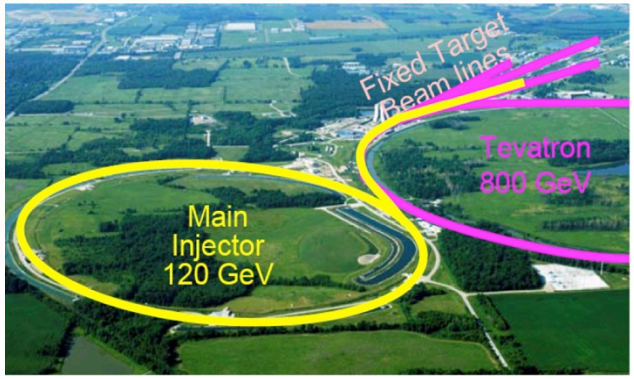
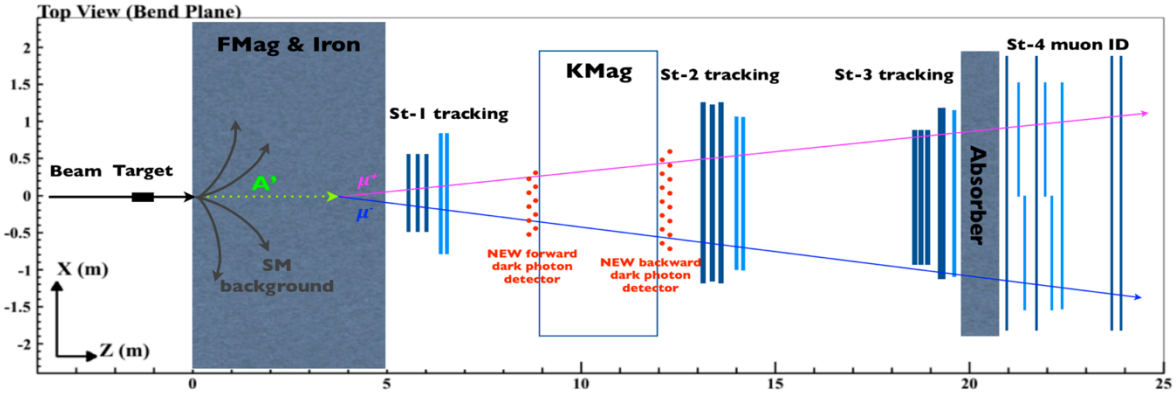
Direct Search for Dark Photons and Dark Higgs in p+A Collisions at Fermilab E-1067 Experiment

Ming Liu

Los Alamos National Laboratory

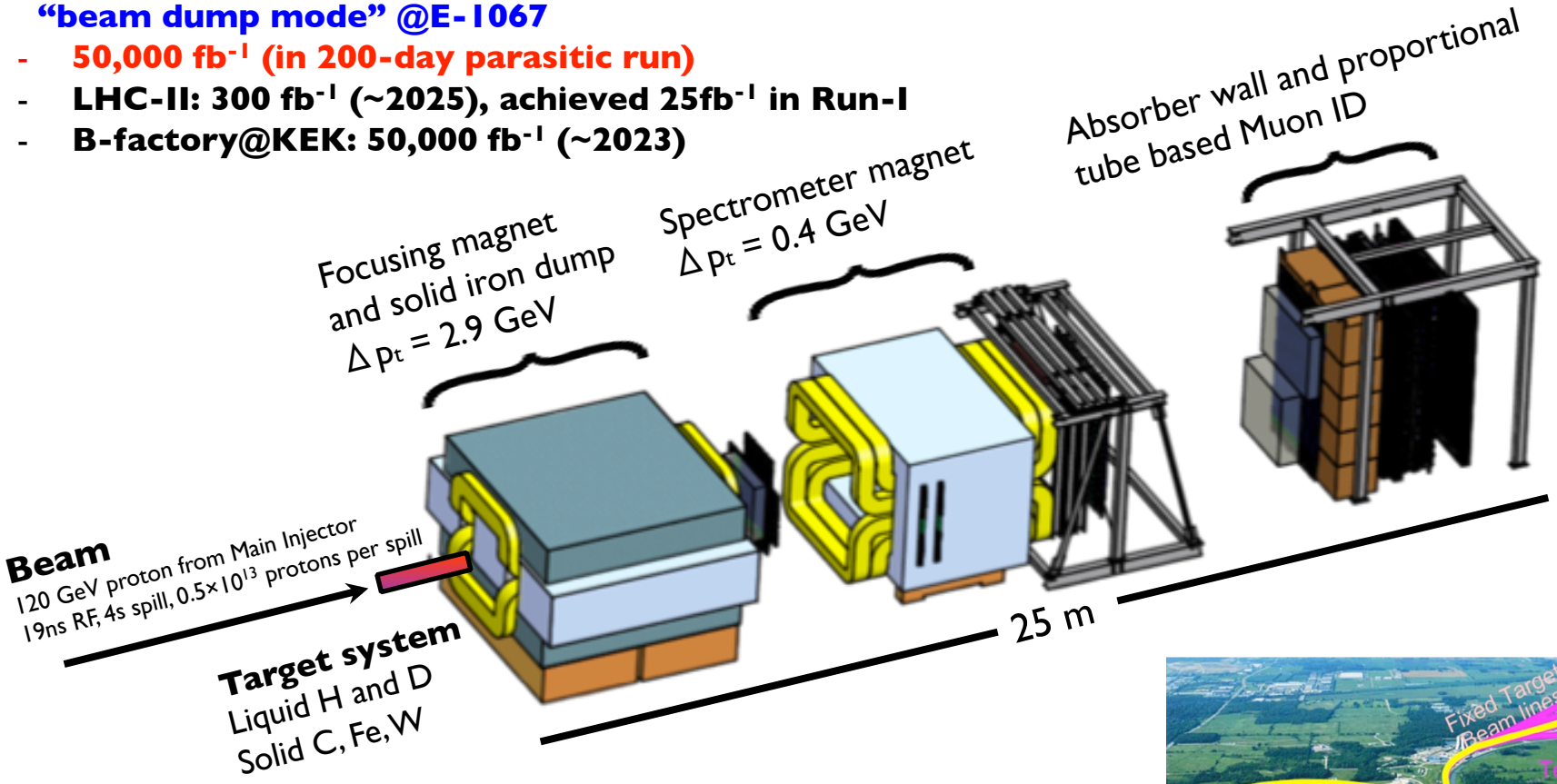


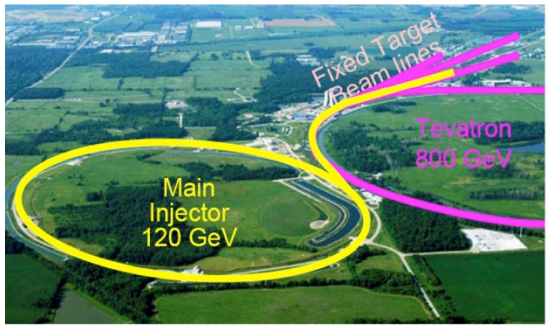


Intensity Frontier at Fermilab: 120 GeV Beam

World's highest intensity high energy proton beam:
"beam dump mode" @E-1067

- **50,000 fb^{-1} (in 200-day parasitic run)**
- **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)

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LOI submitted to Fermilab PAC on May 20, 2015

A joint experimental and theoretical collaboration (most E906/E1039 + new members, ~60)

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

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

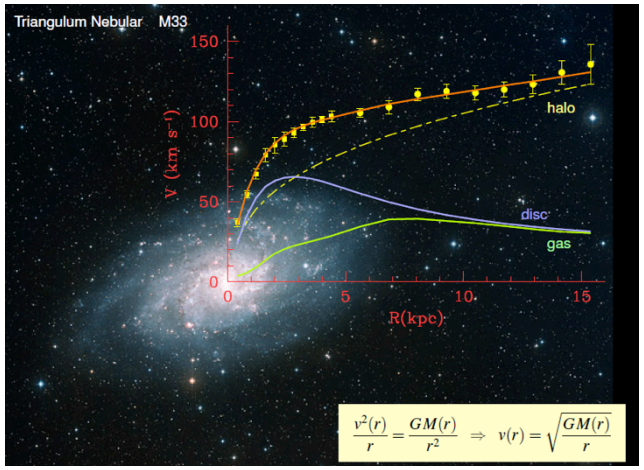
cc: D. Bortoletto, G. Bock, P. Reimer, J. Shank, S. Geer, P. McBride, D. Geesaman, J. Lykken, T. Meyer, A. Stone

Outline

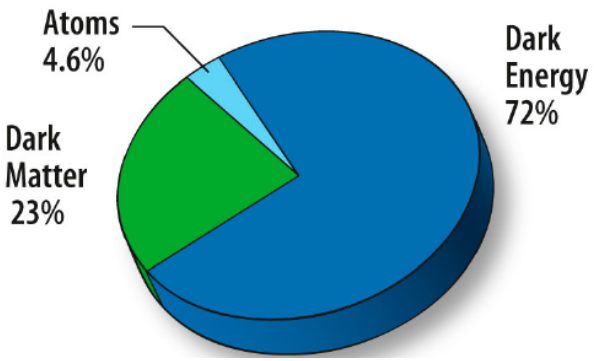
- Motivation
  - Dark Matter, dark photons and dark Higgs
- Current SeaQuest/E906 at Fermilab
  - Nucleon/Nuclear structures physic with Drell-Yan
- E-1067: a new search of dark photons/Higgs
  - Phase-I, 2017-2019 with a new trigger
  - Phase-II, 2020+ with detector upgrade, see Kun Liu's talk Friday

Dark Matter?

Galaxies' rotation curve



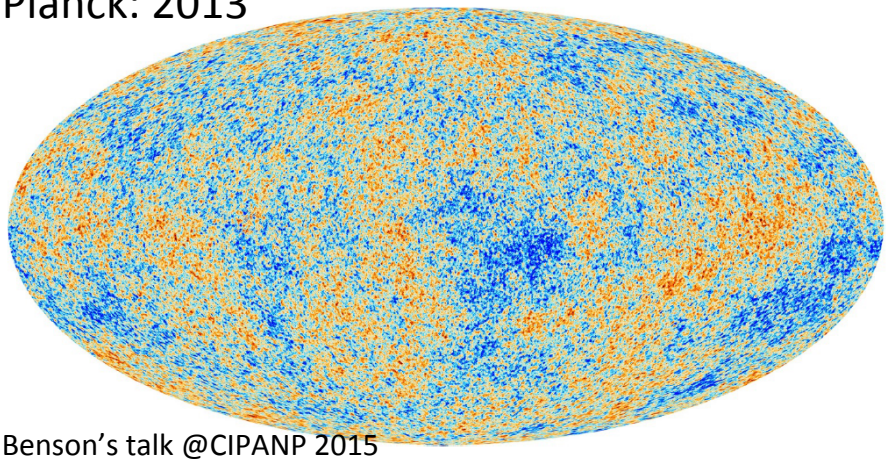
F. Zwicky, ApJ 86 (1937) 217, V. Rubin et al, ApJ 238 (1980) 471



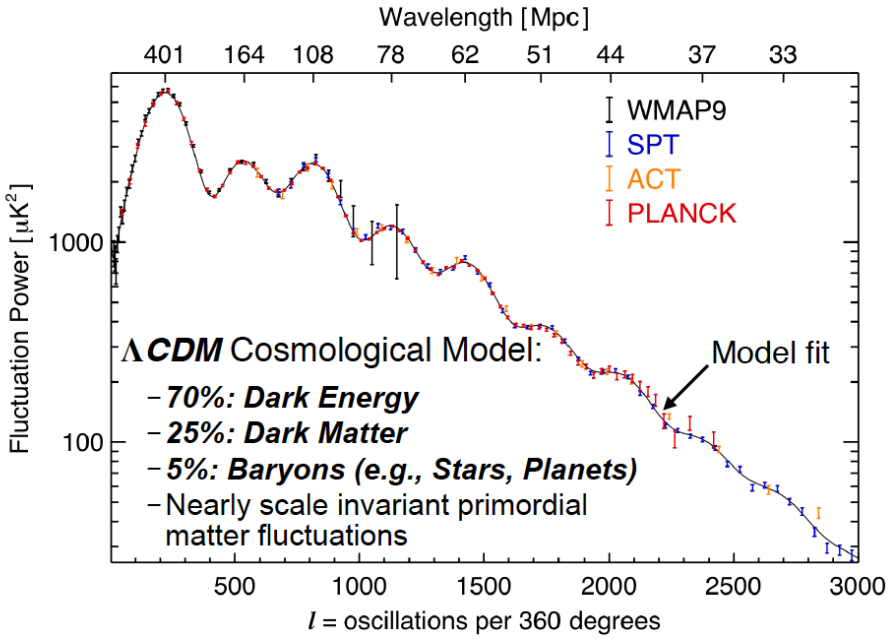
Gravitational lensing (Hubble 2007)

30μK RMS fluctuations on 3 K background

Planck: 2013



Benson's talk @CIPANP 2015



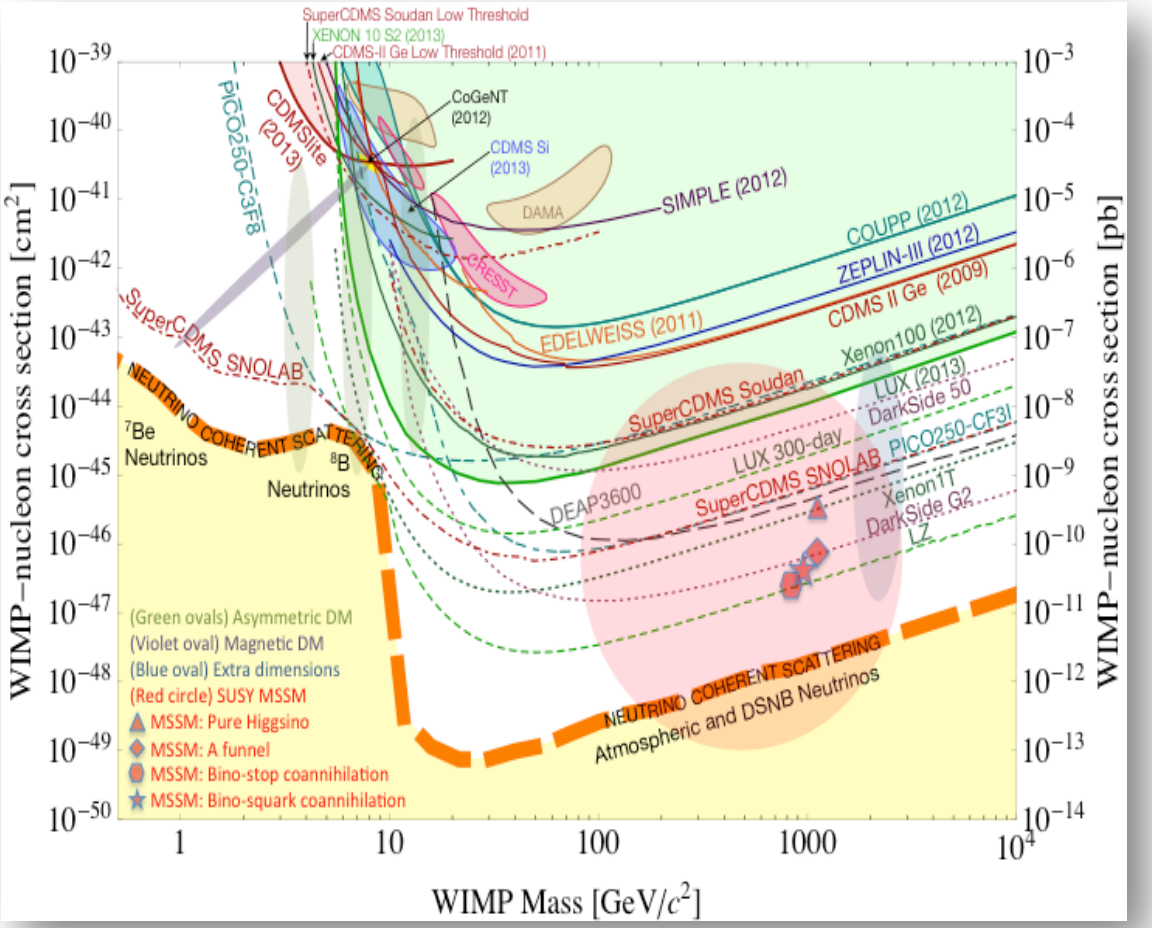
Direct Search for WIMP

- 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 portal": dark photon**
  - **"scalar portal": dark Higgs**
  - **"neutrino portal" and more …**

"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 etc.) offer an ideal environment to probe these new ideas.



Vector Portal and Dark Photon

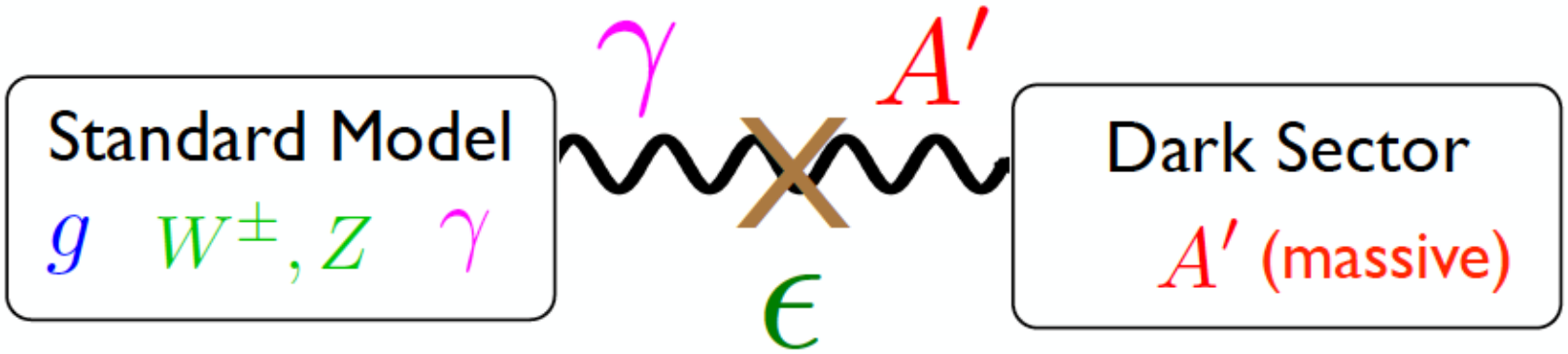
A simplest model of dark sector

- An extra $U(1)_X$, kinetic mixing
- Not suppressed by mass scale

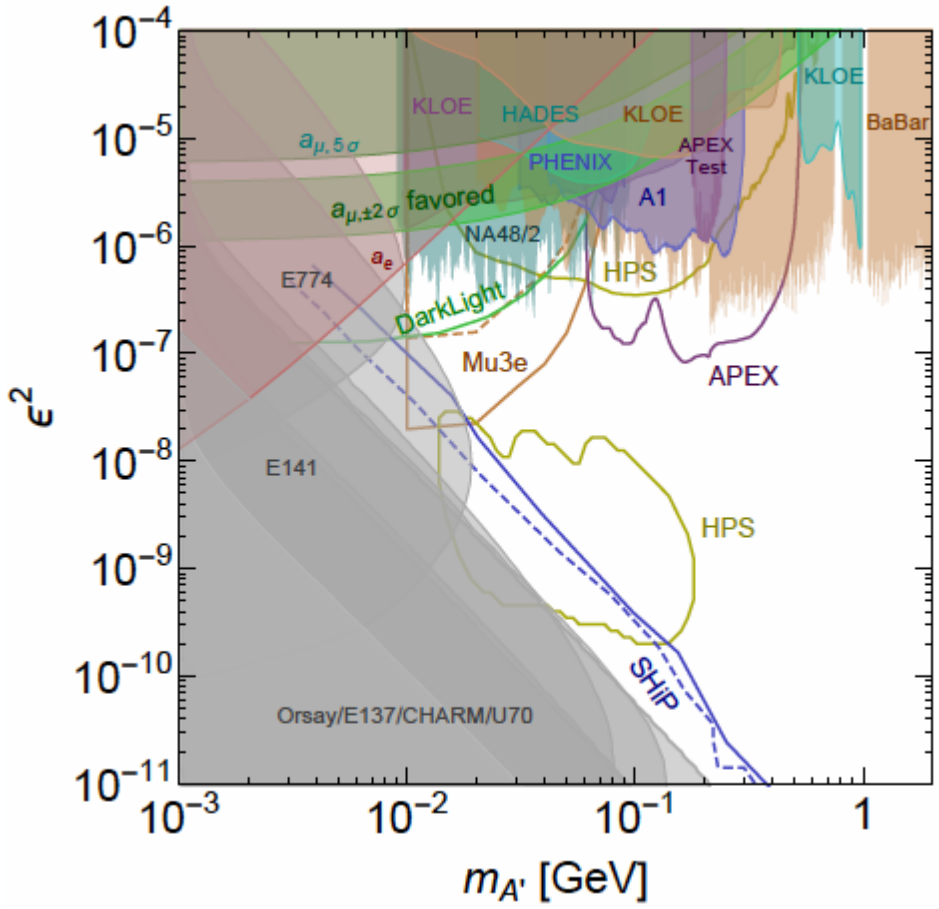
Holdom
Galison, Manohar

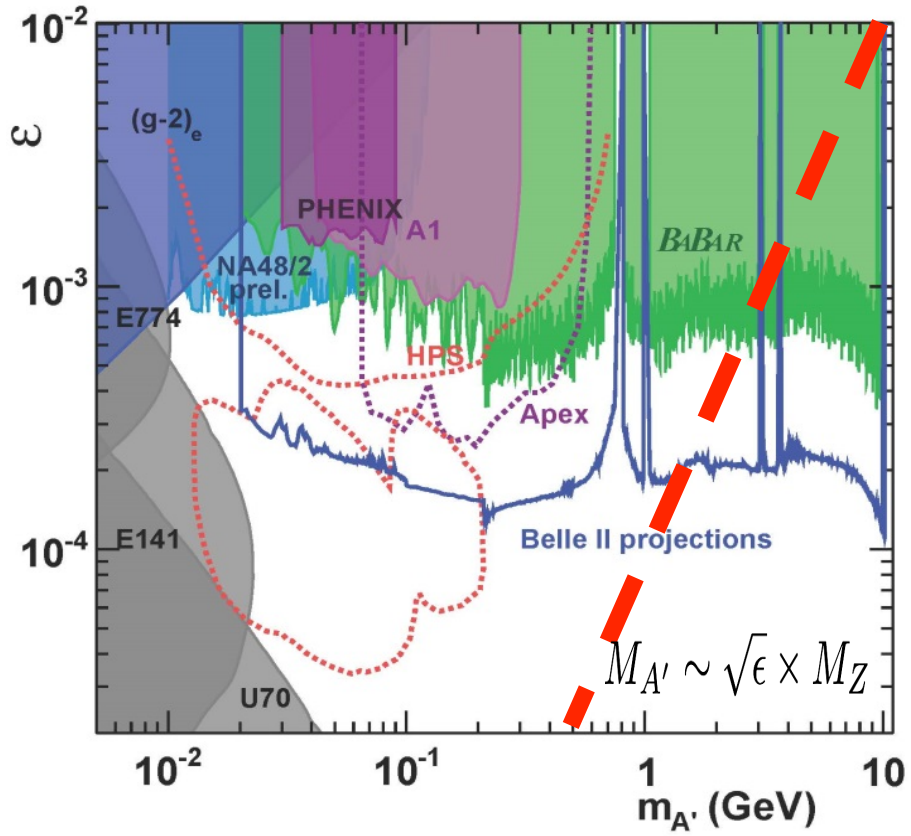
$SU(3)_C \times SU(2)_L \times U(1)_Y \times \mathbf{U(1)_X}$

$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$



Dark Photon Current and Future Limits





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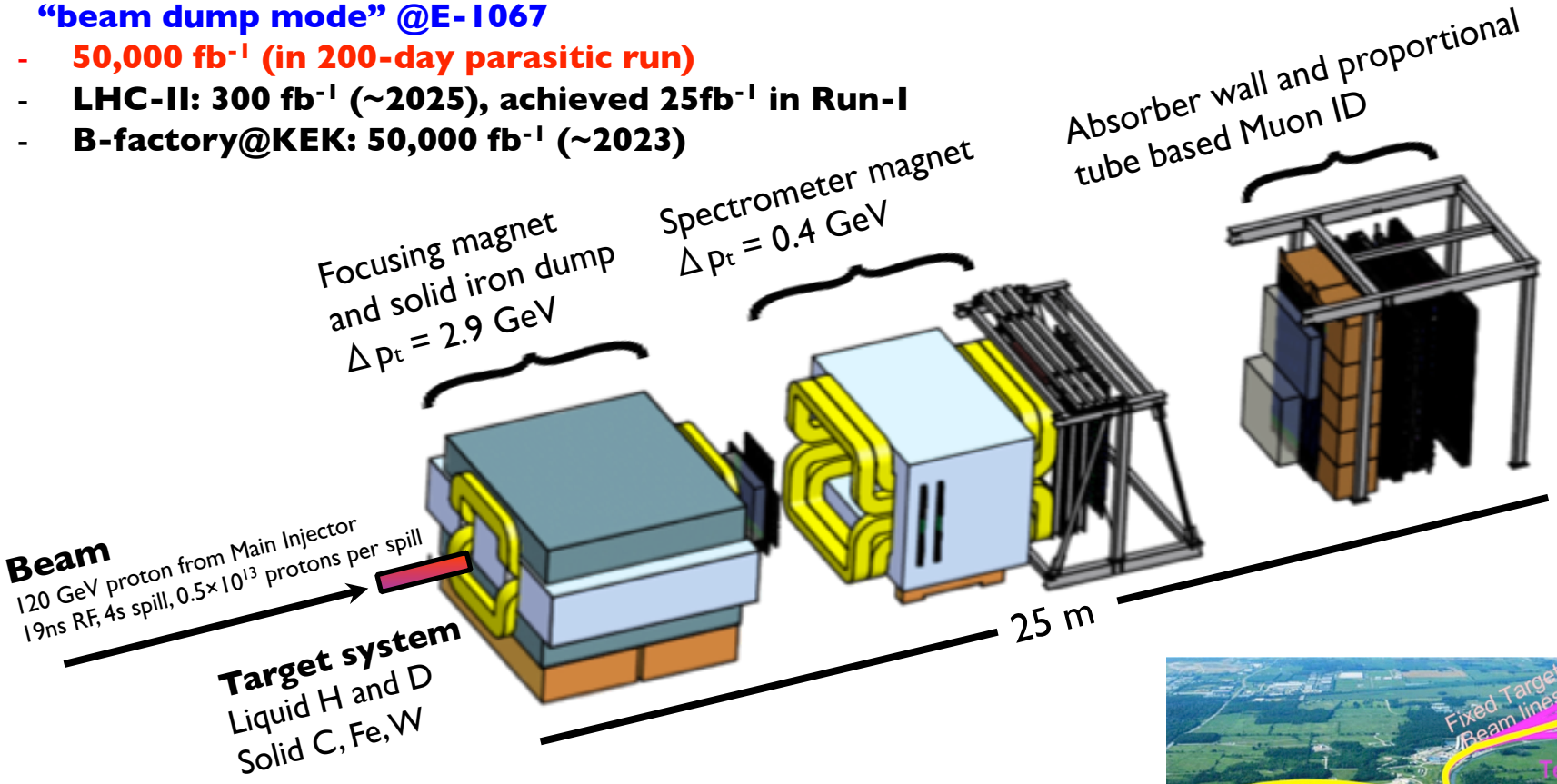
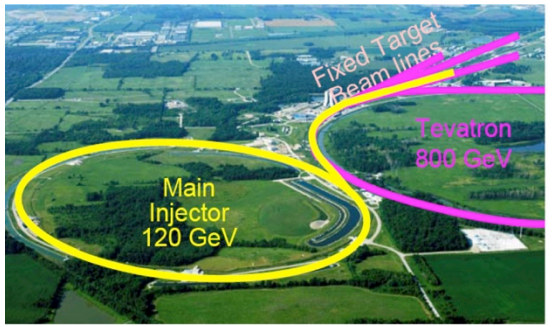
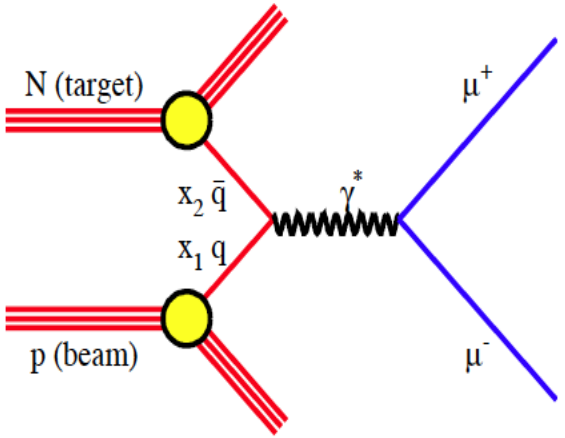


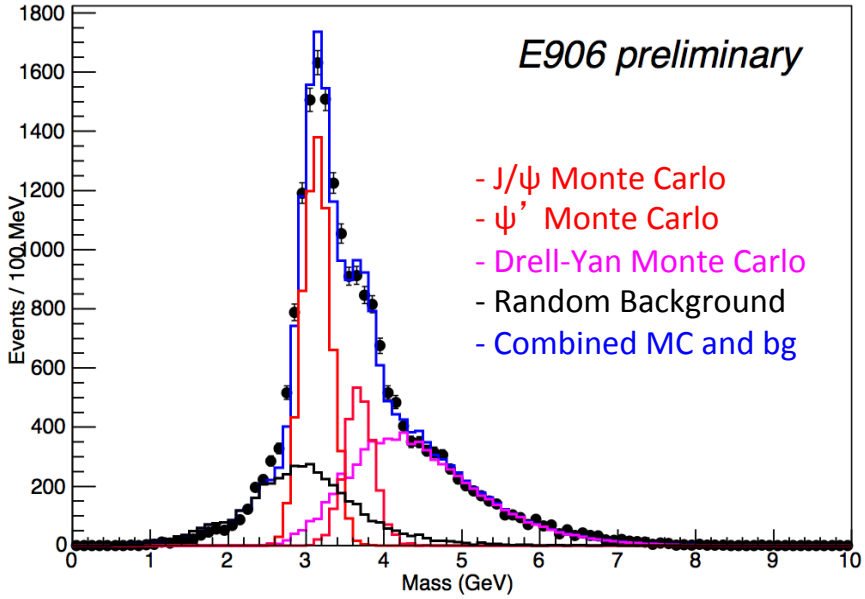


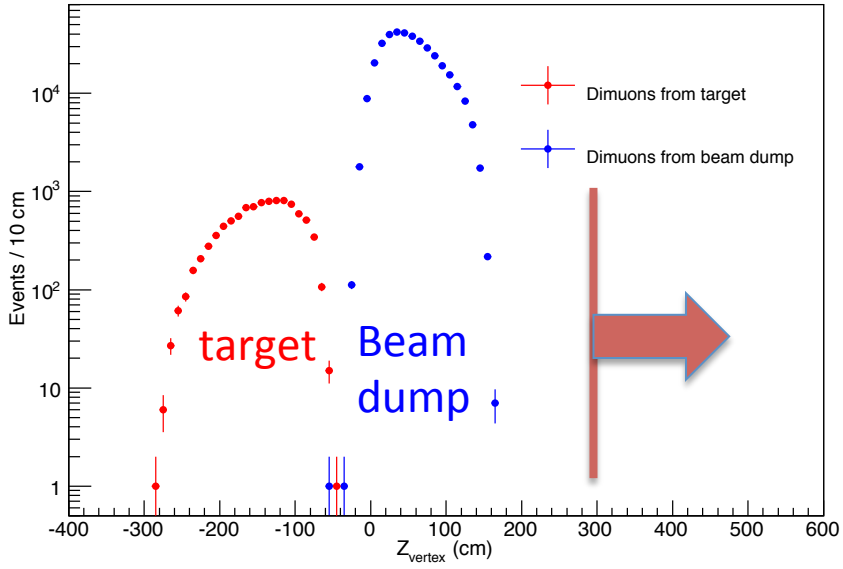
- Capture most beam in beam dump mode: p+Fe collisions!
- Parasitic run mode possible with other experiments, E906/E1039

Current E-906 Drell-Yan Acceptance

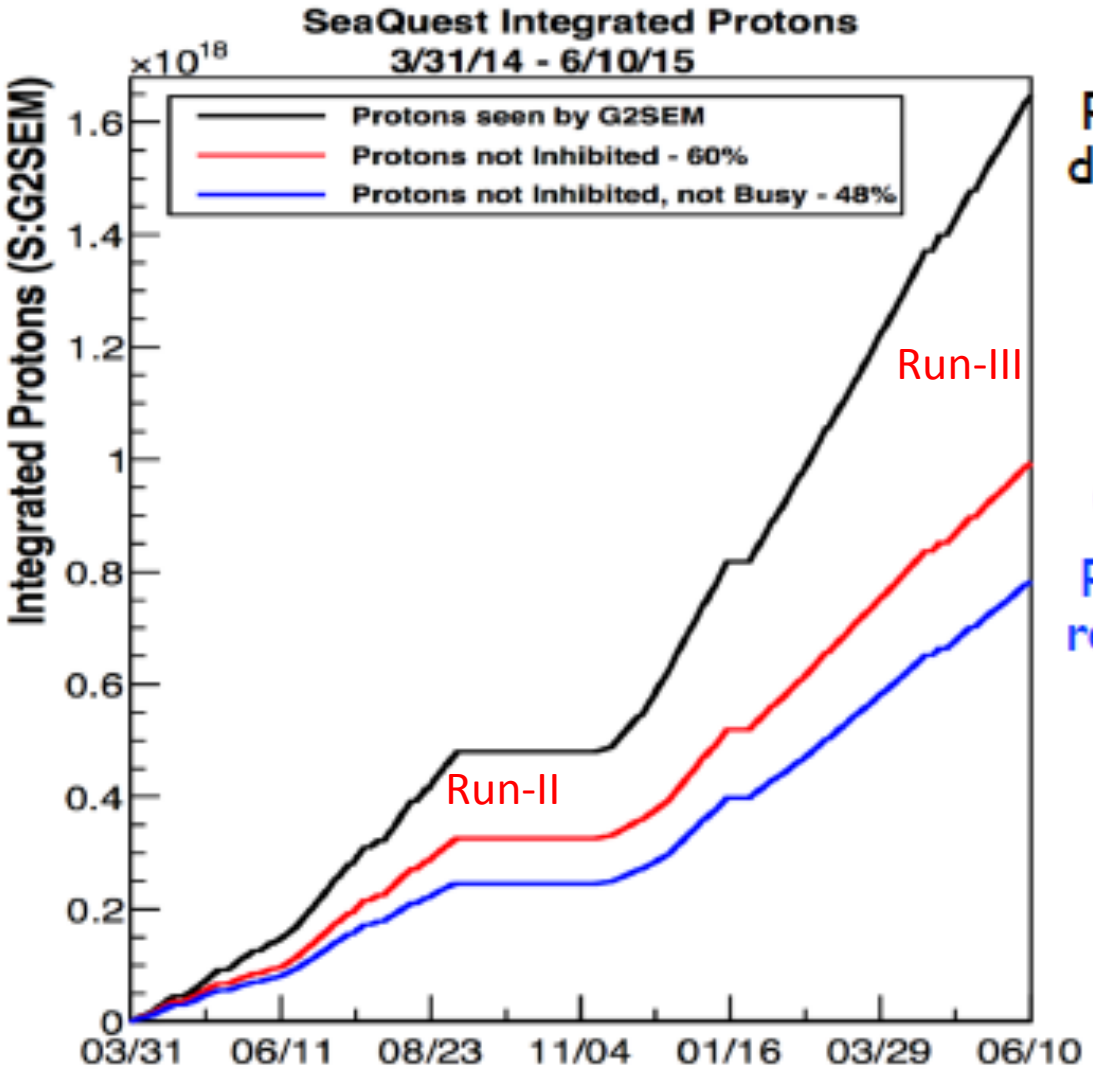


Run-II data: 5% of total projected stat.
Run-III data: 30% of total proj. stat.





E906 Run-II and III Performance



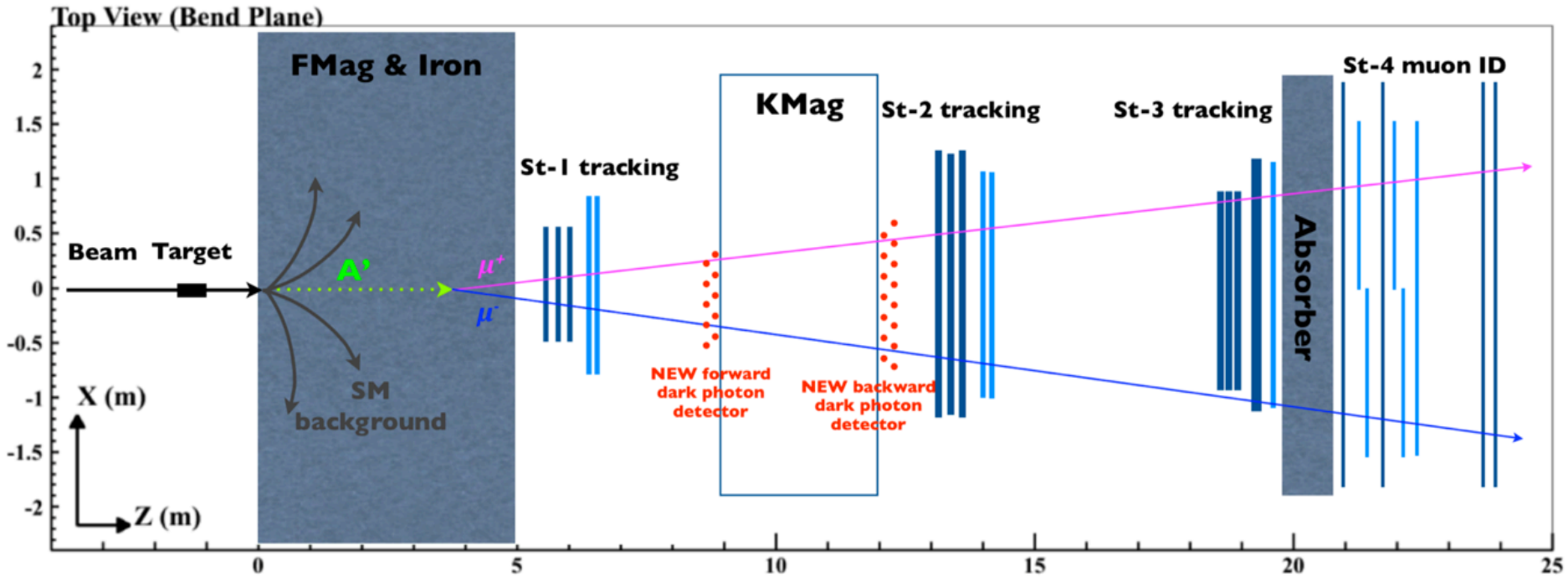
1.6E18 protons delivered

0.7E18 protons recorded

~ 10^{18} POT/year
Run-4 on-going

~5% proton budget @MI

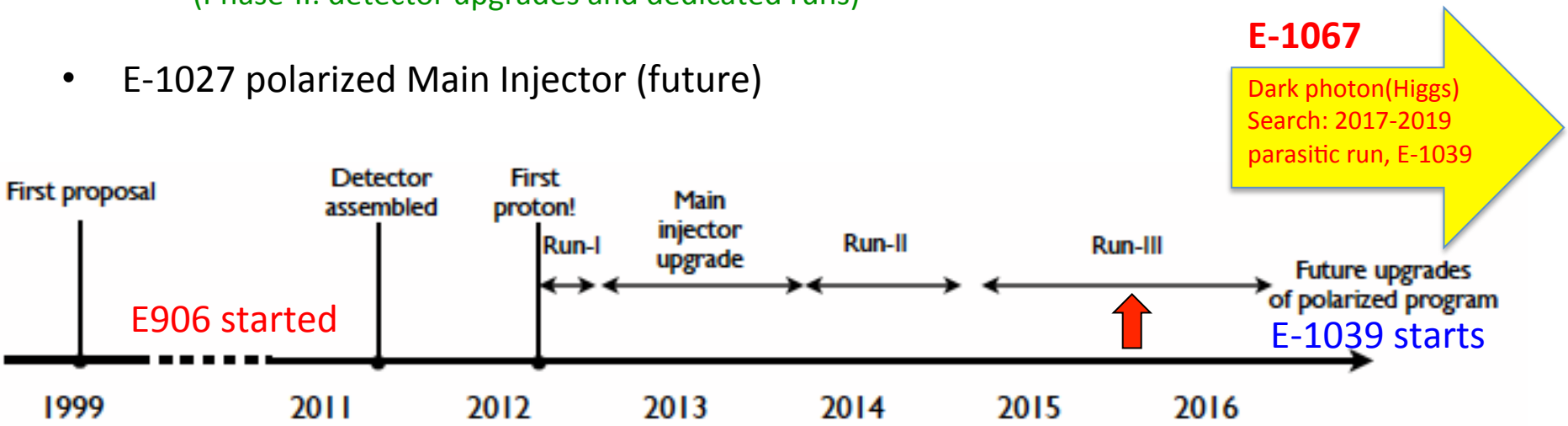
E-1067: A New Program to Probe Dark Sector in Beam Dump Mode



E906/E1039: Target thickness ~10% λ_I
~90% in beam dump!

Schedules of SeaQuest Experiments

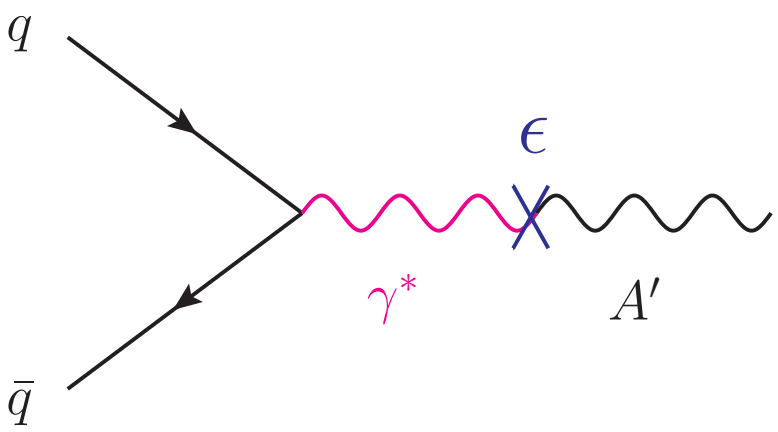
- E-906 complete data taking in summer 2016
  - E906 targets are located ~1.3m upstream of the beam-dump, ~10% λ_I.
- E-1039 will replace current E906 targets with a polarized NH_3 target.
  - No change to E906 spectrometer setup
  - New target located about 3.5m upstream of the beam-dump, ~6% λ_I.
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



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

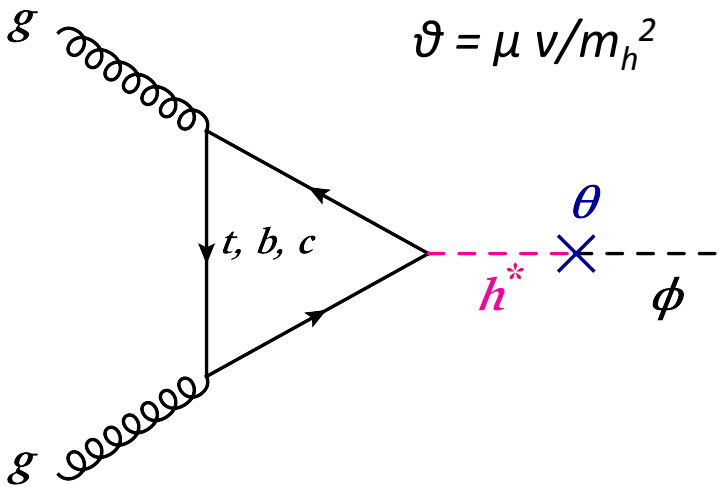
Photon portal: "vector"

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



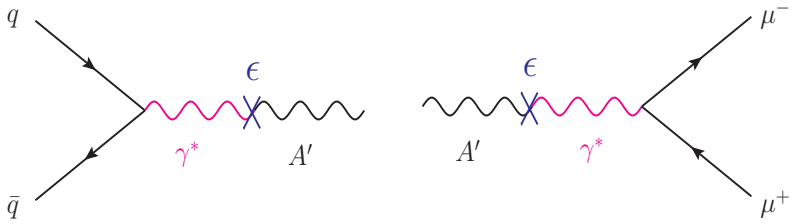
Higgs portal: "scalar"

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

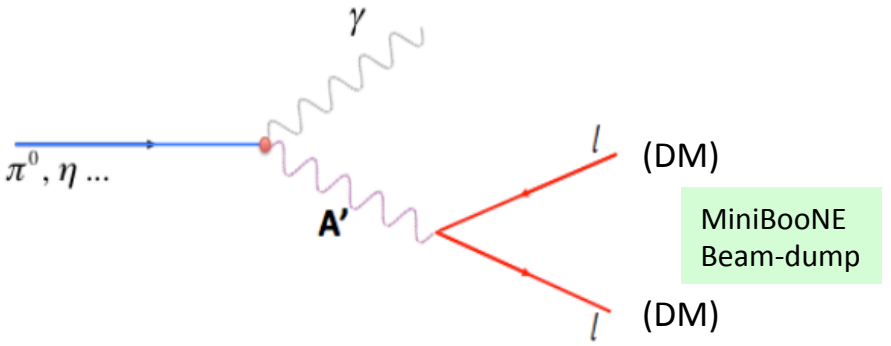


Dark Photon Detection in Dimuon Decay Channel

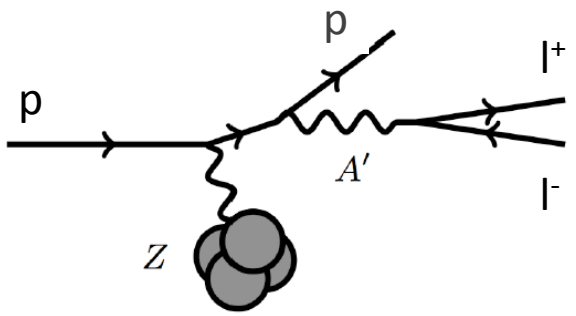
1. Drell-Yan like



2. π^0, η, … decay



3. Bremsstrahlung

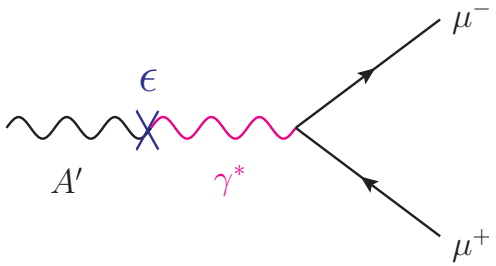


Also see: S. Gori, S. Gardner and K Liu's talks

Dark Photon Decay Modes

"Minimal" Decay:

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

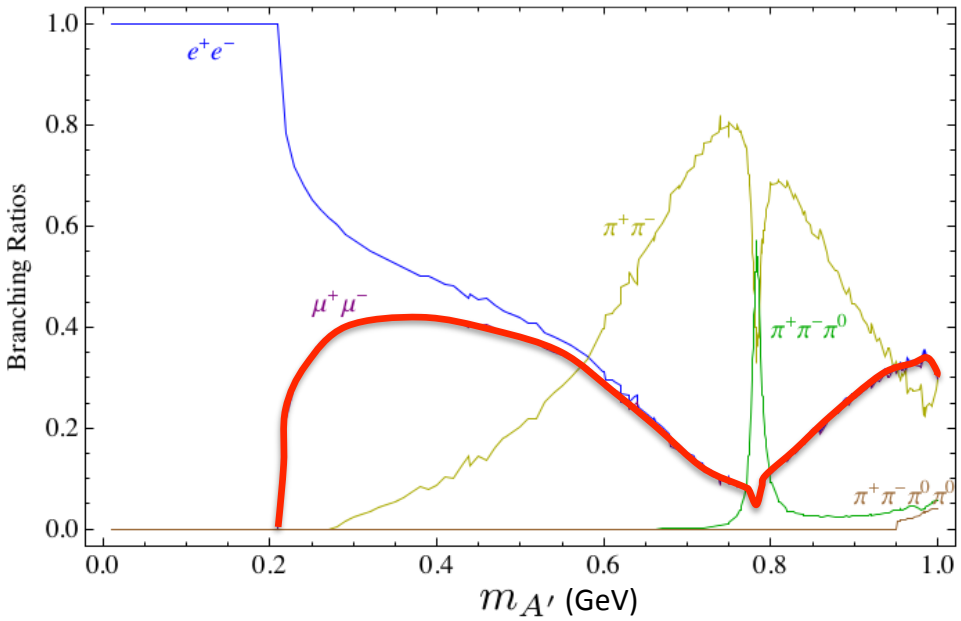


$$\Gamma(A' \to f + \bar{f}) = C\frac{\epsilon^2 m_{A'}}{3} e_f^2 \alpha_{\rm em} \left(1 + \frac{2m_f^2}{m_{A'}^2}\right) \sqrt{1 - \frac{4m_f^2}{m_{A'}^2}},$$

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

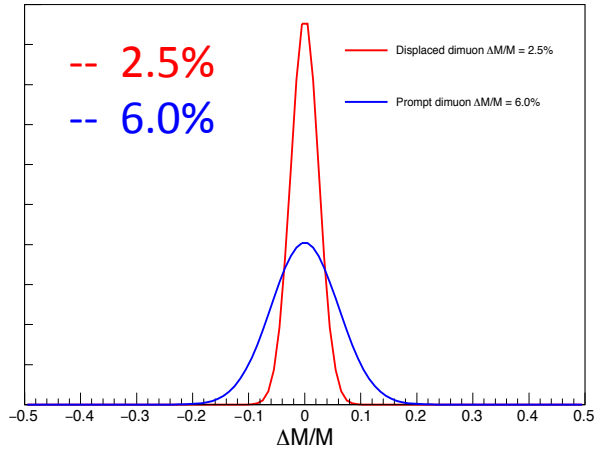


"General" Decay:

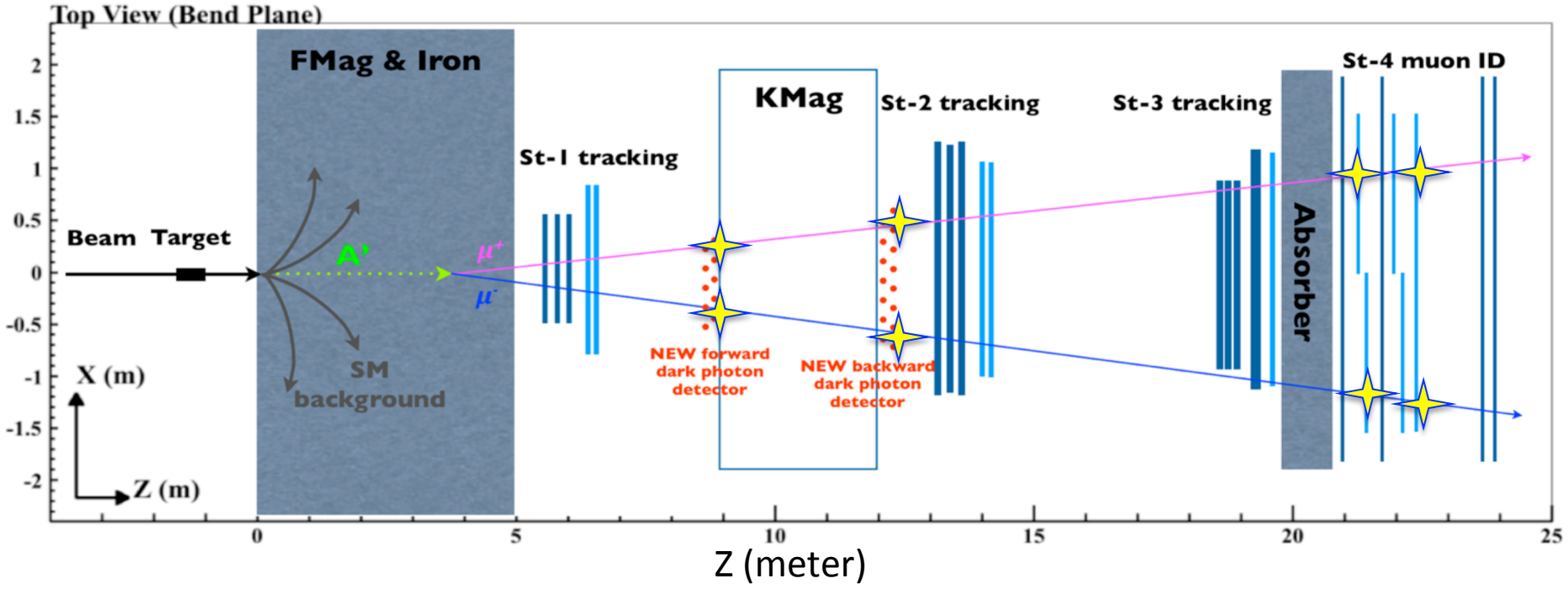
- Decay into other dark particles, dominant channel if allowed
  1. Dark -> Dark
  2. Dark -> SM particles

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



Dimuon mass resolution

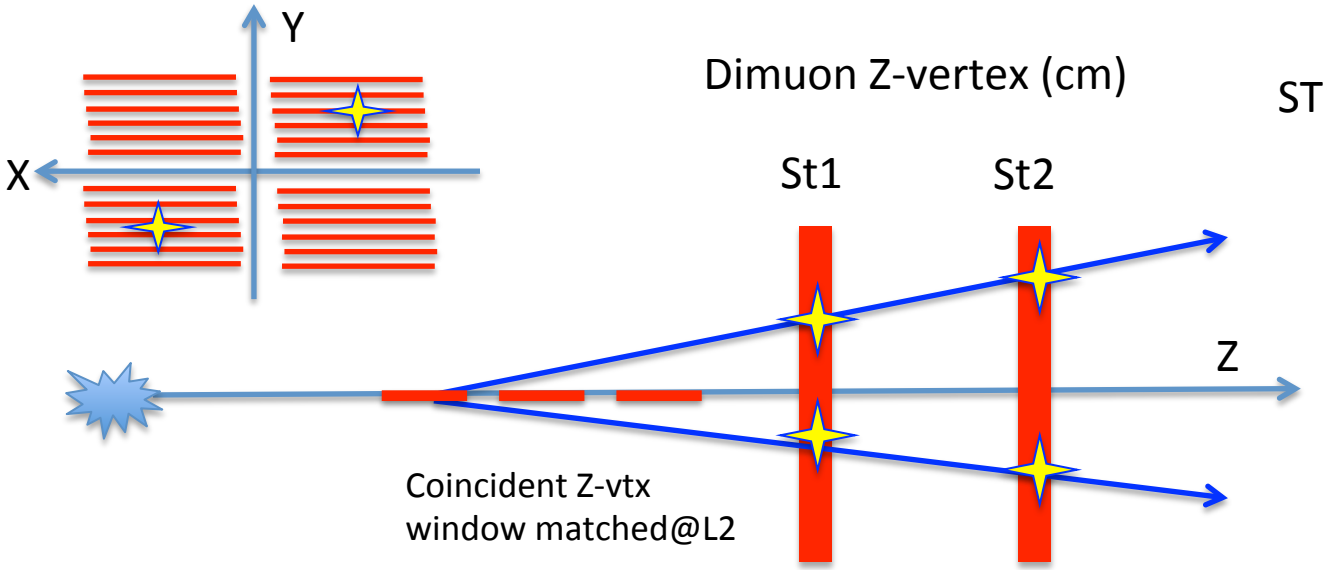


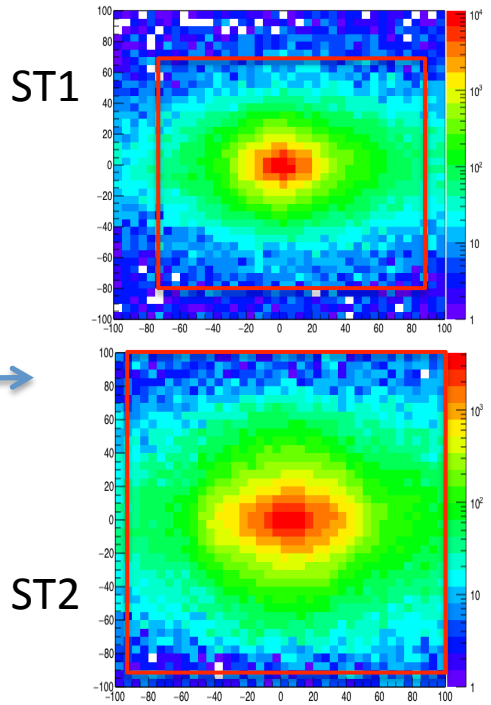
A New High-Granularity Displayed Dimuon Vertex Trigger

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

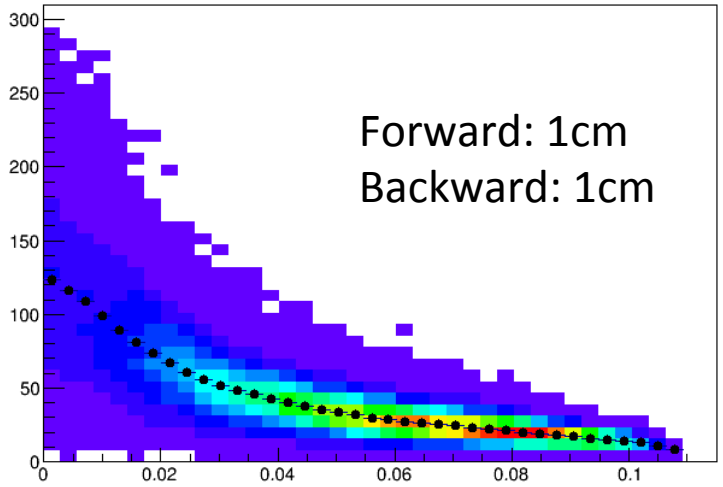
Y-Plane (non-bending) Trigger:

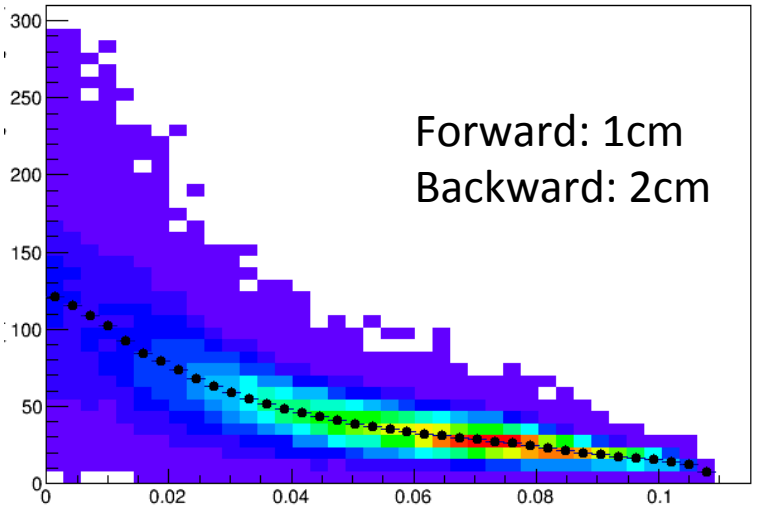
- A quadrant panel: 80cm x 80cm, 1cm thick/(100x100x2)
  - ST1: 1cm x 1cm x 80 cm scintillating strips, SiPM readout
  - ST2: 2cm x 2 cm x 100 cm strips
- Straight line projection, 30cm Z-vertex resolution
- Displaced z-vertex, mostly low mass < 3GeV

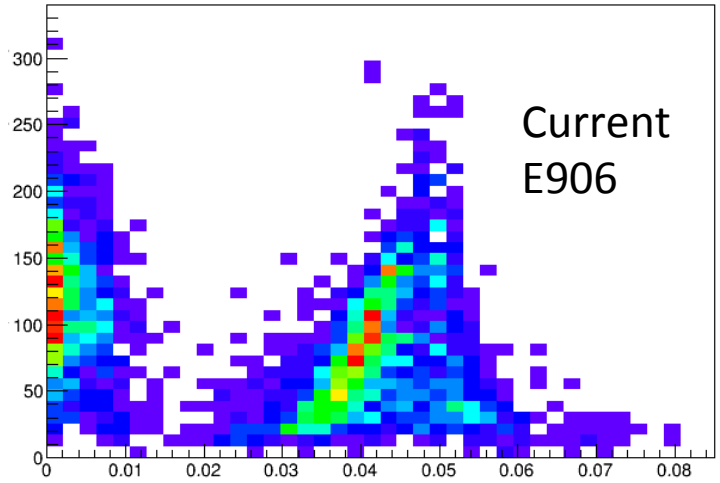


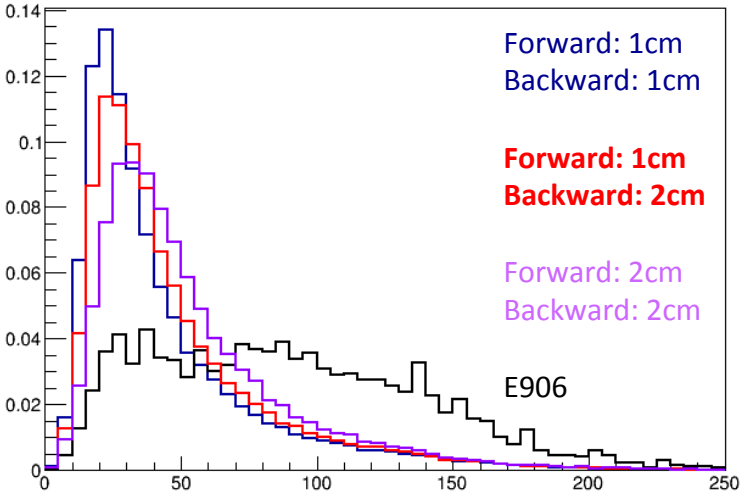


Muon Z-Vertex Resolutions









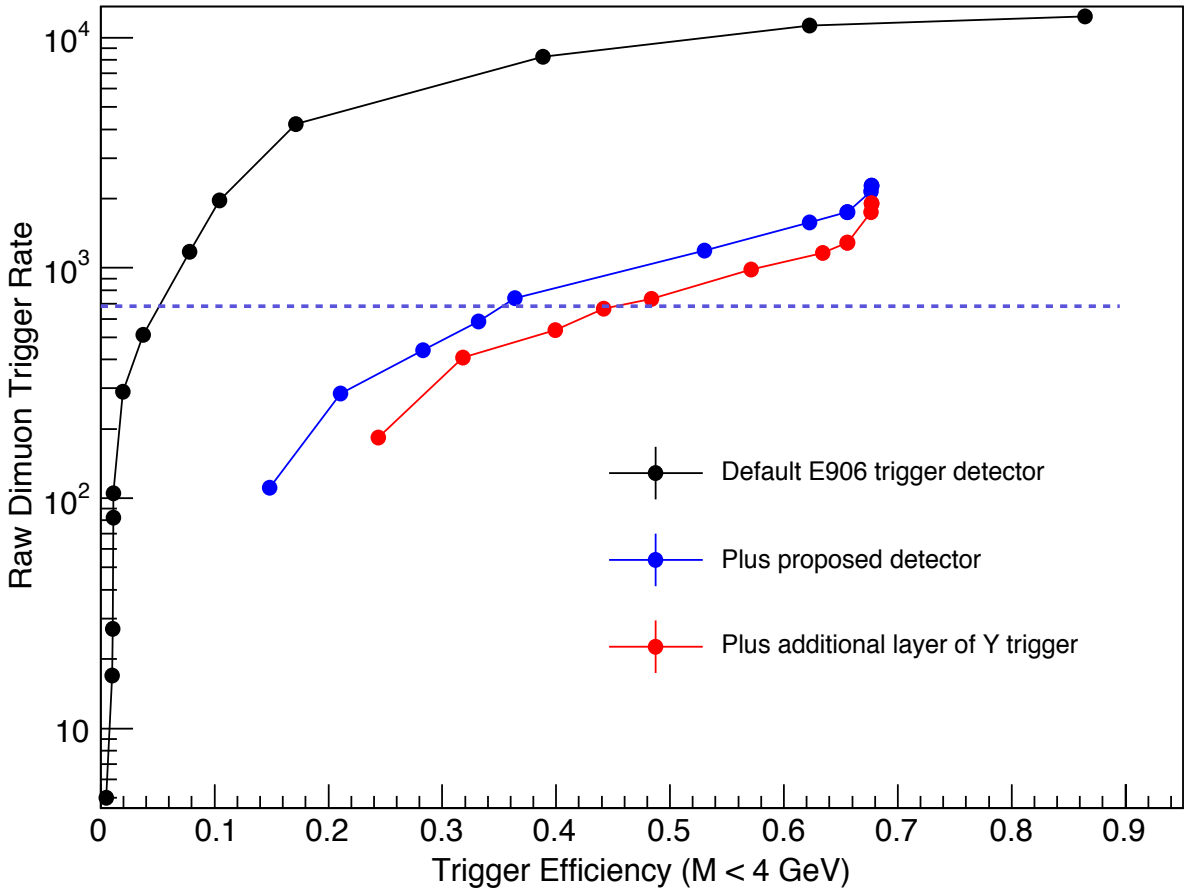
Low Mass Prompt Dimuon Trigger Rate Study in 2015

- 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

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

Parasitic mode: use up to ~10% DAQ bandwidth

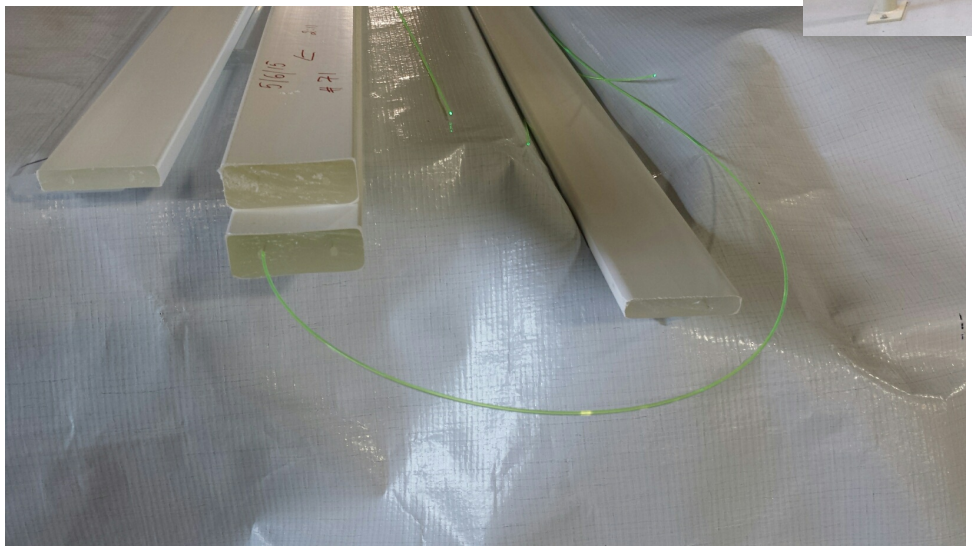


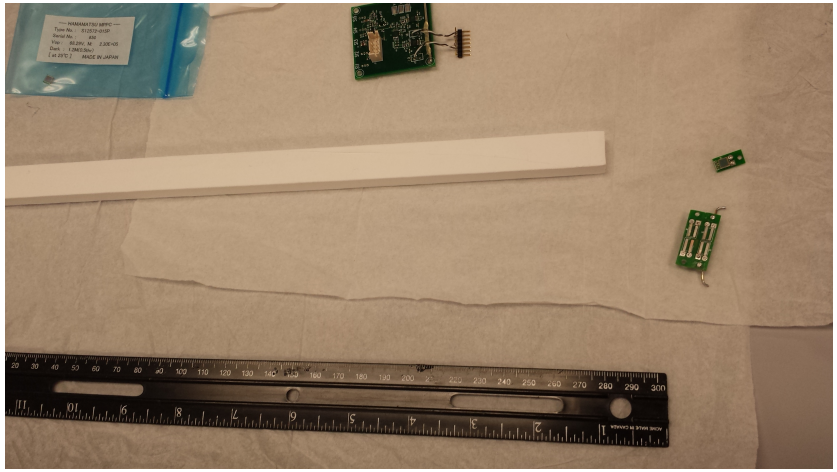
Expected (Prompt)Low mass dimuon trigger performance

Fermilab Extruded Scintillators

Work in progress trigger upgrade

- Extruded scintillators + WLSF
- SiPM readout
- Low cost, large area





Search Mode (1): Long-lived Dark Photons

Reconstructed dimuons with downstream Z-vertex:

3m < Z-vertex < 6m

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

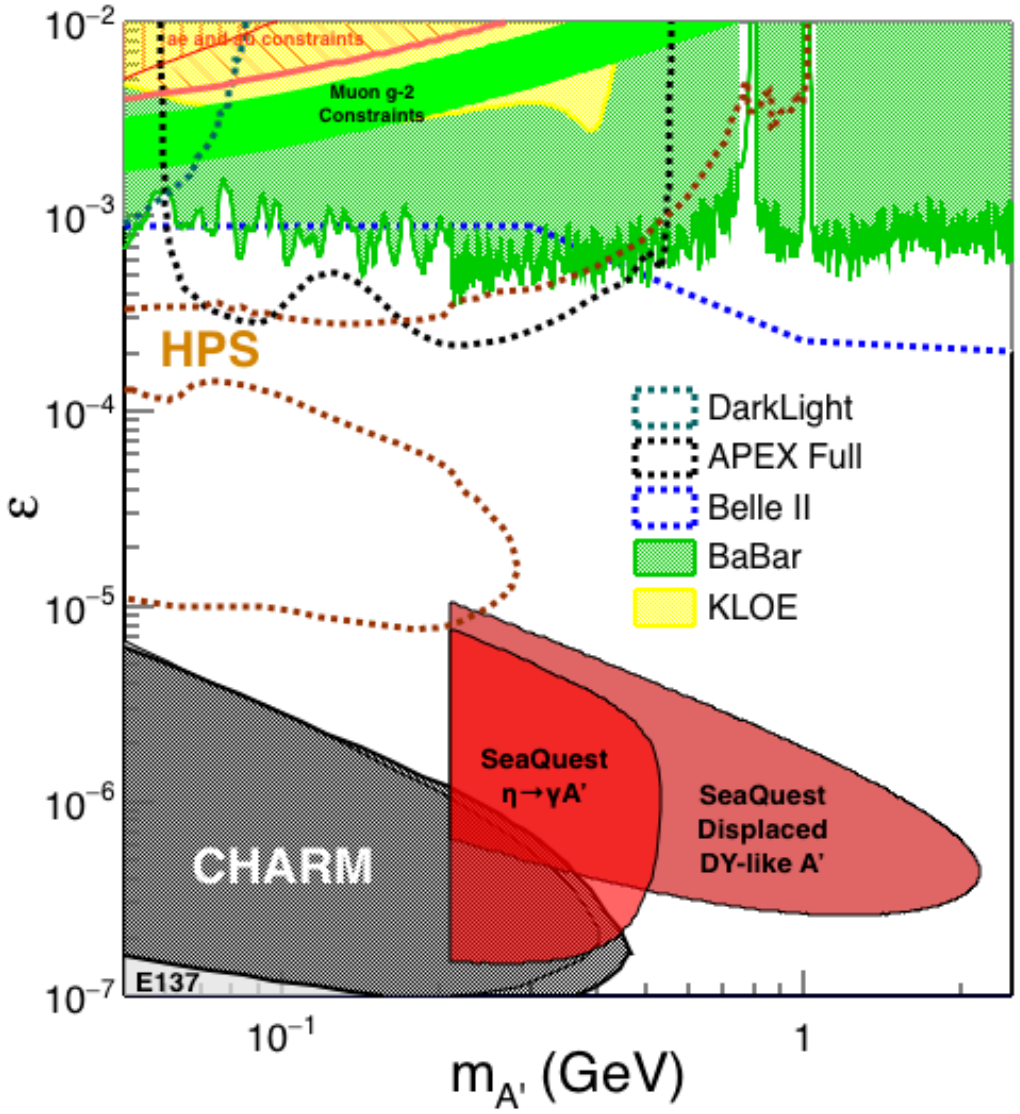
- $5x10^{12}$ ppp (current E906)
- 200 days

1.4×10^{18} POT (recorded)

- 4 events contours (2-sigma)

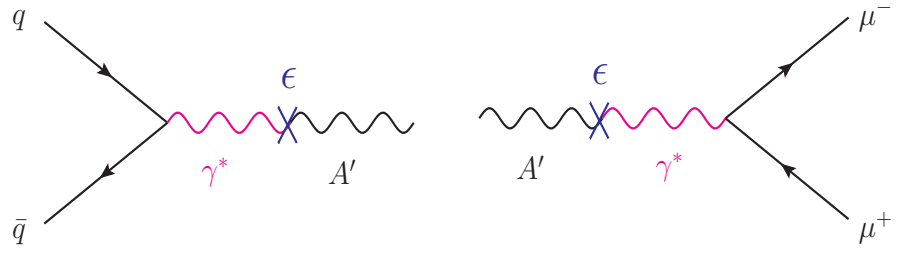
2-sigma (95%) exclusion plots

Excellent coverage of uncharted region!



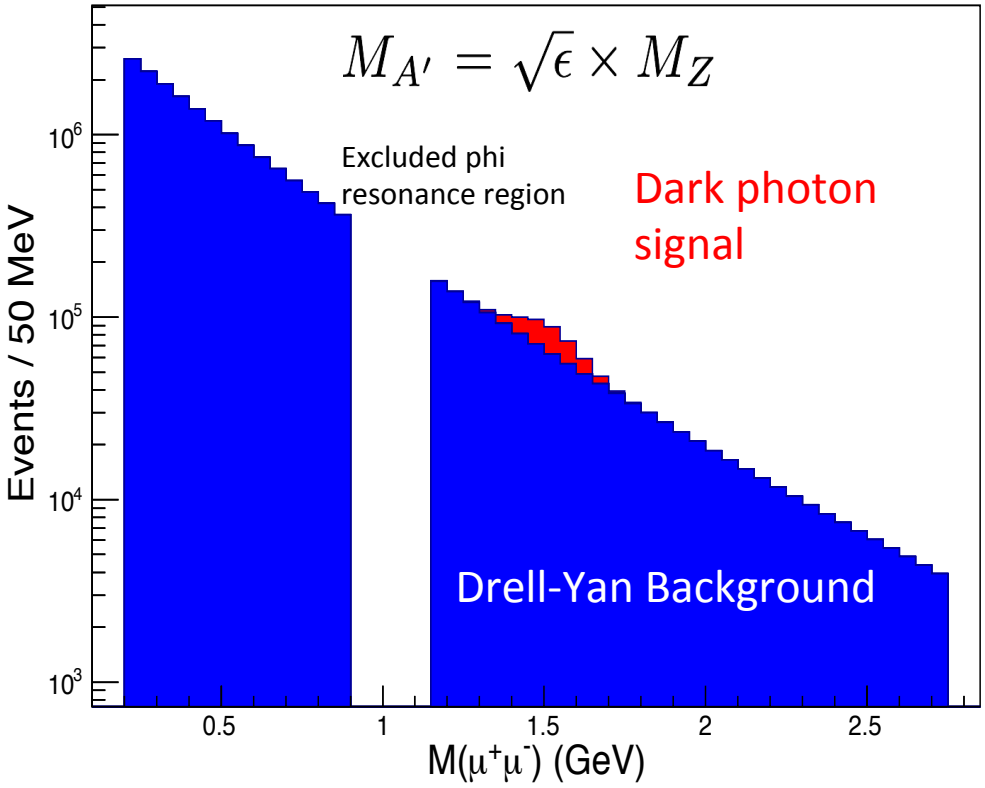
Search Mode (2): "Prompt" Dark Photons vs Drell-Yan

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 …

Summary: Dark Photon Sensitivity

(parasitic run w/ E1039)

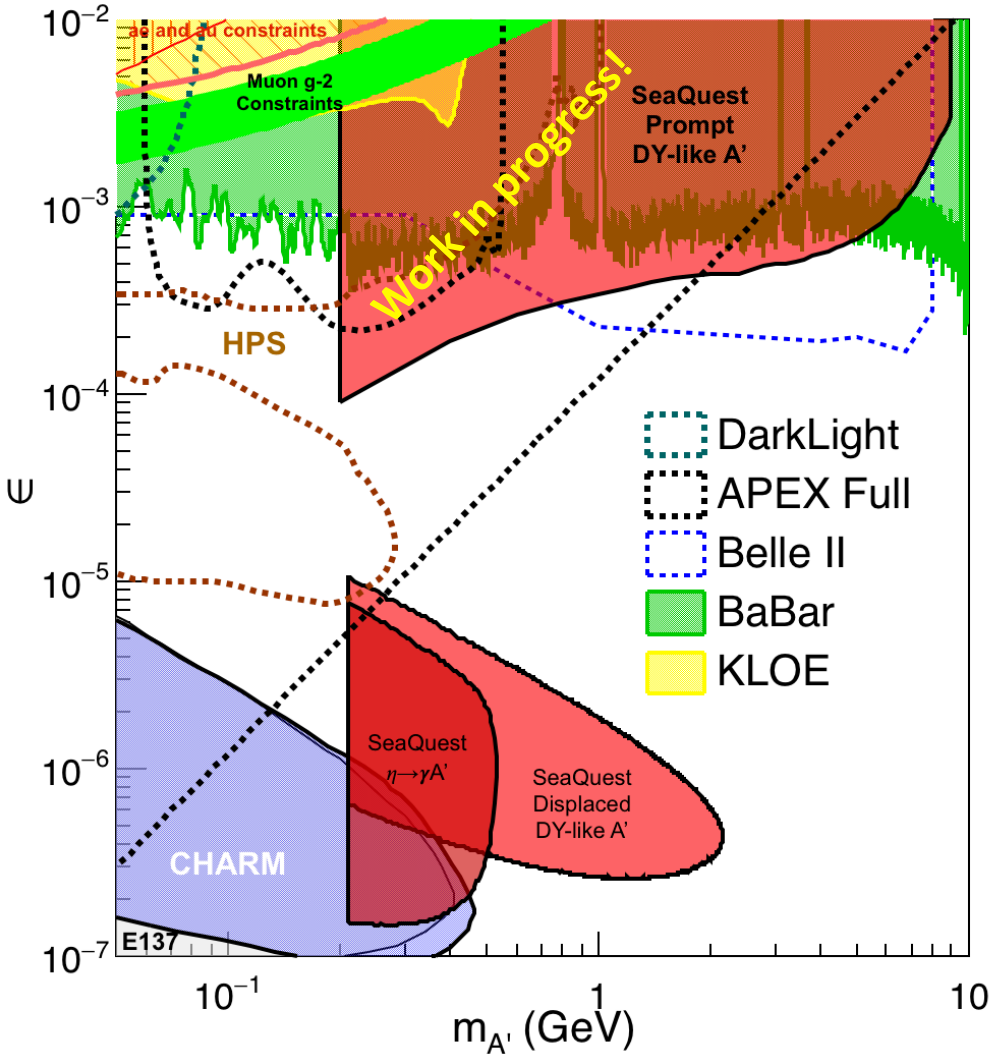
Signals considered:

- Drell-Yan like
- Eta decays
- Bremsstralung

Covers a wide range of unexplored parameter phase space

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

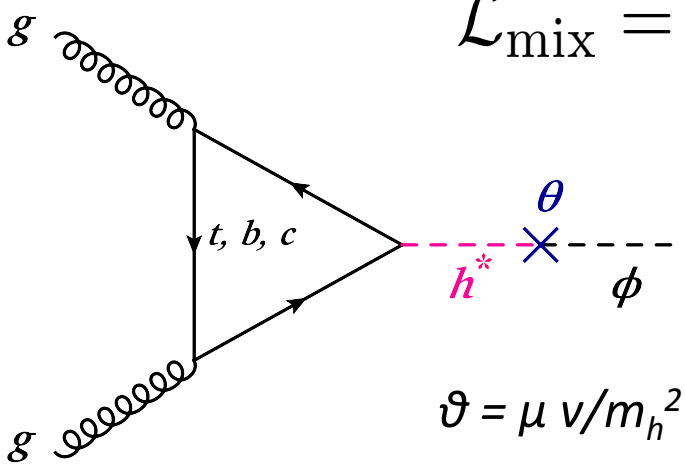
  Access below 200MeV with di-electrons (add EMCal)

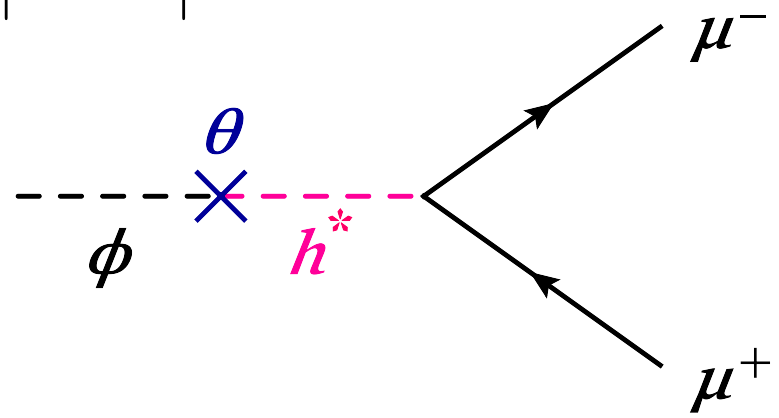


Dark Higgs Search at E-1067

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

Y. Zhang et al, arXiv:1502.06983





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

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

Phase-I:

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

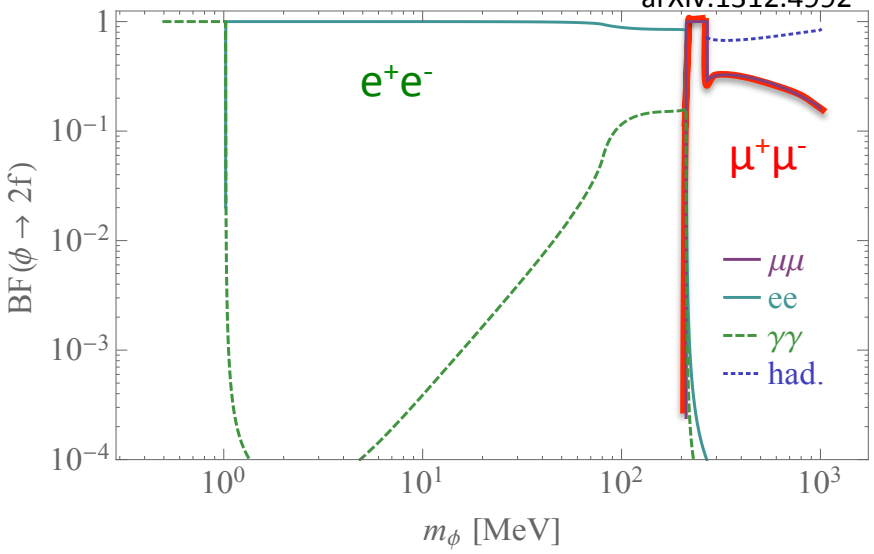
Advantage of using hadron beams with muon probes over electrons

Phase-II:

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

High-mass: hadrons, (5x)

arXiv:1312.4992

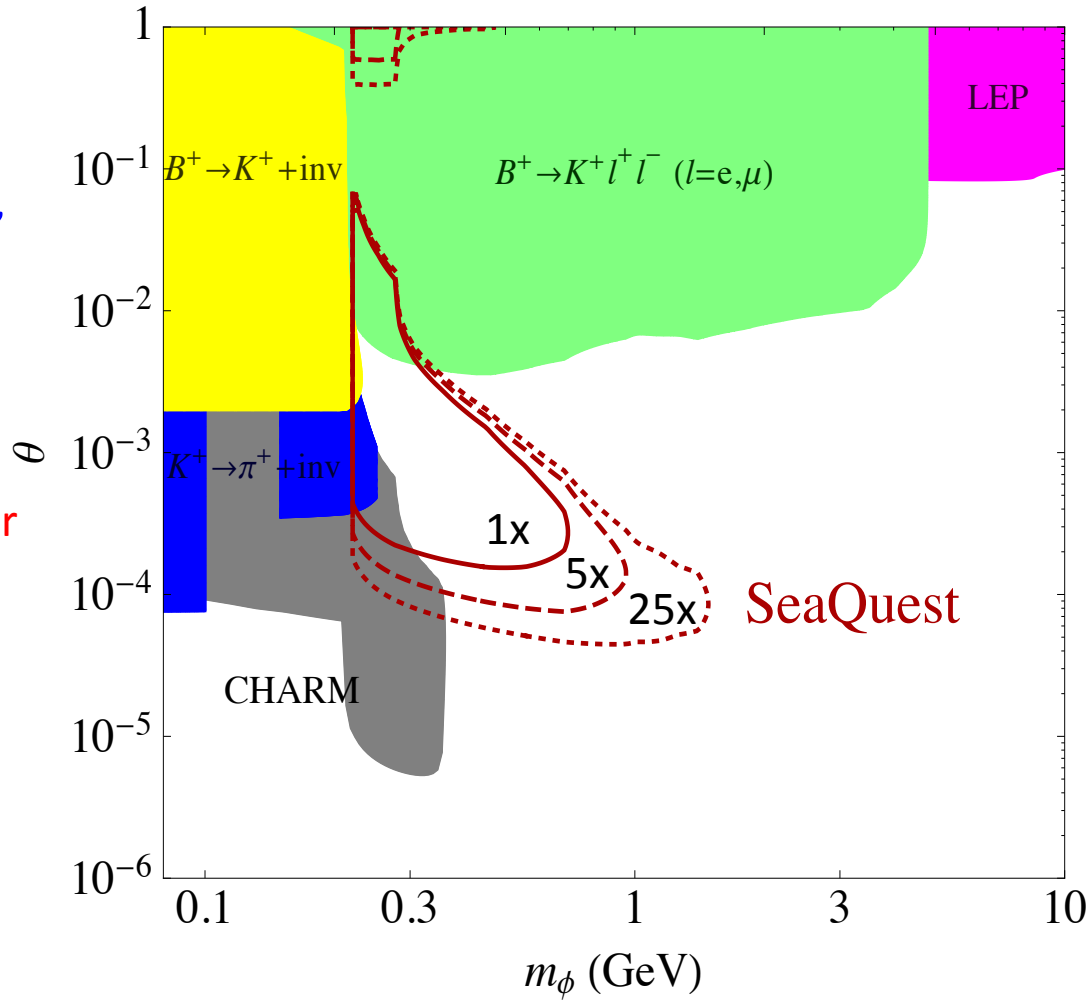


E-1067 Dark Higgs Sensitivity

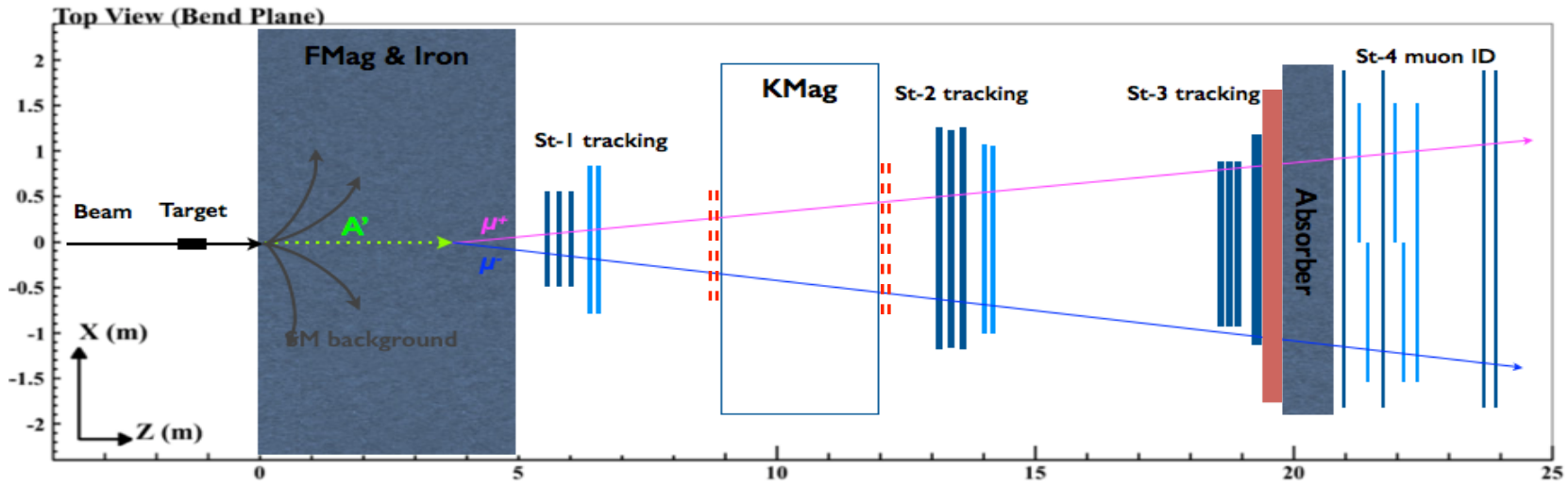
POT:1.4x10^{18} (Phase-I)

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

Y. Zhang (2015)



E1067/SeaQuest Upgrade Plan(2020+)



Fine-pitched vertex trigger

- Efficiently trigger on the dilepton pairs generated from downstream while suppressing the background rate
- Significantly enlarge the fiducial region from ~2m to ~6m
- Supported by LANL LDRD

EMCal/HCal

- Add $e^{+/-}$ and $\pi^{+/-}$ capabilities to SeaQuest spectrometer
- Extend the physics reach to A' from π^0 decay, dark $\boldsymbol{\rho}$, and hadronic decay mode for heavier A'
- Re-commission the existing detectors (EMCal from PHENIX being considered)

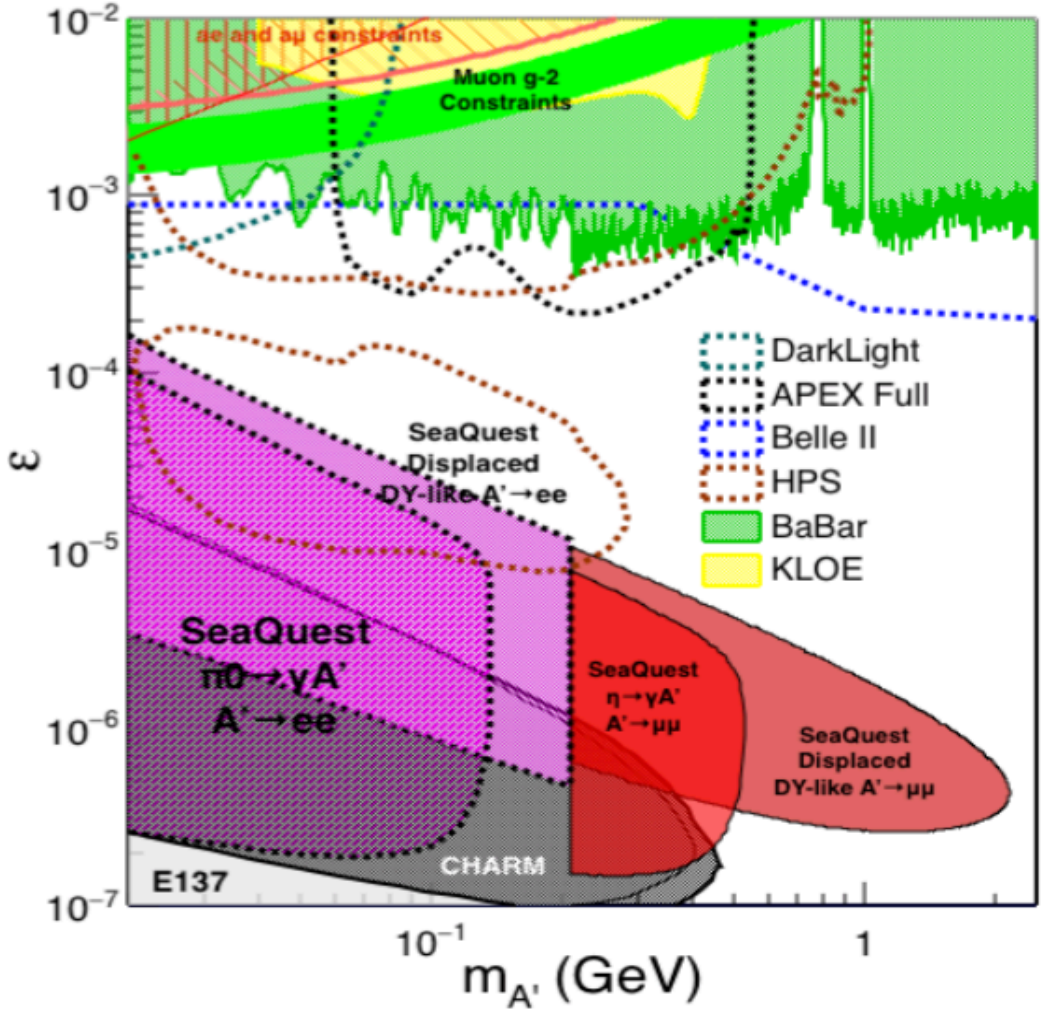
Modest upgrades with significantly increased physics reach.
Data taking expected to start in summer 2017!

Phase-II: Displaced Dark Photons

with future detector "EMCal/HCal" upgrades

Projection: POT 1.4 x 10^{18}

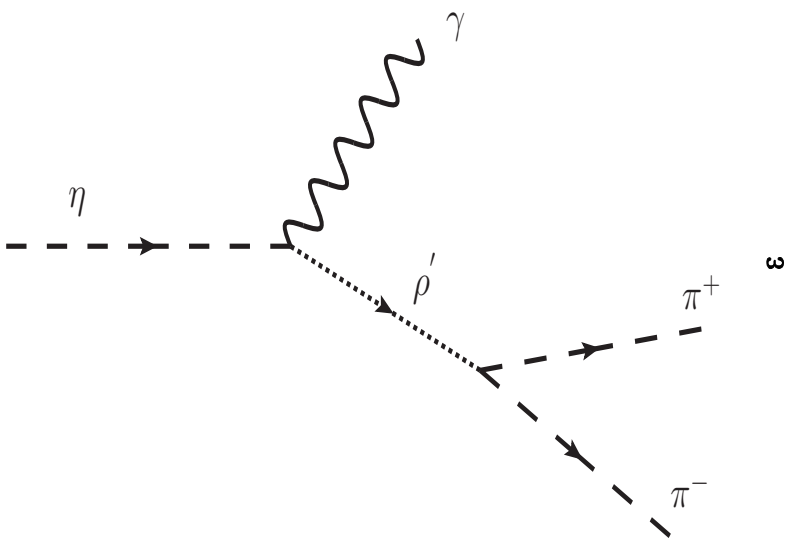
- Detector upgrades
  - EMCal: $e^{+/-}$
  - HCal: $\pi^{+/-}$
  - Recycle from other experiments, PHENIX/RHIC etc
- DAQ upgrade
  - 100+ kHz
- Timeline of dedicated runs
  - 2020+
- Detector configuration
  - Access low mass region with optimized Fmag settting



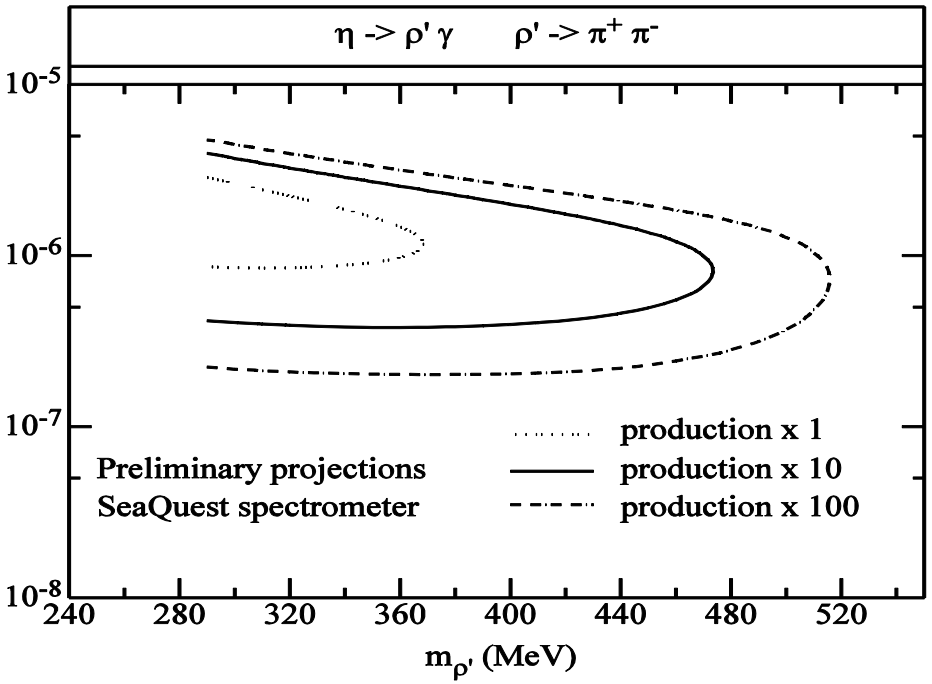
Phase-II: Probe Non Abelian Dark Sector

with future detector "HCal" upgrades

non-Abelian dark sector process



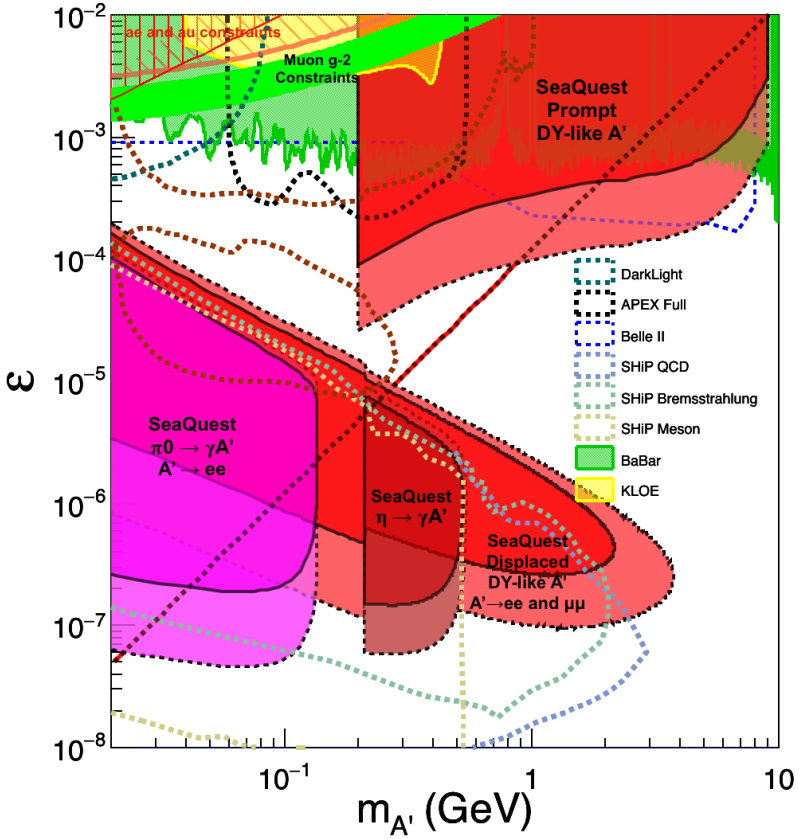
S. Gardner and R. Holt



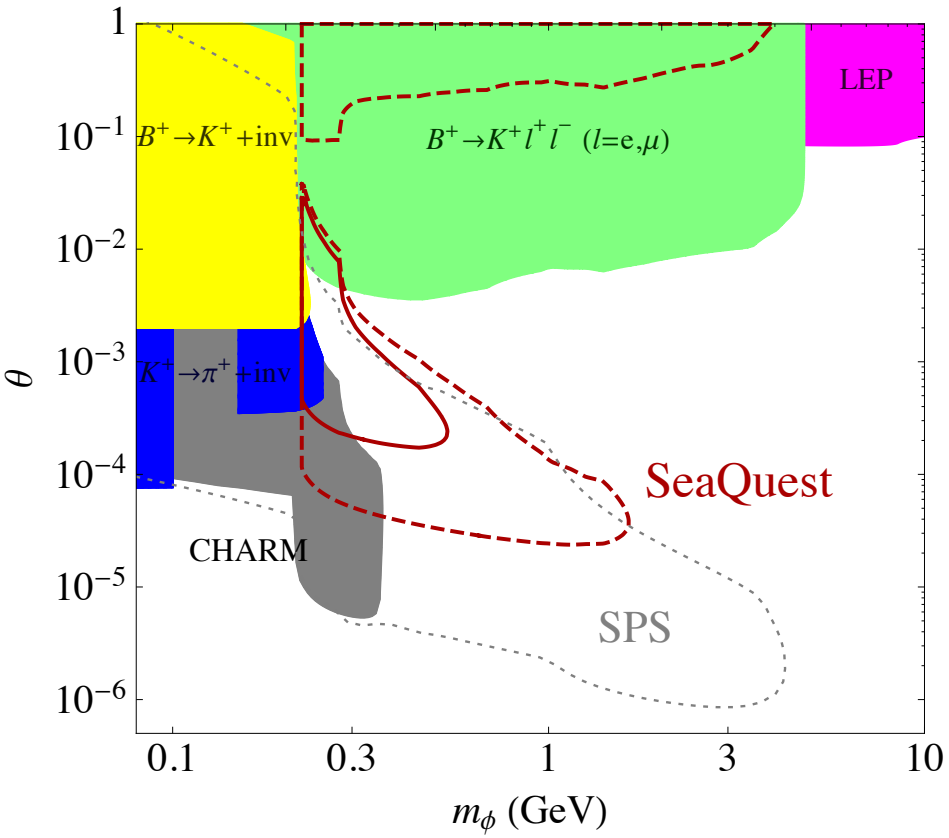
[Note: Batell, Pospelov, and Ritz, PRD 80 (2009) 095024 for a review re fixed target expts.]
Here we consider a non-Abelian (gluon) portal
[Baumgart et al., JHEP 0904, 014 (2009); Gardner and He, PRD 87 (2013) 116012]
The "shining through walls" design – unique to Seaquest – makes this possible ,
to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

Comparison with SHiP Proposal

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

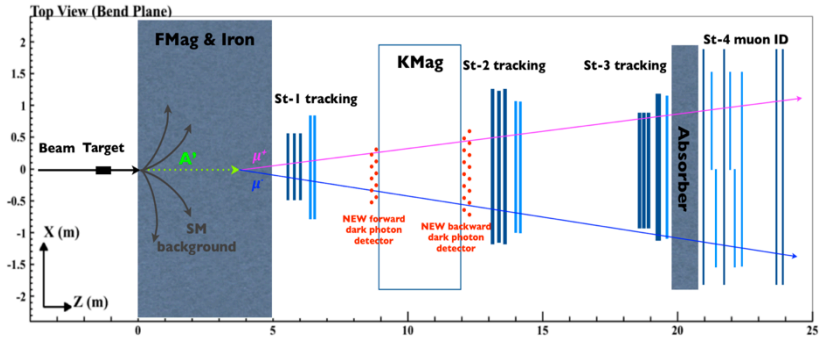


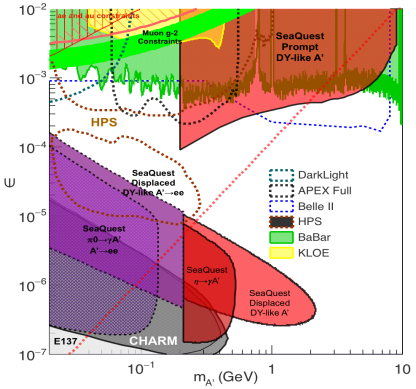
400 GeV@SPS: 2025 -2030
4x10^{20} POT

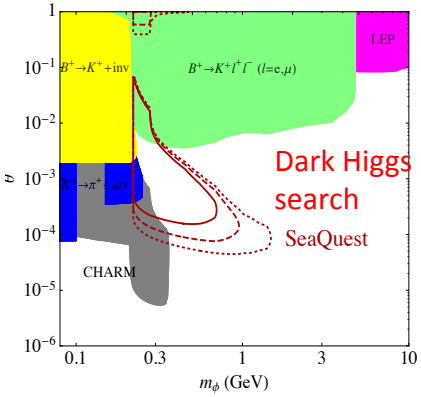


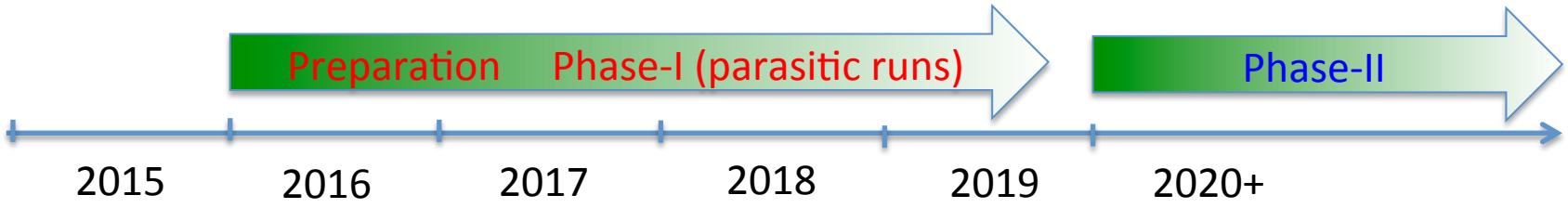
Summary and Outlook

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









backup

Many good discussions with

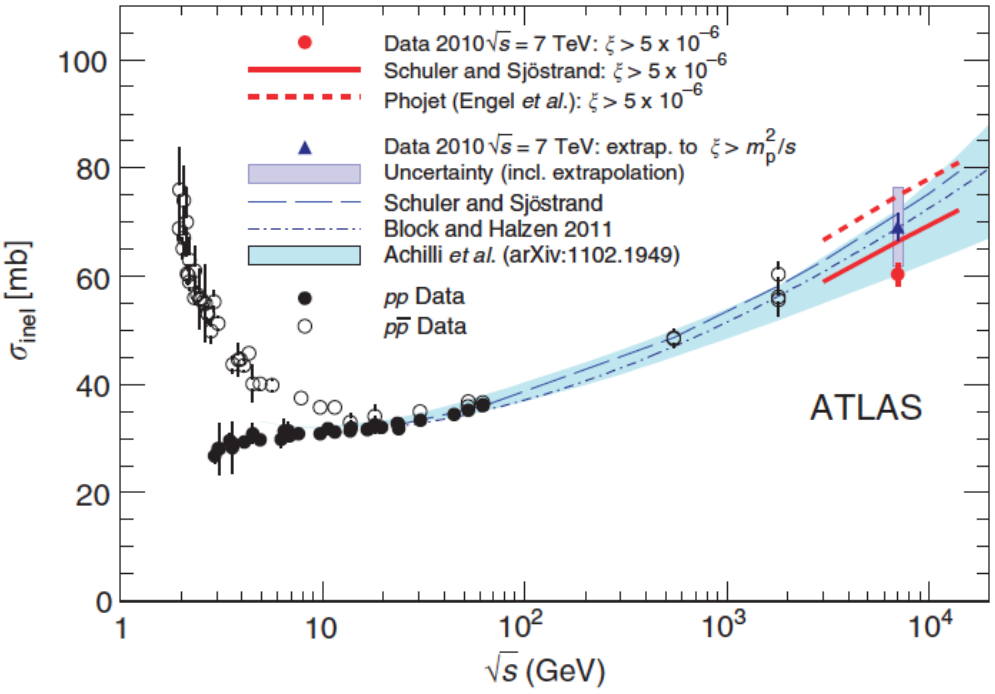
K. Liu, Z.-B. Kang, S. Gori, N. Toro, R. Holt, J-C. Peng, Y. Zhang, P. McGaughey, Y. Zhong, P. Reimer, C. Brown, R. van der Water, P. Schuster, R. Essig, S. Gardner et al

and the new/growing E-1067 Collaboration at Fermilab

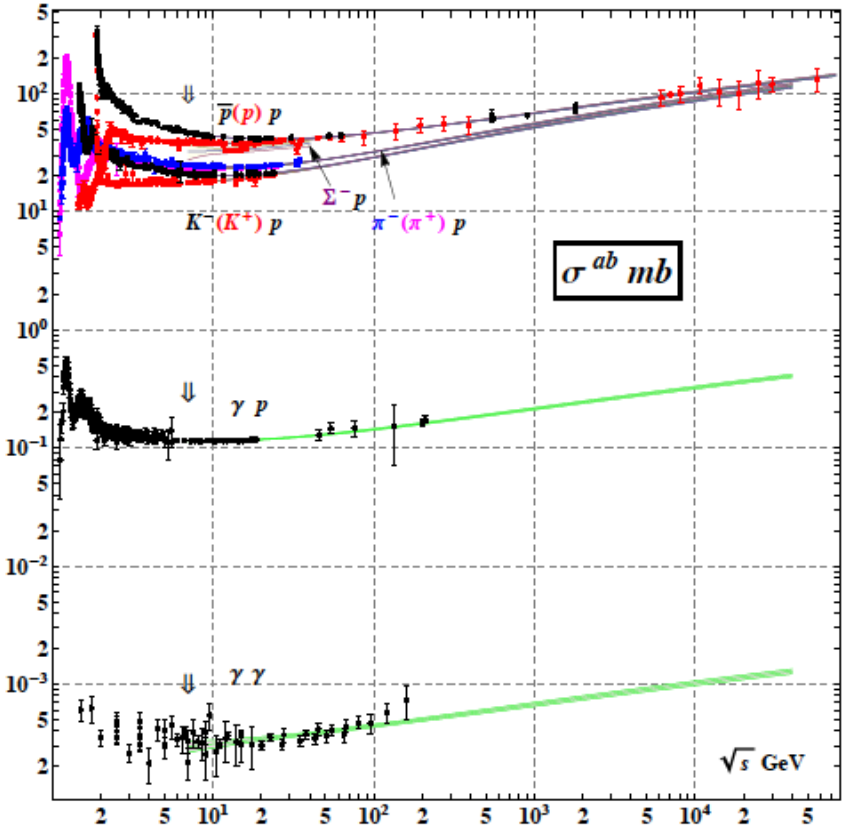
Inelastic Cross Section: pp

@SeaQuest sqrt(s) = 15GeV

Sig_tot = 40mb
Sig_inel = 30mb



Total_cross section



A New High-Granularity Displayed Dimuon Vertex Trigger

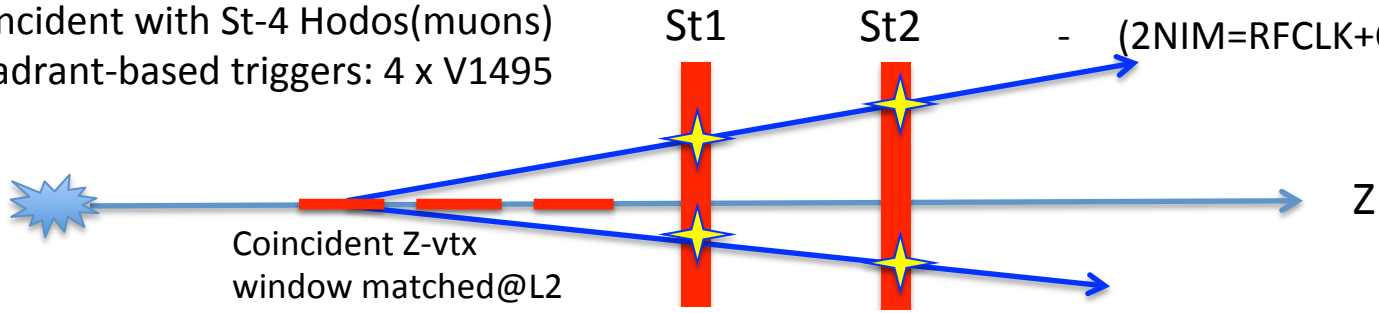
High rejection power, very low rate, << 1 kHz(E906 DAQ limit)

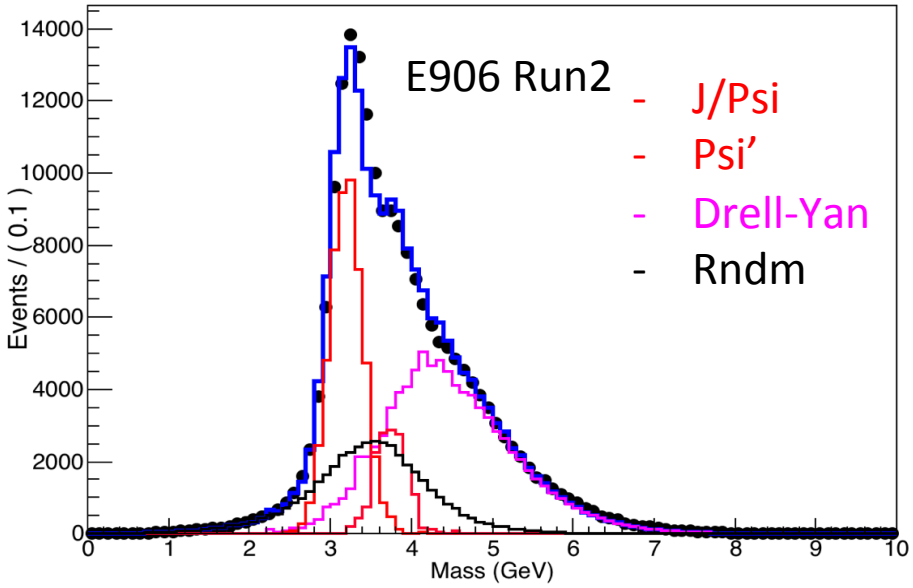
Y-Plane Trigger:

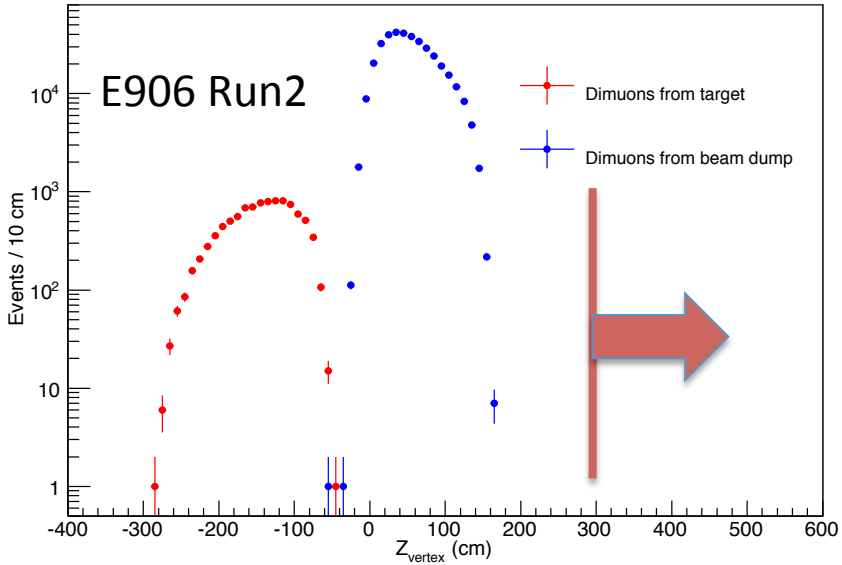
- A quadrant panel: 50cm x 50cm, 1cm thick
  - 1cm x 1cm x 50 cm scintillating strips, SiPM readout
- Straight line projection, 30cm Z-vertex resolution
- Displaced z-vertex, mostly low mass < 3GeV
- Coincident with St-4 Hodos(muons)
- Quadrant-based triggers: 4 x V1495

Y-channels per quadrant:

- 1x V1495
- 50(St1) + 50(St2) + 8x2 (St4-Y1,2) = 116
- 96+64 = 160 possible
  - 72+72+16 = 160 (possible)
  - (2NIM=RFCLK+ComSTOP)

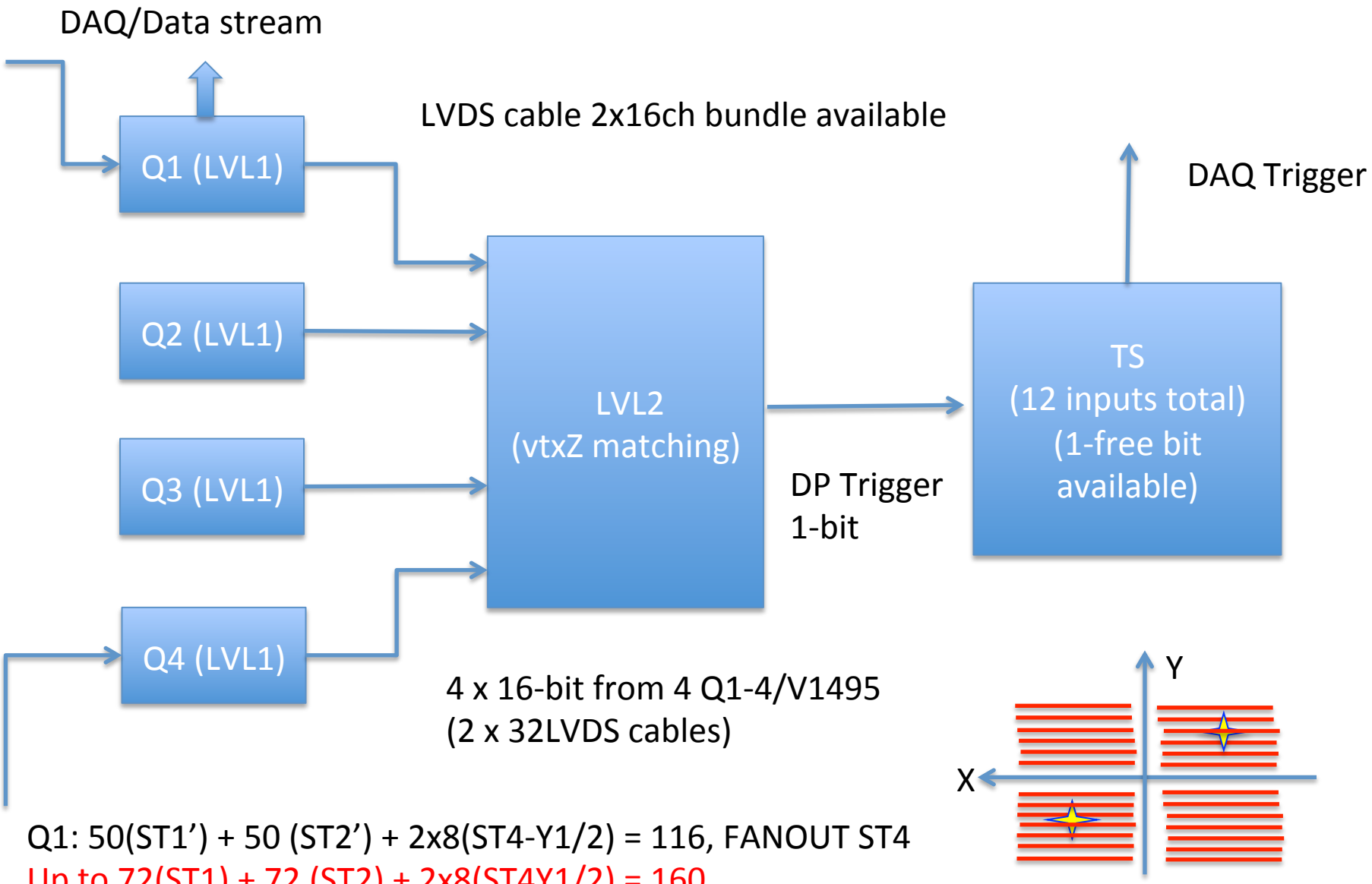






Dimuon Z-vertex (cm)

Displaced Dark Photon Trigger

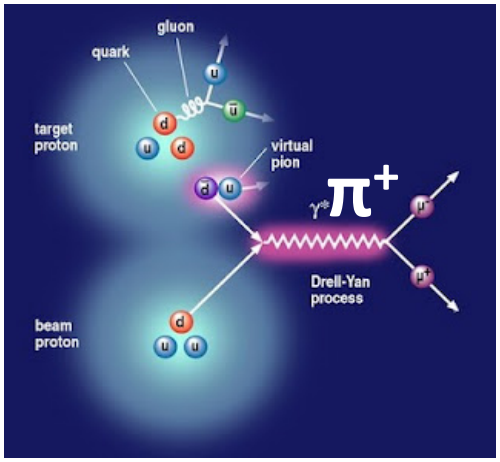


Q1: 50(ST1') + 50 (ST2') + 2x8(ST4-Y1/2) = 116, FANOUT ST4

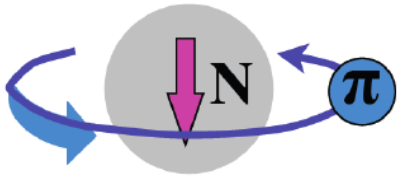
Up to 72(ST1) + 72 (ST2) + 2x8(ST4Y1/2) = 160

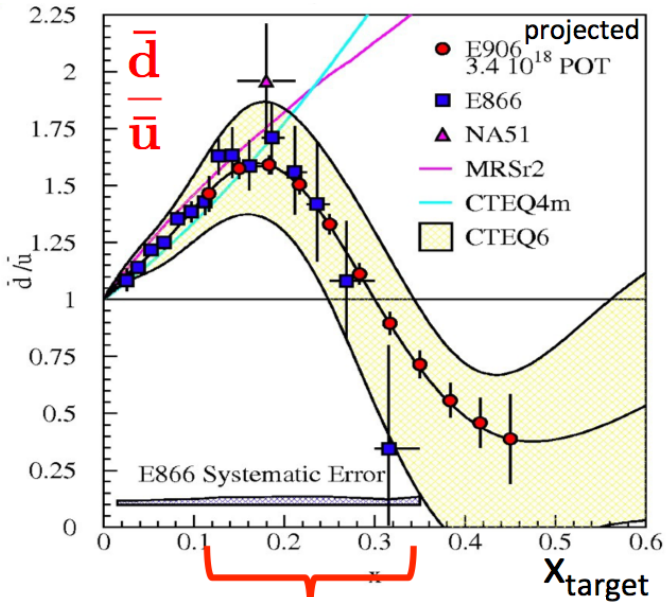
E906 Physics Programs: 2009-2016

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



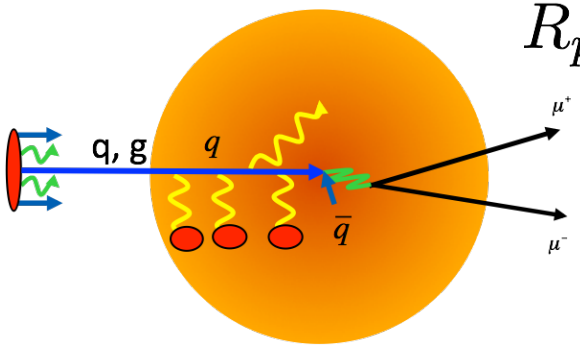
$$|p>=|p^0>+|n>|\pi^+>$$

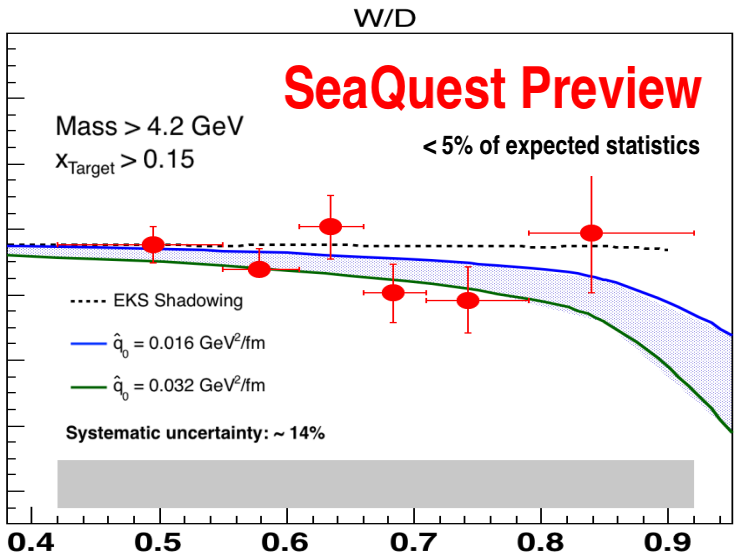




- Quark energy loss in p+A

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

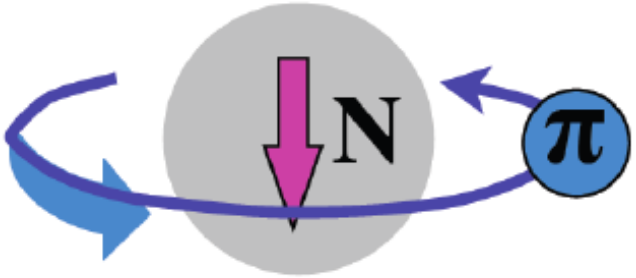


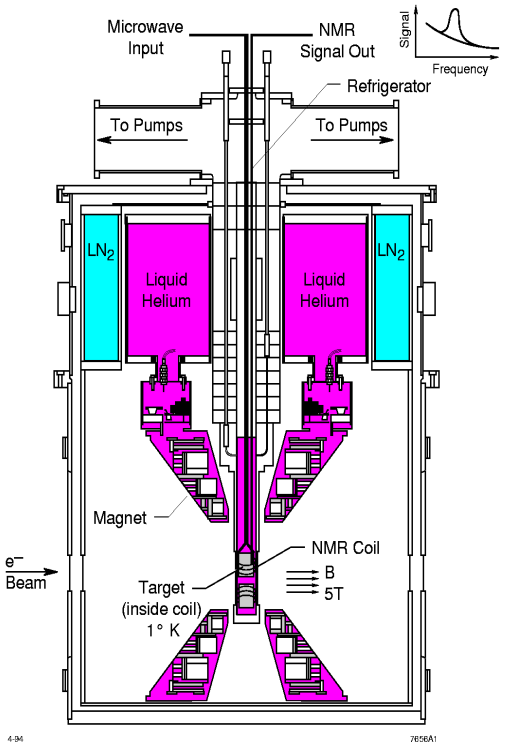


E1039 Physics Program: 2017-2019

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