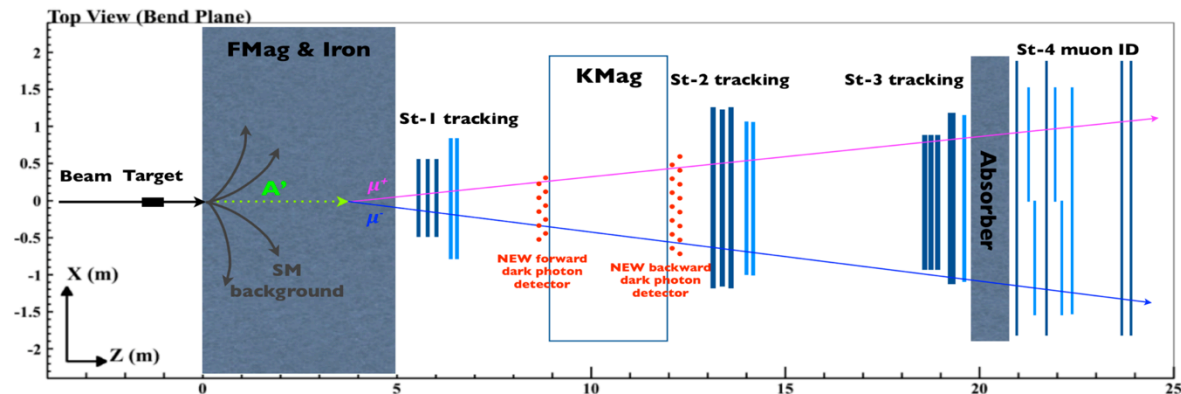
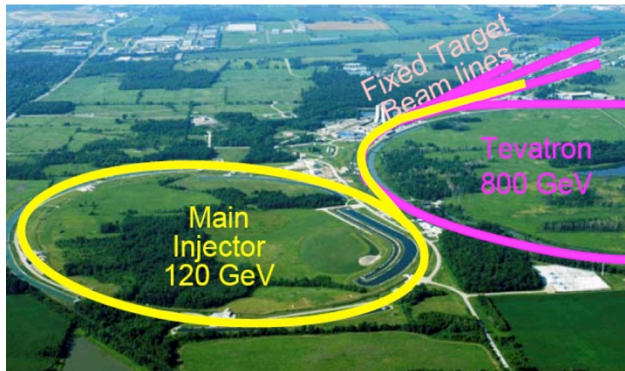


Direct search for dark photons and dark Higgs in p+A collisions at Fermilab E-1067/SeaQuest Experiment

Ming Liu

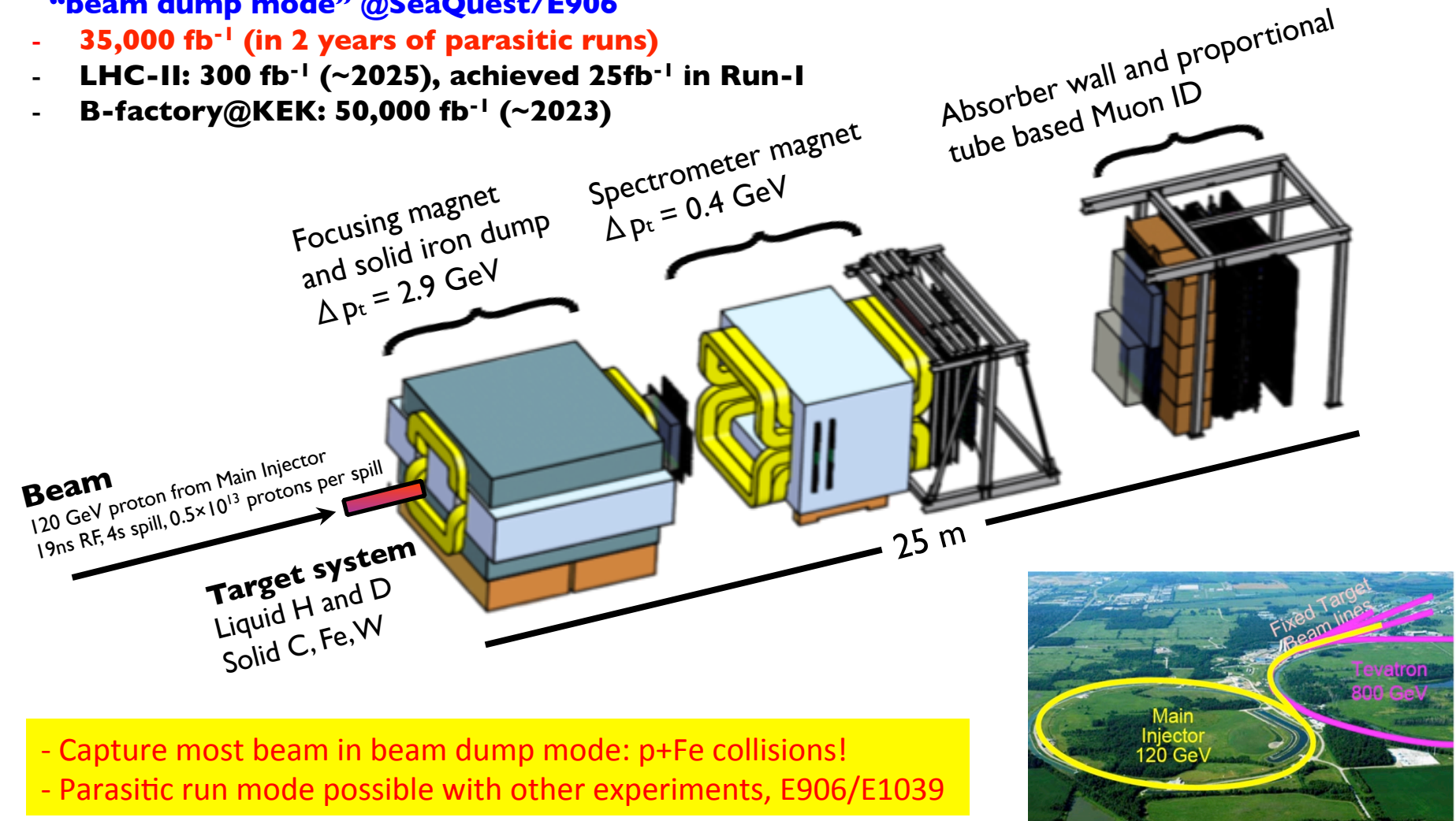
Los Alamos National Laboratory



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, E906/E1039

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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Argonne National Laboratory, Argonne, IL 60439

J. Huang
Brookhaven National Laboratory, Upton, NY 11973

Y. Zhang
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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
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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 Cruces, 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: (parasitic runs)

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

Phase-II: (upgrade)

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

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

July 15, 2015

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

NEW EXPERIMENT! E-1067

Ming Liu
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dear Ming,

Thank you very much for your presentation: "P-1067 LOI: Direct Search for Dark Photon and Dark Higgs" at the June meeting of the Fermilab Physics Advisory Committee (PAC). The Committee explicitly mentioned its appreciation of the carefully prepared presentations for this meeting.

Future initiatives were an important topic at the meeting. Excerpts on your LOI from the PAC report are attached. As you can see, the committee "... recognizes the exciting opportunity brought by P1067 to search directly for a dark photon and dark Higgs in high-energy proton-nucleus collisions using existing SeaQuest Spectrometer." The PAC noted that in the LOI the collaboration requests approval for inclusion of the new elements in the detector needed to make a dark sector trigger, and approval of parasitic data collection during E-1039 running. The committee "... believes that P-1067 offers exciting physics prospects and recommends the Laboratory to grant these modest requests." The PAC also suggests "A proposal for a dedicated experiment, or a parasitic experiment with electron and hadron calorimeters, should be based on the results obtained with this first phase."

I accept the PAC recommendations, and wish you good luck in implementing a dark sector trigger.

Sincerely,



Nigel S. Lockyer
Director of Fermilab

cc: D. Bortoletto
G. Bock
P. Reimer
J. Shank

S. Geer
P. McBride
D. Geesaman

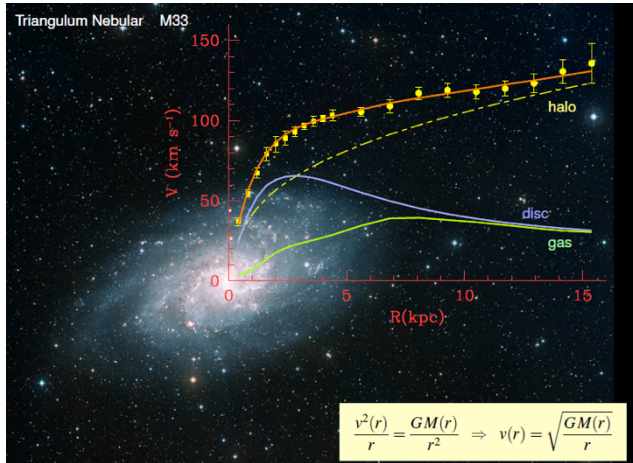
J. Lykken
T. Meyer
A. Stone

Outline

- Motivation
 - Dark Matter, dark photons and dark Higgs
- Current E-906/SeaQuest at Fermilab
 - Nucleon/Nuclear structures physic with Drell-Yan
- E-1067: a new search of dark photons/Higgs
 - Phase-I 2017-2019
 - Phase-II with upgrade 2020+

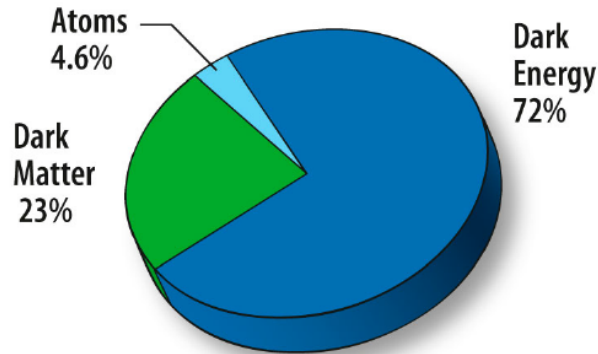
Dark Matter?

Galaxies' rotation curve

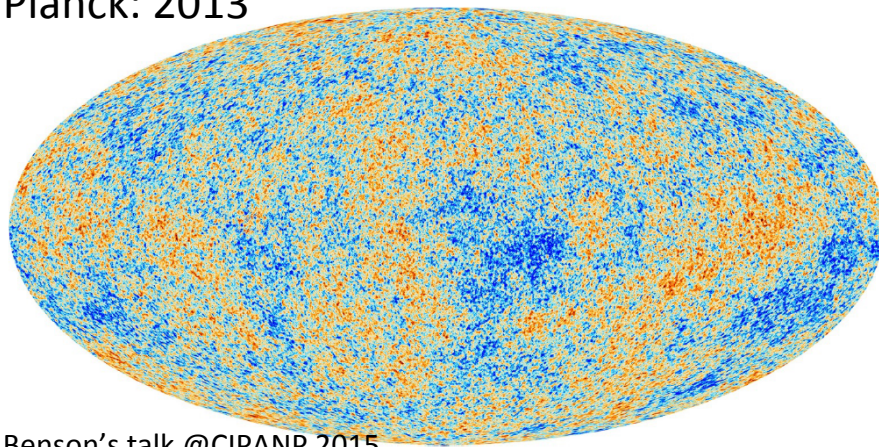


F. Zwicky, ApJ 86 (1937) 217, V. Rubin et al, ApJ 238 (1980) 471

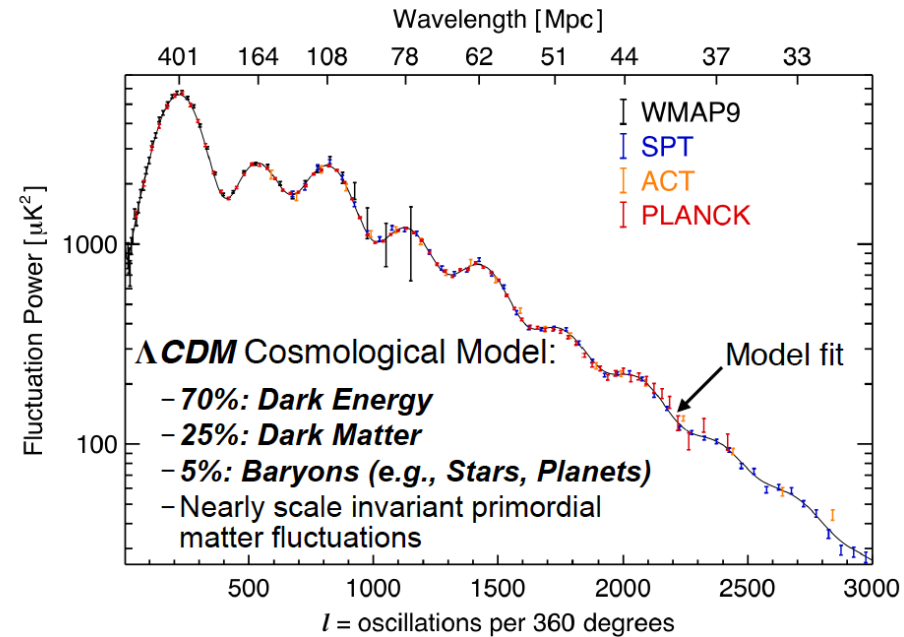
Gravitational lensing (Hubble 2007)



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



Benson's talk @CIPANP 2015



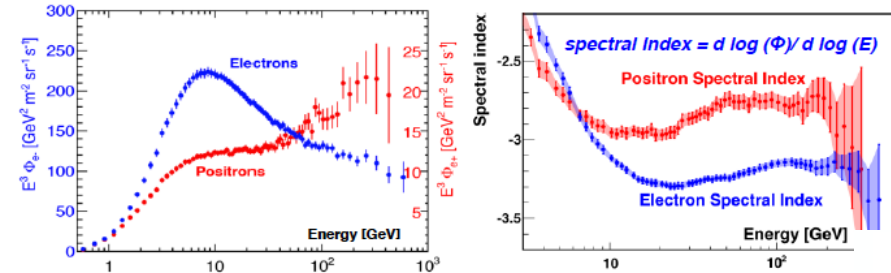
Highlights from AMS-02

Dark Matter Annihilation ?

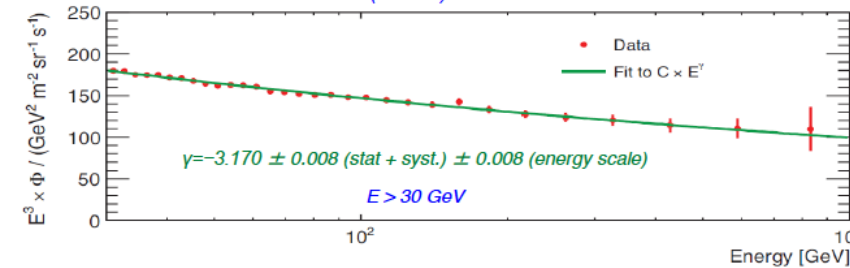
Plots from Sam Ting 4/2015

Cosmic-ray excess of e^- , e^+ , p , He , Li ...

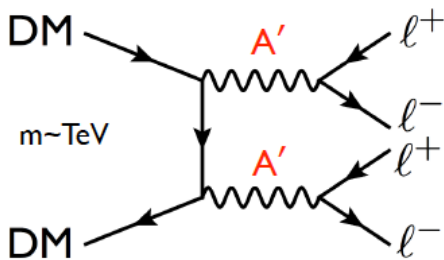
The Electron Flux and the Positron Flux



$$\Phi(e^+e^-) = C E^\gamma$$

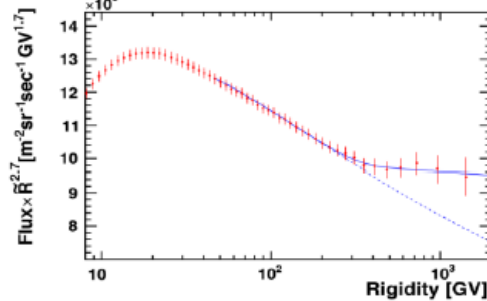


Arkani-Hamed et al.; Cholis et al.; Pospelov & Ritz

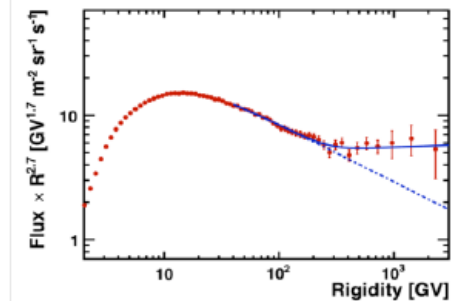


(decays involving A' also possible)

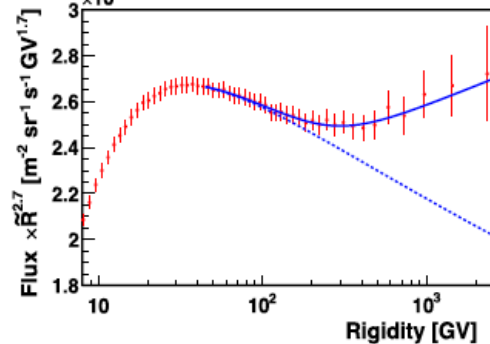
AMS proton flux



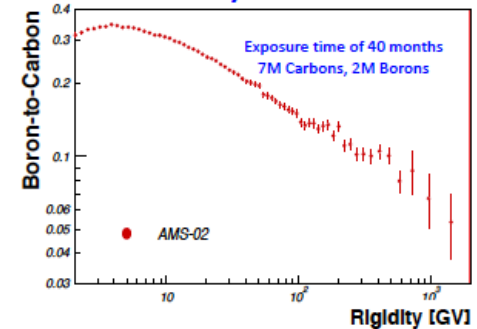
Lithium flux



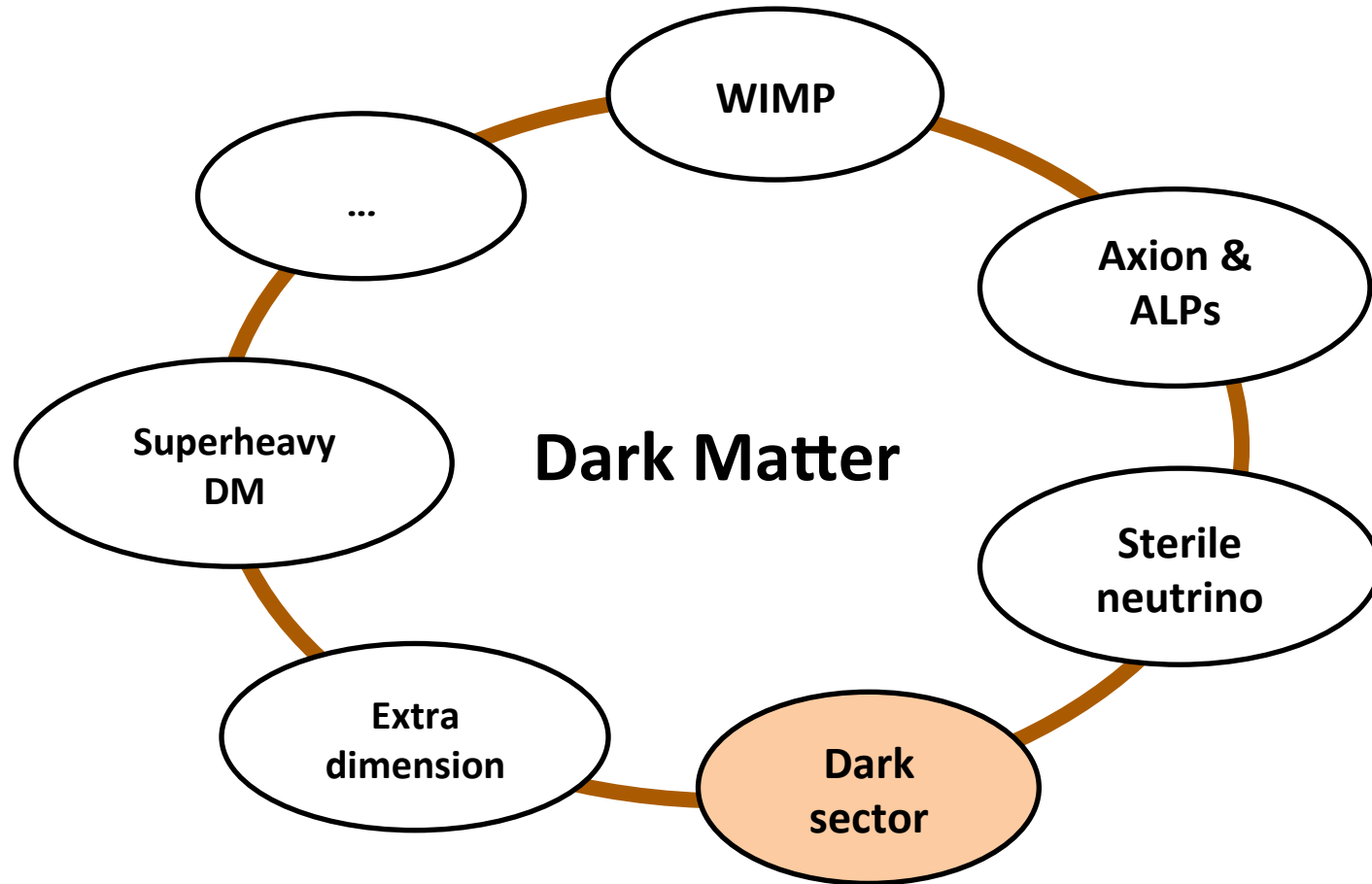
AMS Helium Flux



B/C Ratio



What is Dark Matter?



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

Direct Search for WIMP

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

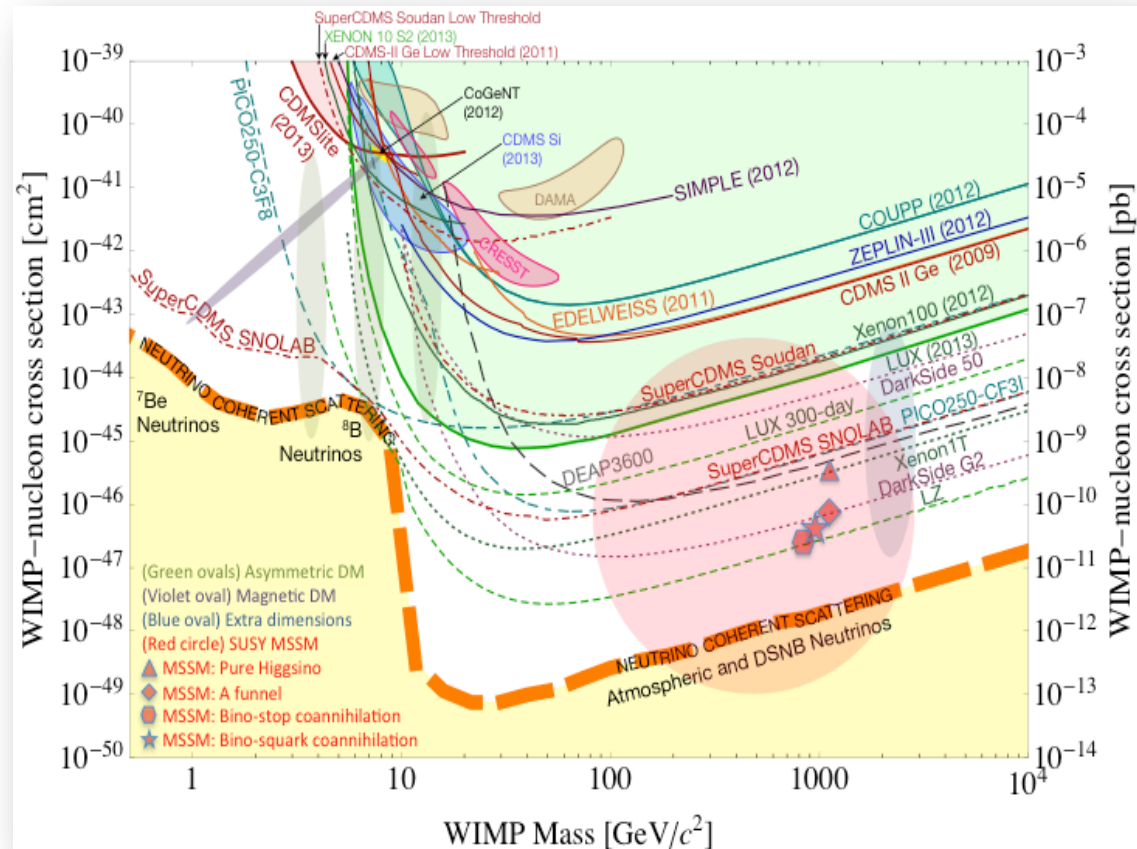
- WIMP being excluded?
- Recent anomalies observed by satellite and terrestrial experiments have motivated dark matter models introducing a new **"dark sector"**
- There are "portals" between the dark sector and the SM.
 - "vector coupling": dark photon
 - "scalar coupling": dark Higgs
 - ...

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

Mass: $O(\text{MeV} \sim \text{GeV})$

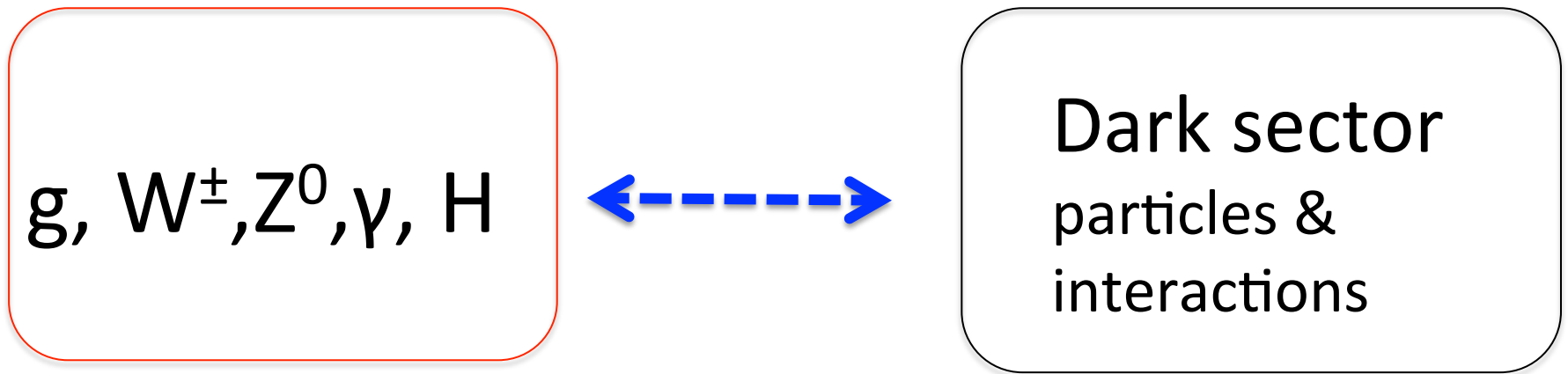
- In particular, high-intensity colliders (B-factories) and fixed target experiments (Fermilab, JLab, LHC) offer an ideal environment to probe these new ideas.

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



Portals to a Dark Sectors?

- SM symmetry limits the allowed couplings
 - scalar, vector, tensor interactions



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

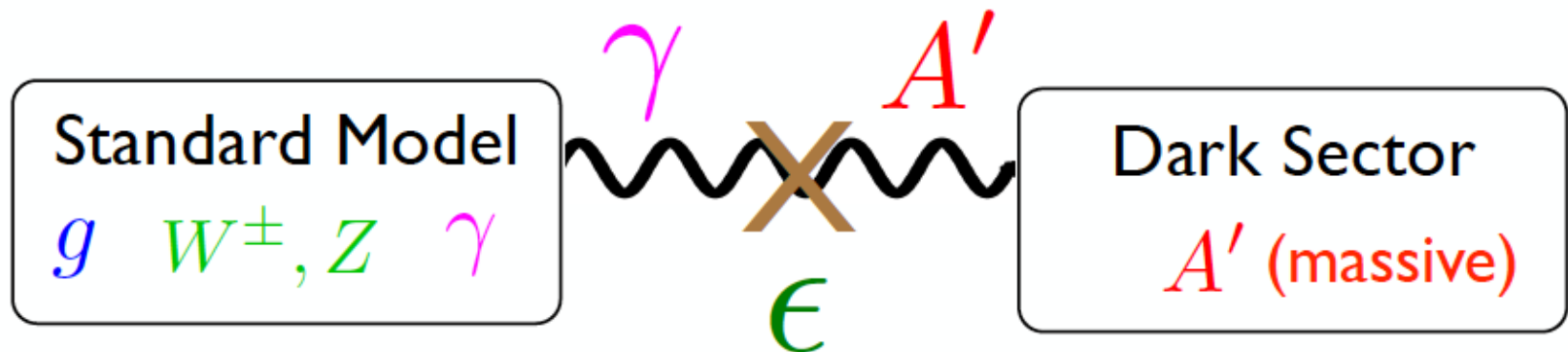
Vector Portal and Dark Photon

A simplest model of dark sector

- Kinetic mixing, an extra $U(1)_X$
- Not suppressed by mass scale

Holdom
Galison, Manohar

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

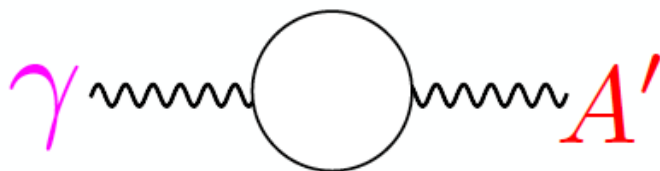


Expectations from GUT

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

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

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



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

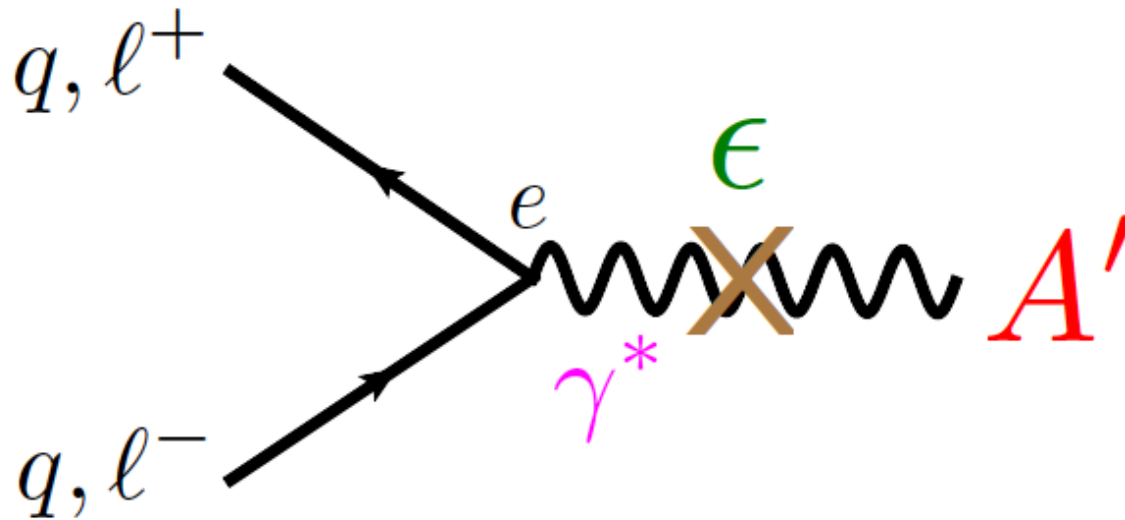
$$\sim 10^{-3} - 10^{-1}$$



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

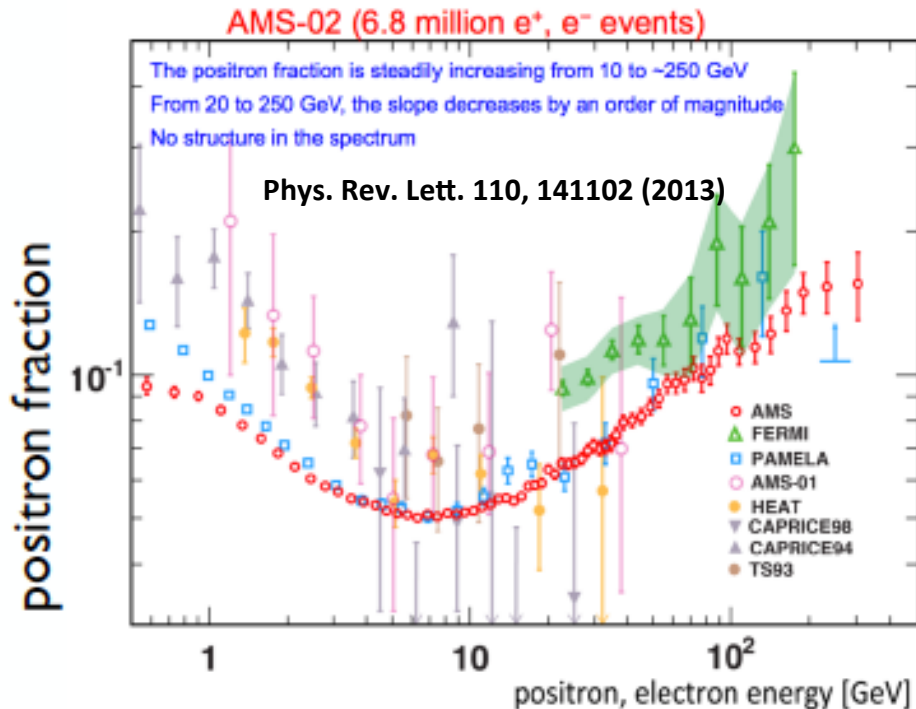
Coupling to SM particles via Photon/ Z^0

- Could explain some of anomalies observed recently
 - AMS-02, muon (g-2) etc.
- Could be well within experimental reach!
 - Production:
 - high intensity beam
 - Decay:
 - optimized S/B for weak signal



AMS-02 Anomalies and Dark Photons

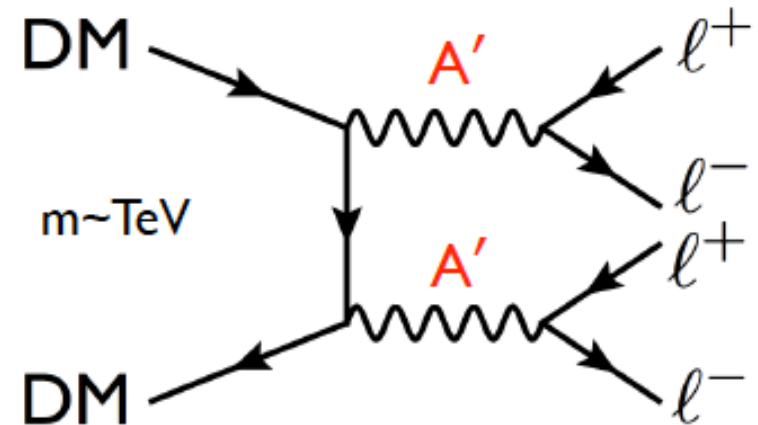
Sparked a renewed interest in this class of models...



cosmic-ray e^+ , e^- excesses?

PAMELA, Fermi, AMS2...

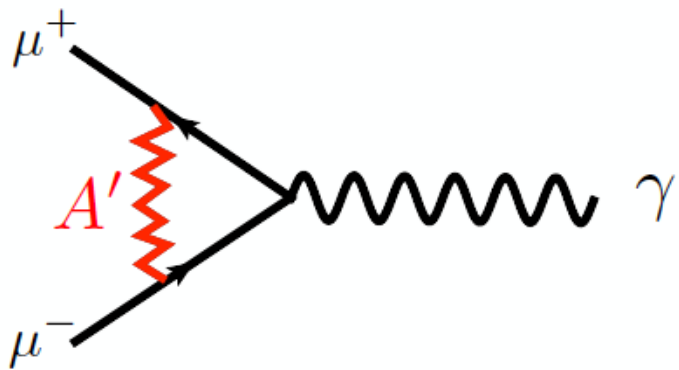
Arkani-Hamed et al.; Cholis et al.; Pospelov & Ritz



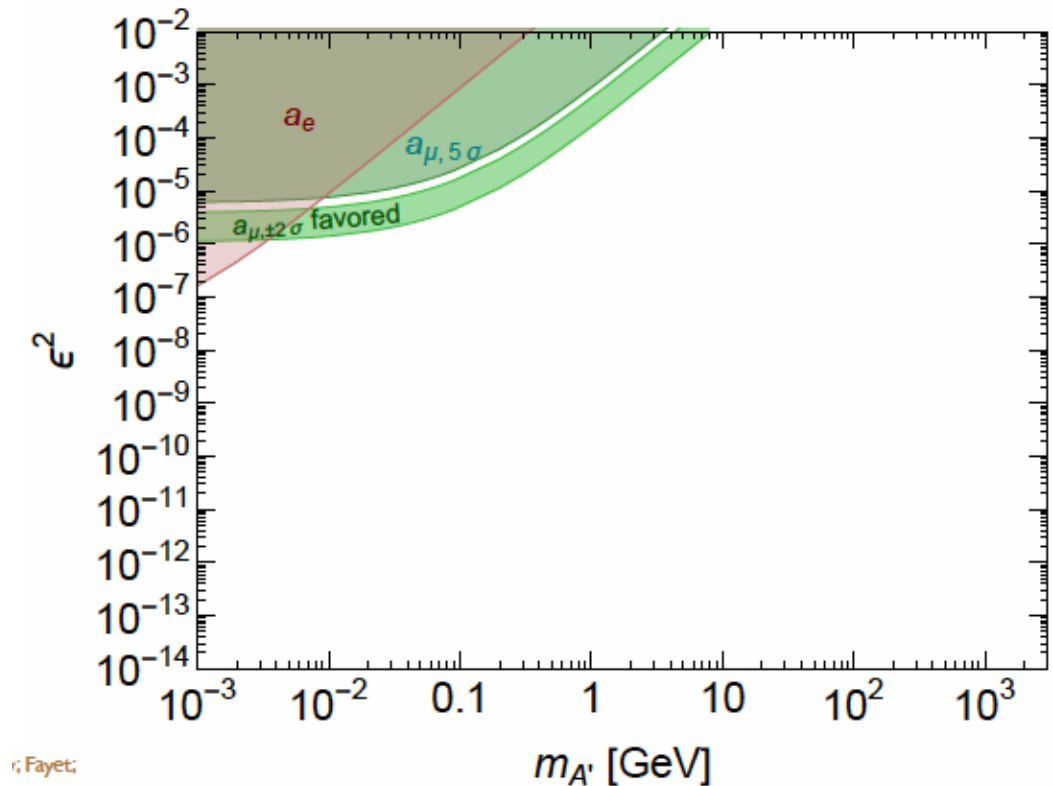
(decays involving A' also possible)

Muon (g-2) Anomaly

- 3.6σ deviation observed
- Possible contributions from dark photon



Boehm, Fayet
Pospelov



Very Active Field

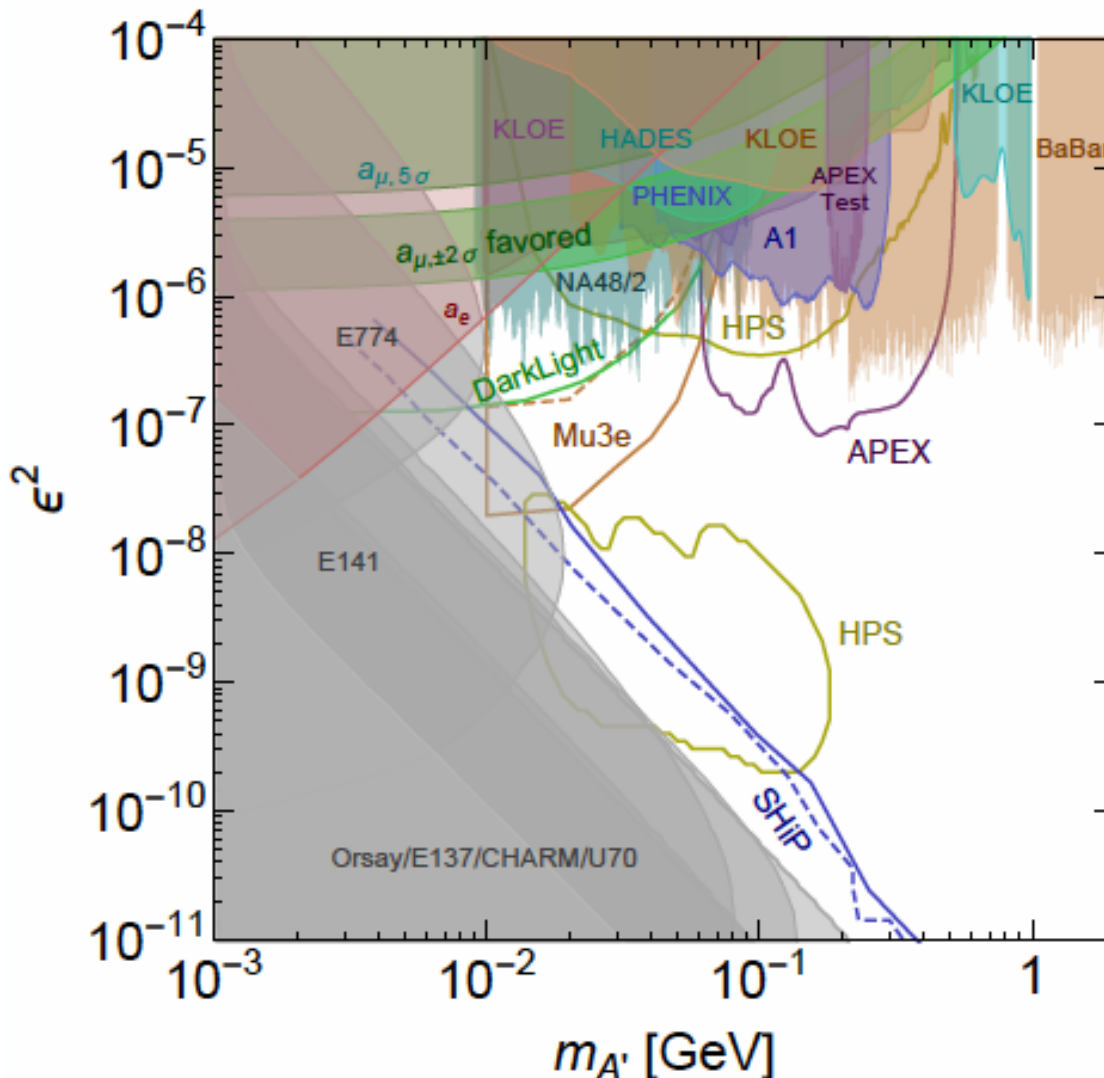
Ongoing A' Searches

- KLOE-2@DAΦNE ($\phi \rightarrow \phi A'$ followed by $A' \rightarrow e+e^-$)
- HADES@GSI ($p+p$, $p+^{93}\text{Nb}$, $p+^{40}\text{Ar}$, $^{84}\text{K}+^{35}\text{Cl}$ 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 at the Fundamental Interactions Town Meeting, Chicago, Sept. 28-29, 2014

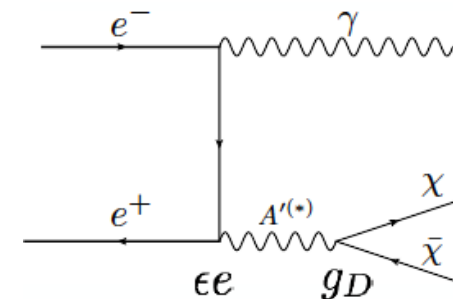
Dark Photon Current and Future Limits



- Many new results in recent years and more to come

Muon (g-2) region disfavored

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



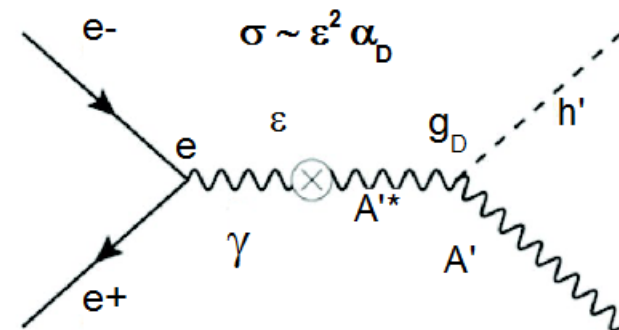
- New experimental proposals

Fermilab E-1067 beam dump experiment with hadron beam

Add a Dark Higgs ...

very rich phenomenology

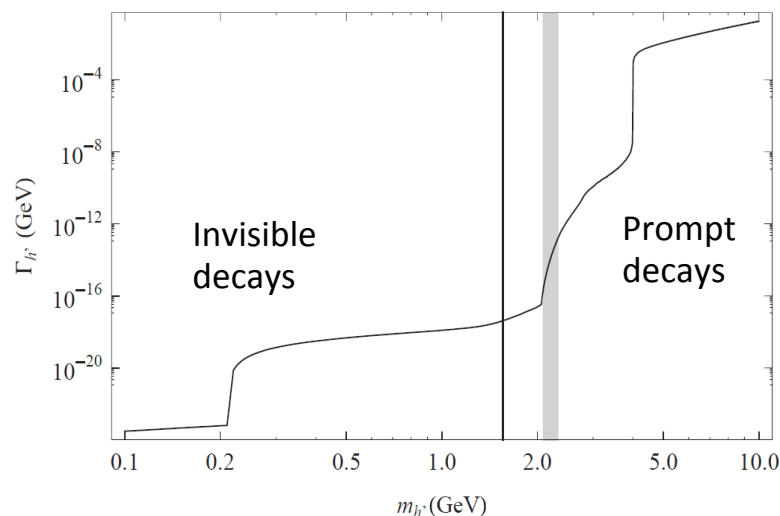
- Dark photon mass is generated via the Higgs mechanism
 - a dark Higgs boson (h')
- A minimal scenario
 - a single dark photon and a single dark Higgs boson.
- Theoretical prejudice for dark Higgs mass at the MeV-GeV scale.
 - Much rich structure could exist, QCD-like $SU(3)_X$



Dark Higgs decay model

$$m_h < m_{A'}$$

$$m_h > 2m_{A'}$$



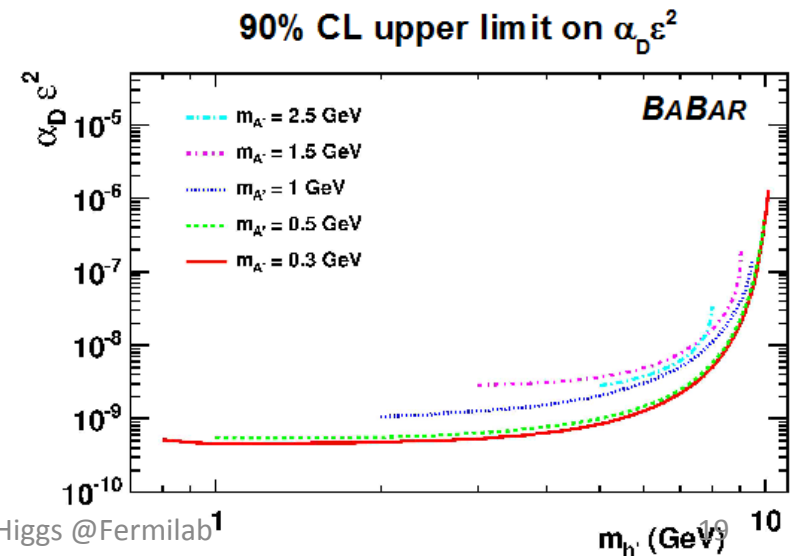
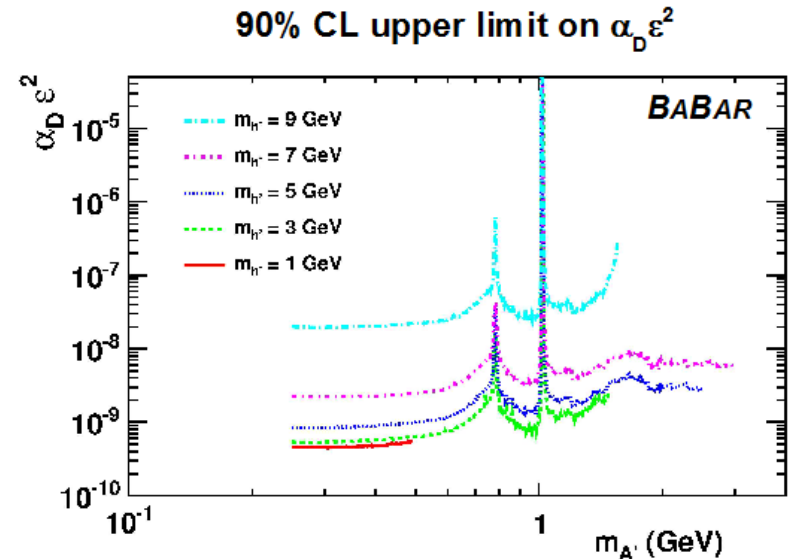
Dark Higgs Search at BaBar

PRL 108 (2012) 211801

- The Higgsstrahlung process

$$e^+e^- \rightarrow A'^* \rightarrow h' A'$$

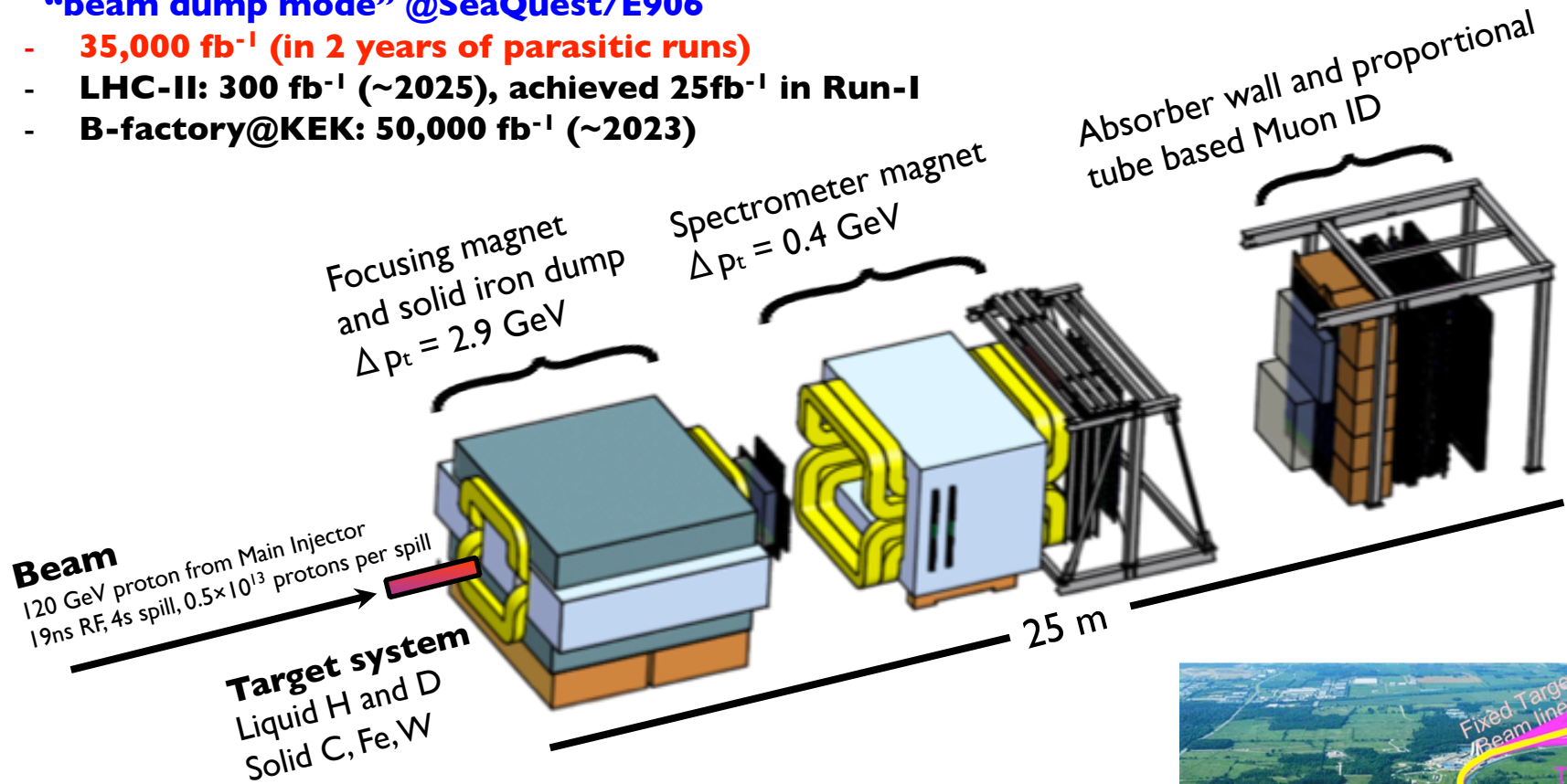
- Very interesting, as it is only suppressed by ϵ^2 and should have low background
- Also sensitive to the dark sector coupling constant $\alpha_D = g_D^2 / 4\pi$
- Search for prompt h' decays at BABAR:
 $e^+e^- \rightarrow A'^* \rightarrow h' A', h' \rightarrow A' A'$



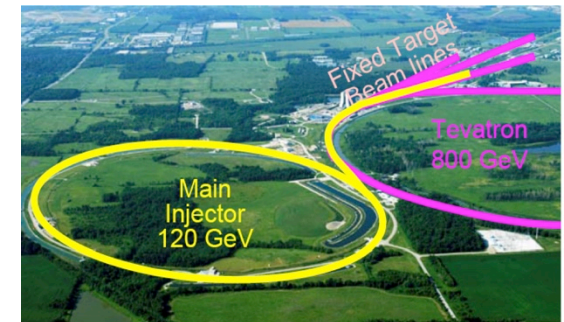
Intensity Frontier at Fermilab: 120 GeV Beam

**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)**

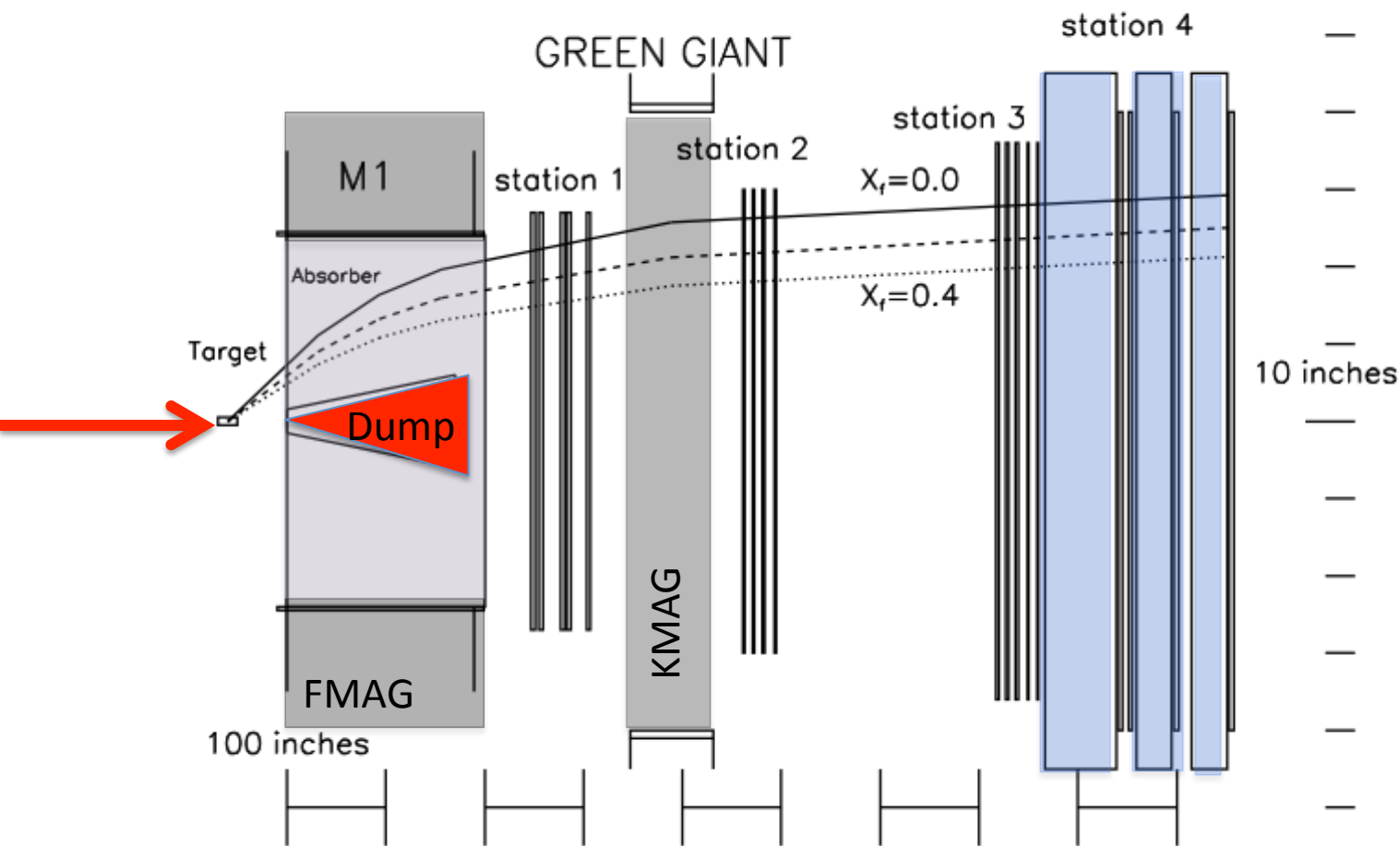


- Capture most beam in beam dump mode: p+Fe collisions!
- Parasitic run mode possible with other experiments, E906/E1039



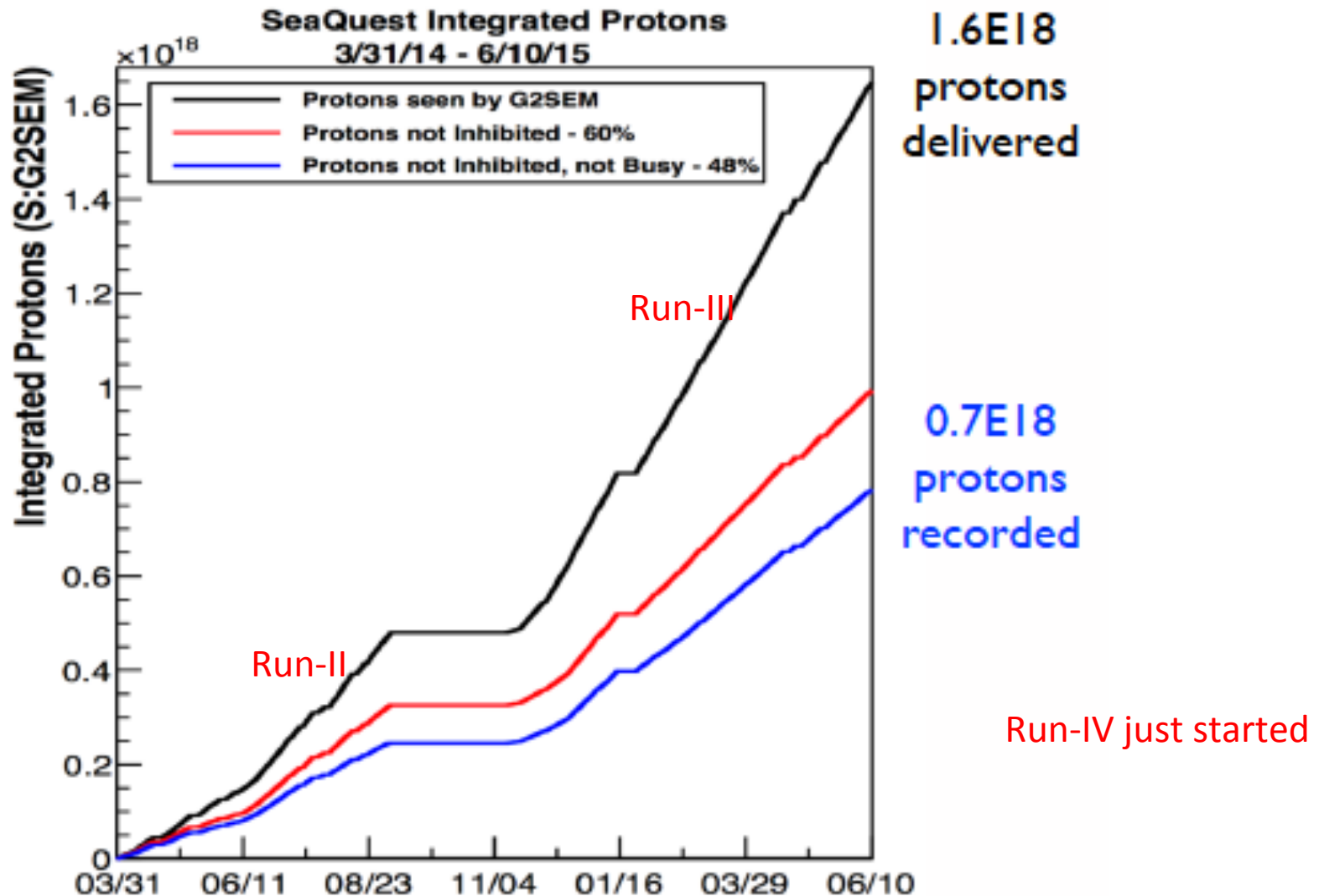
SeaQuest Detector Top View

Mass = 7.0 GeV $X_t = .0, .2, .4$



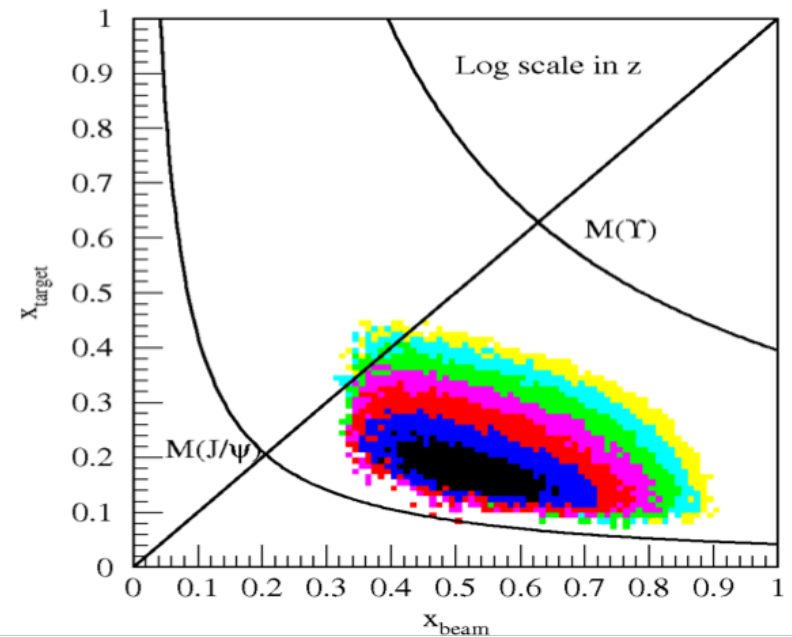
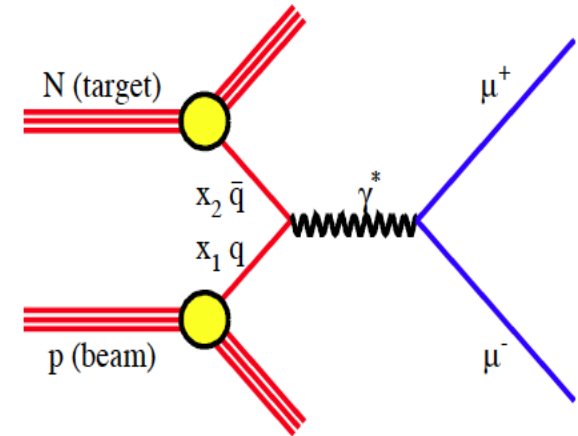
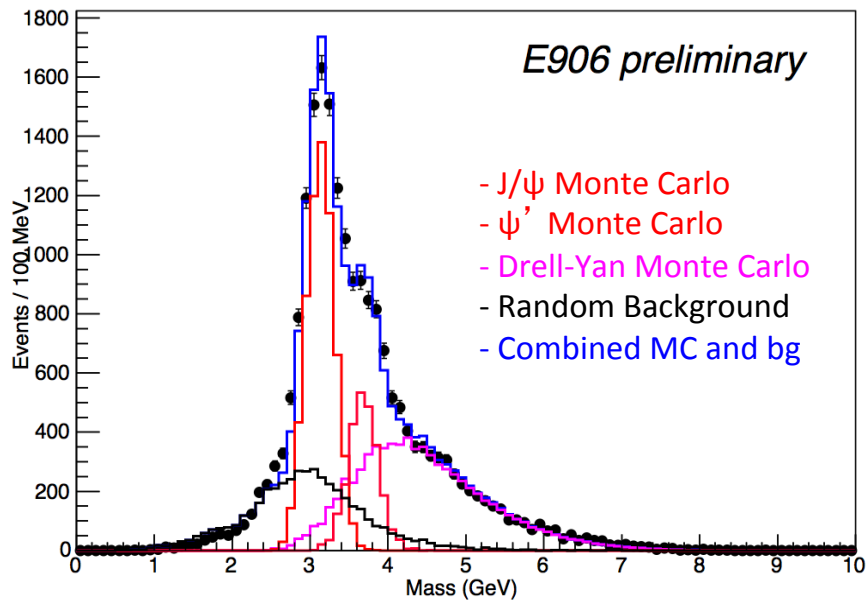
- 4 scintillator hodoscope stations (x and y)
- 4 tracking stations (x and stereos) MWPC

E906 Run-II and III Performance



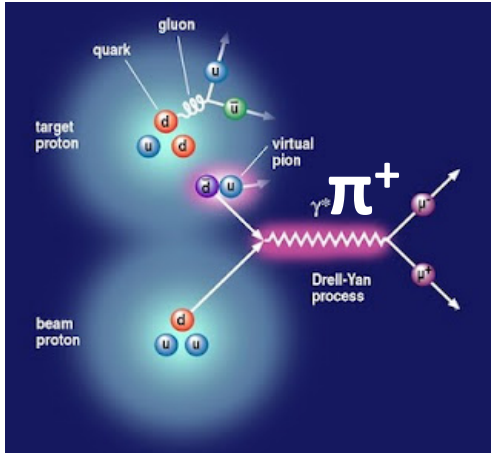
E-906 Drell-Yan Acceptance

Run-II data: 5% of total projected stat.
Run-III data: 30% of total proj. stat.

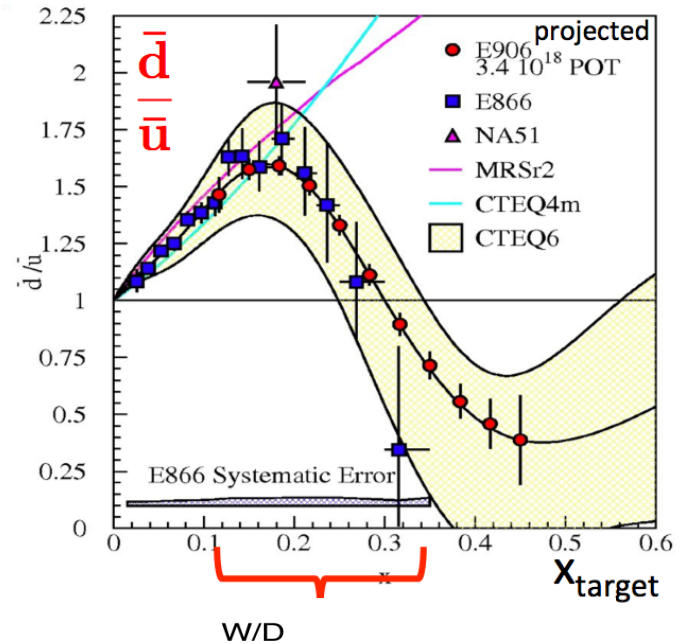
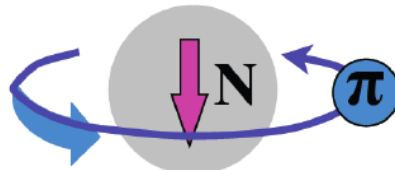


E906 Physics Programs: 2009-2016

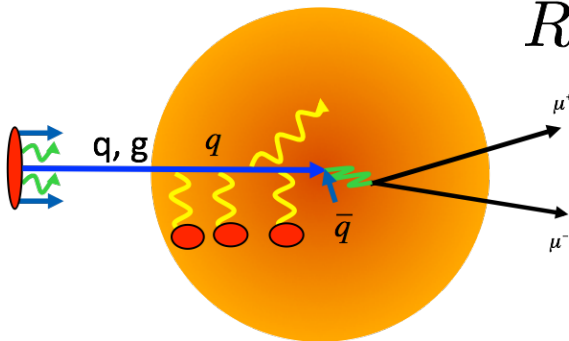
- Sea quark flavor asymmetry p+p
 - Pion cloud model



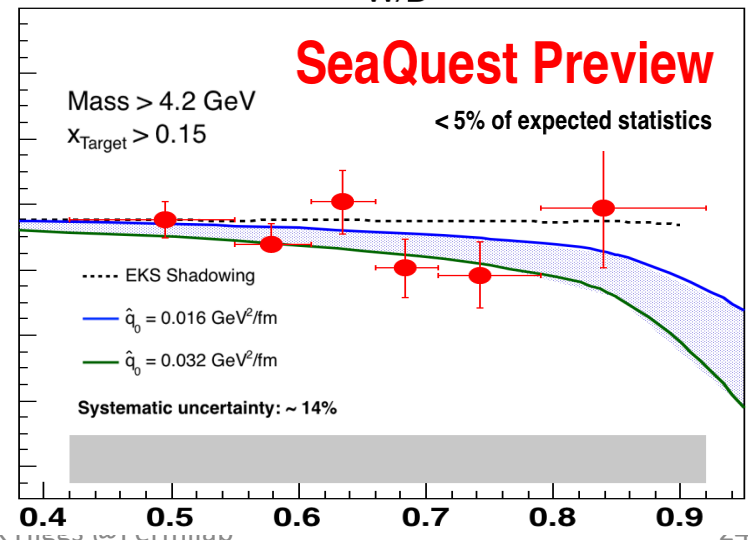
$$|p\rangle = |p^0\rangle + |n\rangle |\pi^+\rangle$$



- Quark energy loss in p+A



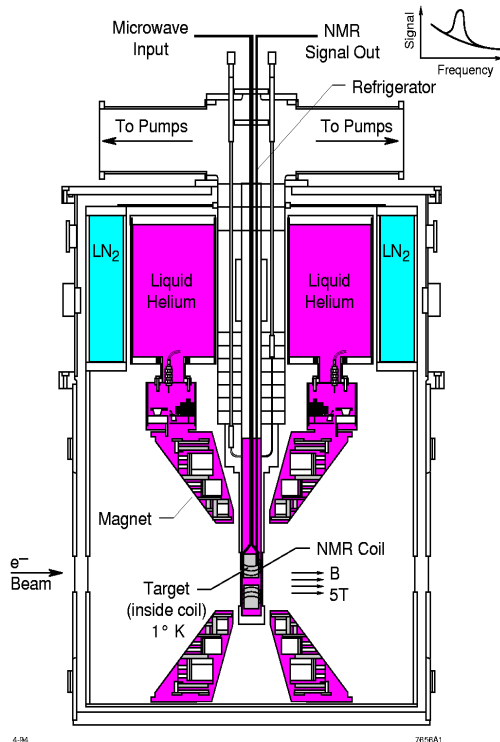
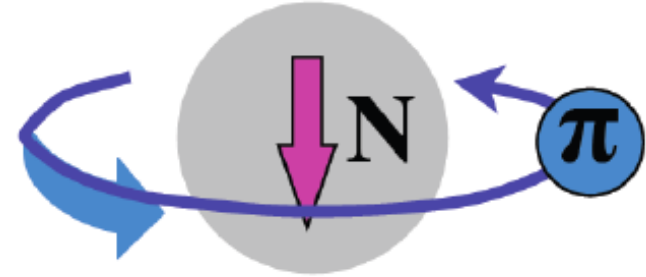
$$R_{pA} = \frac{\sigma^{pA}}{A \times \sigma^{pp}}$$



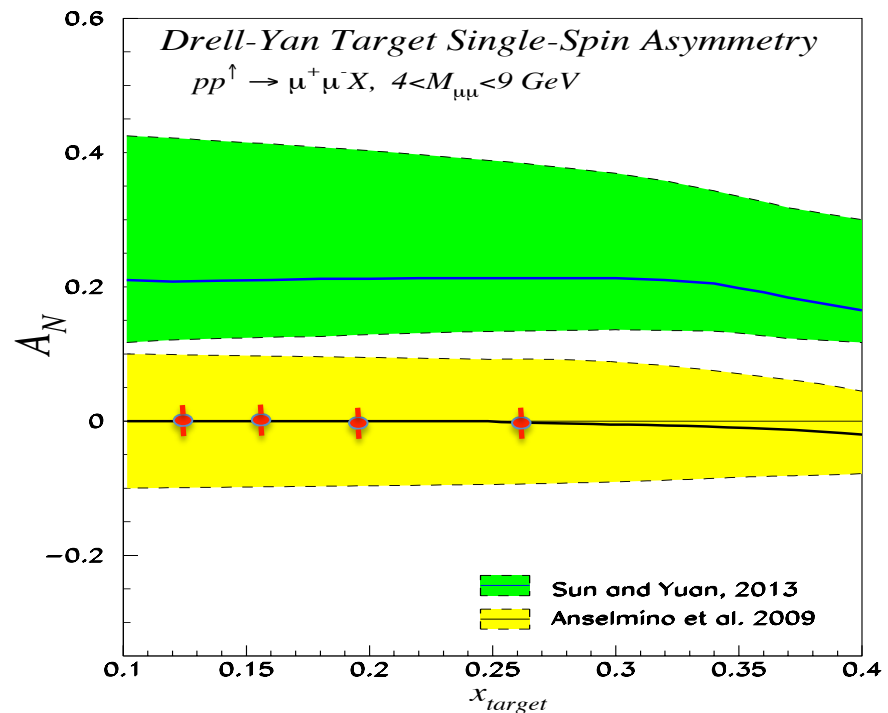
E1039 Physics Program: 2017-2019

Polarized Fixed Target Drell-Yan Experiment

- Sea quark flavor asymmetry and OAM
 - Pion cloud and OAM
 - Non-zero Drell-Yan Sivers Transverse Spin Asymmetry

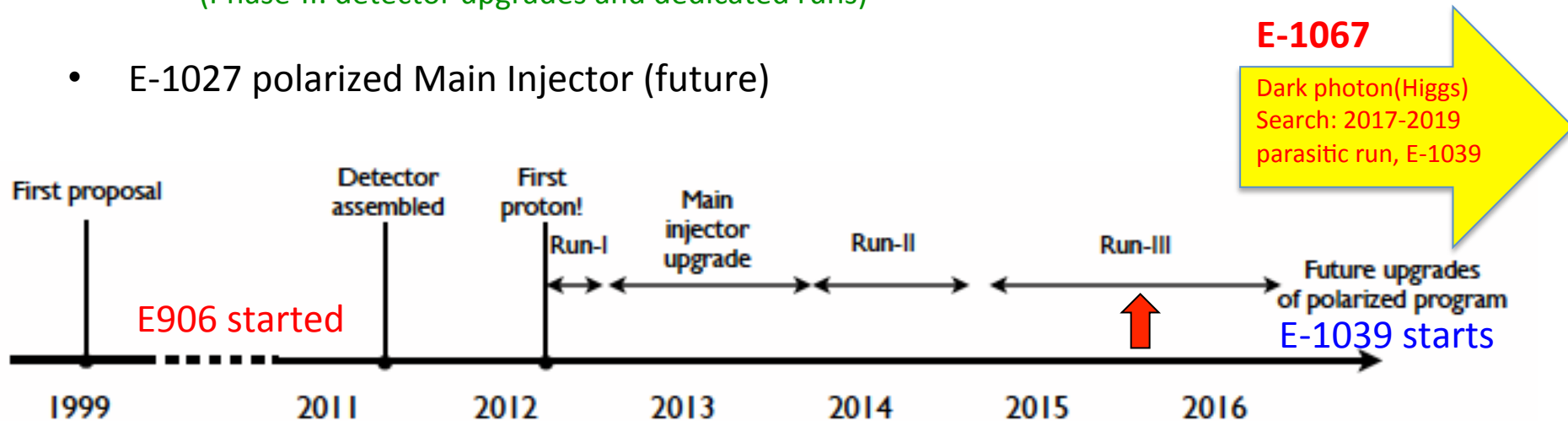


LANL polarized proton (NH_3) target

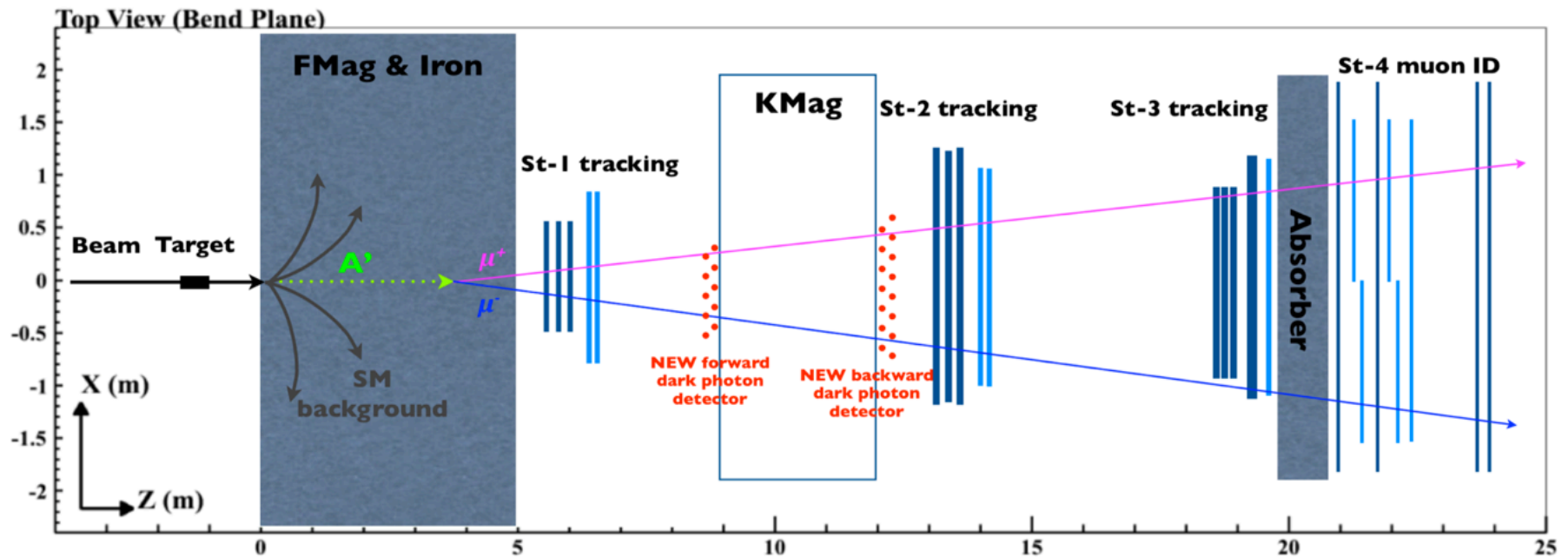


Schedules of SeaQuest Experiments

- E-906 complete data taking in summer 2016
 - E906 targets are located $\sim 1.3\text{m}$ upstream of the beam-dump, $\sim 10\% \lambda_I$.
- E-1039 will replace current E906 targets with a polarized NH_3 target.
 - No change to E906 spectrometer setup
 - New target located about 3.5m upstream of the beam-dump, $\sim 6\% \lambda_I$.
 - Target/trigger installation: 2016 - 2017
 - Data taking: 2017 – 2019
- **E-1067 Timeline**
 - Phase-I (Parasitic run) with E1039: 2017-2019
 - (Phase-II: detector upgrades and dedicated runs)
- E-1027 polarized Main Injector (future)



E-1067: A New Program to Probe Dark Sector in Beam Dump Mode

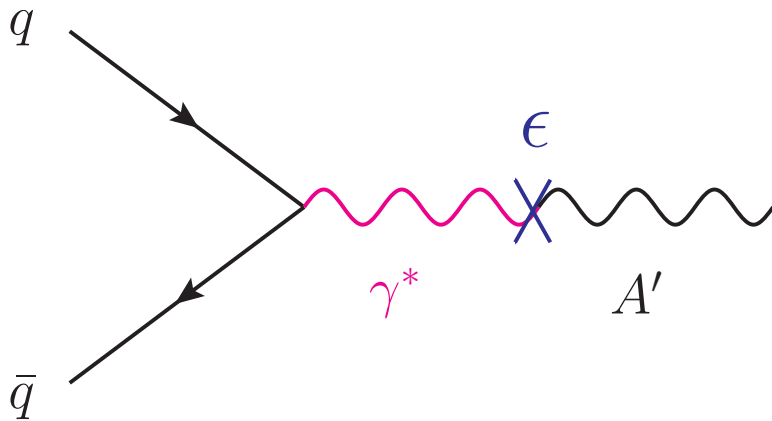


E906/E1039: Targets $\sim 10\% \lambda_1$

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

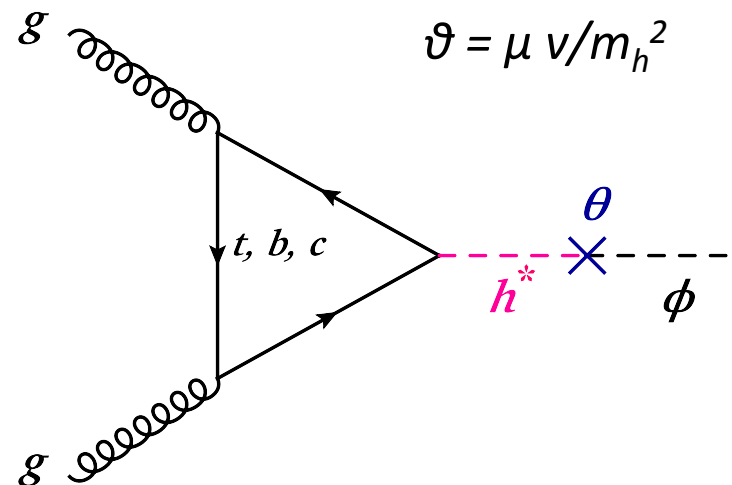
Photon portal: “vector”

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



Higgs portal: “scalar”

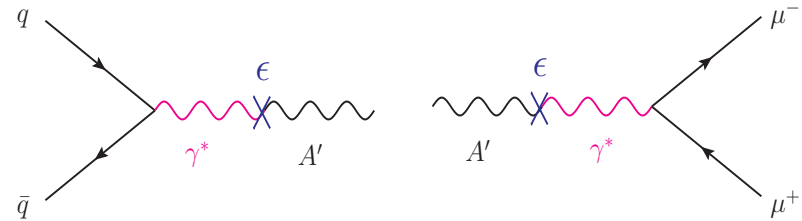
$$\mathcal{L}_{\text{mix}} = \mu\phi|H^\dagger H|$$



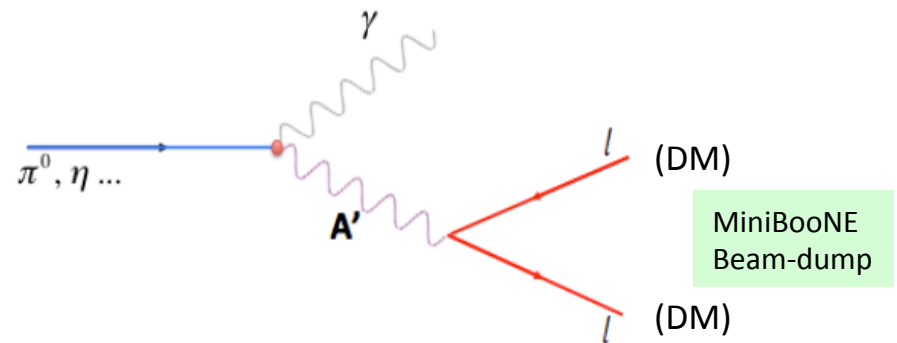
Dark Photon Search in Dimuon Decay Channel

SeaQuest in Beam Dump Mode (p+Fe)

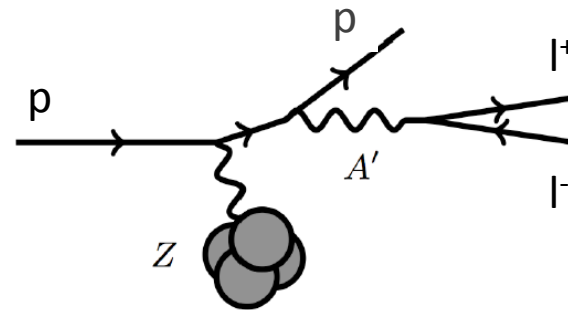
1. Drell-Yan like



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



3. Bremsstrahlung



Dark Photon Decay Modes

“Minimal” Decay:

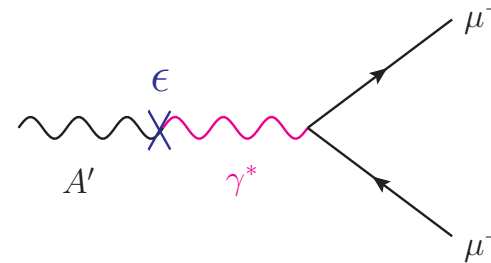
- Dark photon is the lightest in the dark sector;
 - SM final state particles only

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

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

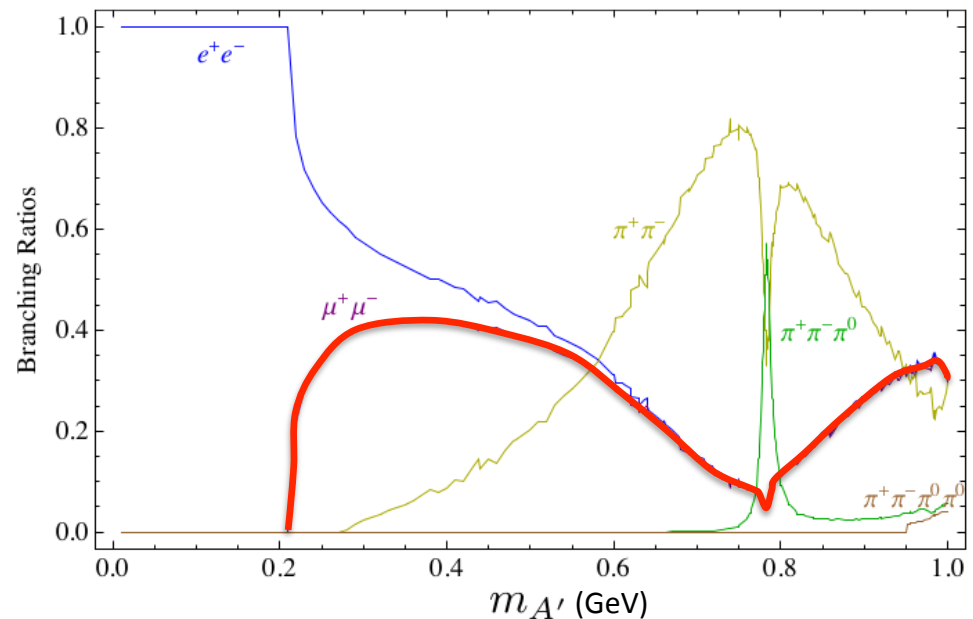
“General” Decay:

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



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

D. Curtin, et al, arXiv: 1312.4992



Detector Upgrade and Expected Signals

- Dark photon trigger upgrade

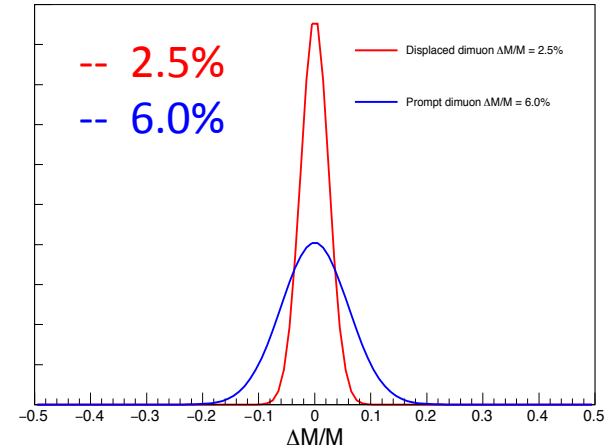
1. Add a fine-granularity scintillating strip based trigger/tracking to tag dimuons from the same decay Z-vertex
2. A new trigger for events with displaced down-stream dimuons

- Unique signals

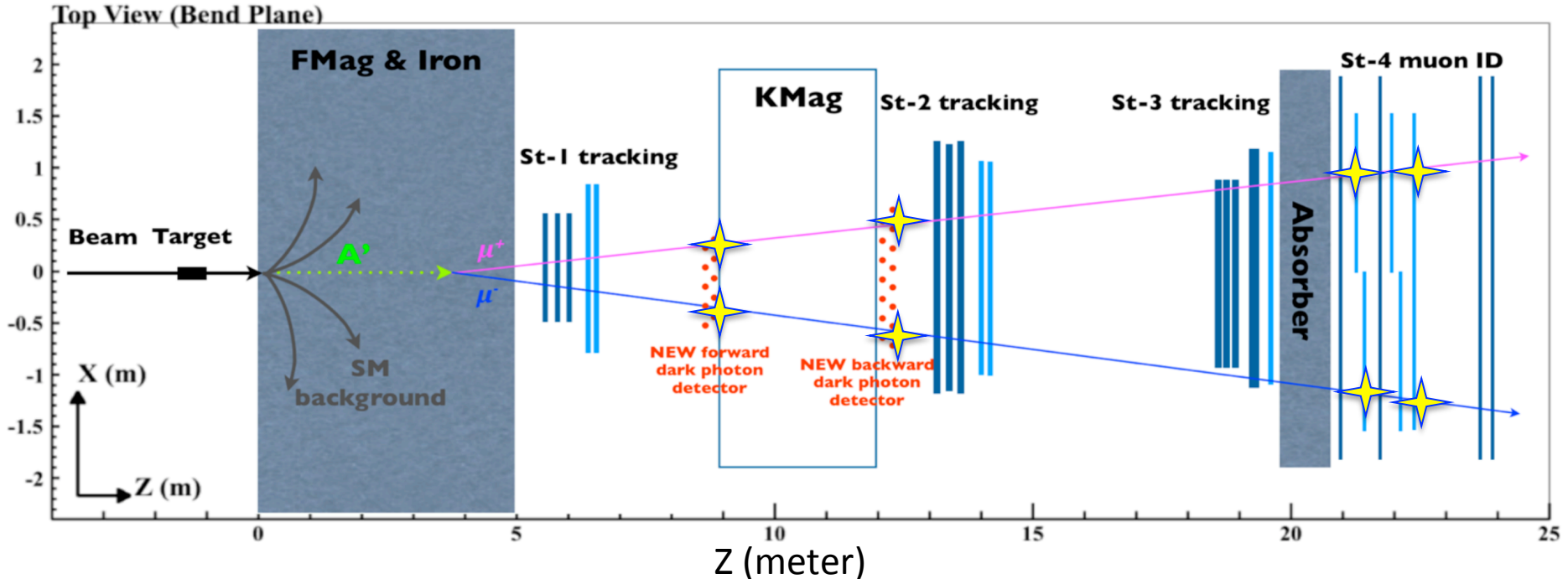
1. Displaced dimuon decay vertex for long-lived particles
2. Invariant mass peak in dimuon mass spectrum
3. Mostly from beam dump (target $\sim 6\% \lambda_c$)

- Beam time

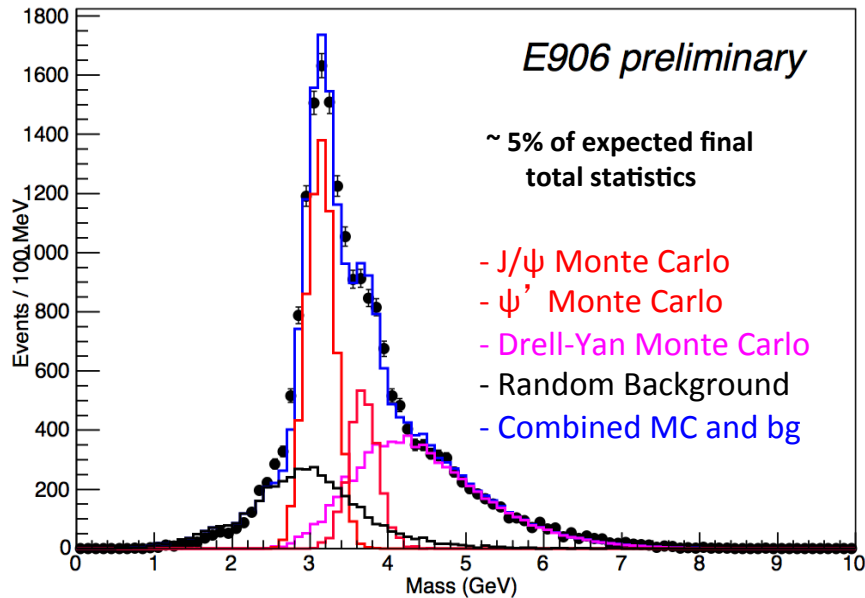
1. Run parasitically with E1039 (2017-2019)
2. Possible dedicated runs later with upgraded ($e^{+/-}$, $h^{+/-}$)



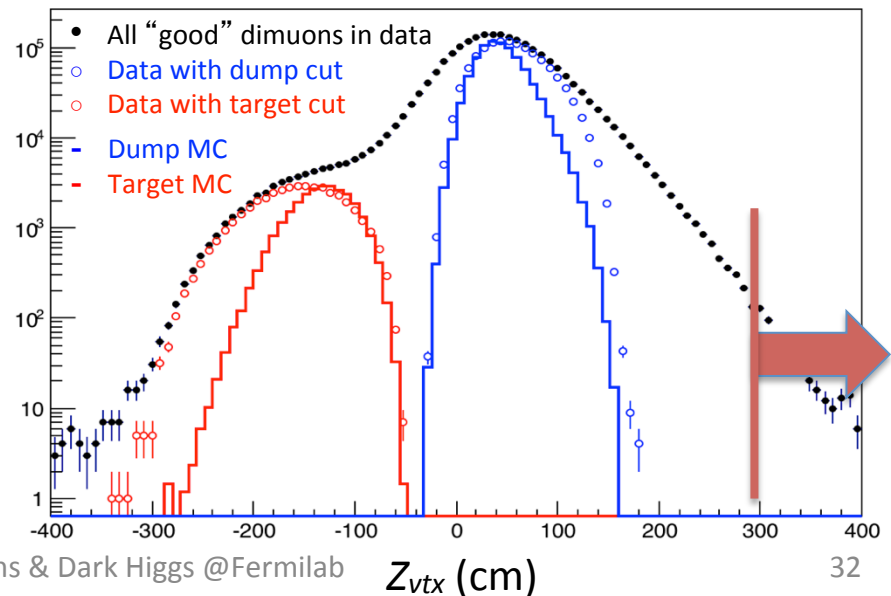
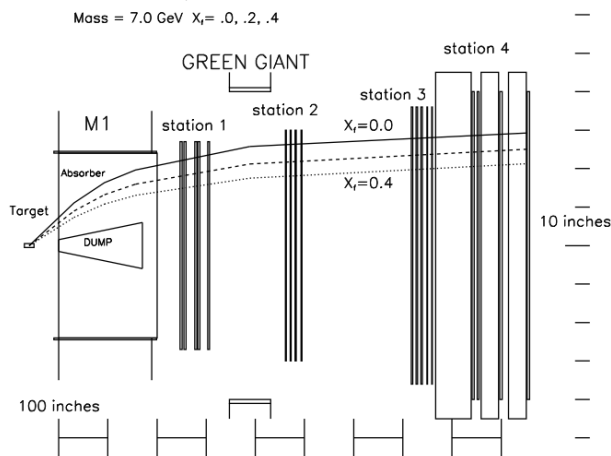
Dimuon mass resolution



Data from Run 2014 (Run-II)



- Monte Carlo describe data well
 - $\sigma_M(J/\psi) \sim 180$ MeV, $\sigma_M(DY) \sim 220$ MeV
 - J/ψ, ψ' separation
 - Clean DY sample
- Good target/beam dump separation



A New High-Granularity Displayed Dimuon Vertex Trigger

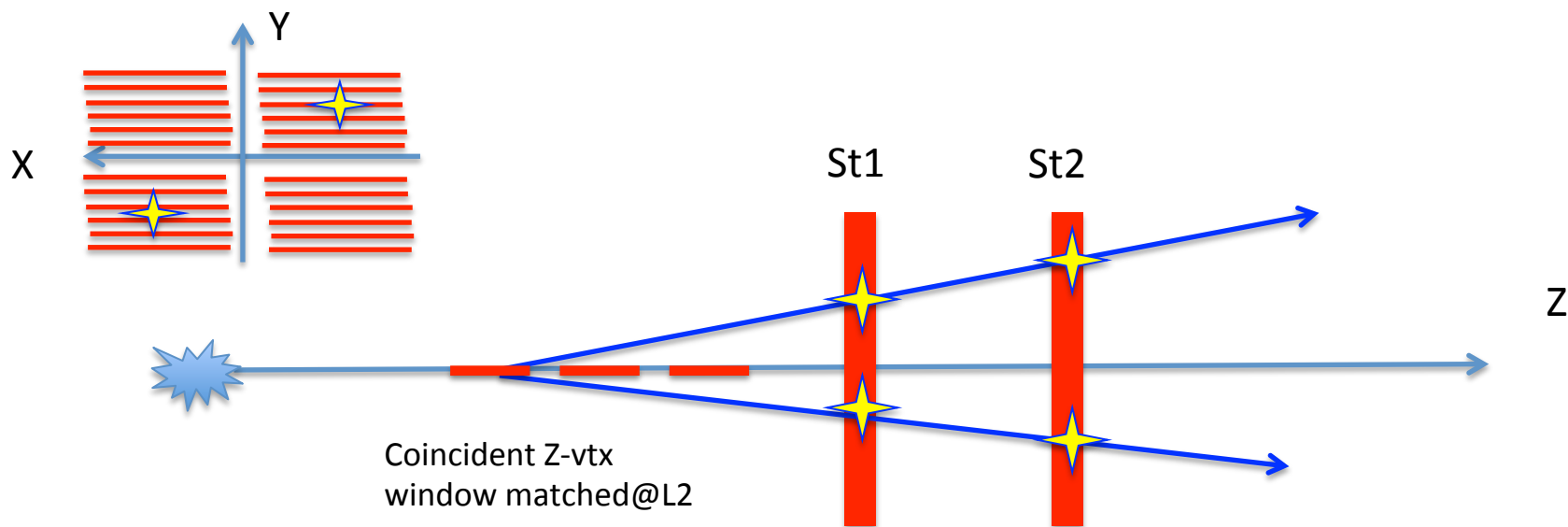
High rejection power, very low rate, $\ll 1$ kHz (E906 DAQ limit)

Y-Plane Trigger:

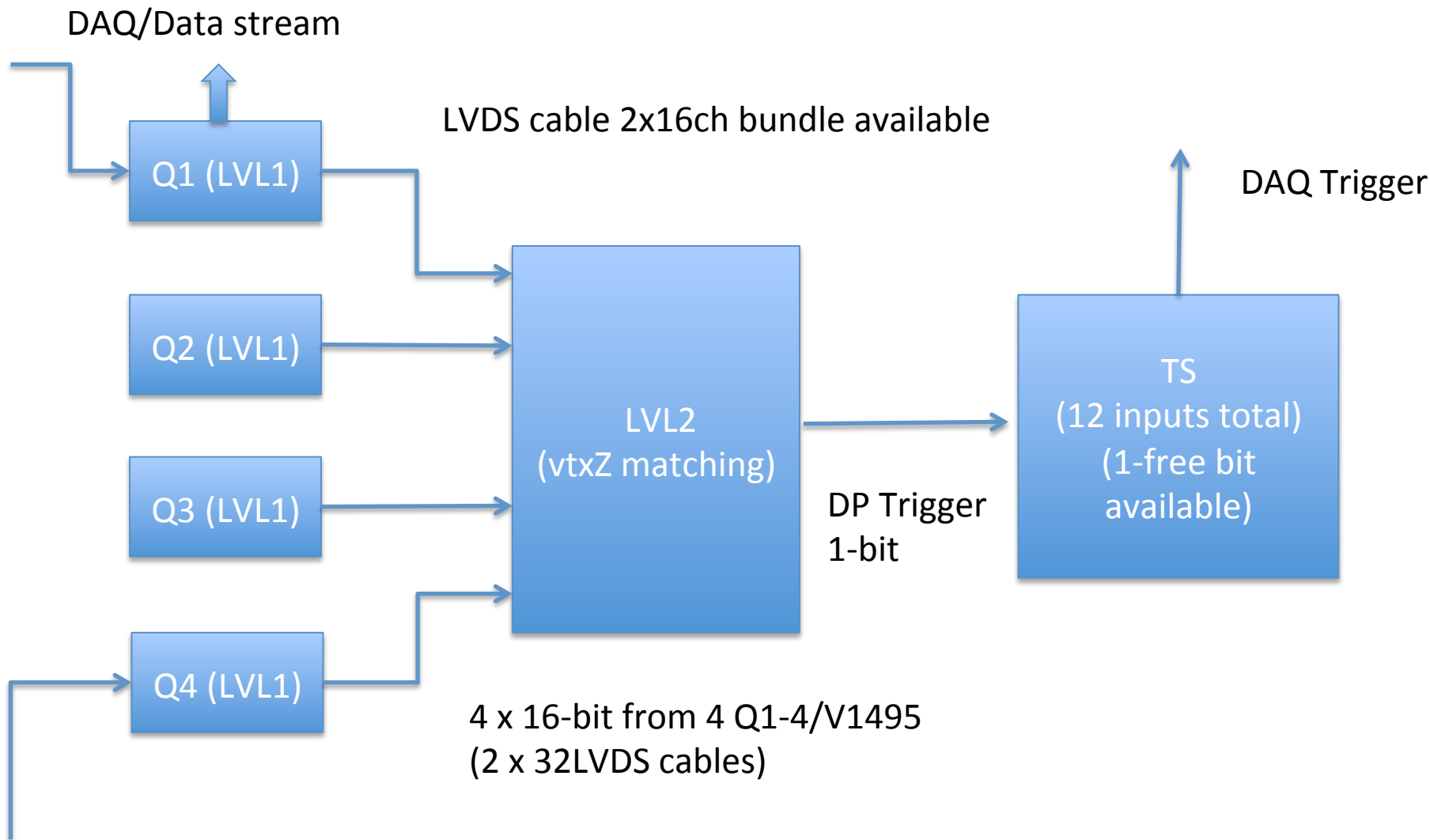
- A quadrant panel: 50cm x 50cm, 1cm thick
 - 1cm x 1cm x 50 cm scintillating strips, SiPM readout
- Straight line projection, 30cm Z-vertex resolution
- Displaced z-vertex, mostly low mass $< 3\text{GeV}$
- Coincident with St-4 Hodos(muons)

Y-channels per quadrant:

- 1x V1495
- $50(\text{St1}) + 50(\text{St2}) + 8 \times 2 (\text{St4-Y1,2}) = 116$
- $96 + 64 = 160$ possible
 - $72 + 72 + 16 = 160$ (possible)
 - $(2\text{NIM} = \text{RFCLK} + \text{ComSTOP})$



Displaced Dark Photon Trigger

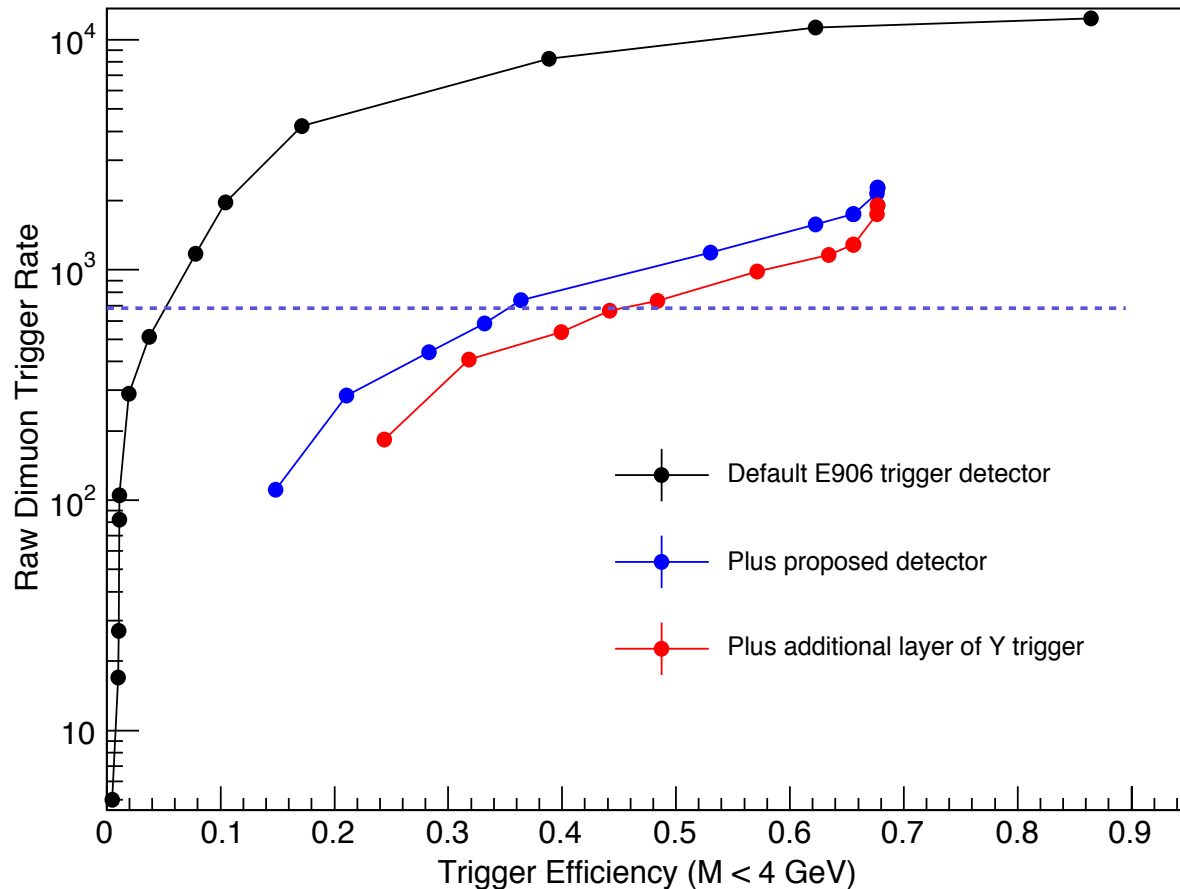


Q1: $50(ST1') + 50(ST2') + 2 \times 8(ST4 - Y1/2) = 116$, FANOUT ST4

Up to $72(ST1) + 72(ST2) + 2 \times 8(ST4 - Y1/2) = 160$

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 (reprogramming trigger firmware etc.)

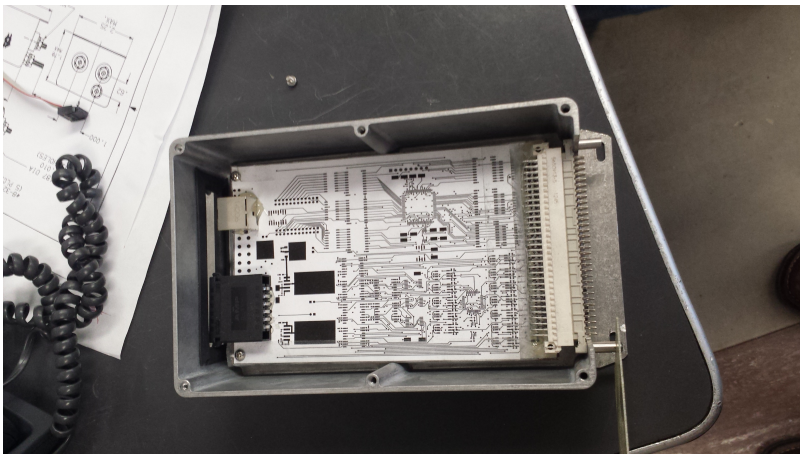
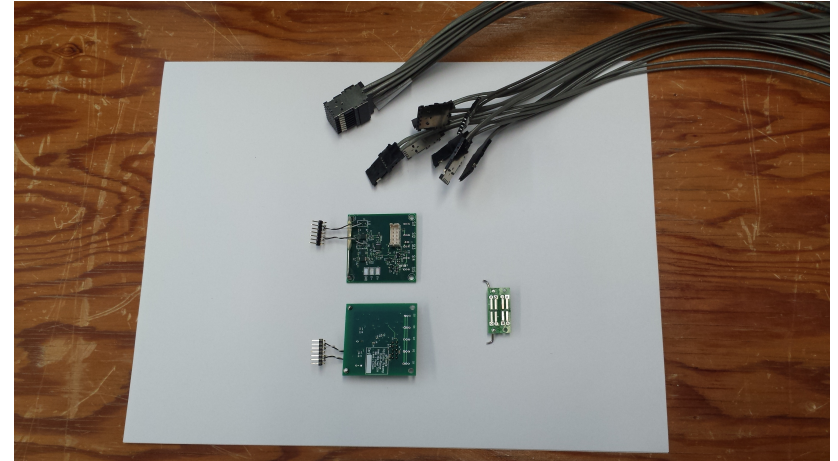
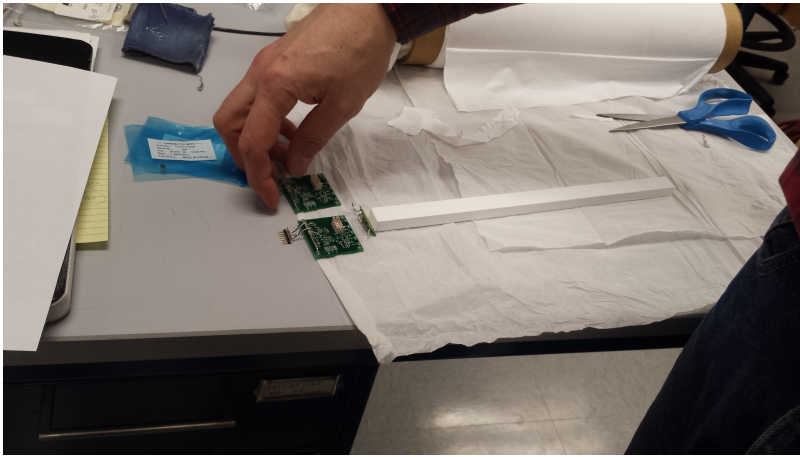


Parasitic mode: use up to ~10% DAQ bandwidth

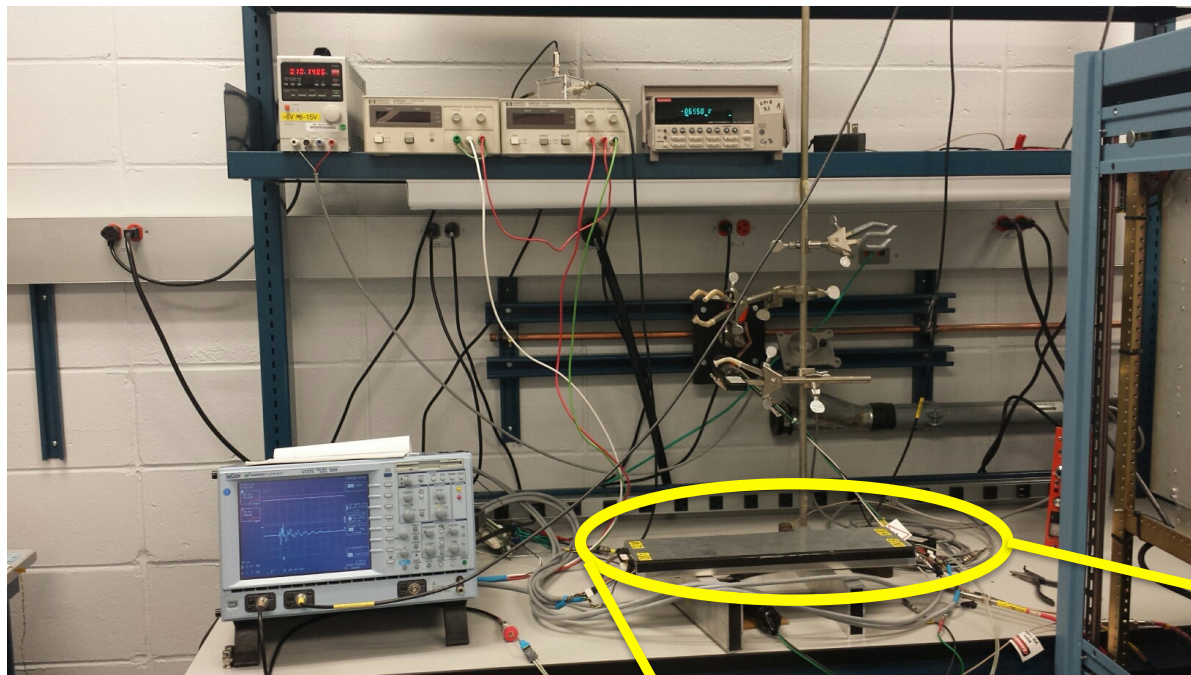
(Prompt)Low mass dimuon trigger performance

Scintillator-based Trigger R&D

- Capable to operate in strong magnetic field
 - SiPM, Scintillator, cost effective
 - A joint R&D with BNL sPHENIX group

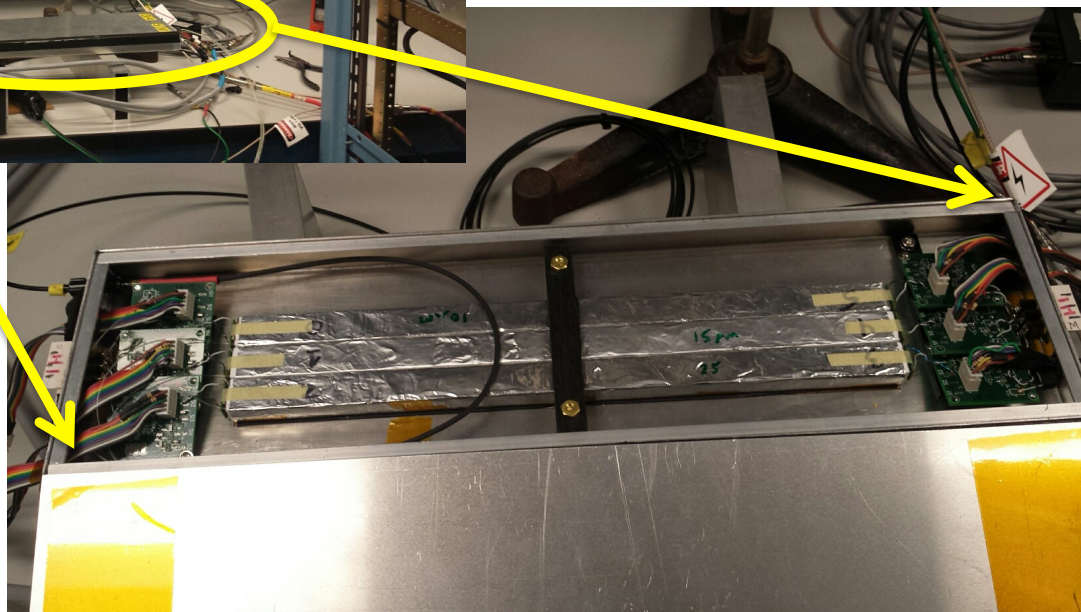
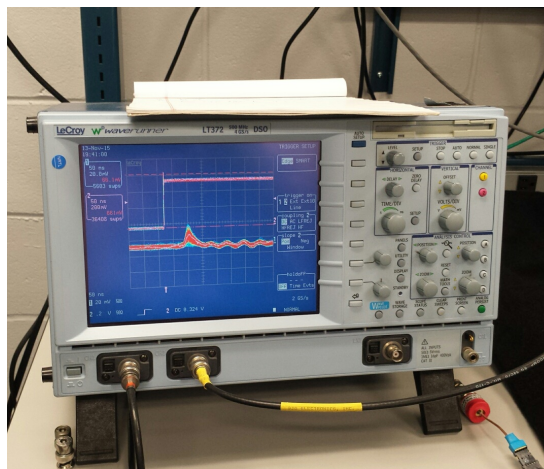


Trigger Prototype R&D



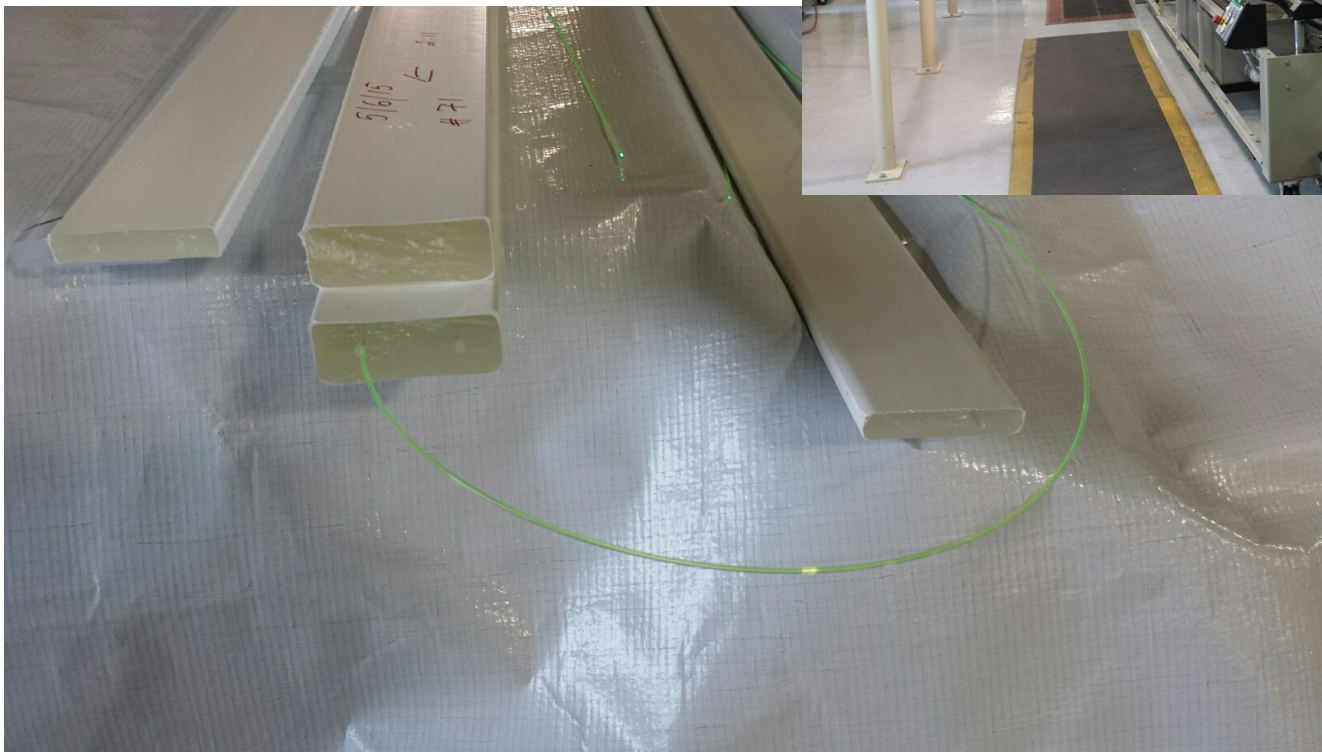
10mm x 10mm x 500 mm
Scintillator + SiPM readout

$< \sim 10\text{ns}$ rising time



Fermilab Extruded Scintillators

- Extruded scintillators + WLSF
- SiPM readout
- Low cost, for large area
- On-going R&D



E906 DAQ Test Stand

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



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

Search Mode (1): Long-lived Dark Photons

Reconstructed dimuons with downstream Z-vertex:

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

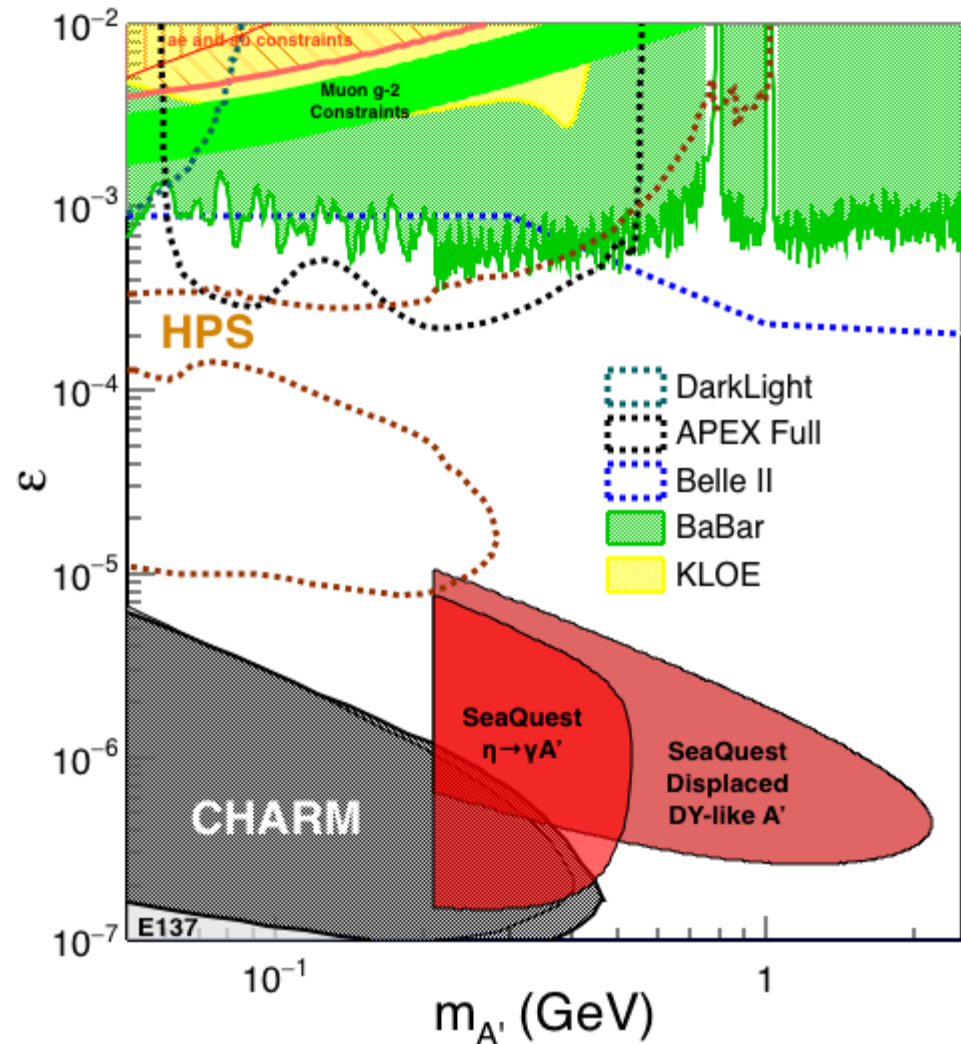
- Very low trigger rate, $\ll 1\text{kHz}$
- SM background free
- Dimuon mass peak

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

1.4×10^{18} POT (recorded)

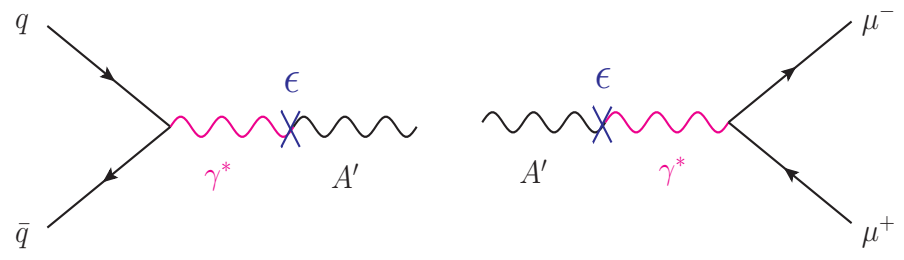
- 4 events contours (2-sigma)
- 2-sigma (95%) exclusion plots

Excellent coverage of uncharted region!



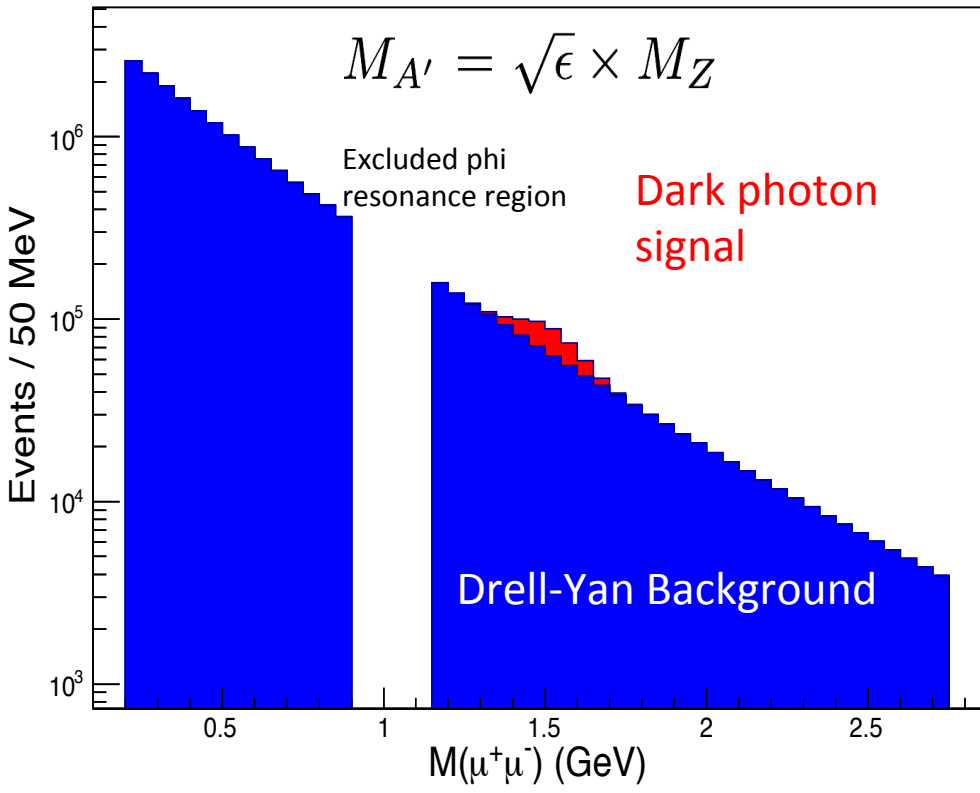
Search Mode (2): “Prompt” Dark Photons vs Drell-Yan

Z-vertx < 3m



Expected Drell-Yan like signal and backgrounds:

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



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

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

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

Work in progress
Further optimization possible

Dark Photon Sensitivity: Summary

POT: 1.4×10^{18} (parasitic w/ E1039)

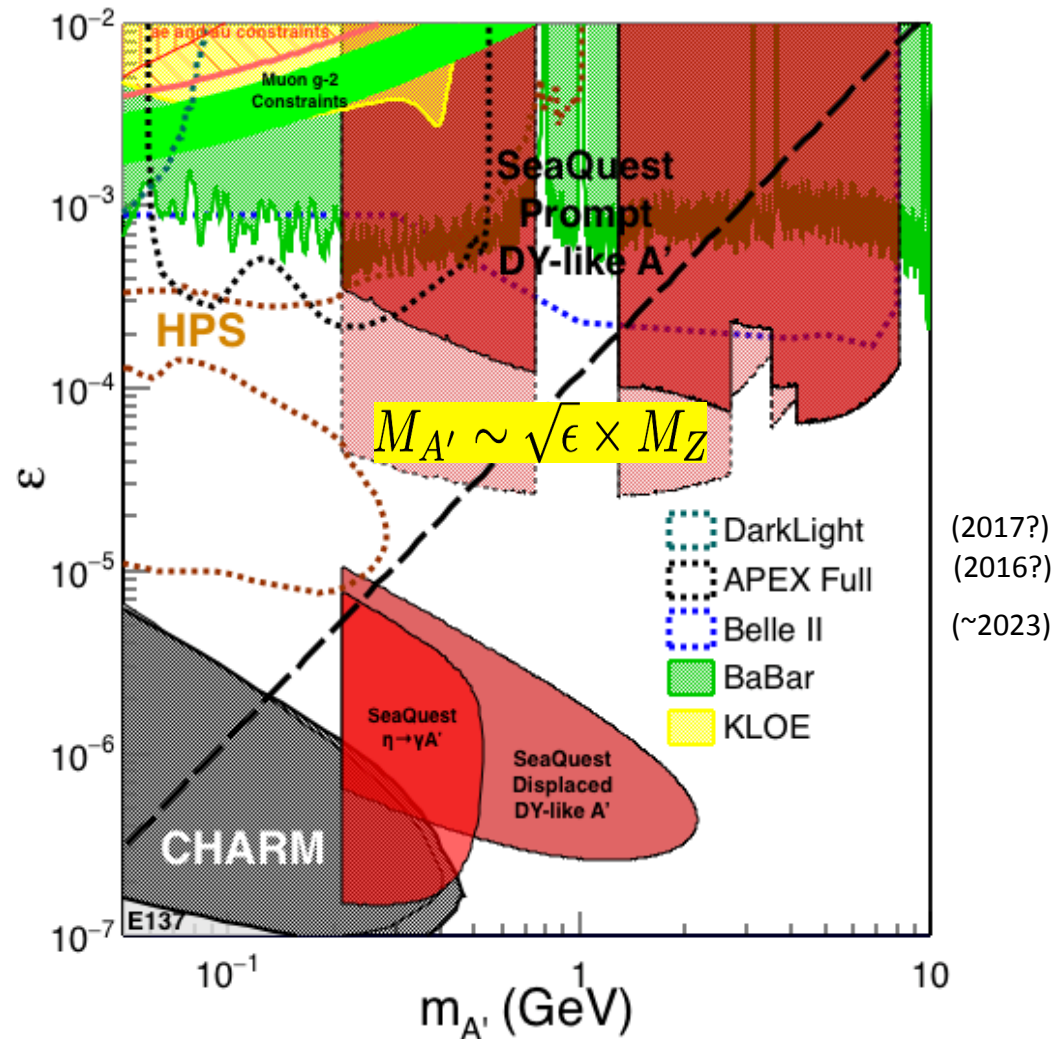
Signals considered:

- Drell-Yan like
- Eta decays
- Bremsstrahlung

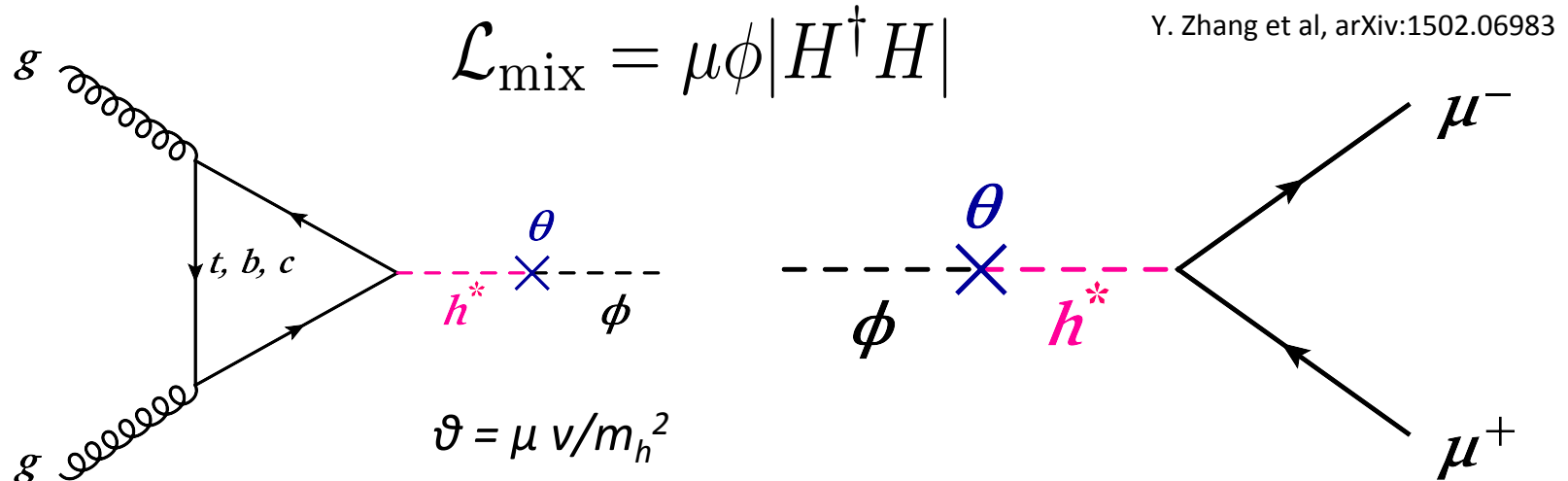
Covers a wide range of unexplored parameter phase space

- Displaced dimuons
 - Minimal SM background
- Prompt dimuons
 - Excellent coverage over BELLE-II projection
 - Possible dedicated runs later to fully restore mass $< 3\text{GeV}$ (Phase-II)
- **Phase-II with upgrades**

Access below 200MeV with di-electrons (add EMCal)



E-1067: Dark Higgs Search at SeaQuest



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

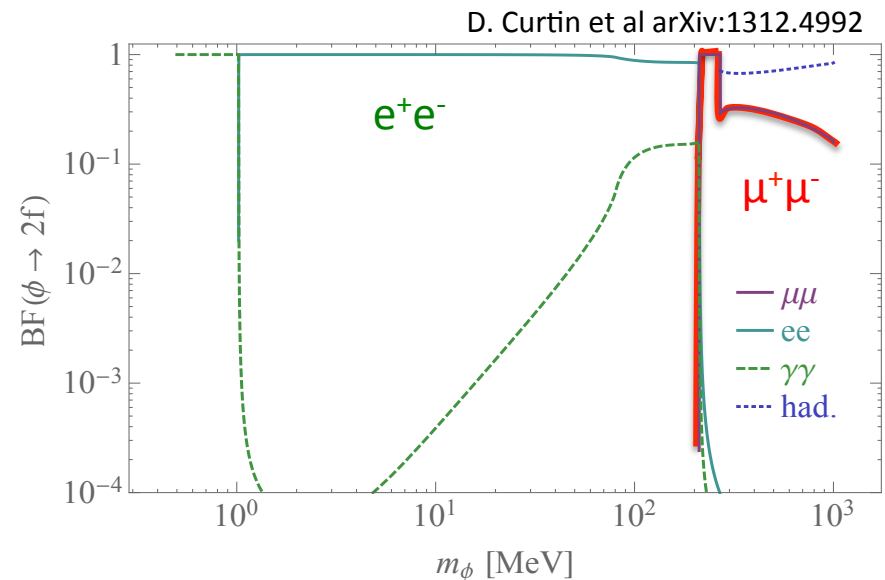
Phase-I:

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

Advantage of using hadron beams
with muon probes over electrons

Phase-II:

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

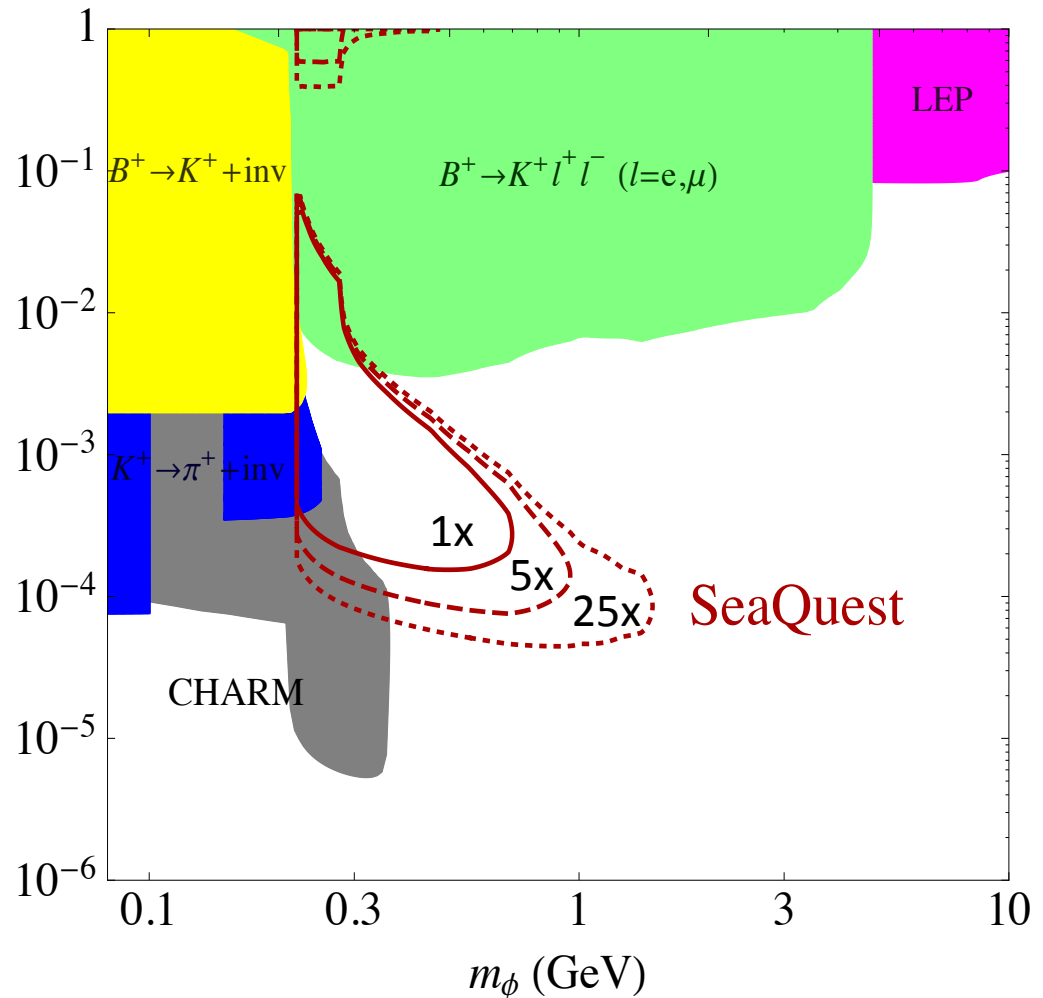


SeaQuest Dark Higgs Sensitivity

POT: 1.4×10^{18} (Phase-I)

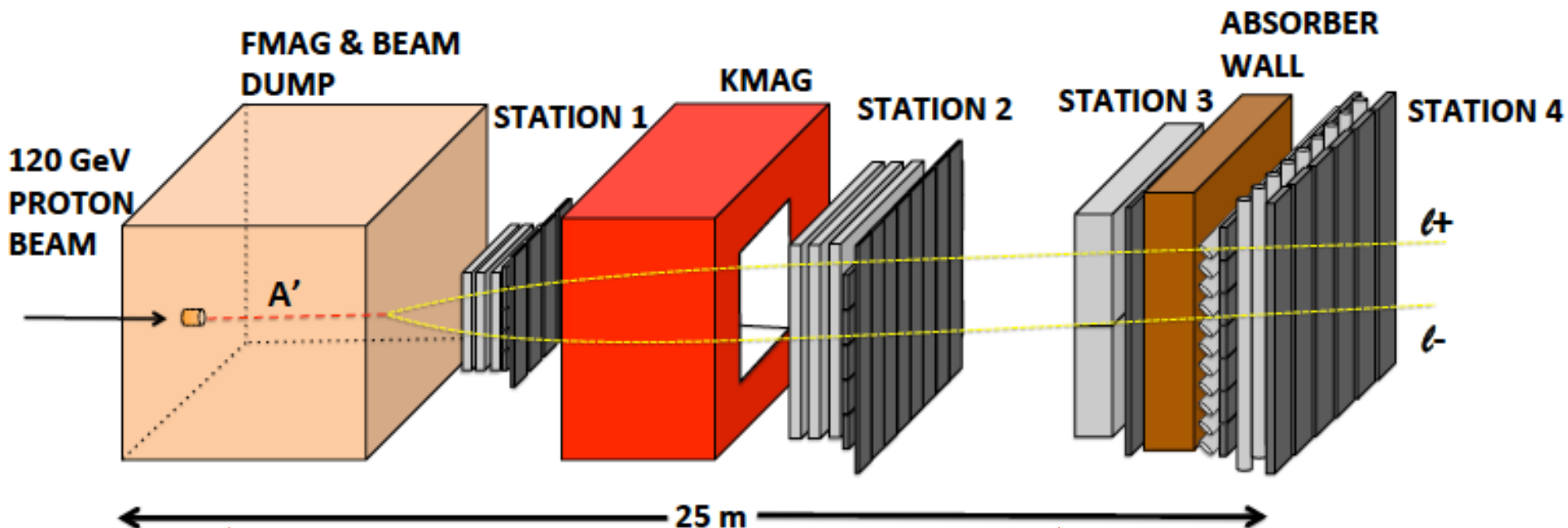
Y. Zhang (2015)

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



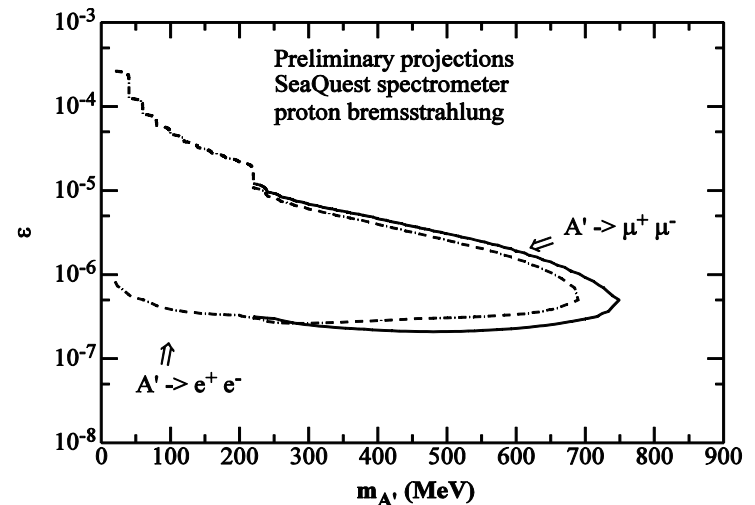
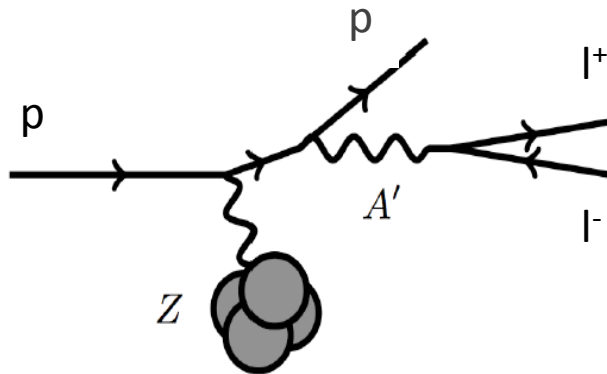
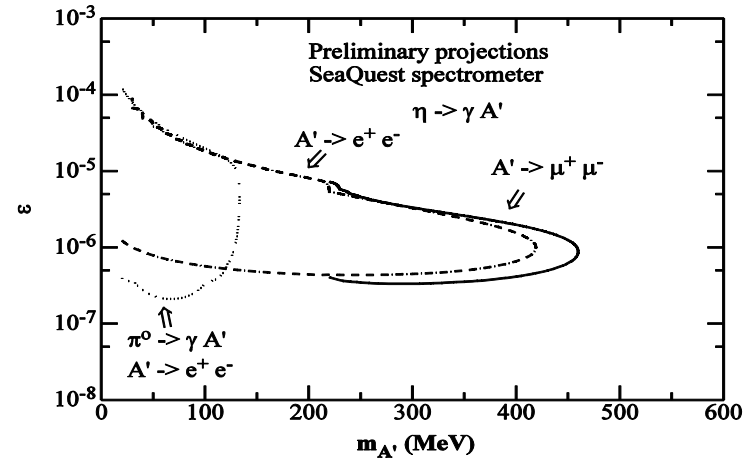
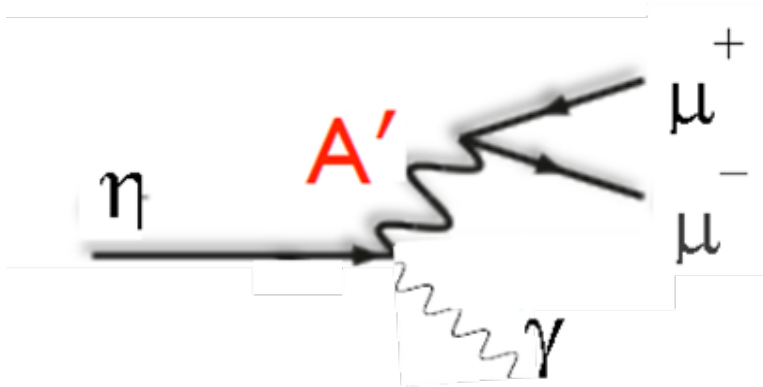
E-1067 Future Upgrade: Phase-II

2020+ ~ 2025 ?



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

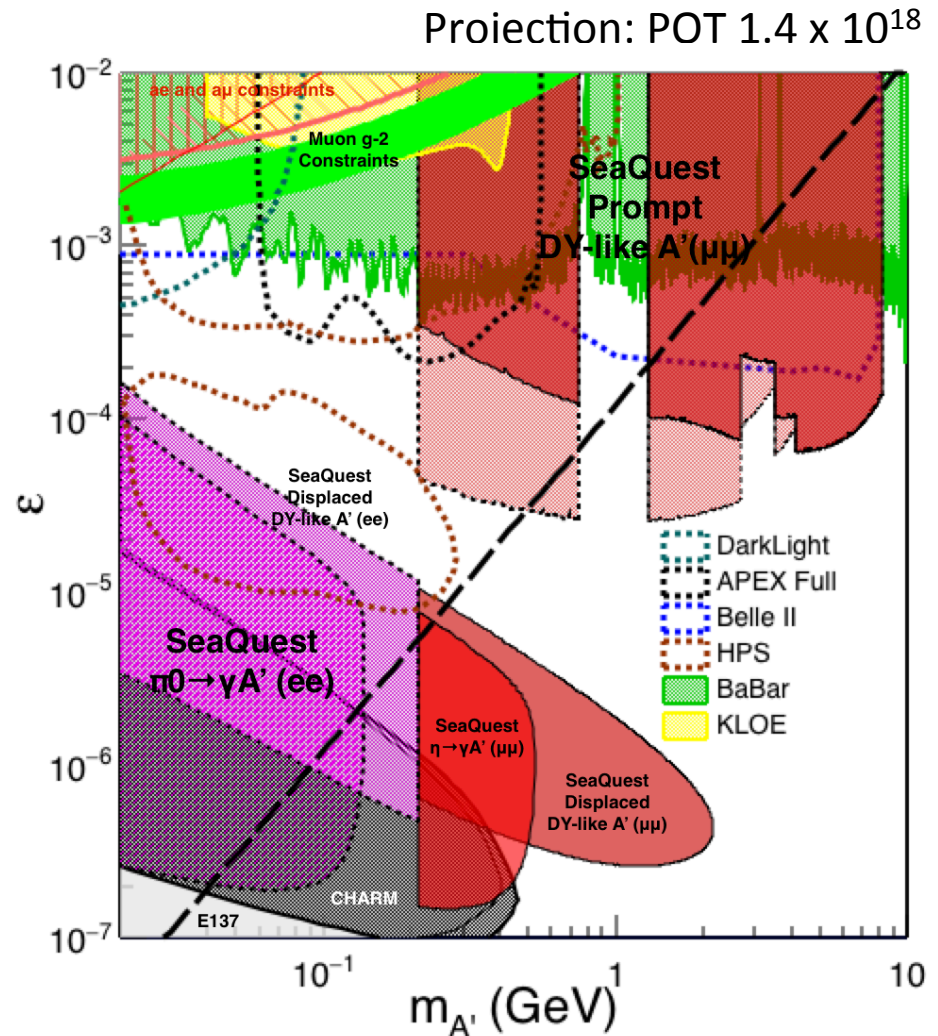
S. Gardner, R. Holt et al



Phase-II: Full Coverage

with future detector “EMCal/HCal” upgrades

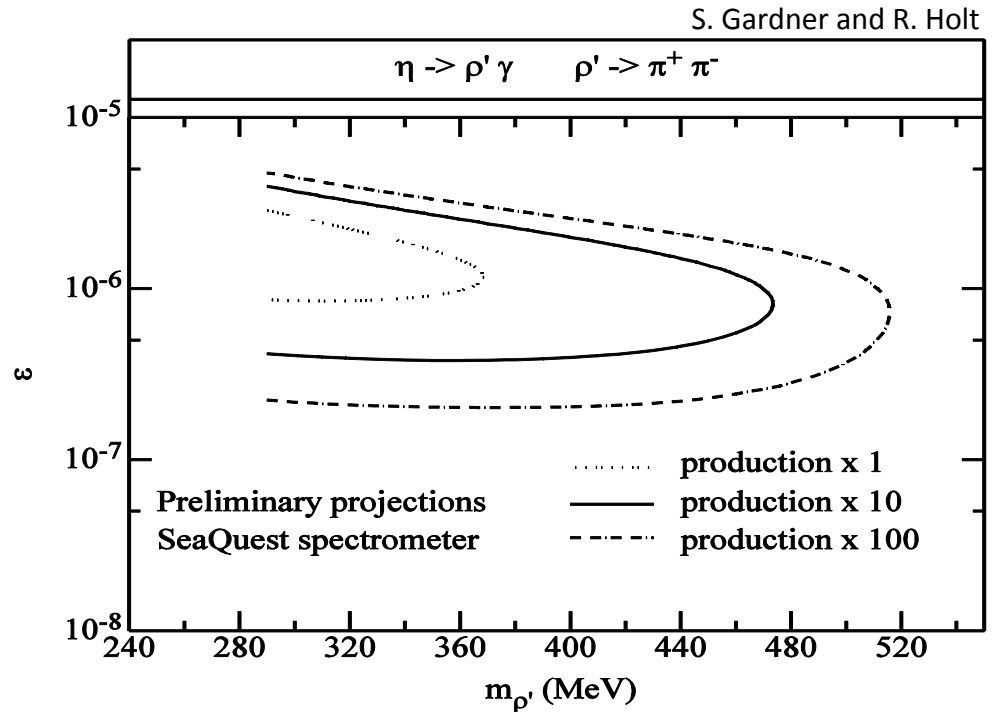
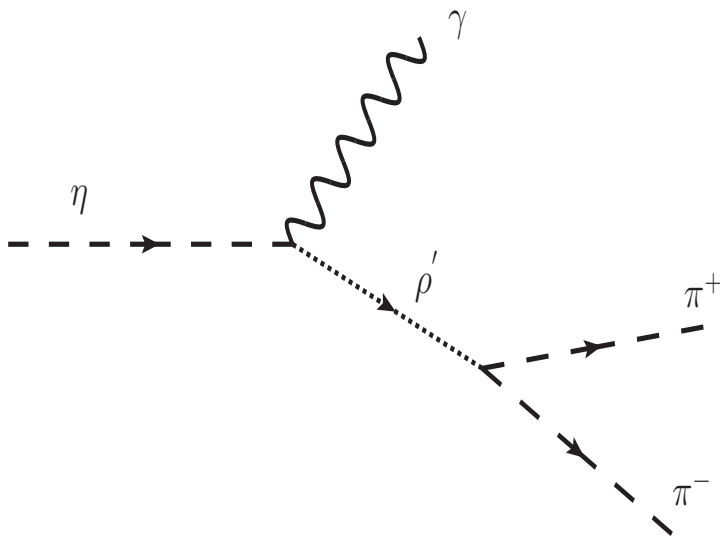
- Detector upgrades
 - EMCal: $e^+/-$
 - HCal: $\pi^+/-$
 - Recycle from other experiments, RHIC/JLab etc.
- DAQ upgrade
 - 100 kHz
- Timeline of dedicated runs
 - 2019+
- Detector configuration
 - Access low mass region with optimized Fmag setting



Phase-II: Probe Non Abelian Dark Sector

with future detector “HCal” upgrades

non-Abelian dark sector process



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

Here we consider a non-Abelian (gluon) portal

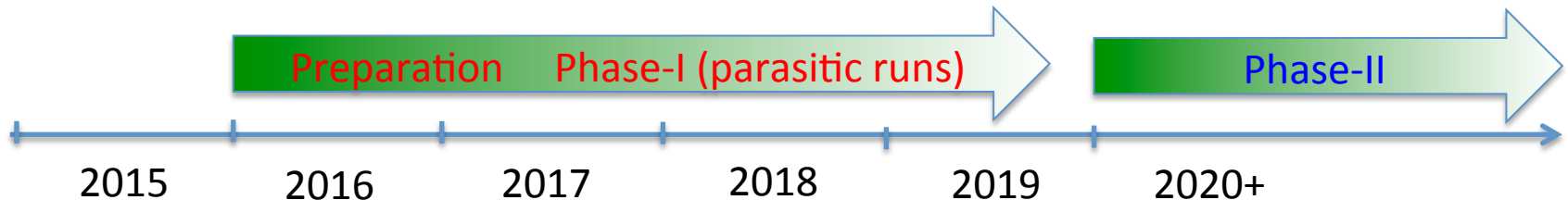
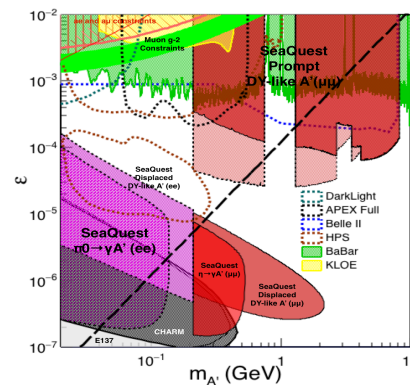
[Baumgart et al., JHEP 0904, 014 (2009); Gardner and He, PRD 87 (2013) 116012]

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

- **Phase-I**

- ***Phase-II***

-



Many good discussions with
R. Holt, J-C. Peng, K. Liu, Z.-B. Kang, Y. Zhang, P.
McGaughey, Y. Zhong, P. Reimer, C. Brown, R.
van der Water, R. Essig, and more

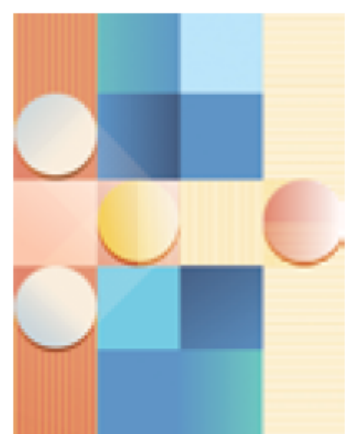
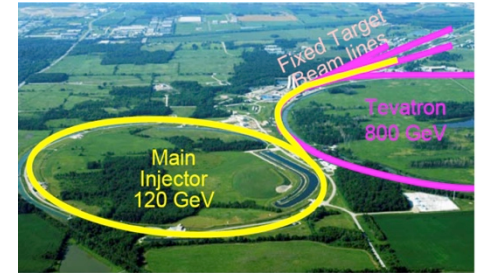
and the new E-1067 Collaboration at Fermilab

Backup slides

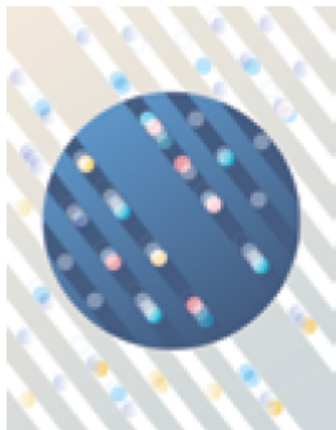
2014 US P-5 Report

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

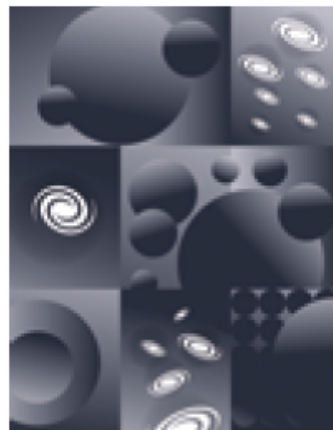
- Use the Higgs boson as a new tool for discovery 😊
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter 😊
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles 😊



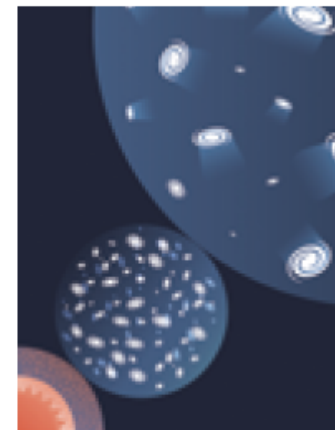
Higgs boson



Neutrino mass



Dark matter



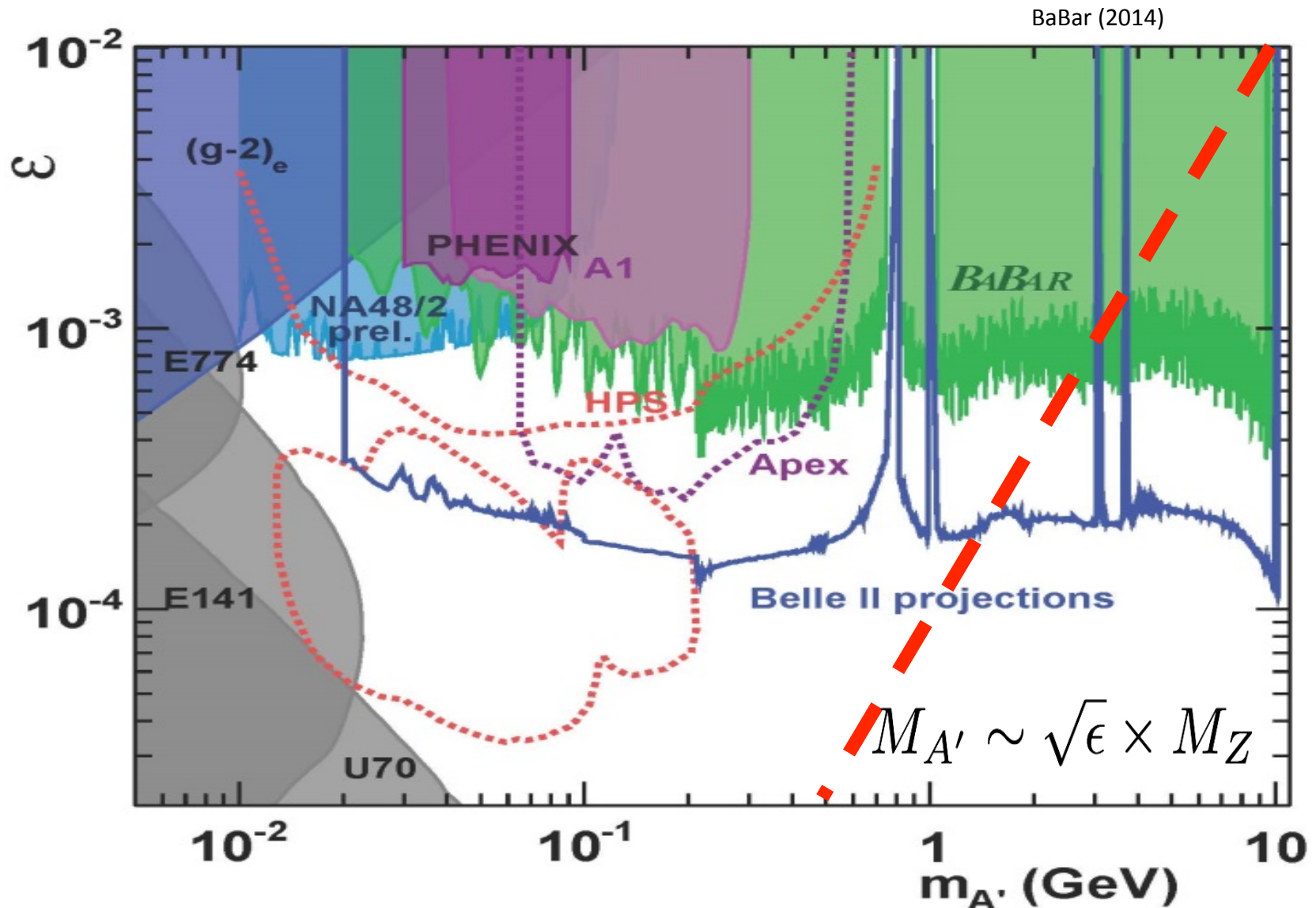
Cosmic acceleration



Explore the unknown

Great Opportunities at the Fermilab Intensity Frontier!!!

Current Limits on Dark Photon Search

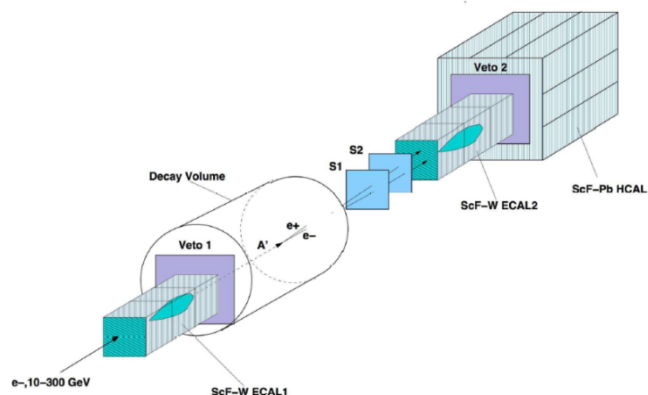


Scope and Compatibility

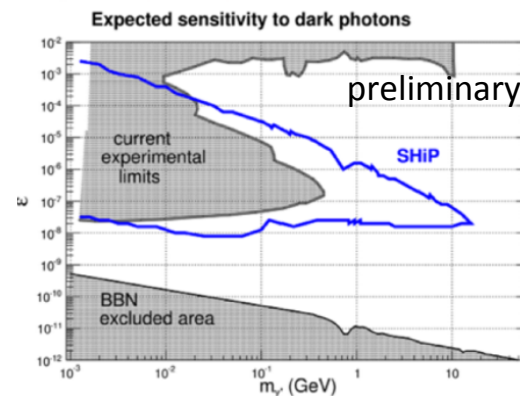
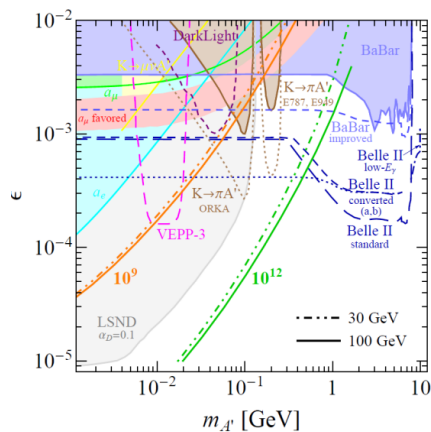
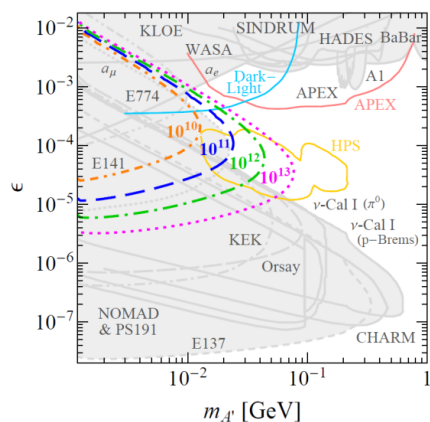
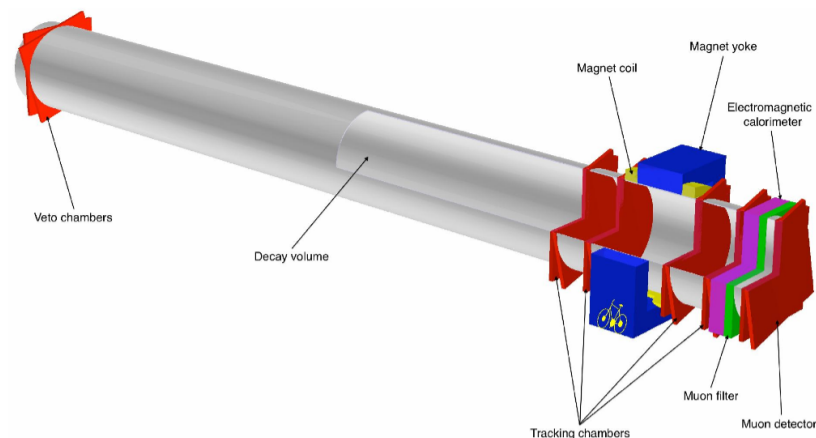
- Preparation work: 2016 – 2017
 - Displaced vertex dimuon trigger upgrade (LANL LDRD \$1M FY2016-2018)
 - Add a new trigger bit
 - No change to existing trigger matrix
 - Possible upgrade of DAQ bandwidth under consideration (external \$\$)
 - 1kHz (E906) -> 10+ kHz
 - Commissioning with cosmic rays
- Parasitic runs w/ E1039: 2017 – 2019
 - Displaced vertex dimuon trigger upgrade
 - Use up to ~10% DAQ bandwidth
 - Achieve 1.44×10^{18} POT
- Possible parasitic runs w/ E1027 and/or dedicated runs later with upgrades: 2019+
 - High luminosity goals:
 - $\text{POT} \gg 1.4 \times 10^{18}$
 - DAQ
 - 10 – 100 kHz capability
 - EMCAL/HCAL/PID
 - Electrons
 - charged hadrons
 - Fully cover the accessible phase space
 - Low mass “prompt photon” region, $M < 3 \text{ GeV}$
 - Possible parasitic runs with other proposals

Beam dump experiment proposal at CERN

Using the CERN SPS e- beam
(arXiv:1312.3309)



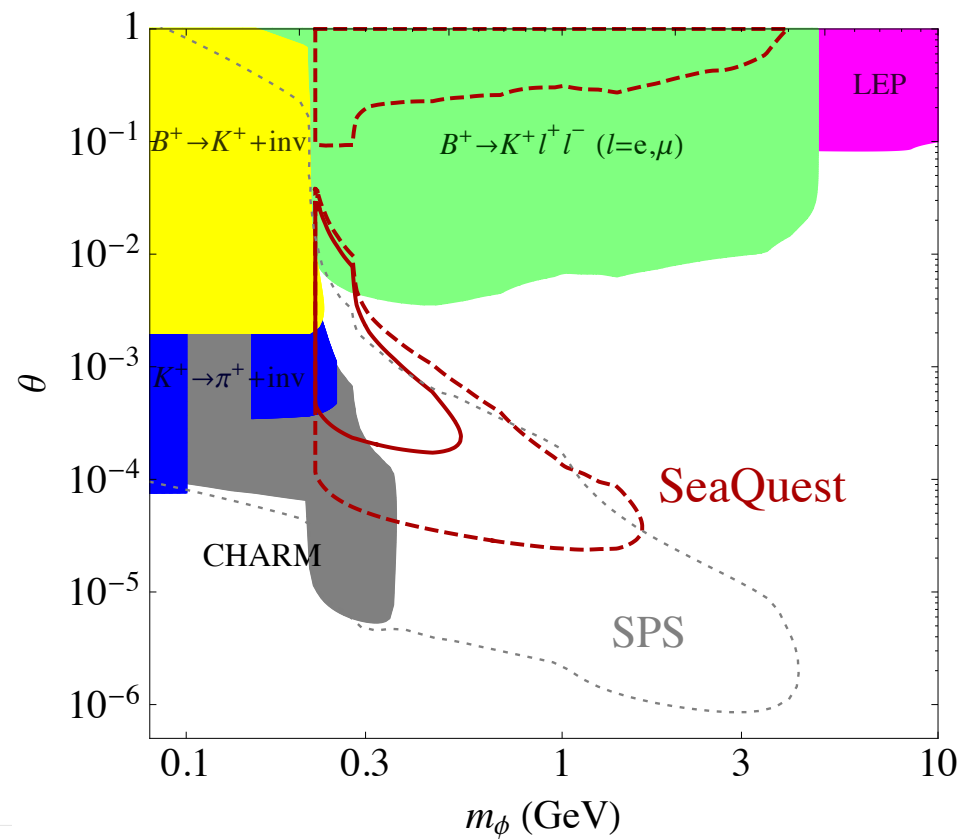
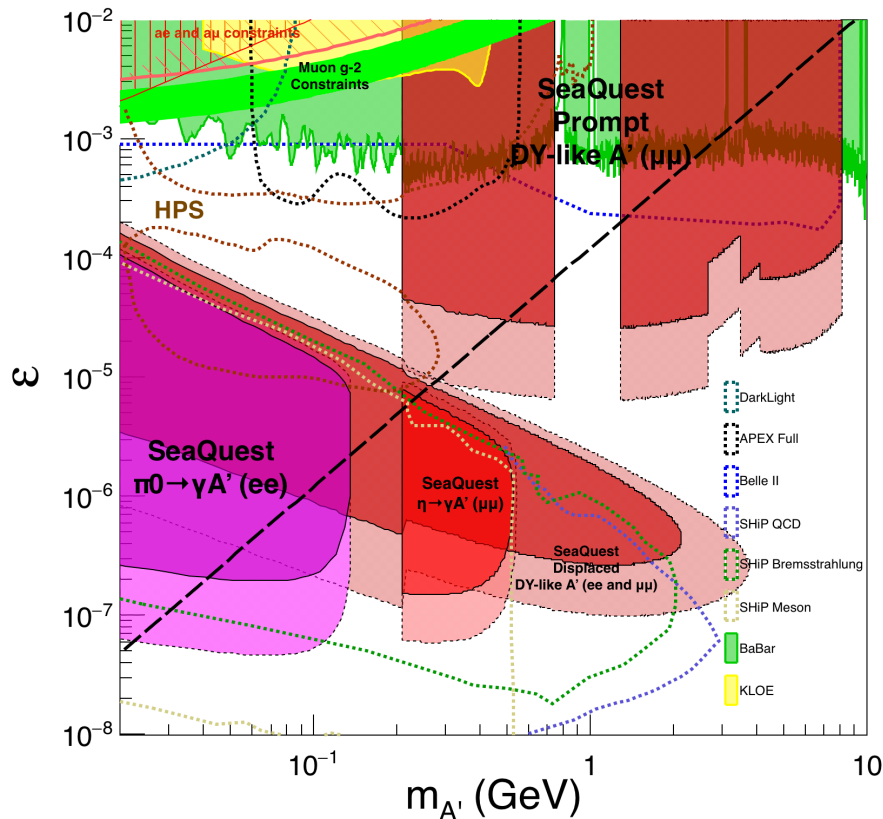
The SHIP proposal at CERN
(<http://ship.web.cern.ch/ship/>)



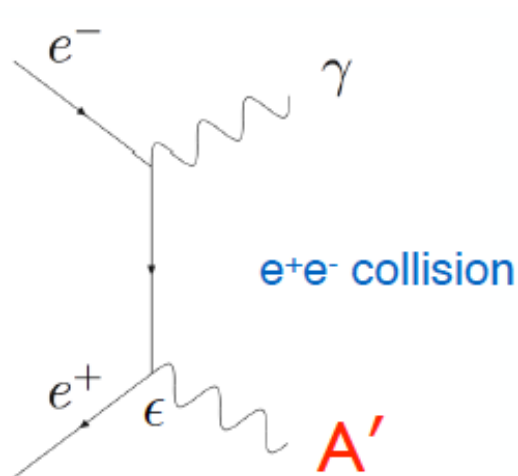
Comparison with SHiP Proposal

120 GeV@FNAL: 2017 -2019
 1.4×10^{18} POT, future dedicated runs

400 GeV@SPS: 2025 -2030
 4×10^{20} POT



A' Production



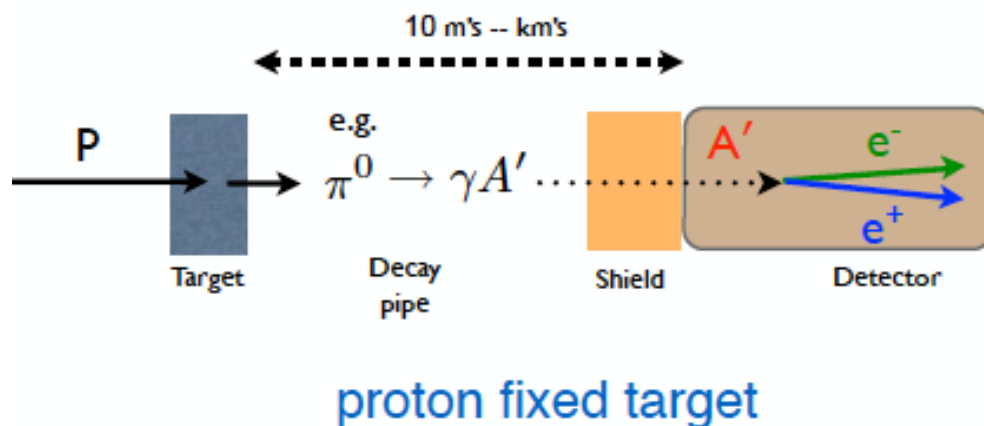
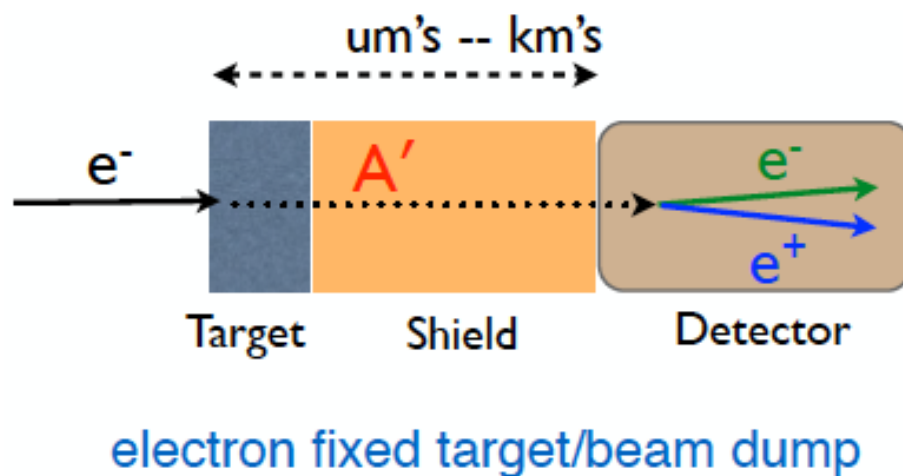
rare meson decays

$$\pi^0 \rightarrow \gamma A'$$

$$\phi \rightarrow \eta A'$$

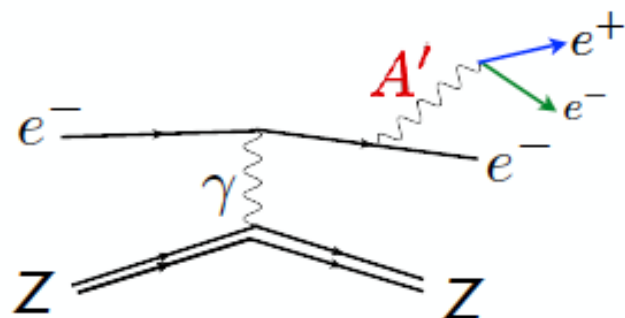
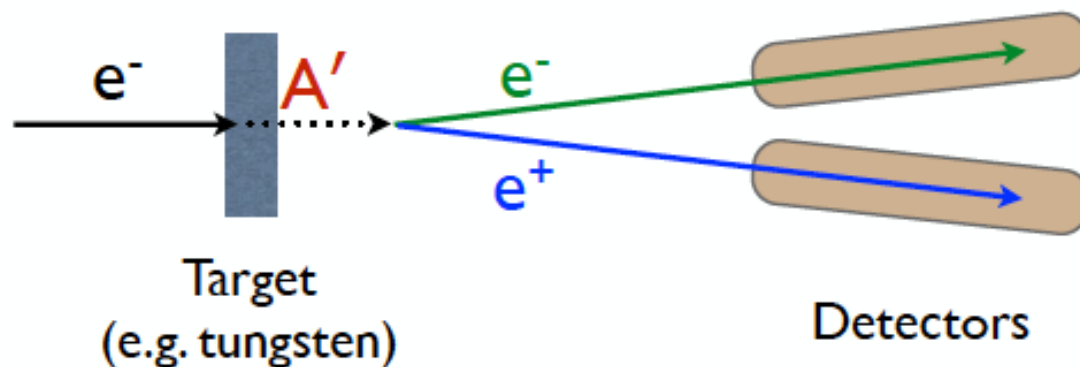
rare Higgs decays

$$h \rightarrow Z A'$$



Electron Beam Fixed Target Experiments

APEX
@J-Lab12

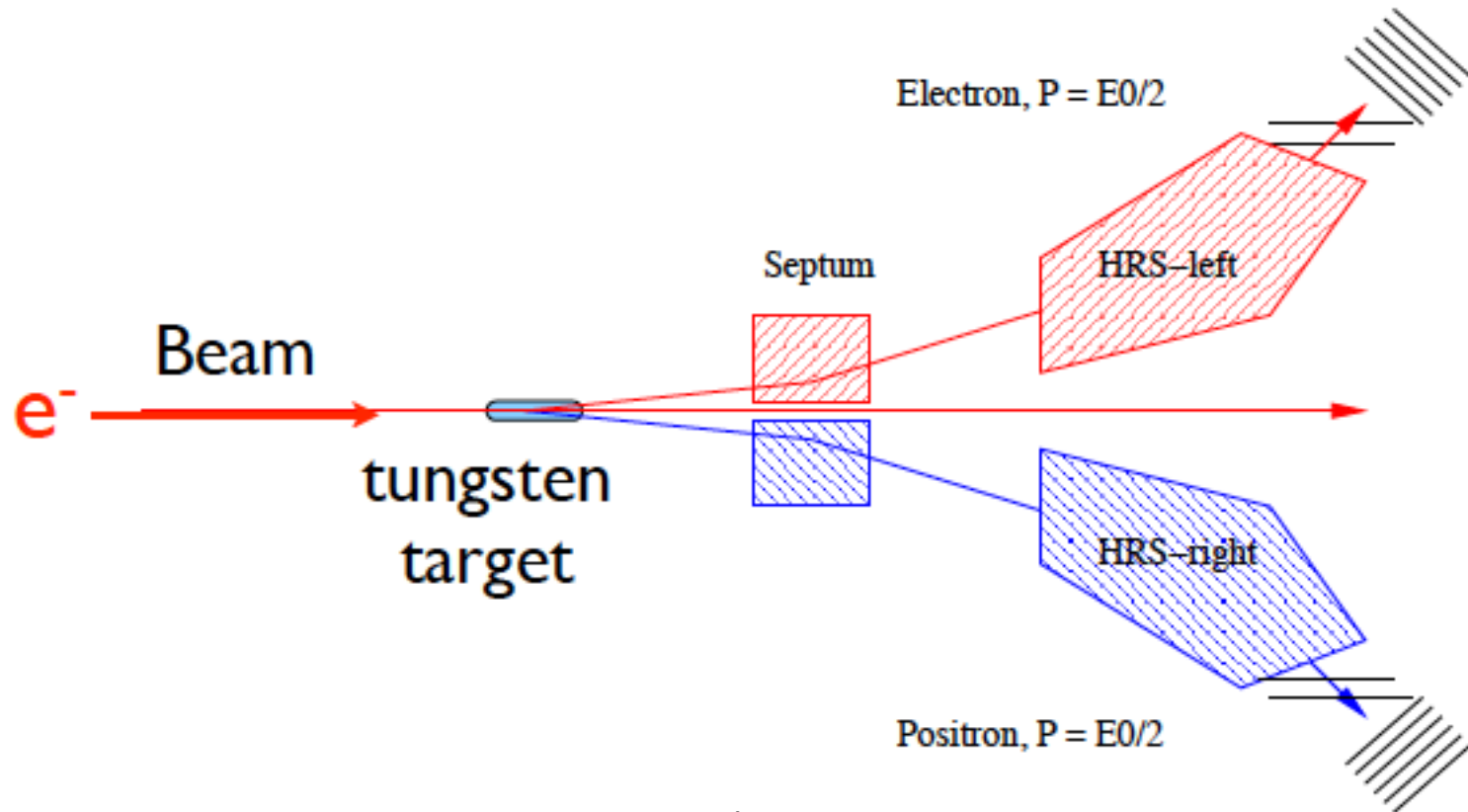


look for $A' \rightarrow e^+e^-$
resonance (“bump hunt”)
or displaced vertex

existing (beam dump) constraints & strategies outlined in

Bjorken, RE, Schuster, Toro *PRD*, 2009

APEX Experiment at J-Lab

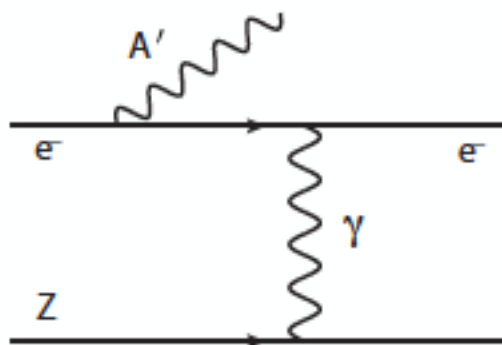


Symmetric configuration to optimize S/B

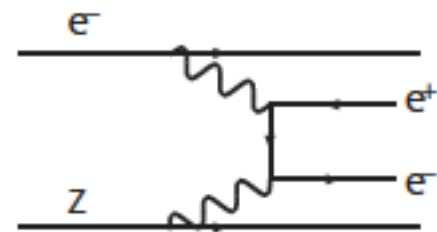
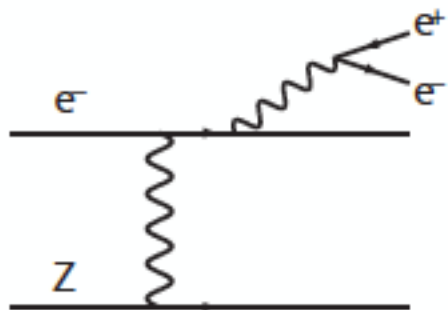
Possible 4 beam energies: 1,2,3,4 GeV @Hall-A

Fall/2017 – Spring/2018: 1 month beam time

Typical Backgrounds



A' signal



Backgrounds

HPS for APEX Experts

APEX

Electron, $P = E_0/2$

HRS-left

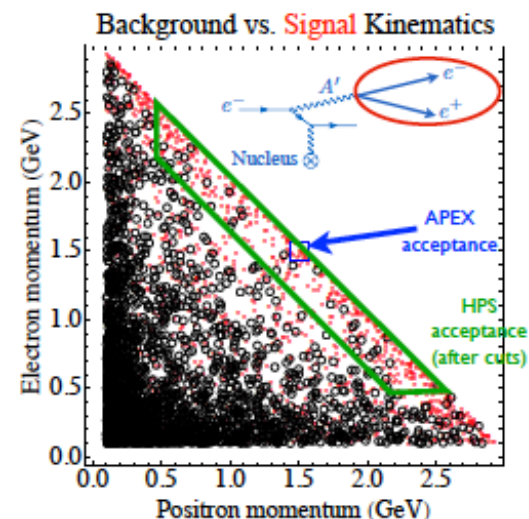
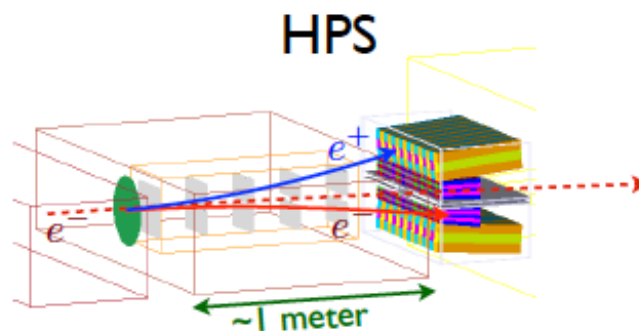
Septum

Sleeve Slit

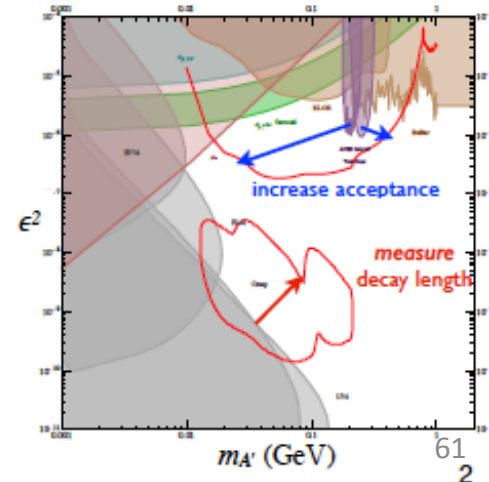
HRS-right

Positron, $P = E_0/2$

Detectors



- is much smaller but still has much larger acceptance
- uses lower currents and thinner targets ($\sim 0.125\% X_0$ @ ~ 200 nA)
- has much better vertex resolution (order 1 mm or so)
- has much worse mass resolution (order 1% or so)
 - compensated for by acceptance
- must deal with close passage of primary beam (down to $500 \mu\text{m}$)
 - requires excellent beam quality, operation in vacuum, high-speed DAQ, high radiation tolerance, tracker movability



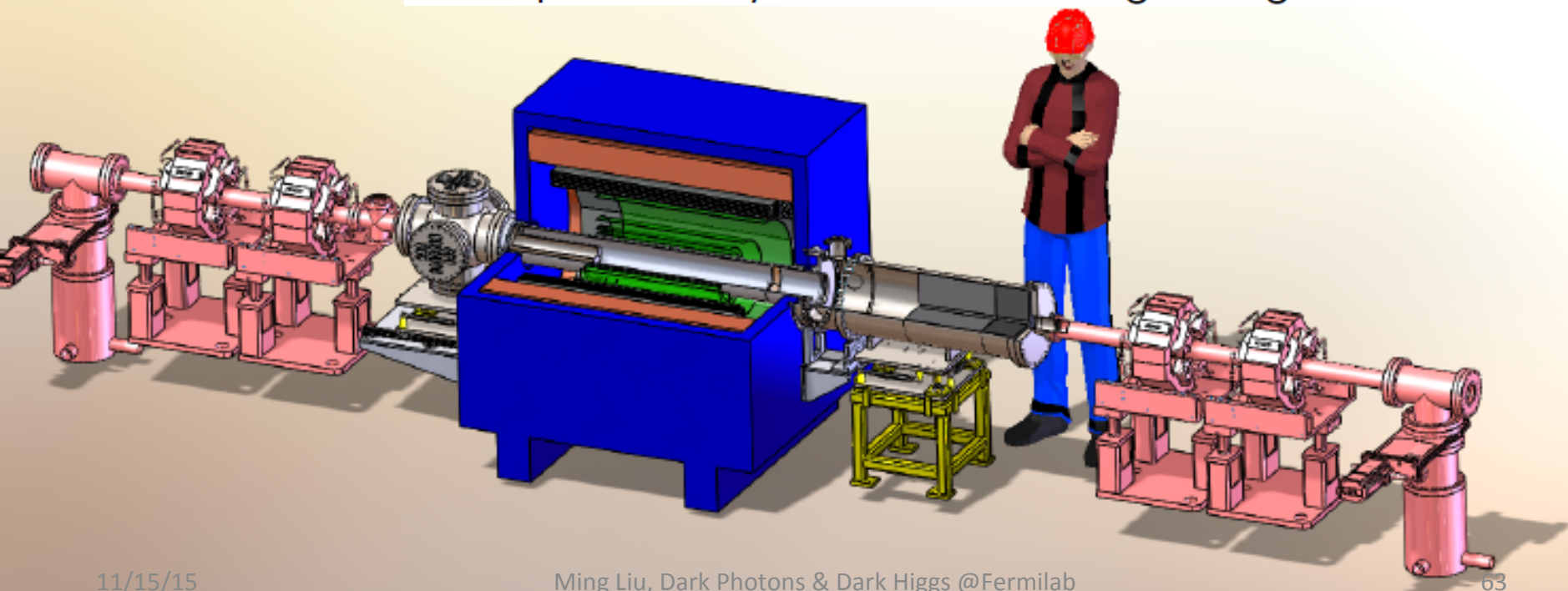
Future HPS Running

The official line:

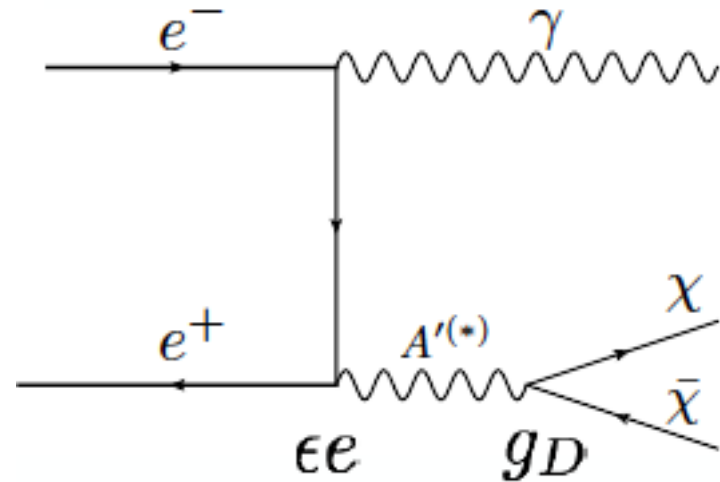
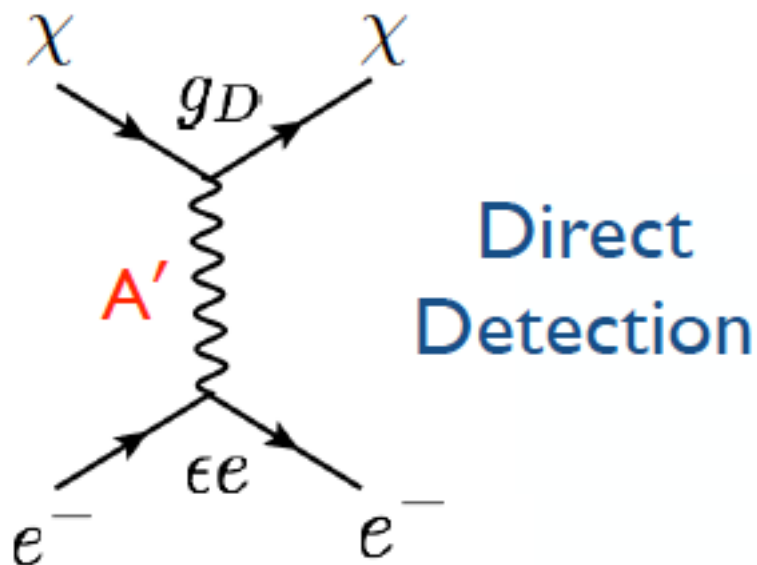
- HPS is scheduled to get more running in Fall 2015, thanks to strong support of JLab management.
- HPS is eager for additional running in FY2016. However, time in Hall B must be shared with magnet construction and commissioning for the CLAS12 Detector over the next year.
- HPS running in Spring 2016 is currently TBD, pending demonstration of HPS operation and a better understanding of demands on Hall B resources.
- HPS must be prepared to take advantage of additional running, so besides analysis of the 2015 data, we are planning to staff shifts, operate the experiment, and analyze data through FY2016.
- In the longer term, HPS expects to run at higher energies in FY2017 and beyond.

Dark Light @JLab

- Measure $e^- + p \rightarrow e^- + p + A' \rightarrow e^- + p + (e^+ + e^-)$
- 100 MeV beam $\Rightarrow$ below pion threshold, simple final state
- *Complete* reconstruction of final state: $e^+ e^-$ pair from decay, scattered electron, recoil proton
 $\Rightarrow$ large acceptance
 $\Rightarrow$ proton only has 1-5 MeV $\Rightarrow$ gas target



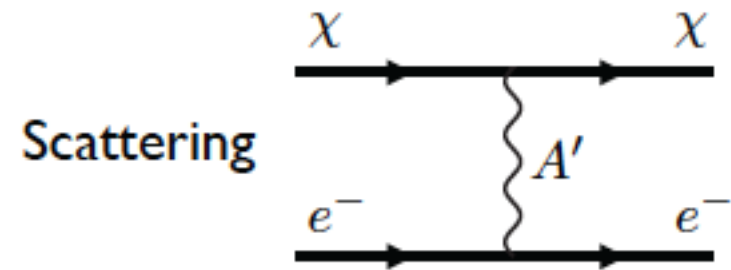
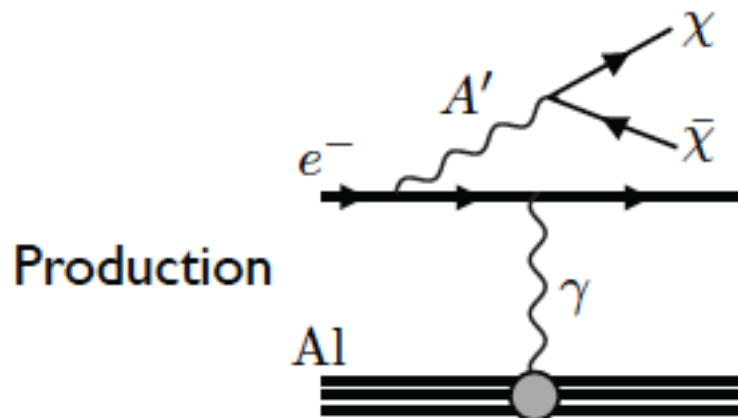
Sub $\sim O(10)$ GeV Dark Matter Interactions via A'



- Direct detection
- Indirect/invisible mode
- Accelerator based search possible
- Very rich phenomenology

Invisible mode:
BaBar, BELLE-II, MiniBooNE

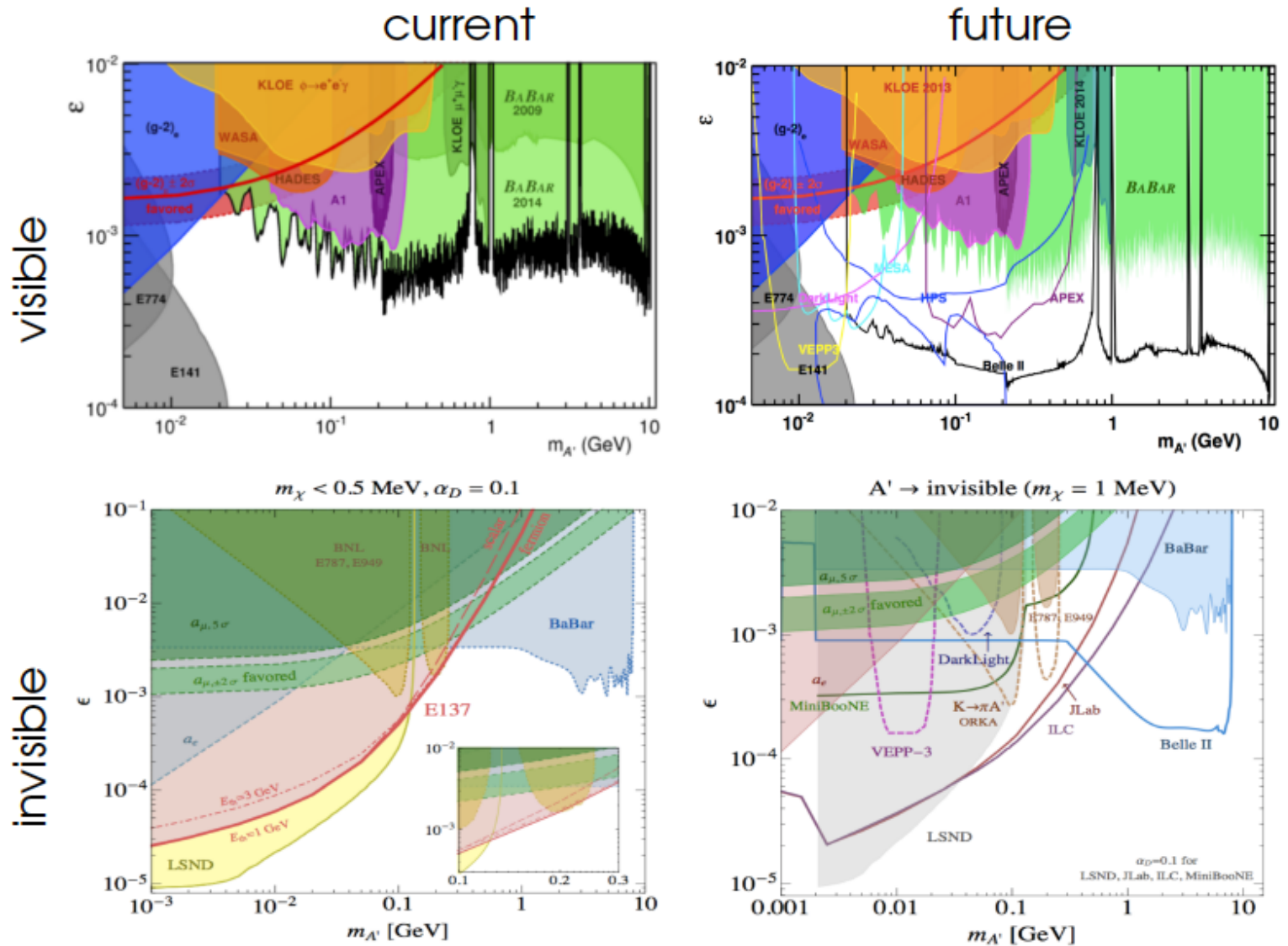
Invisible Mode in Beam Dump Search



see e.g. Batell, Pospelov, Ritz; Deniverville, Pospelov, Ritz; Deniverville, McKeen, Ritz; Aguilar-Arevalo et.al.; Krnjaic, Izaguirre, Schuster, Toro; Diamond, Schuster; Batell, RE, Surujoni; BDX Collaboration

Dark Photon Current and Future Limit

(2014 Projections)



Cold Dark Matter “Small-scale” Challenges

Slide from
R. Essig 4/2015

- “Cusp-core problem”:

some galaxies appear less dense in the center than predicted by simulations

e.g. Navarro et al. 1997

- “Missing satellites problem” & “Too big too fail problem”:

simulations predict too many low-mass subhalos & dozens of “dark” satellites more massive than the dwarf spheroidals

e.g. Klypin et al. 1999; Moore et.al. 1999

Boylan-Kolchin et.al. 2011

- Resolution?

- baryonic physics?

- warm dark matter? (e.g. $\sim$ keV sterile neutrino?)

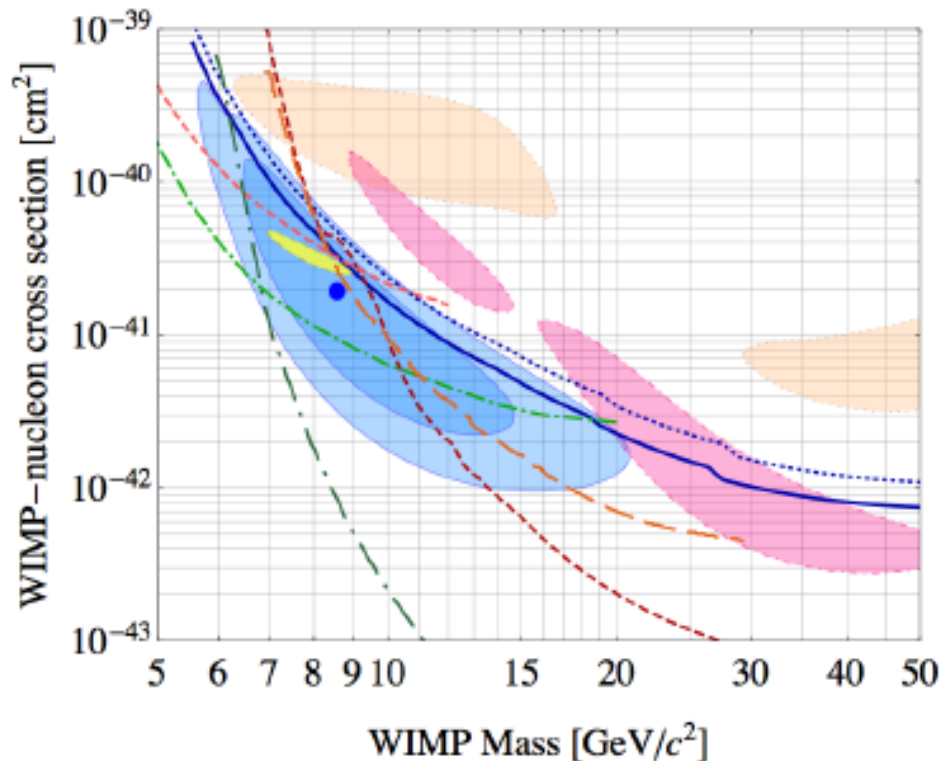
- self-interacting dark matter?

Spiegel, Steinhardt 1999

- ... Ming Liu, Dark Photons & Dark Higgs @Fermilab

Hints from WIMP Search

New dark matter interactions?

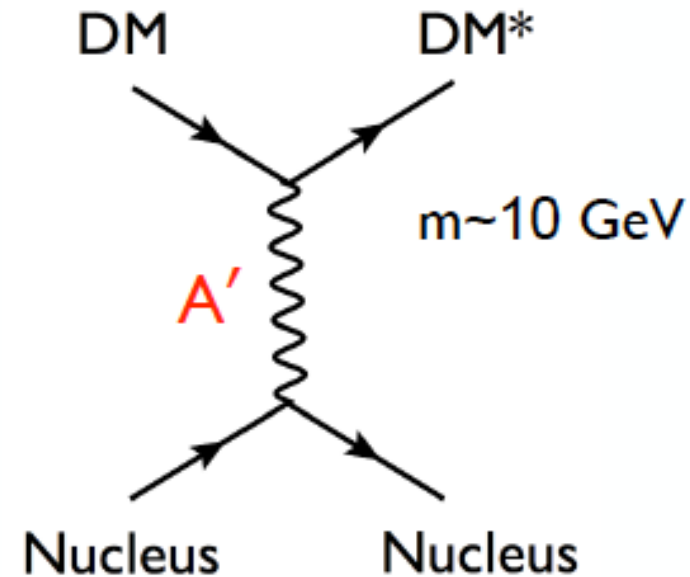


direct detection hints?

DAMA, CoGeNT, CRESST, CDMS-Si

11/15/15

Ming Liu, Dark Photons & Dark Higgs @Fermilab



hard for Standard Model
mediators, easier for
light mediators

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A New High-Granularity Displayed Dimuon Vertex Trigger

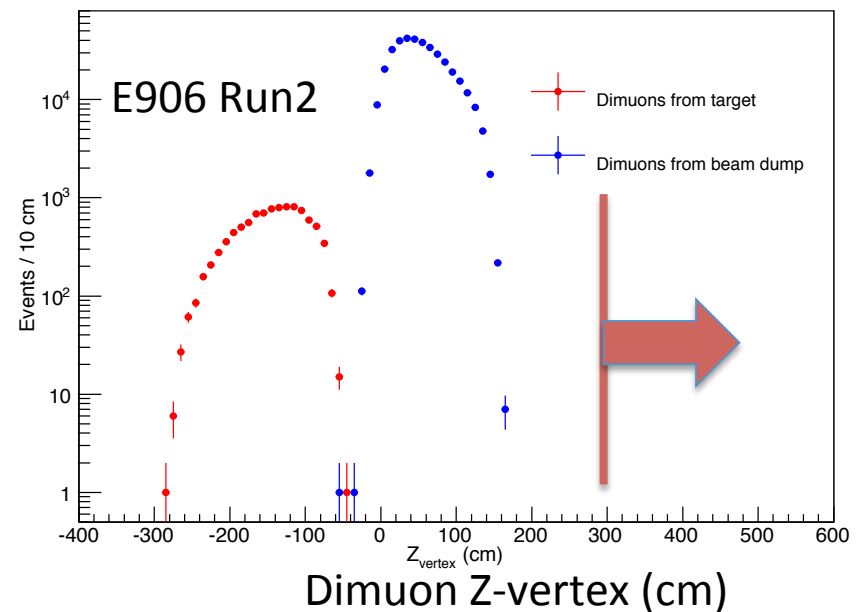
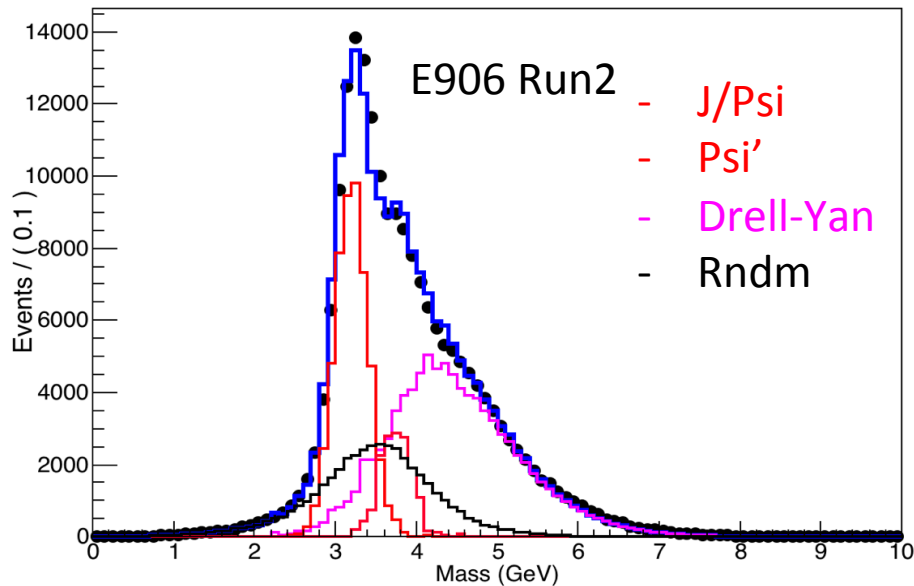
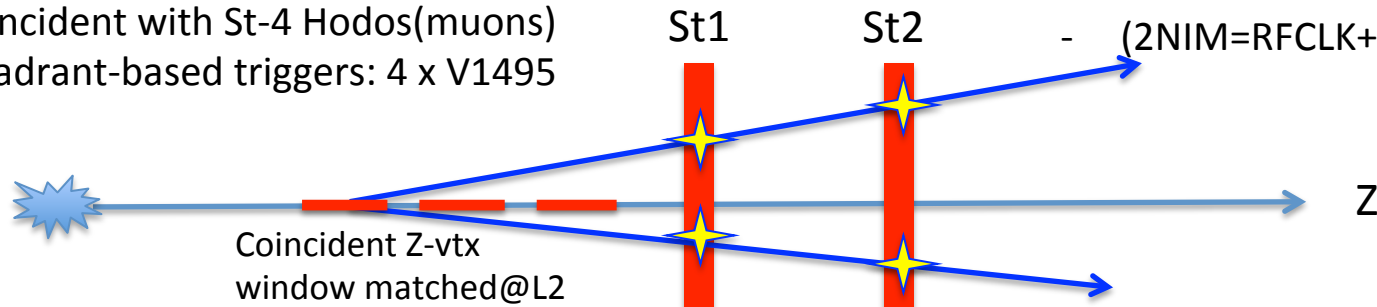
High rejection power, very low rate, $\ll 1$ kHz (E906 DAQ limit)

Y-Plane Trigger:

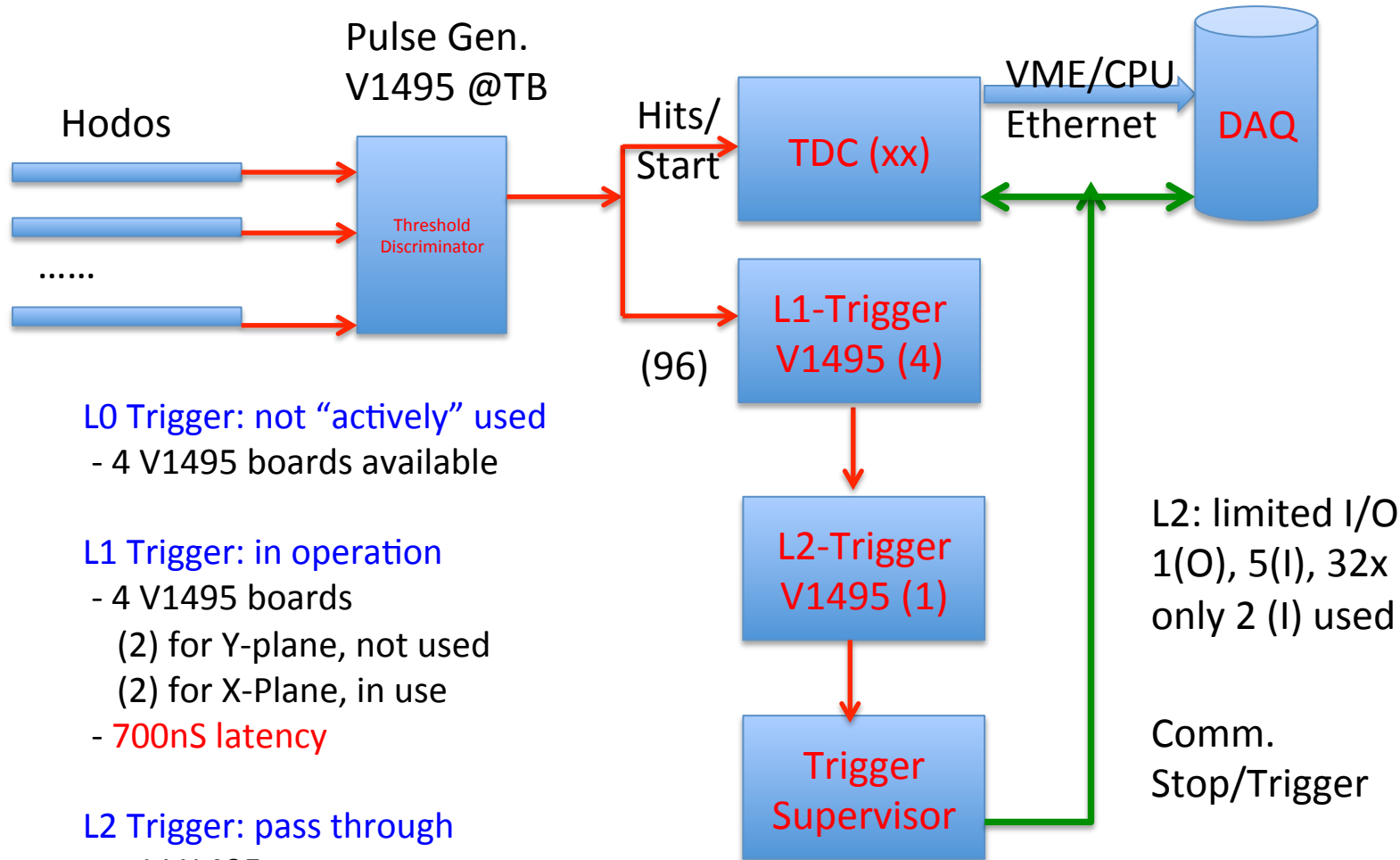
- A quadrant panel: 50cm x 50cm, 1cm thick
 - 1cm x 1cm x 50 cm scintillating strips, SiPM readout
- Straight line projection, 30cm Z-vertex resolution
- Displaced z-vertex, mostly low mass < 3 GeV
- Coincident with St-4 Hodos(muons)
- Quadrant-based triggers: 4 x V1495

Y-channels per quadrant:

- 1x V1495
- $50(\text{St1}) + 50(\text{St2}) + 8 \times 2 (\text{St4-Y1,2}) = 116$
- $96 + 64 = 160$ possible
 - $72 + 72 + 16 = 160$ (possible)
 - $(2\text{NIM} = \text{RFCLK} + \text{ComSTOP})$



Current E906 Trigger & DAQ System



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

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

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

TS: Trigger Supervisor

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

Comm.
Stop/Trigger

V1495 Board

2 Altera FPGA Chips: Cyclone-V

Trigger lookup table



Experimental Hall

