Heavy Neutral Lepton and Dark-Sector-related searches at *BABAR*

Alberto Lusiani, for the *BABAR* collaboration
orcid.org/0000-0002-6876-3288

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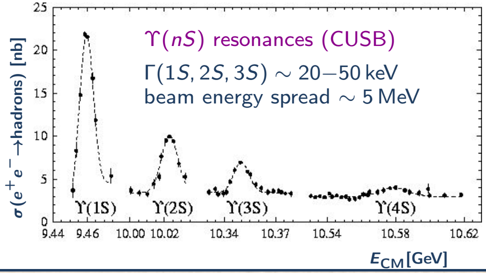
Outline

- Search for Heavy Neutral Lepton in Tau Decay at *BABAR*
  - PRD 107, 052009 (23 Mar 2023)
- Search for B mesogenesis at *BABAR* (search for $B \to$ baryon + dark-matter anti-baryon)
  - PRD 107, 092001 (May 2023) – $B \to \Lambda\psi_{\mathrm{DM}}$
  - *BABAR* prelim. Moriond EW 2023 – $B \to p\psi_{\mathrm{DM}}$

BABAR asymmetric *B*-factory at PEP-II, SLAC National Accelerator Laboratory

center-of-mass energies



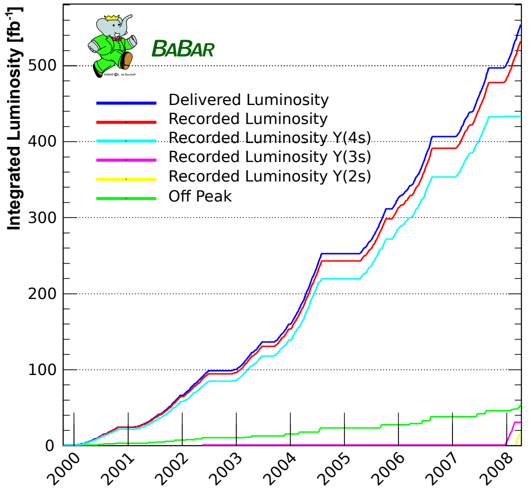
$\mathcal{L}$ vs. $\sqrt{s}$

energy	$\mathcal{L}(fb^{-1})$
$\Upsilon(4s)$	430
$\Upsilon(3s)$	30.2
$\Upsilon(2s)$	14.5
off-peak	54

pairs production

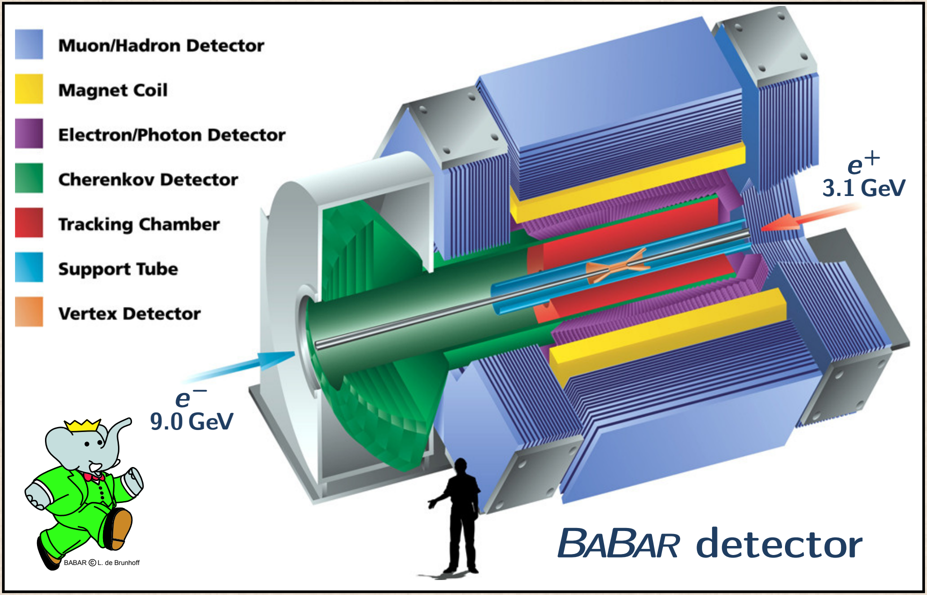
flavour	events
$B\bar{B}$	$470 \cdot 10^6$
$c\bar{c}$	$690 \cdot 10^6$
$\tau^+\tau^-$	$485 \cdot 10^6$

integrated luminosity over time



data-taking ended in April 2008

BABAR general purpose detector



focused on study of CP violation in B mesons, but good for several other measurements and searches

Search for Heavy Neutral Lepton at *BABAR*

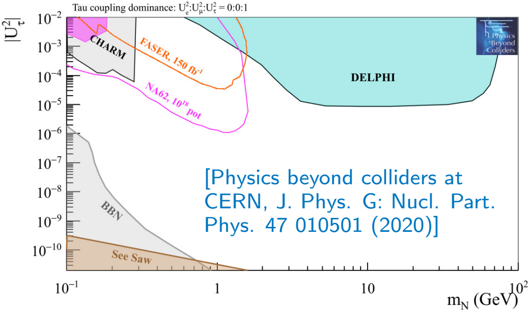
[PRD 107, 052009 (23 Mar 2023)]

Heavy neutral lepton searches motivations

Theory

- HNLs in several beyond Standard Model (BSM) theories to explain:
  - Neutrino oscillations and origins of their mass via seesaw models [Phys. Rev. D 23, 165]
  - Baryonic asymmetry of Universe [Phys. Rev. Lett. 81, 1359]
    - CPV in sterile neutrino → → lepton-antilepton asymmetry → → baryon-antybaryon asymmetry
  - Dark matter candidate [Phys. Lett. B 631, 151]
- HNLs can mix with tau neutrino → → fraction of tau decays will have HNL instead of tau neutrino

2019 experimental limits on tau-coupled HNL



[Physics beyond colliders at CERN, J. Phys. G: Nucl. Part. Phys. 47 010501 (2020)]

limits on $|U_{\tau 4}|^2$ vs. $m(\nu_s)$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} = \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \vdots \end{pmatrix}$$

HNL mixing with tau neutrino in hadronic tau decays

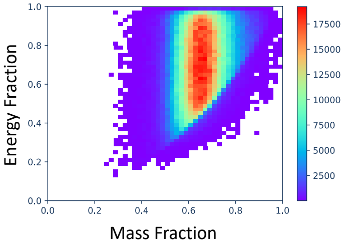
SM Tau Decay — **BSM Tau Decay**

$$\frac{d\Gamma_{\text{tot}}(\tau^- \to \nu h^-)}{dm_h dE_h} = (1 - |U_{\tau 4}|^2)\,\frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\bigg|_{m_\nu=0} + |U_{\tau 4}|^2\,\frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\bigg|_{m_\nu=m_4}.$$

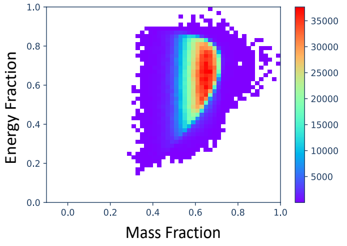
(center of mass E_h) [from Sophie Middleton, Moriond EW 2023]

Simulated 2D m_h/m_τ, $E_h^{\text{CM}}/(\sqrt{s}/2)$ distribution of tau decays with HNL

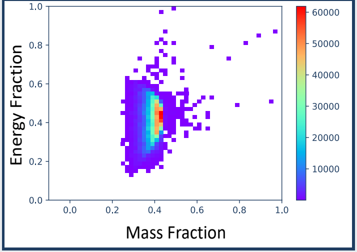
$m_{\text{HNL}} = 0\ MeV$, same as SM



$m_{\text{HNL}} = 500\ MeV$



$m_{\text{HNL}} = 1000\ MeV$



- 13 HNL masses from 100 MeV to 1300 MeV, for τ^+ & τ^- decays
- events generated with modified Tauola, full *BaBar* simulation (Geant4, *BaBar* reconstruction)

Analysis method, selection

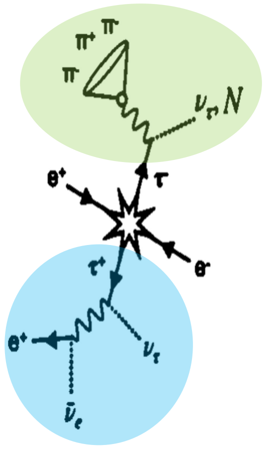
analysis method

- search for evidence of HNL from modification of kinematics of tau decays due to fraction of decays having a massive HVL instead of tau neutrino (following ALEPH [EPJC 2, 395 (1998)])
- quasi-model-independent, no detection of HNL
- search using $\tau \to 3\pi\nu$ events kinematics
  (in the following h sometimes used to denote the 3π hadronic system)
- total leptonic BR ~35%, $\mathcal{B}(\tau \to 3\pi\nu) \simeq 9\%$

main selection requirements

- $e^+e^- \to \tau^+\tau^-$ in 1-3 charged tracks topology
- thrust > 0.85, $p_T > 0.9\%\sqrt{s}$, $p_{\text{miss}}^{\text{CM}} > 0.9\%\sqrt{s}$,
- 1-prong track id. as electron or muon, 3-prong tracks id. as pions
- accept neutrals in 1-prong side if compatible with Bremsstrahlung
- veto unassociated neutrals with $E_{\text{lab}} >$
  1 GeV (electron), 0.5 GeV (muon), 0.2 GeV (3-prong)

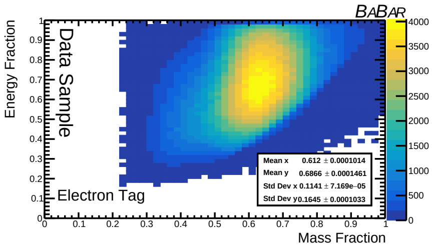
1-3 topology $\tau^+\tau^-$



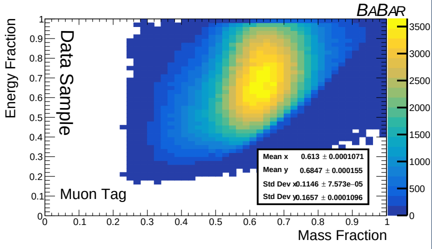
[PRD 107, 052009]

Selected candidates compared to MC-simulated SM $\tau \to 3\pi\nu$

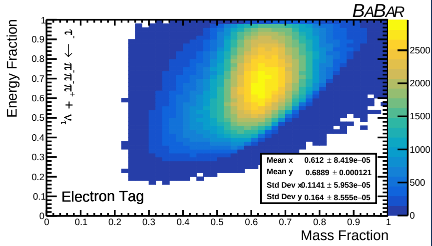
Data



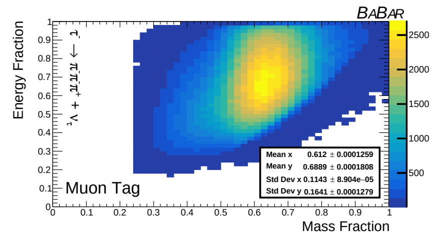
Data



$\tau \to 3\pi\nu$ SM [or $m(\psi_{DM}) = 0$]

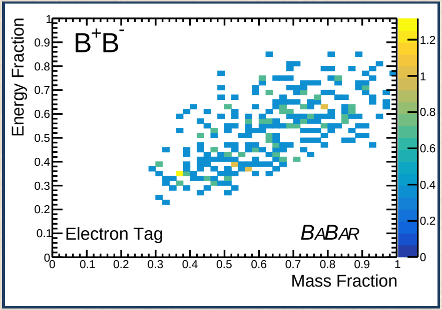


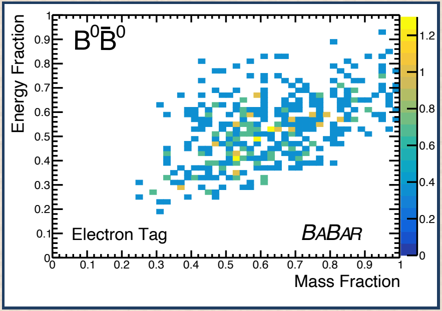
$\tau \to 3\pi\nu$ SM [or $m(\psi_{DM}) = 0$]

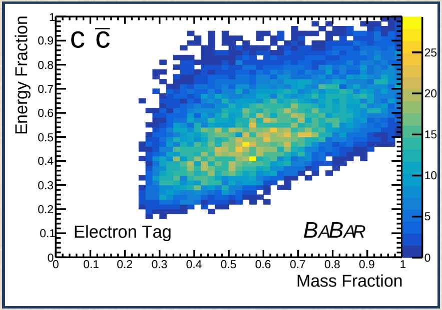


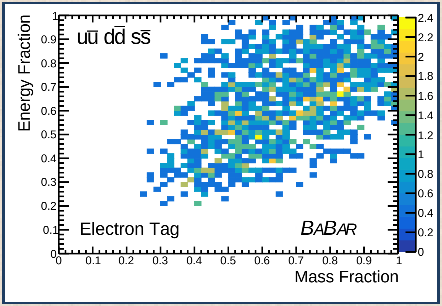
[PRD 107, 052009]

MC simulated backgrounds, electron tag



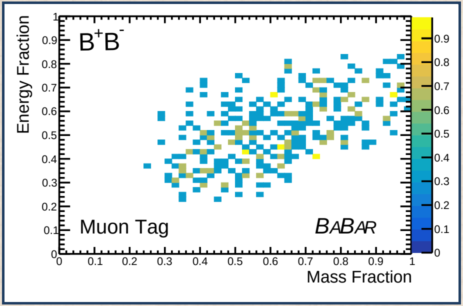


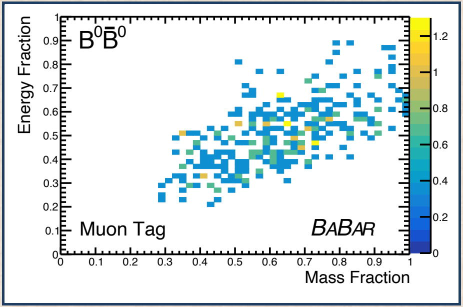


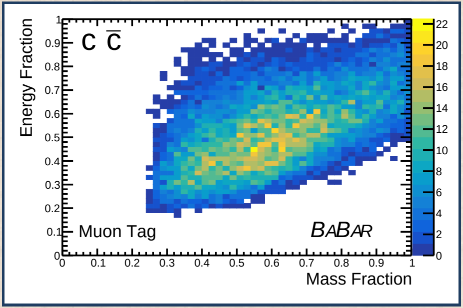


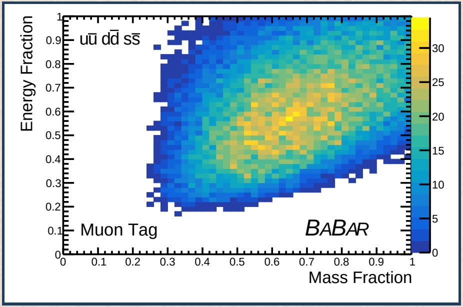
[PRD 107, 052009]

MC simulated backgrounds, muon tag









[PRD 107, 052009]

ML fit of bin contents of 2D m_h/m_τ, $E_h^{CM}/(\sqrt{s}/2)$ data distribution

Events observed　　Parameter of Interest　　Extracted From MC

$$\mathcal{L} = \prod_{\text{charge}}^{+-}\left(\prod_{\text{channel}}^{e\mu}\left(\prod_{\text{bin}}^{ij}\left(\frac{1}{n_{\text{obs},ij}!}\left[N_{\tau,\text{gen}}\cdot|U_{\tau 4}|^2\cdot p_{\text{HNL},ij} + N_{\tau,\text{gen}}\cdot(1-|U_{\tau 4}|^2)\cdot p_{\tau-\text{SM},ij} + n^{\text{reco}}_{BKG,ij}\right]^{(n_{\text{obs}})_{ij}} \times \right.\right.\right.$$
$$\left.\left.\left. exp\left[-\left(N_{\tau,\text{gen}}\cdot|U_{\tau 4}|^2\cdot p_{HNL,ij} + N_{\tau,\text{gen}}\cdot(1-|U_{\tau 4}|^2)\cdot p_{\tau-SM,ij} + n^{\text{reco}}_{BKG,ij}\right)\right]\right)_{\text{bin}} \times \prod_k f(\theta_k,\tilde{\theta}_k)\right)_{\text{channel}}\right)_{\text{charge}}$$

Nuisance parameters

Number of generated taus:

$$N_{\tau,gen} = \mathcal{L} * \sigma * BR(3\pi) * BR(lepton)$$

Contains information from the reconstructed 2D templates:

$$p_{s\,(or\ \tau-SM),ij} = \varepsilon_{reco}\varepsilon_{sel}\frac{n_{ij}}{\sum_i^N \sum_j^M n_{ij}}$$

Find parameter of interest through minimizing ratio:

$$q = -2\ln\left(\frac{\mathcal{L}_{H_0}(|U_{\tau 4}|_0^2;\hat{\hat{\theta}}_0,\text{data})}{\mathcal{L}_{H_1}(|\hat{U}_{\tau 4}|^2;\hat{\theta},\text{data})}\right) = -2\ln(\Delta\mathcal{L}).$$

Where n_{ij} is content of a given bin in 2D template, N and M are number of bins on each direction (=50)

[slide from S.Middleton, Moriond EW 2023]

[PRD 107, 052009]

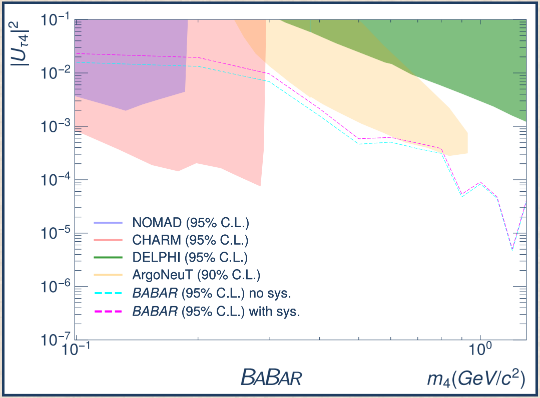
Systematics

Uncertainty	Yield Change (±)
Luminosity $\sigma(ee \to \tau\tau)$	0.44% 0.31%
Branching Fractions (1 prong)	e: 0.22% μ: 0.22%
Branching Fractions (3 prong)	3π: 0.57%
PID Efficiency	e: 2% μ: 1% π: 3%
Bhabha Contamination $q\bar{q}$ Contamination (data)	0.2% 0.1%
Tracking Efficiency Detector Modeling	negligible negligible
Beam Energy Tau Mass	negligible negligible
hadronic tau decay simulation (conservatively varying mass and width of a_1 resonance)	1−2% (on mean of distributions) 6−7% (on RMS spread of distributions)

[PRD 107, 052009]

95% CL upper limits

- for each HNL mass, compute limits for coupling using likelihood-ratio test statistics function of coupling



- NOMAD [PLB 506, 27 (2001)]
- CHARM [PLB 550, 8 (2002)]
- DELPHI [Z.Phys.C 74, 57 (1997)]
- ArgoNeut [PRL 127, 121801 (2021)]

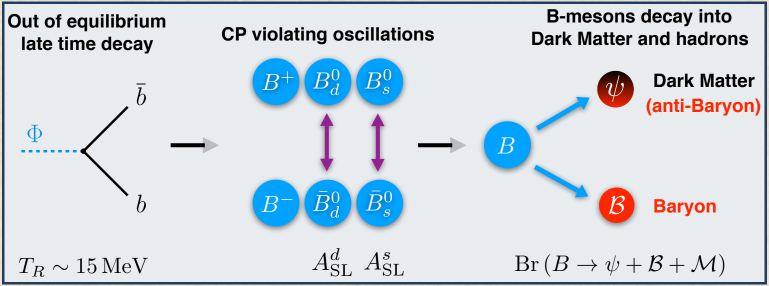
[PRD 107, 052009]

Search for B mesogenesis at *BaBar*

[PRD 107, 092001 (May 2023)], [*BaBar* prelim. Moriond EW 2023]

Introduction

- may explain both Dark Matter (DM) abundance and Baryon Asymmetry (BAU)
- Alonso-Álvarez, Elor, Escudero, PRD 99, 035031 (2019) (neutral B)
- Alonso-Álvarez, Elor, Escudero, PRD 104, 035028 (2021)
- Elahi, Elor, McGehee, PRD 105, 055024 (2022) (charged B^+, B_c^+)

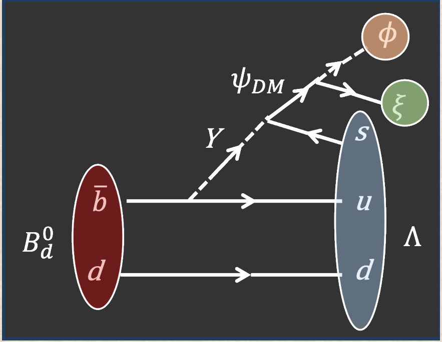


- several B decays to baryon + DM anti-baryon possible

Experimental signatures in *BaBar*

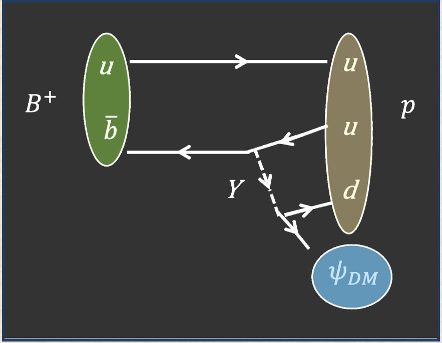
▶ B decay to baryon + invisible

$B^0 \to \Lambda\psi_{\mathrm{DM}}$



PRD 107, 092001 (May 2023)

$B^+ \to p\psi_{\mathrm{DM}}$

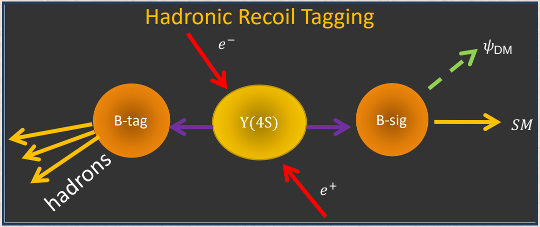


BaBar prelim. Moriond EW 2023

Y	TeV-scale mediator
ψ_{DM}	Dark Matter anti-baryon
ξ	DM Majorana fermion
ϕ	DM scalar baryon

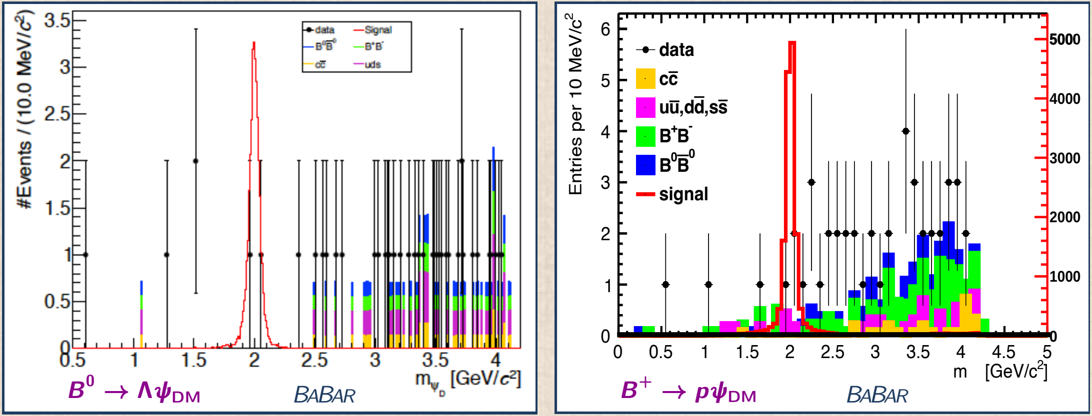
Selection of events

- analysis of 398fb^{-1}of BABAR data at $\Upsilon(4s)$
- require one well reconstructed B
  - $\sqrt{E^2_{\text{beam}} - p^2_B} = m_{\text{ES}} > 5.20\,\text{GeV}$
  - $|E_B - E_{\text{beam}}| = |\Delta E| < 0.12\,\text{GeV}$
  - efficiency $\simeq 0.3\%$
- require just one baryon and nothing else
  - B^0 tag $\Rightarrow$ reconstructed $\Lambda \to p\pi$
  - B^- tag $\Rightarrow$ identified p
- ψ_{DM} 4-momentum = missing 4-momentum
- further bkg rejection with trained Boosted Decision Tree (BDT) classifier



[PRD 107, 092001 (May 2023)], [BABAR prelim. Moriond EW 2023]

Selected candidates vs. MC-simulated 2 GeV ψ_{DM}



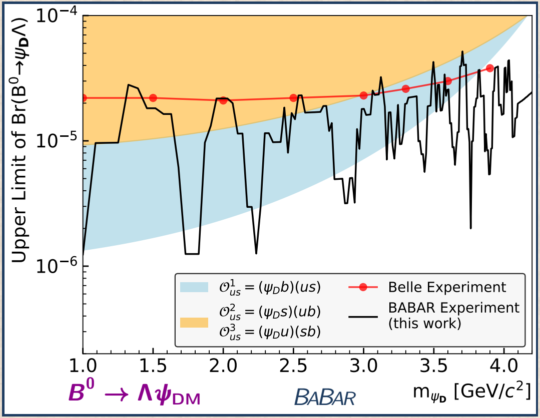
[PRD 107, 092001 (May 2023)], [BABAR prelim. Moriond EW 2023]

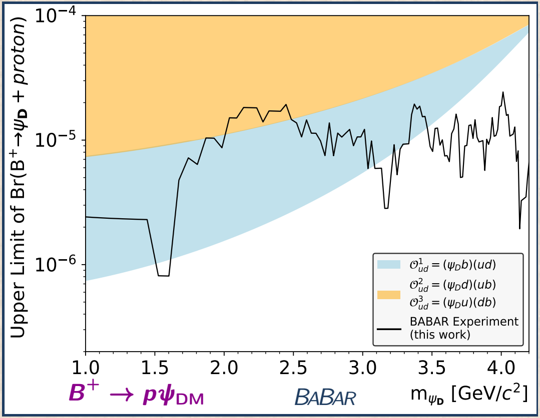
Search for $\psi_{\rm DM}$

- search for $\psi_{\rm DM}$ in 193 mass hypotheses from 1 to 4.2 GeV
- MC signal simulated for 8 masses between 1 and 4.2 GeV to interpolate, as function of $\psi_{\rm DM}$ mass, efficiency ($[5.9 \to 2.1]\cdot 10^{-4}$) and $\psi_{\rm DM}$ mass resolution ($90 \to 6$ MeV)
- count candidates within $\pm 3 \times [\psi_{\rm DM}$ mass resolution]
- subtract background estimated from sidebands
- largest significance (Poisson statistics) $2.3\,\sigma$, comsistent with look-elsewhere effect ($0.4\,\sigma$ global)
- compute 90% CL upper limits with profile likelihood method
- efficiency modeled as Gaussian including all systematics (7.8% – 9.1%)

[PRD 107, 092001 (May 2023)], [BABAR prelim. Moriond EW 2023]

90% CL upper limits for B mesogenesis parameters





- recent Belle search PRD 105, L051101 (2022)
  - limits extrapolated from few mass points

[PRD 107, 092001 (May 2023)], [BABAR prelim. Moriond EW 2023]

Final slide

Other recently published BABAR searches

- Search for an Axion Like Particle (ALP), PhysRevLett.128.131802 (2022)
- Search for Darkonium, PhysRevLett.128.021802 (2022)

Conclusions

- e^+e^- B-factories at $\Upsilon(4s)$ provide very good basis for light new physics searches
- many searches published by BABAR in recent years provide valuable constraints for theory models
- BABAR data continue to be useful, other searches on-going (e.g. $B^+ \to \Lambda_c^+ \psi_{\rm DM}$)

– end –

Backup Slides

Notes on likelihood-ratio-based upper limit calculation for HNL

- compute likelihood of observing in each bin of the 2D mass fraction vs. energy fraction distribution the selected candidates given the simulation-predicted signal and background expected events, this is a function of the expected number of events with HNL and proportional to its mixing parameter
- predictions are modeled with Poisson distribution convoluted with Gaussians with nuisance parameters corresponding to estimated systematic uncertainties
  [J. S. Conway, in PHYSTAT 2011 (CERN, Geneva, 2011), pp. 115–120]
- likelihood-ratio test statistics $q = -2\ln\left(\frac{\mathcal{L}_{H_0}(|U_{\tau 4}|^2_0; \hat{\hat{\theta}}_0, \text{data})}{\mathcal{L}_{H_1}(|\hat{U}_{\tau 4}|^2; \hat{\theta}, \text{data})}\right) = -2\ln(\Delta\mathcal{L})$.

  $\mathcal{L}$ in both numerator and denominator describes the maximized likelihood, for two instances. The denominator is the maximized (unconditional) likelihood giving the maximum likelihood estimator of $|U_{\tau 4}|^2$ and the set of nuisance parameters $(\hat{\theta})$; $\hat{\theta}$ is a vector of nuisance parameters which maximize the likelihood. In the numerator the nuisance parameters are maximized for a given value of $|U_{\tau 4}|^2$ i.e. it is the conditional maximum-likelihood. The ratio, LR, is consequently a function of $|U_{\tau 4}|^2$ through the numerator. It must be noted that the numerator denotes the hypothesis for any given value of $|U_{\tau 4}|^2$ (including the background only case i.e. $|U_{\tau 4}|^2 = 0$). More details in [G. Cowan, K. Cranmer, E. Gross, and O. Vitells, EPJC 71, 1554 (2011); 73, 2501(E) (2013)]
- using Wilk's theorem [S. Algeri, J. Aalbers, K. Dundas Morå, and J. Conrad, Nat. Rev. Phys. 2, 245 (2020).], q asymptotically approaches a χ^2 distribution under H_0. To find a $100(1-\alpha)\%$ confidence interval we move to the left and to the right of the minimum value of q to find the points where the function increases by the α percentile of a χ^2 distribution with a number degrees of freedom equal to the number of parameters