a place of mind

Dark Photons

Christopher Hearty
University of British Columbia/IPP
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on behalf on the BaBar collaboration

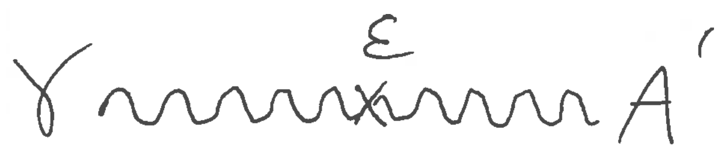
INSTITUTE OF PARTICLE PHYSICS

- Introduction
- Existing limits
- The BaBar search for dark photons
- Future projects
- Summary

- *My apologies to the groups whose work I will not have time to show today.*

Dark Sector

- Dark sector contains massive particles that carry a “dark charge”; new force moderated by a “dark photon” A′.
- A′ mixes with the ordinary photon with strength ε.

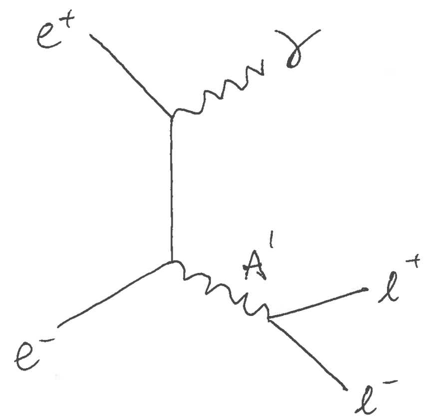


- Any process that creates a photon can create an A′

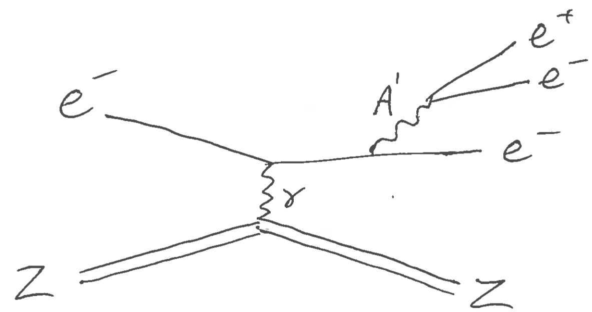
B. Holdom, Phys. Lett. B 166, 196 (1986).

- A couple of production mechanisms:

e⁺e⁻ collider



fixed target

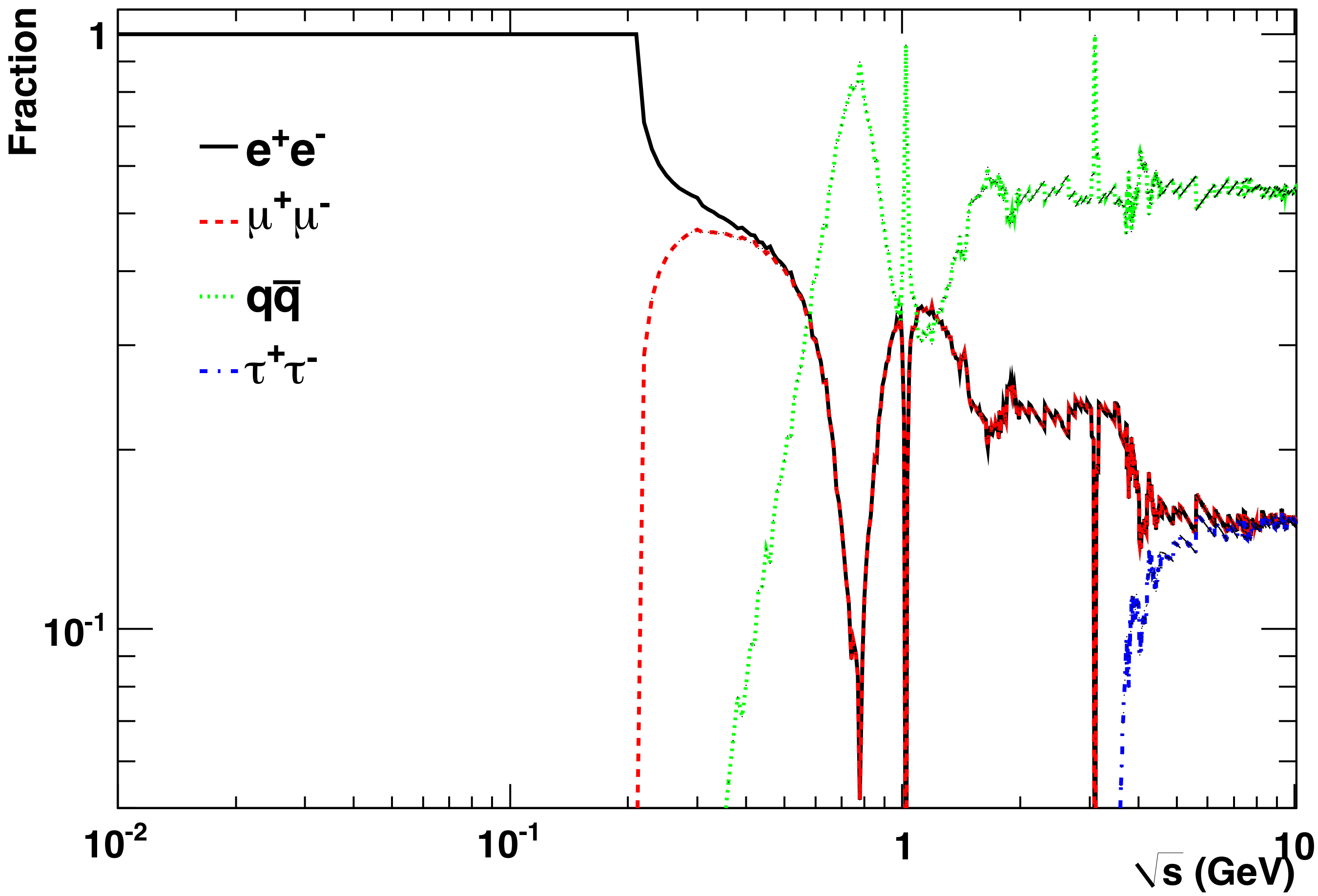


$$\sigma \propto \epsilon^2\alpha^2/E_{CM}^2 \qquad \sigma \propto \epsilon^2\alpha^3 Z^2/M_{A'}^2$$

- There are naturalness arguments that say that ε should be in the range 10^{-5}—10^{-2} and $M_{A'}$ in the range MeV—GeV.

- If the A′ is the lightest dark sector particle, it will decay to standard model fermions.

- Branching fractions are the same as a virtual photon of mass $M_{A'}$ (i.e. $e^+e^- \to \gamma^* \to X$)

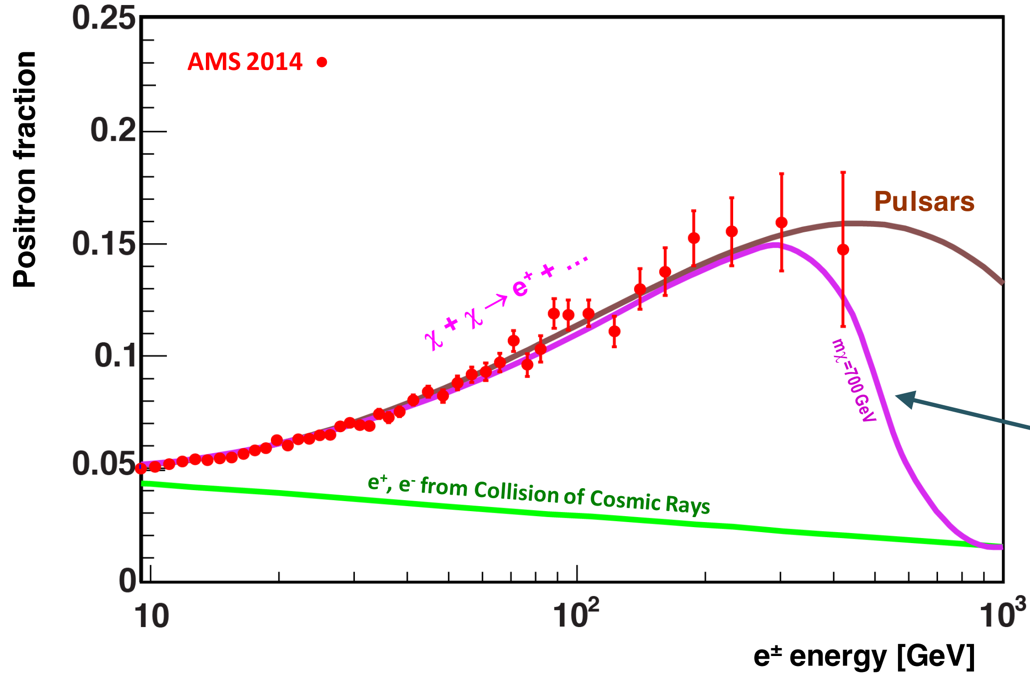


Bertrand Echenard

- Lifetime (and decay length) $\propto 1/\left(M_{A'}\epsilon^2\right)$

Connection to dark matter

- Dark matter could be TeV scale dark fermions. They would annihilate into A′ pairs, which in turn would decay to e^+e^- ⇒ astronomical excess of positrons.



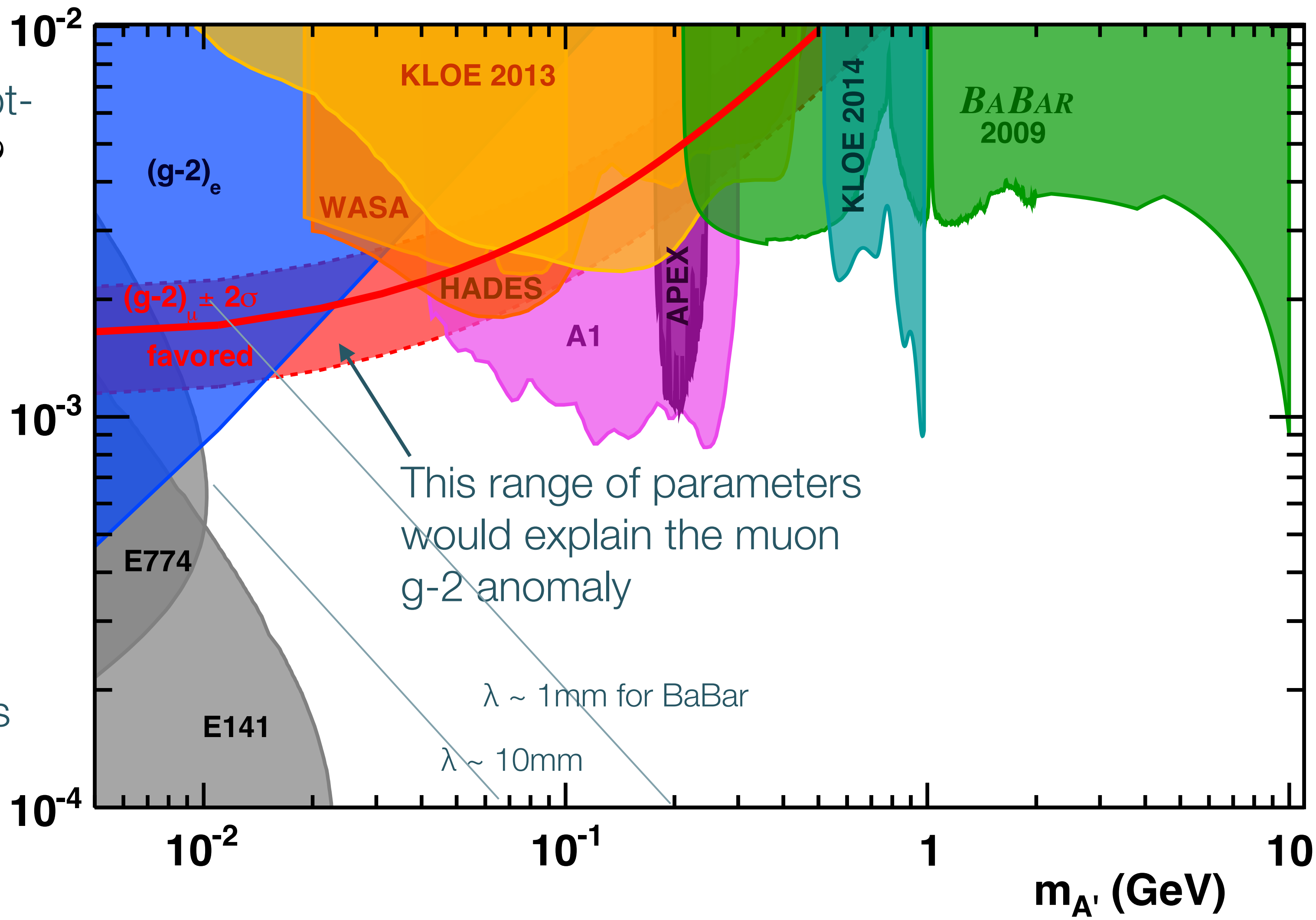
AMS-02 collaboration, Phys. Rev. Lett. 110, 141102 (2013); this plot from update at http://ams.nasa.gov/AmsScientificPublications.html

Should see rate drop above ~1/2 the dark matter mass

- No excess of anti-protons observed, which could indicate an A′ mass less than a few GeV.

Existing limits on ε and $M_{A'}$

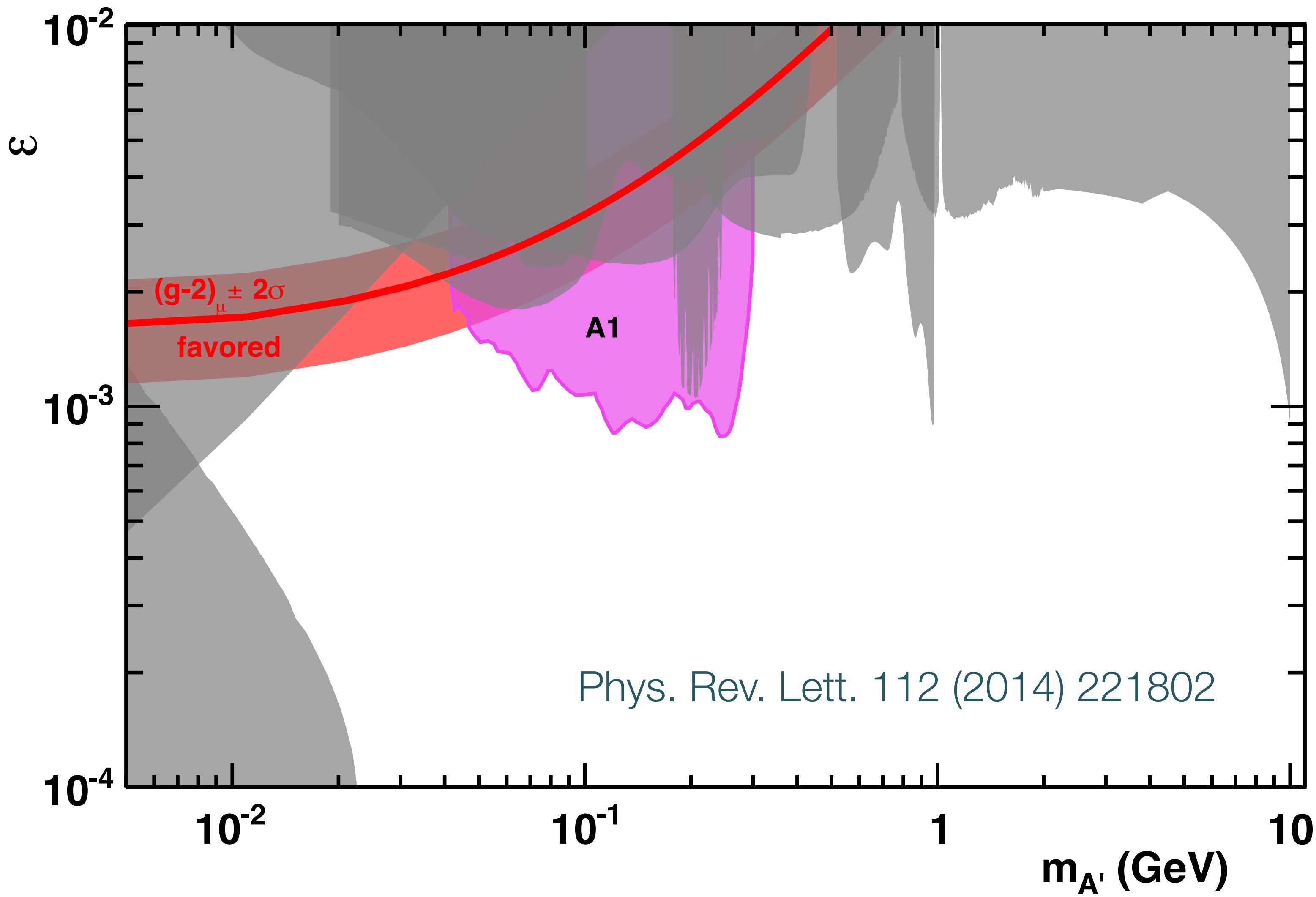
Searches for narrow peaks on large prompt-decay backgrounds



This range of parameters would explain the muon g-2 anomaly

Searches for displaced vertices (beam dumps)

A1 experiment at the Mainz Microtron (MAMI)

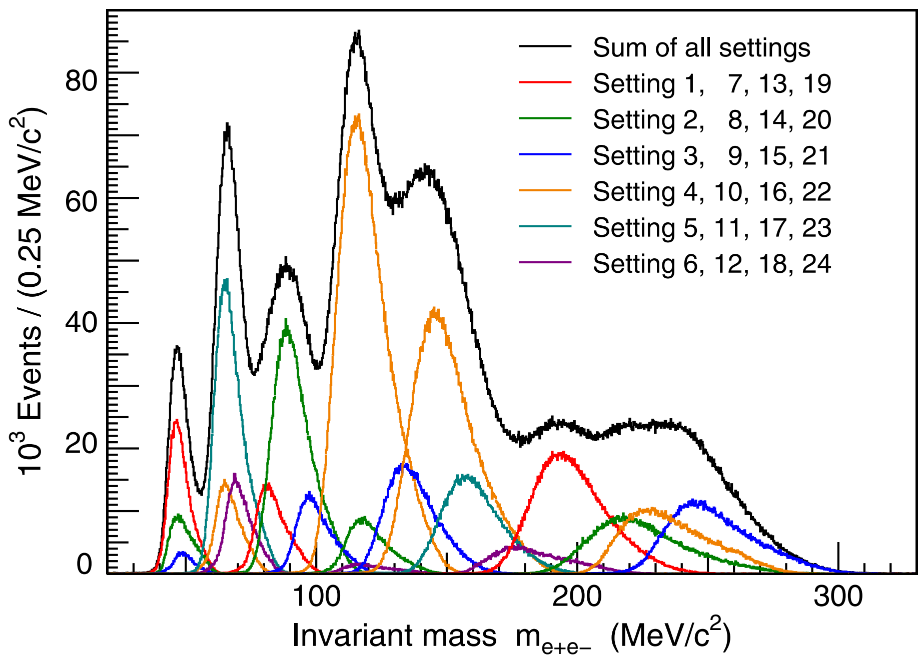


- 180—855 MeV e^- beam on tantalum foils

- Two high-resolution spectrometers. Not a 4π detector! Adjust beam energy and magnets (22 settings) to scan mass. Mass resolution ~0.1—0.4 MeV/c^2.

- Normalize to QED background:

$$R = \frac{d\sigma\left(X \to A'Y \to e^+e^-Y\right)}{d\sigma(X \to \gamma^* Y \to e^+e^-Y)} \propto \frac{\epsilon^2 M_{A'}}{\delta_M}$$



No evidence for an A′, a single bin excess on smooth QED background

BaBar search for dark photons

- $e^+e^- \to \gamma A'; \ A' \to e^+e^- \text{ or } \mu^+\mu^-$
- Reconstruct photon plus both leptons.
- Prompt decay; narrow peak on high backgrounds.

Low mass region, $M_{A'} < 220$ MeV/c^2

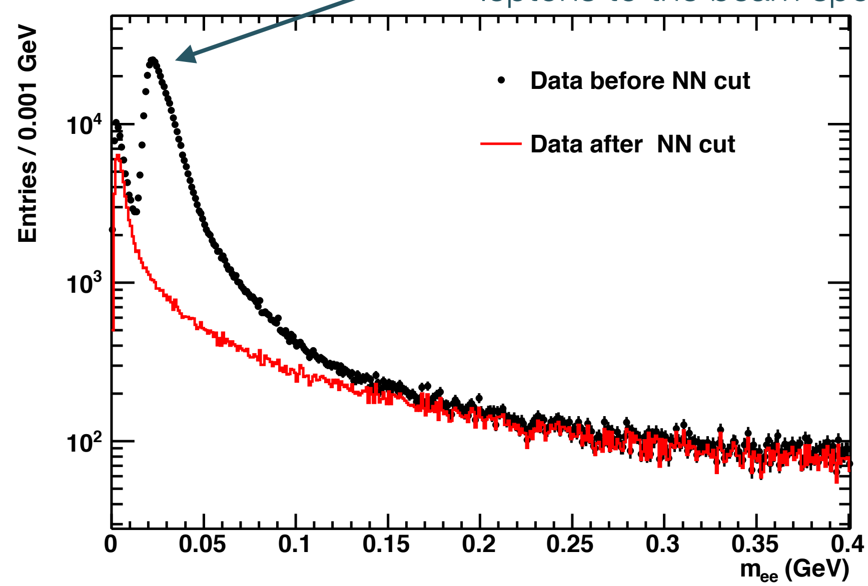
- Decays to e^+e^- only. Several challenges:

- Factor of 2 loss of efficiency due to trigger scaling.

- Large peaking background from $e^+e^- \rightarrow \gamma\gamma$, where one γ converts in detector material to e^+e^-.

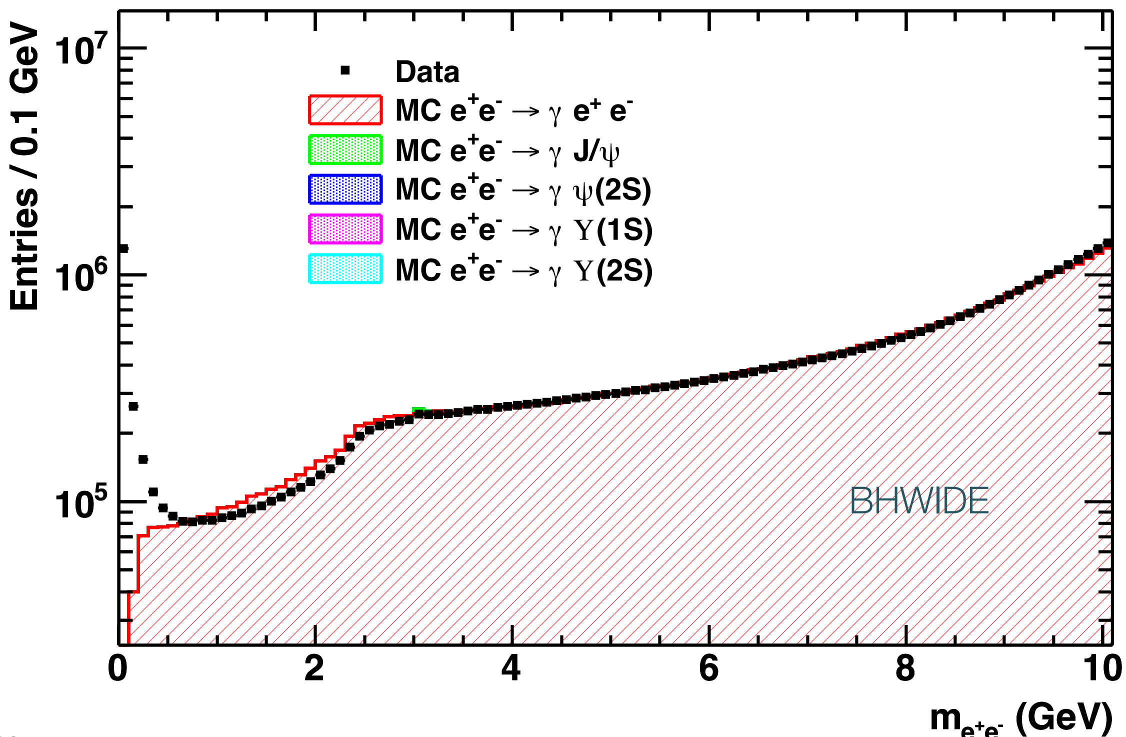
- Suppress with neural net; flight length + event topology

conversion peak is shifted by kinematic fit, which constrains the leptons to the beam spot



- Event generator (BHWIDE) does not simulate the low-mass region, where the two electrons are nearly co-linear. (MADGRAPH does a good job).
  - Signal extraction does not rely on MC prediction.

Final mass distribution of A′ candidates in electron final state



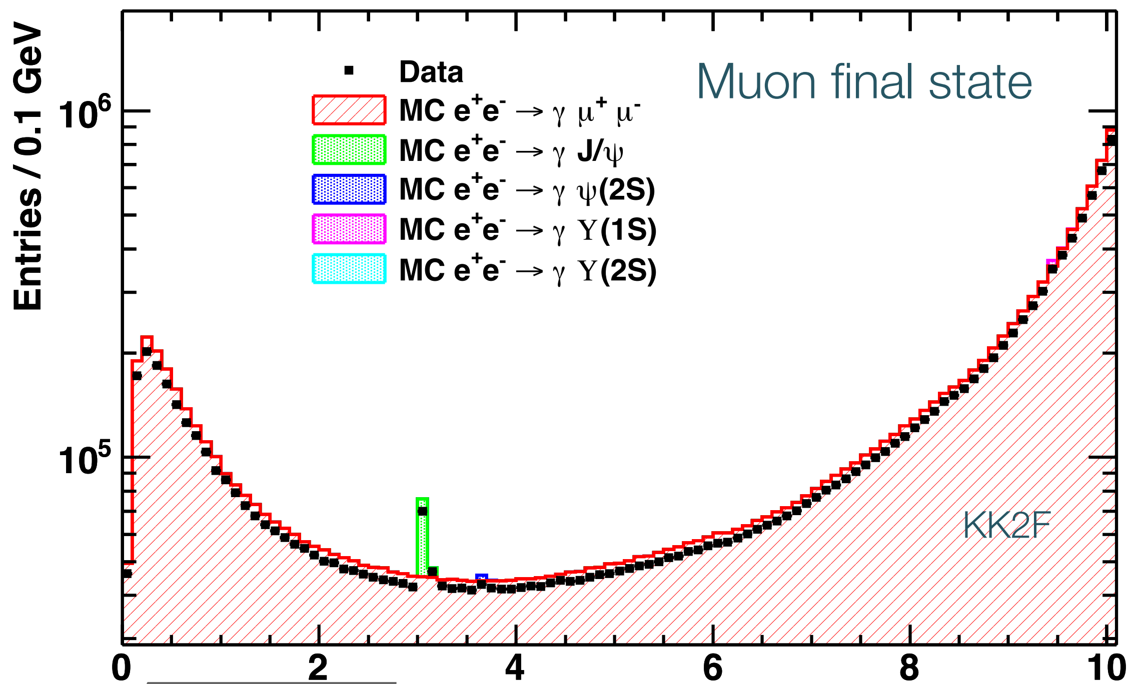
High mass region $0.22 < M_{A'} < 10.2$ GeV/c^2

- Sensitivity is completely dominated by muon final state. Better efficiency and lower backgrounds.

- Peaking backgrounds from initial-state radiation of vector states, e.g.

$$e^+e^- \to \gamma J/\psi;\ J/\psi \to \mu^+\mu^-$$

- no limits in ω, ϕ, J/ψ, ψ(2S), Υ(1S), Υ(2S) mass regions.

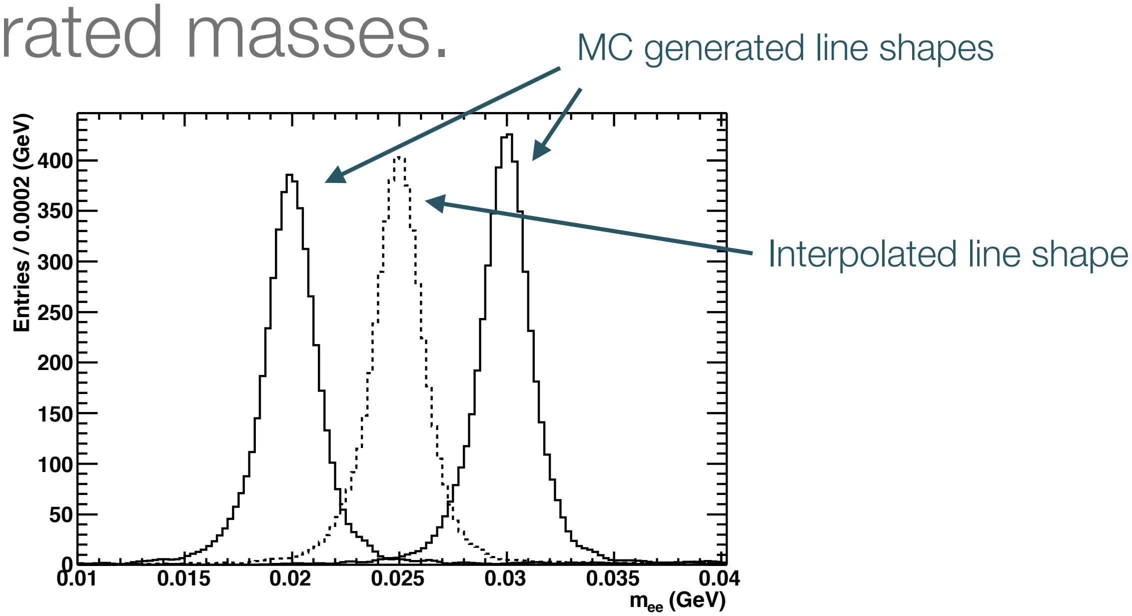


$$m_R \equiv \sqrt{m_{\mu\mu}^2 - 4m_\mu^2}$$

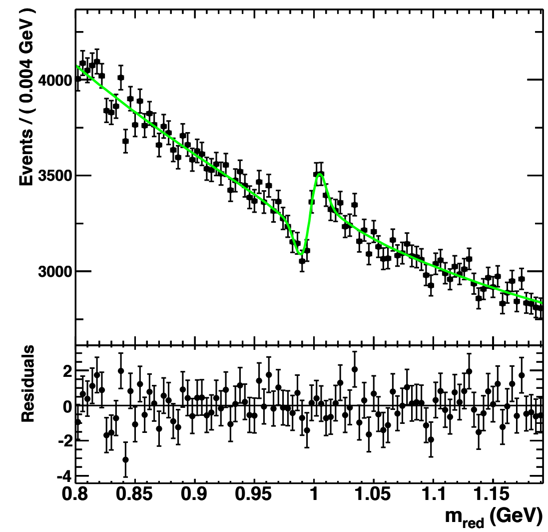
smoother behavior at threshold

Signal extraction

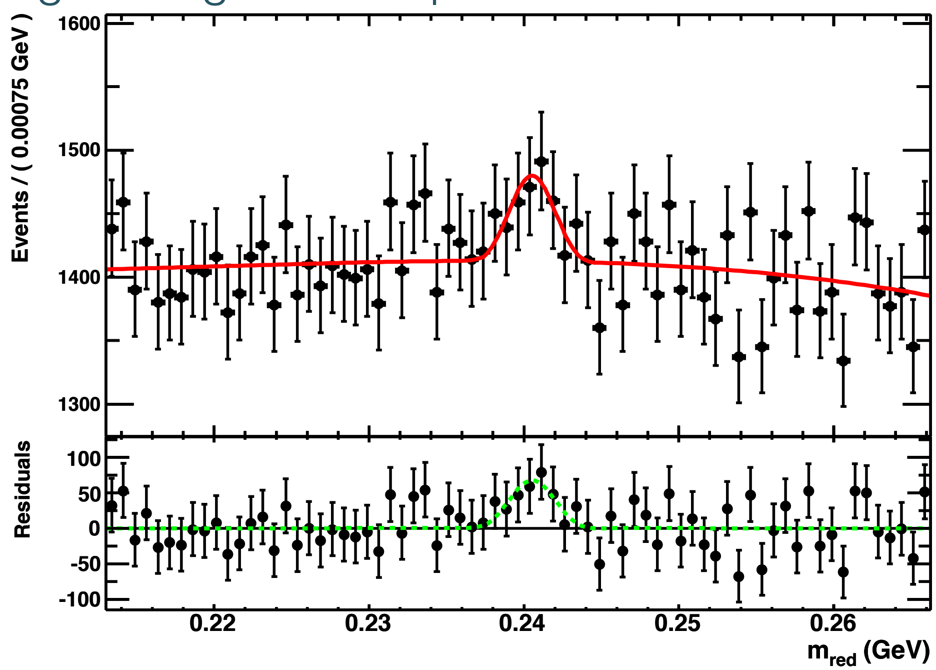
- Fit ±10x mass resolution around each A′ mass hypothesis (5704 for e^+e^-, 5370 for $\mu^+\mu^-$).
  - Resolution 1.5—8 MeV/c^2
- PDF shape for signal from MC; interpolate between generated masses.



- Polynomial for smooth background;
- Crystal ball/Gaussians for peaking background;
- Interference terms at the ω and ϕ.

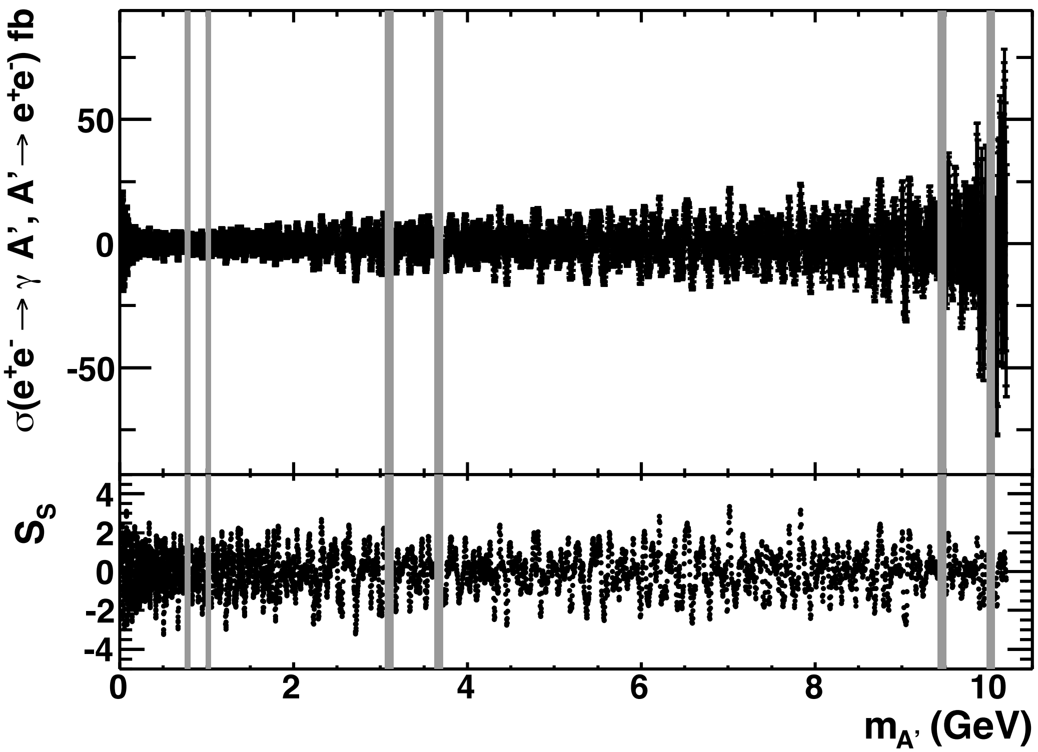


Highest significance peak in the muon final state



Data minus background fit

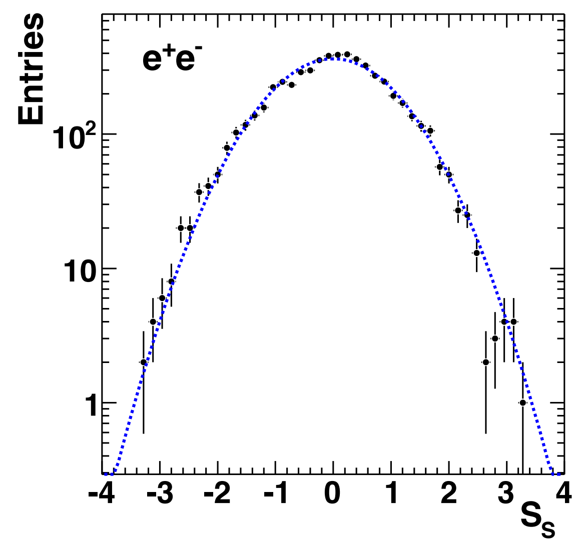
Electron results



Cross section vs mass

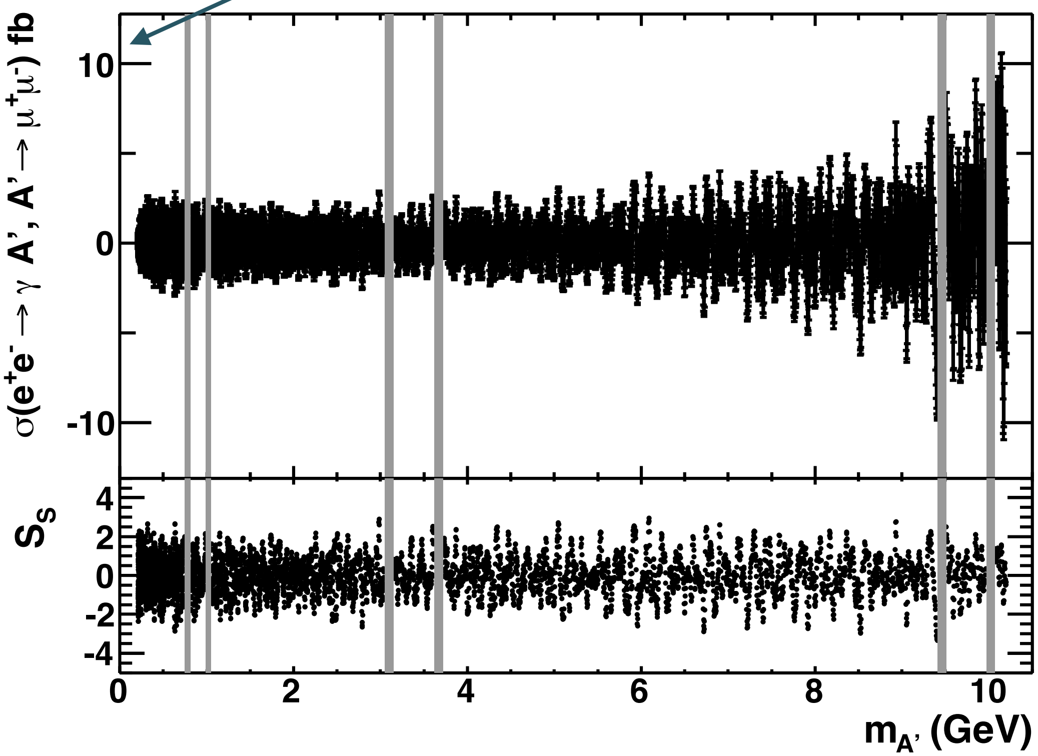
Significance of signal vs mass

Significance of all 5704 mass hypotheses



Muon results

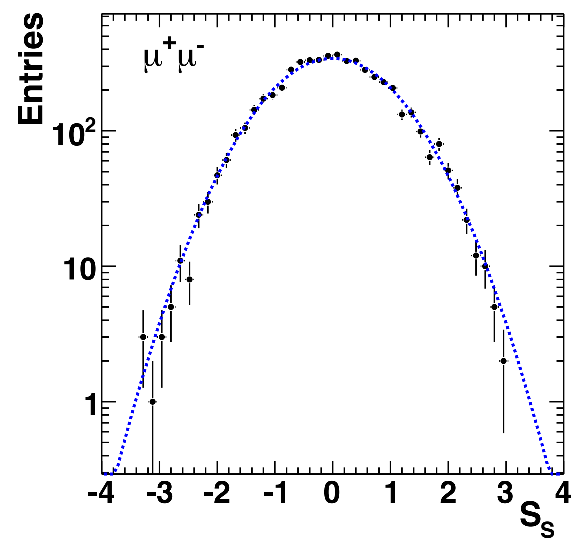
note the difference in scale; 10 vs 50



Cross section vs mass

Significance of signal vs mass

Significance of all 5370 mass hypotheses



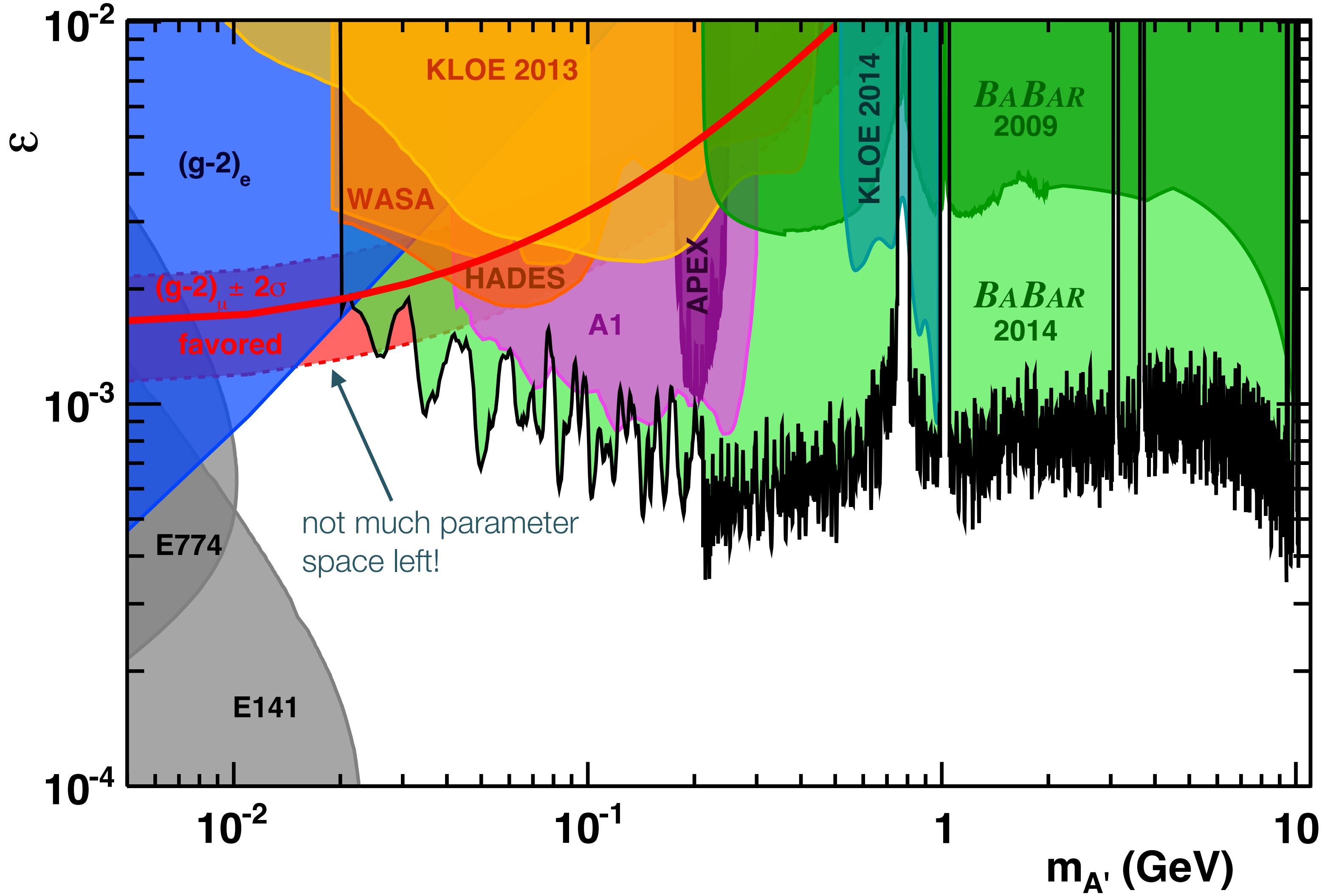
Limits

- Only significant systematic error is in the assumed shape of the smooth background. Comparable to statistical errors at lowest e^+e^- masses, and near $\Upsilon(1S)$, $\Upsilon(2S)$.

- Combine the electron and muon cross section measurements to obtain limits on ε and $M_{A'}$.

arXiv 1406.2980 [hep-ex] (2014)
to appear in Phys. Rev. Lett.

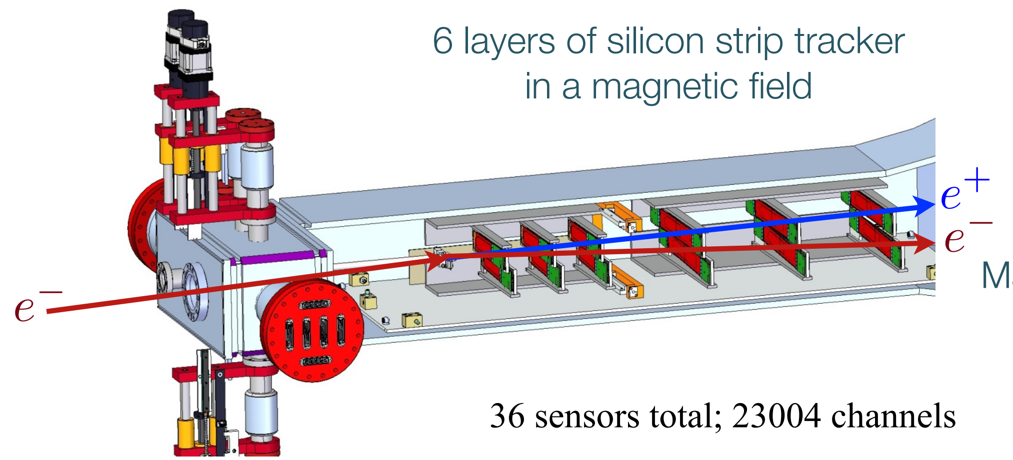
BaBar limits on heavy photon parameters



The future

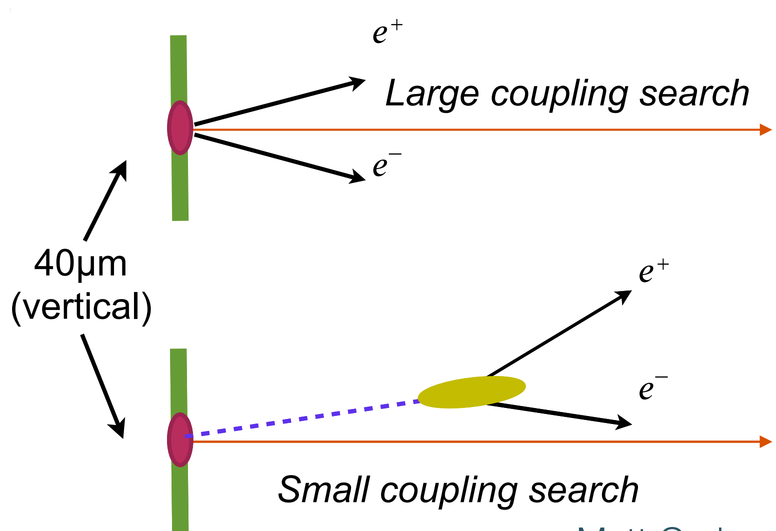
- Quite a few dedicated experiments planned or proposed. Generally fixed-target electron beams.
  - HPS, APEX, and DarkLight at Jefferson laboratory
  - A1 at MAMI: plans to search for displaced vertices, ~10mm
  - A1 collaboration at MESA (Mainz energy-recovering superconducting accelerator); 105 MeV e^- beam on a gas target, high power.
  - VEPP-3; 500 MeV e^+ beam on a hydrogen target; photon detection only.

HPS — Heavy Photon Search at JLab



- Reconstruct e^+e^- only. Good mass resolution for prompt decays due to small beam (beam spot constraint).

- Worse resolution for displaced vertices. 2D search in lifetime and mass.

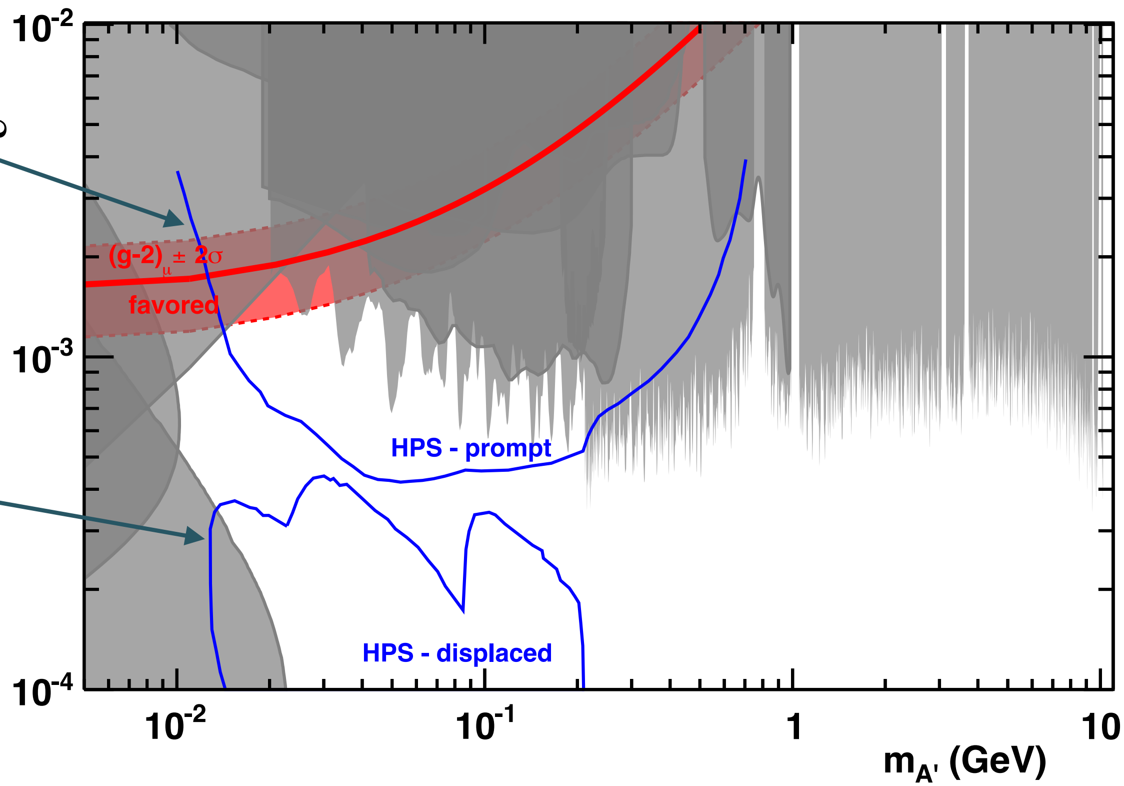


HPS projection

- JLab Hall B. Commissioning in December, then 3 weeks of data in 2015 (between CLAS installation).

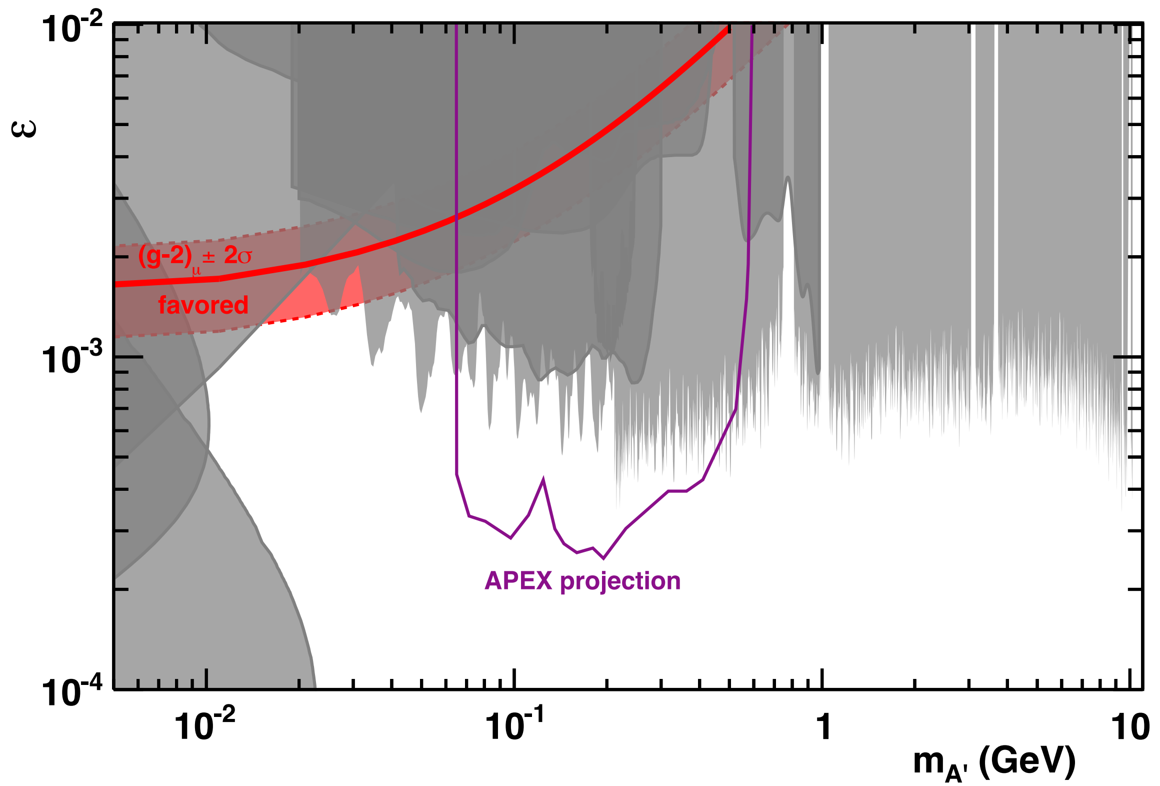
rate is high enough to see bump on large backgrounds

lifetime is long enough to distinguish from prompt backgrounds



APEX (A′ experiment) at JLab

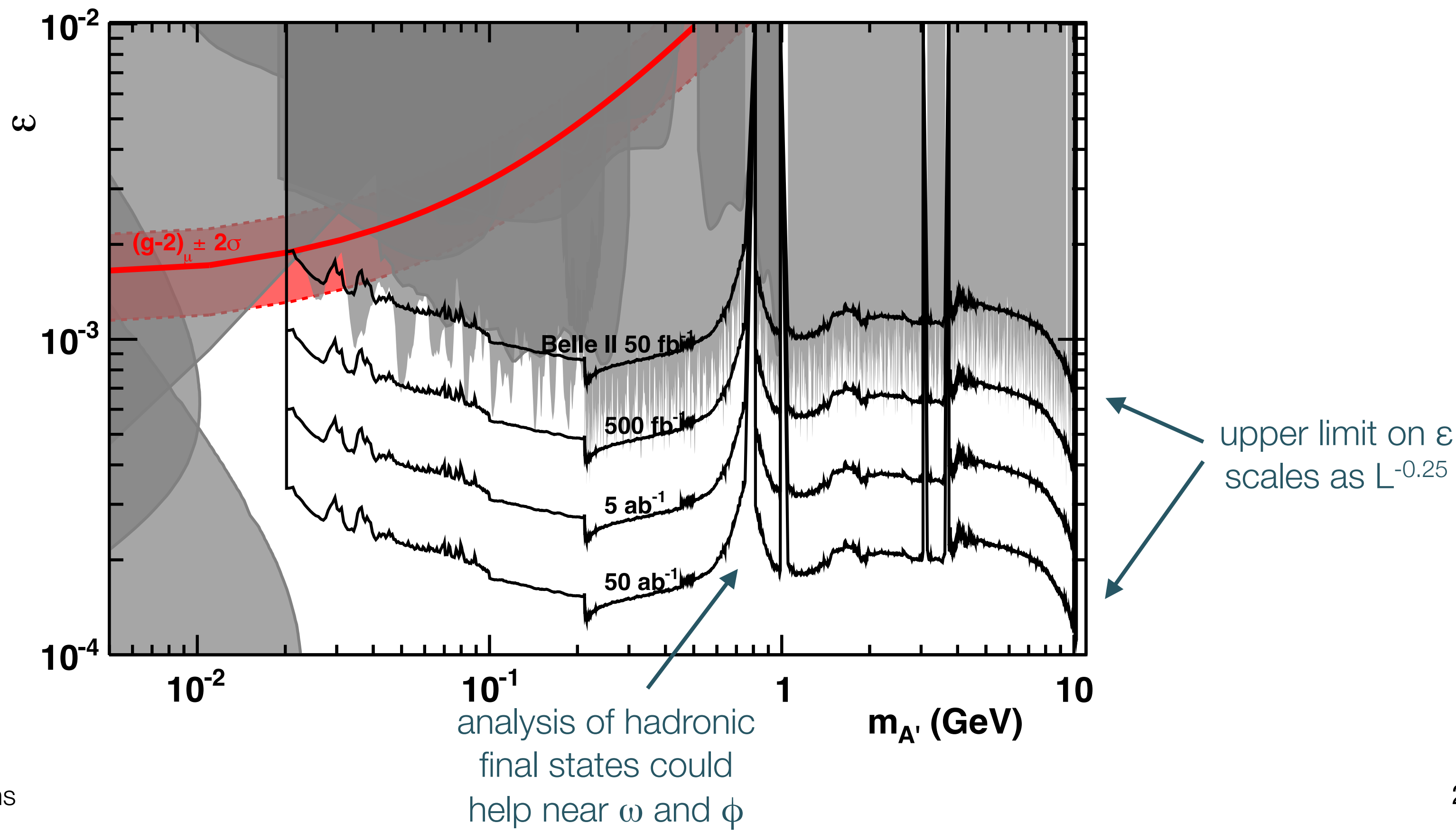
- Hall A; CEBAF 1—4 GeV CW e^- beam on tantalum foil. High resolution spectrometers. Beam in 2015? Or 2016.



Test run results published in Phys. Rev. Lett. 107, 191804 (2011).

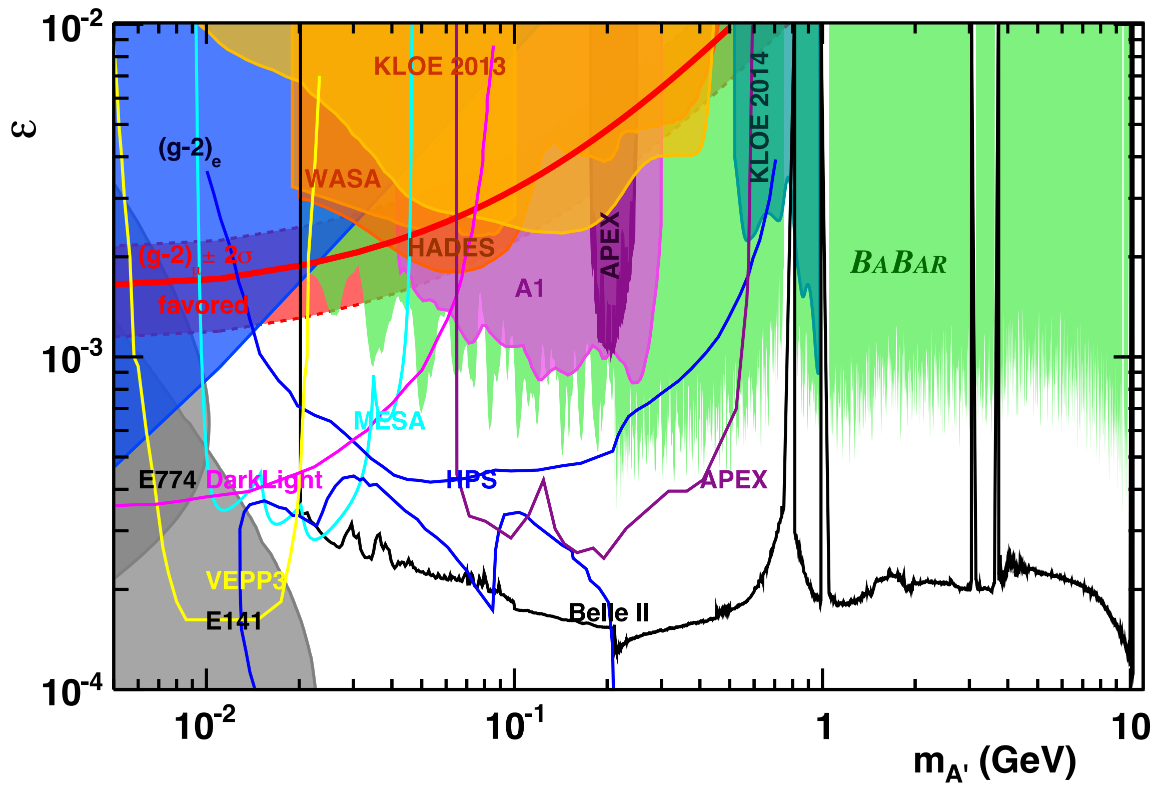
Belle II

- Goal of Belle II is ~100x BaBar integrated luminosity by 2023. Also much better mass resolution (large drift chamber), and higher trigger efficiency for e^+e^-.



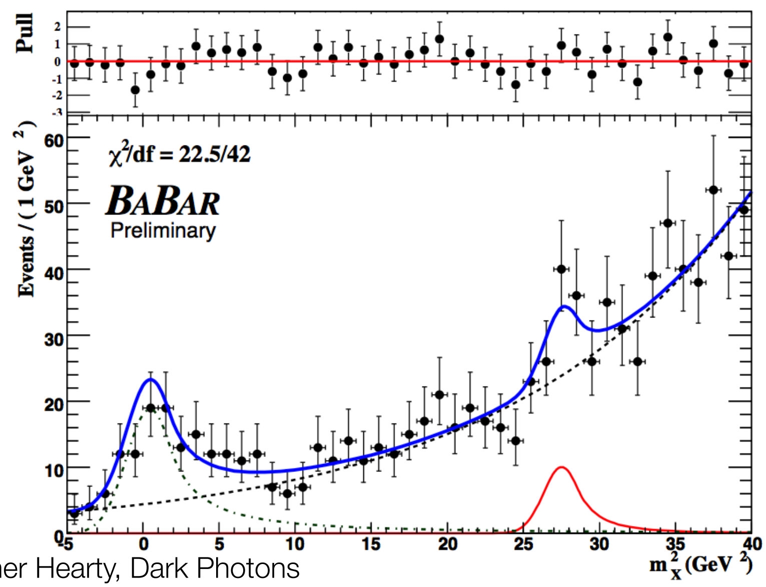
Putting it all together…

- Most of this region of parameter space will be examined over the next few years, generally by more than one experiment.



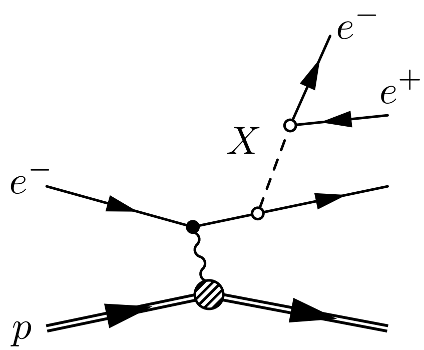
Invisible decays of the A′

- If the A′ is not the lightest dark particle, it can decay to invisible states, leaving only a photon in the final state: $e^+e^- \to \gamma A'; \;\; A' \to \chi\chi$
- BaBar recorded Y(2,3S) data with single photon trigger. Light Higgs search; A′ search in progress.



- Large backgrounds from $e^+e^- \to \gamma\gamma$ with 1 photon missed, or $e^+e^- \to e^+e^-\gamma$ with both tracks down the beam pipe.
- arXiv:0808.0017 [hep-ex] (2008). Interpreted as A′ search by R. Essig et al, arXiv:1309.5084 [hep-ph]

- DarkLight (JLab FEL 100 MeV e^- beam on a hydrogen target) will reconstruct all final state particles in a compact magnetic spectrometer, including the recoil proton and the scattered electron.
  ⇒ detect invisible decays via missing mass.



JHEP 1001 (2010) 111 [arXiv:0909.2862 [hep-ph]]

  - data in 2016?

- BDX: proposal to produce invisible pairs in an electron beam dump at JLab; detect via nuclear recoil following a thick absorber. arXiv 1406.3028 [physics.ins-det]

Summary

- A dark sector could explain dark matter and produce new phenomena at relatively low energies.
- The new BaBar search did not observe evidence for a dark photon, and excludes a significant region of parameter space.
- A large number of experiments over the next few years will pursue searches for dark photons in leptonic and invisible final states.