Search for Low-Mass New Physics States at BABAR

EPS-HEP, Gent, July 12, 2019
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Motivation for dark sector searches

Visible dark photon decays

Invisible dark photon decays

Muonic force
Dark Sector

Dark Matter exists, awaiting for discovery

H. Murayama, Granada European Strategy Meeting

Search methods

Annihilations
(Indirect Detection)

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Scattering
(Direct Detection)

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Production
(Accelerators)

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July 12, 2019

F. Forti, Babar Low mass states
Portals

• Access to dark sector through “portals”

• Possible sub-GeV scale scenario: light dark sector weakly coupled to SM through a light mediator $X$
  - Vector portal $\rightarrow$ Dark Photon $A'$
  - Scalar portal $\rightarrow$ Dark Higgs Scalars
  - Pseudo-scalar portal $\rightarrow$ Axion Like Particles (ALPs)
  - Neutrino portal $\rightarrow$ Sterile Neutrinos
Dark photon

- Minimal dark sector: add a new U(1) gauge symmetry → spin-1 “dark photon” $A'$
- Can mix with SM photon providing a “portal” to the dark sector.
- Kinetic mixing of strength $\epsilon$
  - Could be as large as $10^{-2}$ with $m_{A'}$ in GeV range
- Lifetime $\sim 1/\epsilon^2 m_{A'}$: prompt or displaced
- Also possible more complex scenarios, with richer phenomenology

Search for decay of $e^+e^- \rightarrow \gamma A'$ via $A' \rightarrow \chi\chi$ or into SM particles
- “Visible” $A' \rightarrow l^+l^-$, decaying promptly or with a displaced vertex
- “Invisible” $A'$ decays, with $A'$ mass determined from missing energy constraints
Visible dark photon decays

- Use 514 fb$^{-1}$ of data
  - All available CM energies
- Use simulation templates to model signal (small width)
- Scan di-lepton invariant mass in the range $0.02 \text{ GeV} < m_{A'} < 10.2 \text{ GeV}$
- Remove resonant background
- Obtain 90% C.L. upper limit on mixing strength $\varepsilon$ as a function of $m_{A'}$

Invisible dark photon decays

- B Factories provide an excellent environment for missing energy searches
  - Precisely known initial state
  - Hermetic detector
- Use 53fb\(^{-1}\) recorded with single γ trigger
  - Only in final running period
- Single isolated photon in the detector
  - Monochromatic for on-shell A’
- Optimize analysis and interpret as dark photon decaying invisibly
  - But no model dependence in analysis

\[ E_{\gamma}^* = E_{beam}^* - \frac{m^2_{A'}}{4E_{beam}^*} \]
Main backgrounds

- $e^+e^- \rightarrow \gamma \gamma$ event
- Additional ISR down the pipe
- $e^+e^- \rightarrow e^+e^-\gamma$ where both electron and positron are lost
Invisible dark photon analysis

- Offline selection with Boosted Decision Tree
- Fit $m_X^2 = s - 2\sqrt{s}E_\gamma^*$ distribution: extract signal, peaking background, smooth background yields

Low-mass, $\Upsilon(3S)$ data, loose selection - separate tight selection not shown

High-mass region, $\Upsilon(2S)+\Upsilon(3S)$

- Signal cluster shape parameters
- Additional calorimeter energy
- Properties of the second most energetic cluster: $E^*, \theta^*, \Delta\Phi^*$
- Properties of muon system cluster $(E^*, \theta^*, \Delta\Phi^*)$ closest to the missing momentum direction

Low Mass
Invisible dark photon results

• No evidence of signal (in 116 mass hypothesis)
• Set limits in $\varepsilon$, $A'$ plane
• Exclude region favored by $g$-2 measurement

Muonic dark force

- Non-minimal dark sector models can permit additional interactions between dark boson and SM particles
  - e.g. Dark boson $Z'$ which couples only to second and third generation leptons ($L_\mu - L_t$ model)

- Motivated by various anomalies observed in the muon sector
  - $g$-$2$ discrepancy
  - could also account for dark matter as sterile neutrinos by increasing their cosmological abundance via new interactions with SM neutrinos.

- “$Z'$-strahlung” production
  - Dark sector $Z'$ in $e^+e^- \rightarrow \mu^+\mu^-$

- No specific model assumed in the analysis
Muonic dark force search

- Search for a di-muon mass peak in $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$
  - QED combinatorial backgrounds,
  - peaking backgrounds from $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ and $\rho$
- First direct experimental limits on $Z'$ coupling
- Excludes most of region favoured by $g$-2 results

Di-muon reduced mass: $m_R = (m_{\mu\mu}^2 - 4m_{\mu}^2)^{1/2}$

Correction factor (ISR): 0.82

Limit (90% C.L.) on $Z'$ coupling

Cross section
The future

• Searches will continue at Belle II and LHCb in the coming years. For example, dark photon perspectives:

\[ A' \rightarrow \mu^+\mu^- \]  
\[ A' \rightarrow \text{invisible} \]

arXiv:1603.08926  
arXiv: 1808.10567
Conclusion and perspectives

• The "dark sector" provides a still unexplored window on possible new physics at low masses

• Babar data still offer interesting analysis opportunities
  • Advantages of the clean environment of $e^+e^-$ collider

• Search for Axion-like-particles on-going, to be presented soon.

• Larger data sets (Belle II, LHCb) will soon be available to improve the sensitivity of these analyses
Additional material
Rare or forbidden decays!

Abi Soffer
Tel Aviv University
On behalf of the BABAR Collaboration
FPCP 2019, Victoria
July 12, 2019

**The BaBar experiment**

- **SVT**: 5 layers double-sided Si. Crucial for measuring $\Delta t$.
- **DCH**: 40 layers in 10 super-layers, axial and stereo.
- **DIRC**: Array of precisely machined quartz bars. Excellent Kaon identification.
- **EMC**: Crystal calorimeter (CsI(Tl))
  - Very good energy resolution.
  - Electron ID, $\pi^0$ and $\gamma$ reco.
- **IFR**: Layers of RPCs within iron. Muon and neutral hadron ($K_L$)

Detector for Internally reflected Cherenkov radiation (DIRC)
Electromagnetic Calorimeter (EMC)
1.5 T Solenoid

Drift chamber (DCH)
Silicon Vertex Detector (SVT)
Instrumented Flux Return (IFR)