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

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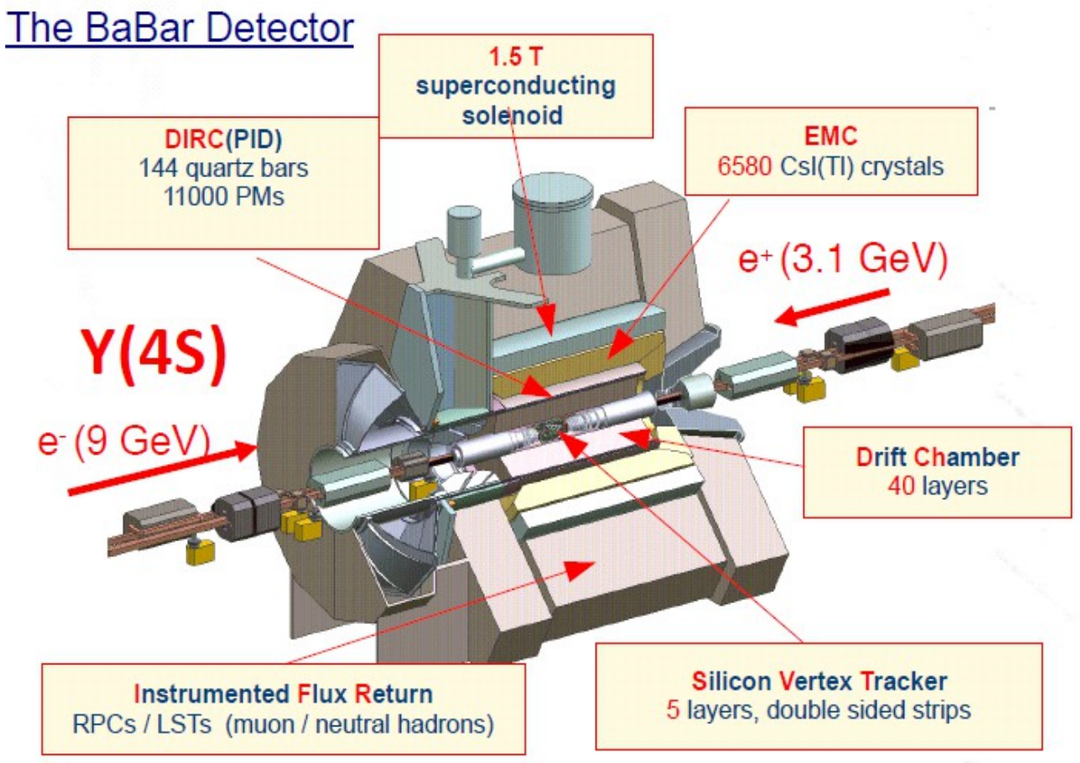
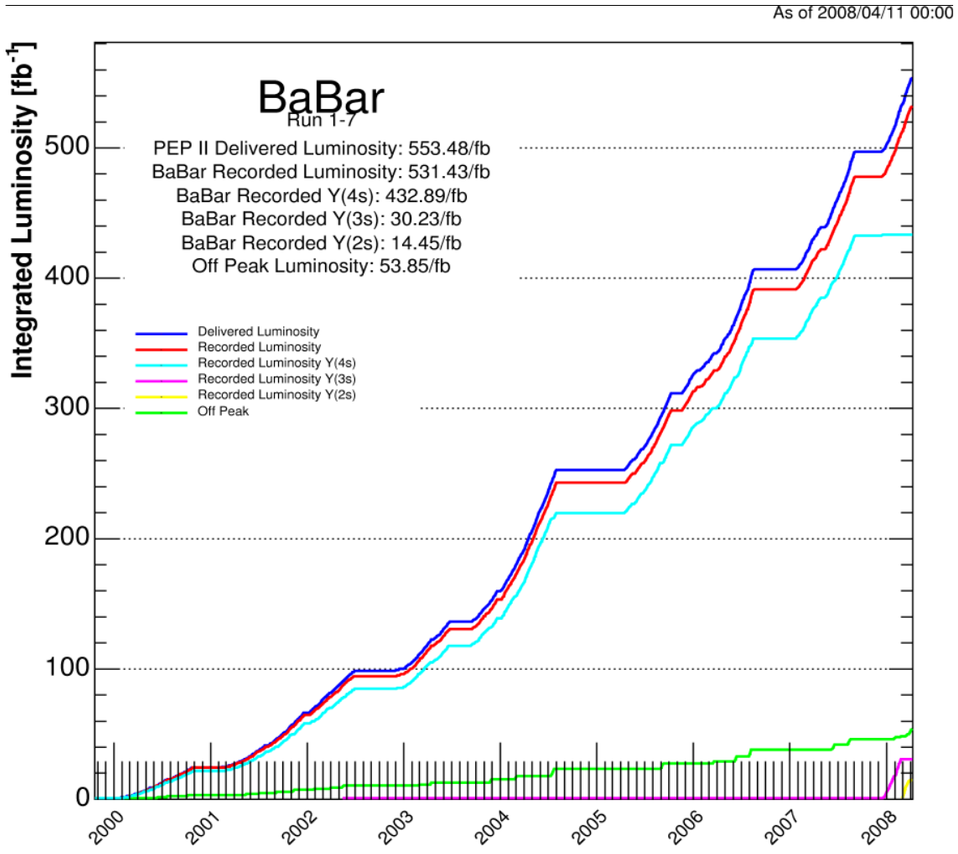
On Behalf of the BABAR Collaboration

Special thanks to Sophie Middleton and Tim Gershon for slide material

# BABAR Experiment: 1999-2008




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




BaBar dataset: 431 $fb^{-1}$ recorded at $\Upsilon(4S)$ (470 $B\bar{B}$ pairs)

Rich physics program: CP violation, flavor mixing, rare decay searches and measurements

Hermetic detector with excellent PID allows accurate reconstruction of missing mass

# Matter-Antimatter Asymmetry

- Abundances of visible and dark matter are two of the great cosmological puzzles

• Need CP violation, baryon number violation, and out-of-equilibrium processes to create matter-antimatter asymmetry from a symmetric early Universe

☞ Standard Model effects do not generate enough matter-antimatter imbalance observed today

• Standard Model does not explain dark matter abundance either

☞ Perhaps one can solve these two problems simultaneously ?

☞ One of the ingredients (CP violation) already observed in B decays

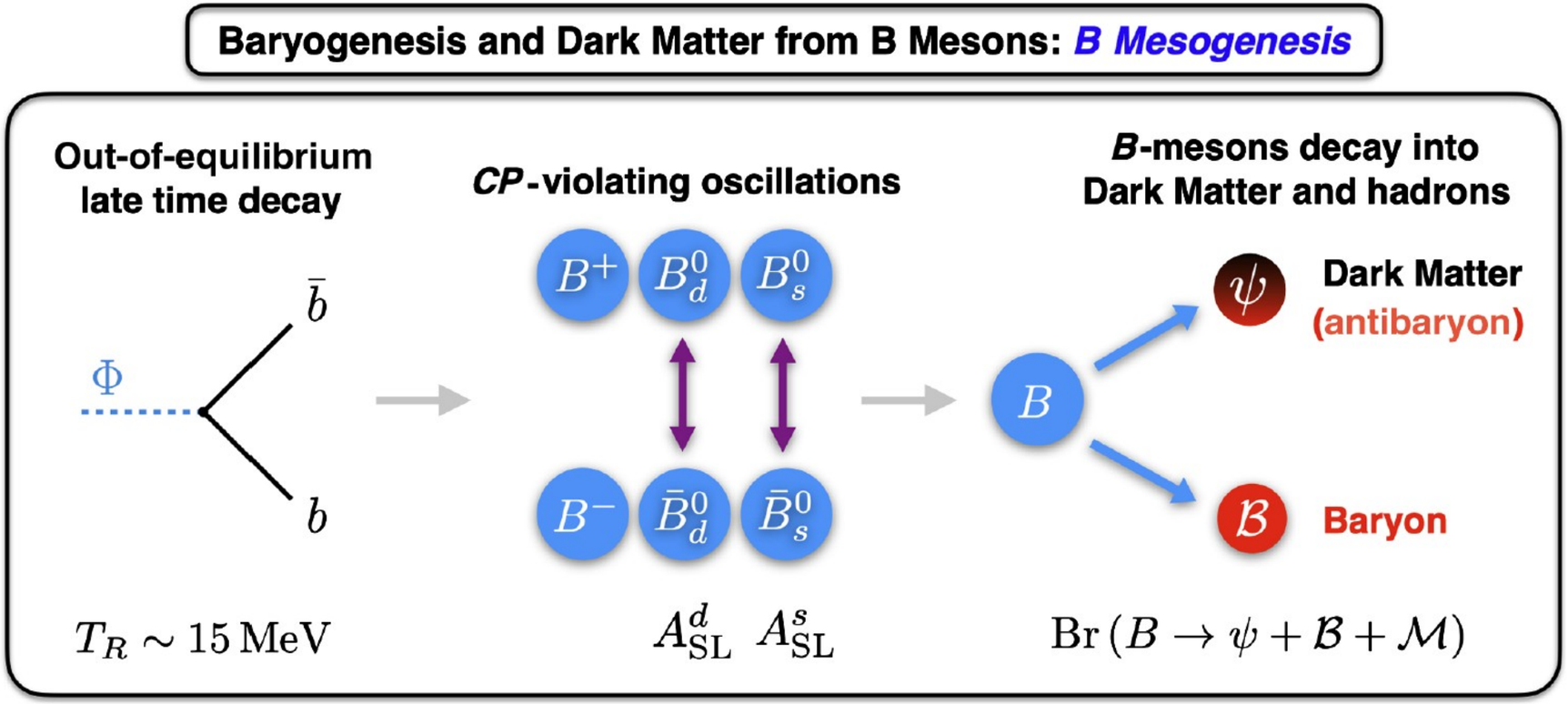

ИЗБРАННЫЕ ТРУДЫ

НАРУШЕНИЕ СР-ИНВАРИАНТНОСТИ, С-АСИММЕТРИЯ И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ

А.Д. Сахаров

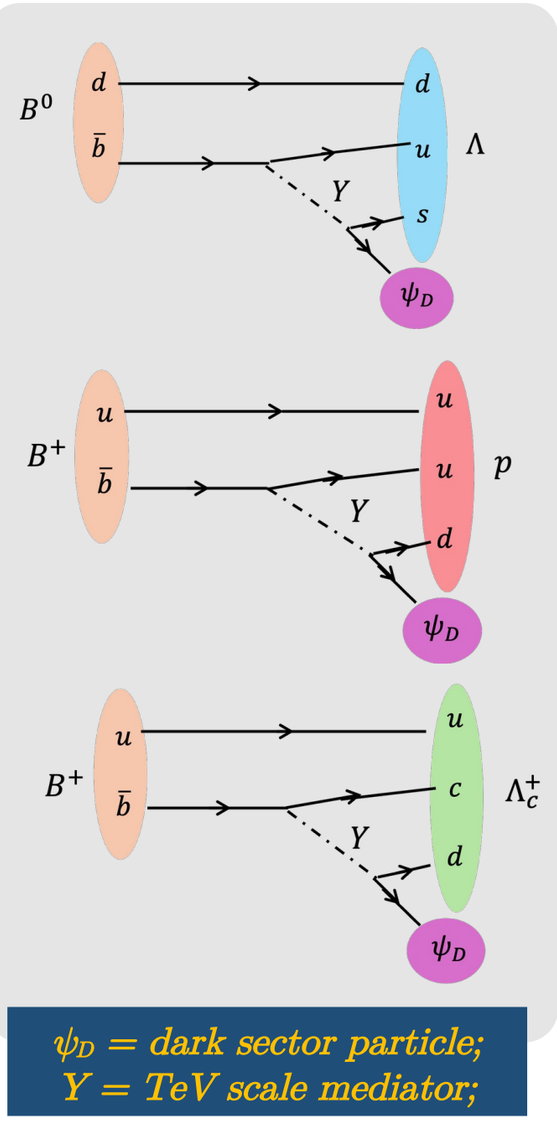
(ЖЭТФ. Письма в редакцию. 1967. Т. 5. вып. 1. С. 32 — 35)

# Baryogenesis through Exotic B Decays




G. Elor, M. Escudero, and A. E. Nelson, PRD 99, 035031 (2019).
G. Alonso-Alvarez, G. Elor, and M. Escudero, PRD **104**, 035028 (2021).

B-Factories are an ideal place to look for these signatures




*$\psi_D$ = dark sector particle;*
*Y = TeV scale mediator;*

# Baryogenesis through Exotic B Decays

- Kinematic constraints require that $\psi_D$ mass is in [0.94-4.34] GeV
- Would like to explore couplings to 1st and 2nd generations:

$$O_{i,j} = (\psi_D\, b)\ (q_i\, q_j)\ (i = u, c\ and\ j = d, s)$$

- One dominant operator expected (flavor constraints)

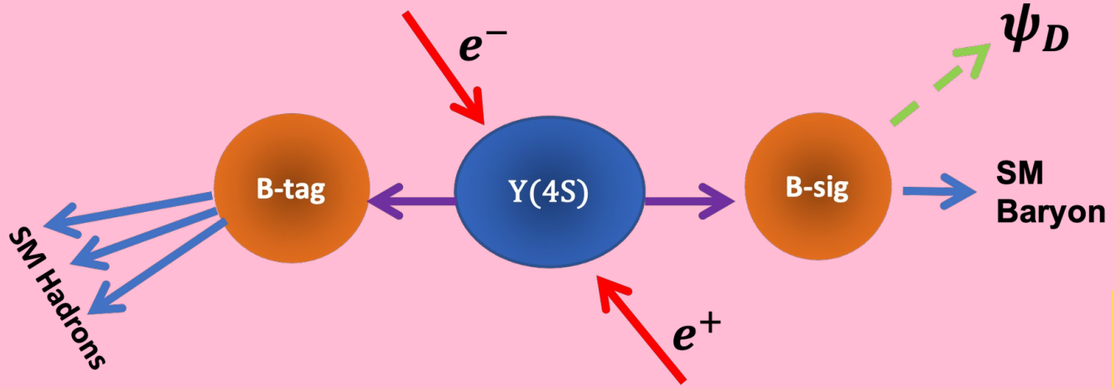
| Initial State | Final State | Operators | ΔM (MeV/c²) | *BABAR Results* |
|---|---|---|---|---|
| $B^0$ | $\psi_D + \Lambda$ | $O_{us}$ | 4163.95 | ***Phys.Rev.D* 107 (2023) 9, 092001** |
| $B^+$ | $\psi_D + p$ | $O_{ud}$ | 4341.05 | ***Phys.Rev.Lett.* 131 (2023) 20, 201801** |
| $B^+$ | $\psi_D + \Lambda_c^+$ | $O_{cd}$ | 2992.86 | ***Phys.Rev.D 111 (2025) 3, L031101*** |
| $B^+$ | $\psi_D + \Xi_c^+$ | $O_{cs}$ | 2810.36 | |

# Event Reconstruction

B-tag selection criteria:

$$-0.2\text{GeV} < \Delta E < 0.2\text{GeV},$$

$$5.2\text{GeV}/c^2 < m_{ES} < 5.3\text{GeV}/c^2,$$




398 fb$^{-1}$ used in final analysis

B-sig selection criteria is channel dependent (see later)

398 fb$^{-1}$ used for analysis: remainder of the On Peak data used to tune analysis prior to unblinding

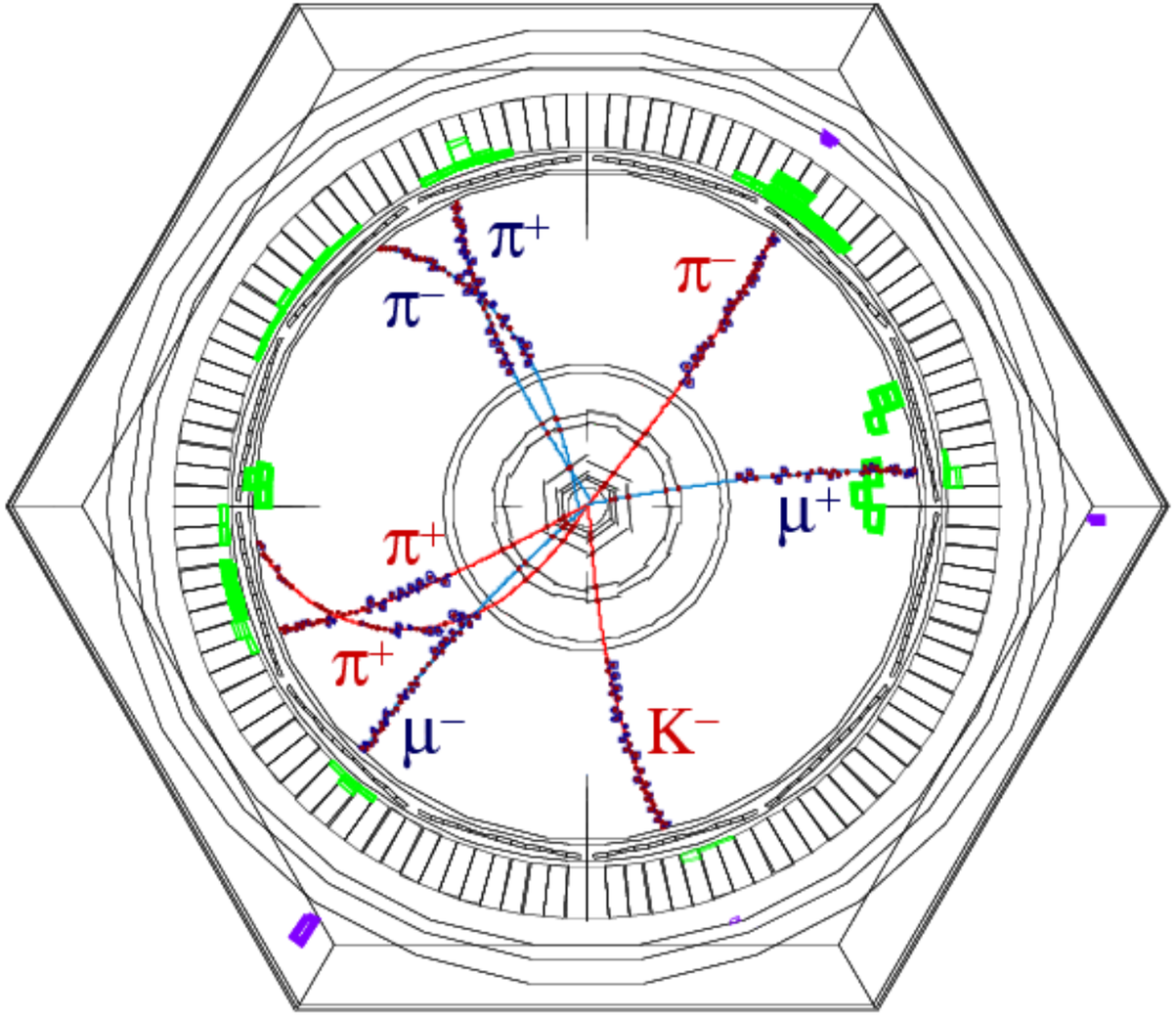
Reconstruct $\Upsilon(4S)$ decay completely: full reconstruction of one B (B-tag) decaying hadronically. Select high-quality tags by two kinematic variables

$$\Delta E = E_{beam} - E_{B_{tag}}$$

$$m_{ES} = \sqrt{E_{beam}^2 - p_{B_{tag}}^2}$$

Signal-side B decays into a fully reconstructed SM baryon and an invisible dark state → look for a peak in the missing mass spectrum

# Example of a Fully Reconstructed Event




- $B^0 \to \psi(2S)\ K_s$

  $\hookrightarrow \mu^+\mu^-$ $\hookrightarrow \pi^+\pi^-$

One of ~470 million recorded decays

- $\overline{B}^0 \to D^{*+}\pi^-$

  $\hookrightarrow D\,\pi^+$

  $\hookrightarrow K^-\pi^+$

# Analysis Method

**MC Generators used to model Standard Model Backgrounds:**

- $q\bar{q}$ (modelled using JETSET);
- $B\bar{B}$ (modelled using EvtGen).

**EvtGen Used to make BSM Signal:**

- Simulate events for 8 signal mass hypotheses for each channel.

Pass through Geant4 model of BABAR, digitization model and standard reconstruction. Uses real conditions information and beam bkg.

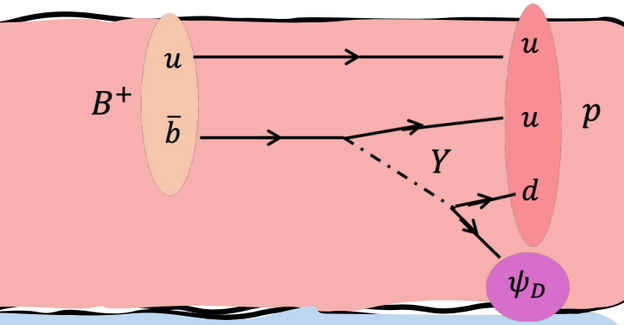
**Scanning method:**

- Use MC to determine signal selection cuts (and background control regions);
- Derive selection efficiency (ε) for 8 possible masses;
- Determine signal resolution (σ) for 8 possible masses;
- Fit functional forms of fit to 8 points, interpolate for any given $\psi_D$ mass;
- Scan across data samples in missing mass - step size dependent on σ.
- Perform profile likelihood fit to determine upper limits on branching rates to BSM channels for given mass.

# Signal pre-selection

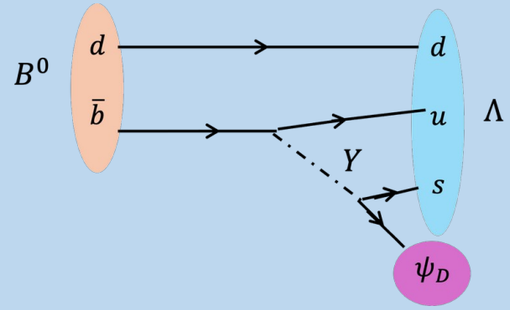
**$B^+ \to \psi_D + p$ ($O_{ud}$)**

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



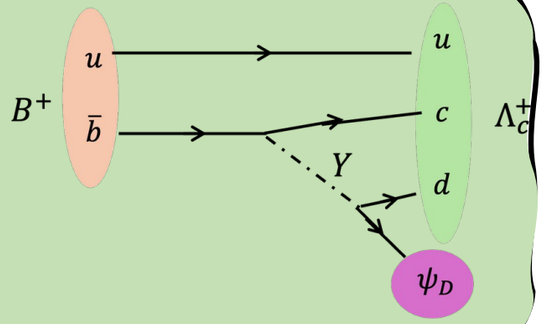

**$B^0 \to \psi_D + \Lambda$ ($O_{us}$)**

- one $\Lambda$ candidate (only) in the signal side;
- $\Lambda \to p\pi^-$ reconstructed; use PID to identify proton and pion candidates;
- significance of $\Lambda$ decay length ($\alpha_\Lambda$) > 1.0;
- four-momentum kinematic fit $\chi^2$ of $\Lambda$ reconstruction ≤ 100.




**$B^+ \to \psi_D + \Lambda_c^+$ ($O_{cd}$)**

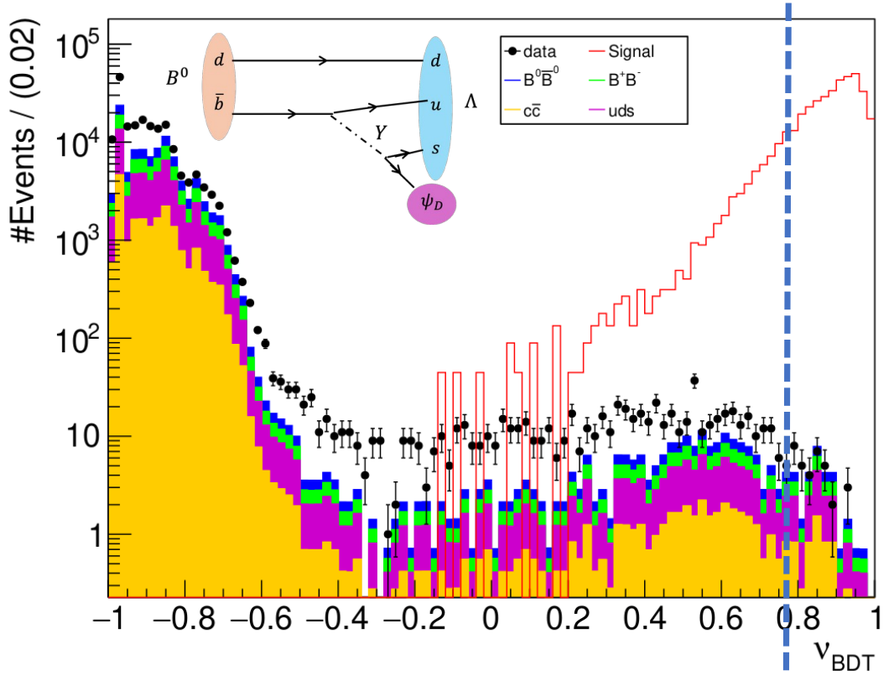
- one $\Lambda_c^+$ candidate (only) in the signal side;
- $\Lambda_c^+ \to pK^-\pi^+$ reconstructed, so three charged tracks required on the signal side;
- high quality charged tracks plus PID requirements for kaon and proton.



# Final Selection (BDT)

**Further signal and background separation obtained using a custom Boosted Decision Tree for each channel.**

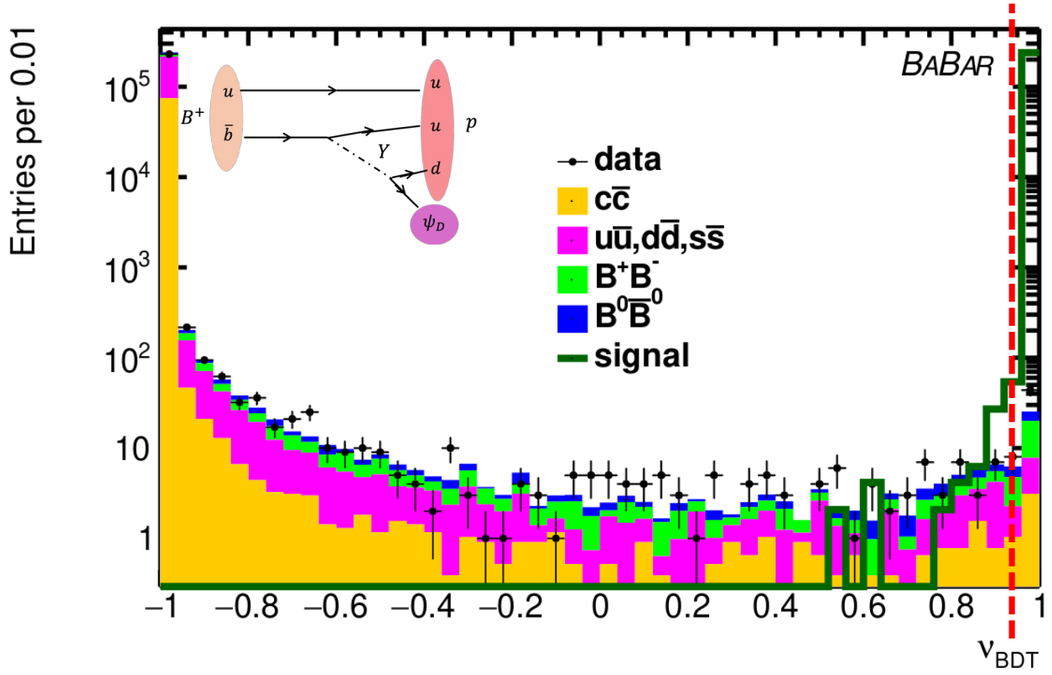
$B^0 \rightarrow \psi_D + \Lambda\ (O_{us})$




*Phys.Rev.D* 107 (2023) 092001

Require $\nu_{BDT} > 0.75$
Provides signal purity > 99%
41 events pass

$B^+ \rightarrow \psi_D + p\ (O_{ud})$



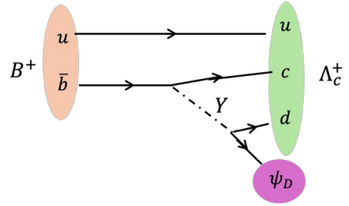

*Phys.Rev.Lett.* 131 (2023) 201801

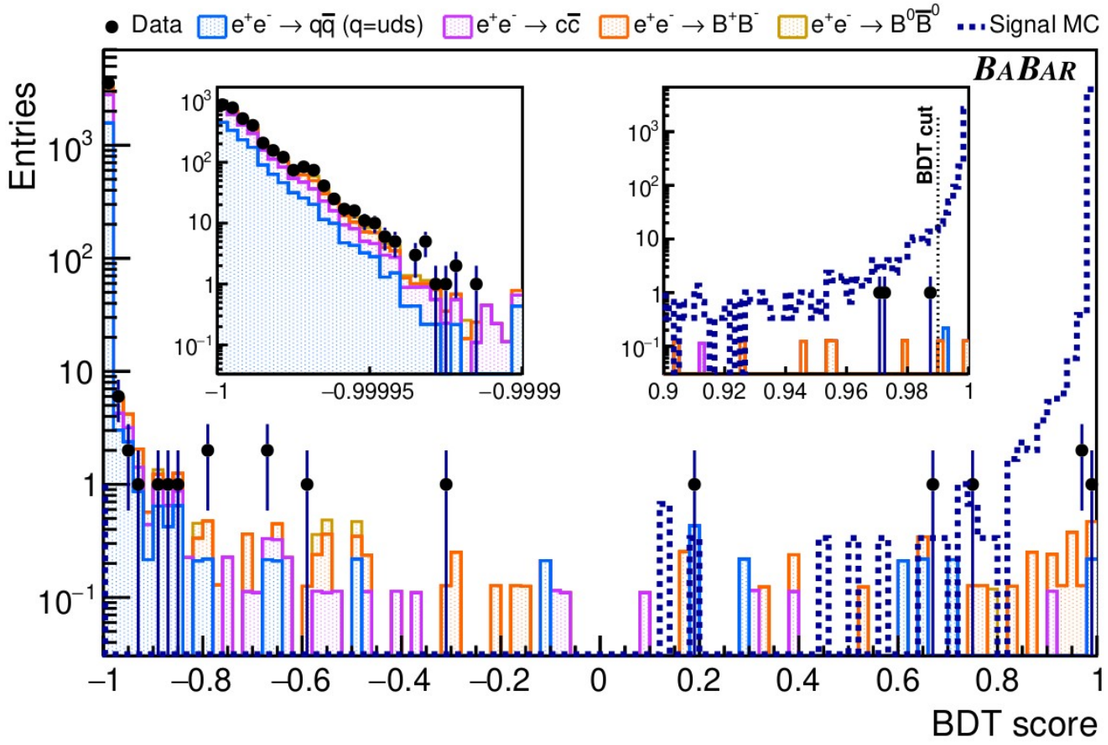
Require $\nu_{BDT} > 0.95$
Provides signal purity > 99%
47 events pass

# Final Selection (BDT)

**Further signal and background separation obtained using a custom Boosted Decision Tree for each channel.**

$B^+ \rightarrow \psi_D + \Lambda_c^+ \ (O_{cd})$




Require $\nu_{BDT} > 0.99$
Signal Purity > 99%
0 events pass!

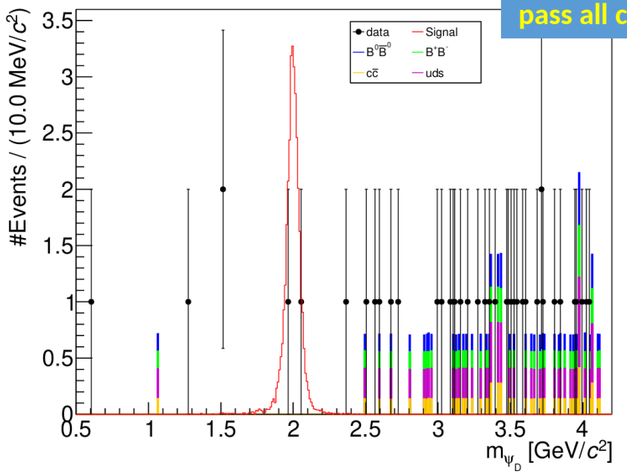
*Phys.Rev.D 111 (2025) L031101*

# Signal Search

- Final analysis steps:
  - ✓ Reconstruct missing mass of $\psi_D$
  - ✓ Determine mass resolution $\sigma(m)$ and efficiency $\varepsilon(m)$ from MC
  - ✓ Scan across kinematically allowed mass range in steps of $\sigma(m)$
  - ✓ Extract limits on BSM branching fractions from a profile likelihood scan

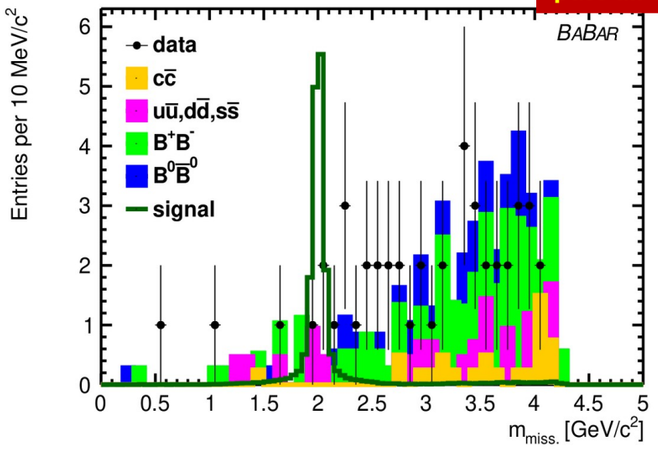
$B^0 \to \psi_D + \Lambda\ (O_{us})$

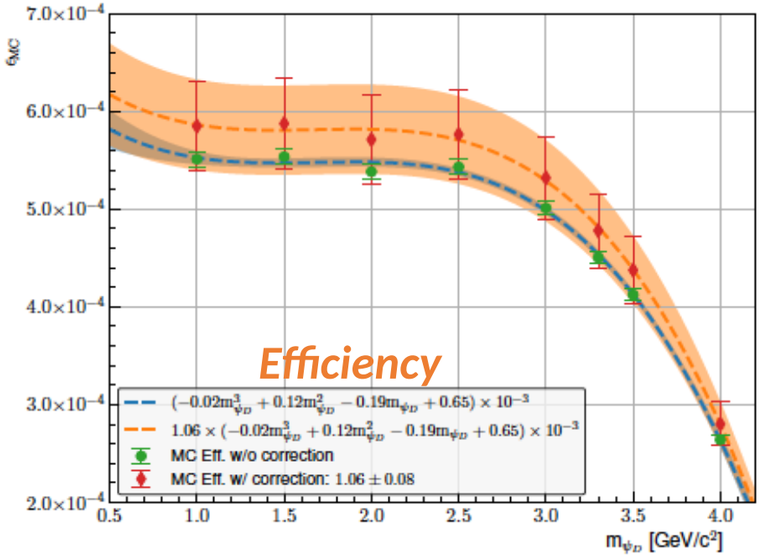
41 events pass all cuts

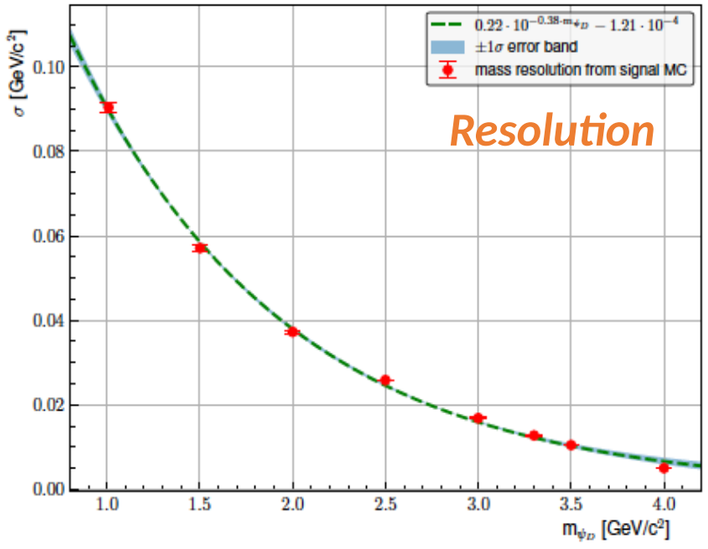



$B^+ \to \psi_D + p\ (O_{ud})$

47 events pass all cuts



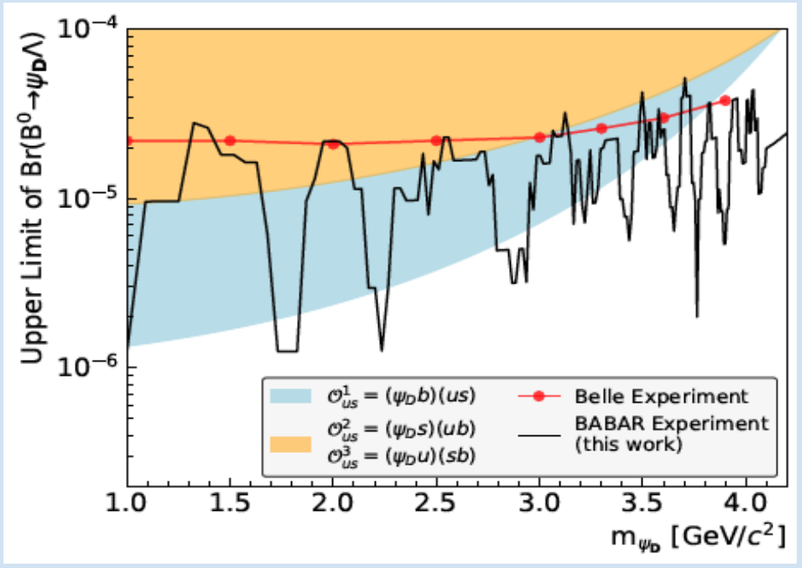




$$m_{\text{miss}}c^2 = \sqrt{(E^*_{B_{\text{sig}}} - E^*_{\text{p}})^2 - |\vec{\text{p}}^*_{B_{\text{sig}}} - \vec{\text{p}}^*_{\text{p}}|^2 c^2}$$

# Results

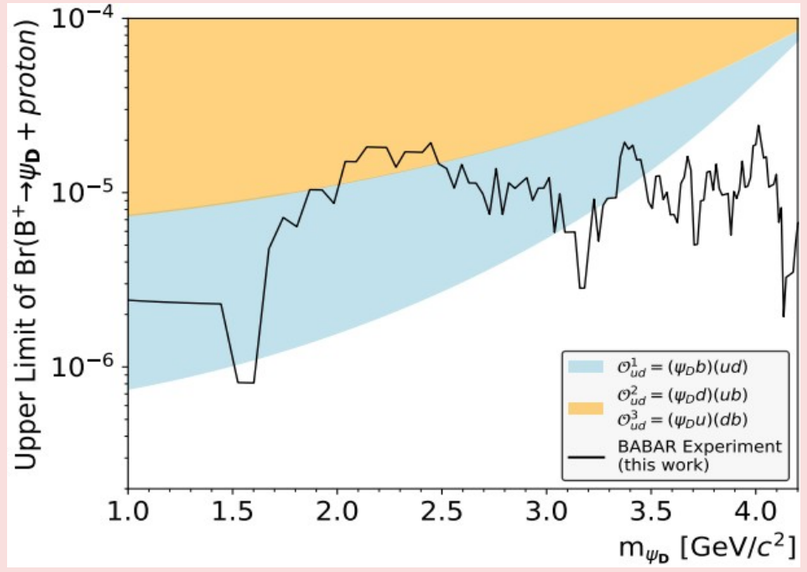
- World-leading and first-ever limits on the B mesogenesis model
- Additional opportunity to search for $O_{cs}$ operator — stay tuned !

**$B^0 \to \psi_D + \Lambda$ ($O_{us}$)**



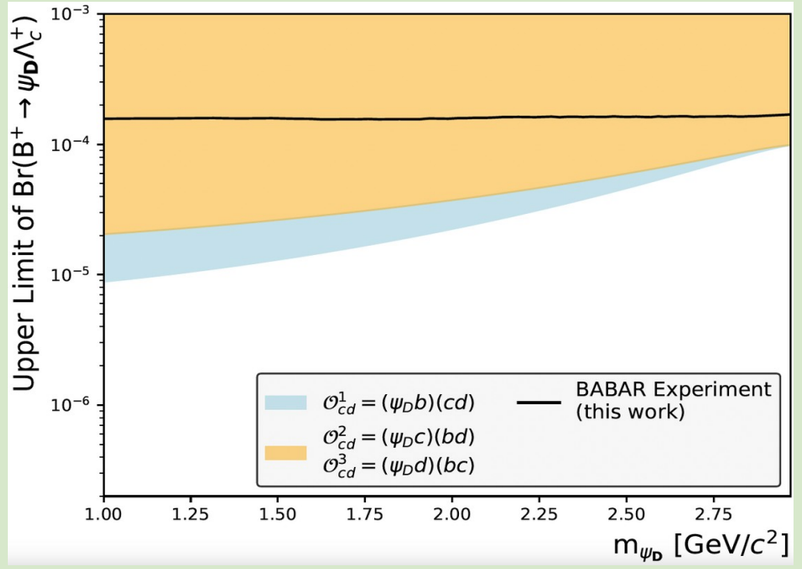

*Phys.Rev.D* 107 (2023) 092001

**$B^+ \to \psi_D + p$ ($O_{ud}$)**




*Phys.Rev.Lett. 131 (2023) 201801*

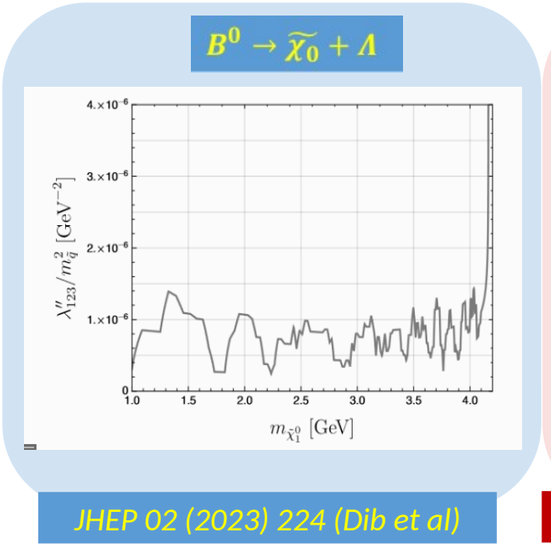
**$B^+ \to \psi_D + \Lambda_c^+$ ($O_{cd}$)**



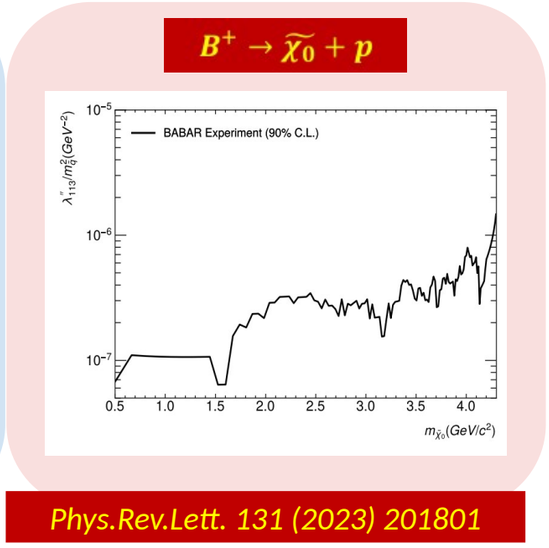

*Phys.Rev.D* 111 (2025) L031101

# Additional Interpretation

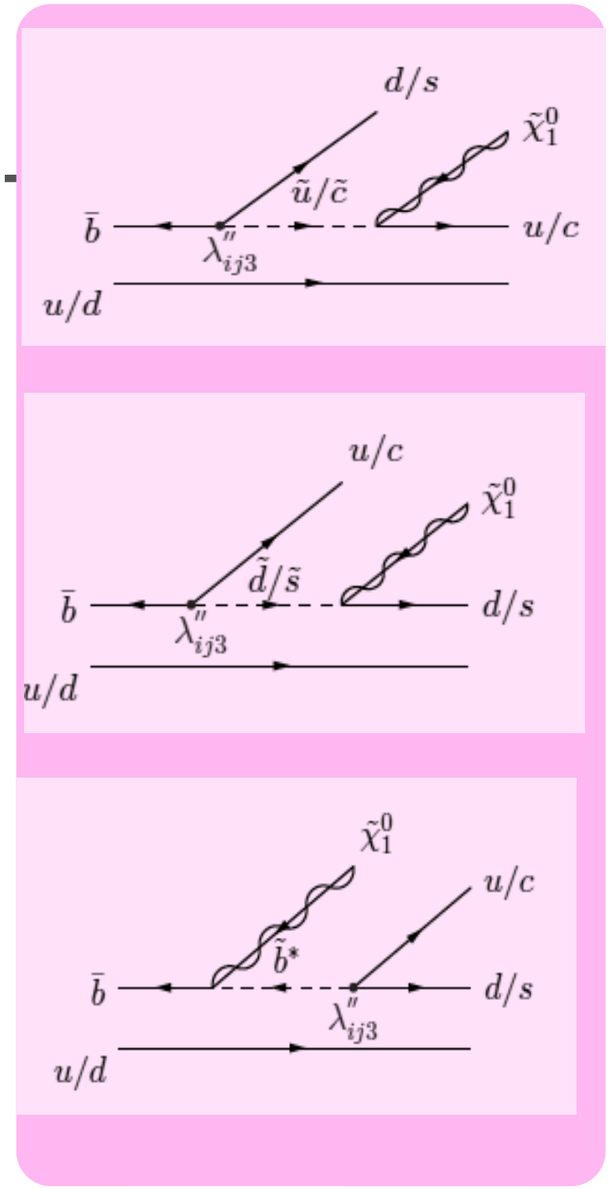
- Since the signature is the missing energy/ momentum, the results can be interpreted in any other model that produces the same final state
  - E.g. RPV SUSY model [JHEP **02**, 224(2023)]
  - First constraints of this kind




JHEP 02 (2023) 224 (Dib et al)




Phys.Rev.Lett. 131 (2023) 201801



# Summary and Outlook

- BABAR continues to provide significant constraints on new physics models
- Results presented here place significant limits on the model of baryogenesis through B meson decays (B mesogenesys)
  - ✓ First constraints on $B^+ \to \psi_D + p$ and $B^+ \to \psi_D + \Lambda_c^+$ channels
  - ✓ Improved limit on $B^0 \to \psi_D + \Lambda$ channel
- Results can be reinterpreted in the context of other models producing same experimental signature
  - ➡ already done for RPV SUSY model, providing first direct constraints
  - ➡ can also be applied to e.g. models of Elahi, Elor, McGahee et al. [PRD **105**, 055024]; Lenz, Mohamed, Wüthrich [arXiv:2412.14947]
- BaBar continues to produce science, 17 years after the end of data taking !

# Backup

# BDT Features ($B^+ \rightarrow \psi_D + \Lambda_c^+$)

| Recoil $B^-$ Features | Signal $B^+$ Features |
|---|---|
| **Decay mode** - the hadronic decay channel of B meson decay. | **npi0**– number of pions on signal side |
| **$B_{tag}$ Purity** - the fraction of $B_{tag}$ mesons that are correctly reconstructed for a given decay mode. | **$\chi^2$** - of the fit applied to the Λ+ candidate |
| **ΔE** - the difference of beam energy and the reconstructed $B_{tag}$ energy. | **$N_{Neut}$** – number of neutral particles in the signal side |
| **$M_{ES}$** - recoil B meson mass distribution. | **$m_{pK\pi}$** – the invariant mass of the Λ+ candidate |
| **Thrust, ThrustZ** - The $B_{tag}$ thrust axis is defined as the axis which maximizes the longitudinal momenta of all the particle for $B_{tag}$ reconstruction. | **$E_{extra}$ - The total extra neutral energy on the signal side in the center-of-mass frame** |

**Plus:**
**r2All -** the ratio of the second to zeroth Fox-Wolfram moment for all tracks and neutral clusters
**cosT -** the cosine of the thrust vector

# BDT Features ($B^+ \rightarrow \psi_D + \Lambda_c^+$)