# Direct Search for Dark Photon and Dark Higgs at SeaQuest/E1067

Ming Liu

Los Alamos National Laboratory

U.S. Cosmic Vision: New Ideas in Dark Matter
Workshop at Univ. of Maryland

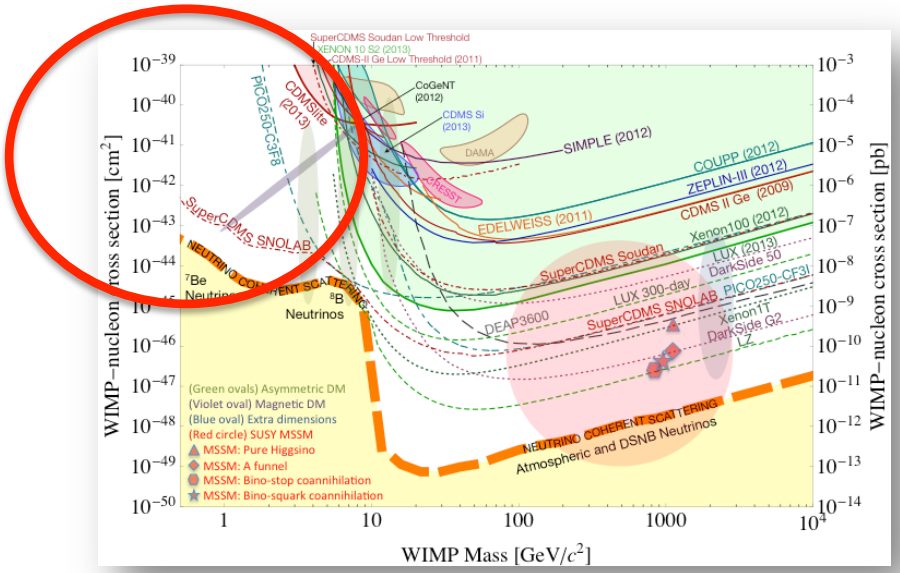
March 24, 2017

# Outline

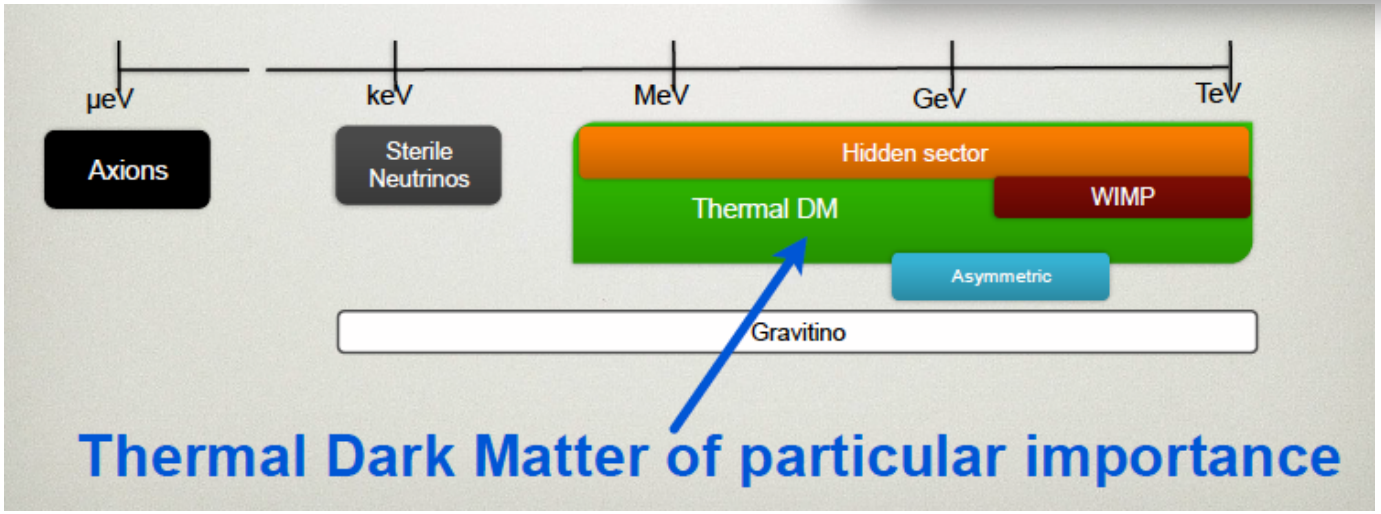
- Dark sector physics @SeaQuest
  - Mass: MeV ~ GeV
- Detector upgrade @SeaQuest
  - DAQ & Displaced dimuon trigger
  - Expected sensitivity
- Future opportunity
  - Electron/hadron ID w/ EMCal upgrade
  - Dedicated dark photon program @Fermilab

# Dark Sector Physics @SeaQuest

Current and near future high-intensity colliders and fixed target experiments offer an ideal environment to probe dark sector physics in MeV ~ GeV



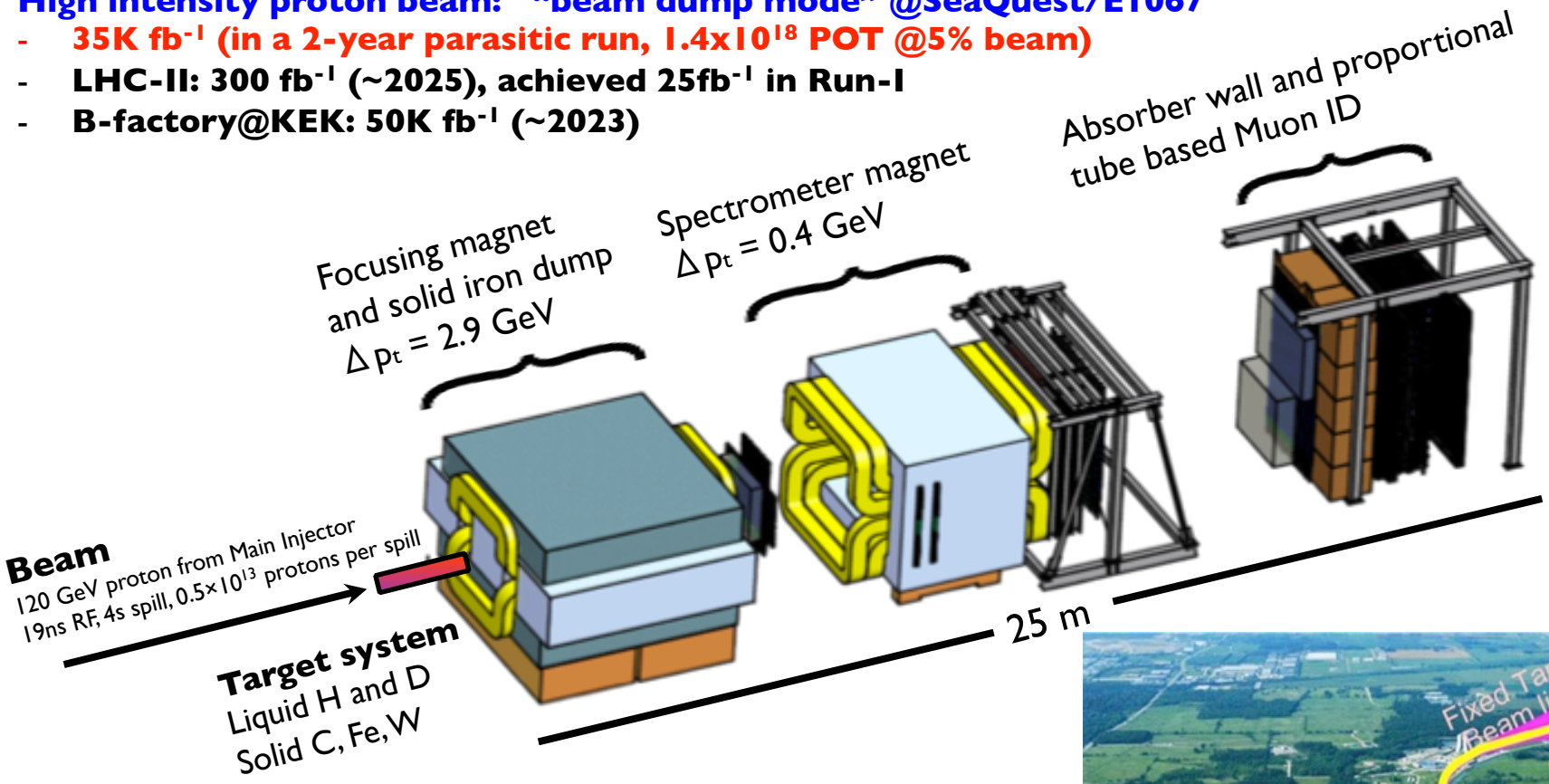

Philip Schuster's talk

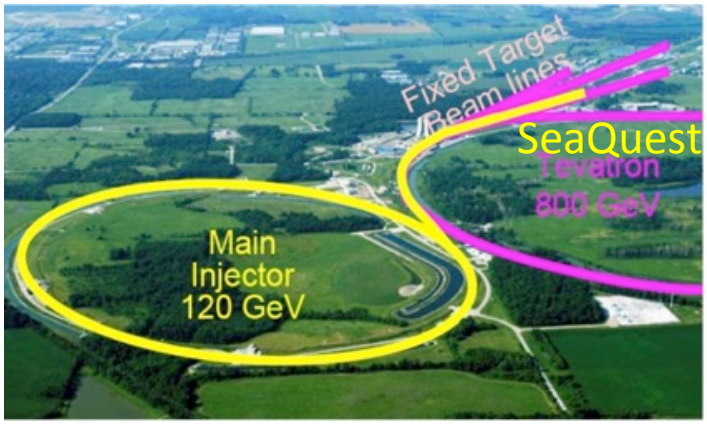


# SeaQuest at the Intensity Frontier at Fermilab

**High intensity proton beam: "beam dump mode" @SeaQuest/E1067**

- **35K fb$^{-1}$ (in a 2-year parasitic run, 1.4x10$^{18}$ POT @5% beam)**
- **LHC-II: 300 fb$^{-1}$ (~2025), achieved 25fb$^{-1}$ in Run-I**
- **B-factory@KEK: 50K fb$^{-1}$ (~2023)**

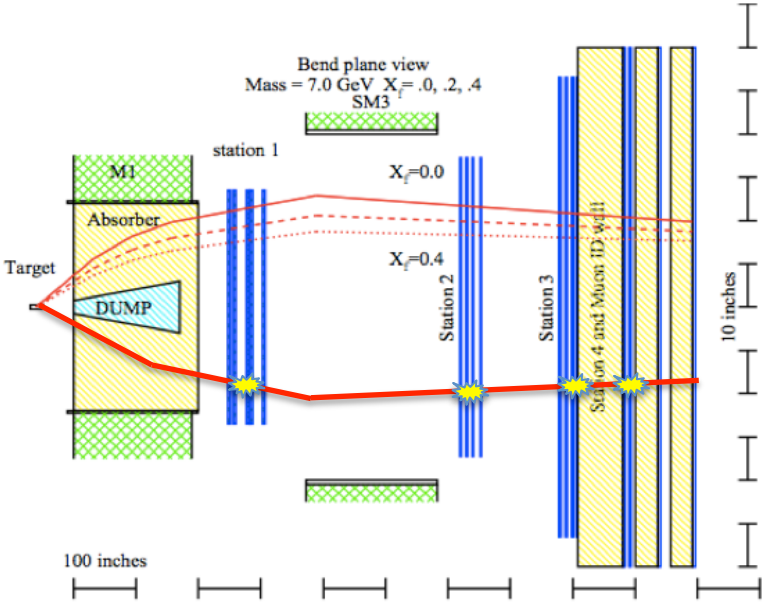


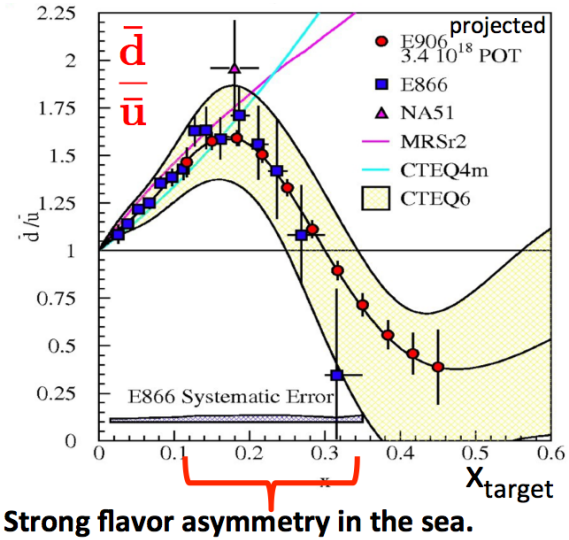




- Beam dump mode: p+Fe collisions! Target ~ 10%$\lambda_I$
- Parasitic run mode possible with other experiments, E906/E1039

# SeaQuest/E906: Nuclear Physics with Drell-Yan

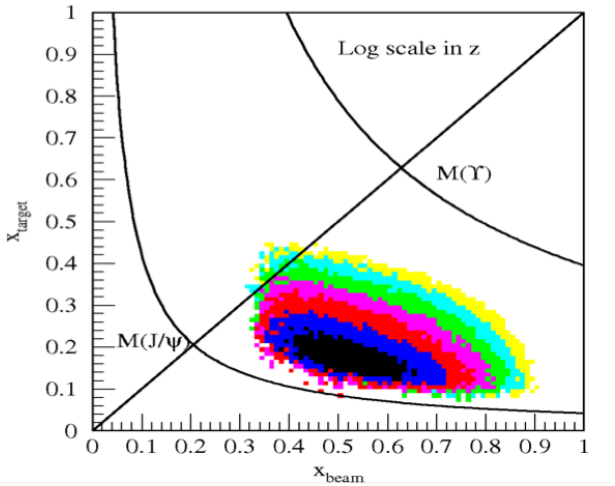
## DOE/NP Program 2012-2017

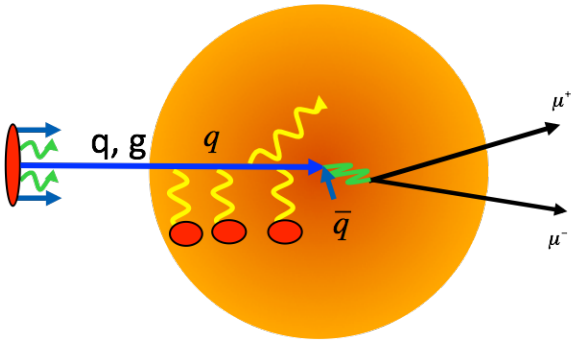



**Strong flavor asymmetry in the sea.**

Drell-Yan Acceptance



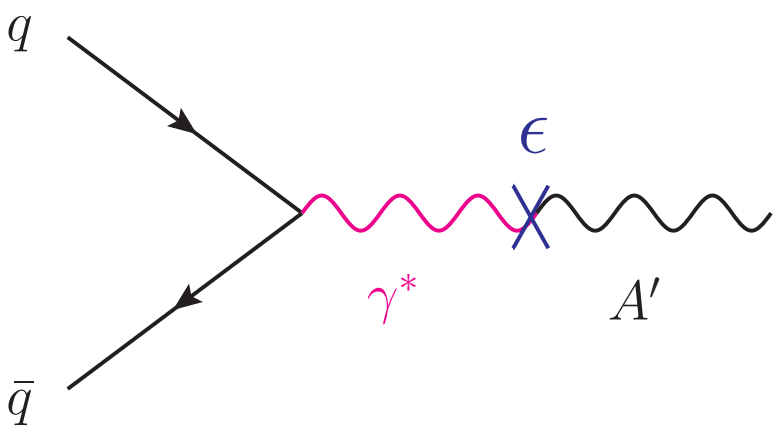

Quark Energy Loss dE/dx in pA

# A Great Opportunity

## Dark Photons and Dark Higgs Search at SeaQuest

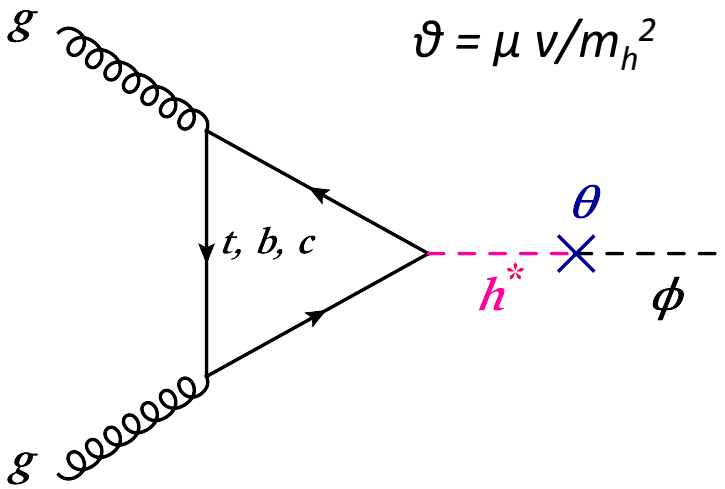
***Photon portal: "vector"***

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



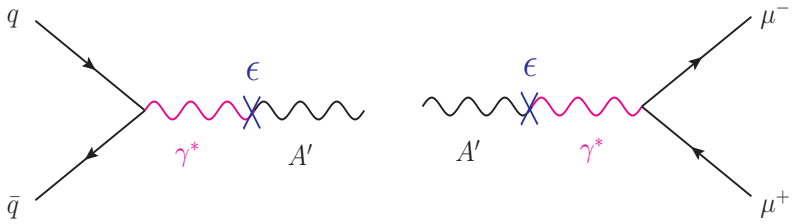

***Higgs portal: "scalar"***

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

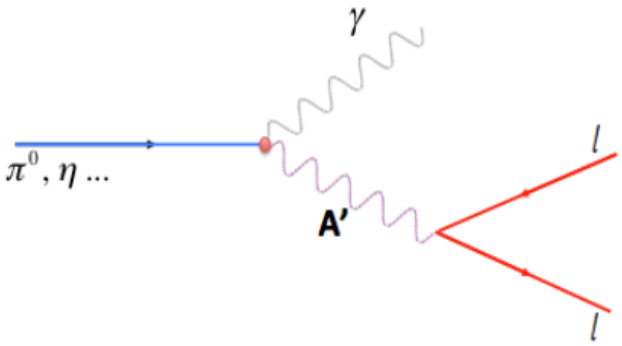


# Dark Photon Detection in Dilepton Channel

1. Drell-Yan like

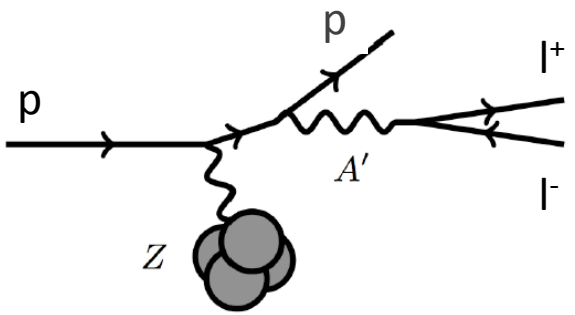



2. $\pi^0$, $\eta$, … decay



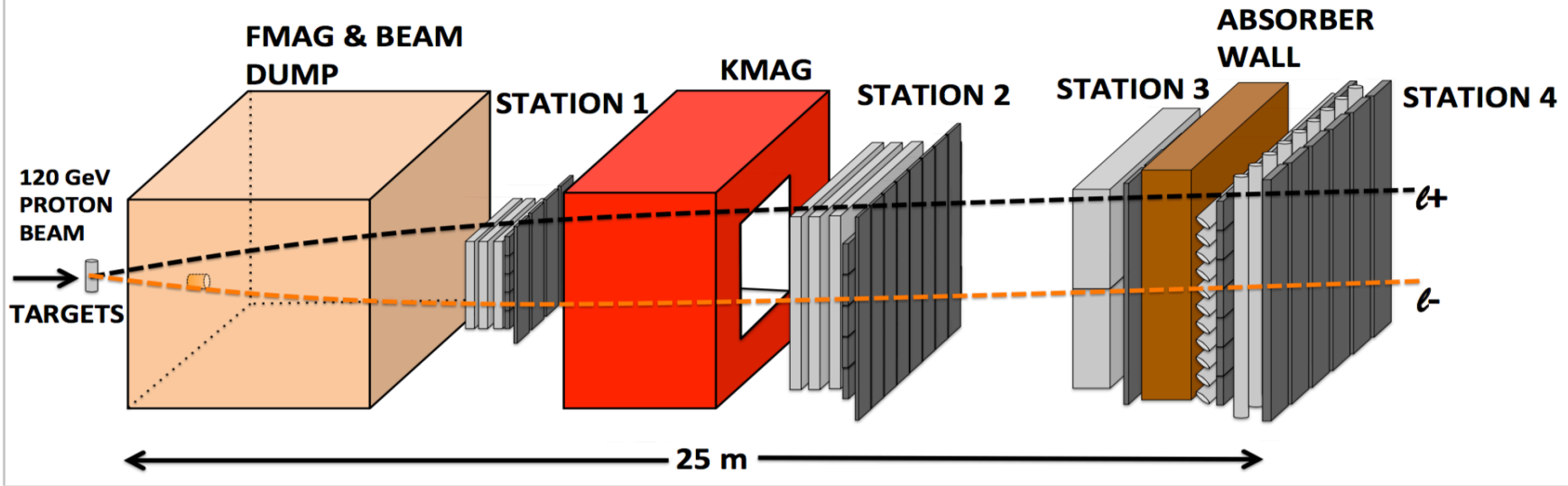

MiniBooNE
Beam-dump

3. Bremsstrahlung

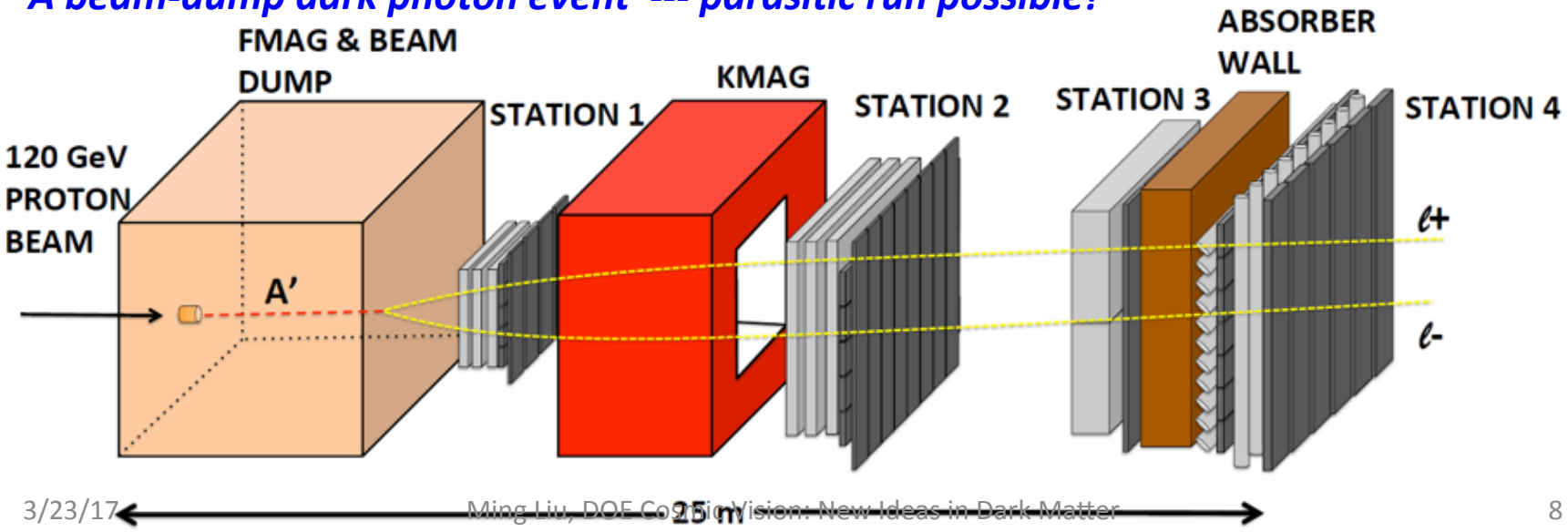



~ Fixed target w/
electron beams

## *A target Drell-Yan event*




## *A beam-dump dark photon event --- parasitic run possible!*



**Letter of Intent for a Direct Search for Dark Photon and Dark Higgs Particles with the SeaQuest Spectrometer in Beam Dump Mode**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LOI submitted to Fermilab PAC
May 20, 2015

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

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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 $1.44 \times 10^{18}$

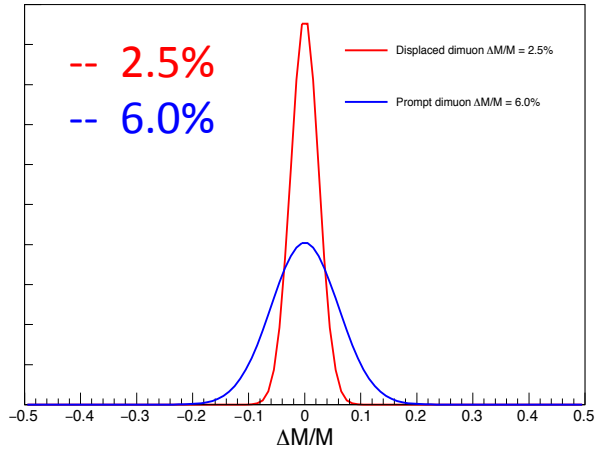
Phase-II: (upgrade)

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: >> $1.4 \times 10^{18}$

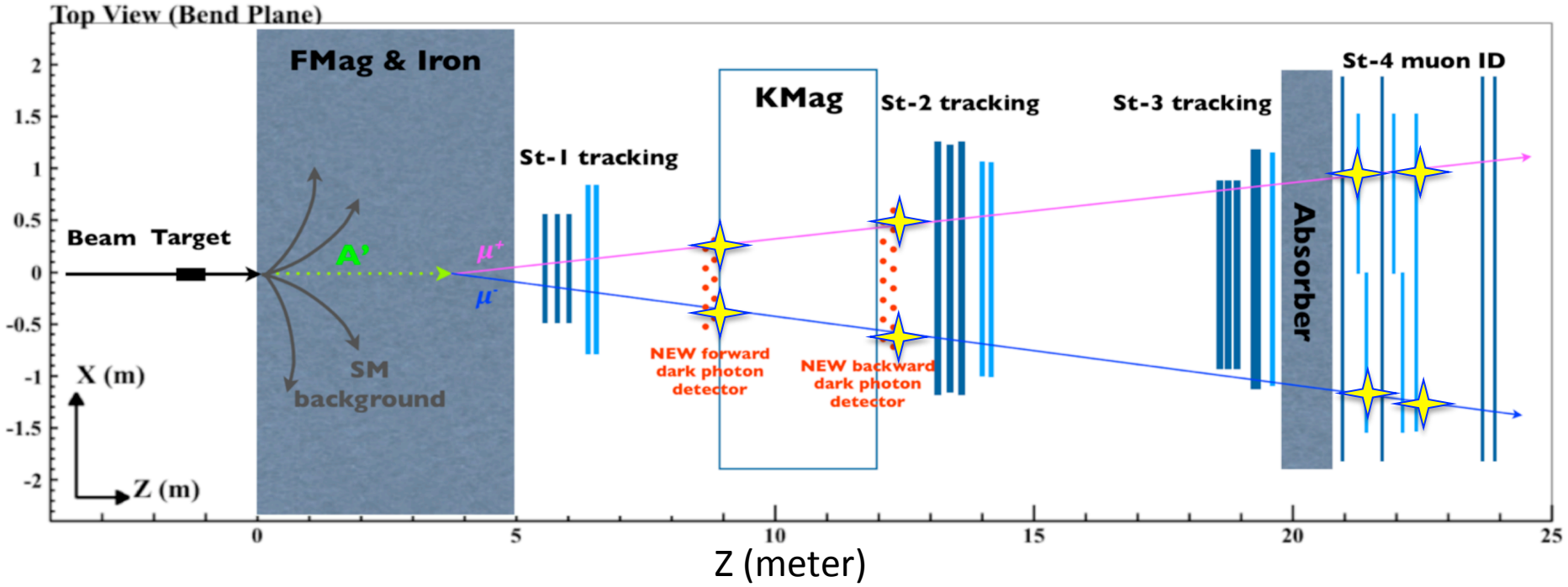
*Phase-II request will be presented to PAC at a later time.*

# 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 ~10% $\lambda_I$.)
- Planned beam time
  1. Run parasitically with E906/E1039 (2017-2020)
  2. Possible dedicated runs later with further upgrade ($e^{+/-}$, $h^{+/-}$)




Dimuon mass resolution

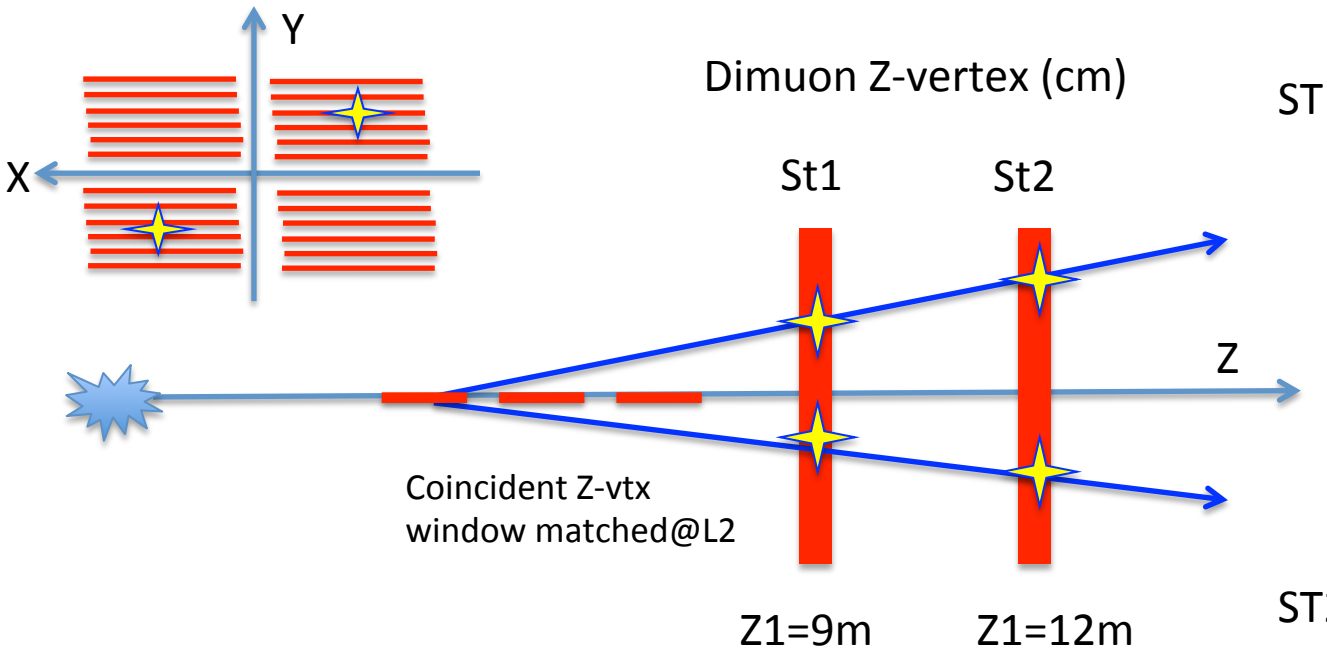


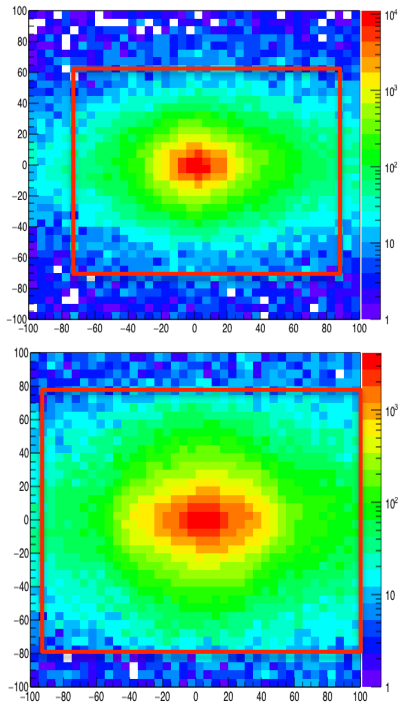
# A New High-Granularity Displayed Dimuon Vertex Trigger

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

Y-Plane (non-bending) Trigger:

- A quadrant panel: 80cm x 80cm (100cmx100cm @ST-2)
  - ST1: 1cm x 1cm x 80 cm scintillating strips, SiPM readout
  - ST2: 2cm x 2 cm x 100 cm strips
- Straight line projection, $\sigma_Z$ ~30cm
- Displaced z-vertex, mostly low mass < 3GeV

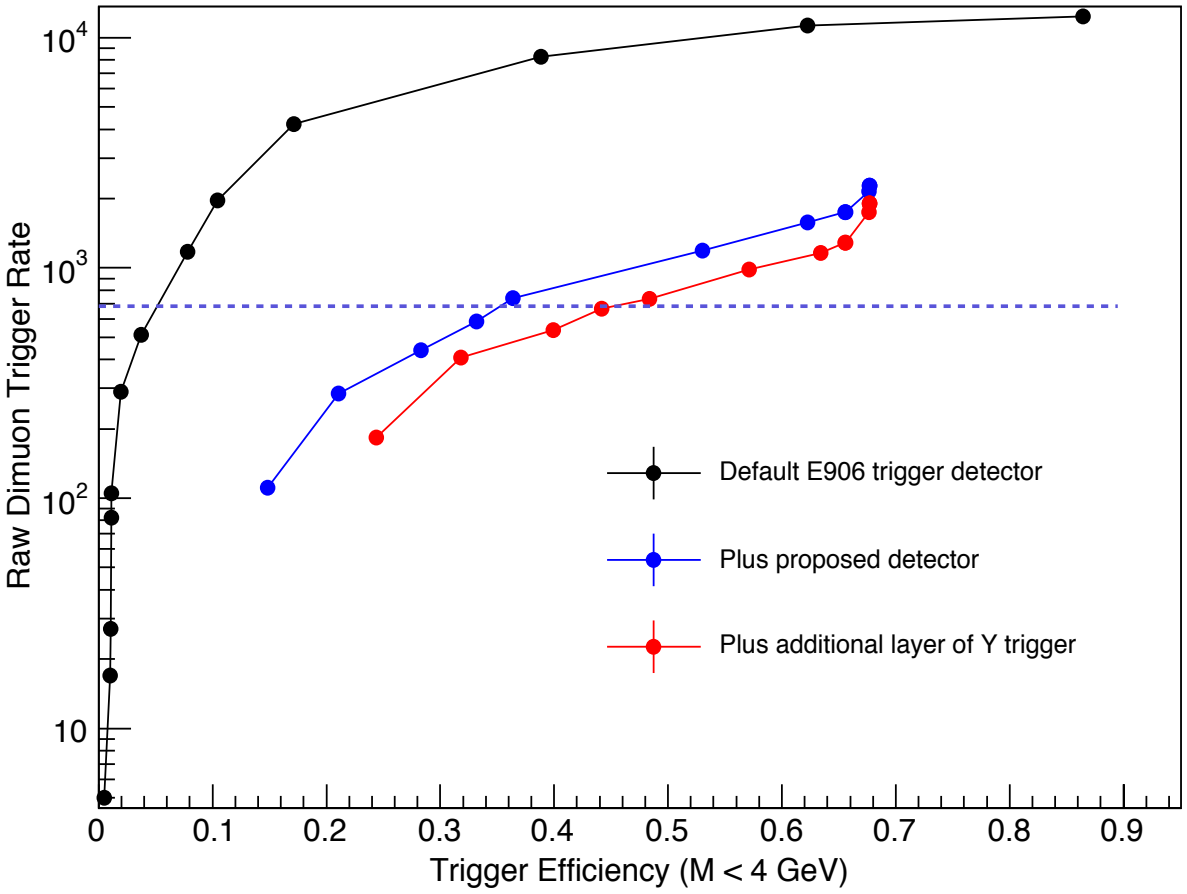


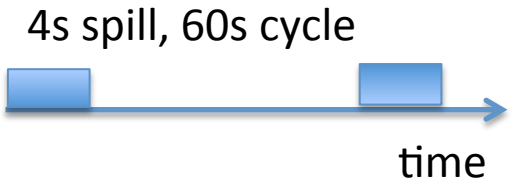
# Low Mass Prompt Dimuon Trigger Rate Study

- 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)

- DAQ upgrade completed
  - Previous E906 DAQ 1kHz
  - Now 10+ kHz
  - Can take all dark photon events of interest



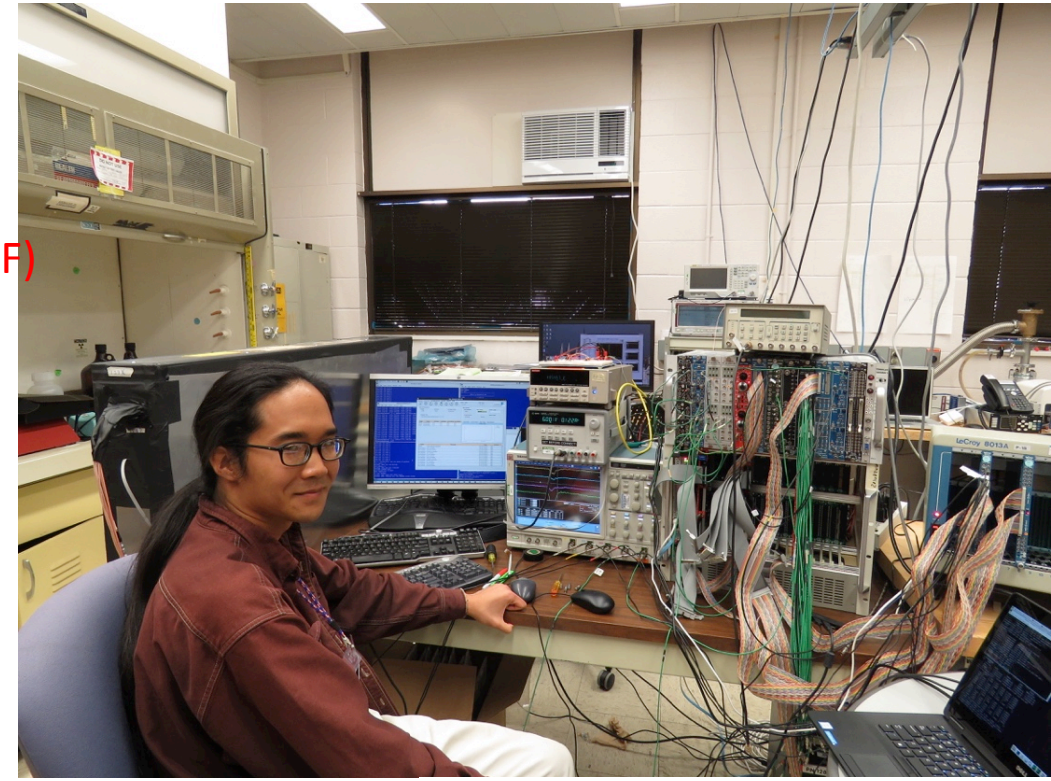

**Expected (Prompt) Low mass dimuon trigger performance**

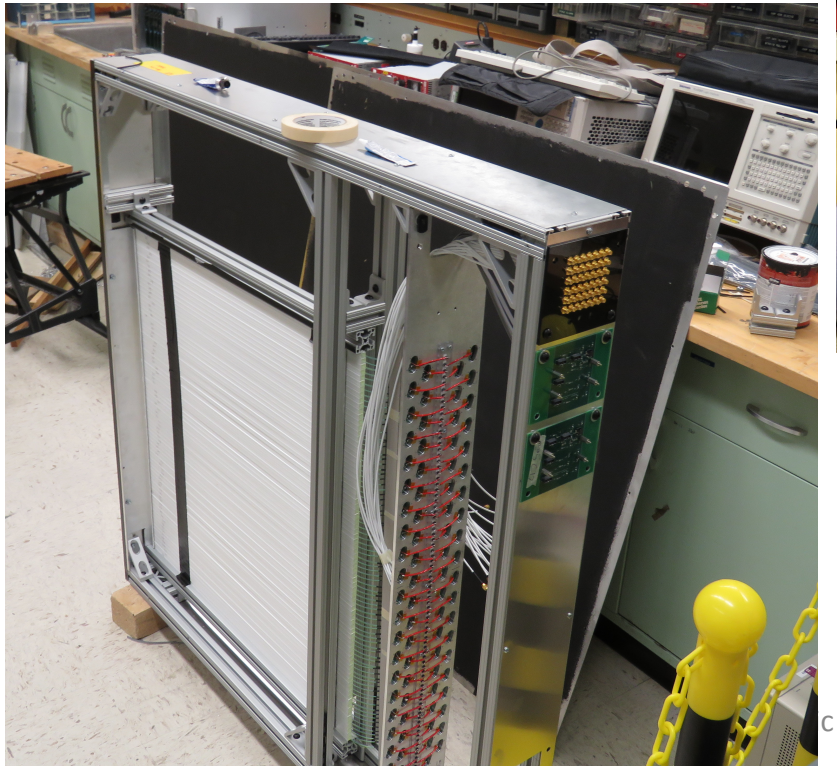


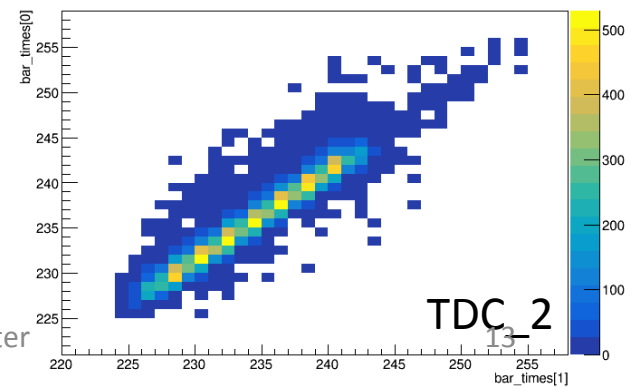
# Trigger and DAQ Upgrade @LANL

- Readout from a full module
  - Cosmic rays
  - Full SiPM readout
  - V1495 trigger logic + TDC read out
  - E906 upgraded DAQ and firmware

- Timing resolution, better than 1nS (19nS RF)
- Detector eff > 96%







# Ready to ship the detectors to Fermilab for installation

# Opportunities and Challenges

- Commissioning run with E906
  - With upgraded DAQ and Dark Photon Trigger
  - April – July, 2017

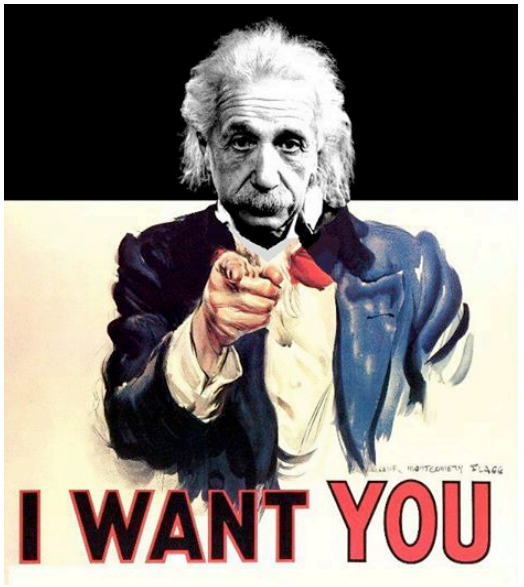
- Parasitic run with SeaQuest/E1037 (polarized target run, NP program)
  - 2 years of data taking, 2018-2020
  - POT: 1.4 x $10^{18}$

- Future upgrade opportunities
  - Di-electrons with EMCal upgrade
    - PHNEIX EMCal available, need readout electronics
  - Installation of EMCal in 2018 possible

- Dedicated dark photon runs after 2020
  - High luminosity runs, POT >> 1.4 x$10^{18}$

***Very important to run the beam beyond 2017, E906***

- A joint NP-HEP effort needed!
- Invite you from HEP to join us!

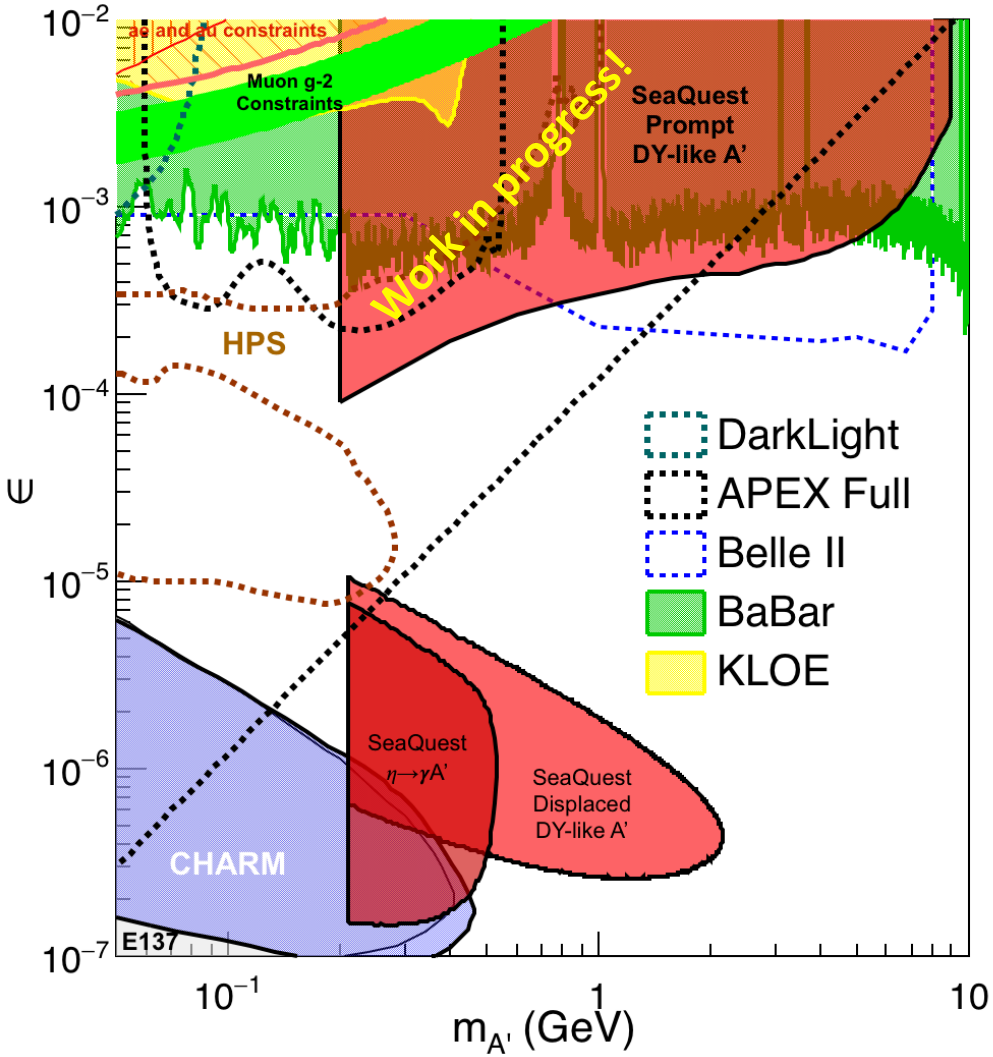


# Phase-I Expectation: Dark Photons
## (parasitic run w/ E906/1039)

Signals considered:
- Drell-Yan like
- Eta decays
- Bremsstralung

Covers a wide range of unexplored parameter phase space

- Displaced dimuons
  - Minimal SM background
- Prompt dimuons
  - Good coverage
  - Possible dedicated runs later to fully restore mass < 3GeV (Phase-II)
- ***Phase-II with upgrades***
  Access below 200MeV with di-electrons ( add EMCal)

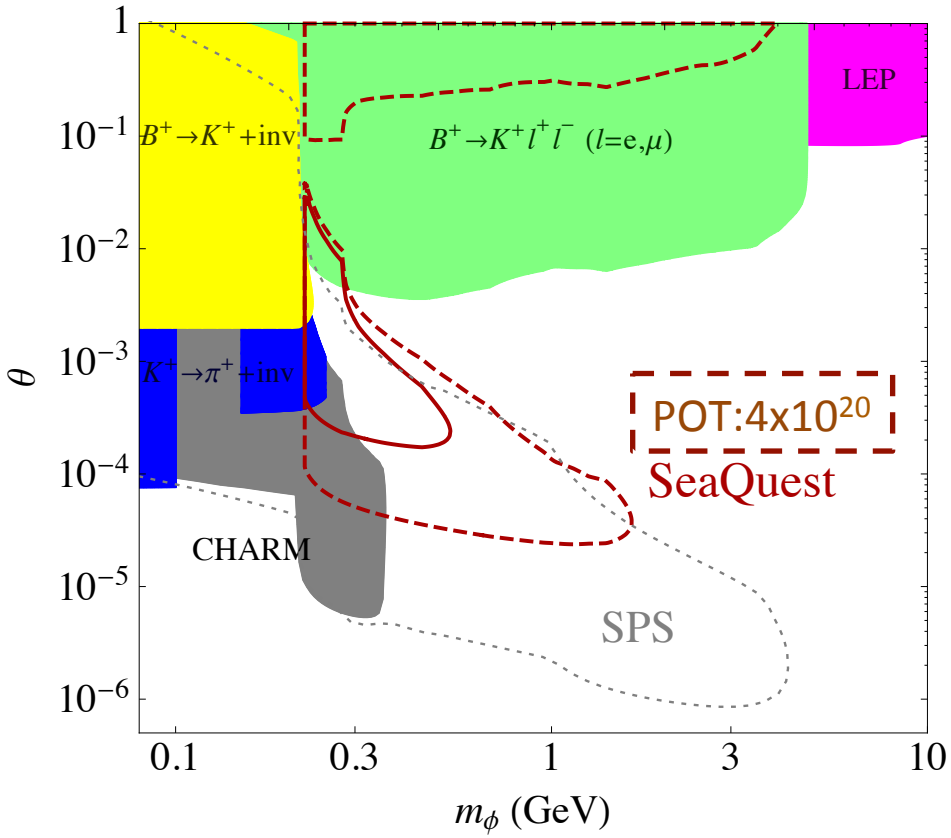


# Projected Dark Higgs Sensitivity

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

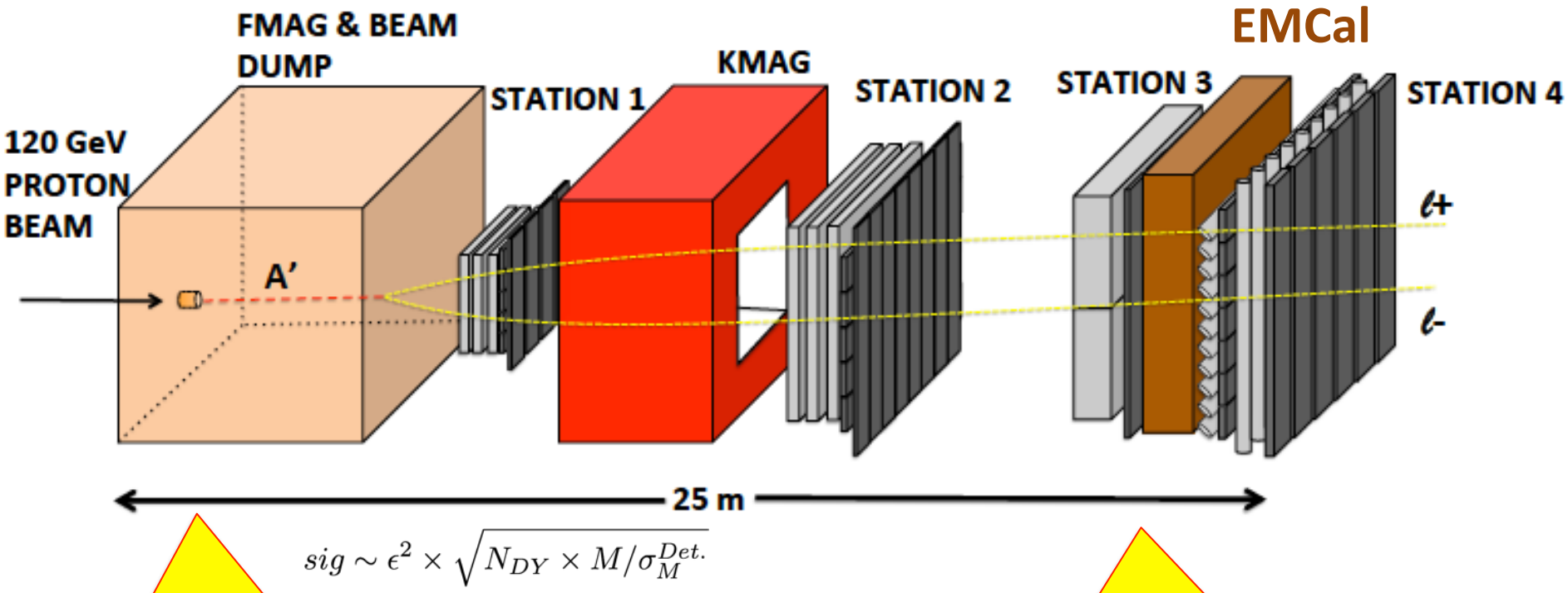
Y. Zhang (2015)

- 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



# E-1067 Future Upgrade: Phase-II

## 2020 ~ 2025+




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

Add tracking detectors close to "target" to improve mass resolution

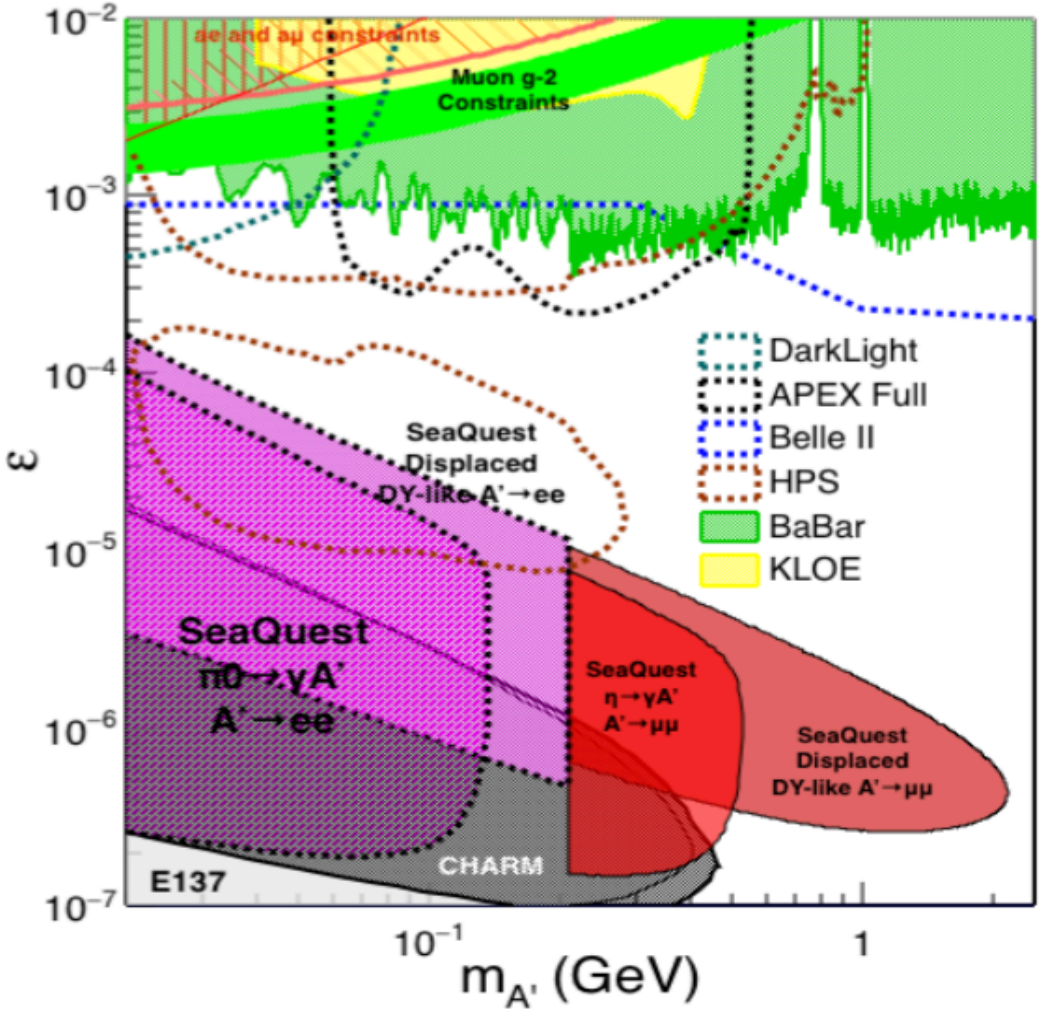
Add EMCal, PID $e^{+/-}$, $h^{+/-}$ , $\pi^{+/-}$

# Phase-II: Displaced Low Mass Dark Photons

## with EMCal upgrades

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

Projection: POT 1.4 x $10^{18}$

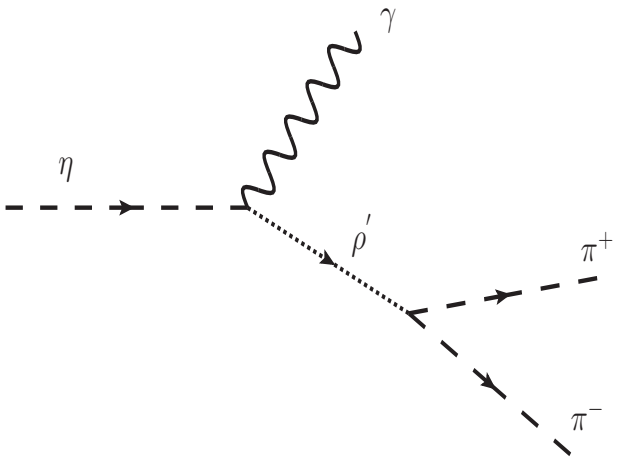


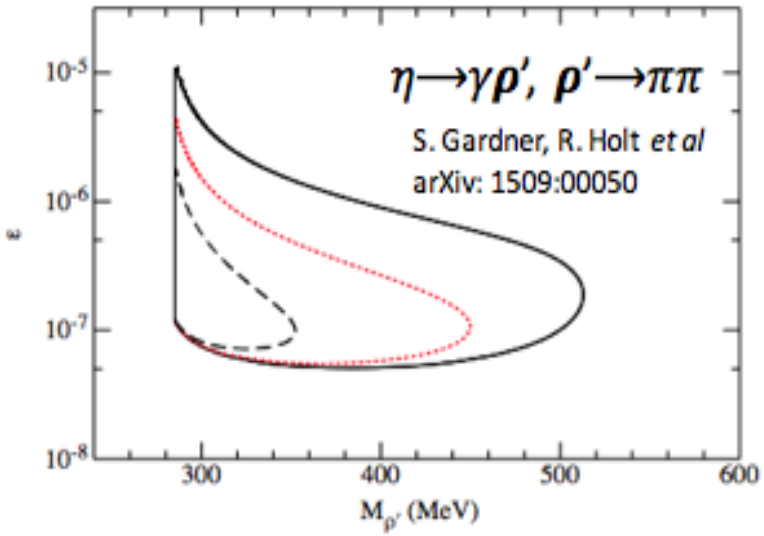
# EMCal Upgrade: More Physics

- 2 sectors (4×4 $m^2$ coverage) PHENIX EMCal are available, need readout eletronics for SeaQuest

- With EMCal installed, we will also be able to access:
  - dark $\rho$ decays to $\pi\pi$
  - enhanced dark higgs sensitivity

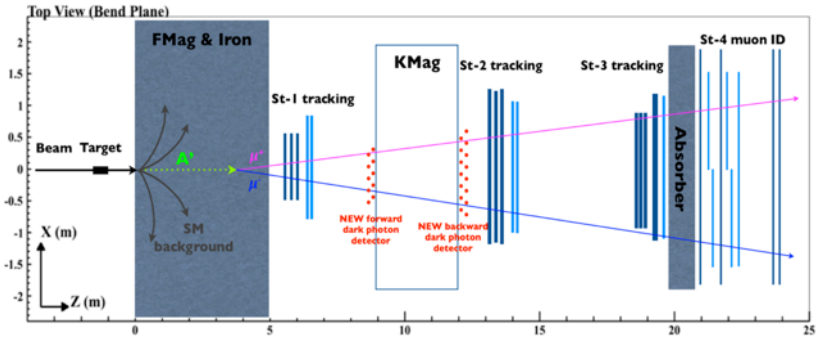
- Potential bonus of better background rejection on trigger level (studies underway).

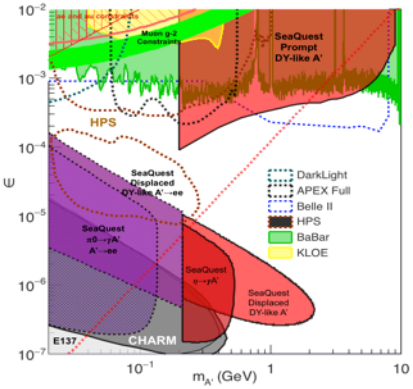


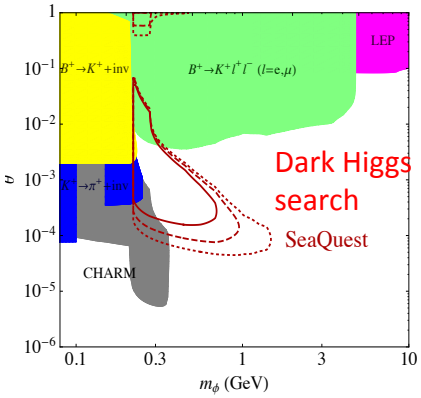



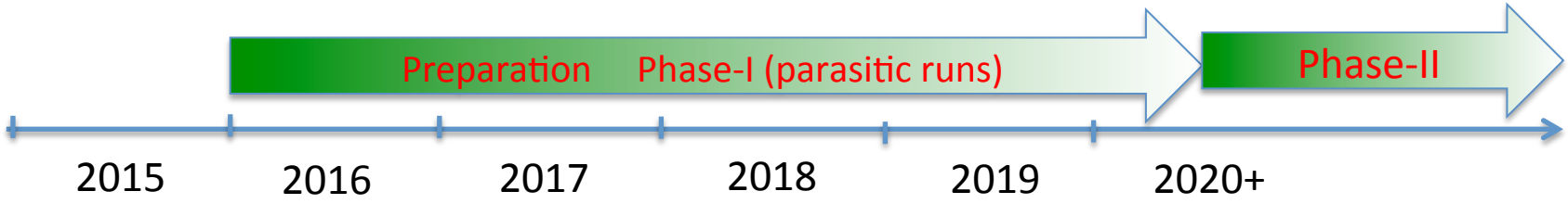
# Summary and Outlook

- ***Phase-I***
  - ***Great discovery potential!***
  - ***A new vertex trigger & DAQ++***
  - ***Early parasitic data taking 2017-2020+***
  - ***POT 1.4 x$10^{18}$ or more***
- ***Phase-II***
  - ***Possible detector upgrade later, add electron and hadron capability***
  - ***A new dedicated dark matter program at Intensity Frontier!***

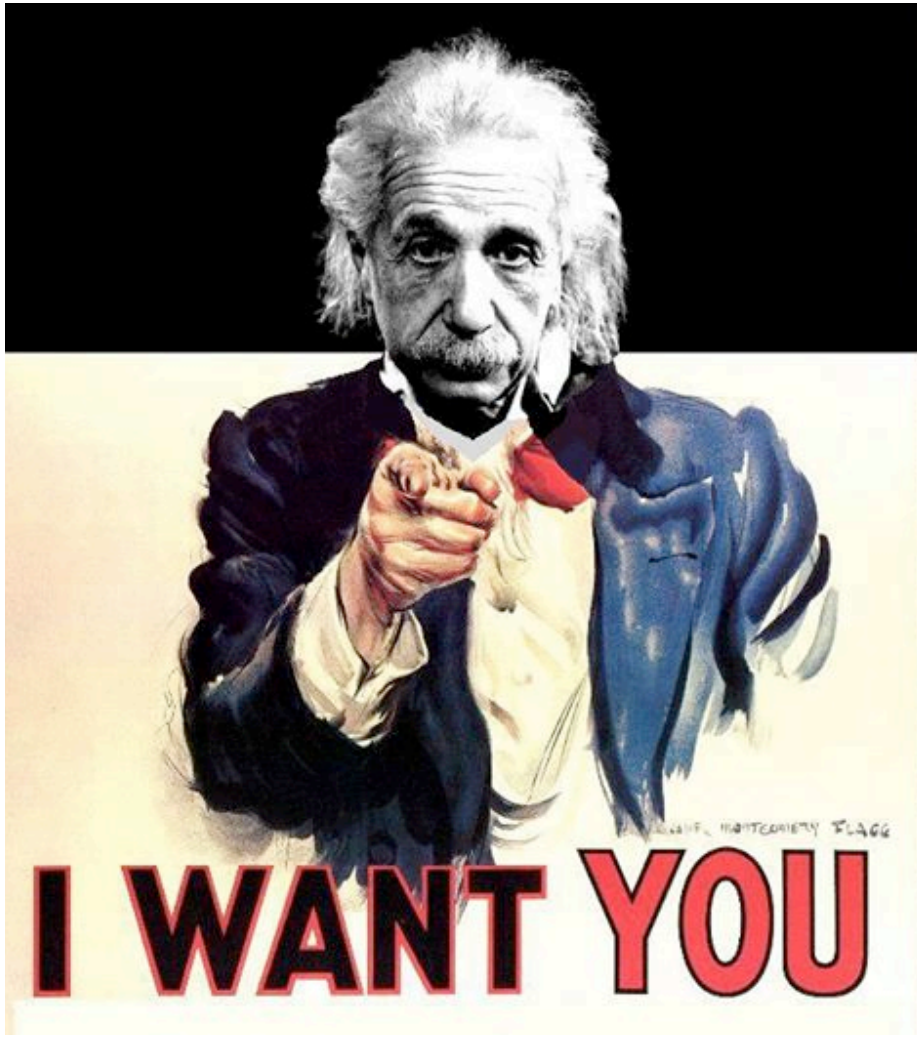


# Important to have a joint NP+HEP Effort



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!

## A NEW EXPERIMENT! SEAQUEST/E-1067

Ming Liu
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P. O. Box 1663
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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

***LANL LDRD support:***

*- FY16-18*

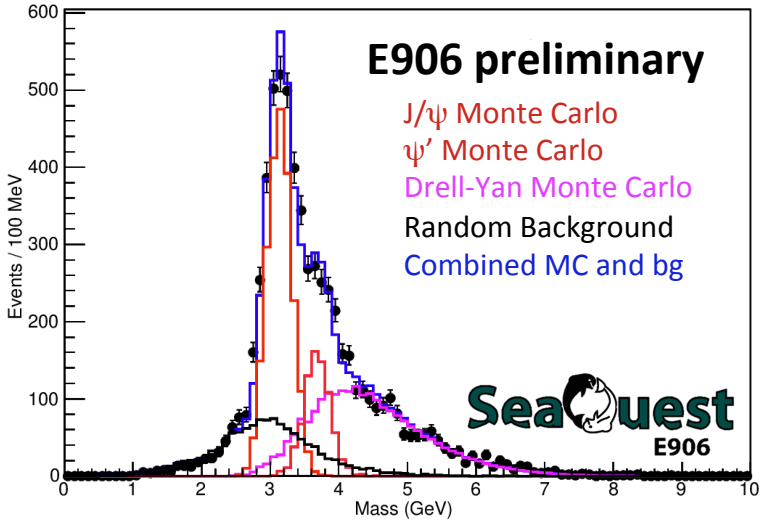
*- $1M to implement the trigger/DAQ upgrade and theory development*

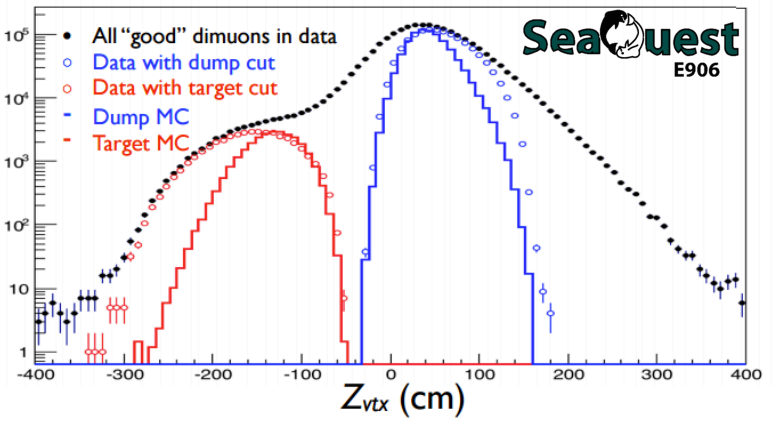
*Goals:*

- *Trigger installed, 2017*
- *Physics run, 2017-20*
- *Preliminary results 2018!*

# Event selection and reconstruction

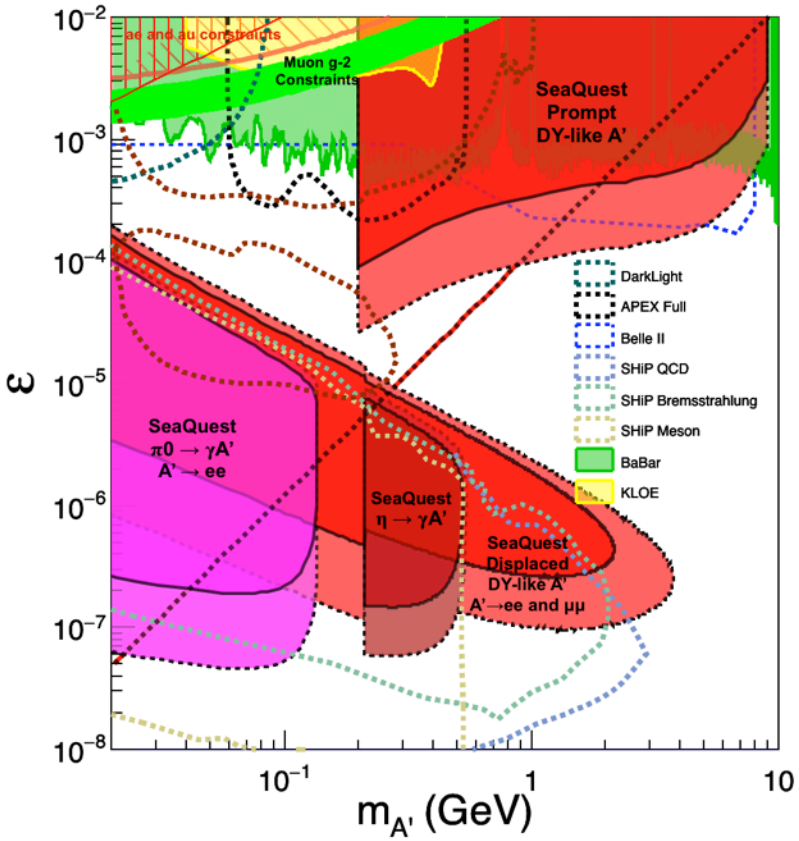
- Invariant mass spectrum for FY 2015 data
- 30% of anticipated data
- Data agrees well with Monte Carlo (spectrometer works as expected)
- Data with Mass > 4.2 GeV are mostly dimuons coming from the Drell-Yan process



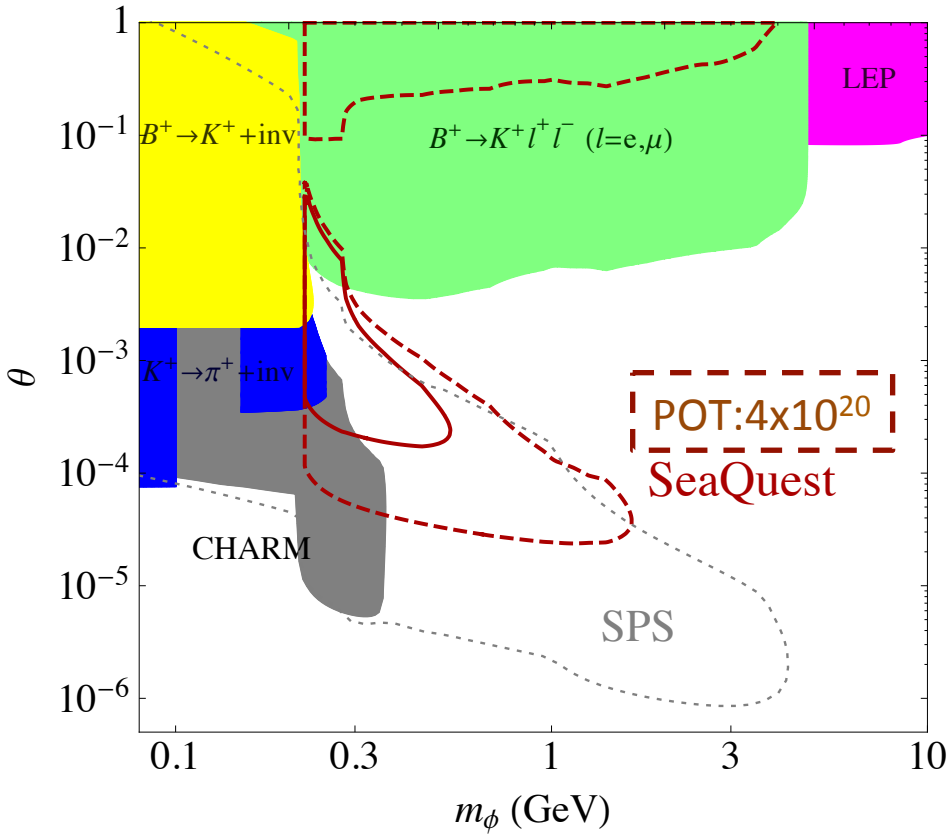



# Comparison with SHiP Proposal

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



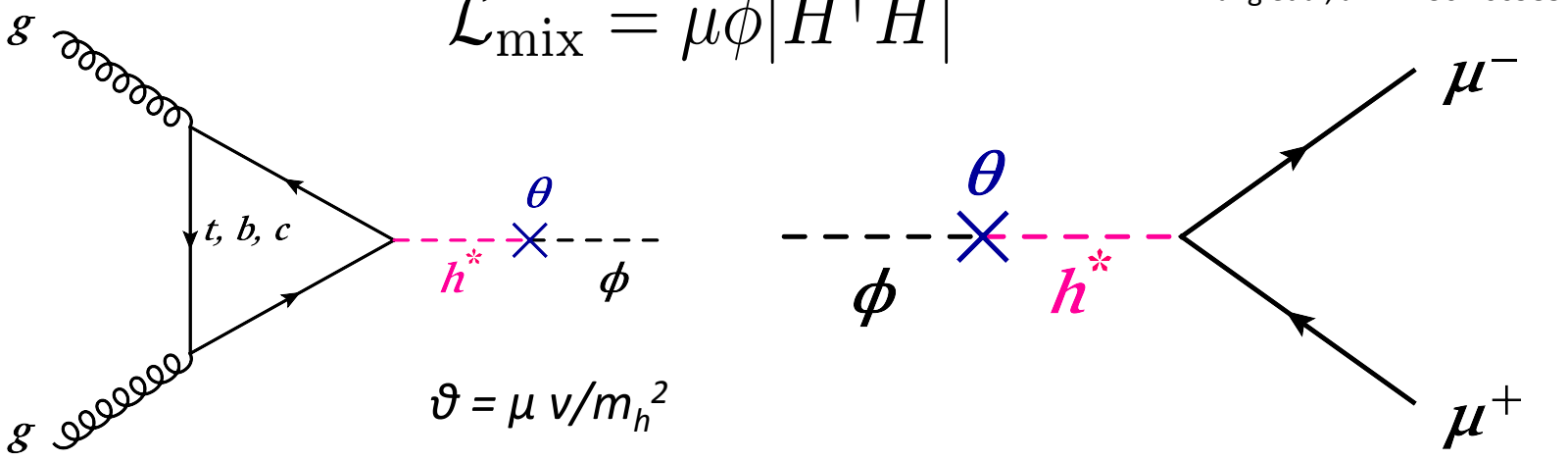

400 GeV@SPS: 2025 -2030
4x10$^{20}$ POT



# Dark Higgs

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

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

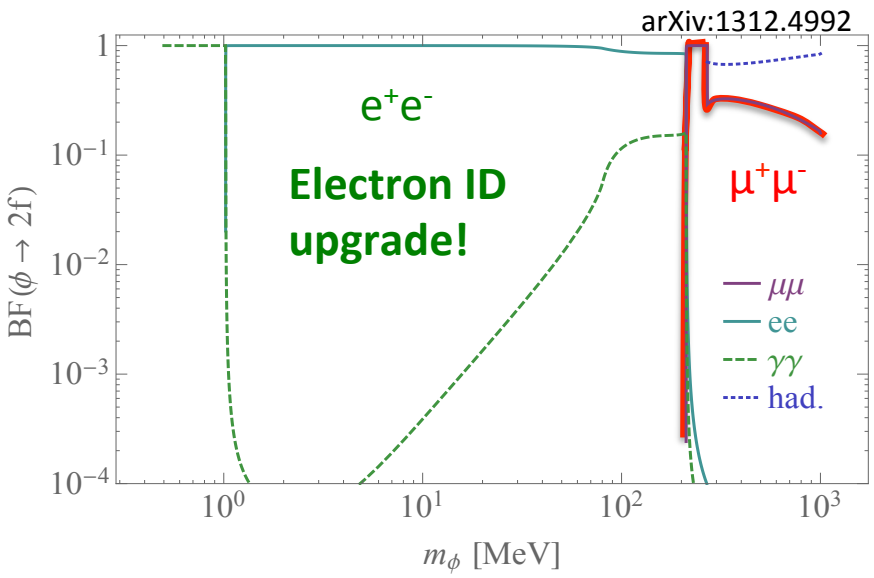
Advantage of using hadron beams with muon probes over electrons

**Phase-II:**

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

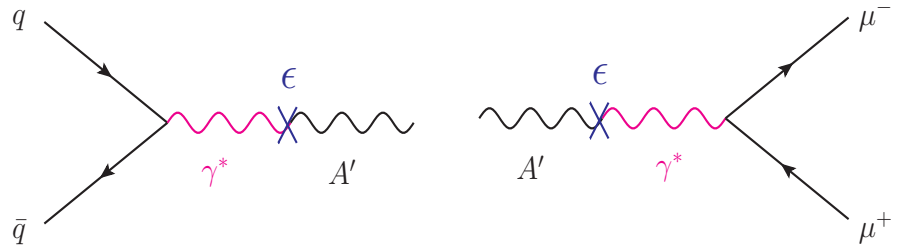
High-mass: hadrons, (5x)

arXiv:1312.4992



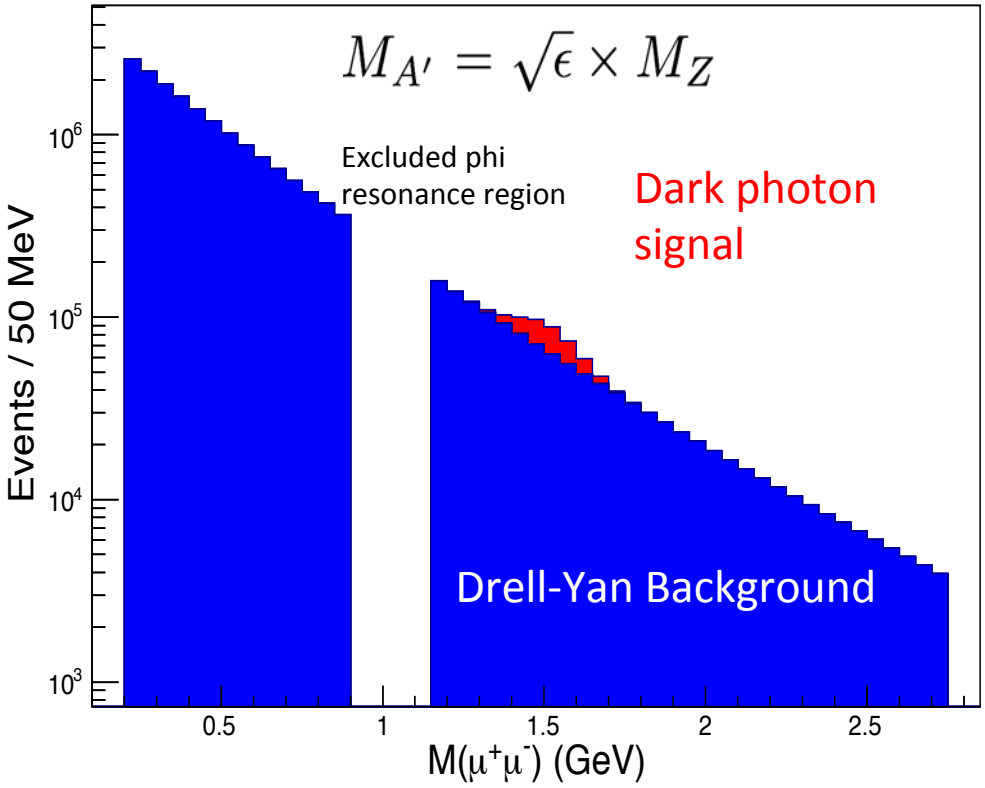
# Search Mode (2): "Prompt" Dark Photons vs Drell-Yan

## Bump hunt at Z-vertx < 3m




Expected Drell-Yan like signal and backgrounds:

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




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

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

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

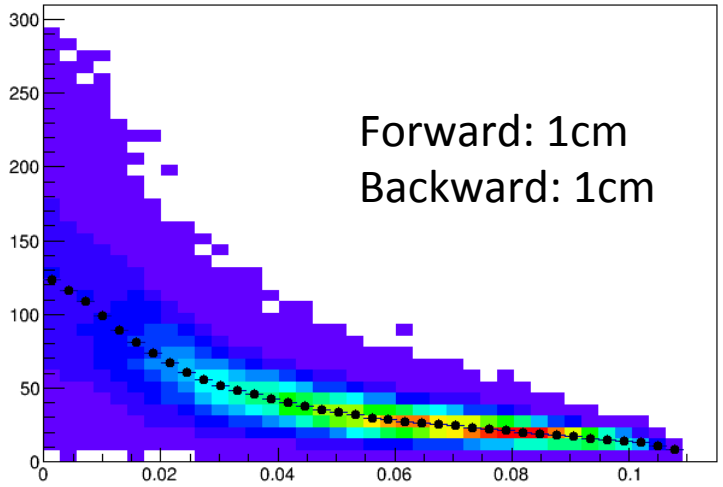
*Work in progress:*

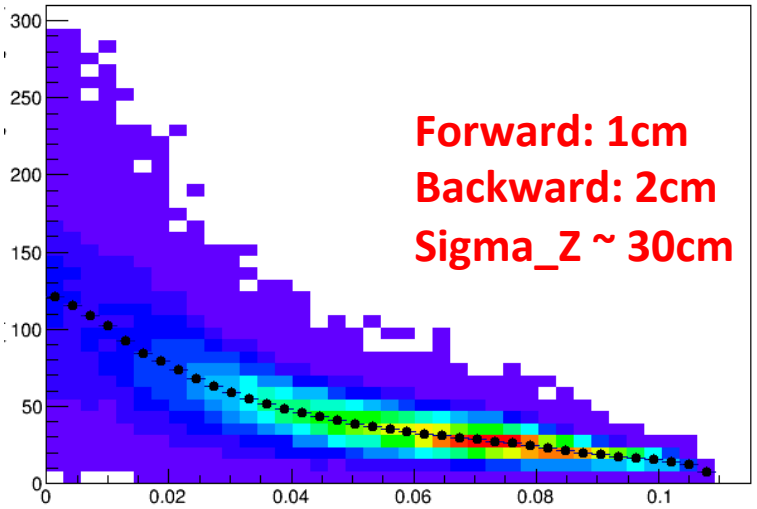
*- optimization …,*

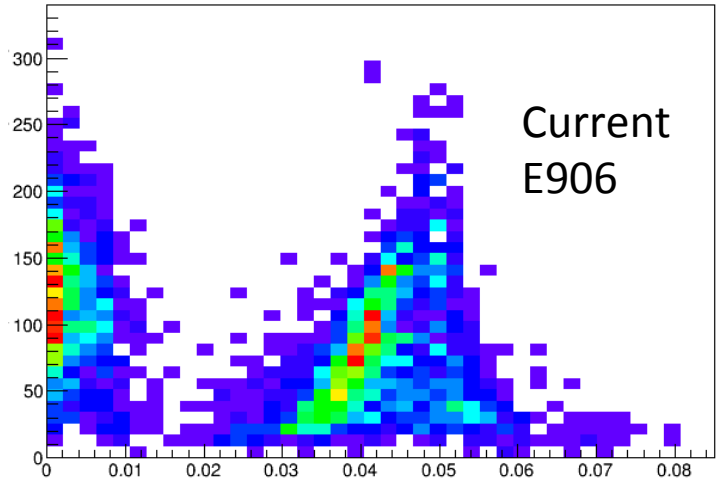
*- understand BG …*

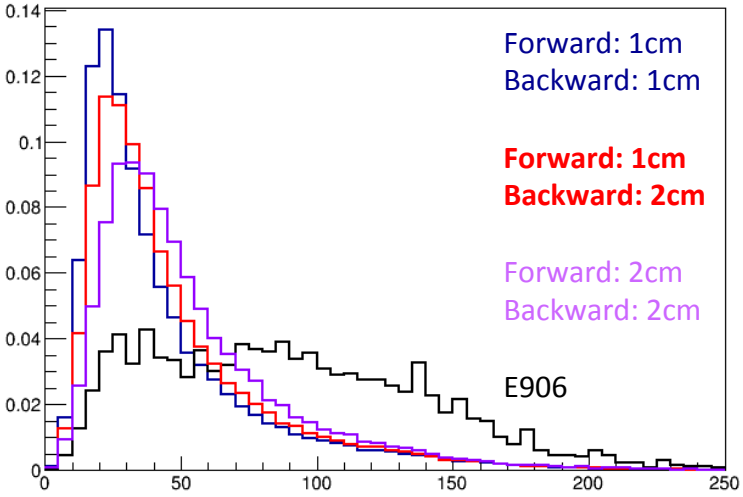
# Trigger Detector Optimization

## Single Muon Z-Vertex Resolutions



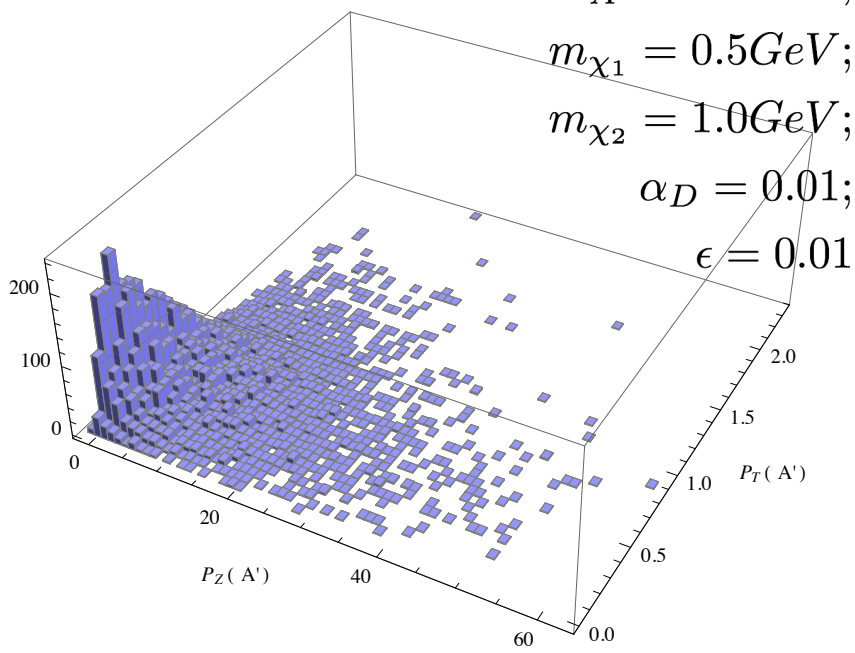



# Beyond Exclusive Channels

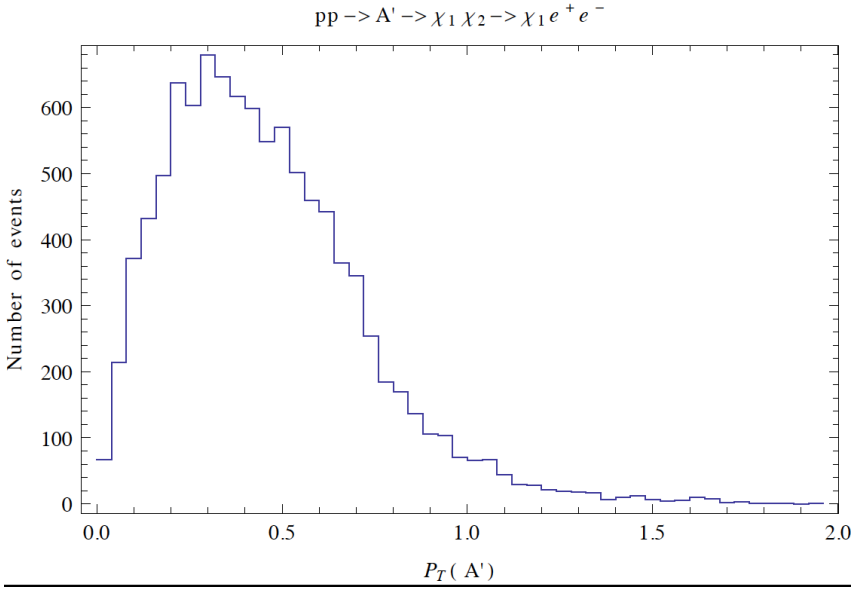
## possible missing pT measurements being explored

$$pp \rightarrow A' \rightarrow \chi_1 \chi_2 \rightarrow \chi_1 e^+ e^-$$

$$m_{A'} = 0.1GeV;$$
$$m_{\chi_1} = 0.5GeV;$$
$$m_{\chi_2} = 1.0GeV;$$
$$\alpha_D = 0.01;$$
$$\epsilon = 0.01$$




Chien-Yi Chen, 2017



# EMCal from PHENIX/RHIC

- 2 EMCal sectors are available from PHENIX experiment at RHIC, ~end of 2016
  - One sector:
    - 2m x 4m, 18 (3x6)super modules
    - Super module = 36 modules; Module = 4 towers
    - 36 x 4 x 18 = 2592 channels
    - Could gang 2x2 (or 3x3) into one ADC/TDC readout

*- dE/E = 8.1%/sqrt(E) + 2.1%*
*- dT < 200 ps*
*- Excellent e/pi separation*