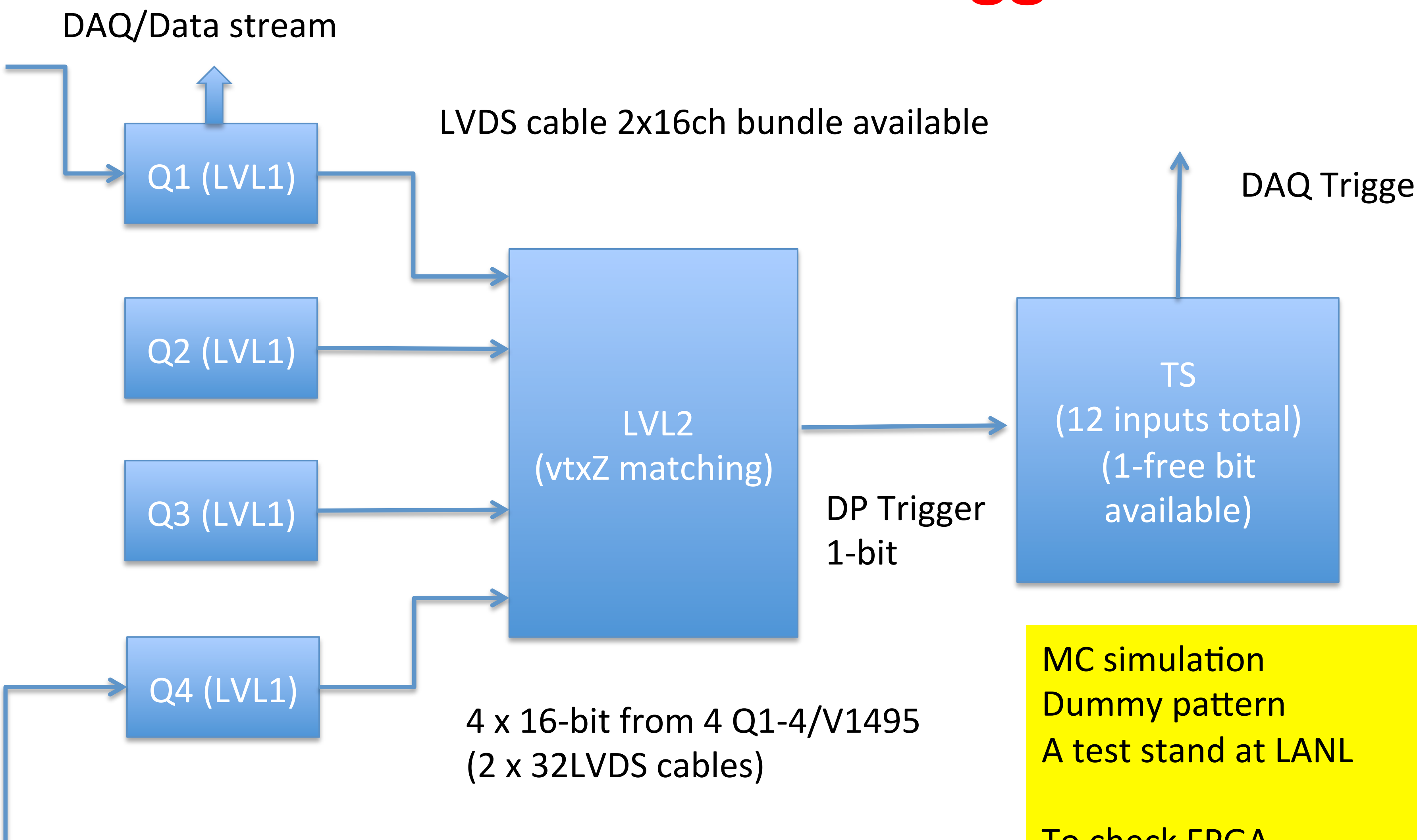
L0 Trigger: not "actively" used
- 4 V1495 boards available

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



MC simulation
Dummy pattern
A test stand at LANL

To check FPGA
- Logic
- Timing

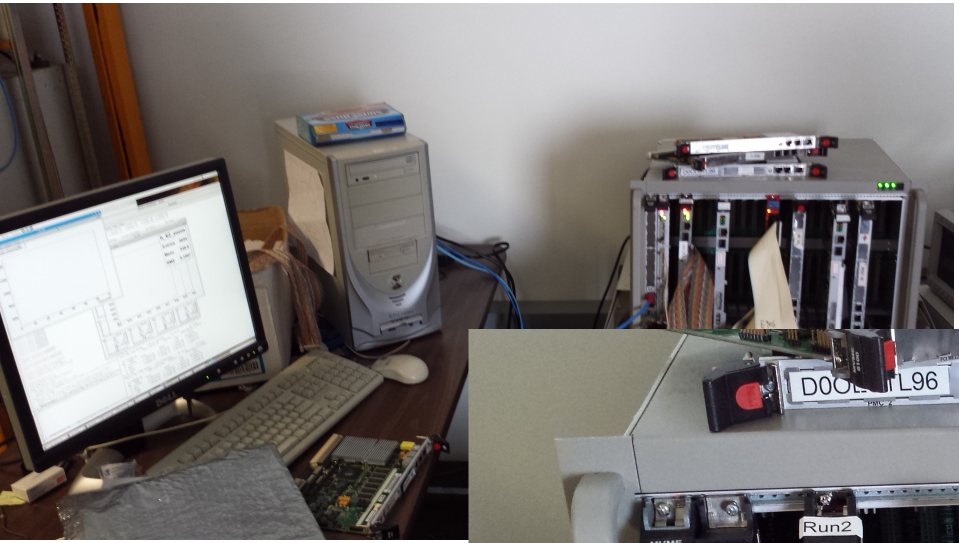
Q1: 40(ST1') + 40 (ST2') + 2x8(ST4-Y1/2) = 96, FANOUT ST4

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

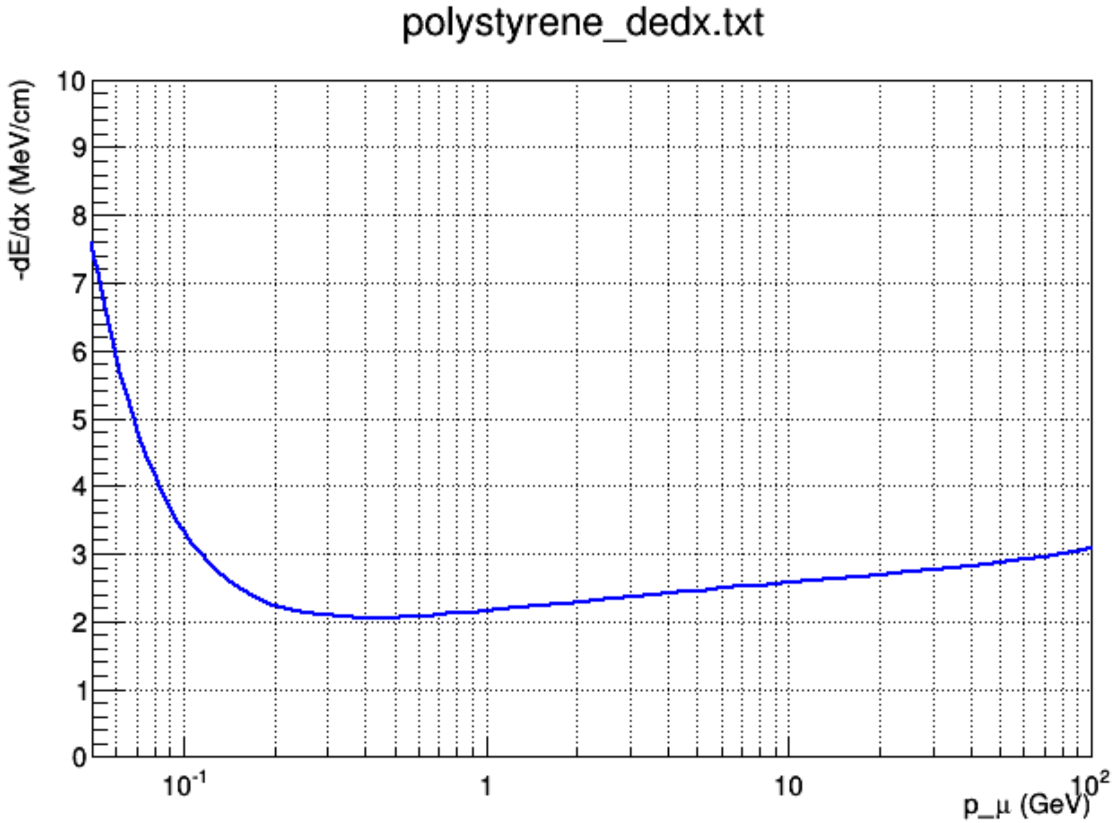
E906 DAQ Test Stand

- 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



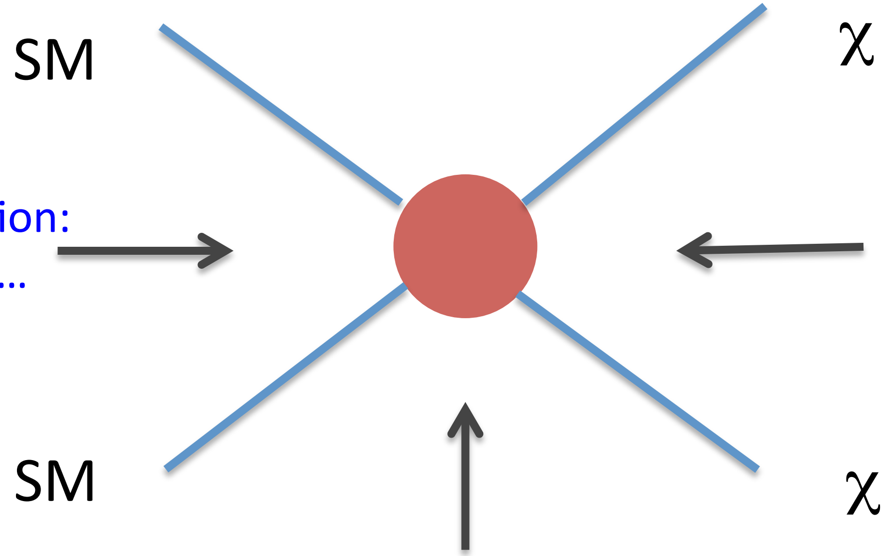
- Using polystyrene as example (same as FNAL scintillator factory)
- Muon dE/dx = 2.41 MeV/cm @ 4 GeV, and 2.69 MeV/cm @ 20 GeV
  - 11.5% difference
- For 4 GeV Kaon vs 20 GeV muon it's an even bigger difference, 26.5%

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%

Dark matter search strategies



Direct production:
LHC, Fermilab …

Indirect search:
PAMELA, Fermi,
HESS, ATIC,
AMS-02, WMAP

Direct search:
CDMS, DAMA, XENON, CREST, LUX
COUPP, PICO, MiniCLEAN, …