Implications of and Search for a Heavy Photon: a new gauge forces, dark photons, dark matter …

part II

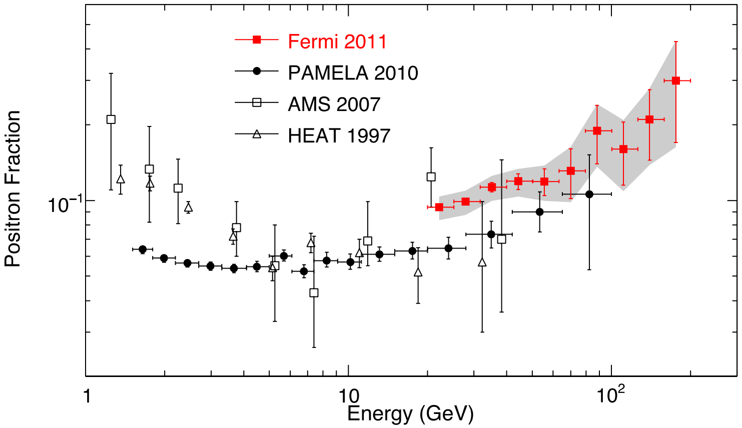
S. Stepanyan, Jefferson Lab

From yesterday

- There are intriguing evidences for the existence of a massive photon-like particle, charged under a new U(1) symmetry. Through kinetic mixing it can obtain a mili-charge, εe, and interact with EM current

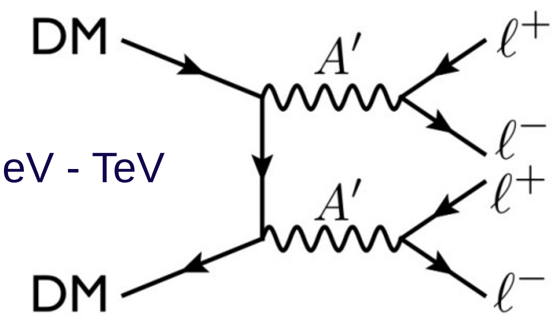
- Such a particle is natural on very general theoretical grounds and may explain some SM anomalies (could be viable solution for the muon g-2 discrepancy)

- The heavy photon would be produced in electron bremsstrahlung off heavy targets, albeit at rates strongly suppressed compared to production of virtual photons of the same mass



Annihilation of particle DM in galactic halo

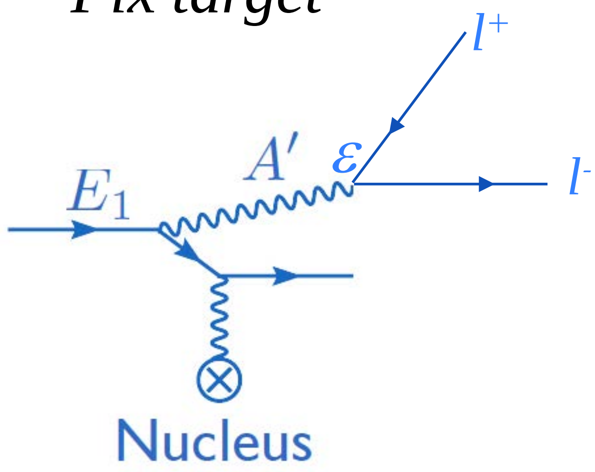
GeV - TeV



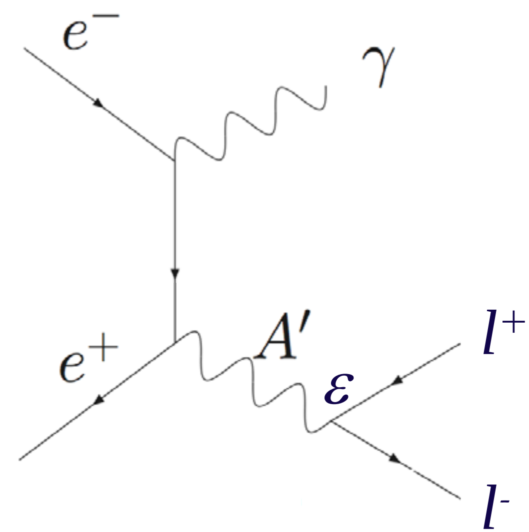
MeV - GeV

Direct searches for heavy photon: $A' \to l^+ l^-$

Fix target | *Beam dump* | *Collider*



[long baseline]



$$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$$

O ab^{-1} per day

$$\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10\ fb)$$

O ab^{-1} in years

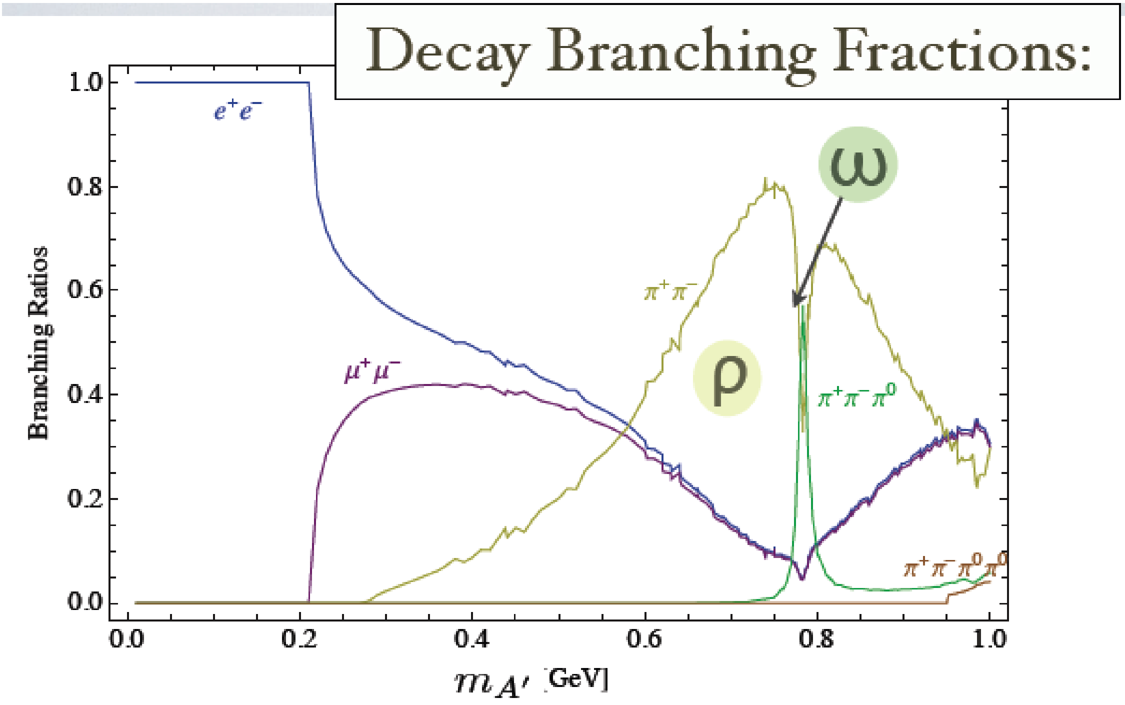
J. D. Bjorken, R. Essig, Ph. Schuster, N. Toro (PR D80, 2009)
R. Essig, Ph. Schuster, N. Toro (PR D80, 2009)

Where and how to search for dark photons

Both “naturalness” arguments and fits to astrophysical data suggest

$$\alpha' / \alpha \equiv \varepsilon^2 \sim 10^{-4} - 10^{-10}$$

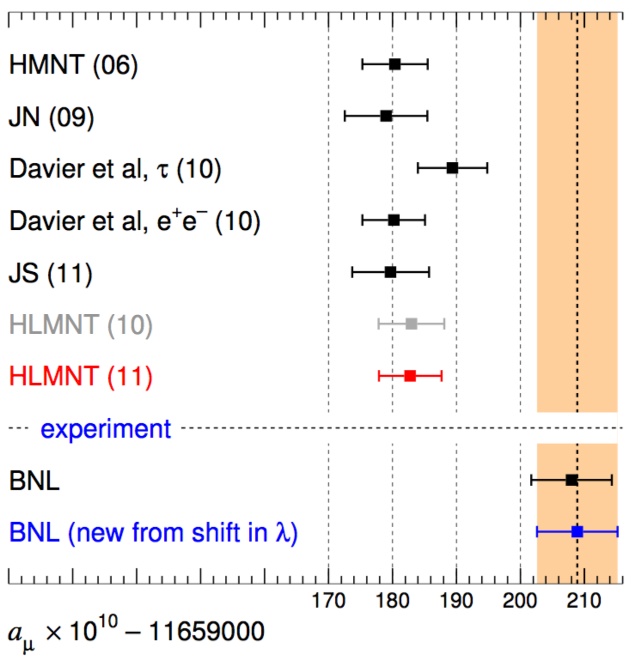
$$m_{A'} \sim \text{MeV - GeV}$$

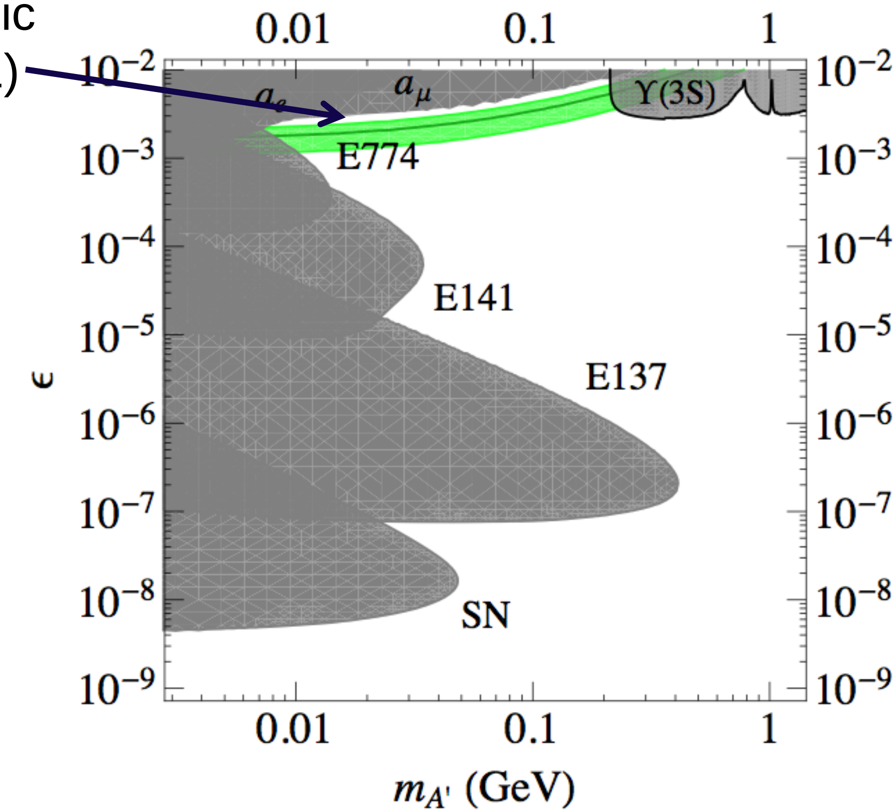


Limit from muon g-2 discrepancy

Muon anomalous magnetic moment (g-2) -
3.2σ discrepancy between theory and experiment

Could be due to uncertainties in hadronic contribution, or due to an additional U(1)

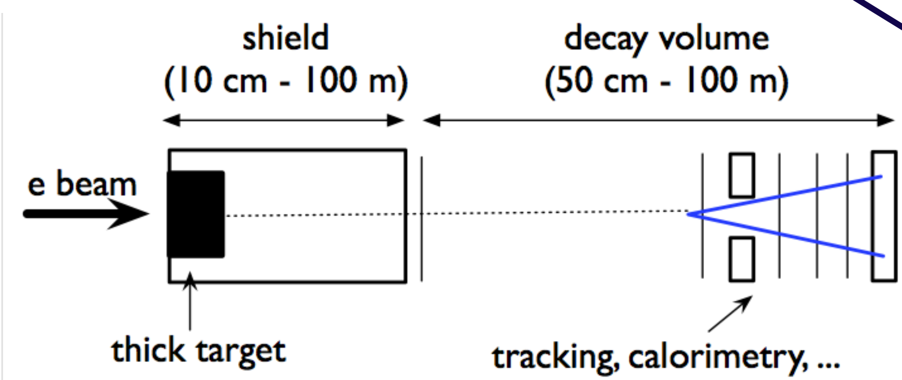


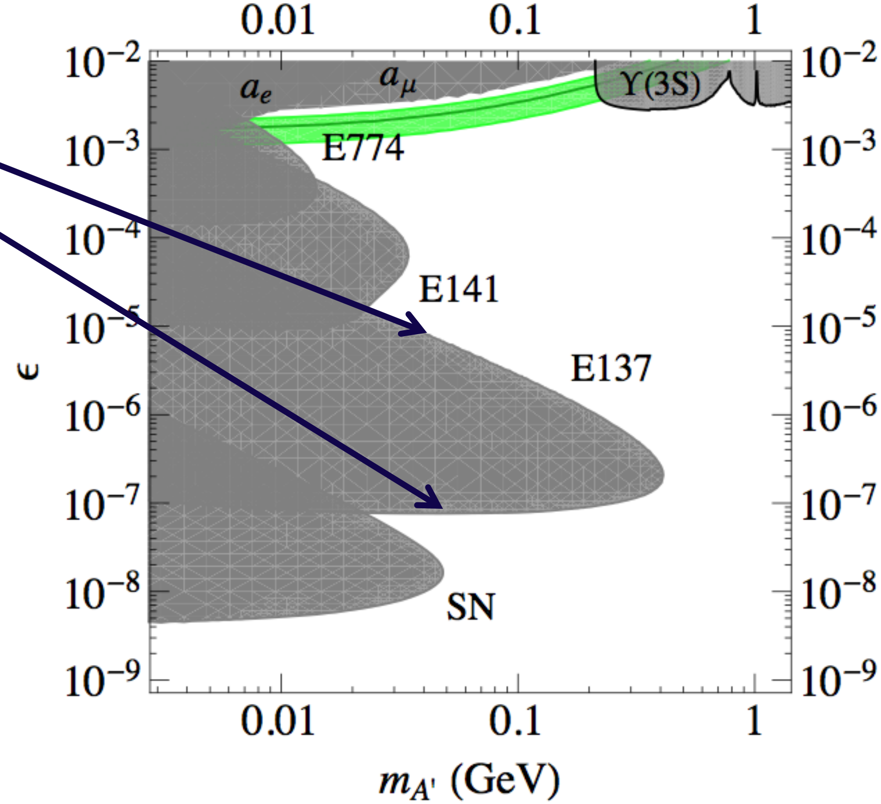


G. Venanzoni, arXiv:1203.1501v1 [hep-ex]

Limits from beam dump experiments

Beam dump experiments -
limits are from life time and rates





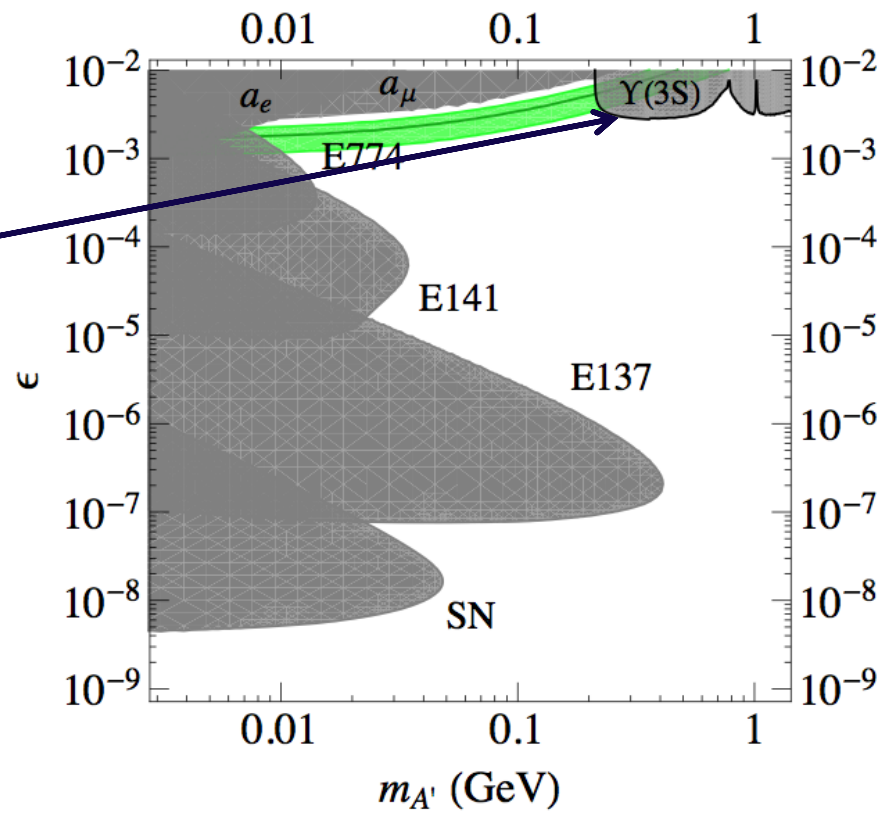
SLAC E137:	10^{20} e^- (30 C)	at 20 GeV,	200m shield
SLAC E141:	10^{16} e^-	at 9 GeV,	12 cm W target
FNAL E774:	10^{10} e^-	at 275 GeV,	20 cm W target

Limits from colliders, BaBar Υ(3S)

No statistical significant signal was found for radiative decay of Y(3S), M=10.355 GeV, to a scaler Higgs state A^0. Upper limit for branching fraction (90% c.l.) – $BF_{EFF} = BF(Y(3S) \rightarrow \gamma A^0) \times BF(A^0 \rightarrow \mu^+\mu^-) < (0.25 - 5.2) \times 10^{-6}$

In radiative decay of Y(3S), A^0 is a scaler. If no decay is found at Y(3S), than $\gamma\mu^+\mu^-$ can come from anything, including vector A', a heavy photon

There are more data from BaBar on Y(4S) to be analyzed

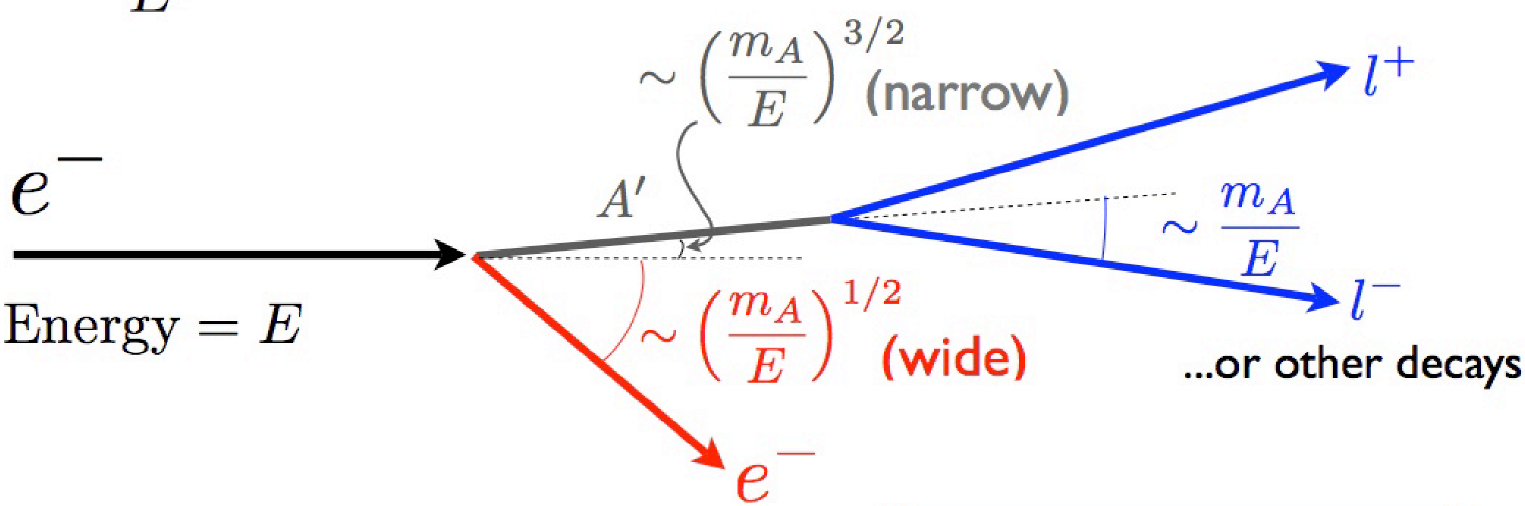


Fix target experiments: kinematics

$$\frac{d\sigma}{dx} \propto \frac{\alpha^3}{\pi} \frac{\epsilon^2}{m_e^2 \cdot x + m_A^2(1-x)/x}$$

$$x = \frac{E_A}{E}$$

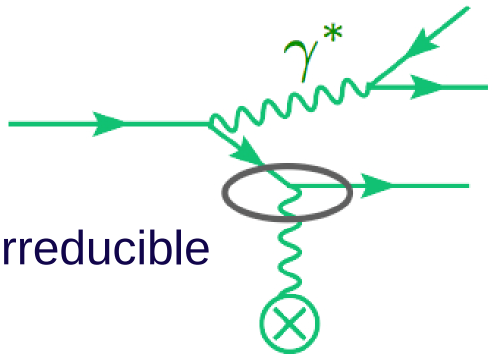
Kinematics **very different** from massless photon bremsstrahlung



Heavier product (here A') takes most of beam energy

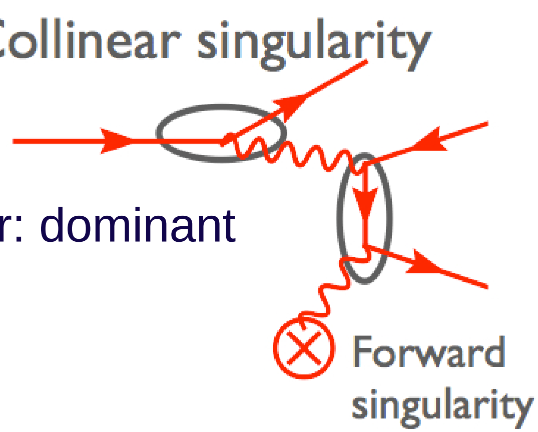
$$\boxed{\begin{array}{l} E_A \sim E - m_A \\ E_e \sim m_A \end{array}}$$

Electromagnetic background

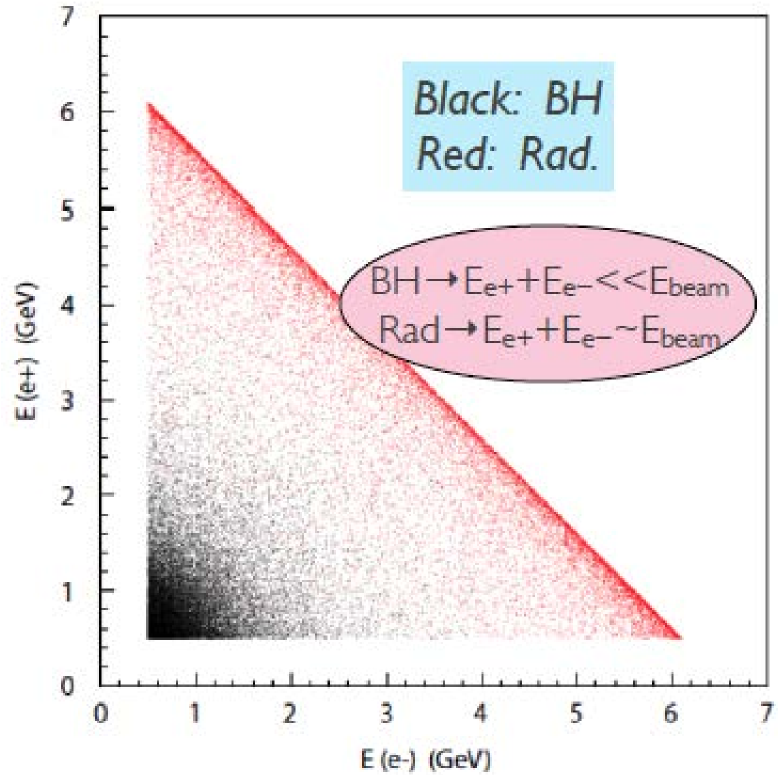


QED tridents: irreducible

$$\frac{d\sigma(e^- Z \to e^- Z(A' \to \ell^+\ell^-))}{d\sigma(e^- Z \to e^- Z(\gamma^* \to \ell^+\ell^-))} = \left(\frac{3\pi\epsilon^2}{2N_{\text{eff}}\alpha}\right)\left(\frac{m_{A'}}{\delta m}\right)$$

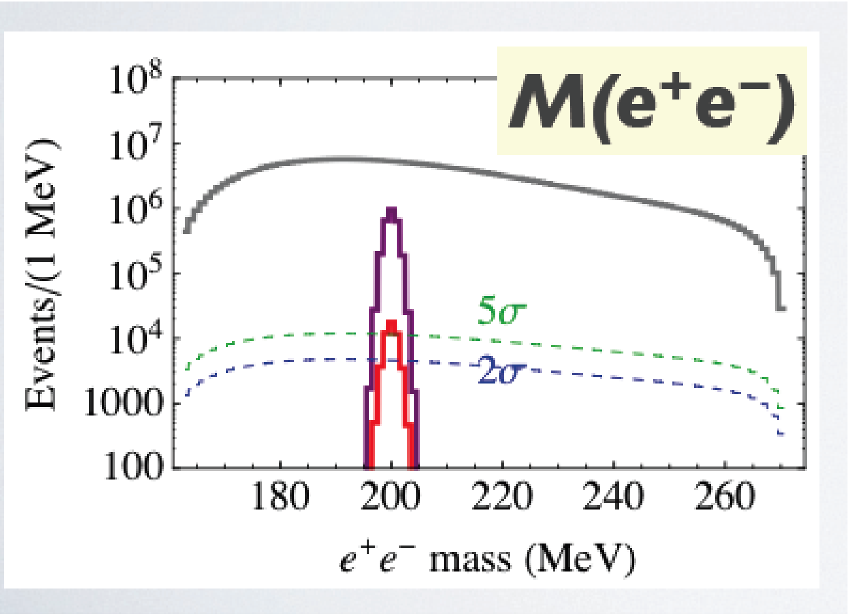


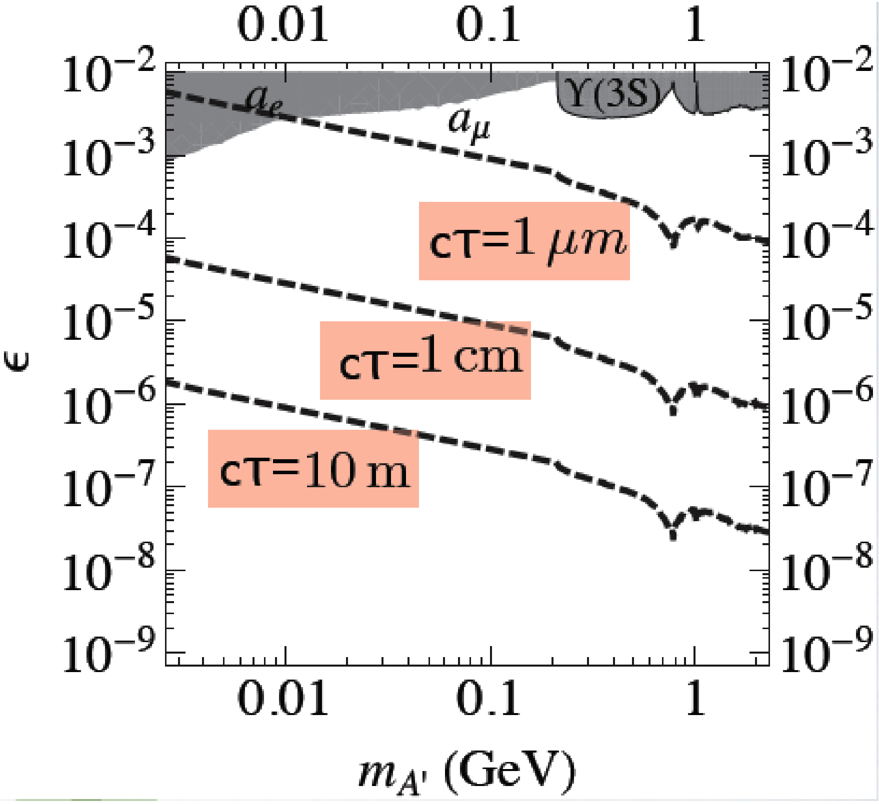
Bethe-Heitler: dominant



Bump hunt and vertexing

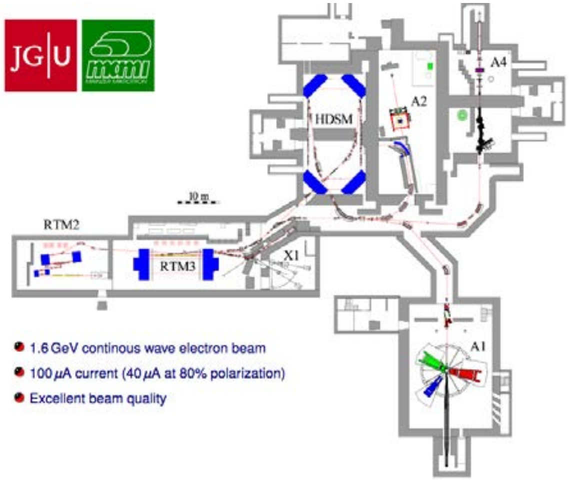
- QED tridents will be produced at Z=0 and will not produce a peak in M(e$^+$e$^-$)
- A' decays can extend to large Z and will produce a narrow peak in M(e$^+$e$^-$)





Excellent mass and vertex resolutions are needed

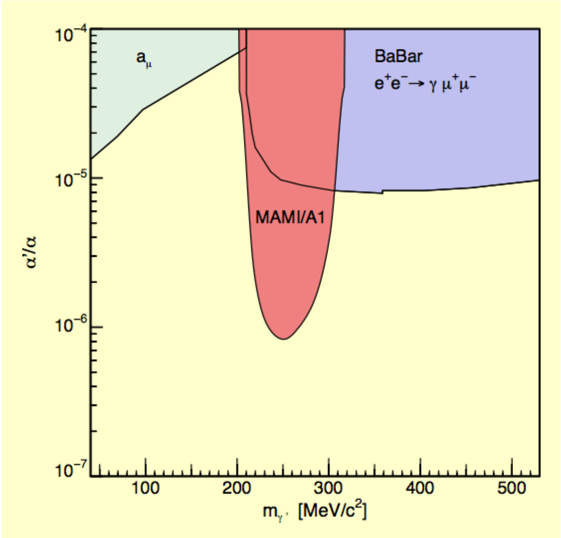
e-Accelerator based searches: Mianz

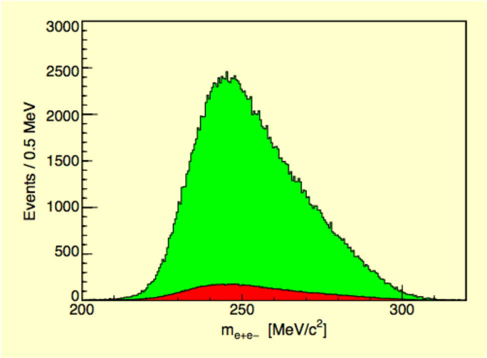


Spectrometer A:
$\alpha > 20^\circ$
$p < 735\,\frac{\mathrm{MeV}}{c}$
$\Delta\Omega = 28\,\mathrm{msr}$
$\Delta p/p = 20\%$

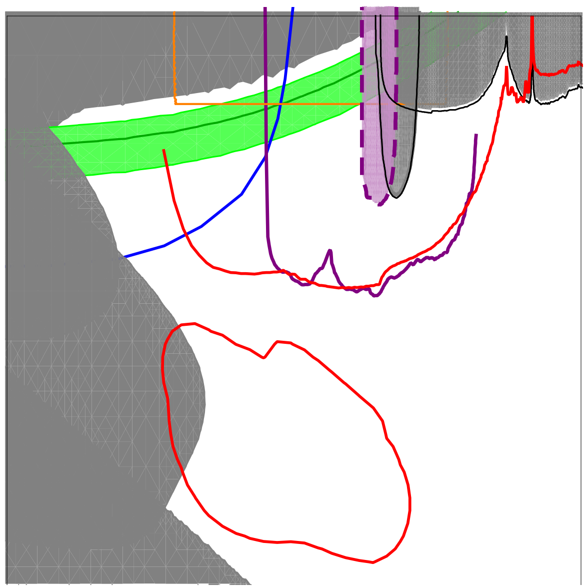
Spectrometer B:
$\alpha > 8^\circ$
$p < 870\,\frac{\mathrm{MeV}}{c}$
$\Delta\Omega = 5.6\,\mathrm{msr}$
$\Delta p/p = 15\%$

Spectrometer C:
$\alpha > 55^\circ$
$p < 655\,\frac{\mathrm{MeV}}{c}$
$\Delta\Omega = 28\,\mathrm{msr}$
$\Delta p/p = 25\%$





Experiments at Jefferson Lab



APEX - uses 1-4 GeV, 150μA electron beam incident on 0.5-10% r.l.. The *e+e−* pairs from the produced *A′* decay will be detected using the Hall A spectrometers at small angles, $\theta \simeq 5^\circ$

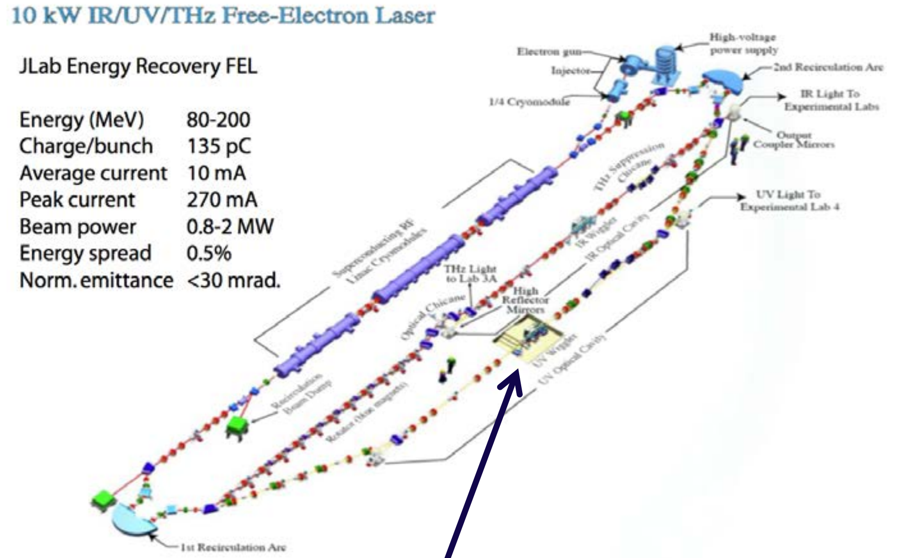
DarkLight - extends the search for *A′* to lower mass values, down to $\sim$ 10 MeV. Experiment utilizes the FEL high intensity (10 mA) electron beam at 140 MeV, incident on a 10^{19} cm^{-2} gas hydrogen target

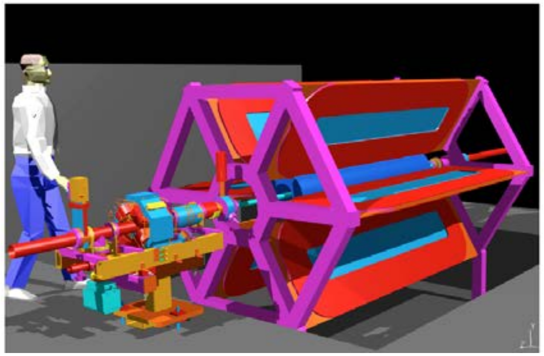
HPS – will detect *A′* decay products, e^+e^- or $\mu^+\mu^-$, at very small production angles, 15mrad. Will perform both bump hunting and dethatched vertex search to get regions of a smaller coupling

Dark Light – at Free Electron Laser facility

- Background reduction by requiring full reconstruction of $e^- + p \rightarrow e^- + p + e^+ + e^-$
- 1 MW 100 MeV FEL electron beam gives 10 mA or $1.6 \times 10^{17} e^-/s$
- Hydrogen gas target with areal density of $10^{19}/cm^2$
- Lepton spectrometer with momentum resolution to reach
- $\sigma_{me+e-} < 1 MeV/c^2$
- Proton detector to identify ~2 MeV recoil proton and measure it momentum with 10% precision.

The FEL can deliver 1/ab of beam in one month of continuous running.



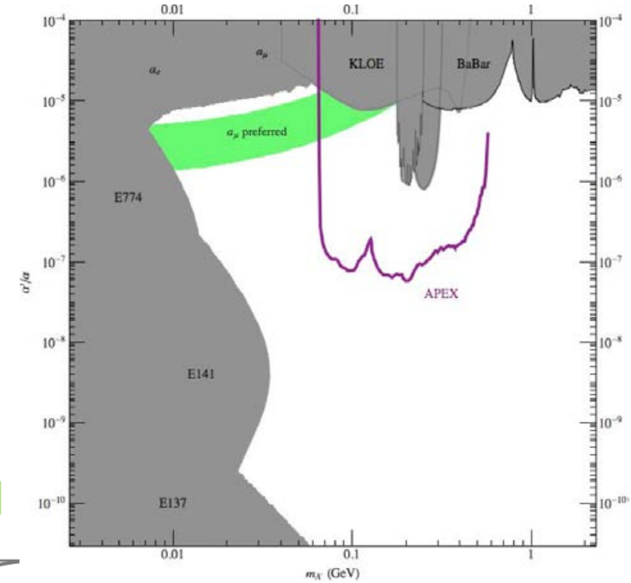


Toroidal magnet

APEX in Hall-A

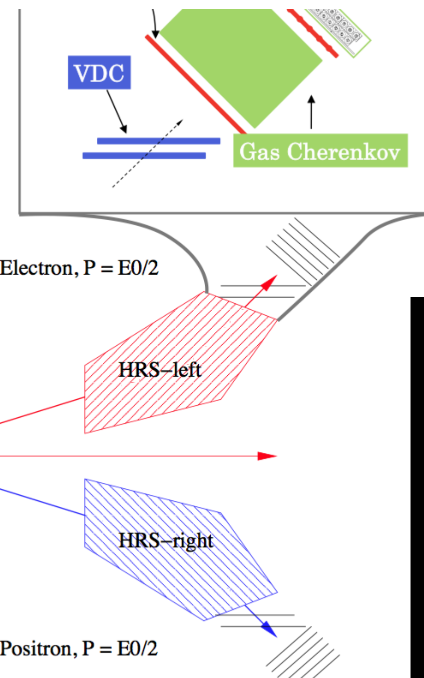
Scan the parameter space by running at various beam energies and spectrometer settings

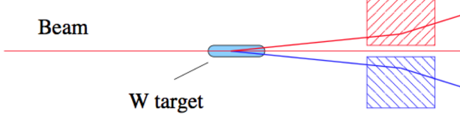
Total beam time: ~34 days



Momentum acceptance	$(\delta p/p)$	$\pm 4.5\%$
Angular acceptance :	Horizontal	± 30 mrad
	Vertical	± 60 mrad
Min. central angle		$12.5°$

Horizontal angular resolution sets scale of mass resolution at ~0.5%





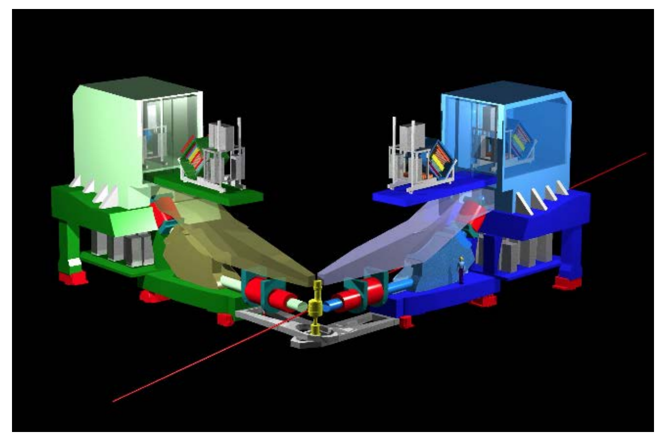
With septa:

5° central angle $m \sim E_{beam}\theta_0$

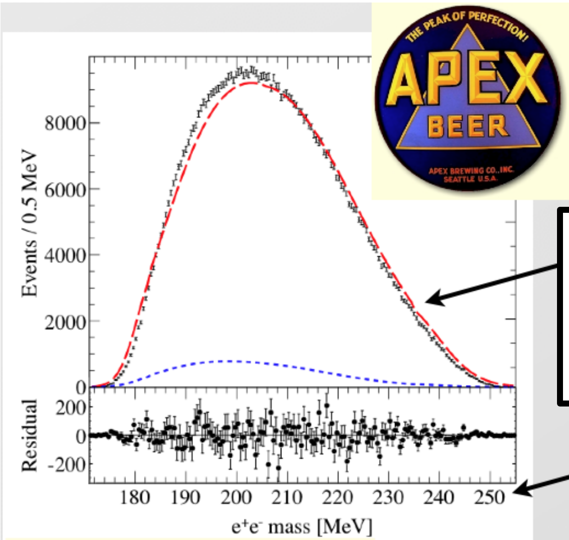
Maximizes **angular acceptance**

4 settings to explore factor of 10 in A′ mass, with beam energies roughly1-4 GeV

(higher energies: no existing septum, lower cross-section, more π background)



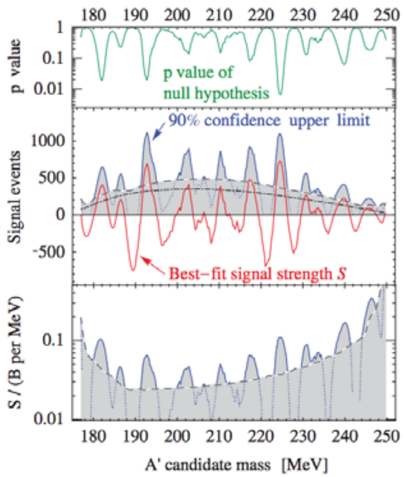
APEX test run

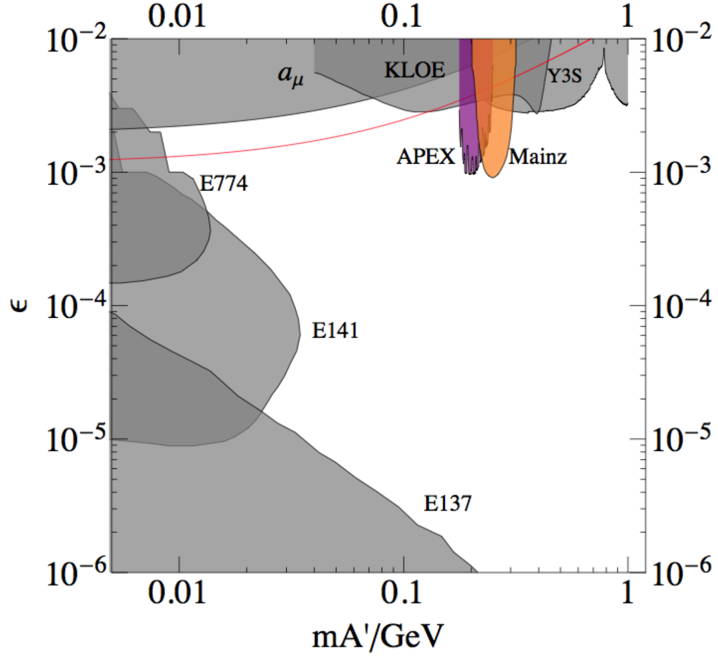


Phys. Rev. Lett. 107 (2011) 191804.

Data taken at 2.2GeV on X0~0.3% Ta target
Mass resolution σ~1 MeV

- black points→data
- red→MC (madgraph)
- blue→e+e− accidentals





Experiment in Hall B – high statistics search for

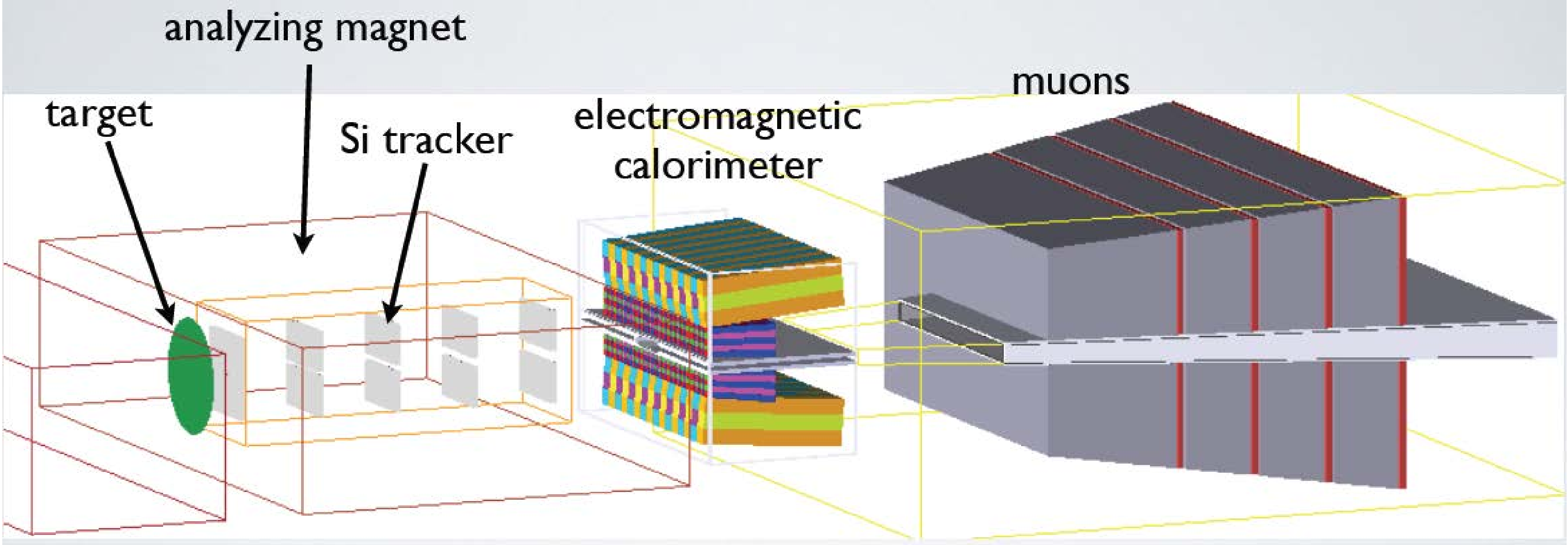
$A' \rightarrow l^+ l^-$ (e^+e^- or $\mu^+\mu^-$)

Bump hunt and vertexing

Heavy Photon Search experiment

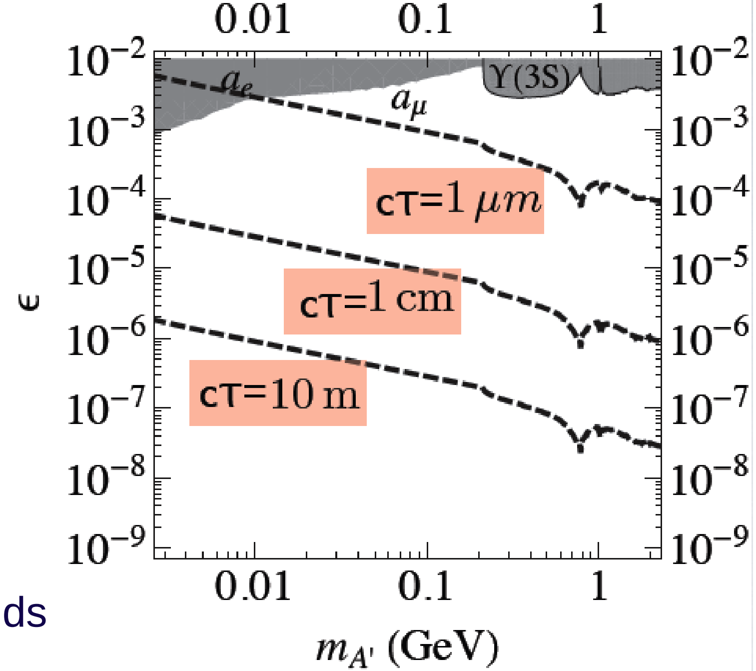
- Thin, 4μm W target positioned 10 cm before the tracker
- Compact Si-microstrip tracker/vertexer in 1T analyzing magnet
- Fast, segmented Ecal for triggering, e ID
- Muon detector for alternate trigger, muon ID

All detectors are split vertically to avoid "wall of flame" occupied by primary beam degraded electrons, bremsstrahlung photons, etc.

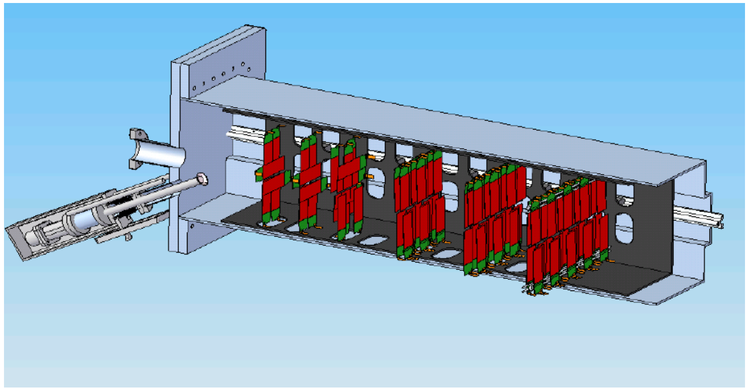


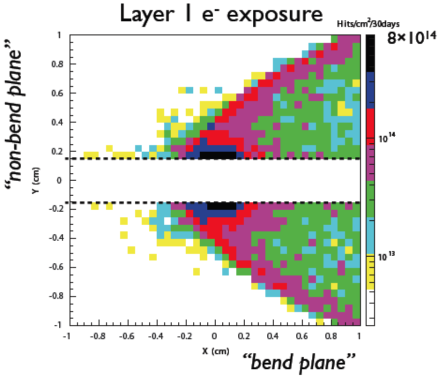
Goal: access low and intermediate ε ranges

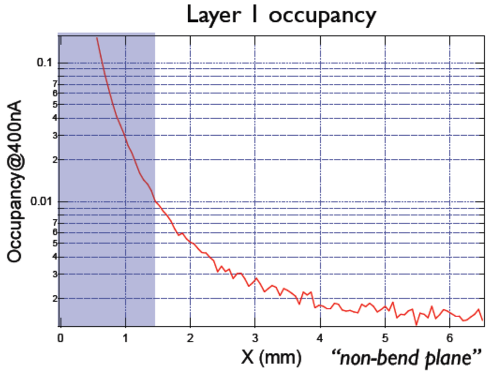
- Search for A' in a wide mass range 20-500 MeV at $\varepsilon > 3\times10^{-4}$ in bump hunting
- Cover the low coupling, $\varepsilon < 10^{-4}$, for intermediate mass (20-200 MeV) region
- Need a high intensity, high precision electron beams (2.2 GeV and 6.6 GeV)
- Detectors that can operate in high background environment



Entire assembly is in vacuum to minimize backgrounds

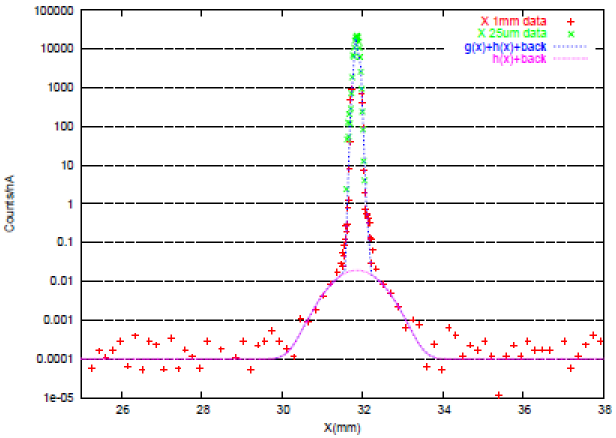


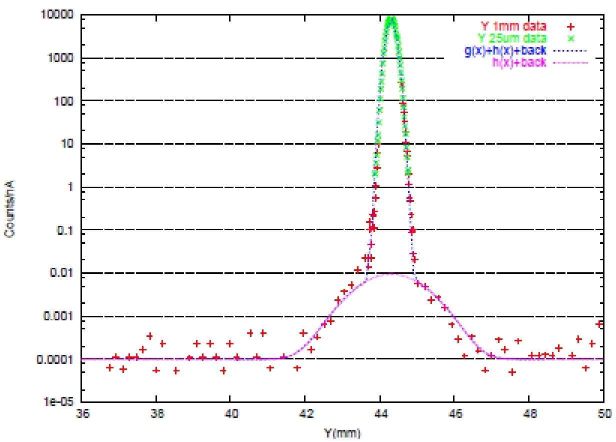




Beam size and position stability

Measured in Hall B

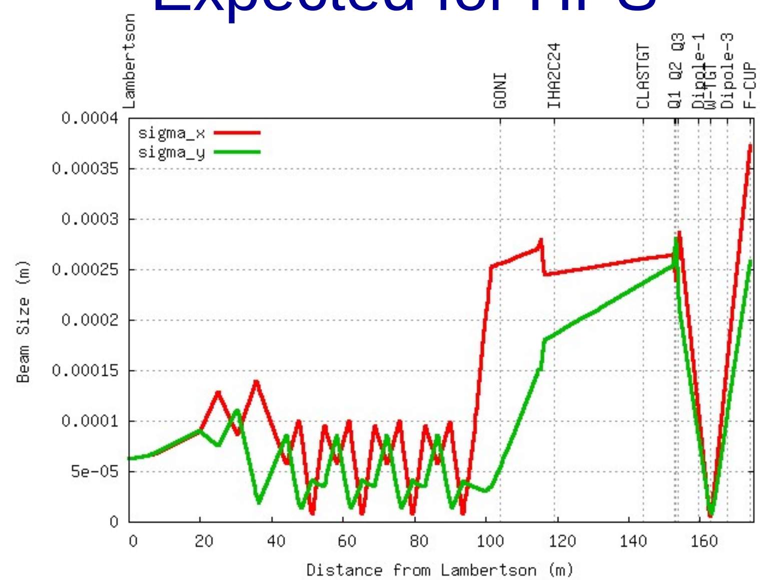




- <u>CEBAF meets Beam Requirements</u>

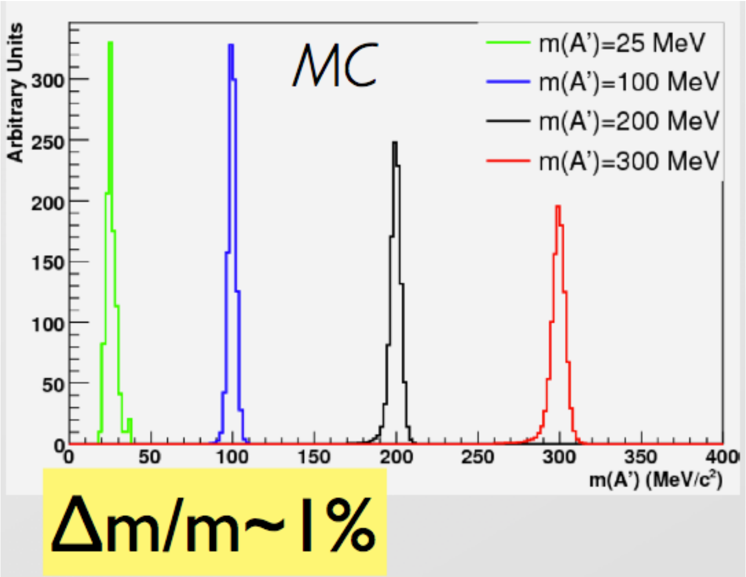
E	2.2, 6.6 GeV
$\Delta p/p$	10^{-4}
I	100-1000 nA
$\Delta I/I$	< 5%
$\sigma_{x,y}$	< 30 µm
halo	$< 10^{-5}$

Expected for HPS



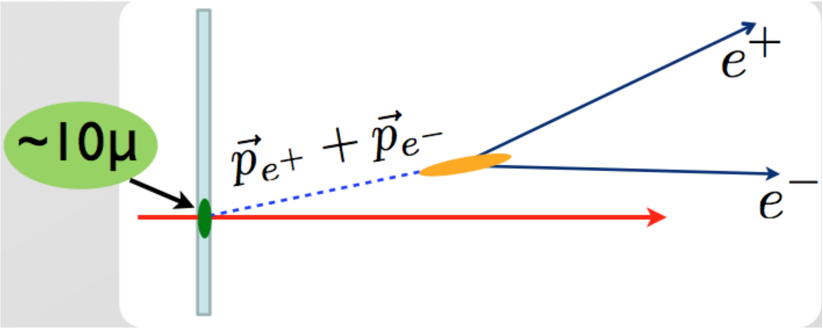
Bump hunt sensitivity

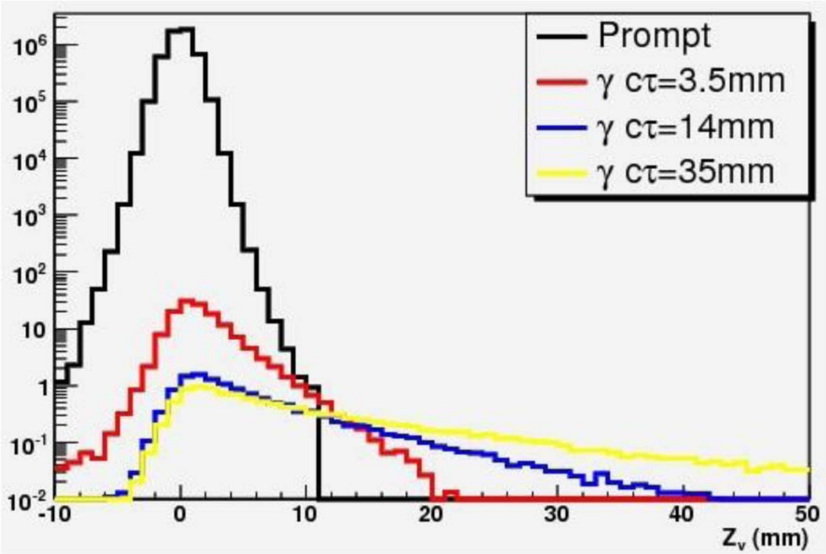
$$\frac{d\sigma\left(e^-Z \to e^-Z(A' \to l^+l^-)\right)}{d\sigma\left(e^-Z \to e^-Z(\gamma^* \to l^+l^-)\right)} = \left(\frac{3\pi\varepsilon^2}{2N_{eff}\alpha}\right)\left(\frac{m_{A'}}{\delta m}\right)$$



$$\left(\frac{S}{\sqrt{B}}\right)_{bin} = \left(\frac{N_{rad}}{N_{tot}}\right)\sqrt{N_{bin}}\left(\frac{3\pi\varepsilon^2}{2N_{eff}\alpha}\right)\left(\frac{m_{A'}}{\delta m}\right)\eta_{bin}$$

Vertexing



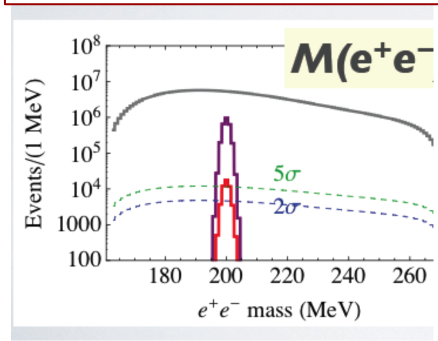


- The black curve represents the fake vertex distribution from trident events with mass in a 2.5σ window about 200 MeV
- The red and yellow curves are the vertex distributions for signal events from an 200 MeV A', with $\alpha'/\alpha \sim 10^{-8.5}$ ($\gamma c\tau$=3.5 mm) and with $\alpha'/\alpha \sim 10^{-9.5}$ ($\gamma c\tau$=35 mm) , respectively

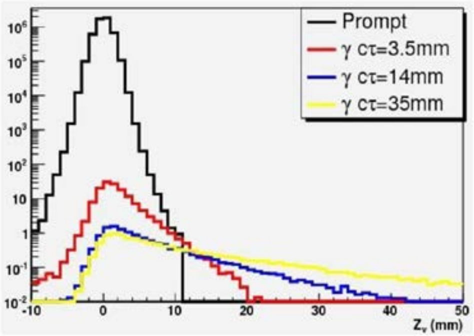
$$S_{bin} = \left(\frac{N_{rad}}{N_{tot}}\right) N_{bin} \left(\frac{3\pi\varepsilon^2}{2N_{eff}\alpha}\right)\left(\frac{m_{A'}}{\delta m}\right)\eta_{bin}(Z_{cut})$$

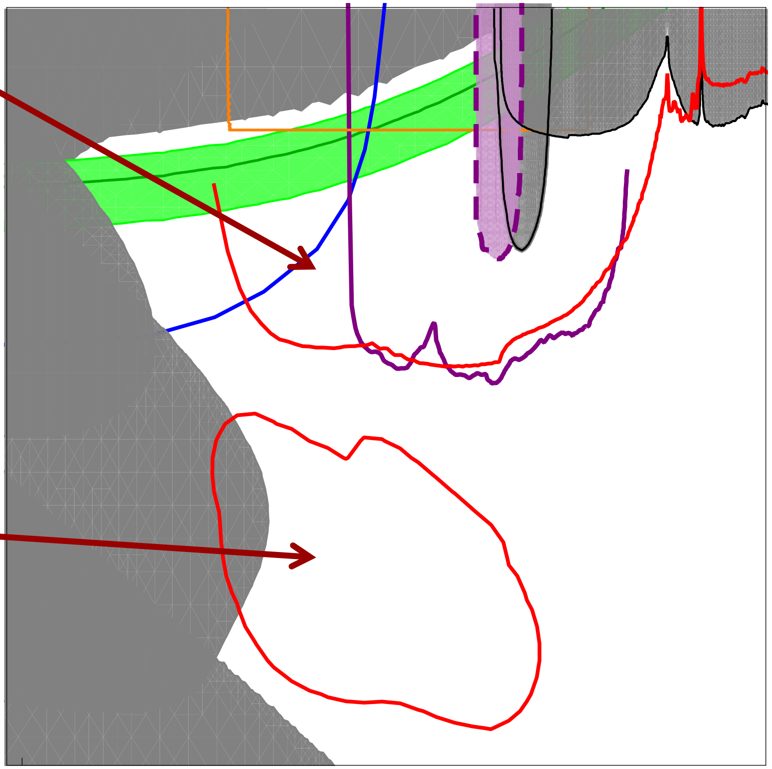
Experimental reach

Bump hunting region



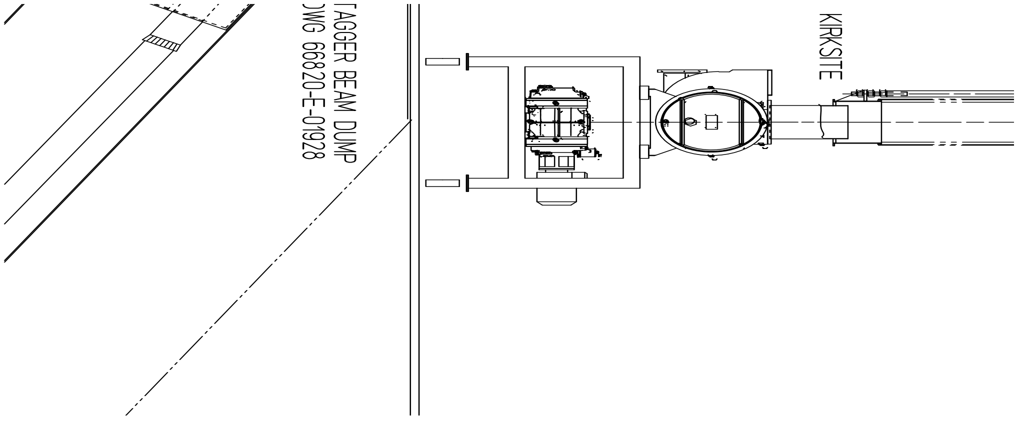
Vertexing region

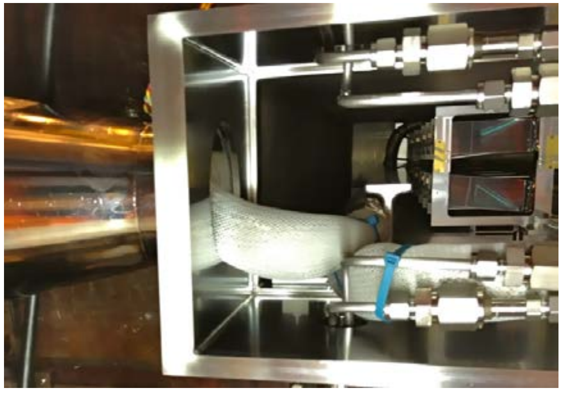




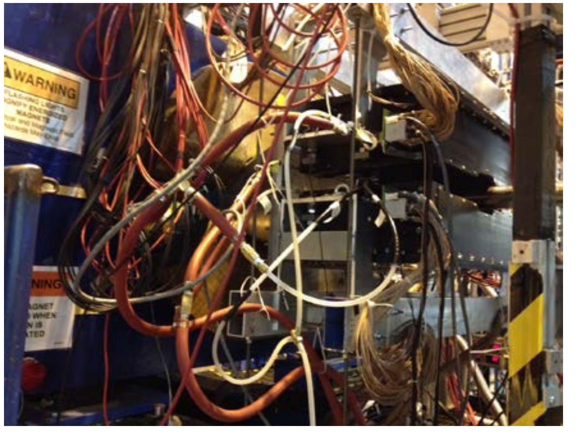
HPS progress and future plans

- Test run apparatus was designed and built in less than a year
- Parasitic tests, staged over the HDice run, were conducted to commission the test run apparatus, trigger





- Performance of the state of the art detector setup was excellent
- HPS will seek full approval from PAC39 and is ready for construction of the full detector



Summary

- Experimental searches for a massive photon like particle gained momentum after intriguing evidences that connect new boson to DM annihilation (excess of cosmic ray positrons at high energies
- If so, heavy photon can be the vector portal between SM and DM
- Subject is topical...high activity both phenomenology and experiment
- Huge parameter space is unexplored, high intensity, high precision accelerators with sensitive detectors are needed
- JLAB experiments will cover huge parameter space in mass and coupling