Search for invisible decays of the dark photon at *BABAR*

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on behalf of the *BABAR* Collaboration

LDMA'17 Light Dark Matter 2017

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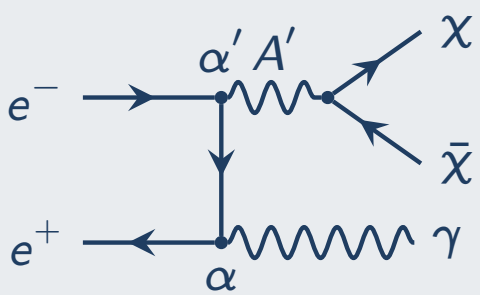
Motivation

- Hidden/Dark sector New Physics models include particles that
  - can be constituents of Dark Matter in the universe
  - explain some astrophysical anomalies
    - e.g. excess of positrons from galactic core [Astron.Astrophys. 407 (2003) L55]
  - explain muon $g-2$ anomaly
- hidden sector can include "dark photon" A'
  - mass of order GeV
  - coupling (loose) to SM matter via kinetic mixing with photon, $\Delta\mathcal{L} = -\frac{1}{2}\epsilon F^{\mu\nu}F'_{\mu\nu}$
- A' may be invisible, decaying into lighter dark-matter particles that escape detection
  - that spoils limits obtained assuming it must decay into ordinary matter particles

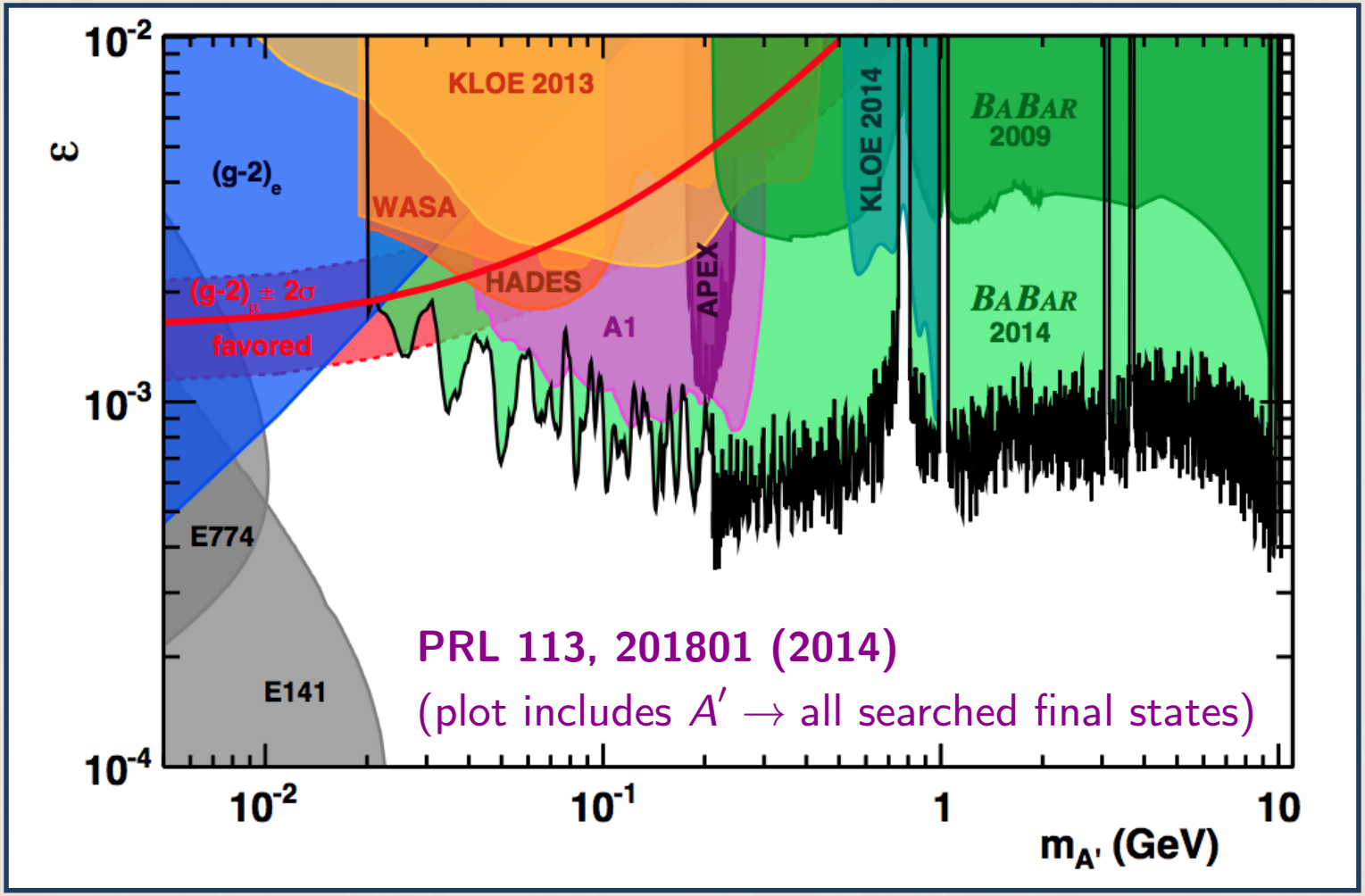
$A' \to$ invisible in *BABAR*



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

Existing upper limits on A' mass and coupling

- PRL 113, 201801 (2014), former *BABAR* search $e^+e^- \to A'\gamma$, $A' \to e^+e^-$, $\mu^+\mu^-$ using 514 fb^{-1} data sample, 90% CL limits on model parameters ϵ, $m_{A'}$

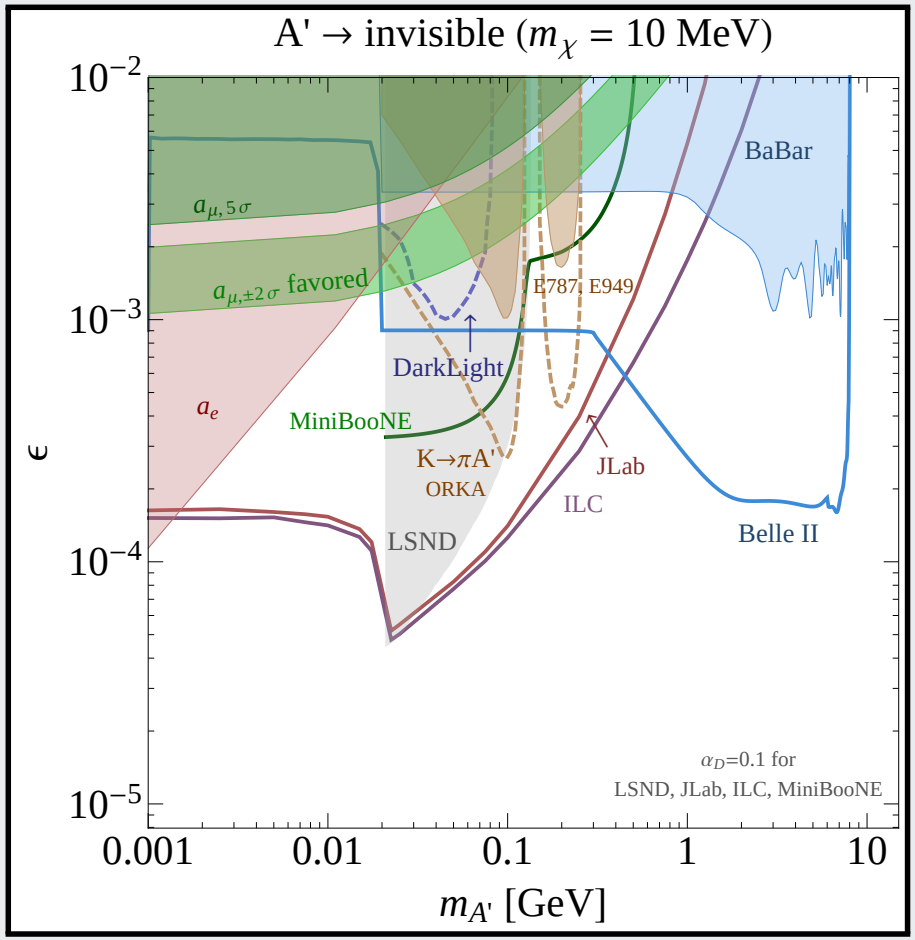


BABAR ICHEP 2008 conf. note, arXiv:0808.0017 [hep-ex]

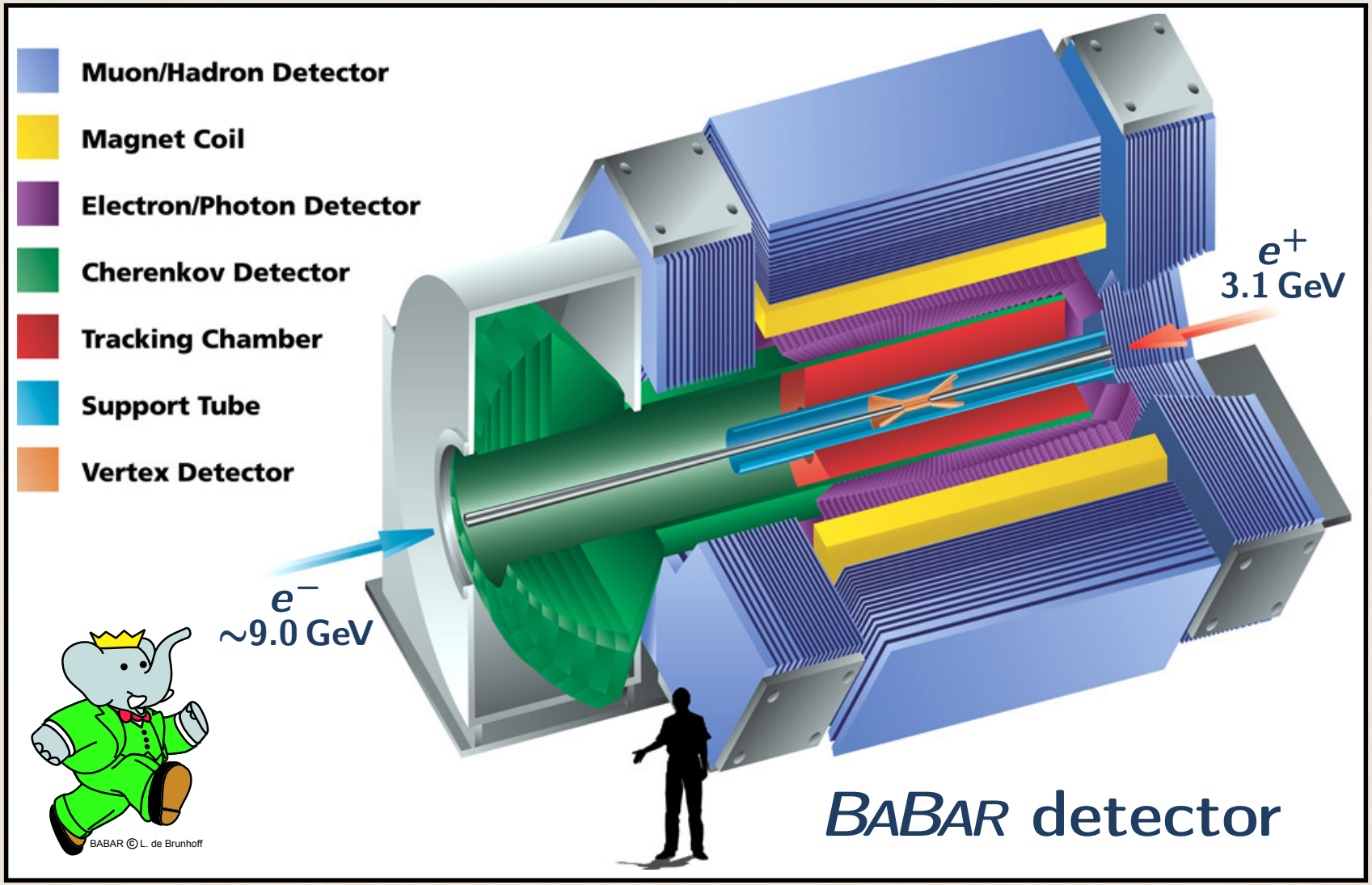
Search for Invisible Decays of a Light Scalar in Radiative Transitions $\Upsilon(3S) \to \gamma A^0$

- *BABAR* light Higgs search
- based on full $\Upsilon(3S)$ sample, $28\,\text{fb}^{-1}$
- conf. note, never published on journal, but has 101 citations in inspirehep
- re-interpreted as Dark Photon search, for instance in "Dark Sectors and New, Light, Weakly-Coupled Particles", R. Essig *et al.*, arXiv:1311.0029

from R. Essig *et al.*, arXiv:1311.0029



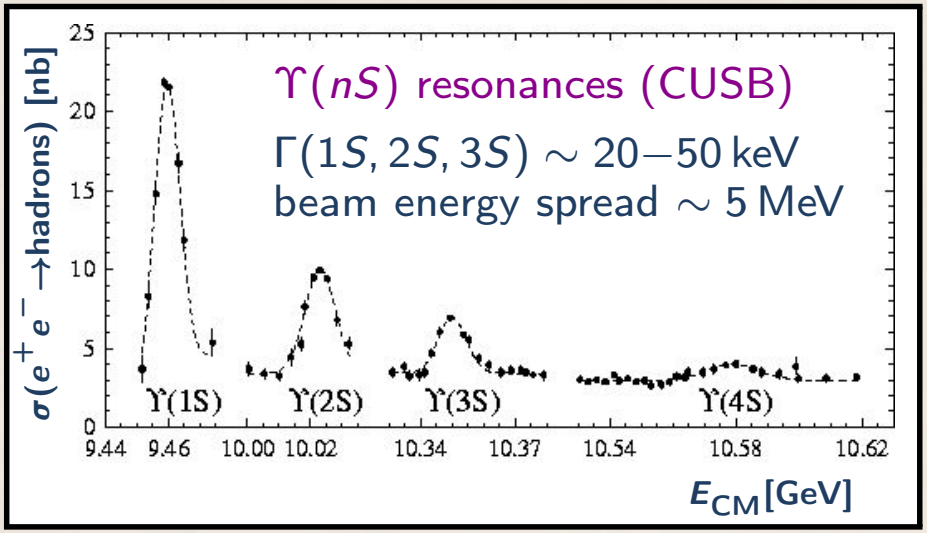
BABAR detector at PEP-II, SLAC National Accelerator Laboratory



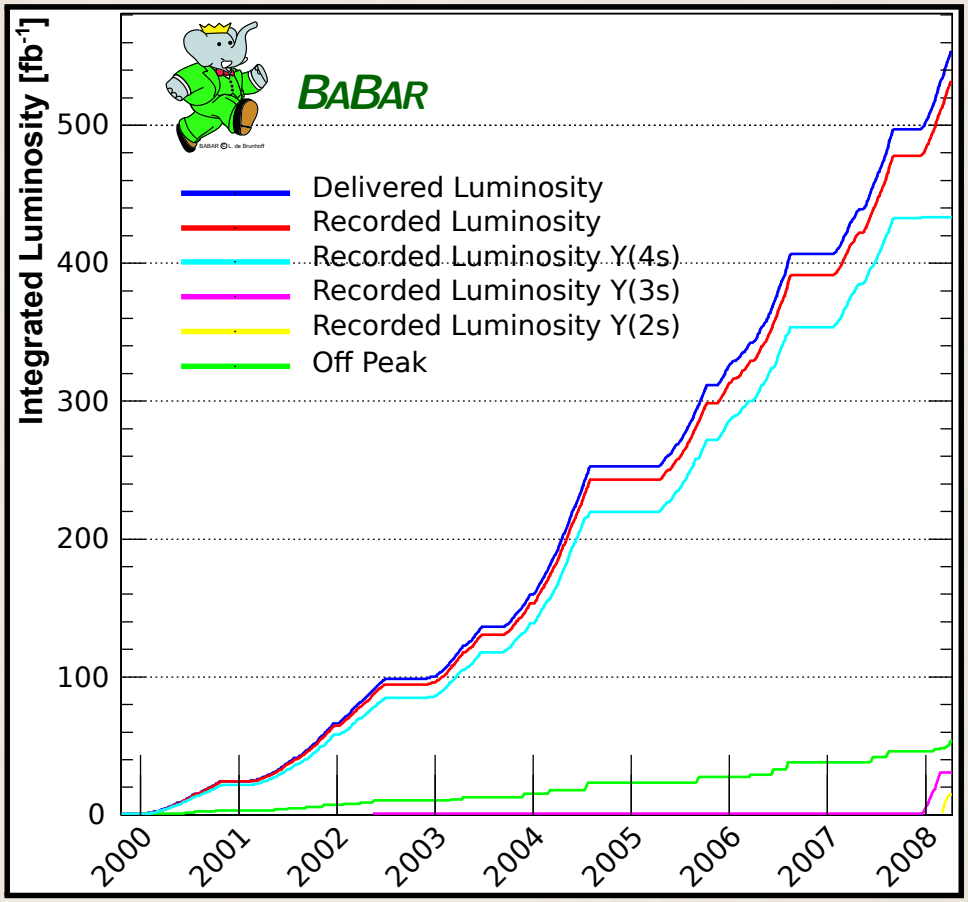
BABAR main focus: study of CP violation in B mesons

BABAR: CM energy, collected luminosity

center-of-mass energies



integrated luminosity over time



data samples (large and clean)

	events	$\mathcal{L}$(fb^{-1})
$\Upsilon(4S) \to B\bar{B}$	$471 \cdot 10^6$	424
$\Upsilon(3S) \to$ visible	$121 \cdot 10^6$	28
$\Upsilon(2S) \to$ visible	$99 \cdot 10^6$	14
off-peak		48
single-γ trigger $\Upsilon(4S, 3S, 2S)$		53

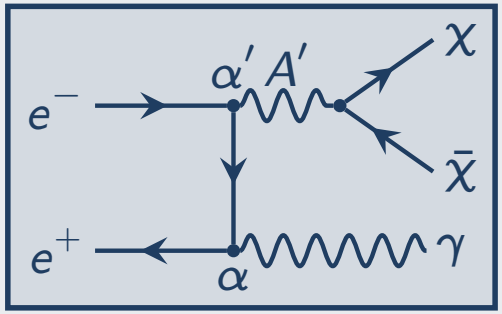
data-taking ended in April 2008


The BABAR search

Analysis strategy

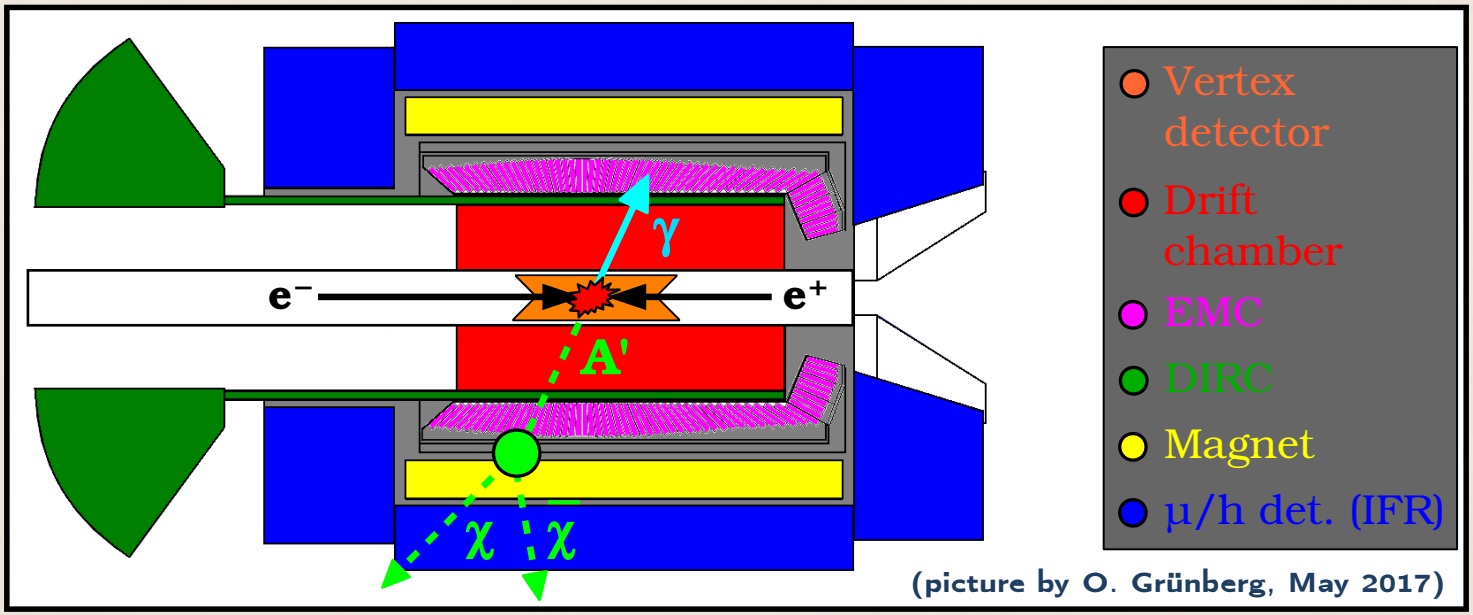
search for

- $e^- e^+ \to \gamma A'$, $A' \to$ invisible (e.g. $\chi\bar{\chi}$)
  i.e. one single photon and nothing else



$$\sigma \propto \alpha' \alpha = \epsilon^2 \alpha^2$$

- reconstruct A' mass, $M^2_{A'} = s - 2\sqrt{s}E^*_\gamma$
- scan $M^2_{A'}$ distribution, fitting bumps over smooth background, compute significance
  [A' decay width $\Gamma_{A'}$ expected $\ll$ experimental resolution on $M_{A'}$]



Trigger

BABAR collected $\sim 53\,\text{fb}^{-1}$ of data with dedicated single photon triggers during its last year of data taking, mostly collected at the $\Upsilon(3S)$ and $\Upsilon(2S)$ peaks

Hardware trigger

- ≥ 1 EMC cluster with $E_{\text{LAB}} > 800\,\text{MeV}$
- $52.9\,\text{fb}^{-1}$ data sample

Software triggers

- high energy photon trigger line
  - $E^*_\gamma > 2\,\text{GeV}$
  - no track from interaction region (SVT [+DCH])
  - active on full $52.9\,\text{fb}^{-1}$ data sample
- low energy photon trigger line
  - $E^*_\gamma > 1\,\text{GeV}$
  - no track from interaction region (SVT [+DCH])
  - active on $35.9\,\text{fb}^{-1}$ out of the total $52.9\,\text{fb}^{-1}$ data sample

Low-mass and high-mass pre-selections

Low-mass $-4 < M^2_{A'} < 36\,\mathrm{GeV}^2$

- approximately $0 < M_{A'} < 5.5\,\mathrm{GeV}$
- background:
  - $e^+e^- \to \gamma\gamma$ with lost γ
  - peaking at $M_{A'} = 0$
  - low tail away from $M_{A'} = 0$
- $E^*_\gamma > 3\,\mathrm{GeV}$
- $|\cos\theta^*_\gamma| < 0.6$ against radiative Bhabha
- no track from interaction region
- no DCH-only track with $p^* > 1\,\mathrm{GeV}$

High-mass $24 < M^2_{A'} < 69\,\mathrm{GeV}^2$

- approximately $5.5 < M_{A'} < 8.0\,\mathrm{GeV}$
- background:
  - $e^+e^- \to e^+e^-\gamma$ with lost e^+e^-
  - tail of $e^+e^- \to \gamma\gamma$
  - large but smooth background
- $E^*_\gamma > 1.5\,\mathrm{GeV}$
- $|\cos\theta^*_\gamma| < 0.6$ against radiative Bhabha
- no track from interaction region
- no DCH-only track with $p^* > 0.1\,\mathrm{GeV}$

Boosted Decision Tree (BTD) discriminant

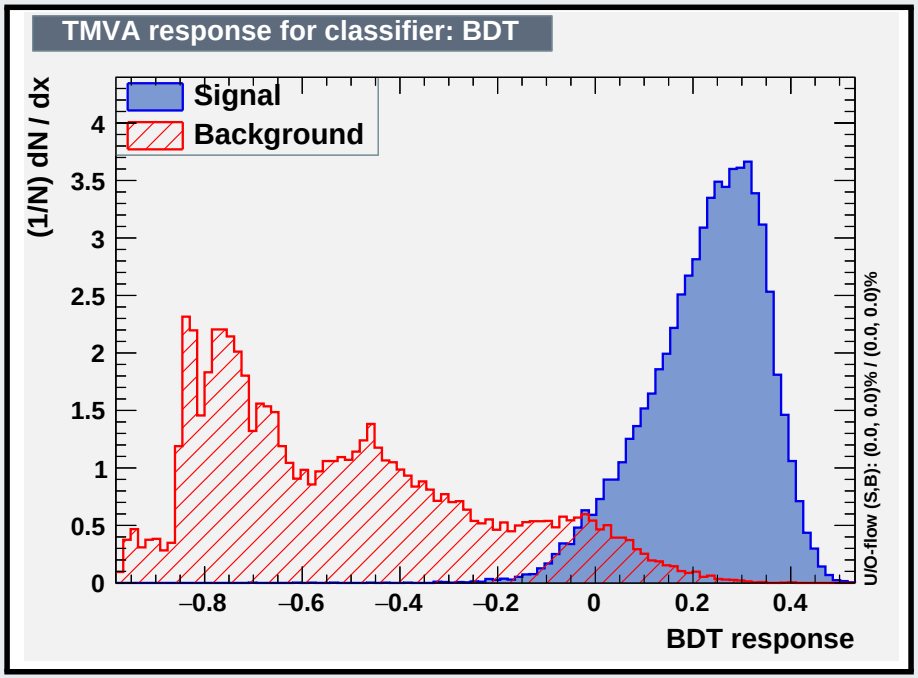
12 input variables

- fired vs. expected EMC crystals
- two transverse moments of EMC shower
- total EMC energy other than most energetic photon
- CM energy and polar angle of 2nd most energetic EMC cluster
- azimuthal angle difference $\Delta\phi_{12}$ between the highest and second-highest energy EMC clusters (the $e^+e^- \to \gamma\gamma$ events with partial energy deposit in the EMC tend to peak at $\Delta\phi_{12} \sim \pi$)
- distance of missing momentum from EMC crystal edges in θ and ϕ
- angle $\Delta\phi_{NH}$ between the primary photon and the IFR cluster closest to the missing momentum direction ($e^+e^- \to \gamma\gamma$ events peak at $\cos\Delta\phi_{NH} \sim -1$)
- variable measuring how close is missing momentum to uninstrumented IFR regions
- $\cos\theta^*_\gamma$ (discriminates between signal and background distributions)

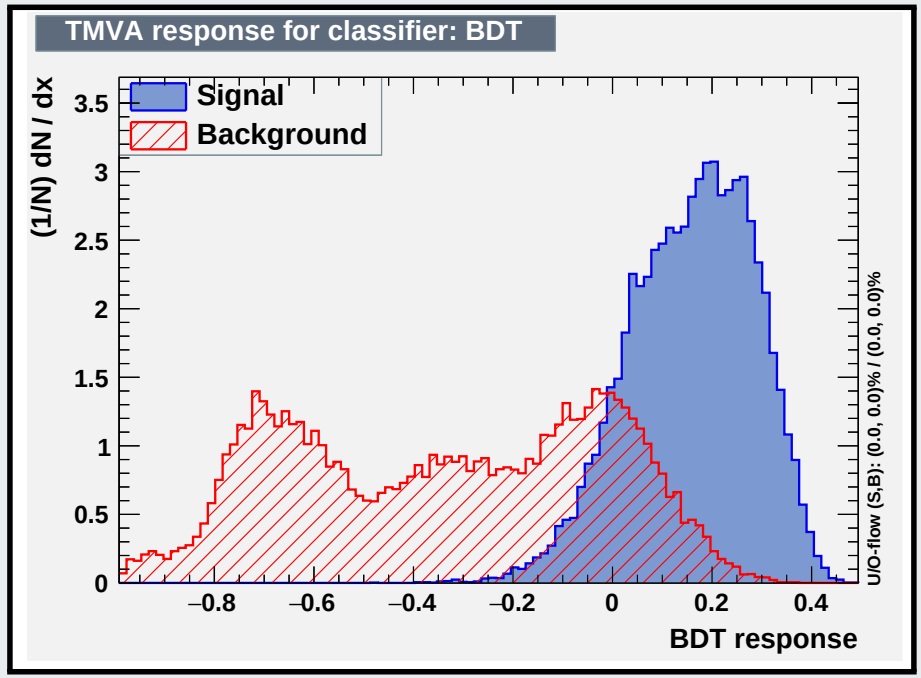
- background sample: 25k ($3\,\text{fb}^{-1}$) of $\Upsilon(3S)$ data
- signal sample: 25k simulated $e^+e^- \to A'\gamma$, $A' \to$ invisible, uniform mass distribution
- BDT trained separately in low-mass and high-mass regions

BDT response

Low-mass selection



High-mass selection



(TMVA = Toolkit for MultiVariate Analysis, `http://tmva.sourceforge.net/`)

Tight, loose and background selection regions

tight selection region, R_T

- BDT cut, $\mathrm{FoM}_1 = \dfrac{\epsilon_S}{\max(N_{\mathrm{BKG}}, 2.3)}$
  - maximal suppression of peaking bkg
  - appropriate for low-mass A'
- $-0.4 < \cos\theta^*_\gamma < 0.6$
  ($e^+e^- \to \gamma\gamma$ photons in EMC barrel)

loose selection region, R_L

- BDT cut, $\mathrm{FoM}_2 = \dfrac{\epsilon_S}{\sqrt{N_{\mathrm{BKG}}}}$
  - appropriate for high-mass A'
  - smooth background

background selection region, R_B

- select background using BDT output
  (use to fit background shape on data)

define 9 + 4 non-overlapping data samples

9 low-mass ($0.0 < M_{A'} < 5.5$ GeV) samples

- $R_{L'} = R_L$, but excluding R_T
- $\{R_{L'}, R_T, R_B\} \times \{2S, 3S, 4S\} = 9$ samples

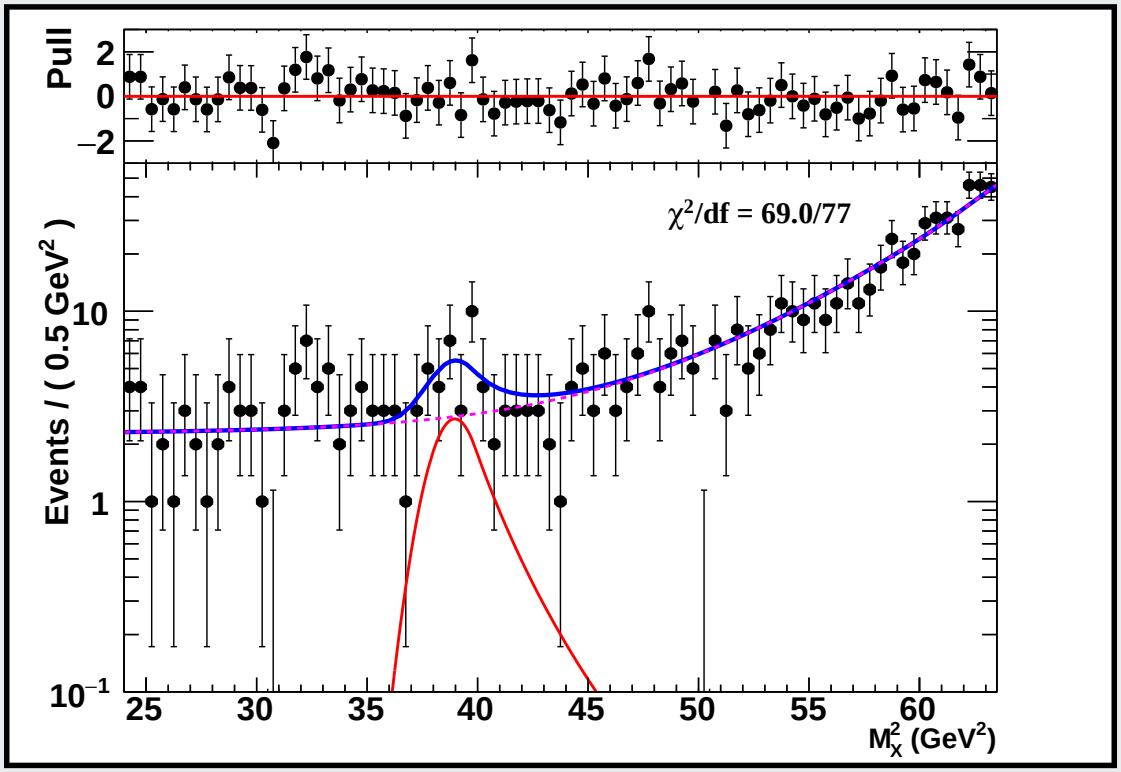
4 high-mass ($5.5 < M_{A'} < 8.0$ GeV) samples

- $\{R_L, R_B\} \times \{2S, 3S\} = 4$ samples

Signal PDF

- Crystal Ball for $e^+e^- \to A'\gamma$, from simulation (parameters depend on $M_{A'}$)
- correct simulated resolution using real data sample $e^+e^- \to \gamma\gamma$, where one photon converts to e^+e^- in detector material

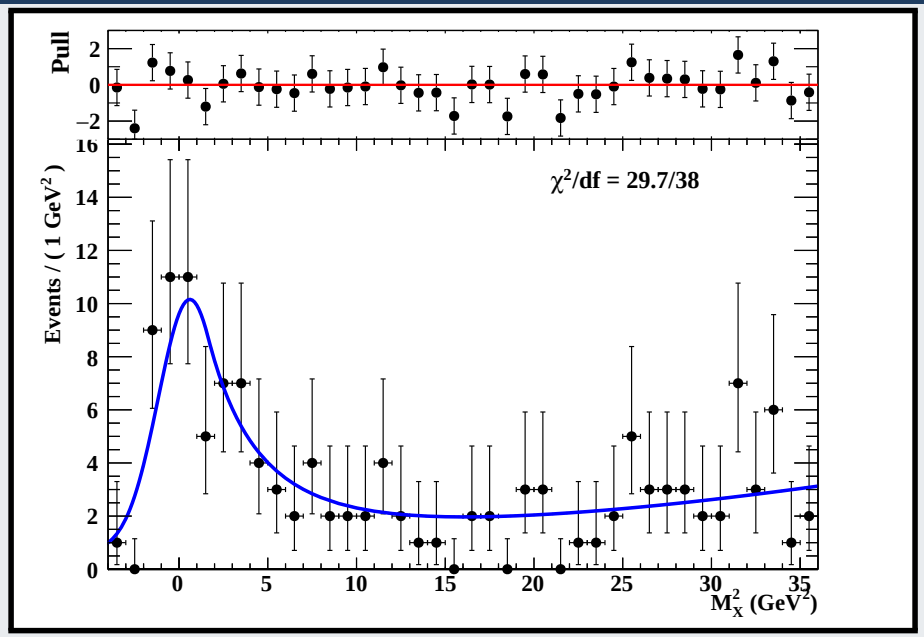
Example signal+background fit



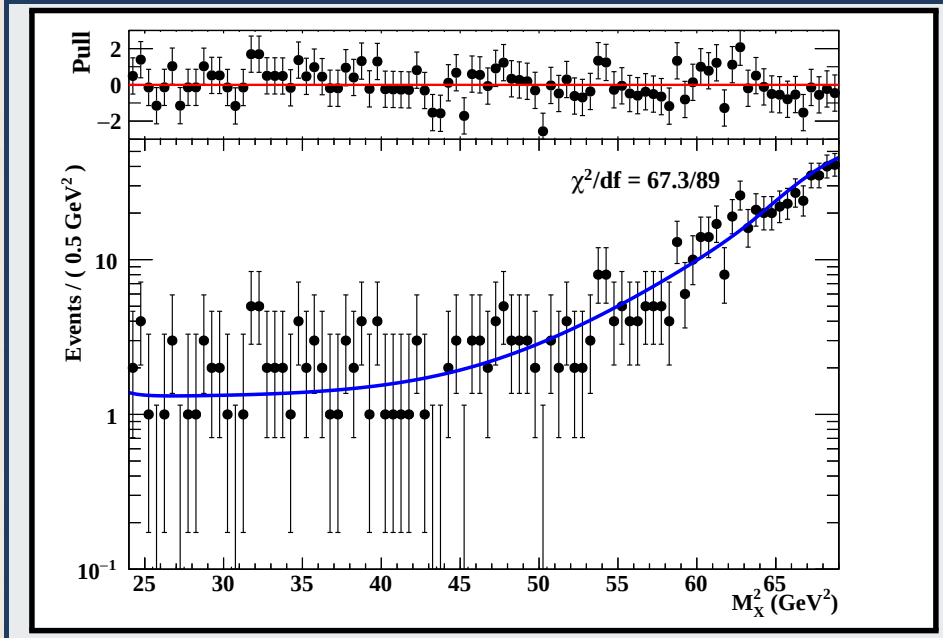
Background PDF

- low-mass region: second-order polynomial + Crystal Ball for $e^+e^- \to \gamma\gamma$
- high-mass region: sum of exponentiated polynomials

Example low-mass background fit



Example high-mass background fit



Fits and signal yield significance

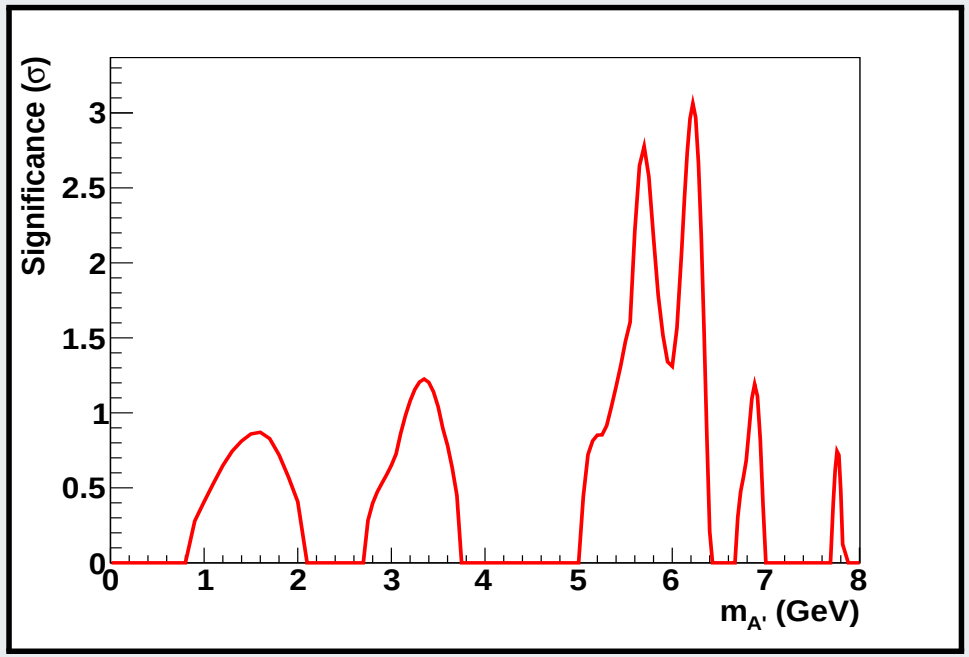
fit

- simultaneous unbinned extended maximum likelihood fit on all 9+4 samples
- signal normalization fixed to zero on 2 background data samples
- fit bkg shape on bkg region, float just bkg normalization on tight/loose signal regions
- scan total of 166 $M^2_{A'}$ values (spaced by about half the resolution)

signal significance

- local significance from likelihood-ratio test
$$\sigma = \sqrt{2 \ln(L_{max}/L_0)}$$
- local maximum of $3.1\,\sigma$ at $M_{A'} = 6.21\,\text{GeV}$
- overall global significance $2.6\,\sigma$ (estimated look-elsewhere effect with parametrized simulations)
- compute upper limits (both bayesian and frequentist)

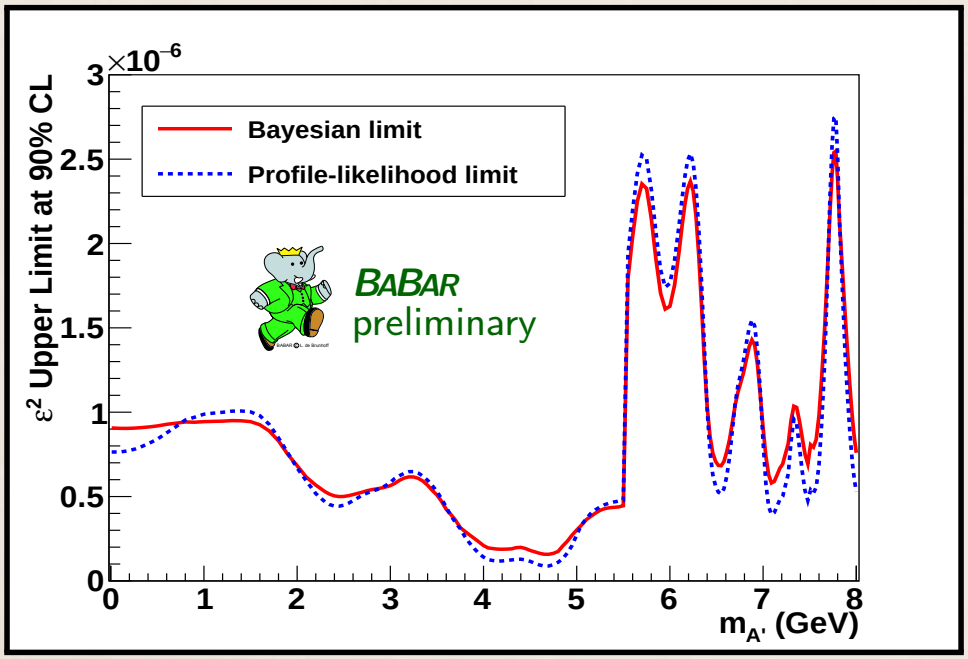
signal significance plot



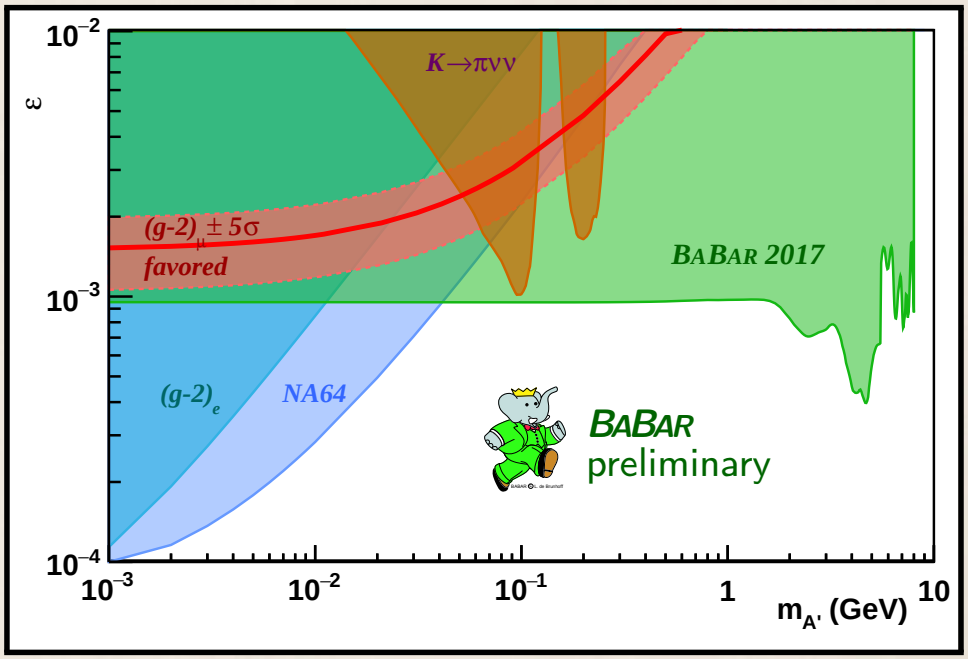
Constraints on Dark Photon theory model

- significant improvement over previous searches
- rule out entire region preferred by possible muon $(g-2)$ anomaly
- search can be re-interpreted to constrain models with invisible narrow resonance

A' mass-dependent limit on ϵ^2



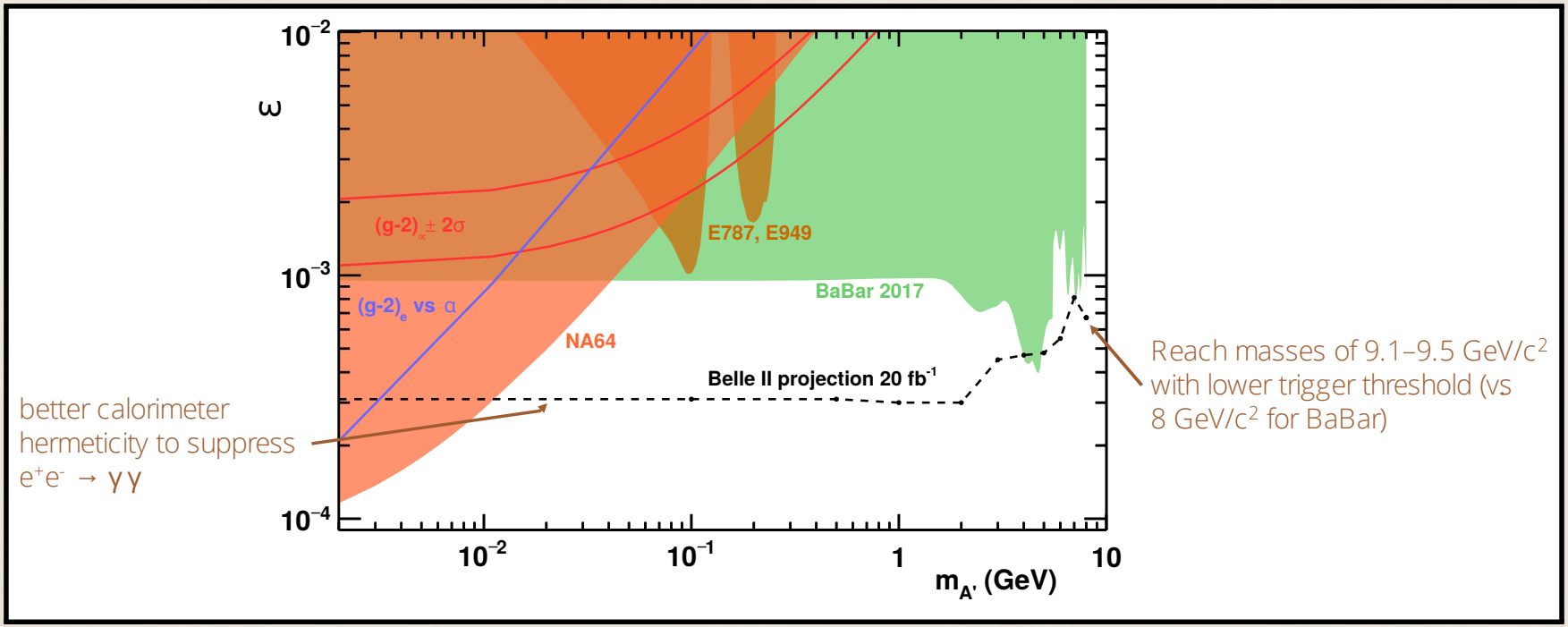
constraints on mass and coupling



arXiv:1702.03327, submitted to PRL

BelleII sensitivity for Dark Photon to invisible

Chris Hearty estimated the BelleII sensitivity for Dark Photon to invisible at U.S. Cosmic Visions: New Ideas in Dark Matter, March 2017



Summary

- *BABAR* searched for Dark Photon decaying to an invisible final state
- no evidence for signal, upper limits on theory model computed
  - results exclude Dark Photon as origin of muon $g-2$ anomaly
  - can be re-interpreted for models with narrow invisible resonance from e^+e^- collisions
- large improvement over previous measurements
- BelleII can significantly improve the search range
- paper submitted to PRL

Backup Slides

References

- **Early SPI/INTEGRAL measurements of galactic 511 keV line emission from positron annihilation**, P.Jean et al., Astron.Astrophys. 407 (2003) L55
- **Dark Sectors and New, Light, Weakly-Coupled Particles**, R. Essig *et al.*, arXiv:1311.0029 [hep-ph]
- **Dark Photon references**,
  P. Fayet, Phys. Lett. B 95 285 (1980), Nucl. Phys. B 187, 184 (1981); B. Holdom, Phys. Lett. B 166, 196 (1986); N. Borodatchenkova, D. Choudhury and M. Drees, Phys. Rev. Lett. 96, 141802 (2006); D. P. Finkbeiner and N. Weiner, Phys. Rev. D 76, 083519 (2007); M. Pospelov, A. Ritz, and M. B. Voloshin, Phys. Lett. B 662, 53 (2008); N. Arkani-Hamed et al., Phys. Rev. D 79, 015014 (2009)
- **Search for Invisible Decays of a Light Scalar in Radiative Transitions $\Upsilon(3S) \to \gamma A^0$**, *BABAR*, arXiv:0808.0017 [hep-ex]
- **Search for a dark photon in e^+e^- collisions at *BABAR*** ($A' \to e^+e^-,\ \mu^+\mu^-$)
  BABAR, PRL 113, 201801 (2014)
- **Search for invisible decays of a dark photon produced in e^+e^- collisions at BABAR**, *BABAR*, arXiv:1702.03327 [hep-ex]