Search for dark sector at BABAR

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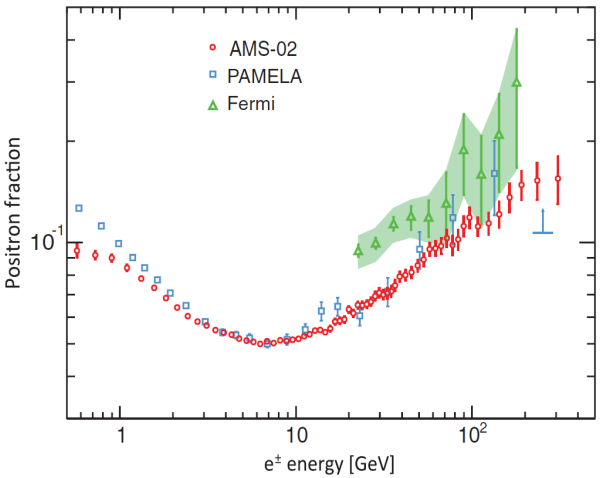
Dark sector

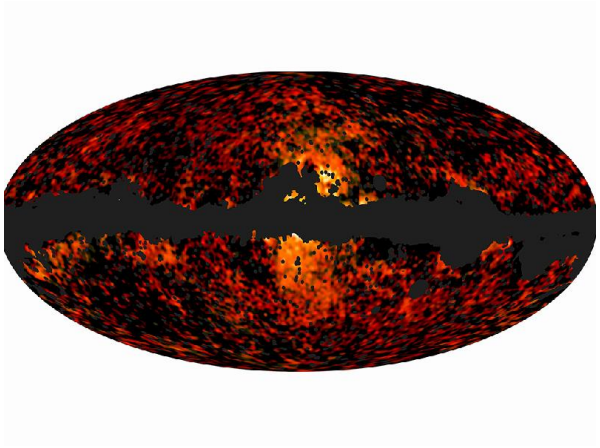
- Models with new 'dark' force mediated by gauge boson with GeV mass: proposed to explain observations of PAMELA, FERMI, AMS, DAMA/LIBRA, …

  e.g. Arkani-Hamed *et al.*, Phys. Rev. D **79**, 015014 (2009)

- Possibility of hidden MeV/GeV-scale sector is poorly constrained ⇒ worth exploring



AMS, Phys. Rev. Lett. **110**, 141102 (2013)



PLANCK galactic haze, arXiv:1208.5483

Dark sector and dark forces

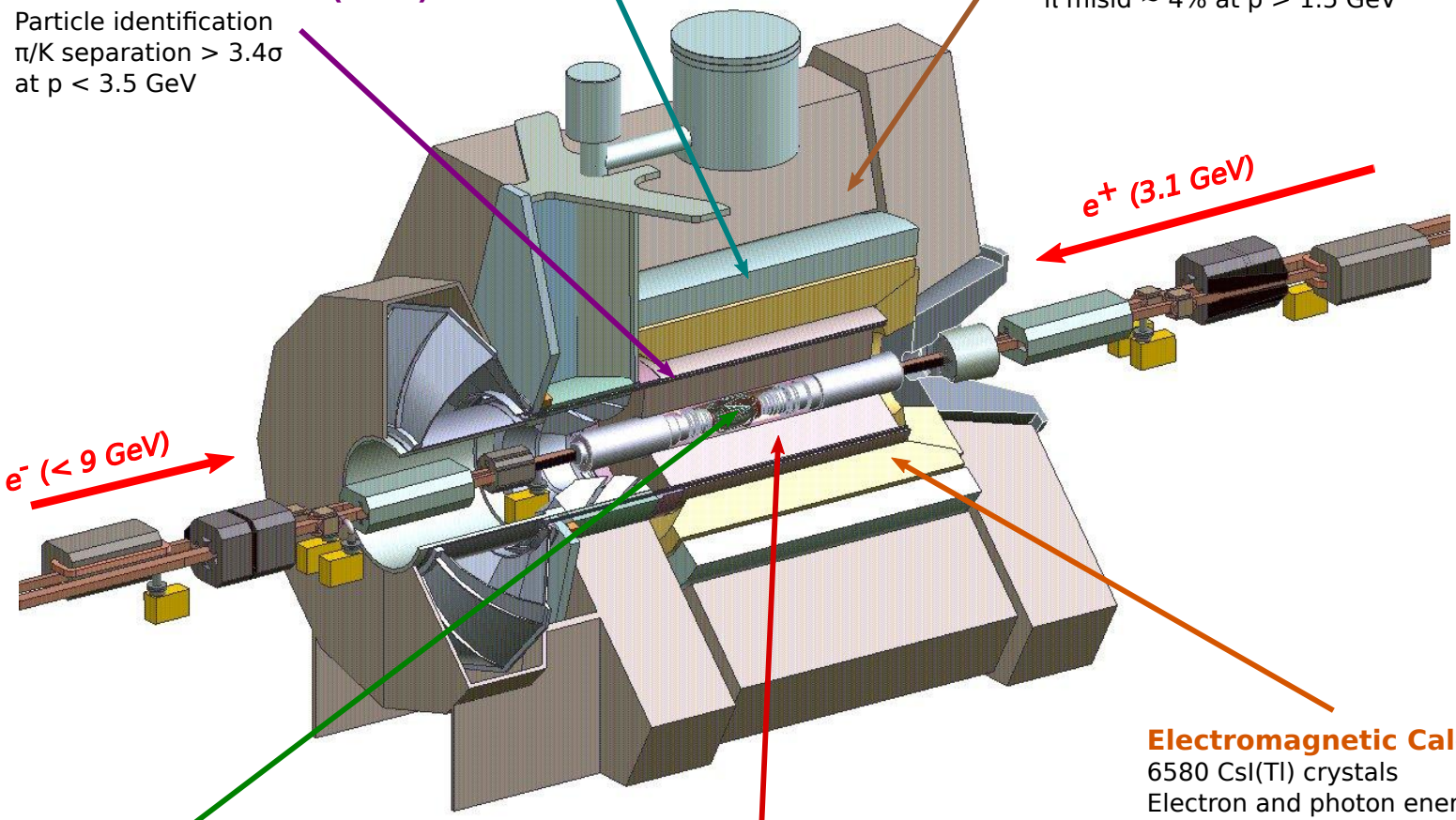
- New dark sector with a $U(1)_D$ gauge group (or something more complicated)
- New gauge boson(s): dark photon A' which could have $\mathcal{O}(\text{GeV})$ mass
- Interaction with SM via kinetic mixing with mixing strength ε

$$\Delta\mathcal{L}_{\text{mix}} = \varepsilon F^{\mu\nu} B_{\mu\nu}$$

- Kinetic mixing generates non-zero coupling of SM fermions to A'; $\alpha' = \alpha\varepsilon$
- In these models, TeV-scale dark matter particles χ can annihilate into pair of A' which then decay into SM fermions

Low-energy high-luminosity e^+e^- colliders offer low-background environment to search for MeV/GeV-scale hidden sector

The BABAR experiment at PEP-II (SLAC)



Instrumented Flux Return
Identification of muons and neutral hadrons
μ efficiency > 85%,
π misid ~ 4% at p > 1.5 GeV

Solenoid 1.5 T

Cherenkov Detector (DIRC)
Particle identification
π/K separation > 3.4σ
at p < 3.5 GeV

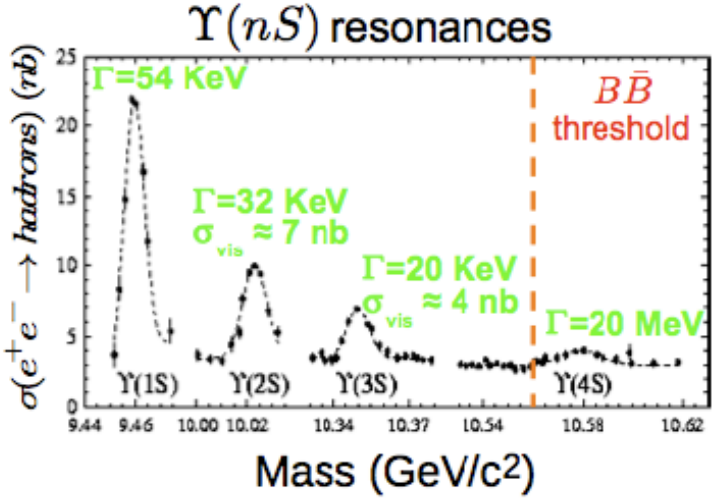
Electromagnetic Calorimeter
6580 CsI(Tl) crystals
Electron and photon energy measurement
$\sigma(E)/E = 1.4\% \, E^{-1/4} \oplus 2.2\%$

Silicon Vertex Tracker
5 layers of double-sided Si-strip detectors
Vertex reconstruction, tracking + dE/dx
Efficiency ~ 97%

Drift chamber
40 layers, momentum measurement for charged particles and dE/dx
$\sigma(p_T)/ p_T = 0.13\% \, p_T \oplus 0.45\%$

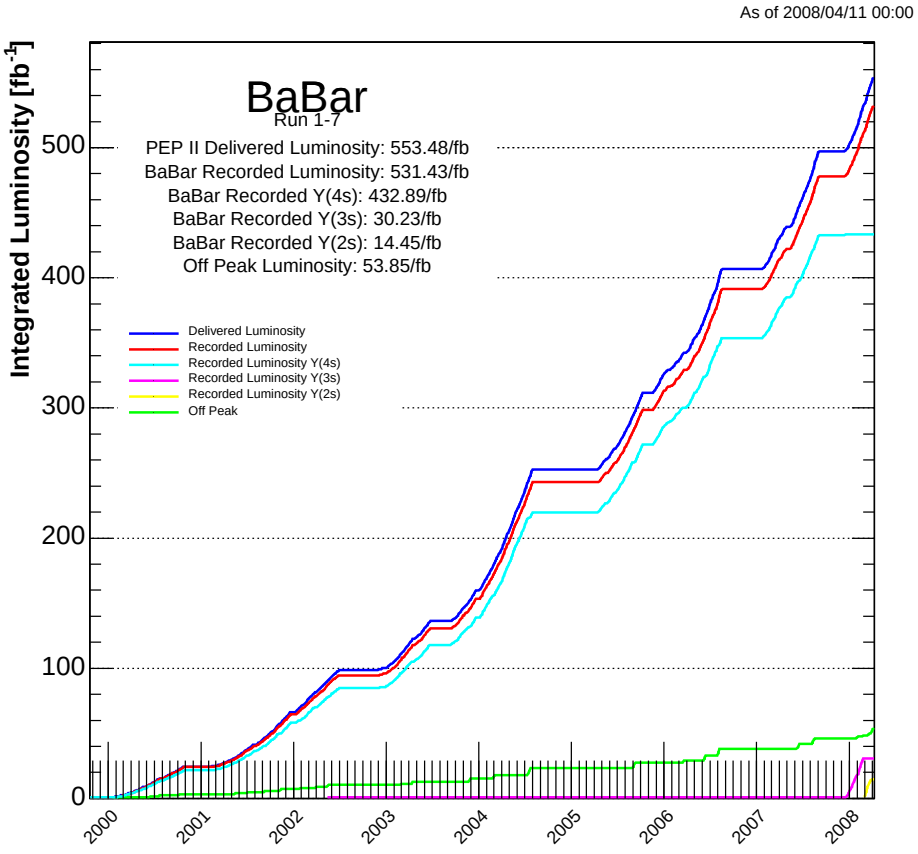
BABAR data set

PEP-II: asymmetric e^+e^- collider, running mostly on $\Upsilon(4S)$



425.6 fb^{-1}	at $\Upsilon(4S)$	➡	467×10^6	$B\bar{B}$
28.0 fb^{-1}	at $\Upsilon(3S)$	➡	122×10^6	$\Upsilon(3S)$
13.6 fb^{-1}	at $\Upsilon(2S)$	➡	99×10^6	$\Upsilon(2S)$
	(18×10^6 $\Upsilon(1S)$ from di-pion tagging)			
3.9 fb^{-1}	scan above $\Upsilon(4S)$			

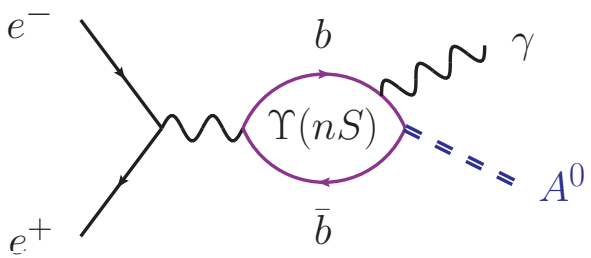
BABAR recorded luminosity



Data taking finished April 2008

Dark matter searches at BABAR

BABAR has searched for a light, (CP-odd) Higgs A^0
(foreseen in several extensions of the SM, e.g. NMSSM)



- Based on $\Upsilon(2,3S)$ data sets
- Different final states ($\mu^+\mu^-$, $\tau^+\tau^-$, hadrons, invisible), pattern of decay depends on A^0 mass
- Obtained limits on A^0 mass
  $e^+e^- \to \gamma A^0$, $A^0 \to \ell^+\ell^-$, $q\bar{q}$, invisible

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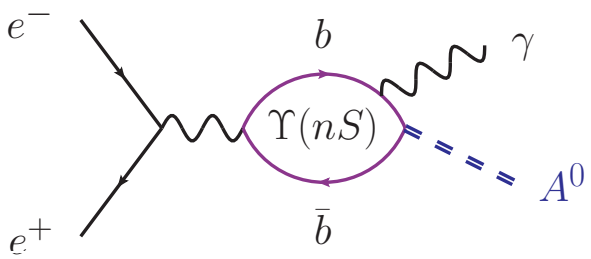

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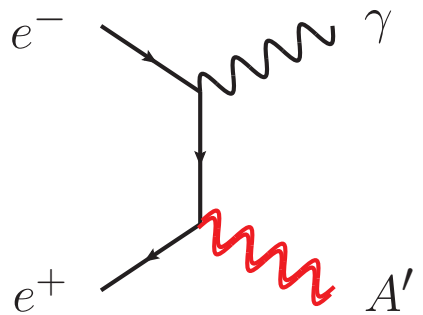
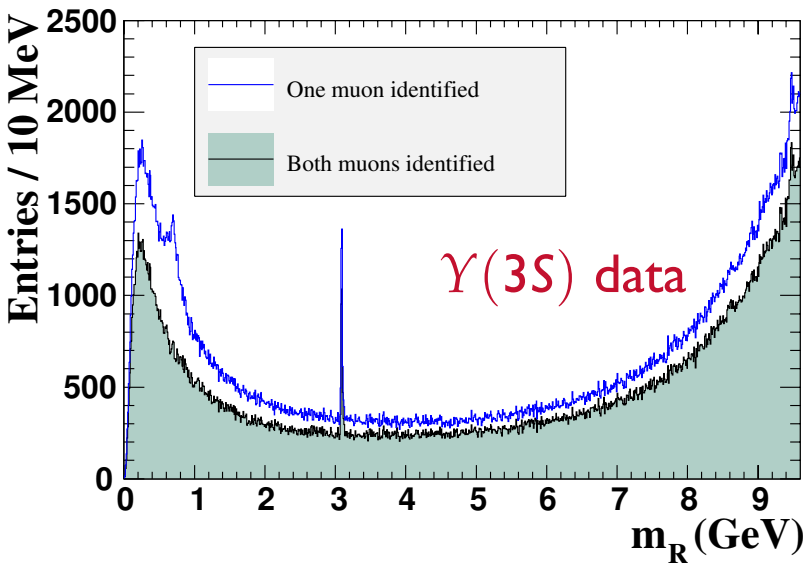


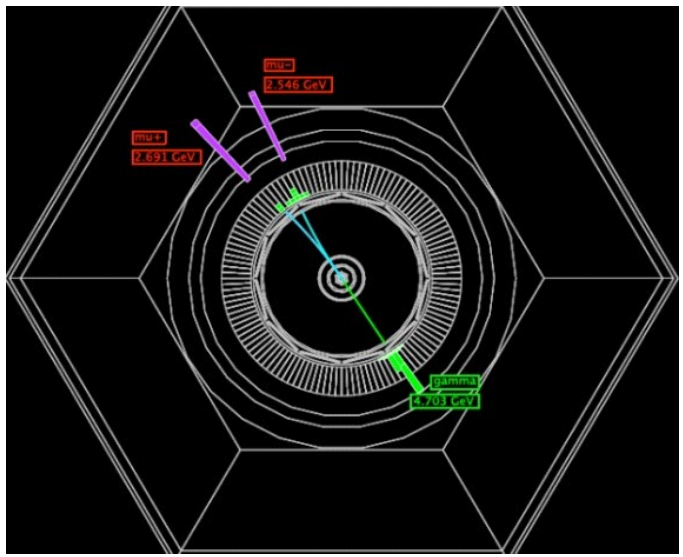
- Reinterpreting this as
  $e^+e^- \to \gamma A', A' \to \ell^+\ell^-, q\bar{q}$, invisible
  variation in efficiency (A' is vector, A^0 is scalar) to be taken into account
- At least order-of-magnitude estimate of limit
- Already re-interpreted: $\Upsilon(3S), \Upsilon(2S) \to \gamma A^0, A^0 \to \mu^+\mu^-$

$\Upsilon(2S,3S) \to \gamma A^0, A^0 \to \mu^+\mu^-$

BABAR, Phys. Rev. Lett. **103** 081803 (2009)

- Events with a single energetic photon ($E^*_\gamma \geq 200\mathrm{MeV}$) and exactly 2 oppositely-charged tracks
- At least one track identified as μ
- Dimuon candidate and γ back-to-back in COM
- Background dominated by QED processes:
  - continuum $e^+e^- \to \gamma\mu^+\mu^-$
  - ISR production of $\rho^0, \phi, J/\psi, \psi(2S)$, and $\Upsilon(1S)$
- Plot yield as function of reduced mass $m_R \equiv \sqrt{m^2_{\mu\mu} - 4m^2_\mu}$



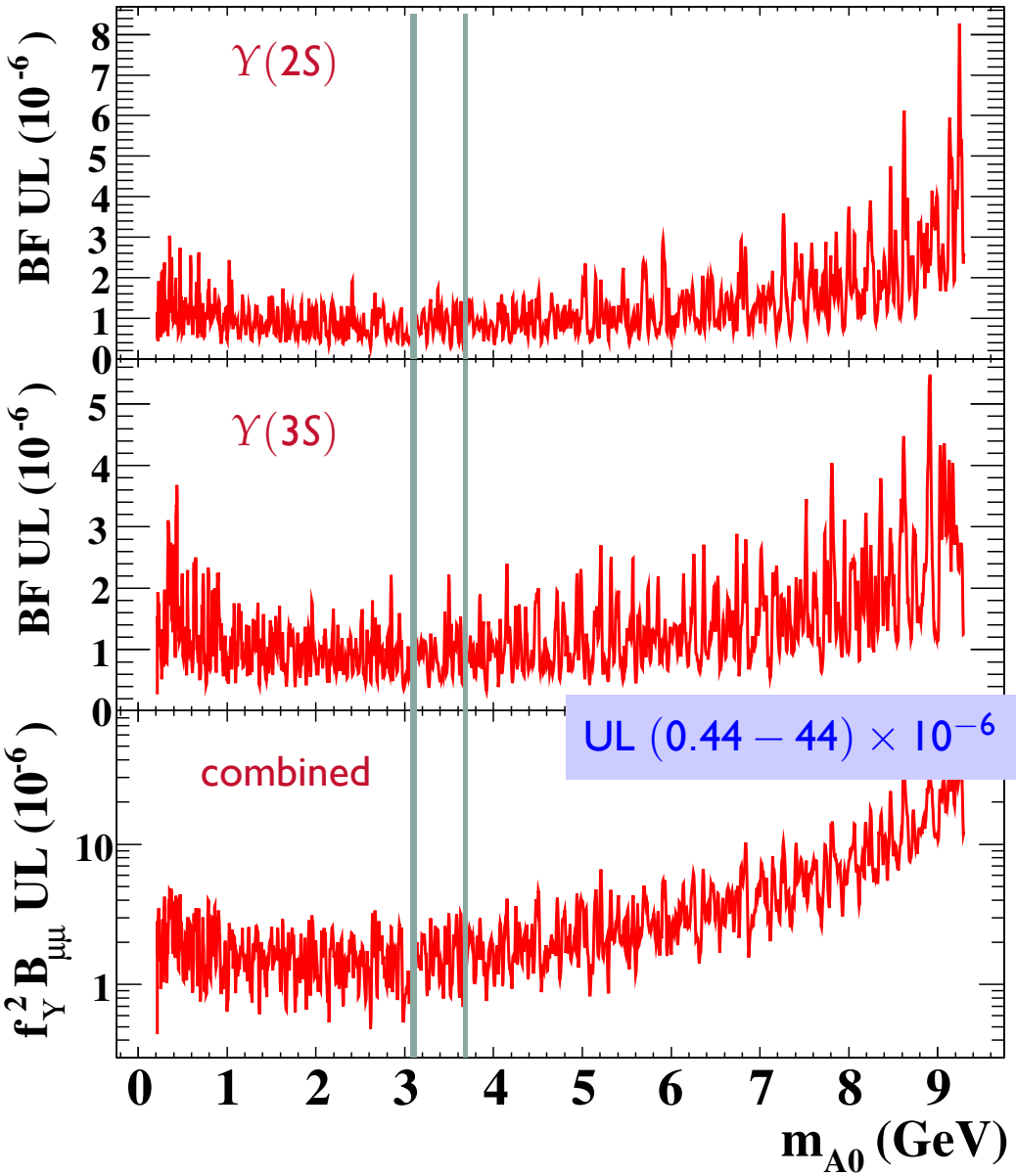


$\Upsilon(2S, 3S) \to \gamma A^0, A^0 \to \mu^+\mu^-$

BABAR, Phys. Rev. Lett. **103** 081803 (2009)

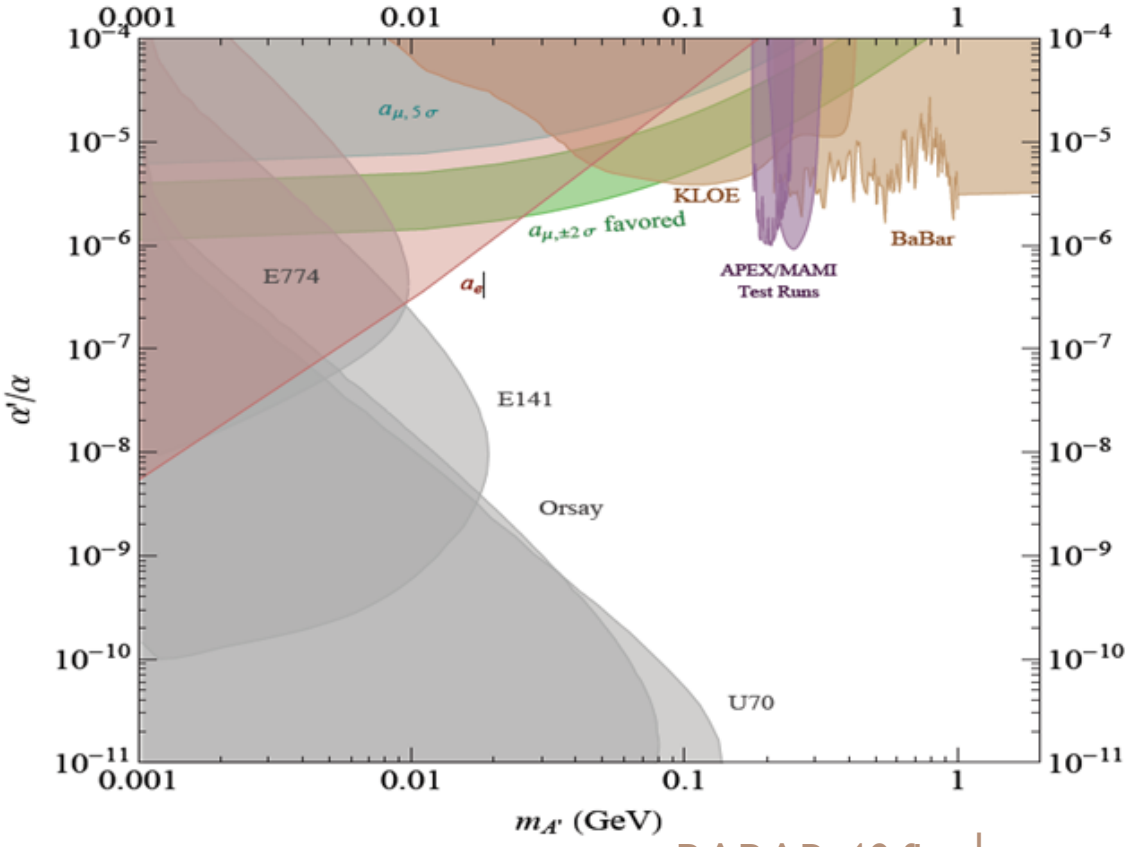
- Signal yield as function of A^0 mass in $0.212 \leq m(A^0) < 9.3\,\text{GeV}$ by unbinned ML fits
- Signal mass resolution $2 - 10\,\text{MeV}$
- Mass steps of $2 - 5\,\text{MeV}$, total of ≈ 1500 independent measurements
- Exclude regions near J/ψ and $\psi(2S)$
- No significant excess of events above background in entire mass range
- Place 90% CL Bayesian UL on product

  $\mathcal{B}(\Upsilon(nS) \to \gamma A^0) \times \mathcal{B}(A^0 \to \mu^+\mu^-)$
- Combined UL on the product of effective coupling and branching fraction, $f_\Upsilon^2 \mathcal{B}_{\mu\mu}$



Search for dark photon

Limit obtained by re-interpreting $\Upsilon(2S, 3S) \to \gamma A^0, A^0 \to \mu^+\mu^-$



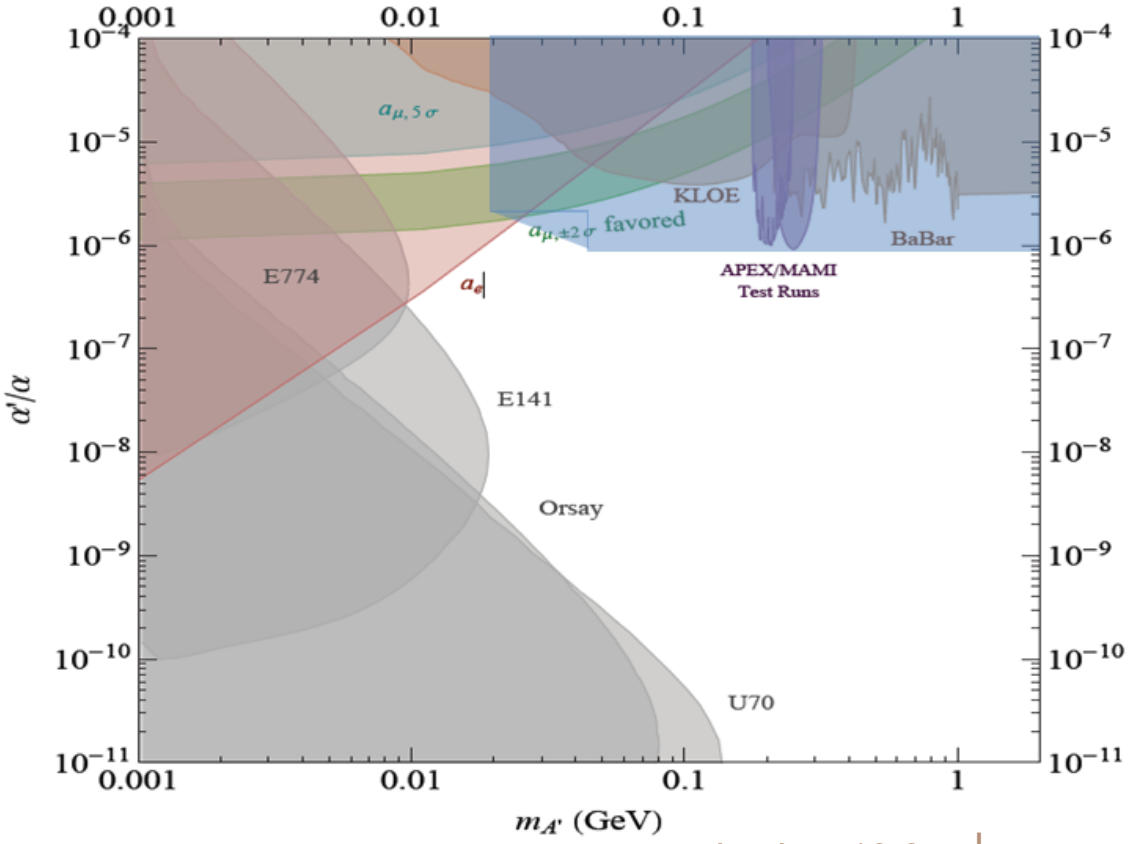
BABAR 40 fb^{-1}

J. Jaros

Search for dark photon

Limit obtained by re-interpreting $\Upsilon(2S, 3S) \to \gamma A^0, A^0 \to \mu^+\mu^-$

In progress: extend analysis to full BABAR dataset



J. Jaros

BABAR 40 fb^{-1}

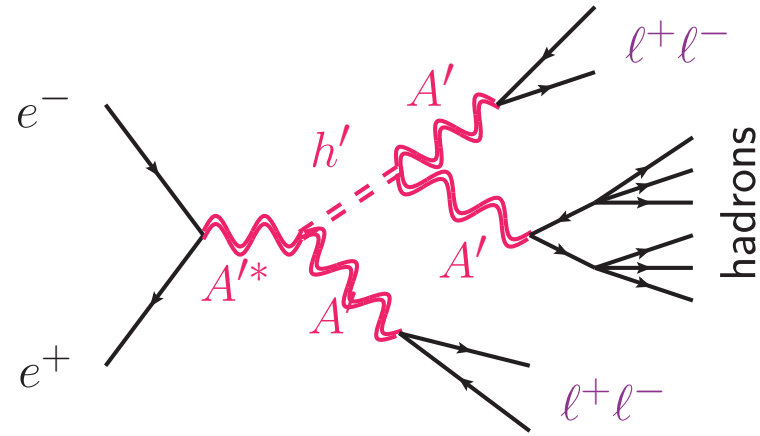
BABAR 500 fb^{-1} reach

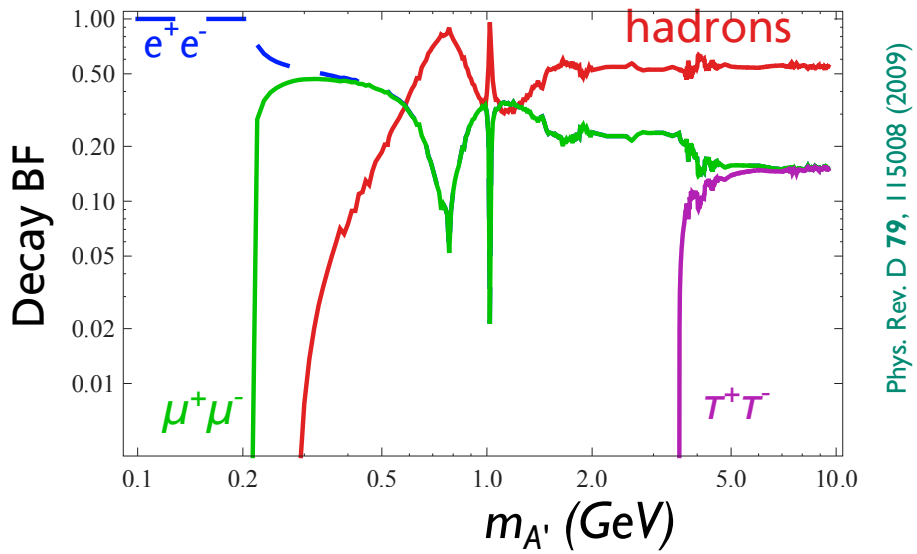
order of magnitude only

Higgsstrahlung

- Minimal gauge group: abelian $U(1)$ broken by Higgs' h'

  Batell *et al.*, Phys. Rev. D **79**, 115008 (2009)
- Look for 'Higgsstrahlung' process $e^+e^- \to A'h'(\to A'A')$
- Accessible final states depend on mass of A'
- Suppressed only by ε^2
- Search for $A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$ combinations





$e^+e^- \to A'h'(\to A'A')$

BABAR, Phys. Rev. Lett. **108** 211810 (2012)

Search strategy: inclusive and exclusive searches, using full BABAR dataset

- Reconstruct $A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$
- **Exclusive final states:**
  - Search for 6 tracks with at least one pair of oppositely charged leptons
  - $3A'$ candidate events must contain $\geq 95\%$ of CM energy
  - A' masses must be within 10 – 140 MeV of each other
  - A' vertices point back to IP
- **Inclusive** $e^+e^- \to 4\ell X (X \neq \pi^+\pi^-)$
  - Search for $4\mu + X$ or $2\mu 2e + X$ final states with mass above 1.2 GeV
  - Di-lepton pairs must point to IP
  - Recoil mass of the system X similar to dilepton A' candidates

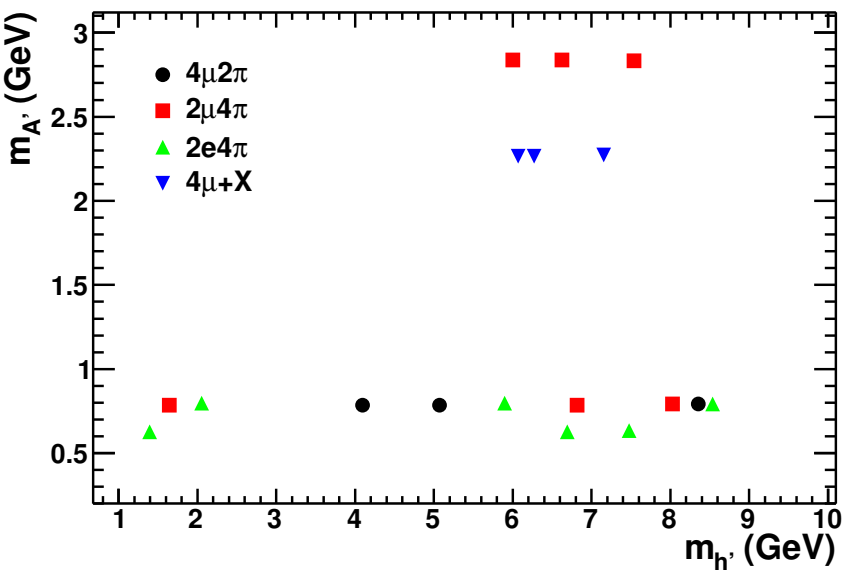
$e^+e^- \to A'h'(\to A'A')$

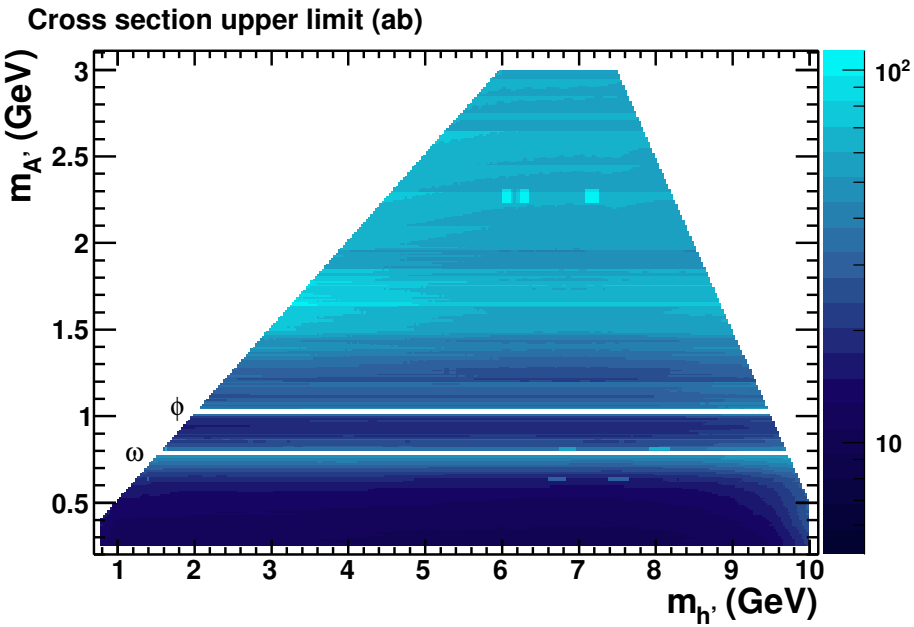
BABAR, Phys. Rev. Lett. **108** 211810 (2012)

Apply vetos to remove ϕ and ω from search

Final event sample contains these signal candidates:

$1 \times 4\mu 2\pi$, $2 \times 2\mu 4\pi$, $2 \times 2e4\pi$, $1 \times 4\mu X$



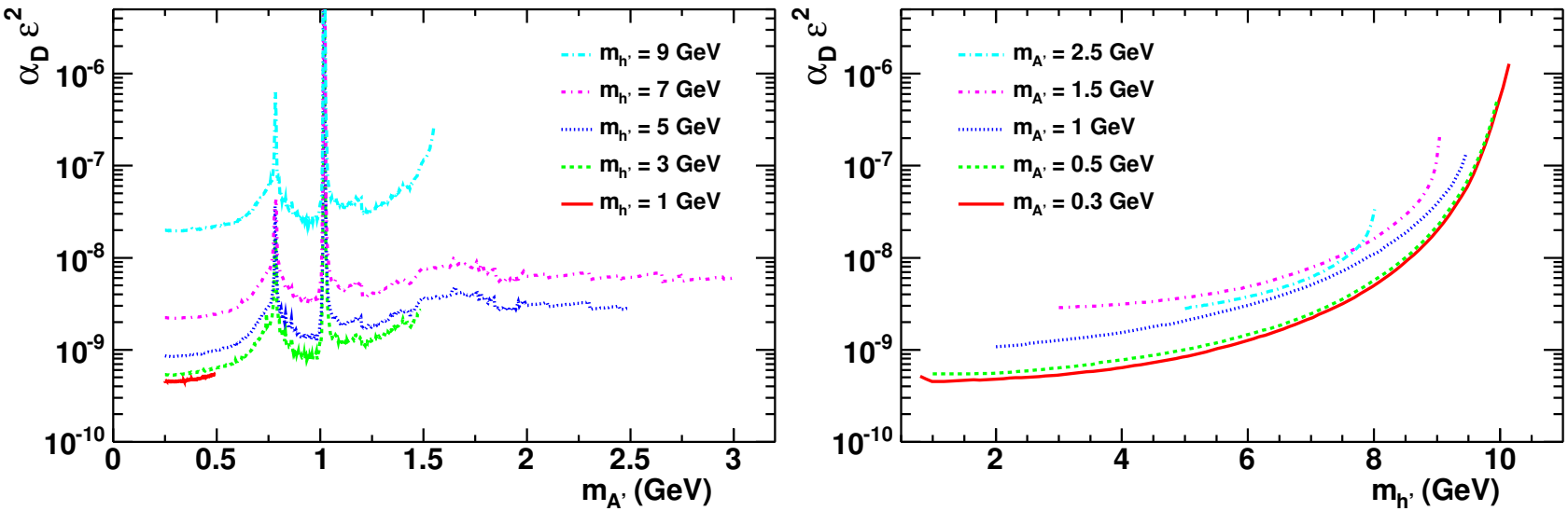


Three combinations per event

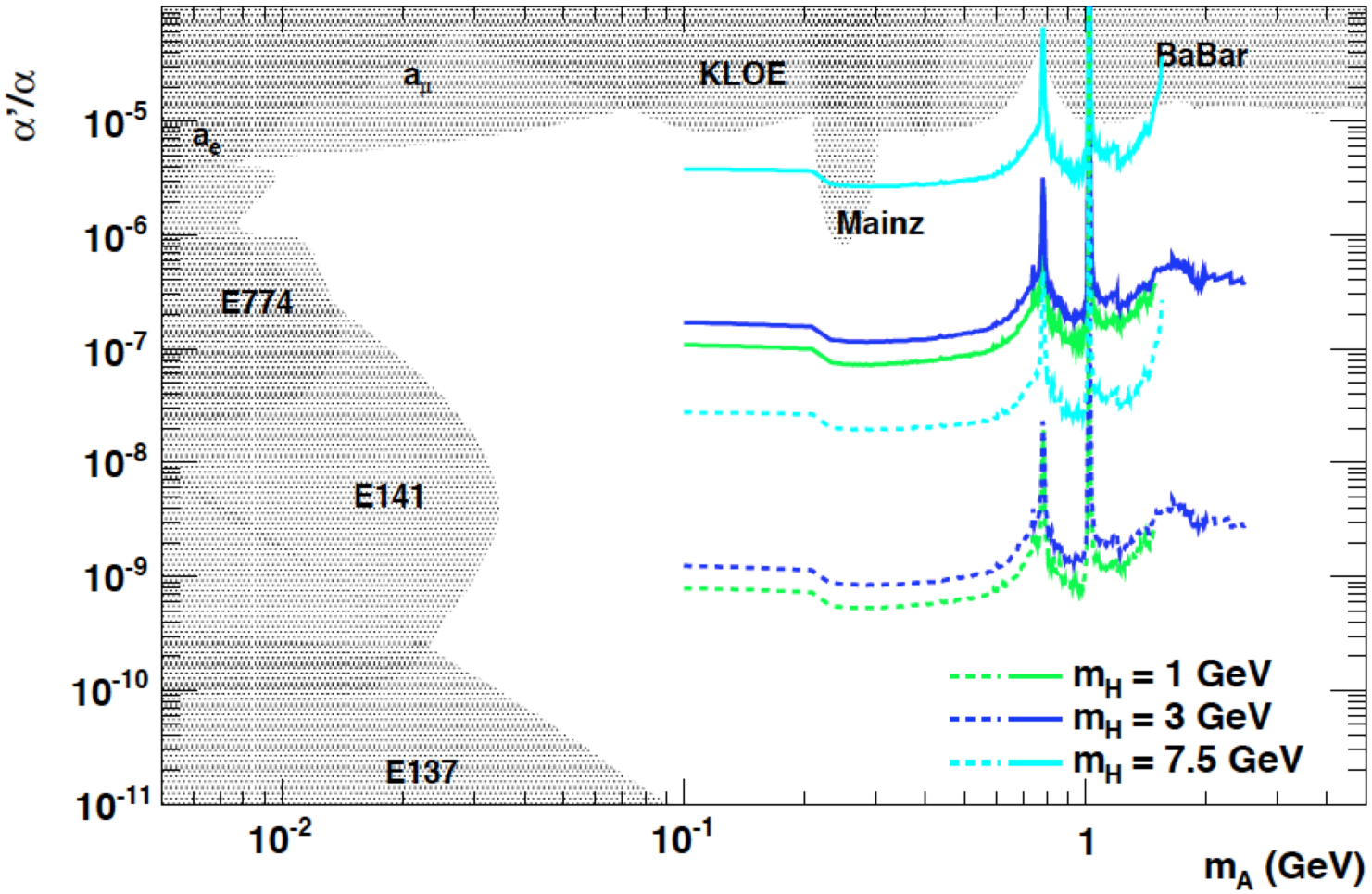
Limits on $\alpha' \varepsilon^2$

BABAR, Phys. Rev. Lett. **108** 211810 (2012)

Dark photon width is proportional to $\alpha' \varepsilon^2$;
place limits on this combination of coupling and mixing



Limits on α'/α



Solid : $\alpha' = 1/137$

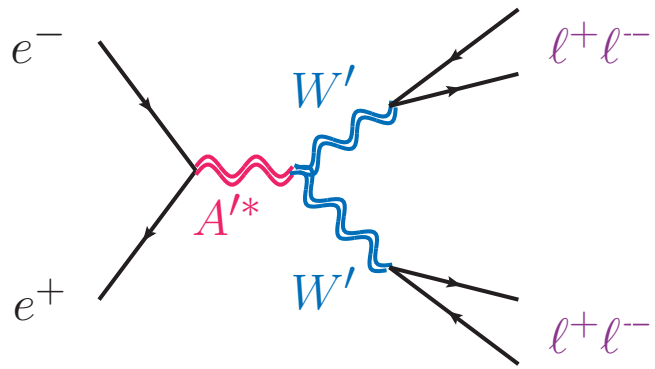
Dashed : $\alpha' = 1$

Multi-lepton searches

BABAR preliminary, arXiv:0908.2821

- If dark sector gauge group non-abelian: additional gauge bosons W'

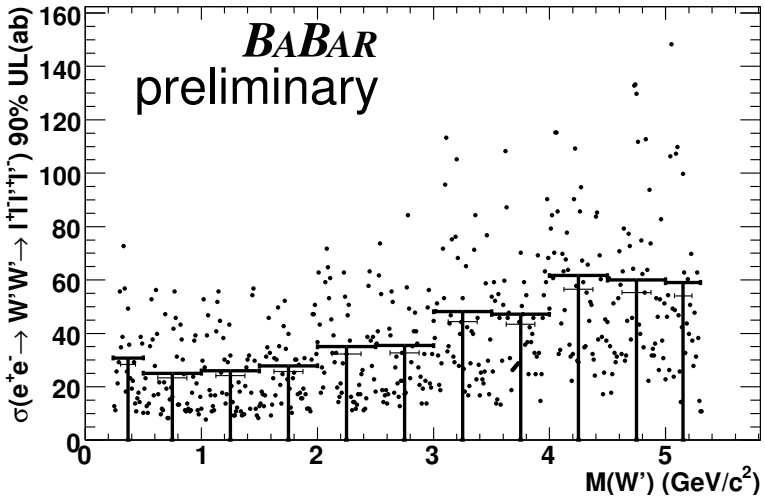
  Essig *et al.*, Phys. Rev. D **80**, 015003 (2009)
- Signature: $e^+e^- \to W'W' \to (\ell^+\ell^-)(\ell'^+\ell'^-)$
- Depending on scenario and coupling to standard model,
  cross section could be $\mathcal{O}(\text{fb})$
  ➡ hundreds of events?

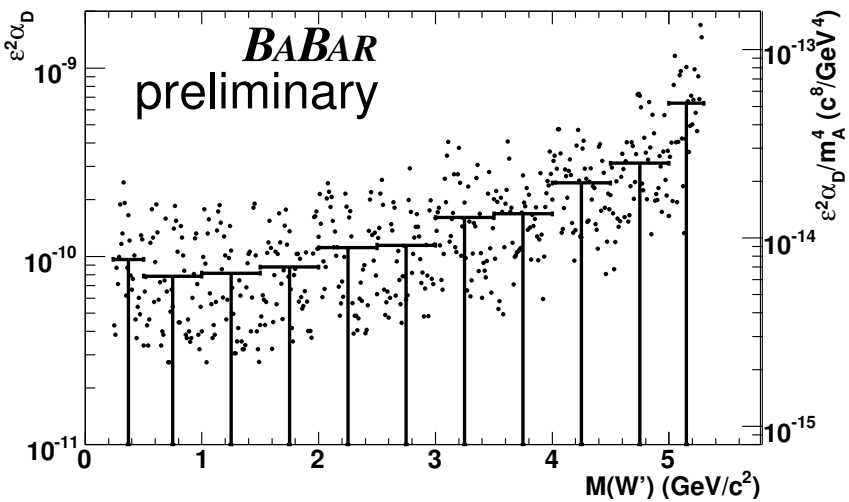


$e^+e^- \to W'W' \to (\ell^+\ell^-)(\ell'^+\ell'^-)$

BABAR preliminary, arXiv:0908.2821

- Search for events with two lepton pairs of $\approx$ equal mass
- Using 536 fb^{-1} of BABAR data
- Mass range $0.24\,\text{GeV} < m(W') < \sqrt{s}/2$
- Cross section limit $\sigma(e^+e^- \to W'W' \to 4\ell) < (25-60)$ ab at 90% C.L.
- $\varepsilon^2\alpha' < 2 \times 10^{-10}$ in most of the mass range





Summary

- Low-energy e^+e^- colliders provide clean environment to explore MeV/GeV-scale dark matter and dark sector.

- So far, no evidence seen of A^0, A', h', W' …
- Several results from Υ decays have already set stringent limits on models of generic dark matter or BSM physics

- Many searches currently being performed at BABAR on full data set; expect results soon

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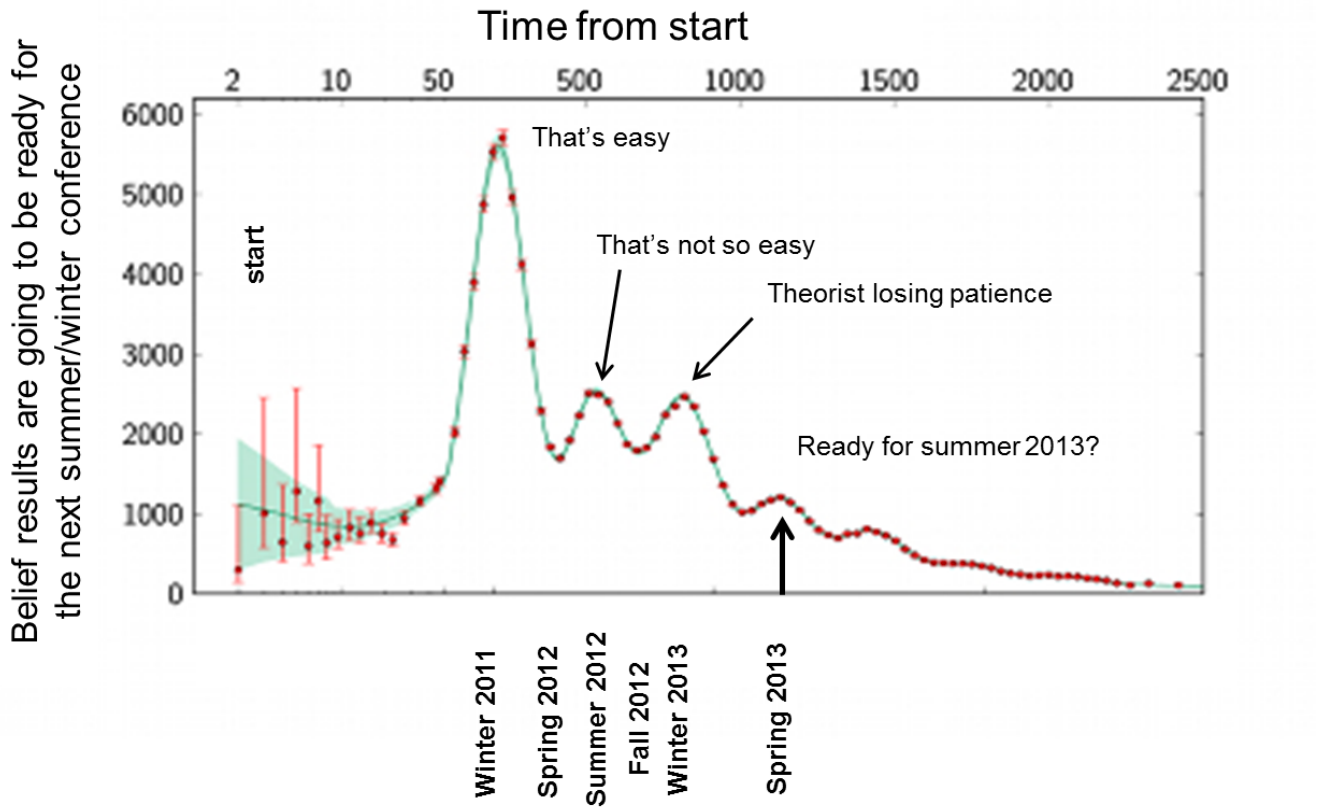
Dark photon searches at BABAR



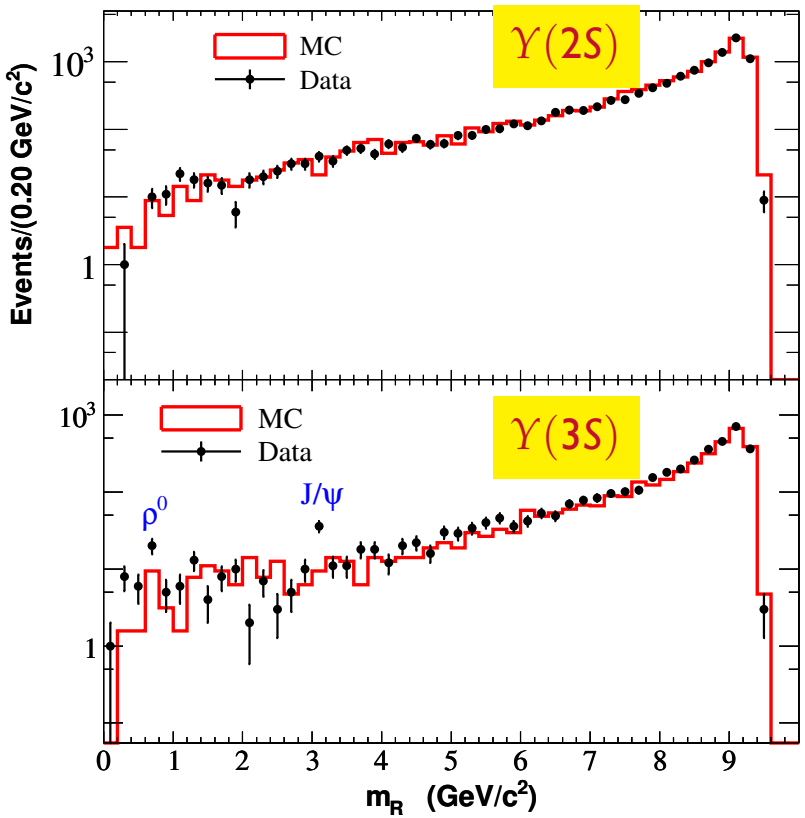
Aim to really have updates by the Summer conferences 2013

Extra Material

$\Upsilon(1S) \to \gamma A^0, A^0 \to \mu^+\mu^-$

BABAR, Phys. Rev. D **87**, 031102(R) (2013)

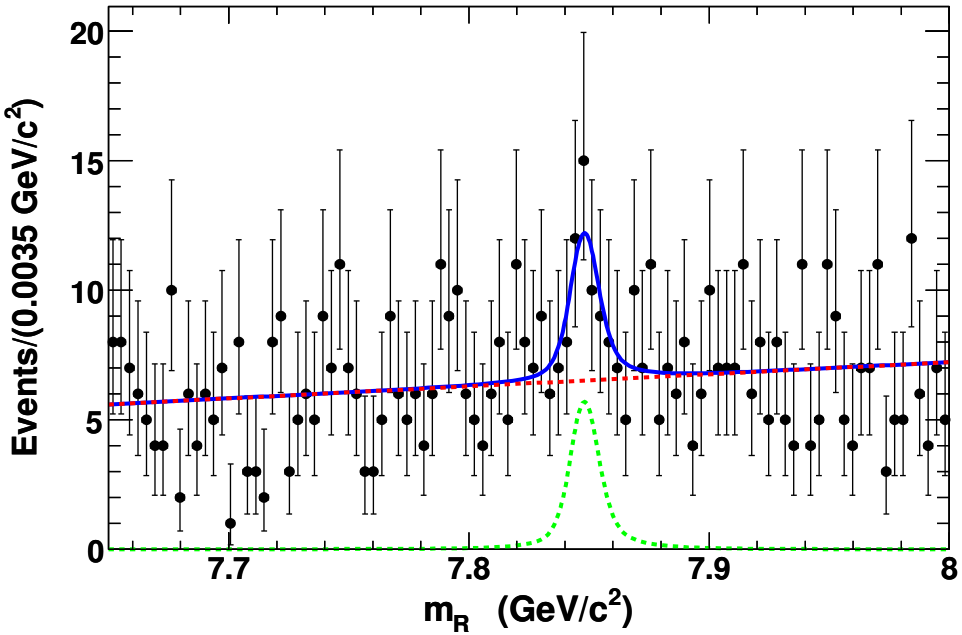
- Clean sample from $\Upsilon(2,3S) \to \pi^+\pi^-\Upsilon(1S)$ transitions
  100M $\Upsilon(2S)$ and 120M $\Upsilon(3S)$ decays
- Tag $\Upsilon(1S)$ production by reconstructing mass recoiling against di-pion system
- Select events with 2 muons and a photon with $E_\gamma > 200\,\text{MeV}$
- Improve energy resolution by beam energy constraint
- Look for peaks in reduced mass spectrum



$\Upsilon(1S) \to \gamma A^0, A^0 \to \mu^+\mu^-$: results

BABAR, Phys. Rev. D **87**, 031102(R) (2013)

- 4885 ML fits in steps of A^0 mass
- All observed deviations consistent with background fluctuations
- largest fluctuation: local significance $\sim 3.6\sigma$ probability $\sim 18\%$ when including 'look-elsewhere effect'



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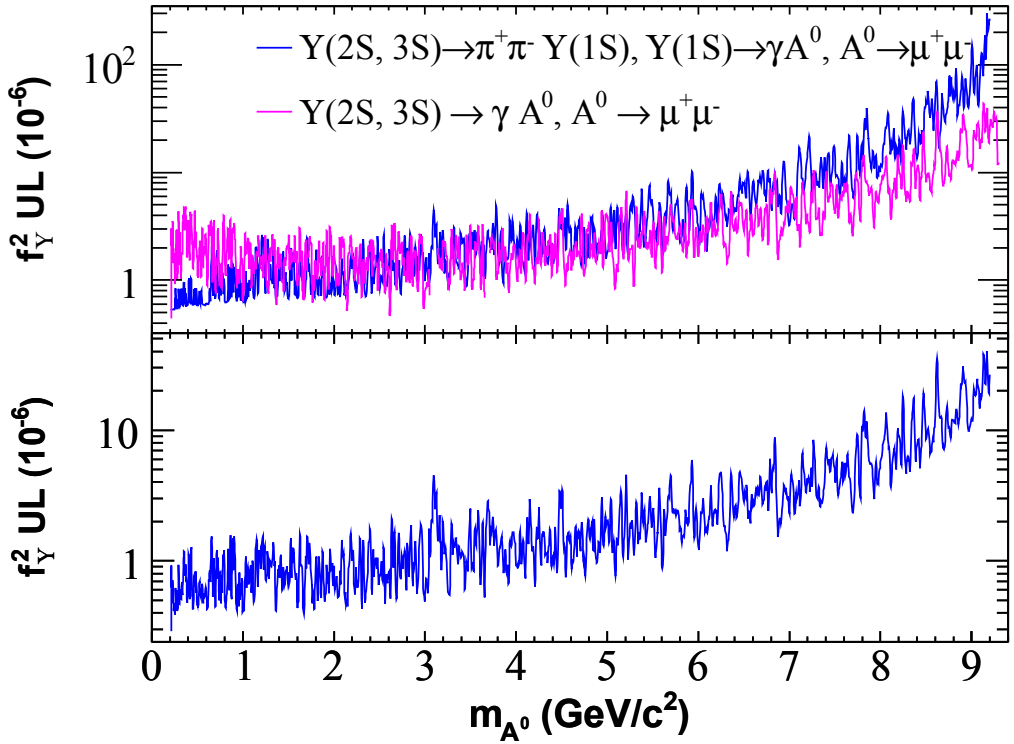

Combined with measurements on $\Upsilon(2,3S)$:

$$f_\Upsilon^2 \times \mathcal{B}(A^0 \to \mu^+\mu^-) < (0.29 - 40) \times 10^{-6} \text{ at } 90\% \text{ C.L.}$$

for $m(A^0) < 9.2\,\text{GeV}$

Dark sector searches at BABAR

- **Light Higgs searches**
  in $\Upsilon(2,3S)$ radiative decays
  - $A^0 \to \mu^+\mu^-$ PRL 103, 081803 (2009)
  - $A^0 \to \tau^+\tau^-$ PRL 103, 181801 (2009)
  - $A^0 \to$ hadrons PRL 107, 221803 (2011)

  in $\Upsilon(1S)$ radiative decays
  - $A^0 \to \mu^+\mu^-$ PRD 87, 031102 (2013)
  - $A^0 \to \tau^+\tau^-$ arXiv:1210.5669
- **Search for dark photon**
  - $e^+e^- \to \gamma A'(\to e^+e^-, \mu^+\mu^-)$ in progress
  - $e^+e^- \to \gamma A'(\to 3h)$ in progress
- **Search for invisible dark photon**
  - $e^+e^- \to \gamma A', A' \to$ invisible in progress
- **Search for dark boson(s)**
  - $e^+e^- \to A'^* \to W'W'$ arXiv:0908.2821
  - $e^+e^- \to \gamma A'^* \to W'W''$