Search for dark photon and long-lived particles at *BABAR*

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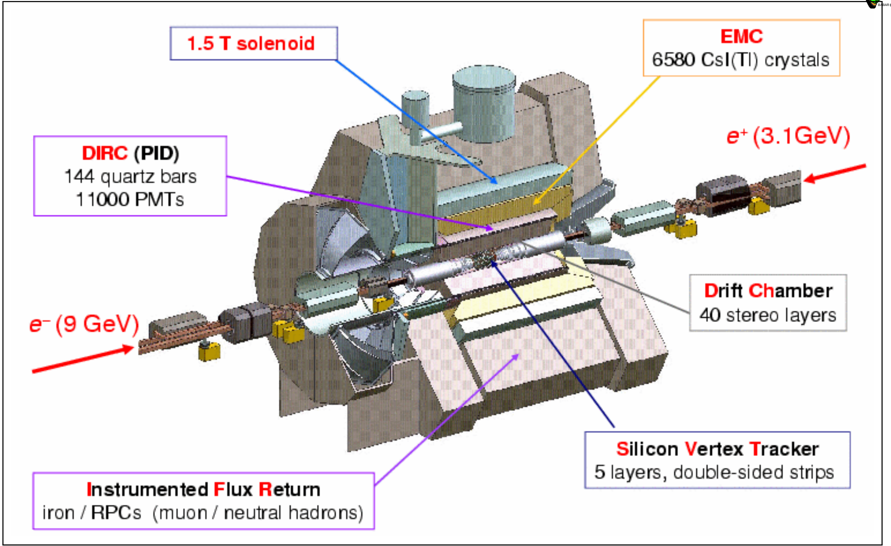
Outline

Introduction

New Physics models with "Hidden" or "Dark" sector

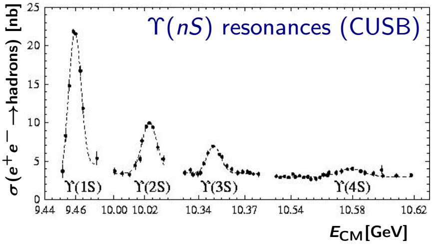
- several New Physics models postulate existence of **"dark sector" particles**
- motivation
  - explain some astrophysical observation anomalies
  - provide Dark Matter candidates
  - may explain the muon $g-2$ anomaly
- main features
  - new particles with mass in MeV to GeV range $\Rightarrow$ accessible in B-factories
  - dark particles loosely coupled to ordinary matter $\Rightarrow$ can be long-lived
  - new dark force, possibly $U(1)_D$ $\Rightarrow$ dark photon
- in the following: **two *BABAR* searches for dark sector particles**
  - Search for a dark photon in e^+e^- collisions at *BABAR*, PRL 111, 201801 (2014)
  - Search for Long-Lived Particles in e^+e^- Collisions, PRL 114, 171801 (2015)

BABAR detector at PEP-II, SLAC National Accelerator Laboratory

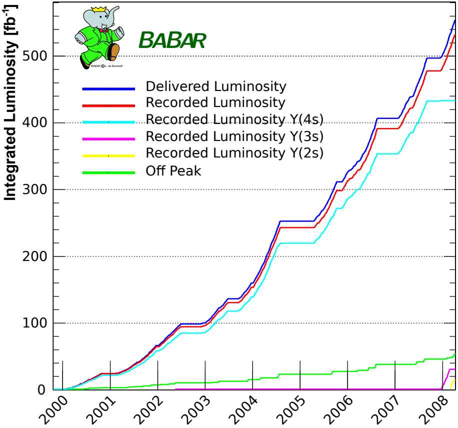


main focus: study of *CP* violation in *B* mesons

BABAR: CM energy, collected luminosity



	$\mathcal{L}(\text{ fb}^{-1})$	events
$\Upsilon(4S)$	424	$471 \cdot 10^6$
$\Upsilon(3S)$	28	$121 \cdot 10^6$
$\Upsilon(2S)$	14	$99 \cdot 10^6$
off-peak	48	
$e^+e^- \to c\bar{c}$		$\sim 650 \cdot 10^6$
$e^+e^- \to \tau^+\tau^-$		$\sim 450 \cdot 10^6$



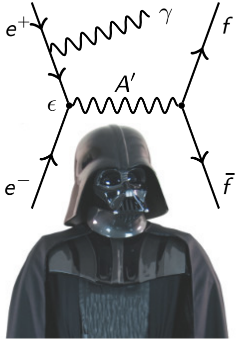
- **large clean data sample**

Search for Dark Photon decaying to e^+e^- or $\mu^+\mu^-$

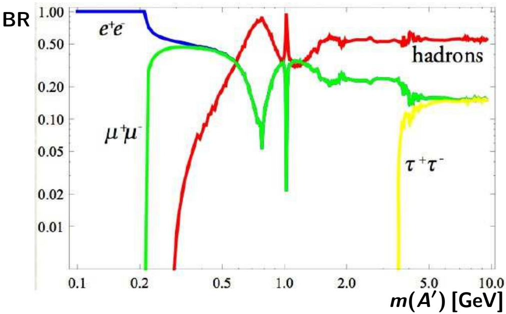
Introduction

- dark photon A' can be produced on-shell in *BABAR* and decay into a fermion pair
  $\Rightarrow$ reconstructed invariant mass would peak at the A' mass
- sizable A' branching fractions to e^+e^- and $\mu^+\mu^-$ permit clean and efficient search [Batell-Pospelov-Ritz, PRD 79, 115008 (2009)]
- favored range of the coupling constant: $10^{-2} < \epsilon < 10^{-7}$

A' production in *BABAR*

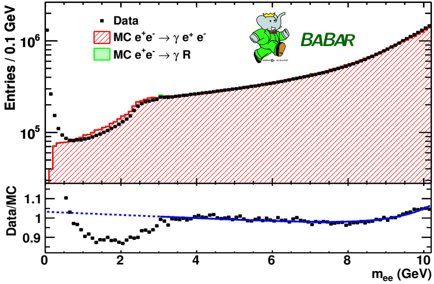


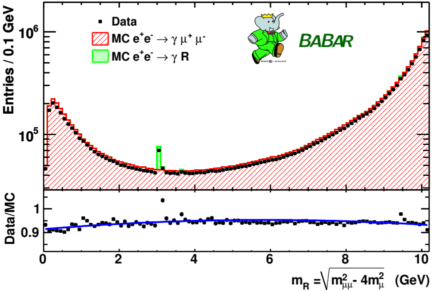
A' decay branching fractions depend on mass



Selection and signal candidates yields

- use all *BABAR* data, 514 fb^{-1}
- require **just one photon and a lepton pair** in the final state
- suppress Bhabha, di-muons, $\gamma\gamma$ bkgs with kinematic cuts and neural network



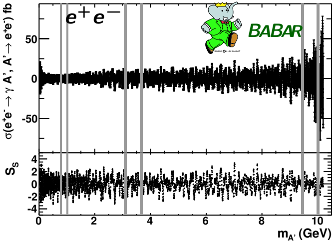


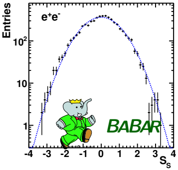
- signal yields compared to Monte Carlo simulation
  - good agreements except for small mass e^+e^- pairs (Bhabha generator BHWIDE known to be inaccurate there)
  - since we fit background on data, **results are unaffected by simulation imperfections**
- estimated signal efficiency $\sim$15% for e^+e^- and $\sim$35% for $\mu^+\mu^-$

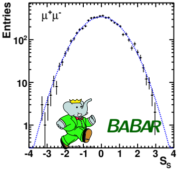
Measure signal yield and significance as function of mass

- fit for signal mass peak over smooth background in steps 1/2 mass resolution
  - mass peak shape from Monte Carlo simulation
  - mass peak width resolution tuned on data resonances
- do not fit at and around known resonances
- determine signed **signal significance** from likelihood ratios
  $S = \mathrm{sign}[N(\mathrm{signal})]\sqrt{2\log[L(\mathrm{signal}+\mathrm{bkg})/L(\mathrm{bkg})]}$
  - systematic effects (mainly from bkg modeling) taken into account

$\sigma(e^+e^- \to \gamma A', A' \to e^+e^-)$
and its significance
no evidence of signal







$\sigma(e^+e^- \to \gamma A', A' \to \mu^+\mu^-)$
and its significance
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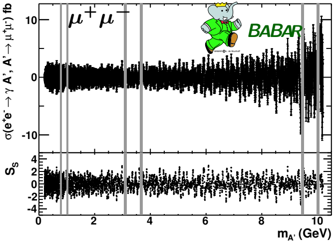
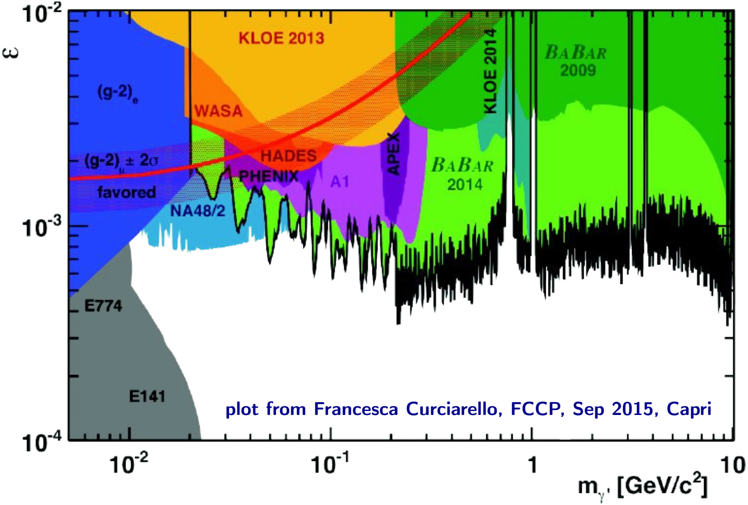


Significance of the mass scan and limits on the Dark Photon

- to get proper *p*-values for the whole scan must account for **"look elsewhere" effect**
  - proper "trial factors" are determined with toy Monte Carlo simulations
  - $\sigma(e^+e^- \to \gamma A', A' \to e^+e^-)$ scan *p*-value is 57%
  - $\sigma(e^+e^- \to \gamma A', A' \to \mu^+\mu^-)$ scan *p*-value is 94%
- $\Rightarrow$ **no evidence for signal** $\Rightarrow$ set limits
- determine $\sigma(e^+e^- \to \gamma A') = \sigma(e^+e^- \to \gamma A', A' \to \ell^+\ell^-)/B(A' \to \ell^+\ell^-)$
  - use $B(A' \to \ell^+\ell^-)$ from Batell *et al.*, PRD 79, 115008 (2009)
  - combine e^+e^- and $\mu^+\mu^-$ to set limits on that NP model
- compute **90% CL flat-prior Bayesian upper limits for ϵ as function of A' mass**
  - muon final state provides much better sensitivity because of lower backgrounds
  - electron final state has more background and its $e^+e^-\gamma$ trigger is 50% downscaled

Dark photon model constraints



this analysis = *BABAR* 2014 = **PRL 113, 201801 (2014)**

Search for Long-Lived Particles in e^+e^- Collisions

Introduction

- several NP models predict new long-lived particles with masses accessible to *BABAR*
- perform a **general-purpose search** for long-lived particle decaying into two fermions
- provide information to compute constraint on any model prediction
- use results to set constraints on one specific NP model

Selection

- complete *BABAR* sample, 489 fb^{-1}, $\Upsilon(4S)$, $\Upsilon(3S)$, $\Upsilon(2S)$, and just below $\Upsilon(4S)$
- select events with $e^+e^- \to LX, \quad L \to f$
  - **L = long-lived particle**
  - final state $f = e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp, \pi^+\pi^-, K^+K^-, \pi^\pm K^\mp$
- each f track must have significant impact parameter w.r.t. beam line, $\boldsymbol{d_0/\sigma_{d_0} > 3}$
- require f tracks crossing at **L vertex with χ^2/d.o.f. < 10**
- require **transverse decay length of L vertex from 1 cm to 50 cm** w.r.t. beam axis
- discard pairs compatible with coming from K_S^0 and Λ decays
- reject events with vertices on beam-pipe and other bulk detector elements
- remaining background from random track crossing and detector interactions

Signal and background modeling

Signal PDF (P_s): Determine from simulation

evaluate at 12 masses for each decay mode

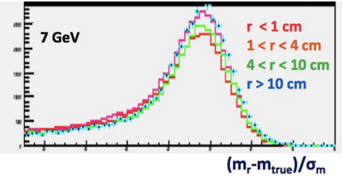
The event's measured mass

$$P_S \propto R\left[\frac{(m - m_0)}{\sigma_m}\right]$$

Scan point hypothesized mass

The event's mass uncertainty

Resolution function from signal simulation



Background PDF (P_B): Determined from data

A 2nd-order polynomial spline with knots separated by 15 times the signal mass resolution (mass-dependent)

Gives optimal balance b/w signal sensitivity and low fake-signal rate

Signal candidates yields

- fit background PDF on data in large bins
- fit signal mass peak + background in steps of 2 MeV
  - fit not performed in mass ranges where simulated background is not smooth

$$m_{e^+e^-} > 0.44\ \text{GeV} \qquad m_{\mu^+\mu^-} < 0.37\ \text{GeV}\ \text{or}\ m_{\mu^+\mu^-} > 0.50\ \text{GeV}$$

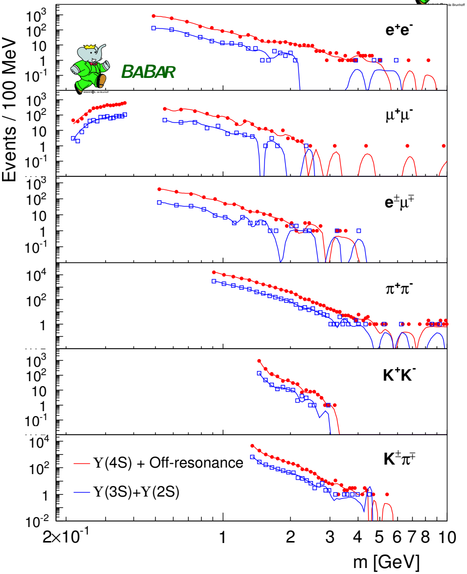
$$m_{e^\pm\mu^\mp} > 0.48\ \text{GeV} \qquad m_{\pi^+\pi^-} > 0.86\ \text{GeV}$$

$$m_{K^+K^-} > 1.35\ \text{GeV} \qquad m_{K^\pm\pi^\mp} > 1.05\ \text{GeV}$$

- signal significance from likelihood ratios

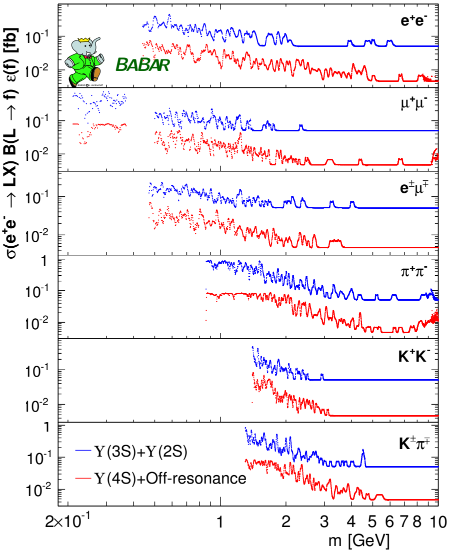
$$S = \text{sign}[N(s)]\sqrt{2\log\left(\frac{L(s+b)}{L(b)}\right)}$$

- plot shows candidates yields over background PDFs for
- **no significant signal yield found**



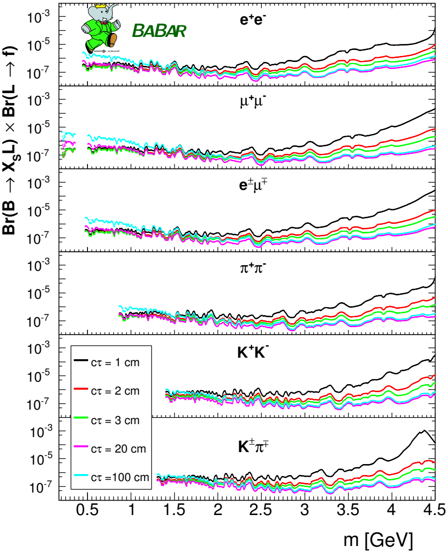
Measure and set limits on signal yields

- compute 90% CL flat-prior Bayesian limits on signal yields
- include systematic errors from signal and background modeling, mass resolution, luminosity
- use luminosity to convert to limits on $\boldsymbol{\sigma(e^+e^- \to LX) \cdot B(L \to f) \cdot \epsilon(f)}$
- $\epsilon(f)$ = selection efficiency for $e^+e^- \to LX, \quad L \to f$ measured with Monte Carlo simulation
- can probe specific models using $\epsilon(f)$ tabulated in supplementary material as function of mass, p_T and $c\tau$
- published on **PRL 114, 171801 (2015)**



Limits on $B(B \to X_s L) \cdot B(L \to f)$ for a specific NP model

- NP model proposed in Bezrukov and Gorbunov, "Light inflaton after LHC8 and WMAP9 results," JHEP 1307, 140 (2013) predicts long lived particle production $B \to X_s L$, where X_s i hadronic system with strangeness -1
- use Monte Carlo simulation to estimate the selection efficiency of the decay chain $e^+e^- \to B\bar{B}, B \to X_s L, L \to f$
- get limits on $B(B \to X_s L) \times B(L \to f)$ using efficiency and the limits on $\sigma(e^+e^- \to LX) \cdot B(L \to f) \cdot \epsilon(f)$
- **significant constraints obtained**



Conclusions

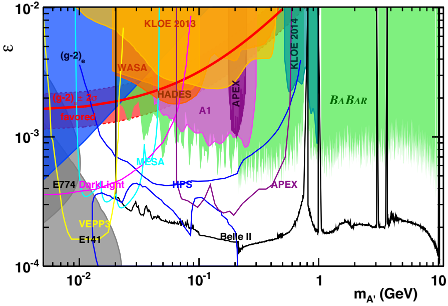
- large & clean *BABAR* data sample valuable to search for light New Physics signals
- future higher luminosity *B*-factories like BelleII can improve the presented limits
- *BABAR* found no evidence for Light Physics beyond the Standard Model
- working on some more light new physics searches, more results forthcoming

Backup Slides

Future experimental prospects for Dark Photon searches

Chris Hearty, "Dark Sector", Belle II Theory Interface Platform meeting, Oct 2014 reviewed the Dark Photon sensitivity of future experiments

$e^+e^- \to \gamma A', \quad A' \to f\bar{f}$



$e^+e^- \to \gamma A', \quad A' \to$ invisible