MELBOURNE
Australia

Recent Dark Matter related searches with the BABAR detector

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Representing the BABAR Collaboration

Outline

Introduction

The BABAR experiment and data sample

Dark Matter related searches –

The directions and the analyses

Results

Summary

Introduction

The Standard Model has been very successfully tested by experiments

However it is not a complete theory

facing some tensions:

naturalness and stability, g-2, W mass, R_K, R_D, R_{D^*} , . . .

can not explain:

existence & mechanism of dark matter and dark energy,

baryon asymmetry of the Universe,

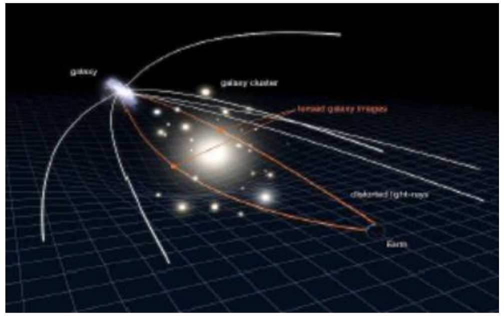
neutrino masses and oscillations, hierarchy

Real opportunities for discovering new physics beyond the SM

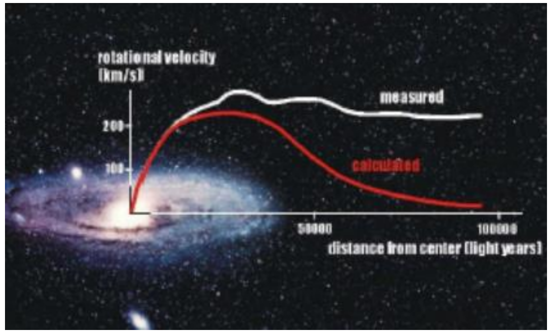
Introduction

Observations of galactic dynamics and Cosmic Microwave Background (CMB) showed that the SM particles are not abundant enough to account for all matter in the universe. Thus the existence and the mechanism of dark matter

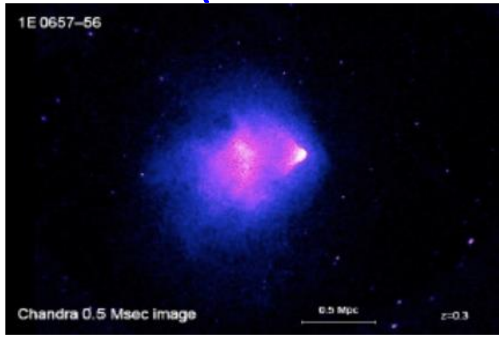
Gravitational lensing



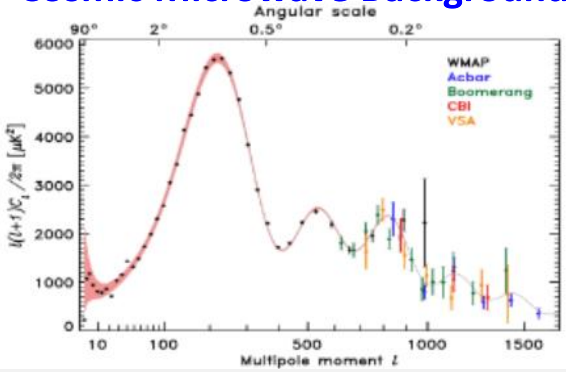
Galactic rotation curve

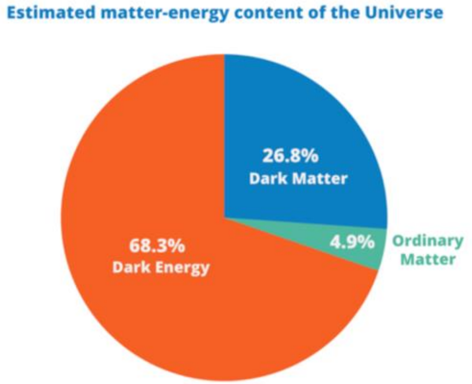


Bullet cluster (DM collision in GM)



Cosmic Microwave Background





Percentage of ordinary matter, dark matter, dark energy (Image: CERN/ESA)

Dark Matter –

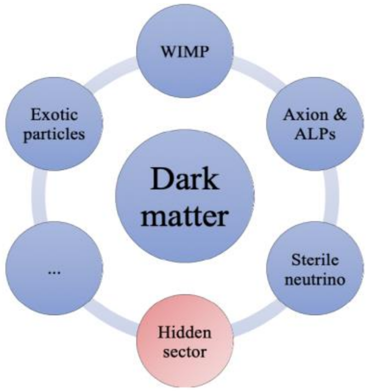
- Inferred from gravitational effect on visible matter
- Outweigh visible matter (~6 to 1)
- Does not interact with strong, or EM forces
- Making it **extremely hard to spot**

Clear astrophysical and cosmological evidence for dark matter

Extensions to the Standard Model

Dark Matter not seen in particle physics experiments yet

SM can not explain DM ⇒ Extending the SM to include DM



Many models are proposed, for example a particular model:

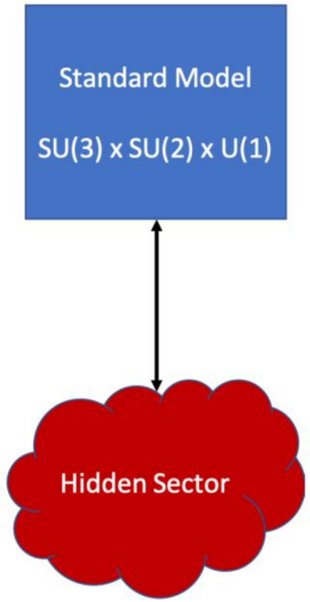
$$\mathcal{L} \supset \begin{cases} -\dfrac{\varepsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}\,, & \text{vector portal} \\ (\mu\phi + \lambda\phi^2) H^\dagger H\,, & \text{Higgs portal} \\ y_n L H N, & \text{neutrino portal} \\ \dfrac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}, & \text{axion portal} \end{cases}$$

A’ kinetic mixing with γ, Z

Dark Higgs (mixes with SM Higgs)

Sterile neutrino

Axion, coupling to DM



Dark Matter States – Searches

Dark Matter accessible at PEP-II/BABAR energies

- Axion-like particles (ALPs) – masses can be well below the electroweak scale. With couplings to electroweak bosons, they could be emitted in flavor-changing B meson decays.
  Search for axion-like particles in B meson decays
- Dark matter bound states (darkonium) could arise if a dark photon A' is light enough to generate an attractive force between 2 dark fermions.
  Search for dark matter bound states
- Model of QCD-scale baryogenesis; B mesons decay to regular baryon+dark baryon
  Search for B Mesogenesis

Benjamin W. Lee and Steven Weinberg. Phys. Rev. Lett. 39, 165 (1977) ,...

The BABAR Experiment and the Data Sample

BABAR data samples
- Large statistics
- Clean data
- Excellent kinematic condition

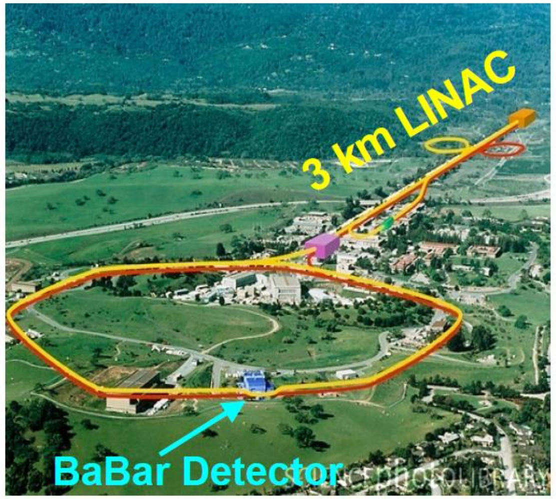
Ideal for DM searches

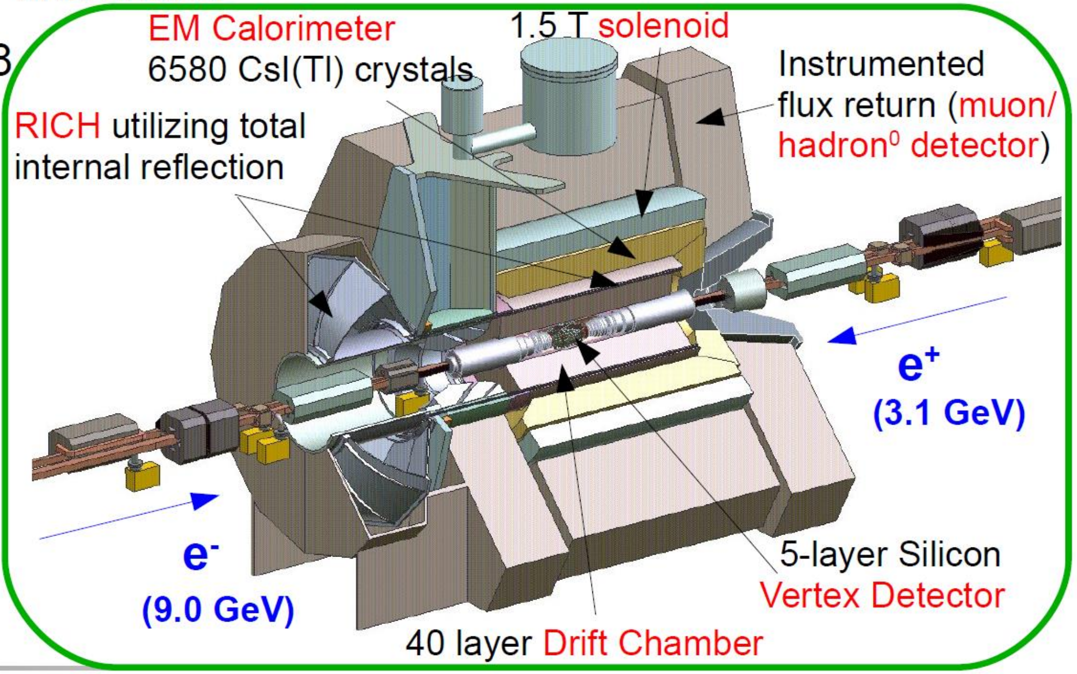
- B-Factory at the PEP-II aymmetric e^+e^- collider located at SLAC
- Collected **424 fb^{-1}** at the CM energy 10.58 GeV for $\Upsilon(4S)\rightarrow B\overline{B}$

  4.72×10^8 $B\overline{B}$ pairs **$4X10^8$ τ pairs**

  - Substantial samples of $\tau^+\tau^-$ and charm
- Data-taking from 1998 to 2008

Design luminosity: 3.0 x 10^{33} cm^{-2} s^{-1}
Record luminosity: 12.07 x 10^{33} cm^{-2} s^{-1}

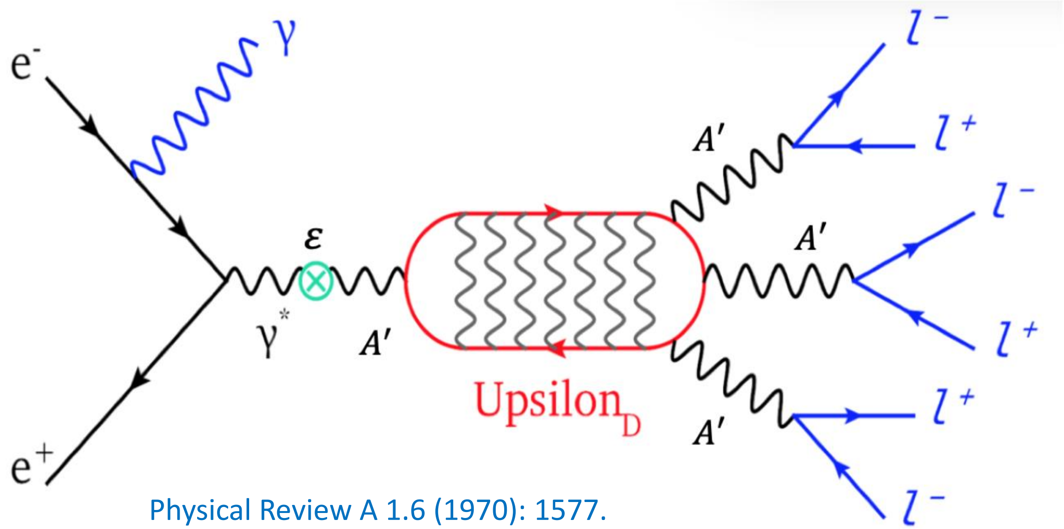




Dark Matter Searches

Productions and decays – dark matter bound states

- A minimal dark sector model contains a single Dirac fermion (χ) charged under a new U(1) gauge group with a coupling constant g_D.
- Sufficiently strong values of g_D could result in the formation of bound states $\chi\bar{\chi}$ (darkonium).
- The existence of stable bound states requires $1.68 m_A \le \alpha_D m_\chi$
- One lowest bound state Upsilon$_D$ ($J^{PC} = 1^{--}$) predicts the process



Physical Review A 1.6 (1970): 1577.
Physical Review Letters 116.15 (2016): 151801.

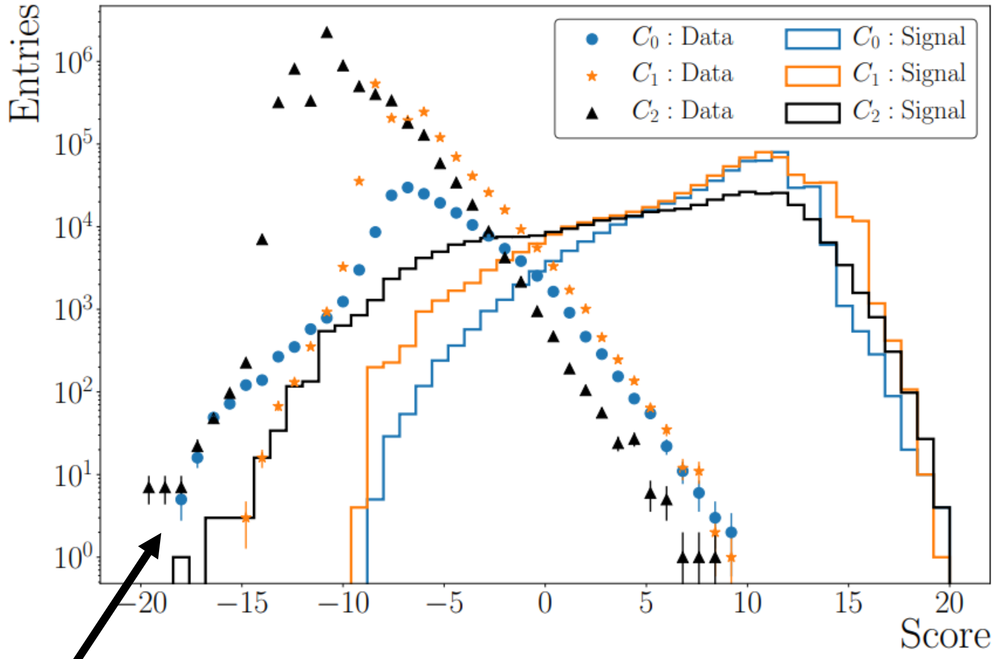
We search for the reaction $e^+e^- \rightarrow \gamma\Upsilon_D$, $\Upsilon_D \rightarrow A'A'A'$, $A' \rightarrow X^+X^-$ ($X = e, \mu, \pi$)

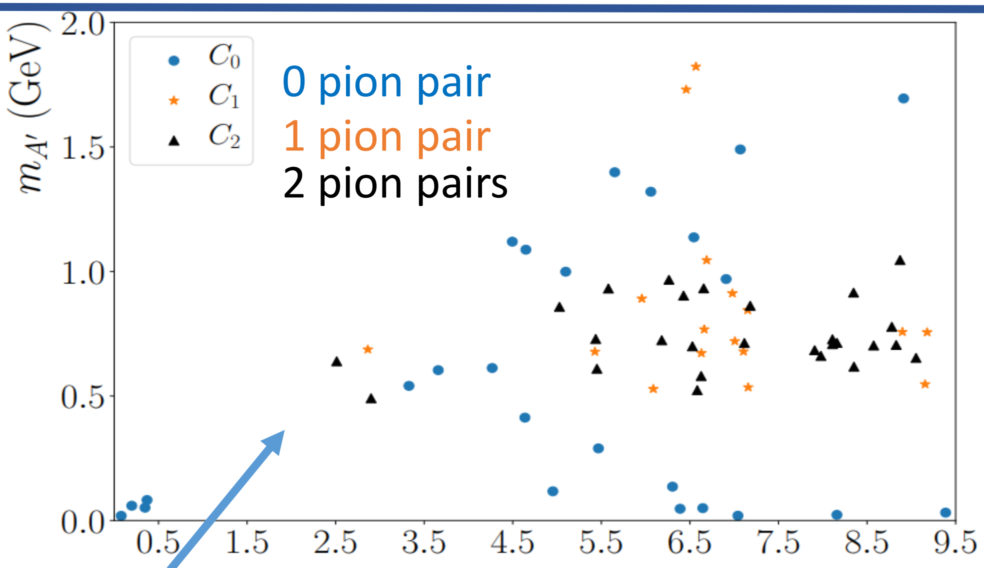
- Final states consist of three pairs of leptons or pions, with two or more electron or muon candidates.
- Dark photons should have same masses.
- Recoil mass against Υ_D should be compatible with the photon hypothesis
- Extra neutral energy should be small.

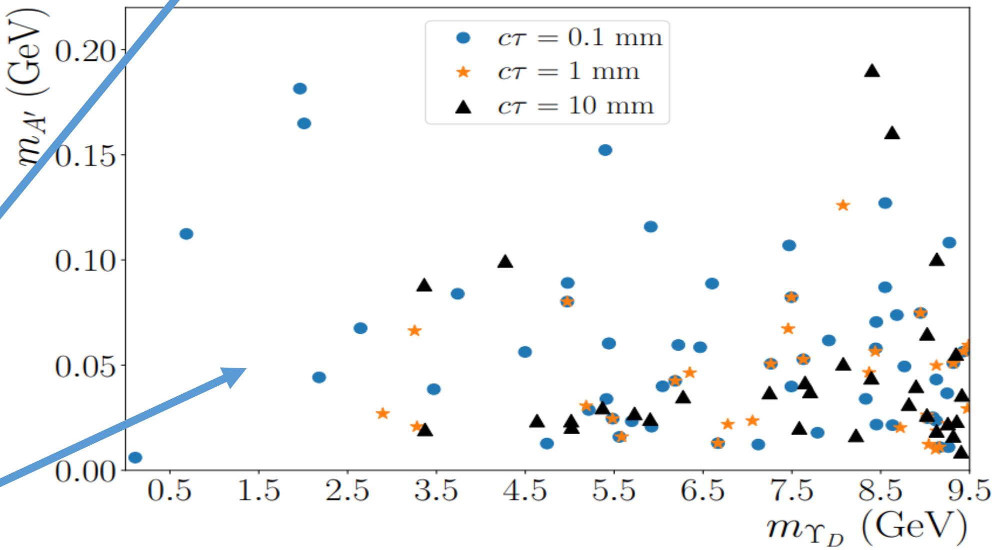
Dark photon is small in mass and could be short or long-lived depending on the dark photon mass, momentum and mixing strength, decay can either be prompt or displaced.

Results

dark matter bound states – analysis



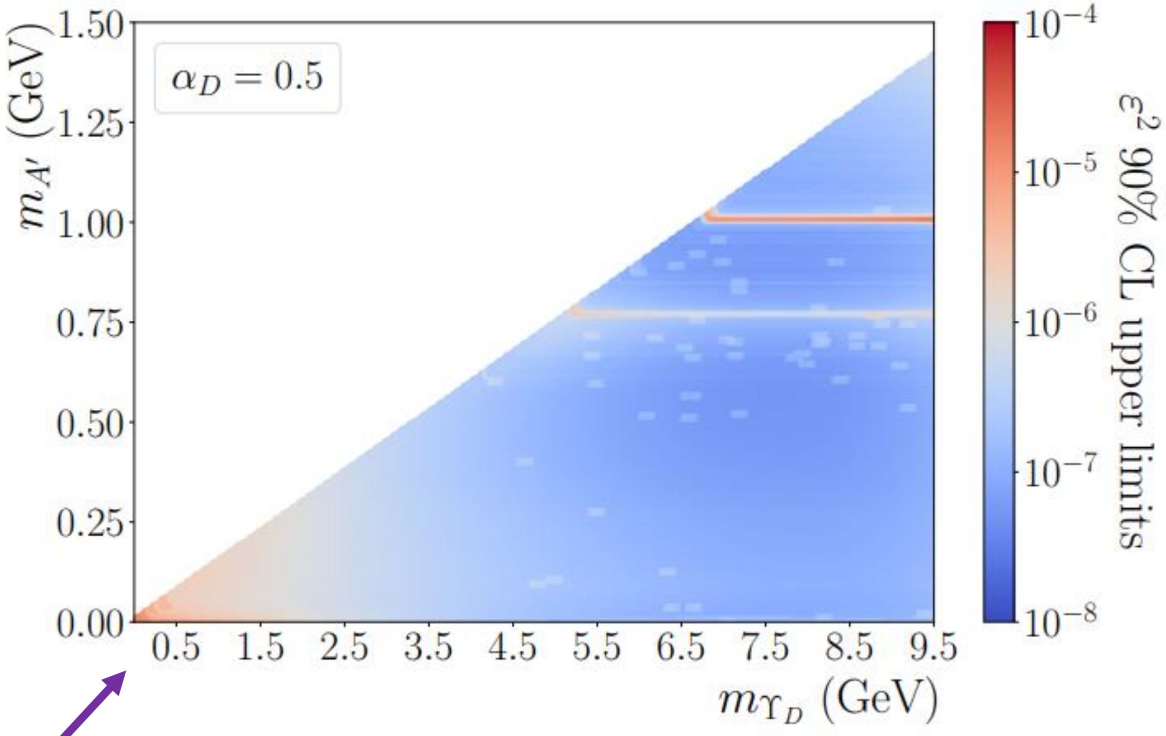


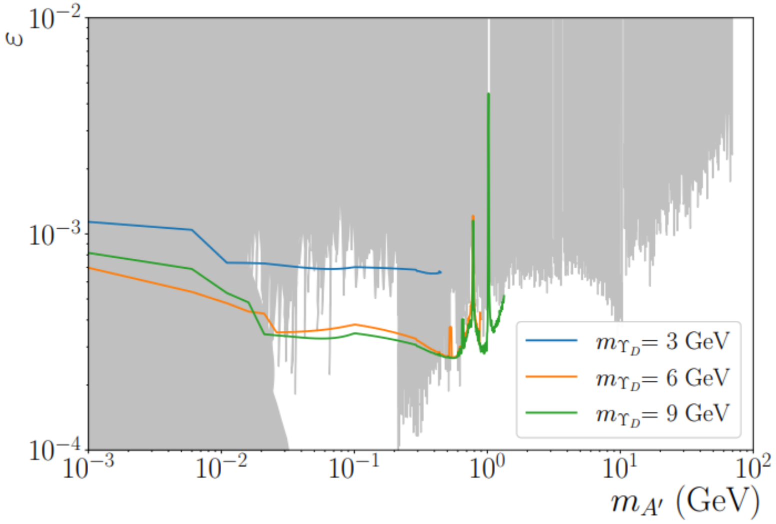


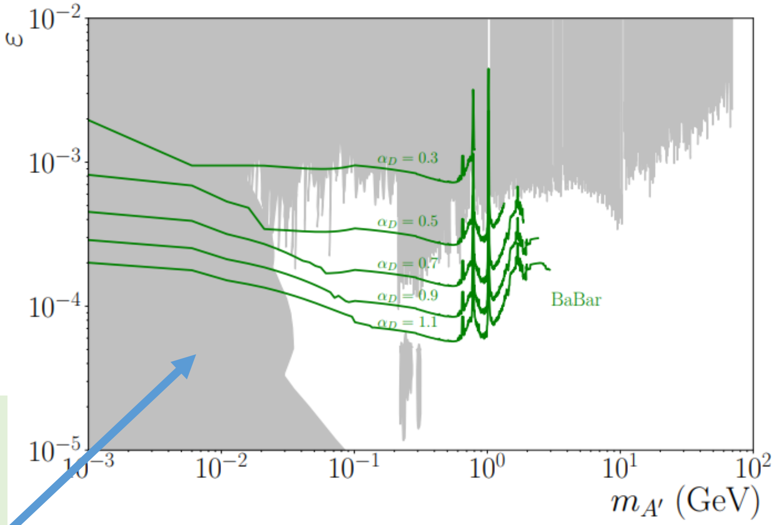
- Data compared with signal MC events for 0,1,2 pion pairs.
- Events passing all selection criteria for prompt dark photon decays.
- Event candidates passing all selection criteria for the datasets optimized for each dark photon lifetime.

Results

dark matter bound states





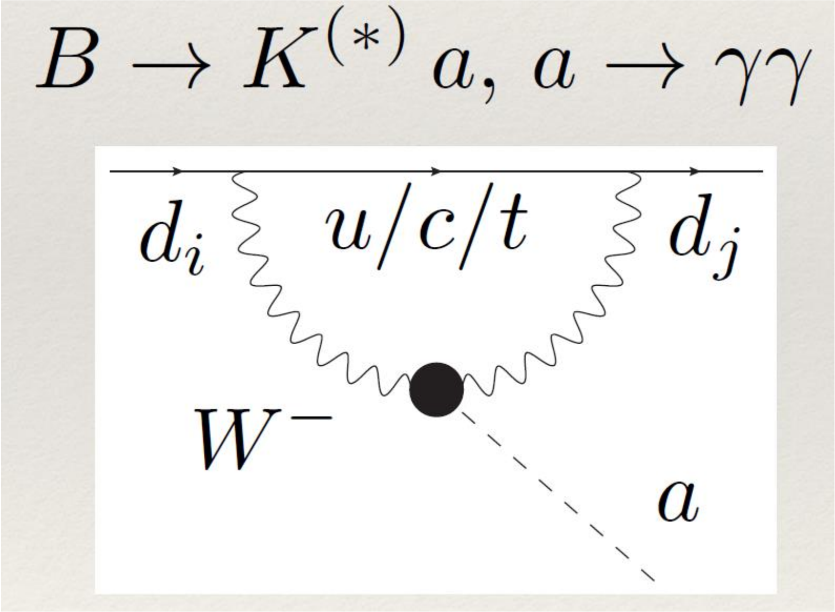


- ✓ Bounds on the kinetic mixing ε^2 down to $10^{-9} - 10^{-6}$ are excluded for a large fraction of the parameter space.
- ✓ Constraints for different values of α_D, $m_{A'}$ and $m_{\Upsilon D}$ are also shown.

Dark Matter Searches

Axion-like particles in B decays

- New light pseudoscalar, couples predominantly to gauge bosons
- In presence of coupling SU(2) gauge bosons, get large FCNC production rate
- At small mass/coupling, lifetime becomes appreciable (*mm* - 10s of *cm*)



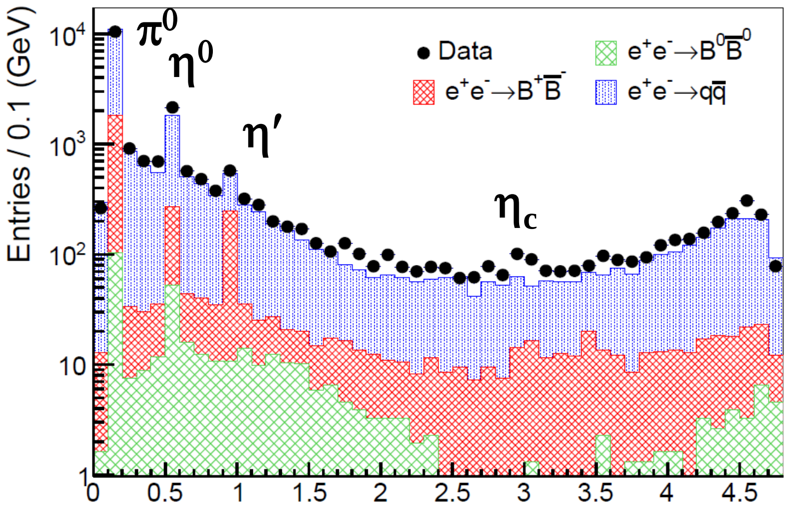
Physical Review Letters (2017, arXiv1611.09355)

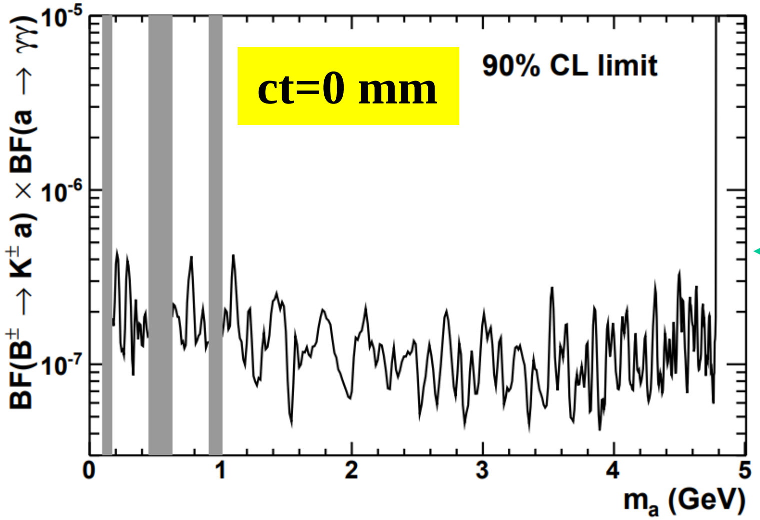
We fully reconstruct $B^{\pm} \to K^{\pm}\gamma\gamma$

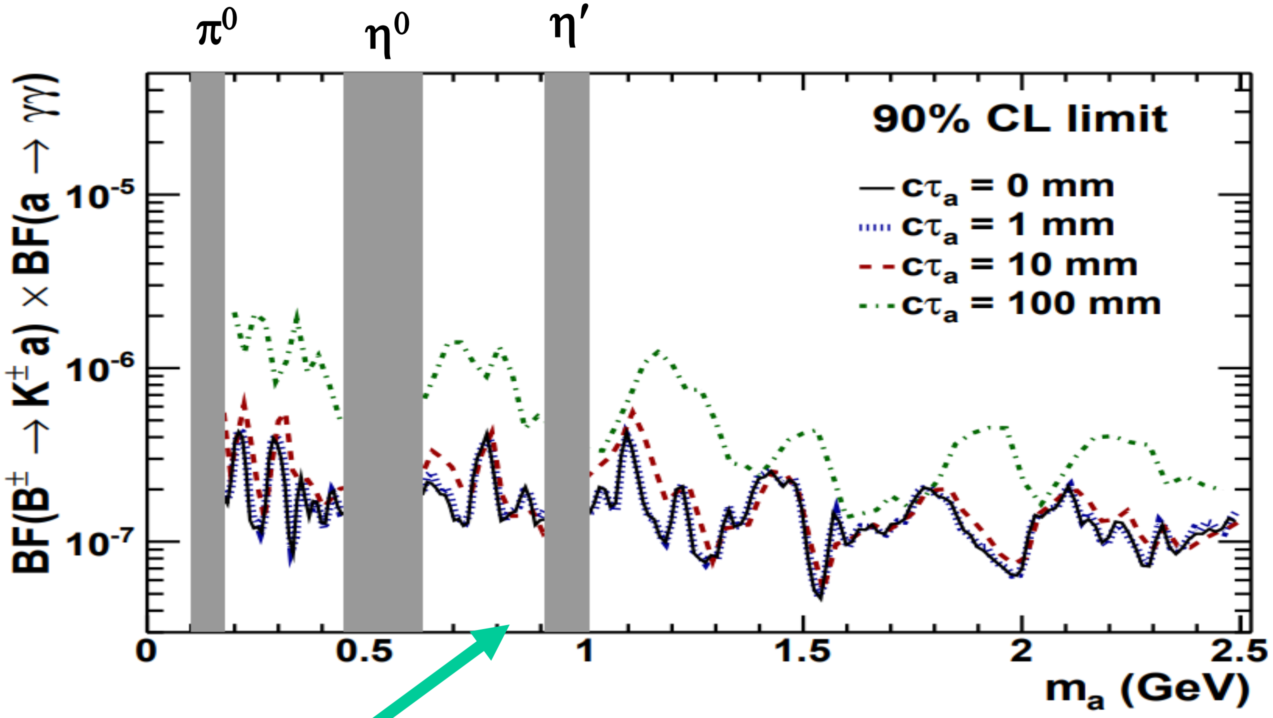
- K and 2γ candidates forming the B.
- Kinematic fit including beam, energy, and mass constraints.
- Loose pre-selection for candidates: $m_{ES} > 5$ GeV, $|E| < 0.3$ GeV
- 13 BDT training observables.

Results

Axion-like particles in B decays







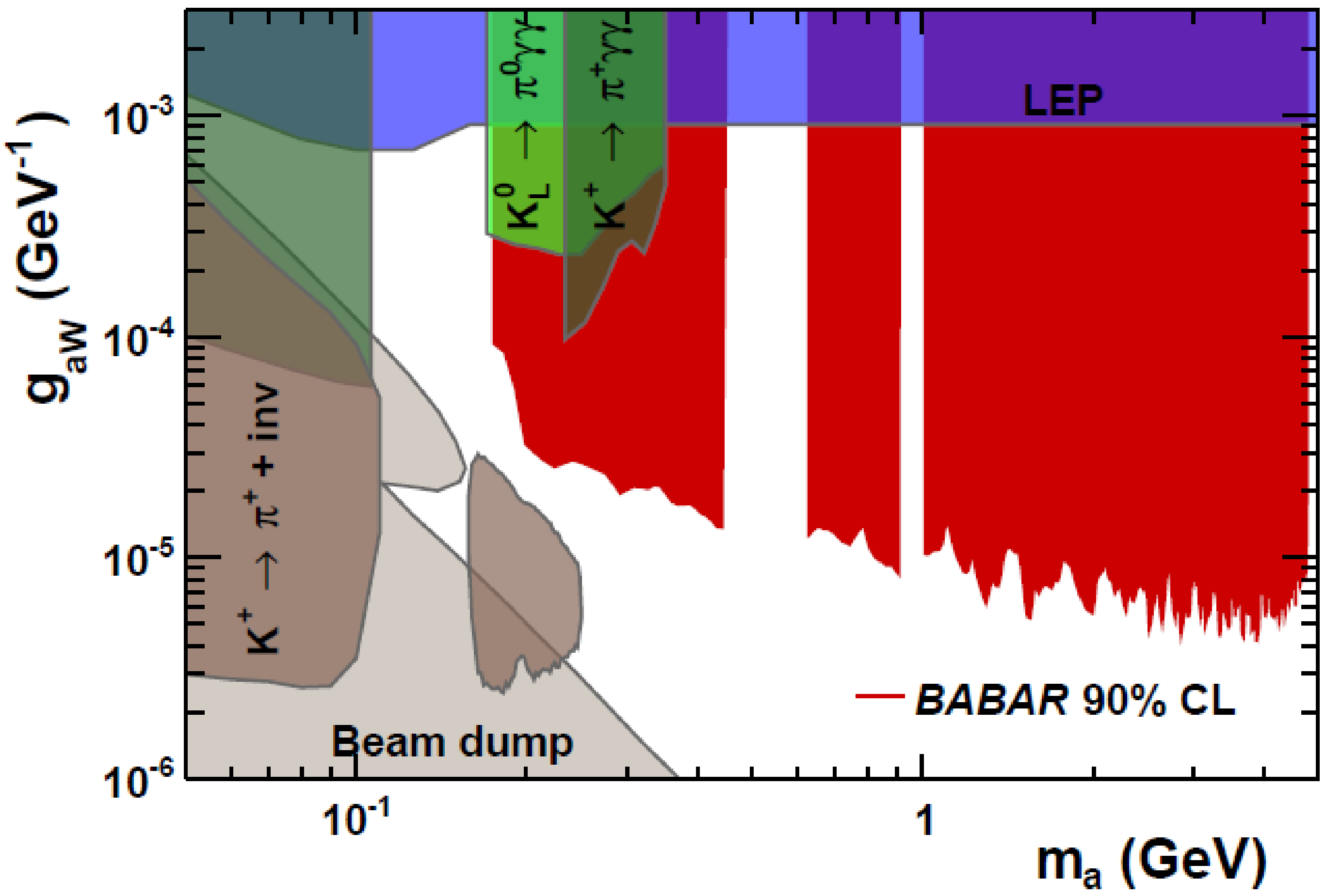
The 90% CL upper limits on the $B^\pm \to K^\pm a$ branching fraction

- For $m_a < 2.5$ GeV and $c\tau_a$ between 0 and 100mm.
- All m_a and $c\tau_a = 0$.

The vertical gray bands indicate the regions excluded from the search in the vicinity of the π^0, η, and η’ masses.

Results

Axion-like particles in B decays

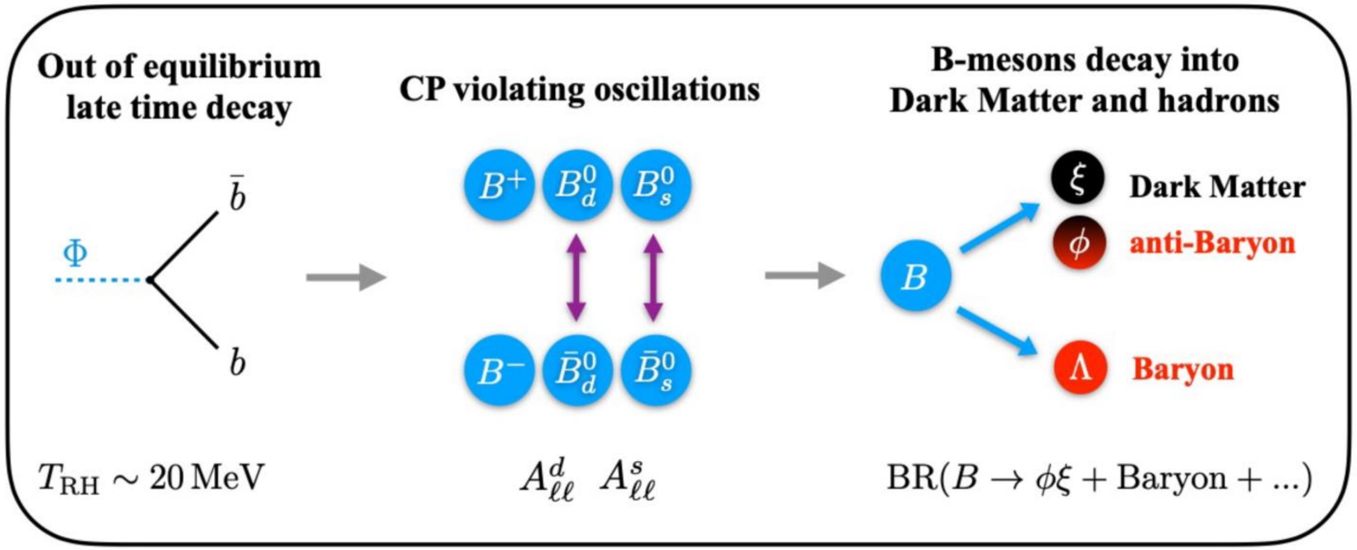


The 90% CL upper limits on the coupling g_{aW} as a function of the ALP mass (red), together with existing constraints (blue, green, brown, and grey)

Significantly extending the limits in 0.2 - ~5 GeV) range

B-Mesogenesis

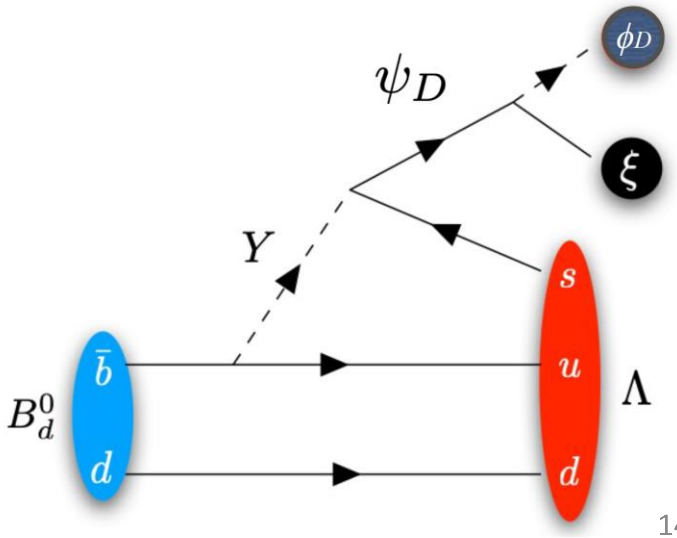
- New mechanism for baryogenesis + Dark Matter (regular + dark baryon) asymmetries produced in CPV decays of B mesons
  G. Elor, M. Escudero, A. Nelson, PRD 99, 035031 (2019); F. Elahi, G. Elor, R. McGehee, PRD 105, 055024 (2022)
- Rare example of viable baryogenesis mechanism in models with low reheat temperature ($T_{RH} \lesssim 100$ MeV)
- Signal depends on flavor structure



PRD 107, 092001 (2023) & arXiv:2306.08490

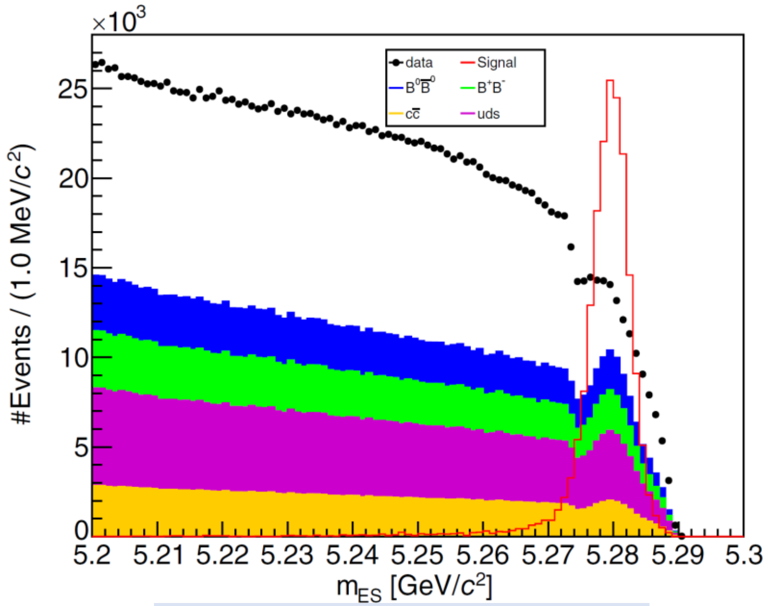
Neutral B meson decays offer the opportunity

$$B^0 \to \Lambda + \psi_D \ ({\rm inv})$$

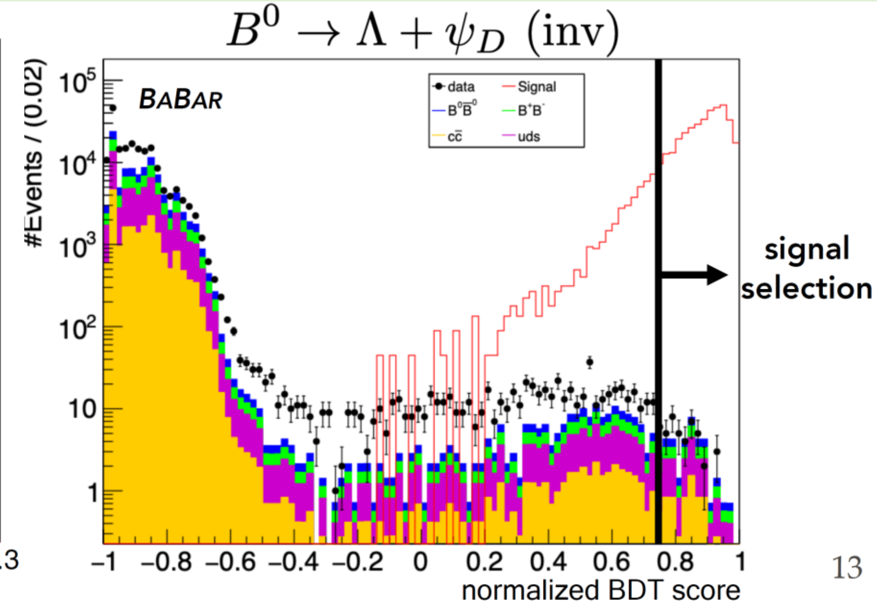


B-Mesogenesis Results

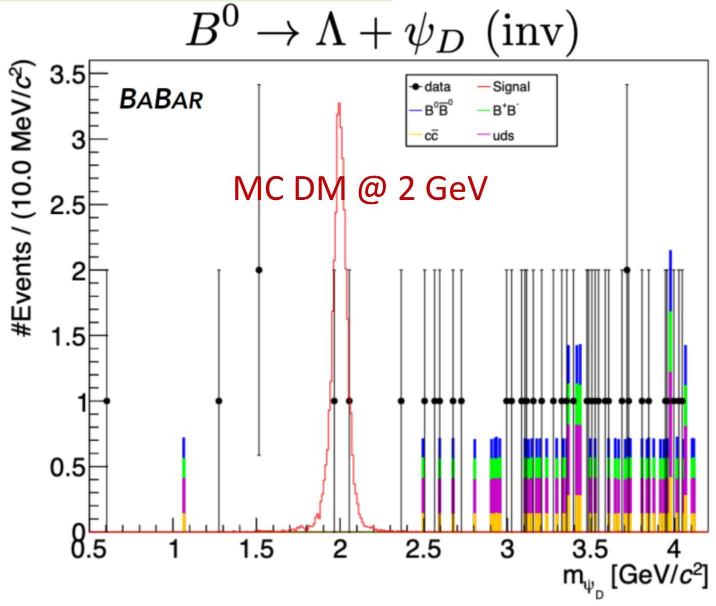
- **Fully reconstruct hadronic decays of a tag B meson, search for regular baryon (Λ or p) with missing mass from the second B meson**
- **Train BDT using kinematic & purity observables to separate tagged B from continuum QCD backgrounds, also kinematic observables for signal B meson (the second B)**
- **Apply the data/MC scale factor extracted from the side bands**



Energy substituted mass distributions for data, MC & assumed $M\psi_D$=2 GeV



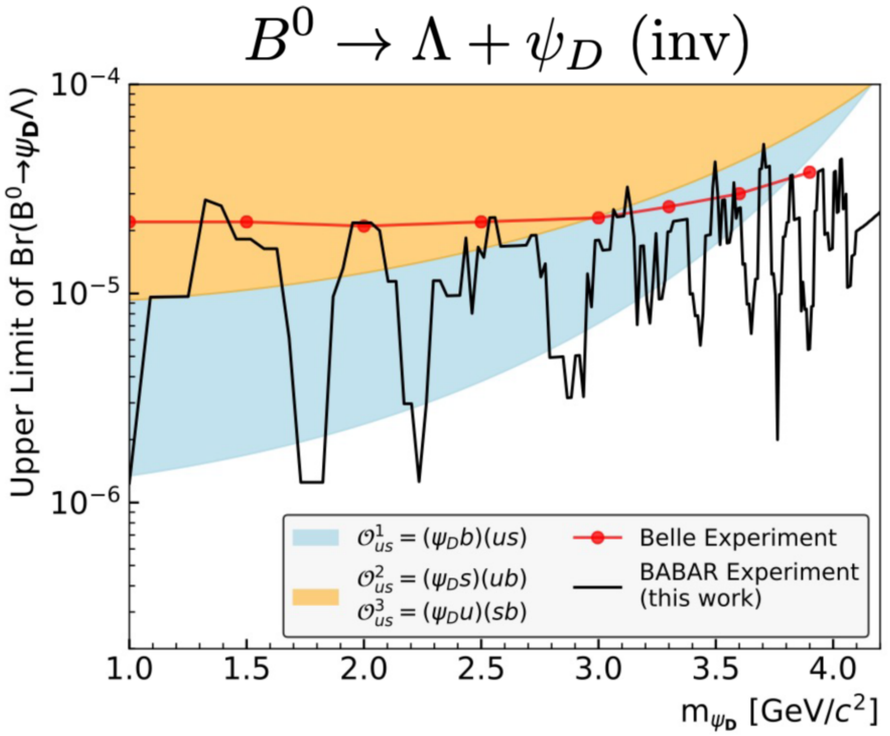
BDT score for various processes. >0.75 is chosen as criteria for signal candidates

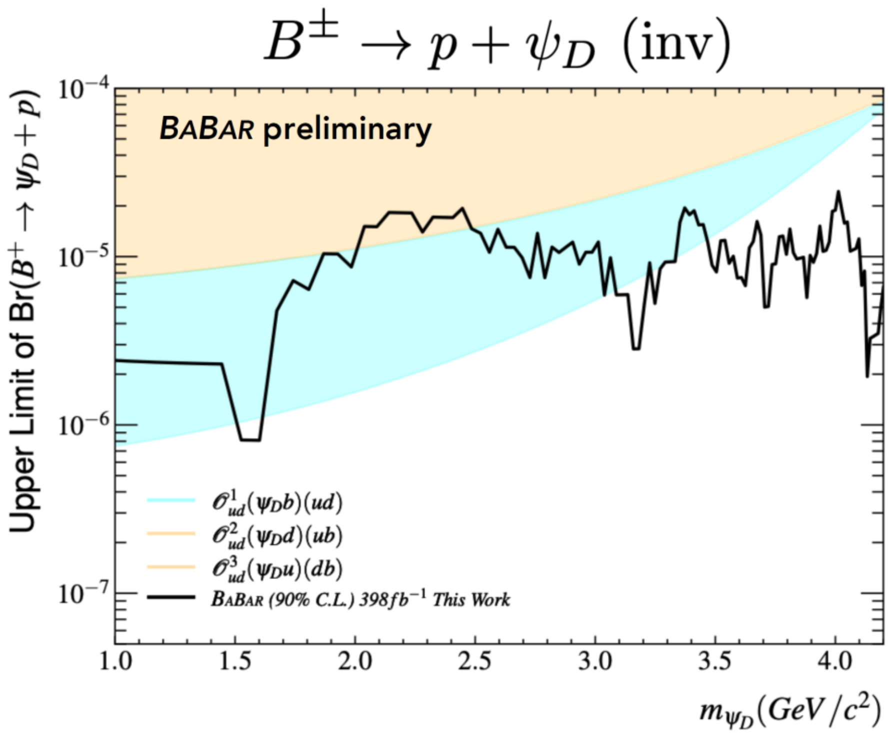


Events with BDT>0.75

B-Mesogenesis Results

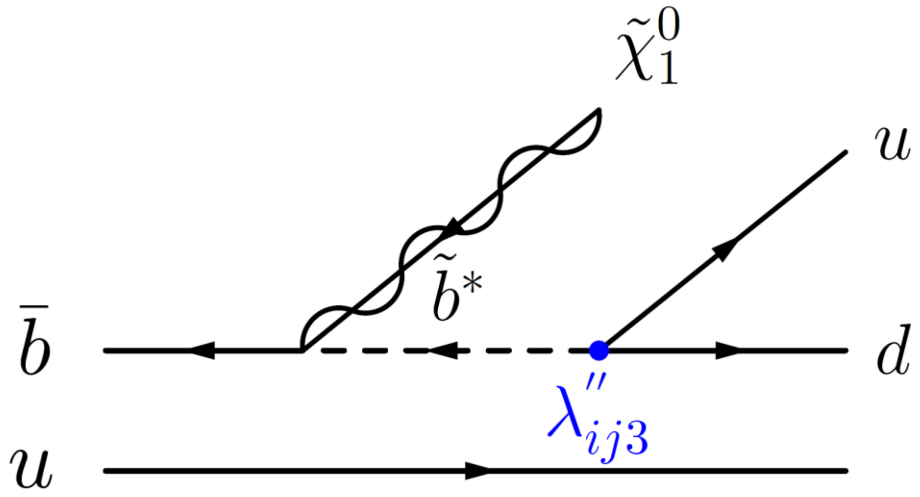
- **Scan over ψ_D mass hypotheses: signal region is 3X mass resolution, background estimated from outer intervals**
- **No significant signal is observed: set limit on signal branching fraction using profile likelihood method**
- **Shaded regions are branching fraction predicted from mesogenesis**

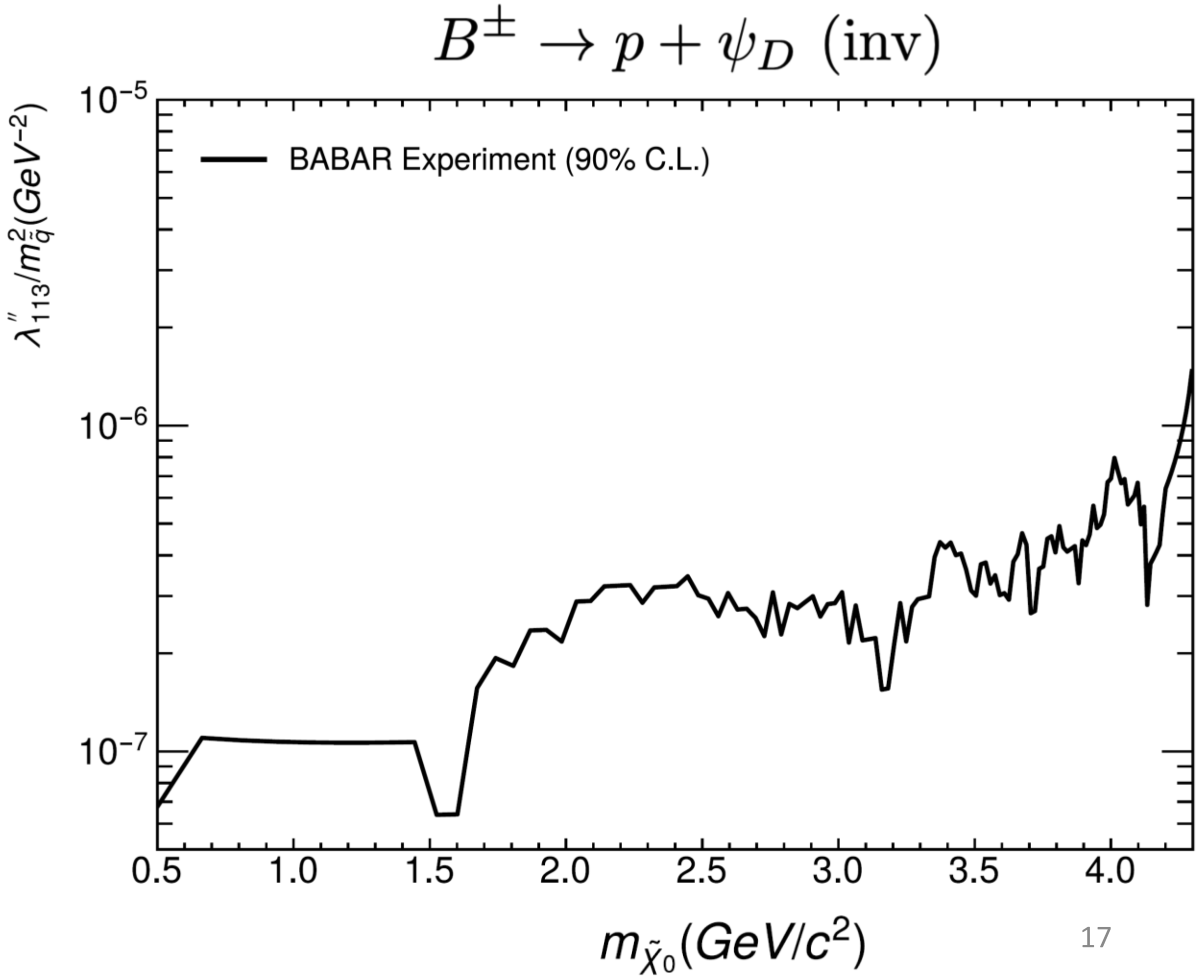




B-Mesogenesis Results

The same results can be re-interpreted to constrain R-parity-violating supersymmetry with low mass neutralinos





Discussion and Prospects

Dark matter bound states

- First search for a dark sector bound state decaying into three dark photons in the range $0.001 < m_{A'} < 3.16$ GeV and 0.05 GeV $< m_{\Upsilon_D} < 9.5$ GeV
- Limits on the γ–A' kinetic mixing ε^2 at the level of $10^{-9} - 10^{-4}$, depending on the values of the model parameters
- **Measurements improve upon existing constraints over a significant fraction of dark photon masses below 1 GeV for large values of the dark sector coupling constant**

Axion-like particles in B decays

- First search for axion-like particles in $B^{\pm} \to K^{\pm}a$, $a \to \gamma\gamma$
- Strongly constrain ALP couplings to EW gauge bosons, improving upon current bounds by several orders of magnitude, except in the vicinity of the π^0, η, and η'
- **Our results demonstrate the sensitivity of flavor-changing neutral current probes of ALP production, which complement existing searches for the ALP coupling to photons below the B meson mass**

B-Mesogenesis

- BABAR probes branching fractions in the range $0.13\text{-}5.2\text{X}10^{-5}$, improving previous constraints by up to an order of magnitude
- These bounds exclude most or significant fraction of the remaining parameter space for the operators
- **Future measurements at Belle-II should be able to fully explore the remaining region**

Summary

- **BABAR continues to produce new and world-leading dark matter results, including recent searches for axionlike particles, DM bound states and non-thermal models of baryogenesis plus dark matter.**
- **B-factories are among the best place to search for GeV- scale hidden sectors**
- BABAR and Belle II will explore untested models and strive to perform searches for DM and to improve significantly the sensitivity.

Special Acknowledgement

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