Dark sector and Light New Physics searches in *BABAR*

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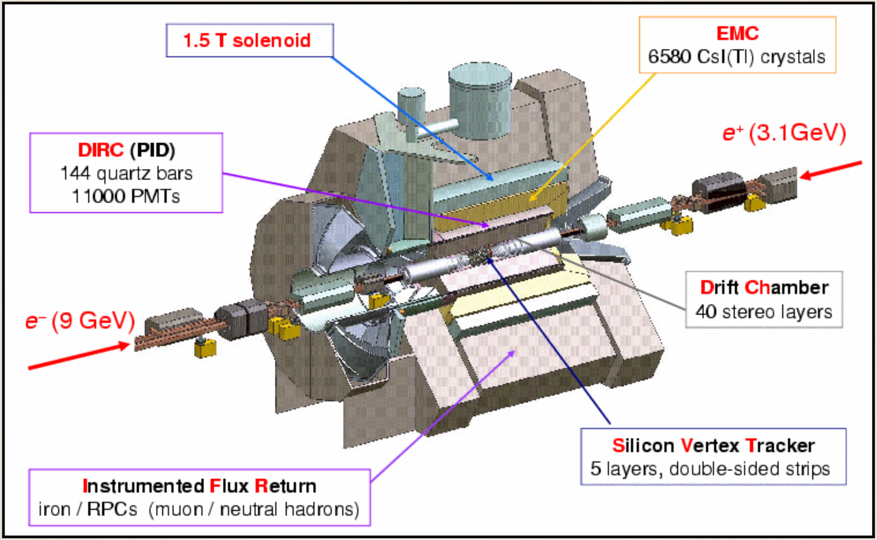
on behalf of the *BABAR* Collaboration

Outline

1. The *BABAR* experiment
2. Search for a Light Higgs decaying to Charm in $\Upsilon(1S)$ Decays
3. Search for Long-Lived Particles in e^+e^- Collisions
4. Search for Muonic Dark Force
5. Conclusions

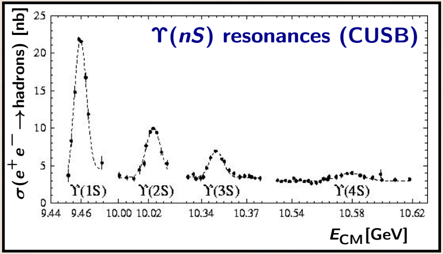
BABAR detector at PEP-II, SLAC National Accelerator Laboratory



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

BaBar: CM energy, collected luminosity

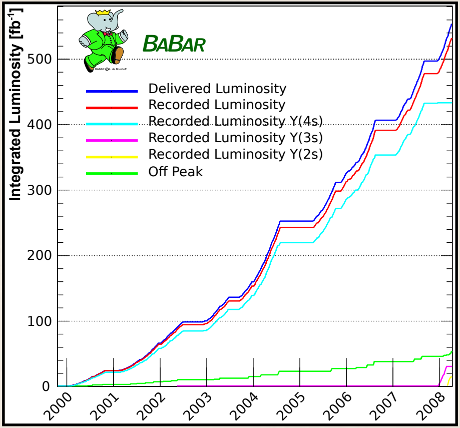
center-of-mass energies



	$\mathcal{L}(\mathrm{fb}^{-1})$	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	
$e^+e^- \to \tau^+\tau^-$		$\sim 450 \cdot 10^6$

large clean data sample

integrated luminosity over time



data-taking ended in April 2008

Search for a Light Higgs decaying to Charm in $\Upsilon(1S)$ Decays

Motivation

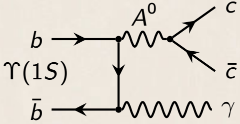
- several New Physics models predict a light CP-odd Higgs boson A^0
  - e.g. nMSSM, Phys.Rep. 496, 1 (2010)
- B-factories can search for light Higgs bosons with mass up to about the $\Upsilon(1S)$
- depending on $\tan\beta$ and other parameters, the light Higgs can couple preferentially to up or down quark and leptons
- for typical Higgs masses accessible to the B-factories
  - at $\tan\beta \simeq 20$ decay to $\tau^+\tau^-$ is dominant
  - at $\tan\beta \simeq 1$ decay to $c\bar{c}$ is dominant
- former *BABAR* searches for light Higgs bosons (no evidence found)

$\boldsymbol{\Upsilon(2S,3S) \to \gamma A^0}$		$\boldsymbol{\Upsilon(1S) \to \gamma A^0}$	
$A^0 \to$ invisible	arXiv:0808.0017 (2008)	$A^0 \to$ invisible	PRL 107, 021804 (2011)
$A^0 \to \mu^+\mu^-$	PRL 103, 081803 (2009)	$A^0 \to \mu^+\mu^-$	PRD 87, 031102 (2013)
$A^0 \to \tau^+\tau^-$	PRL 103, 18181 (2009)	$A^0 \to \tau^+\tau^-$	PRD 88, 071102 (2013)
$A^0 \to$ hadrons	PRL 107, 221801 (2011)	$A^0 \to gg, s\bar{s}$	PRD 88, 031701 (2013)

- this search: $\boldsymbol{\Upsilon(1S) \to \gamma A^0}$, $\boldsymbol{A^0 \to c\bar{c}}$

Introduction

- search for $e^+e^- \to \Upsilon(2S)$, $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to c\bar{c}$
- tagged $\Upsilon(1S)$: smaller statistics but **cleaner sample**
  - 13.6fb^{-1}at $\Upsilon(2S)$ peak $\Rightarrow$ $(98.3 \pm 0.9) \cdot 10^6$ $\Upsilon(2S)$
    $(17.5 \pm 0.3) \cdot 10^6$ $\Upsilon(1S)$ via $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$
- production graph:

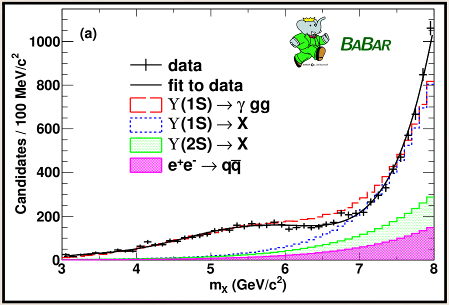


Selection

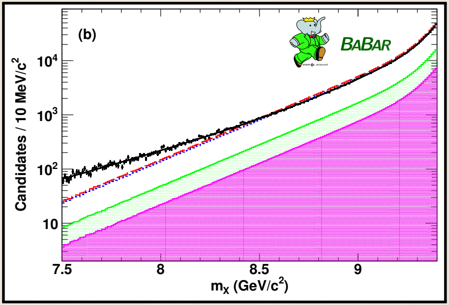
- require final state containing: $\boxed{\textbf{one photon}}$, $\boxed{\textbf{one pion pair } \pi^+\pi^-}$, $\boxed{\textbf{one } D \textbf{ meson}}$
- reconstruct recoiling system mass as $m_R^2 = m^2_{\Upsilon(2S),\mathrm{PDG}} + m^2_{\pi\pi} - 2m_{\Upsilon(2S),\mathrm{PDG}} E_{\pi\pi}$ and require $m_R = m_{\Upsilon(1S),\mathrm{PDG}}$ within 10 MeV
- reconstruct candidate A^0 mass as $m_X^2 = (P_{e^+e^-} - P_{\pi^+\pi^-} - P_\gamma)^2$
- reconstruct **5 *D* decay chains**:
  $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D^0 \to K^-\pi^+\pi^+\pi^-$
  $D^0 \to K^0\pi^+\pi^-$, $D^*(2010)^+ \to \pi^+ D^0$ with $D^0 \to K^-\pi^+\pi^0$
- consider two **2 Higgs mass regions** separately
  - low Higgs mass region (< 8.0GeV) $\Rightarrow$ hard photon $\Rightarrow$ low background
  - high Higgs mass region (> 7.5GeV) $\Rightarrow$ soft photon $\Rightarrow$ high background
- train **BDT** (Boosted Decision Tree) classifiers to select signal over background
  10 BTDs, one for each combination of 5 D decay chains $\times$ 2 Higgs mass regions

Yields of A^0 candidates vs. reconstructed mass m_X on data & simulation

low mass region A^0 candidates



high mass region A^0 candidates

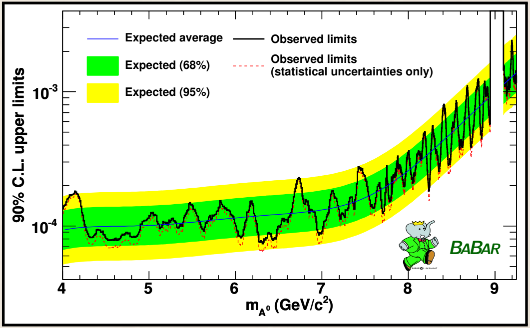


Signal extraction, limits on $B(\Upsilon(1S) \to \gamma A^0) \times B(A^0 \to c\bar{c})$

- scan fitting **peak on smooth BKG** every 10 MeV (low mass), 2 MeV (high mass)
  - skip $8.95 < m_{A^0} < 9.10$ GeV where $\Upsilon(2S) \to \gamma\chi_{bJ}(1P)$, $\chi_{bJ}(1P) \to \gamma\Upsilon(1S)$
- max local significances 2.3σ (low mass) and 2.0σ (high mass) (on simulations, this happens with 54% (low mass) and 80% (high mass) probability)
- **no evidence for signal**
- 90% CL flat-prior Bayesian limits are computed, including systematic uncertainties

- expected/observed upper limits on $B(\Upsilon(1S) \to \gamma A^0) \times B(A^0 \to c\bar{c})$
- observed upper limits range: $< \mathbf{7.4 \cdot 10^{-5} - 2.4 \cdot 10^{-3}}$ **90% CL**
- **Phys. Rev. D 91, 071102 (2015)**

limits on $B(\Upsilon(1S) \to \gamma A^0) \times B(A^0 \to c\bar{c})$



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

Introduction

- several Dark Matter New Physics models typically include particles **loosely coupled to Standard Model particles**, through "**portals**"

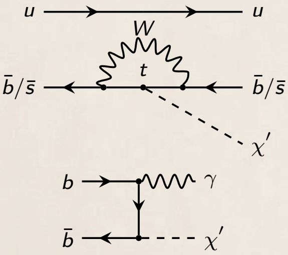
from Snowmass 2013 report "Dark Sectors and New, Light, Weakly-Coupled Particles"

Portal	Particles	Operator(s)
"Vector"	Dark photons	$-\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}$
"Axion"	Pseudoscalars	$\frac{a}{f_a} F_{\mu\nu}\widetilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i\mu\nu}\widetilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
"Higgs"	Dark scalars	$(\mu S + \lambda S^2)H^\dagger H$
"Neutrino"	Sterile neutrinos	$y_N LHN$

- if DM particles can only decay to SM particles, they can be **long-lived**
- $\Rightarrow$ **general-purpose search for long-lived particles in *BaBar***

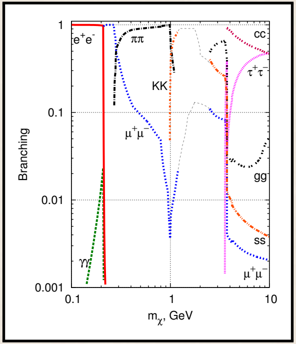
Dark matter particles with Higgs-like coupling, possibly long-lived

Clarke, Foot, Volkas, arXiv:1310.8042
Higgs portal with DM scalar mixing with SM Higgs

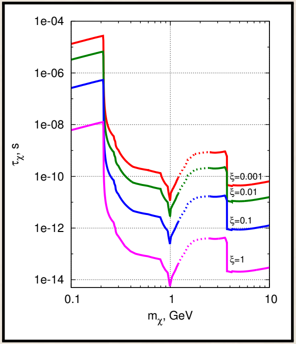


Bezrukov, Gorbunov, 1303.4395, 0912.0390
Light inflaton with Higgs-like couplings and decaying to light SM fermions

Branching fractions



Lifetime



Motivation

- searches for long-lived particles have been conducted for $m \ll$ GeV
  - on beam dump experiments: Andreas, Niebuhr, Ringwald, 1209.6083
  - on π^0 decays: Gninenko, 1112.5438
  - NuTeV, hep-ex/0104037
- ... and for $m \gg$ GeV
  - D0: hep-ex/0607028, 0906.1787
  - CDF: hep-ex/9805017
  - ATLAS: 1210.7451, 1203.1303
  - CMS: 1409.4789, 1411.6977
  - LHCb: 1412.3021
- ... but few searches in $\mathcal{O}$(GeV) range
  - Belle: long-lived heavy neutrino 1301.1105

Selection

- complete *BABAR* sample, 489fb^{-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^0_S 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 candidates yields

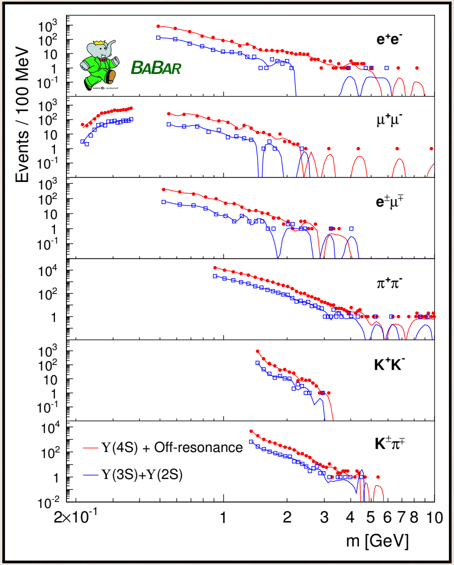
- Red: $\Upsilon(4S)$ data
- Blue: $\Upsilon(3S) + \Upsilon(2S)$ data
- points are data, line is simulation
- this search skips mass regions where simulated background is not a smoothly varying function of the mass

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

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

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

Selected events vs. mass



Search for signal

search for signal by fitting a mass peak over smooth backgroung

- signal PDF: mass peak with shape determined by Monte Carlo simulation
  - simulated 12 masses for each final state, then interpolation from closest masses
- background PDF: smoothly varying 2nd order polinomial spline fitted on data
  - use large bins to average out possible narrow peaks

compute local signal significances using likelihood ratios

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

compute global significance of maximum local significance of each channel scan

- compute trial factors with toy MC simulations to account for "look elsewhere effect"
- $\Rightarrow$ compute global significance for each channel
- **no evidence for signal in any channel**
- $\Rightarrow$ compute upper limits

Limits on signal events production cross-section

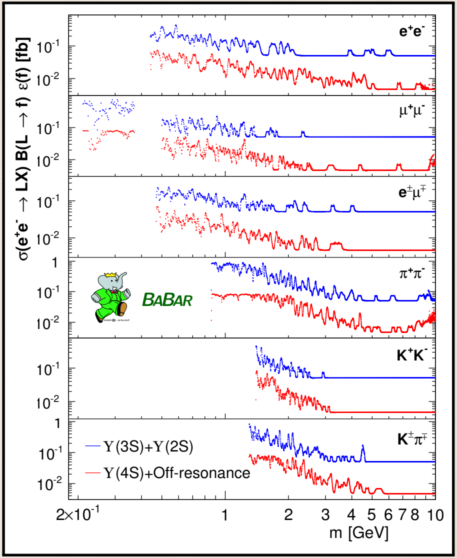
Limits on signal yields

- compute 90% CL flat-prior Bayesian limits on signal yield
- include systematic uncertainties by convolving the signal yield likelihood with the appropriate Gaussian distributions to account for uncertainties on signal modeling, background modeling, etc.

Limits on signal cross-section

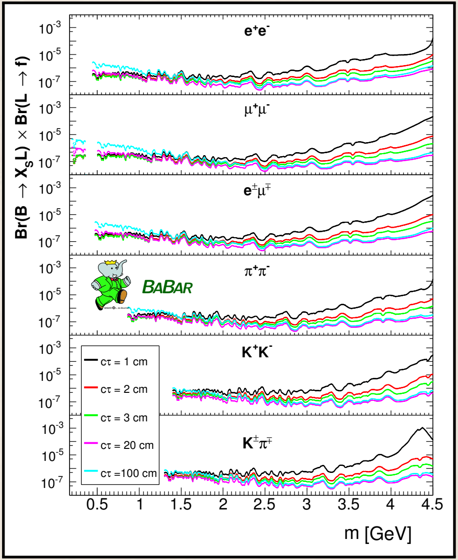
- divide by luminosity to get limits on $\boldsymbol{\sigma(e^+e^- \to LX) \cdot B(L \to f) \cdot \epsilon(f)}$
- $\epsilon(f)$ = selection efficiency for $e^+e^- \to LX, \quad L \to f$ measured with Monte Carlo simulation
- publication: **PRL 114, 171801 (2015)**
- to make it easier to constrain any New Physics model, publication includes $\epsilon(f)$ as as function of mass, p_T and $c\tau$

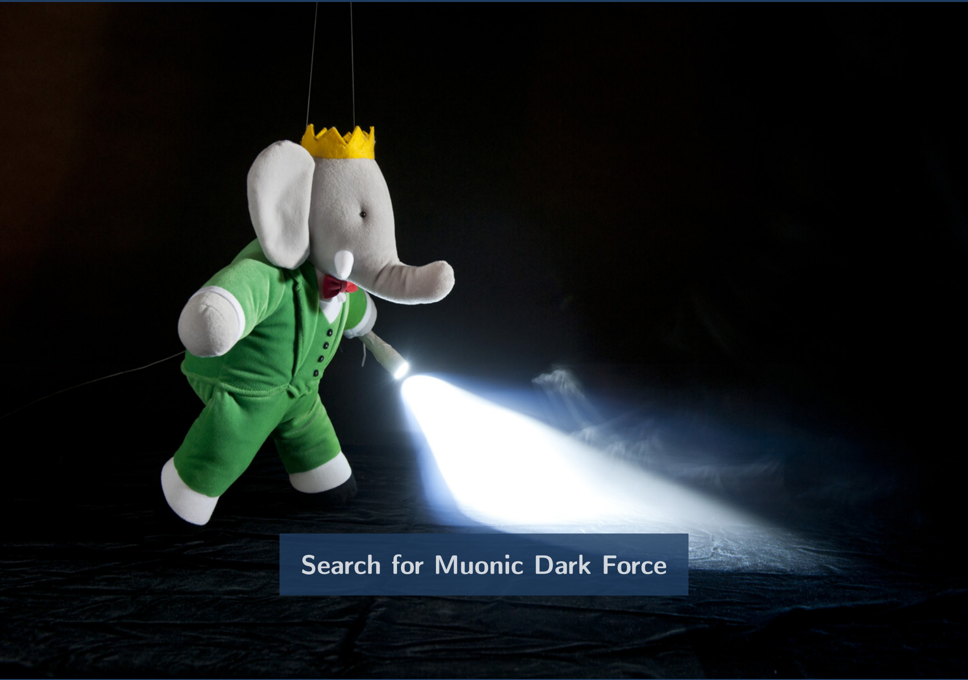
90% CL upper limits on signal cross-section



Limits on $B(B \to X_s L) \cdot B(L \to f)$ for a DM light inflaton model

- 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 is 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 $\sigma(e^+e^- \to LX) \cdot B(L \to f) \cdot \epsilon(f)$



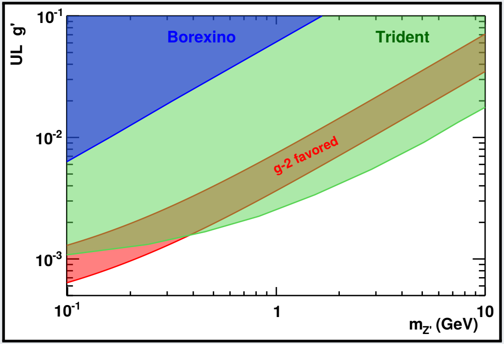


Search for Muonic Dark Force

Introduction

- some Dark Matter models postulate Dark Boson Z' coupled to μ & τ but not e
  - X. G. He, G. C. Joshi, H. Lew and R. R. Volkas, Phys. Rev. D **43**, 22 (1991).
  - X. G. He, G. C. Joshi, H. Lew and R. R. Volkas, Phys. Rev. D **44**, 2118 (1991).
- could account for
  - muon $g-2$ theory vs. experiment discrepancy
  - discrepancy on Lamb shift vs. muonium determination of proton radius

Existing experimental limits on mass $m_{Z'}$ and coupling g'



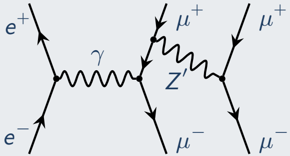
- W. Altmannshofer, S. Gori, M. Pospelov and I. Yavin, Phys. Rev. Lett. **113**, 091801 (2014).
- A. Kamada and H. B. Yu, Phys. Rev. D **92**, 113004 (2015).
- current limits rely on coupling Z' – neutrinos, which is absent in some models

Data set and selection

Dataset

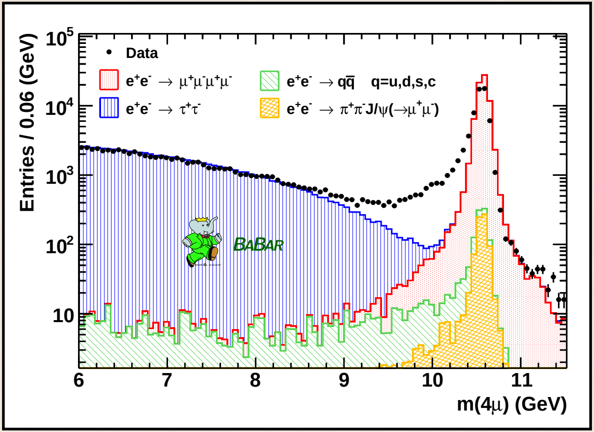
- dataset: $514\,\text{fb}^{-1}$ at and around $\Upsilon(4S)$, $\Upsilon(3S)$, $\Upsilon(2S)$

Selection



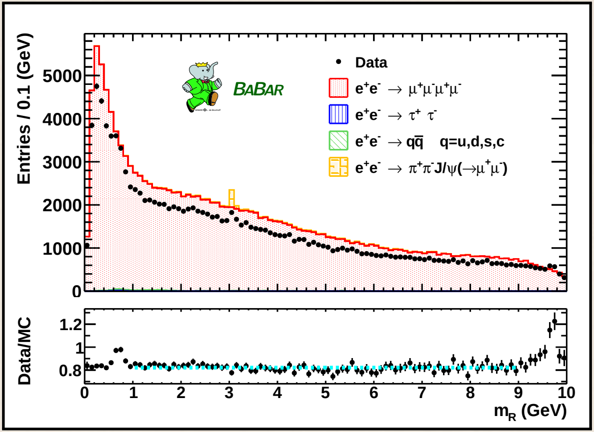
- select final states of exactly 4 tracks in two oppositely charged pairs, $t_1^+\ t_1^-\ t_2^+\ t_2^-$
- extra neutral energy $< 200\,\text{MeV}$
- require muon id. on either same-sign track pair (either on $t_1^+ \& t_2^+$ or on $t_1^- \& t_2^-$)
- four muon invariant mass within $500\,\text{MeV}$ of event center-of-mass energy
- to suppress events with $\Upsilon(2S,3S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \mu^+\mu^-$
  $\Rightarrow$ reject candidates with any $t_i^+ t_j^-$ invariant mass within $10\,\text{MeV}$ of $\Upsilon(1S)$ mass

Data vs. background simulation yields on 4μ invariant mass distribution



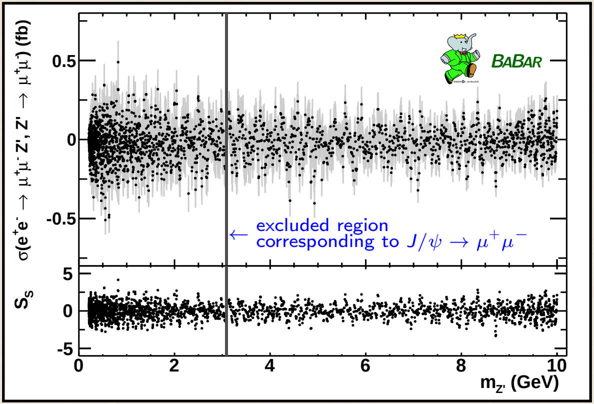
- background dominated by $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$
- contribution from $e^+e^- \to \pi^+\pi^- J/\psi,\ J/\psi \to \mu^+\mu^-$
- Diag36 generator simulates $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$, **does not have ISR simulation**
  - $\Rightarrow$ data have 30% lower peak at event energy and ISR radiation tail on the left
  - **does not harm this search**, where background is fit on $m(Z')$ data sidebands
- kinematic fit with $m_{4\mu}{=}m_{\text{event}}$ improves momentum resolution for events on peak

Reduced dimuon mass $\left[m_R = \sqrt{m^2_{\mu^+\mu^-} - 4m^2_\mu}\right]$ distribution



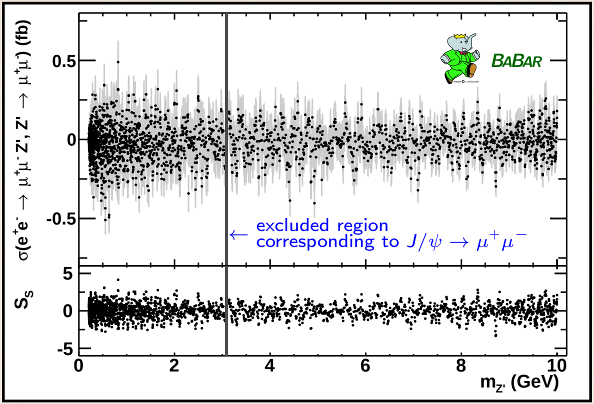
- all oppositely charged muon candidate pair combinations are plotted
- background dominated by $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$
- contribution from $e^+e^- \to \pi^+\pi^- J/\psi$, $J/\psi \to \mu^+\mu^-$
- get signal efficiency correction from data/MC in 1–9 GeV interval (light blue line)

Cross-section $\sigma(e^+e^- \to \mu^+\mu^- Z',\ Z' \to \mu^+\mu^-)$ and significance



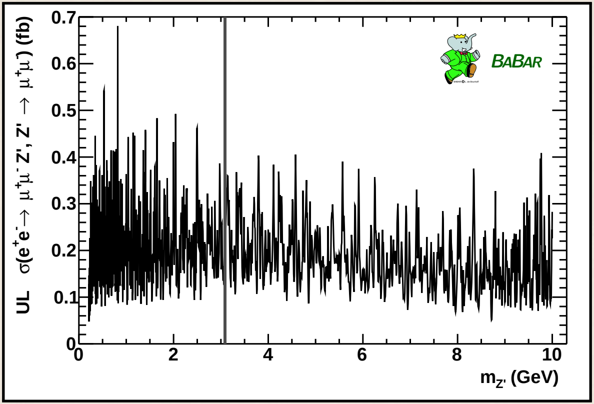
- 2219 unbinned max. likelihood fits for $0 < m_R < 10$ GeV on m_R intervals $\sim 50 \times \sigma(m_R)$
  - signal shape from simulation
- exclude m_R region corresponding to $J/\psi \to \mu^+\mu^-$
- $\sigma(e^+e^- \to \mu^+\mu^- Z',\ Z' \to \mu^+\mu^-) = N_{\text{sig}}(\text{fit})/(\epsilon_{\text{sig}} \cdot \langle\text{integrated luminosity}\rangle)$
  - ϵ_{sig} from simulation with correction factor from data
- signal MC: MadGraph 5 + Pythia 6, simulated for several masses and interpolated

Cross-section $\sigma(e^+e^- \to \mu^+\mu^- Z',\ Z' \to \mu^+\mu^-)$ and significance (2)



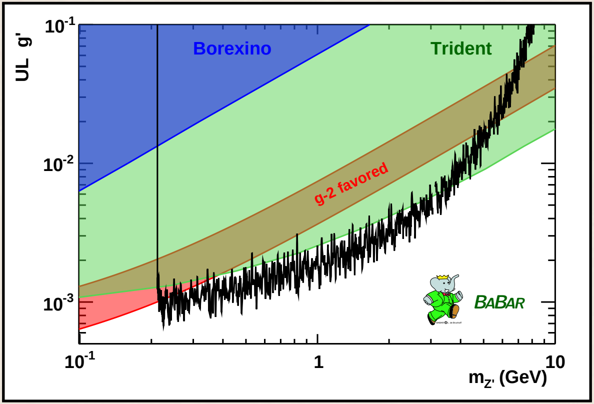
- significance $S_S = \mathrm{sign}(N_{\mathrm{sig}})\sqrt{2\log(\mathcal{L}/\mathcal{L}_0)}$
  ($\mathcal{L}$ max. likelihood signal+background, $\mathcal{L}_0$ max. likelihood background only)
- maximum local significance $4.3\,\sigma$ at $m_{Z'} = 0.82$ GeV
- compute trial factors to account for "look elsewhere" effect with toy MC
  $\Rightarrow$ **global significance of largest significance is 1.6 σ**
  $\Rightarrow$ compute upper limits

Upper limits on cross-section $\sigma(e^+e^- \to \mu^+\mu^- Z',\ Z' \to \mu^+\mu^-)$



- 90% CL Bayesian upper limits assuming uniform prior for σ integrating likelihood
- use combined likelihood for the 3 samples
- per-sample & common systematics included by convolving with appropriate Gaussians (5% on signal efficiency, 0.6% on luminosity, bkg modeling, signal interpolation, MC stat.)

Upper limits on Muonic Force model parameters



- upper limits down to $7 \cdot 10^{-4}$ on coupling constant near dimuon threshold
- can be interpreted as constraint on NP vectors fields that interact with muons
- published in **Phys. Rev. D. 94, 011102 2016**

Conclusions

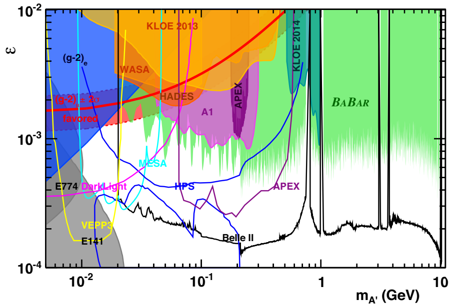
- large & clean *BABAR* data sample valuable to search for light New Physics signals
- *BABAR* found no evidence for Light Physics beyond the Standard Model
- some more searches are being perfomed on *BABAR* data, more results forthcoming
- future higher luminosity *B*-factories like BelleII can improve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

Backup Slides

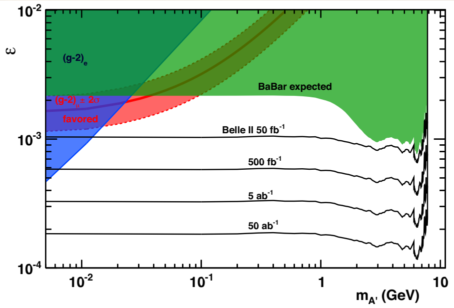
Future experimental prospects for Dark Photon searches

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

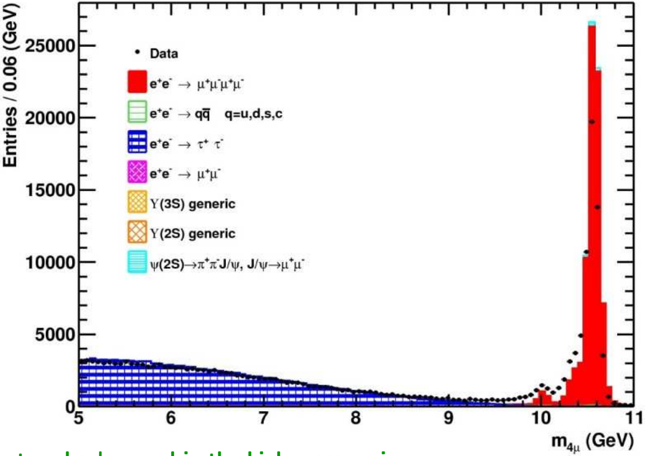
$e^+e^- \to \gamma A', \quad A' \to f\bar{f}$



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



Four-Muon Invariant Mass

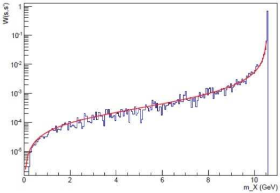


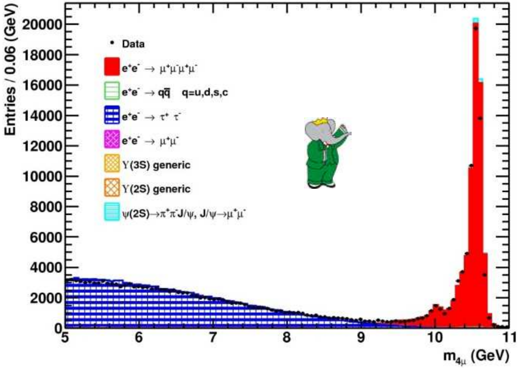
★ Almost no background in the high mass region

★ Monte Carlo $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$ lacks radiative corrections (disagreement in high mass region)

Four-Muon Invariant Mass (ISR Corrected)

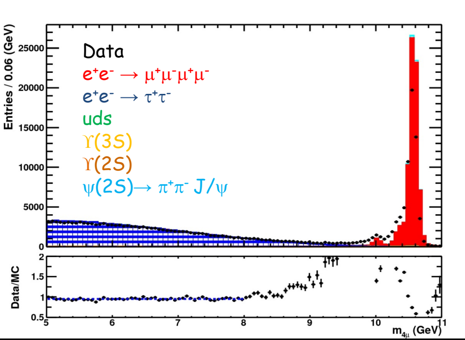
★ **QED radiator (ISR emission probability)**





★ **We convolve the mass spectrum with the QED radiator to correct the ISR: $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$**

Alternative efficiency corrections

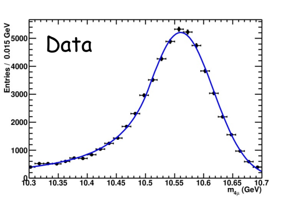


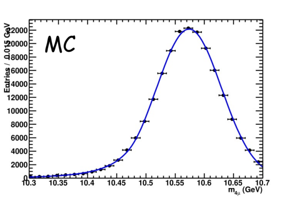
- Fit the data/MC ratio in the range $5.5 < m(4\mu) < 8.5$ GeV to derive corrections for all sources but the ISR contribution. This range is dominated by $e^+e^- \to \tau^+\tau^-$ events, well understood. A ratio of 0.95 is found.
- Multiply this value by the ISR correction estimated from the QED radiator (0.86).
- Both methods are in good agreement.

Bertrand Echenard - BABAR Jamboree - Mar 2016 - p.8

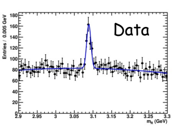
Resolution – agreement data/MC

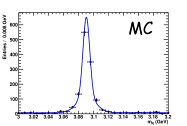
Full energy peak





J/ψ





- We compare the width of the full energy peak of the data and the $e^+e^- \to 4\mu$ MC.
- Fit the spectrum with a Crystal Ball function. The core resolution (σ) should not be too sensitive to ISR corrections.
- Both resolutions agree (1.01 ± 0.04.). Observe agreement on the J/ψ peak as well with the limited statistics.
- No corrections are applied.

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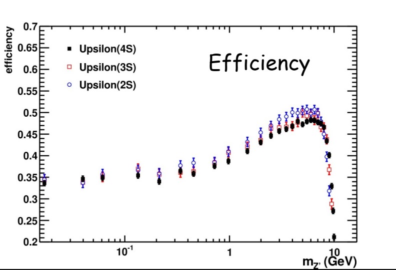
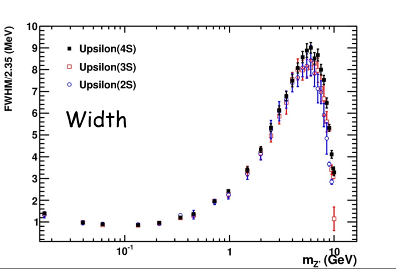
Signal MC

Generate signal Monte Carlo with Madgraph for several masses between 0.212 GeV and 10 GeV (9 GeV) for Run 1-6 (Run 7 because of the $\Upsilon(1S)$ cut)

Fit the mass spectra with a sum of Gaussians and extract the FWHM and defined the width as FHWM/2.35. The width varies between 1-10 MeV.

Efficiency drops at high masses due to acceptance and PID requirements.





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Signal extraction

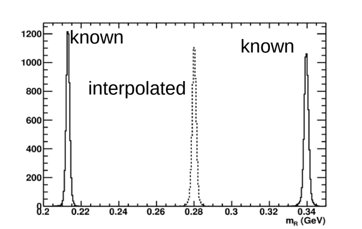
Perform a scan to extract the signal as a function of the dimuon reduced mass. Scan step is taken as the width for the given mass – total of 2219 fits.

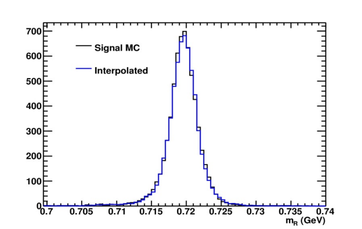
Below m_R = 0.2 GeV, unbinned likelihood fit over a fixed range of 0-0.3 GeV

Above m_R = 0.2 GeV, unbinned likelihood fit over a window of $\pm$ 50σ.

Fit function:

The signal is modeled directly from the MC mass spectrum, using an interpolation between known masses.





Signal extraction

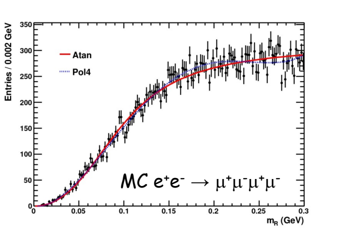
Perform a scan to extract the signal as a function of the dimuon reduced mass. Scan step is taken as the width for the given mass – total of 2272 fits.

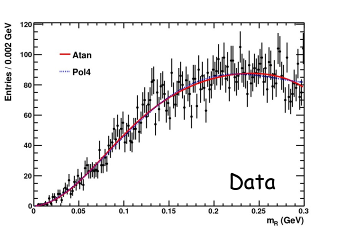
Below m_R = 0.2 GeV, unbinned likelihood fit over a fixed range of 0-0.3 GeV

Above m_R = 0.2 GeV, unbinned likelihood fit over a window of $\pm 50\sigma$.

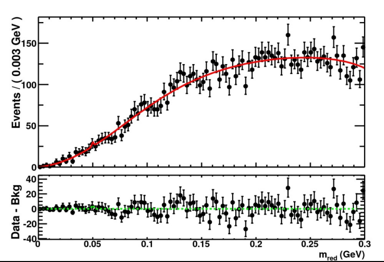
Fit function:

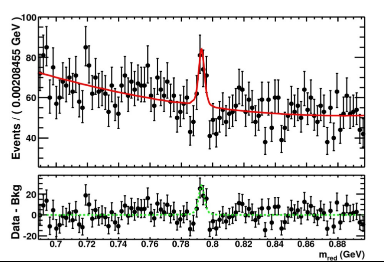
The background is a second order polynomial above m_R = 0.2 GeV. Below that threshold, we use a function of the form $\mathrm{atan}(ax+bx^2+cx^3)$.



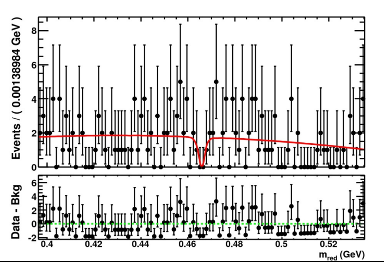


Examples of fit



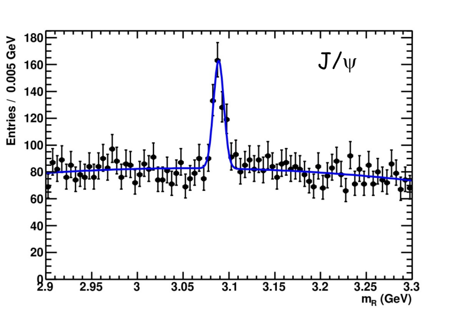


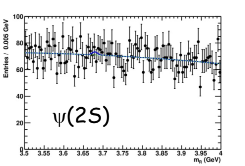
Force the pdf to be everywhere non-negative if it runs towards –infinity (this happens if there are no events in the signal region).

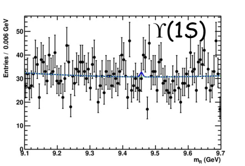


Resonances

Fit to extract the J/ψ, ψ(2S) and ϒ(1S) contribution (mass fixed to PDG value)

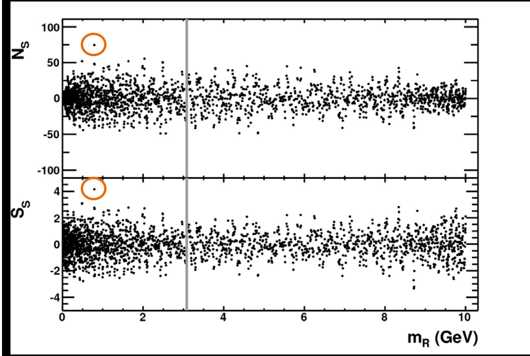


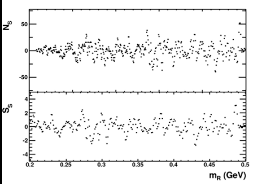


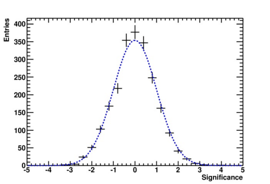


- Resolution agree with MC within large uncertainties for the J/ψ
- Exclude J/ψ region in a window of ±30 MeV in the fits
- No significant ψ(2S), ϒ(1S) signal, just scan as usual

Scan results – Combined dataset





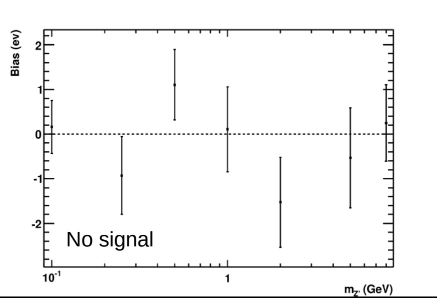


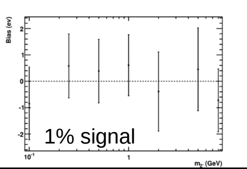
Datasets are fit separately and combined – see BAD 2675 for the individual results

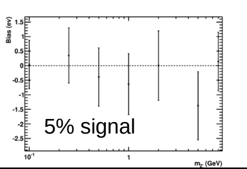
Largest significance: 4.3σ at m_R= 0.79 GeV. With trial factors, this dilutes the significance to 1.6σ.

Bias / Trial factors

Generate large ensemble of pseudo-experiment at various masses to estimate fit bias and the trial factors







Bias are found to be compatible with zero.

Systematic uncertainties

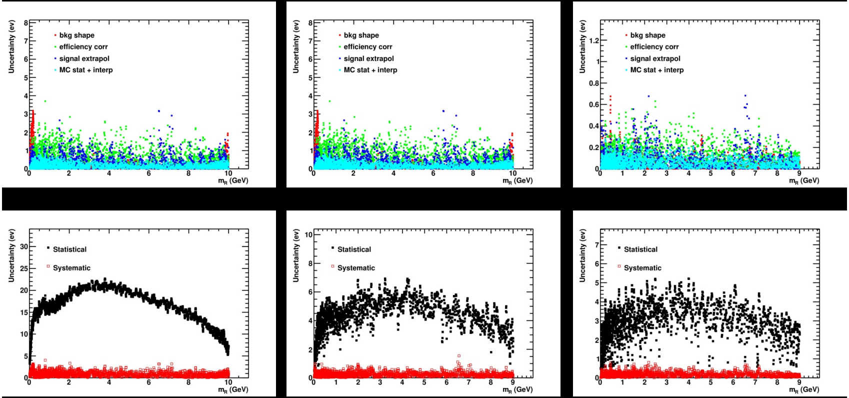
Include the following systematic uncertainties:

- Background modelling, take difference with fit using 3rd order polynomial above m_R = 0.2 GeV. Below that threshold, use a forth order polynomial constrained to pass through the origin.
- Signal interpolation, by taking the next-to-closest instead of the closest mass point to interpolate.
- PID / efficiency correction: uncertainty of 5%, covering the small variations between data-taking periods and the uncertainties on the $e^+e^- \rightarrow 4\mu$ cross-section.
- MC statistics and efficiency interpolation
- Luminosity: 0.6% uncertainty

Systematic uncertainties have a limited impact on the analysis

Systematic uncertainties

Run 1-6 Y(3S) Y(2S)



Systematic uncertainties have a limited impact on the analysis

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