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

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On behalf of the BABAR Collaboration

Outline

- B mesogenesis:
  - Baryogenesis and Dark Matter from B Mesons
- Experimental signals at colliders
- The Babar experiment and dataset
- The $B^0 \to \psi_D \Lambda$ and $B^+ \to \psi_D \mathrm{p}$ analyses
- Results and interpretation
- Conclusion and perspectives

Standard Model Incompleteness

- 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

Standard Model Incompleteness

- Dark Matter
- Baryon Asymmetry of the Universe (BAU)

Zwicky, AcHPhys 6 (1933); et seq

- Dark matter existence well established from astrophysical evidence, but its nature is unknown
- Baryogenesis is required to generate the BAU

$$\eta = \frac{N_B}{N_\gamma} \approx \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}}$$

Canetti et al., NJOP 14 (2012) 095012

- Sakharov conditions: Sakharov, A D, JETP 5 (1967) 24
  - Baryon number violation
  - C and CP violation
  - Deviation from thermal equilibrium

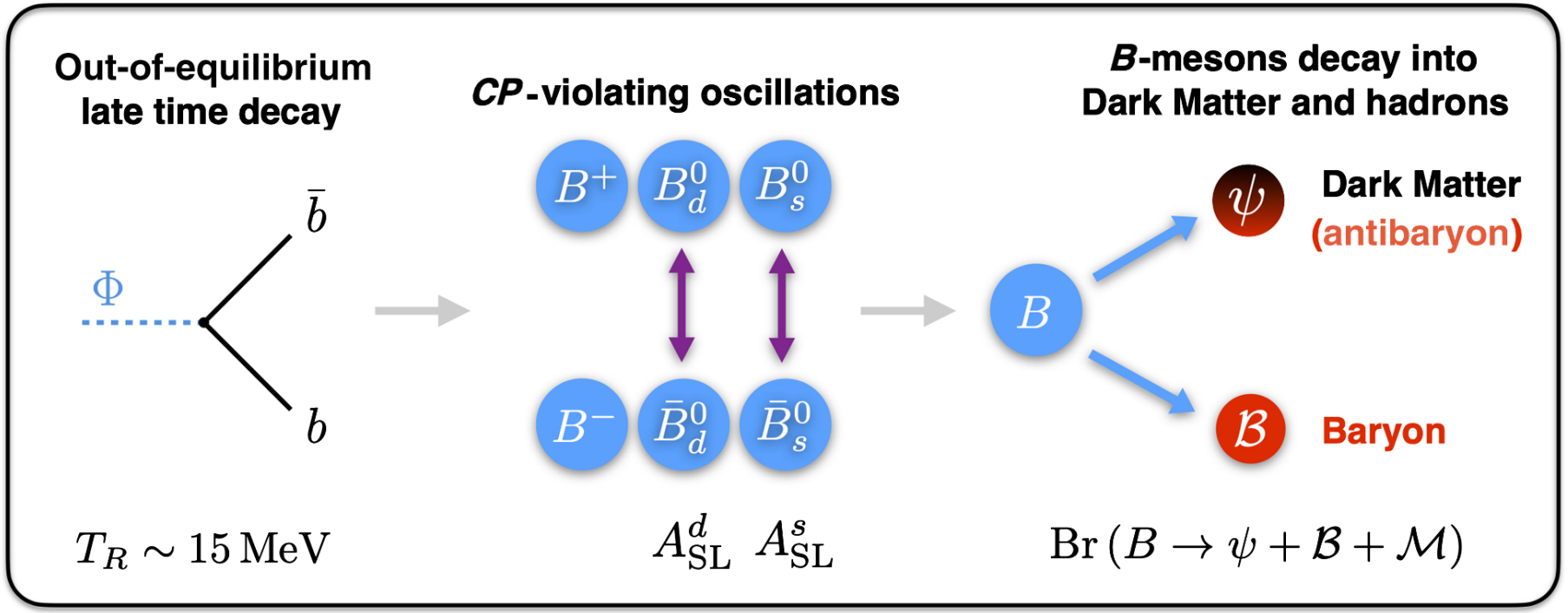
SM measured parameters are quantitatively insufficient to explain the level of BAU

Baryogenesis and Dark Matter from B Mesons: B Mesogenesis

Elor, Escudero, Nelson, PRD 99 (2019) 035031

- New concept:
  - There exist non-SM dark baryons and anti-baryons
  - Baryon number conservation counts both SM and dark (anti)baryons
  - B meson can decay as $B \to \mathcal{B} + \psi_D + \mathcal{M}$
  - SM baryon $\mathcal{B}$ + neutral dark anti-baryon ψ_D + additional mesons $\mathcal{M}$
- CP violation from $B^0 - \bar{B}^0$oscillations generates a matter-antimatter asymmetry, which can originate from SM or BSM processes
- B^0 decays into baryons slightly dominate over $\bar{B}^0$ 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



- "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"

Alonso-Alvarez, Elorand, Escudero, PRD 104, (2021) 035028

Experimental signatures

Collider Signals of Baryogenesis and Dark Matter from B Mesons (*B Mesogenesis*)

Direct Signals

Semileptonic asymmetry: $A_{\rm SL}^q > 10^{-4}$ — Belle II, LHCb, ATLAS, CMS

New *B*-meson decay: $B \to \psi \mathcal{B}$ — *BABAR*, Belle, Belle II, LHCb

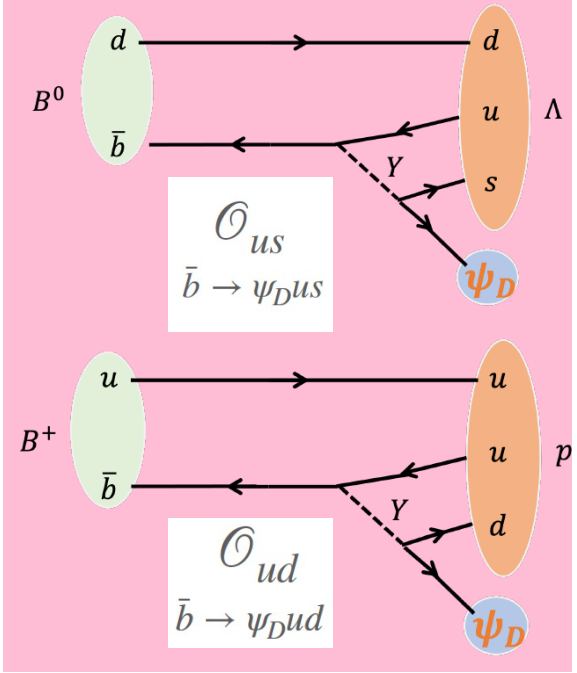
New *b* baryon decay: $\mathcal{B}_b \to \bar{\psi} \mathcal{M}$ — LHCb, ATLAS??, CMS??

Indirect Signals

***B*⁰-meson CPV and oscillation observables:** $\phi_{12}^{d,s}$ $\Delta M_{d,s}$ $\Delta\Gamma_{d,s}$ — LHCb, Belle II, ATLAS, CMS

New TeV-scale color-triplet scalar, *Y* — $Y \to q q'$, $Y \to \psi q$ — ATLAS, CMS

B-Meson Decays:



Testable at B factories:

Kinematic constraints

→ $0.94 < M(\psi_D) < 4.34$ GeV

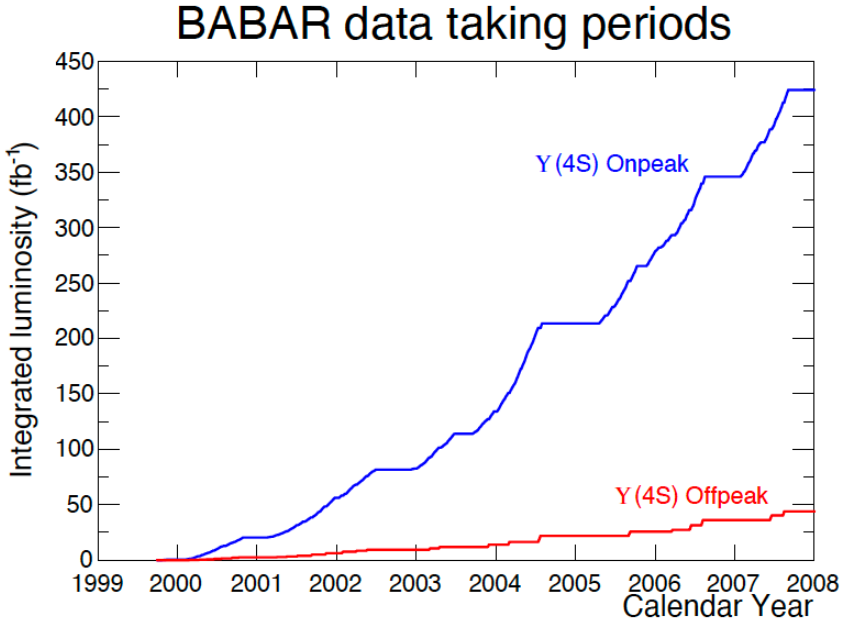
$$B^+ \to \psi_D + p \qquad B^0 \to \psi_D + \Lambda$$
$$B^0 \to \psi_D + \pi^- + \Lambda_c^+$$

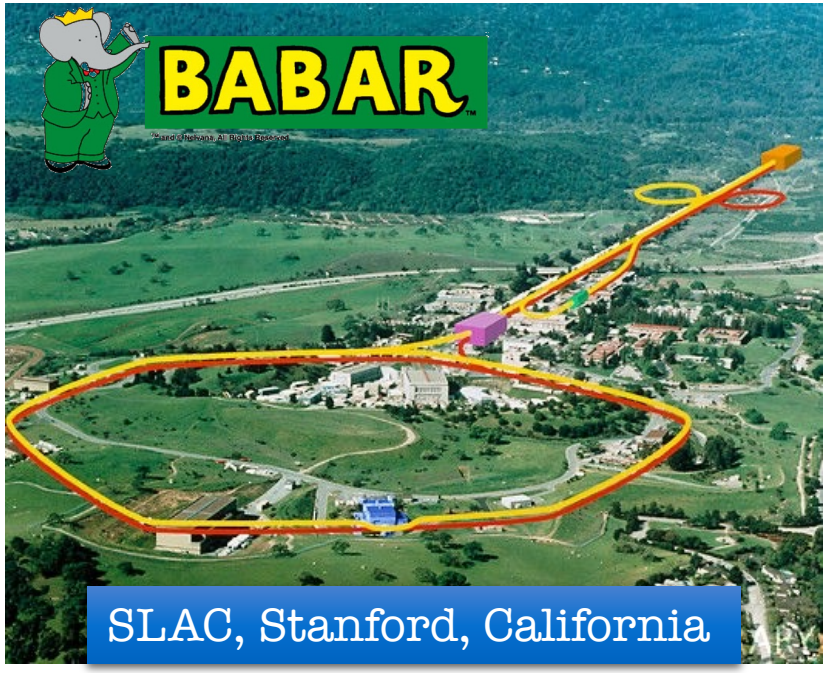
Interpret limits as constraints on operators

$$\mathcal{O}_{us}^1 = (\psi_D b)(us)$$
$$\mathcal{O}_{us}^2 = (\psi_D s)(ub)$$
$$\mathcal{O}_{us}^3 = (\psi_D u)(sb)$$

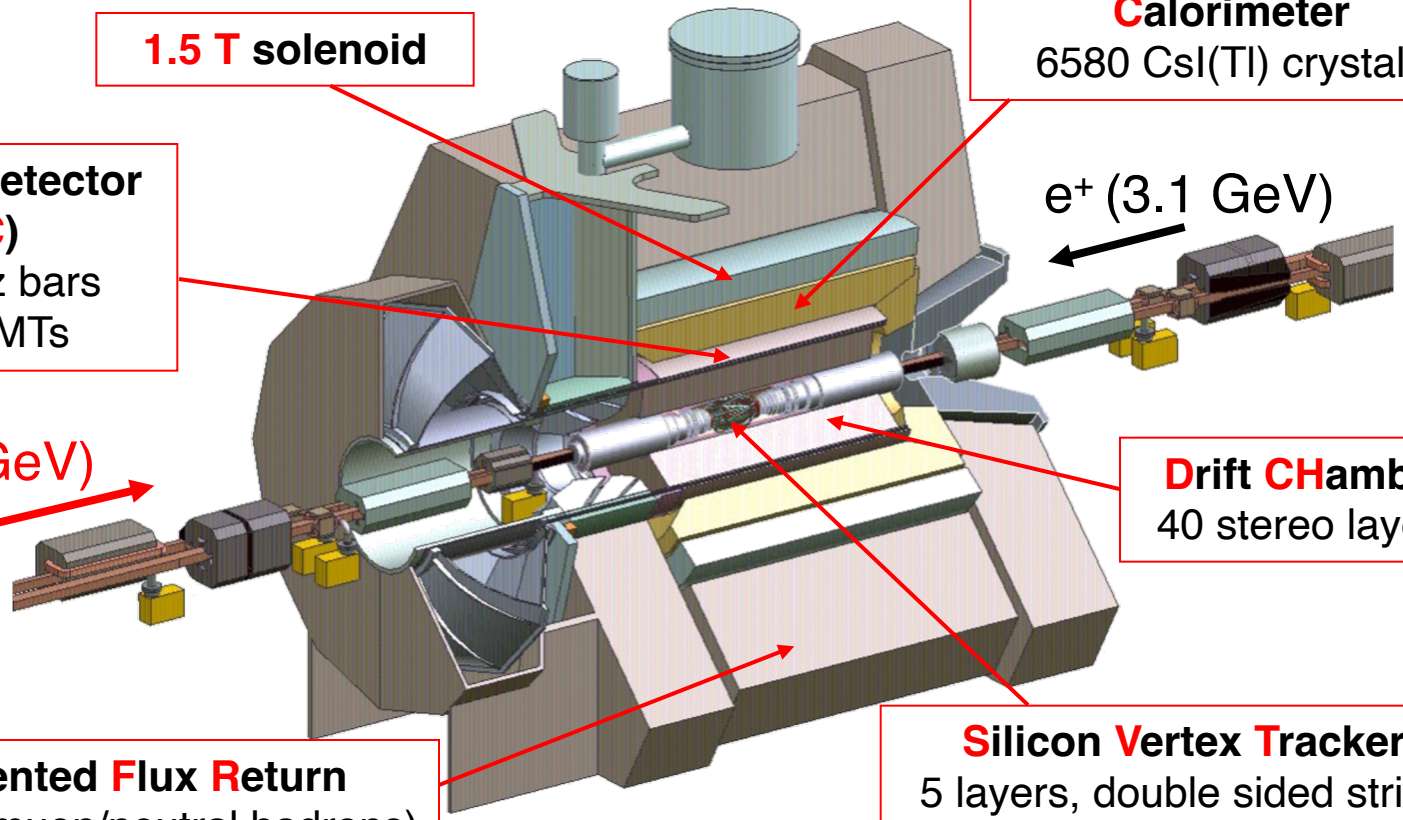
BABAR @ PEP II

- Running from 1999 to 2008
- Asymmetric collider @ $\sqrt{s}$ = 10.58 GeV at the Y(4S) resonance
  - 9 GeV electrons on 3 GeV positrons
- Result based on 398.5 fb^{-1}
  - 4.4×10^8 $B\bar{B}$
- Additional 32.5 fb^{-1} used as control and analysis strategy optimization sample (excluded from final results)





BABAR Detector



NIM A479,1 (2002)
NIM A729, 615 (2013)

SVT: 97% efficiency, 15 μm z hit resolution (inner layers, ⊥ tracks)

SVT+DCH: $\sigma(p_T)/p_T = \mathbf{0.13\ \%} \times \mathbf{p_T\ (GeV)} + \mathbf{0.45\ \%}$

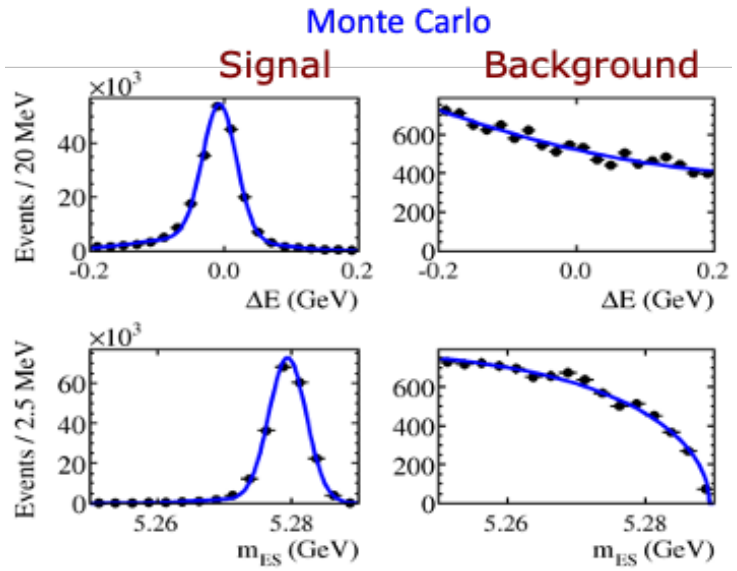
DIRC: K-π separation 4.2σ @ 3.0 GeV/c → >3.0σ @ 4.0 GeV/c

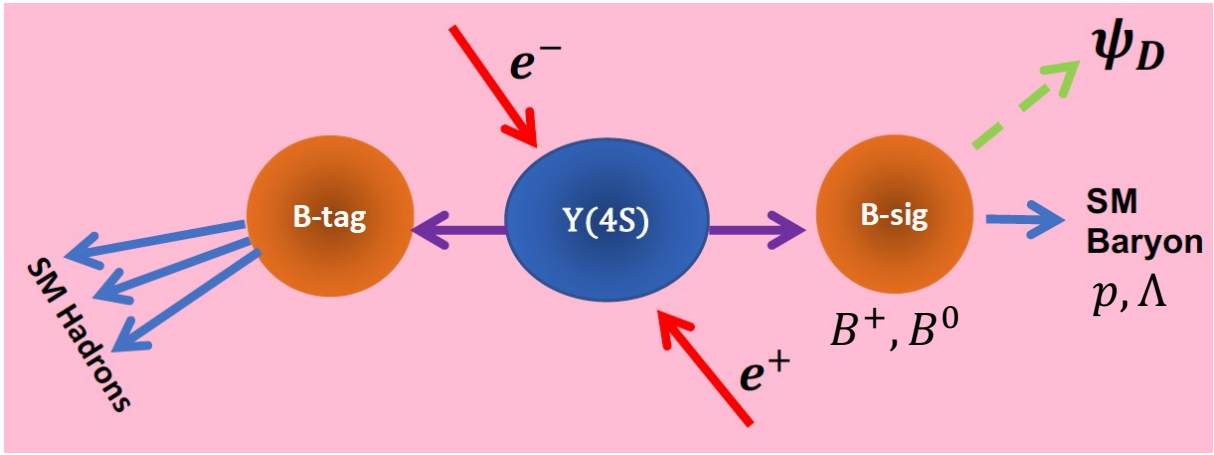
EMC: $\sigma_E/E = \mathbf{2.3\ \%} \times \mathbf{E(GeV)^{-1/4}} \oplus \mathbf{1.9\ \%}$

The $B^0 \to \psi_D \Lambda$ and $B^+ \to \psi_D \mathrm{p}$ analyses

PRD 107 (2023) 092001 PRL 131 (2023) 201801

- 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
- Constraint on B-tag:
  - $-200\mathrm{MeV} < \Delta\mathrm{E} < 200\mathrm{MeV}$
  - $5.2\mathrm{GeV} < \mathrm{m_{ES}} < 5.3\mathrm{GeV}$





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

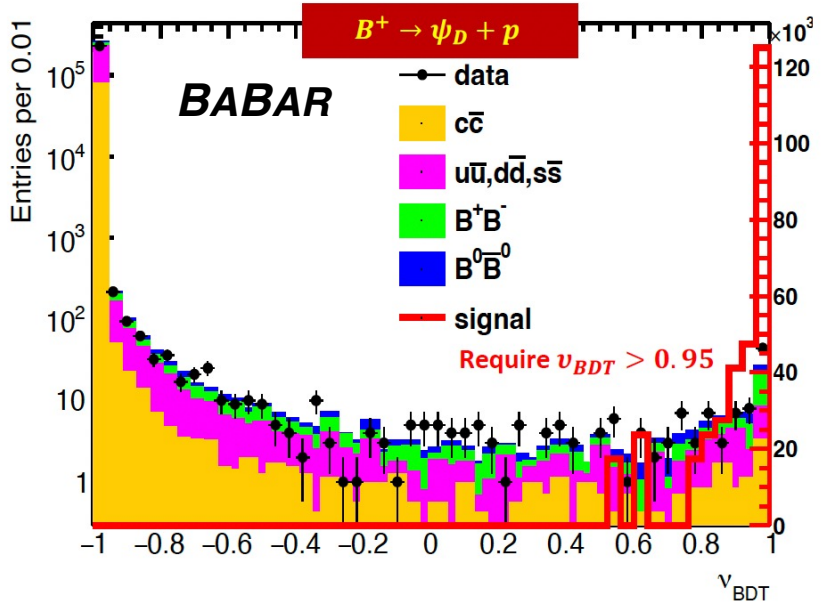
Beam-energy-substituted mass

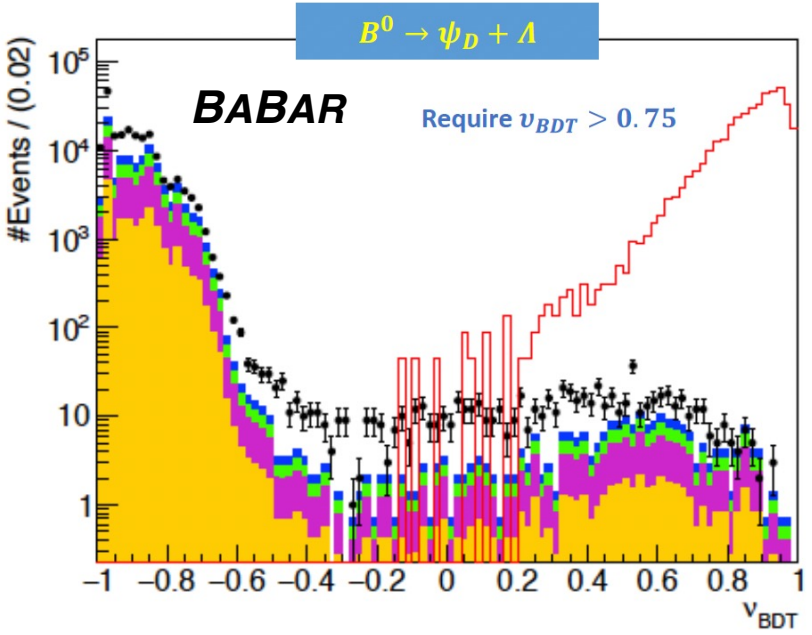
$$\Delta\mathrm{E} = E^{*}_{beam} - E^{*}_{Btag}$$

CMS beam energy minus reconstructed B-tag energy

Selection criteria

- For the p channel:
  - BABAR proton PID can be used to identify proton candidate;
  - B-sig must have + charge and only one charged particle
- For the Λ channel:
  - two charged tracks required on the signal side;
  - one Λ candidate in the B-sig, with $\Lambda \to p\pi^-$;
  - significance of the Λ decay length
    - (flight length)/σ > 1.0
  - kinematic fit of Λ reconstruction: $\chi^2 \leq 100$
- For both channels:
  - Optimization against background with Boosted Decision Tree
  - Using kinematical and event shape variables



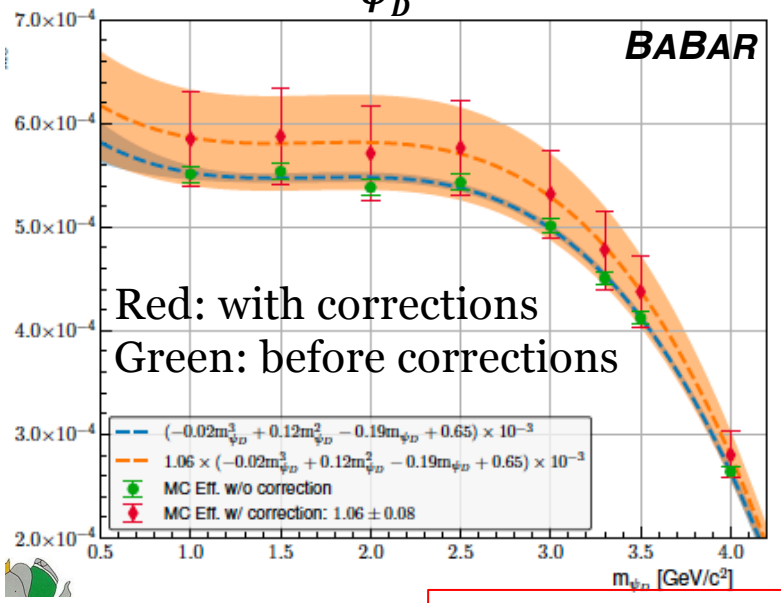


Extraction of results

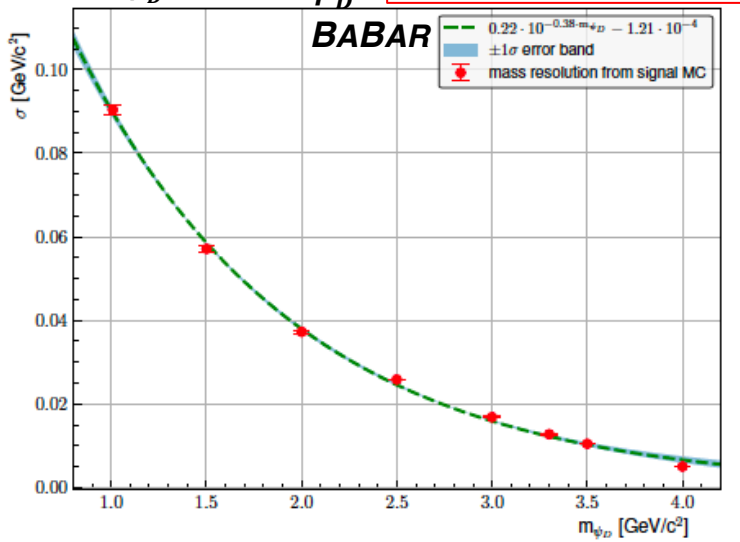
- Montecarlo
  - Standard model background (BB and continuum)
  - Signal generated with ψ_D mass varying between 1 and 4.2 GeV
  - Extract efficiency and resolution from fits to signal MC
- Estimate signal and backgrounds in data from MC study with corrections to MC from data-driven studies
- Count events in a $\pm 3\sigma_m$ window around the m_{ψ_D} mass hypothesis.

$$m_{\psi_D} = m_{\text{miss}} = \sqrt{(E^*_{B_{\text{sig}}} - E^*_{p/\Lambda})^2 - (\vec{p}^{\,*}_{B_{\text{sig}}} - \vec{p}^{\,*}_{p/\Lambda})^2}$$

ε_{MC} *vs* m_{ψ_D}



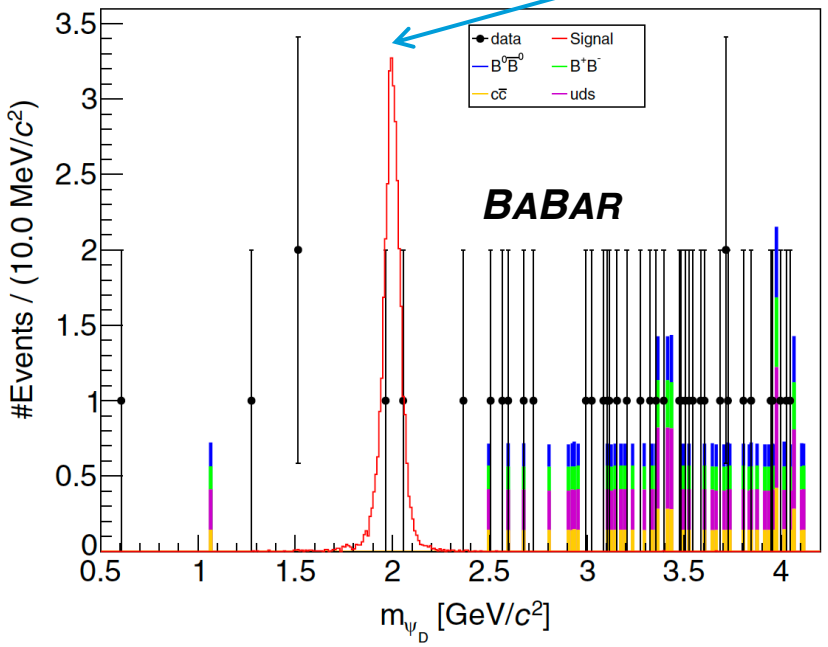
σ_{ψ_D} *vs* m_{ψ_D}

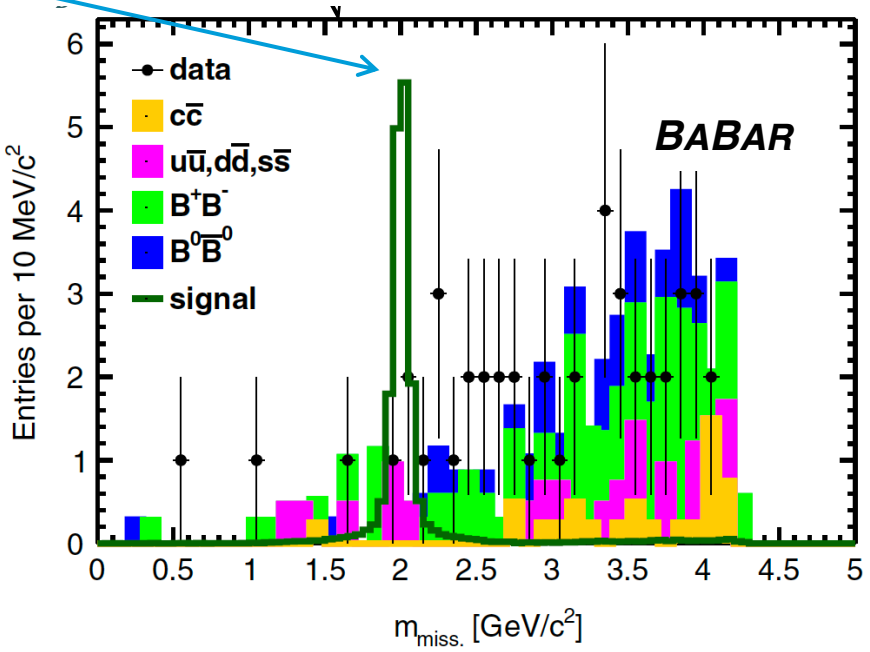


$B^0 \to \psi_D + \Lambda$

Extraction of final results

Simulated signal sample for $m_{\psi_D} = 2GeV$





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

41 events survive in data

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

$B^+ \to \psi_D + p$

46 events survive in data

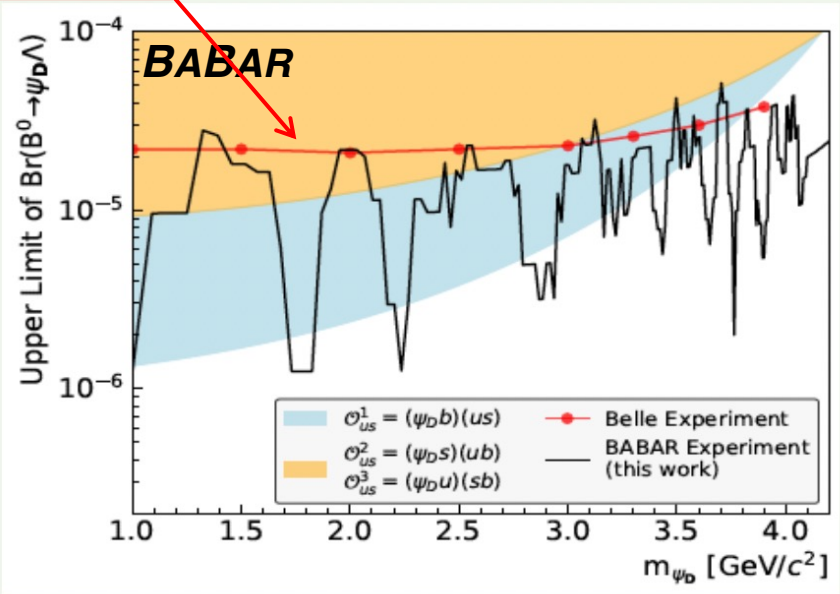
3.5σ at 3.3 GeV: largest local significance
=> a 1 σ global significance

Final results on B.F.

Limits on effective operators to allow B mesogenesis

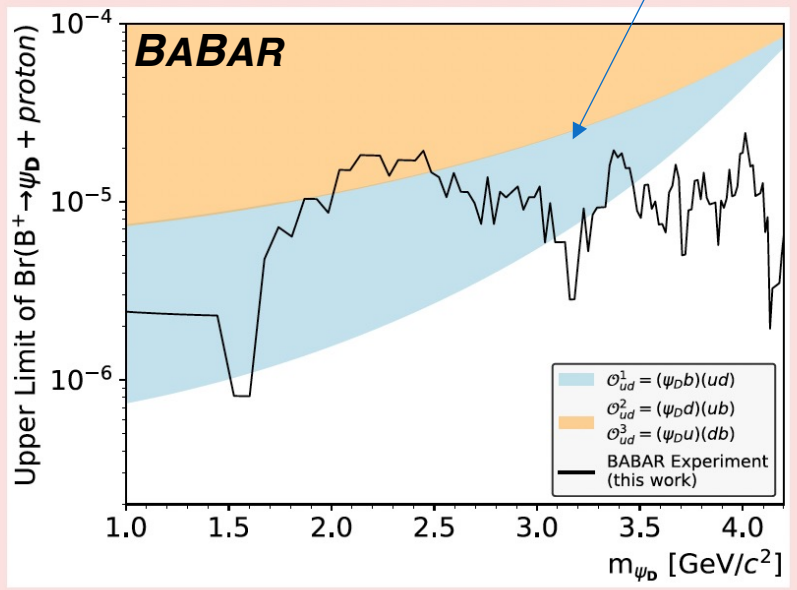
BELLE Result
PRD 105, L051101 (2022)

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



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

$B^+ \to \psi_D + p$



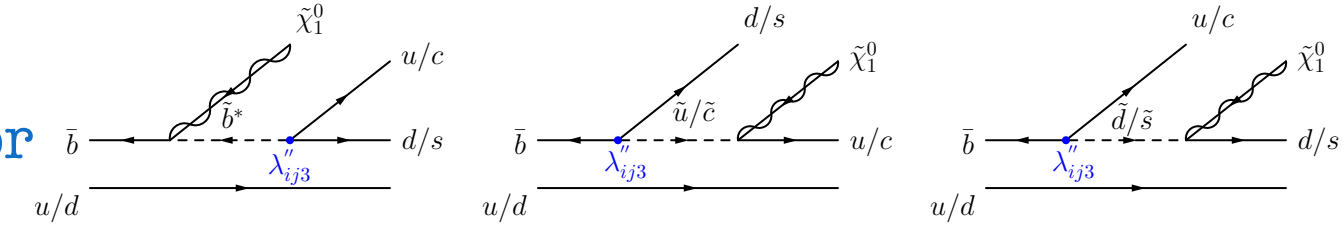
Phys.Rev.Lett. 131 (2023) 20, 201801

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

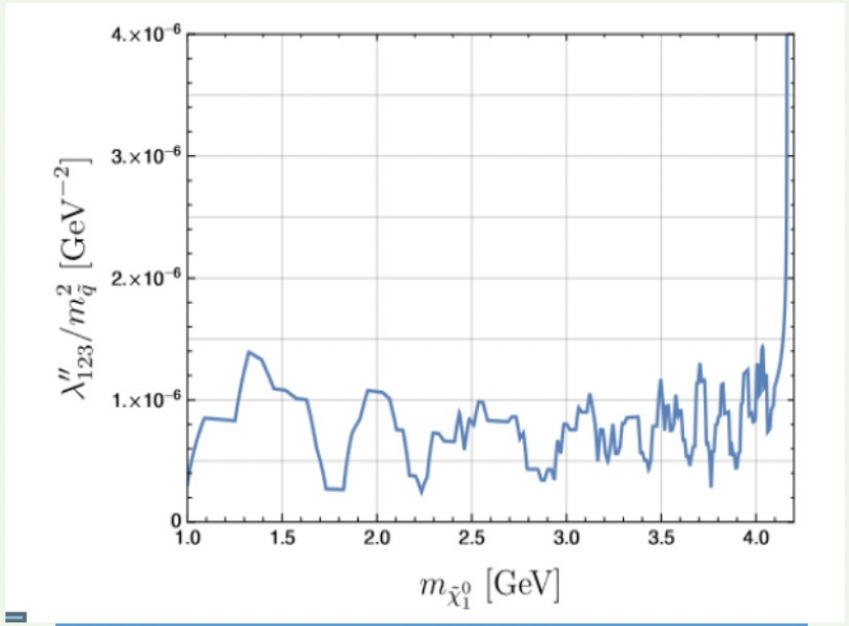
First direct search for $B^+ \to \psi_D + p$ places tight constraints on the specified model of Dark Matter + Baron Asymmetry of the Universe

Interpretation for SUSY with R-parity violation

- Neutralino and baryon
- First limits for this SUSY model for both channels

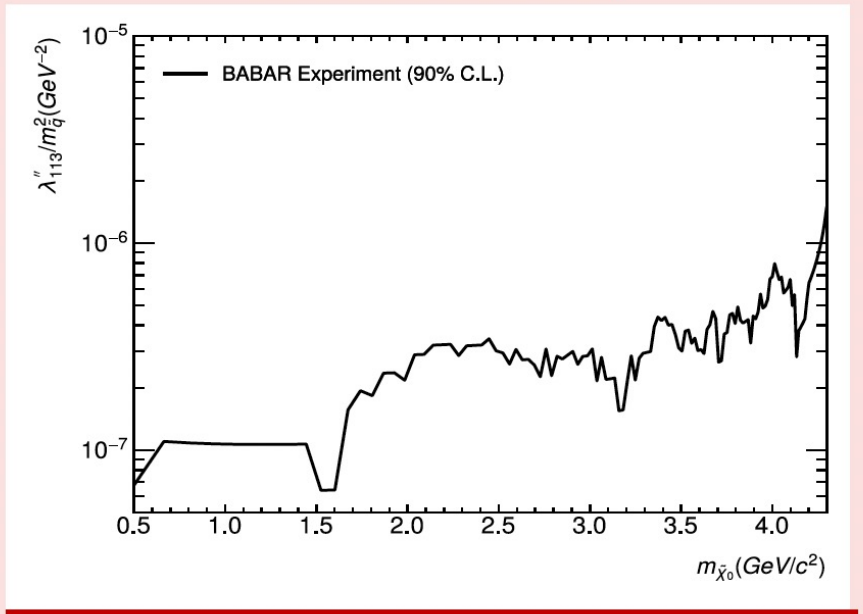


$B^0 \rightarrow \widetilde{\chi_0} + \Lambda$



JHEP 02 (2023) 224

$B^+ \rightarrow \widetilde{\chi_0} + p$



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

Conclusions and next steps

- BABAR Published in 2023 limits on
  - $B^0 \to \psi_D \Lambda$ - PRD 107 (2023) 092001: improving Belle result
  - $B^+ \to \psi_D \mathrm{p}$ - PRL 131 (2023) 201801: first measurement
- B-Mesogenesis parameter space vastly reduced, almost excluded for some operators
- Must explore additional operators to fully exclude this B-Mesogenesis model
- Expect results from Belle II high luminosity running
- Coming soon from BABAR: $B^0 \to \psi_D + \pi^- + \Lambda_c^+$
- Still producing results after all these years