# Search for Baryogenesis and Dark Matter in *B*-Meson Decays at *BABAR*

**David Norvil Brown,**
**Ogden College of Science & Engineering**
**Western Kentucky University**
**On behalf of the *BABAR* Collaboration**

**Tau2023: The 17th International Workshop on Tau Lepton Physics**

December 4-8 2023

## Search for Baryogenesis and Dark Matter in *B*-Meson Decays at *BABAR*

## Outline of the Talk

- Motivation - Baryogenesis, Dark Matter
- The *BABAR* Experiment
- Search for $B^+ \to \psi_D + p$ Lees, *et al.,* PRL **131 (2023) 201801**
- Interpretation of Results

Charge conjugation implied throughout

# Motivation: Search for the Dark Sector

Zwicky, AcHPhys 6 (1933); *et seq*

- **The *Existence* of dark matter is well-established from astrophysical evidence, but its nature is not known**
- **Collider experiments allow for:**
  - **Direct searches for dark matter particles through decays to/with Standard Model (SM) particles**
- **Electron-positron collider experiments are particularly clean environments and in many cases provide the best reach in searches for new physics (NP)**

# Motivation: Baryogenesis

**Baryon Asymmetry of the Universe (BAU) implies baryogenesis**

Canetti *et al.*, NJOP 14 (2012) 095012

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

Sakharov, A D, JETP 5 (1967) 24

**Baryogenesis requires Sakharov conditions:**

1. **Baryon number violation**
2. **C and CP violation**
3. **Deviation from thermal equilibrium**

**Conditions are all compatible with the Standard Model (SM), but current measurements don't allow necessary level of baryogenesis to explain BAU. Several New Physics models could introduce necessary ingredients to explain observed level of baryogenesis.**

# Motivation: Baryogenesis and Dark Matter, Together

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

**Consider the following possibility:**

- **There exist non-SM dark baryons and anti-baryons**
- **The concept of baryon number conservation counts dark baryons and anti-baryons equivalently to SM baryons and anti-baryons**

Note that the dark baryons must be charge neutral

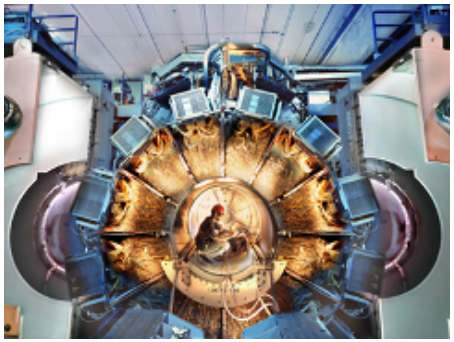
**Propose a new dark sector anti-baryon, $\psi_{\mathrm{D}}$, and search for:**

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

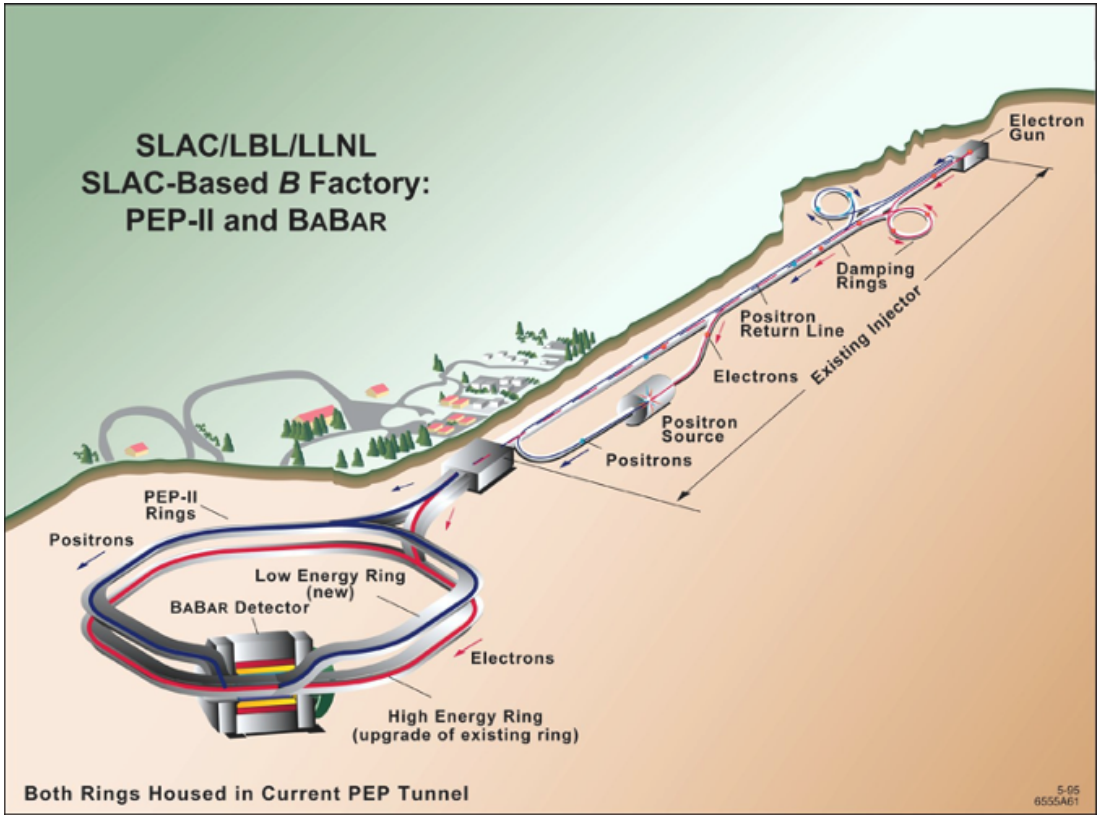
**Will have a distinct experimental signature**

Charge conjugation implied throughout

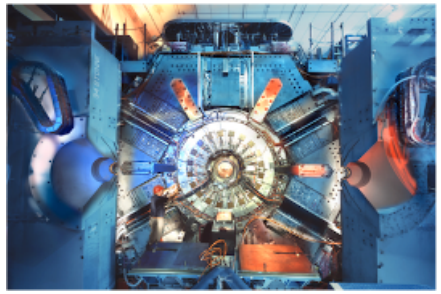
# *BABAR* Basics



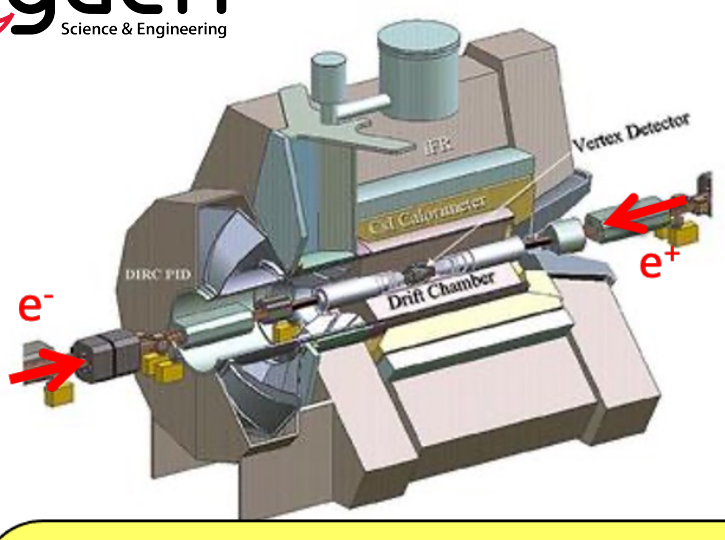
Collaboration formed 1993
- celebrating 30 years of teamwork




electron-positron collider experiment at SLAC

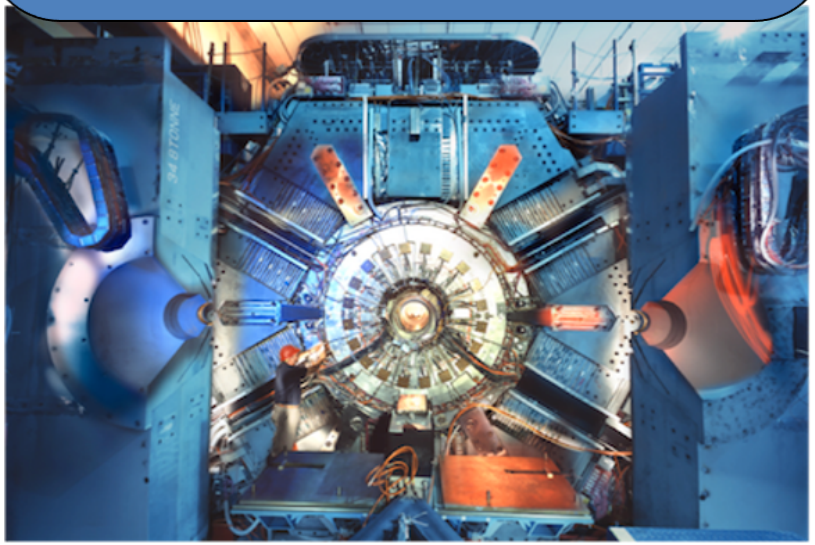


# The *BABAR* Detector



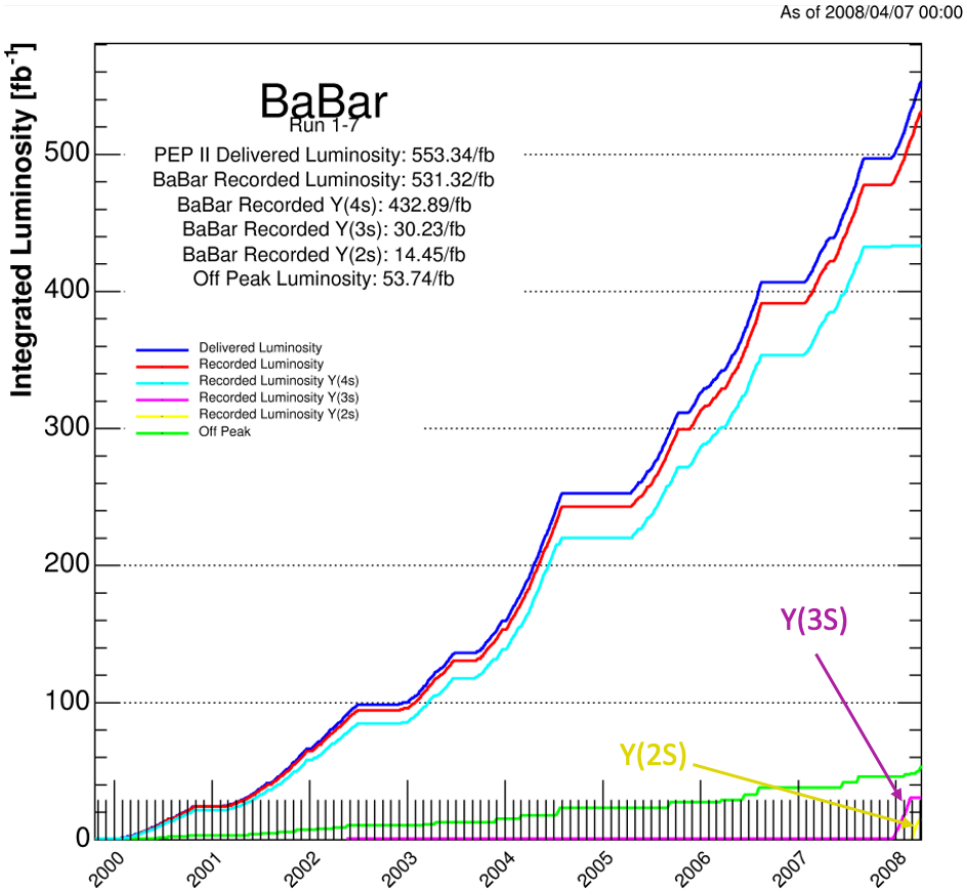

- Asymmetric-energy beams for boost
- Modern/state of the art detector
- 5 cylindrical subdetector systems with a 40-layer drift chamber + 5-layer vertex detector
- Excellent electromagnetic calorimetry
- Multiple measurements for particle identification
- Excellent momentum resolution

- Primarily designed for study of *CP*-violation in *B* meson decays
- Quality and general-purpose design make it suitable for a large variety of studies

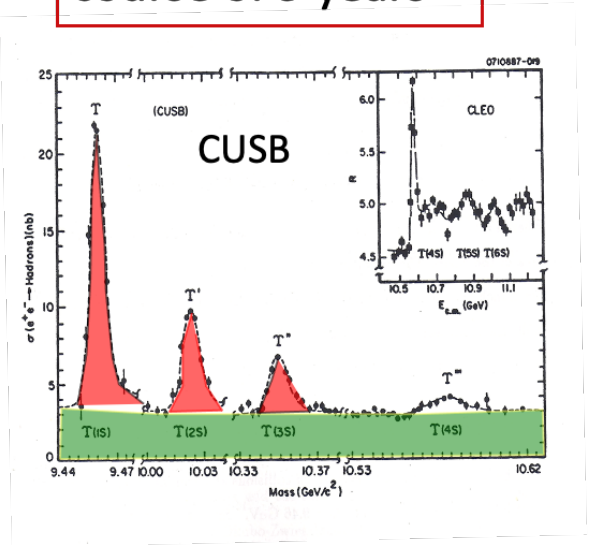


NIM A479,1 (2002)
update: NIM A729, 615 (2013)

# The *BABAR* Running Era



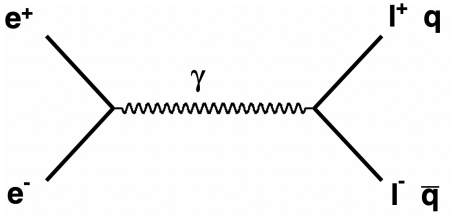

7 Runs over the course of 9 years



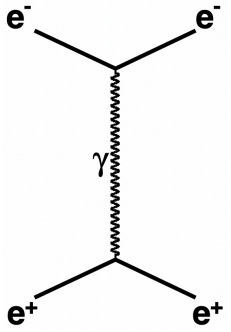

This analysis uses 398 $fb^{-1}$ of data

- First collisions with *BABAR* 1999
- Final data taken 12:43 p.m., April 7, 2008

# Fundamental Processes in $e^+e^-$ Colliders




First-order processes




excellent calibration samples

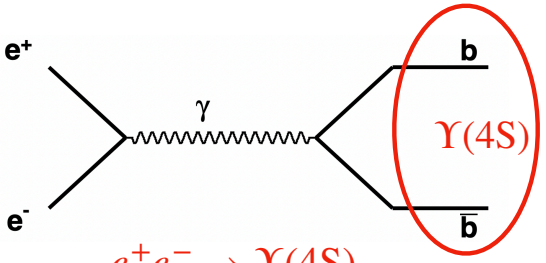
$(q = u, d, s, c, b)$

$(l = e, \mu, \tau)$

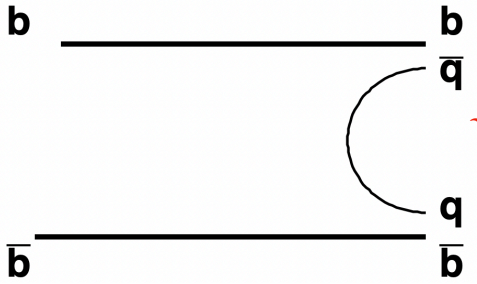
$e^+e^- \to q\bar{q}$ hadronic

$e^+e^- \to l^+l^-$

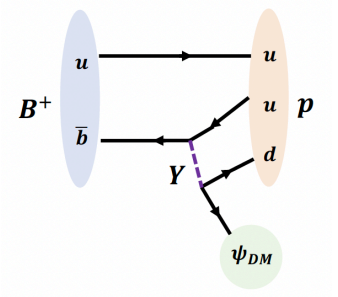
**Special case can occur at the $\Upsilon(4S)$ energy**




$e^+e^- \to \Upsilon(4S)$



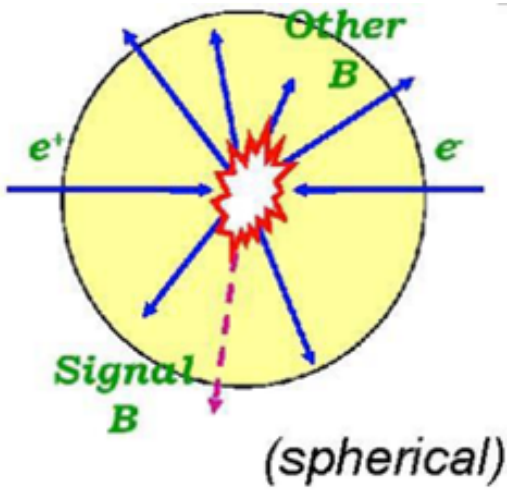

$\Upsilon(4S) \to B\bar{B}$




**Study of $B^+ \to \psi_{\mathrm{D}} + p$**

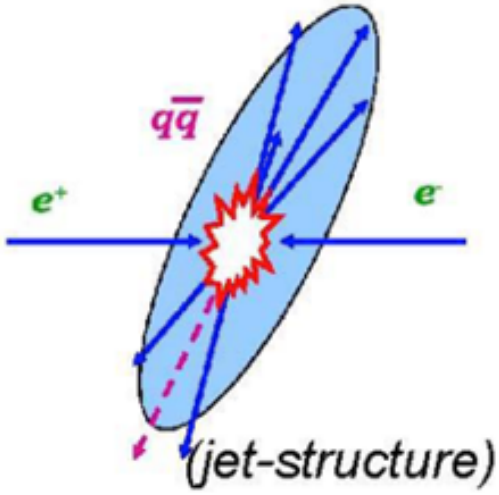
Lees, *et al.,* PRL **131 (2023) 201801**

# Typical *B* backgrounds and *B* Tagging



(spherical)

- **Dominant backgrounds are $q\bar{q}$ $(q = u, d, s, c)$, exhibiting a jet-like topology, whereas $B\bar{B}$ events are more "spherical"**
- **We separate and suppress continuum background, using several variables sensitive to event shape**
- **One *B* meson is reconstructed through a common mode and serves as a 'Tag.' In events with multiple tag candidates, the one with the CM energy closest to the beam CM energy is selected as the tag. The rest of the event is assigned to the studied signal *B***

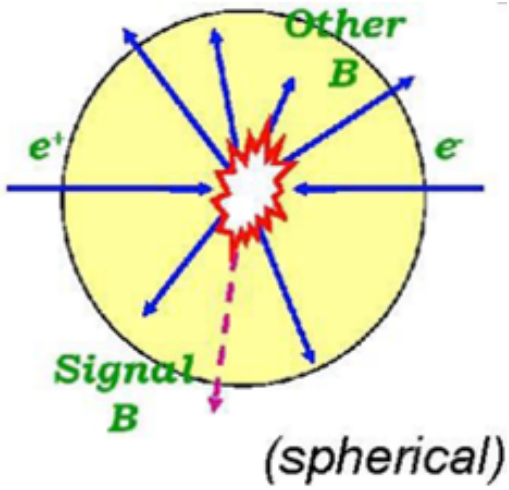


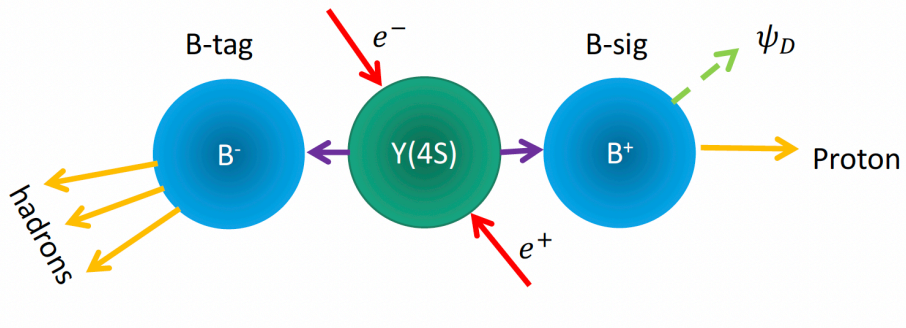
(jet-structure)

# Event Selection for This Study

Select events with:

- Hadrons
- At least one tag *B* consistent with beam energy and in good agreement with know *B* mass
- Only one charged particle not used in tag *B* reconstruction
  - Identified as consistent with proton
- Missing energy from the signal *B* reconstruction



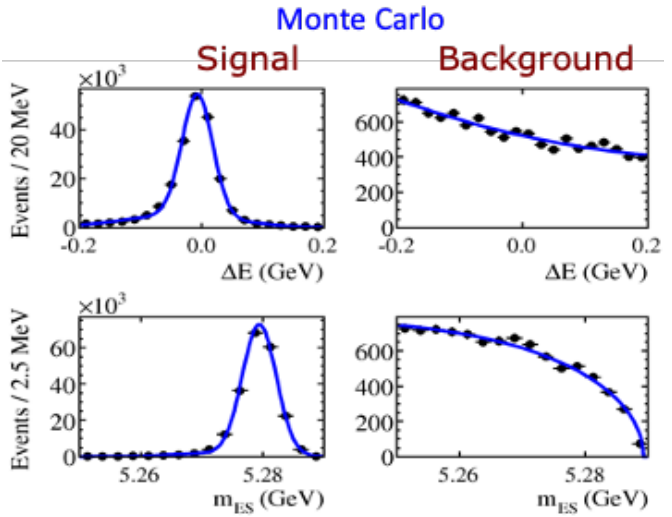
# Kinematics of *B* Decays

Fully reconstructed *B* mesons: two variables are commonly used (exploiting the precise knowledge of the beam energy):

Using units such that $c = 1$

$$\Delta E = E_{meas} - E_{beam}$$

$$m_{ES} = \sqrt{E_{beam}^2 - \mathbf{p}_{meas}^2}$$




Invariant mass can also be used: $m_B = \sqrt{E_{meas}^2 - \mathbf{p}_{meas}^2}$

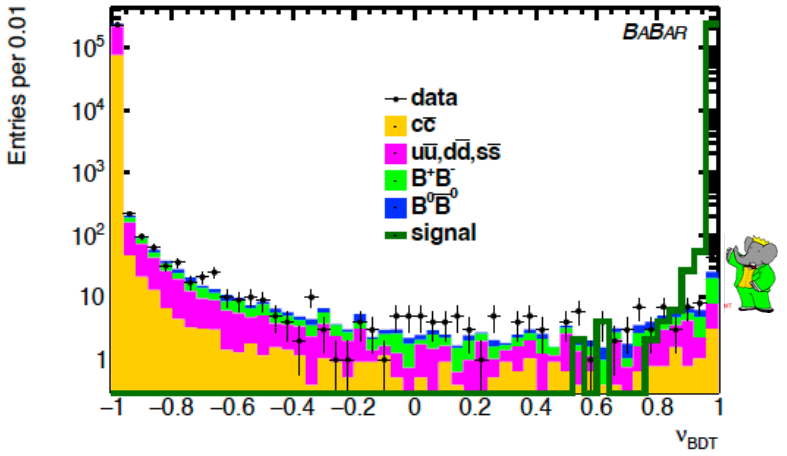
# Study of $B^+ \to \psi_D + p$

To further reduce background for this study, use a Boosted Decision Tree (BDT). Variables include:

- $m_{ES}$ and $\Delta E$

$$m_{ES} = \sqrt{E_{beam}^2 - \mathbf{p}_{meas}^2} \qquad \Delta E = E_{meas} - E_{beam}$$

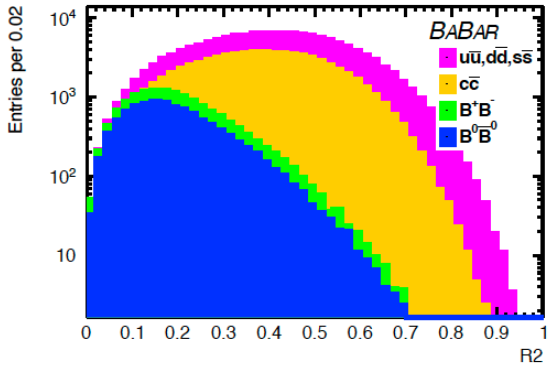
- tag $B$ decay channel information
- magnitude and direction of thrust vector
- extra neutral energy on the signal side of event
- direction of the missing momentum vector
- number of $\pi^0$ candidates on the signal side
- ratio of the second to zeroth Fox-Wolfram moments, $R_2$




In CM Frame…

$$H_l = \Sigma_{i,j} \frac{|\vec{p}_i||\vec{p}_j|}{s} P_l(\cos\Omega_{ij}) \qquad R_2 \equiv \frac{H_2}{H_0}$$

*Spherical* $0 \leftarrow R_2 \rightarrow 1$ *Colinear*

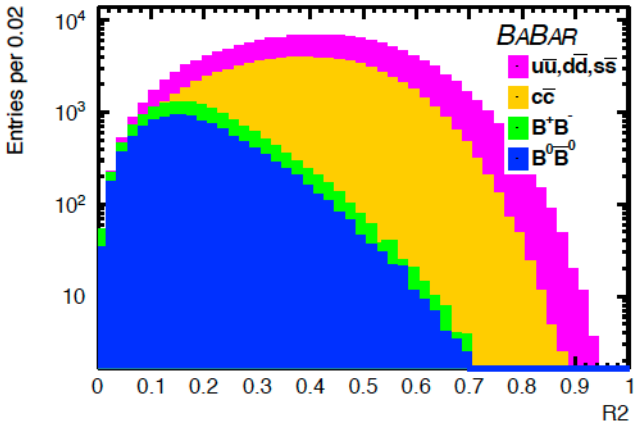


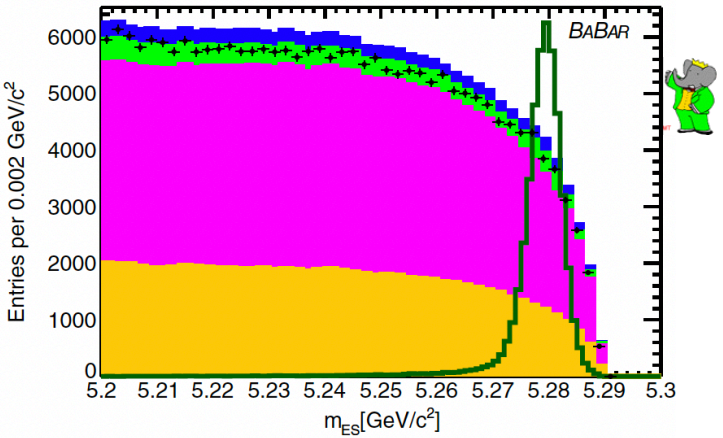

Events are required to have $\nu_{BDT} > 0.95$
This retains > 99% of simulated signal events while significantly reducing simulated backgrounds

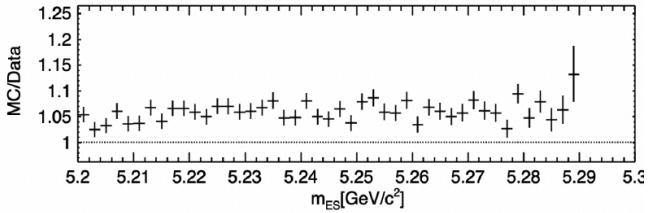
# Study of $B^+ \to \psi_D + p$

Correction for discrepancy of simulation of $q\bar{q}$ events relative to $B\bar{B}$ events

- $f_{q\bar{q}} = 1.05 \pm 0.03$ determined from $R_2 > 0.7$
- $f_{B\bar{B}} = 0.85 \pm 0.07$ determined from $R_2 < 0.7$
- Assume $f_{B\bar{B}}$ is mode-independent



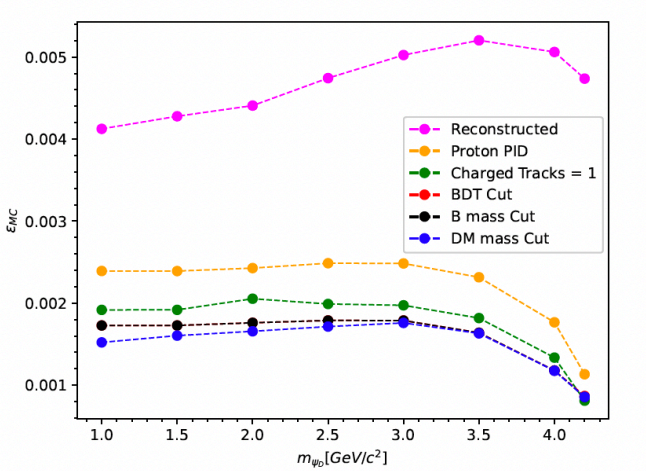

# Study of $B^+ \to \psi_D + p$

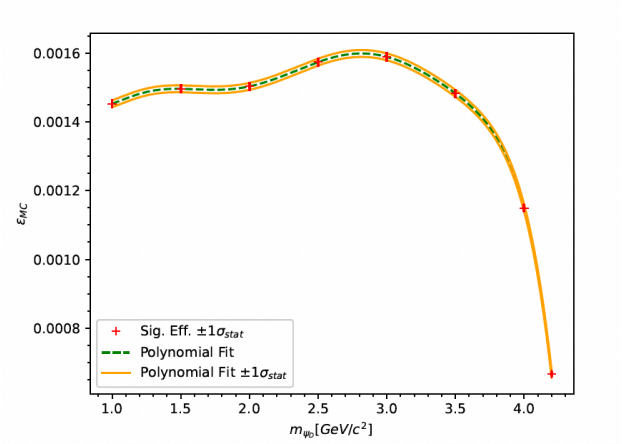
Overall signal efficiency is dependent on the simulated mass of the $\psi_D$

0.145 % for $m_{\psi_D} = 1.0\ \mathrm{GeV/c^2}$

0.06 % for $m_{\psi_D} = 4.2\ \mathrm{GeV/c^2}$

Eight $\psi_D$ mass hypotheses simulated. Efficiency fit to a smooth curve to allow interpolation to any mass for reconstruction




Fitted overall efficiency as a function of mass

# Study of $B^+ \to \psi_D + p$

Fit to missing mass as a measure for signal

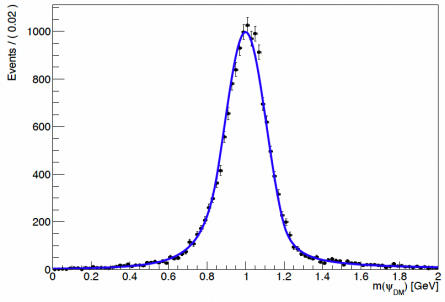
$$m_{\text{miss}} = \sqrt{(E^*_{B_{\text{sig}}} - E^*_{\text{p}})^2 - |\vec{p}^{\,*}_{B_{\text{sig}}} - \vec{p}^{\,*}_{\text{p}}|^2}$$

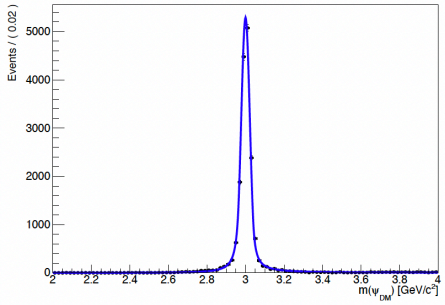
Using units such that $c = 1$

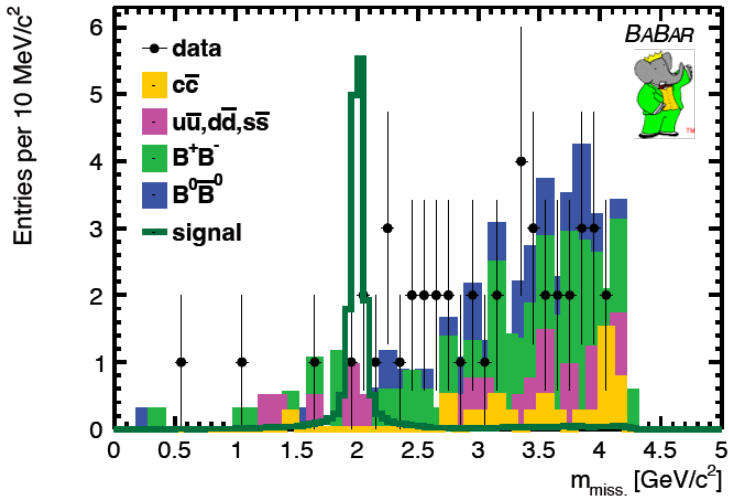
Missing mass should be the mass of the $\psi_D$

Use double-sided Crystal Ball function to extract signal mass width from simulation.

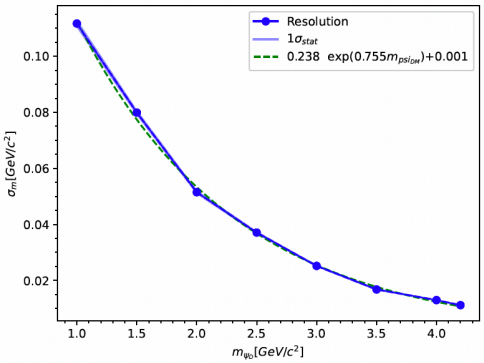
Fit the widths to a smooth curve for interpolation in reconstruction.




Sample showing data overlaid with simulated backgrounds and expected signal



# Study of $B^+ \to \psi_D + p$

## Systematics

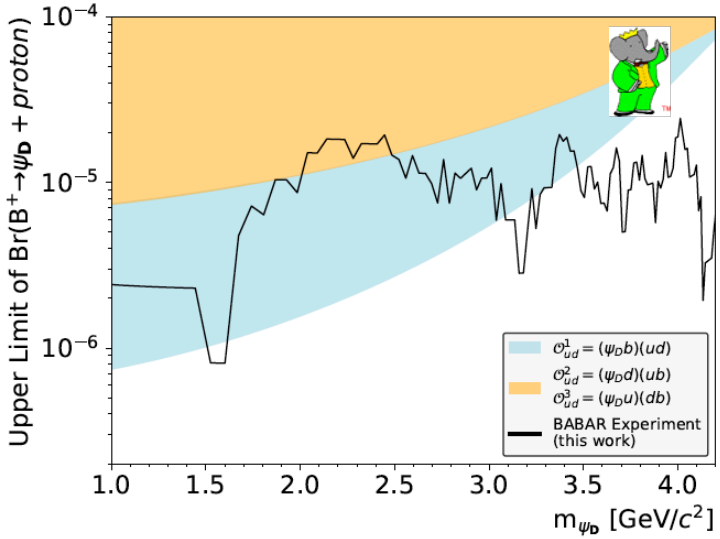
- Dominant systematic, 8.2%, comes from the MC/Data correction
- Uncertainty on Luminosity/number of $\Upsilon(4S)$ is 0.6%
- Uncertainty on $\Upsilon(4S) \to B^+B^-$ contributes 1.2%
- Particle ID of proton contributes 1% uncertainty
- Overall uncertainty on signal efficiency is 8.4%

Analysis developed with data from one run period. Other 5 run periods used in final analysis, performed blind.

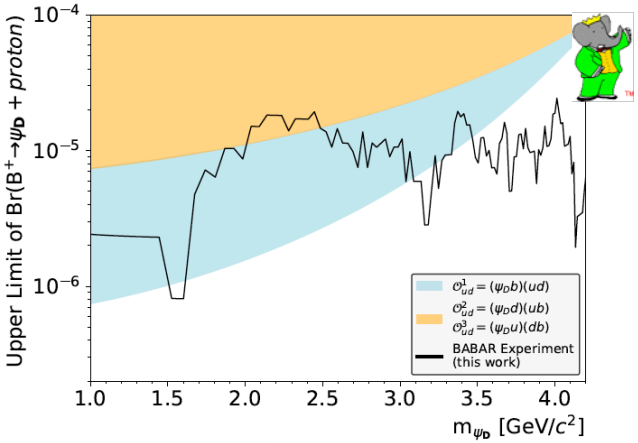
## Results

- We perform the fitting analysis with 127 test masses between ~ $1\ \mathrm{GeV/c^2}$ and ~$4.2\ \mathrm{GeV/c^2}$
- No observed signal. Largest local significance $3.5\ \sigma$ at $3.3\ \mathrm{GeV/c^2}$, corresponding to global significance $1\ \sigma$
- For masses with no fitted signal use profile likelihood method

1 to 2 Orders of Magnitude improvement over previous most stringent upper limits



# Implications

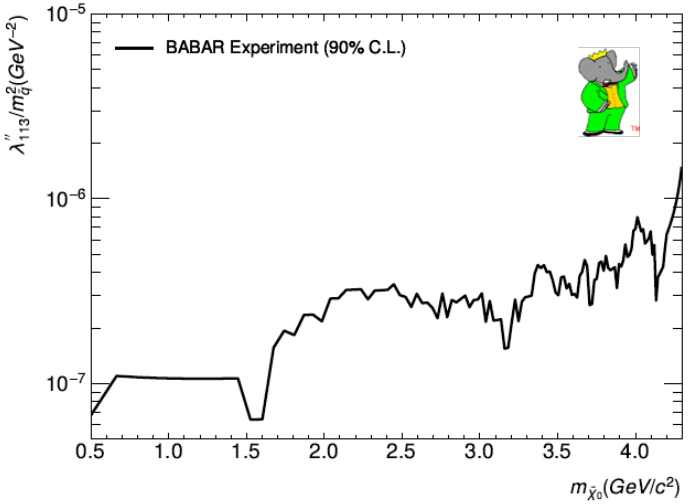



Our results impact BSM theories

| Operator and Decay | Initial State | Final State | $\Delta M$ (MeV) |
|---|---|---|---|
| $\mathcal{O}_{ud} = \psi b u d$ $\bar{b} \to \psi u d$ | $B_d$ | $\psi + n\,(udd)$ | 4340.1 |
| | $B_s$ | $\psi + \Lambda\,(uds)$ | 4251.2 |
| | $B^+$ | $\psi + p\,(duu)$ | 4341.0 |
| | $\Lambda_b$ | $\bar{\psi} + \pi^0$ | 5484.5 |
| $\mathcal{O}_{us} = \psi b u s$ $\bar{b} \to \psi u s$ | $B_d$ | $\psi + \Lambda\,(usd)$ | 4164.0 |
| | $B_s$ | $\psi + \Xi^0\,(uss)$ | 4025.0 |
| | $B^+$ | $\psi + \Sigma^+\,(uus)$ | 4090.0 |
| | $\Lambda_b$ | $\bar{\psi} + K^0$ | 5121.9 |
| $\mathcal{O}_{cd} = \psi b c d$ $\bar{b} \to \psi c d$ | $B_d$ | $\psi + \Lambda_c + \pi^-\,(cdd)$ | 2853.6 |
| | $B_s$ | $\psi + \Xi_c^0\,(cds)$ | 2895.0 |
| | $B^+$ | $\psi + \Lambda_c^+\,(dcu)$ | 2992.9 |
| | $\Lambda_b$ | $\bar{\psi} + \overline{D}^0$ | 3754.7 |
| $\mathcal{O}_{cs} = \psi b c s$ $\bar{b} \to \psi c s$ | $B_d$ | $\psi + \Xi_c^0\,(csd)$ | 2807.8 |
| | $B_s$ | $\psi + \Omega_c\,(css)$ | 2671.7 |
| | $B^+$ | $\psi + \Xi_c^+\,(csu)$ | 2810.4 |
| | $\Lambda_b$ | $\bar{\psi} + D^- + K^+$ | 3256.2 |

Alonso-Álvarez, *et al.*, PRD **104** (2021) 035028

Implications for $\mathcal{O}_{ud}$ operators




Dib, *et al.*, JHEP **2023** (02 224 (2021))

SUSY with R-parity violation and a light neutralino.
Our results convert to limits on RPV coupling $\lambda''_{123}$

Result can be interpreted in terms of charged *B*-mesogenesis

Elahi, *et al.*, PRD **105** (2022) 055024

## Conclusions


- Dark sector poorly understood. Implications for particle physics
- potential for a gateway to New Physics (NP)
- We have presented a study of $B^+ \to \psi_D + p$ and set upper limits on branching fraction

  Lees, *et al.*, PRL **131 (2023) 201801**
- Has implications for BSM
- 15 years after end of data taking, *BABAR* continues to produce important results


Thank you!