

Recent Results of *B* Mesogenesis and Dark Sector at *BABAR*

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B Mesogenesis and Dark Sector

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Outline

- Physics Motivation and Experiment Introduction
- 2 Searches for *B* Mesogenesis and Dark Matter
 - B Mesogenesis and Dark Matter
 - Axionlike Particle
 - Dark Matter Bound State



Motivatio

Motivation: Dark Matter and Baryon Asymmetry



- Cosmology studies indicate **normal matter** and **dark matter** are ~5% and ~27% of the energy budget of universe today,
- Dark matter: undetected component of matter inferred by gravitation,
- Most common view that DM is non-baryonic, primary candidate is some more exotic undiscovered subatomic particle.



- Universe born with equal parts **matter** and **anti-matter**, predicted by the SM of cosmology,
- Baryogenesis required to generated the **matter-antimatter asymmetry**:

 $Y_B \equiv \frac{n_B - n_{\bar{B}}}{s} = (8.718 \pm 0.004) \times 10^{-11}$ (s = 7.04n_{\gamma} is the entropy density)

- Sakharov conditions:
 - C and CP violation (CPV),
 - baryon number violation,
 - interaction out of thermal equilibrium.

Motivation

DM and B Mesogenesis at B Factory





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B-Mesogenesis

Axionlike Particle (ALPs)

Self-interacting DM

- Model of QCD-scale baryogenesis,
- *B* mesons decay to baryon + dark baryon.
- ALP from *B* mesons decay via gauge bosons coupling.
- Dark photon, large coupling to DM,
- Search for DM bound states.

☞ PRD 107 (2023) 092001☞ arXiv:2306.08490

IN PRL 128 (2022) 131802

PRL 128 (2022) 021802

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Motivation

Introduction: The BABAR Experiment



- Designed primarily for the research of CP-violation in B-meson decays,
- General-purpose design of detector and high quality of data suit for a large variety of studies,
- Ten years data taking to collect 531 fb⁻¹ luminosity mainly at $\Upsilon(4S)$.

B Mesogenesis and Dark Matter via B Meson Decay



rs PRD **99** (2019) 035031, rs PRD **104** (2021) 035028

- A new mechanism proposed recently to explain **Baryon Asymmetry of the Universe (BAU)** and **Dark Matter (DM) abundance** simultaneously,
- BAU from *B* meson decay into a baryon (Λ/p) and a dark sector anti-baryon (ψ_D) + possible additional light meson (not included in these analyses),
- Matter and antimatter asymmetries are equal but opposite for visible and dark sectors (total baryon number is conserved).

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Search for DM and B Mesogenesis at BABAR



• Two independent analyses performed to search for *B* mesogenesis and DM at *BABAR*:

 $B^0 \to \Lambda + \psi_D$ and $B^+ \to p + \psi_D$,

- Fully reconstruct hadronic decay of "tag" B meson based on the *BAB4*R data with total luminosity of 398 fb⁻¹,
- Search for single SM baryon (A or *p*) and missing mass in the signal *B* decay,
- For the $B^0 \to \Lambda + \psi_D$ channel, kinematic fit of $\Lambda \to p + \pi^-$, including displaced vertex significance requirement,
- Train BDT using kinematic&purity observables that distinguish tagged *B* from continuum QCD events, as well as kinematic observables for signal *B*,
- The Λ channel analysis is published on PRD, and the *p* channels analysis is submitted to PRL.

RPRD 107 (2023) 092001

☞ arXiv:2306.08490

Events Selected from DM and B Mesogenesis Studies



BABAR Results

B Mesogenesis + DM

Results of DM and B Mesogenesis Studies



- Scan over ψ_D mass hypotheses: signal region size is 3 times signal resolution, background is estimated from adjacent sideband regions,
- Due to no significant signal seen: 90% CL limits set on signal branching fraction using profile likelihood method,
- The upper limits from both channel exclude large fraction of parameters space allowed for *B* mesogenesis,



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ALPs

Axion Like Particle via B Meson Decay



Through the *B* meson decay: $B^+ \to K^+ a$ and $a \to \gamma \gamma$

$$\mathcal{L}=-\tfrac{g_{aW}}{4\pi}aW_{\mu\nu}\tilde{W}^{\mu\nu}$$

R PRL 118 (2017) 111802

- Axionlike particles (ALPs): pseudoscalars that couples to pair of gauge bosons,
- May help to resolve issues of naturalness of SM parameters (*i.e.* CP strong Pb) and server as mediators to dark sectors,
- Primarily **ALPs** couple to pairs of SM gauge bosons, and can be produced in FCNC *B* decay processes.
- Very small branching fraction of $B \rightarrow K\gamma\gamma$ if only decay mechanism with SM,
- The lifetime of ALPs can be "long" for low axion mass and small coupling g_{aW} .

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ALPs

Search for Axion Like Particle at BABAR



- Search for ALPs at BABAR with data of 424 fb⁻¹ integrated luminosity $(4.72 \times 10^8 B\bar{B} \text{ pairs})$,
- Reconstruct $B^{\pm} \to K^{\pm}a$, $a \to \gamma\gamma$ candidates with a kenimatic fit to improve resolution,
- Two BDTs used to separate the signal from continuum and $B\bar{B}$ background events,
- Search for peaks in the reconstructed $\gamma\gamma$ mass, peaking contributions from π^0 , η and η' , which regions are excluded.

Results ALPs

Result of Axion Like Particle from BABAR



BABAR Results

Darkonium

Darkonium: Dark Matter Bound State



- DM bound state: dark photon (A') couples strongly to the dark matter fermion (χ) via coupling α_D and A' mixes with SM photon via kinetic mixing with strength ε
- Lowest bound states: $\eta_D (J^{PC} = 0^{-+}), \Upsilon_D (J^{PC} = 1^{--}),$
- Via ISR process: $e^+e^- \rightarrow \gamma_{\rm ISR} \Upsilon_D$ and $\Upsilon_D \rightarrow A'A'A'$

PRL 128 (2022) 021802

- Search for Dakonium at BABAR,
- A' decay to pairs of leptons and/or pions: $A' \rightarrow f^+ f^- (f = e, \mu, \pi),$
- Six charged tracks in the final states in this analysis,
- At least one pair of leptons $(e^+e^-/\mu^+\mu^-)$,
- Data with 514 fb⁻¹ total luminosity at $\Upsilon(4S)$, $\Upsilon(3S)$ and $\Upsilon(2s)$
- Dark photon lifetime can be long for small masses and small kinetic mixing *ϵ* hence prompt and displaced vertex signatures.
- ISR photon: energetic shower if emitted in detector acceptance, or recoil massless photon from Υ_D reconstruction.

BABAR Results

Darkonium

Search for Darkonium at BABAR



- MVA with the logistic regressions stacked on top of random forest (RF) classifiers to improve the purity,
- Three categories, C_n (n = 0, 1, 3), corresponds to n pair of pions in the final states,
- Total 69 events passed all the selection criteria,
- Consider window around each mass in the Υ_D A' plane of width 8x signal resolution,
- Background estimated from adjacent windows.

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Darkonium Result from BABAR



- In absence of significant signal, 90% CL upper limits are set on kinetic mixing ϵ as function of DM coupling by using profile likelihood method, with $\alpha_D = \frac{g_D^2}{4\pi}$,
- The upper limits are set for scenario of different Υ_D mass (m_{Υ_D}) and different coupling strength α_D ,
- Improve upon existing constraints over a significant fraction of dark photon masses below 1 GeV for large values of the dark sector coupling constant.

R PRL 128 (2022) 021802

Conclusion

- Searching for various New Physics beyond the Standard Model with *BABAR* data after the experiment stop running for ~15 years,
- Recent searches for *B* mesogenesis + DM, axionlike particle and DM bound states are performed at *BABAR* experiment,
- Clean *B*-factory experiment environment: extremely well suited to search for light dark sector, new results improve constraints in the dark sector significantly,
- A new search for the *B* mesogenesis + DM with the decay channel $B^+ \rightarrow \Lambda_c^+ + \psi_D$ is expected soon.

