EPS-HEP2023 conference, August 20-25, 2023
University of Hamburg

Recent Dark Matter related searches with the *BABAR* detector

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BABAR™

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Recent Dark Matter related searches with the $BABAR$ detector

Paper one: Baryogenesis and Dark Matter

✓ Search for Baryogenesis and Dark Matter in $B^+ \to \psi_D + p$ Decays at BABAR

arXiv:2306.08490v3 (First presented at Moriond EW 2023), submitted to PRL

Paper two: Mesogenesis

✓ *Search for B mesogenesis at BABAR*

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

Motivations

- Existence of Dark Matter (DM) is evident from astrophysical observations

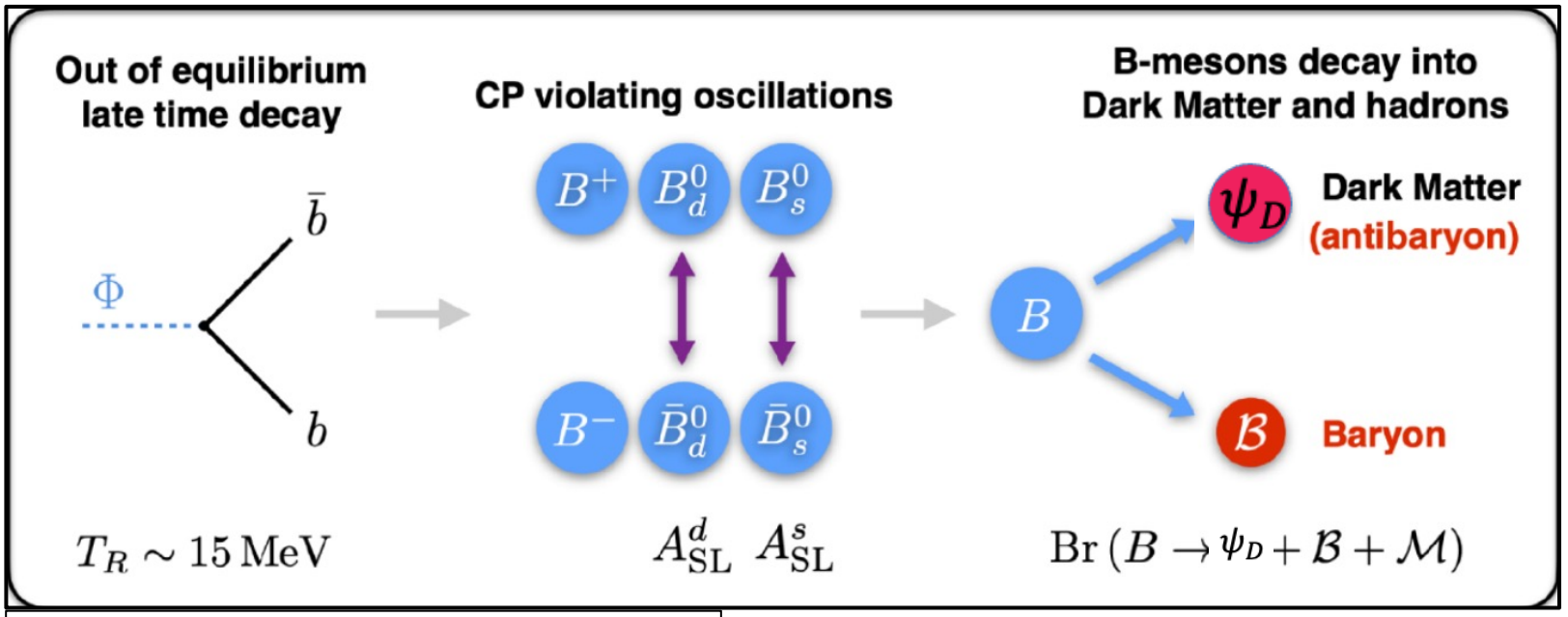
- Understanding the mass scale and nature of DM leads to new physics beyond the standard model (BSM)

- Understanding the baryon asymmetry of the universe (BAU) is also a pressing issue in modern particle physics

- A new mechanism has been proposed to simultaneously explain the DM abundance and the BAU arising from B-meson oscillation that could be testable in B-factories

- Contrary to typical baryogenesis scenarios, B-Mesogenesis operates at very low temperatures

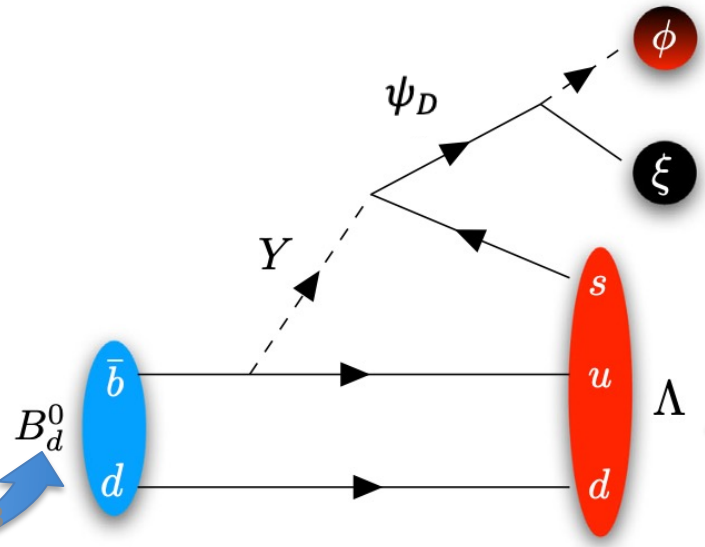
Theoretical Background



1. Phys. Rev. D 99, 035031 (2019)
2. Phys. Rev. D 104, 035028 (2021)

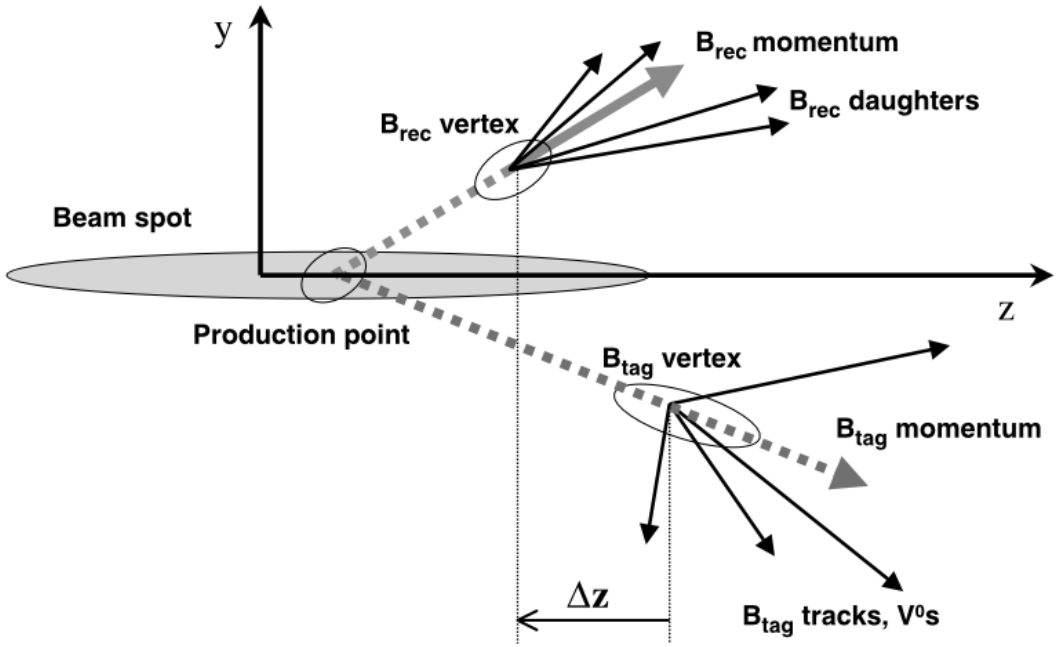
Paper one: $B^+ \to \psi_D + p$

Paper two: $B^0 \to \psi_D + \Lambda$



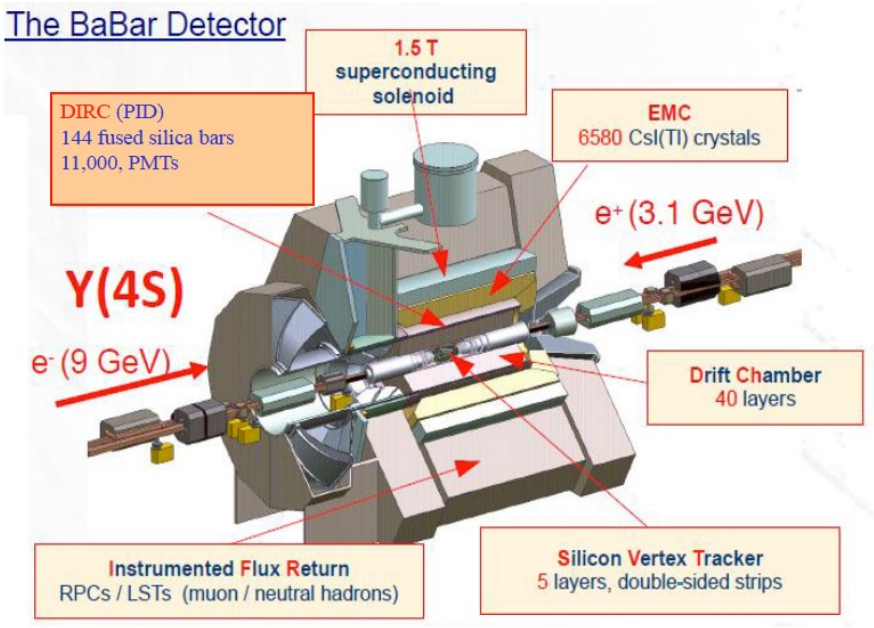
Signal B-tagging

Eur. Phys. J. C (2014) 74:3026

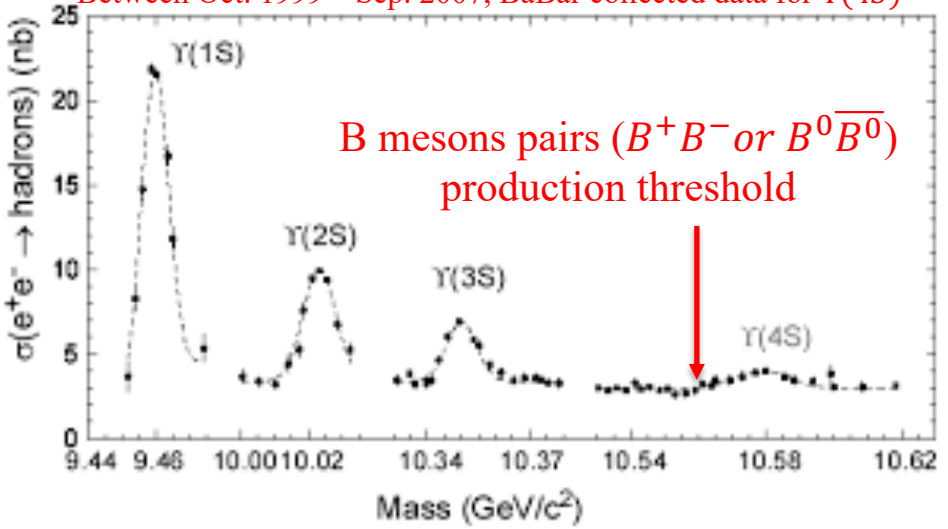


- Schematic view of the geometry in the yz plane for a $\Upsilon(4S) \rightarrow B\bar{B}$ decay
- The goal of B-flavor tagging is to determine the flavor of a B meson (i.e. whether it contains a b or a $\bar{b}$ quark) at the time of its decay

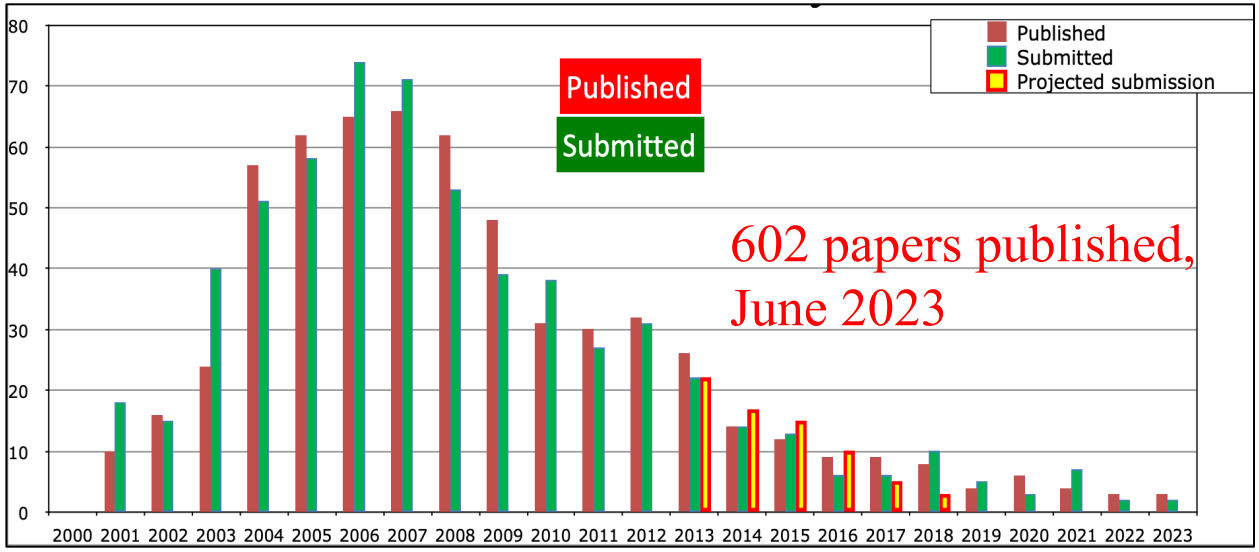
BaBar Detector

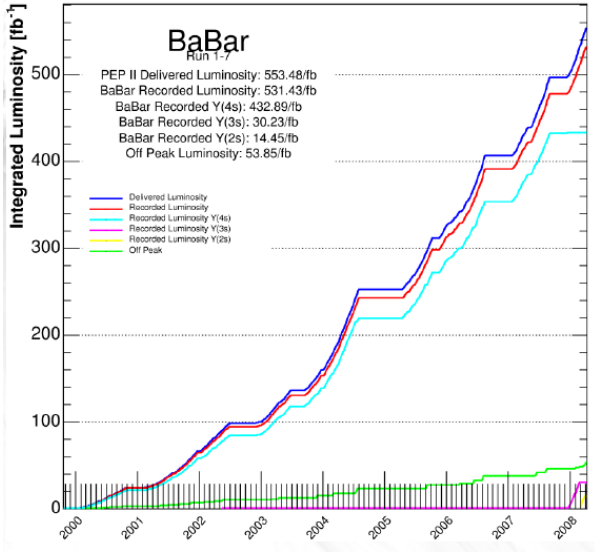


Between Oct. 1999 – Sep. 2007, BaBar collected data for $\Upsilon(4S)$



NIMA 726 (2013) 203-213





Analysis Details

Baryogenesis and Dark Matter $B^+ \to \psi_D + p$	Mesogenesis $B^0 \to \psi_D + \Lambda$

Data

- **398.5 fb^{-1} $\Upsilon(4S)$ [main analysis]**
- **32.5 fb^{-1} $\Upsilon(4S)$ [optimize the analysis strategy]**

Signal

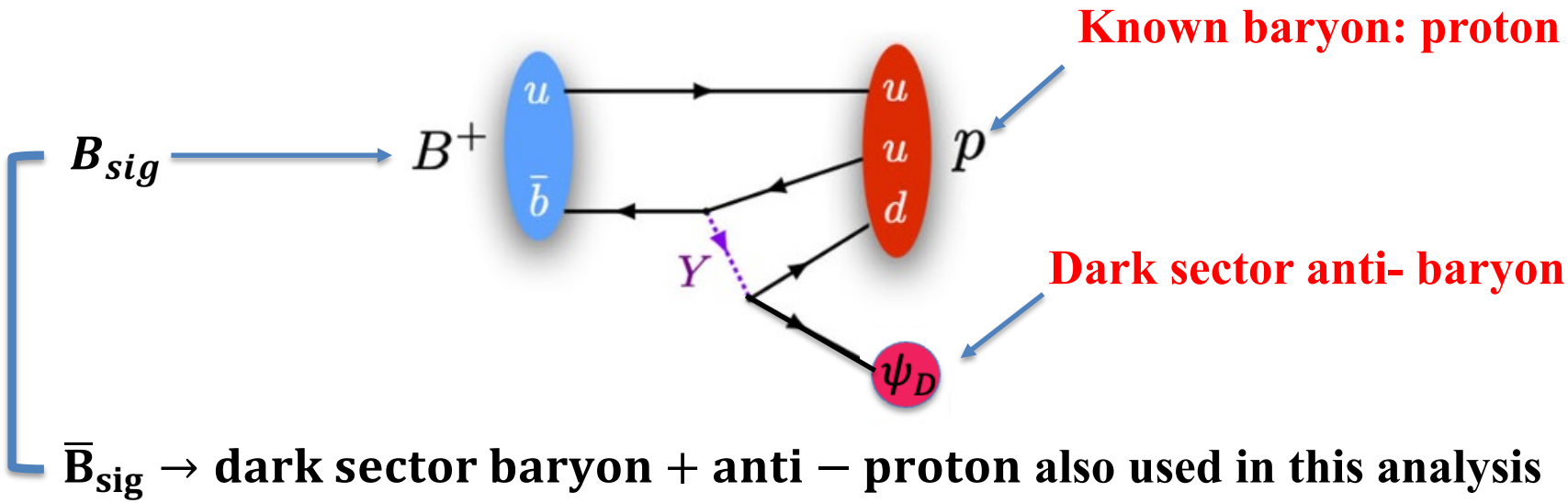
- **Simulated signal events are created using the EVTGEN**

MC

- **inclusive $e^+e^- \to B\bar{B}$ (EVTGEN)**
- **continuum $e^+e^- \to q\bar{q}$(JETSET)**

Baryogenesis and Dark Matter

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



- $B^+ \rightarrow \psi_D + p$ decays are selected in events in which a hadronic decay of the B^- meson is fully reconstructed
- The ψ_D is identified as the system recoiling against the B_{tag} and p candidates
- $B \rightarrow \psi_D \mathcal{B}$ decay can occur only if $m_{\psi_D} < m_B - m_p$
- Proton stability requires: $m_{\psi_D} > m_p - m_e$
- Samples were made for eight different ψ_D mass hypotheses: 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0 and 4.2 GeV/c^2

Baryogenesis and Dark Matter
$B^+ \to \psi_D + p$ (reconstruction)

B_{tag} side	B_{sig} side

➢ B_{tag} meson decay kinematics: a) energy substituted mass m_{ES} and b) energy difference ΔE
• $m_{ES}c^2 = \sqrt{E^{*2}_{beam} - \vec{p}^{*2}_{B_{tag}} c^2}$; *where* $m_{ES} \sim 5.27 - 5.29 \frac{GeV}{c^2}$
• $\Delta E = E^*_{beam} - E^*_{B_{tag}}$ (lowest ΔE if multiple B_{tag} candidates); $E^*_{B_{tag}}$ must be within ± 0.2 GeV of the beam energy $E^*_{beam} = \frac{\sqrt{s}}{2}$ in the CM frame
	• One and only one track is required (proton hypothesis)
	• Multivariate classifier based on a boosted decision tree (BDT) that includes:
	  • kinematic variables from B_{tag} (ΔE & m_{ES}):
	  • information about the hadronic decay channel and its purity
	  • magnitude of the thrust vector
	  • features from the B_{sig}:
	  • the total extra neutral energy on the signal side in the CM frame
	  • the cosine of the polar angle of the missing momentum vector
	  • number of neutral particles and the number of π^0 candidates

Baryogenesis and Dark Matter
$B^+ \to \psi_D + p$ (reconstruction)

FIG. 1. BDT response for data and all backgrounds.

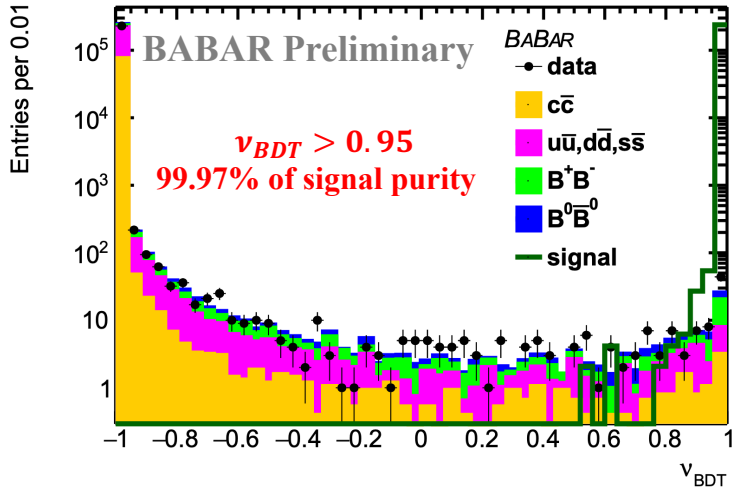
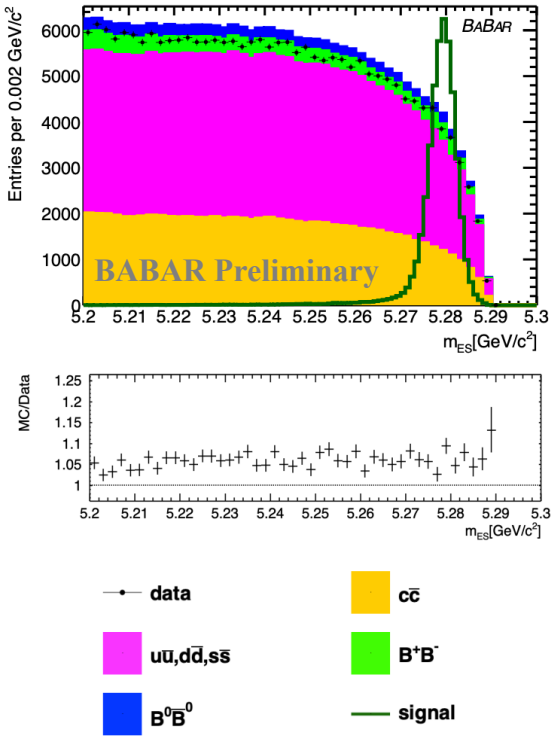


FIG. 2. The energy-substituted mass (m_{ES}) of the B_{tag} candidate for MC background processes and data.



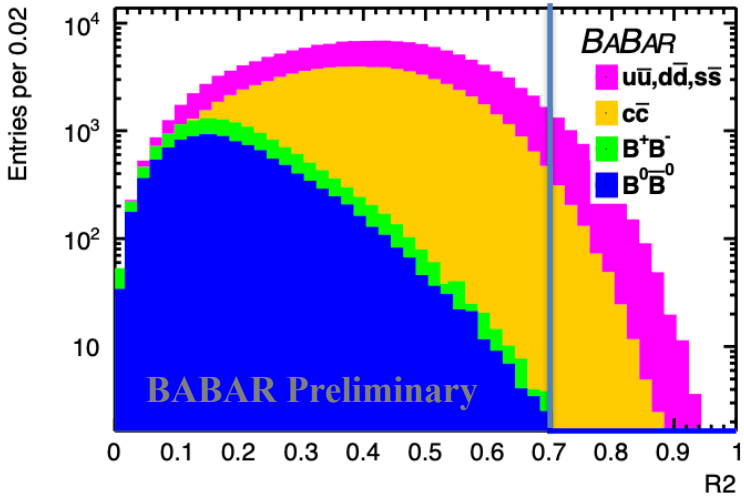
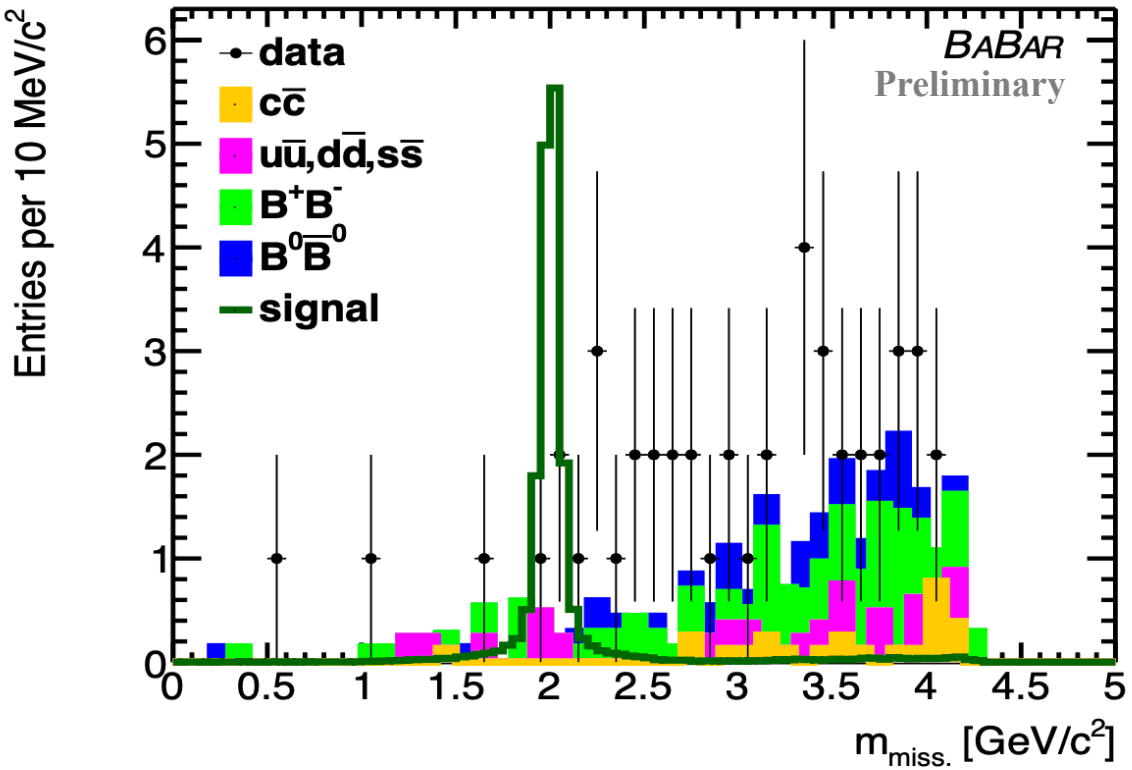


FIG. 3. Simulated distributions of the ratio of the second-to-zeroth Fox-Wolfram moment for all tracks (denoted as R_2).

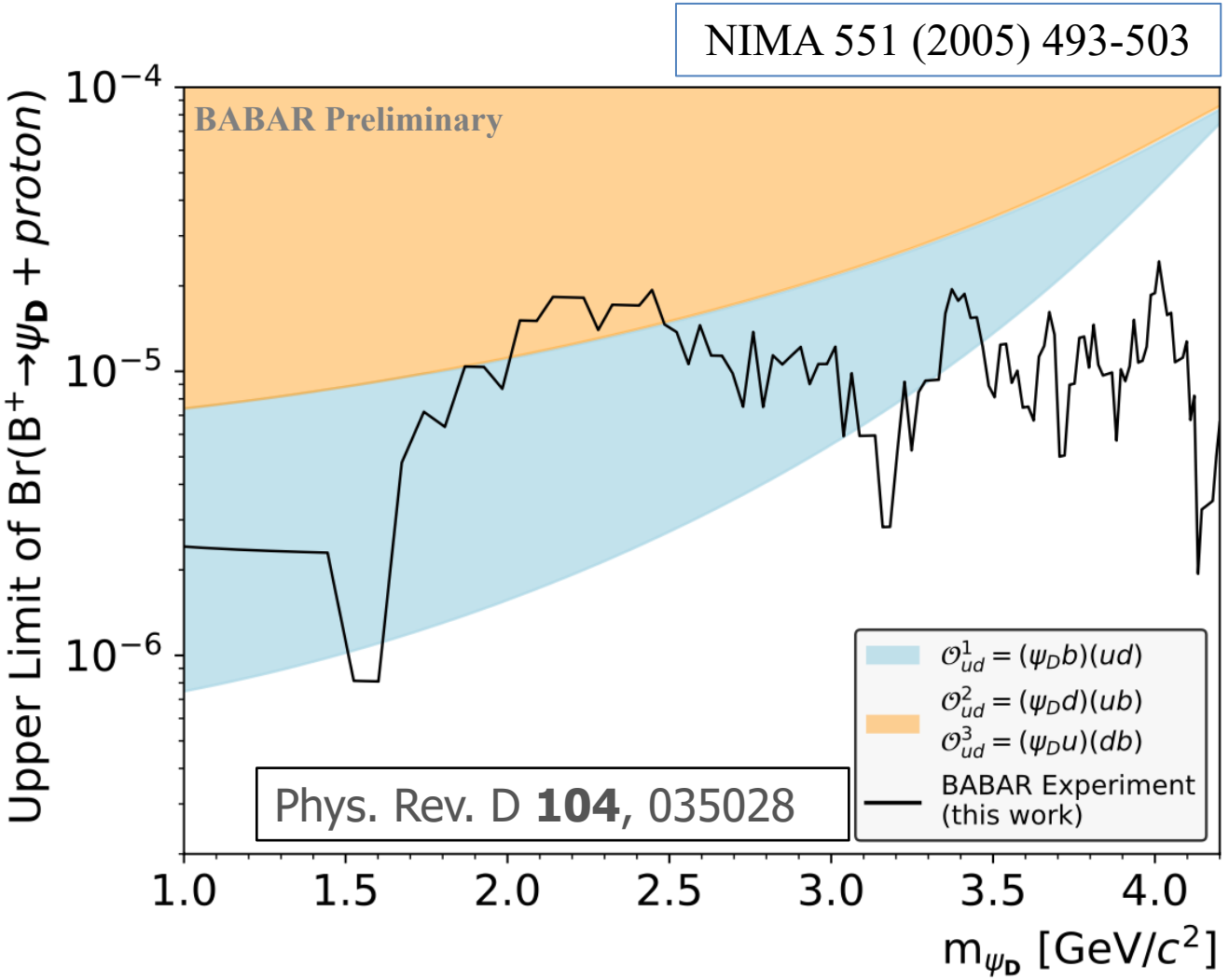
Baryogenesis and Dark Matter
$B^+ \to \psi_D + p$ (missing-mass)



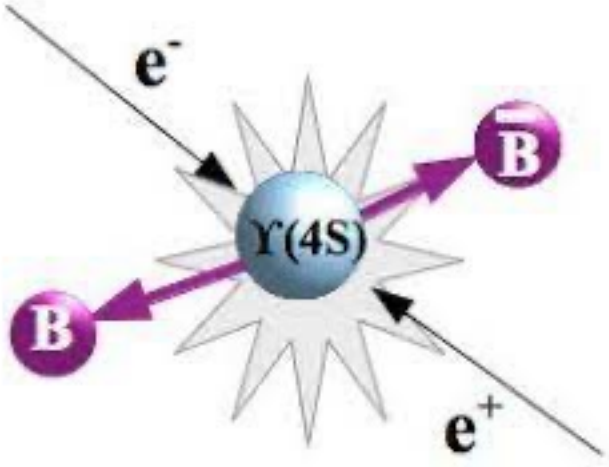
$$m_{\mathrm{miss}}c^2 = \sqrt{(E^*_{B_{\mathrm{sig}}} - E^*_{\mathrm{p}})^2 - |\vec{\mathrm{p}}^{\,*}_{B_{\mathrm{sig}}} - \vec{\mathrm{p}}^{\,*}_{\mathrm{p}}|^2 c^2}$$

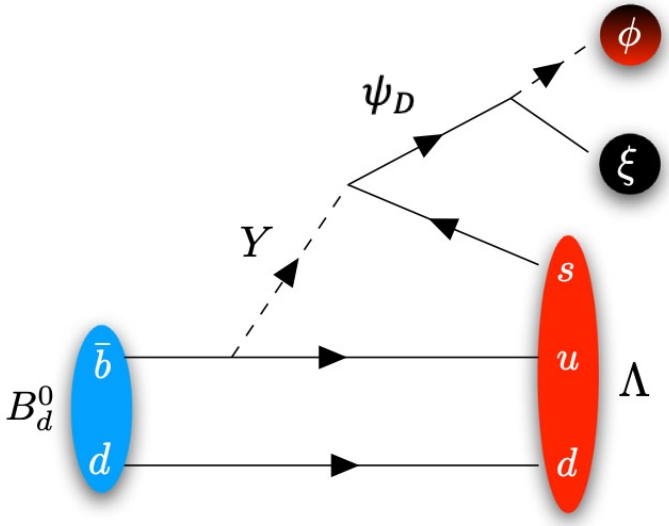
- 127 mass hypotheses were considered in the range $1.0 < m_{miss} < 4.29\ \frac{GeV}{c^2}$

Baryogenesis and Dark Matter
$B^+ \to \psi_D + p$ (upper limits on BF)



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



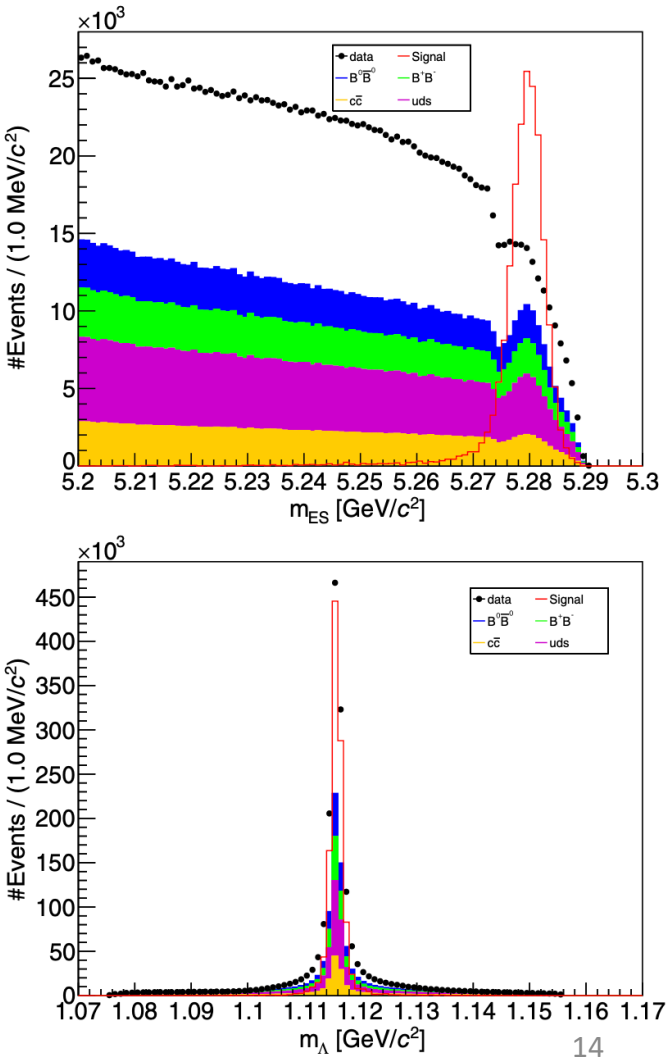


- In a similar procedure as the previous analysis, the ψ_D is identified as the system recoiling against the B_{tag} and A candidates
- $B_{tag} \approx SX$; S = "seed" meson and X = kaons and/or pions with total charge 0 or ± 1
- B_{tag} candidate selections are based on two kinematic variables; ΔE & m_{ES}
- $B_{sig} \approx \Lambda\psi_D; \Lambda \approx p\pi$
- Multivariate classifier based on a boosted decision tree (BDT) is used to further increase the signal purity.

Mesogenesis
$B^0 \rightarrow \psi_D + \Lambda$ (reconstruction)

PHYS. REV. D 107, 092001 (2023)

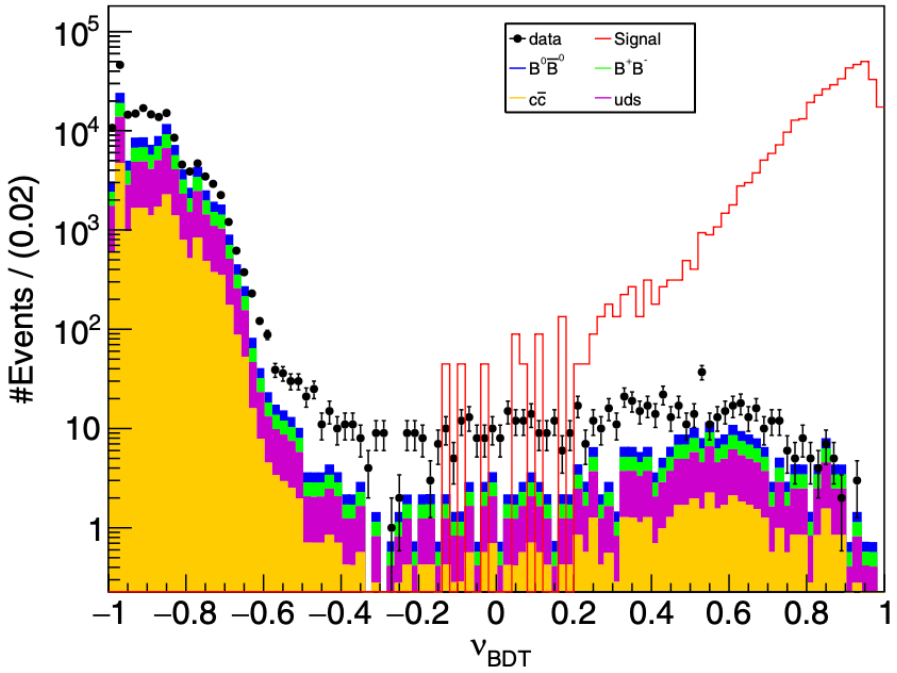
- If more than one combination of Λ candidates is found, the one with the smallest χ^2 from the kinematic fit is selected
- After reconstructing the B_{tag} and Λ candidates, no additional track must be present in the event
- $5.27 < m_{ES} < 5.29 \ \frac{GeV}{c^2}$
- $1.110 < m_{\Lambda} < 1.121 \ \frac{GeV}{c^2}$



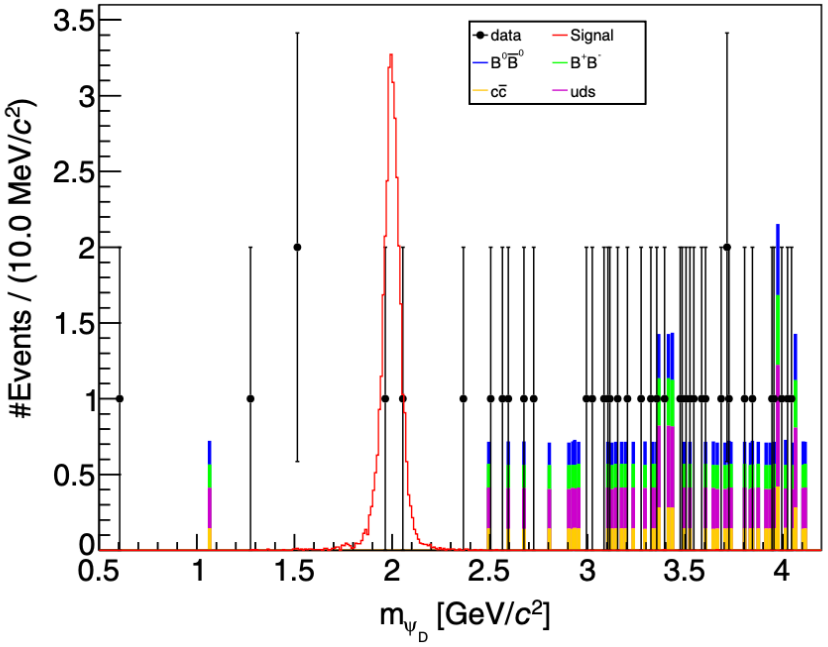
Mesogenesis
$B^0 \to \psi_D + \Lambda$ (reconstruction)

PHYS. REV. D 107, 092001 (2023)

- The distribution of the BDT score

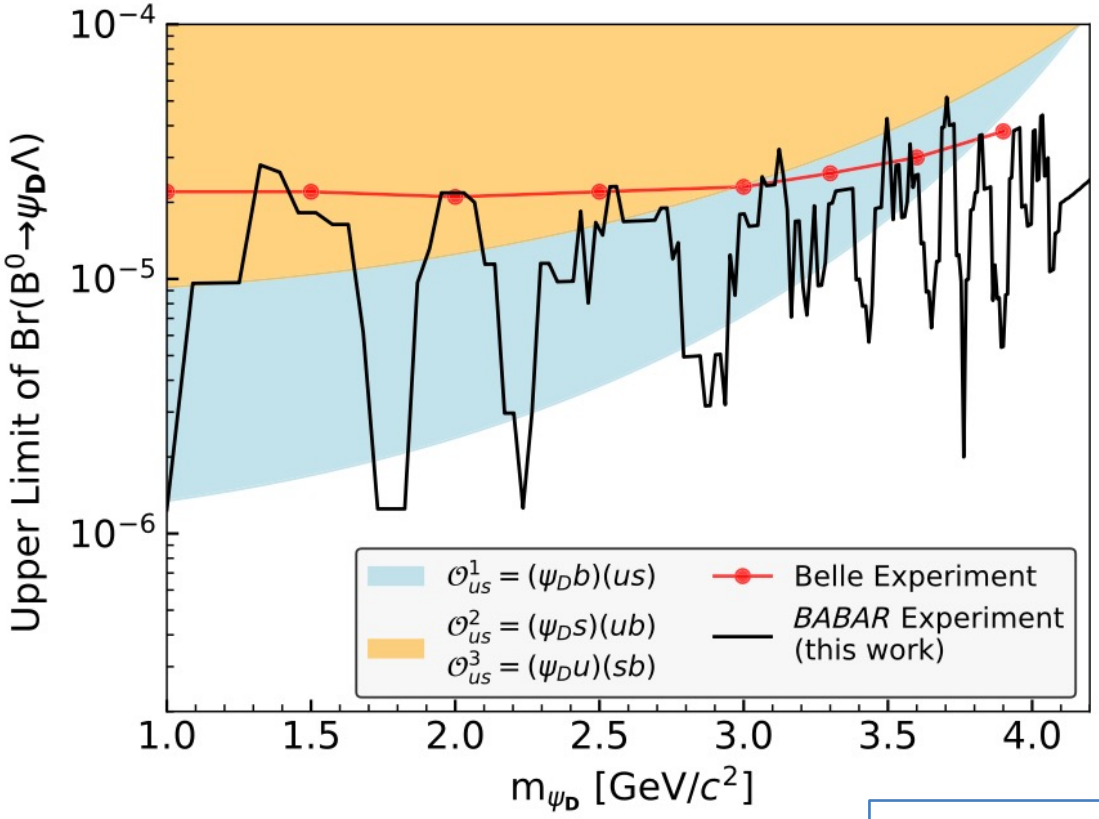


- The distribution of the ψ_D mass (m_{ψ_D}) after applying all selection criteria



Mesogenesis
$B^0 \to \psi_D + \Lambda$ (upper limit on BF)

PHYS. REV. D 107, 092001 (2023)



Belle Paper:
PHYS. REV. D 105, L051101 (2022)

Summary

- BABAR has made a significant contribution on searches for Physics Beyond the Standard Model, and Dark Sector in particular
- $B^+ \to \psi_D + p$ is the first attempt to directly search for this channel. No signal is observed and 90% C.L upper limits from 10^{-7} – 10^{-5} are set on the branching fraction
- We also report a search for baryogenesis and dark matter in the process $B^0 \to \psi_D + \Lambda$ with a fully reconstructed B_{tag} meson
- No significant signal is observed, and upper limits on the branching fraction at the level of 10^{-6} –10^{-5} are set
- These results exclude a large fraction of the parameter space allowed by B mesogenesis
- Future measurements at Belle-II should be able to fully explore the remaining region

Back-up Slide -- one

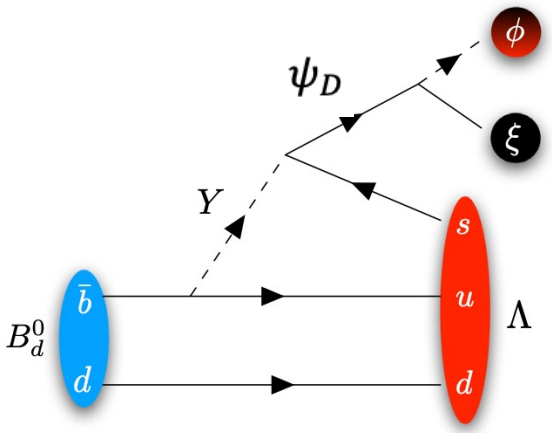


TABLE I. Summary of the additional fields (in both the UV and the effective theory), their charges, and properties required in our model.

Field	Spin	$Q_{\rm EM}$	Baryon no.	$\mathbb{Z}_2$	Mass
Φ	0	0	0	+1	11–100 GeV
Y	0	$-1/3$	$-2/3$	+1	$\mathcal{O}$(TeV)
ψ	1/2	0	-1	+1	$\mathcal{O}$(GeV)
ξ	1/2	0	0	-1	$\mathcal{O}$(GeV)
ϕ	0	0	-1	-1	$\mathcal{O}$(GeV)

For the decay $B \to \psi_D \mathcal{B}\mathcal{M}$ to exist:

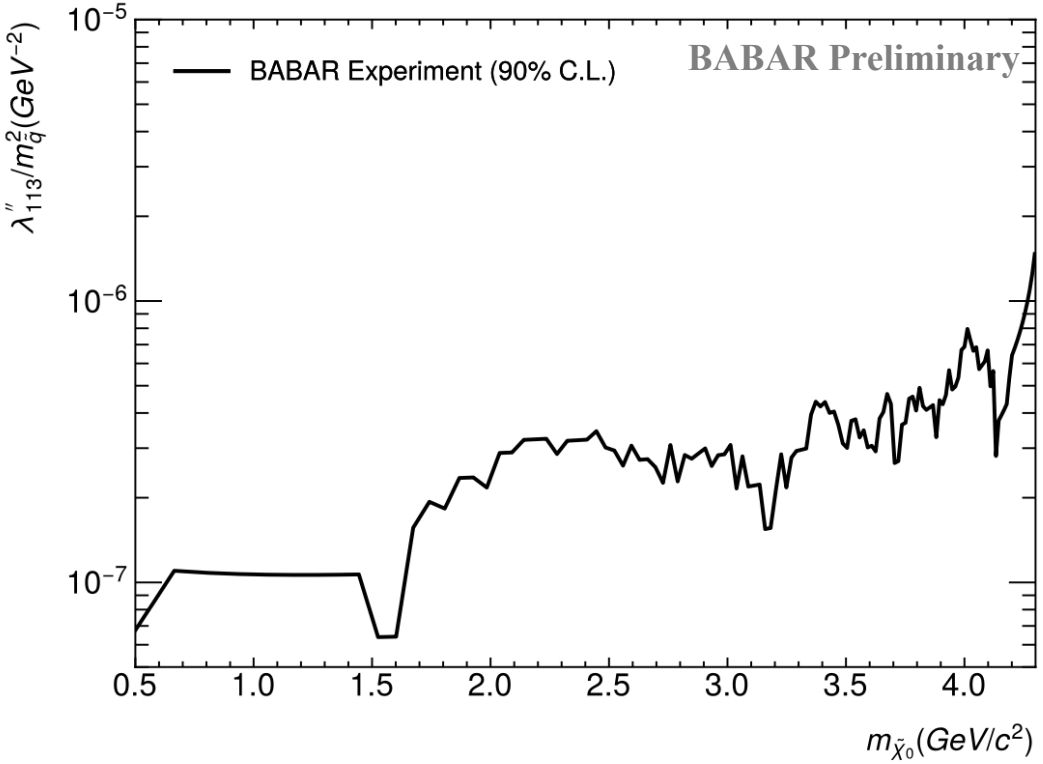
a) a new BSM TeV-scale bosonic mediator Y is needed
b) Y is a color-triplet scalar couples to dark sector antibaryon and SM quarks
c) The couple depends on a low energy Lagrangian with an effective operator $\mathcal{O}_{i,j} : \mathcal{L}_{eff} = \sum_{i,j} \mathcal{O}_{u_i d_j} \frac{y_{ij}^2}{M_Y^2}$ where y_{ij}^2 being the product of the two relevant dimensionless couplings, e.g.,

$$\mathcal{O}_{ud} = \psi_D bud; \mathcal{O}_{us} = \psi_D bus; \mathcal{O}_{cd} = \psi_D bcd; \mathcal{O}_{cs} = \psi_D bcs$$

Back-up Slide -- two

Baryogenesis and Dark Matter

$B^+ \to \psi_D + p$ (constrain a SUSY model: JHEP 2023 (2)



- Model with: R-parity Violation (RPV) & Light Neutralino $\tilde{\chi}_0$
- Limits on the RPV coupling λ_{123}'' divided by the relevant squark mass squared