Search for Baryogenesis & Dark Matter in B-meson decays at *BABAR*

XV International Conference on Beauty, Charm and Hyperons (BEACH)

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Representing the BABAR Collaboration

Outline

- Motivation - Shortcomings of Standard Model
- Dark Matter and Baryogenesis
- Searching for Baryogenesis in B Decays
- The BABAR Experiment
- Two NEW *BABAR* searches for Baryogenesis & Dark Matter in B-meson decays
- Results and Interpretations
- Summary

Introduction and Motivation

Standard Model is extremely successful

It describes and explains so much of what we observe in nature to excruciating precision

BUT: There are still a few shortcomings of the Standard Model:

- We have no idea what **Dark Matter** is
- And absolutely no idea what **Dark Energy** is
- Can't explain **Baryon Asymmetry of the Universe** (BAU)
- Origin of the **Neutrino Mass**?
- **Hierarchy problem:** Higgs mass is so low / fine-tuned
- No **quantum theory of gravity**

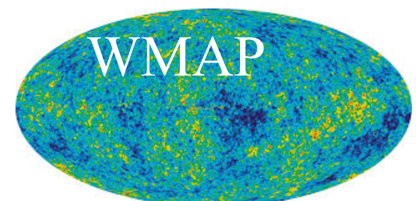
Dark Matter

NASA photo

Compelling indirect evidence for Dark Matter

American Museum of Natural History

We have no idea what dark matter is or where it comes from.
No evidence for WIMPS, despite years of direct WIMP searches.
Could dark matter couple to ordinary matter via a new "dark force"?
Could there be a whole new "dark sector" of particles?



NASA/WMAP Science Team

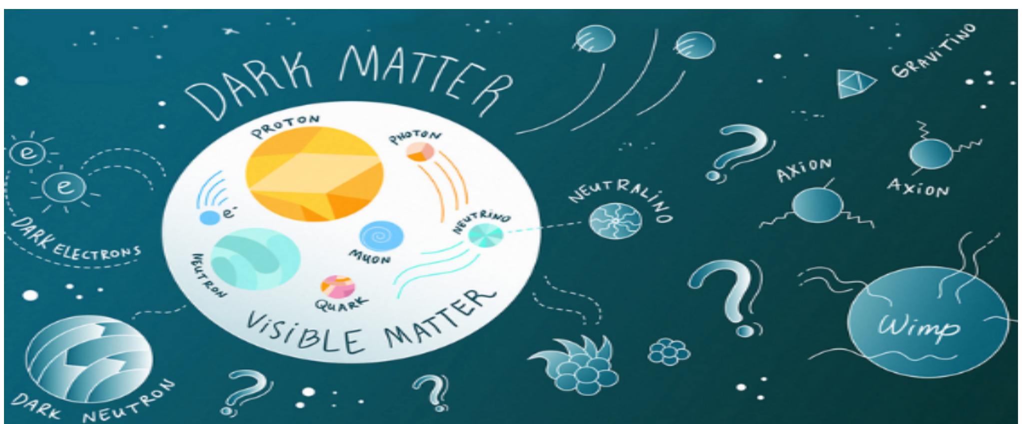
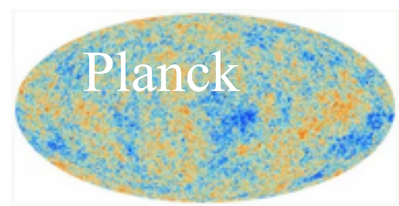
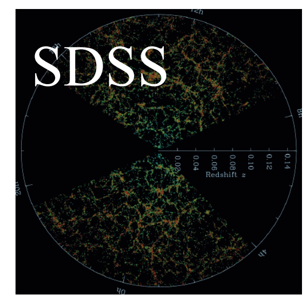


Illustration by Sandbox Studio, Chicago with Ana Kova



ESA and the Planck Collaboration

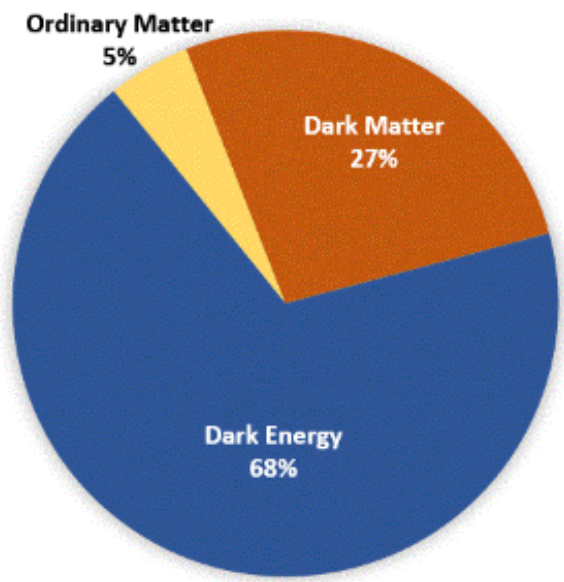


SDSS

The Dark Sector

We still have no idea what Dark Matter is

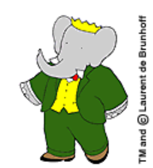
• WIMPs - Weakly Interacting Massive Particles - had been a favoured dark matter candidate, but never observed in many MANY searches: underground, produced at accelerators and searches in space using satellites.



so we turned to:

Dark Sector Models:

- Dark Matter could be not just one new particle, particles from a whole new "dark sector"
- Dark sector particles could couple weakly to ordinary SM particles



Searches for the Dark Sector at BABAR

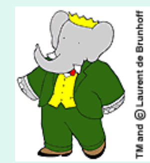
Distant past: BABAR (and other collider experiments) have conducted a broad program to look for direct evidence of Dark Matter via the Dark Sector

No evidence for any dark sector particles in any of these searches ☹

We set stringent limits on dark sector production

1. **Dark Sector Higgs Boson PRL 108, 211801 (2012)**

   (Final State: 3 fermion-antifermion pairs)



2. **Dark Photon to Lepton Pair PRL 113, 201801 (2014)**

   (Final State: photon + lepton pair)

3. **Dark Sector Muonic Dark Force PRD 94 011102(R) (2016)**

   (Final State: 2 lepton pairs)

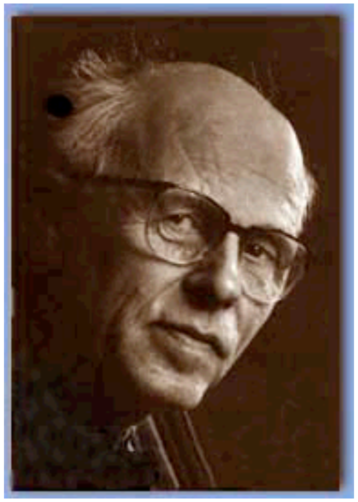
4. **Invisible Decays of Dark Photon PRL 119, 131804 (2017)**

   (Final State: one single photon)

1. No solution yet to the Dark Matter problem

Baryogenesis

Andrei Sakharov: conditions for baryogenesis / cosmological formation of matter-antimatter asymmetry: A.D. Sakharov, JETP Lett. 5, 24 (1967)



- Absence of thermal equilibrium
- Baryon number violation
- CP violation

These conditions are all compatible with Standard Model, but don't accommodate the required level of baryogenesis to explain the BAU.

Primordial matter-antimatter asymmetry measurements come from Big Bang Nucleosynthesis and Cosmic Microwave Background measurements give an asymmetry much too small to explain BAU

Need new mechanisms to explain the observed level of BAU.

2. No solution yet to the baryogenesis problem
(not enough primordial matter-antimatter asymmetry)

Baryogenesis and Dark Matter

Could there be ONE solution to these two problems in Standard Model?

B-mesogenesis is a mechanism of baryogenesis which simultaneously explains the baryon asymmetry of the universe AND the existence and formation of dark matter

We have models with mechanisms to simultaneously generate a baryon asymmetry, AND produce an abundance of dark matter in early universe:

Baryogenesis and dark matter from B mesons
Gilly Elor, Miguel Escudero, Ann E. Nelson Phys. Rev. D 99, 035031 (2019)

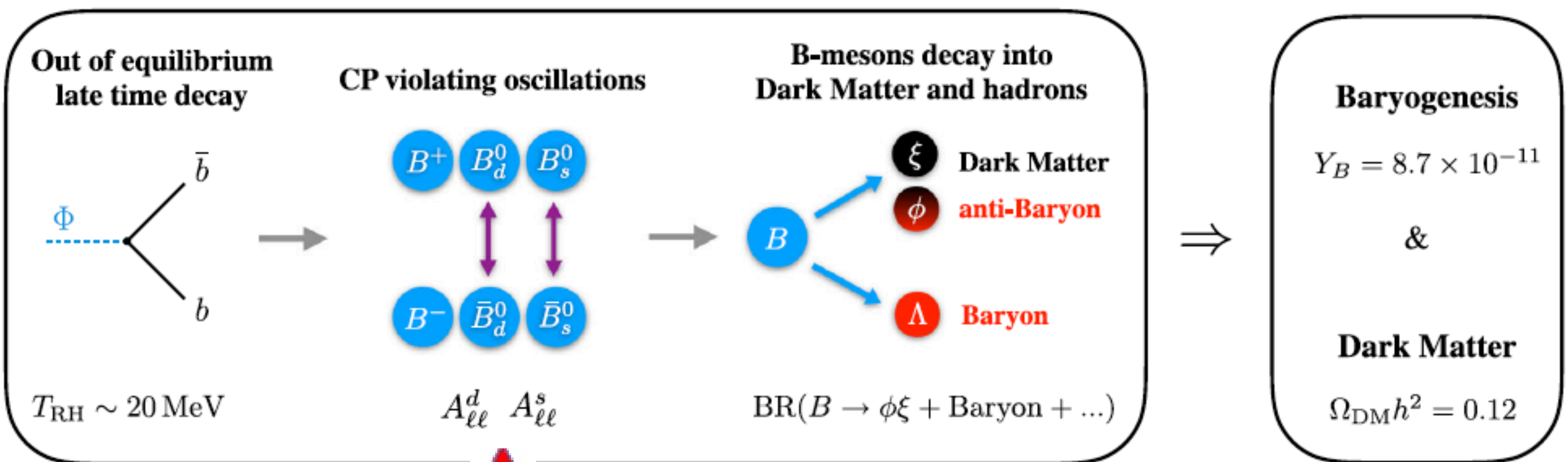
And the experimenter's guide:

Collider signals of baryogenesis and dark matter from B mesons: A roadmap to discovery
Gonzalo Alonso-Álvarez, Gilly Elor, Miguel Escudero Phys. Rev. D 104, 035028 (2021)

B - Mesogenesis: Baryogenesis and Dark Matter from B-meson decay

This model has non-SM dark-sector baryons and anti-baryons

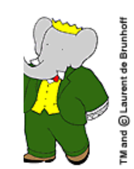
- in early universe, a long-lived particle produces b and $\bar{b}$ quarks
- they hadronize into B and $\overline{B}$ mesons, and undergo CP violating oscillations
- $B/\overline{B}$ mesons then decay into SM particles AND dark sector particles



Elon, Escudero, Nelson, PRD 99 035031

CPV in B-mixing --> charge asymmetry in B SL decays
which limits Br of inclusive B decay into dark sector baryon

Measurements by Planck collaboration



B - Mesogenesis: Baryogenesis and Dark Matter from B-meson decay

The Standard Model B mesons then decay :

- a Standard Model baryon ($\mathcal{B}$)
- a dark sector baryon (ψ_D)
- additional Standard Model meson(s) ($\mathcal{M}$)

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

- The dark sector baryon is undetected - dark matter
- The CP violation from $B^0 - \overline{B^0}$ oscillations generates the matter-antimatter asymmetry
- Due to the CP violation, $B \rightarrow \psi_D + \mathcal{B} + \mathcal{M}$

dominates slightly over $\overline{B} \rightarrow \overline{\psi_D} + \overline{\mathcal{B}} + \overline{\mathcal{M}}$ decays

Yields excess of baryons in our sector, excess of anti-baryons in dark sector

B - Mesogenesis: Baryogenesis and Dark Matter from B-meson decay

This model yields:

excess of baryons in our visible sector,

excess of anti-baryons in dark sector

Baryon number within universe is conserved, net excess of baryons in our visible sector.

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

The dark sector baryon, ψ_D, decays into other stable dark sector particles

Kinematics requires the ψ_D mass to be in the 0.94 - 4.34 GeV range.

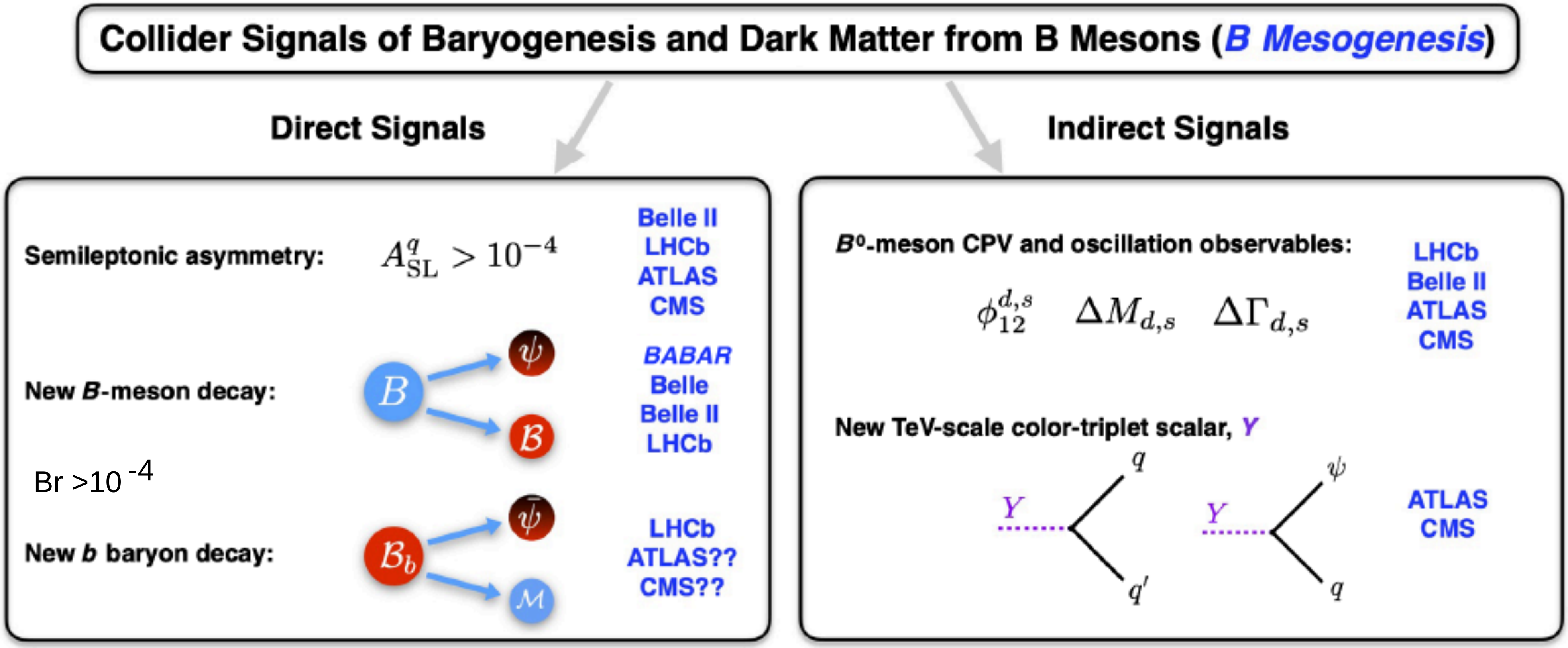
BUT: Bounds on incusivel b decays with missing energy, plus searches by LHC on colour-triplet scalars, plus dark matter stability require the mass to be in 0.94 -3.9GeV range

This model requires a large inclusive branching fraction

for $B \rightarrow \psi_D + \mathcal{B} + \mathcal{M}$

Br > 10^{-4}, and depends on semileptonic asymmetries $A_{SL}^{d,s}$

Testable Experimental Signals



Alonso-Alvarex, Elor, Escudero, PRD 104 035028 (2021)

Due to the large inclusive branching ratio, this is experimentally testable !
With *BABAR* detector, we searched for:

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

$$B^+ \to p + \psi_D$$

$$\text{and in progress} : B^+ \to \Lambda_C^+ + \psi_D$$

Very distinct signature: Baryon + missing energy

Similar to SUSY signatures / searches

Testable Experimental Signals

With BABAR we have searched for:

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

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

(cc implied)

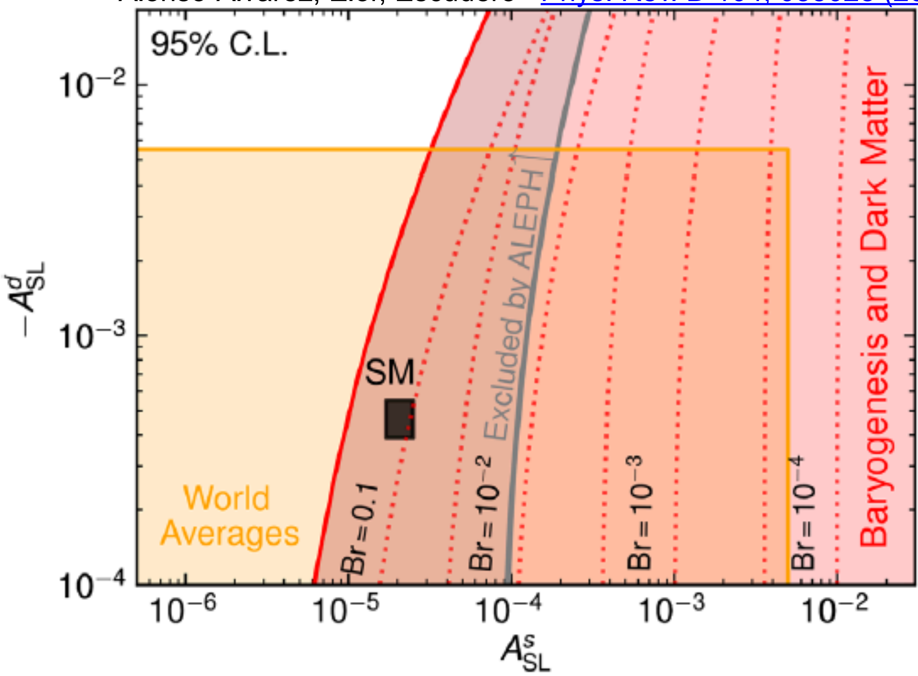
and in progress : $B^+ \rightarrow \Lambda_C^+ + \pi^- + \psi_D$

Very distinct signature: Baryon + missing energy

Operator and decay	Initial state	Final state	ΔM (MeV)
$\mathcal{O}_{ud} = \psi bud$	B_d	$\psi + n(udd)$	4340.1
$\bar{b} \rightarrow \psi ud$	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
$\bar{b} \rightarrow \psi us$	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
$\bar{b} \rightarrow \psi cd$	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
$\bar{b} \rightarrow \psi cs$	B_s	$\psi + \Omega_c(css)$	2671.7
	B^+	$\psi + \Xi_c^+(csu)$	2810.4
	Λ_b	$\bar{\psi} + D^- + K^+$	3256.2

Alonso-Álvarez, Elor, Escudero Phys. Rev. D 104, 035028 (2021)

Alonso-Álvarez, Elor, Escudero Phys. Rev. D 104, 035028 (2021)



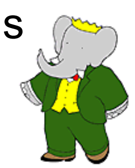
Contours: minimum Br ($B \rightarrow \psi_D\ \mathcal{B}\ \mathcal{M}$)
as a function of semileptonic asymmetries

The type of baryon produced depends on the operator mediating the interaction, leading to a variety of final states.

Probe all channels - any one of these 4 operators could be the one responsible for B mesogenesis

Belle/Belle II have also conducted dark sector searches.

Together, Babar, Belle II + LHCb, ATLAS, CMS can test the entire parameter space of B-mesogenesis



Testable Experimental Signals

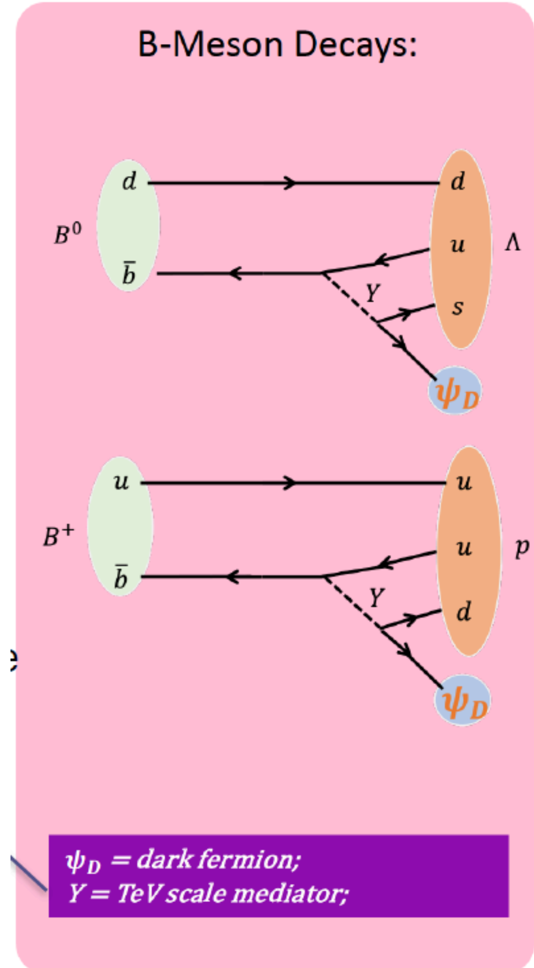
To fully test this model, must examine all 4 operators:

Definitive test

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

Y_B is the baryon asymmetry of the universe (BAU) and is measured by Planck:

$Y_B = (8.718 \pm 0.004) \times 10^{-11}$ Astron.Astrophys 641, A6 (2020)



Set limits on operators:

$\mathcal{O}_{us}$

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

$\mathcal{O}_{ud}$

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

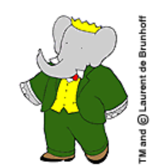
Sophie Middleton, April 2024 APS talk

A^q_{SL} are the semileptonic asymmetries in neutral B^0_q decays

α_q is bounded by the dependence on the mass and lifetime of the field coupled to the initial $b\bar{b}$

Measured limits can be interpreted as constraints on these $\mathcal{O}$ operators

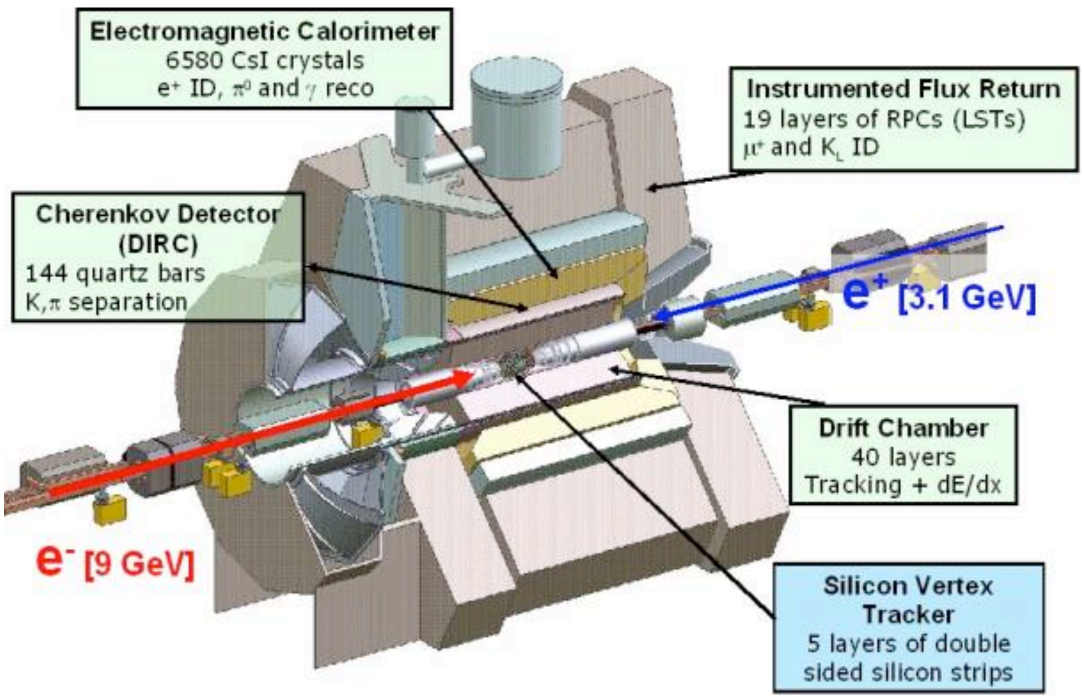
Also simplified by flavour constraints which imply that only one of these operators can be active in the early universe, one dominates (eg not a combination of the operators)



Babar Experiment

432 fb^{-1} 4.7×10^8 $B \bar{B}$

$\Upsilon(4S)$ threshold



at SLAC

Asymmetric e^+e^- collider

Primary goals: B physics,

CP physics

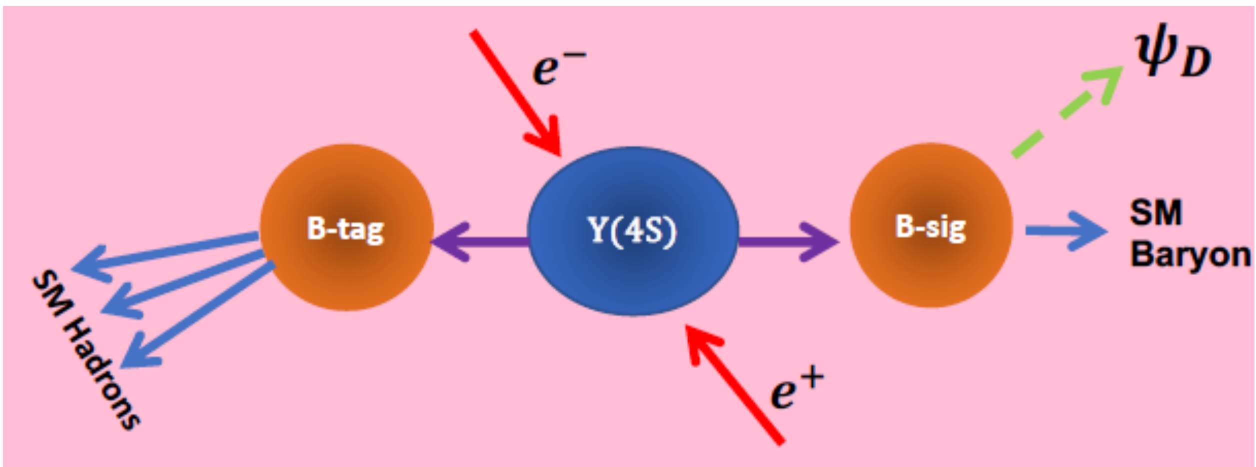
Expt run: 1999-2008

Stopped data taking 16 years ago, still publishing new analyses!

BABAR Analysis

Produce B mesons: $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\overline{B}$

Tag B fully reconstructed B-meson in Standard Model decay channel
Signal B possible signal, search for missing mass



signal dark baryon recoils against B tag & SM baryon

Sophie Middleton, April 2024 APS talk

Reconstructed B-tag: -100 MeV < ΔE < 100 MeV and 5.2 GeV < m_{ES} < 5.3 GeV

$$\Delta E = E^*_{beam} - E^*_{tag}$$ (CMS beam energy - recon B-tag energy)

$$m_{ES} = \sqrt{E^{*2}_{beam} - \vec{p}^{\,*2}_{tag}}$$ (beam energy substituted mass)

Signal and Monte Carlo simulated backgrounds

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

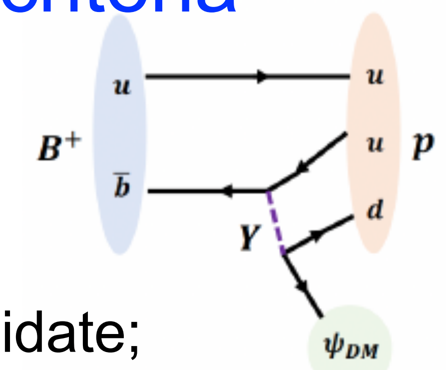
Analysis Method:

- MC simulated 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.

Yields determined via data-driven Poisson counting method.
Background & signal region defined from study of background and signal MC simulations.

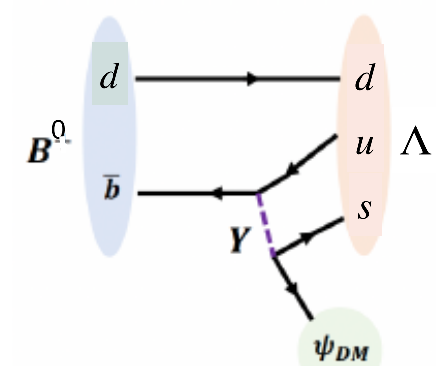
Event selection

Additional channel-dependent selection criteria



For the $B \rightarrow \psi_D \; p$ channel:

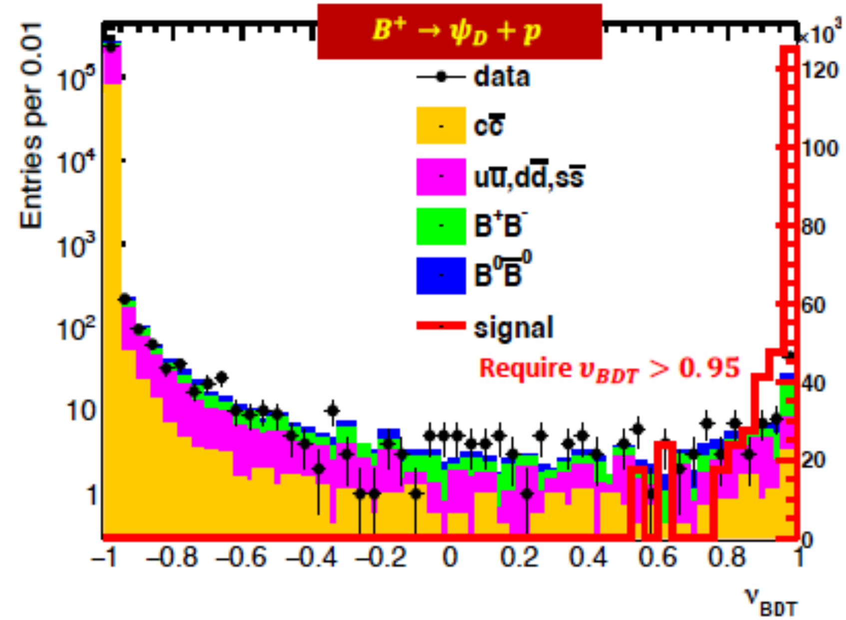
- BABAR proton PID can be used to identify proton candidate;
- signal side must have + charge and only one charged particle

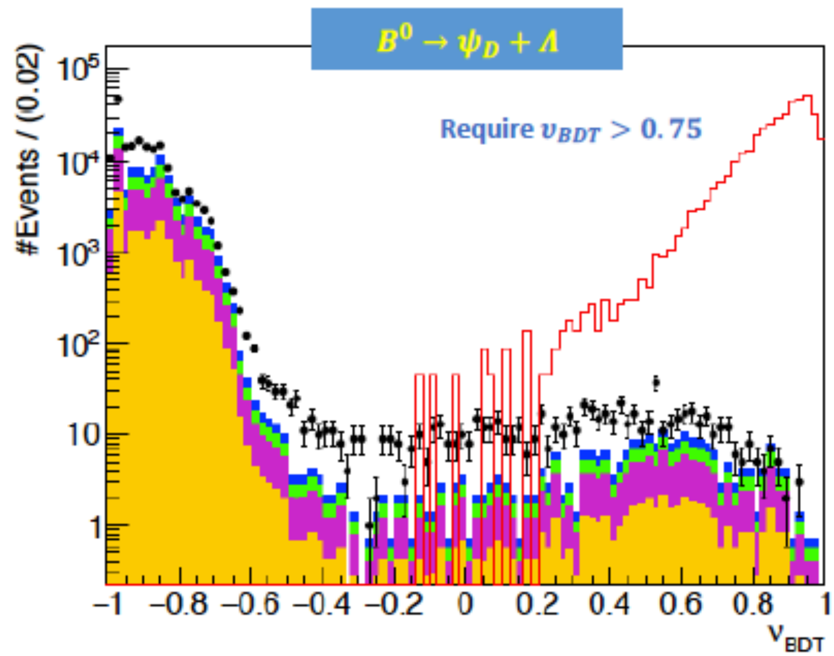


For the $B \rightarrow \psi_D \; \Lambda$ channel:

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

Event selection





For both cases further signal and background separation found using a Boosted Decision Tree custom to each channel.

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

(discrepancy in simulation corrected using sideband)

BDT MVA inputs for $B^+ \longrightarrow \psi_D \; p$

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

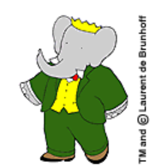
TAG SIDE:

- the hadronic decay channel of B-meson tag & purity
- CMS beam energy minus reconstructed B-tag energy: $\Delta E = E^*_{beam} - E^*_{tag}$
- B-meson tag mass distribution: $m_{ES} = \sqrt{E^{*2}_{beam} - \vec{p}^{\,*2}_{tag}}$
- the 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



BDT MVA inputs for $B^0 \longrightarrow \psi_{\mathrm{D}}\ \Lambda$

- The significance of the Λ decay length
- The $\chi 2$ of the Λ fit
- Energy and momentum of Λ lab frame
- Momentum vector of signal B

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

TAG SIDE:

- the hadronic decay channel of B-meson tag & purity
- CMS beam energy minus reconstructed B-tag energy: $\Delta E = E^*_{beam} - E^*_{tag}$
- B-meson tag mass distribution: $m_{ES} = \sqrt{E^{*2}_{beam} - \vec{p}^{*2}_{tag}}$
- the 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" candidates on the signal side

Extracting 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) and efficiency (ε_{MC}) from fits to MC
- ε_{MC} signal ranges

For Λ:

ε_{MC} = 5.9×10^{-4} for ψ_D = 1GeV and 2.1×10^{-4} for ψ_D = 4.2GeV

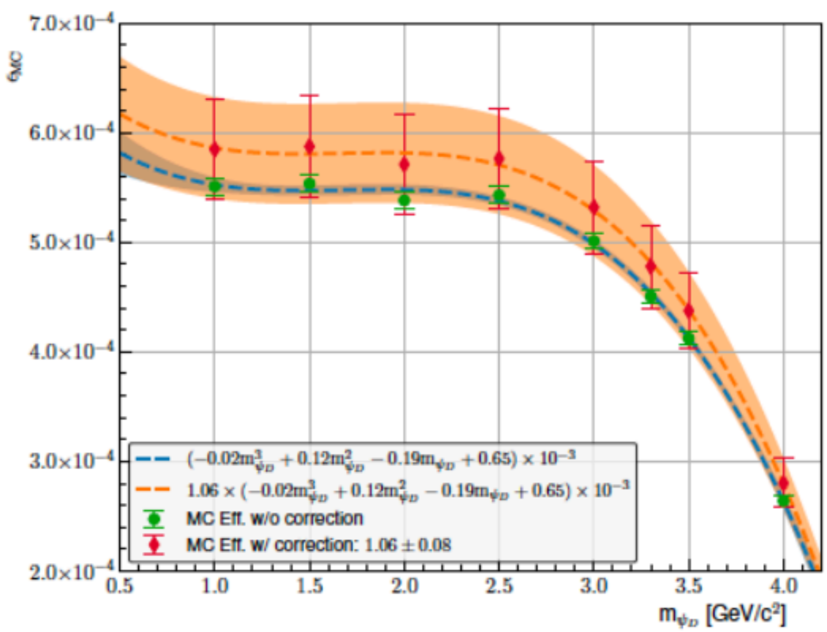
For p:

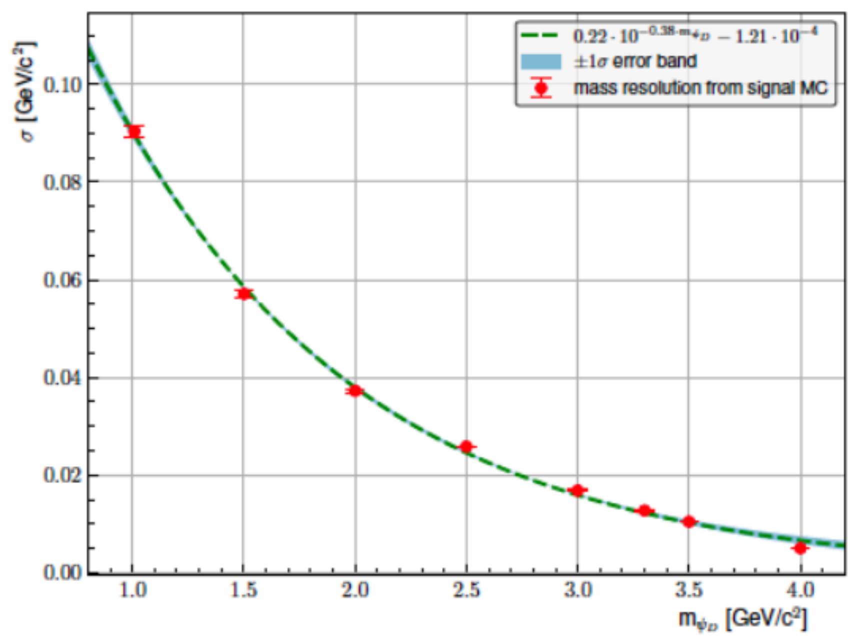
ε_{MC} =1.5×10^{-3} for ψ_D = 1GeV and 6×10^{-3} for ψ_D = 4.2GeV

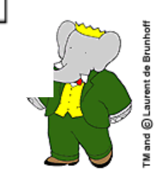
Extracting Final Results

- 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) and efficiency (ε_{MC}) from fits to MC;
- estimate signal and backgrounds in data using definitions from MC study

Obtain upper limits on Beyond SM branching fractions:

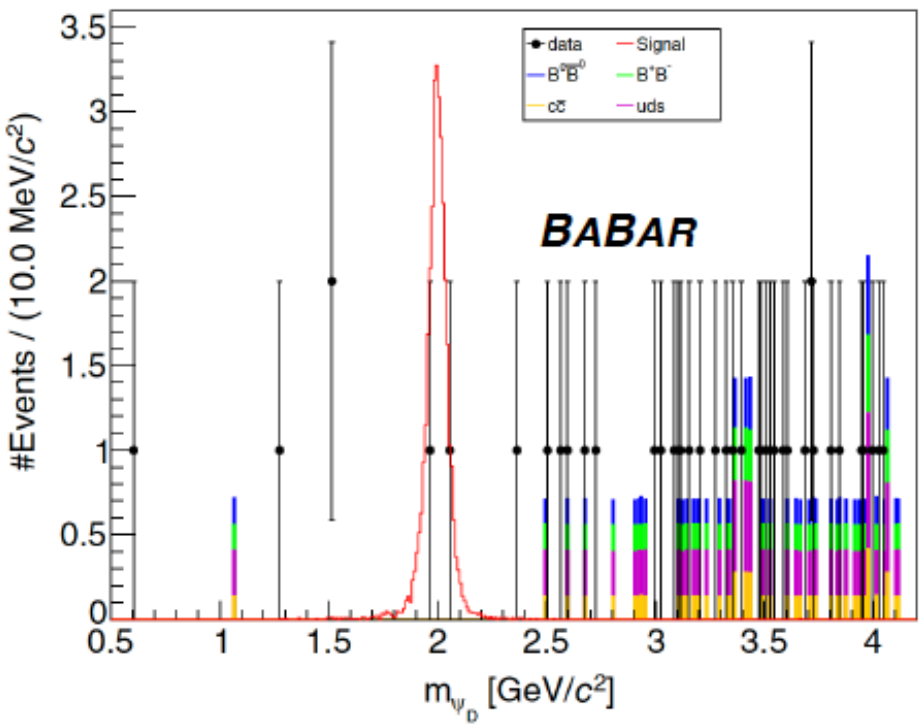


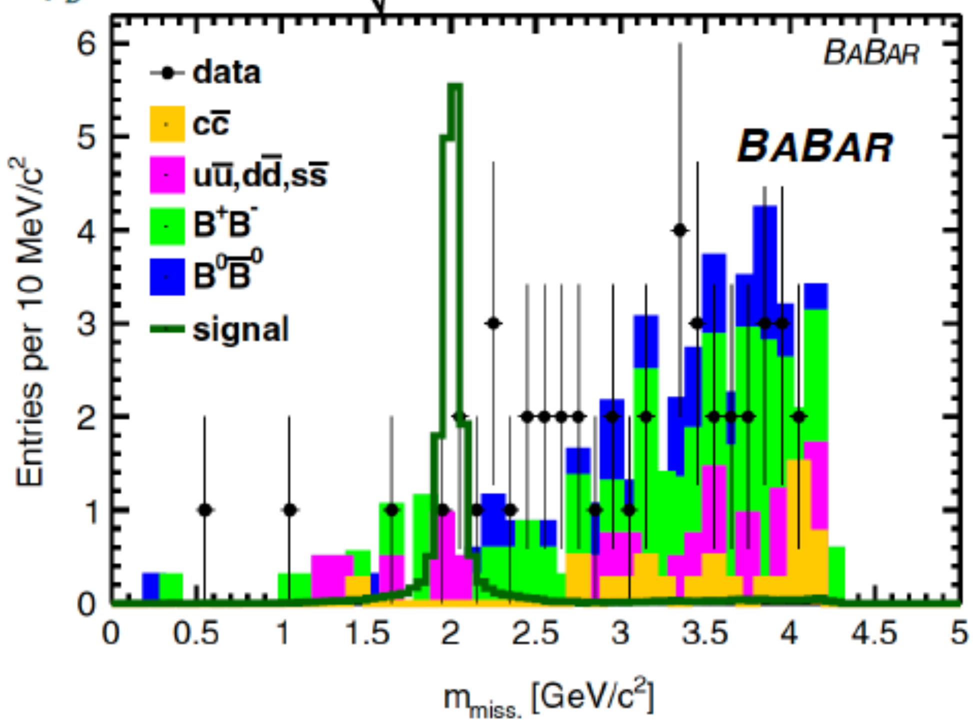




Final Results

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





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

$B^+ \to \psi_D + p$

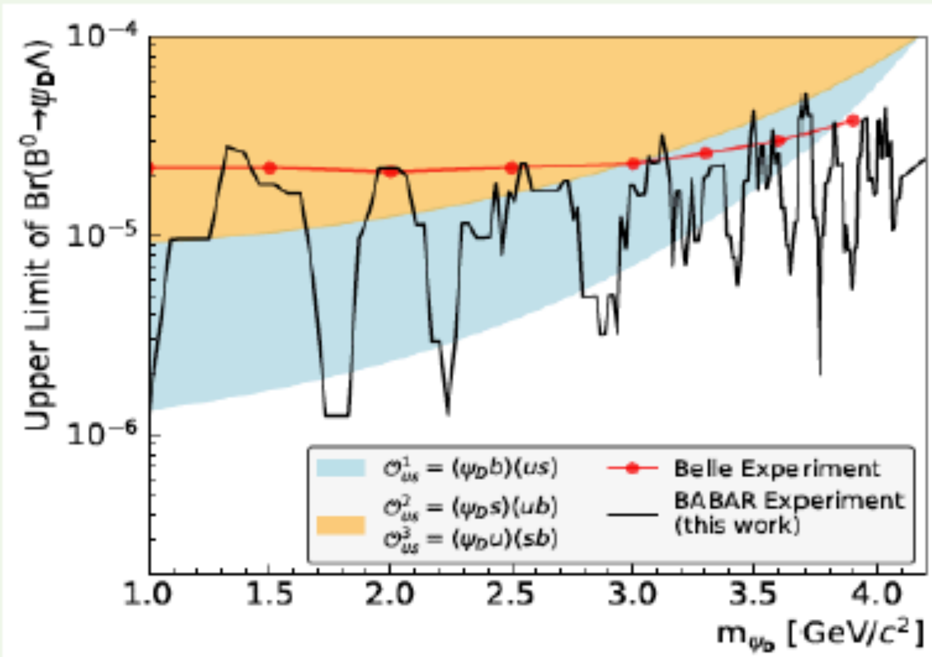
In both channels, absence of signal allows us to set upper limit on branching ratios.

Search for Evidence of Baryogenesis and Dark Matter in $B^+ \to \psi_D + p$ Decays at *BABAR* PRL 131 201801 (2023)

Search for B mesogenesis at *BaBar* PRD 107 092001 (2023)

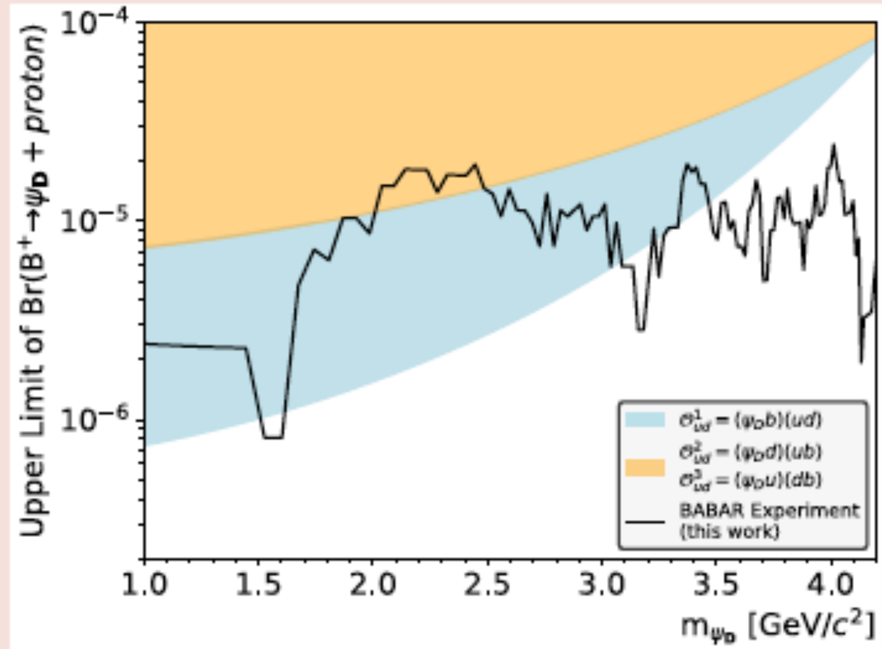
Final Babar Results/Limits

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



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

$B^+ \to \psi_D + p$



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

we exclude most of the parameter space for 2 of the operators

Search for Evidence of Baryogenesis and Dark Matter in $B^+ \to \psi_D + p$ Decays at *BABAR* [PRL 131 201801 (2023)]

Search for B mesogenesis at *BABAR* [PRD 107 092001 (2023)]

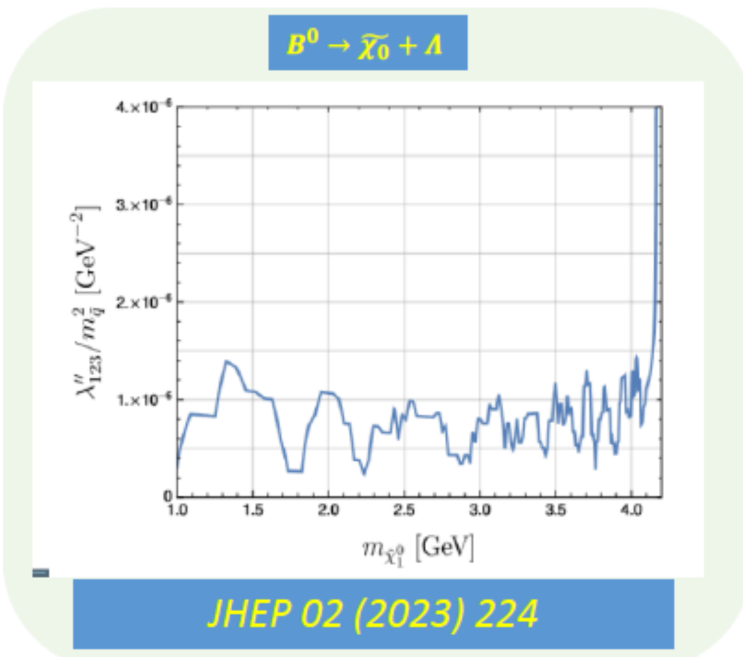
Results

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

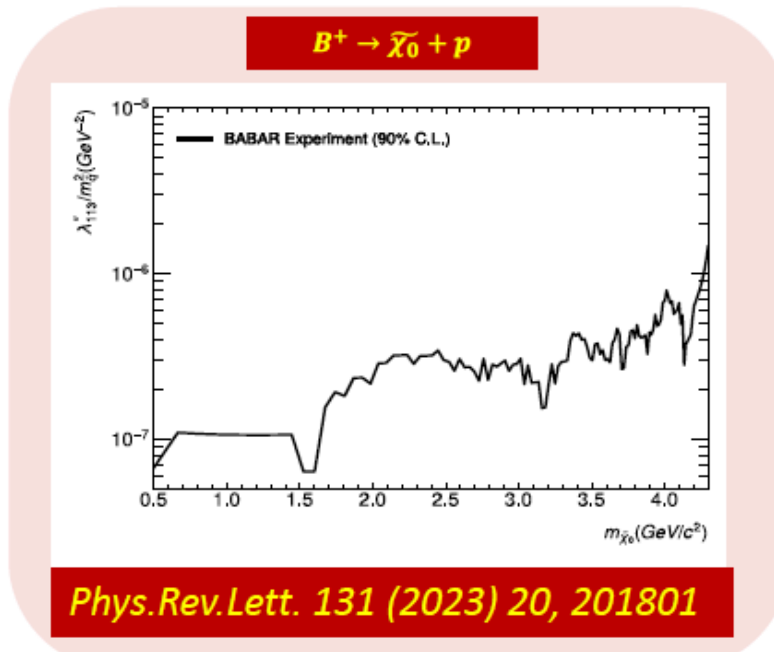
Need to examine other operators to fully exclude this B mesogenesis model

Because these analyses are essentially looking for missing mass in the final state, this search can be applied to any such model (eg SUSY)

Extended search to provide first limit on RPV SUSY model described in JHEP 2023 (02 224 (2023)). Dib et al



JHEP 02 (2023) 224



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

Summary and Conclusions

- Babar has conducted a search for signatures in a model which explains both dark matter and baryogenesis.
- Improved limits on $B^0 \to \psi_D \; \Lambda$
- First direct limits on $B^+ \to \psi_D \; p$
- Upcoming Babar analysis with $B^+ \to \psi_D \; \Lambda_C^+ \pi$
- Results can be applied to other missing mass in final state models

You can mine your data for **years** when you have hundreds of millions of B’s!


BIG BANG SCALE
ASYMMETRY
Seems to be a big difference.
MATTER
ANTI-MATTER