# Searches for Baryogenesis and Dark Matter in B-meson decays at BABAR

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On behalf of the BABAR Collaboration

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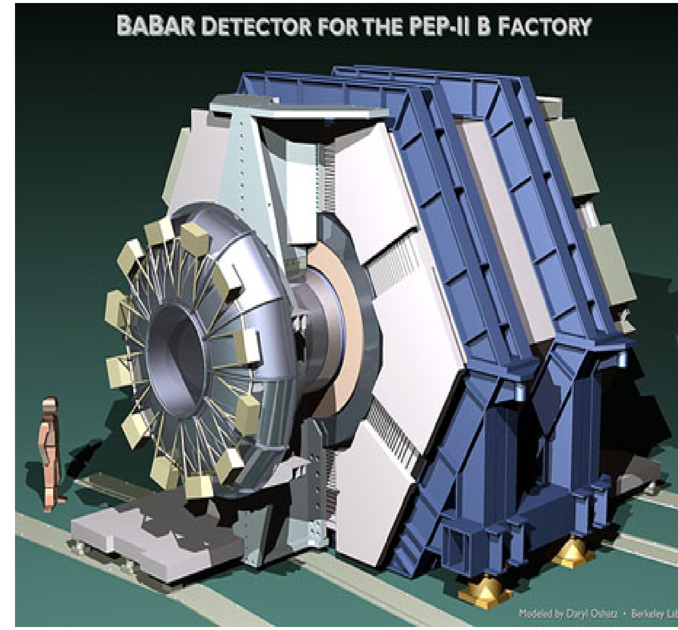
INSTITUTE OF PARTICLE PHYSICS

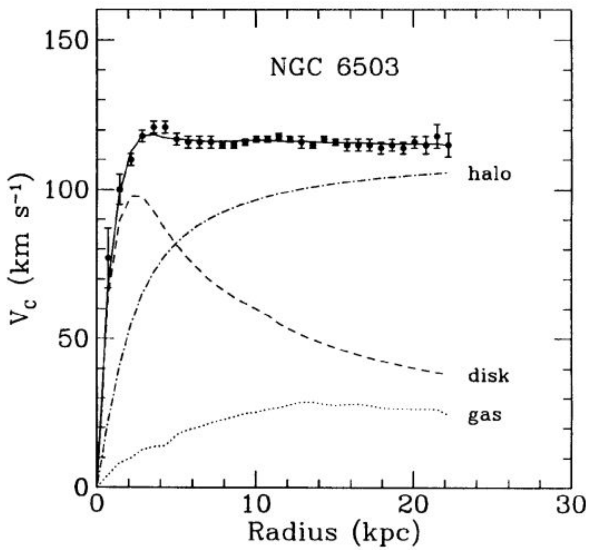
# Outline




- B-baryogenesis introduction
- BABAR overview
- Searches:
  - $B^+ \rightarrow p + \psi_D$ Phys. Rev. Lett. 131, 201801 (2023)
  - $B^0 \rightarrow \Lambda + \psi_D$ Phys. Rev. D 107, 092001 (2023)
  - $B^+ \rightarrow \Lambda_c^+ + \psi_D$ Phys. Rev. D 3, L031101 (2025)

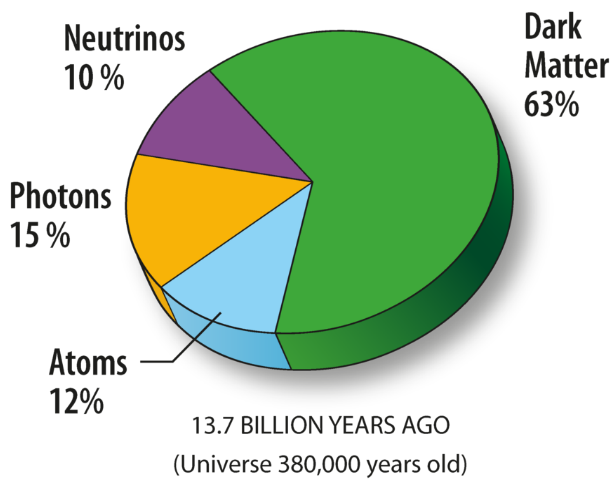
# Dark matter and the BAU

The particle physics Standard Model has no explanation for two of the biggest problems in cosmology:




**The Baryon Asymmetry of the Universe (BAU)**

- Sakharov conditions: Sakharov, A.D., JETP 5 (1967) 24
  - Baryon number violation
  - $C$ and $CP$ violation
  - Deviation from thermal equilibrium




**The nature of dark matter:**

- Astronomical evidence for dark matter is overwhelming, all measurements to date are gravitational in nature
- The majority of the matter in the universe has an unknown composition

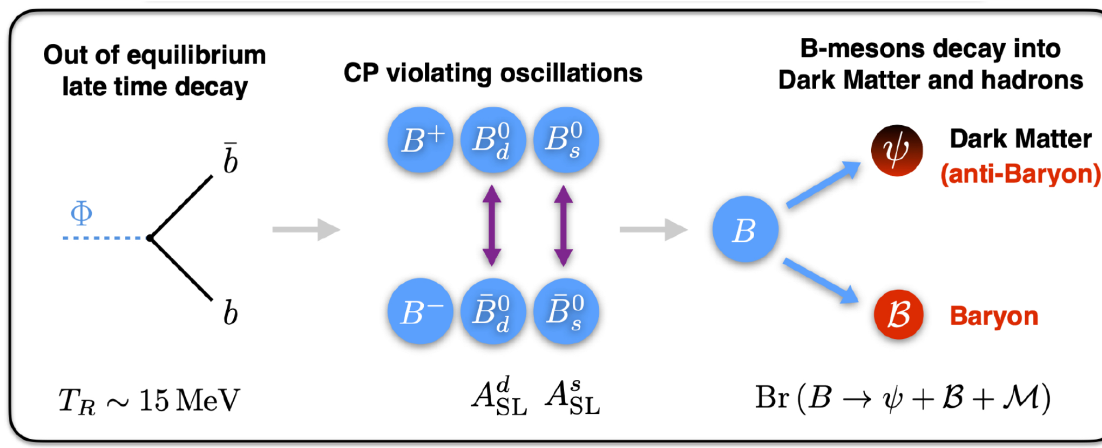
# B Baryogenesis

Model provides a possible mechanism to explain dark matter abundance and baryon asymmetry of the universe (BAU):

- Postulates the existence of a light dark-sector anti-baryon ($\psi_D$) and a TeV-scale color-triplet bosonic mediator (**Y**)
- Matter – antimatter asymmetry arises from CP violation in $B^0$ - $\bar{B}^0$ oscillations
- BAU results from $B$ meson decays into a baryon and a dark sector anti-baryon $\psi_D$ (+ mesons)

**G. Elor, M. Escudero and A. E. Nelson, Phys. Rev. D 99, 035031 (2019).**

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




Visible and dark sectors have equal but opposite baryon number asymmetries, but total baryon number is conserved

- Experimentally testable predictions of $B \longrightarrow \psi_D + \mathcal{B}$ (+ additional light mesons)

# Decay modes

Baryon asymmetry is produced by $B^0$ decays, but the same operators produce analogous charged $B^+$ decays as well:

Y couples b to u, and d to $\psi_D$

| Operator and Decay | Initial State | Final State | $\Delta M$ (MeV) |
|---|---|---|---|
| $\mathcal{O}_{ud} = \psi\, b\, u\, d$<br>$\bar{b} \to \psi\, u\, d$ | $B_d$ | $\psi + n\,(udd)$ | 4340.1 |
| | $B_s$ | $\psi + \Lambda\,(uds)$ | 4251.2 |
| | $B^+$ | $\psi + p\,(duu)$ | 4341.0 |
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| $\mathcal{O}_{cd} = \psi\, b\, c\, d$<br>$\bar{b} \to \psi\, c\, d$ | $B_d$ | $\psi + \Lambda_c + \pi^-\,(cdd)$ | 2853.6 |
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| | $B^+$ | $\psi + \Lambda_c^+\,(dcu)$ | 2992.9 |
| | $\Lambda_b$ | $\bar{\psi} + \overline{D}^0$ | 3754.7 |
| ? $\mathcal{O}_{cs} = \psi\, b\, c\, s$<br>$\bar{b} \to \psi\, c\, s$ | $B_d$ | $\psi + \Xi_c^0\,(csd)$ | 2807.8 |
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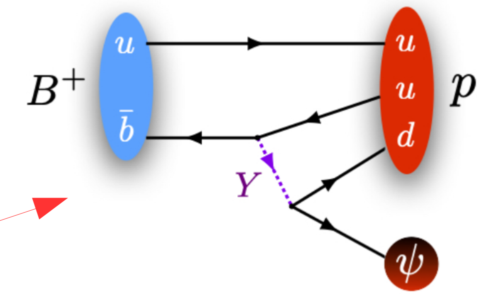
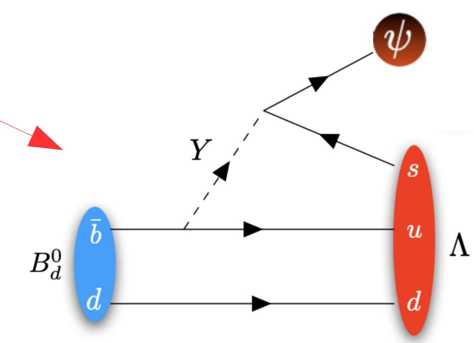
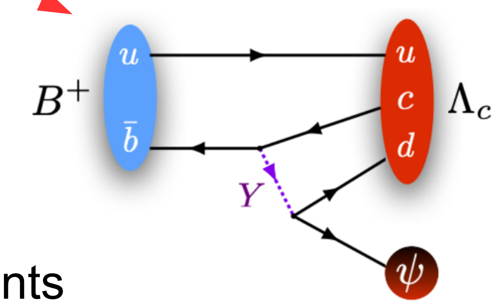
| | $\Lambda_b$ | $\bar{\psi} + D^- + K^+$ | 3256.2 |



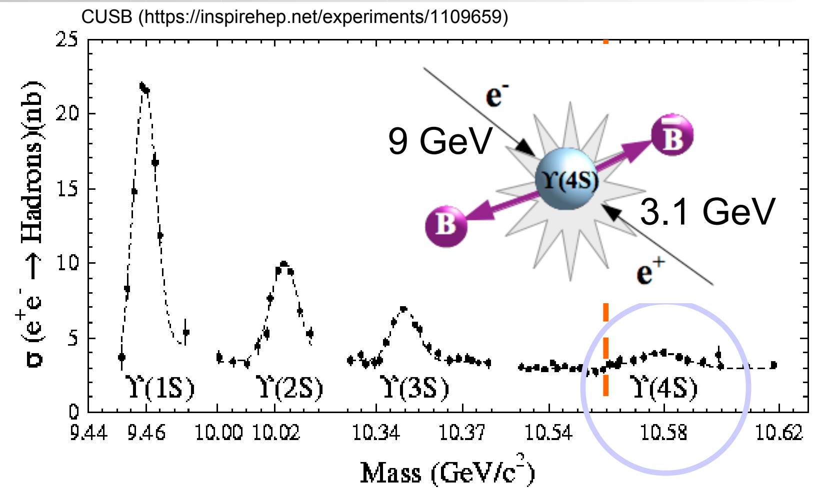




- $B^+$ and $B_d$ modes potentially accessible at B factory experiments

# BABAR experiment

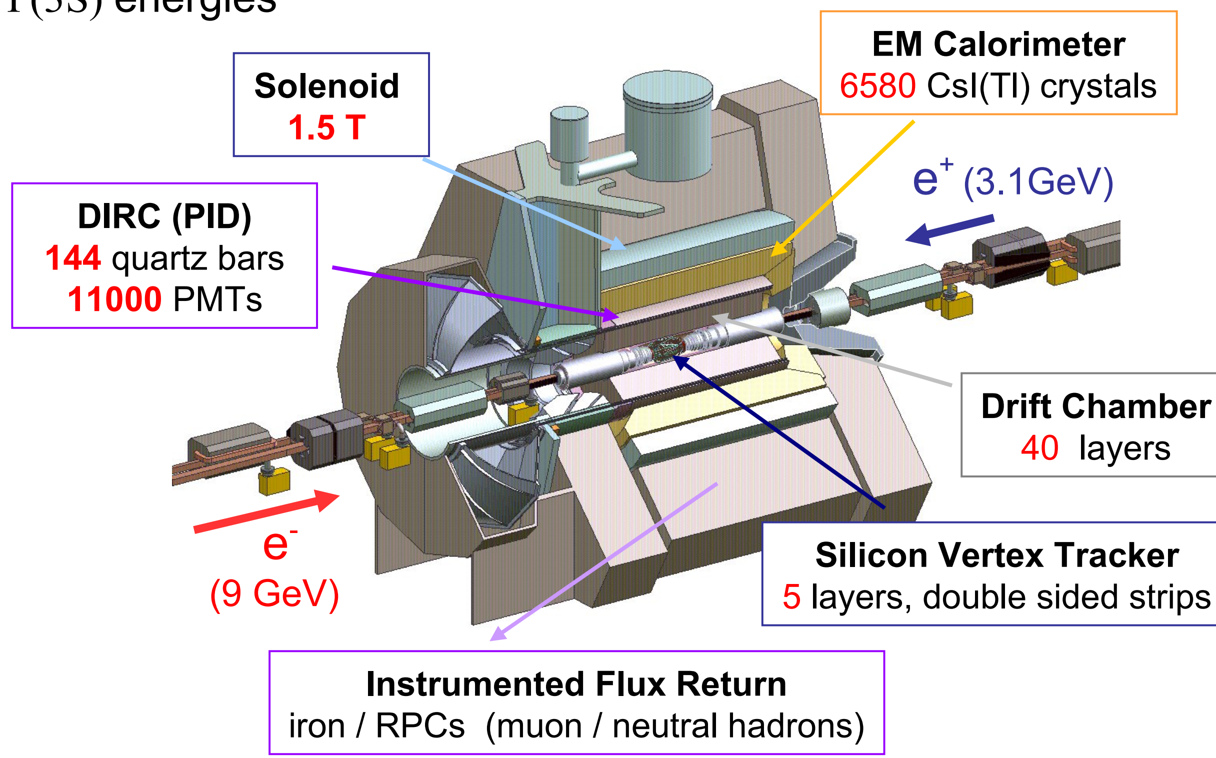
Asymmetric B Factory experiment at the SLAC National Accelerator Laboratory

- **BABAR** collected data from1999 until 2008:
- **432 fb$^{-1}$ $\Upsilon(4S)$ "on peak"** (~470 x $10^6$ $B\bar{B}$ pairs)
- 53 fb$^{-1}$ non-resonant "off peak"
- Smaller samples at the $\Upsilon(2S)$ and $\Upsilon(3S)$ energies




Optimized for tracking and B vertex reconstruction, K - π particle identification, precision calorimetry, and μ ID

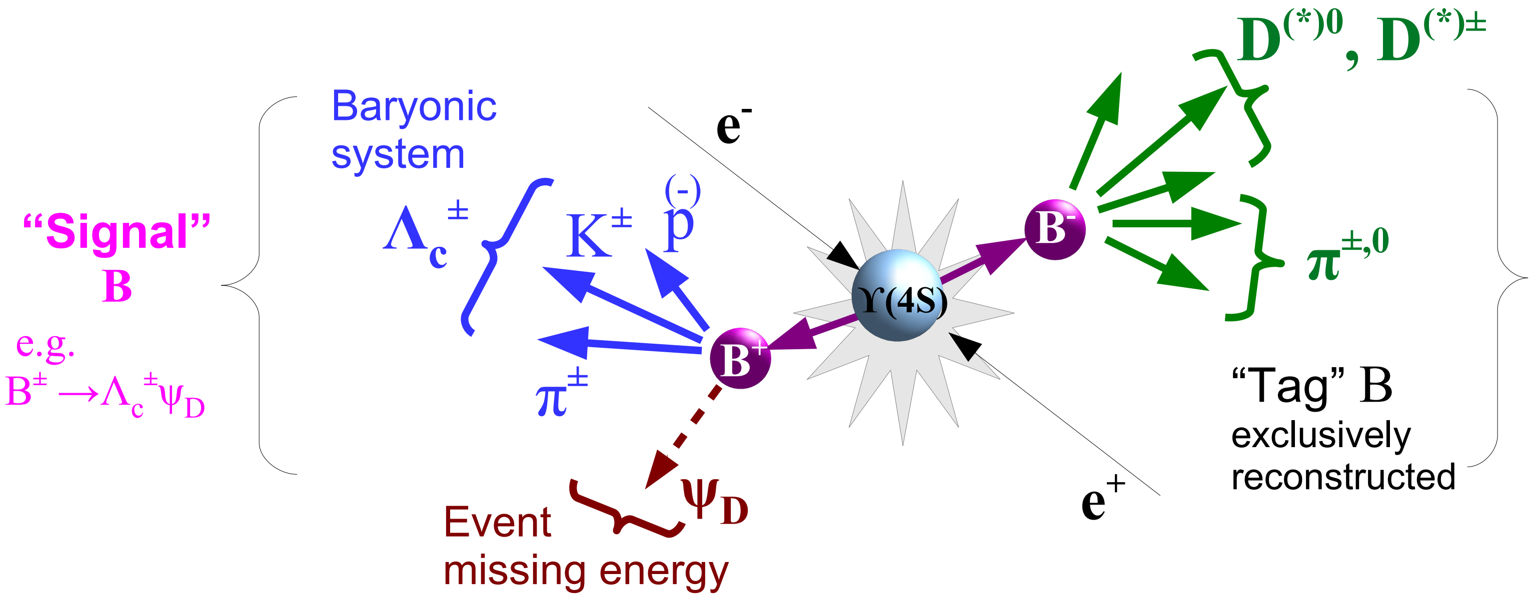
- **Clean** environment with large solid-angle detector coverage and good missing energy reconstruction
- **Inclusive trigger** ($N_{tracks}$>3) as well as dedicated low-multiplicity triggers

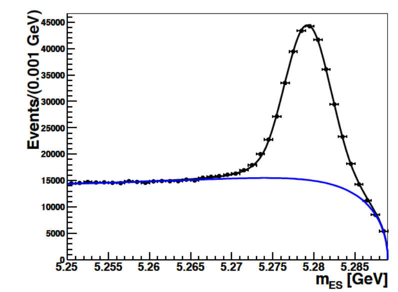


# Methodology

B meson decays with missing energy have limited kinematic information available to uniquely identify the signal decay

- Instead, exclusively reconstruct one of the B meson decays ("**Tag B**") in one of several thousand possible hadronic decay modes:




$$m_{ES} \equiv \sqrt{E^{*2}_{\mathrm{beam}} - p^{*2}_{B}}$$
$$\Delta E^{*} \equiv E^{*}_{B} - E^{*}_{\mathrm{beam}}$$

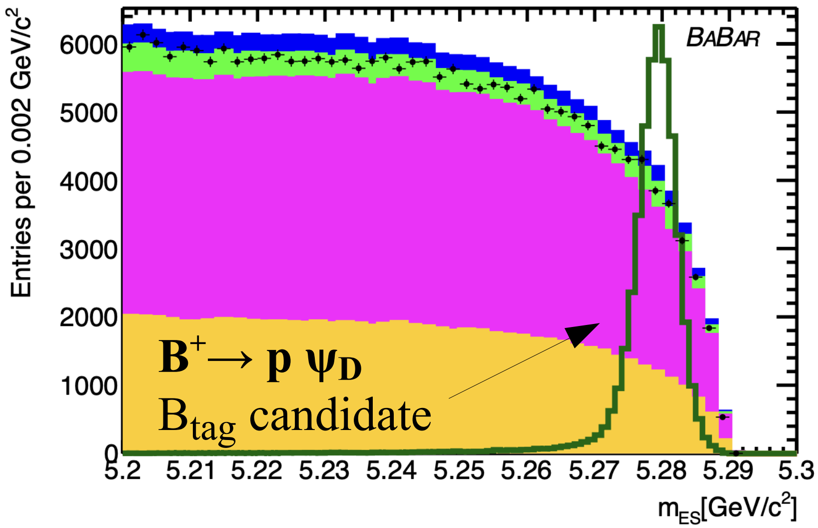
- Advantage: improves knowledge of signal kinematics and missing energy, and strongly suppresses combinatorial backgrounds
- Disadvantage: low reconstruction efficiency (~0.1%)

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

**and**

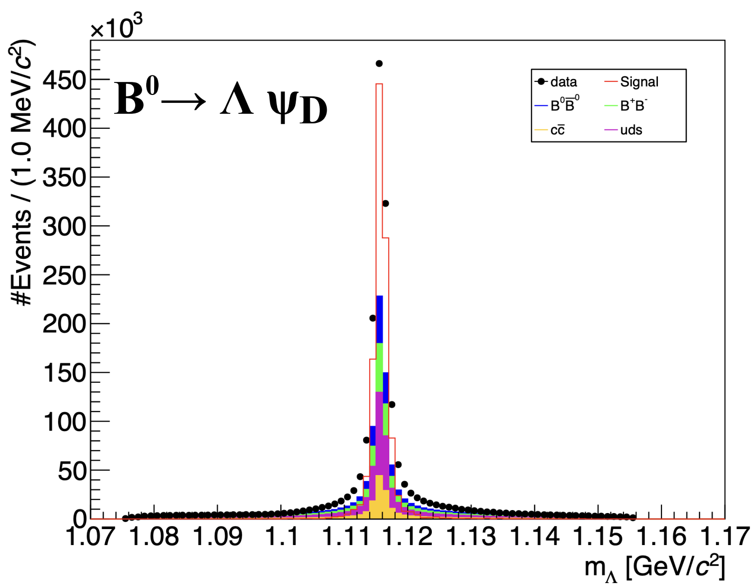
$$B^0 \rightarrow \Lambda + \psi_D$$

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

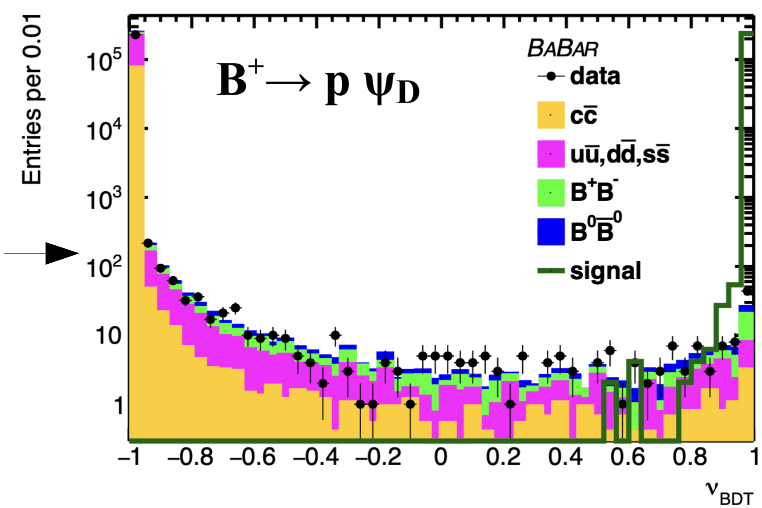



Reconstruct accompanying B meson from $\Upsilon(4S) \to B^+B^-$ and (or $B^0\bar{B}^0$) and look for signal signature in the remainder of the event:

- identified proton (and no additional tracks), or
- reconstruct $\Lambda^0 \to p\ \pi^-$, including displaced vertex significance requirement and kinematic fit




Boosted decision tree used to suppress continuum backgrounds based on event shape and kinematic variables



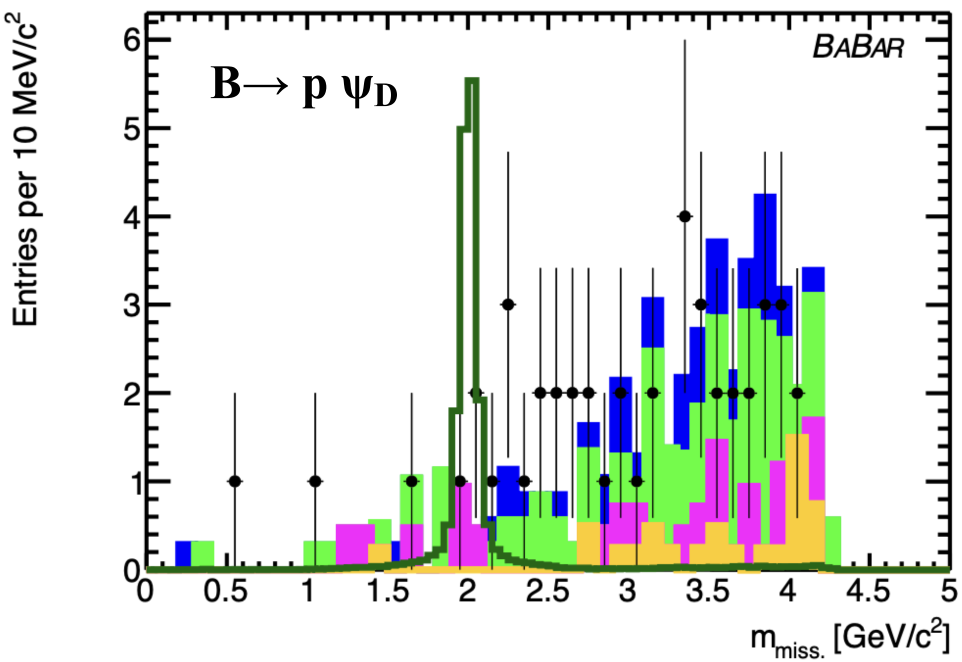

The dark sector $\psi_D$ escapes undetected, but can be inferred from the event kinematics

# Dark anti-baryon reconstruction

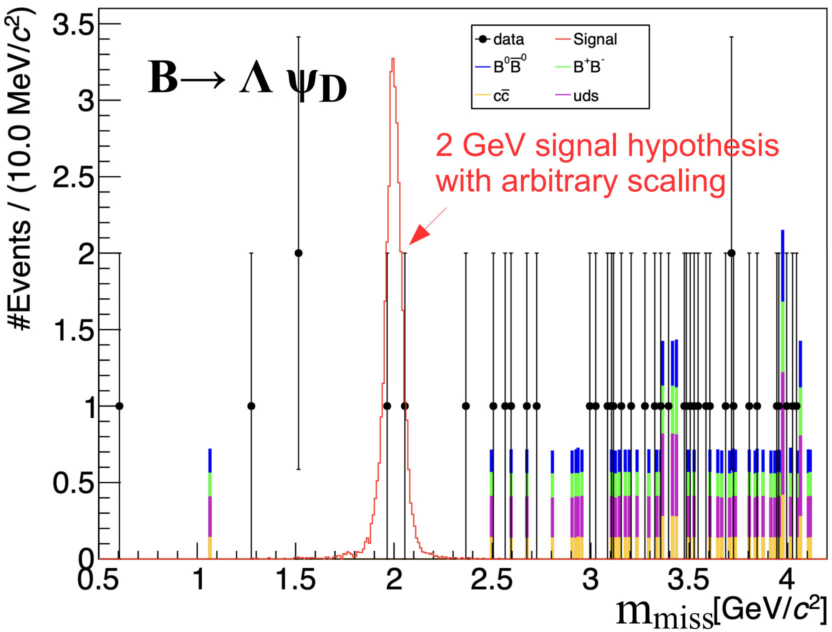
Missing energy 4-vector of "recoil" against the $\mathrm{p}$ or $\Lambda$ yields the $\psi_D$ invariant mass

$$m_{\text{miss}}c^2 = \sqrt{(E^*_{B_{\text{sig}}} - E^*_{\mathrm{p}})^2 - |\vec{\mathrm{p}}^{\,*}_{B_{\text{sig}}} - \vec{\mathrm{p}}^{\,*}_{\mathrm{p}}|^2 c^2}$$

- For $B \to p\, \psi_D$, $m_{miss}$ resolution varies from ~110 MeV/c$^2$ (low mass) to ~11 MeV/c$^2$ (high mass)
- Background estimated directly from $m_{miss}$ sideband data




46 events pass signal selection




41 events pass signal selection

Scan the recoil $m_{miss}$ distribution in steps of $\sigma(m_{miss})$ for evidence of a narrow signal peak above a smoothly varying background

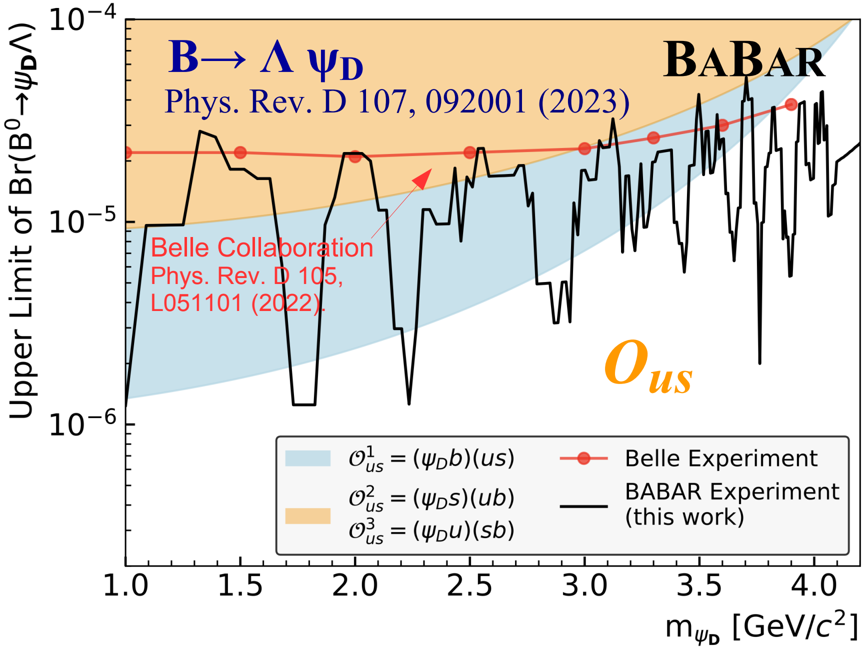
# Branching fraction limits

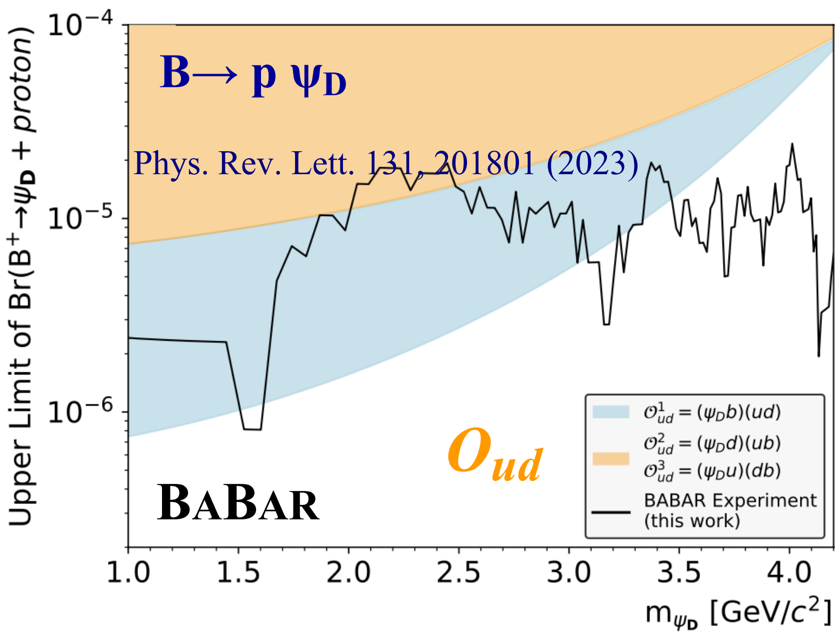
$B \to p\,\psi_D$ :

- a total of 127 mass hypotheses are tested
- largest local significance @ 3.3 GeV/c$^2$ corresponds to ~1 σ global significance

$B \to \Lambda\,\psi_D$ :

- 193 mass hypotheses are tested
- largest local significance @ 3.7 GeV/c$^2$ corresponds to ~0.4 σ global significance



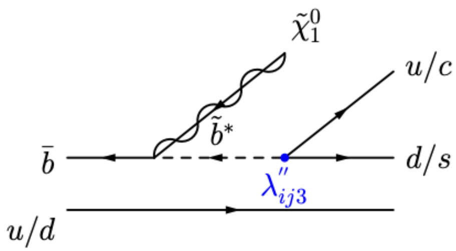

Branching fraction 90% confidence limits obtained at level of $10^{-6} - 10^{-5}$ for both modes:

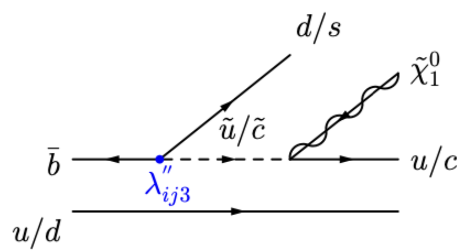
- Probes effective operators $O_{i,j} = (\psi_D b)(q_i q_j)$ with $q_i = \mathrm{u}$ and $q_j = \mathrm{d,s}$
- Results exclude a large fraction of the model parameter space

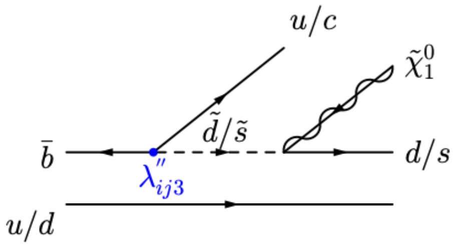
# RPV SUSY interpretation

$B \rightarrow \mathcal{B}$ + (missing energy) signature can also be generically interpreted in other new physics models

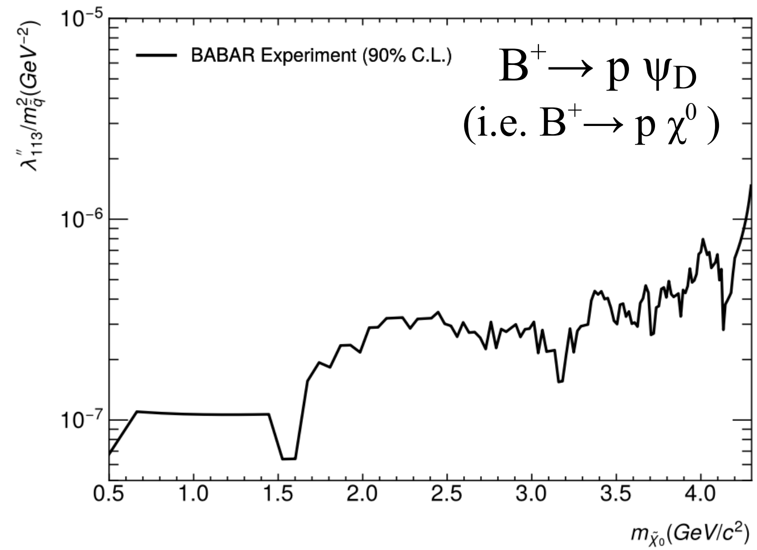
- e.g. missing neutralino in $B \rightarrow \mathcal{B} + \chi^0$ in R-Parity Violating SUSY model:

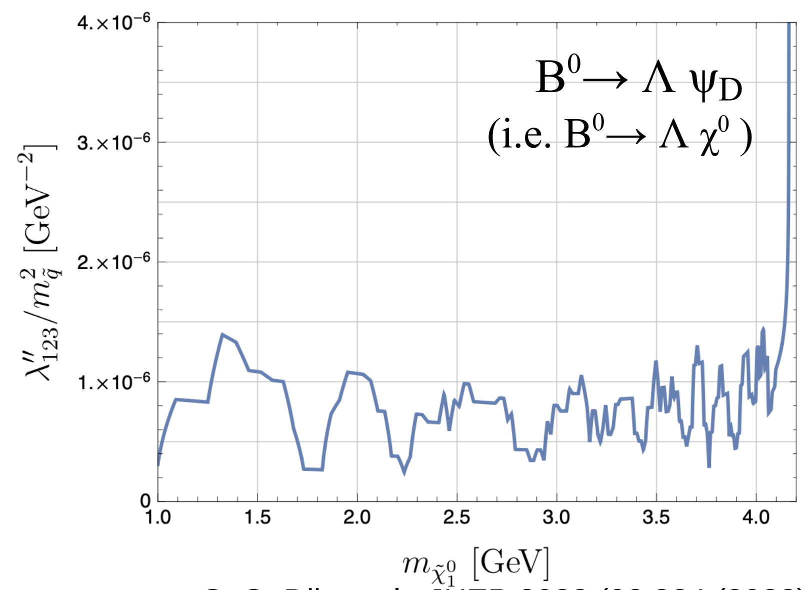



- Interpret as limits on RPV couplings $\lambda''_{113}$ and $\lambda''_{123}$




C. O. Dib et al., JHEP 2023 (02 224 (2023))

# Decay modes

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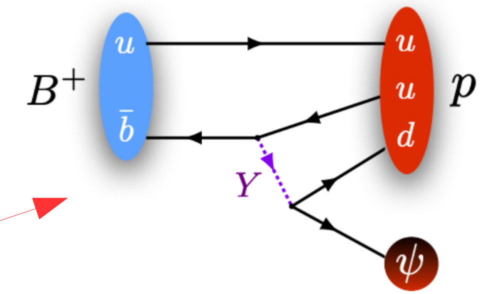


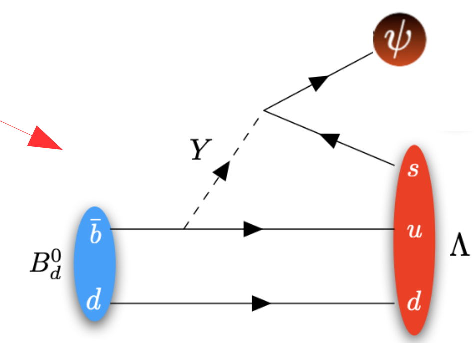


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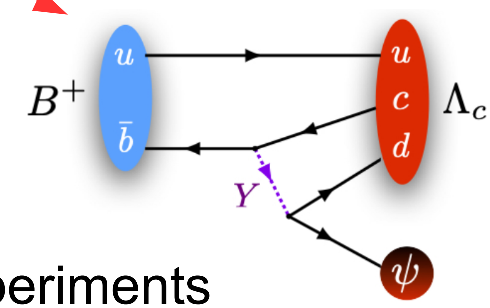


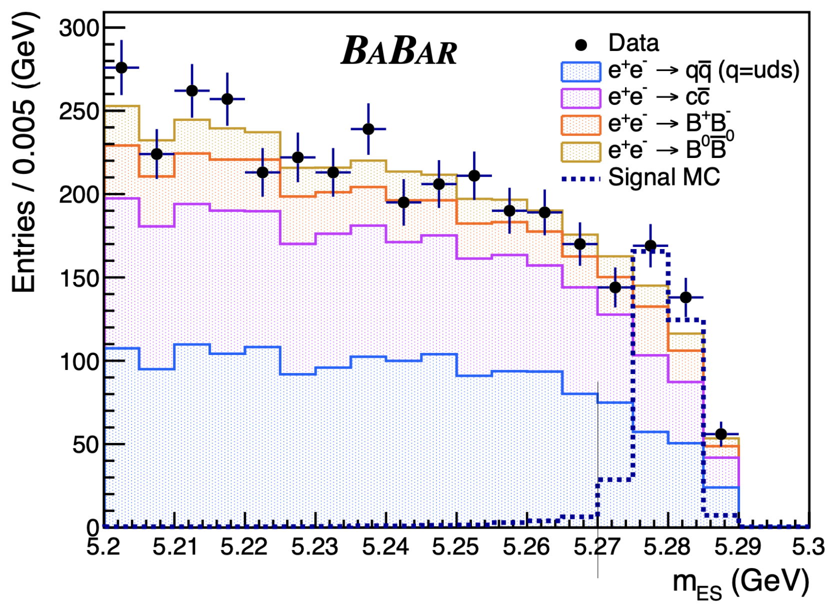

- $B^+$ and $B_d$ modes potentially accessible at B factory experiments

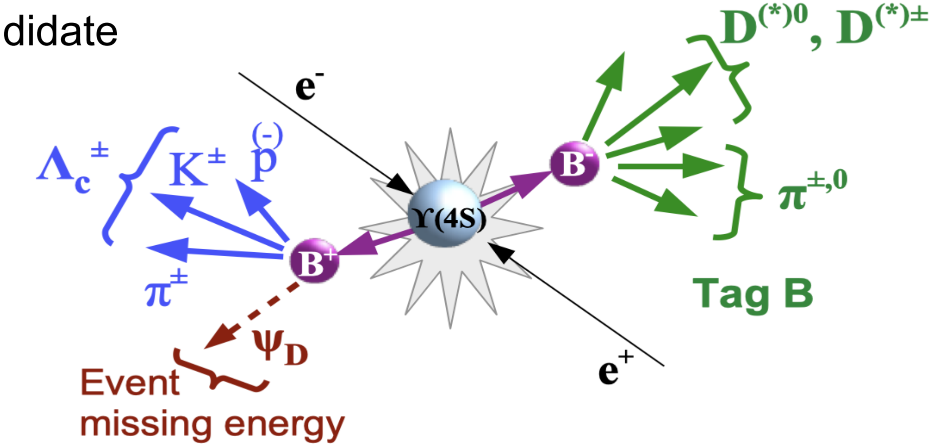
$$B^+ \rightarrow \Lambda_c^+ + \psi_D$$

# $B^+ \to \psi_D + \Lambda_c^+$

Operator $O_{cd} = \psi bcd$ can be accessed via $B^+ \to \Lambda_c^+ \psi_D$ mode

- Hadronic tag reconstruction of $B_{tag}$ with $\Lambda_c^+$ candidate reconstructed from remaining tracks
- $\Lambda_c^+$ reconstructed via $\Lambda_c^+ \to p K^- \pi^+$ (all charged tracks)



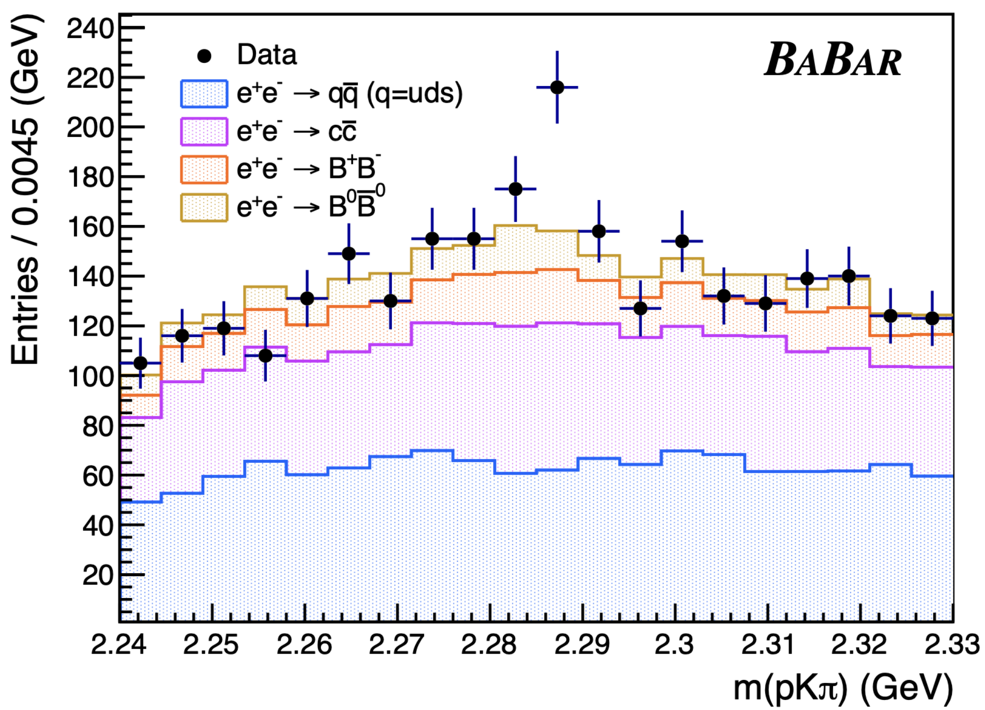

- Require exactly three high quality tracks, satisfying $\Lambda_c^+ \to p K^- \pi^+$ charge and particle ID expectations
- Backgrounds arise primarily from $q\bar{q}$ (continuum); very low background from $B \to$ baryons $+ X$;

- Analysis based on 399 $fb^{-1}$ of data (~2 x $10^8$ $B^+B^-$ events), with an additional 32 $fb^{-1}$ used for (unblinded) analysis optimization and subsequently discarded

# Signal reconstruction

Signal $\Lambda_c^+$ reconstruction is validated using $m_{ES}$ sideband region data

- Clear $\Lambda_c^+$ peak visible from continuum $q\bar{q}$ $(q = u,d,s,c)$ with an incorrectly reconstructed $B_{tag}$
- Not present in continuum MC, but enables data-driven background estimate in $m_{ES}$ signal region, as well as check of resolution of $m(pK\pi)$ in data




$\Lambda_c^+$ candidates in $m_{ES}$ sideband region

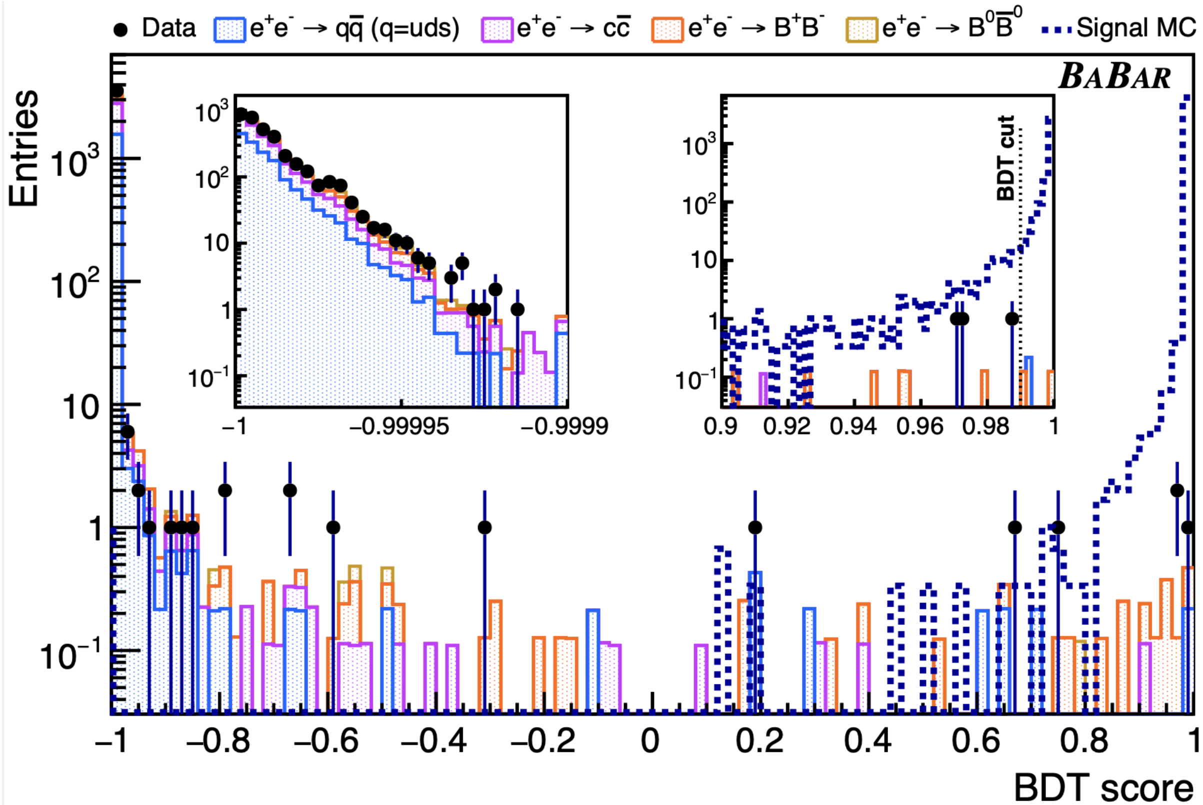
Continuum $\Lambda_c^+$ events and $B \to$ baryons$+X$ backgrounds typically have low missing energy and additional neutral particles besides the $B_{tag}$ and $\Lambda_c^+$ candidates

- Multivariate (BDT) selector to suppress remaining backgrounds
- 14 inputs, based on overall event shape, $B_{tag}$ properties, $\Lambda_c^+$ candidate properties, and additional detector activity in the event

# Background rejection

Boosted decision tree (BDT) provides extremely high suppression of remaining backgrounds with little loss of signal efficiency

- 32 fb$^{-1}$ data sample used for input validation and training, then discarded
- Signal samples spanning full kinematically accessible $\psi_D$ mass range.
- Optimization was performed blinded
- Require BDT score > 0.99




No events survive the BDT selection ( ~0.4 expected background )

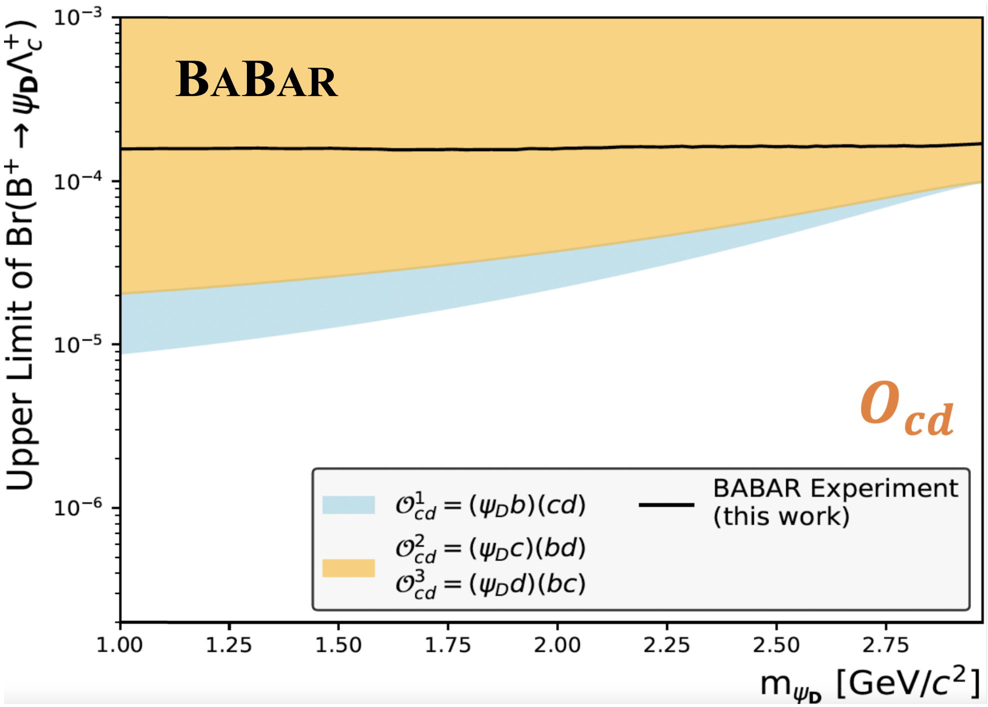
- Three events close to signal region were examined and found to be consistent with $q\bar{q}$ continuum production of $\Lambda_c^+$

# Results

Phys. Rev. D 3, L031101 (2025)

Signal significance determined as a function of $\psi_D$ mass by scanning across $m(\psi_D)$ in steps of $\sigma(m(\psi_D))$

- 4-vector of $\psi_D$ obtained from inferred $B_{sig}$ kinematics in range
  $0.94 < m(\psi_D) < 2.99$ GeV/c$^2$
- $m(\psi_D)$ resolution varies from 60 – 20 MeV/c$^2$ as a function of mass




Branching fraction limit @ 90% CL
$B(B^+ \to \Lambda_c^+ \psi_D) < (1.6 – 1.7) \times 10^{-4}$
over kinematically accessible mass range

Exclusive $B^+ \to \Lambda_c^+ \psi_D$ branching fraction expected to range from 10% - 100% of inclusive $B(B^+ \to \Lambda_c^+ \psi_D X)$, depending on mass

- Substantial new constraint on model parameter space for $O_{cd}$ operator

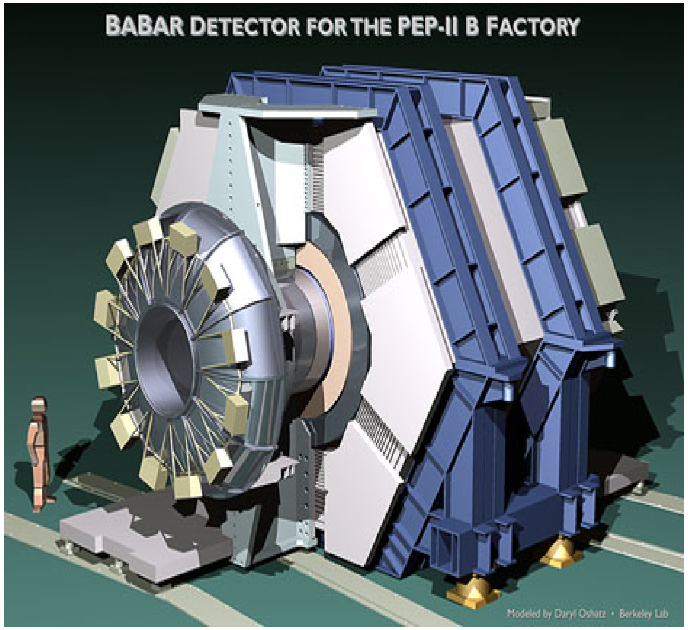
# Conclusion

Clean B factory environment is extremely well suited to searches for light dark sector signatures, and precision probes of new physics:

- Two 2023 BABAR papers substantially reduce parameter space for B-mesogenesis operators $O_{ud} = \psi bud$ and $O_{us} = \psi bus$
- 2025 results for $B^+ \to \Lambda_c^+ \psi_D$ search constrain operator $O_{cd} = \psi bcd$

| | |
|---|---|
| $B^0 \to \Lambda\, \psi_D$ | Phys. Rev. D 107, 092001 (2023) |
| $B^+ \to p\, \psi_D$ | Phys. Rev. Lett. 131, 201801 (2023) |
| $B^+ \to \Lambda_c^+\, \psi_D$ | Phys. Rev. D 3, L031101 (2025) |

Unique **BABAR** data set remains productive more than 17 years after the end of data taking!



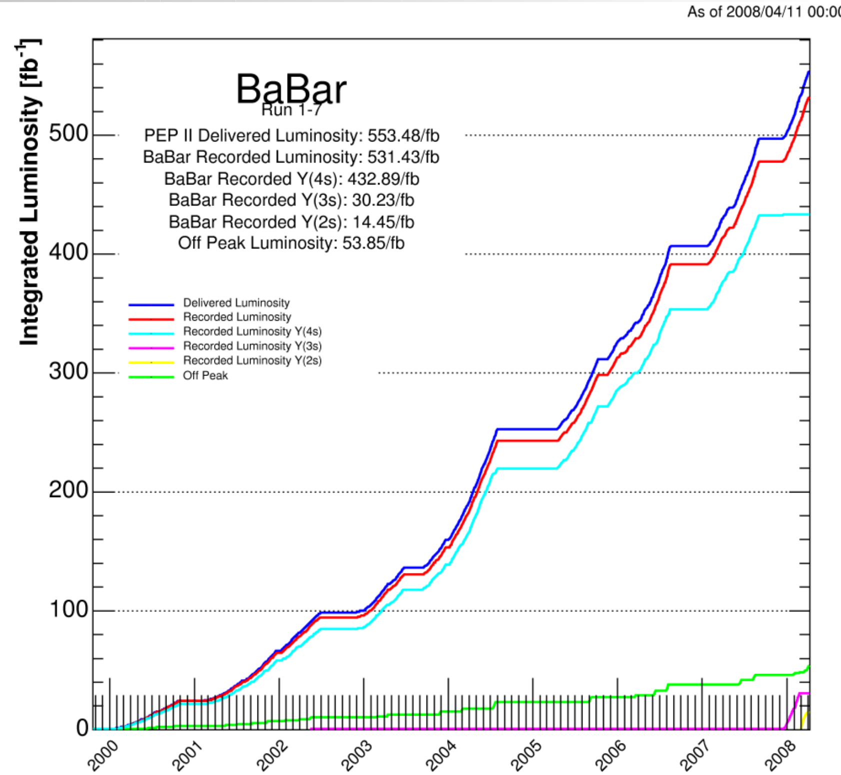
# Extra Material

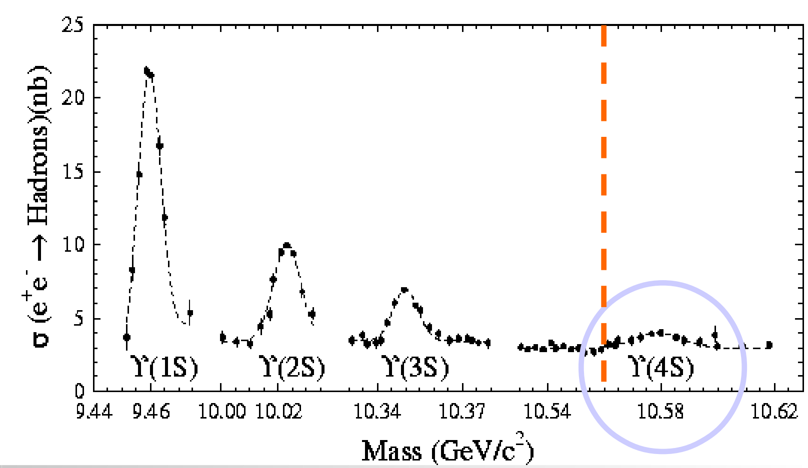
# BABAR data sets

**BABAR** collected data from 1999-2008

- 432 fb$^{-1}$ $\Upsilon(4S)$ "onpeak"
  (~470 x $10^6$ $B\bar{B}$ pairs)
- 53 fb$^{-1}$ non-resonant "offpeak"
  - collected ~40MeV below $\Upsilon(4S)$ peak
- Samples of "narrow $\Upsilon$" events collected during last few months of running:
  - 122 x $10^6$ $\Upsilon(3S)$ decays
  - 99 x $10^6$ $\Upsilon(2S)$ decays

| Process | Cross section (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 |



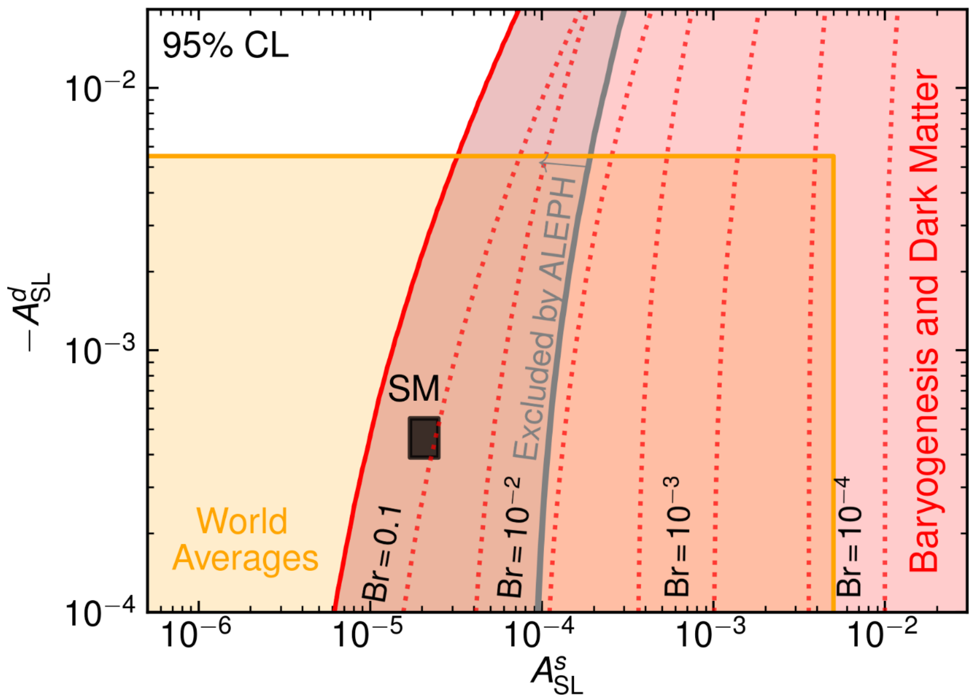



# $B^+ \rightarrow \Lambda_c^+ + \psi_D$

BDT inputs:

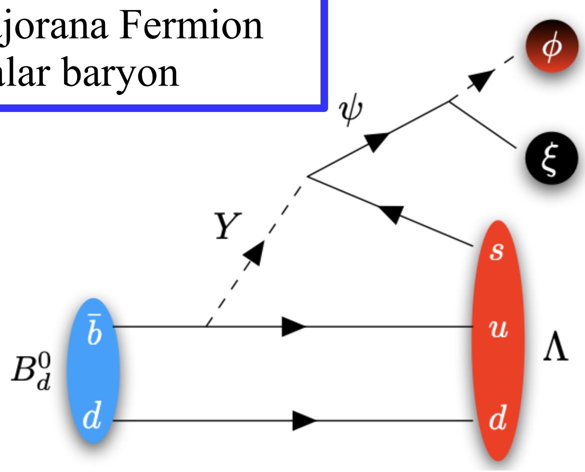
| Input | Type | Description |
|---|---|---|
| $R_2$ | Event shape | Ratio of the second to the zeroth Fox-Wolfram moment [20] computed using all tracks and neutral clusters |
| purity | $B_{\rm tag}$ | Fraction of correctly reconstructed $B$ mesons in each $B_{\rm tag}$ mode |
| intpurity | $B_{\rm tag}$ | Integrated purity of the overall $B_{\rm tag}$ sample as a function of the value of a cut applied on purity |
| $B_{\rm mode}$ | $B_{\rm tag}$ | Reconstructed decay mode of the $B_{\rm tag}$ |
| $m_{\rm ES}$ | $B_{\rm tag}$ | $B_{\rm tag}$ invariant mass |
| $\Delta E$ | $B_{\rm tag}$ | Difference between the $B_{\rm tag}$ energy and the beam energy |
| $B_{\rm thrust}$ | $B_{\rm tag}$ | The magnitude of the $B_{\rm tag}$ thrust |
| $B_{\rm thrustZ}$ | $B_{\rm tag}$ | Component of the $B_{thrust}$ along the $z$-axis (i.e. the $e^+e^-$ collision axis) |
| $m_{pK^+\pi^-}$ | $\Lambda_c^+$ | Reconstructed invariant mass of the $\Lambda_c^+$ candidate |
| $\chi^2$ | $\Lambda_c^+$ | $\chi^2$ of the fit of the $\Lambda_c^+$ candidate |
| $N_{\rm neut}$ | ECL | Total number of additional neutral clusters |
| $N_{\pi^0}$ | ECL | Number of additional $\pi^0$ candidates |
| $E_{\rm extra}$ | ECL | Sum of the energies of all additional neutral clusters |
| $\cos\theta_{\psi_D}$ | $\psi_D$ | Cosine of the polar angle of the missing energy 4-vector in the laboratory frame. |

- Baryon number asymmetry depends on the level of CP violation in B mixing, and on the branching fraction to dark baryons
- Dark baryon mass must be large enough to protect against proton decay but small enough to permit production from B meson decays




$\Phi$ = heavy scalar field
$\psi_D$ = dark fermion
Y = TeV scale mediator
$\xi$ = Majorana Fermion
$\varphi$ = scalar baryon

$$Y_{\mathcal{B}} \simeq 8.7 \times 10^{-11} \frac{\mathrm{Br}(B \to \psi\, \mathcal{B}\, \mathcal{M})}{10^{-3}} \sum_q \alpha_q \frac{A^q_{\mathrm{SL}}}{10^{-3}}$$




- Dark baryon must decay rapidly into other dark sector particles (i.e. astronomical dark matter), to avoid decay to SM particles

# Dark sector and BSM @

Dark matter may carry charges for non-SM gauge interactions:

- Effective Field Theory (EFT) provides a number of "portals" to access this dark sector:

**Darkonium** :
Phys. Rev. Lett. 128 021802 (2022)

**Axion-like particles** :
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)

SM ⟷ Dark Sector

Portal mediators

$$\mathcal{L} = \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{(\mathrm{SM})} \mathcal{O}_l^{(\mathrm{med})} = \mathcal{L}_{\mathrm{portals}} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

$$= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

Vector portal — Higgs portal — Neutrino portal

## Dark sector @ BaBar:

- Production of on-shell dark bosons via $e^+e^- \rightarrow \gamma Z'$ "**radiative**" and $e^+e^- \rightarrow f\,f\,Z'$ "**-strahlung**" processes
- Light dark sector particles can be produced in **decays** of B and D mesons

**Extensive BaBar program of dark sector and BSM searches**

# Axion-Like Particles

Many extensions of SM include spontaneously-broken global symmetries, resulting in pseudo-Goldstone bosons known as **Axion-Like Particles (ALPs)**

- Can potentially help resolve issues of naturalness of SM parameters but may also serve as mediators to dark sectors
- ALPs (a) couple primarily to pairs of SM gauge bosons.

coupling

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

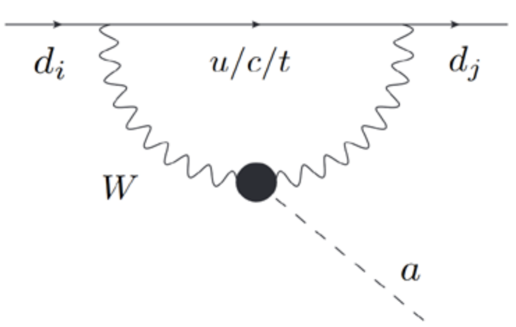
$SU(2)_W$ field strength tensor

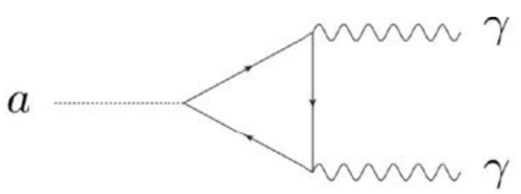
E. Izaguirre et al., PRL 118 (2017) 111802

Can be produced in FCNC B decay processes, specifically $\mathbf{B \to Ka}$

- $\mathbf{a \to \gamma\gamma}$ with nearly 100% BF for $m(a) < m(W)$
- For low axion mass and small coupling, the axion lifetime can become “long”, i.e. non-prompt.

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



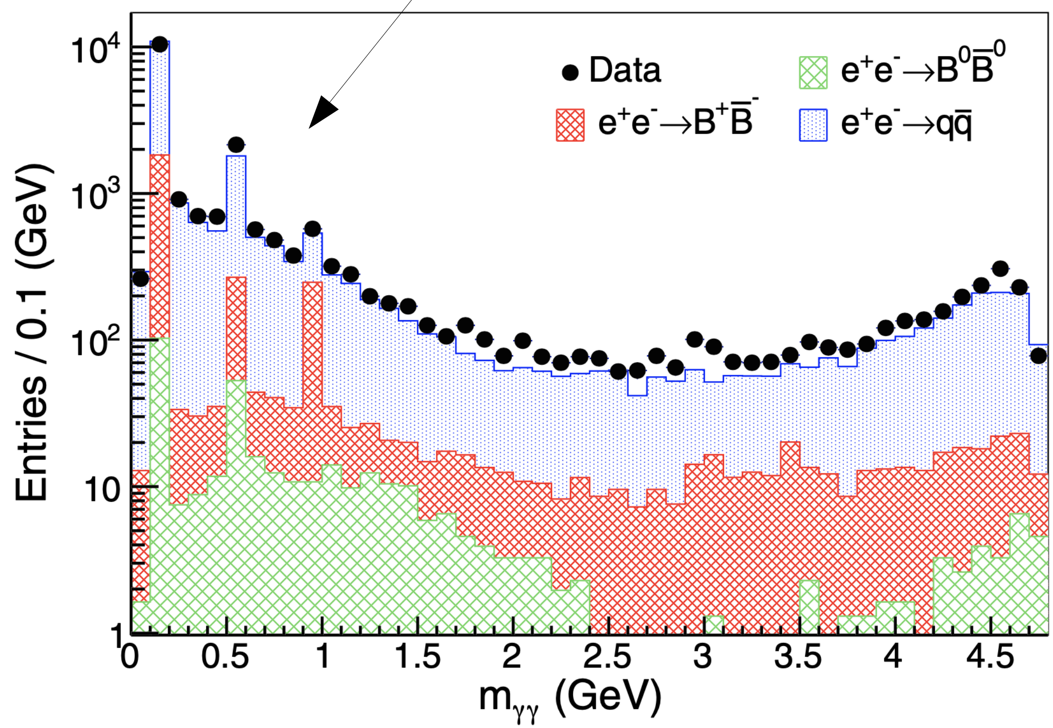
# Axion-Like Particles

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

BABAR searches for ALPs in $B^+ \rightarrow K^+ a$ $(a \rightarrow \gamma\gamma)$ in 4.72 x $10^8$ $B\bar{B}$ pairs (424 $fb^{-1}$) collected at the $\Upsilon(4S)$ energy.

- Exclusively reconstruct $B$ meson via well-identified $K$ and photons, then "bump hunt" in the reconstructed $\gamma\gamma$ mass
- Kinematic fit to improve resolution
- Boosted decision trees using kinematic variables from "rest of event" to suppress continuum $e^+e^- \rightarrow qq$ $(q = u,d,s,c)$ and $BB$ backgrounds
- Analysis optimized and validated on 8% of data set (subsequently discarded), then search performed on remainder of (blinded) dataset

peaking contributions from $\pi^0$, $\eta$, $\eta'$ $\eta_c$



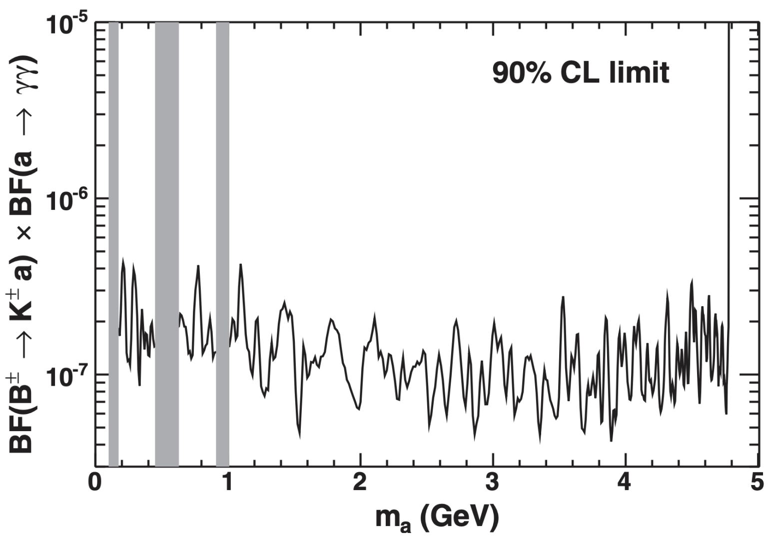
# Axion-Like Particles

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

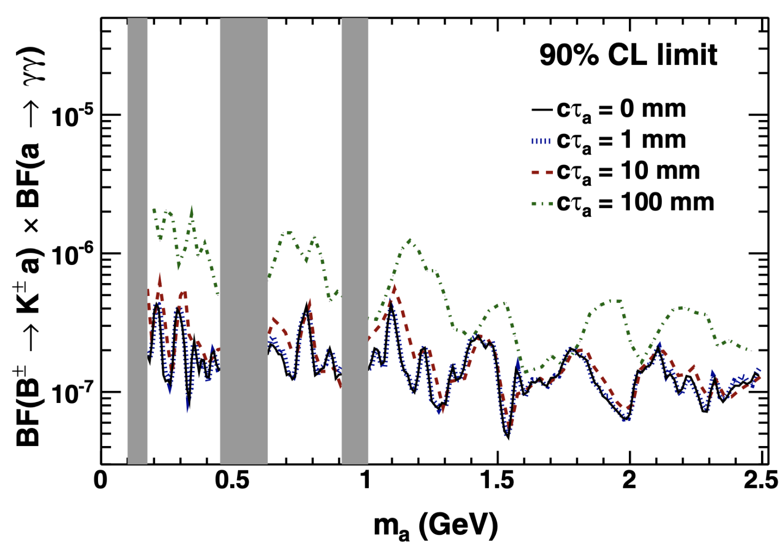
Scan $m_{\gamma\gamma}$ with steps equal to the signal mass resolution (~ 8 – 14 MeV)

- 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

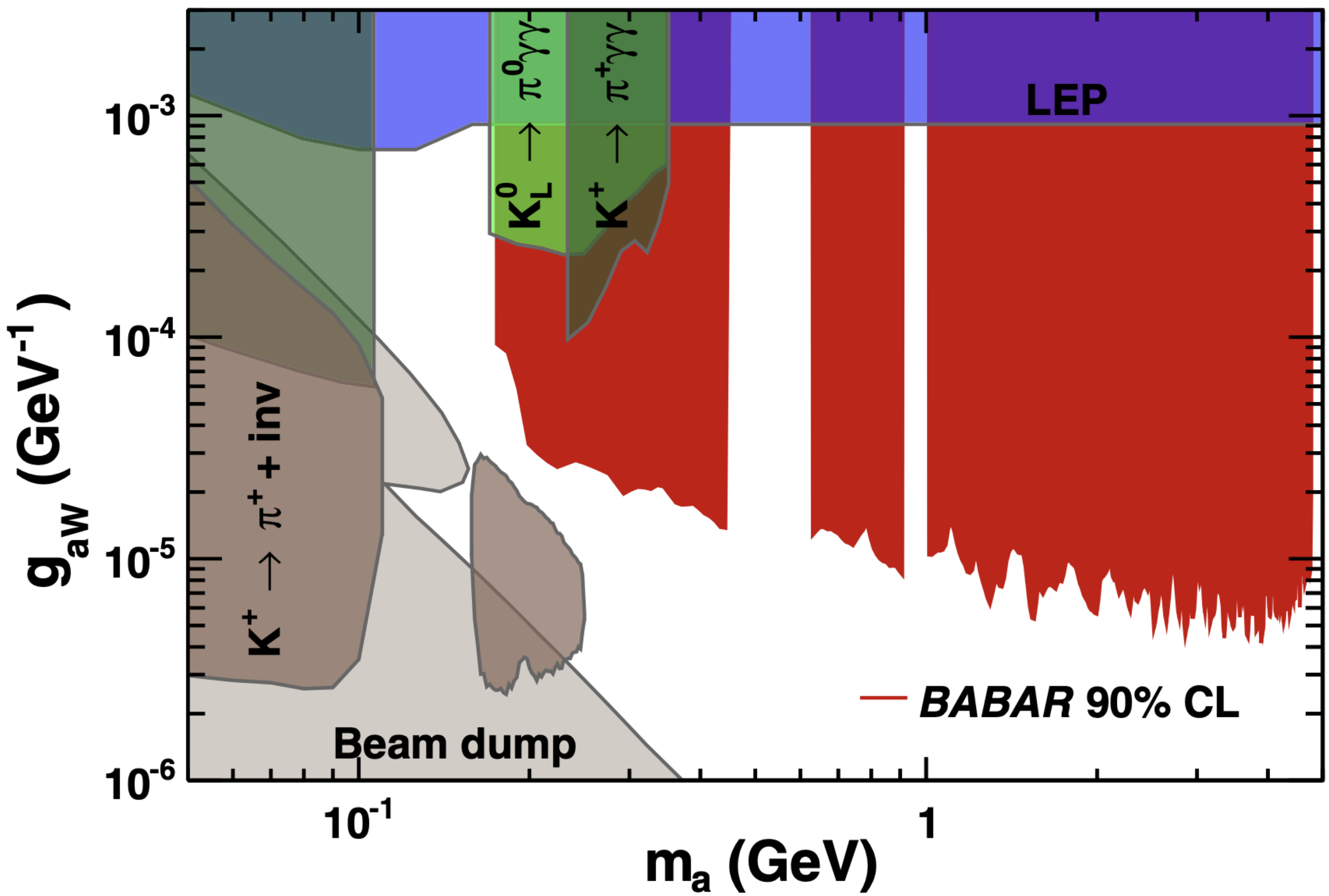



In low mass region ($m_{\gamma\gamma}$ < 2.5 GeV) the signal sensitivity is also assessed for non-prompt signal hypotheses: $c\tau$ = 1, 10, 100mm

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

# Axion-Like Particles

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




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

- Improvements of up to two orders of magnitude over previous limits

# Search for Darkonium

Self-interacting dark matter, i.e. dark matter bound states can arise in simple dark photon models in which the A' couples strongly to the dark matter fermion ($\chi$) via coupling $\alpha_D$

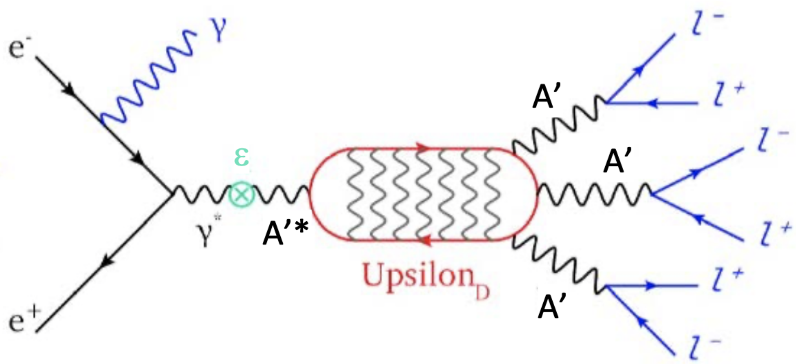
H. An et al., PRL 116 (1026) 151801

- Two lowest bound states are $\eta_D$ ($J^{PC} = 0^{-+}$) and $\Upsilon_D$ ($J^{PC} = 1^{--}$)
- Dark photon A' mixes with SM photon via kinetic mixing with strength $\varepsilon$

Produced via $e^+e^- \rightarrow \gamma\,\Upsilon_D$, with

$\Upsilon_D \rightarrow A'A'A'$ and $A' \rightarrow f\bar{f}$ ( $f = e, \mu, \pi$)

- Dark photon lifetime can be long for small masses and small kinetic mixing $\varepsilon$ hence prompt and displaced vertex signatures
- BABAR search in six-track final state in 514 fb$^{-1}$



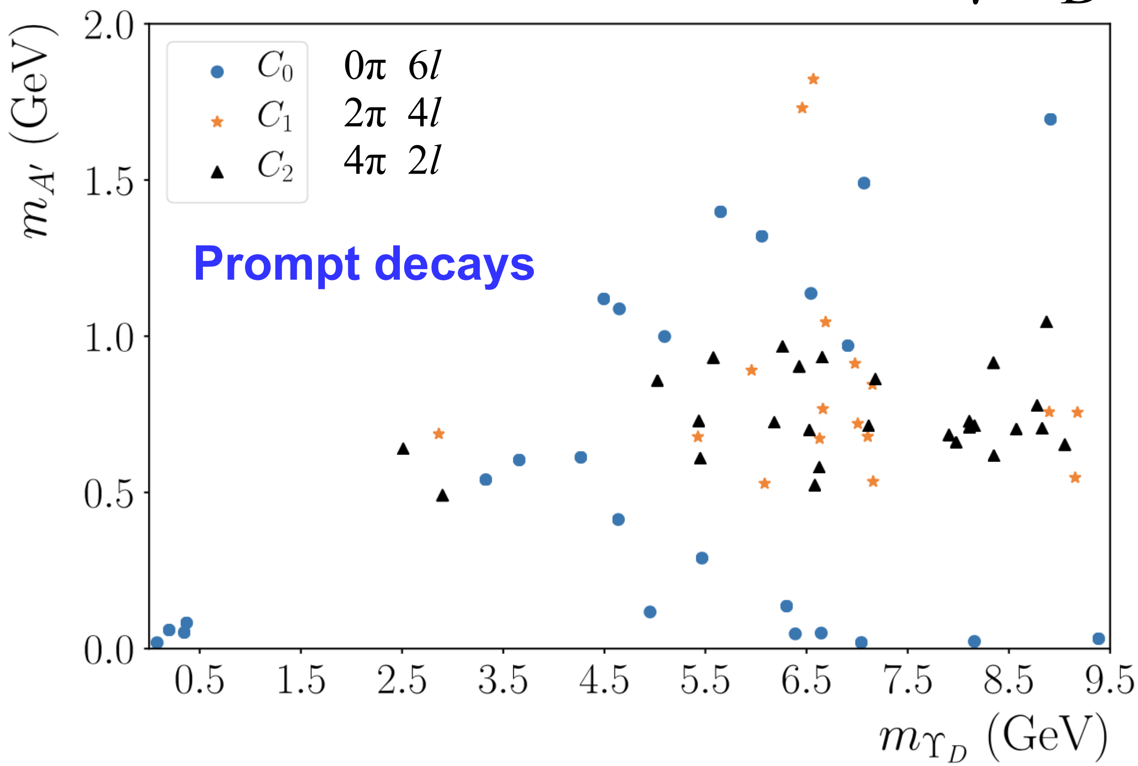
# Search for Darkonium

PRL 128, 021802 (2022)

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

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

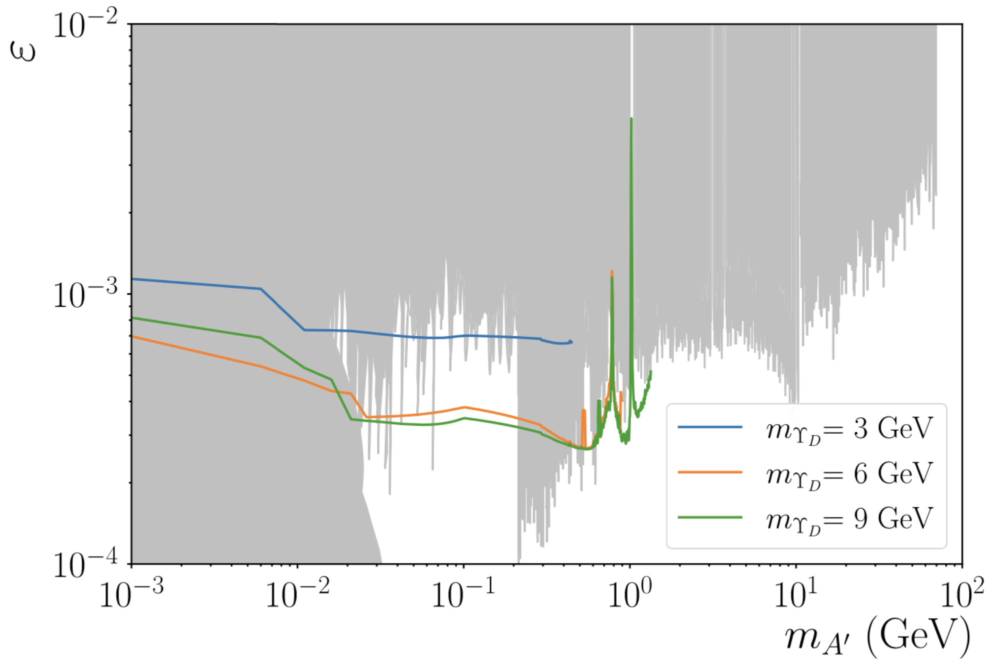
- Reconstruct $\Upsilon_D$ mass
- ISR photon may or may not be detected, but recoil mass against $\Upsilon_D$ should be consistent with zero
- MVA used to suppress backgrounds
- Scan $m(\Upsilon_D)$ - $m(A')$ for evidence of peaks

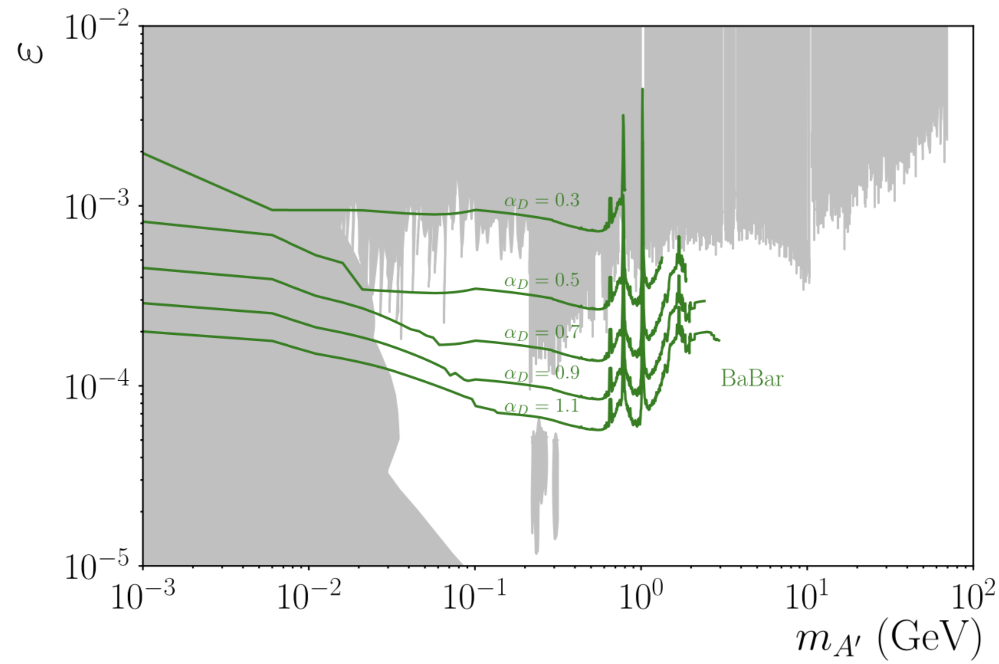



No significant signals observed in either prompt or displaced decay searches

# Search for Darkonium

PRL 128, 021802 (2022)




90% C.L. Upper limits placed on the kinetic mixing parameter $\varepsilon$

- As a function of m(A')
- For different values of $m(\Upsilon_D)$ and $\alpha_D$

# Dark sector and BSM @

| | |
|---|---|
| $B^+ \to \Lambda_c^+ \psi_D$ | Phys. Rev. D 111 (2025) 3, L031101 |
| $B^+ \to p\, \psi_D$ | Phys. Rev. Lett. 131, 201801 (2023) |
| $B^0 \to \Lambda\, \psi_D$ | Phys. Rev. D 107, 092001 (2023) |

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

Darkonium
Phys. Rev. Lett. 128 021802 (2022)

Axion-like particles
Phys. Rev. Lett. 128, 131802 (2022).

Dark Leptophilic scalar
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Dark Higgs bosons
Phys. Rev. Lett. 108, 211801 (2012)

Search for heavy neutral leptons in $\tau$ decays
Phys. Rev. D 107, 5, 052009 (2023)

Search for LFV in $\Upsilon(3S) \to e\, \mu$
Phys. Rev. Lett. 128, 091804 (2022)

Lepton universality in $\Upsilon(3S)$ decays
Phys. Rev. Lett .125, 241801 (2020)

Rare and forbidden D decays
Phys. Rev. Lett. 124, 071802 (2020)

Search for LFV in $D^0 \to X^0 e^+ \mu^-$
Phys. Rev. D 101, 112003 (2020)