Recent dark sector results from the BABAR experiment

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On behalf of the BABAR Collaboration

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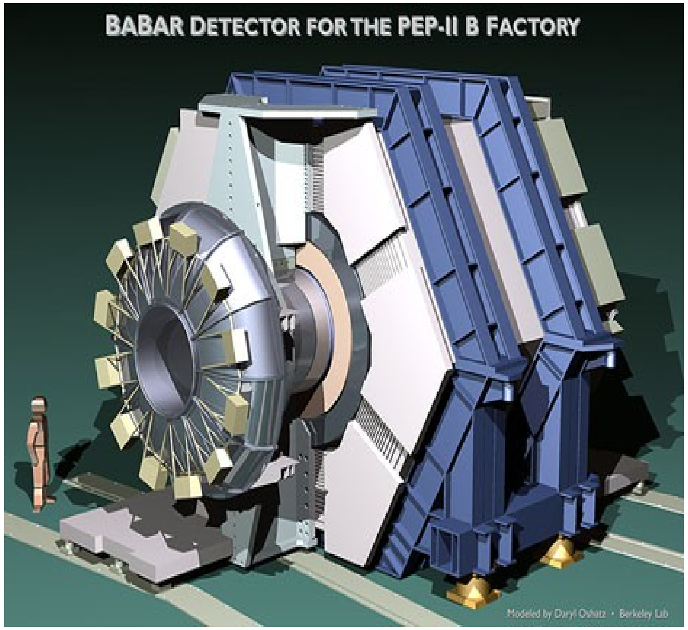
INSTITUTE OF PARTICLE PHYSICS

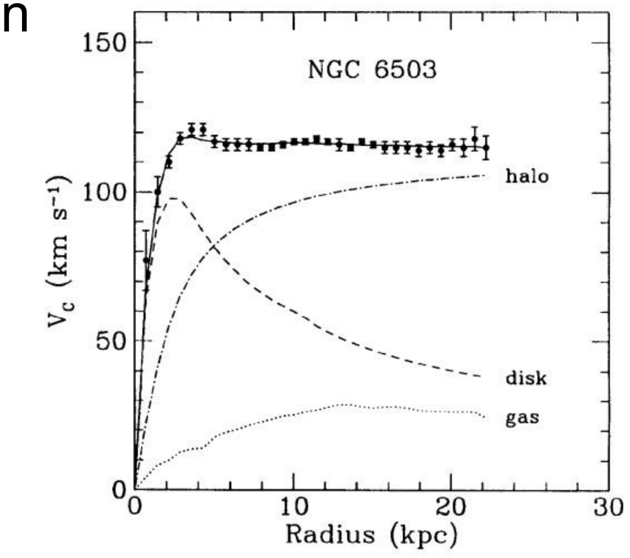
Outline



- B-mesogenesis 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)
  - $B^+ \rightarrow \Lambda_c^+ + \psi_D$ Submitted to Phys. Rev. D Lett.

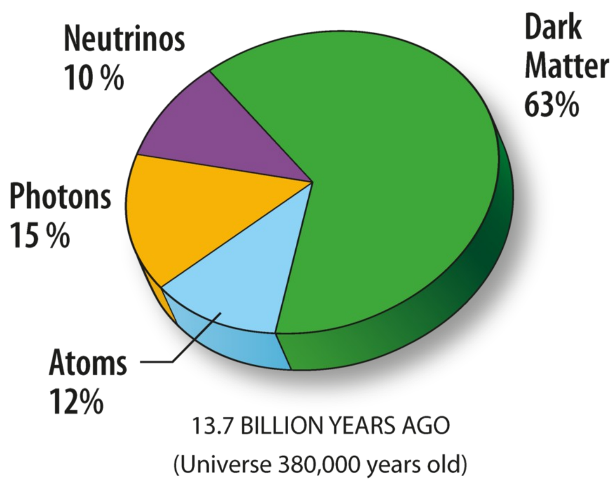
Dark matter and the BAU

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



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



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

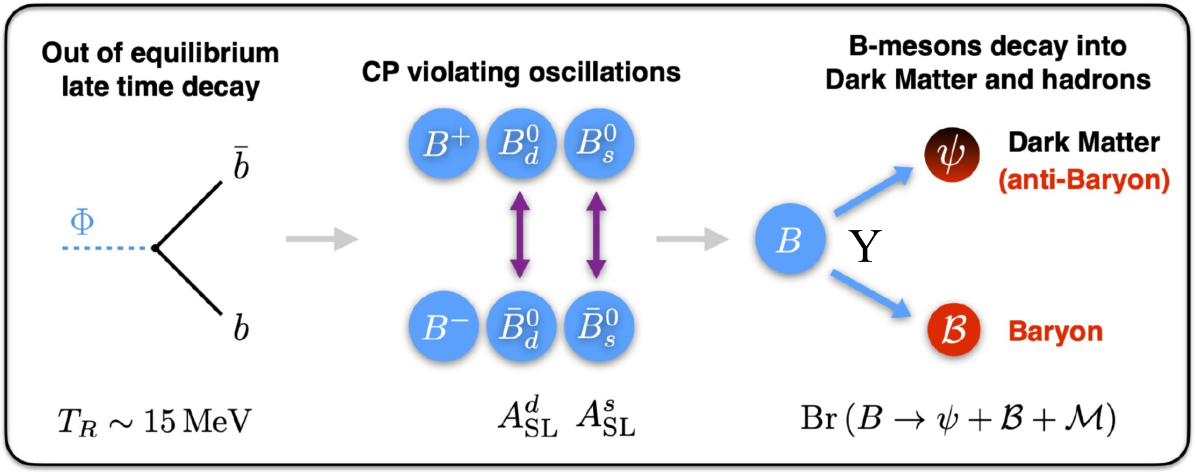
B Mesogenesis

Possible mechanism to explain dark matter abundance and BAU:

- **Baryon number conservation includes both visible and dark sector**
- Postulates the existence of a light dark-sector anti-baryon and a TeV-scale color-triplet bosonic mediator (Y)

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

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



- 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 ψ_D (+ mesons)

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

- Experimentally testable predictions of $\mathbf{B} \longrightarrow \psi_D + \mathcal{B}$ (+ $\mathcal{M}$)

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 ψ_D

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
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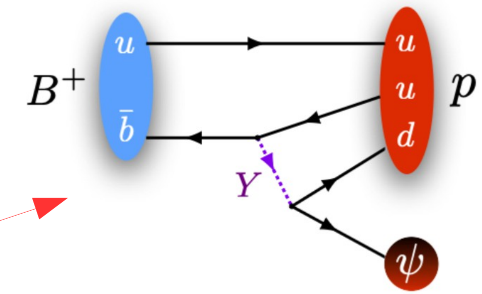
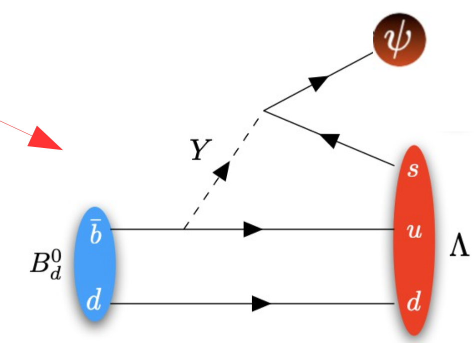
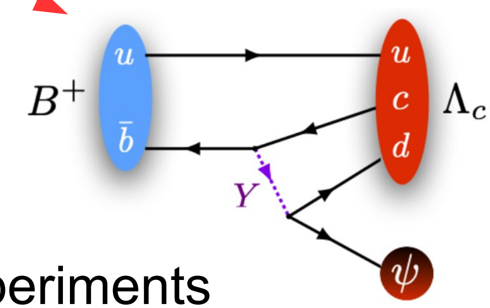
	B_s	$\psi + \Xi^0\,(uss)$	4025.0
	B^+	$\psi + \Sigma^+\,(uus)$	4090.0
	Λ_b	$\bar{\psi} + K^0$	5121.9
$\mathcal{O}_{cd} = \psi\, b\, c\, d$ $\bar{b} \to \psi\, c\, d$	B_d	$\psi + \Lambda_c + \pi^-\,(cdd)$	2853.6
	B_s	$\psi + \Xi_c^0\,(cds)$	2895.0
	B^+	$\psi + \Lambda_c^+\,(dcu)$	2992.9
	Λ_b	$\bar{\psi} + \overline{D}^0$	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







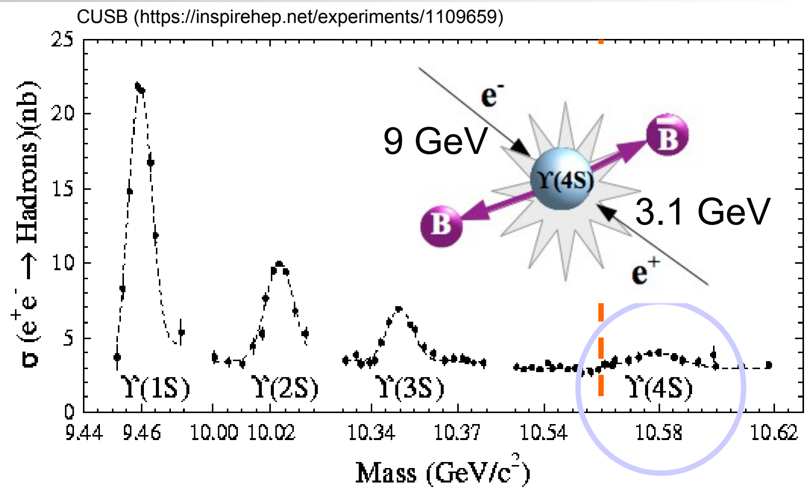
Expect only one operator to dominate

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

BABAR experiment

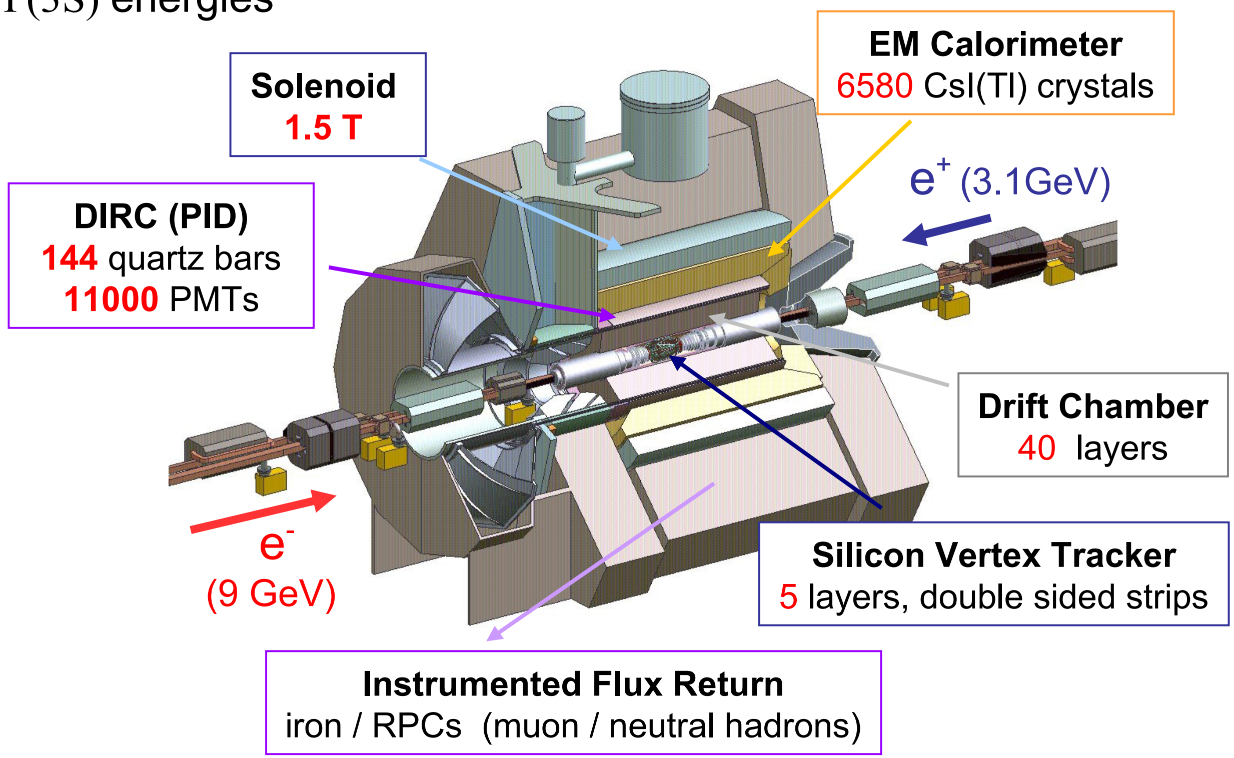
Asymmetric B Factory experiment at the SLAC National Accelerator Laboratory

- **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



Dark sector and BSM @ [BaBar logo]

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:

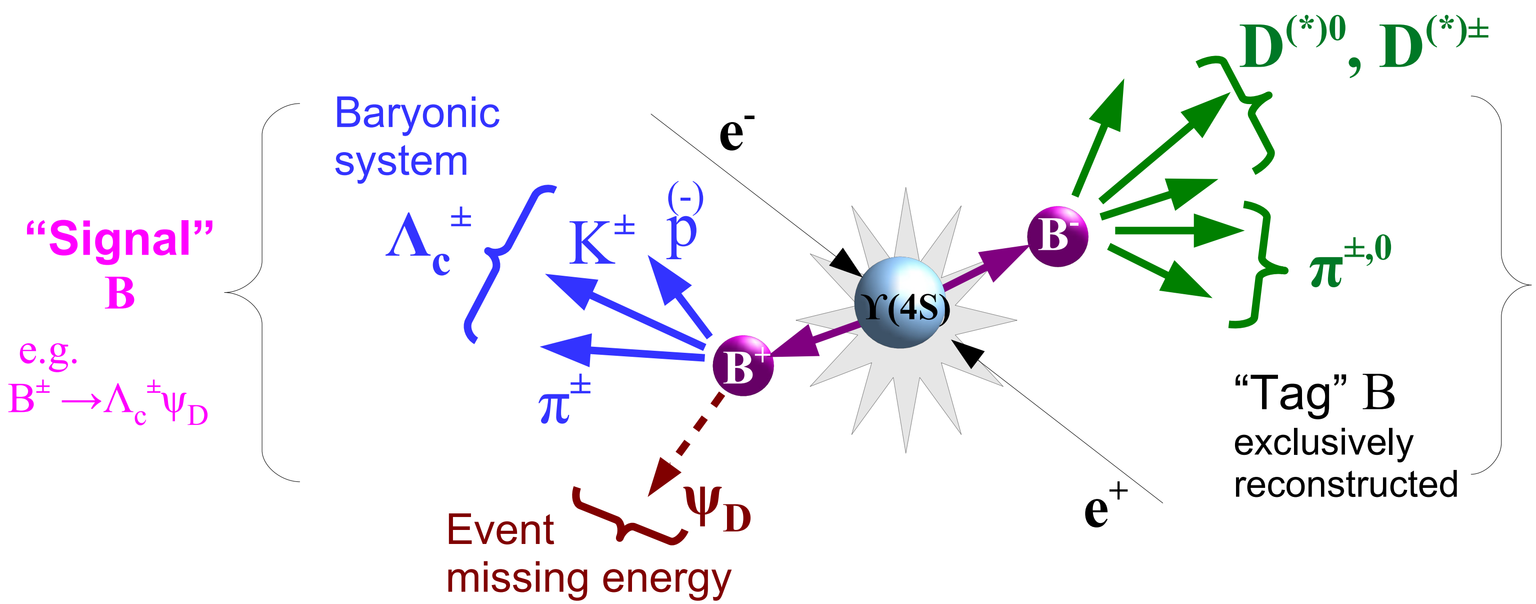
- Production of on-shell dark bosons via $e^+e^- \to \gamma Z'$ "**radiative**" and $e^+e^- \to f\,f\,Z'$ "**-strahlung**" processes
- Light dark sector particles can be produced in **decays** of B and D mesons

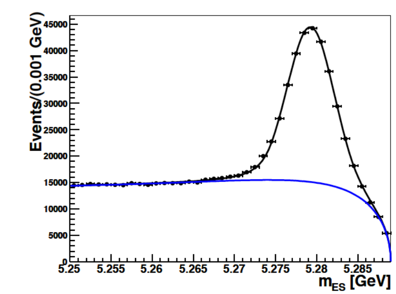
Extensive BABAR program of dark sector and BSM searches

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:





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

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

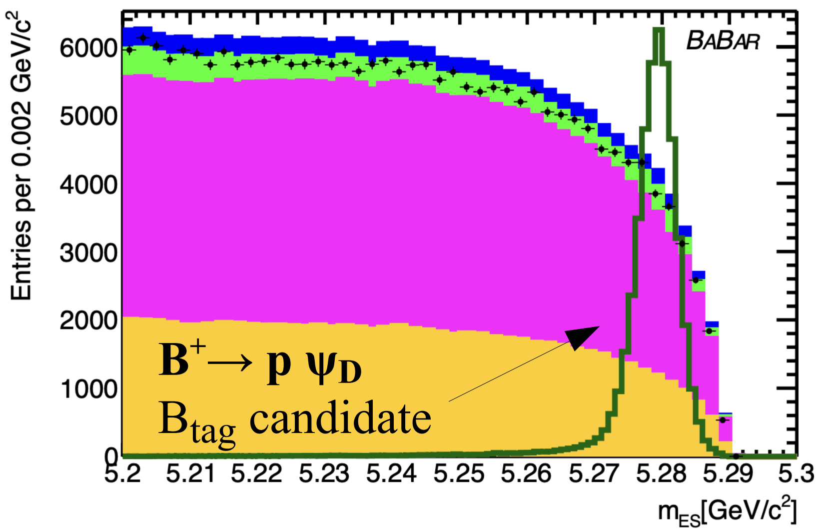
Hadronic tag reconstruction method extensively used for semileptonic/leptonic decay studies and rare/forbidden decay searches

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

and

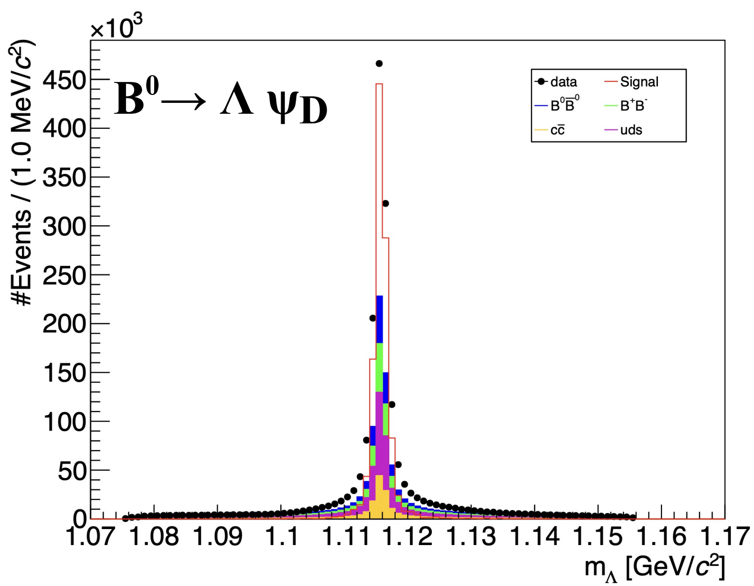
$$B^0 \rightarrow \Lambda + \psi_D$$

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

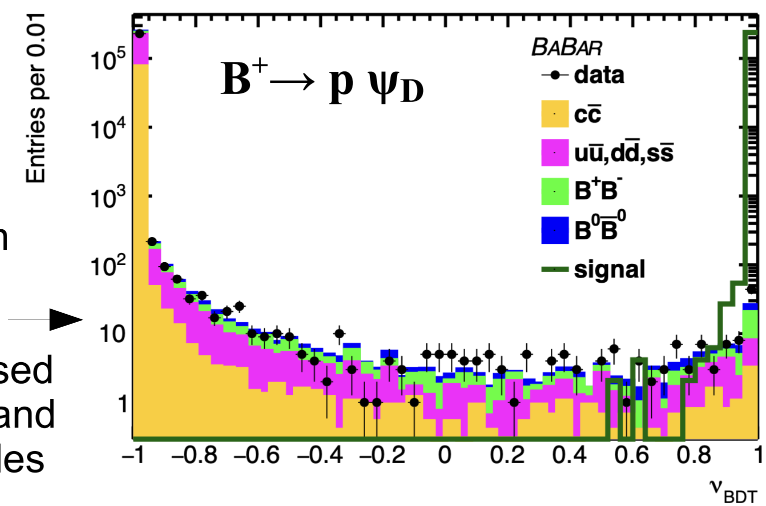


Reconstruct accompanying $\overline{B}$ meson from $\Upsilon(4S) \rightarrow B^+B^-$ and (or $B^0\overline{B}^0$) and look for signal signature in the remainder of the event:

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



- Boosted decision tree suppresses continuum backgrounds based on event shape and kinematic variables



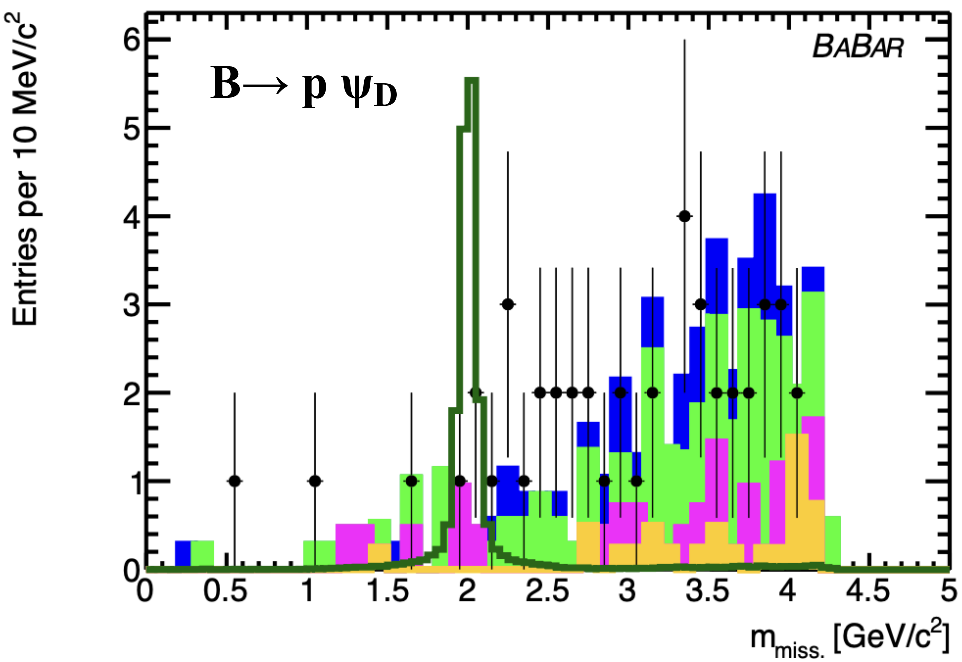
The dark sector ψ_D escapes undetected, but can be inferred from the event kinematics

Dark anti-baryon reconstruction

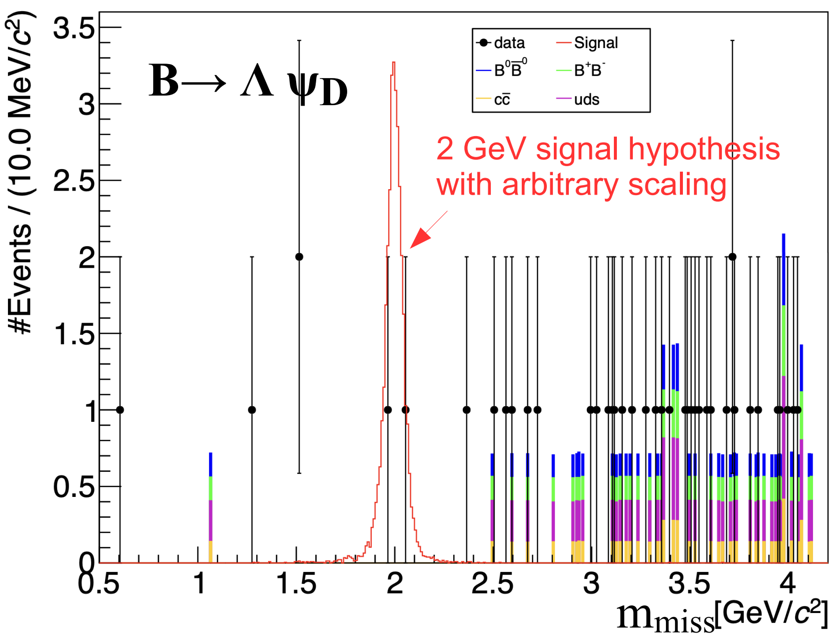
Missing energy 4-vector of "recoil" against the p or Λ yields the ψ_D invariant mass

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

- 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

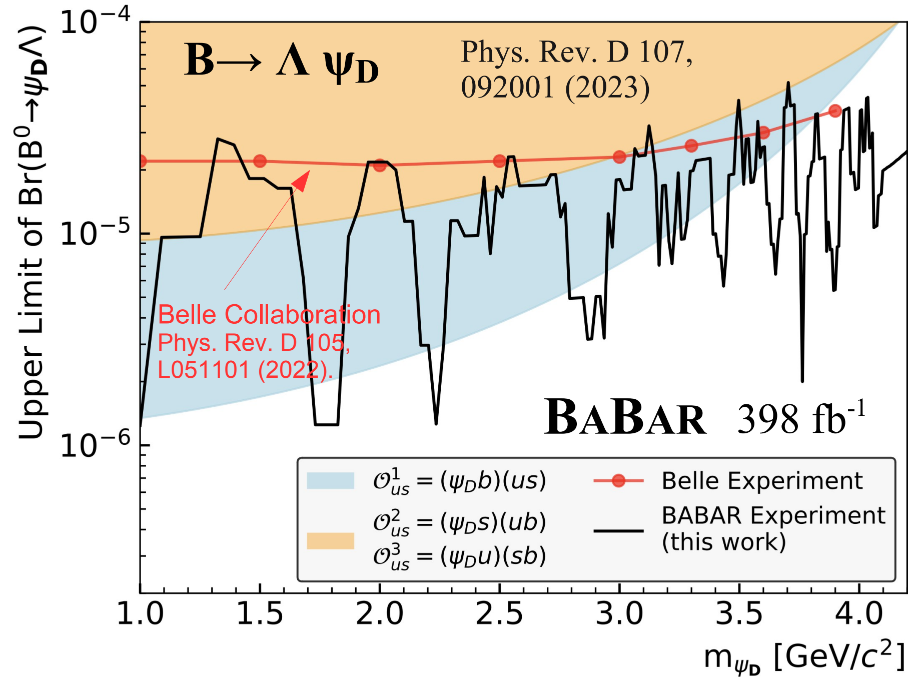
Branching fraction limits

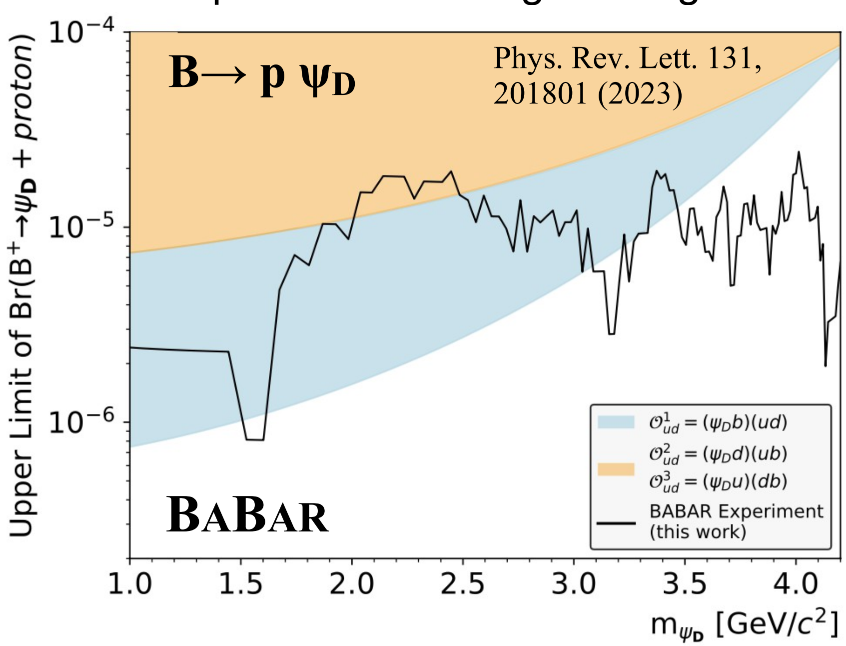
$B \rightarrow p\,\psi_D$:

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

$B \rightarrow \Lambda\,\psi_D$:

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





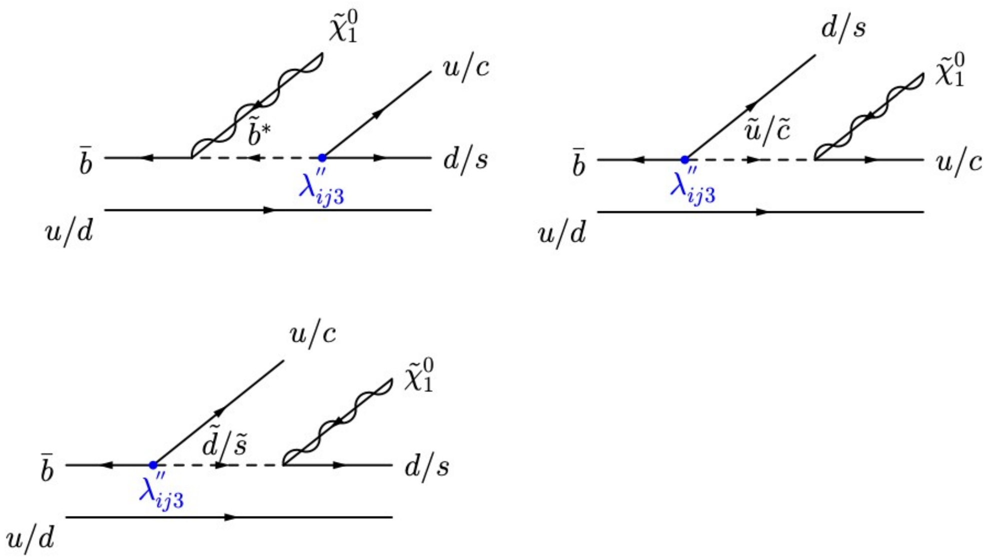
Branching fraction 90% confidence limits obtained at level of 10^{-6} – 10^{-5} for both modes:

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

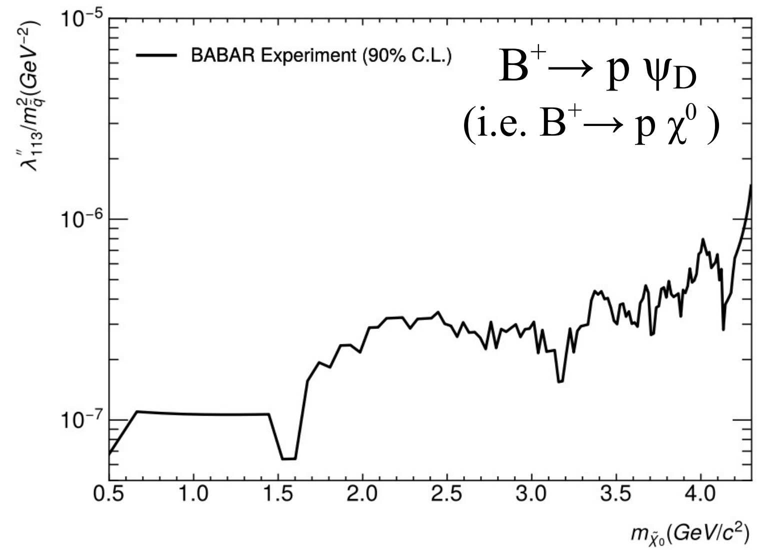
RPV SUSY interpretation

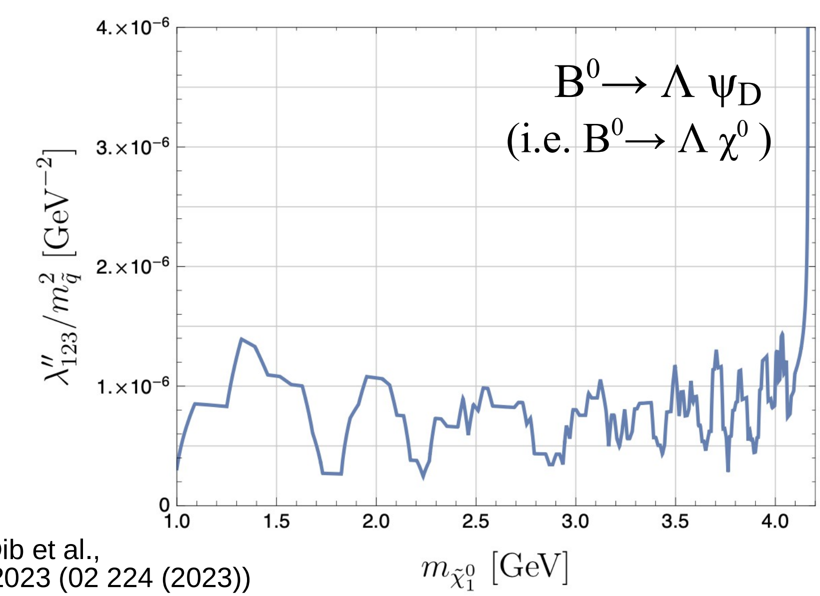
$B \rightarrow \mathcal{B}$ + (missing energy) signature can also be generically interpreted in other new physics models

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



- Results in limits on RPV coupling λ''_{113} and λ''_{123}





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

Decay modes

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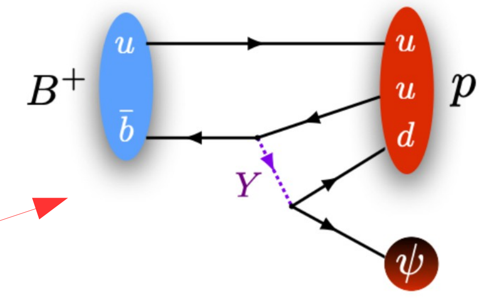

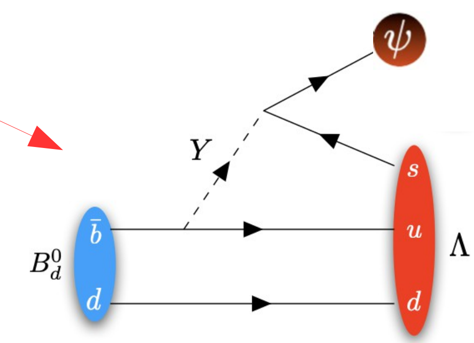

Expect only one operator to dominate

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

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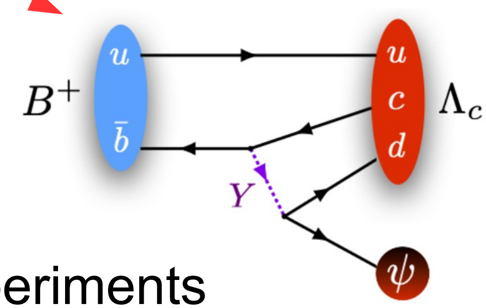
NEW! this week

Expect only one operator to dominate

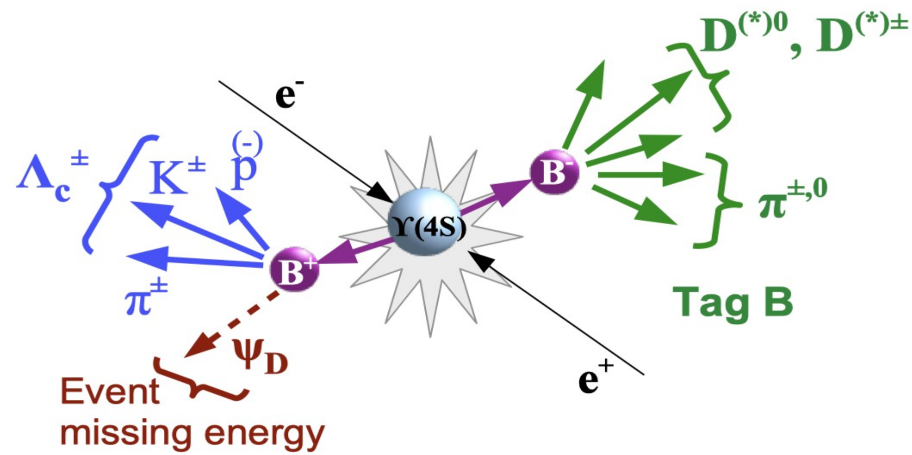


- B^+ and B_d modes potentially accessible at B factory experiments

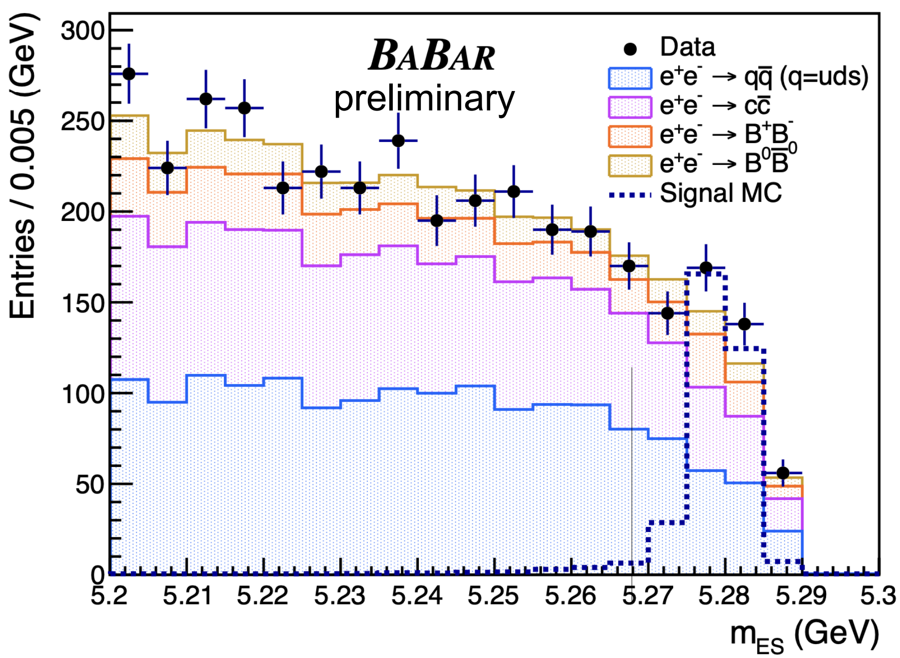
$$B^+ \rightarrow \Lambda_c^+ + \psi_D$$

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

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



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



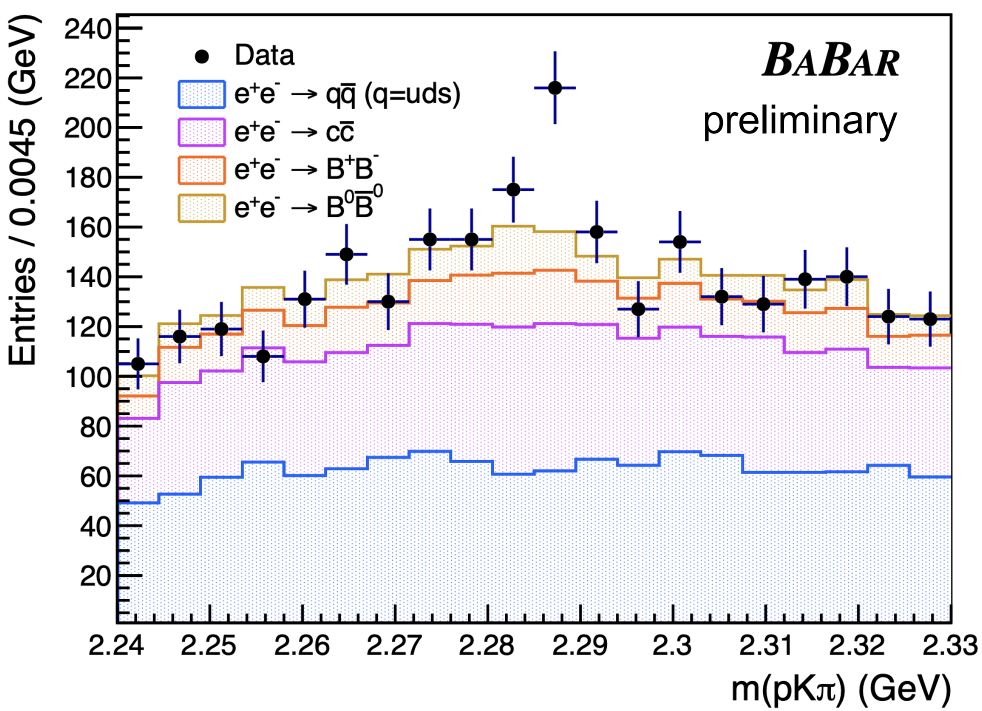
- Require exactly 3 high quality tracks, satisfying $\Lambda_c^+ \rightarrow p K^- \pi^+$ charge and particle ID expectations
- Very low background from $B \rightarrow$ baryons + X; backgrounds arise primarily from $q\bar{q}$ (continuum) sources.

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

Signal reconstruction

Signal Λ_c^+ reconstruction is validated using m_{ES} sideband region data

- Clear Λ_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



Λ_c^+ candidates in m_{ES} sideband region

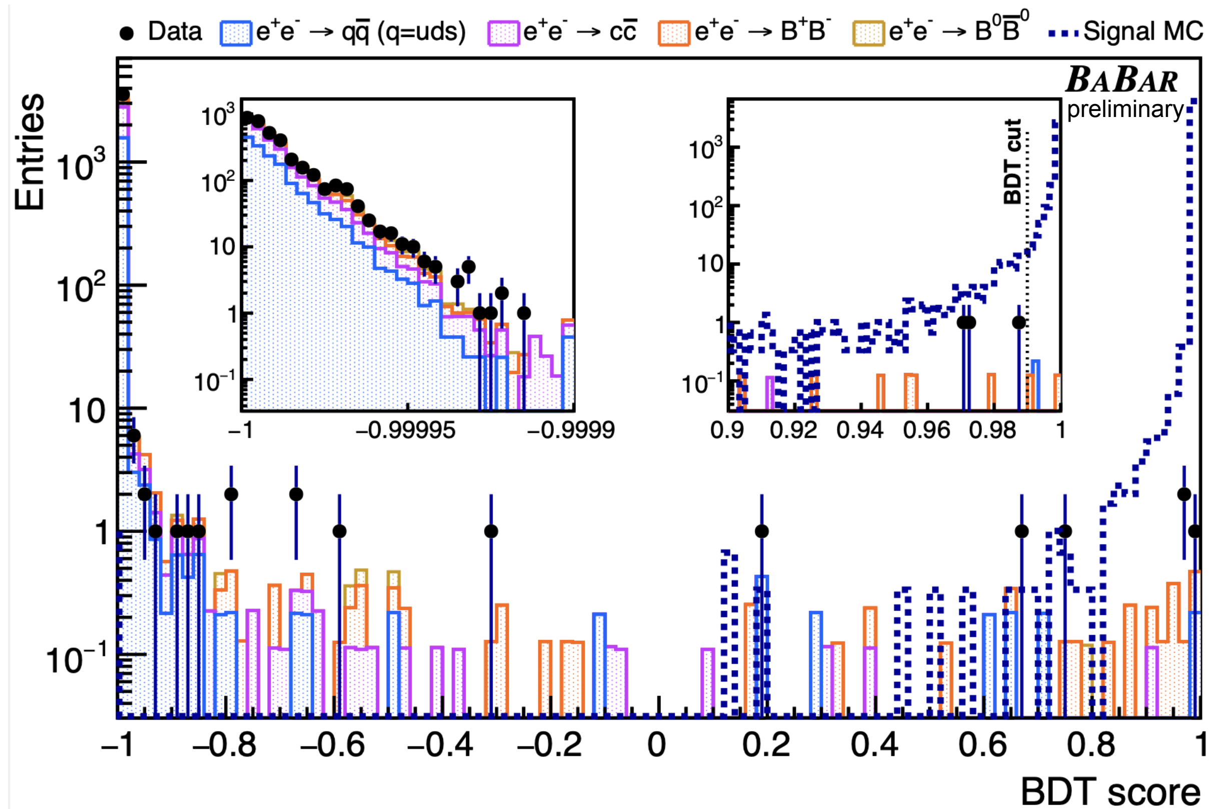
Continuum Λ_c^+ events and $B \to$ baryons+X backgrounds typically have low missing energy and additional neutral particles besides the B_{tag} and Λ_c^+ candidates

- Multivariate (BDT) selector to suppress remaining backgrounds
- 14 inputs, based on overall event shape, B_{tag} properties, Λ_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 ψ_D mass range.
- Optimization performed blinded
- BDT score > 0.99



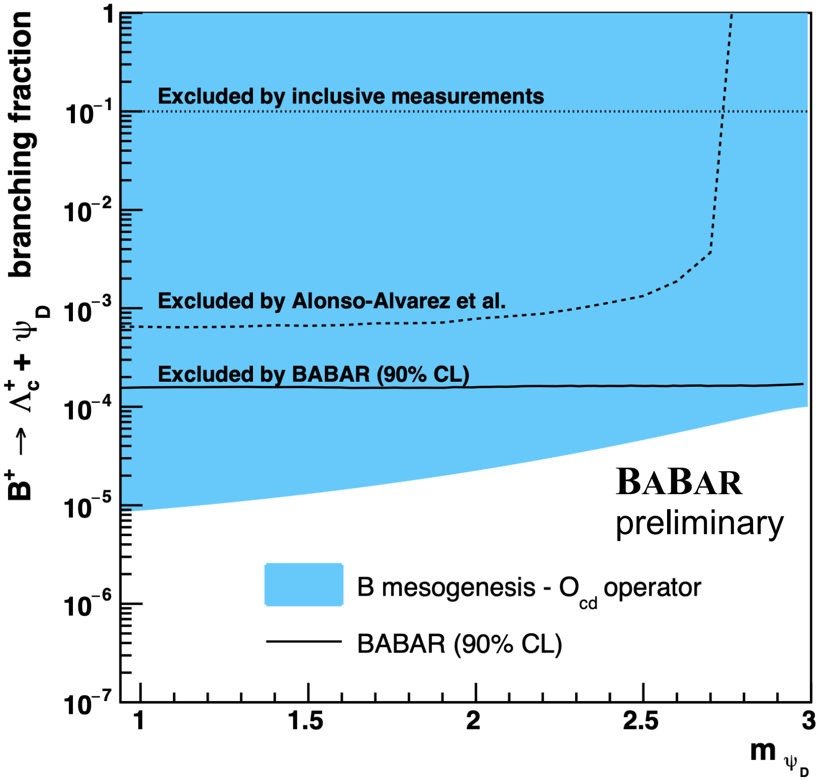
No events survive BDT selection (~0.4 expected background)

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

Results

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

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



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

- Exclusive $B^+ \to \Lambda_c^+ \psi_D$ branching fraction expected to range from 10% - 100% of inclusive $\mathcal{B}(B^+ \to \Lambda_c^+ \psi_D X)$, depending on mass
- Substantial new constraint on model parameter space for O_{cd} operator

Conclusion

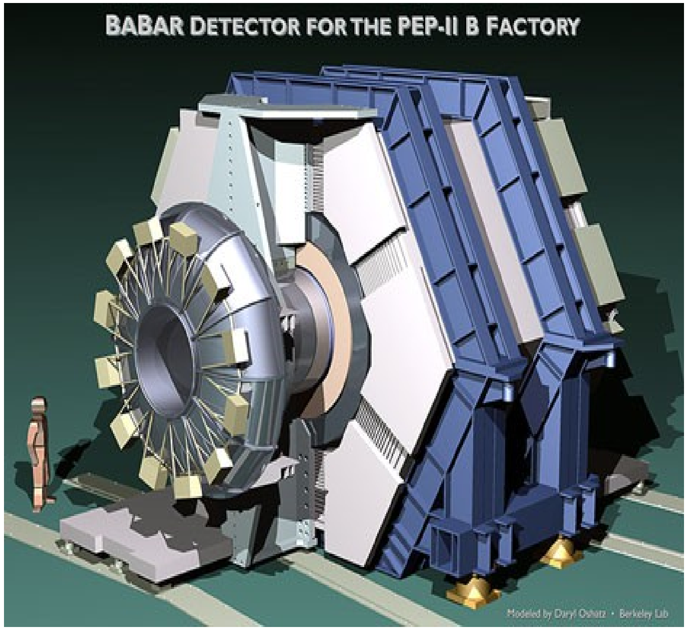
Clean B factory environment is extremely well suited to searches for light dark sector signatures, and precision probes of new physics:

- Two 2023 BABAR papers substantially reduce parameter space for B-mesogenesis operators $O_{ud} = \psi bud$ and $O_{us} = \psi bus$
- New 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)
$B^+ \to \Lambda_c^+ \psi_D$	arXiv:xxxxxxxxx[hep-ex] (submitted to Phys. Rev. D Lett.)

TODAY

Unique BABAR data set remains productive more than 15 years after the end of data taking!



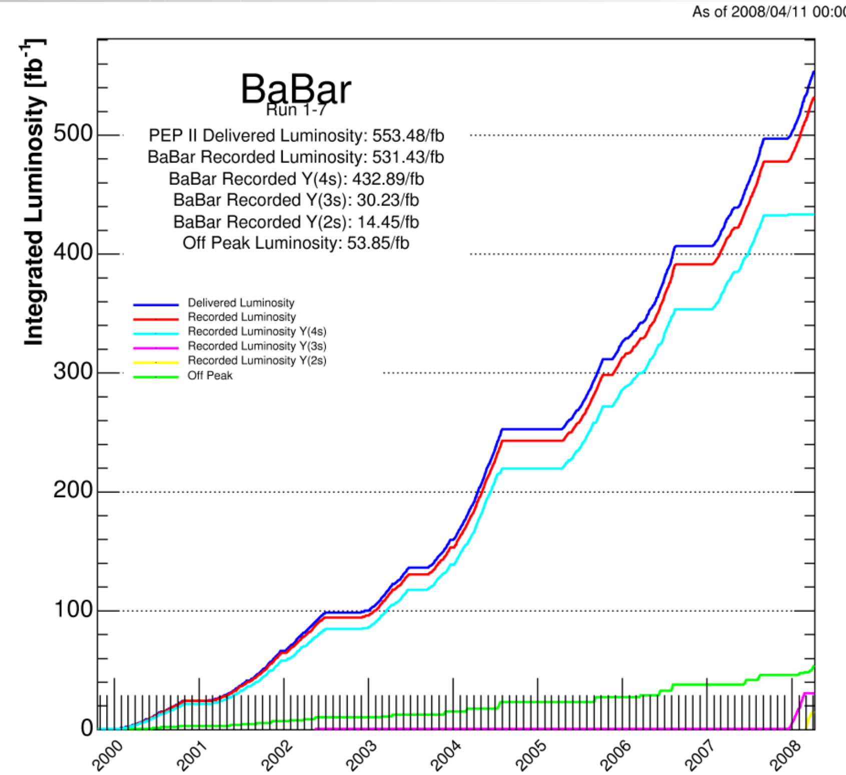
Extra Material

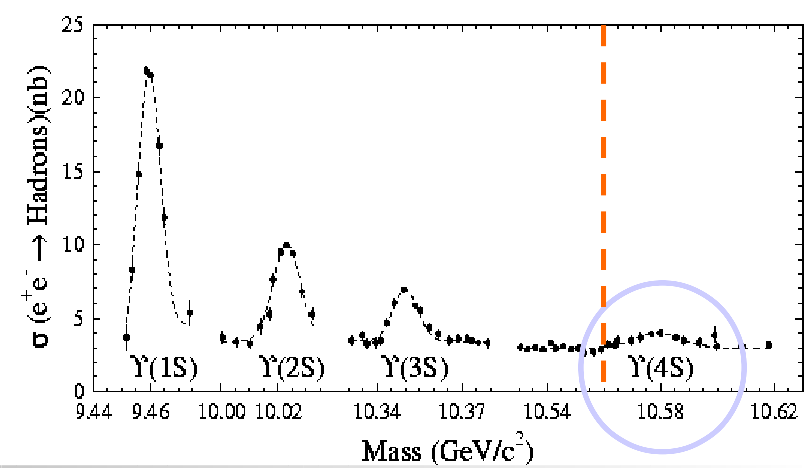
BABAR data sets

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 Υ" 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



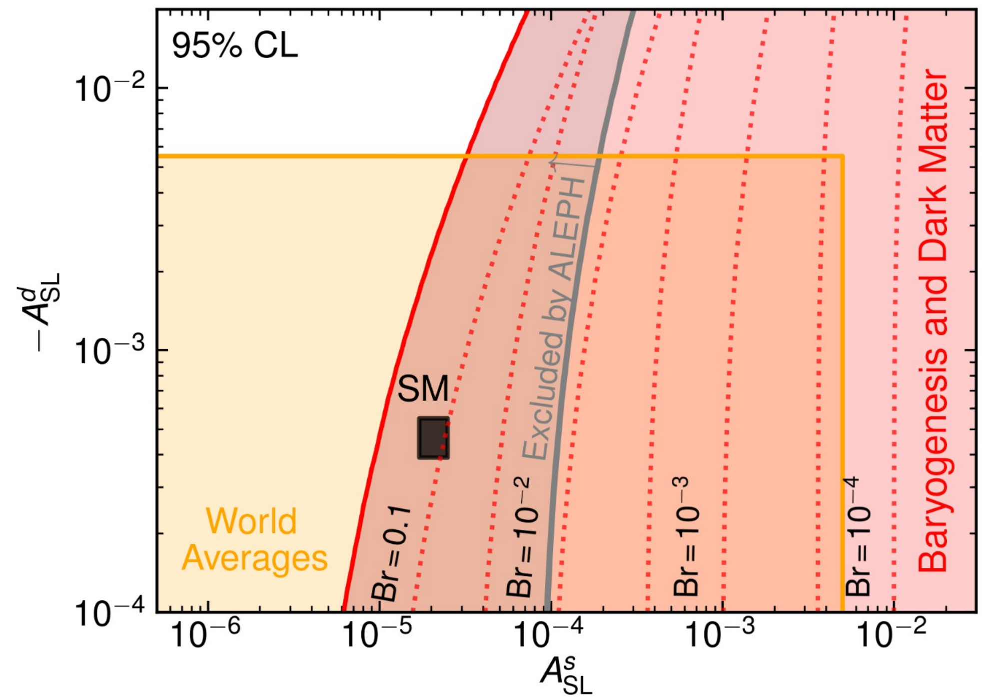


$B^+ \to \Lambda_c^+ + \psi_D$

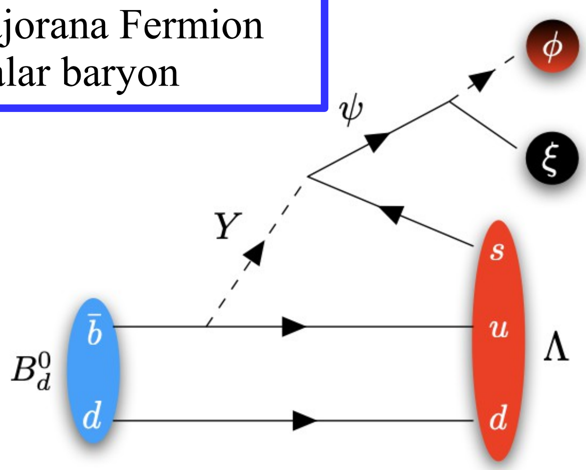
BDT inputs:

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
ΔE	$B_{\rm tag}$	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)
$m_{pK^+\pi^-}$	Λ_c^+	Reconstructed invariant mass of the Λ_c^+ candidate
χ^2	Λ_c^+	χ^2 of the fit of the Λ_c^+ candidate
$N_{\rm neut}$	ECL	Total number of additional neutral clusters
N_{π^0}	ECL	Number of additional π^0 candidates
$E_{\rm extra}$	ECL	Sum of the energies of all additional neutral clusters
$\cos\theta_{\psi_D}$	ψ_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



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