Dark photon search with Drell-Yan-like mechanism

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HUGS student seminar talk
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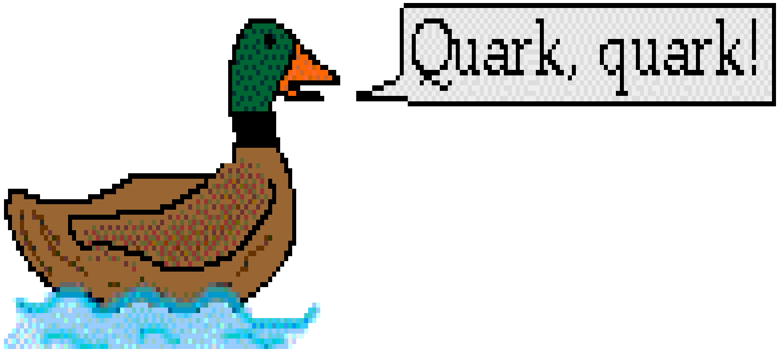
Outline

- What is dark photon ?
- Existing search mechanisms
- Drell-Yan-like mechanism
- SeaQuest
- Sensitivity calculation
- Summary



Pushing beyond standard model

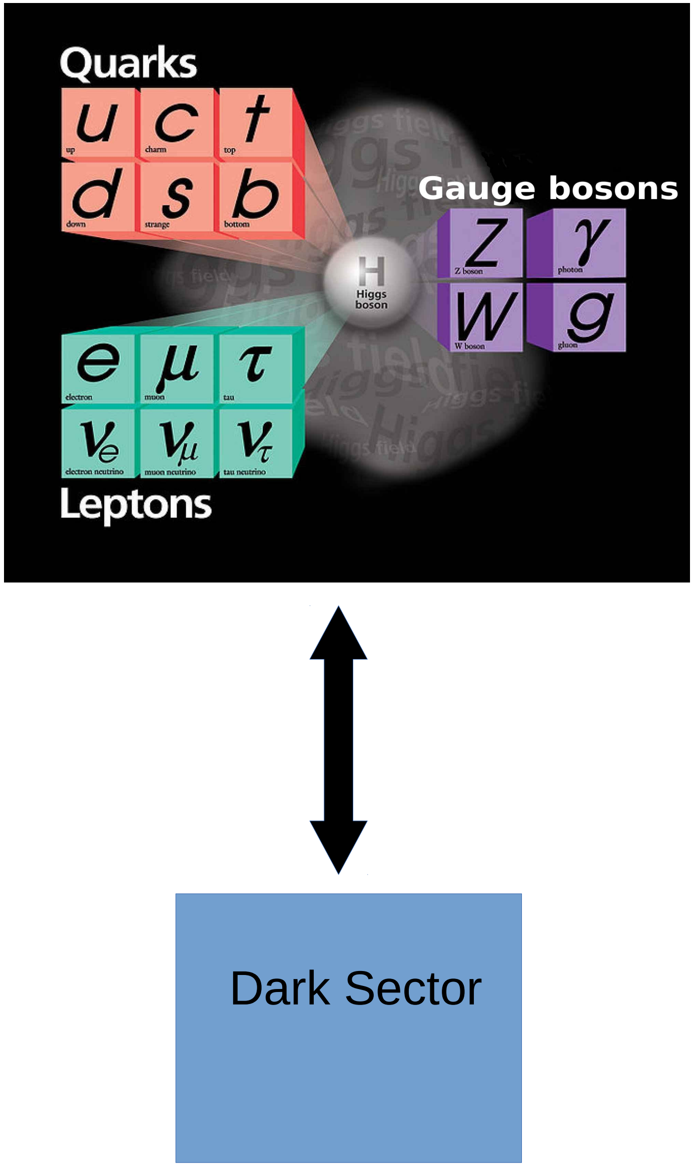
- Our current understanding of matter and forces is explained fairly well by Standard Model.
- We know it is incomplete.

  -Standard Model (~5%)

  -Dark matter (~27%)

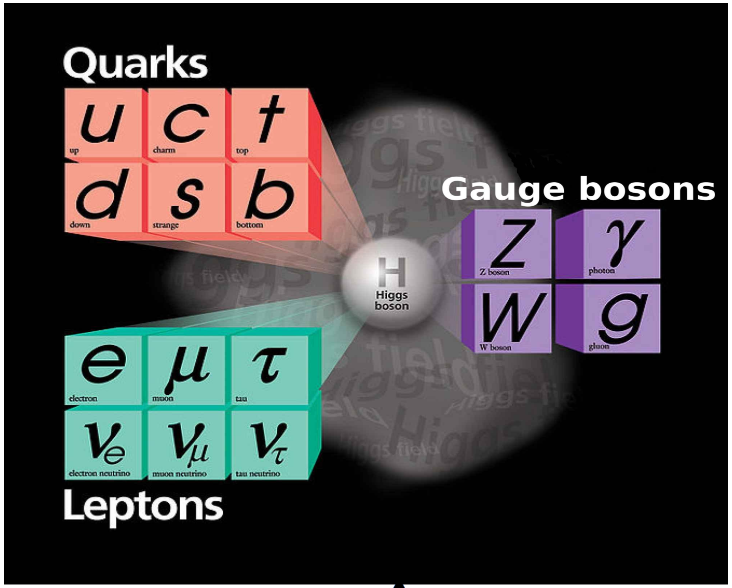
  -Dark energy (~68%)
- Gravitational interaction provides link between dark sector and standard model
- Dark photon could provide another link.

Portal	Particles	Operators
Scalar	Higgs	$(\mu S + \lambda S^2)H^\dagger H$
Pseudoscalar	Axions	$\frac{a}{f_a} G_{i\mu\nu}\tilde{G}_i^{\mu\nu}$
Vector	Dark photons	$-\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu}F'^{\mu\nu}$
Fermion	Sterile neutrinos	$y_N LHN$



What is dark photon?

- Gauge boson.
- Supposed to be mediator of 'Dark Electromagnetism'
- Massive, finite lifetime.
- Could also couple to standard model particles through kinetic mixing.
- Addition of dark photon to SM Lagrangian allows a kinetic mixing term leading to interaction of A' (dark photon) with SM electromagnetic current.
- Effective lagrangian

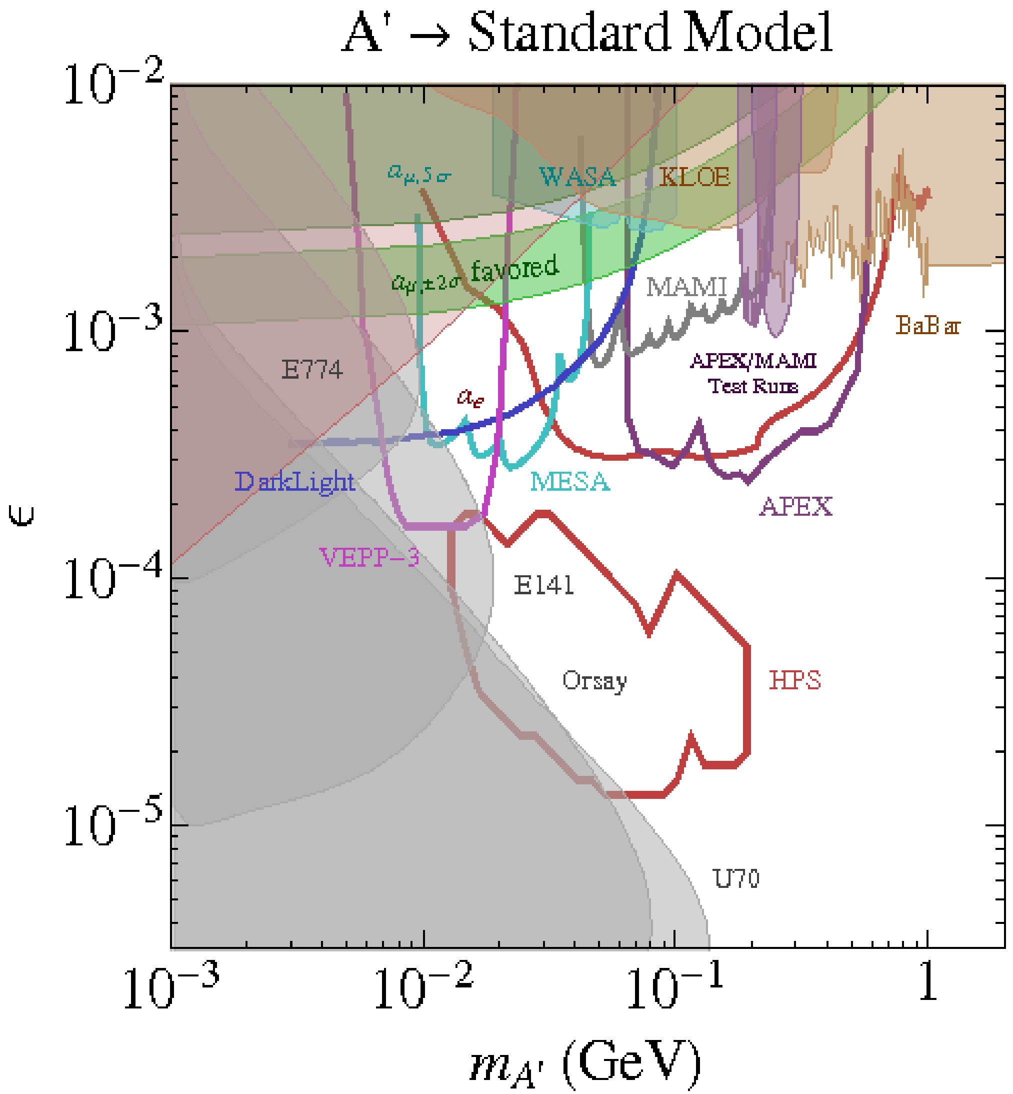


$$\epsilon e A'_{\mu} J^{\mu}_{EM}$$

Dark Sector

$$L \sim -\frac{1}{4} F^{SM}_{\mu\nu} F^{\mu\nu}_{SM} - \frac{1}{4} F^{hidden}_{\mu\nu} F^{\mu\nu}_{hidden} + \frac{1}{2} \epsilon F^{SM}_{\mu\nu} F^{\mu\nu}_{hidden} + m^2_{A'} A^{hidden}_{\mu} A^{\mu}_{hidden}$$

Reach of existing and future experiments



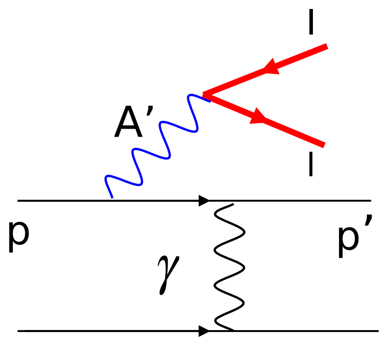
(arxiv: 1311.0029v1)

- A lot of interest in exploring the parameter space in search of this exotic particle.
- For dark photon mass > 1MeV it can decay into electron-positron pair.
- Large unexplored region in ϵ and $m_{A'}$

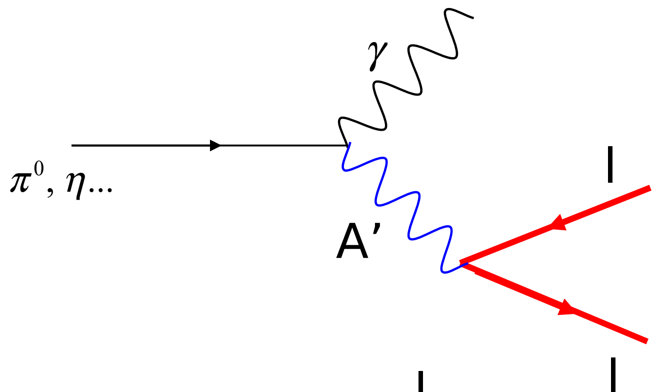
Existing search mechanisms

Several dark photon production mechanisms have been studied so far.

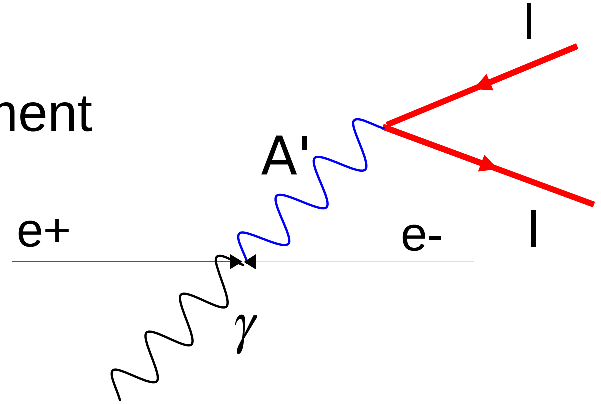
- Bremsstrahlung



- Meson decay



- e-e+ collider experiment



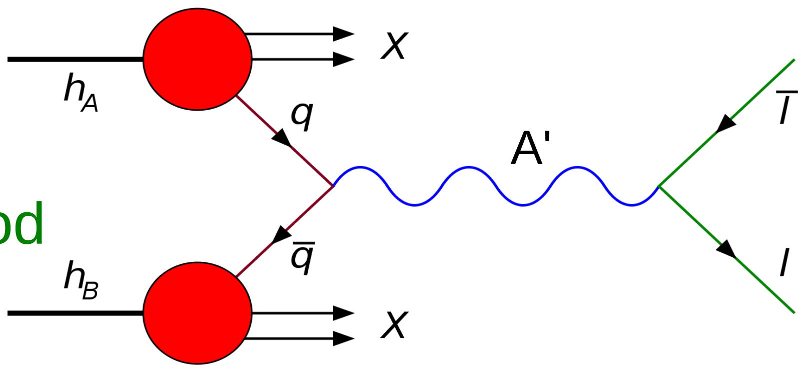
Drell-Yan-like mechanism

A new approach

- Drell-Yan process : Quark and anti-quark annihilate to form a virtual photon which decays into lepton pair.

$$\frac{d^2\sigma}{dx_F dM^2} = \frac{4\pi\alpha^2}{9M^4}\frac{x_1x_2}{x_1+x_2}\sum_i Q_i^2[q_i(x_1)\bar{q}_i(x_2)+\bar{q}_i(x_1)q_i(x_2)]$$

- Quark and anti-quark from beam and target annihilate to form a dark photon instead.



-High mass reach
-Drell-Yan mechanism well understood

- Differential cross section

$$\frac{d\sigma}{dx_F} = \frac{4\pi^2\alpha\epsilon^2}{3M_A^2}\frac{x_1x_2}{x_1+x_2}\sum_i Q_i^2[q_i(x_1)\bar{q}_i(x_2)+\bar{q}_i(x_1)q_i(x_2)]$$

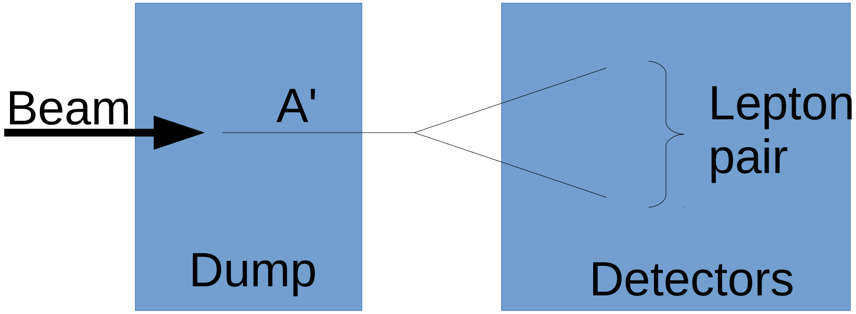
Unique mass Suppression

How do we look for dark photons?

- Signature

  - peak in the mass spectrum

  - displaced decay vertex



- Challenges

  - Large standard model background

  - Small production cross section

- However, finite lifetime of dark photon allows it to travel certain distance before decaying into lepton pair. A shield can stop the SM background, thereby removing the background to a large extent.

- This decay length depends on ϵ and $m_{A'}$

$$l_0 \equiv \gamma c \tau \propto \frac{\gamma}{m_{A'} \epsilon^2}$$

For $\epsilon = 10^{-6}$ $m_{A'} = 500$ MeV
$\gamma = 20$

Decay length is approximately 4 m.

- SeaQuest can be used to look into this process.

SeaQuest experiment

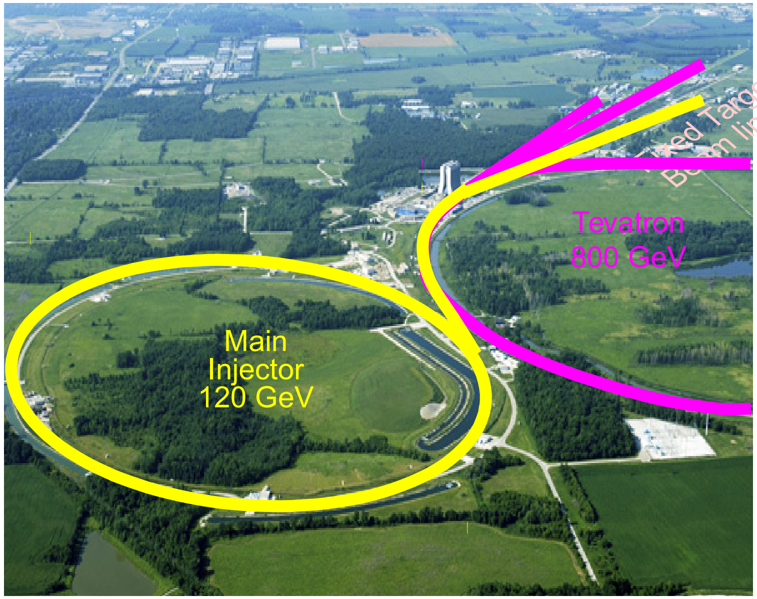
- Fixed target experiment at FermiLab
- Drell-Yan process
- 120 GeV beam on target
- Physics at SeaQuest

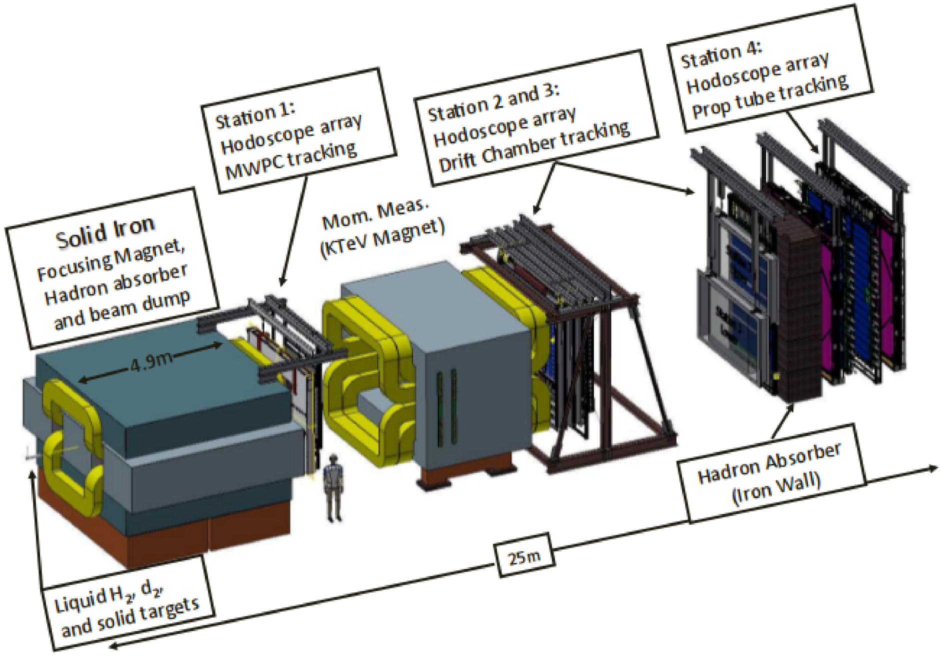
  -light sea quark asymmetry

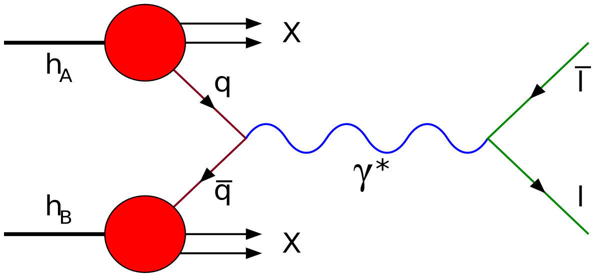
  -EMC effect

  -angular distributions

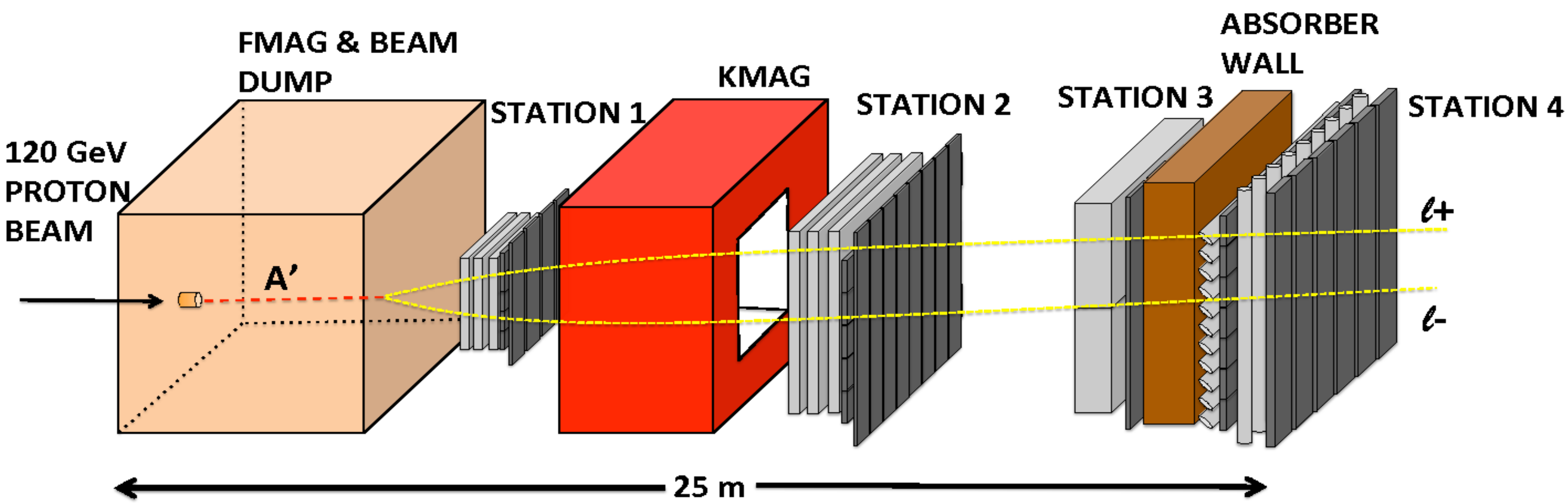
  -dark photon search







SeaQuest spectrometer



(Gardner et. al. 1509.00050v1)

- SeaQuest spectrometer is designed to measure high mass (>4 GeV) muon pairs produced in Drell Yan process. The trigger selects high mass muon pairs.
- However, an upgrade of SeaQuest trigger has been proposed to look for events with lower mass.
- 5 meters long beam dump can suppress the background, while A' can travel through the beam dump and decay downstream.
- High intensity beam interacting with beam dump implies high luminosity.

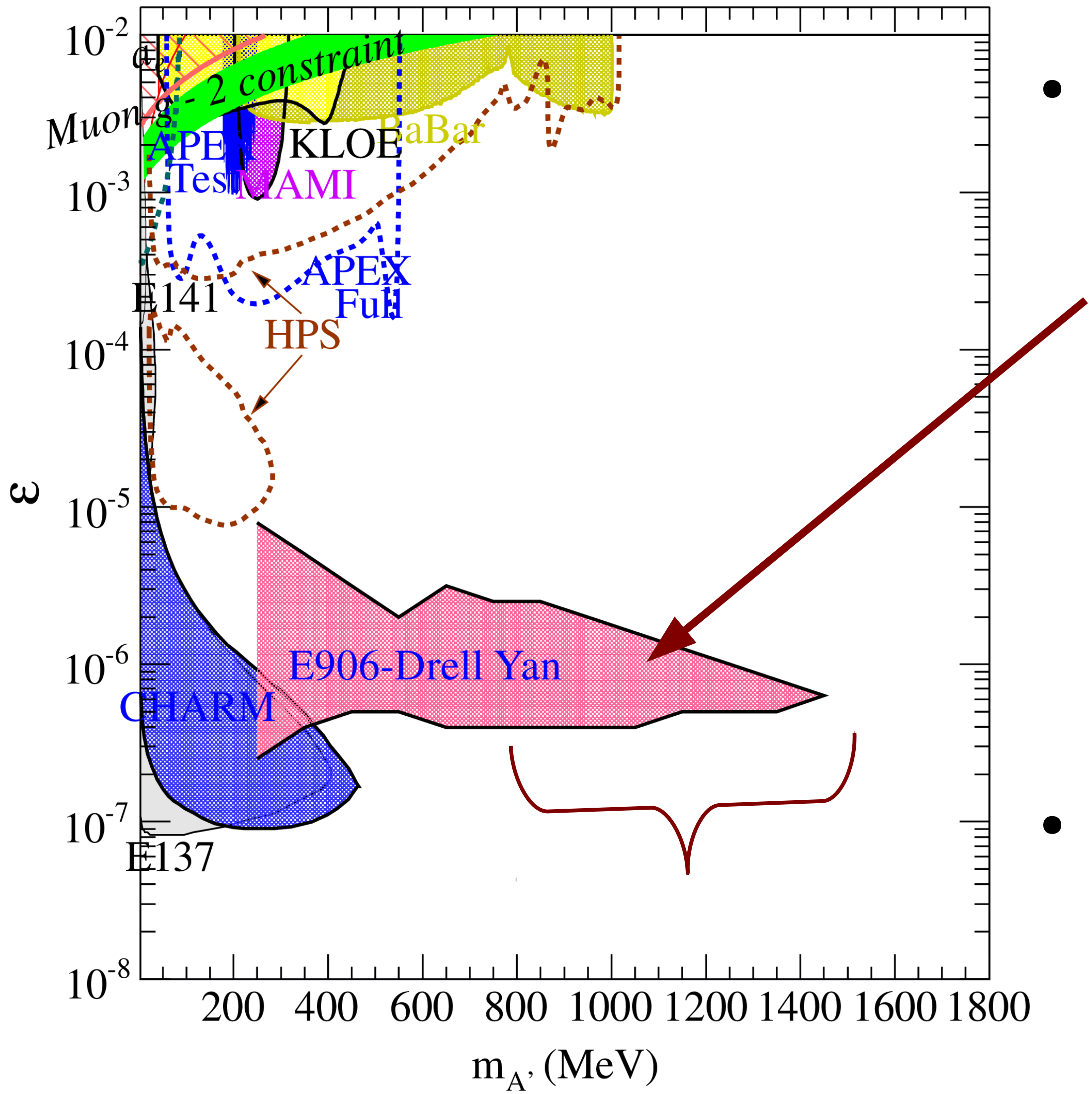
Sensitivity calculation for $pA \rightarrow A' \rightarrow \mu^+\mu^-$

$$\frac{d\sigma}{dx_F} = \frac{4\pi^2\alpha\epsilon^2}{3M_A^2}\frac{x_1x_2}{x_1+x_2}\sum_i Q_i^2\underbrace{[q_i(x_1)\bar{q}_i(x_2)+\bar{q}_i(x_1)q_i(x_2)]}$$

Structure function : CTEQ 5M
K Factor: 1.25

- For M > 210 MeV , dark photon can decay into muon pairs
- The unknowns in the equation are ϵ and $m_{A'}$
- For MC simulation, mass is taken in the range .25 GeV to 1.75 GeV and ϵ in the range $10^{-7} - 10^{-5}$
- A' is produced in the Fe dump which decays in a region dz at a distance z from its creation point according to exponential decay $exp(-z/l_0)$ where l_0 is the average decay length of A' in lab frame.

Sensitivity calculation for $pA \rightarrow A' \rightarrow \mu^+\mu^-$



- With 2e12 protons/sec on Fe Dump,for 200 days,

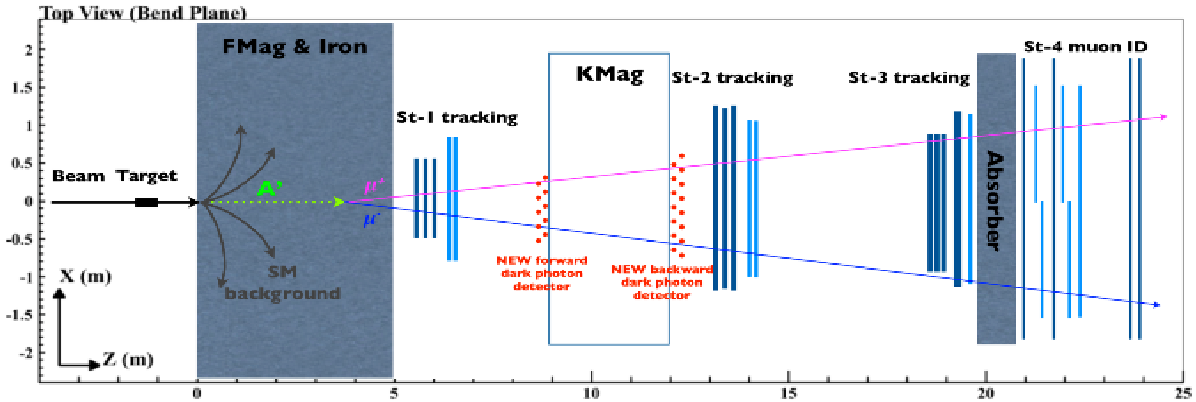
  a preliminary simulation shows 2-sigma (95%) exclusion plot.

  Fiducial region considered here is approximately 3 m long.

- Its reach in higher mass is encouraging. It will be able to set limits in the unexplored regions.

Summary

- With the dark photon produced by Drell-Yan-like mechanism, one can explore higher masses, unlike the meson decay mechanism which is restricted by the mass of the meson.
- Optimization can be done by reducing the size or changing the magnetic field of focusing magnet since these are low mass events.
- A new experiment, E1067 has been proposed to take 2 years of parasitic data with E1039, successor of SeaQuest.



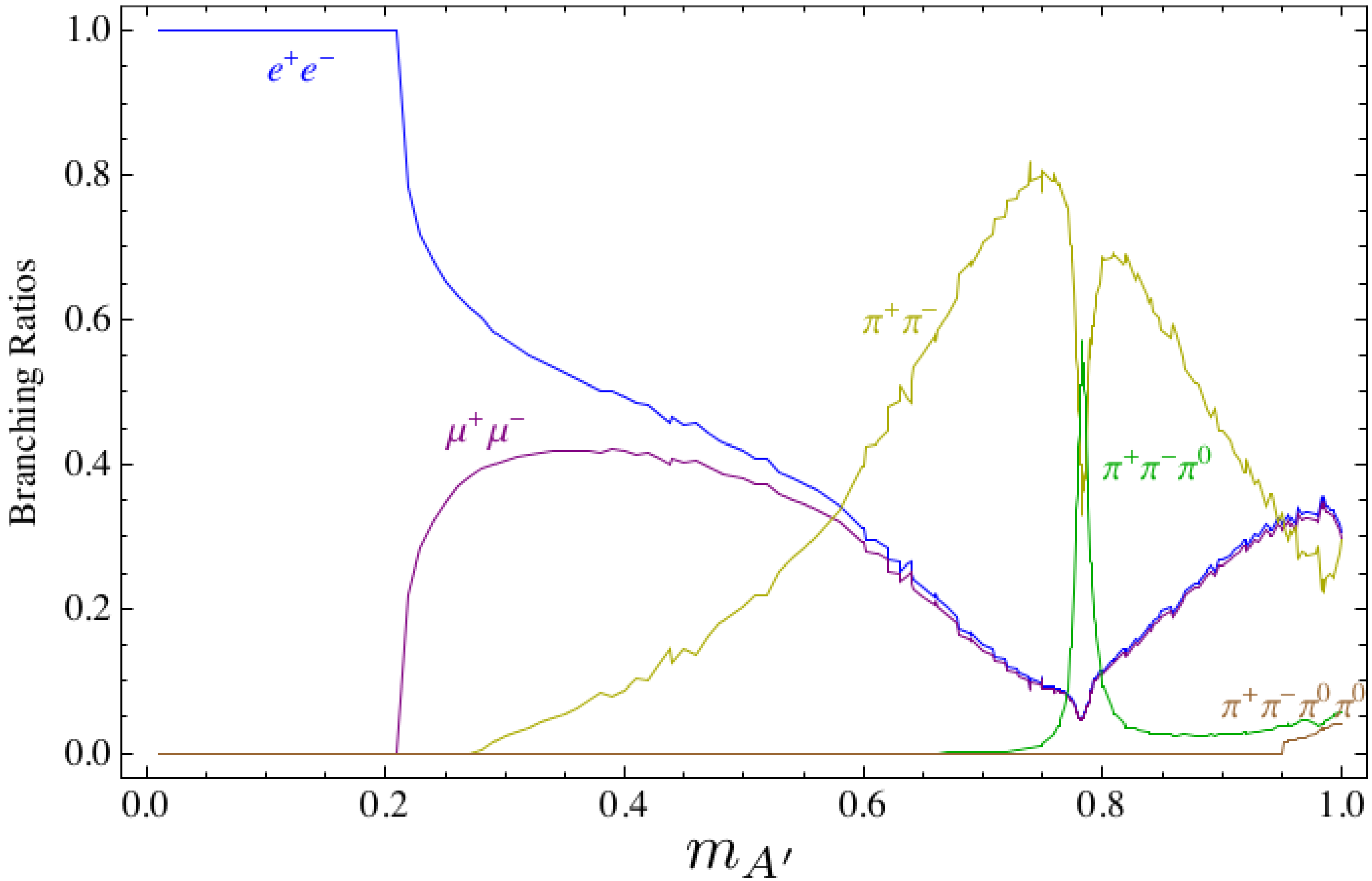
Thank you.

Backup slides

Branching ratio

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

D. Curtin, et al, arXiv: 1312.4992



Cross section derivation

$$\hat{\sigma} = \frac{4\pi\alpha^2\epsilon^4}{3}\frac{\hat{s}}{(\hat{s}-M_A^2)^2+M_A^2\Gamma_A^2} \tag{14}$$

In narrow width approximation

$$\frac{1}{(\hat{s}-M_A^2)^2+M_A^2\Gamma_A^2} \simeq \frac{\pi}{M_A\Gamma_A}\delta(s-M_A^2) \tag{15}$$

So,

$$\hat{\sigma} = \frac{4\pi^2\alpha^2\epsilon^4}{3}\frac{\hat{s}}{M_A\Gamma_A}\delta(\hat{s}-M_A^2) \tag{16}$$

Total cross section is convolution of σ with quark densities, including color factor of 1/3

$$\sigma = \frac{1}{3}\int_0^1 dx_1 \int_0^1 dx_2 \sum q(x_1, M_A^2)\bar{q}(x_2, M_A^2)\hat{\sigma} \tag{17}$$

$$dx_1 dx_2 = \frac{d\hat{s}dy}{s} \qquad dy = \frac{dx_F}{x_1+x_2}$$

$$\frac{d\sigma}{dx_F} = \frac{4\pi^2\alpha^2\epsilon^4}{9}\frac{1}{M_A\Gamma_A}\frac{x_1x_2}{x_1+x_2}\sum Q^2 q(x_1, M_A^2)\bar{q}(x_2, M_A^2)$$

If one substitutes for Γ_A as $\frac{N_{eff}m_A\alpha\epsilon^2}{3}$

$$\frac{d\sigma}{dx_F} = \frac{4\pi^2\alpha\epsilon^2}{3N_{eff}M_A^2}\frac{x_1x_2}{x_1+x_2}\sum Q^2 q(x_1, M_A^2)\bar{q}(x_2, M_A^2)$$

Dark Higgs