Direct Search for Dark Photons and Dark Higgs in Beam-dump Mode at E-1067/SeaQuest at Fermilab

Ming X. Liu

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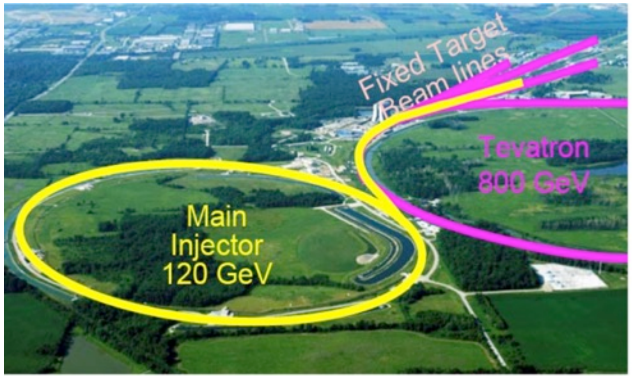
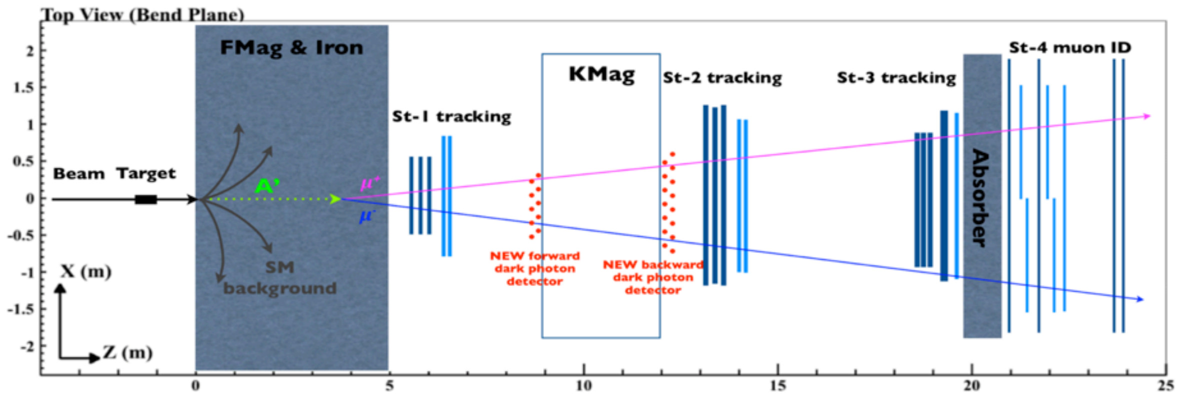
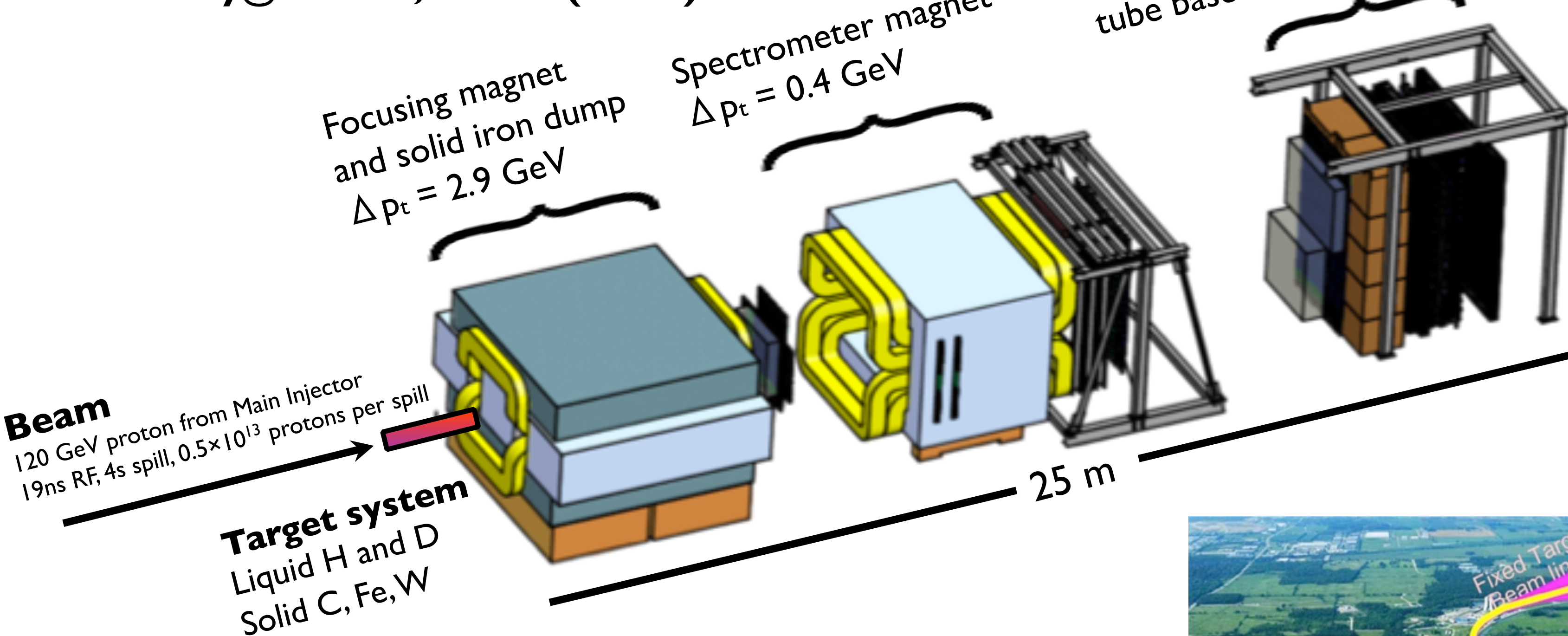




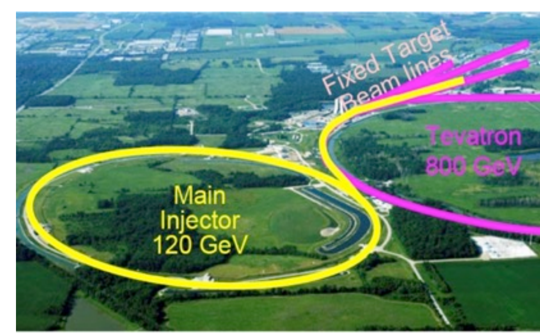
Intensity Frontier at Fermilab: 120 GeV Beam

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

- **50,000 fb^{-1} (in 1 year of 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 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.

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

NEW EXPERIMENT! E-1067

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

LANL LDRD support:

- FY16-17-18

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

Goals:

- *Trigger installed, 2017*
- *Physics run, 2017-18*
- *Preliminary results 2018!*

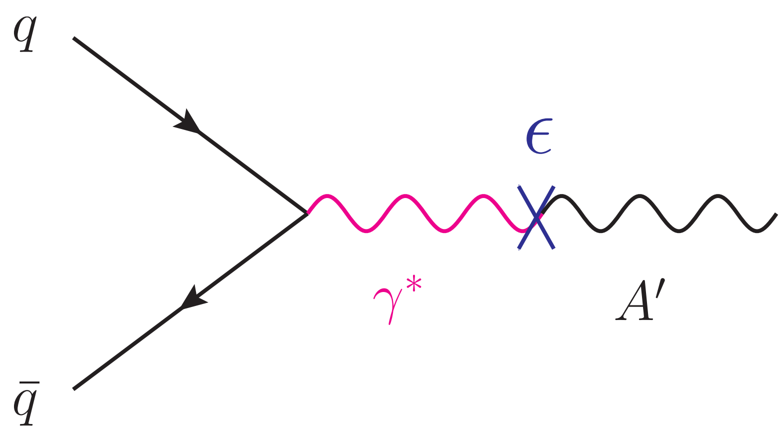
Outline

- Physics of dark sectors
  - Mass: MeV ~ GeV
- Detector upgrade
  - Displaced dimuon trigger
  - DAQ improvement
- New opportunity
  - EMCal from PHENIX, available this fall
  - Electron/hadron ID
- Schedules

Dark Photons and Dark Higgs Productions in p+Fe/BeamDump at Fermilab

Photon portal: "vector"

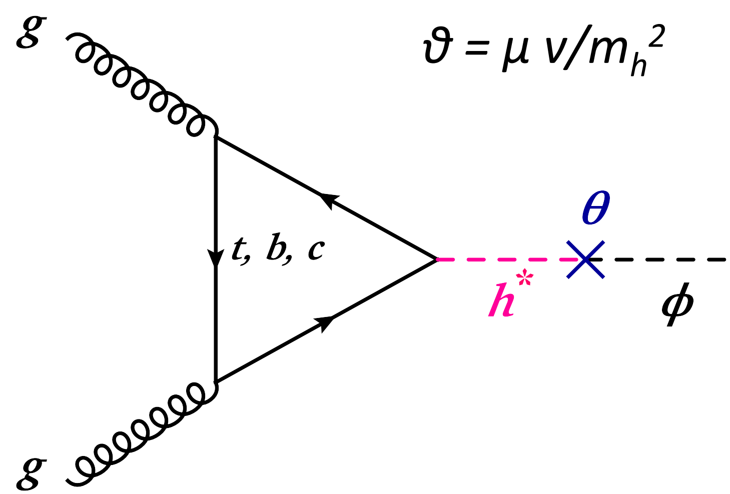
$$\mathcal{L}_{\text{mix}} = \frac{\epsilon}{2} F_{\mu\nu}^{\text{QED}} F_{\text{Dark}}^{\mu\nu}$$



Higgs portal: "scalar"

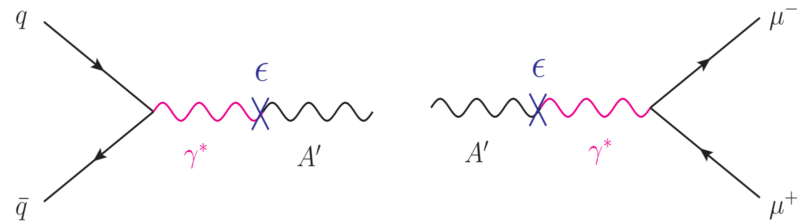
$$\mathcal{L}_{\text{mix}} = \mu\phi \left| H^\dagger H \right|$$

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

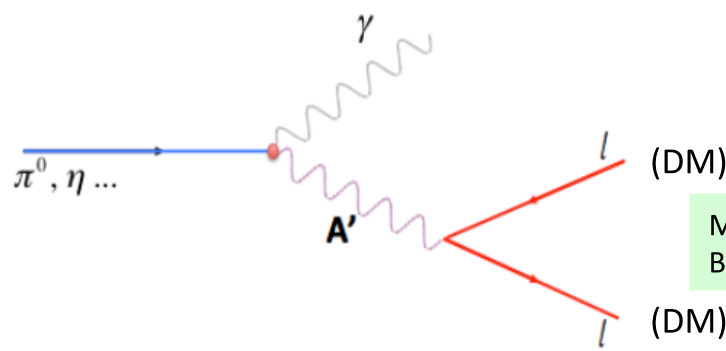


Dark Photon Detection in Dilepton Decay Channel

1. Drell-Yan like

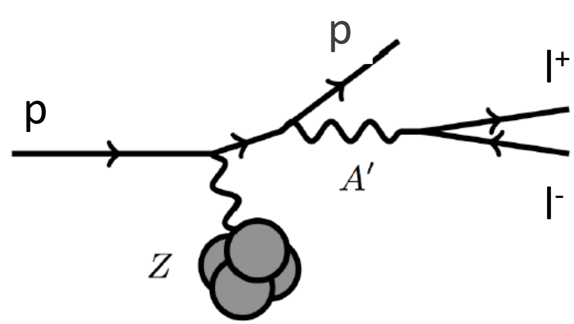


2. π^0, η, … decay



MiniBooNE
Beam-dump

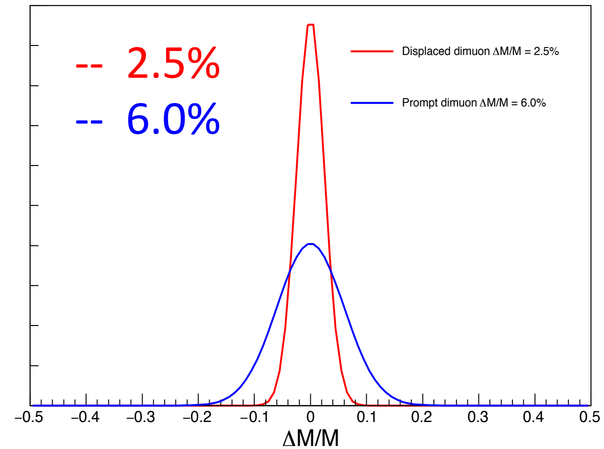
3. Bremsstrahlung



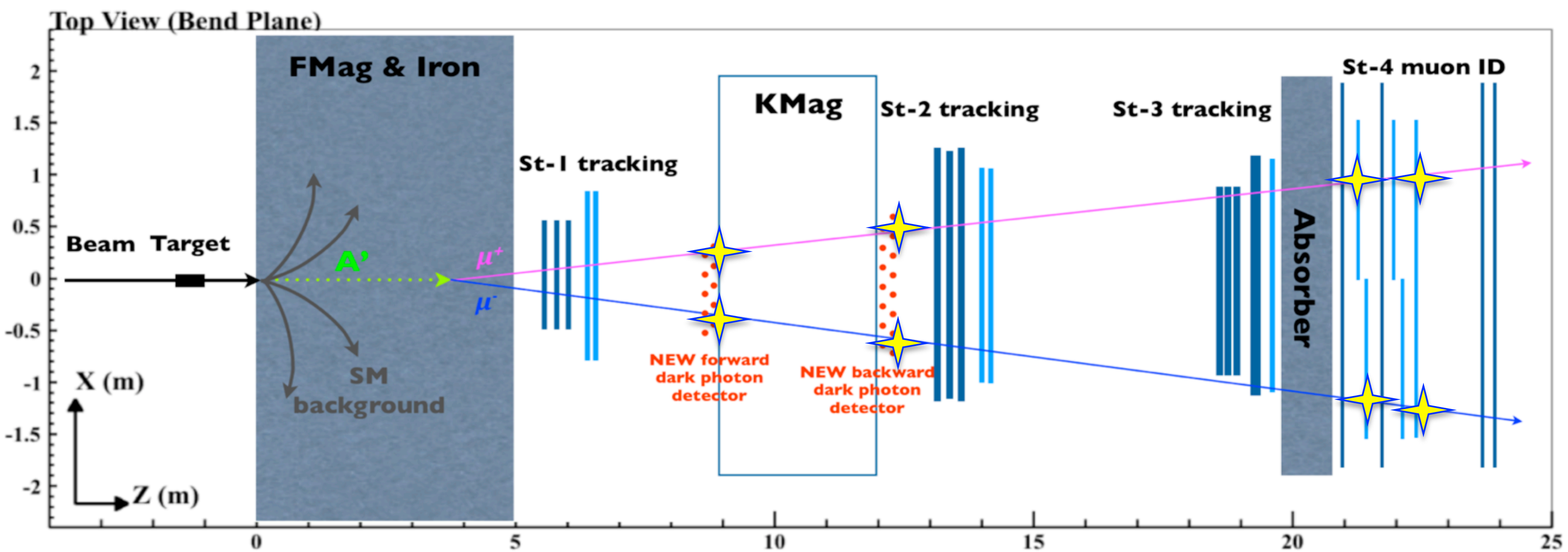
~ Fixed target w/
electron beams

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% λ_I.)
- Beam time
  1. Run parasitically with E906/E1039 (2017-2019)
  2. Possible dedicated runs later with upgrade ($e^{+/-}$, $h^{+/-}$)



Dimuon mass resolution



Z (meter)

A New High-Granularity Displayed Dimuon Vertex Trigger

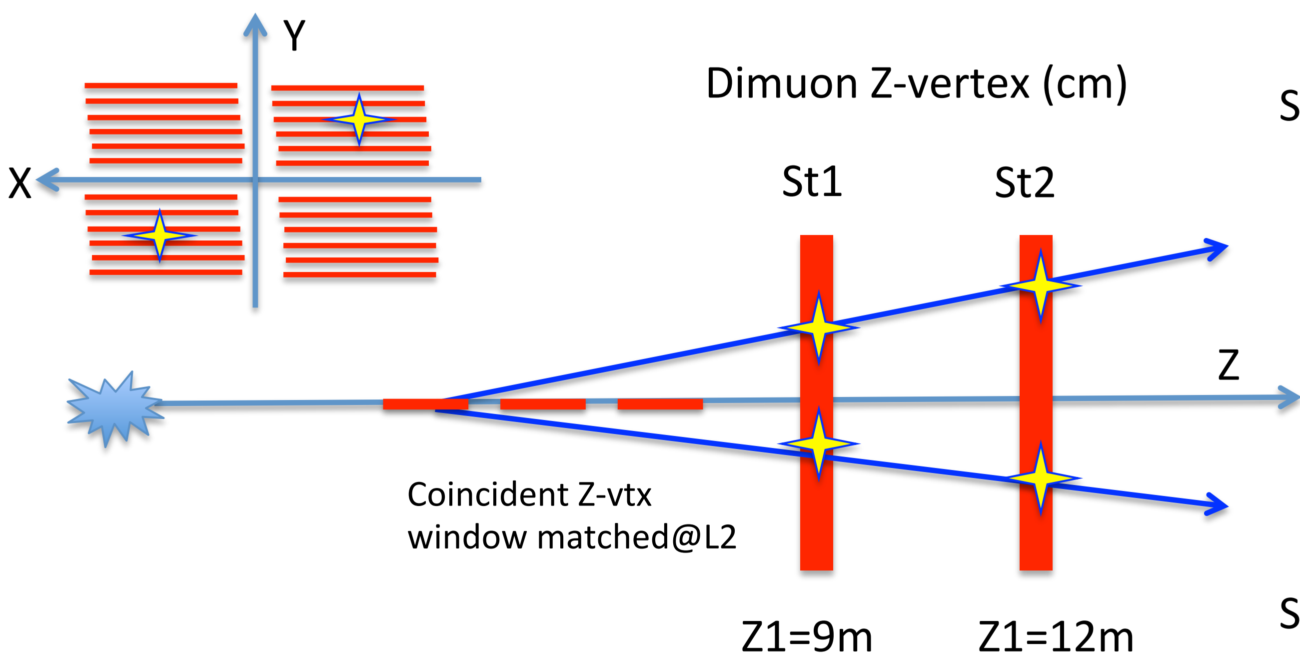
High rejection power, low rate, << 1 kHz(current E906 DAQ limit)

Y-Plane (non-bending) Trigger:

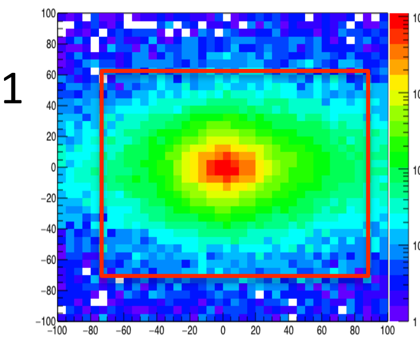
- A quadrant panel: 80cm x 80cm (100cmx100cm @ST-2)
  - ST1: 1cm x 1cm x 80 cm scintillating strips, SiPM readout
  - ST2: 2cm x 2 cm x 100 cm strips
- Straight line projection, σ_Z ~30cm
- Displaced z-vertex, mostly low mass < 3GeV

Y-channels per quadrant:

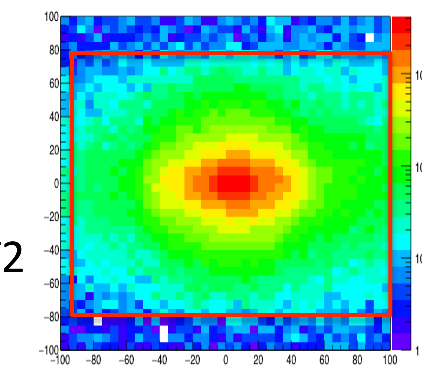
- 1x V1495
- 80(St1) + 50(St2) + 8x2 (St4-Y1,2) = 146
- 96+64 = 160 inputs possible
  (2NIM=RFCLK+ComSTOP)



ST1

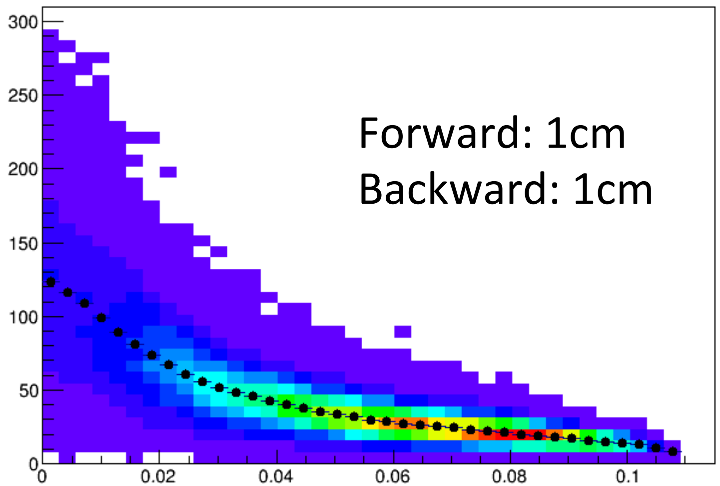


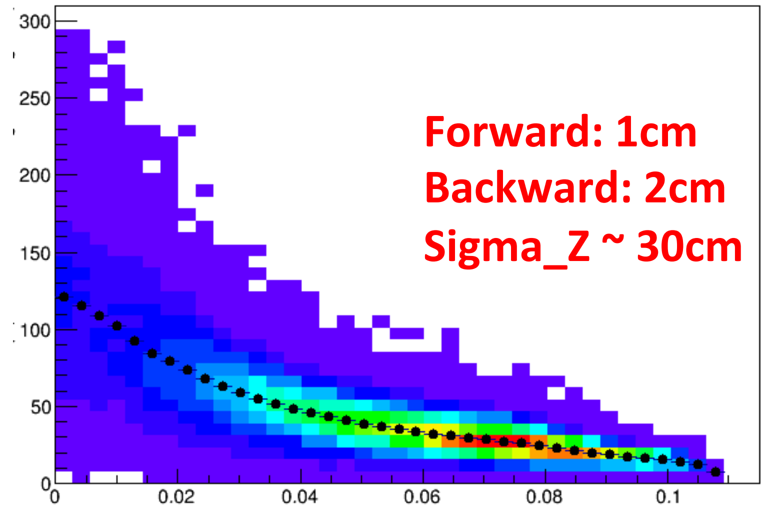
ST2

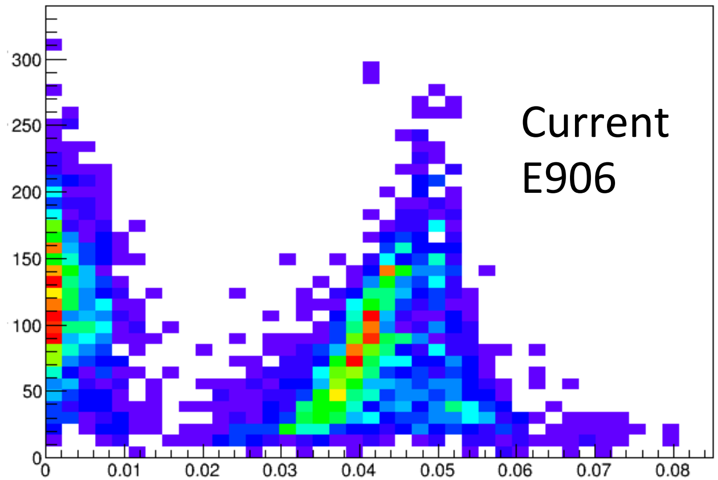


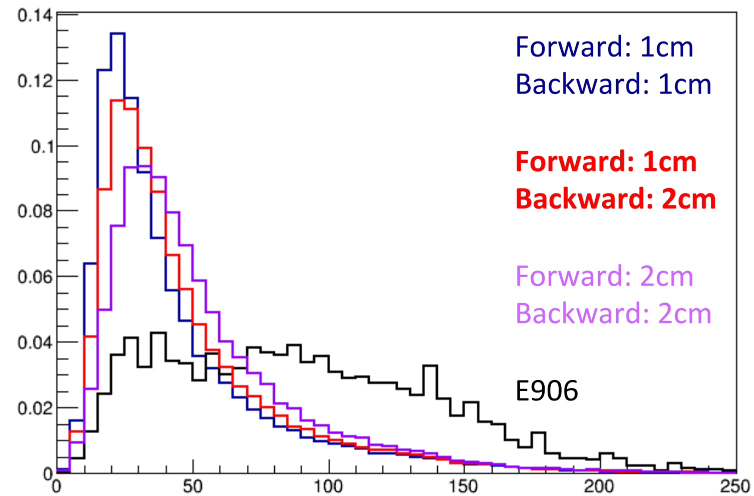
Trigger Detector Optimization

Single Muon Z-Vertex Resolutions









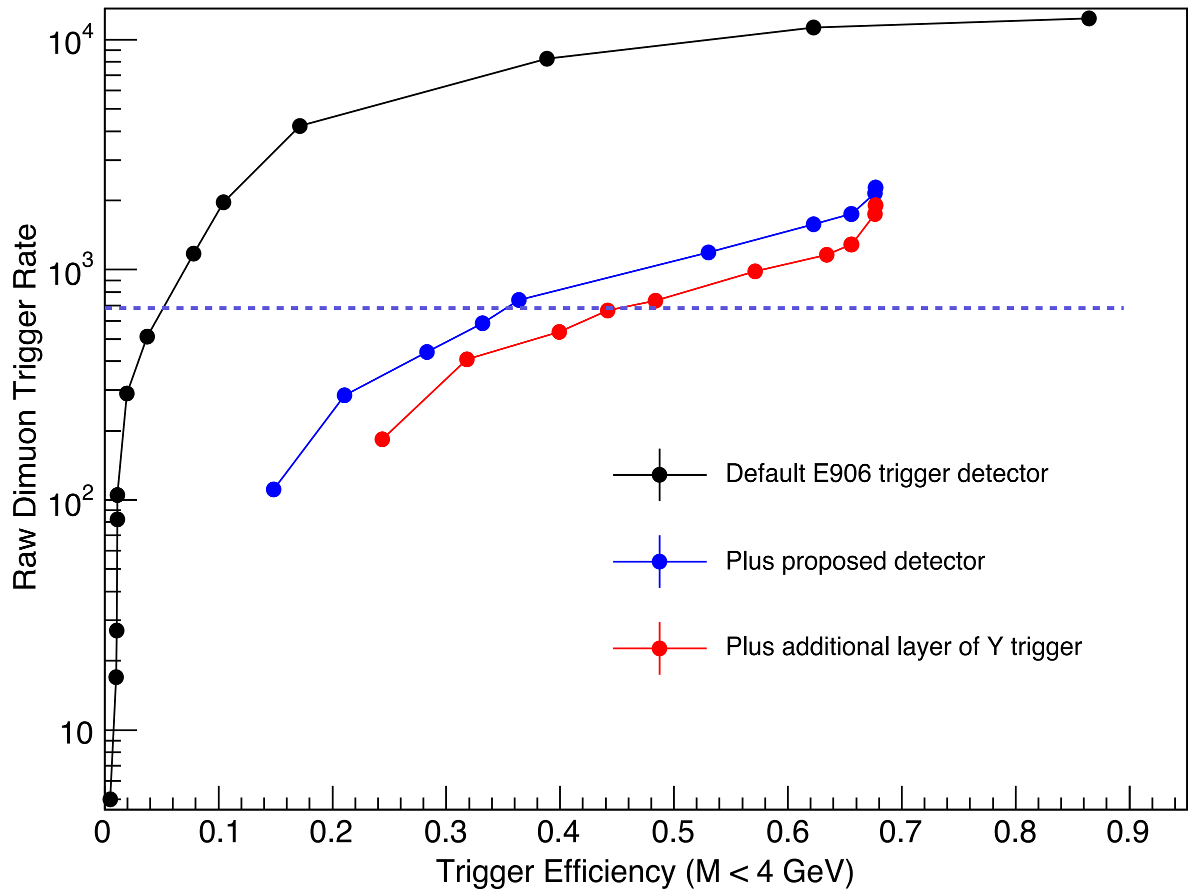
Low Mass Prompt Dimuon Trigger Rate Study

- 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 ~10+kHz with small cost

- 20+kHz possible for next run (reprograming trigger firmware etc.)

Parasitic mode: use up to ~10% DAQ bandwidth

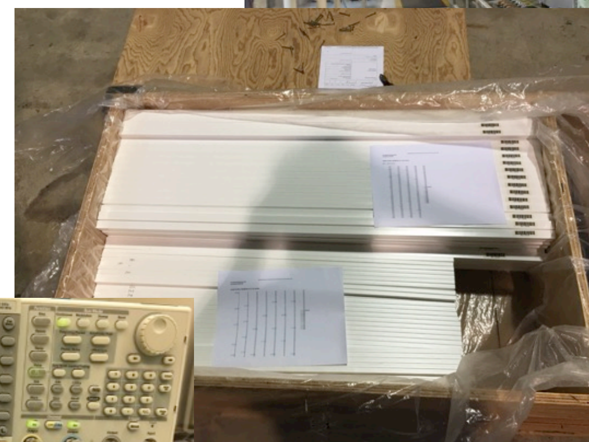


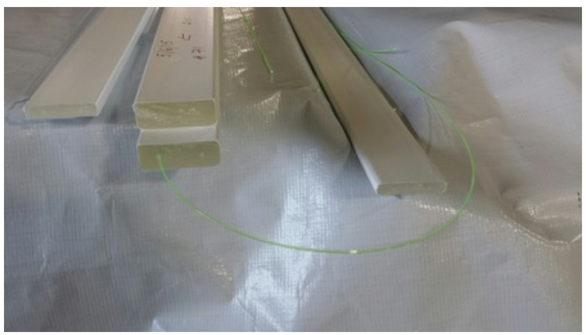
Expected (Prompt) Low mass dimuon trigger performance

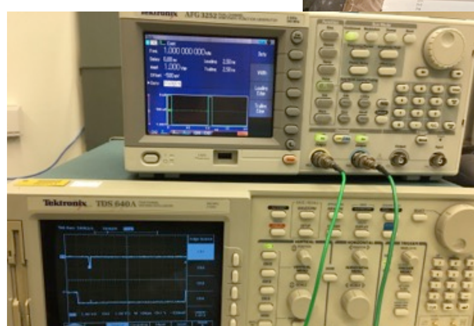
Trigger/DAQ Upgrade

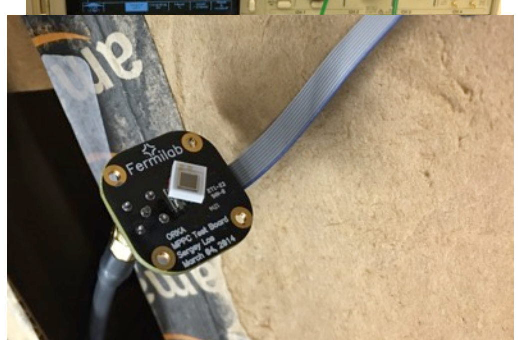
In good progress, to be installed by 2016

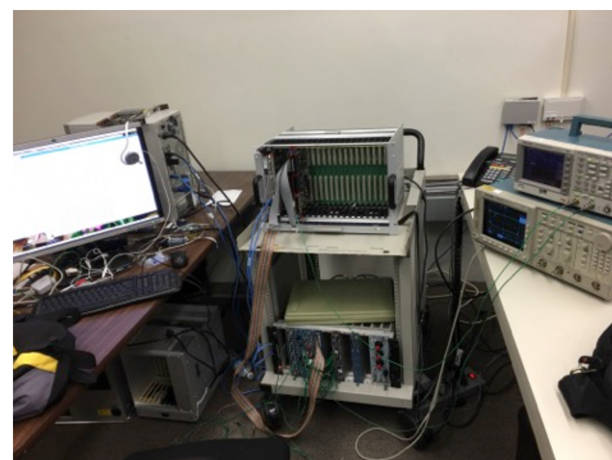
- Extruded scintillators + WLSF
- SiPM readout, frames
- Improve DAQ rate, x20+ expected











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

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

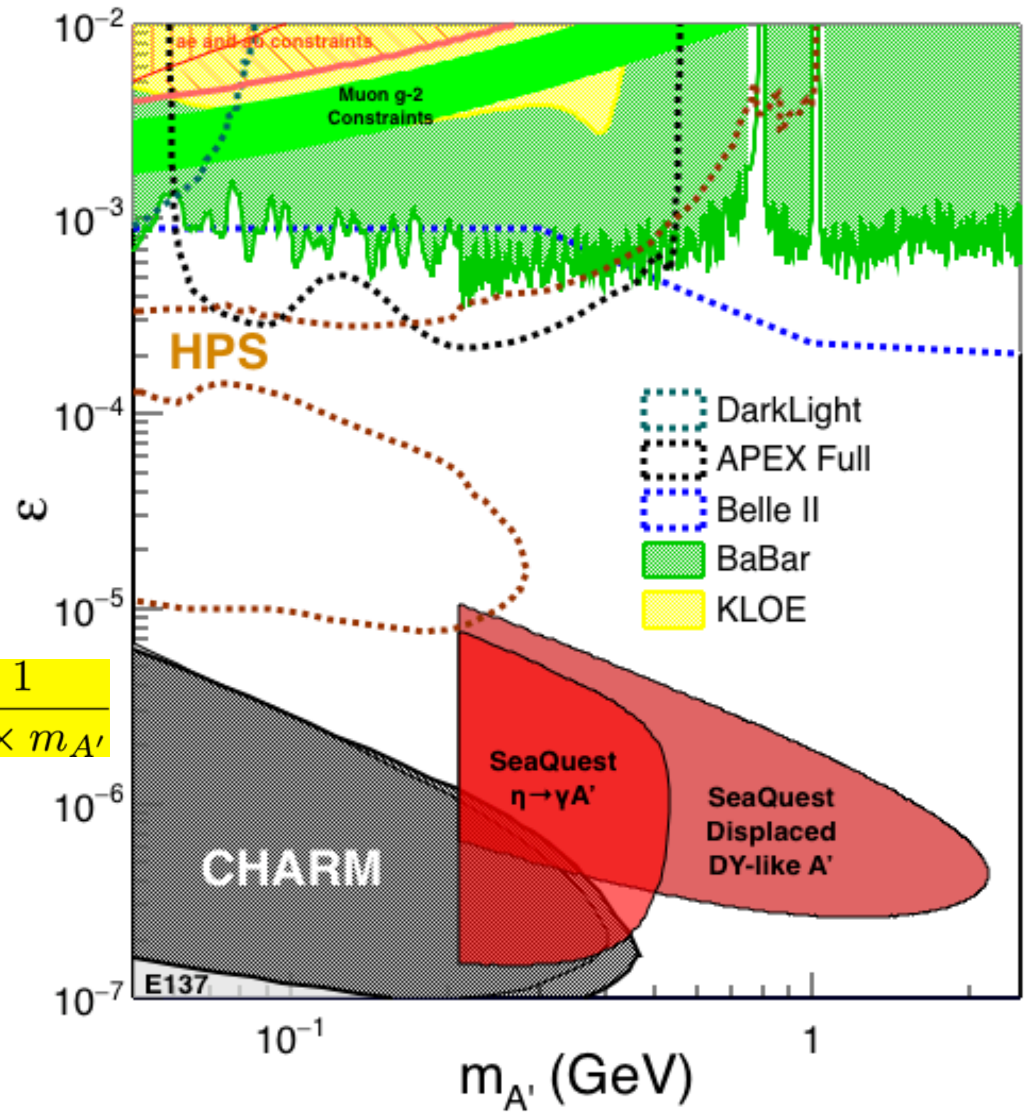
1.4 x 10^{18} POT (recorded)

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

- 4 events contours (2-sigma)

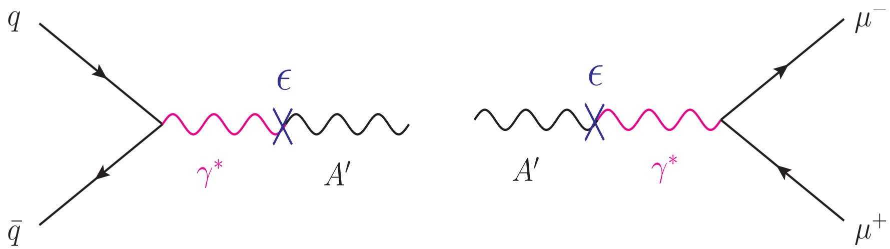
2-sigma (95%) exclusion plots

Excellent coverage of uncharted region!



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

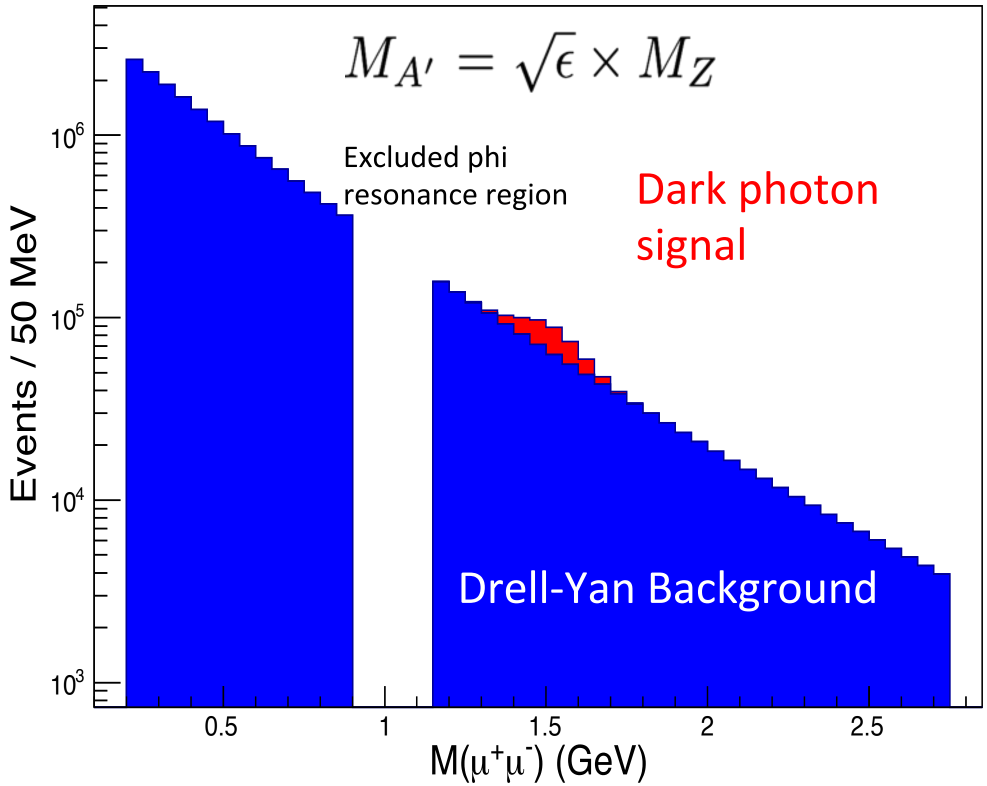
Bump hunt at Z-vertx < 3m



Expected Drell-Yan like signal and backgrounds:

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

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



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

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

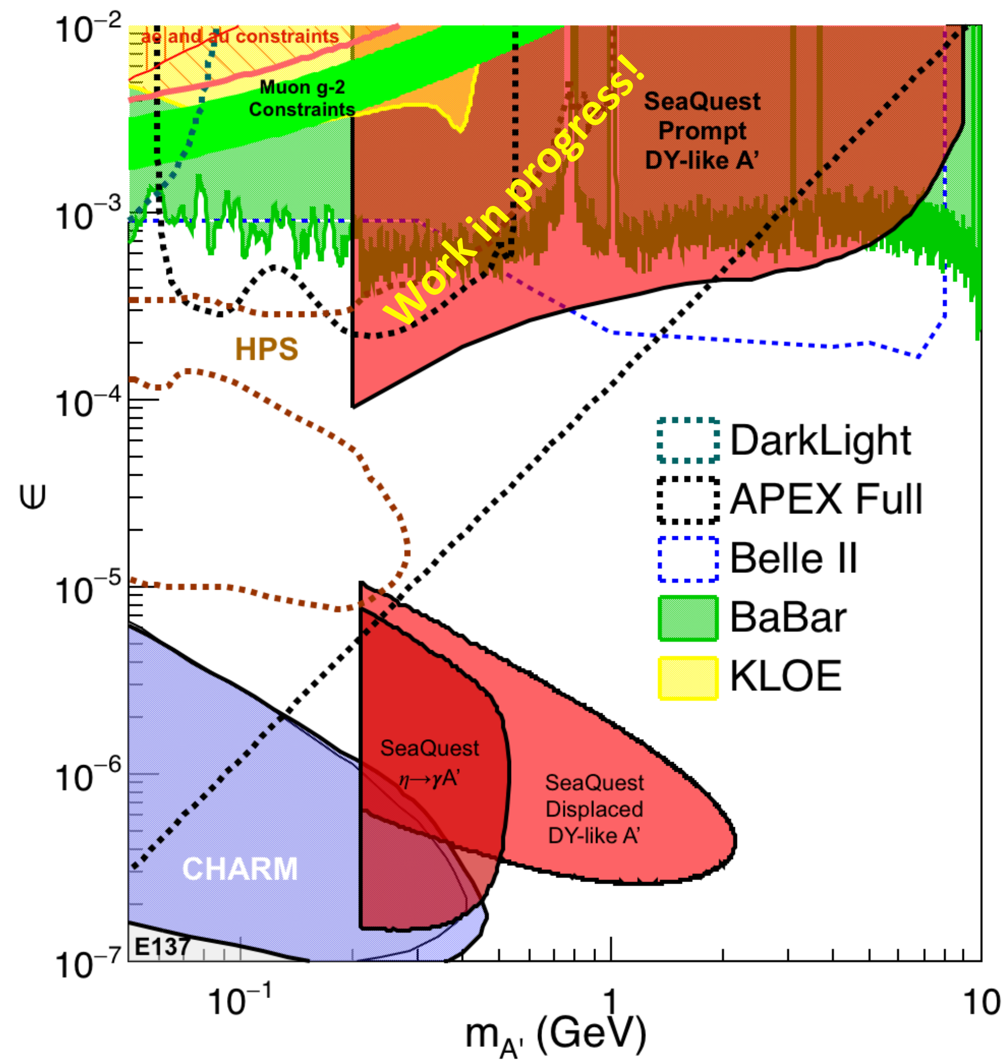
Work in progress:
- *optimization ...,*
- *understand BG ...*

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

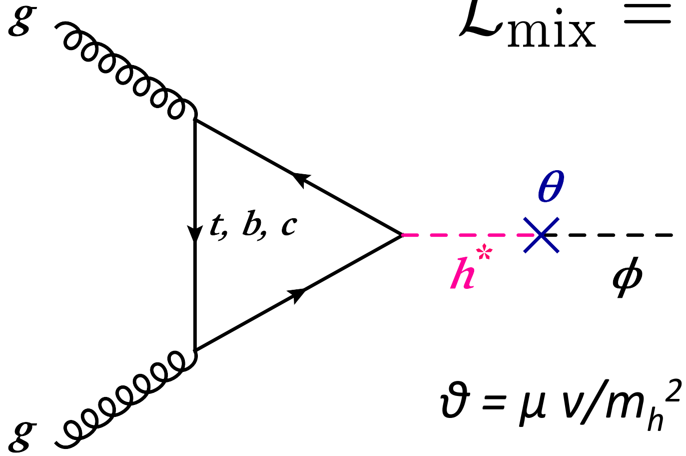
- Displaced dimuons
  - Minimal SM background
- Prompt dimuons
  - Excellent coverage over BELLE-II projection
  - Possible dedicated runs later to fully restore mass < 3GeV (Phase-II)
- ***Phase-II with upgrades***
  Access below 200MeV with di-electrons (add EMCal)



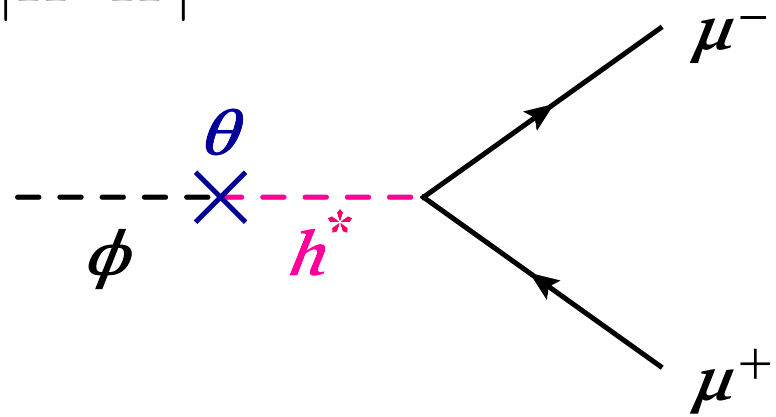
Dark Higgs

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

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

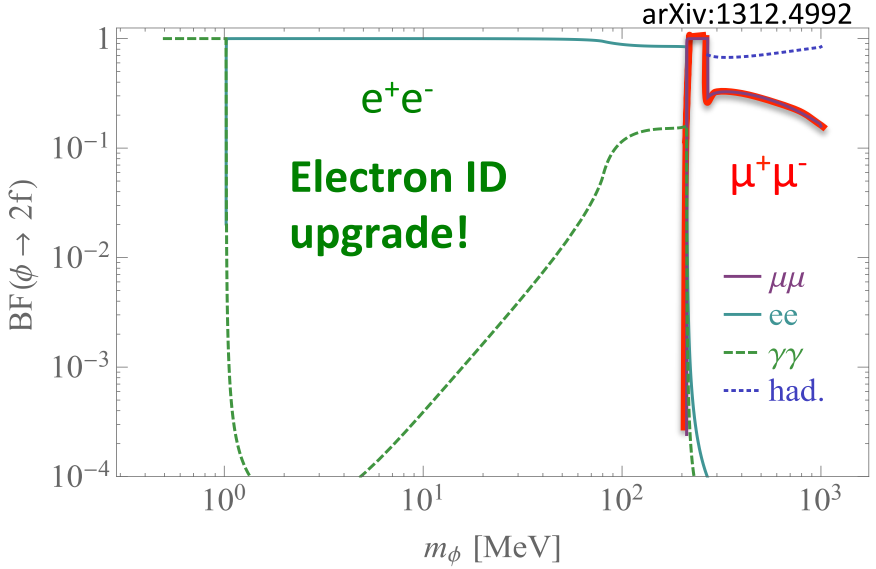
Advantage of using hadron beams with muon probes over electrons

Phase-II:

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

High-mass: hadrons, (5x)

arXiv:1312.4992

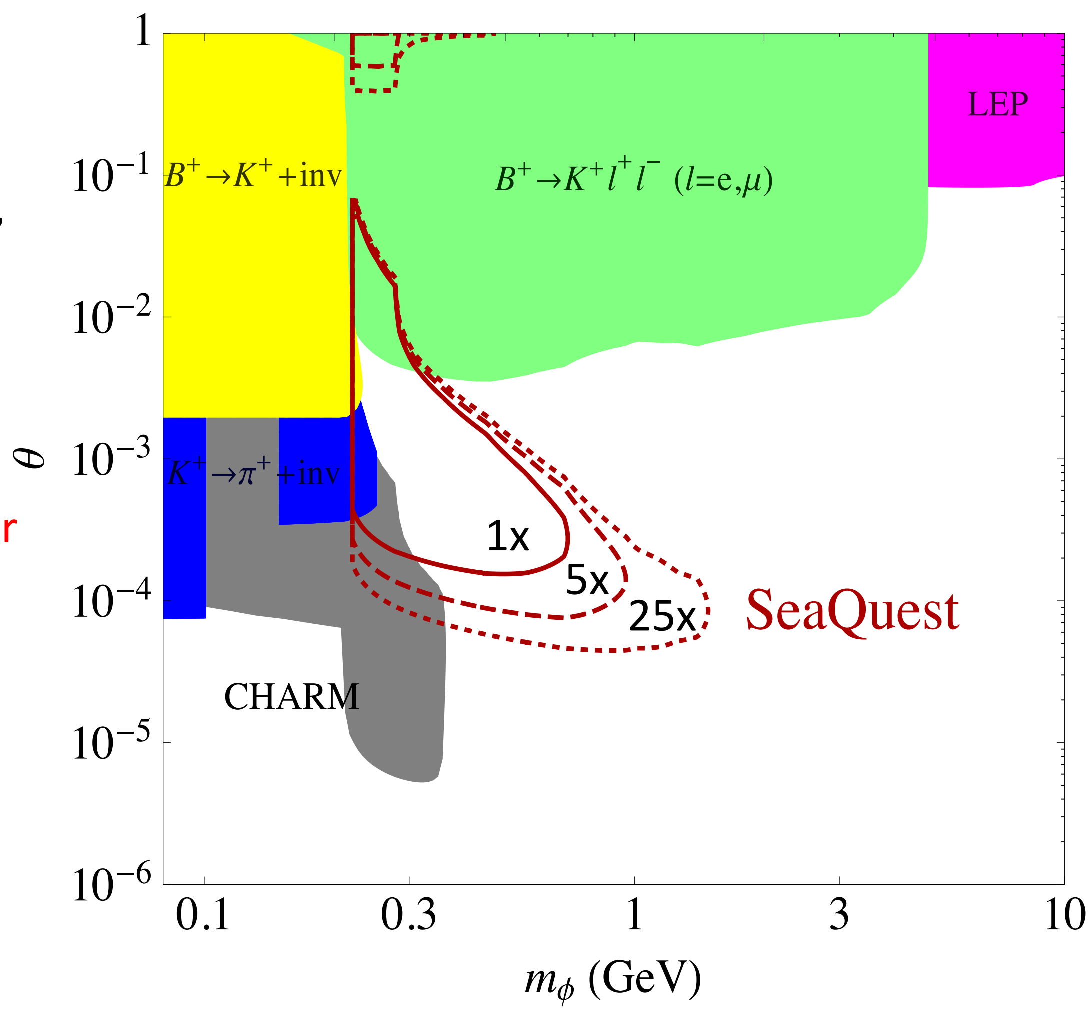


Projected Dark Higgs Sensitivity

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

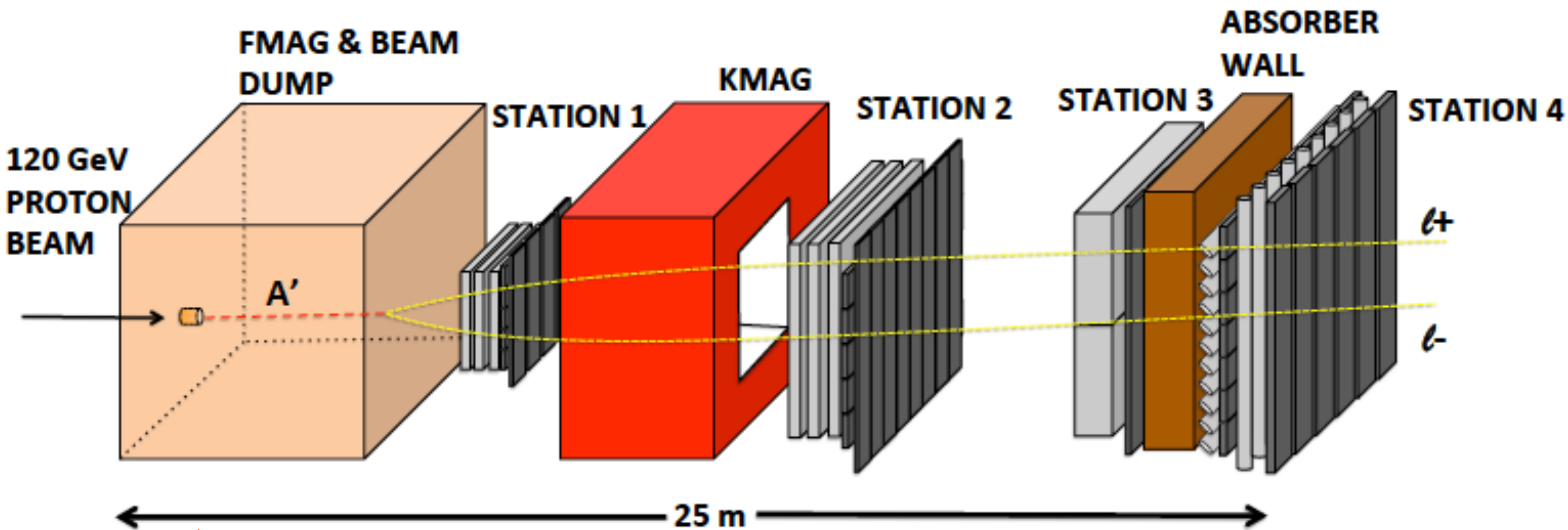
- Dimuons with downstream displaced decay vertices
- Limited sensitivity to "prompt" large mixing case due to small cross-section
- Dark Higgs or dark photons?
  - Dimuon kinematic and angular distributions
- Phase-II
  - Dedicated high luminosity runs optimized for low mass acceptance, mass<3GeV

Y. Zhang (2015)



E-1067 Future Upgrade: Phase-II

2020 ~ 2025+



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

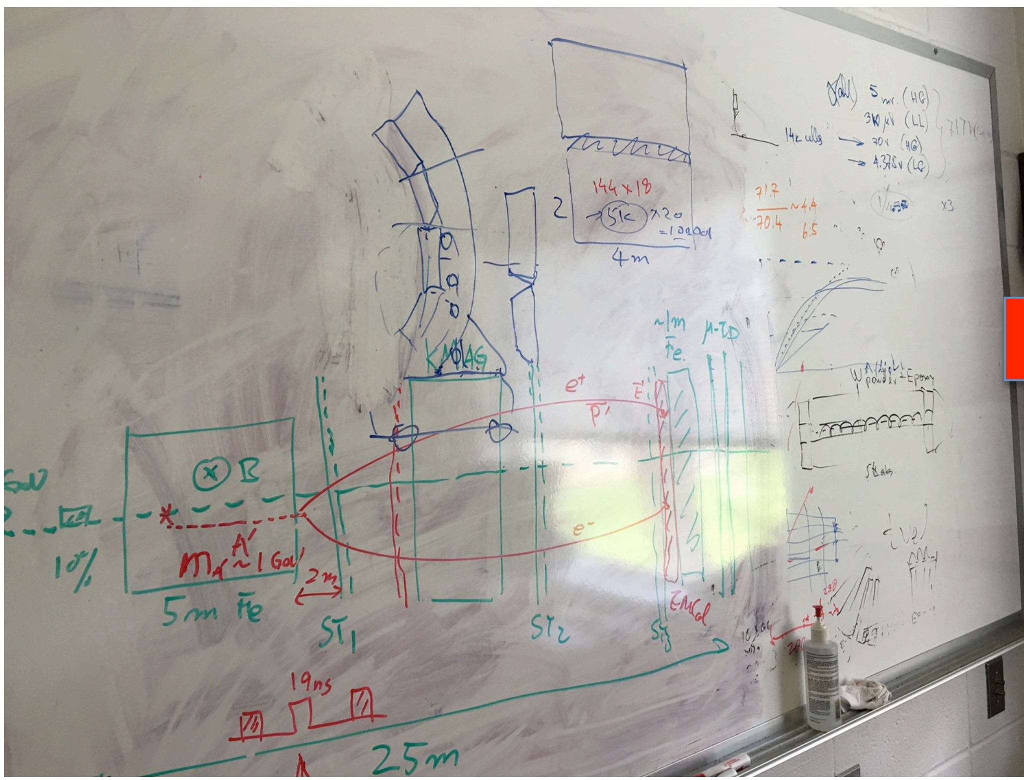
Add tracking detectors close to “target” to improve mass resolution

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

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

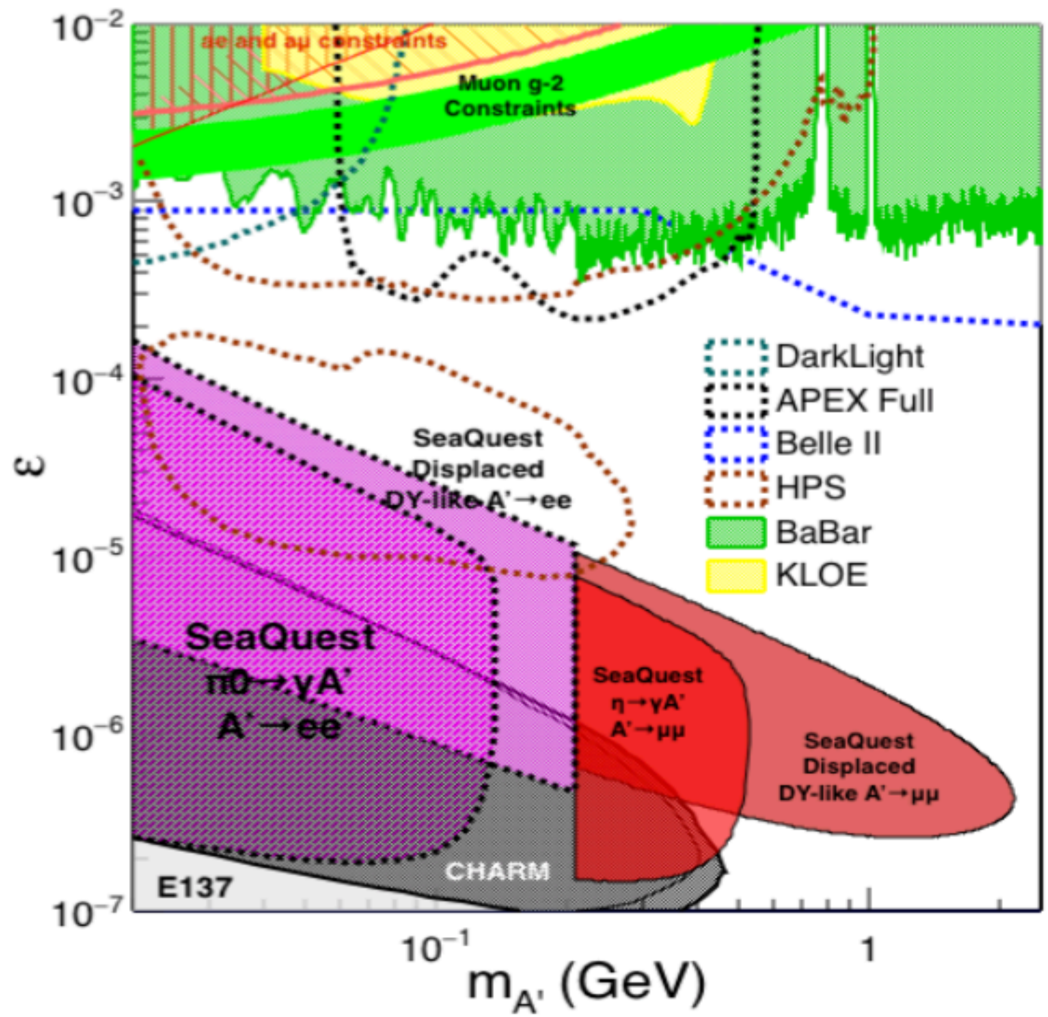


Phase-II: Displaced Low Mass Dark Photons

with EMCal upgrades

- 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

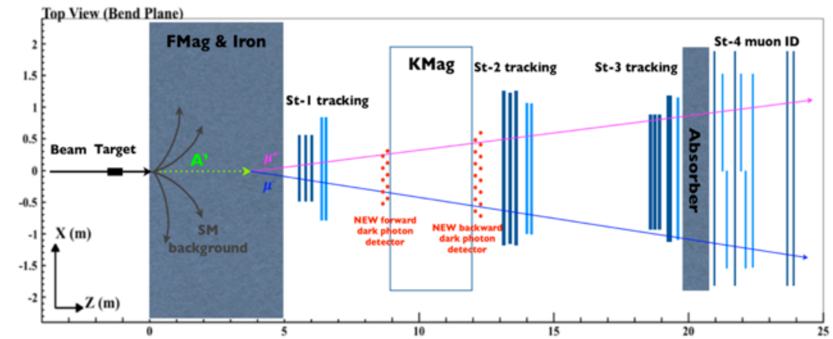
Projection: POT 1.4 x 10^{18}

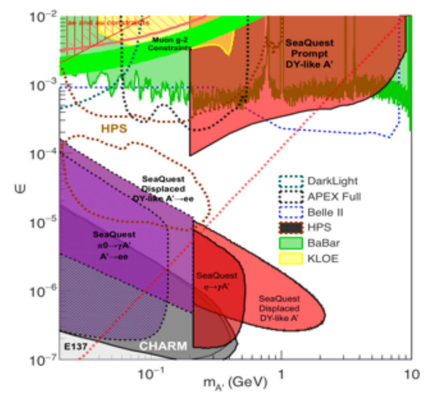


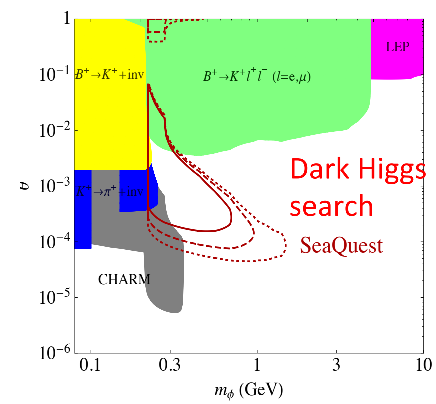
Summary and Outlook

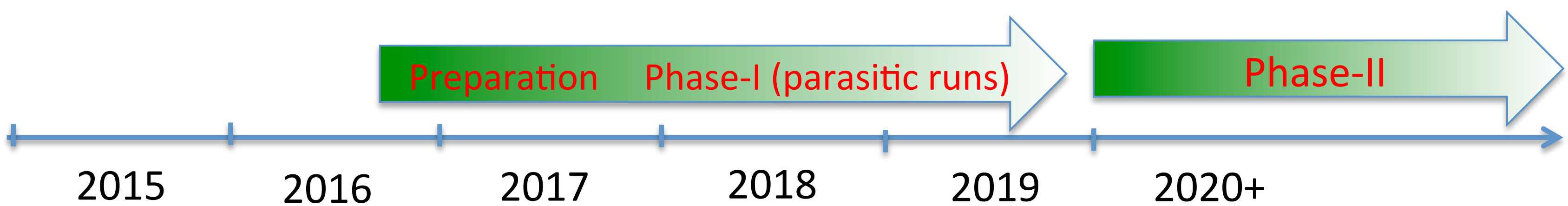
- *Phase-I*
  - *Great discovery potential!*
  - *A new vertex trigger & DAQ++*
  - *Early parasitic data taking 2017-2019+*
  - *POT 1.4 x10^{18} or more*

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









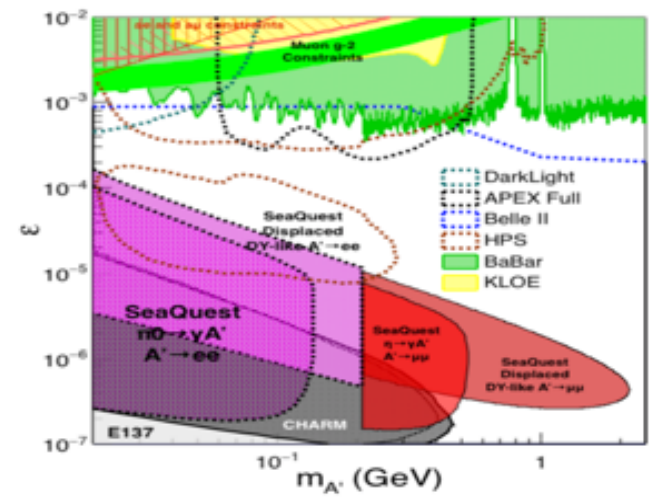
EMCal Upgrade: More Opportunities

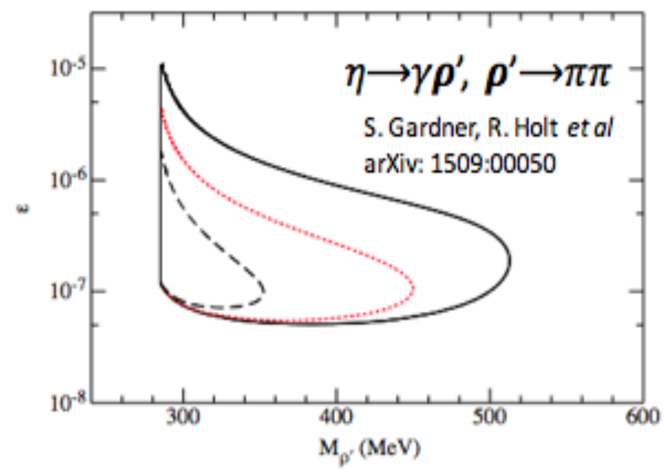
- 2 sectors (4×4 m^2 coverage) PHENIX EMCal will be available after this summer almost for free (not including shipping and instrumentation)

- With EMCal installed, we will be able to access:
  - dark photon from π^0 decay
  - dark ρ decays to $\pi\pi$
  - enhanced dark higgs sensitivity

- Two different scenarios of including EMCal have been studied via MC, and it poses little impact to our primary physics goal

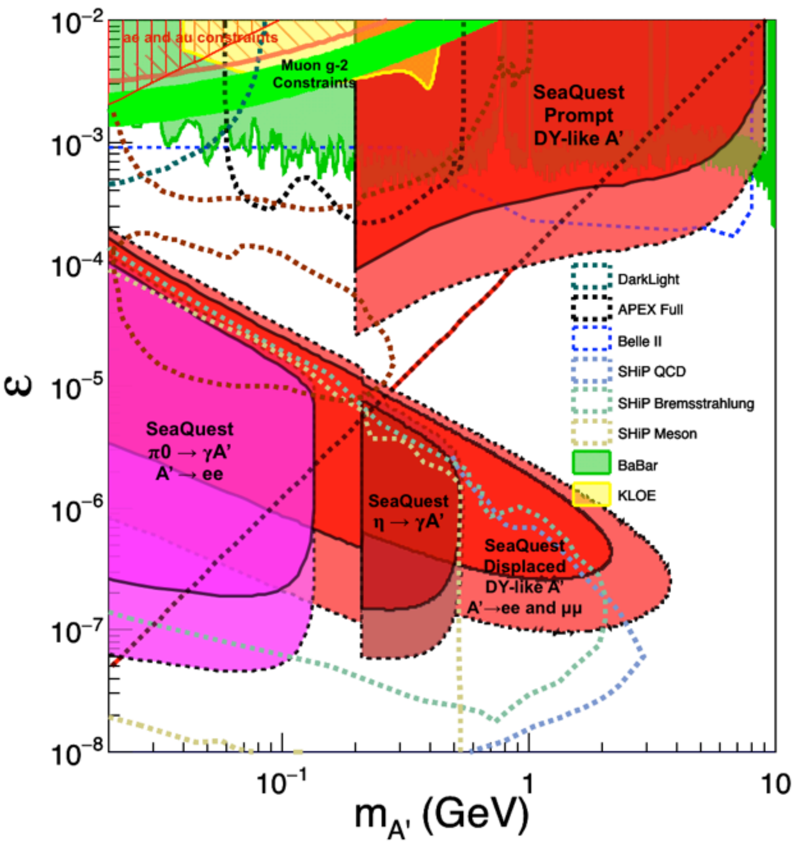
- Potential bonus of better background rejection on trigger level (studies underway).



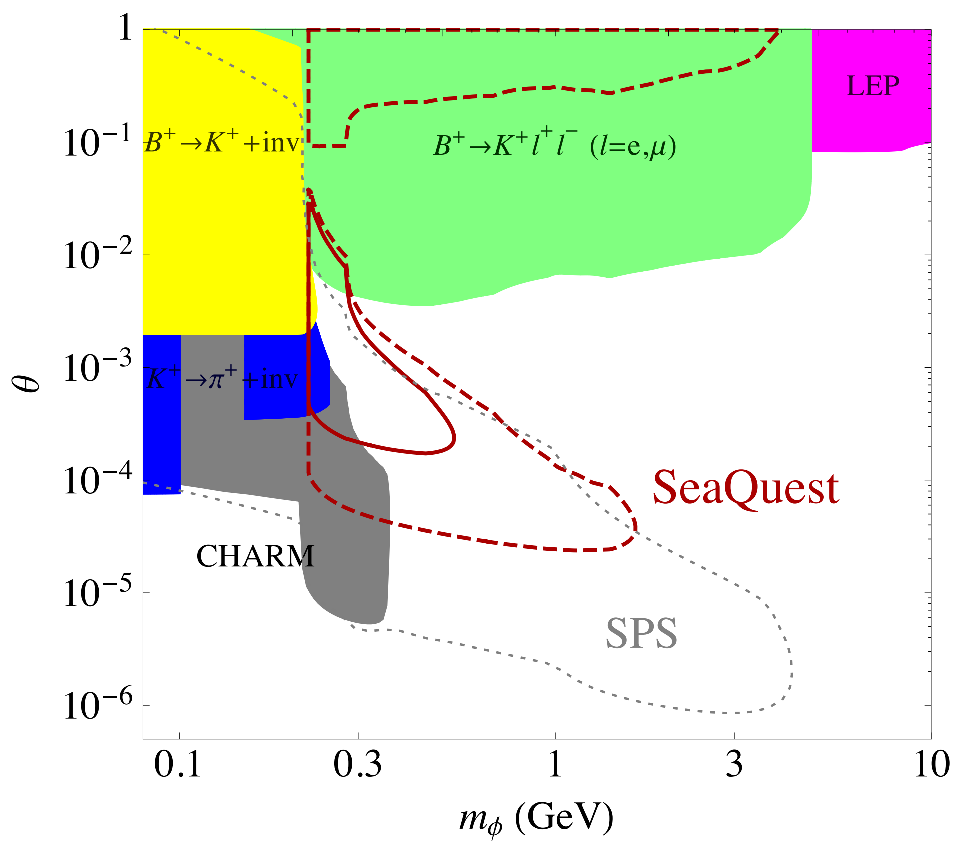


Comparison with SHiP Proposal

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



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



Dark Photon Decay Modes

"Minimal" Decay:

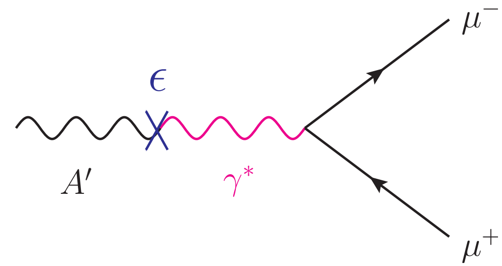
- Dark photon is the lightest in the dark sector;
  - SM final state particles only

Proper decay length: L_0 ~ *O(1m)*

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

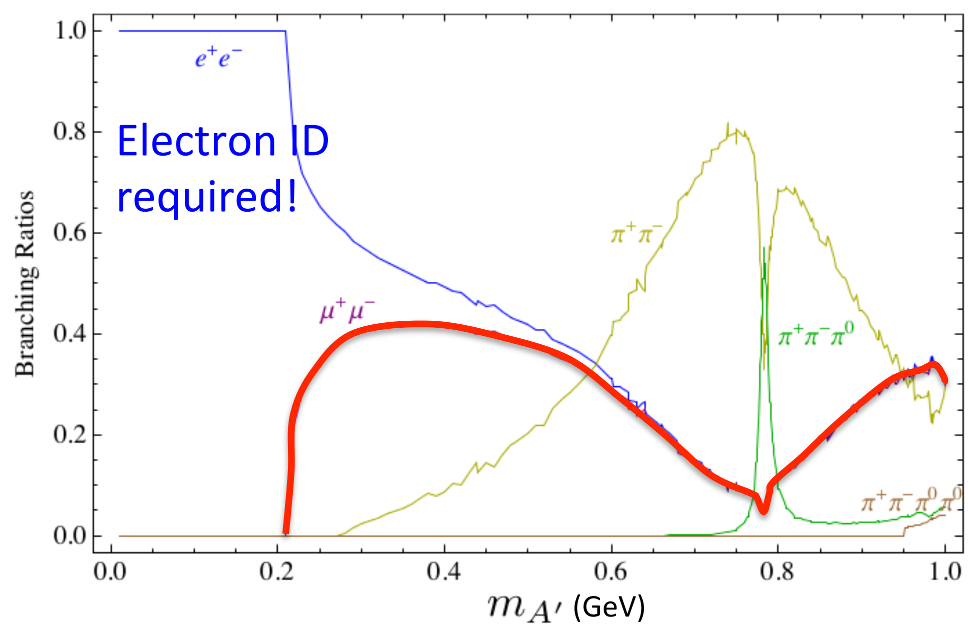
"General" Decay:

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

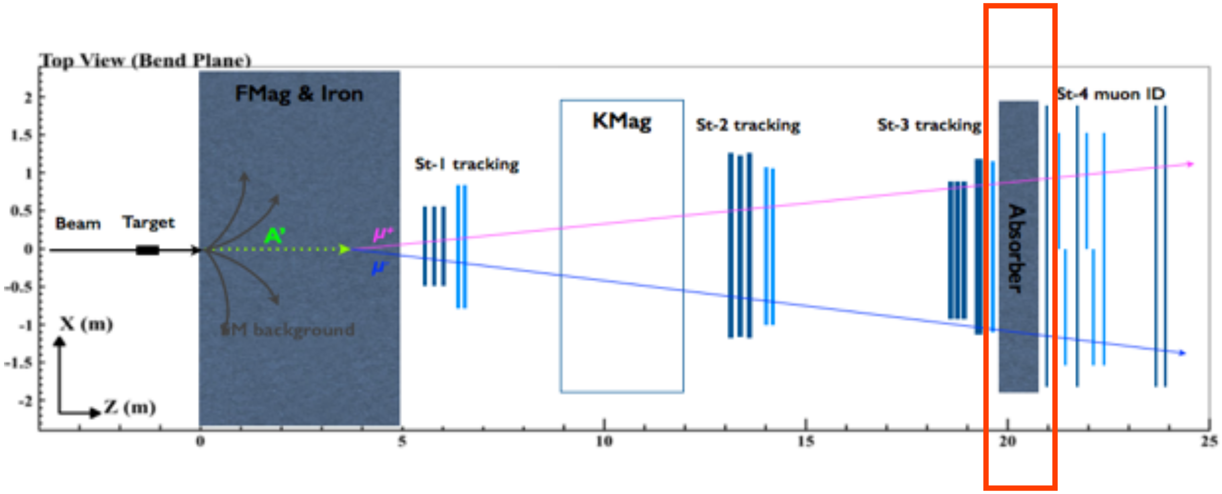


$$\Gamma(A' \to f + \bar{f}) = C\frac{\epsilon^2 m_{A'}}{3} e_f^2 \alpha_{\rm em} \left(1 + \frac{2m_f^2}{m_{A'}^2}\right) \sqrt{1 - \frac{4m_f^2}{m_{A'}^2}},$$

D. Curtin, et al, arXiv: 1312.4992



Two Possible Configurations and Their Impacts



Two configurations:

Option I: use EMCal to replace the absorber
Option II: insert EMCal between H3 and absorber (will need to slightly adjust station-3 position)

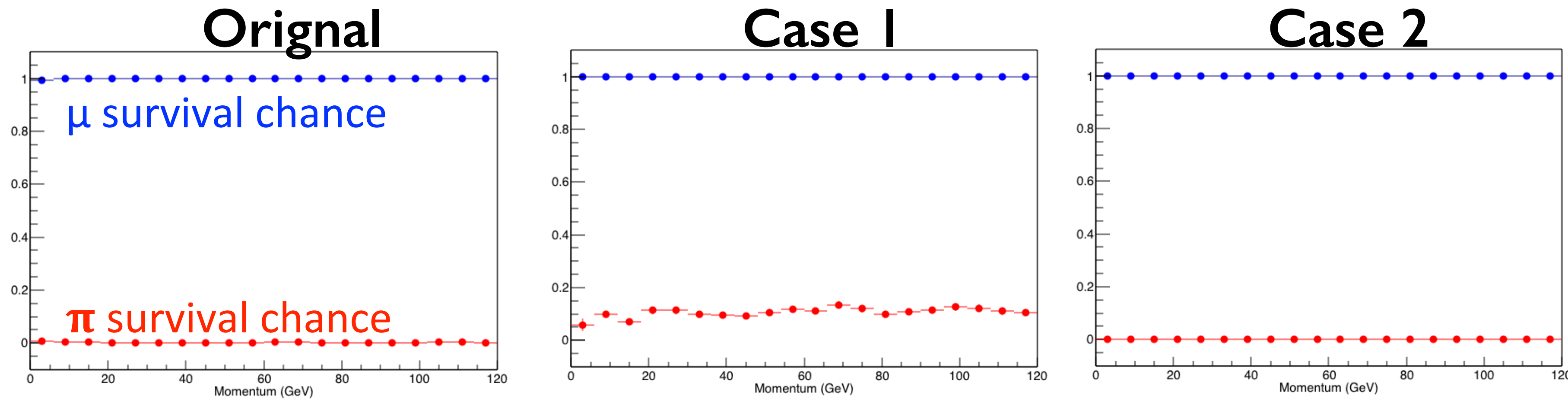
Test MC samples (for each scenario):

- 500k single **π**/μ/e tracks with 5 GeV < *P* < 115 GeV
- 1M high mass (M > 4 GeV) target DY pairs
- 2E10 inclusive pp collisions (see, *MC simulation talk by David K.*)

Potential impacts on our primary physics goal:

- Muon identification power
- Acceptance? (*MC shows no impact*)
- Occupancy in station-4 and thus our raw trigger rate
- Data volume and DAQ deadtime?

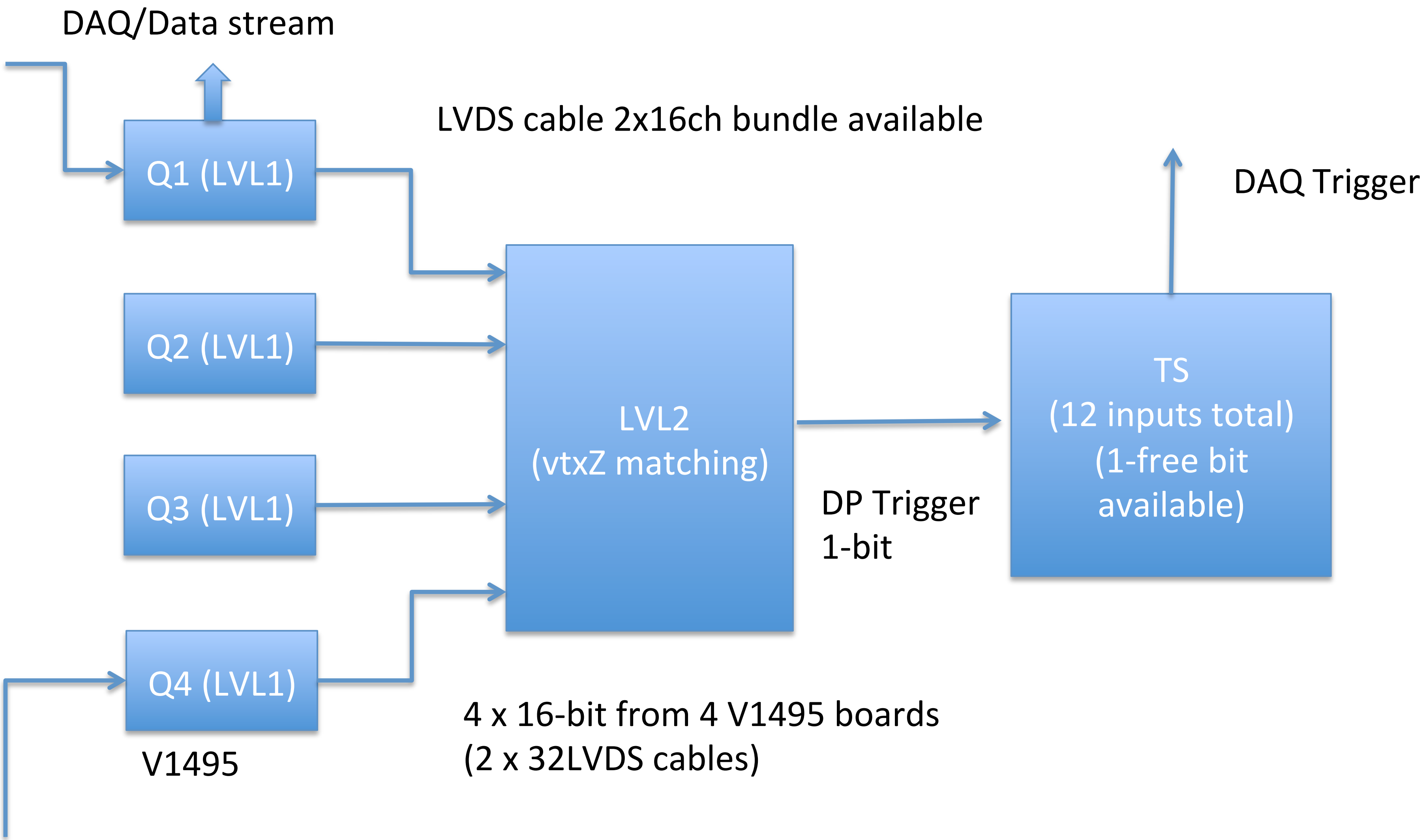
μ/π separation: case 1 vs. case 2 vs. original



- For μ survival chance (or μ-ID efficiency), all 3 cases are very close to 100%
- For **π** survival change (or **π** contamination):
  - original design is around 0.5%
  - case 1 is around 10%
  - case 2 is around 0.1%

μ identification favors case 2

Displaced Dark Photon Trigger



Q1: 80(ST1’) + 50 (ST2’) + 2x8(ST4-Y1/2) = 146, FANOUT ST4 Hodo (or EMCal Cluster)