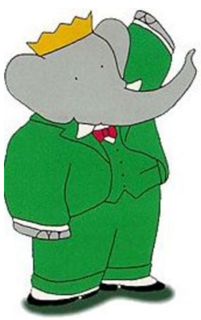
Dark Matter and Baryogenesis in *B* decays



J. Michael Roney
mroney@uvic.ca

On behalf of the *BABAR* Collaboration

31 May 2024

The Standard Model is wonderful!

The Standard Model is wonderful!

BUT….

What about

- *Dark Matter*
- *Baryon Asymmetry of the Universe (BAU)*
- *Origins of neutrino mass*
- *Existence of Dark Energy*
- *Fine tuning requirements (e.g. Higgs mass)*
- *Gravity at the quantum scale*

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Recent dark sector searches by Belle and Belle II reported by Savino Longo at this meeting

D. Biswas et al. (Belle Collaboration) *Search for a dark leptophilic scalar produced in association with $\tau^+\tau^-$ pair* Phys. Rev. D 109, 032002 (2024) —- 626 fb^{-1}

M. Nayak, S. Dey, A. Soffer, et al. (Belle Collaboration), *Search for a heavy neutral lepton that mixes predominantly with the tau neutrino* to appear in PRD(L) arXiv:402.02580 —- 915 fb^{-1}

I.Adachi et al. (Belle II Collaboration) *Search for a $\tau^+\tau^-$ Resonance in $e^+e^- \to \mu^+\mu^- \tau^+\tau^-$ Events with the Belle II Experiment,* Phys. Rev. Lett. 131, 121802 (2023) —- 62.8 fb^{-1}

I.Adachi et al. (Belle II Collaboration) *Search for a $\mu^+\mu^-$ resonance in four-muon final states at Belle II,* Accepted to PRD arXiv:2403.02841 —- 178 fb^{-1}

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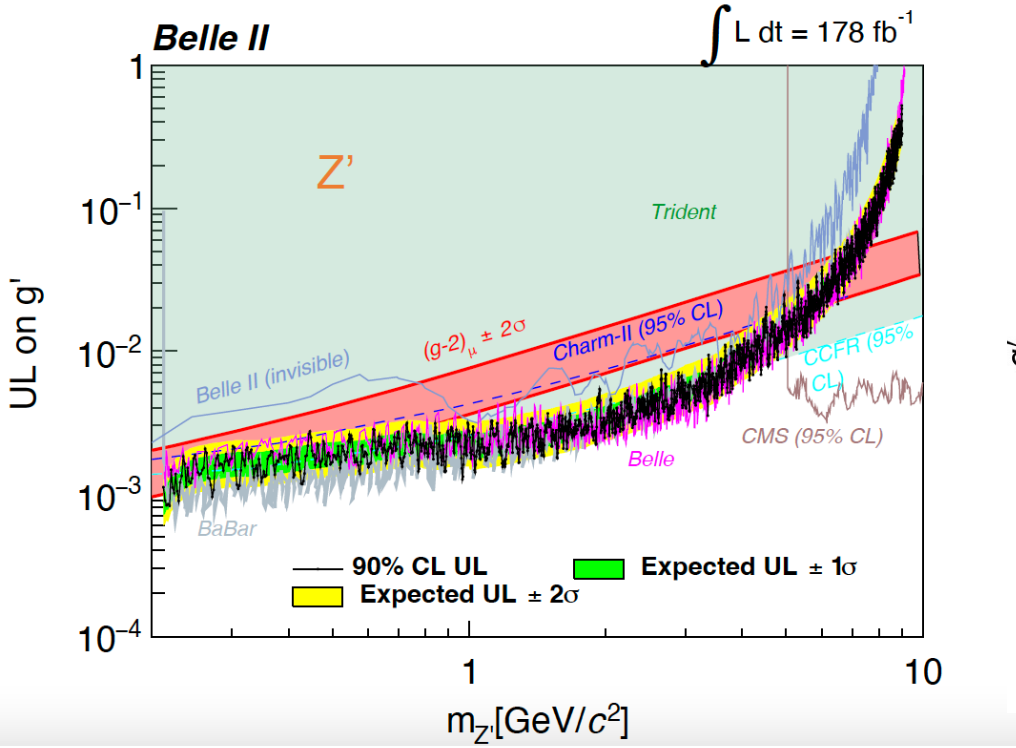
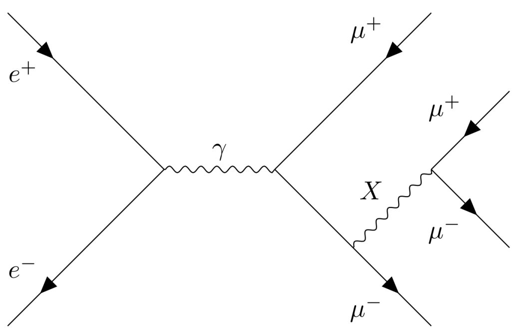
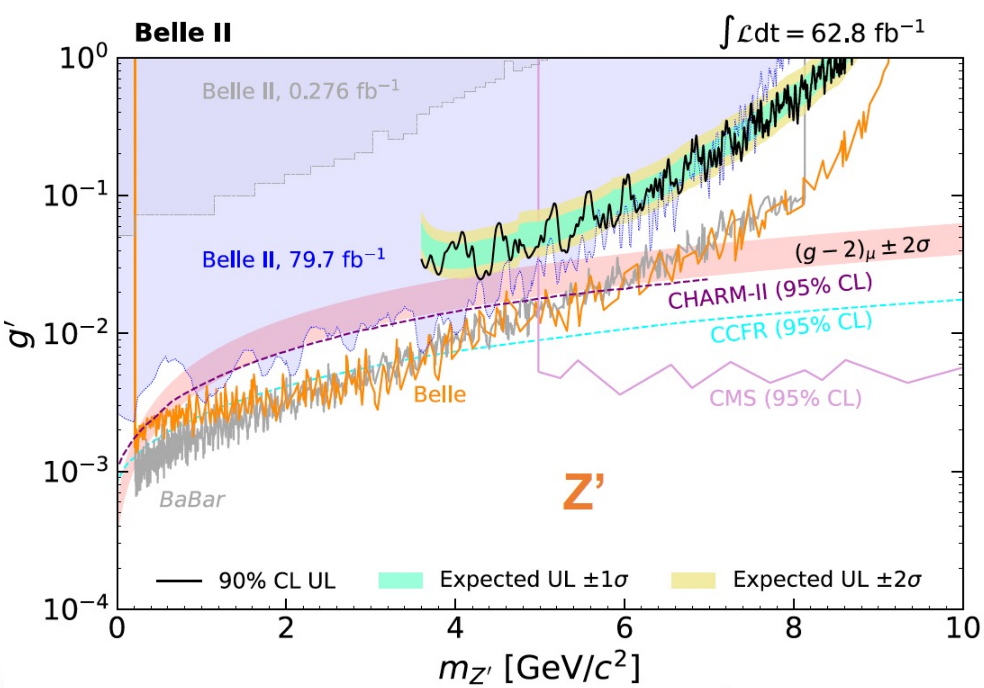


Search for a resonance $\mu^+\mu^-$





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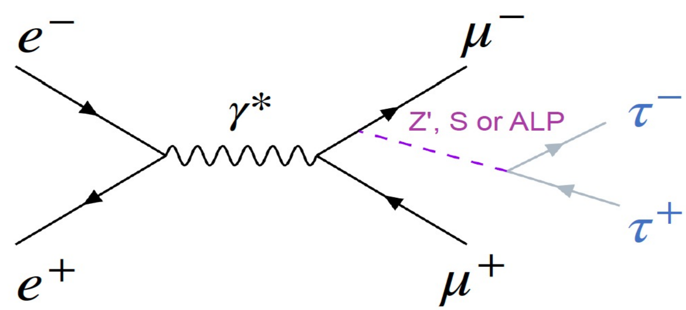

Require $\tau^{\pm}$ decay as
$\tau^- \to \ell^- \nu\nu$ or $\tau^- \to \pi^- \nu n \pi^0$

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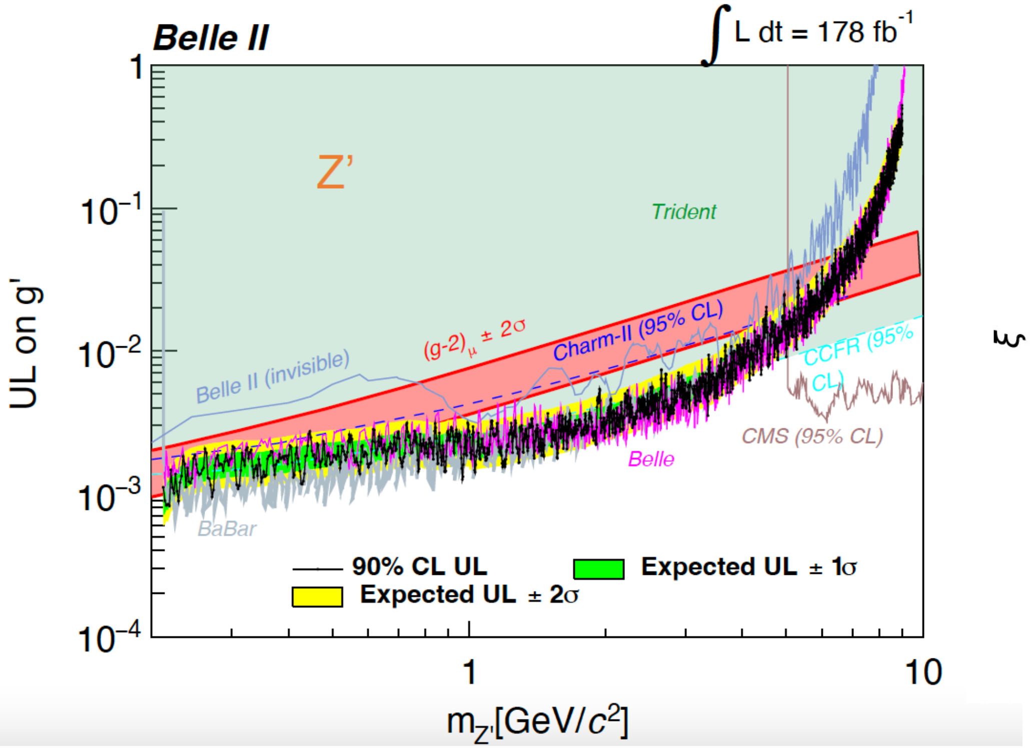

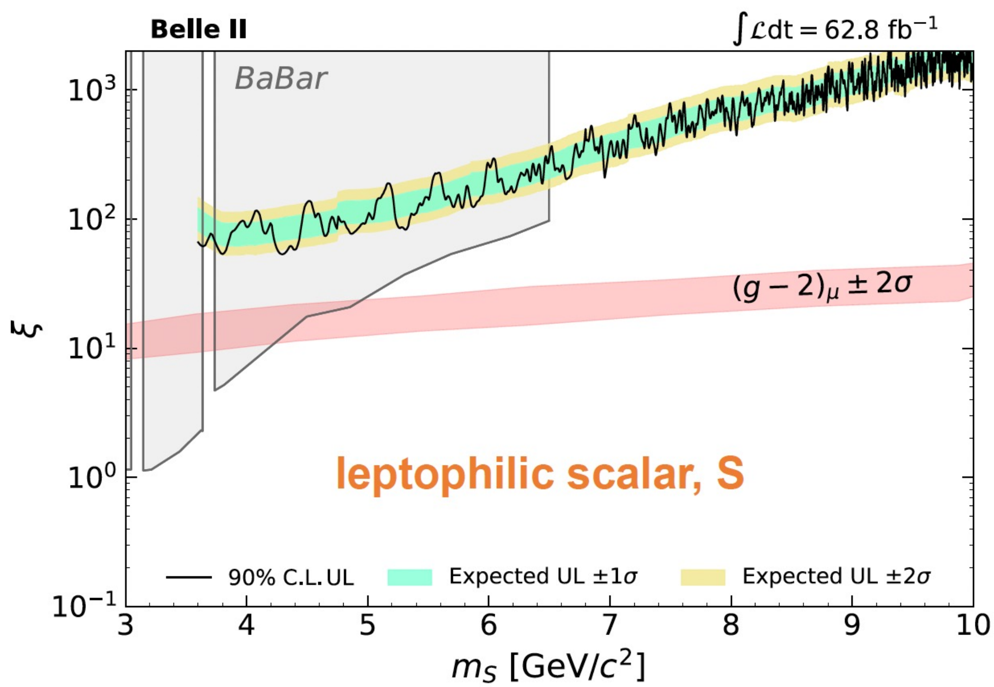

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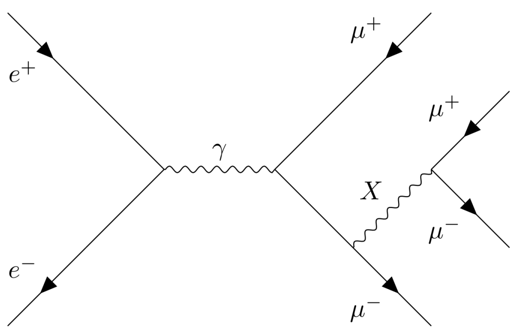

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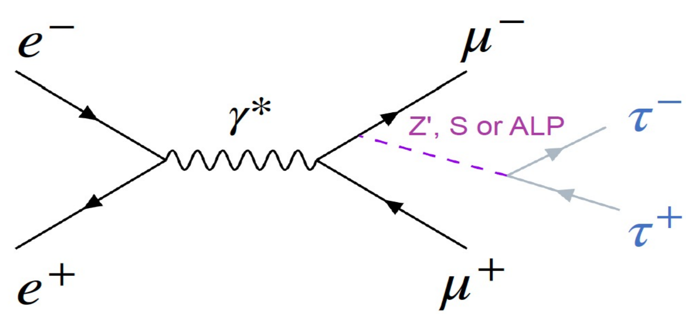

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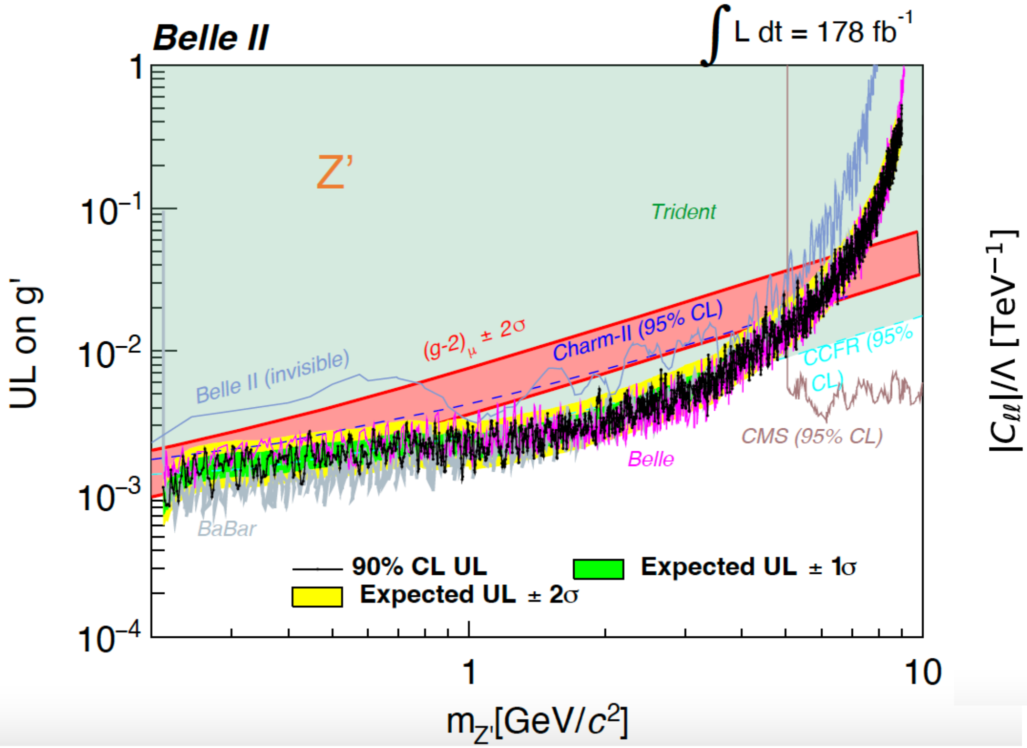

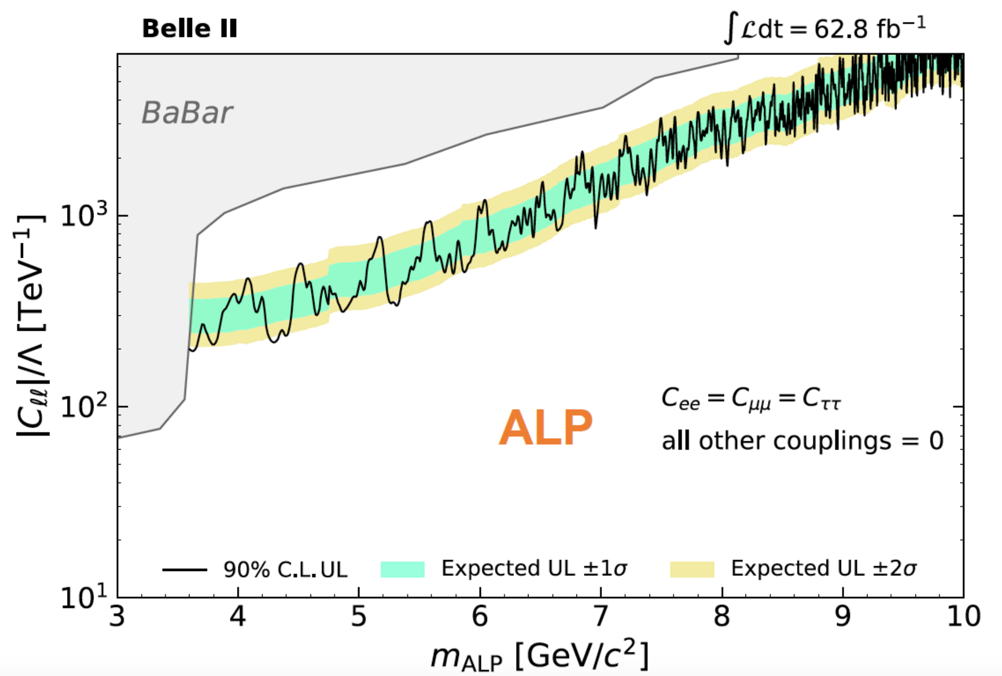

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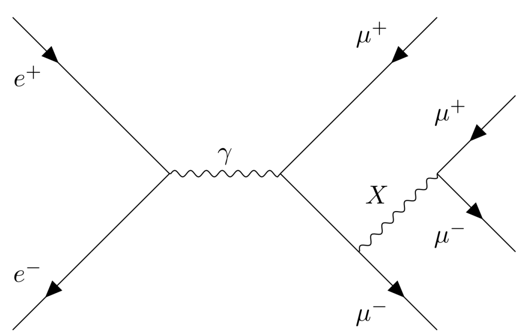

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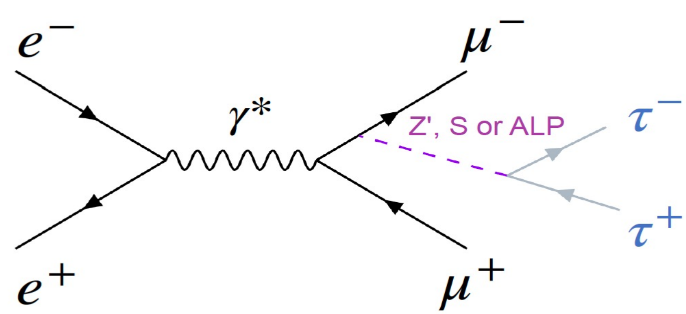

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University of Victoria

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Baryogenesis and Dark Matter from B mesons

Gilly Elor, Miguel Escudero, and Ann E. Nelson

Phys. Rev. D 99, 035031 (2019)

Baryogenesis and Dark Matter from B mesons

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Phys. Rev. D 99, 035031 (2019)


The New York Times

Published 2019

Ann Nelson, Expert on Particle Physics, Is Dead at 61

Dr. Nelson was celebrated for helping to address flaws in the Standard Model, the longtime basis for explaining how particles interact.

This work documents Ann Nelson's last research focus, see also:

"Baryogenesis from *B* meson oscillations", Ann E. Nelson and Huangyu Xiao, Phys. Rev. D 100, 075002

"A supersymmetric theory of baryogenesis and sterile sneutrino dark matter from B mesons", Gonzalo Alonso-Alvarez, Gilly Elor, Ann E. Nelson, and Huangyu Xiaob, *JHEP* 03 (2020) 046 1907.10612 [hep-ph] [1]

[1] Ann Nelson passed away after this manuscript was written. Her contribution made this work possible, particle physics a richer field and the whole world a little bit brighter. We are forever grateful for her kindness and inspiration.

Baryogenesis and Dark Matter from B mesons

Phys. Rev. D 99, 035031 (2019)

Elor, Escudero and Nelson kill two birds with one stone!

introducing a new mechanism of baryogenesis and dark matter production arising from neutral *B* meson oscillations & subsequent decays that simultaneously addresses **both**

the dark matter relic abundance and

the baryon asymmetry

Baryogenesis and Dark Matter from B mesons

Phys. Rev. D 99, 035031 (2019)

``In the early universe, decays of a long-lived particle produce *B* mesons and anti-mesons out of thermal equilibrium.

These mesons/anti-mesons then undergo CP-violating oscillations before quickly decaying into visible and dark sector particles.

Dark matter will be charged under the baryon number so that the visible sector baryon asymmetry is produced without violating the total baryon number of the Universe.''

Baryogenesis and Dark Matter from B mesons

Phys. Rev. D 99, 035031 (2019)

Elor, Escudero and Nelson postulate that:

In the early universe $b\,\bar{b}$ pairs hadronize to produce *B* mesons

B mesons decay to:

a baryon ($\mathcal{B}$),

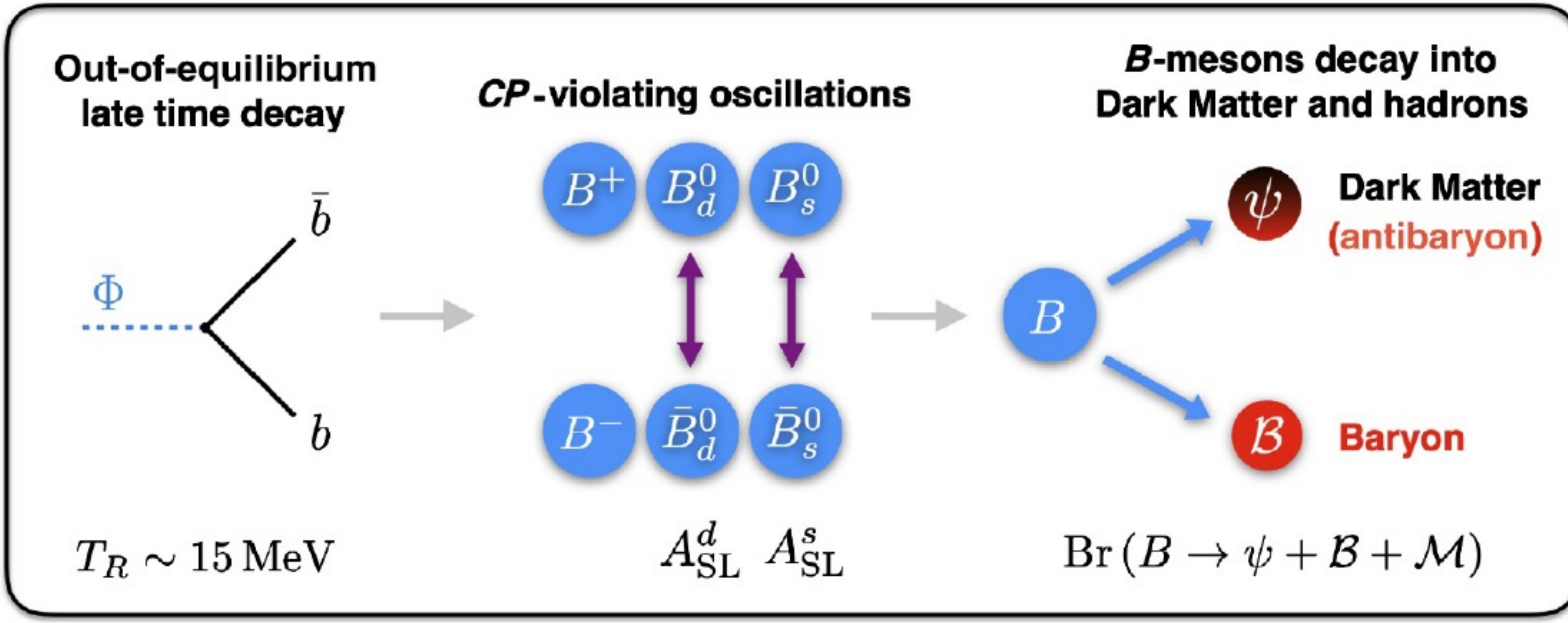
a dark-sector baryon (ψ_D),

and additional mesons ($\mathcal{M}$)

$$B \longrightarrow \mathcal{B} + \psi_D + \mathcal{M}$$

Baryogenesis and Dark Matter

Baryogenesis and Dark Matter from B Mesons: *B Mesogenesis*



$$B \longrightarrow \mathcal{B} + \psi_D + \mathcal{M}$$

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

Baryogenesis and Dark Matter from B mesons

Phys. Rev. D 99, 035031 (2019)

- CP violation from $B^0 - \overline{B^0}$ oscillations generates a matter-antimatter asymmetry, which can originate from SM or BSM processes
- Because of CP violation, $B \rightarrow \mathcal{B} + \psi_D + \mathcal{M}$ decays slightly dominate over the $\bar{B} \rightarrow \bar{\mathcal{B}} + \overline{\psi_D} + \bar{\mathcal{M}}$ decays

Yields net excess of baryons in the visible sector and excess anti-baryons in the dark sector

Baryogenesis and Dark Matter from B mesons: B Mesogenesis

Phys. Rev. D 99, 035031 (2019)

- CP violation from $B^0 - \overline{B^0}$ oscillations generates a matter-antimatter asymmetry, which can originate from SM or BSM processes
- B^0 decays slightly dominate over $\overline{B^0}$ decays into anti-baryons

Yields net excess of baryons in the visible sector and excess anti-baryons in the dark sector

Baryon number in the whole universe is conserved, but a net excess is present in the visible sector

Baryogenesis and Dark Matter from B mesons: B Mesogenesis

Phys. Rev. D 99, 035031 (2019)

"The produced baryon asymmetry will be directly related to the leptonic charge asymmetry in neutral B decays: an experimental observable: A_{SL}^{q}

Dark matter is stabilized by an unbroken discrete symmetry, and proton decay is simply evaded by kinematics"

Baryogenesis and Dark Matter from B mesons: B Mesogenesis

Phys. Rev. D 99, 035031 (2019)

Their model is not constrained by di-nucleon decay, does not require a high reheat temperature, and has unique experimental signals:

- positive leptonic asymmetry in *B* meson decays,
- new decay of *B* mesons into a baryon and missing energy, and
- new decay of *b*-flavored baryons into mesons and missing energy.

All three observables are testable at collider experiments

Followed up by Alonso-Alvarez, Elor and Escudero

PHYSICAL REVIEW D **104**, 035028 (2021)

Editors' Suggestion

Collider signals of baryogenesis and dark matter from *B* mesons: A roadmap to discovery

Gonzalo Alonso-Álvarez,[1,2,*] Gilly Elor,[3,†] and Miguel Escudero[4,‡]

(Received 20 January 2021; accepted 20 July 2021; published 27 August 2021)

" …. This mechanism for baryo- and dark matter genesis from B mesons gives rise to distinctive signals at collider experiments, which we scrutinize in this paper.

We study CP-violating observables in the B_q^0 - $\overline{B_q^0}$ system, discuss current and expected sensitivities for the exotic decays of B mesons into a visible baryon and missing energy, and explore the implications of direct searches for a TeV-scale colored scalar at the LHC and in meson-mixing observables.

Remarkably, we conclude that a combination of measurements at BABAR, Belle, Belle II, LHCb, ATLAS, and CMS can fully test B-Mesogenesis."

The type of baryon produced depends on the operator mediating the interaction, leading to a variety of final states. Must explore all possibilities to fully test this scenario. Four possible flavorful operators that can lead to B-Mesogenesis:

$$Y_B \simeq 8.7 \times 10^{-5}\,\mathrm{BR}(B \to \mathcal{B} + \psi_D + \mathcal{M}) \sum_{q=s,d} \alpha_q A_{SL}^q$$

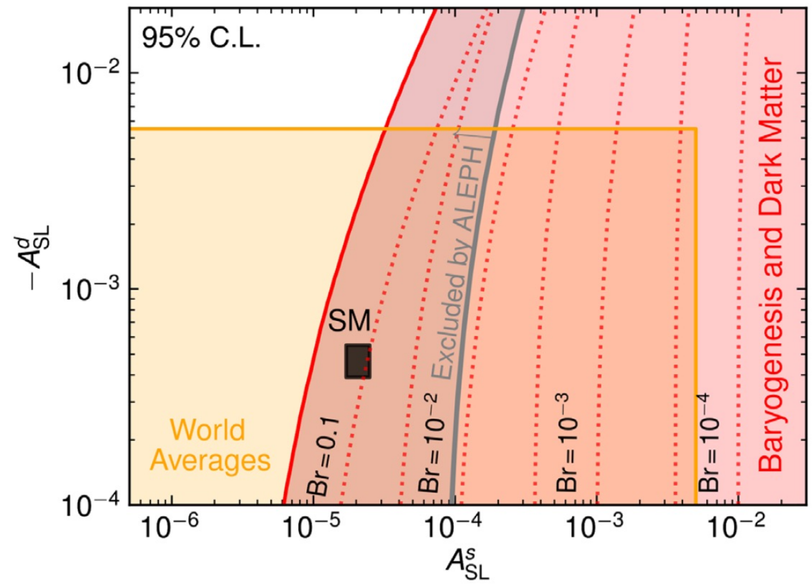
Operator and decay	Initial state	Final state	ΔM (MeV)
$\mathcal{O}_{ud} = \psi bud$	B_d	$\psi + n(udd)$	4340.1
$\bar{b} \to \psi ud$	B_s	$\psi + \Lambda(uds)$	4251.2
	B^+	$\psi + p(duu)$	4341.0
	Λ_b	$\bar{\psi} + \pi^0$	5484.5
$\mathcal{O}_{us} = \psi bus$	B_d	$\psi + \Lambda(usd)$	4164.0
$\bar{b} \to \psi us$	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

ΔM = difference in mass between initial and final SM hadron

Y_B is baryon asymmetry of Universe measured by Planck Collab [Astron. Astrophys 641, A6 (2020)]:

$$Y_{\mathcal{B}} = (n_{\mathcal{B}} - n_{\bar{\mathcal{B}}})/s = (8.718 \pm 0.004) \times 10^{-11}$$

s is the entropy density of Universe ~$7.04 n_\gamma$



Alonso-Alvarez, Elor and Escudero
PHYSICAL REVIEW D 104, 035028 (2021)

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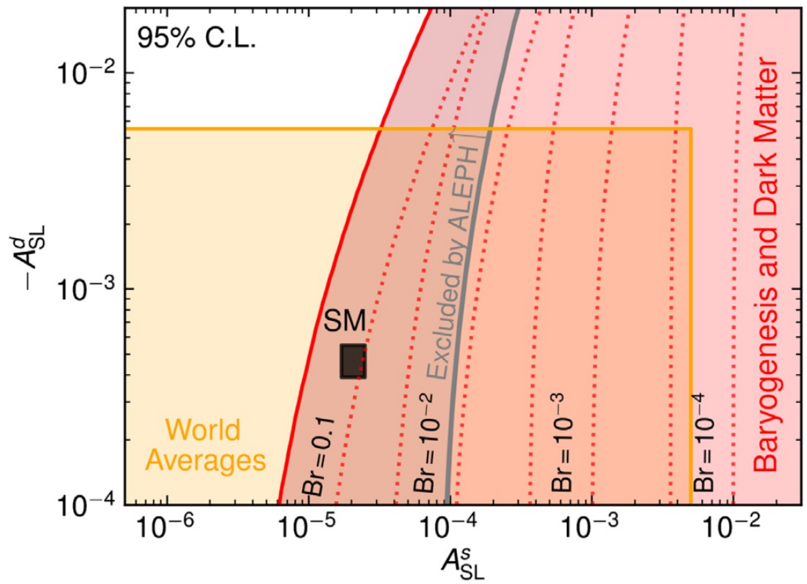


Alonso-Alvarez, Elor and Escudero
PHYSICAL REVIEW D 104, 035028 (2021)

At the e^+e^- B-factories we can look for

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

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

$$B^0 \rightarrow \psi_D + \pi^- + \Lambda_c^+$$

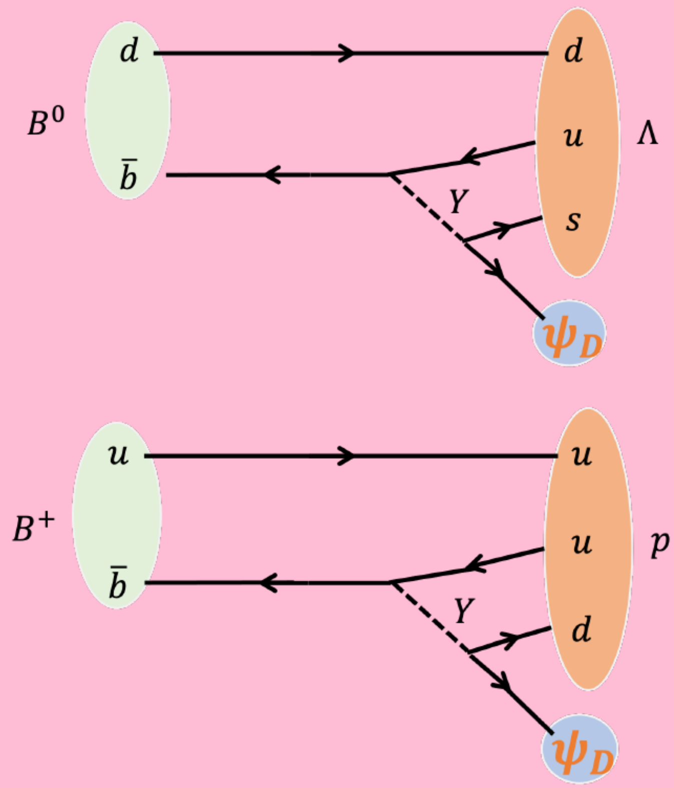
ψ_D decays into stable dark sector particles producing currently observed relic abundance

Decay mediated by colour-triplet scalar

Kinematic constraints

→ $0.94 < M(\psi_D) < 4.34$ GeV

B-Meson Decays:



ψ_D = *dark fermion;*
Y = *TeV scale mediator;*

Set limits on operators:

$\mathcal{O}_{us}$

$\bar{b} \rightarrow \psi_D u s$

$\mathcal{O}_{ud}$

$\bar{b} \rightarrow \psi_D u d$

S. Middleton April 2024 APS talk

Interpret limits as constraints on the Operators

Different combinations of the quarks in the dimension-six operators lead to different contractions of external momenta. Given this dependence on the kinematic structure of the matrix element, the operators are further classified

"type-1" $\mathcal{O}^1_{us} = (\psi_D b)(us)$

"type-2" $\mathcal{O}^2_{us} = (\psi_D s)(ub)$

"type-3" $\mathcal{O}^3_{us} = (\psi_D u)(sb)$

Operator types for $B^0 \to \psi_D + \Lambda$

(for $B^0 \to \psi_D + p$, swap $s \to d$)

type-2 and type-3 combinations have similar phase-space and always yields a larger phase-space ratio ($\frac{\mathrm{Br}(B \to \mathcal{B}_{ij} + \psi)}{\mathrm{Br}(B \to \mathcal{B}_{ij} + \psi + \mathcal{M})}$) than type-1

Belle's 2022 paper looked for $B^0 \rightarrow \psi_D + \Lambda$

PHYSICAL REVIEW D **105,** L051101 (2022)

Letter

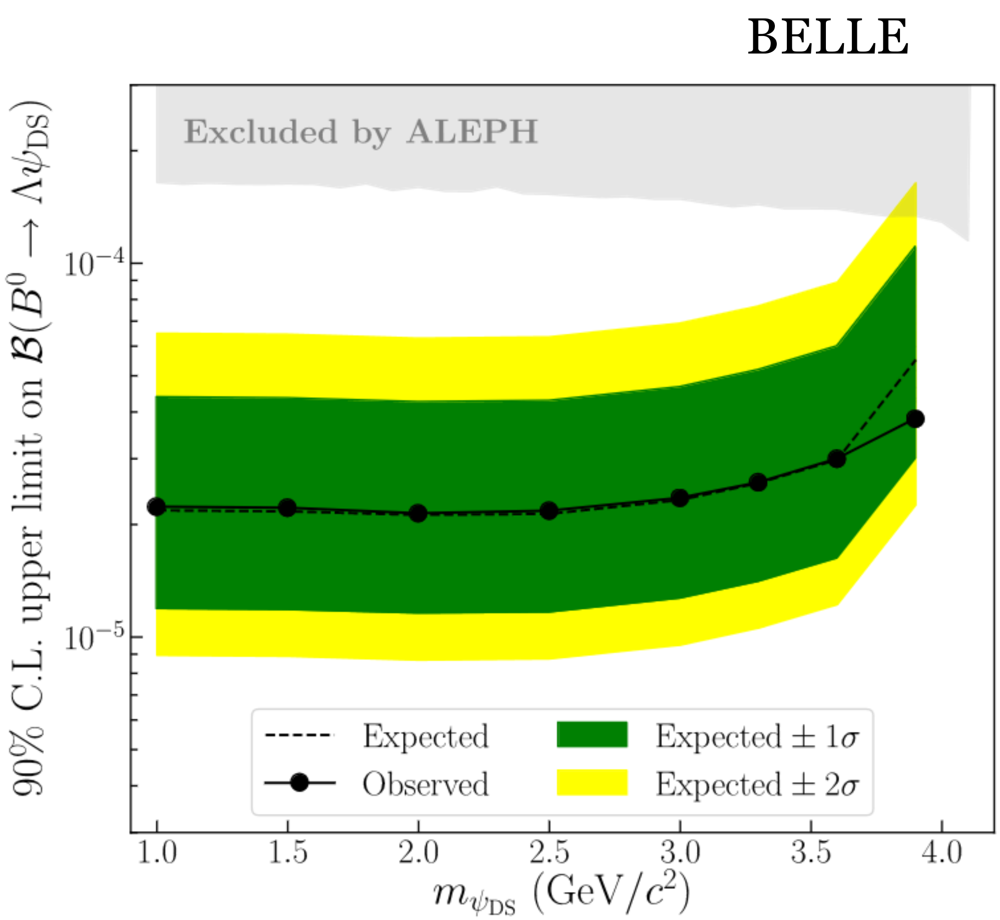
Search for B^0 meson decays into Λ and missing energy with a hadronic tagging method at Belle

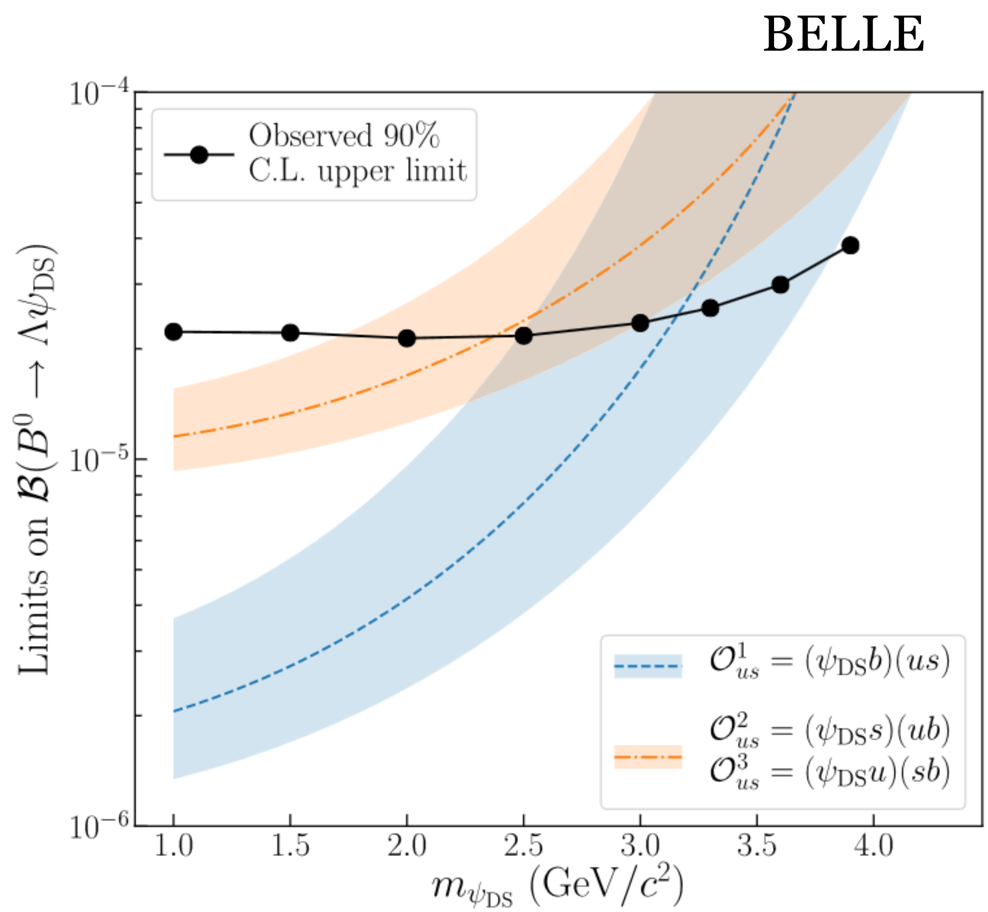
C. Hadjivasiliou,[61] B. G. Fulsom,[61] J. F. Strube,[61] I. Adachi,[16,12] H. Aihara,[78] D. M. Asner,[3] H. Atmacan,[6] T. Aushev,[18] V. Babu,[7] K. Belous,[28] J. Bennett,[47] M. Bessner,[15] V. Bhardwaj,[21] B. Bhuyan,[22] T. Bilka,[5] J. Biswal,[33] D. Bodrov,[18,39] J. Borah,[22] A. Bozek,[56] M. Bračko,[44,33] P. Branchini,[30] T. E. Browder,[15] A. Budano,[30] M. Campajola,[29,51] D. Červenkov,[5] M.-C. Chang,[9] P. Chang,[55] A. Chen,[53] B. G. Cheon,[14] K. Chilikin,[39] H. E. Cho,[14] S.-K. Choi,[13] Y. Choi,[71] S. Choudhury,[23] D. Cinabro,[82] S. Cunliffe,[7] S. Das,[43] G. De Pietro,[30] F. Di Capua,[29,51] Z. Doležal,[5] T. V. Dong,[10] D. Dossett,[46] D. Epifanov,[4,59] T. Ferber,[7] R. Garg,[62] V. Gaur,[81] A. Giri,[23] P. Goldenzweig,[34] T. Gu,[64] K. Gudkova,[4,59] H. Hayashii,[52] W.-S. Hou,[55] C.-L. Hsu,[72] T. Iijima,[50,49] K. Inami,[49] G. Inguglia,[27] A. Ishikawa,[16,12] M. Iwasaki,[60] Y. Iwasaki,[16] W. W. Jacobs,[25] S. Jia,[10] Y. Jin,[78] J. Kahn,[34] A. B. Kaliyar,[73] K. H. Kang,[37] G. Karyan,[7] C. Kiesling,[45] C. H. Kim,[14] D. Y. Kim,[70] K. T. Kim,[36] Y.-K. Kim,[84] P. Kodyš,[5] T. Konno,[35] A. Korobov,[4,59] S. Korpar,[44,33] E. Kovalenko,[4,59] P. Križan,[40,33] R. Kroeger,[47] P. Krokovny,[4,59] R. Kumar,[65] K. Kumara,[82] Y.-J. Kwon,[84] S. C. Lee,[37] L. K. Li,[6] S. X. Li,[10] Y. B. Li,[63] L. Li Gioi,[45] J. Libby,[24] K. Lieret,[41] C. MacQueen,[46] M. Masuda,[77,66] D. Matvienko,[4,59,39] M. Merola,[29,51] K. Miyabayashi,[52] R. Mizuk,[39,18] G. B. Mohanty,[73] R. Mussa,[31] M. Nakao,[16,12] Z. Natkaniec,[56] A. Natochii,[15] M. Nayak,[75] N. K. Nisar,[3] S. Nishida,[16,12] K. Nishimura,[15] H. Ono,[57,58] P. Oskin,[39] P. Pakhlov,[39,48] G. Pakhlova,[18,39] T. Pang,[64] S.-H. Park,[16] S. Paul,[74,45] T. K. Pedlar,[42] L. E. Piilonen,[81] T. Podobnik,[40,33] V. Popov,[18] E. Prencipe,[19] M. T. Prim,[2] M. Röhrken,[7] A. Rostomyan,[7] N. Rout,[24] G. Russo,[51] D. Sahoo,[73] S. Sandilya,[23] A. Sangal,[6] L. Santelj,[40,33] T. Sanuki,[76] V. Savinov,[64] G. Schnell,[1,20] C. Schwanda,[27] Y. Seino,[58] K. Senyo,[83] M. Shapkin,[28] C. P. Shen,[10] J.-G. Shiu,[55] B. Shwartz,[4,59] F. Simon,[45] J. B. Singh,[62] E. Solovieva,[39] M. Starič,[33] Z. S. Stottler,[81] M. Sumihama,[11] T. Sumiyoshi,[80] M. Takizawa,[69,17,67] K. Tanida,[32] F. Tenchini,[7] M. Uchida,[79] T. Uglov,[39,18] Y. Unno,[14] S. Uno,[16,12] R. Van Tonder,[2] G. Varner,[15] A. Vinokurova,[4,59] E. Waheed,[16] C. H. Wang,[54] E. Wang,[64] M.-Z. Wang,[55] P. Wang,[26] X. L. Wang,[10] S. Watanuki,[38] L. Wood,[61] B. D. Yabsley,[72] W. Yan,[68] H. Ye,[7] J. Yelton,[8] J. H. Yin,[36] Z. P. Zhang,[68] V. Zhilich,[4,59] and V. Zhukova[39]

(Belle Collaboration)

(Received 29 October 2021; accepted 17 February 2022; published 4 March 2022)

Belle's 2022 paper looked for $B^0 \to \psi_D + \Lambda$

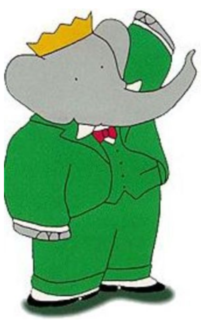


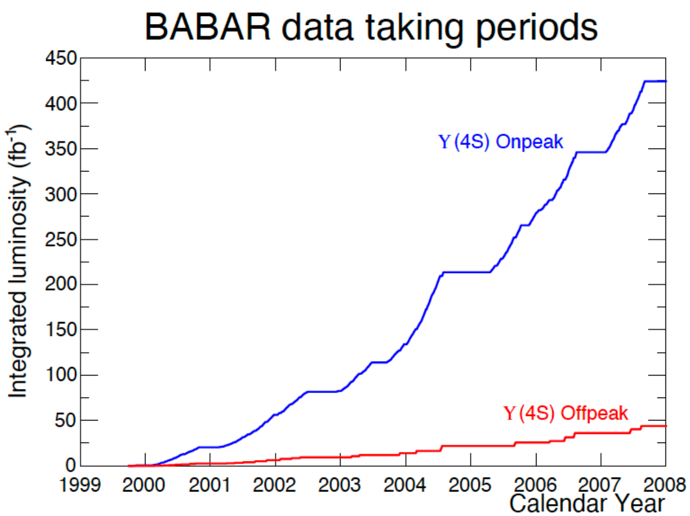


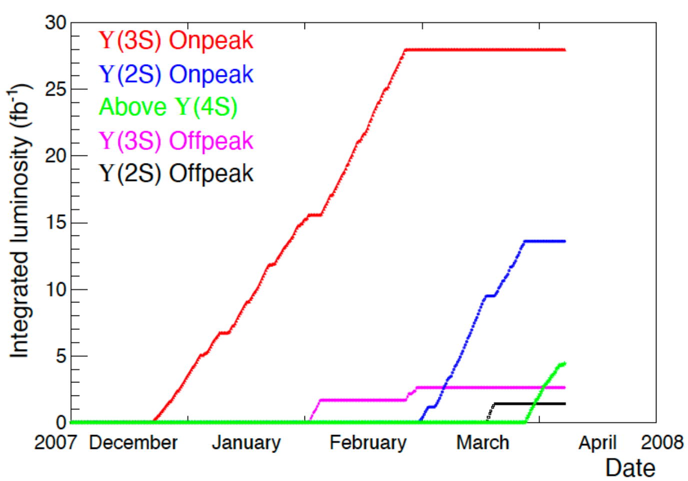
PHYS. REV. D 105, L051101 (2022)

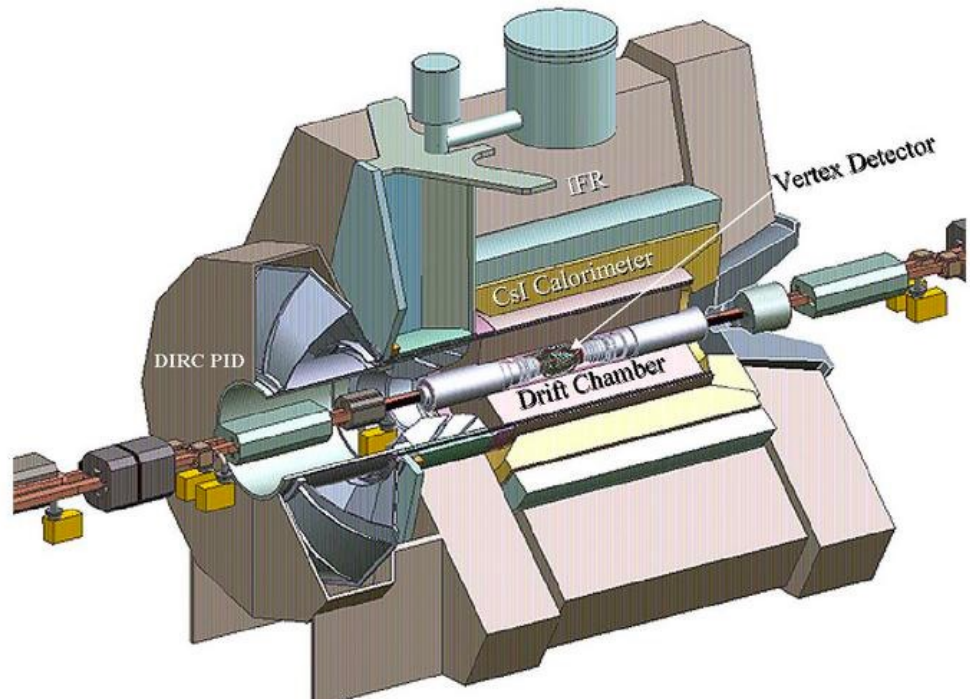
The BABAR Experiment

- Details of experiment: **Nucl. Instrum. Meth. A 729, 615 (2013)**
- Asymmetric collider @ $\sqrt{s}$ = 10.58 GeV at the Υ(4S) resonance
  - 9 GeV electrons collided with 3 GeV positrons
- **Total Υ(4S) luminosity: 4.7x10^8 $B\bar{B}$ on peak**





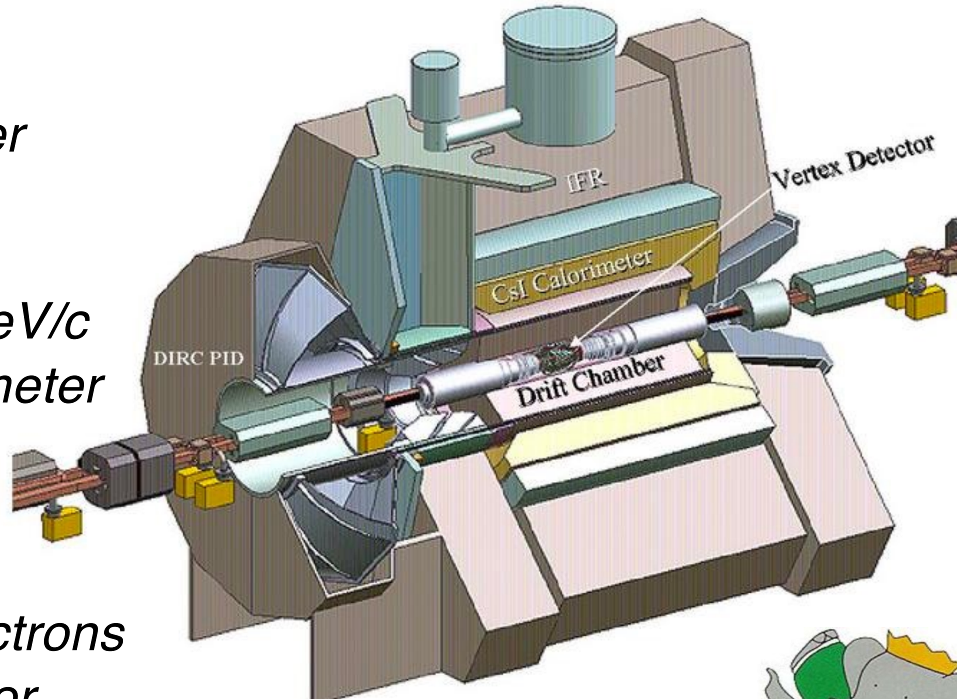




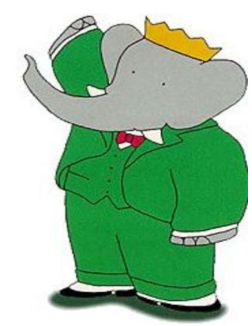
Result based on 398.5 fb^{-1} (4.4x10^8 $B\bar{B}$)
Additional 32.5 fb^{-1} used as control and analysis strategy optimization sample (excluded from final results)

The BABAR Experiment

•Details of experiment: **Nucl. Instrum. Meth. A 729, 615 (2013)**
•Asymmetric collider @ $\sqrt{s}$ = 10.58 GeV at the Υ(4S) resonance:
9 GeV electrons collided with 3 GeV positrons
•**Total Υ(4S) luminosity: 4.7x10^8 $B\overline{B}$ on peak**



- ***Reconstruct tracks:*** *Silicon Vertex Tracker (SVT) + 40-layer Drift Chamber (DCH), in 1.5-T solenoid.*
  - *Momentum resolution = 0.47% at 1 GeV/c*
- ***Measure energy:*** *Electromagnetic Calorimeter (EMC)*
  - *Energy resolution = 2.9% at 1 GeV.*
- **PID:**
  - *Identify charged pions, kaons and electrons using Ring Imaging Cherenkov detector (DIRC) + ionization loss measurements in the SVT and DCH.*
  - *Instrumented flux return of solenoid used to identify muons.*



BABAR's 2023 paper seeking $B^0 \to \psi_D + \Lambda$

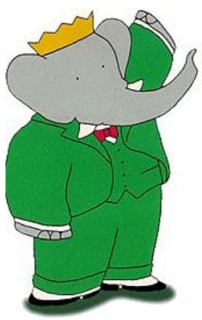
PHYSICAL REVIEW D **107,** 092001 (2023)

Search for *B* mesogenesis at *BABAR*

J. P. Lees, V. Poireau, V. Tisserand, E. Grauges, A. Palano, G. Eigen, D. N. Brown, Yu. G. Kolomensky, M. Fritsch, H. Koch, R. Cheaib, C. Hearty, T. S. Mattison, J. A. McKenna, R. Y. So, V. E. Blinov, A. R. Buzykaev, V. P. Druzhinin, E. A. Kozyrev, E. A. Kravchenko, S. I. Serednyakov, Yu. I. Skovpen, E. P. Solodov, K. Yu. Todyshev, A. J. Lankford, B. Dey, J. W. Gary, O. Long, A. M. Eisner, W. S. Lockman, W. Panduro Vazquez, D. S. Chao, C. H. Cheng, B. Echenard, K. T. Flood, D. G. Hitlin, Y. Li, D. X. Lin, S. Middleton, T. S. Miyashita, P. Ongmongkolkul, J. Oyang, F. C. Porter, M. Röhrken, B. T. Meadows, M. D. Sokoloff, J. G. Smith, S. R. Wagner, D. Bernard, M. Verderi, D. Bettoni, C. Bozzi, R. Calabrese, G. Cibinetto, E. Fioravanti, I. Garzia, E. Luppi, V. Santoro, A. Calcaterra, R. de Sangro, G. Finocchiaro, S. Martellotti, P. Patteri, I. M. Peruzzi, M. Piccolo, M. Rotondo, A. Zallo, S. Passaggio, C. Patrignani, B. J. Shuve, H. M. Lacker, B. Bhuyan, U. Mallik, C. Chen, J. Cochran, S. Prell, A. V. Gritsan, N. Arnaud, M. Davier, F. Le Diberder, A. M. Lutz, G. Wormser, D. J. Lange, D. M. Wright, J. P. Coleman, D. E. Hutchcroft, D. J. Payne, C. Touramanis, A. J. Bevan, F. Di Lodovico, G. Cowan, Sw. Banerjee, D. N. Brown, C. L. Davis, A. G. Denig, W. Gradl, K. Griessinger, A. Hafner, K. R. Schubert, R. J. Barlow, G. D. Lafferty, R. Cenci, A. Jawahery, D. A. Roberts, R. Cowan, S. H. Robertson, R. M. Seddon, N. Neri, F. Palombo, L. Cremaldi, R. Godang, D. J. Summers,* G. De Nardo, C. Sciacca, C. P. Jessop, J. M. LoSecco, K. Honscheid, A. Gaz, M. Margoni, G. Simi, F. Simonetto, R. Stroili, S. Akar, E. Ben-Haim, M. Bomben, G. R. Bonneaud, G. Calderini, J. Chauveau, G. Marchiori, J. Ocariz, M. Biasini, E. Manoni, A. Rossi, G. Batignani, S. Bettarini, M. Carpinelli, G. Casarosa, M. Chrzaszcz, F. Forti, M. A. Giorgi, A. Lusiani, B. Oberhof, E. Paoloni, M. Rama, G. Rizzo, J. J. Walsh, L. Zani, A. J. S. Smith, F. Anulli, R. Faccini, F. Ferrarotto, F. Ferroni, A. Pilloni, C. Bünger, S. Dittrich, O. Grünberg, T. Leddig, C. Voß, R. Waldi, T. Adye, F. F. Wilson, S. Emery, G. Vasseur, D. Aston, C. Cartaro, M. R. Convery, W. Dunwoodie, M. Ebert, R. C. Field, B. G. Fulsom, M. T. Graham, C. Hast, P. Kim, S. Luitz, D. B. MacFarlane, D. R. Muller, H. Neal, B. N. Ratcliff, A. Roodman, M. K. Sullivan, J. Va'vra, W. J. Wisniewski, M. V. Purohit, J. R. Wilson, S. J. Sekula, H. Ahmed, N. Tasneem, M. Bellis, P. R. Burchat, E. M. T. Puccio, J. A. Ernst, R. Gorodeisky, N. Guttman, D. R. Peimer, A. Soffer, S. M. Spanier, J. L. Ritchie, J. M. Izen, X. C. Lou, F. Bianchi, F. De Mori, A. Filippi, L. Lanceri, L. Vitale, F. Martinez-Vidal, A. Oyanguren, J. Albert, A. Beaulieu, F. U. Bernlochner, G. J. King, R. Kowalewski, T. Lueck, C. Miller, I. M. Nugent, J. M. Roney, R. J. Sobie, T. J. Gershon, P. F. Harrison, T. E. Latham, and S. L. Wu

(The *BABAR* Collaboration)

(Received 1 February 2023; accepted 23 March 2023; published 3 May 2023)



BABAR's 2023 paper seeking $B^+ \rightarrow \psi_D + p$

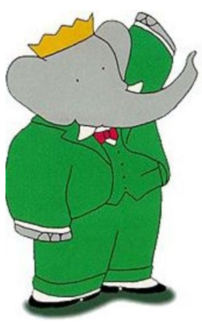
PHYSICAL REVIEW LETTERS **131,** 201801 (2023)

Search for Evidence of Baryogenesis and Dark Matter in $B^+ \rightarrow \psi_D + p$ Decays at BABAR

J. P. Lees, V. Poireau, V. Tisserand, E. Grauges, A. Palano, G. Eigen, D. N. Brown, Yu. G. Kolomensky, M. Fritsch, H. Koch, R. Cheaib, C. Hearty, T. S. Mattison, J. A. McKenna, R. Y. So, V. E. Blinov, A. R. Buzykaev, V. P. Druzhinin, E. A. Kozyrev, E. A. Kravchenko, S. I. Serednyakov, Yu. I. Skovpen, E. P. Solodov, K. Yu. Todyshev, A. J. Lankford, B. Dey, J. W. Gary, O. Long, A. M. Eisner, W. S. Lockman, W. Panduro Vazquez, D. S. Chao, C. H. Cheng, B. Echenard, K. T. Flood, D. G. Hitlin, Y. Li, D. X. Lin, S. Middleton, T. S. Miyashita, P. Ongmongkolkul, J. Oyang, F. C. Porter, M. Röhrken, B. T. Meadows, M. D. Sokoloff, J. G. Smith, S. R. Wagner, D. Bernard, M. Verderi, D. Bettoni, C. Bozzi, R. Calabrese, G. Cibinetto, E. Fioravanti, I. Garzia, E. Luppi, V. Santoro, A. Calcaterra, R. de Sangro, G. Finocchiaro, S. Martellotti, P. Patteri, I. M. Peruzzi, M. Piccolo, M. Rotondo, A. Zallo, S. Passaggio, C. Patrignani, B. J. Shuve, H. M. Lacker, B. Bhuyan, U. Mallik, C. Chen, J. Cochran, S. Prell, A. V. Gritsan, N. Arnaud, M. Davier, F. Le Diberder, A. M. Lutz, G. Wormser, D. J. Lange, D. M. Wright, J. P. Coleman, D. E. Hutchcroft, D. J. Payne, C. Touramanis, A. J. Bevan, F. Di Lodovico, G. Cowan, Sw. Banerjee, D. N. Brown, C. L. Davis, A. G. Denig, W. Gradl, K. Griessinger, A. Hafner, K. R. Schubert, R. J. Barlow, G. D. Lafferty, R. Cenci, A. Jawahery, D. A. Roberts, R. Cowan, S. H. Robertson, R. M. Seddon, N. Neri, F. Palombo, L. Cremaldi, R. Godang, D. J. Summers,* G. De Nardo, C. Sciacca, C. P. Jessop, J. M. LoSecco, K. Honscheid, A. Gaz, M. Margoni, G. Simi, F. Simonetto, R. Stroili, S. Akar, E. Ben-Haim, M. Bomben, G. R. Bonneaud, G. Calderini, J. Chauveau, G. Marchiori, J. Ocariz, M. Biasini, E. Manoni, A. Rossi, G. Batignani, S. Bettarini, M. Carpinelli, G. Casarosa, M. Chrzaszcz, F. Forti, M. A. Giorgi, A. Lusiani, B. Oberhof, E. Paoloni, M. Rama, G. Rizzo, J. J. Walsh, L. Zani, A. J. S. Smith, F. Anulli, R. Faccini, F. Ferrarotto, F. Ferroni, A. Pilloni, C. Bünger, S. Dittrich, O. Grünberg, T. Leddig, C. Voß, R. Waldi, T. Adye, F. F. Wilson, S. Emery, G. Vasseur, D. Aston, C. Cartaro, M. R. Convery, W. Dunwoodie, M. Ebert, R. C. Field, B. G. Fulsom, M. T. Graham, C. Hast, P. Kim, S. Luitz, D. B. MacFarlane, D. R. Muller, H. Neal, B. N. Ratcliff, A. Roodman, M. K. Sullivan, J. Va'vra, W. J. Wisniewski, M. V. Purohit, J. R. Wilson, S. J. Sekula, H. Ahmed, N. Tasneem, M. Bellis, P. R. Burchat, E. M. T. Puccio, J. A. Ernst, R. Gorodeisky, N. Guttman, D. R. Peimer, A. Soffer, S. M. Spanier, J. L. Ritchie, J. M. Izen, X. C. Lou, F. Bianchi, F. De Mori, A. Filippi, L. Lanceri, L. Vitale, F. Martinez-Vidal, A. Oyanguren, J. Albert, A. Beaulieu, F. U. Bernlochner, G. J. King, R. Kowalewski, T. Lueck, C. Miller, I. M. Nugent, J. M. Roney, R. J. Sobie, T. J. Gershon, P. F. Harrison, T. E. Latham, and S. L. Wu

(BABAR Collaboration)

(Received 19 June 2023; accepted 12 October 2023; published 16 November 2023)



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Method: Event Reconstruction & Pre-selection

Hadronic recoil tagging method used to reconstruct event

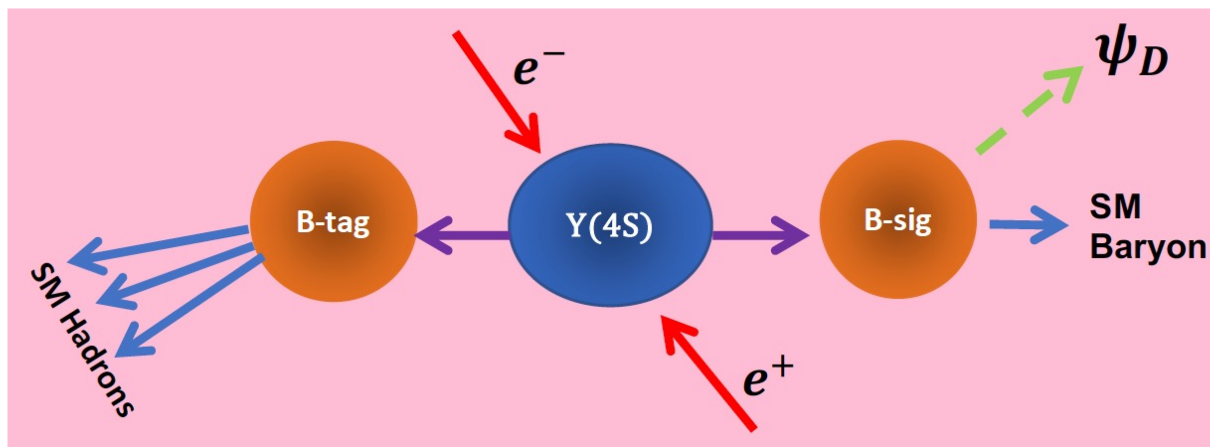
- **B-tag** = Fully reconstructed Standard Model decay mode
- **B-sig** = Potential for signal, search here for missing mass

B-tag candidate must have:

-200 MeV < ΔE < 200 MeV

and

5.2GeV < m_{ES} <5.3 GeV



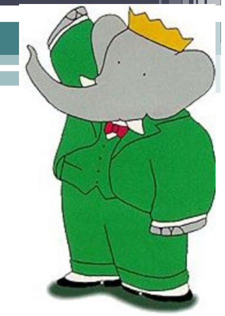
Where:

$\Delta E = E^*_{beam} - E^*_{Btag}$

CMS beam energy minus reconstructed B-tag energy

$$m_{ES} = \sqrt{E^{*2}_{beam} - \vec{p}^{*2}_{Btag}}$$

Beam-energy-substituted mass)
(same as m_{bc})



Monte Carlo

Standard Model Backgrounds:

$q\bar{q}$ *u,d,s,c* were modelled using JETSET

$B\bar{B}$ modelled using EvtGen

Signal:

EvtGen used to generate 8 signal masses separately for *p* and Λ:

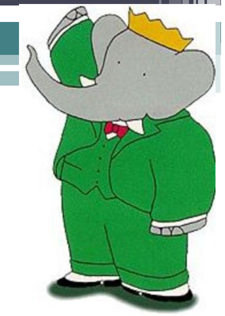
1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0 and 4.2 GeV

Analysis Method:

Samples passed through full reconstruction with efficiency and resolution determined from fits to MC;

- Functional forms of fit used to extract resolution and efficiency for any given ψ_D mass – scan across entire mass range.

In the final analysis, yields were found via a data-driven Poisson counting method, with background and signal regions defined from the study of the background and signal MC simulations



Further Channel-dependent Selection Criteria

For the *p* channel:

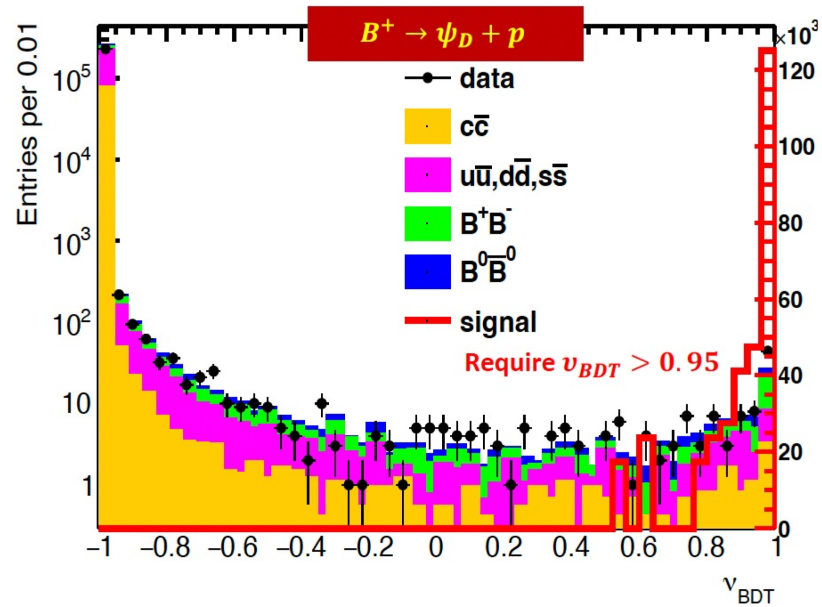
- *BABAR* proton PID can be used to identify proton candidate;
- signal side must have + charge and only one charged particle

For the *Λ* channel:

- one Λ candidate in the B-sig, $\Lambda \to p\,\pi^-$;
- two charged tracks required on the signal side;
- significance of the Λ decay length (flight length/$\sigma > 1.0$)
- four-momentum kinematic fit χ^2 of Λ reconstruction ≤ 100

(Charge-conjugate decays assumed throughout)

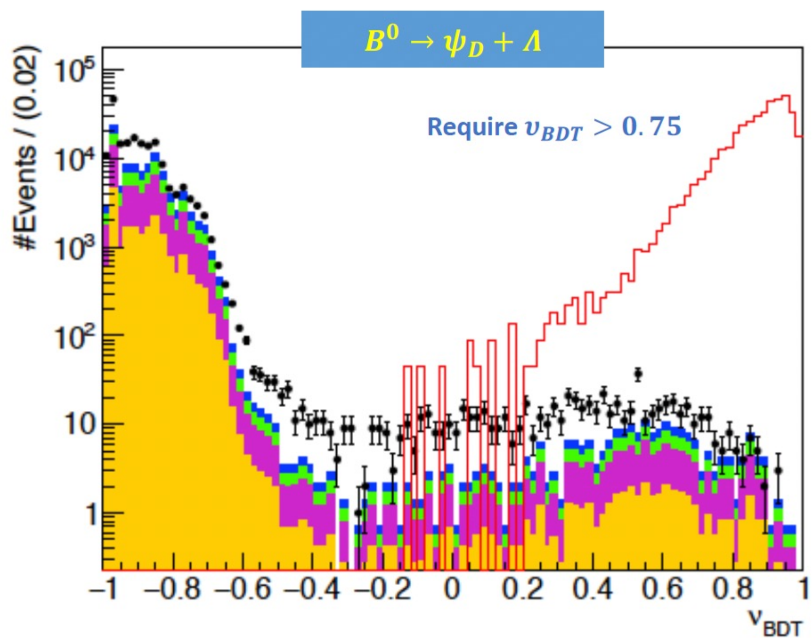
Further Channel-dependent Selection Criteria

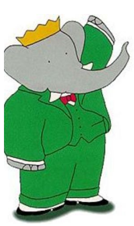


For both channels:

additional optimization of signal to background obtained using a Boosted Decision Trees customized to each channel

- p cut at $\upsilon_{\text{BDT}} > 0.95$ yields signal purity > 99 %
- Λ cut at $\upsilon_{\text{BDT}} > 0.75$ yields signal purity > 99 %





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Quantities input into the *BABAR* BDT MVA for $B^+ \rightarrow \psi_D + p$

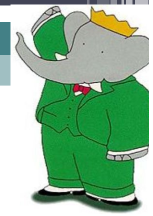
- cosine of the thrust vector
- the ratio of the second to zeroth Fox-Wolfram moment for all tracks and neutral clusters (R_2)

TAG SIDE:

- the hadronic decay channel of *B* meson tag & purity
- ΔE = $E^*_{beam} - E^*_{Btag}$
- $m_{ES} = \sqrt{E^{*2}_{beam} - \vec{p}^{*2}_{Btag}}$
- B-tag thrust magnitude (thrust axis defined as the axis which maximizes the longitudinal momenta of all the particles for B-tag reconstruction)

SIGNAL SIDE:

- total extra neutral energy on signal side in CM frame
- number of neutral particles in the signal side
- the number of π^0 candidates on the signal side
- the polar angle of the missing momentum vector recoiling against the B-tag meson and the signal candidate



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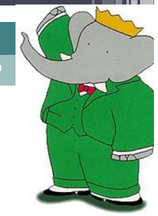


Quantities input into the *BABAR* BDT MVA for $B^0 \to \psi_D + \Lambda$

- **The significance of the Λ decay length**
- **The χ^2 of the Λ fit**
- **Energy and momentum of Λ lab frame**
- **Momentum vector of B_{sig}**

- cosine of the thrust vector
- the ratio of the second to zeroth Fox-Wolfram moment for all tracks and neutral clusters (R_2)

TAG SIDE:

- the hadronic decay channel of *B* meson tag & purity
- $\Delta E = E^*_{beam} - E^*_{Btag}$
- $m_{es} = \sqrt{E^{*2}_{beam} - \vec{p}^{*2}_{Btag}}$
- B-tag thrust magnitude

SIGNAL SIDE:

- total extra neutral energy on signal side in CM frame
- number of neutral particles in the signal side
- the number of π^0 candidates on the signal side

Extraction of Final Results

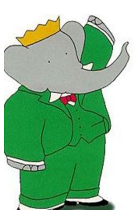
- Reconstruct ψ_D from missing energy 4-vector on signal side
- Scan across mass range, with step size equivalent to σ at that mass
- Extract resolution (σ_{ψ_D}) and efficiency (ε_{MC}) from fits to MC
- ε_{MC} signal ranges

  For Λ:

  $5.9\text{x}10^{-4}$ for ψ_D = 1GeV and $2.1\text{x}10^{-4}$ for ψ_D = 4.2GeV

  For p:

  $1.5\text{x}10^{-3}$ for ψ_D = 1GeV and $6\text{x}10^{-3}$ for ψ_D = 4.2GeV

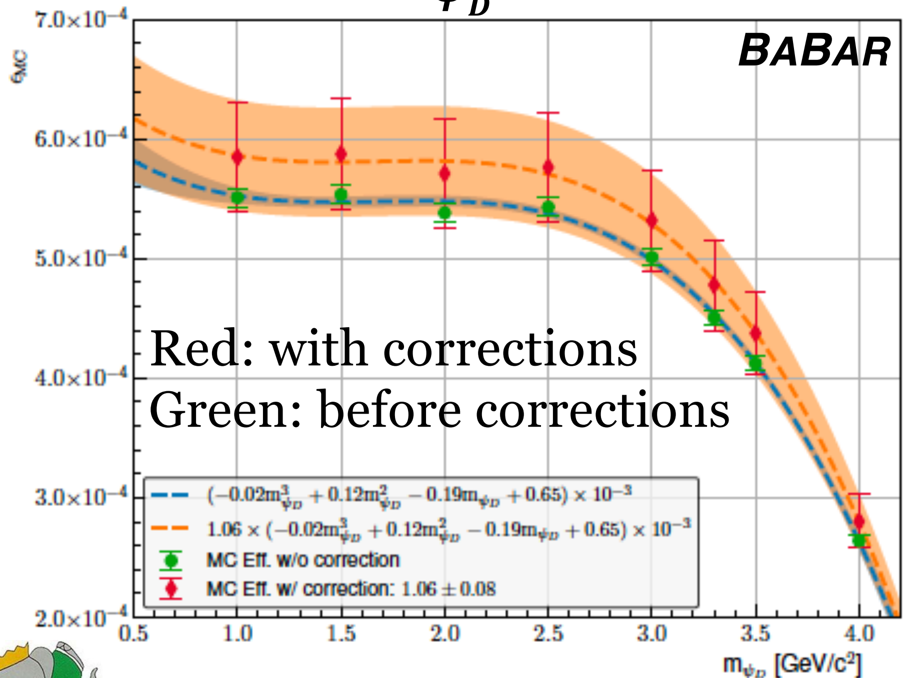


Extraction of Final Results

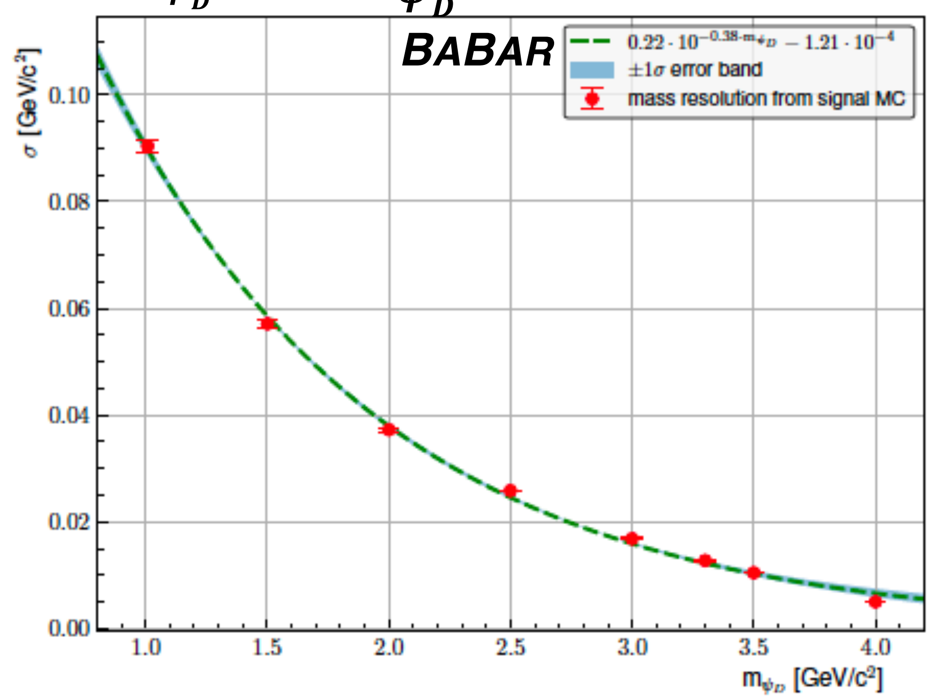
Estimate signal and backgrounds in data from MC study with corrections to MC from data-driven studies

$e.g.$ in $B^0 \rightarrow \psi_D + \Lambda$ analysis:

ε_{MC} *vs* m_{ψ_D}



σ_{ψ_D} *vs* m_{ψ_D}



$$m_{\psi_D} = m_{miss} = \sqrt{(E^*_{Bsig} - E^*_{\Lambda})^2 - |\vec{p}^{\,*}_{Bsig} - \vec{p}^{\,*}_{\Lambda}|^2}$$

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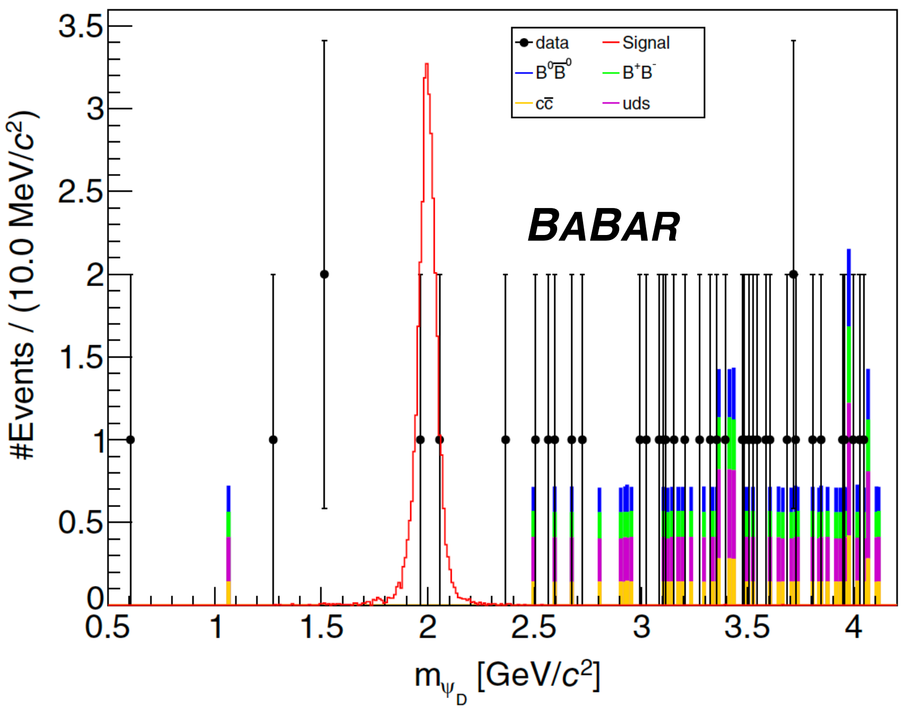
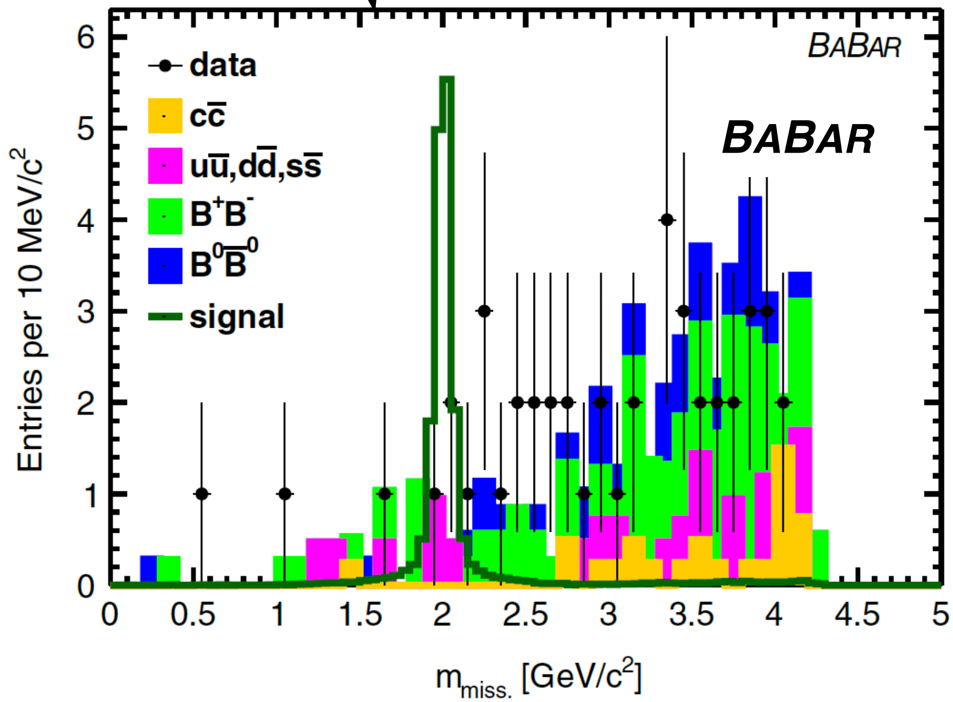
Extraction of Final Results

$$m_{\psi_D} = m_{miss} = \sqrt{(E^*_{Bsig} - E^*_p)^2 - |\vec{p}^*_{Bsig} - \vec{p}^*_p|^2}$$





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

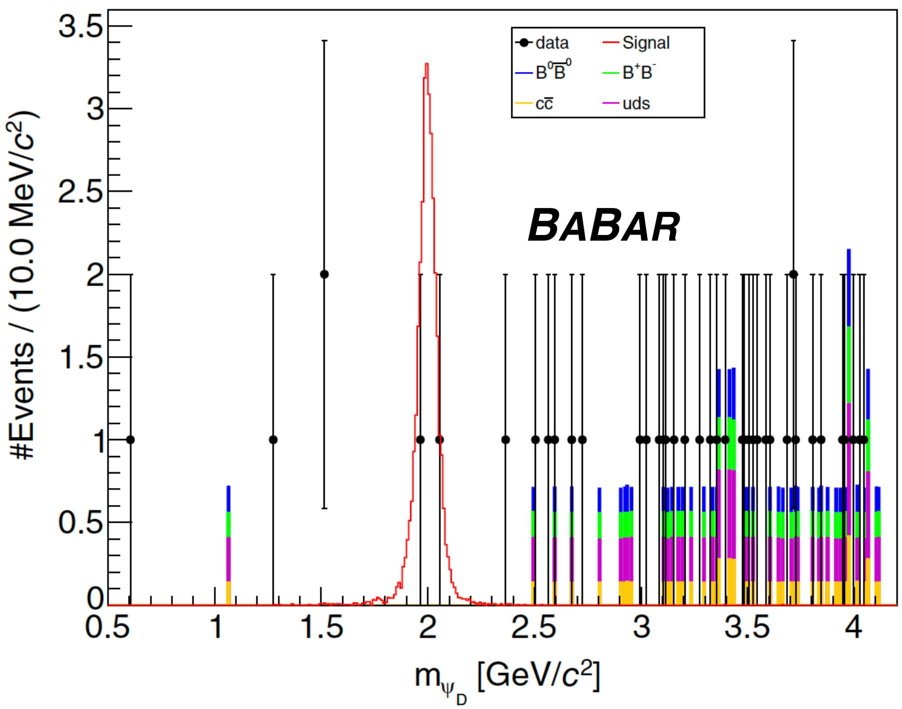
41 events survive in data

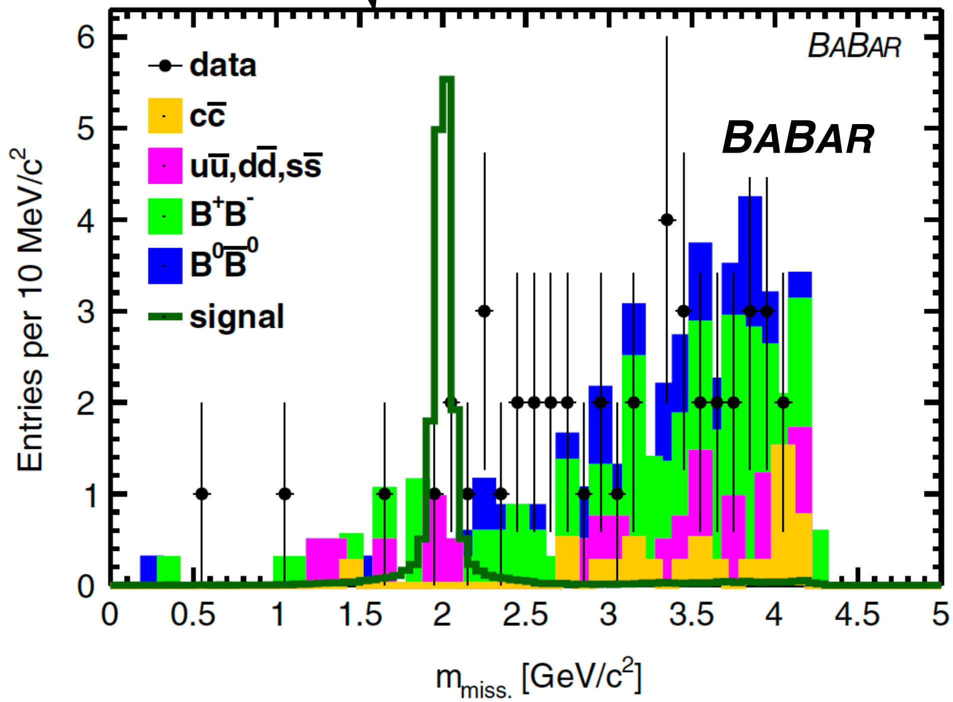
$$B^+ \rightarrow \psi_D + p$$

47 events survive in data

Extraction of Final Results

$$m_{\psi_D} = m_{miss} = \sqrt{(E^*_{Bsig} - E^*_p)^2 - |\vec{p}^*_{Bsig} - \vec{p}^*_p|^2}$$





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

41 events survive in data

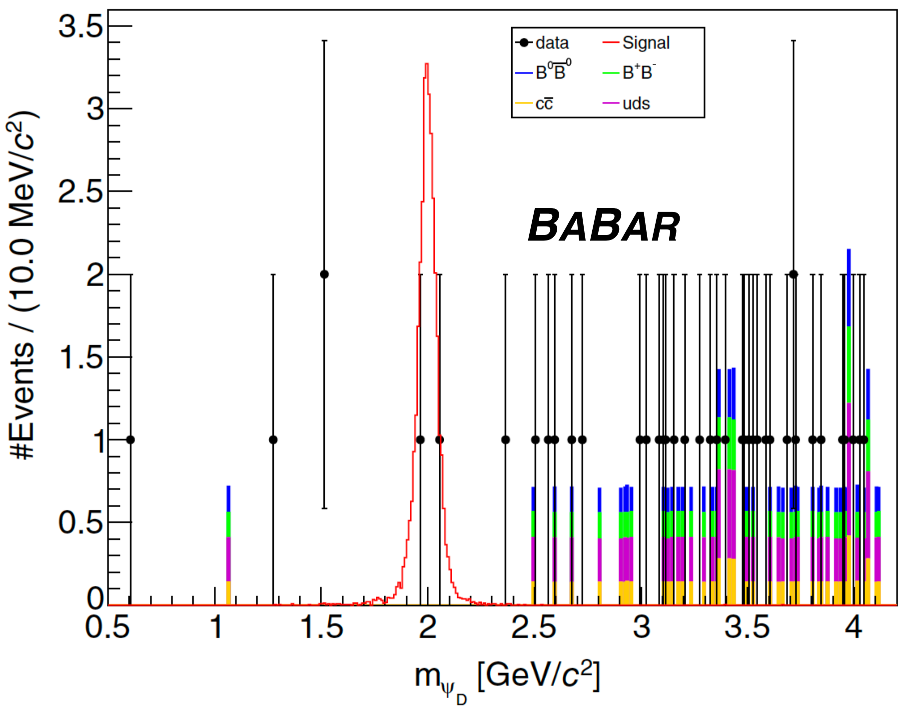
2.3σ at 3.7 GeV: largest local significance
=> a 0.4 σ global significance

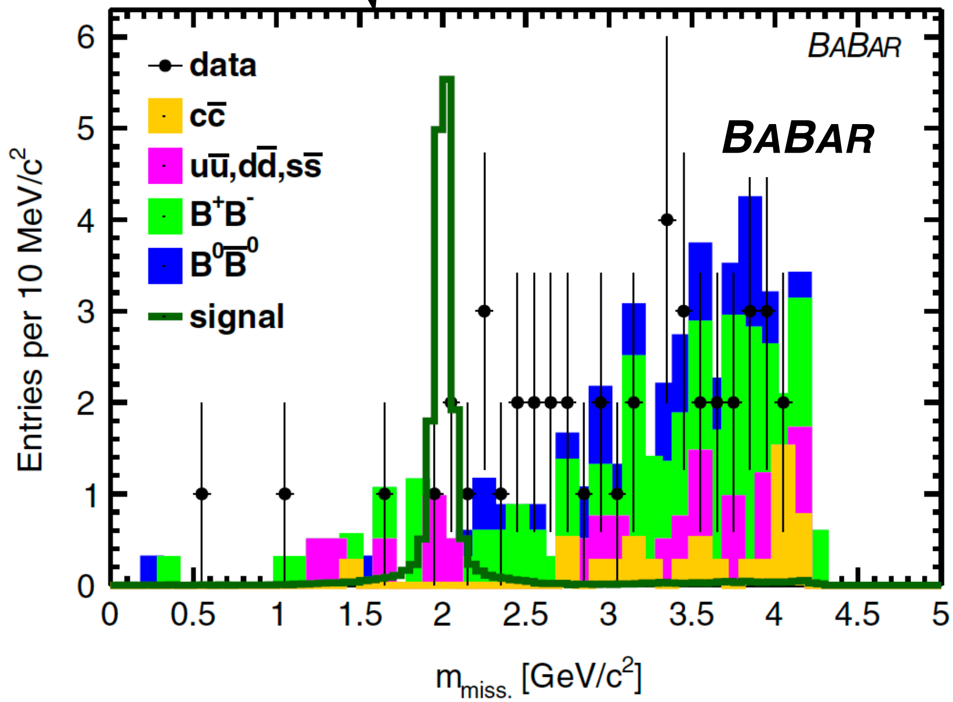
$B^+ \rightarrow \psi_D + p$

47 events survive in data

Extraction of Final Results

$$m_{\psi_D} = m_{miss} = \sqrt{(E^*_{Bsig} - E^*_p)^2 - |\vec{p}^*_{Bsig} - \vec{p}^*_p|^2}$$





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

41 events survive in data

2.3σ at 3.7 GeV: largest local significance
=> a 0.4 σ global significance

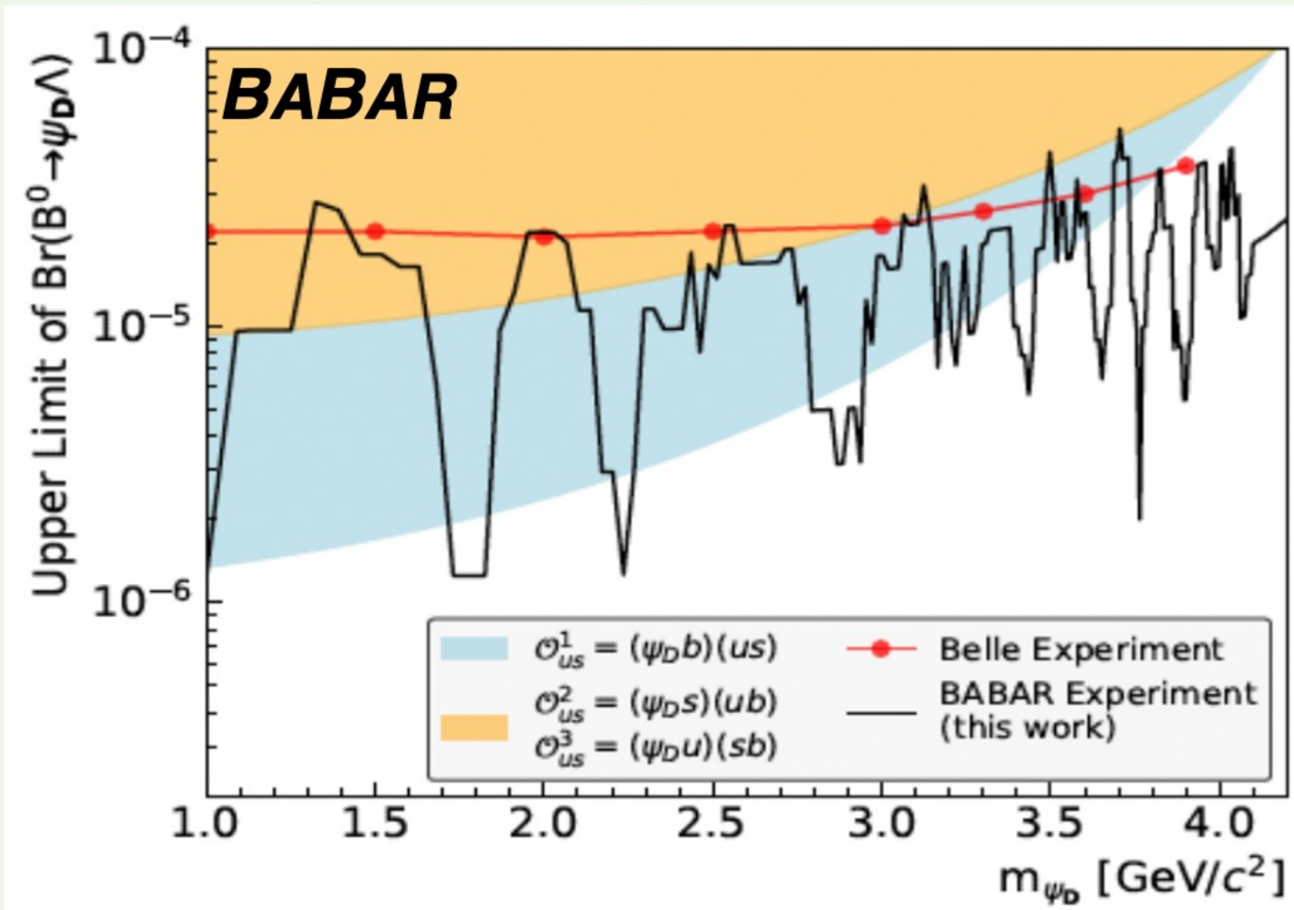
$B^+ \rightarrow \psi_D + p$

47 events survive in data

3.5σ at 3.3 GeV: largest local significance
=> a 1 σ global significance

Final Results

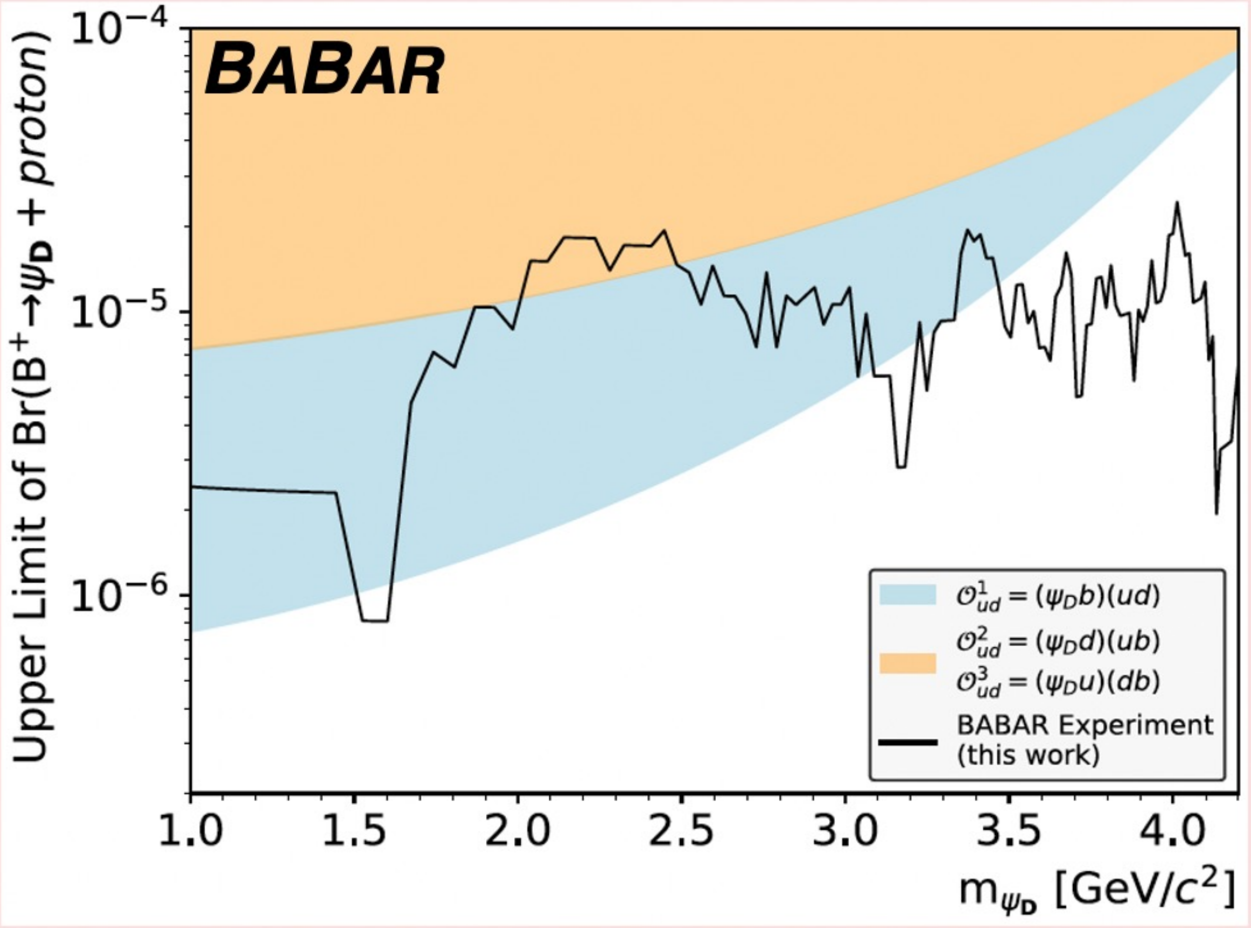
$B^0 \to \psi_D + \Lambda$



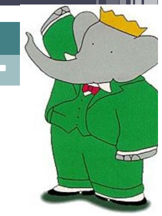
Phys.Rev.D 107 (2023) 9, 092001

Final Results

$B^+ \to \psi_D + p$

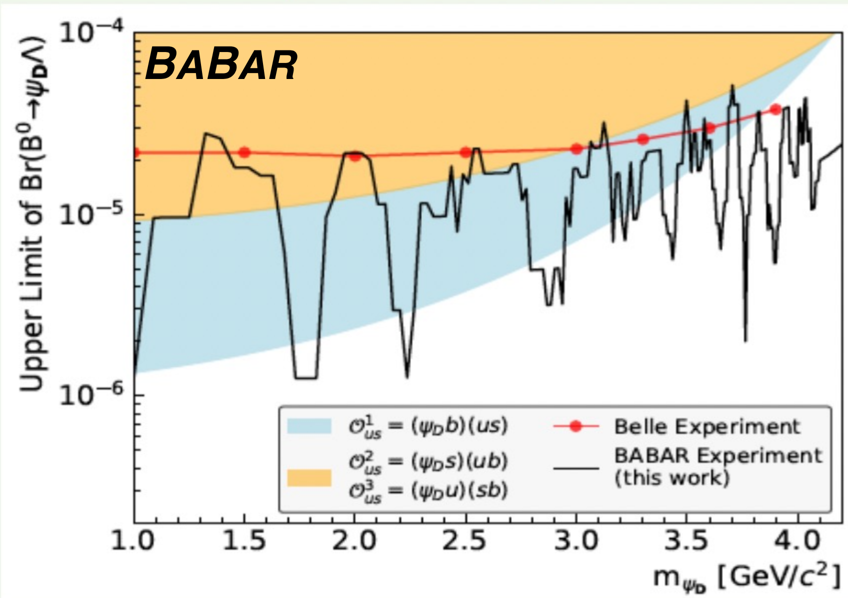


Phys.Rev.Lett. 131 (2023) 20, 201801



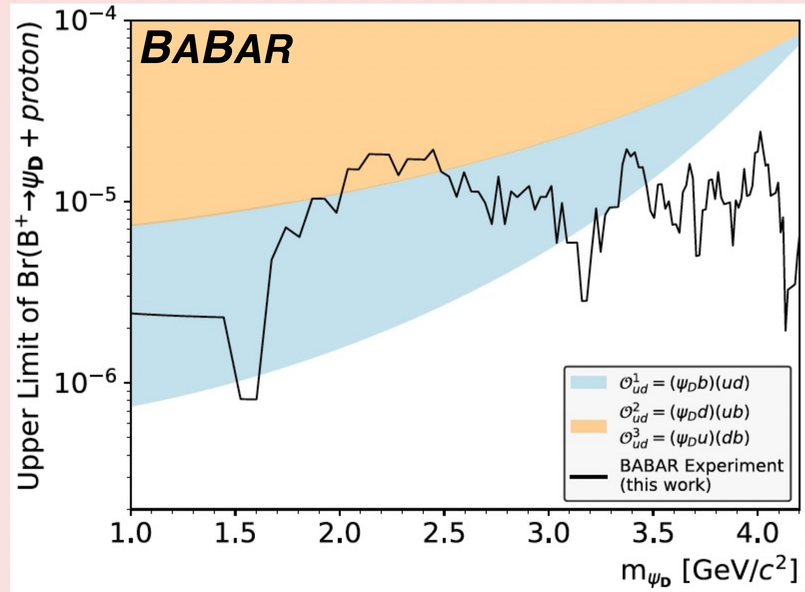
Final Results

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



Phys.Rev.D 107 (2023) 9, 092001

$B^+ \to \psi_D + p$



Phys.Rev.Lett. 131 (2023) 20, 201801

World-leading result for $B^0 \to \psi_D + \Lambda$ improving on Belle result and further constraining models

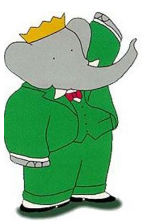
First direct search for $B^+ \to \psi_D + p$ places tight constraints on the specified model of Dark Matter + Baron Asymmetry of the Universe

BUT WAIT!!!!!

If you send us with a theory sensitive to the

$$B^{+} \rightarrow Missing + p$$

we'll set a limit on it, but you needed to act fast



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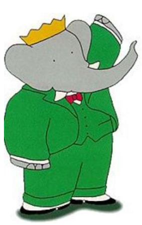
If you send us with a theory sensitive to the

$$B^{+} \rightarrow Missing + p$$

we'll set a limit on it, but you needed to act fast (‘cause we already published .... :)



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JHEP02(2023)224

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Claudio O. Dib,[a] Juan Carlos Helo,[b,c] Valery E. Lyubovitskij,[d,a,c] Nicolás A. Neill,[e] Abner Soffer[f] and Zeren Simon Wang[g,h]

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$$B^0 \to \widetilde{\chi}^0 + \Lambda$$

$\widetilde{\chi}_0$ is the lightest neutralino

Cast the measurements in terms of the RPV coupling, λ''_{123} (for Λ) or λ''_{113} (for p), divided by the relevant squark mass squared as function of the neutralino mass

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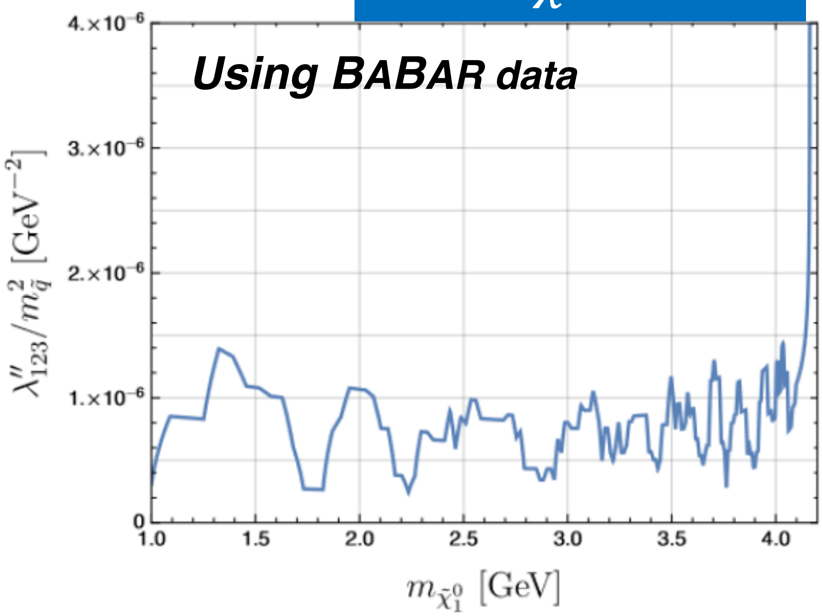
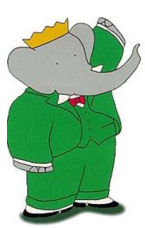


Using preliminary results from "Search for B Mesogenesis at *BABAR*" arXiv:2302.00208v1. 1 Feb 2023 [published shortly after as *PHYSICAL REVIEW D* **107**, *092001 (2023)*]



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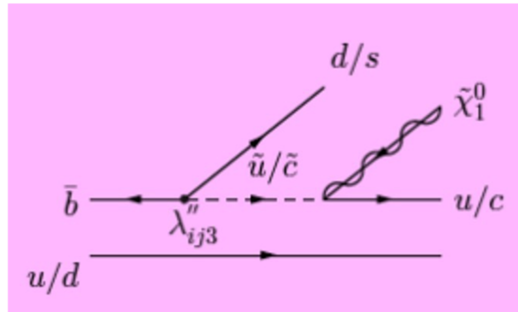
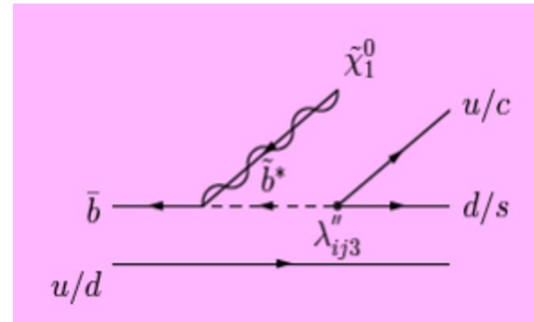
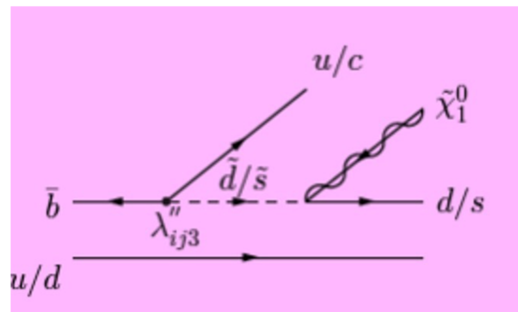
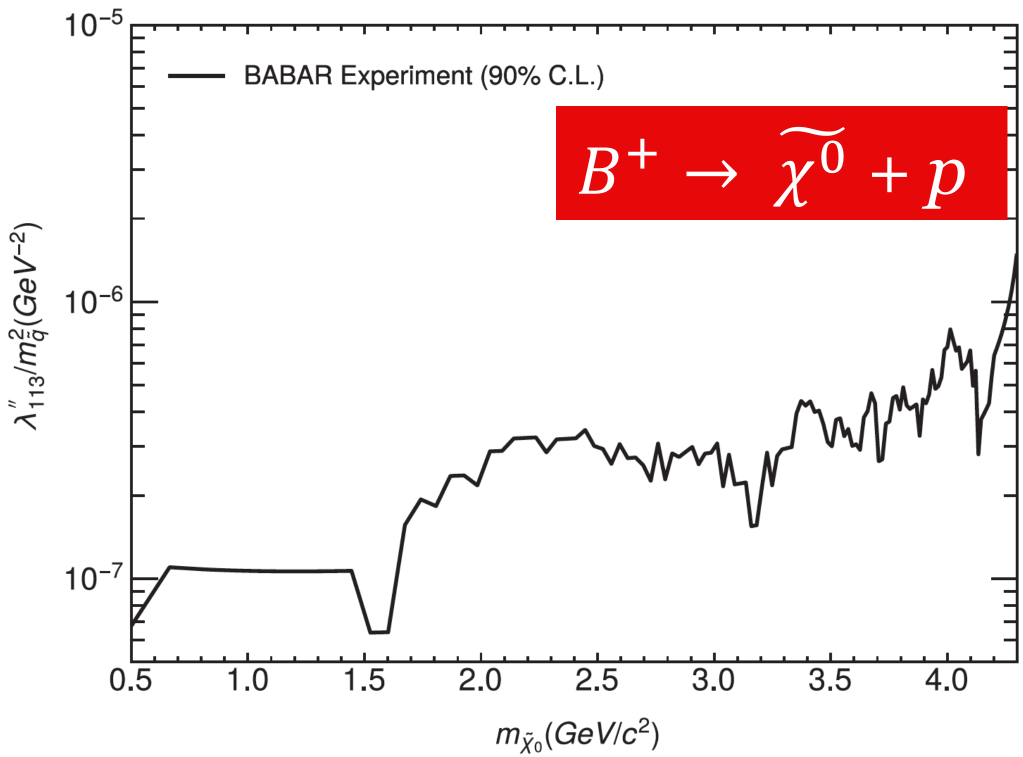
BABAR result on RPV search

Use $B^+ \to \psi_D + p$ search to provide first limit on RPV SUSY model λ''_{113} /m²$(\tilde{q})$ vs m$(\widetilde{\chi^0})$ described in JHEP 2023 (02 224 (2023))





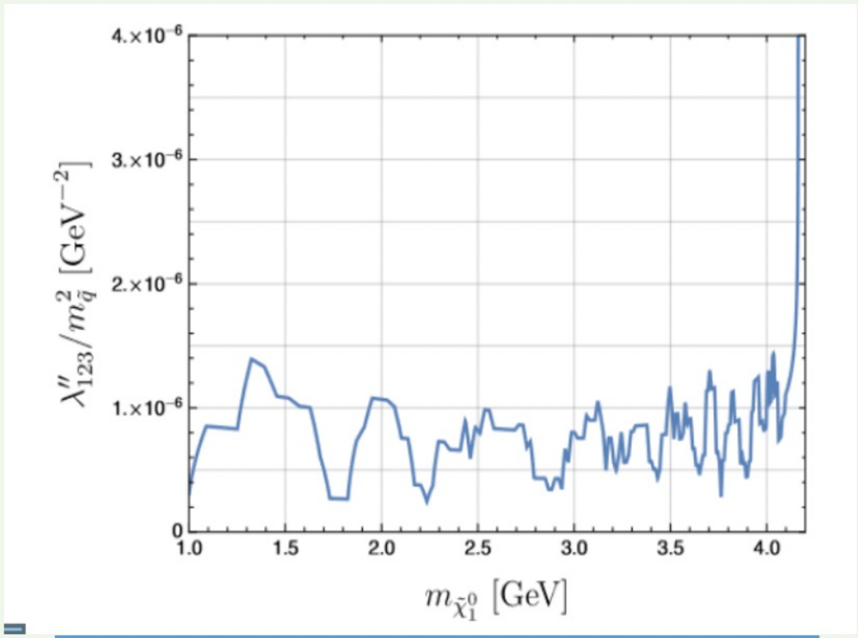




BABAR results on RPV searches

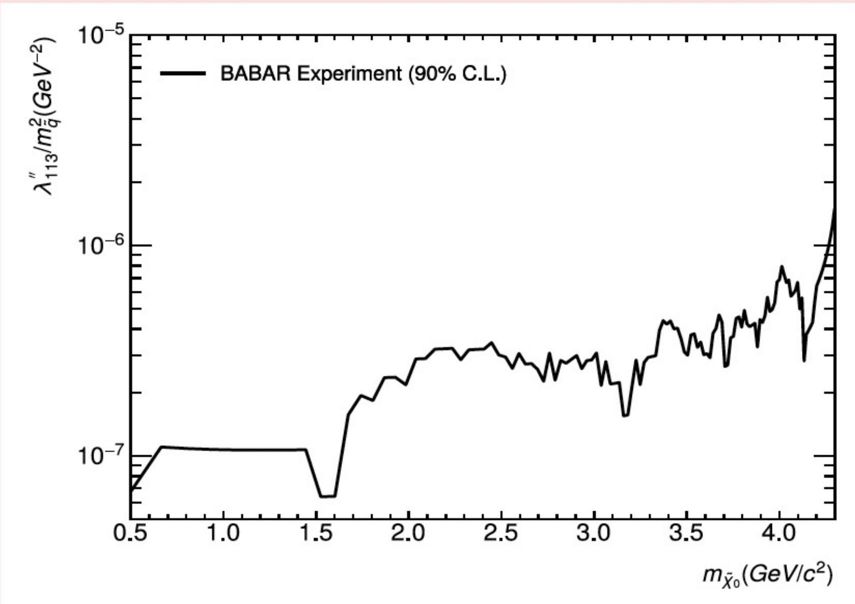
First limits on this SUSY model for both channels

$B^0 \to \widetilde{\chi}_0 + \Lambda$



JHEP 02 (2023) 224

$B^+ \to \widetilde{\chi}_0 + p$



Phys.Rev.Lett. 131 (2023) 20, 201801

Summary & Next Steps

In 2023 *BABAR* finalized & published results on

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

Search for B mesogenesis at *BABAR*,
BABAR Collaboration, Phys.Rev.Lett. 131 (2023) 20, 201801; 2306.08490[hep-ex]

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

Search for Evidence of Baryogensis and Dark Matter in $B^+ \rightarrow \psi_D + p$ at BABAR,
BABAR Collaboration, Phys.Rev.Lett. 131 (2023) 20, 201801; 2306.08490[hep-ex]

Summary & Next Steps

B-Mesogenesis parameter space vastly reduced, almost excluded for some operators

Must explore additional operators to fully exclude this B-Mesogenesis model

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B-Mesogenesis parameter space vastly reduced, almost excluded for some operators

Must explore additional operators to fully exclude this B-Mesogenesis model

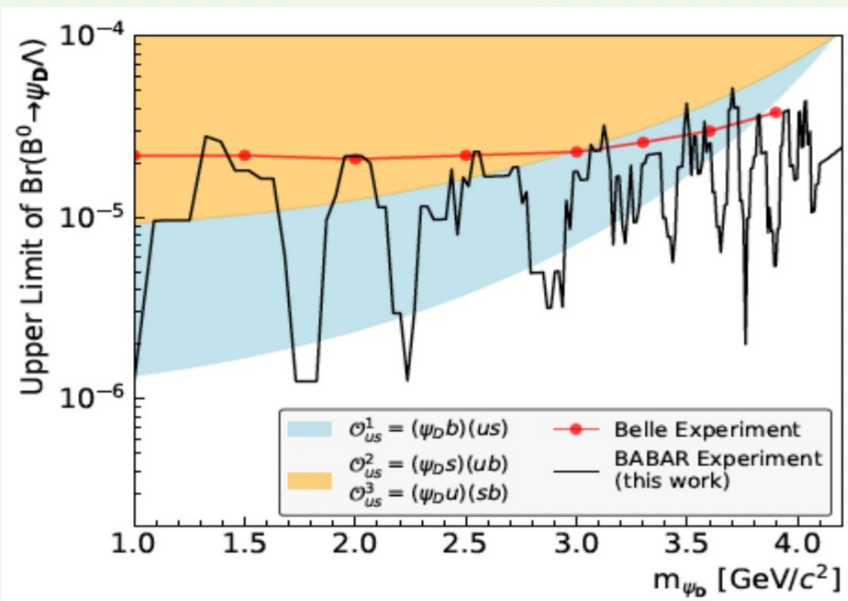
Coming soon from *BABAR:*

$$B^0 \to \psi_D + \pi^- + \Lambda_c^+$$

Summary & Next Steps

We also look forward to seeing Belle II address the operator regions where we have not been able to exclude B-Mesogenesis once it collects sufficient data from its high luminosity running

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



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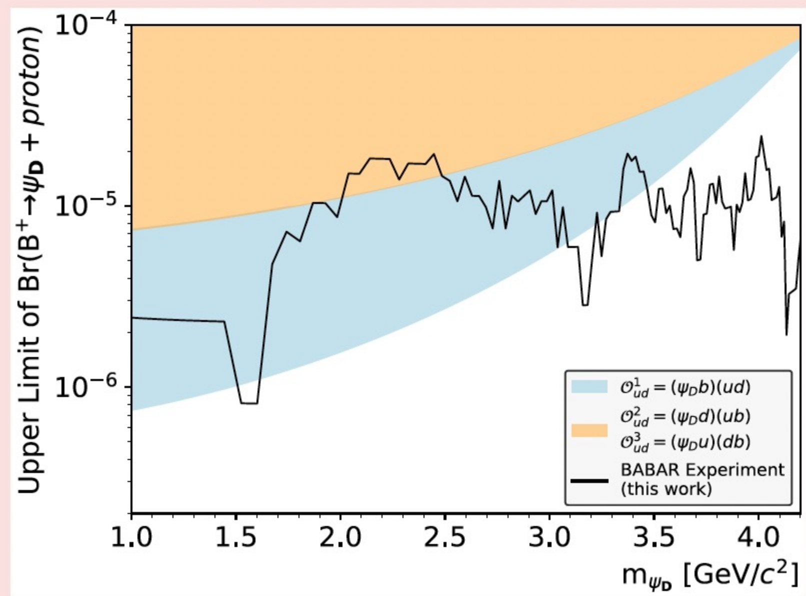
$B^+ \to \psi_D + p$



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Thankyou for your attention…

Additional Information

PHYSICAL REVIEW D **104,** 035028 (2021)

Editors' Suggestion

Discussion of Operators in

Collider signals of baryogenesis and dark matter from B mesons: A roadmap to discovery

Gonzalo Alonso-Álvarez,[1,2,*] Gilly Elor,[3,†] and Miguel Escudero[4,‡]

C. Exotic B-meson decays

As discussed in the Introduction, one of the key predictions of B-Mesogenesis is the presence of a new decay mode of B mesons into a dark antibaryon ψ, a visible baryon $\mathcal{B}$, and any number of light mesons with a branching fraction $\mathrm{Br}(B \to \psi \mathcal{B} \mathcal{M}) \gtrsim 10^{-4}$.

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

$$\mathcal{O}_{ud} = \psi b u d, \tag{15a}$$

$$\mathcal{O}_{us} = \psi b u s, \tag{15b}$$

$$\mathcal{O}_{cd} = \psi b c d, \tag{15c}$$

$$\mathcal{O}_{cs} = \psi b c s, \tag{15d}$$

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" $\mathcal{O}_{ij}^1 = (\psi b)(u_i d_j)$, "type 2" $\mathcal{O}_{ij}^2 = (\psi d_j)(u_i b)$, and "type 3" $\mathcal{O}_{ij}^3 = (\psi u_i)(d_j b)$. This distinction becomes relevant for some of the constraints discussed in the next sections.

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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

For each operator $\mathcal{O}_{ij} = \psi b u_i d_j$, the phase-space integration depends on the matrix element obtained from the effective Lagrangian (45a). Different combinations of the quarks in the dimension-six operators in Eq. (15) lead to different contractions of external momenta. Given this dependence on the kinematic structure of the matrix element, we choose to separate the results of different quark combinations in Figs. 6 and 7. In these figures, the left panel corresponds to the "type-1" operator $\mathcal{O}_{ij}^1 = (\psi b)(u_i d_j)$, while the right one corresponds to the "type-2" and "type-3" cases $\mathcal{O}_{ij}^2 = (\psi d_j)(u_i b)$ and $\mathcal{O}_{ij}^3 = (\psi u_i)(d_j b)$, for which the phase-space integration is very similar. Note that the type-2 and type-3 combinations always yields a larger phase-space ratio than the type-1 one. This means that it is easier to probe the inclusive branching ratio $B \to \psi \mathcal{B} \mathcal{M}$ by measuring the exclusive channel $B \to \psi \mathcal{B}$ if the effective operators are of the former types.

PHYSICAL REVIEW D **104**, 035028 (2021)

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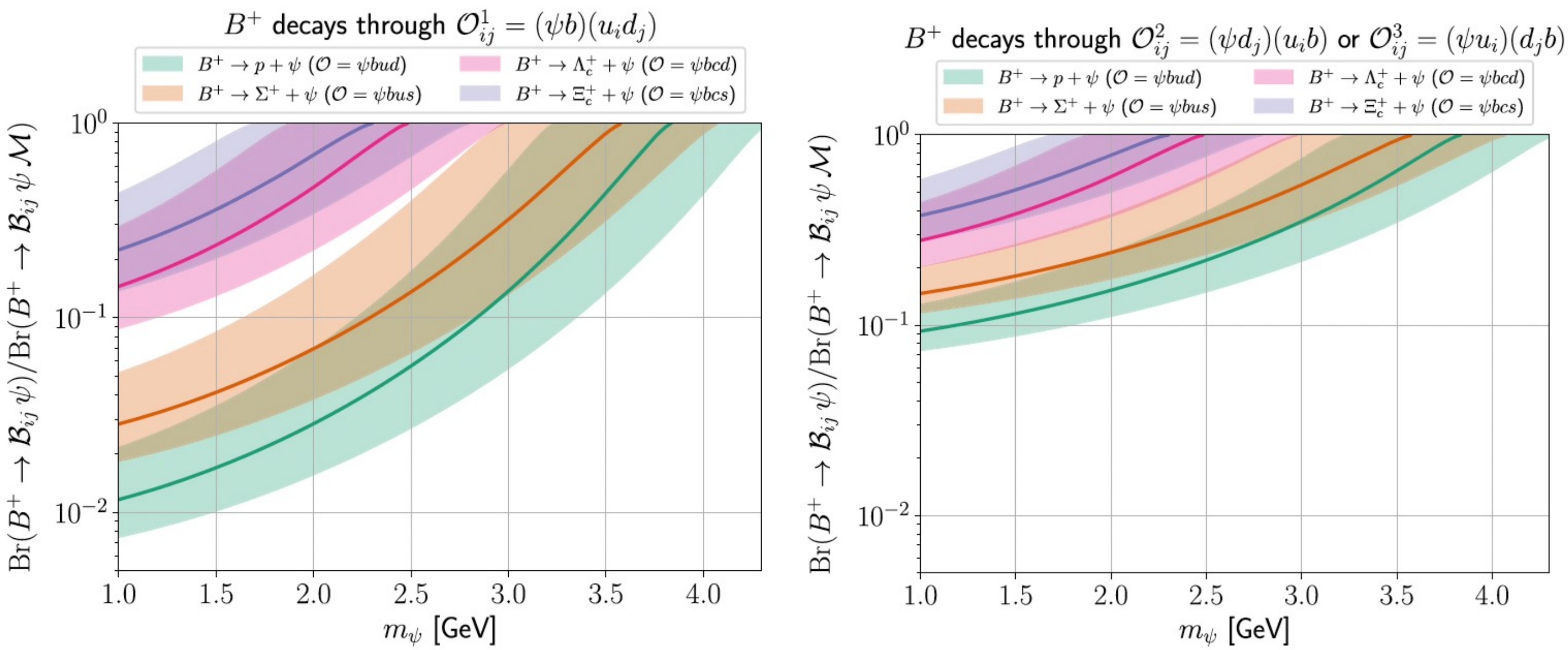

FIG. 6. Fraction of $B^+ \to \psi\mathcal{B}\mathcal{M}$ decays that are not expected to contain hadrons other than $\mathcal{B}$ in the final state, as a function of the mass of the dark fermion ψ. Different colors correspond to decays induced by the different operators listed in Table I. Each panel corresponds to a different kinematic structure of the effective four-fermion operator as listed in Table II. The width of the band represents an estimation of the uncertainty in our computations and is obtained by varying the b-quark mass used in the calculation between $\bar{m}_b(\mu = \bar{m}_b)$, m_b^{pole} (solid line), and $m_{B_d^0}$.

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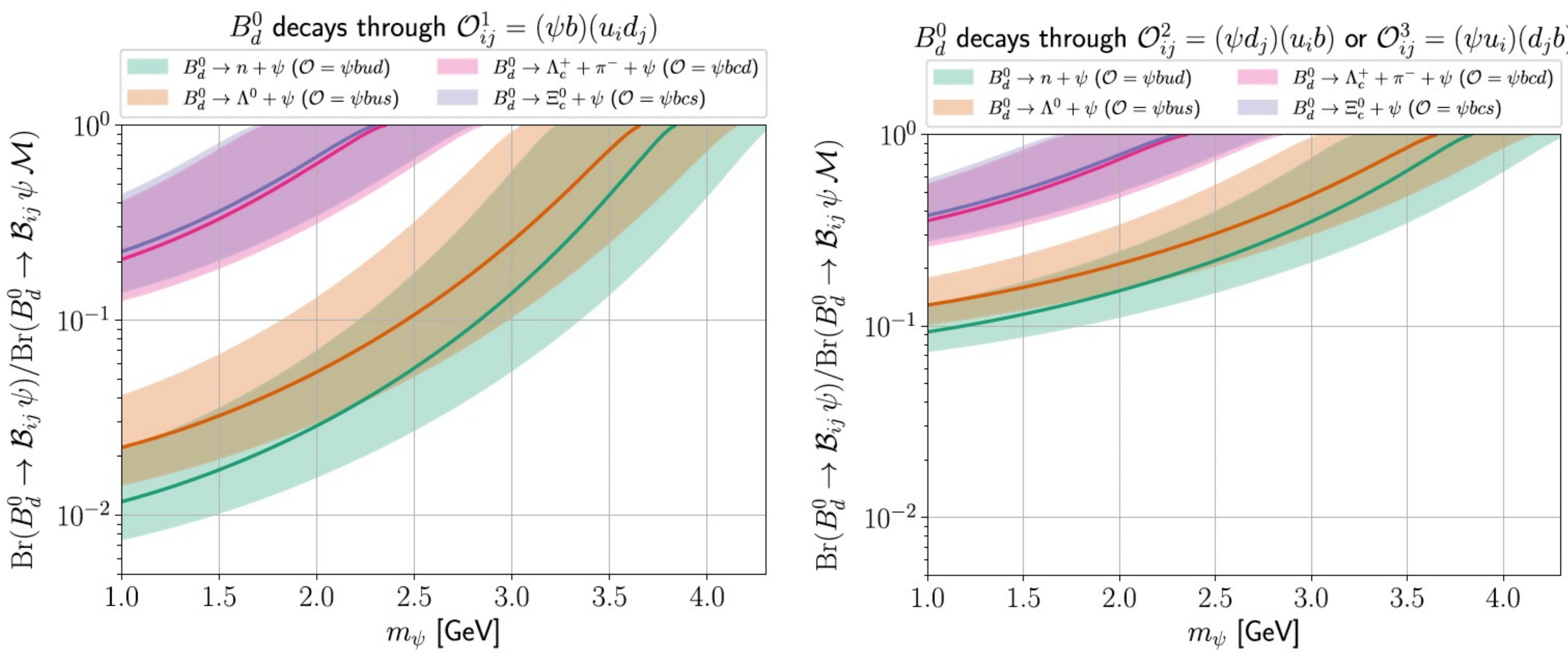

FIG. 7. Same as Fig. 6 but for $B_d^0 \to \psi\mathcal{B}\mathcal{M}$ decays.