Search for low-mass New Physics states from B-meson decays at *BABAR*

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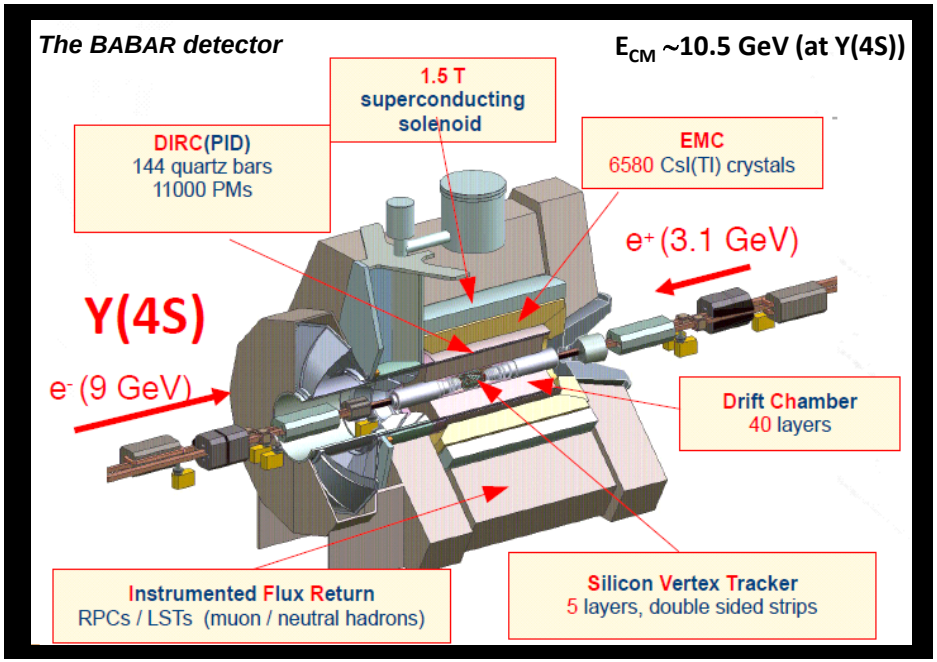
Overview – *BABAR* and the Analyses



Search for evidence of dark sector physics in two analyses:

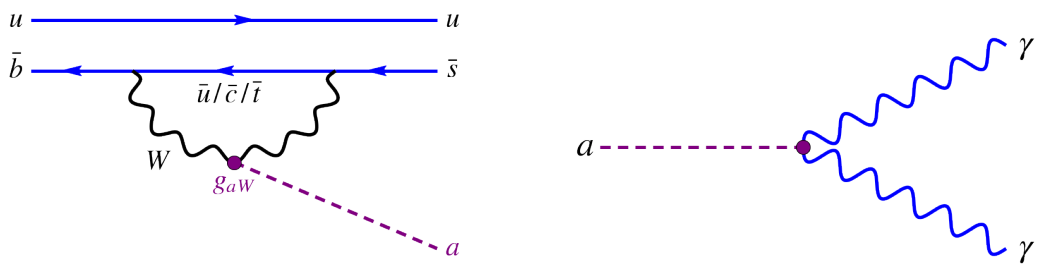
- $B^+ \to K^+ a$; $a \to \gamma\gamma$ where a is an **axion-like particle** (ALP);
- $B \to \Lambda \psi_D$ where ψ_D is a **dark anti-baryon**.

Spoiler Alert: we do not see signals; we do exclude significant regions of relevant parameter spaces.

Search for an ALP coupling to the W-boson

in the decay $B^+ \to K^+ a$ $\quad (0.175\,\mathrm{GeV} < m_a < 4.78\,\mathrm{GeV})$

The original axion was introduced to the Standard Model by Roberto Peccei and Helen Quinn to "solve" the strong CP problem – that the neutron electric dipole moment is very small. Many models of New Physics have axion-like particles (ALPs) that **couple to pairs of Standard Model exchange bosons**.



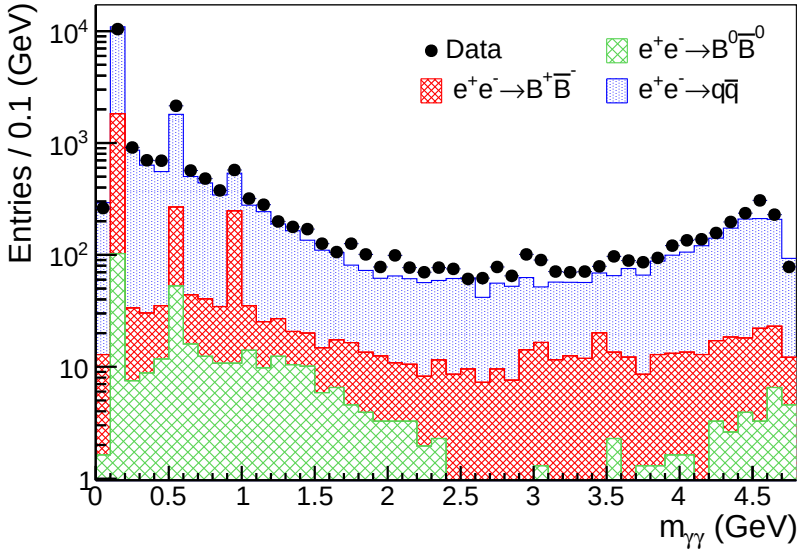
Following PRL **118**, 111802 (2017), we consider a minimal ALP model with coupling g_{aW} to the $SU(2)$ W-boson and Lagrangian

$$\mathcal{L} = -\frac{g_{aW}}{4} a W_{\mu\nu} \tilde{W}^{\mu\nu}$$

Candidate selection and $\gamma\gamma$ invariant mass distribution

We measure the $m_{\gamma\gamma}$ distribution from $B^+ \to K^+ a$; $a \to \gamma\gamma$ candidates assuming all signal is produced with a decaying promptly.

- use simulated signal with m_a spanning the allowed region, and a subset of the data (later discarded) to optimize candidate selection;
- two BDTs are trained to separate signal from background; one uses $q\bar{q}$ MC as background and the other uses B^+B^- as background;
- validate simulation using $B^+ \to K^+\pi^0$, $B^+ \to K^+\eta$ decays;
- the data sample corresponds to 4.7×10^8 $B\overline{B}$ meson pairs.

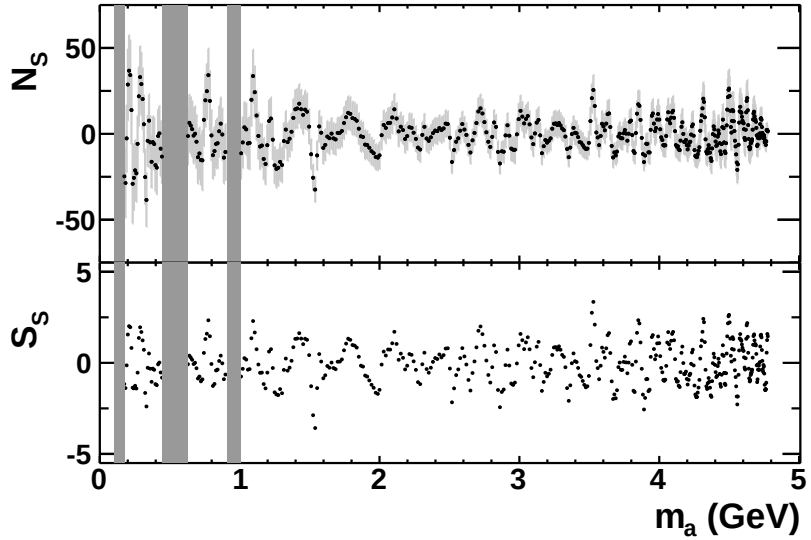


The **diphoton mass distribution** of ALP candidates, together with Monte Carlo predictions of leading background processes normalized to the data luminosity.

Fitting the $\gamma\gamma$ invariant mass distribution

We measure the $B^+ \to K^+ a$; $a \to \gamma\gamma$ product branching fraction assuming all signal is produced with a decaying promptly.

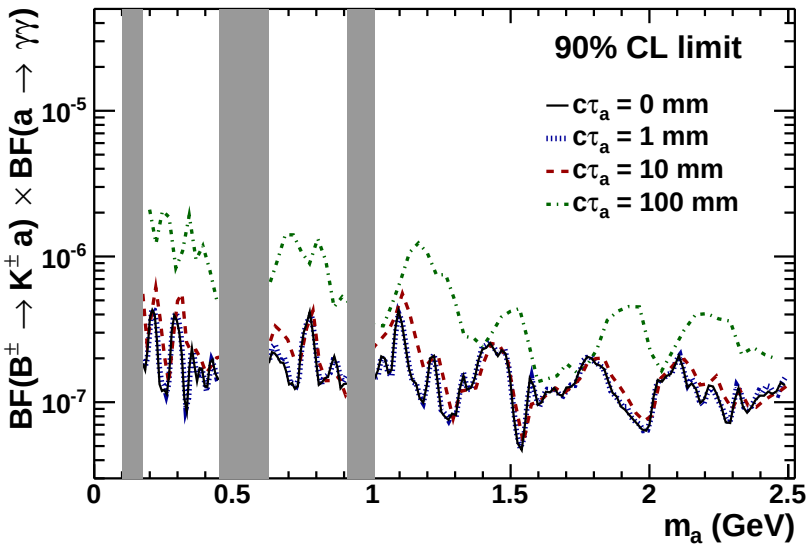
- fit data for **461 signal mass hypotheses** with scan step size equal to signal resolution, $\sigma_{\gamma\gamma}$ that ranges from 8 MeV near $m_a = 0.175\,\mathrm{GeV}$ to 14 MeV near $m_a = 2\,\mathrm{GeV}$ and back down to 2 MeV near $m_a = 4.78\,\mathrm{GeV}$;
- background is fit over $m_{\gamma\gamma}$ intervals with widths in the range $(24 - 60)\,\sigma_{\gamma\gamma}$;
- contributions from $B^+ \to K^+\pi^0$, $B^+ \to K^+\eta$, $B^+ \to K^+\eta'$, and $B^+ \to K^+\eta_c$ are included.



The distribution of **signal events** (N_S) and **local signal significance** (S_S) from fits for prompt ALP decays.

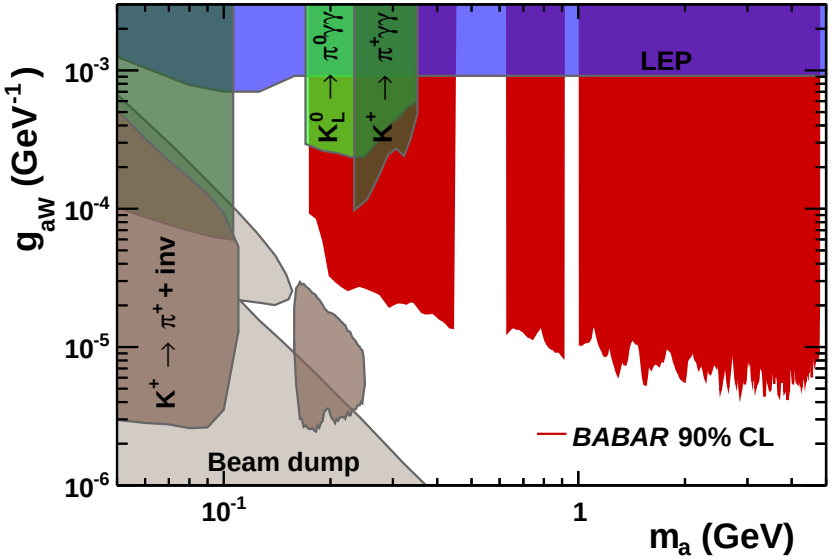
$B^+ \to K^+ a$; $a \to \gamma\gamma$ search results

for details, see PRL **128**, 131802 (2022)



90% CL upper limits on the $B^+ \to K^+ a$ branching fraction for $m_a < 2.5\,\mathrm{GeV}$ and **$c\tau_a$ between 0 and 100 mm**.

The ALP has a decay width $\Gamma = g_{aW}^2 m_a^3 \sin^4\theta_W / 64\pi$, so we determine the branching fractions from efficiencies of $c\tau_a$ values of 1, 10, and 100 mm for $m_a < 2.5\,\mathrm{GeV}$



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).

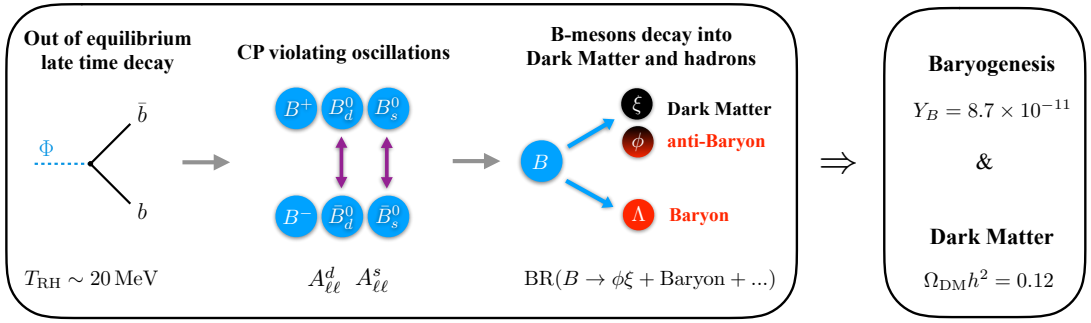
The existing constraints are taken from PRL **118**, 111802 (2017)

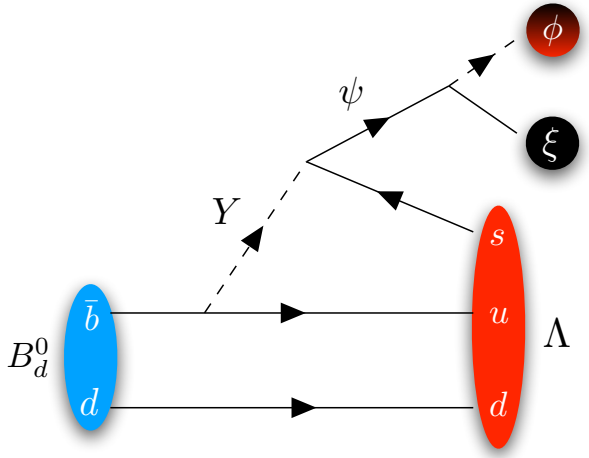
Why search for dark anti-baryons?

based on Phys. Rev. D **99**, 035031 (2019)

Elor, Escudero, and Nelson suggested that dark baryons can simultaneously explain dark matter production and baryogenesis.

- $b\bar{b}$ pairs are produced in the early universe, $T_{RH} \sim \mathcal{O}(10\,\mathrm{MeV})$;
- neutral B mesons quickly undergo CP violating oscillations before decaying out of thermal equilibrium into visible baryons, dark sector **scalar baryons ϕ** and dark **Majorana fermions ζ**;
- a minimal model also includes an unstable **Dirac fermion ψ carrying baryon number**; $m_\phi + m_\zeta < m_\psi$; two solar mass neutron star stability $\rightarrow m_\psi > m_\phi > 1.2\,\mathrm{GeV}$.

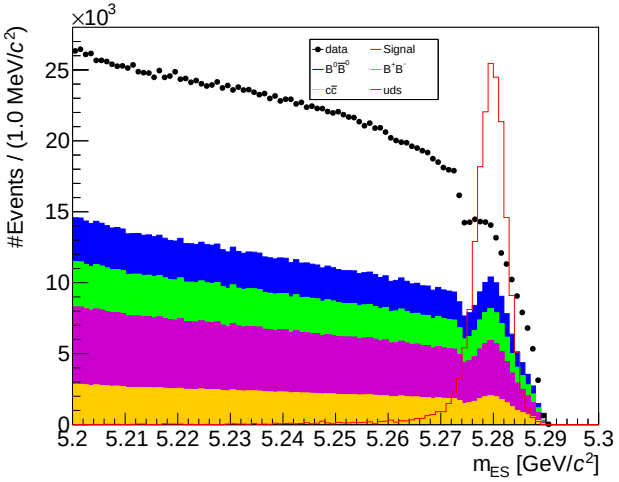


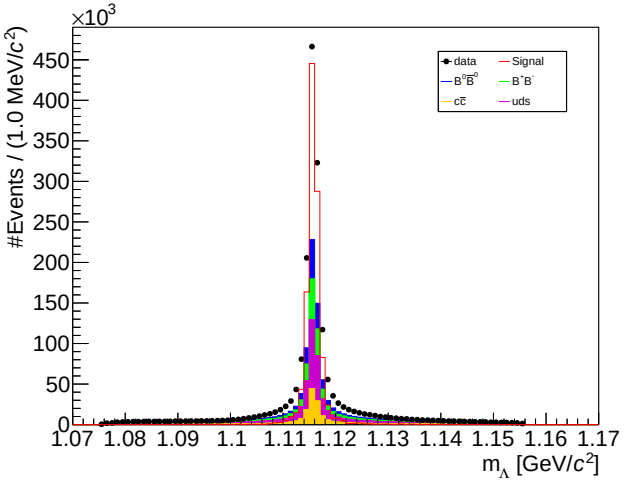


$B \to \Lambda\psi_D$ search strategy

We fully reconstruct the second B meson ($B_{\rm tag}$) using hadronic decay and require one additional Λ in the event.

- $B_{\rm tag}$ candidates are built from $D^{(*)0}$, $D^{(*)\pm}$, $D_s^{*\pm}$, or J/ψ seed mesons plus up to 5 kaons or pions.
- they are characterized by $\Delta E = E_{\rm beam} - E_{\rm tag}$ and $m_{\rm ES} = \sqrt{E_{\rm beam}^2 - p_{\rm tag}^2}$ where $E_{\rm tag}$, $p_{\rm tag}$ and $E_{\rm beam}$ are evaluated in the e^+e^- CM.
- $\Lambda \to p\pi$ candidates are reconstructed from oppositely charged pairs of tracks identified as protons and pions; kinematic fit is done constraining the two tracks to emerge from a common origin and that the momentum vector point to the beam interaction region.
- after reconstructing $B_{\rm tag}$ and the Λ candidate, no additional track may remain.

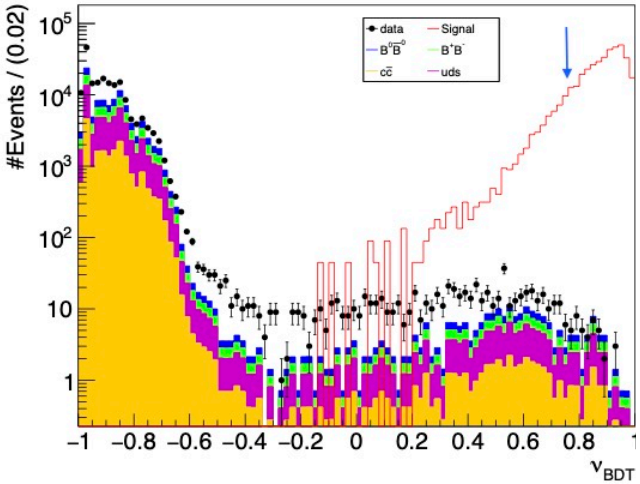




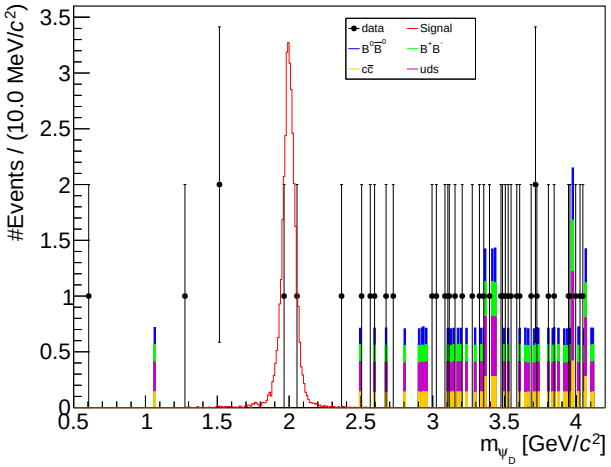
$B \to \Lambda\psi_D$ event selection

After requiring $5.27\,\mathrm{GeV} < m_{ES} < 5.29\,\mathrm{GeV}$ and $1.110\,\mathrm{GeV} < m_\Lambda < 1.121\,\mathrm{GeV}$, we use a **boosted decision tree** (BDT) to increase signal purity.

- BDT features include B_{tag} kinematic and purity variables;
- BDT features include kinematic variables associated with the Λ candidate;
- to limit bias in the classifier, the BDT is trained on a signal sample spanning a wide range ψ_D masses.



The distribution of the BDT scores **after** applying all other selection criteria for data (points), signal MC for $m_{\psi_D} = 2.0\,\mathrm{GeV}$ (red histogram) and inclusive background MC predictions). Signal normalization is arbitrary.



The distribution of m_{ψ_D} after applying all selection criteria for data, **including $\nu_{\mathrm{BDT}} > 0.75$**, (points), signal MC for $m_{\psi_D} = 2.0\,\mathrm{GeV}$ (red histogram) and inclusive background MC predictions (stacked histogram). Signal normalization is arbitrary.

$B \to \Lambda\psi_D$ upper limits

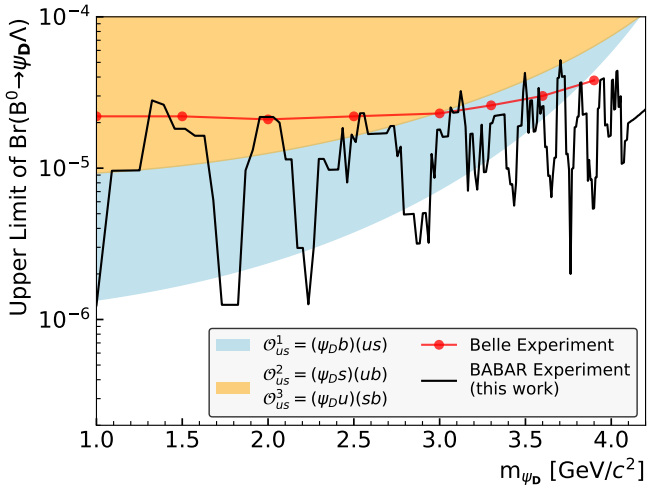
arXiv:2302.00208v1

Branching fraction calculations account for

- signal efficiencies that vary between 5.9×10^{-4} at $m_{ES} = 1.0\,\mathrm{GeV}$ and 2.1×10^{-1} near $4.2\,\mathrm{GeV}$;
- discrepancies between MC predictions for background and data in m_{ES} sidebands and lower ν_{BDT} regions;
- data/MC differences in the ratios of $B^0\bar{B}^0$ and B^+B^- production.

We extract signal yields by scanning the ψ_D mass spectrum in steps of mass resolution, σ_m, **probing 193 mass hypotheses**.

- σ_m ranges from $90\,\mathrm{MeV}$ at $m_{\psi_D} = 1.0\,\mathrm{GeV}$ to $6\,\mathrm{MeV}$ at $m_{\psi_D} = 4.2\,\mathrm{GeV}$;
- signal region yield is determined by counting the numbers of events in a window $\pm 3\,\sigma_m$ centered around the ψ_D mass hypothesis;
- background is estimated from two sideband regions of $\pm 3\,\sigma_m$ surrounding the signal window.

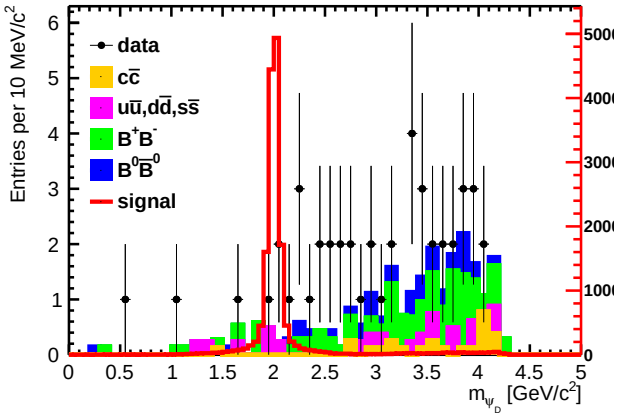


Upper limits on the $B^0 \to \psi_D\Lambda$ branching fraction at 90% CL, together with previous constraints from Belle. The light blue and orange (orange only) region shows the values of the $B^0 \to \psi_D\Lambda$ branching fraction allowed to successfully generate B-Mesogenesis for the $\mathcal{O}^1_{us} = (\psi_D b)(us)$ ($\mathcal{O}^2_{us} = (\psi_D s)(ub)$ and $\mathcal{O}^3_{us} = (\psi_D u)(sb)$) effective operators from calculations presented in Phys. Rev. D **104**, 035028 (2021)

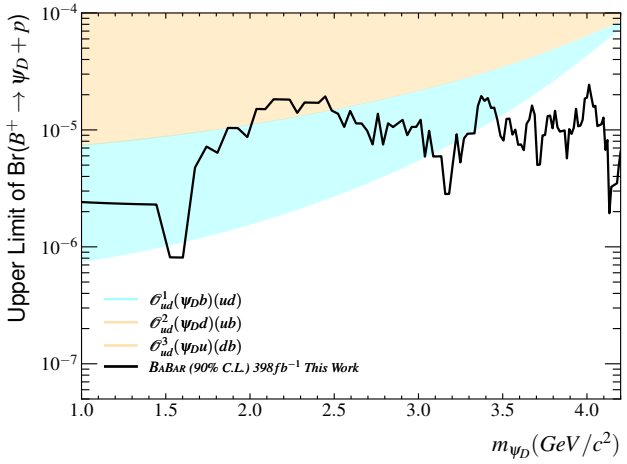
BONUS: $B \to p\psi_D$ search results

first presented at Moriond EW (in La Thuile) last week: see Sophie Middleton's talk

A search for $B \to p\psi_D$ has been done following the same general outline as for $B \to \Lambda\psi_D$.



The distribution of m_{ψ_D} after applying all selection criteria for data, including ν_{BDT}, (points), signal MC for $m_{\psi_D} = 2.0\,\mathrm{GeV}$ (red histogram) and inclusive background MC predictions (stacked histogram). Signal normalization is arbitrary.



Upper limits on the $B^0 \to \psi_D p$ branching fraction at the 90% CL, along with $B^0 \to \psi_D p$ branching fractions allow to generated B-Mesogenesis for the indicated operators.

Summary and Conclusions

We have searched for evidence of dark matter produced in B meson decays in data **collected** by the *BABAR* detector **between 1999 and 2008**.

- We have set limits on couplings of axion-like particles to W-bosons that complement the limits from kaon and beam dump experiments;
- We have set limits on the branching fractions of $B^0 \to \psi_d \Lambda$ and $B^0 \to \psi_d p$ that exclude some of the phase-space that would allow a minimal model of (dark anti-baryons) + (B oscillations) to simultaneously "explain" dark matter and the Baryon Asymmetry of the Universe (BAU).

The Standard Model has been established as correctly describing the strong and electro-weak interactions of ordinary matter. Probing the quantum/particle nature of dark matter and understanding the BAU remain outstanding problems in high energy physics.

Belle II will be able to extend the reach of studies similar to these.

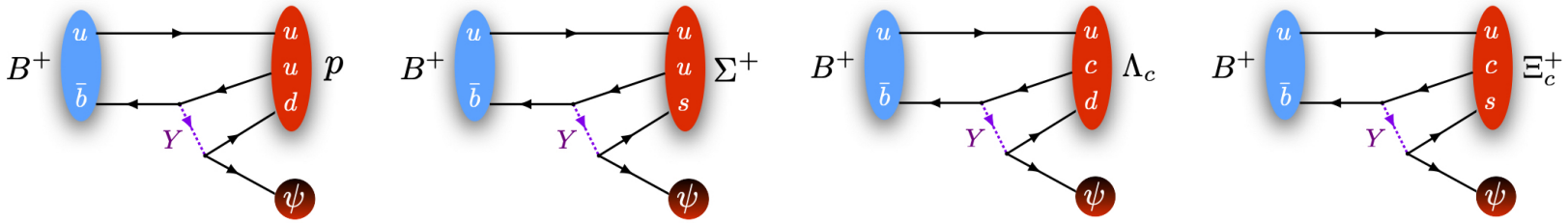
Backup – mesogenesis operators

extracted from Phys. Rev. D **104**, 035028 (2021)

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

Backup – mesogenesis Feynman diagrams

extracted from Phys. Rev. D **104**, 035028 (2021)



The decay of the B^+ meson to the lightest possible baryon as triggered by the four different flavor operators. Note that any of the four can lead to successful baryogenesis and dark matter production. As usual, the light dark sector antibaryon ψ would appear as missing energy in the detector, and Y is a heavy color-triplet scalar mediator with $M_Y > 1.2\,\text{TeV}$.