Recent Dark Matter related searches with BaBar

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On Behalf of the BABAR Collaboration

FPCP 2023, May 30 2023

Outline

Charge conjugate implicit through talk

Recent BaBar results on searches for low mass New Physics

- **Physics motivation and experimental frame**

- **Search for B Mesogenesis:**

$B^0 \to \Lambda \ \psi_D$ **Phys. Rev. D 107, 092001** – Published May 3 2023

Dark Baryon

$B^+ \to p \ \psi_D$ **NEW** **Preliminary :**
First presentation at Moriond EW 2023

- **Recently published other searches for New Physics**

  - Search for an **Axion Like Particle** (**ALP**) :

PhysRevLett.128.131802 (2022)

  - Search for **Darkonium** Υ_D :

PhysRevLett.128.021802 (2022)

In B decays

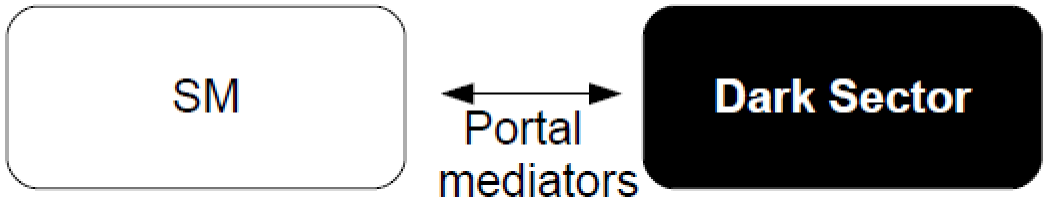
$e^+e^- \to \gamma_{ISR} \Upsilon_D$

Physics motivation

Understand what Dark Matter **(DM)** is made of and its mass scale

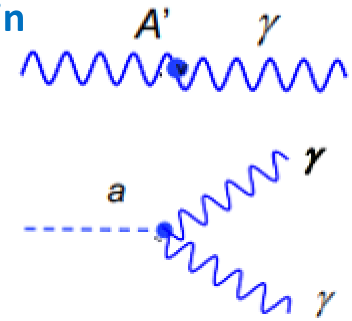
Plethora of models !

Effective theory approach provides different « portals » to access the dark sector



M. Pospelov, A. Ritz, M. Voloshin

PLB 662, 53 (2008)



Dark photon A’

Axion Like Particle a

Experiments can constrain operators, masses, couplings…

B Factories : great window to search for low mass New Physics

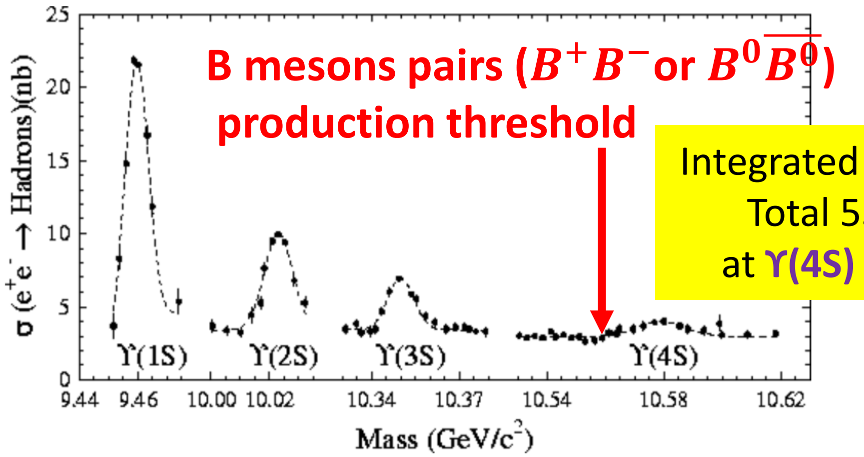
produced through mixing between portals mediators and SM particles in :

- B mesons decays
- Dark matter produced in $e^+ e^-$ interactions

B mesogenesis : recent approach to explain both

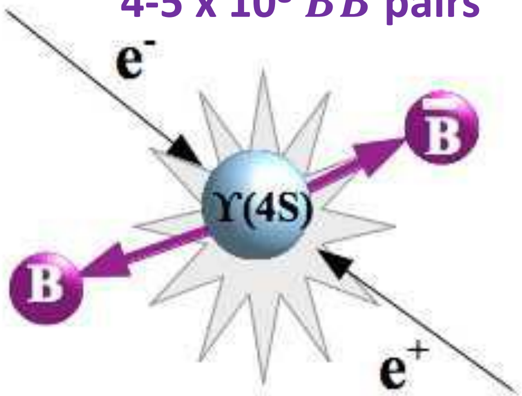
Dark Matter and **Baryon Asymmetry in the Universe**

Production mechanisms at BaBar – PEP II



Integrated luminosity
Total 531 fb $^{-1}$
at ϒ(4S) 432 fb $^{-1}$

~ 4-5 x 10^8 $B\overline{B}$ pairs



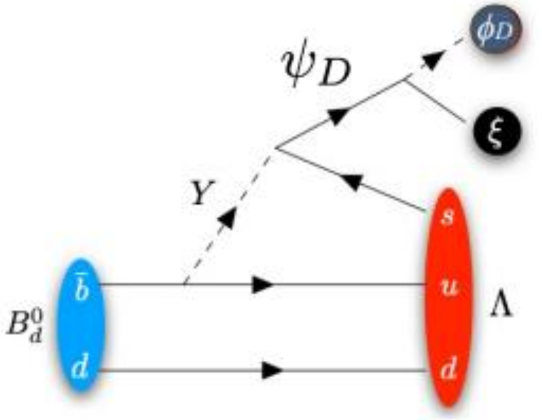
Continuum background
for B decays analyses

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

This talk

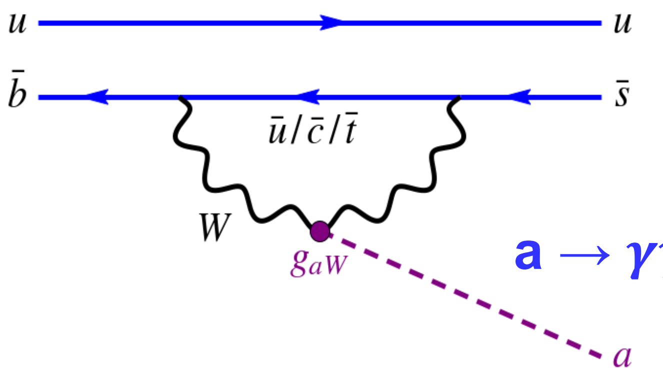
B Mesogenesis

dark anti-baryon ψ_D



Axion Like Particle

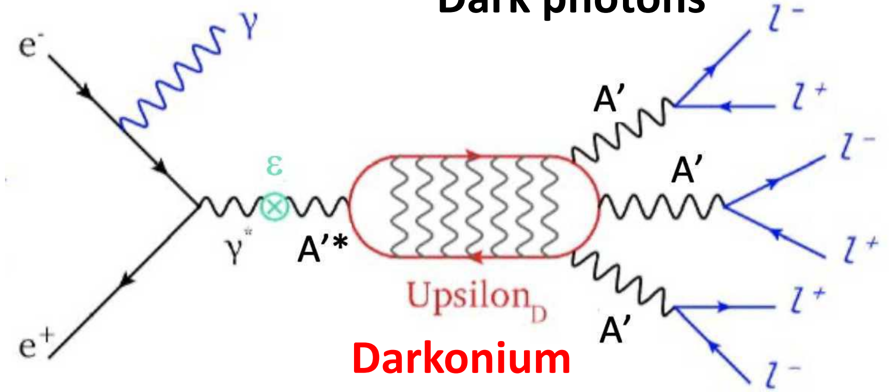
B → K + a (ALP)



$a \to \gamma\gamma$

Darkonium

Dark photons



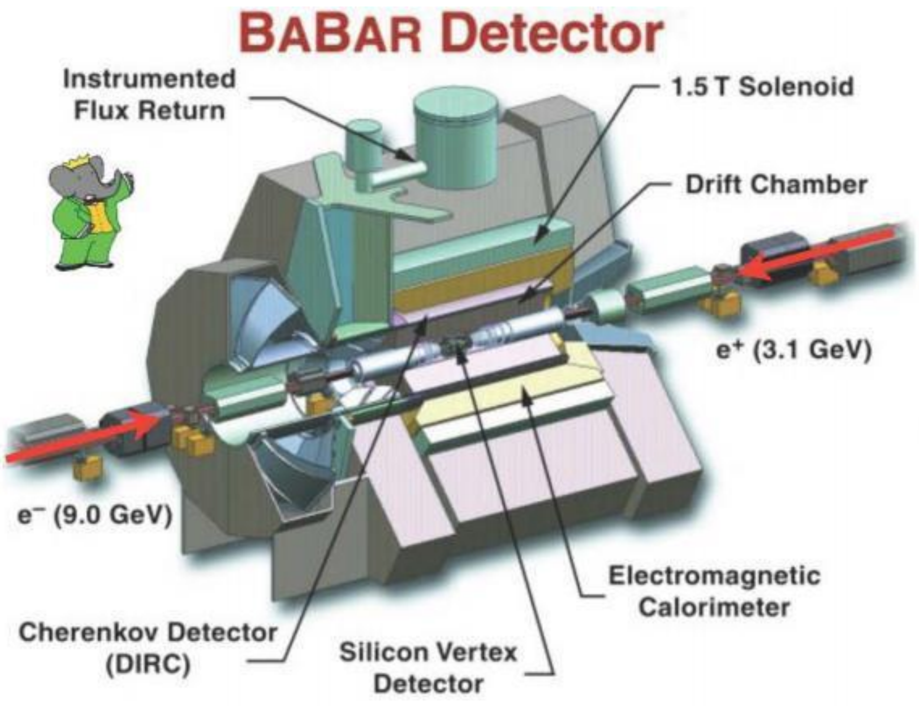
Darkonium

Detector performances for DM searches

B factories very well suited to dark sector searches:

Analyses optimized and validated on <10% of data set, discarded before search performed

- **Clean** e^+e^- environment with quasi **hermetic** detector coverage; good missing energy (potential dark matter) reconstruction
- **Reconstruct displaced vertices** from long-lived particles
- Precise **Particle Identification** and reconstruction
- **High statistics** "precision frontier" data samples

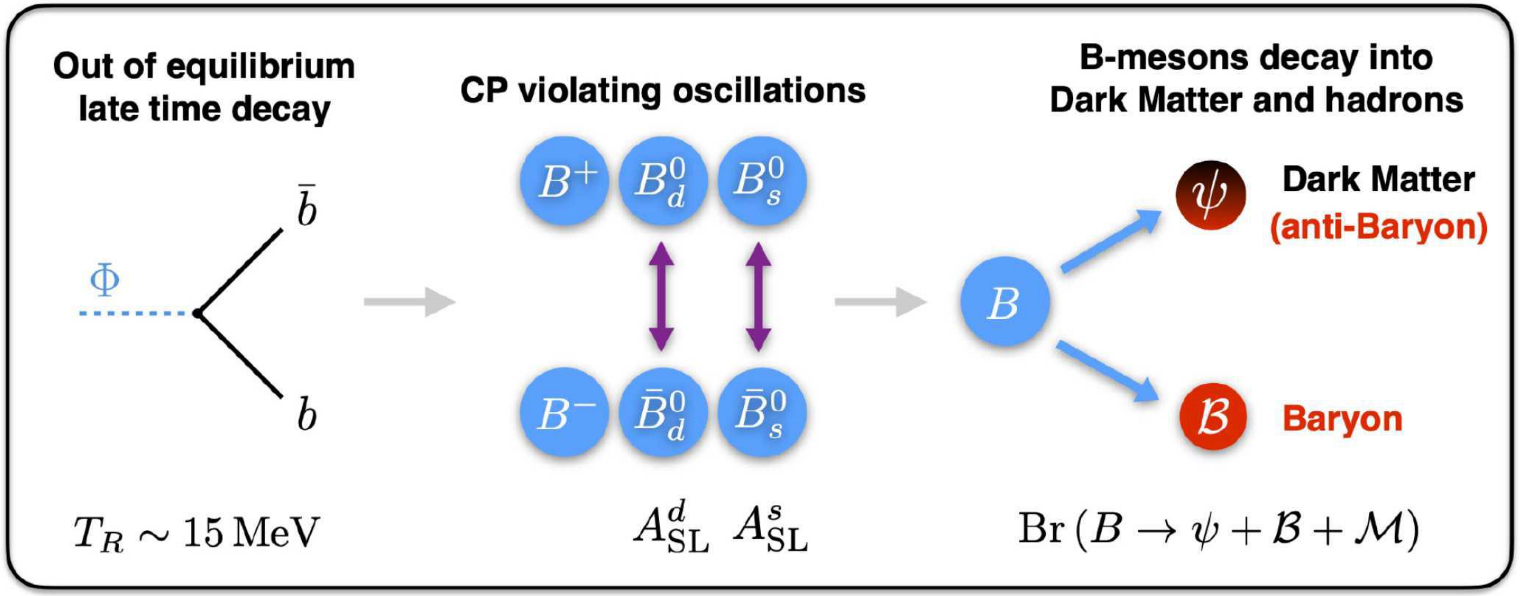


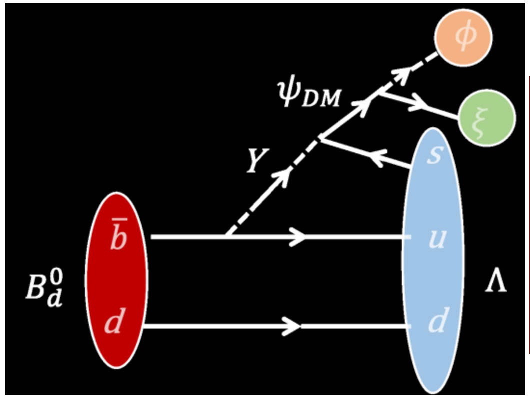
Long history : more than 10 years of DM searches even if different from initial (CP violation) goal

Search for **B Mesogenesis** (1)

Recently proposed mechanism to explain dark matter abundance and Baryon Asymmetry of the Universe (BAU)

- **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).**





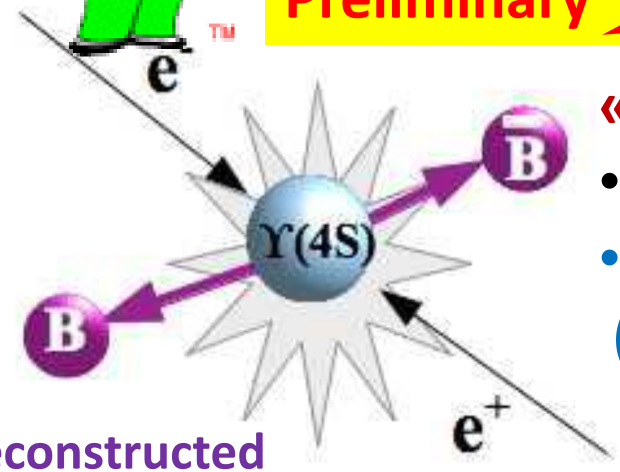
Φ = heavy scalar field;
ψ_D = dark fermion;
Y = TeV scale mediator;
ξ = Majorana Fermion;
ϕ = scalar baryon.

- BAU from B meson decays into a **SM baryon (Λ, p, Λ_c …)** and a **dark sector anti-baryon ψ_D** + possible **SM** light mesons $\mathcal{M}$ (not in our analyses channels)
- Visible and dark sectors have equal but opposite matter-antimatter asymmetries (but total baryon number is conserved)

Search for B Mesogenesis (2)

Preliminary **NEW**

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 escaping detection)

$B^0 \rightarrow \Lambda \ \psi_D$ **PRD 107, 092001**

$B^+ \rightarrow p \ \psi_D$ **Preliminary** **Presented at Moriond EW 2023**

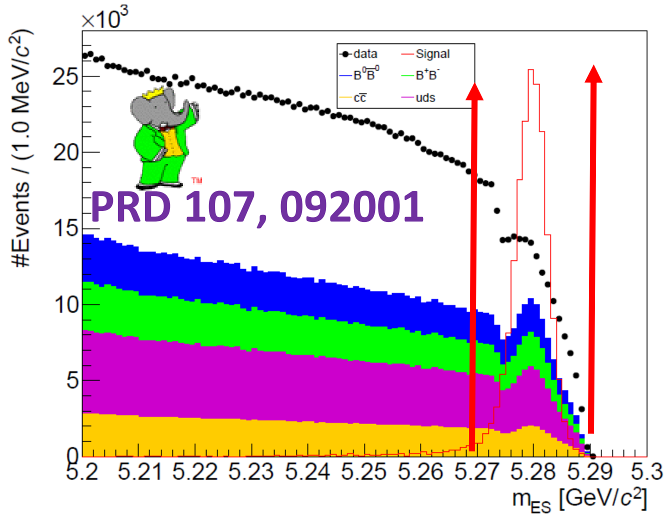
$B^+ \rightarrow \Lambda_c^+ \ \psi_D$ **will be out soon**

- Boosted Decision Tree (BDT) to suppress residual combinatorial backgrounds from $q\bar{q}$ and $B\bar{B}$ decays
- Background estimated directly from m(ψ_D) sideband data
- Many m(ψ_D) mass hypotheses tested

In $B^0 \rightarrow \Lambda \ \psi_D$ analysis, kinematic fit of $\Lambda \rightarrow p \ \pi$,
including displaced vertex significance requirement

Background rejection

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



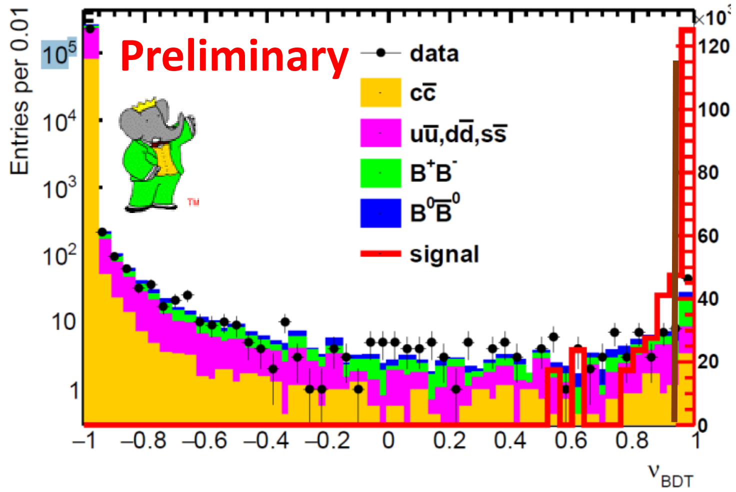
- Beam energy substituted mass m_{ES} : $\sqrt{E_{beam}^2 - p_{B_{Tag}}^2}$

  Peaks at B meson mass for signal
- ΔE relative to the beam energy : $E_{beam} - E_{B_{Tag}}$

  Centered at 0 for B signal events
- Event topology variables to separate $B\bar{B}$ more « spherical » events from more « jet-like » $q\bar{q}$ continuum events

BDT output variable ν_{BDT}

combines background rejection variables,
with B_{TAG} reconstruction quality,
Λ reconstruction quality for $B^0 \to \Lambda\ \psi_D$ channel,
etc.

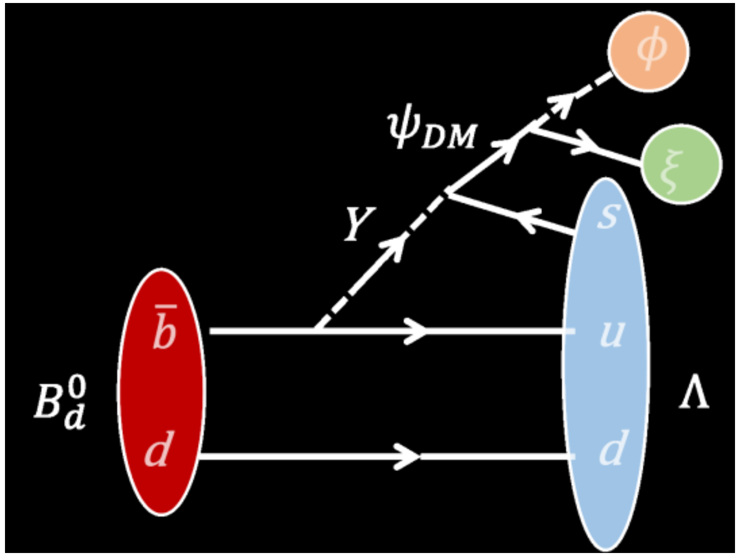


$B^\pm \to \overset{(-)}{p}\ \psi_D$

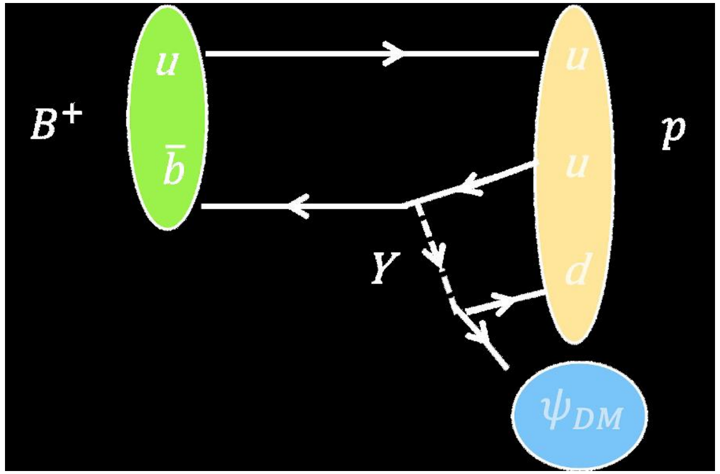
NEW

ν_{BDT} > 0.95 required for signal

Main systematics from Monte-Carlo-Data correction in BDT distributions using control region in data



Probes $\mathcal{O}_{us}$



Probes $\mathcal{O}_{ud}$

G. Alonso-Alvarez, G. Elor, and M. Escudero
Phys.Rev. D 104, 035028 (2021).

Dark SM SM

For the decay $B \to \psi_D\ \mathcal{B}\ \mathcal{M}$ to exist :
new BSM TeV-scale color triplet scalar Y,
coupling ψ_D and SM quarks

Effective low energy Lagrangian integrating out heavy mediator Y

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

y_{ij}^2 Product of couplings

Four possible flavor combination
$\mathcal{O}_{u_i,d_j}$ operators for B meson decays

Only one active in early universe
Need to test four possibilities

$\mathcal{O}_{ud=\psi bud}$

$\mathcal{O}_{us=\psi bus}$

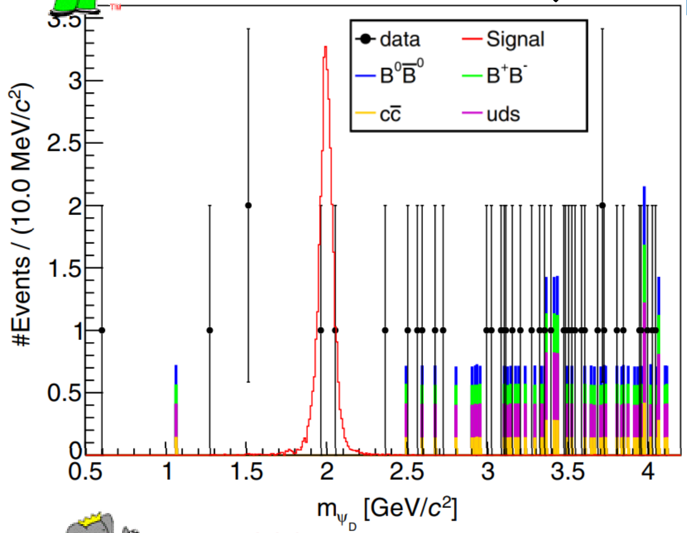
$\mathcal{O}_{cd=\psi bcd}$

$\mathcal{O}_{cs=\psi bcs}$

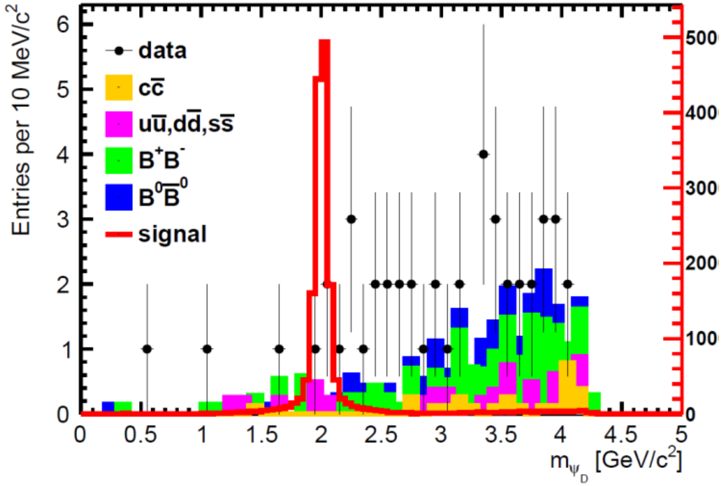
Search for **B Mesogenesis** (4)

Distribution of m(ψ_D) (missing energy)

PRD 107, 092001 $B^0 \rightarrow \Lambda\ \psi_D$



NEW Preliminary $B^+ \rightarrow p\ \psi_D$

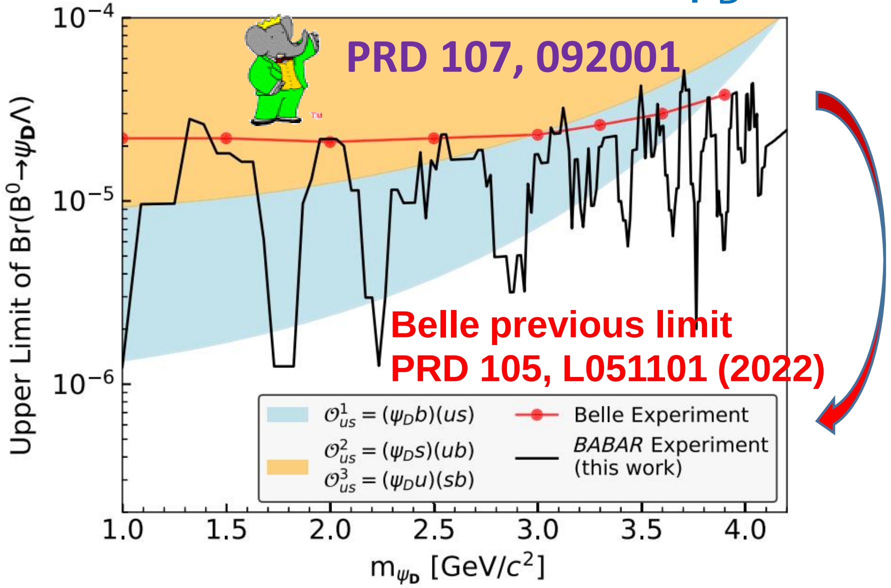


Exclude large fraction of parameter space for B mesogenesis

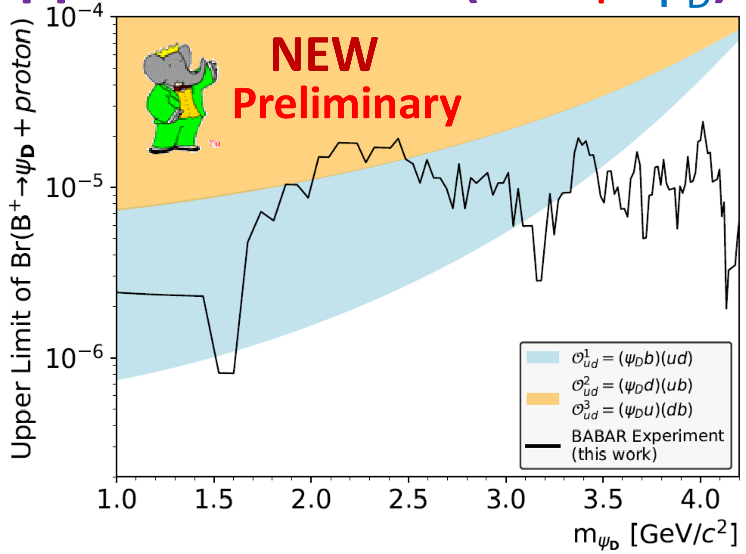
BaBar analyses scan (many) mψ_D hypotheses
As Belle looks at discrete mψ_D hypotheses

Result also useful to constrain SUSY model jhep02(2023)224
(see back-up)

90% C.L. Upper limits on Br($B^0 \rightarrow \Lambda\ \psi_D$**) vs** m($\psi_D$)



90% C.L. Upper limits on Br($B^+ \rightarrow p\ \psi_D$**) vs** m($\psi_D$)



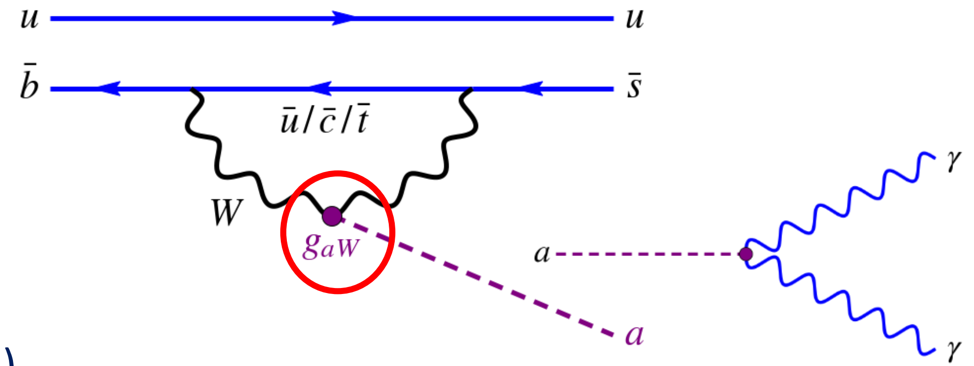
Search for an **Axion-Like Particle** (**ALP**) in **$B^+ \to K^+ a$ ($a \to \gamma\gamma$)**

PhysRevLett.128.131802 (2022)

Pseudo-Goldstone bosons : **Axion-Like Particles (ALPs)**
resulting from Spontaneously-broken global symmetries,
Could help resolve naturalness issues of SM parameters
(like CP strong Pb) and serve as mediators to dark sectors

Can be produced in FCNC B decay processes, like
$B \to K a$, with **$a \to \gamma\gamma$** (SM BR prediction very small for **$B \to K \gamma\gamma$**)

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



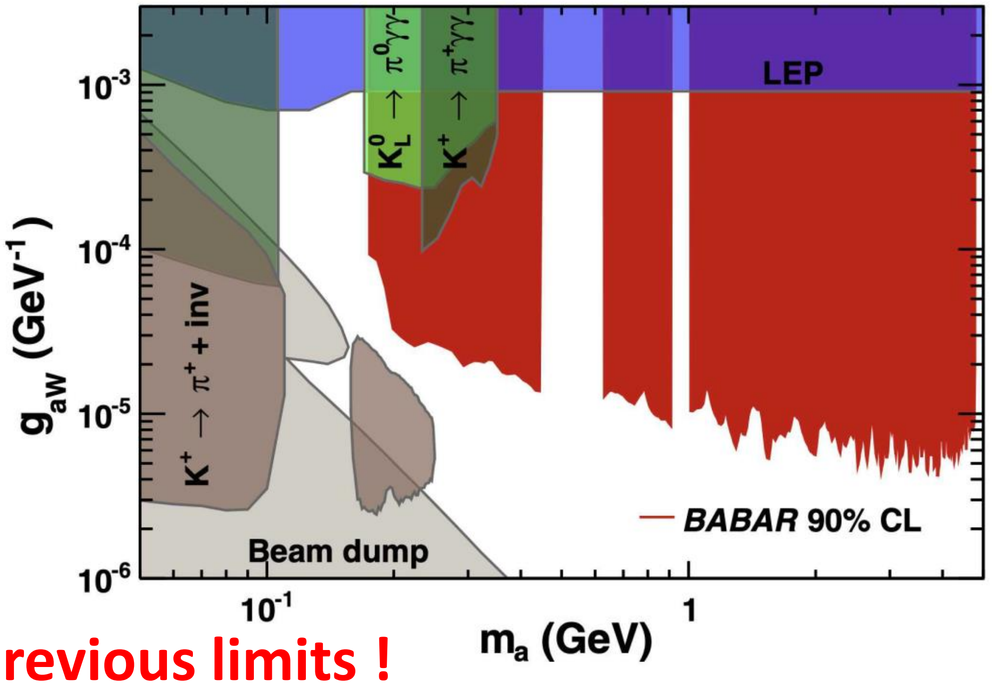
Search for peak in reconstructed $\gamma\gamma$ mass

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

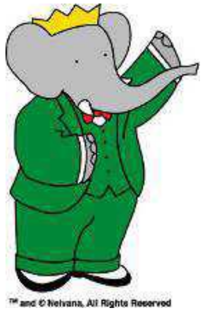
$SU(2)_W$ field strength tensor

coupling

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



Up to two orders of magnitude improvements over previous limits !



Search for **Darkonium**:

PhysRevLett.128.021802 (2022)

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

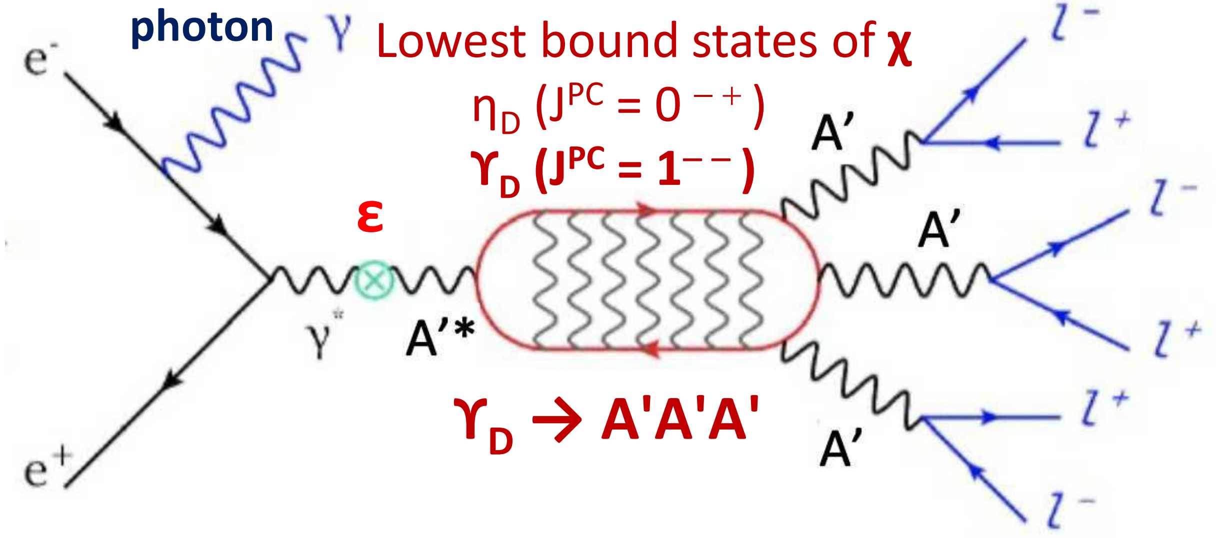
Dark photon A' couples strongly to the **dark matter fermion (χ)** via coupling α_D and A' mixes with SM photon via kinetic mixing with strength **ε**

Darkonium

Lowest bound states of **χ**

η_D ($J^{PC} = 0^{-+}$)

Υ_D ($J^{PC} = 1^{--}$)



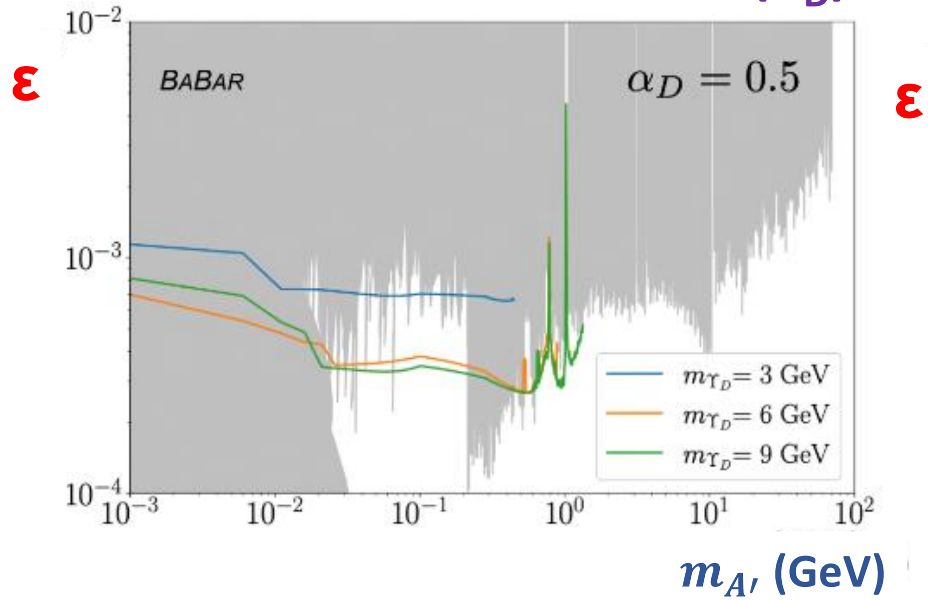
$\Upsilon_D \rightarrow A'A'A'$

3 dark photons A'

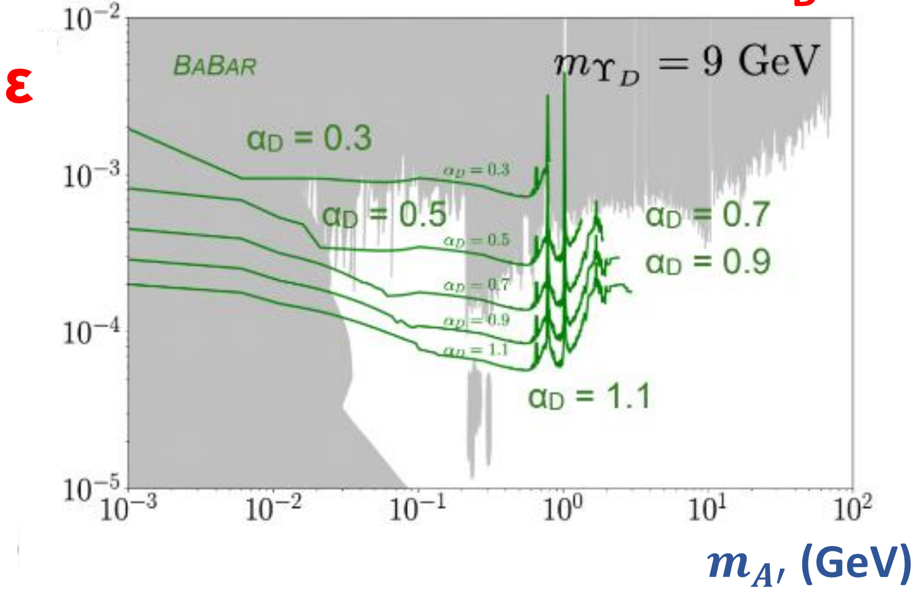
Six tracks final state :
$A' \rightarrow f^+f^-$ (f = e, μ,π)

90% C.L. upper limits on the kinetic mixing parameter ε versus $m_{A'}$

For different values of $m(\Upsilon_D)$



For different values of α_D



CONCLUSION

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
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.

One of the recent *BaBar* results not covered in this talk :
Search for Heavy Neutral Leptons from Taus (see back-up)
Phys. Rev. D 107, 052009 – Published 23 March 2023

BACK-UP SLIDES

BABAR papers

Presentation at Lake Louise 2023

Extensive program of searches for physics beyond the Standard Model, and dark sector in particular:

- Search for heavy neutral leptons in τ decays
  arXiv 2207.09575 [hep-ex] (accepted to PRD)
- Lepton universality in Y(3S) decays
  Phys. Rev. Lett .125, 241801 (2020)
- Search for LFV in Y(3S) $\rightarrow e\, \mu$
  Phys. Rev. Lett. 128, 091804 (2022)
- Rare and forbidden D decays
  Phys. Rev. Lett. 124, 071802 (2020)
- Search for LFV in $D^0 \rightarrow X^0\, e\, \mu$
  Phys. Rev. D 101, 112003 (2020)
- B mesogenesis
  arXiv:2302.00208 [hep-ex]
- Search for Darkonium
  Phys. Rev. Lett. 128 021802 (2022)
- Axion like particle
  Phys. Rev. Lett. 128, 131802 (2022).
- Dark Leptophilic scalar
  Phys. Rev. Lett. 125,181801 (2020).
- Six quark dark matter
  Phys. Rev. Lett. 122, 072002 (2019).
- Dark photon
  Phys. Rev. Lett. 113, 201801 (2014);
  Phys. Rev. Lett. 119, 131804 (2017).
- Muonic dark force
  Phys. Rev. D 94, 011102 (2016).
- Dark Higgs bosons
  Phys. Rev. Lett. 108, 211801 (2012)

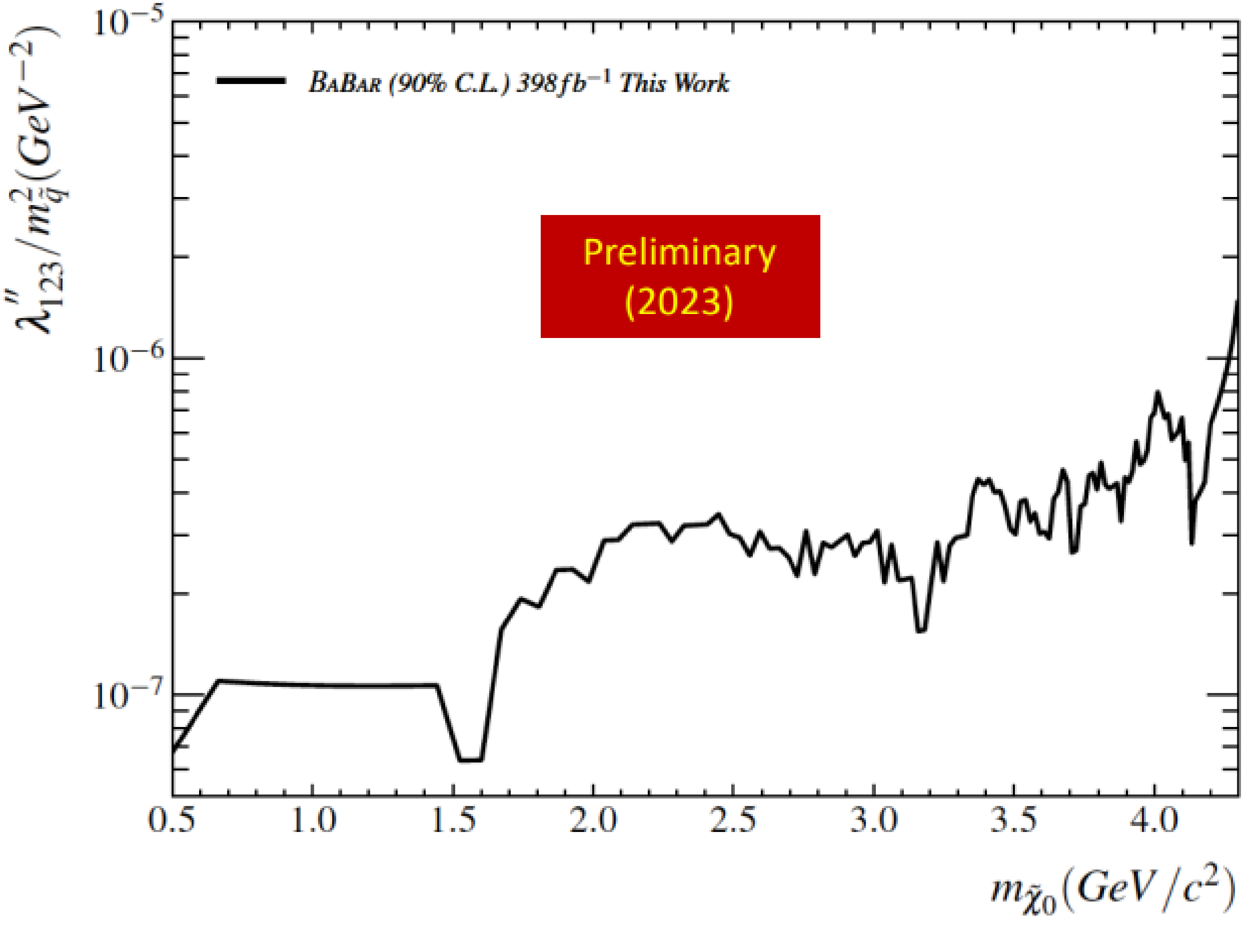
SUSY constraints from $B^{\pm} \to \overset{(-)}{p}$ + **invisible**

C. O. Dib et al.

SUSY model: (Journal of High Energy Physics 2023 - **jhep02(2023)224**) also constrained by this result

Model with :
R-parity violation (RPV) and
Light neutralino $\tilde{\chi}_0$

Limits on the RPV coupling λ''_{123} divided by the relevant squark mass squared



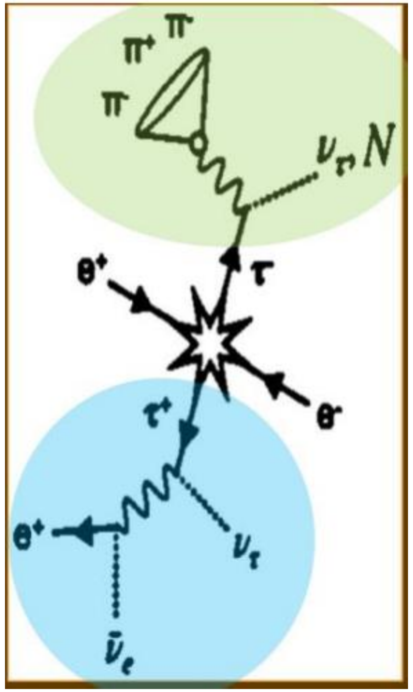
Search for Heavy Neutral Leptons from τ decays

Search for heavy neutral leptons using tau lepton decays at *BABAR*

Phys. Rev. D 107, 052009 – Published 23 March 2023 (Analysis covered at Moriond EW 2023)

Heavy neutral leptons : additional neutrino states ν_n ("sterile neutrinos") mixing with active neutrinos ν_l with mixing strength $|U_{ln}|^2$, U_{ln} element of the extended PMNS matri

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_L \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{L1} & U_{L2} & U_{L3} & U_{L4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$



Model independent search :

- looking only at kinematics
- For a HNL $N=\nu_4$ mixing with ν_τ
- **Signal side : 3-prong pionic τ decay**
- Tag side : leptonic τ decay

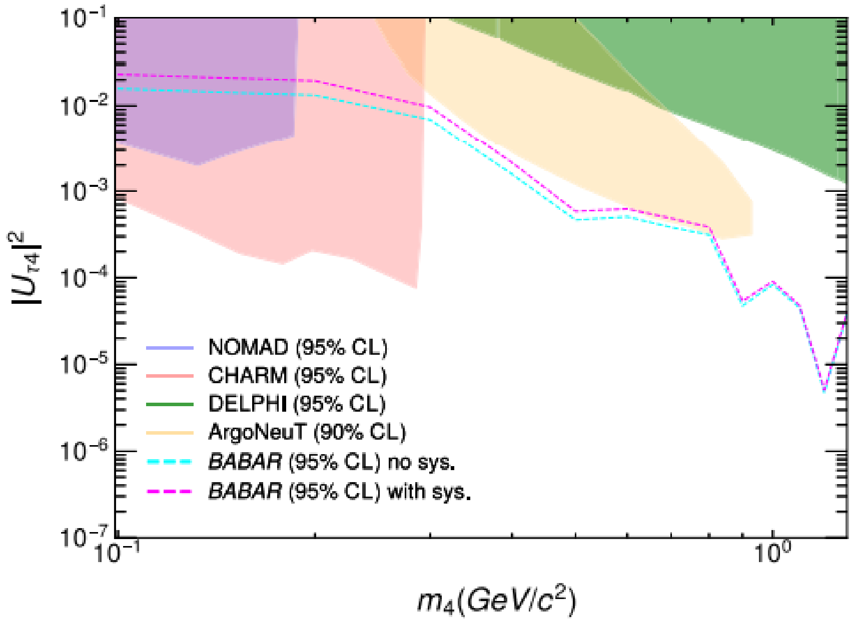


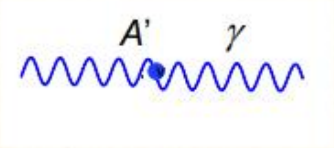
FIG. 10. Upper limits at 95% CL on $|U_{\tau 4}|^2$. The magenta line represents the result when uncertainties are included. The magenta line is expected to be a very conservative upper limit. Limits from Nomad [29], Charm [20], and Delphi [30] are also shown for reference. The recent ArgoNeuT result is also shown [31].

Link between SM and Dark Matter

- The SM may be connected to the dark sector through so-called portals, these links are the lowest-dimensional operators that may provide coupling of the dark sector to the SM (higher-dimensional operators are mass suppressed)

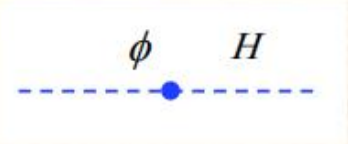
PLB **662**, 53 (2008)

- **Vector**
  $\varepsilon F_Y^{\mu\nu} F'_{\mu\nu}$ (dim. 4)



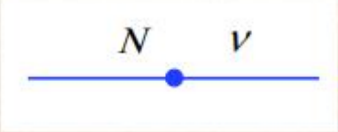
new U(1) symmetry → dark photon, coupling to SM γ/Z via kinetic mixing ε

- **Scalar**
  $H^2(\mu\phi + \lambda\phi^2)$ (dim. 4)



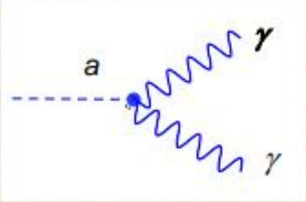
new dark scalar, mixing with Higgs

- **Neutrino**
  $\kappa H \ell N$ (dim. 4)



new heavy neutral lepton, mixing with left-handed SM doublet and Higgs

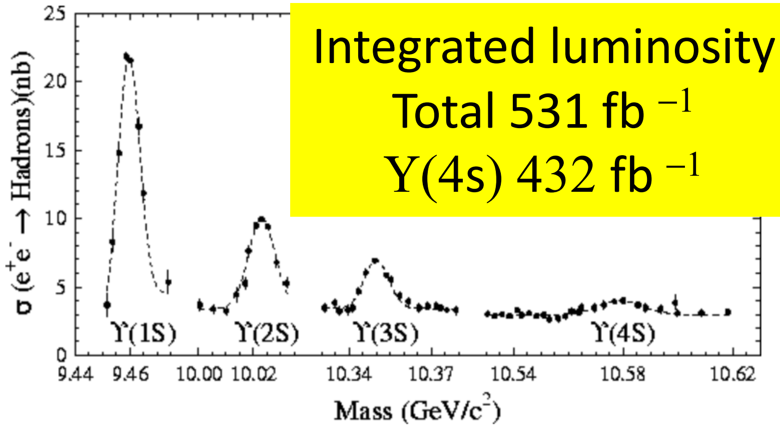
- **Axion-like**
  $f_a^{-1} F^{\mu\nu} F_{\mu\nu} a$ (dim. 5)



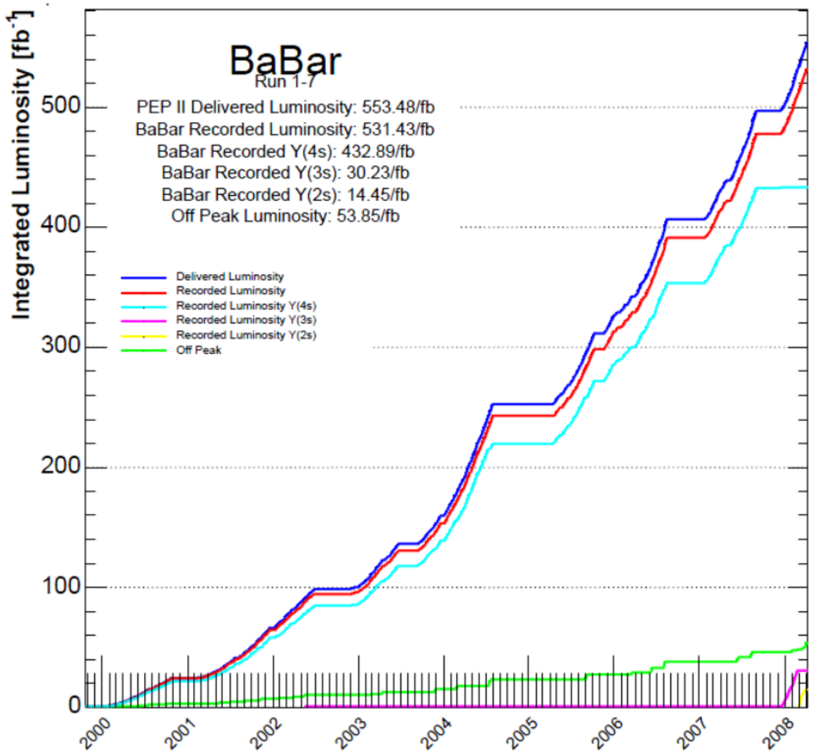
new axion/axion-like particle, coupling to SM gauge and fermion fields

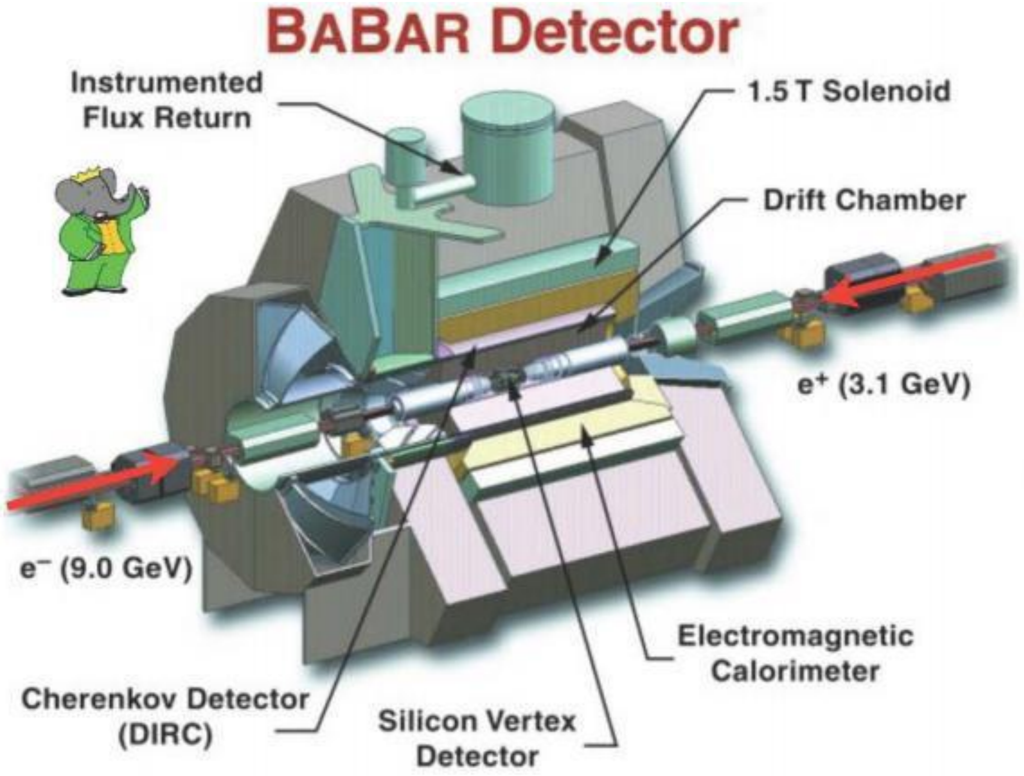
- *B* factories provide tests of vector, scalar and axion-like portals in the lower-mass region

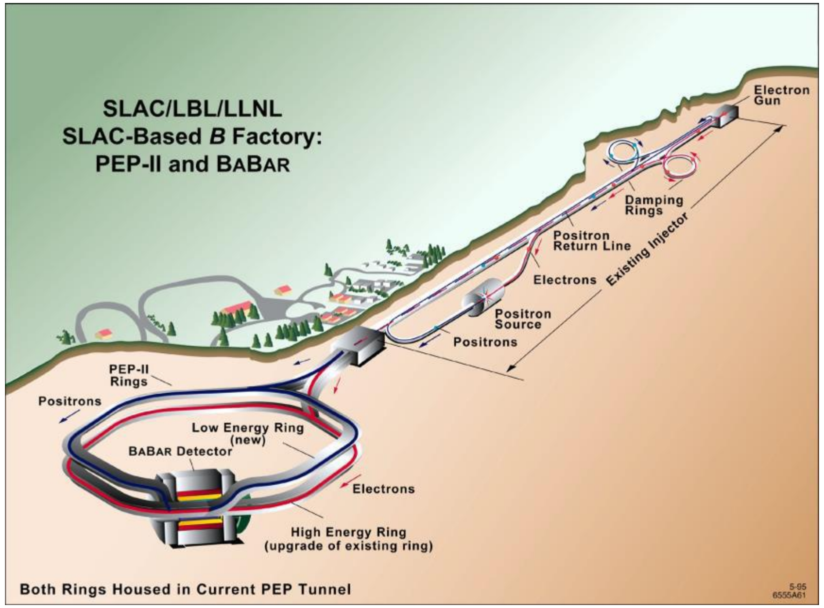
BaBar at SLAC PEPII : 1999 - 2008



Integrated luminosity
Total 531 fb^{-1}
$\Upsilon(4s)$ 432 fb^{-1}







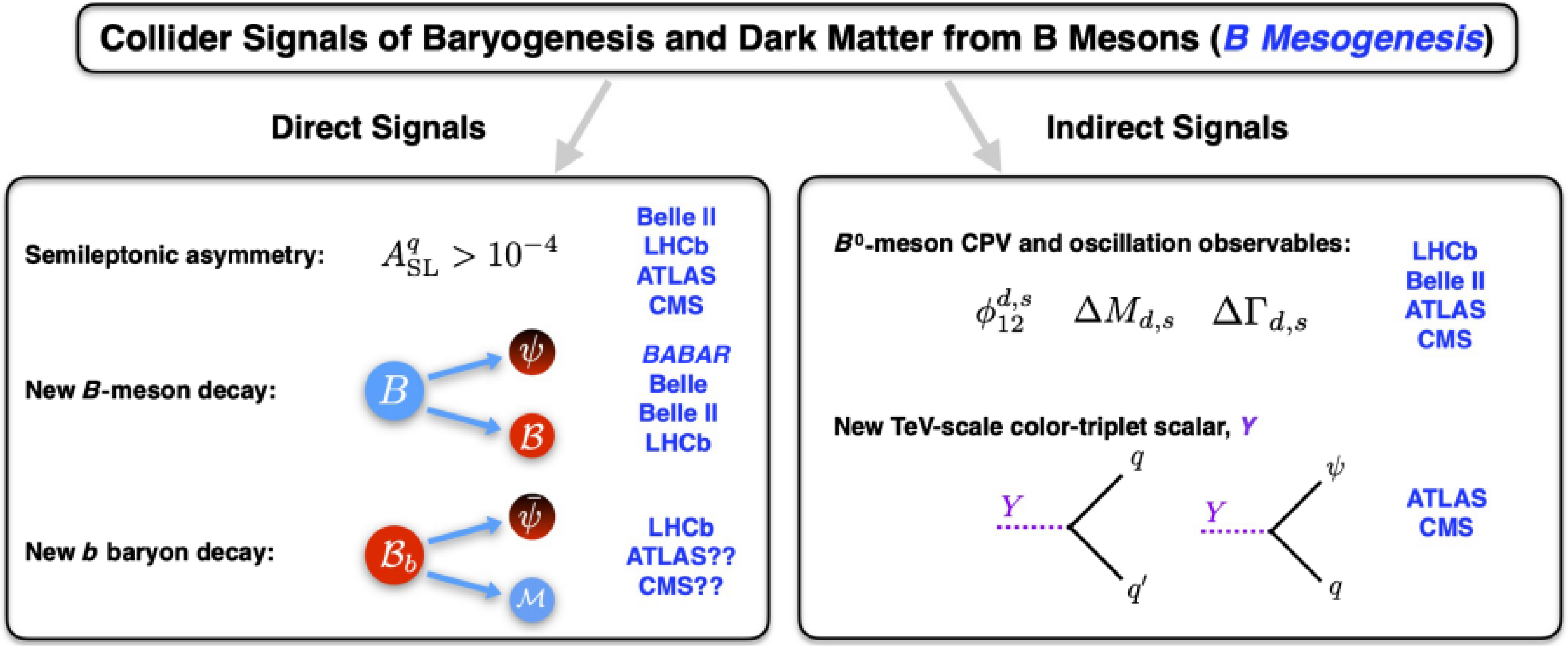
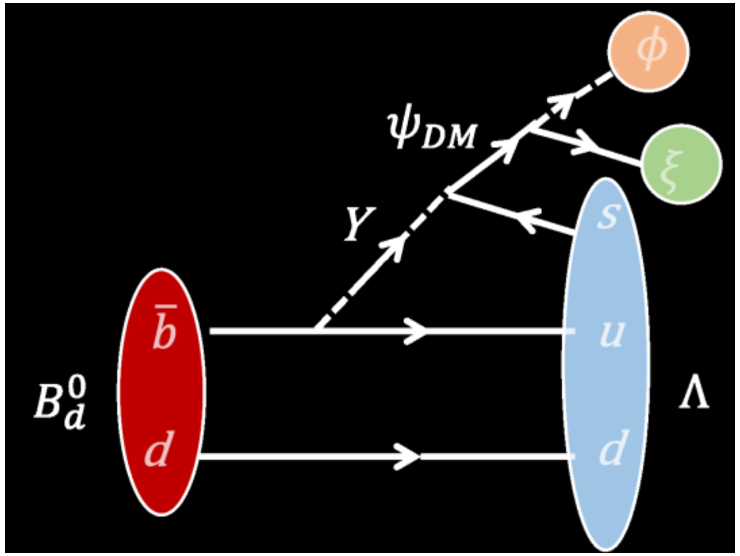
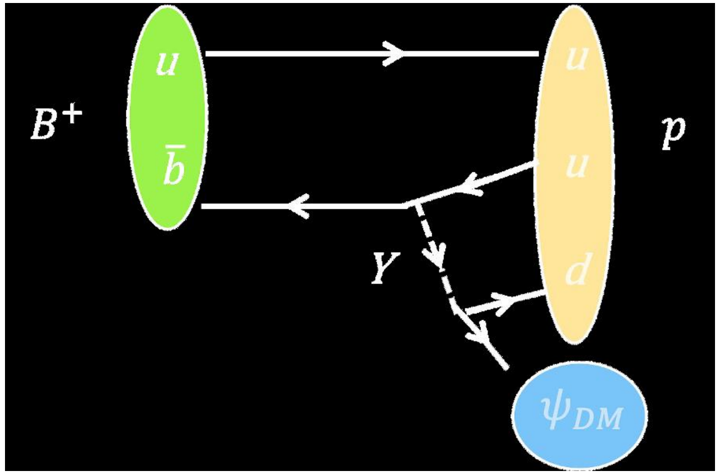


FIG. 1. Summary of the collider implications of baryogenesis and dark matter from B mesons [39], i.e., *B-Mesogenesis*. The distinctive signals of the mechanism are (i) the requirement that at least one of the semileptonic (CP) asymmetries in B_q^0 decays is $A^q_{SL} > 10^{-4}$, (ii) that both neutral and charged B mesons decay into a dark sector antibaryon (appearing as missing energy in the detector), a visible baryon, and any number of light mesons with $\mathrm{Br}(B \to \psi \mathcal{B} \mathcal{M}) > 10^{-4}$, and (iii) that b-flavored baryons should decay into light mesons and missing energy at a rate $\mathrm{Br}(\mathcal{B}_b \to \bar{\psi} \mathcal{M}) > 10^{-4}$. In addition, we include as indirect signals the various oscillation observables in the $B_q^0 - \bar{B}_q^0$ system as they are linked to A^q_{SL}, and the presence of a new TeV-scale color-triplet scalar Y that is needed to trigger the $B \to \psi \mathcal{B} \mathcal{M}$ decay. We also highlight the existing experiments that can probe each corresponding signal. Notation: B, B meson; $\mathcal{B}$, SM baryon; $\mathcal{M}$, any number of light mesons; ψ, dark sector antibaryon (ME in the detector).



Probes $\mathcal{O}_{us}$



Probes $\mathcal{O}_{ud}$

G. Alonso-Alvarez, G. Elorand, and M. Escudero, Phys.Rev. D 104, 035028 (2021).

In order for the $B \to \psi \mathcal{B} \mathcal{M}$ decay to exist, a new BSM TeV-scale bosonic mediator is needed. In particular, this state should be a color-triplet scalar Y which couples to ψ and SM quarks. The LHC and flavor observables set relevant constraints on the mass and couplings of this color-triplet scalar which we discuss in detail in Sec. V. This heavy mediator can be integrated out to yield a low energy Lagrangian of the form $\mathcal{L}_{\text{eff}} = \sum_{i,j} \mathcal{O}_{u_i d_j} \frac{y_{ij}^2}{M_Y^2}$, with y_{ij}^2 being the product of the two relevant dimensionless couplings. The four possible flavor combination operators $\mathcal{O}_i$ of interest for B-meson decays are

$$\mathcal{O}_{ud} = \psi bud, \quad (15a)$$

$$\mathcal{O}_{us} = \psi bus, \quad (15b)$$

$$\mathcal{O}_{cd} = \psi bcd, \quad (15c)$$

$$\mathcal{O}_{cs} = \psi bcs, \quad (15d)$$

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$$\mathcal{O}_{cs} = \psi bcs, \quad (15d)$$

where all fermions are assumed to be right-handed[6] and color indices are contracted in a totally antisymmetric way. These operators can induce the decay of the $\bar{b}$ quark within the B meson into two light quarks and a dark antibaryon ψ. The resulting possible hadronic processes are summarized in Table I for the different operators in Eq. (15). Matrix elements involving the operators in Eq. (15) depend on the precise pairing of the spinors. Each of the operators can come in three different versions: "type 1" $\mathcal{O}^1_{ij} = (\psi b)(u_i d_j)$, "type 2" $\mathcal{O}^2_{ij} = (\psi d_j)(u_i b)$, and "type 3" $\mathcal{O}^3_{ij} = (\psi u_i)(d_j b)$. This distinction becomes relevant for some of the constraints discussed in the next sections.

As we will see in Sec. V, flavor constraints on the Y triplet scalar imply that only one of these operators can be active in the early Universe. In practice, this means that we only expect one dominant flavor combination of these possible operators at collider experiments and not a combination of the above. Therefore, only one of the sets of decay channels listed in Table I is expected to have a sizeable branching ratio, while all others should be suppressed.

TABLE I. The lightest final state resulting from the new decay of b quarks as necessary to give rise to baryogenesis and dark matter production. We list each of the possible flavorful operators that can equally lead to B-Mesogenesis; see Eq. (15). For a given operator, the rate of each decay is fairly similar given that $m_{B^\pm} \simeq m_{B_d^0} \simeq m_{B_s^0} \sim m_{\Lambda_b}$. ΔM refers to the difference in mass between the initial and final SM hadron. Note that additional light mesons can be present in the final state, which act to decrease ΔM by their corresponding masses.

Operator and decay	Initial state	Final state	ΔM (MeV)
$\mathcal{O}_{ud} = \psi bud$	B_d	$\psi + n(udd)$	4340.1
$\bar{b} \to \psi ud$	B_s	$\psi + \Lambda(uds)$	4251.2
	B^+	$\psi + p(duu)$	4341.0
	Λ_b	$\bar{\psi} + \pi^0$	5484.5
$\mathcal{O}_{us} = \psi bus$	B_d	$\psi + \Lambda(usd)$	4164.0
$\bar{b} \to \psi us$	B_s	$\psi + \Xi^0(uss)$	4025.0
	B^+	$\psi + \Sigma^+(uus)$	4090.0
	Λ_b	$\bar{\psi} + K^0$	5121.9
$\mathcal{O}_{cd} = \psi bcd$	B_d	$\psi + \Lambda_c + \pi^-(cdd)$	2853.6
$\bar{b} \to \psi cd$	B_s	$\psi + \Xi_c^0(cds)$	2895.0
	B^+	$\psi + \Lambda_c^+(dcu)$	2992.9
	Λ_b	$\bar{\psi} + \bar{D}^0$	3754.7
$\mathcal{O}_{cs} = \psi bcs$	B_d	$\psi + \Xi_c^0(csd)$	2807.8
$\bar{b} \to \psi cs$	B_s	$\psi + \Omega_c(css)$	2671.7
	B^+	$\psi + \Xi_c^+(csu)$	2810.4
	Λ_b	$\bar{\psi} + D^- + K^+$	3256.2

Recent BaBar results

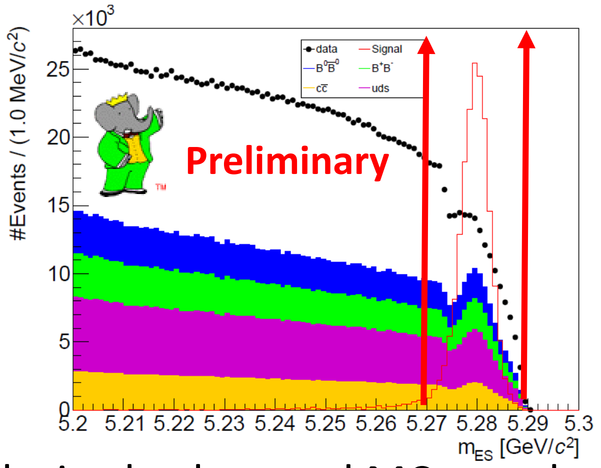
BaBar Result Coming soon

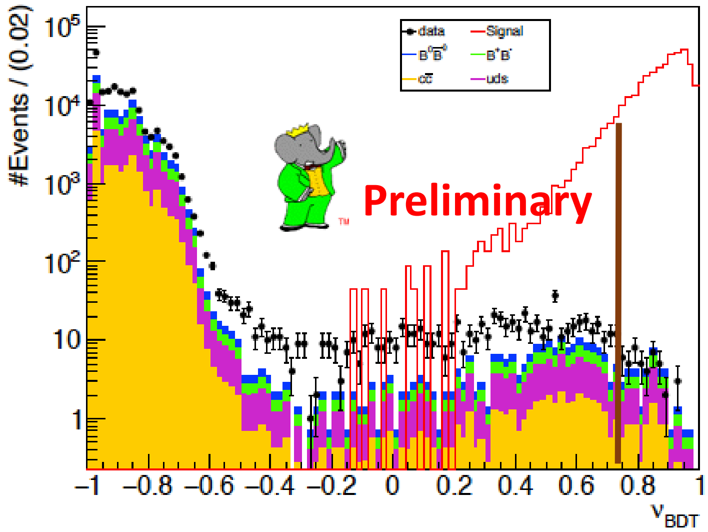
$B^0 \to \Lambda \quad \psi_D$ analysis

arXiv:2302.00208v1
(submitted to Phys. Rev. D)

Main systematics from Monte-Carlo-Data correction in BDT distributions using control region in data

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





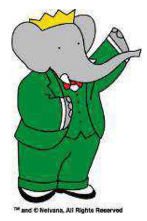
$B^0 \to \Lambda \quad \psi_D$

ν_{BDT} **> 0.75 required for signal**

The inclusive background MC samples do not accurately reproduce the data. This discrepancy arises from a mis-modeling of several branching fractions used in the simulation, resulting in differences in Btag reconstruction efficiencies, as well as differences in charged and neutral particle reconstruction efficiencies, PID efficiencies, and the modeling of variables used in the BDT. We **correct the simulation in a two-step procedure**, **using sideband data** selected with the criteria, described above, applied before the BDT selection, except with the looser requirement $5.20 < m_{ES} < 5.29$ GeV/c^2.

- The region $-0.5 <$ BDT < 0.75, largely dominated by $e^+e^- \to q\bar{q}$ (q = u; d; s; c) events, is used to extract a correction factor for continuum production, f_{udsc}, by rescaling the corresponding MC predictions to the number of observed events.
- The correction factor for $B\bar{B}$ production, is determined from data in the complementary region BDT < -0.5, assuming

equal contributions from $B^0\overline{B^0}$ and B^+B^-. We obtain $f_{udsc} = 1.34 \pm 0.10$ and f $B^0\overline{B^0} = 1.06 \pm 0.08$. Under the assumption that the $B^0\overline{B^0}$ correction factor is independent of the signal B decay mode, we rescale the signal efficiency by f $B^0\overline{B^0}$ and propagate the corresponding uncertainty as a systematic uncertainty.



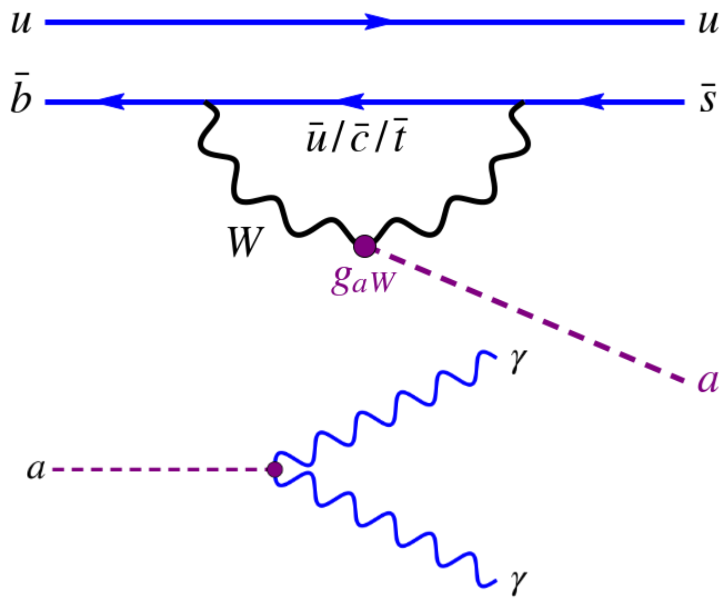
Search for **Axion-Like Particles** (ALP)- (1)

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

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 (like CP strong Pb) and serve as mediators to dark sectors

Very Small SM BR prediction for : **B → K γγ**

ALPs (a) couple primarily to pairs of SM gauge bosons (coupling g_{aW}).
Can be produced in FCNC B decay processes, like
B → K a, with **a → γγ** (nearly 100% BF for m(a) < m(W))



For low axion mass and small coupling g_{aW}, the axion lifetime can become "long", i.e. non-prompt

$\tau \sim 1 / m_a^3 \, g_{aW}^2$

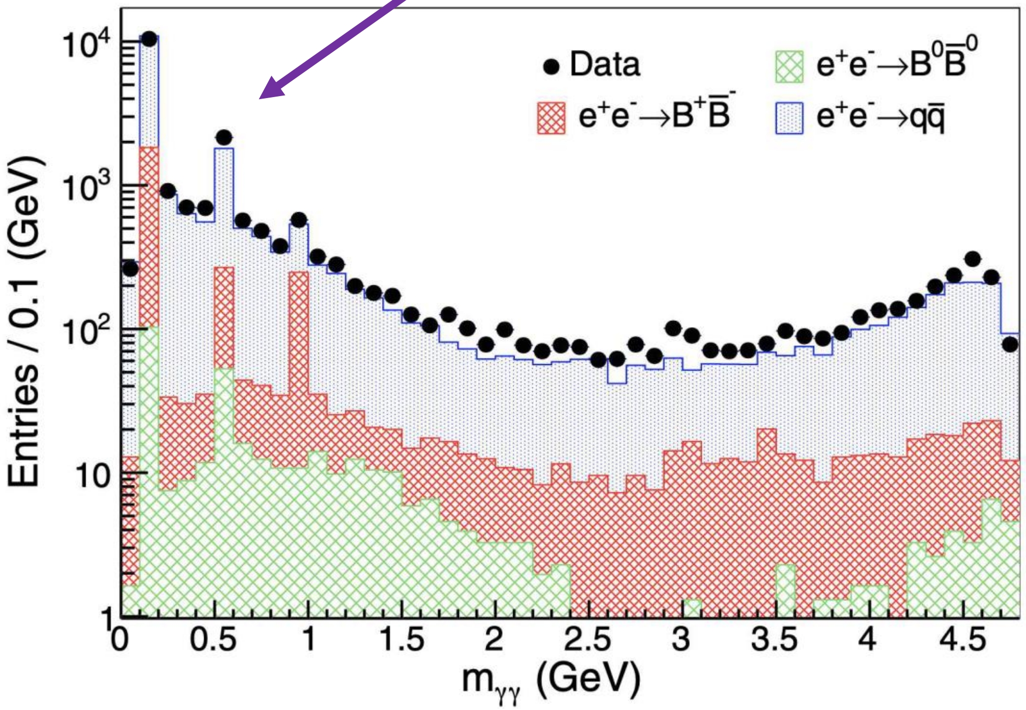
Search for **Axion-Like Particles** (ALP)- (2)

Searches for ALPs in $B^+ \to K^+ a$ ($a \to \gamma\gamma$)

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

Search for peak in the reconstructed γγ mass

peaking contributions
from π0, η, η' ηc

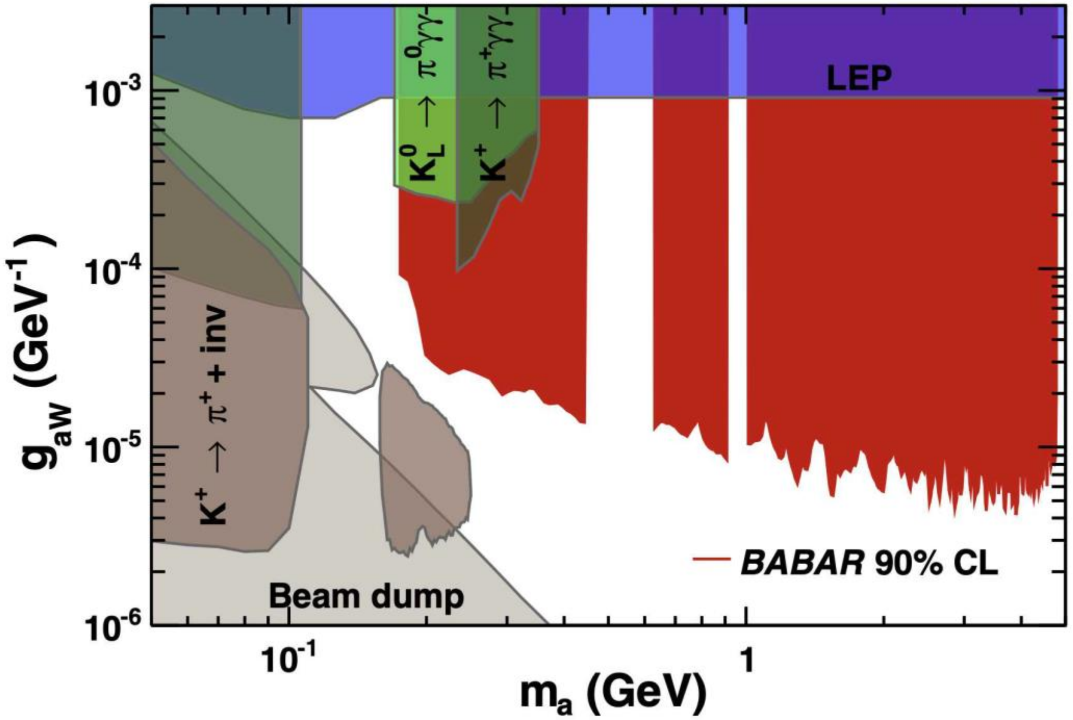


coupling

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

$SU(2)_W$ field strength tensor

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



Up to two orders of magnitude improvements over previous limits

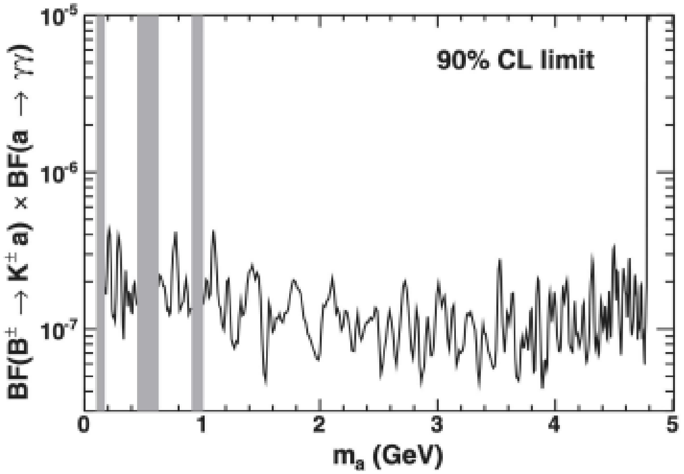
Axion-Like Particles

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

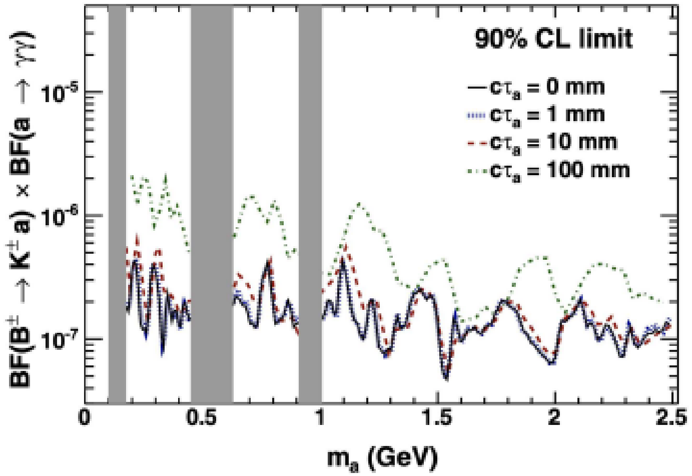
Scan $m_{\gamma\gamma}$ with steps equal to the signal mass resolution (~ 8 – 14 MeV)

- 461 signal mass hypotheses fit with unbinned ML fits to a hypothetical signal peak + smooth background over range of ~24 – 60 σ around each hypothesis

Prompt decay hypothesis



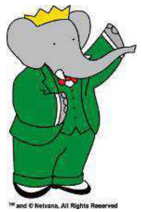
Displaced decay hypothesis



In low mass region ($m_{\gamma\gamma}$ < 2.5 GeV) the signal sensitivity is also assessed for non-prompt signal hypotheses: $c\tau$ = 1, 10, 100mm

- displaced vertex not reconstructed, but ALP resolution degraded
- No significant excess observed

Presentation at Lake Louise 2023



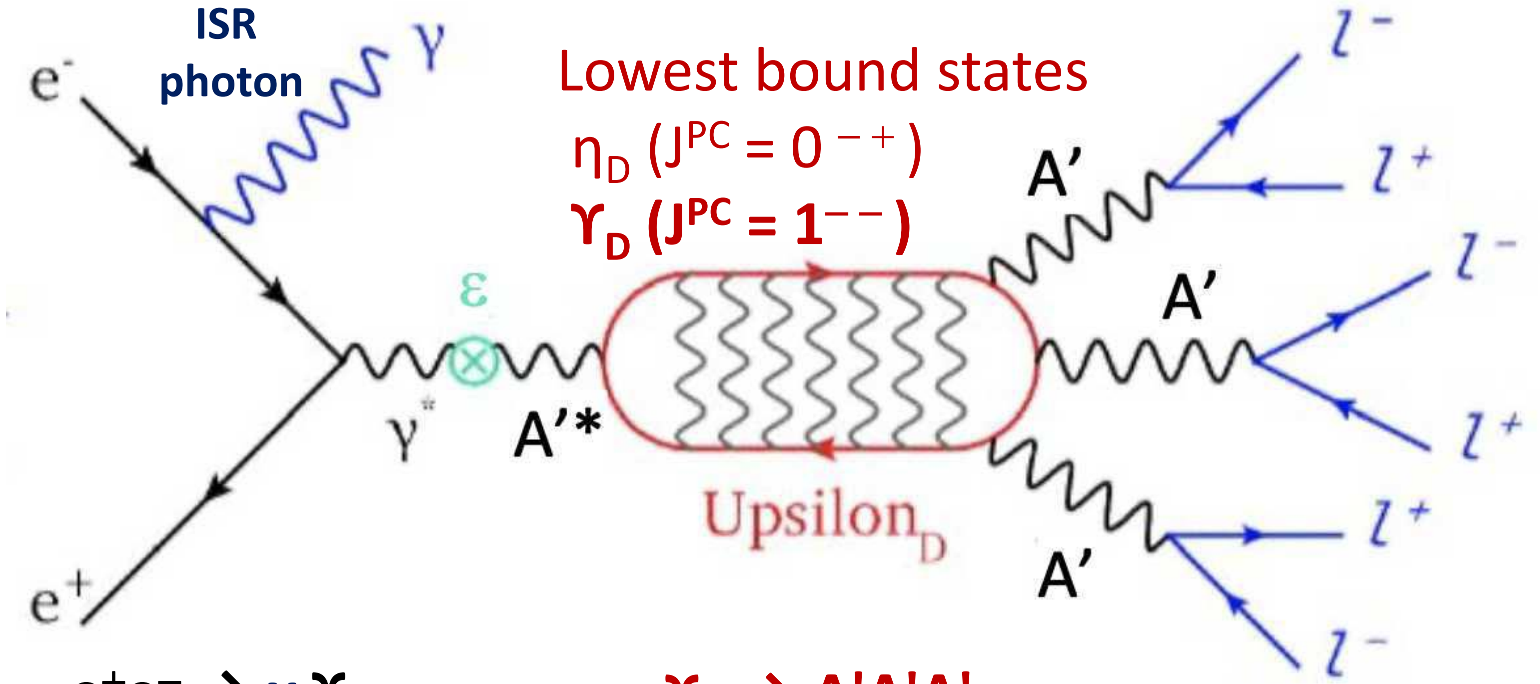
Search for **Darkonium** (1)

PRL 128, 021802 (2022)

Dark matter bound states arise in some simple dark photon (A') models in which : the A' couples strongly to the dark matter fermion (χ) via coupling $\boldsymbol{\alpha_D}$ and A' mixes with SM photon via kinetic mixing with strength $\boldsymbol{\varepsilon}$

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

Final state :
A' → f^+f^- (f = e, μ,π)

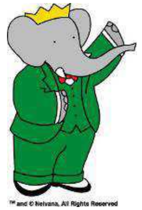


$\mathbf{e^+e^- \rightarrow \gamma\, \Upsilon_D}$

$\mathbf{\Upsilon_D \rightarrow A'A'A'}$

Dark photons A' decay to pairs of leptons or pions
BaBar search in **six-track final state** in 514 fb^{-1}

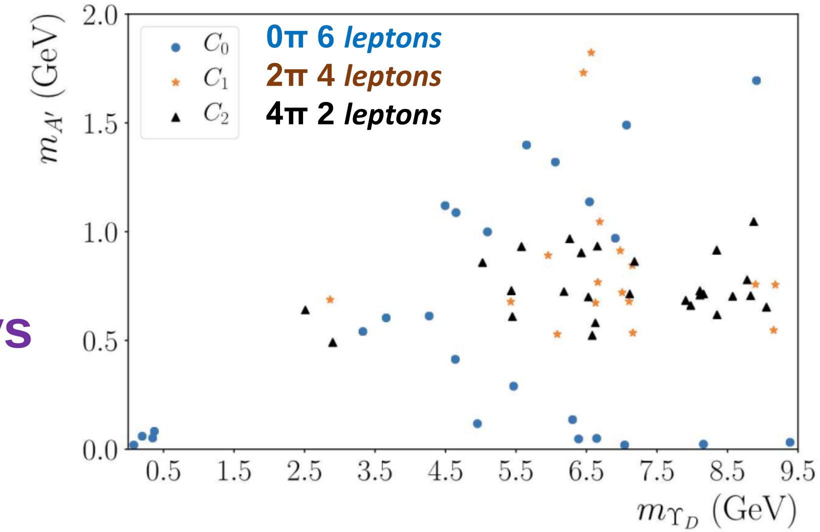
Dark photon lifetime can be long for small masses and small kinetic mixing ε hence prompt and displaced vertex signatures



Search for **Darkonium** (2)

PRL 128, 021802 (2022)

Search for 3 dark photons Prompt decays

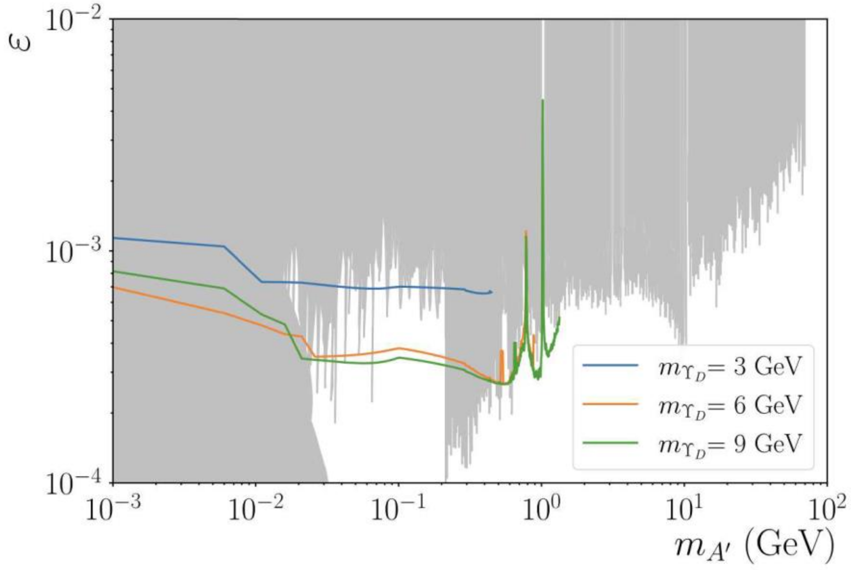


No significant signals observed in either prompt or displaced decay searches

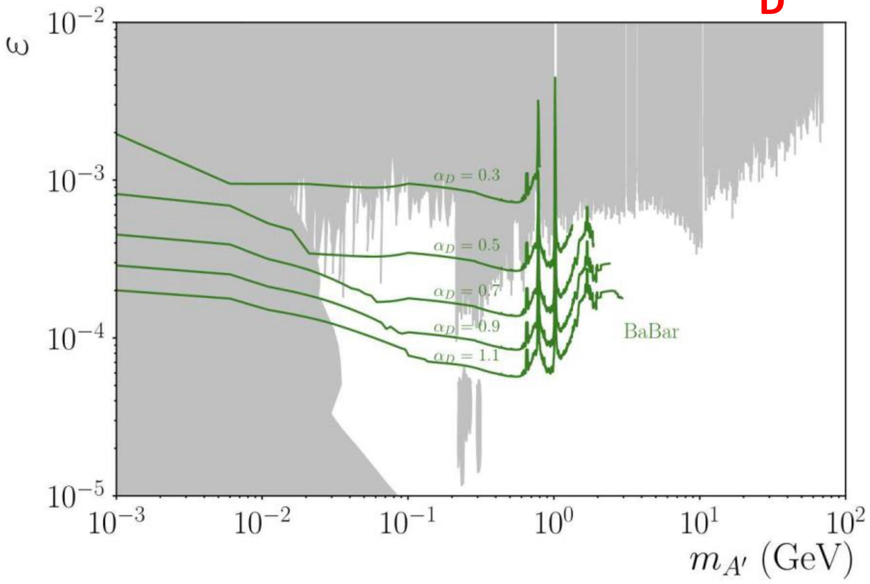
Dark photon A' couples strongly to the **dark matter fermion (χ)** via coupling α_D and A' mixes with SM photon via kinetic mixing with strength **ε**

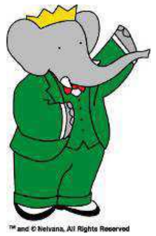
90% C.L. Upper limits on the kinetic mixing parameter **ε** as a function of m(A')

For different values of **m(ϒD)**



For different values of α_D



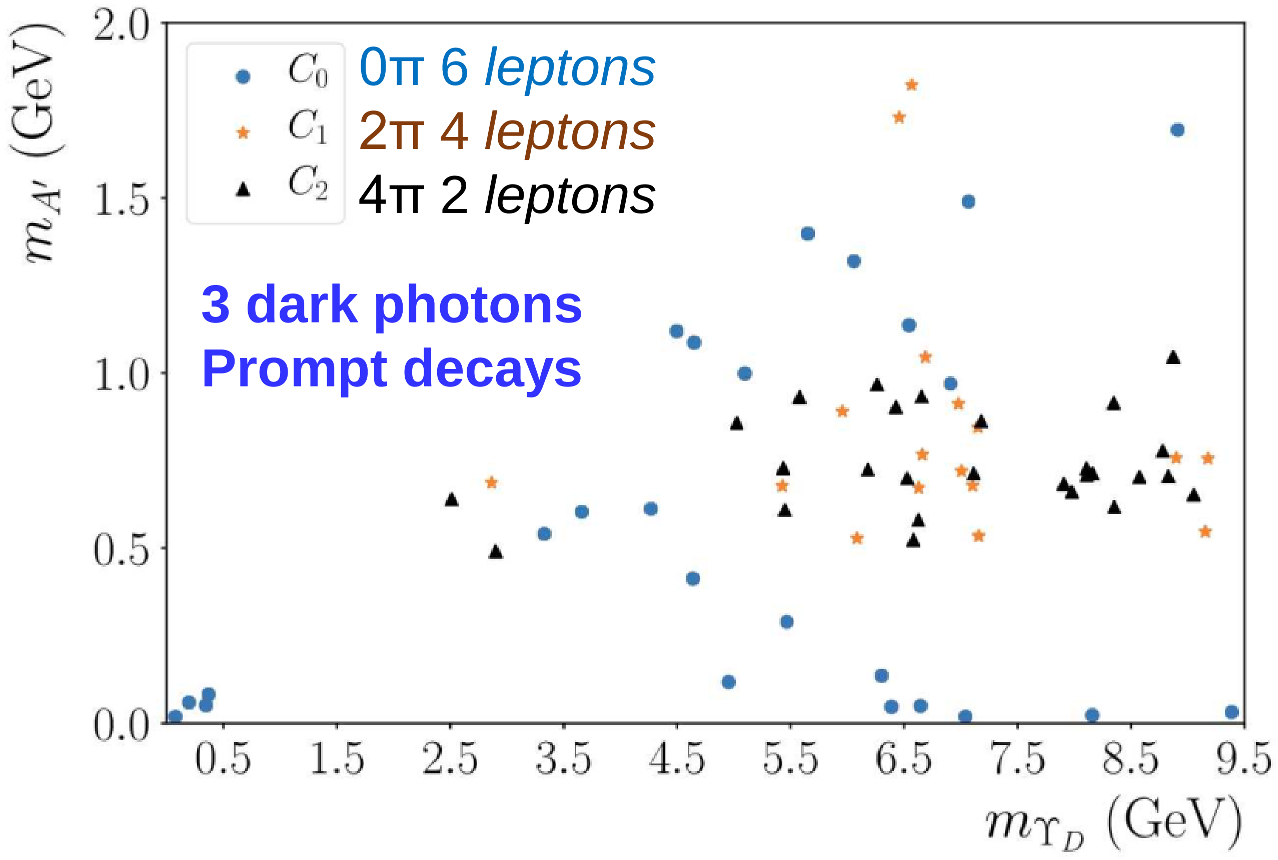


Search for **Darkonium**

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 used to suppress backgrounds
- Scan m(ϒD) - m(A') plane

PRL 128, 021802 (2022)



No significant signals observed in either prompt or displaced decay searches

Search for **Darkonium**

PRL 128, 021802 (2022)

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 used to suppress backgrounds

- Scan m(ϒD) - m(A') plane

3 dark photons
Non prompt decays

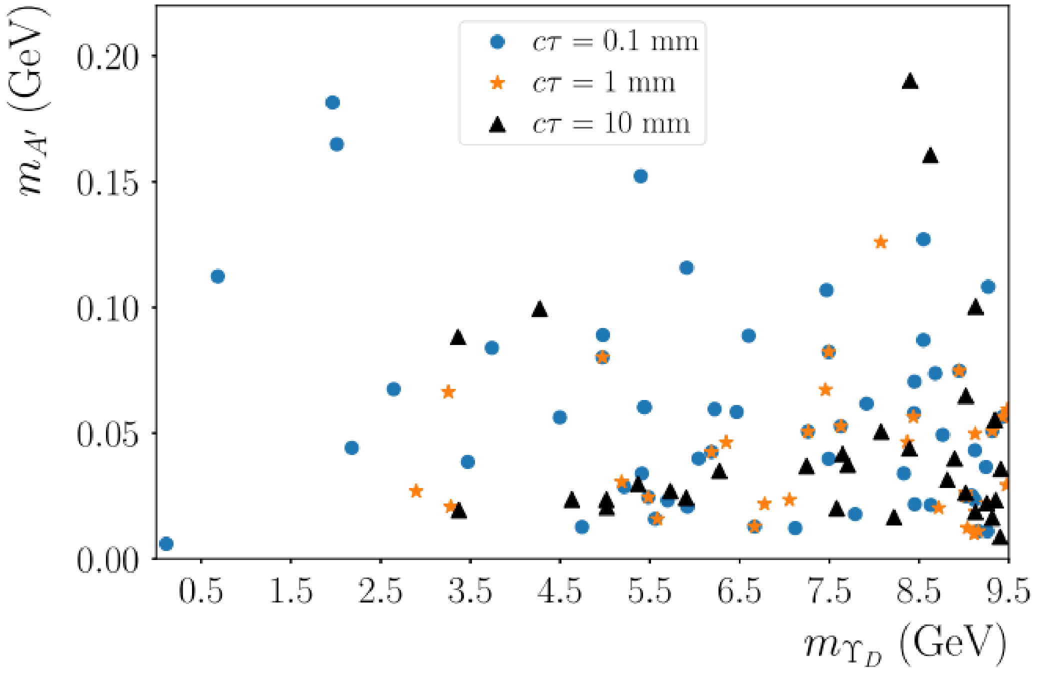


FIG. 4. The $(m_{\Upsilon_D}, m_{A'})$ mass distribution of event candidates passing all selection criteria for the datasets optimized for each dark photon lifetime.

No significant signals observed in either prompt or displaced decay searches

Search for **Darkonium**

From PHYSICAL REVIEW LETTERS 128, 021802 (2022)

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Constraints other than Recent BaBar result (gray)

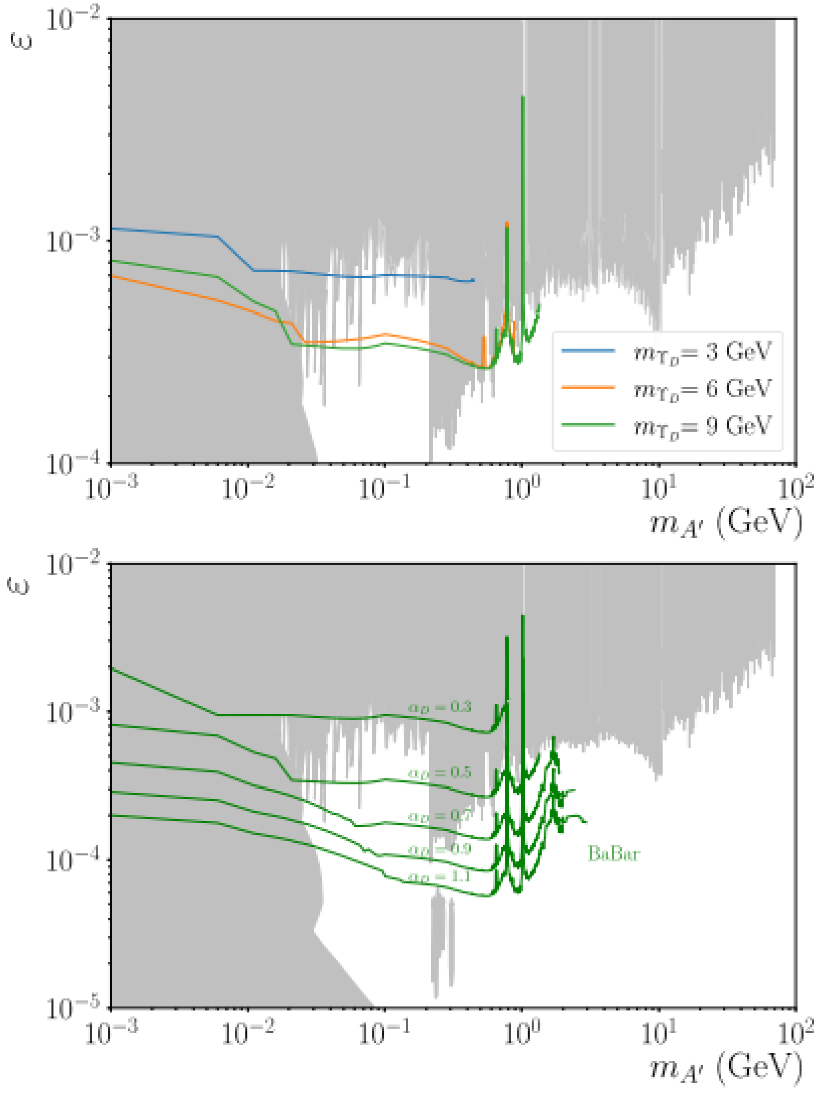

FIG. 6. The 90% C.L. upper limits on the kinetic mixing ε for (top) various Υ_D masses assuming $\alpha_D = 0.5$ and (bottom) various α_D values assuming $m_{\Upsilon_D} = 9$ GeV together with current constraints (gray area) [8–18].