Recent Dark Sector Related Searches with the BABAR Detector

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On behalf of the BaBar Collaboration

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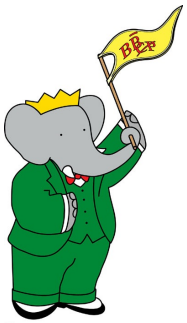
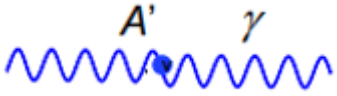


Dark Matter

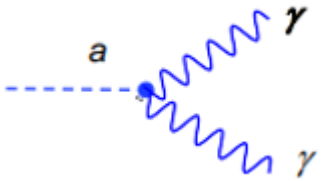
- Goal is to understand what DM is and its mass scale.
  - Many models!
- Effective theory approach provides different "portals" to access the dark sector.

SM Particles ⟷ Portals ⟷ Dark Matter

Portal examples



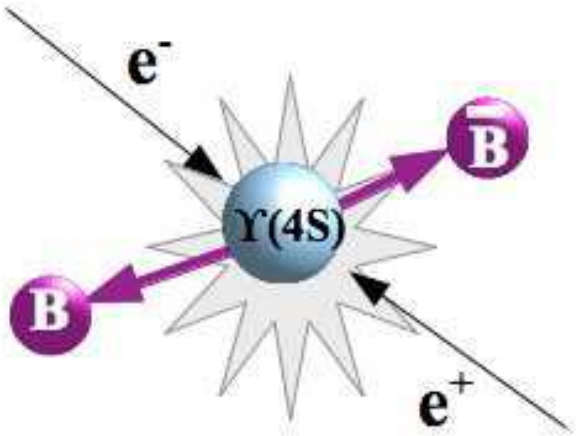
Dark photon A'



Axion Like Particle a

- Experiments can constraint mass, operators, and couplings
- (Super)B factories offer a great opportunity to search for low mass DM produced through interactions between SM particles and portal mediators in:
  - B mesogenesis, a recent approach to explain both DM and baryon asymmetry in the universe
  - B meson decays
  - Dark matter production in e+e- collisions

Production Mechanism at BaBar

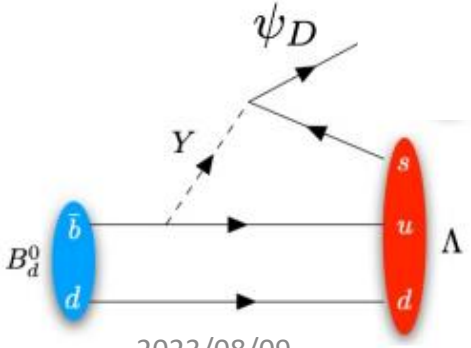


Continuum background
for B decays analyses

Process	σ (nb)
$b\bar{b}$	1.1
$c\bar{c}$	1.3
Light quark $q\bar{q}$	~2.1
$\tau^+\tau^-$	0.9
e^+e^-	~40

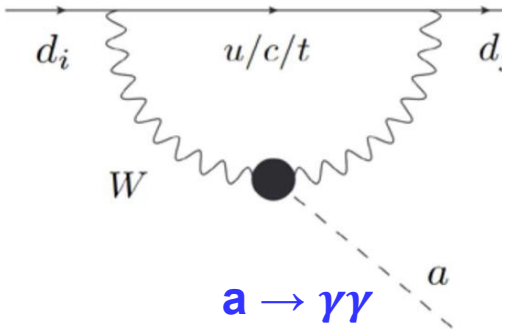
B Mesogenesis

dark anti-baryon Ψ_D



Axion Like Particle

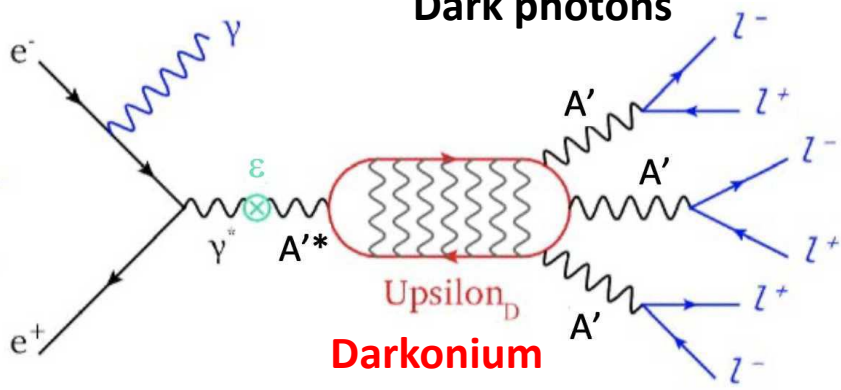
B → K + a (ALP)



a → γγ

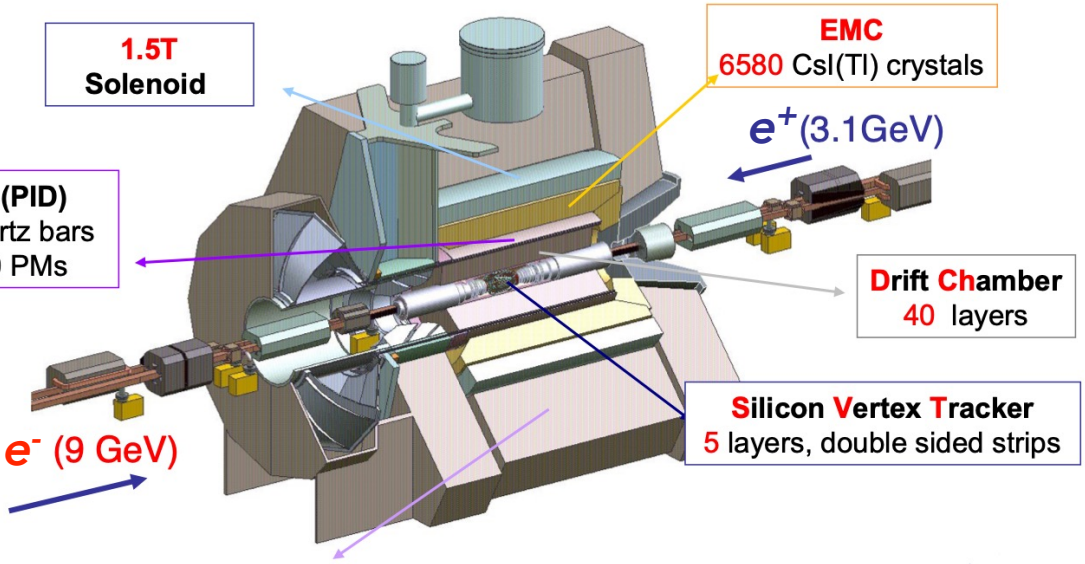
Darkonium

Dark photons

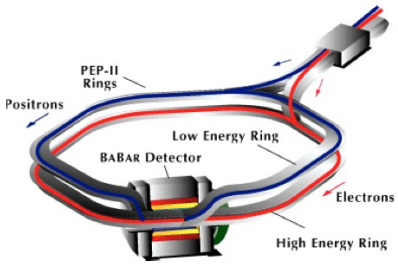


Darkonium

The BaBar Experiment



1999-2008



432 fb^{-1} @ Υ(4S)

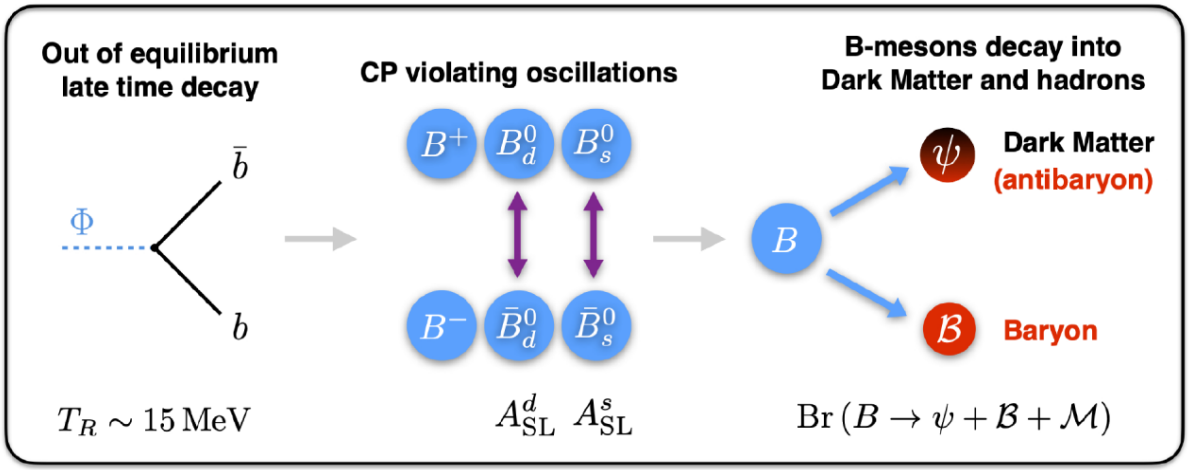
O(450) million B meson pairs

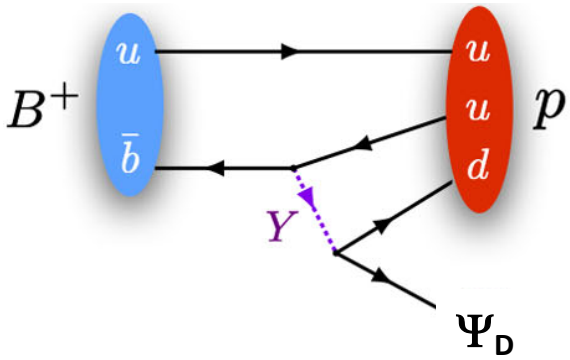
Smaller samples @ Υ(2S), Υ(3S), and off-peak

- Clean e^+e^- environment with good detector coverage
- Good missing energy (potential dark matter) reconstruction in the recoil of a fully reconstructed B meson
- Reconstruct displaced vertices from long-lived particles
- Precise Particle Identification and reconstruction
- Long history : more than 10 years of DM searches even if different from initial (CP violation) goal

G. Elor, M. Escudero and A. E. Nelson,Phys. Rev. D 99, 035031 (2019)
G. Alonso-Alvarez, G. Elor, and M. Escudero,Phys.Rev. D 104, 035028 (2021)

B-mesogenesis: What It Is ?





- Out-of-thermal-equilibrium production of b and $\bar{b}$ quarks in the early universe through the decay of a massive, long-lived scalar field Φ
- A fraction of these quarks hadronize into B^0 and $\bar{B}^0$ mesons, which undergo CP-violating oscillations before decaying into a baryon $\mathcal{B}$, a dark-sector antibaryon Ψ_D, and any number of additional light mesons $\mathcal{M}$.
- Matter- antimatter asymmetries are generated in the visible and dark sectors with equal but opposite magnitudes, keeping the total baryon number conserved.

B-mesogenesis in B Decays

A BSM TeV-scale color triplet scalar Y is needed. It can be integrated out to give an effective Lagrangian:

$$\mathcal{L}_{\text{eff}} = \sum_{i,j} \mathcal{O}_{u_i d_j} \frac{y_{ij}^2}{M_Y^2}$$

Product of couplings

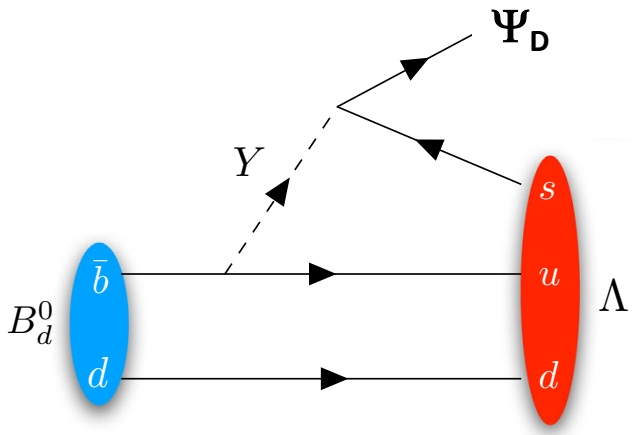
Flavor combination operators

$$\mathcal{O}_{ud} = \psi b u d$$

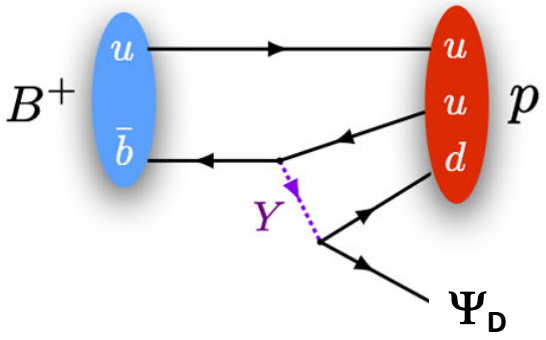
$$\mathcal{O}_{us} = \psi b u s$$

$$\mathcal{O}_{cd} = \psi b c d$$

$$\mathcal{O}_{cs} = \psi b c s$$



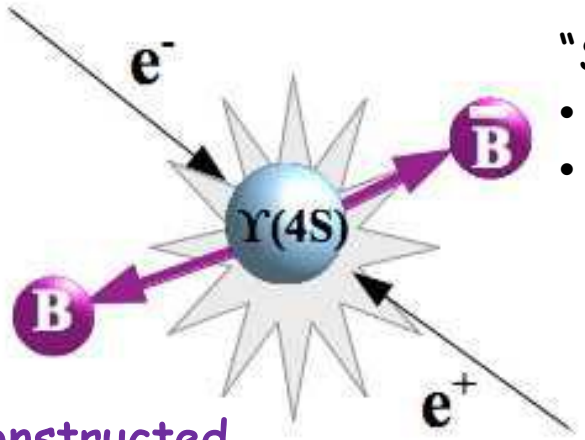
Probes O_{us}



Probes O_{ud}

Search of B-mesogenesis @ BaBar

Hadronic recoil method



Fully reconstructed "Tag " B meson in known hadronic modes

"Signal" B meson:

- Reconstructed baryon (Λ, p)
- Missing Ψ_D 4-momentum (dark anti-baryon Ψ_D escapes detection)

$B^0 \rightarrow \Lambda \Psi_D$ PHYS. REV. D 107, 092001 (2023)

$B^+ \rightarrow p \Psi_D$ arXiv:2306.08490v2

- Boosted Decision Tree (BDT) to suppress residual combinatorial backgrounds from $q\bar{q}$ and $B\bar{B}$ decays
- In $B^0 \rightarrow \Lambda \Psi_D$ analysis, kinematic fit of $\Lambda \rightarrow p \pi$, including displaced vertex significance requirement

Background Rejection in $B^0 \to \Lambda \Psi_D$

Full reconstruction of "Tag" B meson

m_{ES} : $\sqrt{E_{beam}^2 - p_{B_{Tag}}^2}$

Peak at B meson mass for signal

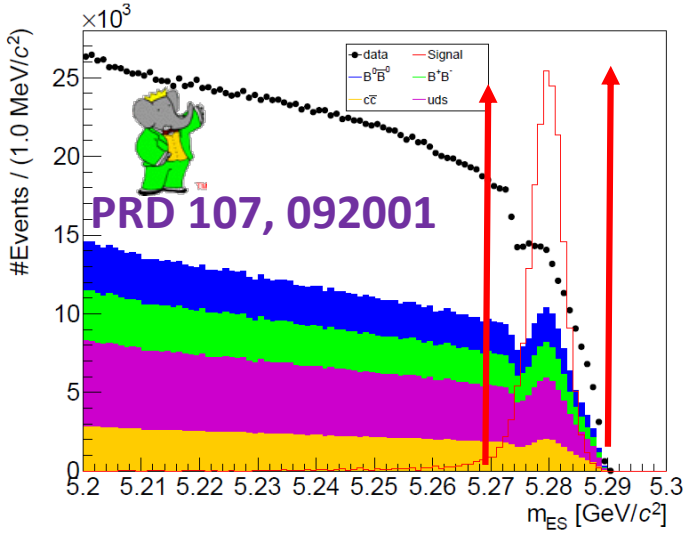
ΔE : $E_{beam} - E_{B_{Tag}}$

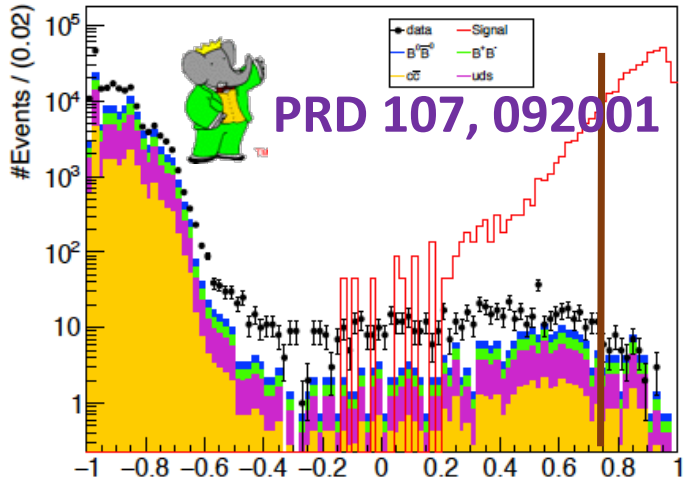
Peak at 0 for signal

Event topology variables to separate BB more «spherical» events from more « jet-like » qq continuum events

BDT output variable ν_{BDT} combines background rejection variables, with B_{TAG} reconstruction quality, Λ reconstruction quality, etc.

m_{ES} for B_{Tag} in $B^0 \to \Lambda \ \psi_D$ analysis



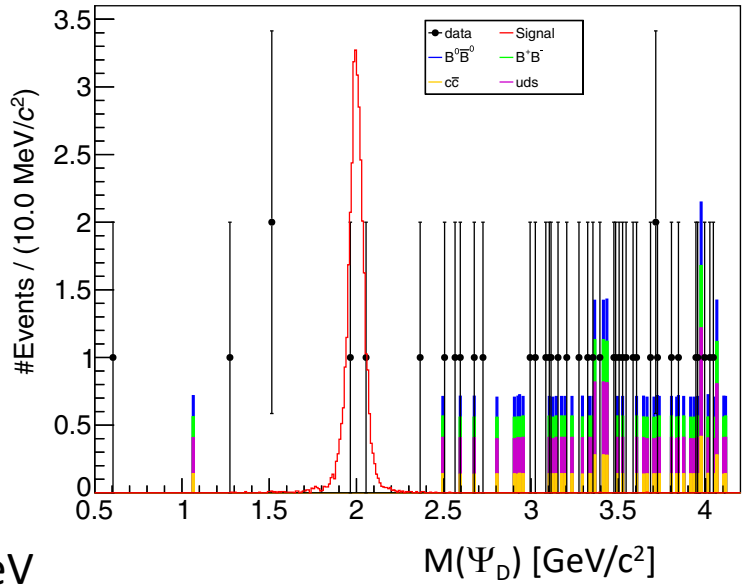


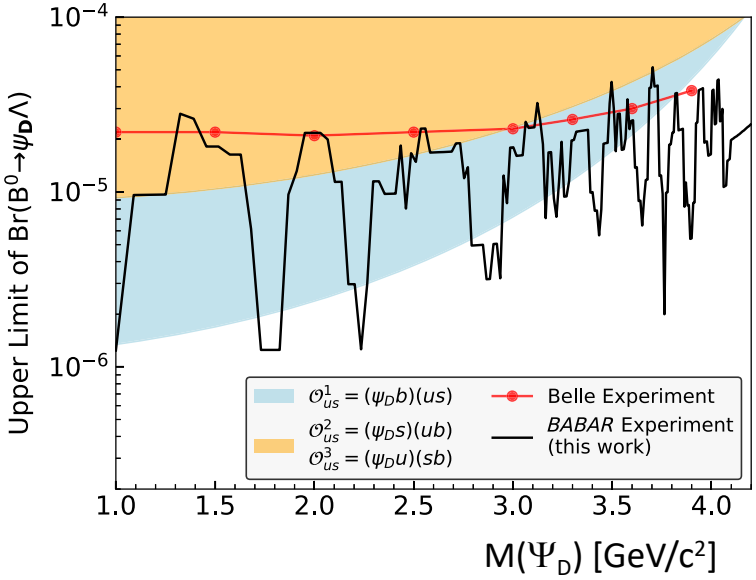
$\nu_{BDT} > 0.75$ for signal

Upper Limits on B-mesogenesis @ BaBar

Scan various $M(\Psi_D)$ hypothesis in step of σ_M, count the number of events within 3 σ_M of $M(\Psi_D)$, set an upper limit

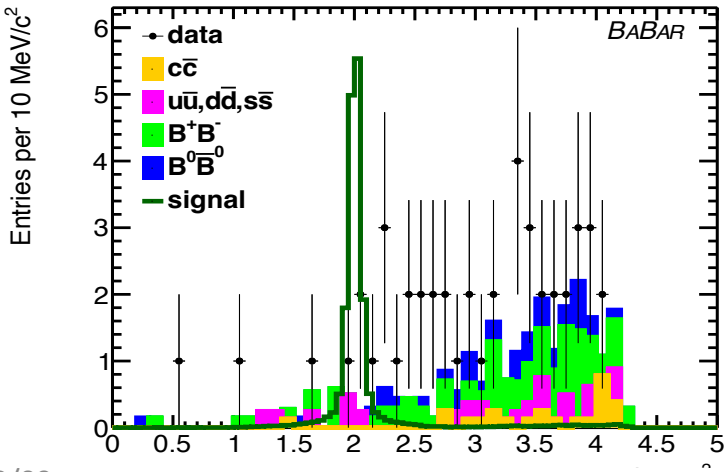
$B^0 \rightarrow \Lambda \Psi_D$

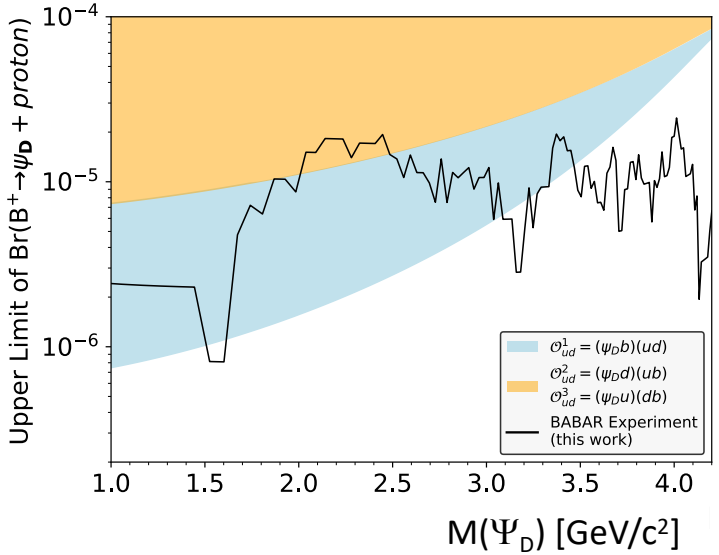




Example:
$M(\Psi_D)$ = 2 GeV

$B^+ \rightarrow p \Psi_D$

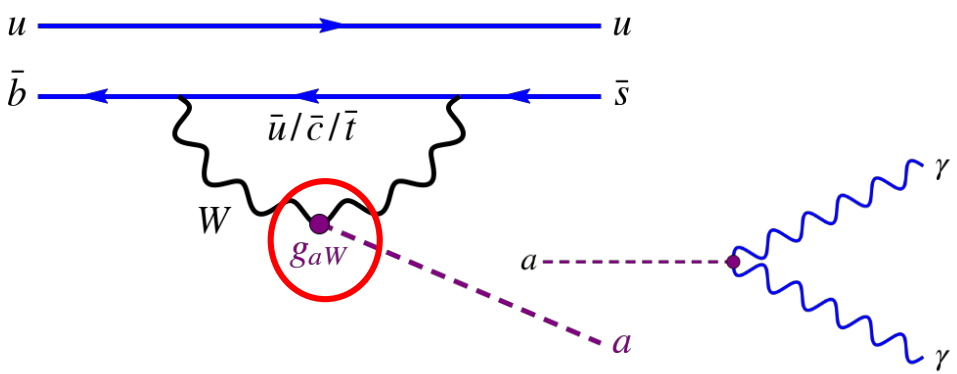




Search for Axion Like Particles @ BaBar in $B \to Ka$ with $a \to \gamma\gamma$

- Many extensions of SM include spontaneously-broken global symmetries, resulting in pseudo-Goldstone bosons : **Axion-Like Particles (ALPs)**
  - Could help resolve issues of naturalness of SM parameters and serve as mediators to dark sectors
- ALPs (a) couple primarily to pairs of SM gauge bosons (coupling g_{aW}).
  - Can be produced in FCNC B decay processes, like $B \to K\,a$, with $a \to \gamma\gamma$
  - (nearly 100% BF for $m(a) < m(W)$)
- $\tau \sim 1/m_a^3 g_{aW}^2$: for low m_a and small g_{aW}, the decay can be "non-prompt"

E. Izaguirre et al., PRL 118 (2017) 111802



$SU(2)_W$ field strength tensor

coupling

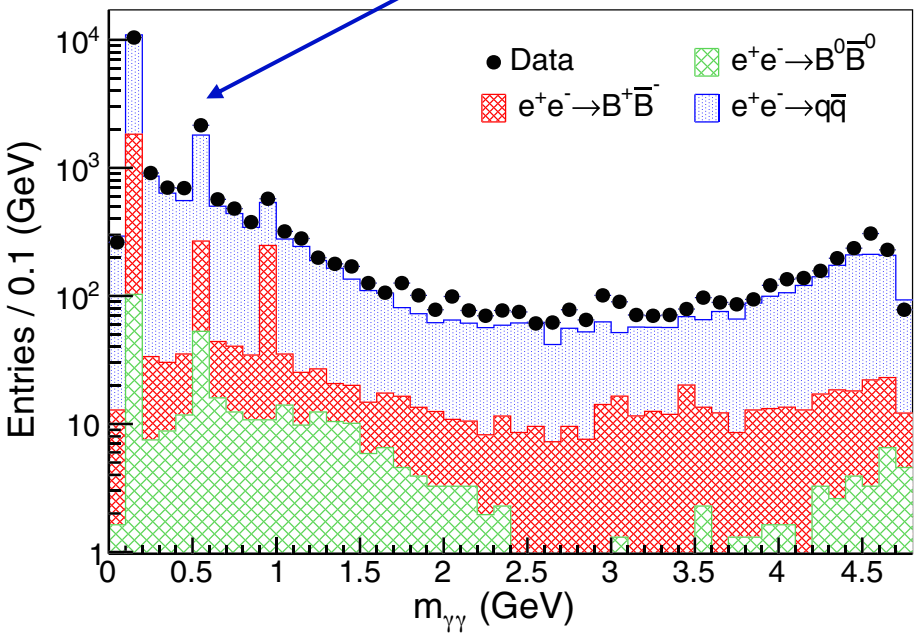
$$\mathcal{L} = -\frac{g_{aW}}{4}\, a\, W^{b}_{\mu\upsilon} \widetilde{W}^{b\mu\upsilon}$$

Search for $B \to Ka\ (a \to \gamma\gamma)$

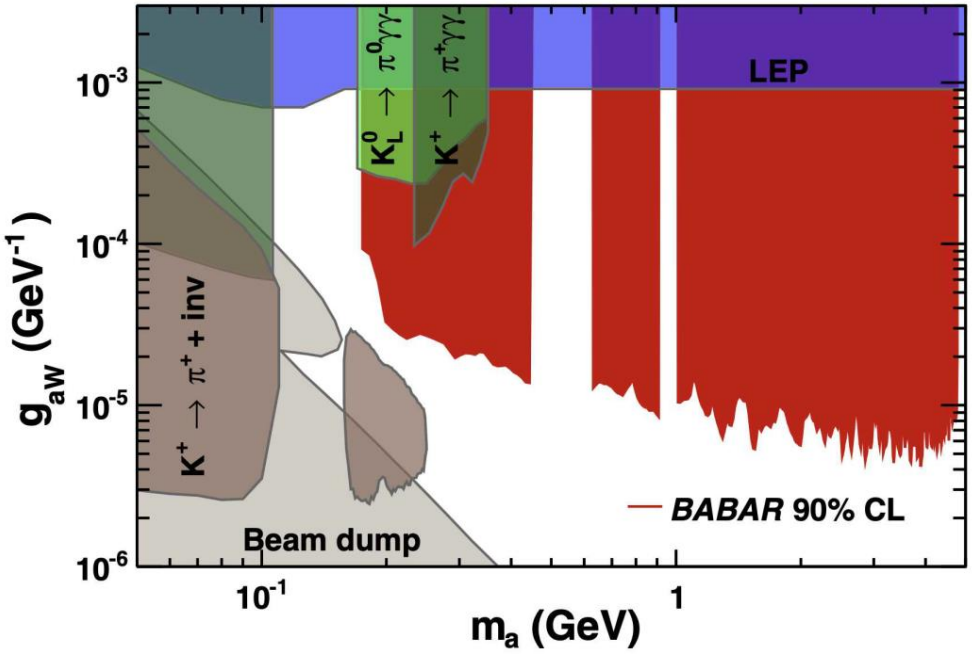
Phys. Rev. Lett. 128, 131802 (2022)

Search for peak in the reconstructed $\gamma\gamma$ mass

Peaking contributions from π^0, η, η'



90% CL exclusion bounds on the ALP coupling g_{aW}

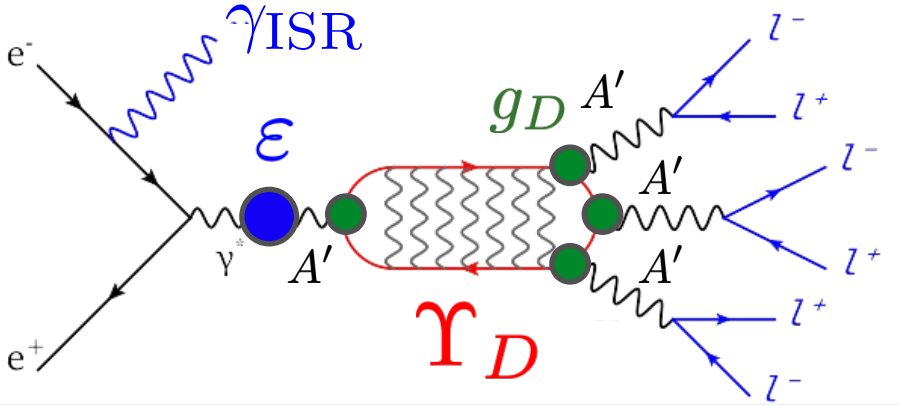


Up to two orders of magnitude improvements over previous limits

Search for Darkonium @ BaBar (1)

- DM bound states (Darkonia) arises in models in which:
  - Dark photon A′ has large coupling α_D to DM fermion
  - A′ mixes with SM γ with kinetic strength ε
- We search for the lightest vector darkonium, Υ_D
- We reconstruct dark photon A′ decays into $e/\mu/\pi$ pairs of similar mass (min. 1 lepton pair)
  - Search for a 6 tracks final state
- Dark photon lifetime can be long for small masses and small kinetic mixing ε hence prompt and displaced vertex signatures

H. An et al., PRL 116 (2016) 151801



$e^+e^- \rightarrow \gamma\, \Upsilon_D,\ \Upsilon_D \rightarrow A'A'A'$

$A' \rightarrow f^+f^-$ (f=e, μ, π)

Search for Darkonium @ BaBar (2)

Final state selection : 3 pairs of opposite-sign tracks (at least one lepton pair) which should all have same invariant mass

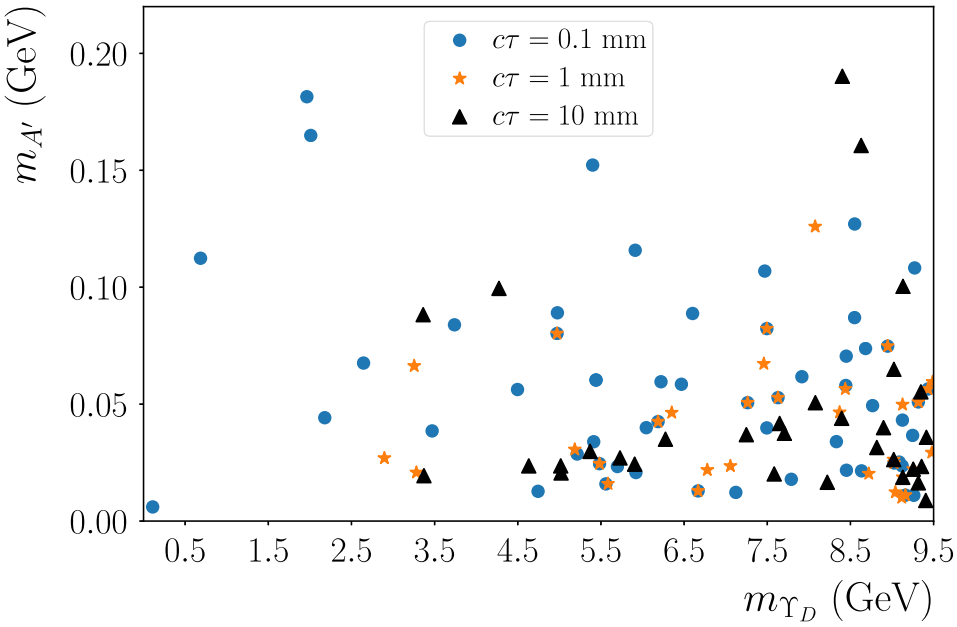
Reconstruct Υ_D mass

ISR photon may or may not be detected, but recoil mass against Υ_D should be consistent with zero

MVA trained on MC sample with different A' lifetimes used to suppress backgrounds

Scan m(Υ_D) - m(A') plane

PRL 128, 021802 (2022)



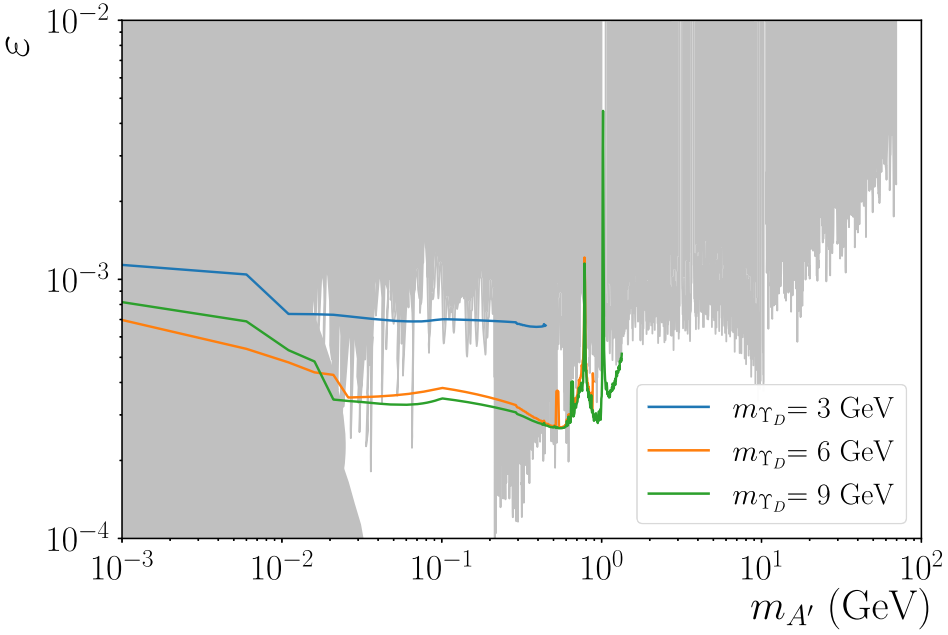
No significant signals observed in either prompt or displaced decay searches

Search for Darkonium @ BaBar (3)

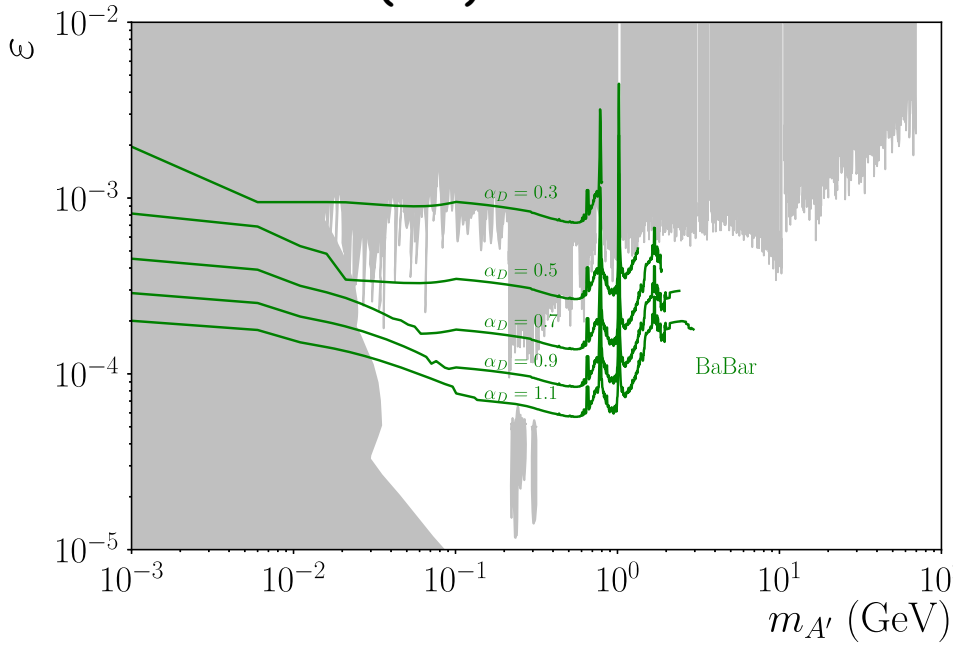
Dark photon A' couples to the dark matter fermion via coupling α_D and A' mixes with SM photon via kinetic mixing with strength ε

90% C.L. Upper limits on the kinetic mixing parameter **ε** as a function of m(A')

For different values of m(Υ_D)



For different values of α_D and m(YD) = 9 GeV



Summary

- BaBar data open an interesting and important window for searching for various physics beyond the Standard Model
- Clean B factory environment : extremely well suited to searches for light dark sector particles
- Significant improvements in constraining dark sector
- B mesogenesis, ALPs and darkonium searches are the most recent in a long, flourishing, and still developing history of dark sector and exotic searches at BaBar.
- The larger datasets that will be collected by Belle II will extend the searches presented here