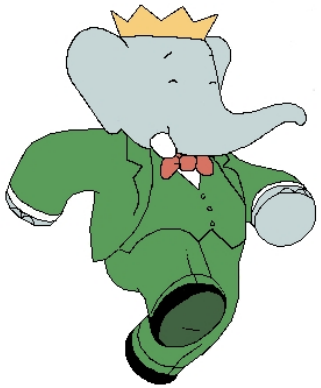
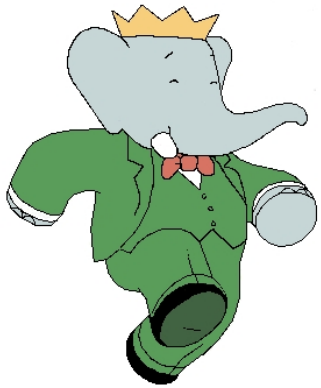
Search for invisible decays of a dark photon produced in e^+e^- collisions at BaBar

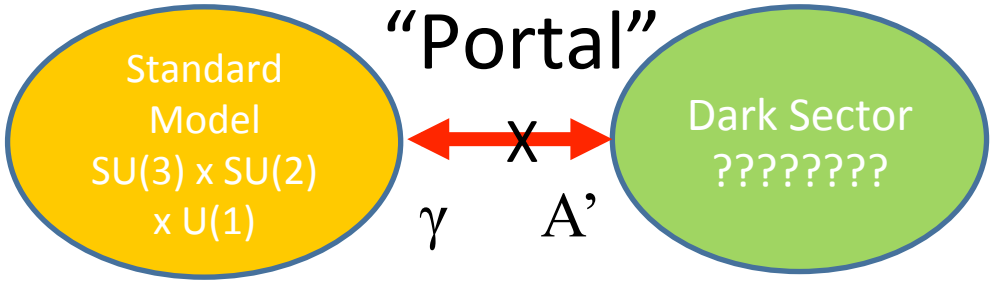


Fergus Wilson
Rutherford Appleton Laboratory
For the BaBar collaboration

WIN 2017

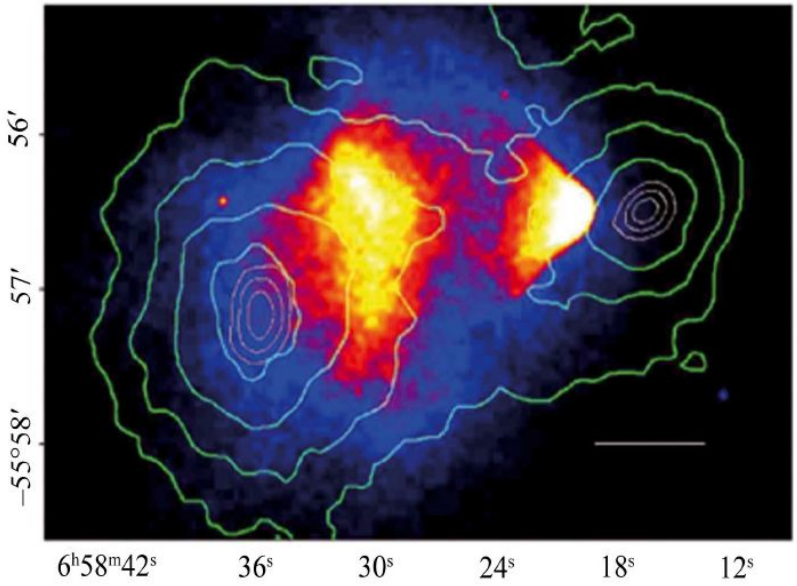


New Interactions beyond the SM



Portal	Coupling Term	Mediator
Higgs	$\varepsilon_h \lvert h\rvert^2 \lvert\phi\rvert^2$	Dark Scalar (A^0)
Neutrino	$\varepsilon_\nu (hL)\psi$	Sterile Neutrino
Axion	$\frac{1}{f_a} a F_{\mu\nu} F^{\mu\nu}$	ALPSs
Vector	$\frac{\varepsilon}{2} F^Y_{\mu\nu} F'^{\mu\nu}$	Dark Photon (A')

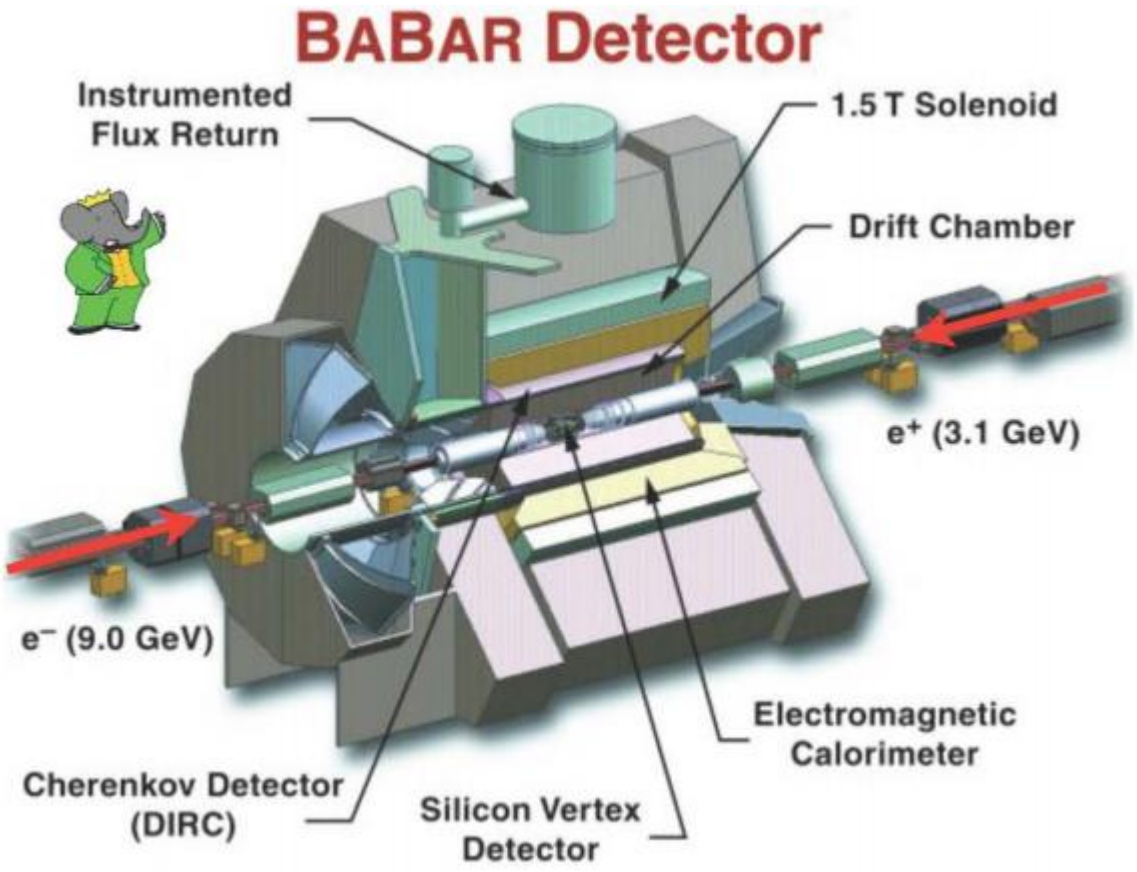
- Dark sector particles couple weakly to the Standard Model.
- Dark sector particles still interact gravitationally.
- Can be in mass range MeV – GeV.
- Dark photon A' could:
  - Mix with SM photon, which in turn couples to SM final states: "Visible"
  - Decay to lighter dark matter particles χ that escape detection: "Invisible".
- Could explain:
  - Dark Matter, muon g-2 anomaly, proton charge radius, …



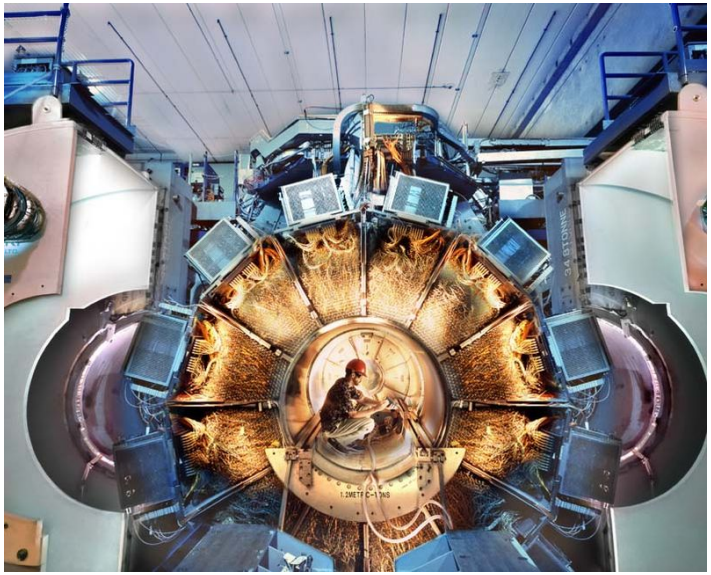
Gravitational lensing

BaBar detector at PEP-II

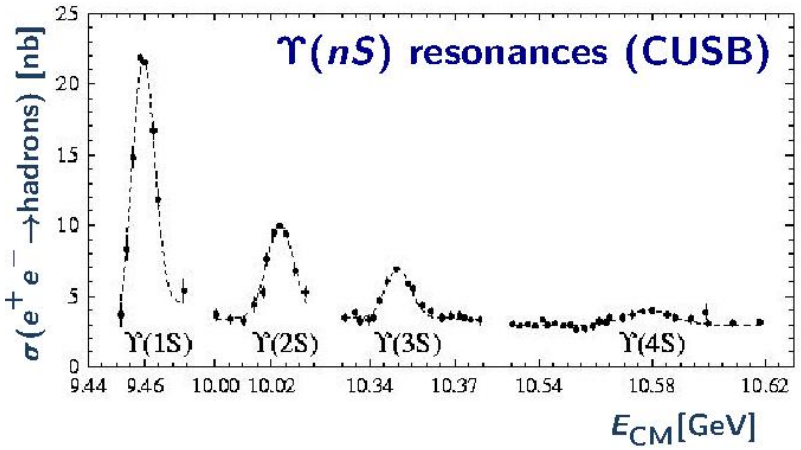
Took data 1999-2008 at PEP-II asymmetric e^+e^- collider



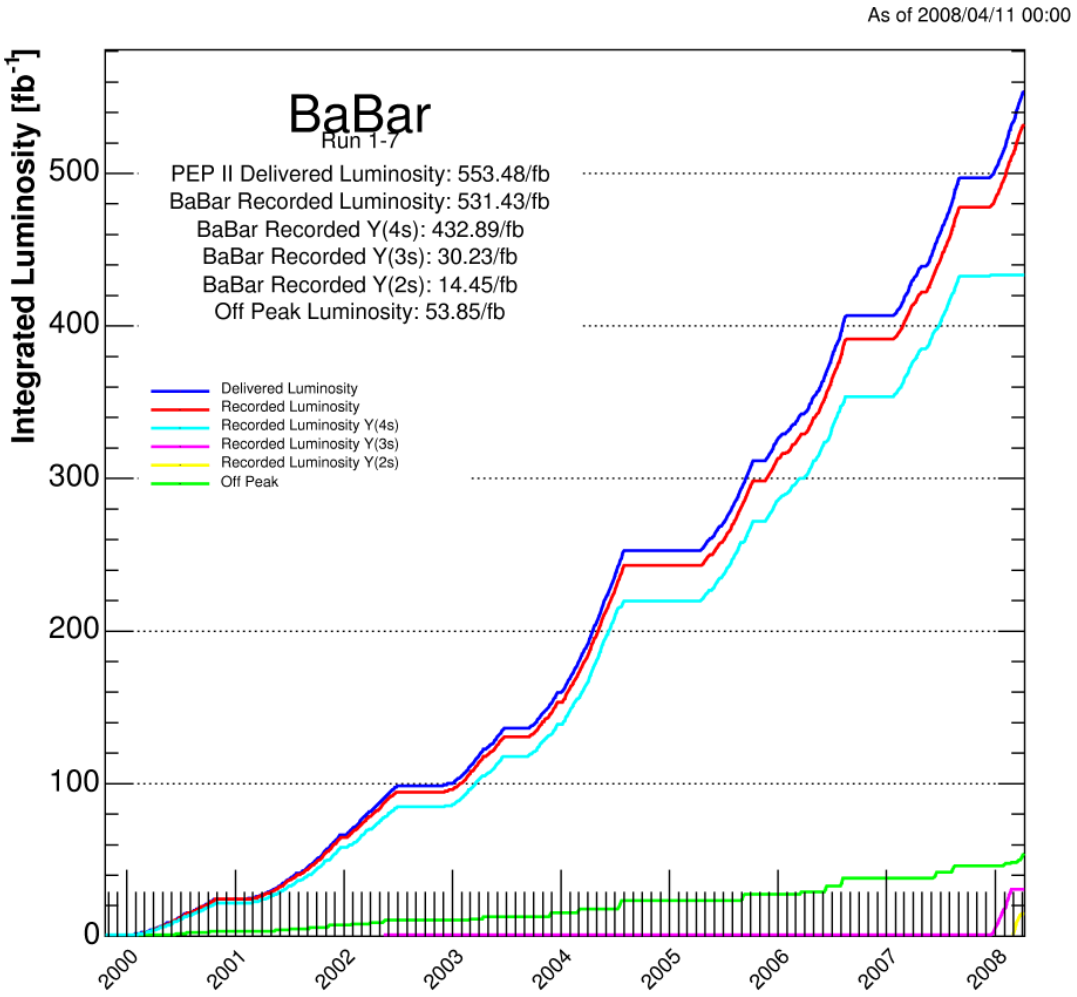
4ns bunch crossing



Luminosity

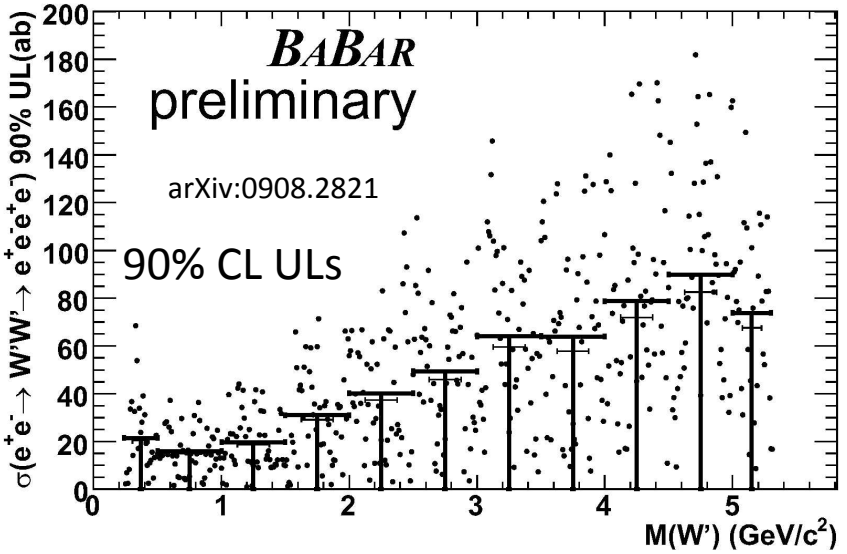


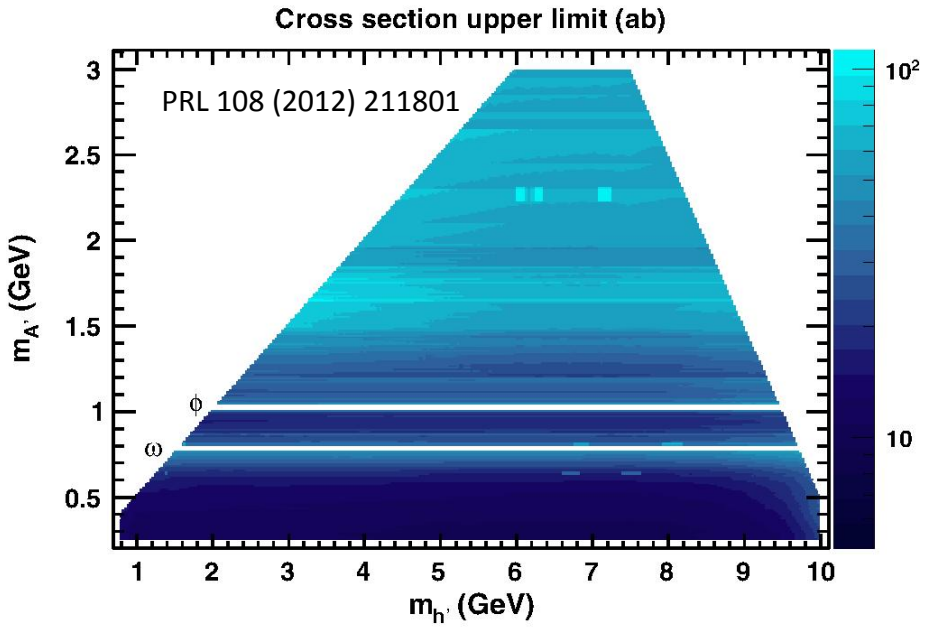
	Visible Modes	Invisible Mode
Trigger	Standard	"single γ"
$\Upsilon(4S)$	$424\,fb^{-1}$	$5.9\,fb^{-1}$
$\Upsilon(3S)$	$28\,fb^{-1}$	$28\,fb^{-1}$
$\Upsilon(2S)$	$14.4\,fb^{-1}$	$14.4\,fb^{-1}$
off-peak	$48\,fb^{-1}$	$4.2\,fb^{-1}$
Total	$514\,fb^{-1}$	$53\,fb^{-1}$



Visible decays of a Dark Sector at BaBar

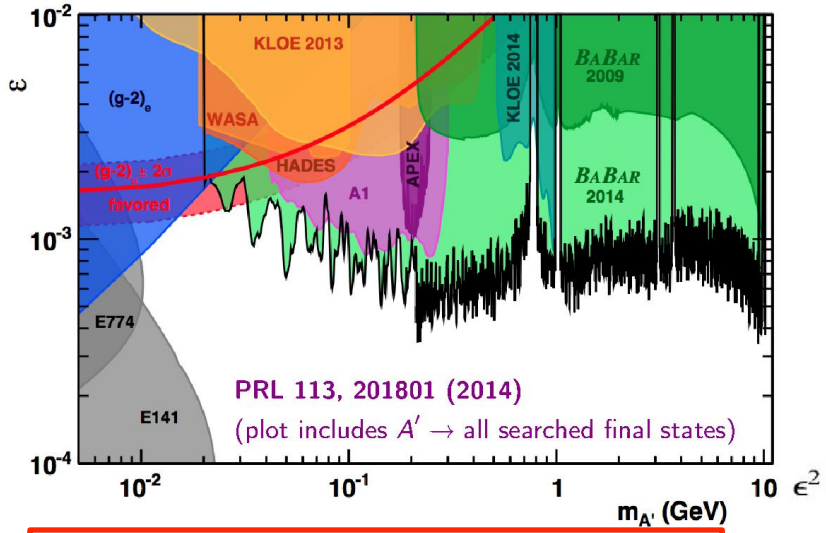
- Dark Photon
  - $e^+e^- \to \gamma A', A' \to l^+l^-$
  - Signal: 2 leptons, 1 photon
  - PRL 113 (2014) 201801
- Dark Sector Higgs Boson
  - $e^+e^- \to A'^* \to A'h', h' \to A'A', A' \to f^+f^-$
  - Signal: 3 pairs of charged particles
    - (f = leptons, mesons)
  - PRL 108 (2012) 211801
- Dark Sector Muonic Dark Force
  - $e^+e^- \to \mu^+\mu^- Z', Z' \to \mu^+\mu^-$
  - Signal: 4 leptons
  - PRD 94 (2016) 011102
- Dark Sector Long-Lived Particle
  - $e^+e^- \to X L', L' \to f^+f^-$
  - Signal: displaced vertex
  - PRL 114 (2015) 171801
- Dark Sector Gauge Boson W'
  - $e^+e^- \to A'^*, A'^* \to W'W', W' \to l^+l^-$
  - Signal: 2 pairs of leptons
  - arXiv:0908.2821



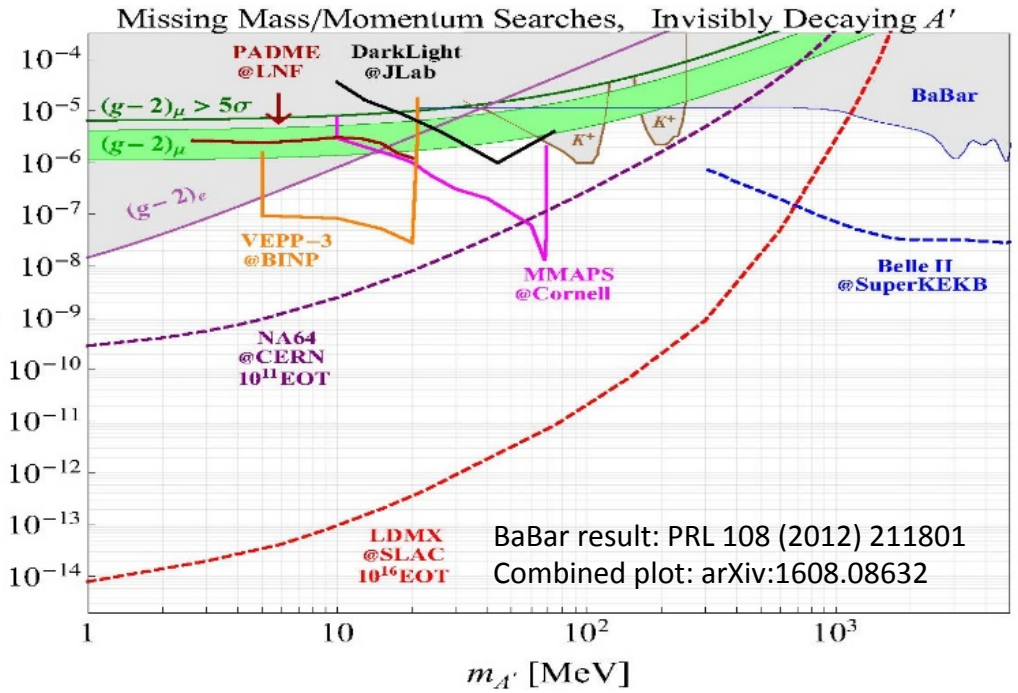


Summary of BaBar visible decay results

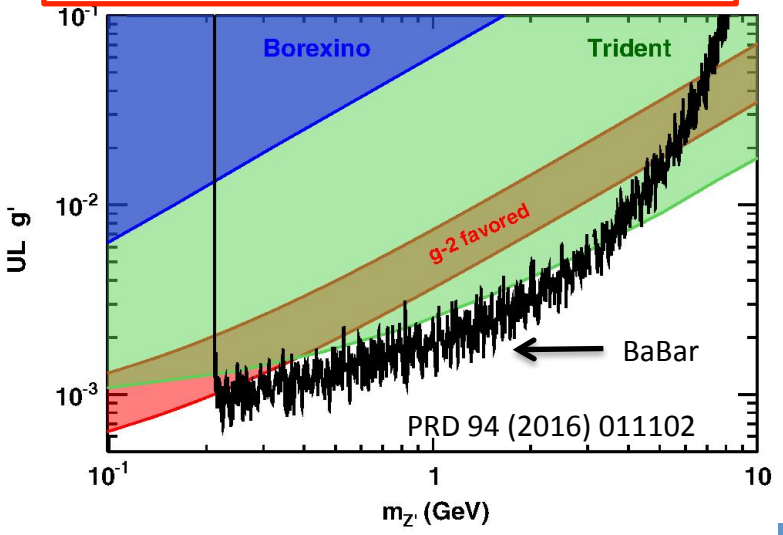
Search for dark photon in $e^+e^- \to \gamma A'$, $A' \to \mu^+\mu^-, e^+e^-$



Search for dark Higgs boson in $e^+e^- \to h' A'$, $h' \to A' A'$, $A' \to f^+ f^-$

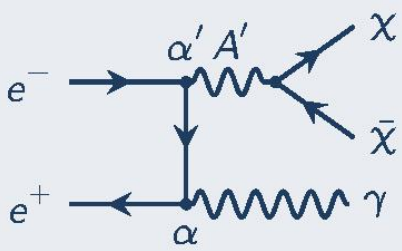


Search for muonic dark forces in $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to \mu^+\mu^-$



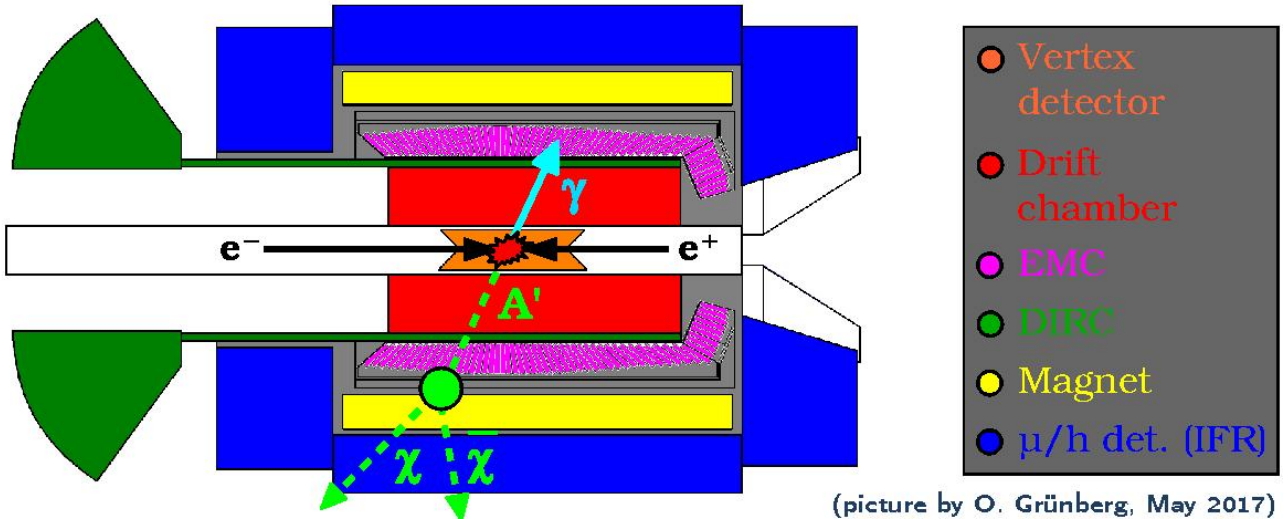
Limits assume no decays to invisible final states

Search for invisible decay of dark photon



$$\begin{cases} \alpha' = \epsilon^2 \alpha \\ \chi = \text{undetectable DM particle} \end{cases}$$

- Search for photon and missing energy/mass in range 0-8 GeV/c^2
- Reconstruct missing mass squared, M_X^2.
- Scan through M_X^2 distribution, looking for bumps above a smooth background.
- Assume A' width < experimental resolution.
- Assume a single A' is present.



(picture by O. Grünberg, May 2017)

$$M_X^2 = s - 2E_\gamma^* \sqrt{s}$$

Dedicated "Single-Photon" Trigger

- Dedicated single-γ trigger required.
- A' production rate expected to be independent of ϒ(nS).
- Two datasets acquired.

	High Mass	Low Mass
$\Upsilon(4S)$	----	$5.9\,fb^{-1}$
$\Upsilon(3S)$	$20\,fb^{-1}$	$28\,fb^{-1}$
$\Upsilon(2S)$	$14.4\,fb^{-1}$	$14.4\,fb^{-1}$
off-peak	$1.5\,fb^{-1}$	$4.2\,fb^{-1}$
Total	$35.9\,fb^{-1}$	$53\,fb^{-1}$

- Hardware level
  - 1 or more calorimeter clusters with $E_{LAB} > 0.8$ GeV
- Software level

Low Mass:

- $E^*_\gamma > 2$ GeV
- No charged track from interaction region
- Used on full 53 fb^{-1} data sample

High Mass:

- $E^*_\gamma > 1$ GeV
- No charged track from interaction region
- Active on ~36 fb^{-1} data sample

Candidate Selection

Low Mass Region

- $0 < M_X < 5.5$ GeV
- Background
  - $e^+e^- \rightarrow \gamma\,\gamma$ with missing γ
  - Peaks at $M_X = 0$
- $E^*_\gamma > 3$ GeV
- $|\cos\theta^*_\gamma| < 0.6$ to reject radiative Bhabhas
- No primary track from interaction region
- No other secondary track with $p^* > 1$ GeV

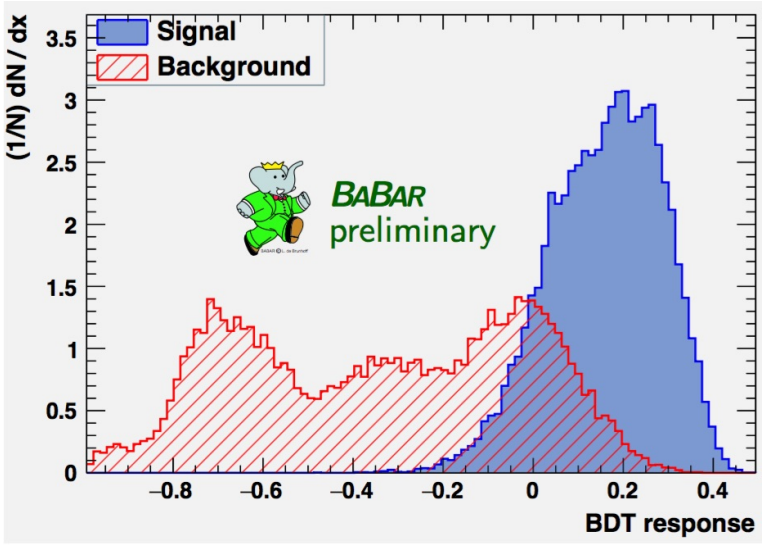
High Mass Region

- $5.5 < M_X < 8.0$ GeV
- Background
  - $e^+e^- \rightarrow e^+e^-\,\gamma$ with missing e^+e^-
  - Increases with M_X
- $E^*_\gamma > 1.5$ GeV
- $|\cos\theta^*_\gamma| < 0.6$ to reject radiative Bhabhas
- No primary track from interaction region
- No other secondary track with $p^* > 0.1$ GeV

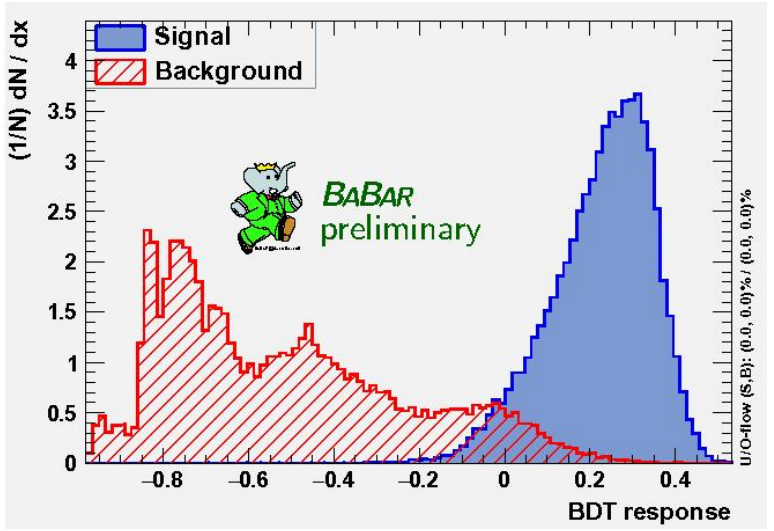
Multivariate discriminant

- Separate signal from background with a Boosted Decision Tree (BDT).
- 12 discriminating variables:
  - Photon quality;
  - Neutral energy not associated with photon;
  - Kinematics of 2nd most-energetic photon and separation from primary photon;
  - Activity in muon chambers along direction of missing momentum.
- Trained in low and high mass regions.

High Mass region



Low Mass region



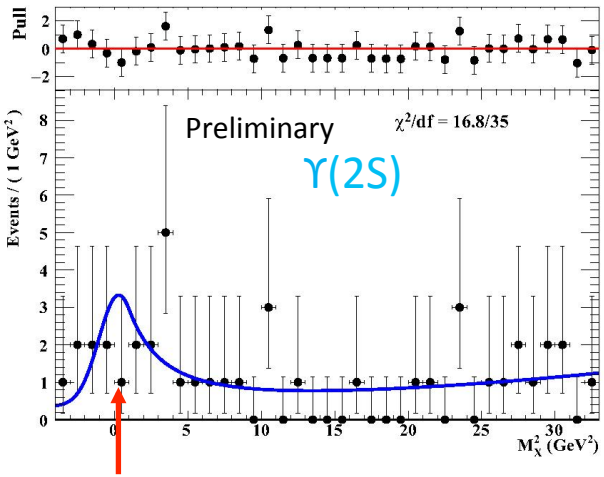
Search for signal

- Data samples:
  - Low Mass Region: 3 BDT selection criteria (Loose Signal, Tight Signal, Background) applied to $\Upsilon(2S)$, $\Upsilon(3S)$, and $\Upsilon(4S)$ samples.
  - High Mass Region: 2 BDT selection criteria (Loose Signal, Background) applied to $\Upsilon(2S)$ and $\Upsilon(3S)$ samples
- Signal extraction from missing mass M_X^2 distribution:
  - Background distribution:
    - Taken from data with -0.5<BDT<0
    - Crystal Ball function (peaking background) plus 2nd order polynomial (low-mass region) or polynomial x exponential function (high-mass region)
  - Signal distribution:
    - Taken from high statistics simulation.
    - Crystal Ball function with M_X^2 mass-dependent width (1.5 – 0.7 GeV^2).
- Simultaneous unbinned maximum likelihood fit to:
  - 9 independent samples for $m_{A'} < 5.5$ GeV.
  - 4 independent samples for $5.5 < m_{A'} < 8.0$ GeV.

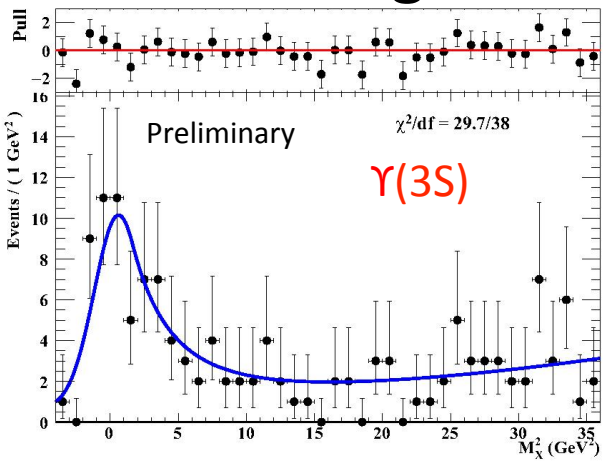
Understanding the background

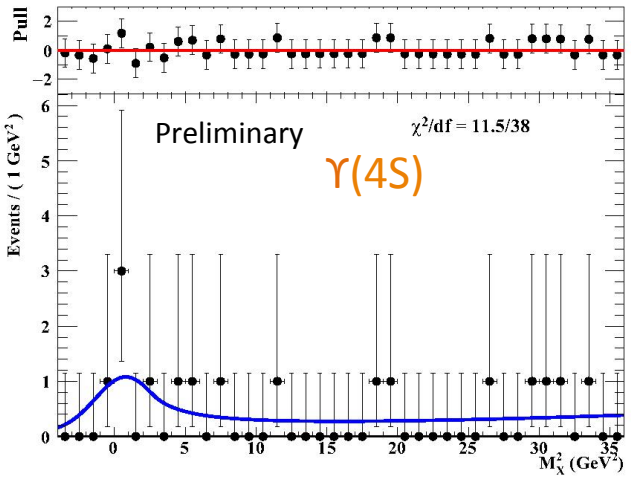
Examples fits to data with blue solid line showing background-only fit with mixing strength ε=0.

Low mass region

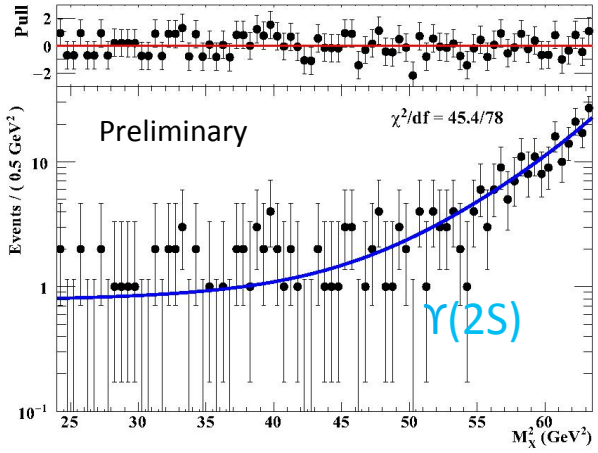


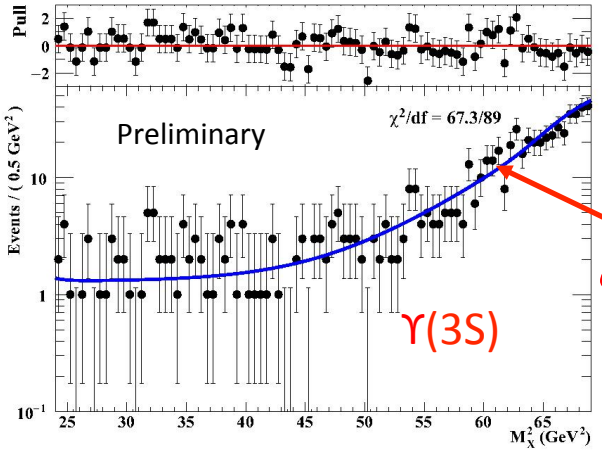
$e^+e^- \to \gamma\gamma$





High mass region





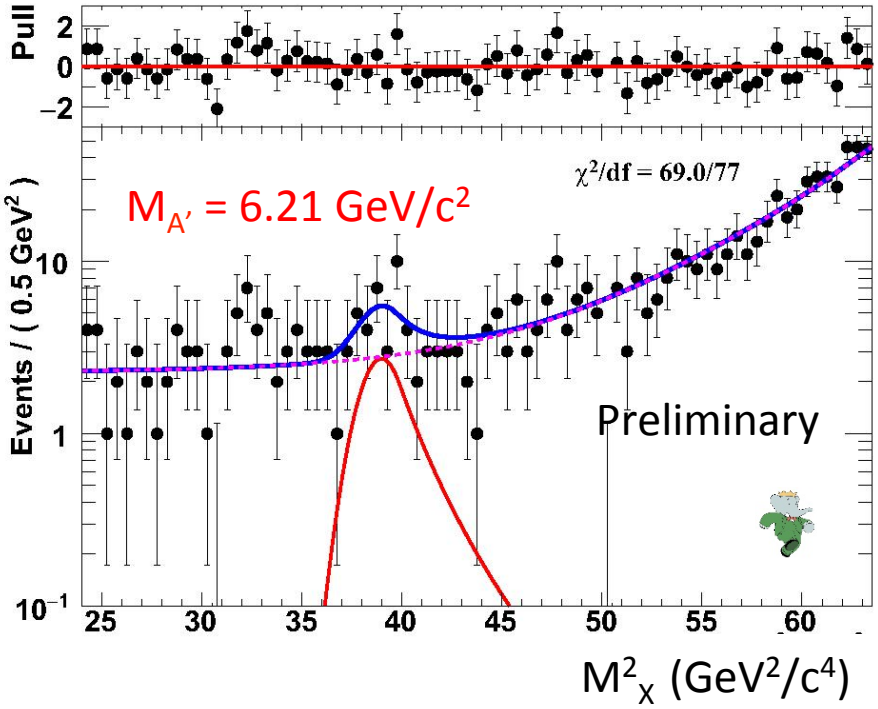
$e^+e^- \to e^+e^-\gamma$

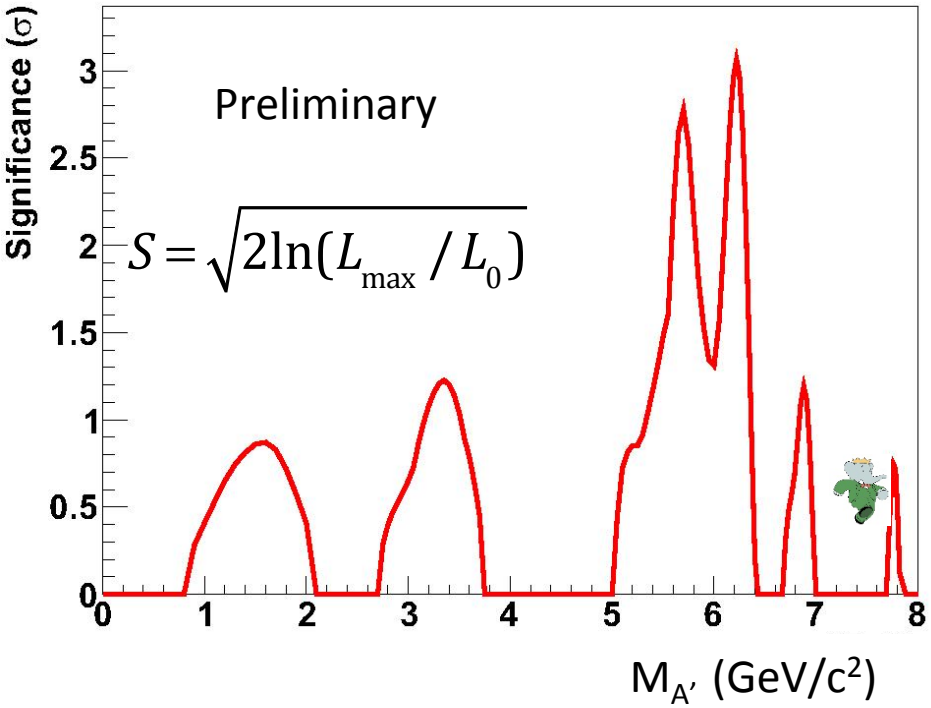
Signal identification

arXiv:1702.03327

Scan through 166 $M_{A'}$ masses (step size ~ half mass resolution)

Most significant fit at $M_{A'}$ = 6.21 GeV/c^2: 3.1σ





No significant signal observed

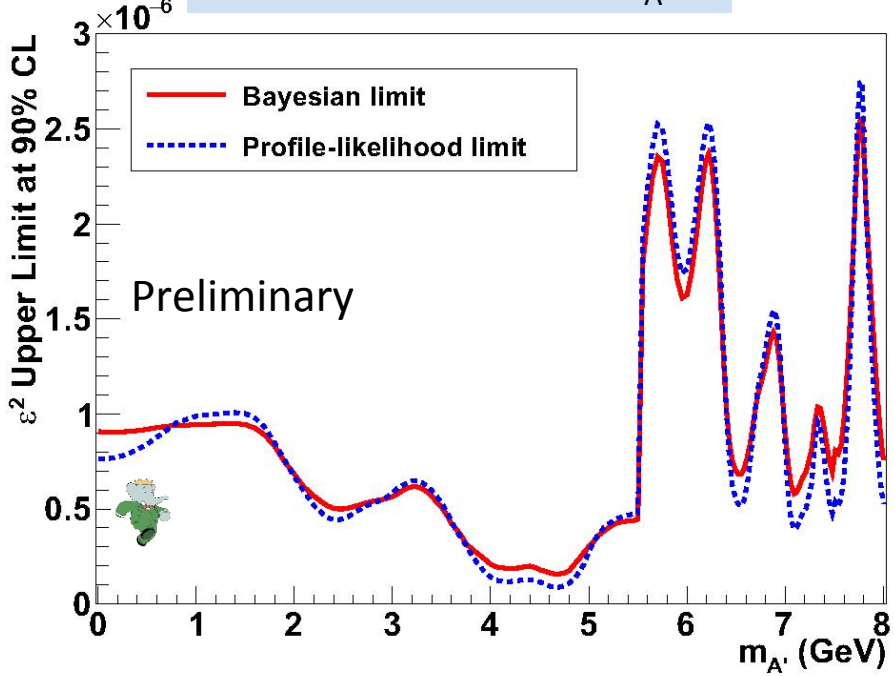
Set upper limits on mixing parameter ε as a function of $M_{A'}$

Constraints

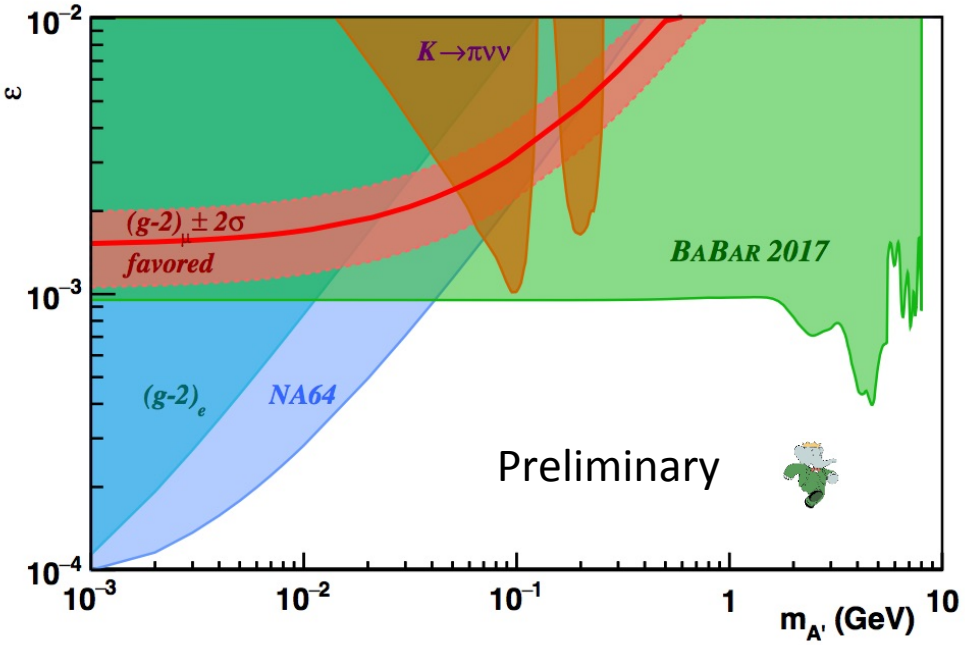
arXiv:1702.03327

Extends excluded range in both ε and $M_{A'}$.
Excludes entire region preferred by the muon g-2 anomaly.
Can be used to constrain any model with invisible narrow resonance.

90% CL on ε^2 versus $M_{A'}$



90% CL on ε versus $M_{A'}$



Conclusion

- BaBar has previously published searches for Dark Sector decays to visible final states.
- Here, report a search for a Dark Photon decaying to an invisible final state.
- No evidence for a signal.
- Upper limits placed on Dark Photon mixing parameter $\varepsilon < 10^{-3}$ in mass range 1 MeV to 10 GeV.
- Region that would explain muon g-2 anomaly now excluded by both visible and invisible decay channels.
- arXiv:1702.03327 submitted to Phys. Rev. Lett.
- BaBar continues to search for a Dark Photon decaying to visible states. Expect more new results soon…