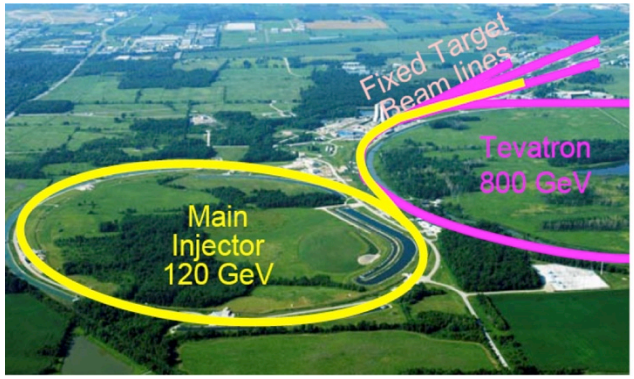
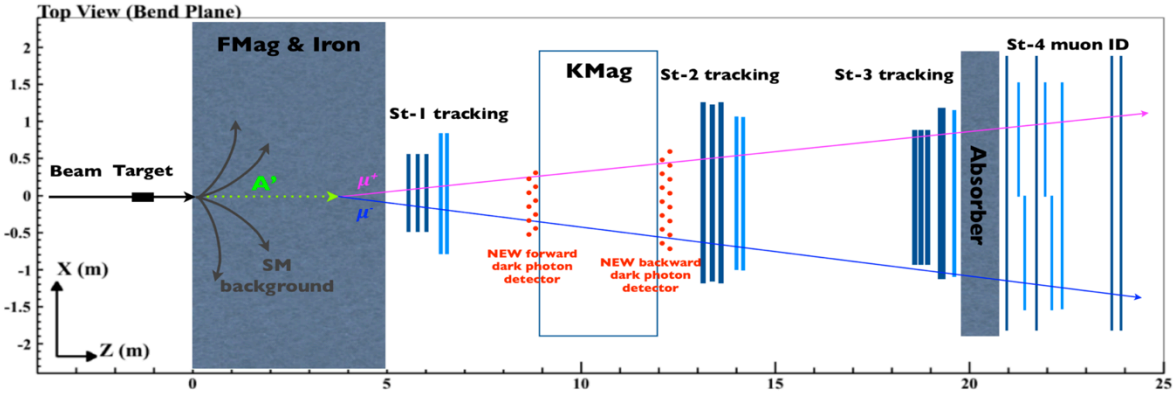
A Direct Search for Dark Photon and Dark Higgs Particles with the SeaQuest Spectrometer in Beam Dump Mode at Fermilab

Ming X. Liu
Los Alamos National Lab

(Fermilab E-1067 Collaboration)





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: (parasitic runs)

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

Phase-II: (upgrade)

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

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

Fermilab

Nigel S. Lockyer
Directorate
TEL 630.840.3211
Lockyer@fnal.gov

July 15, 2015

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

Dear Ming,

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

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

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

Sincerely,

Nigel S. Lockyer
Director of Fermilab

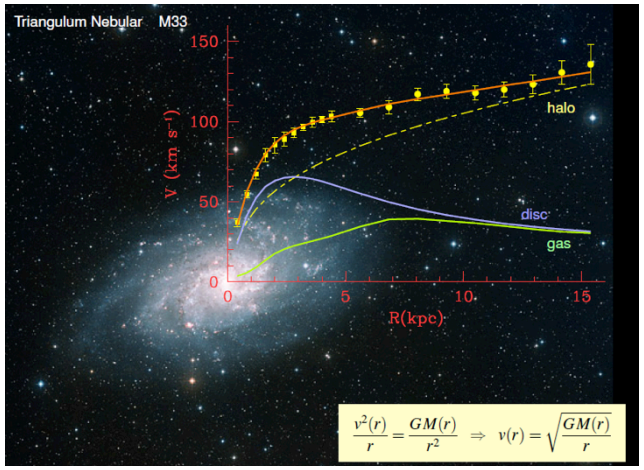
cc: D. Bortoletto, G. Bock, P. Reimer, J. Shank, S. Geer, P. McBride, D. Geesaman, J. Lykken, T. Meyer, A. Stone

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

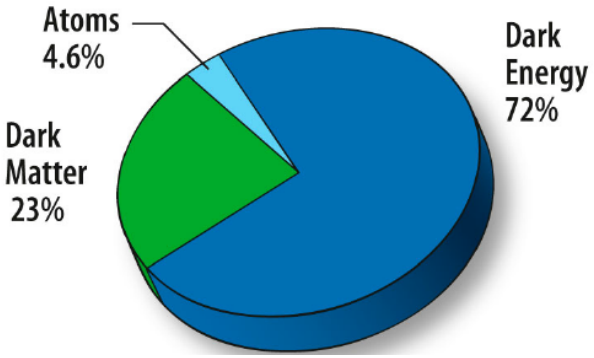
NEW EXPERIMENT! E-1067

Dark Matter?

Galaxies' rotation curve



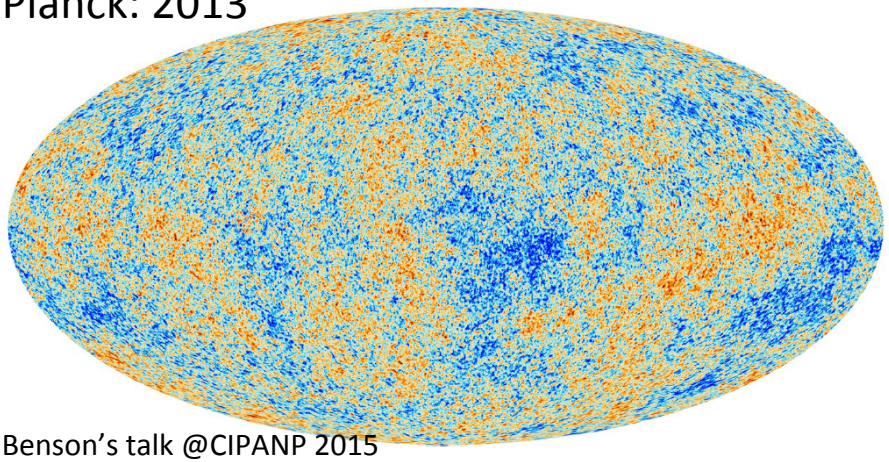
F. Zwicky, ApJ 86 (1937) 217, V. Rubin et al, ApJ 238 (1980) 471



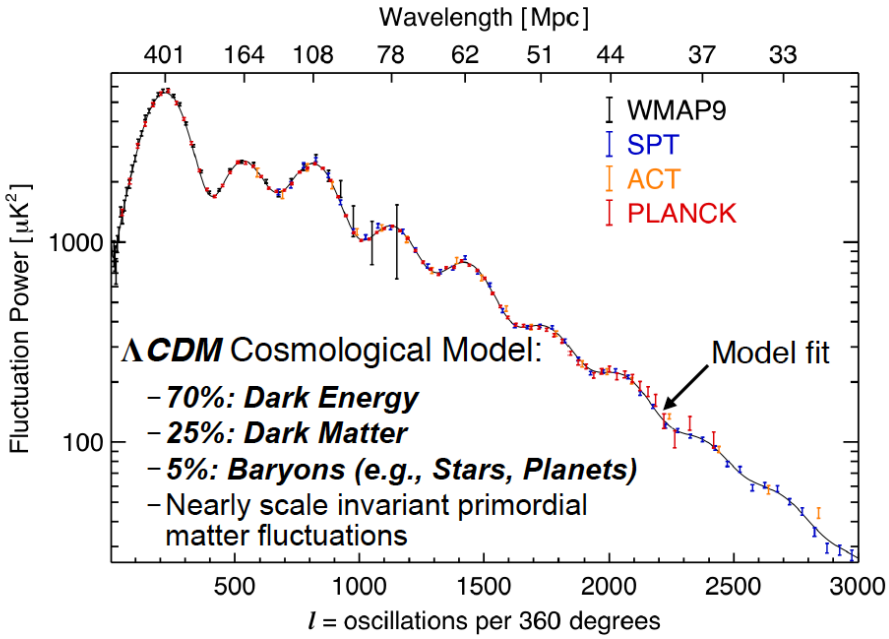
Gravitational lensing (Hubble 2007)

30μK RMS fluctuations on 3 K background

Planck: 2013



Benson's talk @CIPANP 2015



What Are the Dark Particles?

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

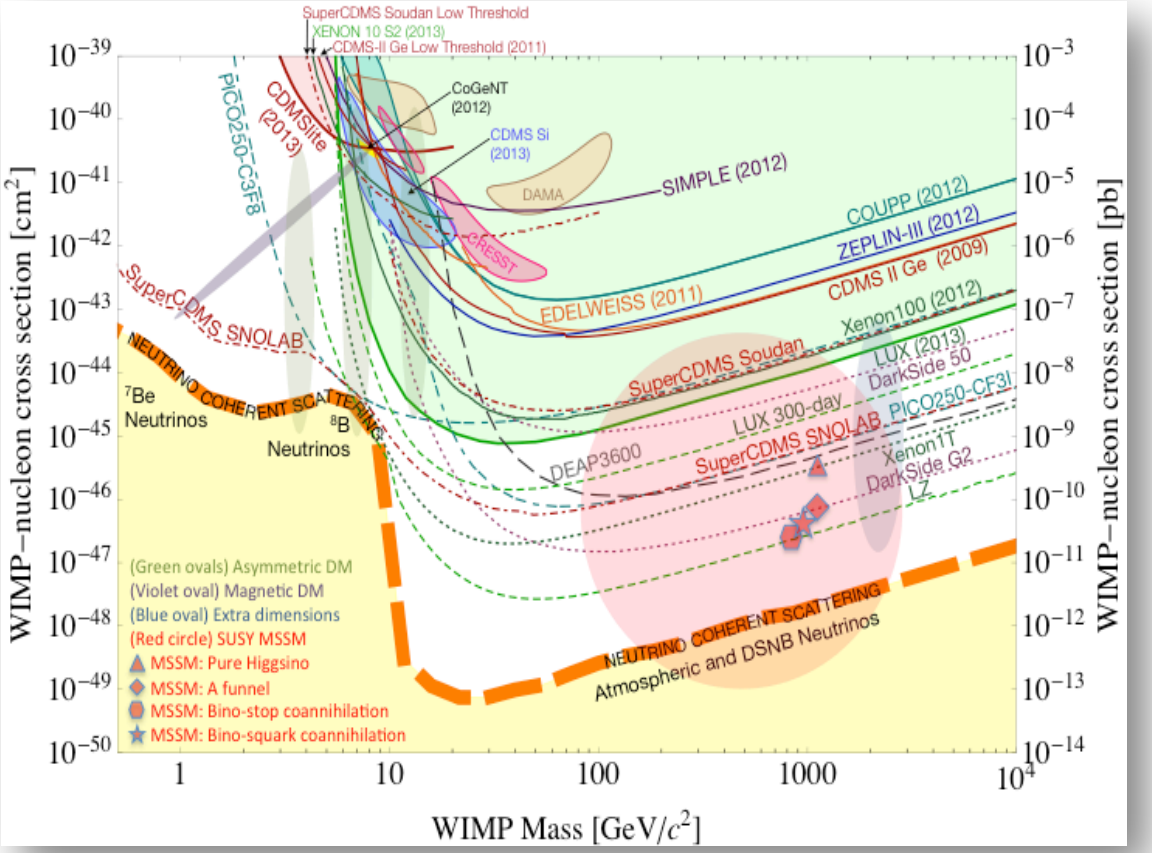
"Sub-GeV" low mass weakly-interacting dark particles become very interesting!

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.

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

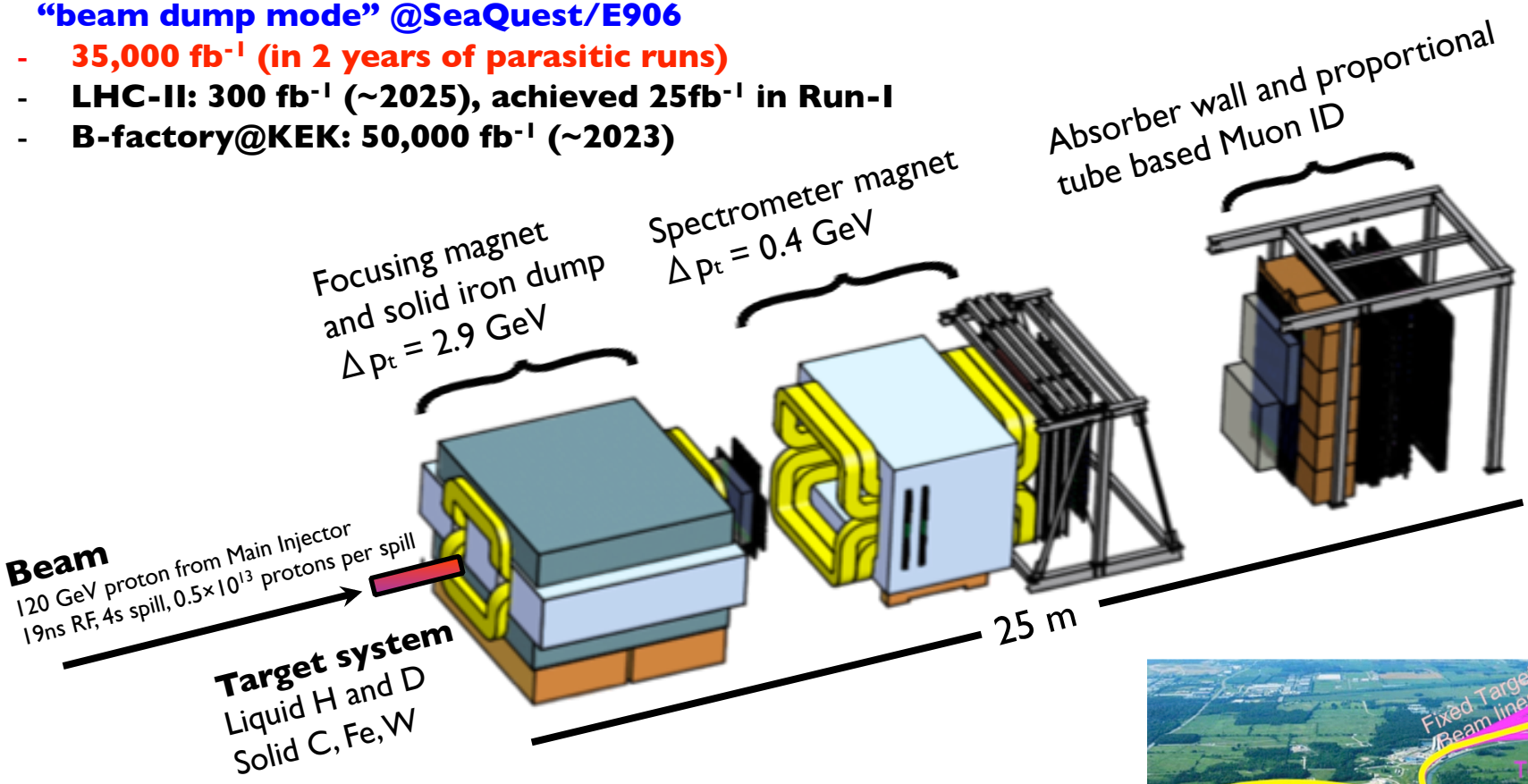
- Imaginable space for these experiments is rapidly disappearing
- the "natural" theory space is also disappearing.
- I like to think that Dark Matter is on solid ground, maybe not!!!

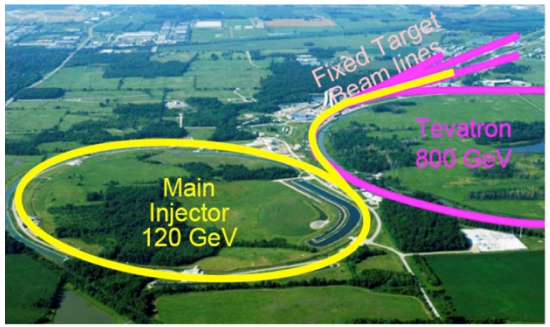


Intensity Frontier at Fermilab: 120 GeV Beam

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)**

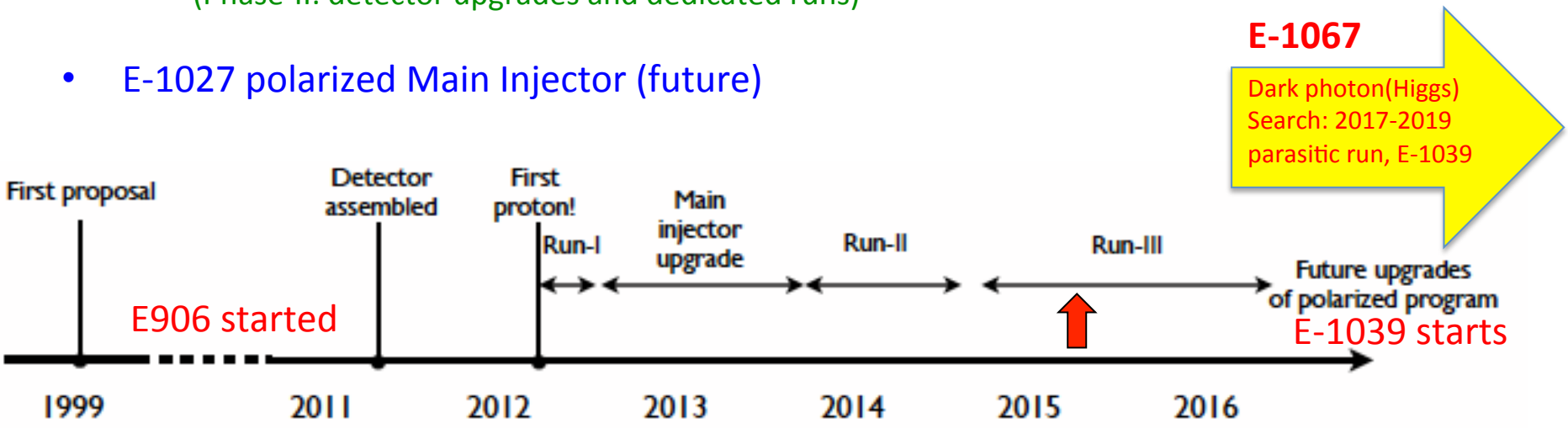




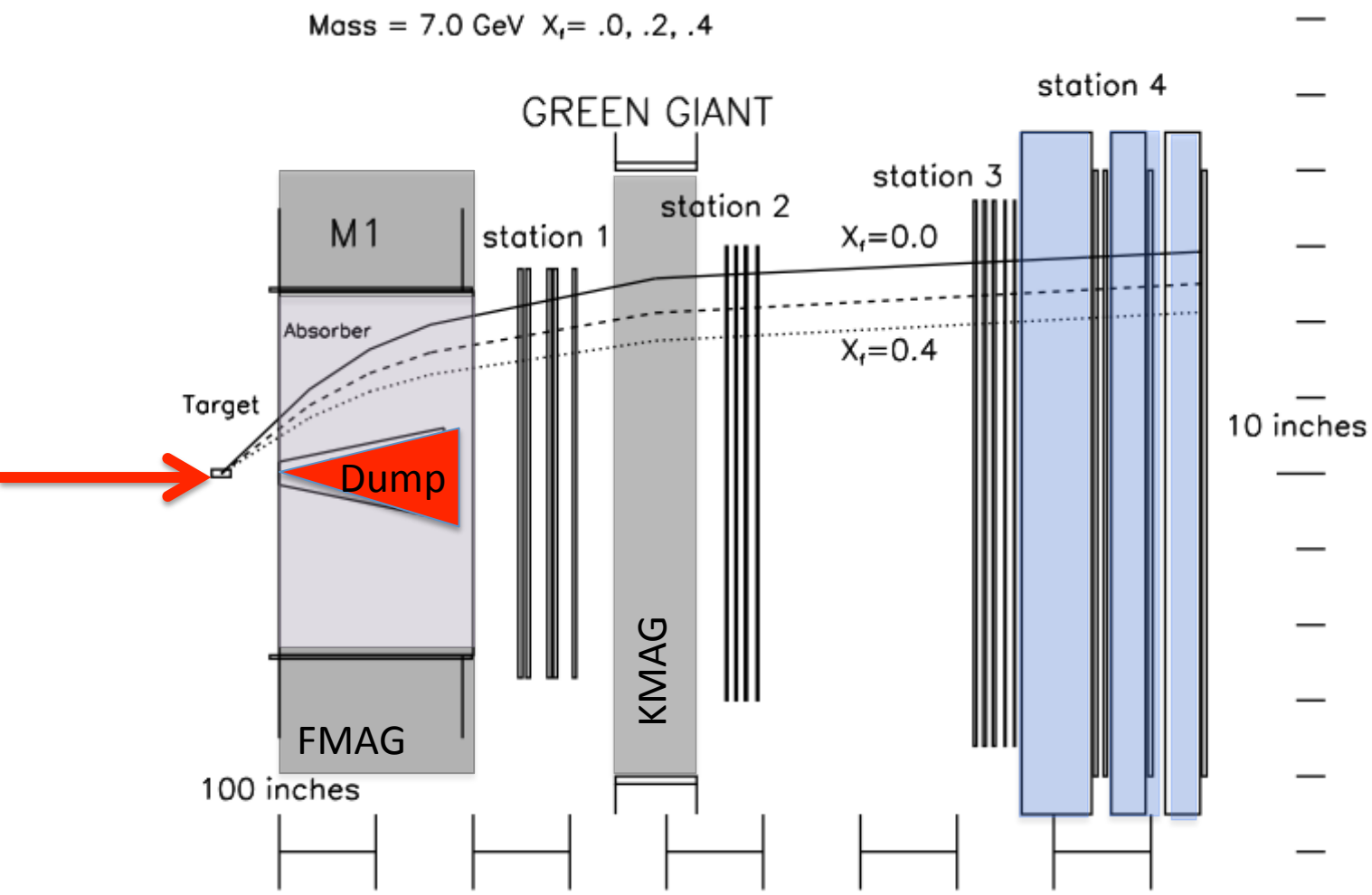
- Capture most beam in beam dump mode: p+Fe collisions!
- Parasitic run mode possible with other experiments, E1039/E1027

Schedules of SeaQuest Experiments

- E-906 complete data taking in summer 2016
  - E906 targets are located ~1.3m upstream of the beam-dump, ~10% λ_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, ~6% λ_I.
  - Target/trigger installation: 2016 - 2017
  - Data taking: 2017 – 2019
- **E1067 Timeline (New!)**
  - Phase-I (Parasitic run) with E1039: 2017-2019
  - (Phase-II: detector upgrades and dedicated runs)
- E-1027 polarized Main Injector (future)

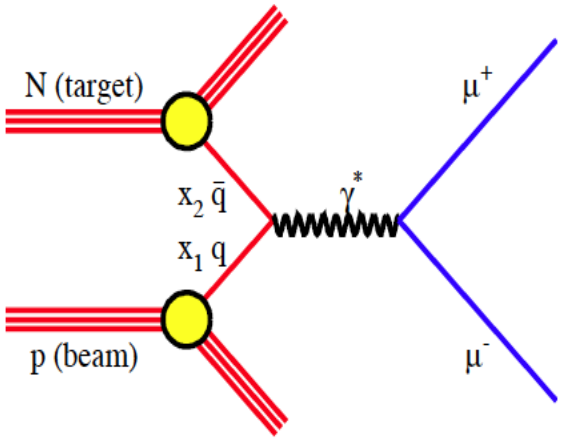


SeaQuest Schematic

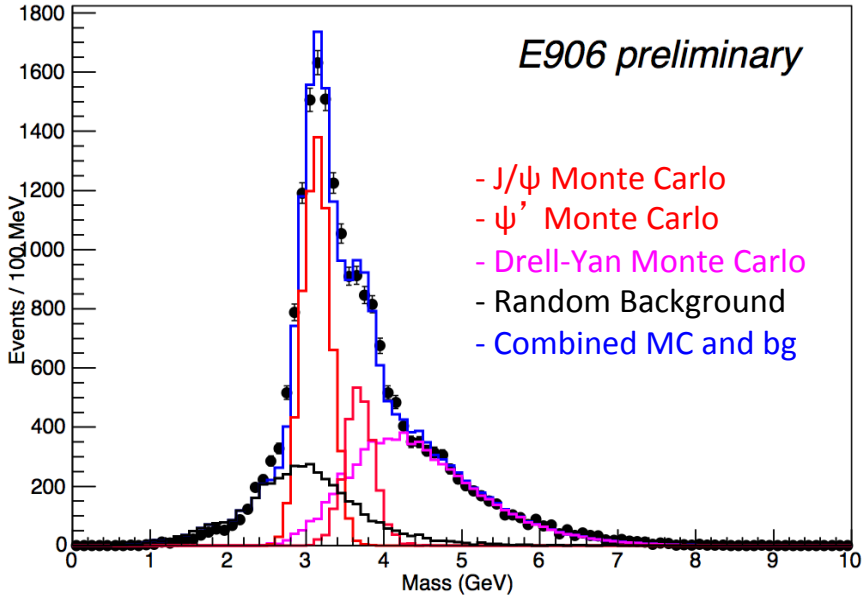


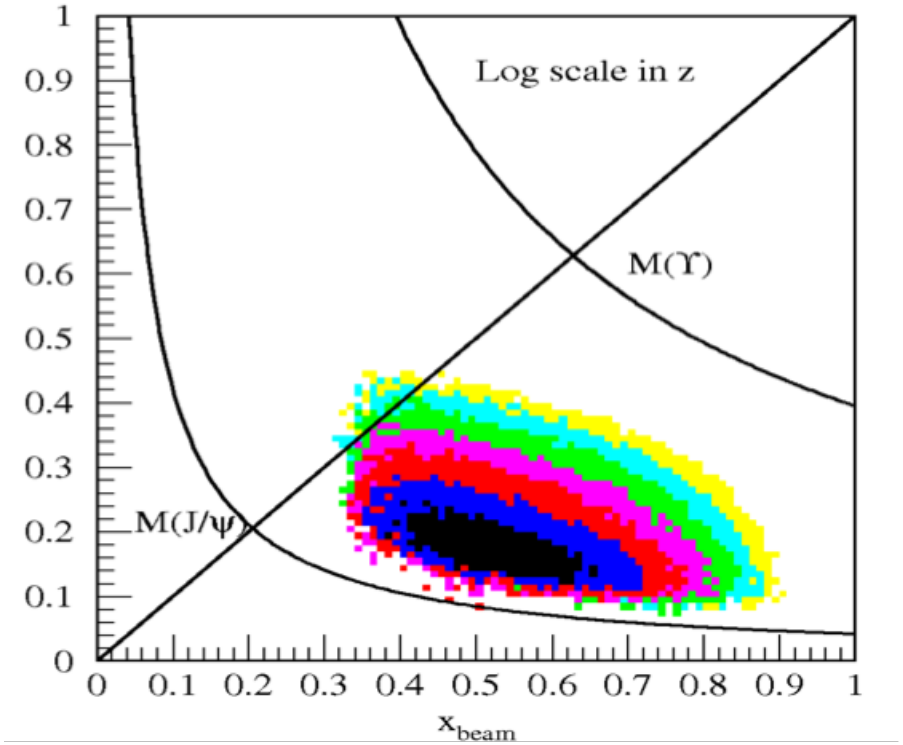
- 4 scintillator hodoscope stations (x and y)
- 4 tracking stations (x and stereos) MWPC

E-906 Drell-Yan Acceptance



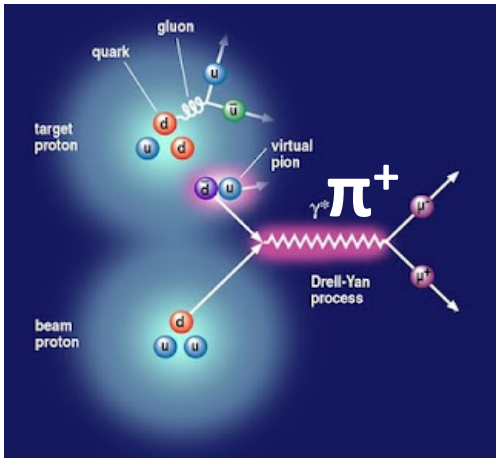
Run-II data: 5% of total projected stat.



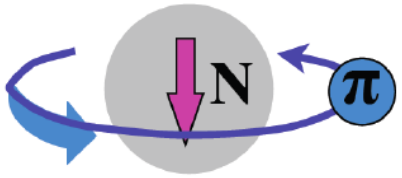


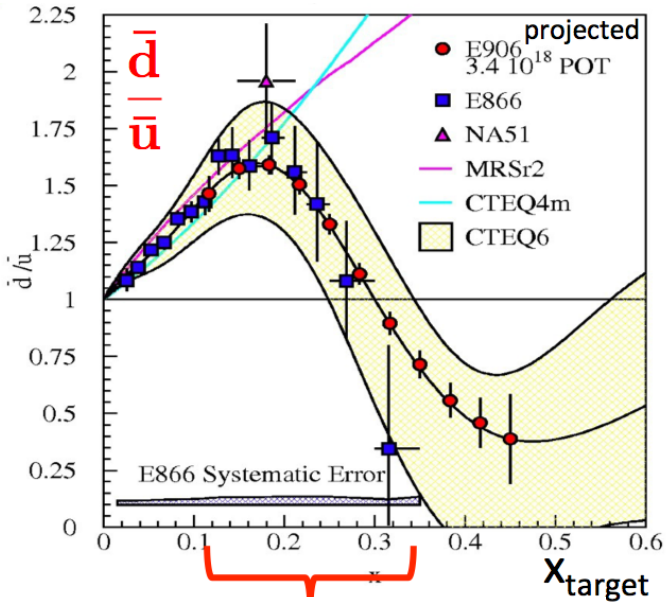
E906 Physics Programs: 2009-2016

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

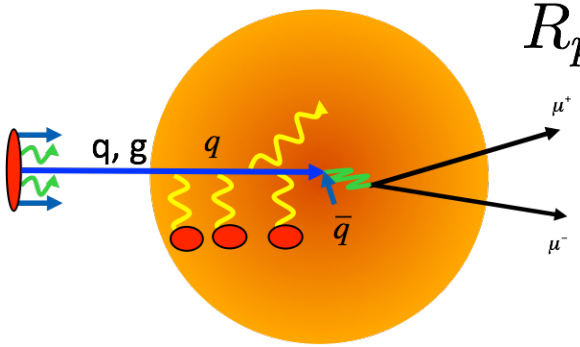


$$|p>=|p^0>+|n>|\pi^+>$$

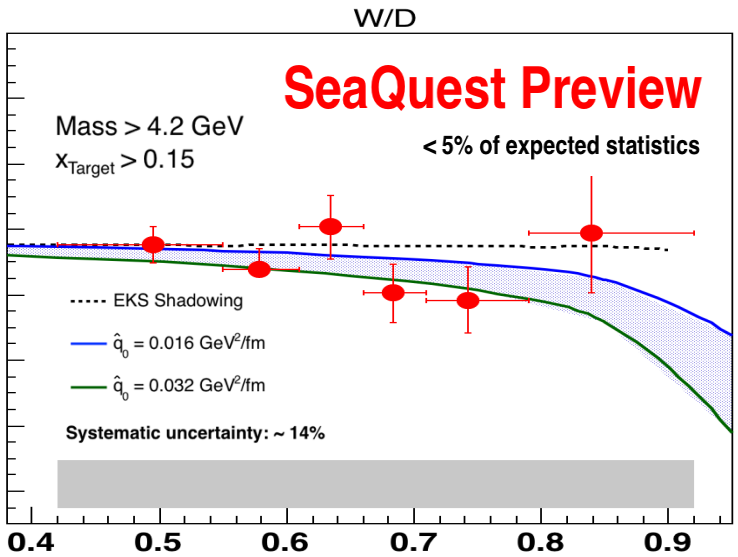




- Quark energy loss in p+A



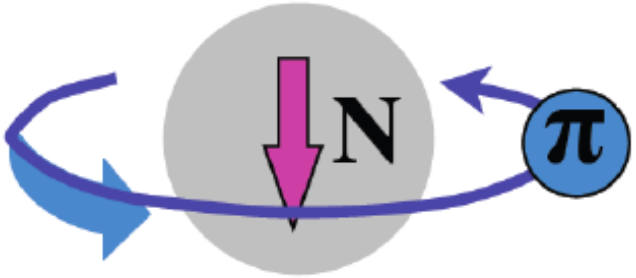
$$R_{pA} = \frac{\sigma^{pA}}{A \times \sigma^{pp}}$$

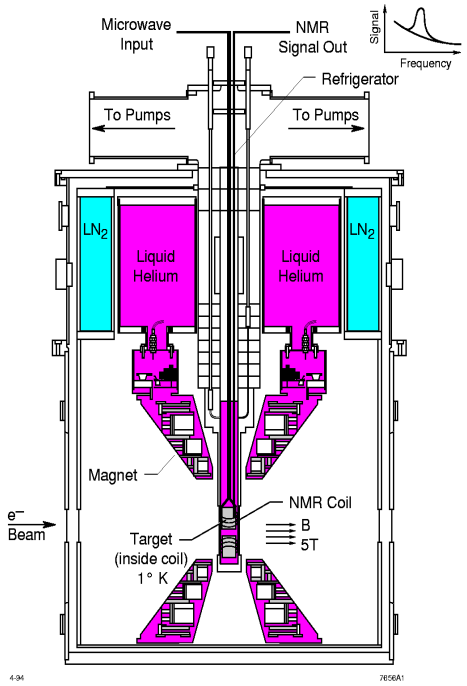


E1039 Physics Program: 2016-2019

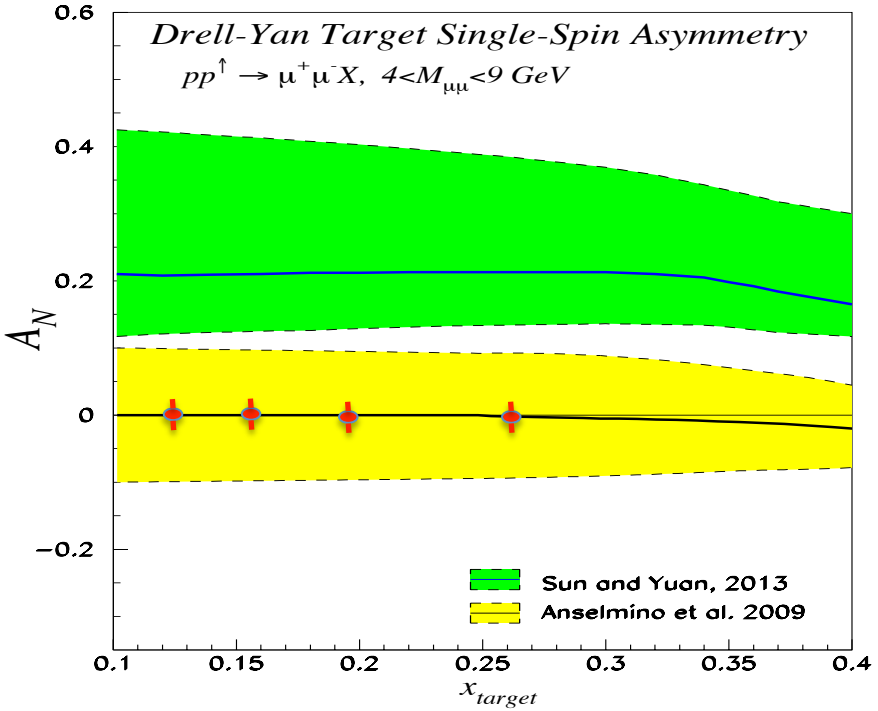
Polarized Fixed Target Drell-Yan Experiment

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





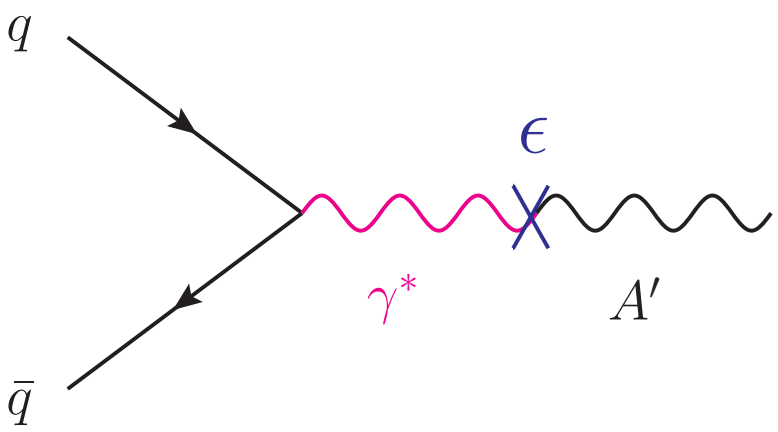
LANL polarized proton (NH_3) target



E-1067: Direct Productions of Dark Photons and Dark Higgs in p+Fe at Fermilab

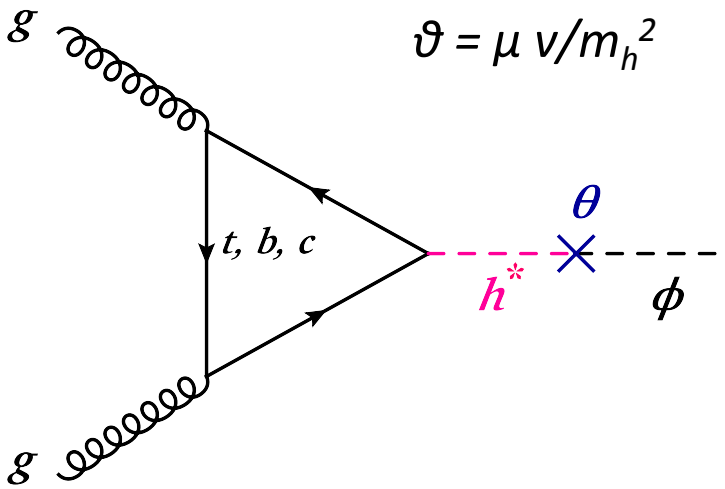
Photon portal: "vector"

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



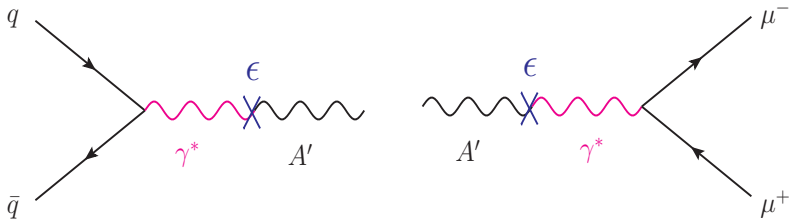
Higgs portal: "scalar"

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

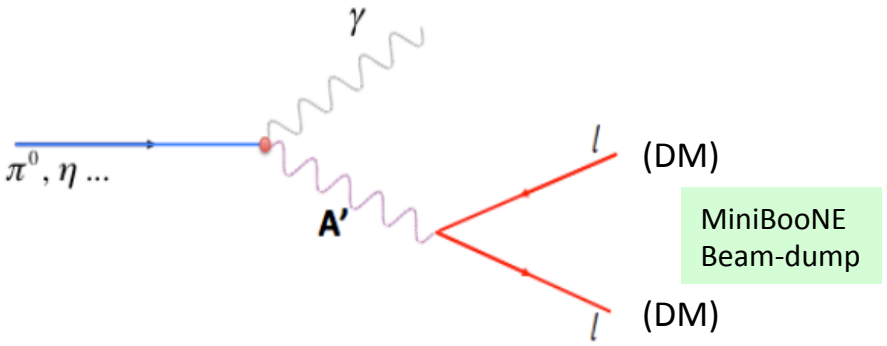


Dark Photon Search in Dimuon Channel at SeaQuest in Beam Dump Mode (p+Fe)

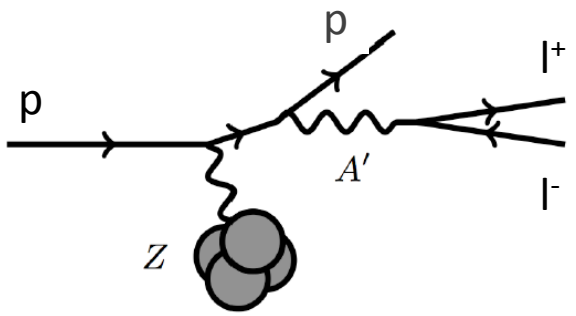
1. Drell-Yan like



2. π^0, η, … decay



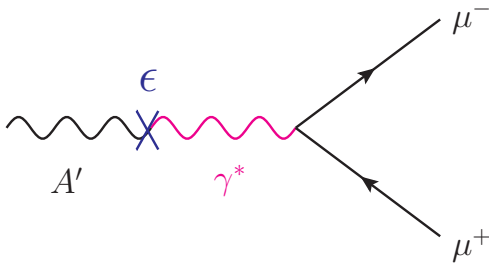
3. Bremsstrahlung



Dark Photon Decay Modes

"Minimal" Decay:

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

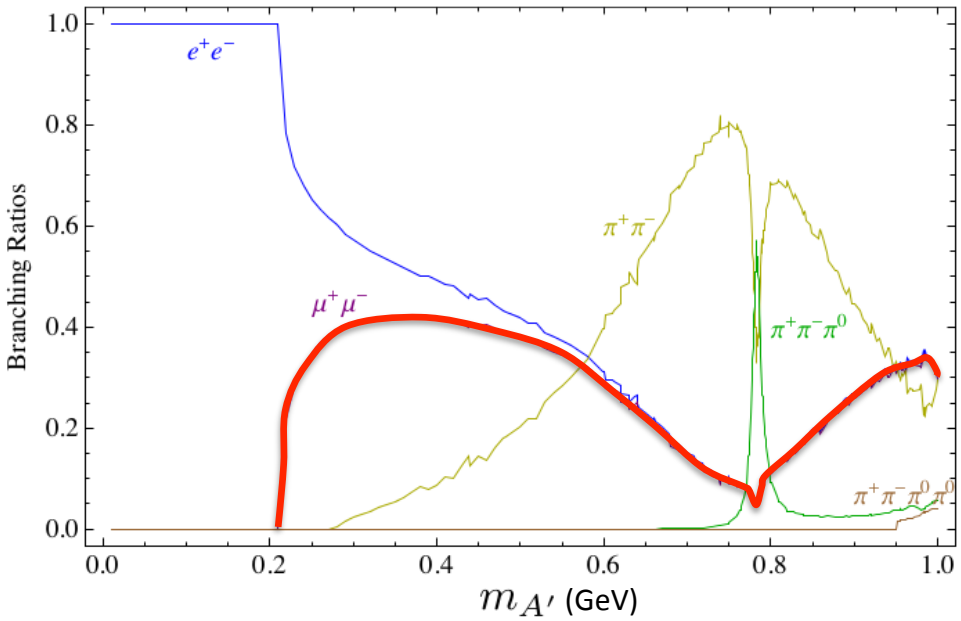


$$\Gamma(A' \to f + \bar{f}) = C\frac{\epsilon^2 m_{A'}}{3} e_f^2 \alpha_{\rm em} \left(1 + \frac{2m_f^2}{m_{A'}^2}\right)\sqrt{1 - \frac{4m_f^2}{m_{A'}^2}},$$

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

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

D. Curtin, et al, arXiv: 1312.4992

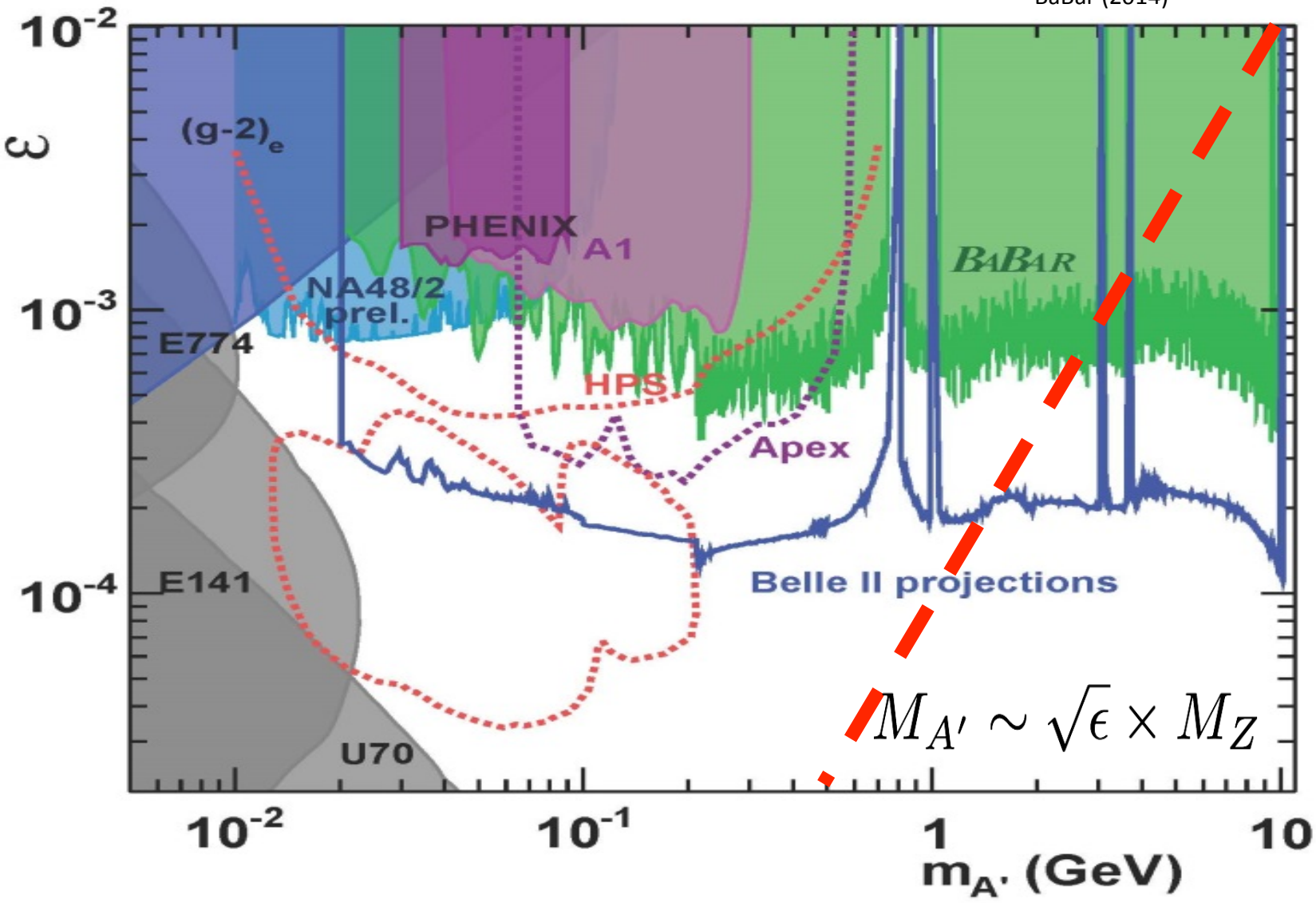


"General" Decay:

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

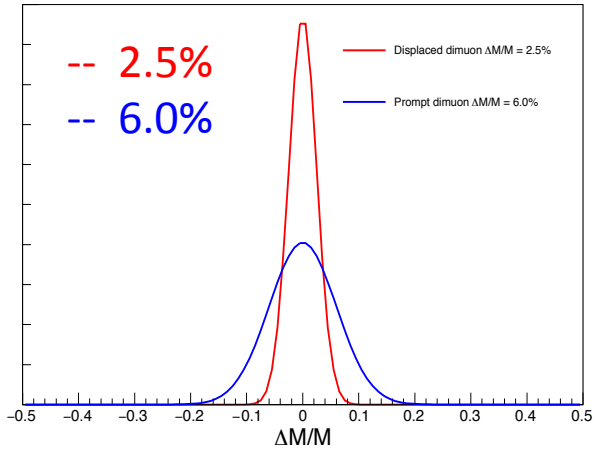
Slide credit: Bertrand Echenard

Current Limits on Dark Photon Search

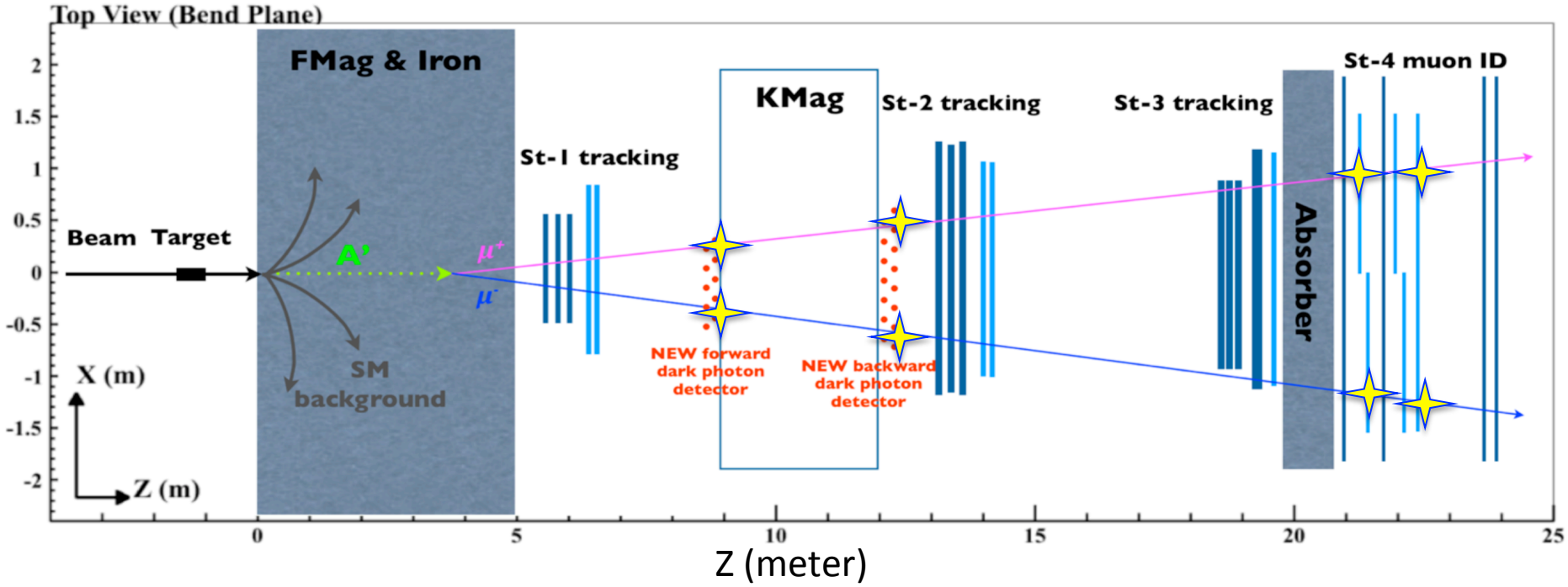


Proposed Experimental Measurements

- 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
  3. Mostly from beam dump (target ~6% λ_I.)
- Beam time
  1. Run parasitically with E1039 (2017-2019)
  2. Possible dedicated runs later with upgraded ($e^{+/-}$, $h^{+/-}$)



Dimuon mass resolution



A New High-Granularity Displayed Dimuon Vertex Trigger

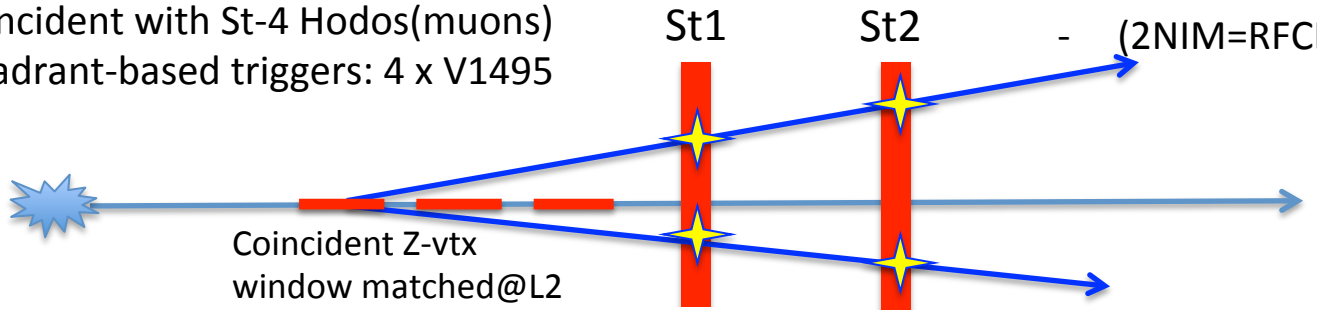
High rejection power, very low rate, << 1 kHz(E906 DAQ limit)

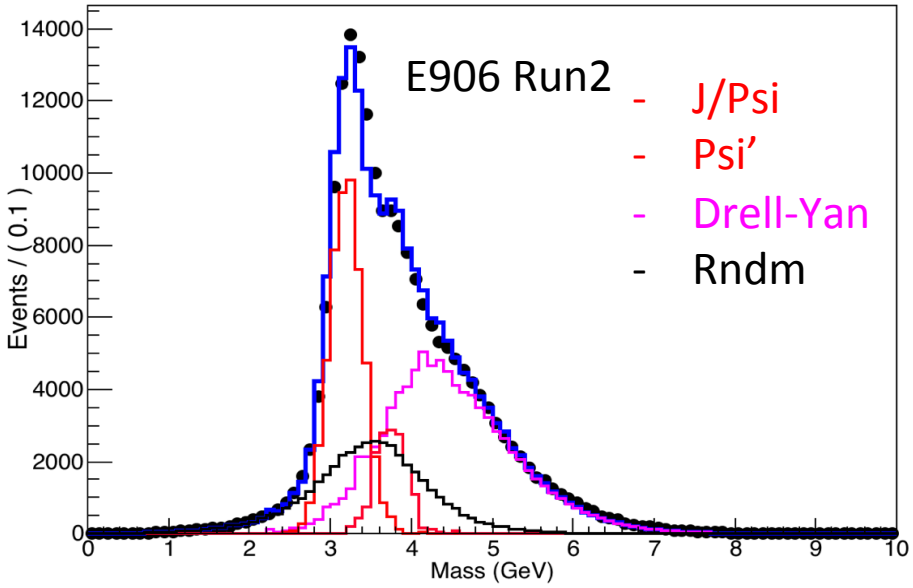
Y-Plane Trigger:

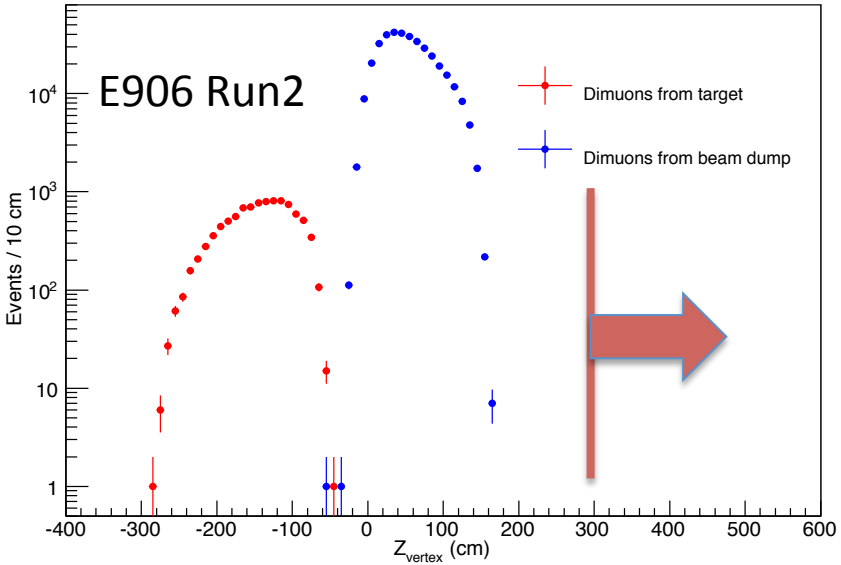
- A quadrant panel: 40 x 40 cm^2, 1cm thinck
  - 40 x 1cm x 40 cm scintillating strips, SiPM readout
- Straight line projection, 30cm Z-vertex resolution
- Displaced z-vertex, mostly low mass < 3GeV
- Coincident with St-4 Hodos(muons)
- Quadrant-based triggers: 4 x V1495

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

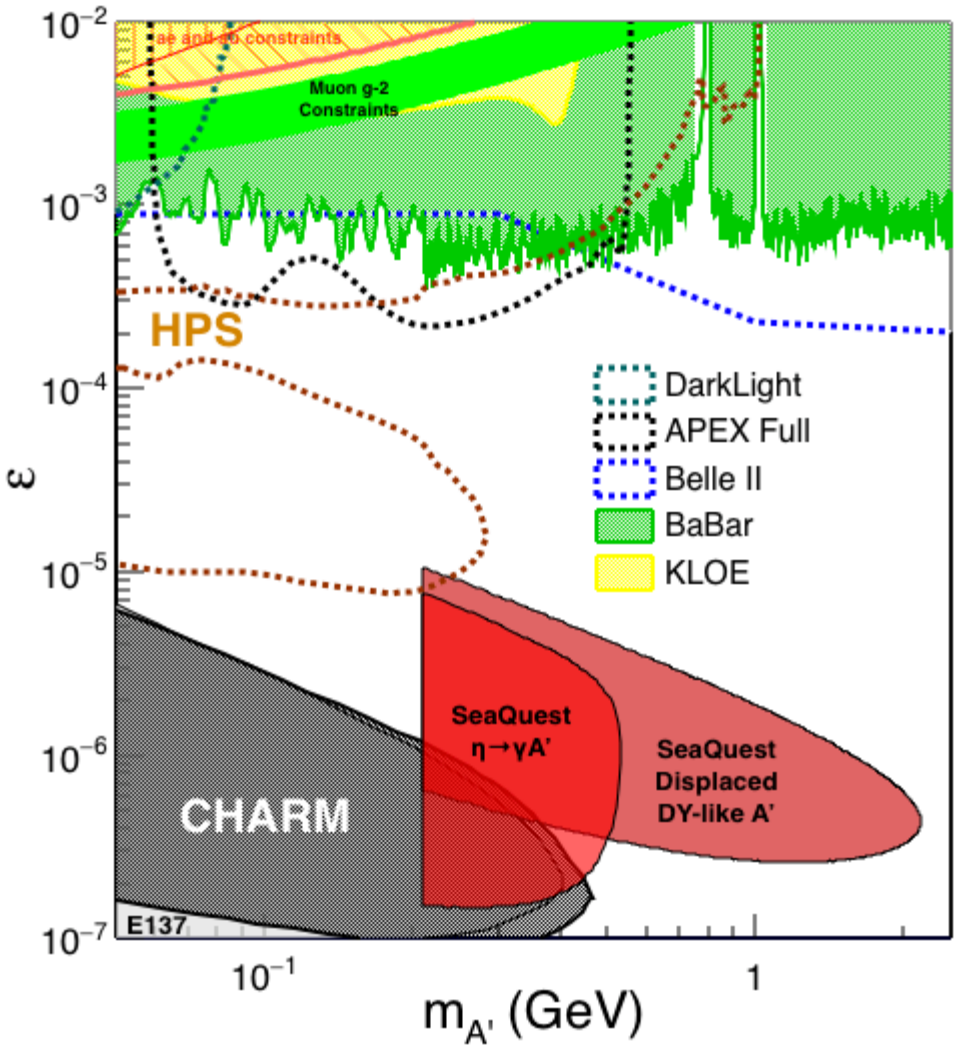
- $5x10^{12}$ ppp (current E906)
- 200 days

1.4×10^{18} POT (recorded)

- 4 events contours (2-sigma)

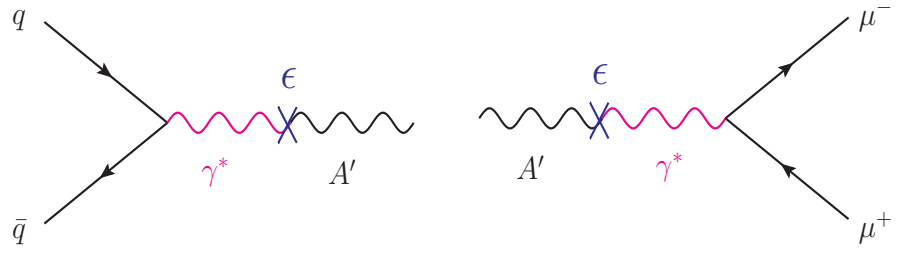
2-sigma (95%) exclusion plots

Excellent coverage of uncharted region!



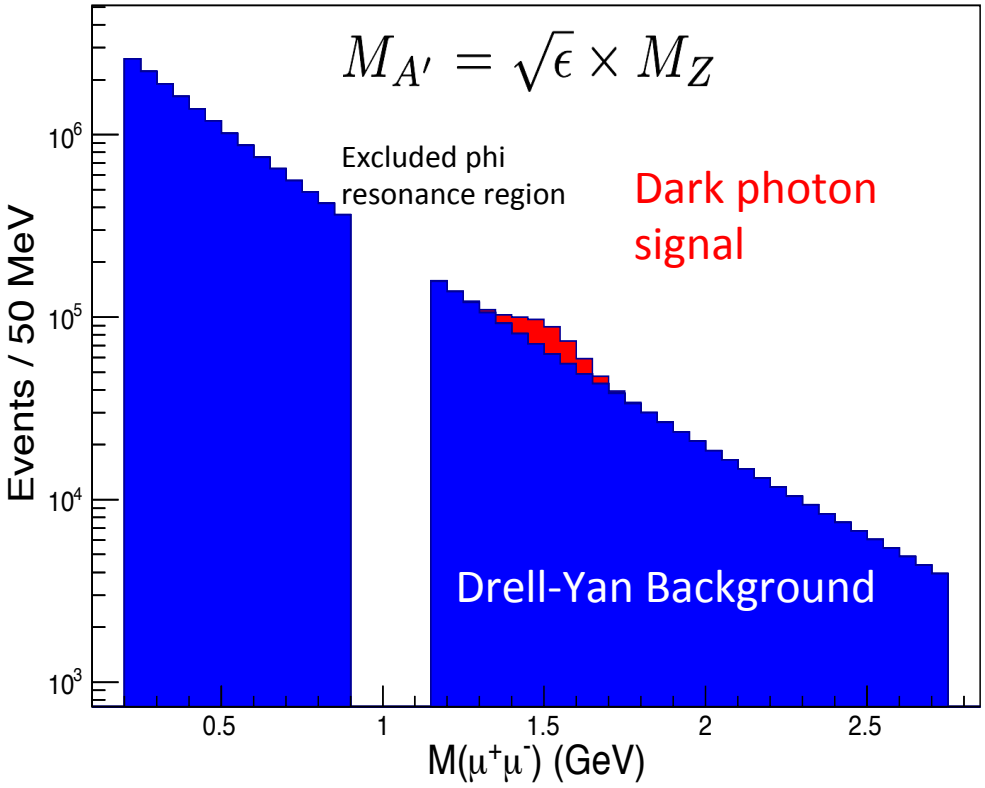
Search Mode (2): "Prompt" Dark Photons vs Drell-Yan

Z-vertx < 3m



Expected Drell-Yan like signal and backgrounds:

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



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

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

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

Work in progress
Further optimization possible

Dark Photon Sensitivity: Summary

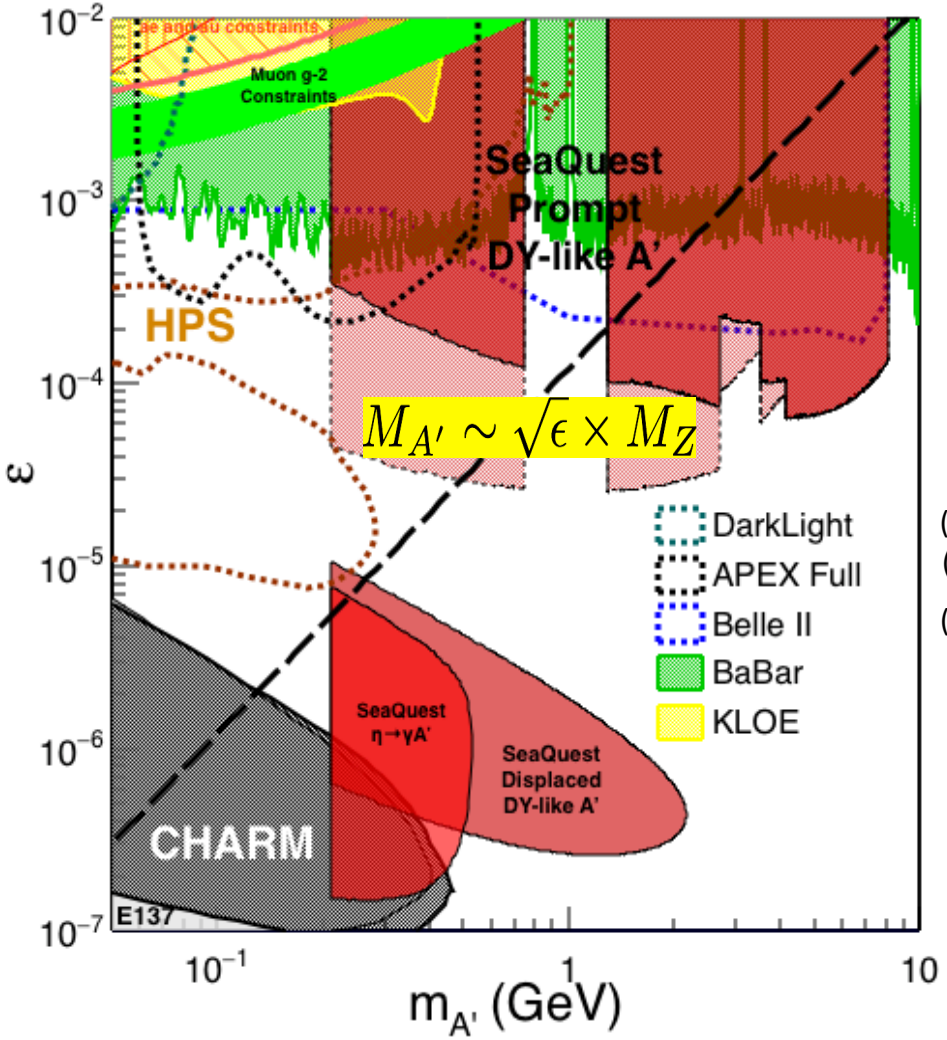
POT:1.4x10^{18} (parasitic w/ E1039)

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)

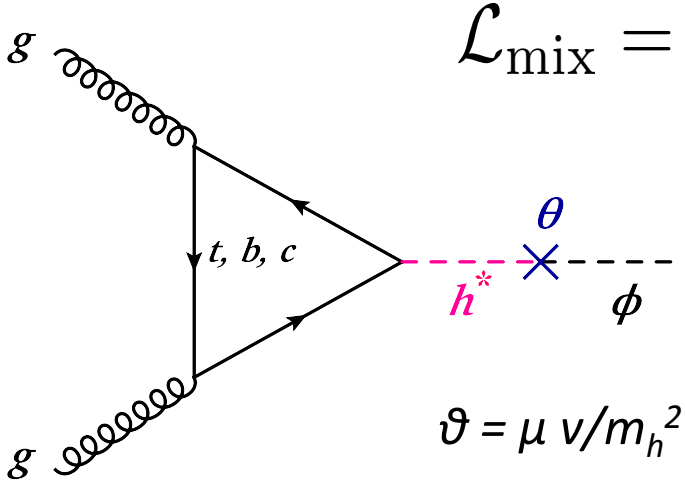


(2017?)
(2016?)
(~2023)

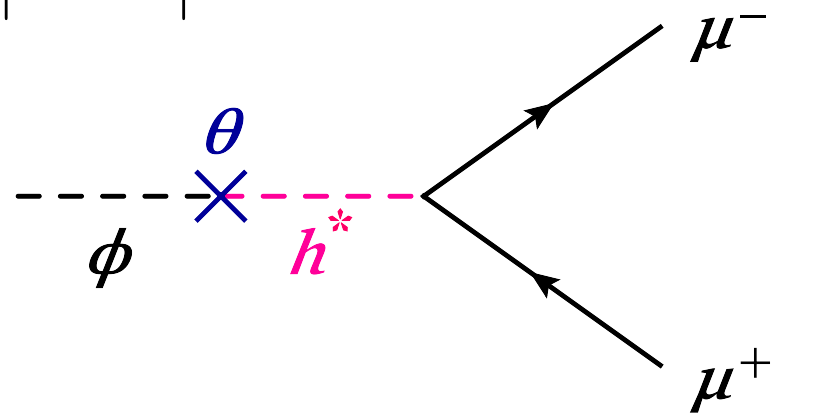
E-1067: Dark Higgs Search at SeaQuest

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

Y. Zhang et al, arXiv:1502.06983

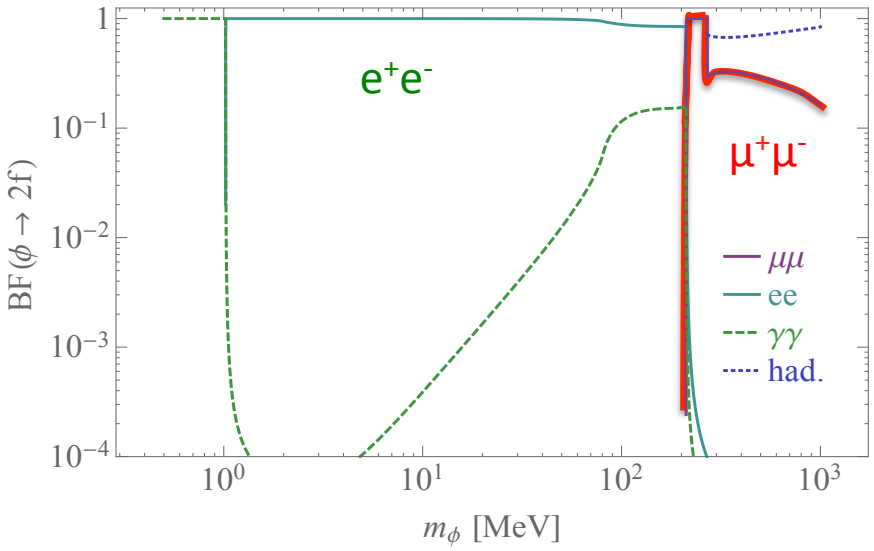


$\vartheta = \mu\, v/m_h^2$



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

D. Curtin et al arXiv:1312.4992



Phase-I:

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

Advantage of using hadron beams with muon probes over electrons

Phase-II:

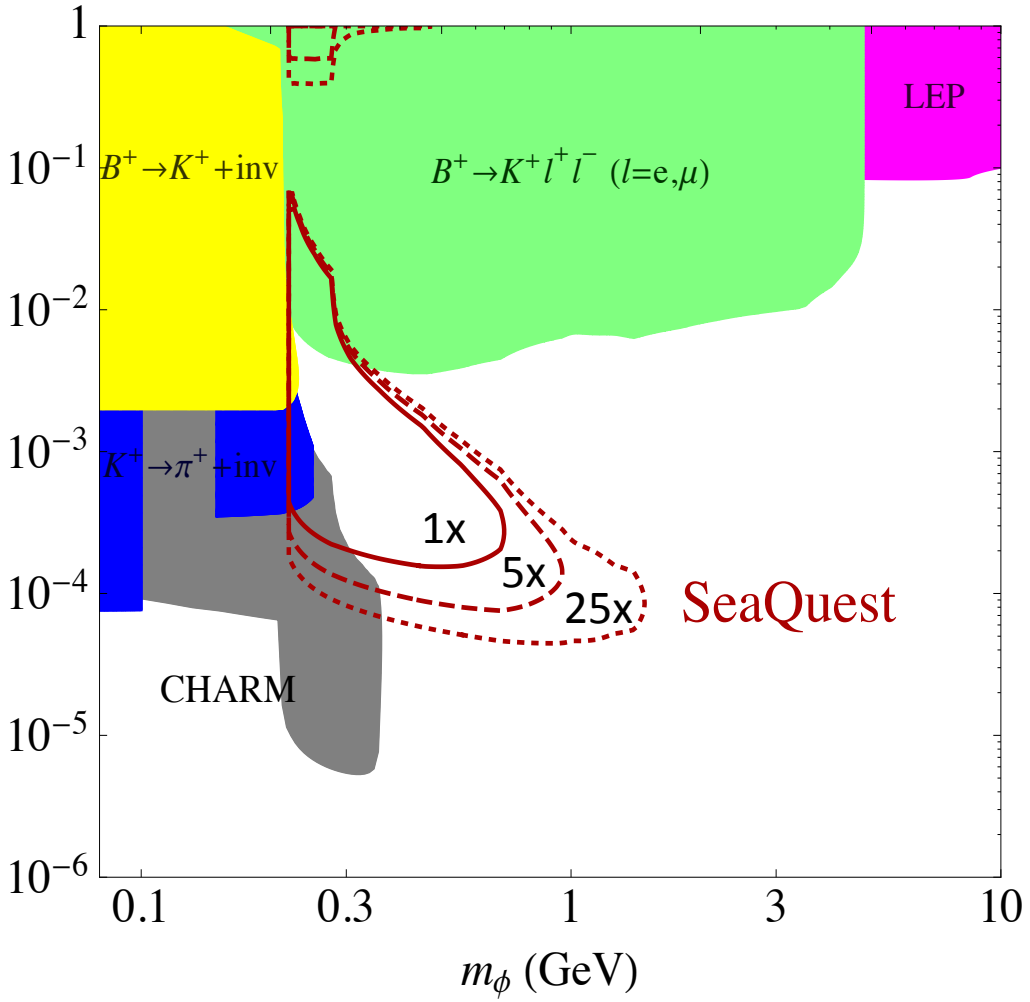
Low-mass: e^+e^-, <200MeV possible

SeaQuest Dark Higgs Sensitivity

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

Y. Zhang (2015)

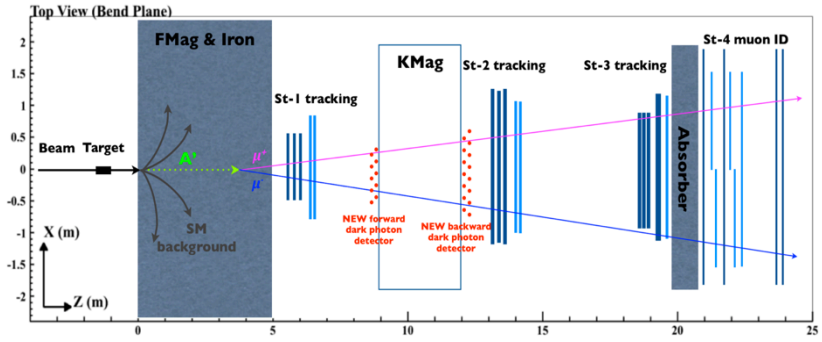
- Dimuons with downstream displaced decay vertices
- Limited sensitivity to "prompt" large mixing case due to small cross-section
- Dark Higgs or dark photons?
  - Dimuon kinematic and angular distributions
- Phase-II
  - Dedicated high luminosity runs optimized for low mass acceptance, mass<3GeV

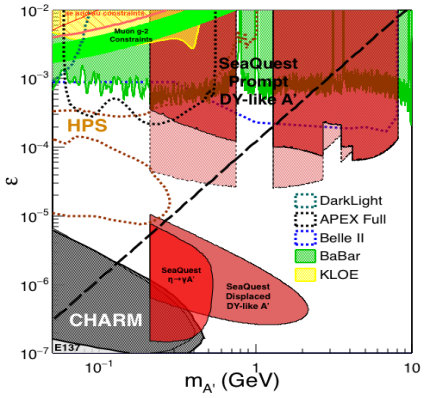


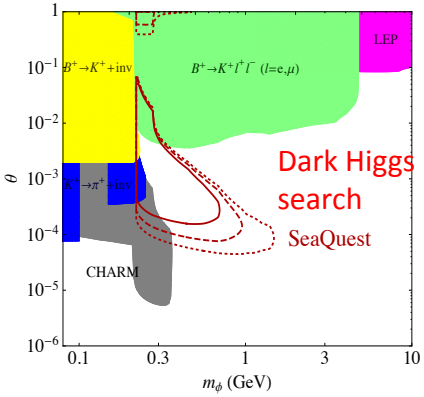
Summary and Outlook

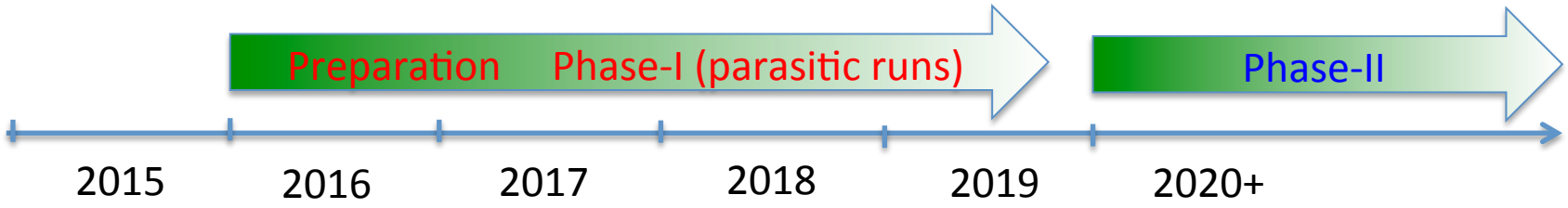
- ***Phase-I***
  - ***Great discovery potential!***
  - ***Add a new displayed vertex trigger***
  - ***Early parasitic data taking 2017-2019+***
    - ***A short dedicated run up to ~1 month if needed***
  - ***POT 1.4 x10^{18}***

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





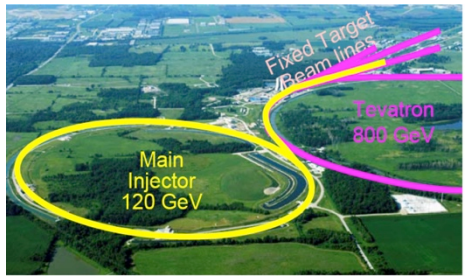


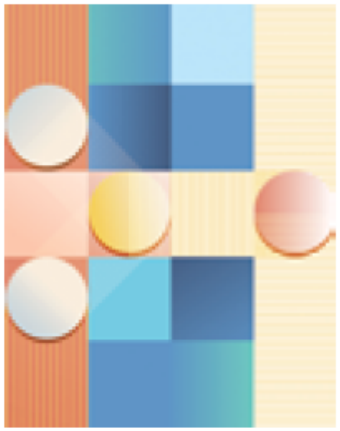


2014 US P-5 Report

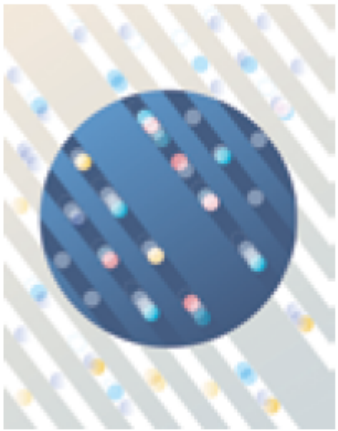
Five intertwined scientific Drivers were distilled from the results of a yearlong community-wide study:

- 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



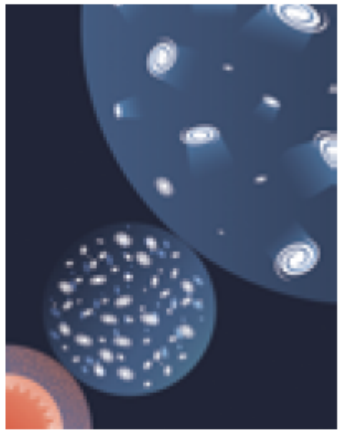


Higgs boson



Neutrino mass

Dark matter



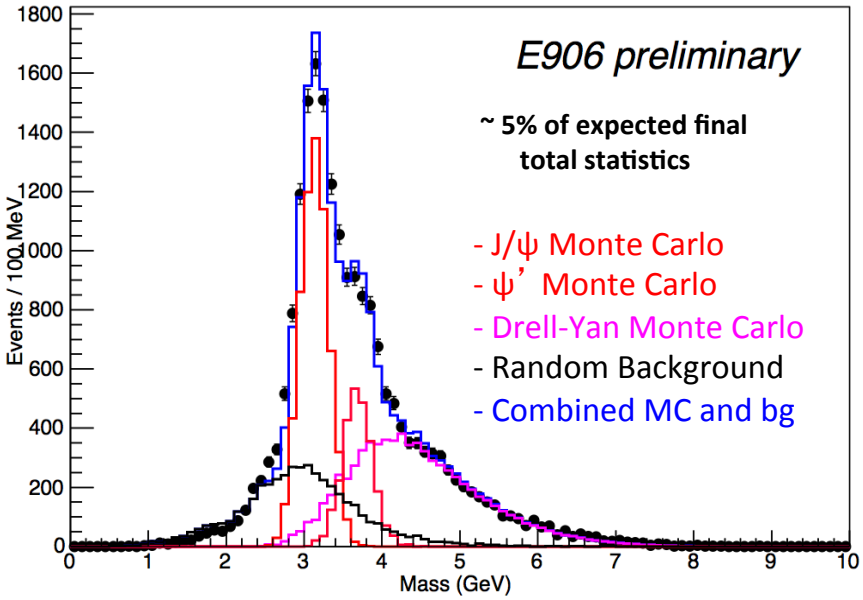
Cosmic acceleration

Explore the unknown

Great Opportunities at the Fermilab Intensity Frontier!!!

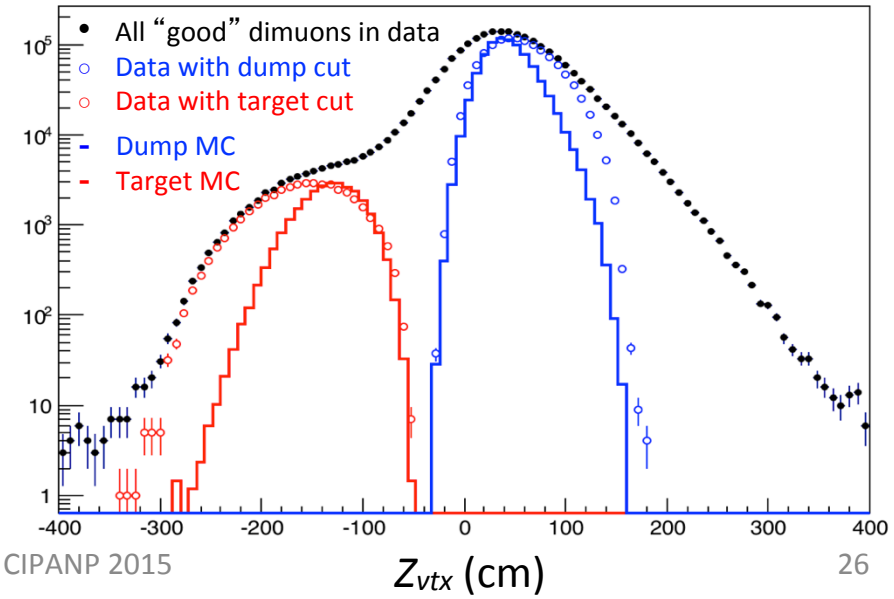
Backup slides

Data from Run 2014 (Run-II)

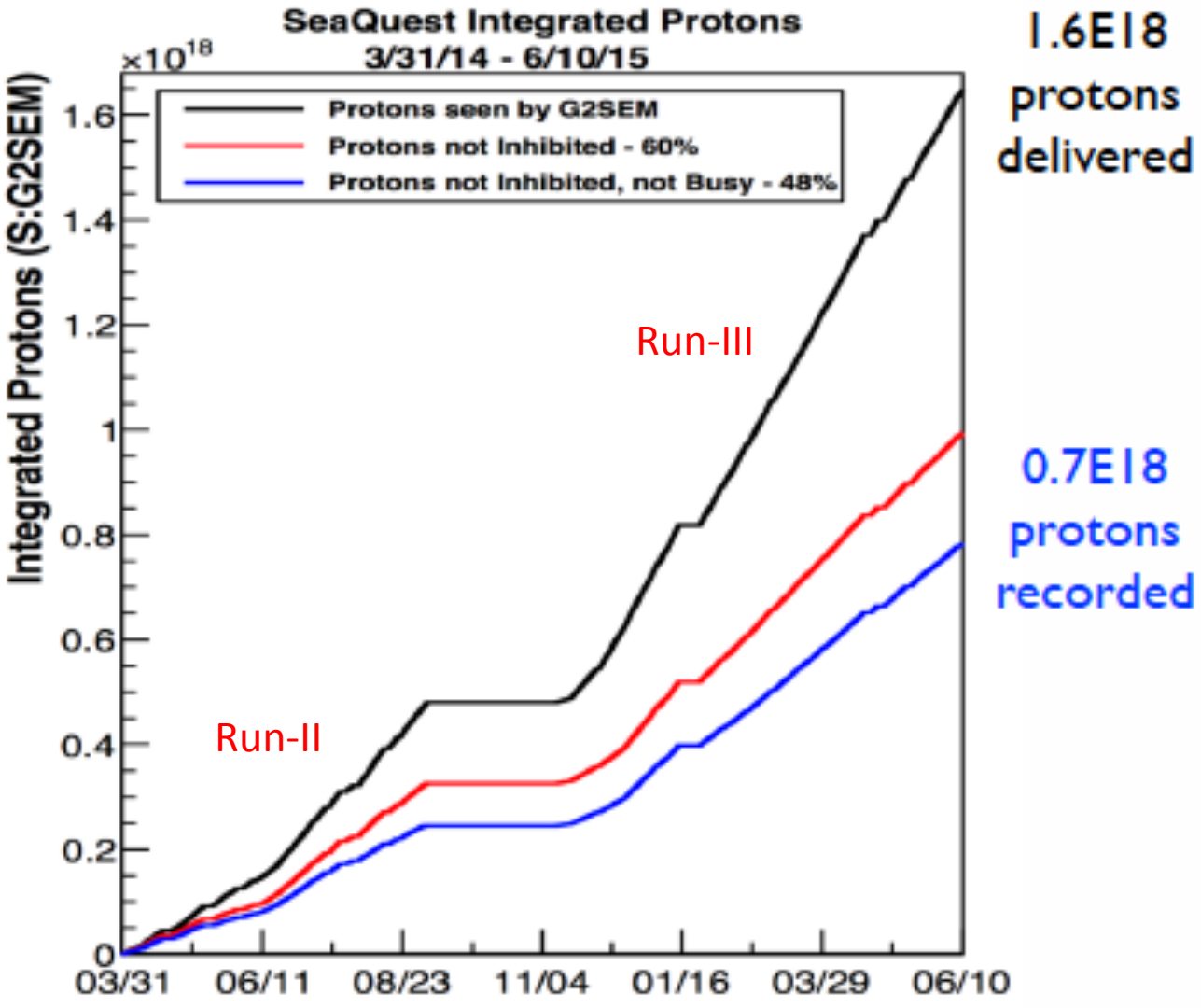


- Monte Carlo describe data well
  - $\sigma_M(J/\psi)$ ~ 180 MeV, σ_M(DY) ~ 220 MeV
  - J/ψ ψ' separation
  - Cleaner DY sample
- Good target/beam dump separation

- Beam quality worse than expected (instantaneous rate much higher than average)
  - live time of spectrometer greatly reduced by the 'super' RF buckets
  - Reconstruction efficiency lower than expected because of the high detector occupancy



E906 Run-II and III Performance



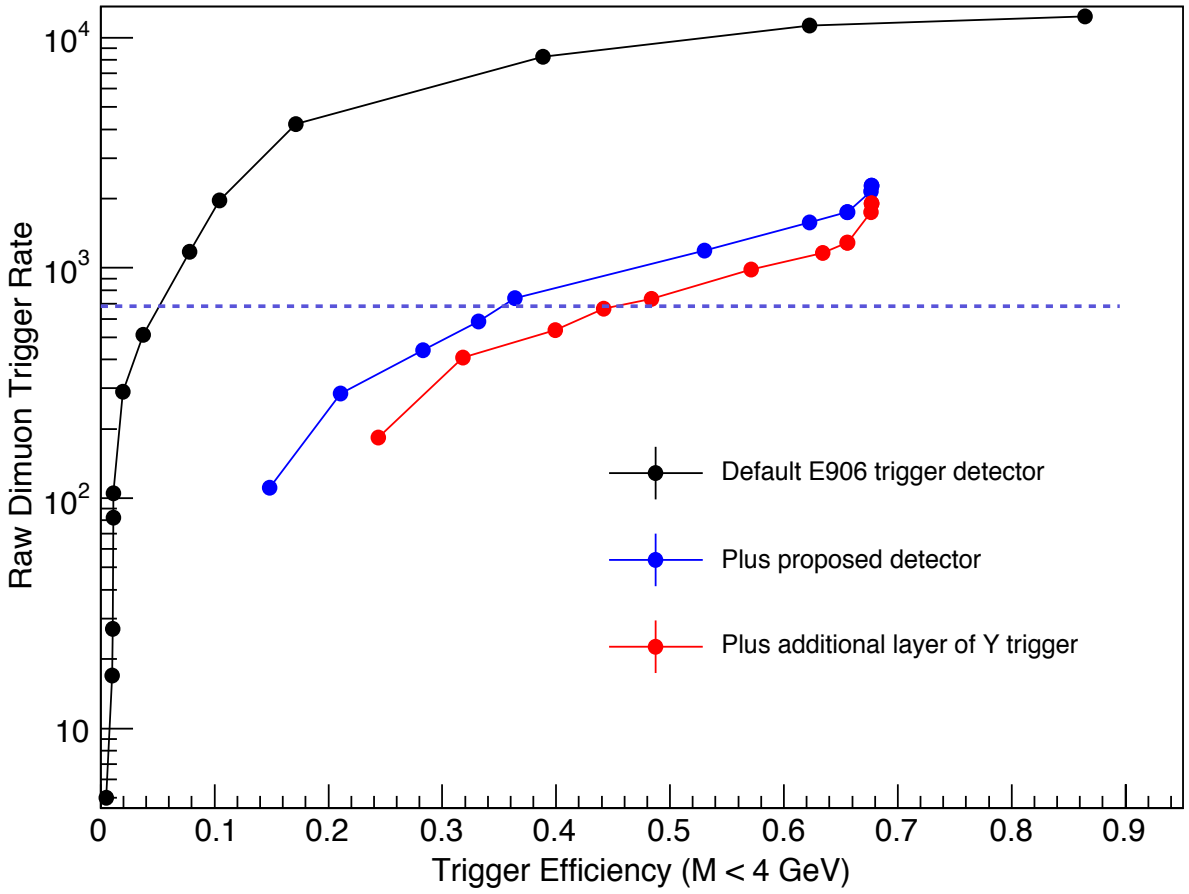
Low Mass Prompt Dimuon Trigger Rate Study

- 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.)

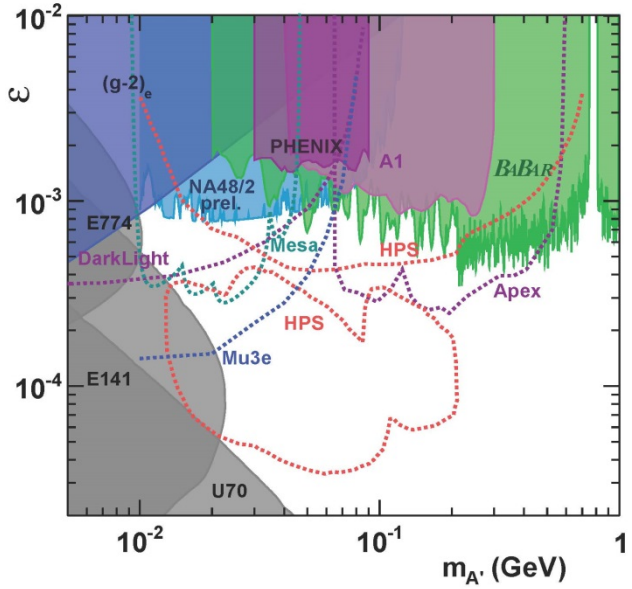
Parasitic mode: use up to ~10% DAQ bandwidth

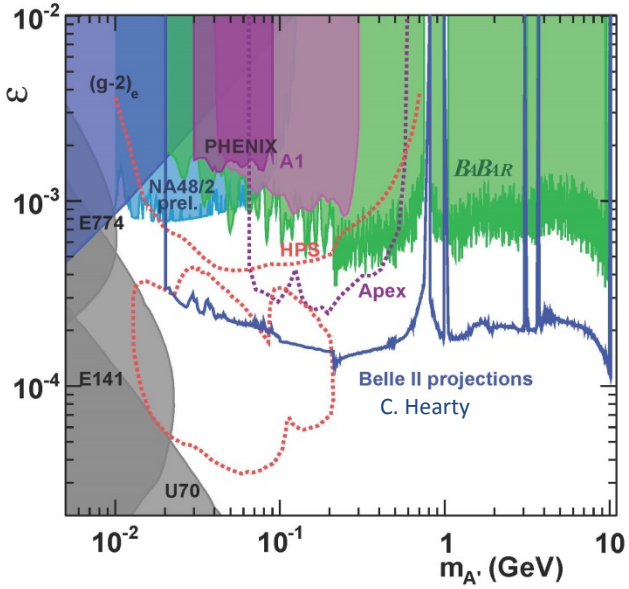


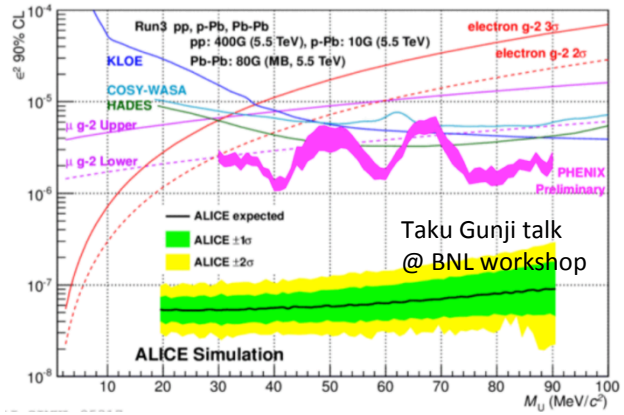
(Prompt)Low mass dimuon trigger efficiency

Expected sensitivity of selected future experiments

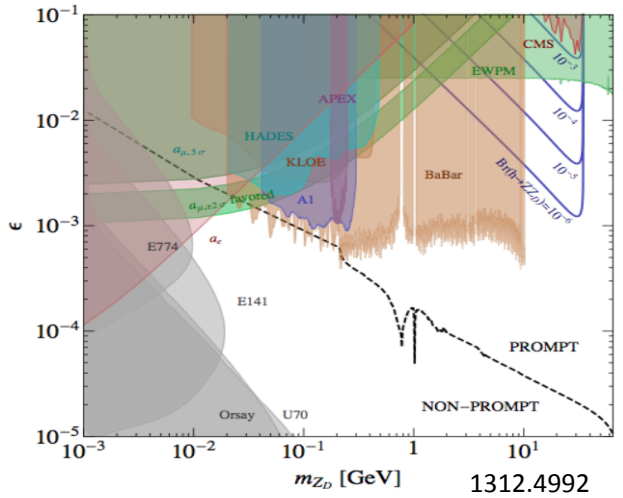
Slide credit: Bertrand Echenard (2014)







Taku Gunji talk
@ BNL workshop

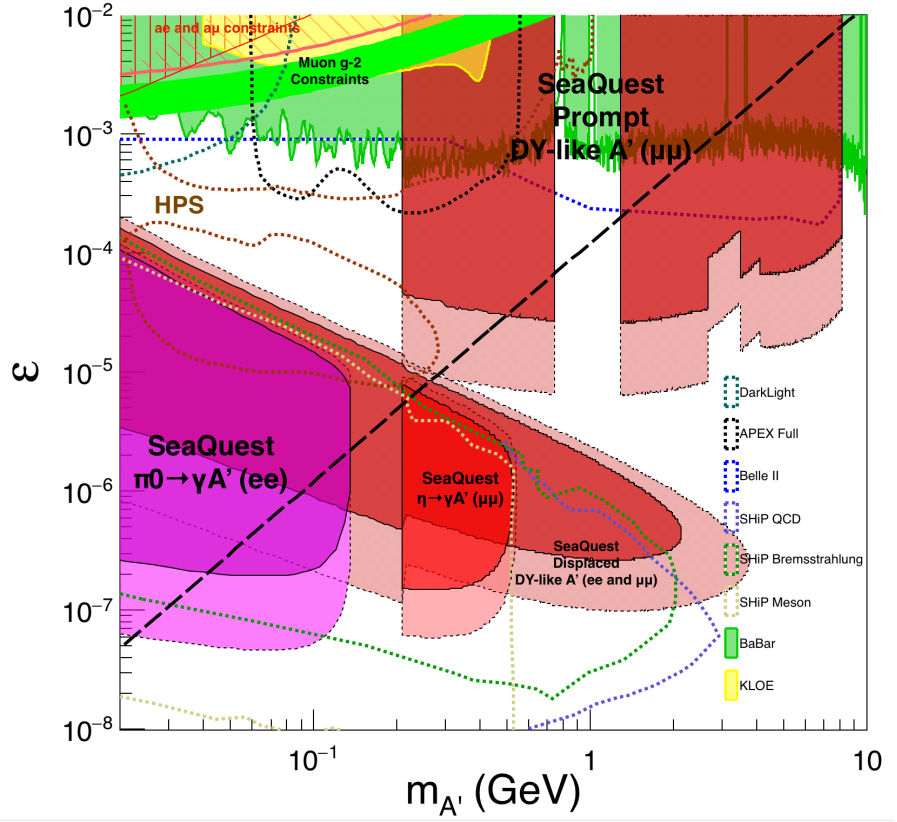


1312.4992

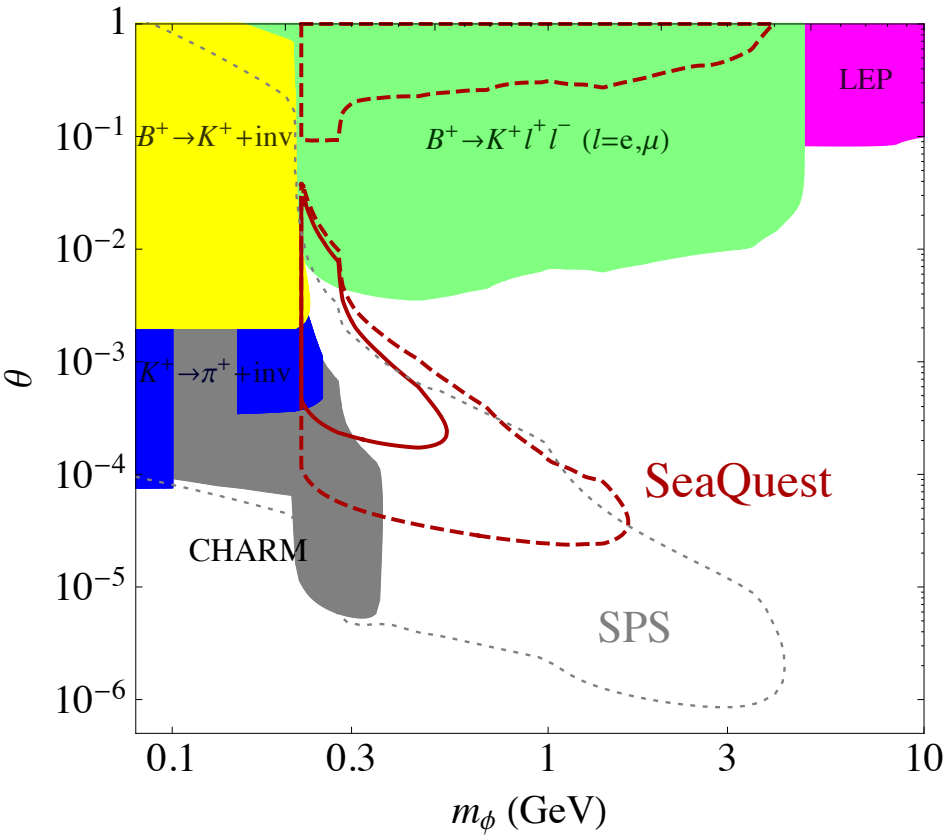
Low mass region will be easily probed, but range above 500 MeV remains difficult to access

Comparison with SHiP Proposal

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



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



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

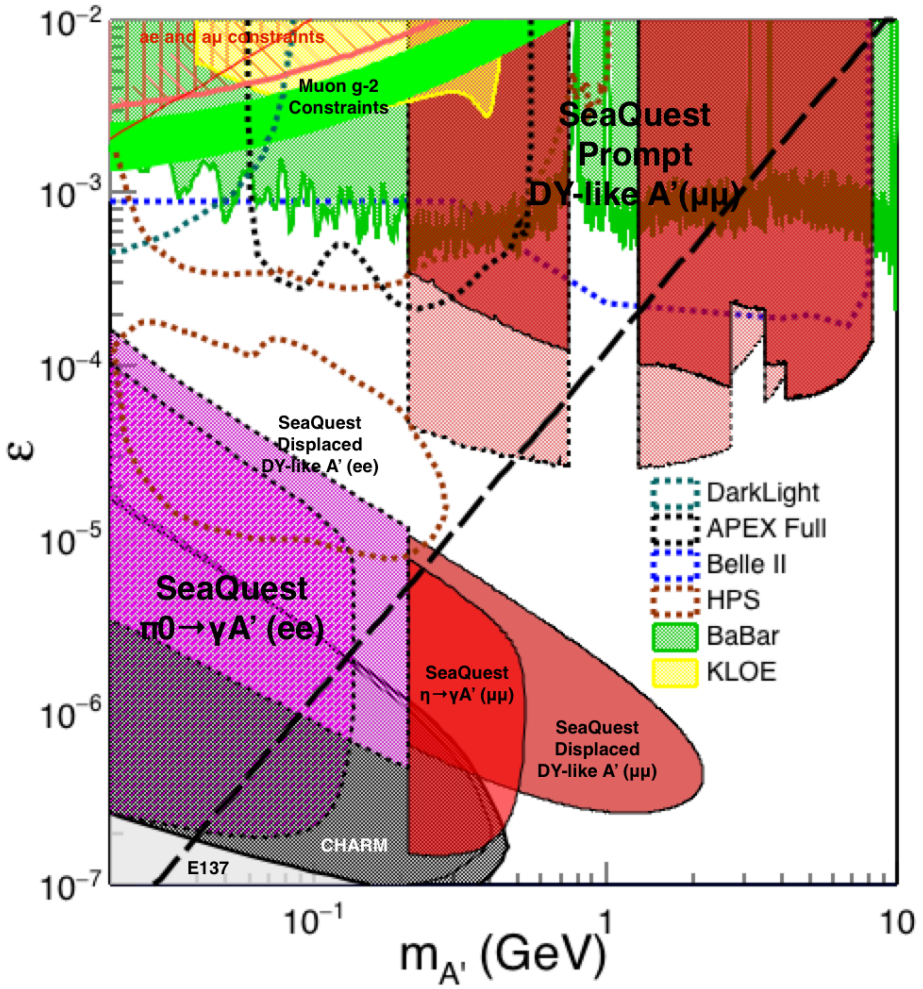
- Possible parasitic runs w/ E1027 and/or dedicated runs later with upgrades: 2019+
  - High luminosity goals:
    - POT >> 1.4x10^{18}
  - DAQ
    - 10 – 100 kHz capability
  - EMCAL/HCAL/PID
    - Electrons
    - charged hadrons
  - Fully cover the accessible phase space
    - Low mass “prompt photon”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

Phase-II: Full Coverage

with future detector "EMCal/HCal" upgrades

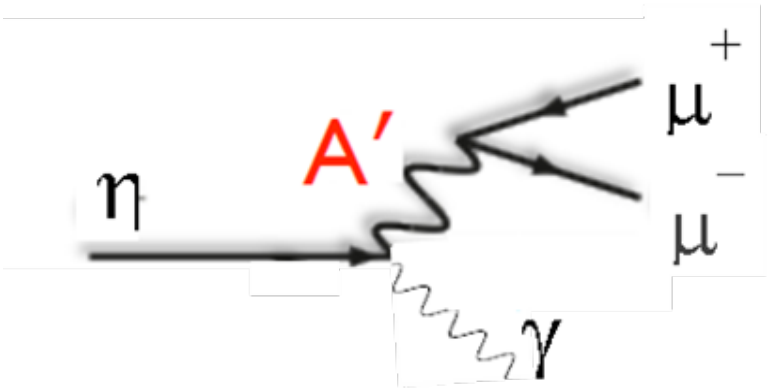
Projection: POT 1.4 x 10^{18}

- 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

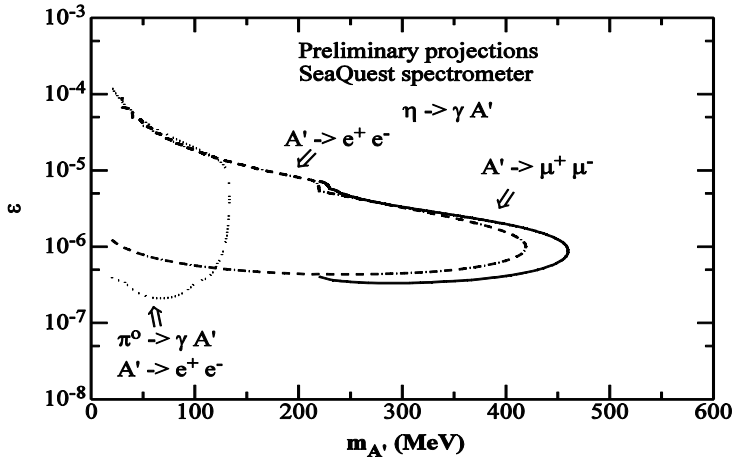


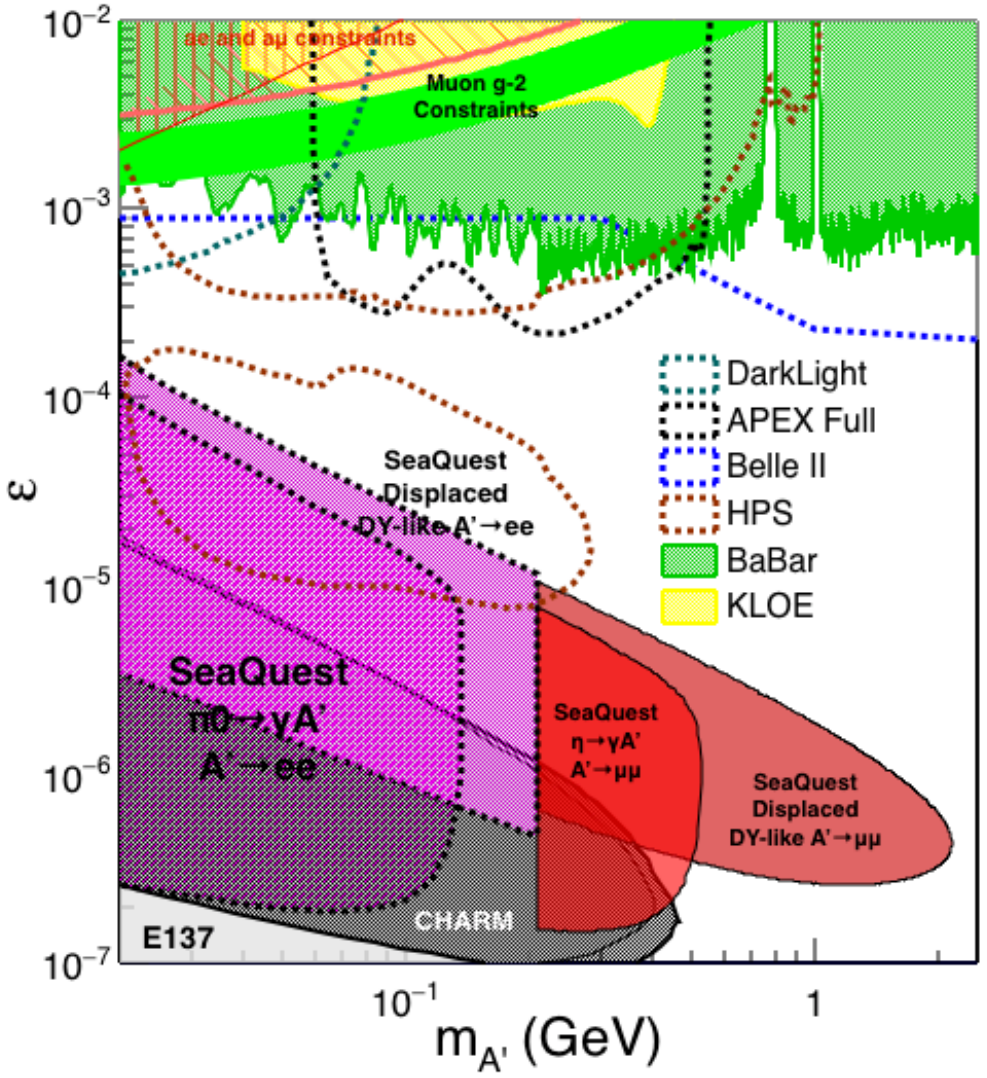
Phase-II: Access Low Mass Region with e^+e^-

with future detector "EMCal" upgrades



S. Gardner, R. Holt et al

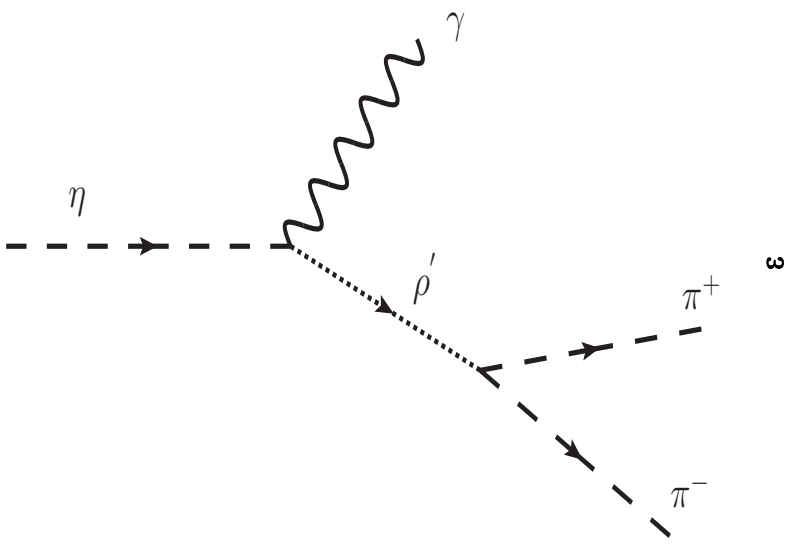




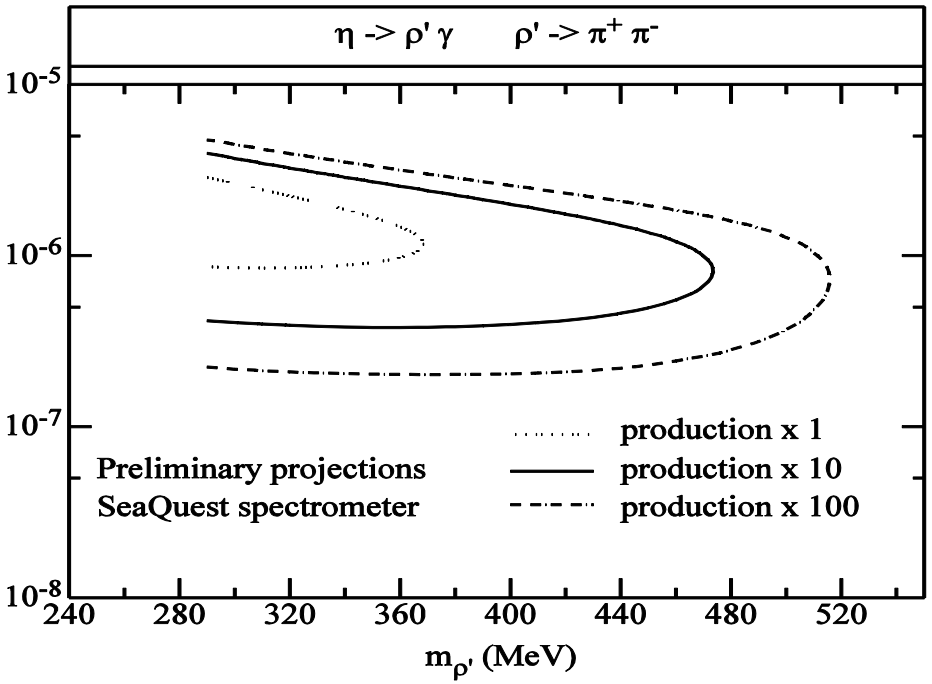
Non Abelian Dark Sector

with future detector "HCal" upgrades

non-Abelian dark sector process



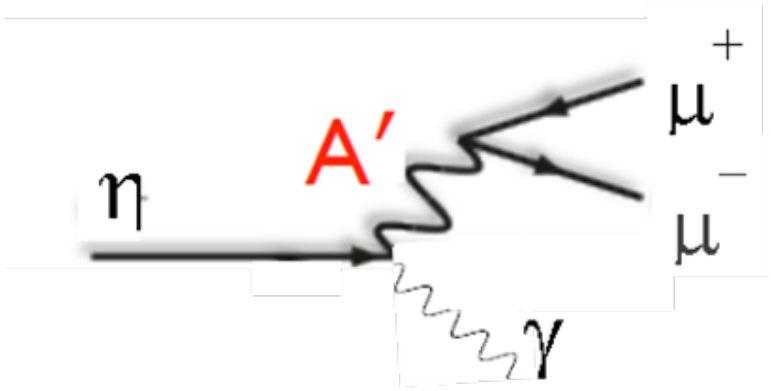
S. Gardner and R. Holt

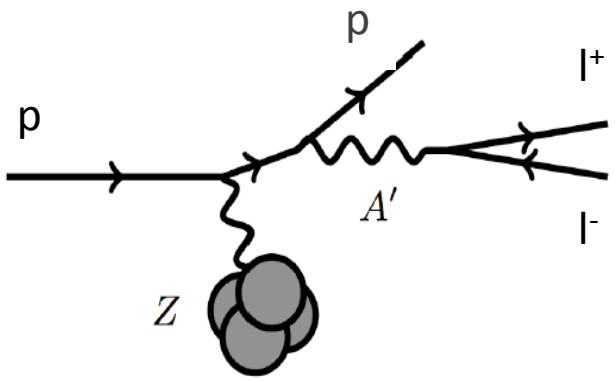


[Note: Batell, Pospelov, and Ritz, PRD 80 (2009) 095024 for a review re fixed target expts.]
Here we consider a non-Abelian (gluon) portal
[Baumgart et al., JHEP 0904, 014 (2009); Gardner and He, PRD 87 (2013) 116012]
The "shining through walls" design – unique to Seaquest – makes this possible ,
to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