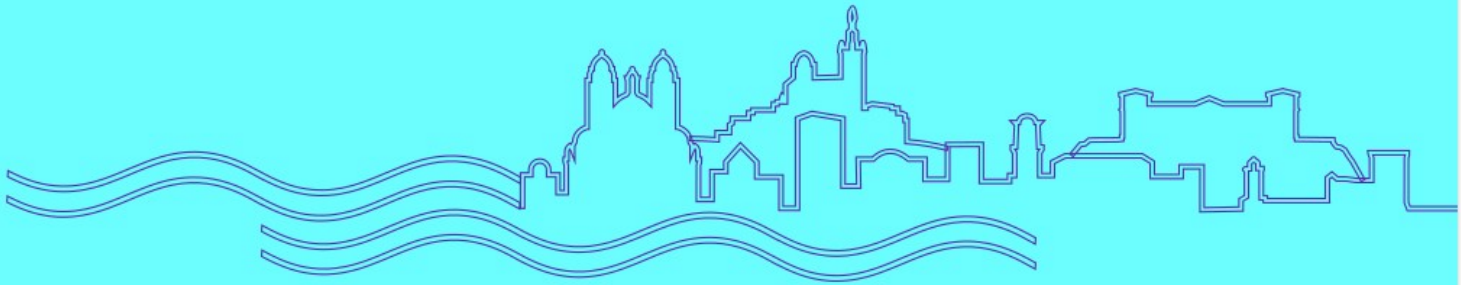
EUROPEAN PHYSICAL SOCIETY

EPS HEP2025 MARSEILLE



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

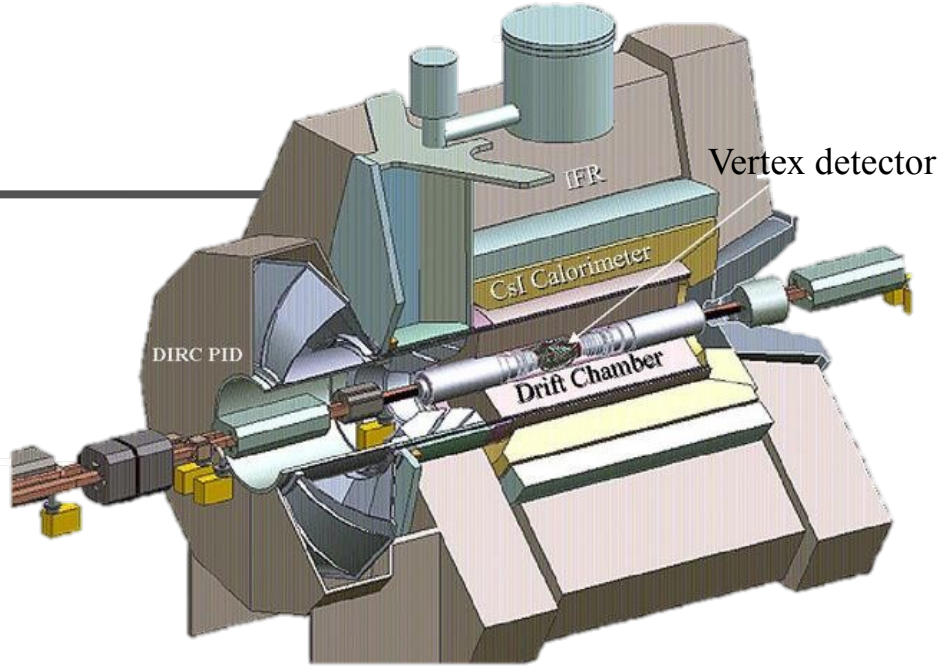
Tim Gershon

on behalf of the BaBar collaboration

11th July 2025

Many thanks to Sophie Middleton for help with the slides

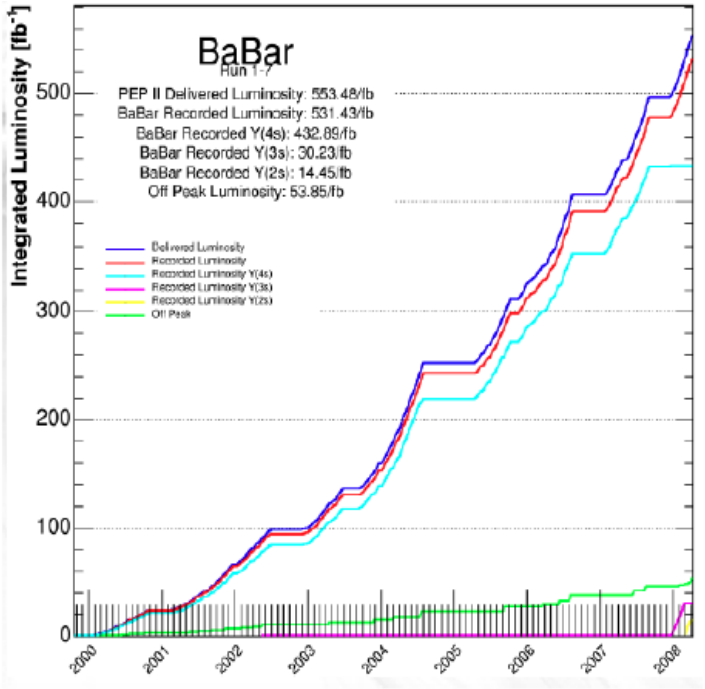
The *BABAR* Experiment



For overview of experiment: **Nucl. Instrum. Meth. A729 (2013) 615.**

- Asymmetric e^+e^- collider with $\sqrt{s}$ = 10.58 GeV i.e. Υ(4S) resonance:
  - 9 GeV electrons collide with 3 GeV positrons.

Total luminosity: 431 fb^{-1} (4.7 x 10^8 $B\overline{B}$ pairs) on Υ(4S) peak.



Still producing new results in 2025!!!

Detectors:

- **Tracks:** Silicon Vertex Tracker (SVT) + 40-layer Drift Chamber (DCH), in 1.5 T solenoid.
  - Momentum resolution = 0.47% at 1 GeV/c
- **Energy:** Electromagnetic Calorimeter (EMC)
  - Energy resolution = 3% at 1 GeV.
- **PID:**
  - Identify charged pions, kaons and electrons using Ring Imaging Cherenkov detector (DIRC) + ionization loss measurements in the SVT and DCH.
  - Instrumented flux return of solenoid used to identify muons.

New Physics in B-Decays?

B-factories an ideal place to explore!

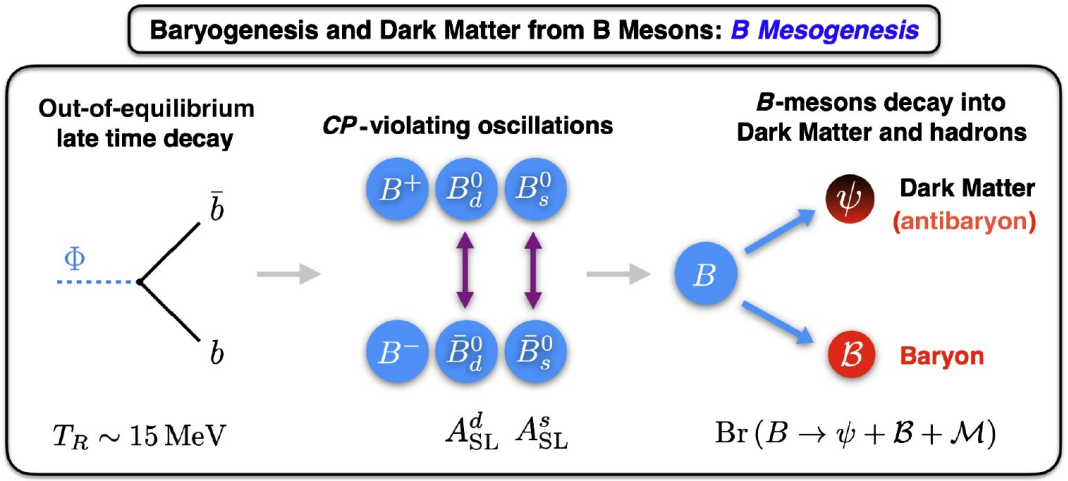
Model-independent searches for missing energy in B decays setting new limits on new physics models: PRL 131 (2023) 201801, PRD 107 (2023) 092001, PRD 111 (2025) L031101

Dark Matter:

- Missing mass could be dark-sector baryon (ψ_D) or some other invisible new physics.
- ψ_D could decay into stable dark sector particles producing the relic abundance we see today.

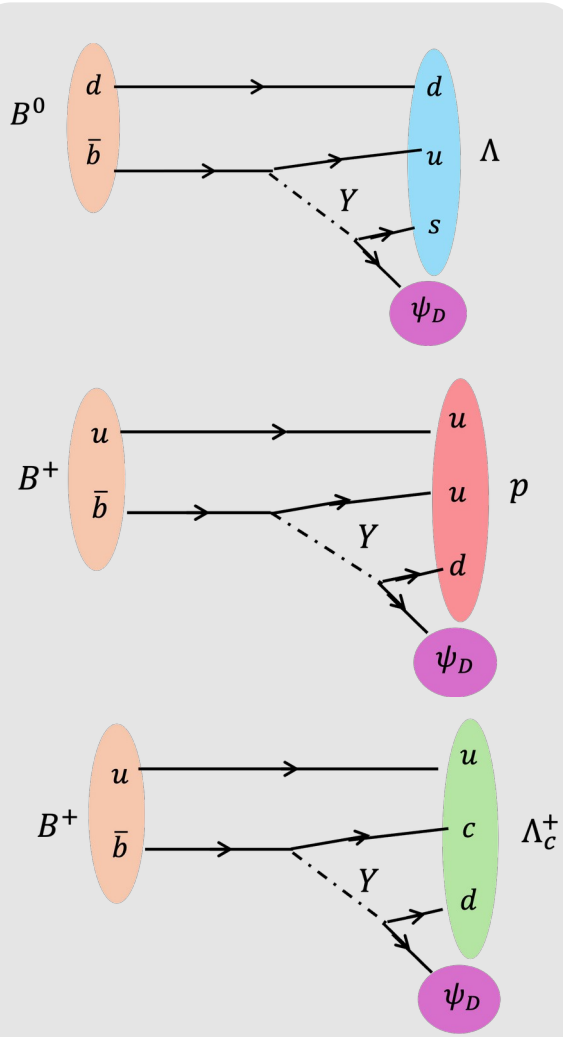
Several models of B-Mesogenesis which also explain BAU e.g.:

- CP violation from B^0–$\overline{B}^0$ oscillations generates a matter-antimatter asymmetry.
- B^0 decays slightly dominate over $\overline{B}^0$ decays into anti-baryons, same for DM-anti-DM.
- Visible and dark sectors have equal but opposite asymmetries → baryon number conserved.



Benchmark model (sensitive to others too)

G. Elor, M. Escudero and A. E. Nelson, Phys. Rev. D 99, 035031 (2019).
G. Alonso-Alvarez, G. Elorand, and M. Escudero, Phys. Rev. D 104, 035028 (2021).



ψ_D = dark sector particle; Y = TeV scale mediator;

B-Mesogenesis and Dark Matter

- Kinematic constraints require that the ψ_D mass lies between 0.94 – 4.34 GeV/c^2
- Need to explore channels which have access to all operators: $O_{i,j} = (\psi_D\, b)\ (q_i\, q_j)$ $(i = u, c\ and\ j = d, s)$;
- Flavour constraints imply only one operator active in the early universe, one dominates, not a combination of operators.

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	

*Other modes probe same operators but lower endpoints

Event Reconstruction & Preselection

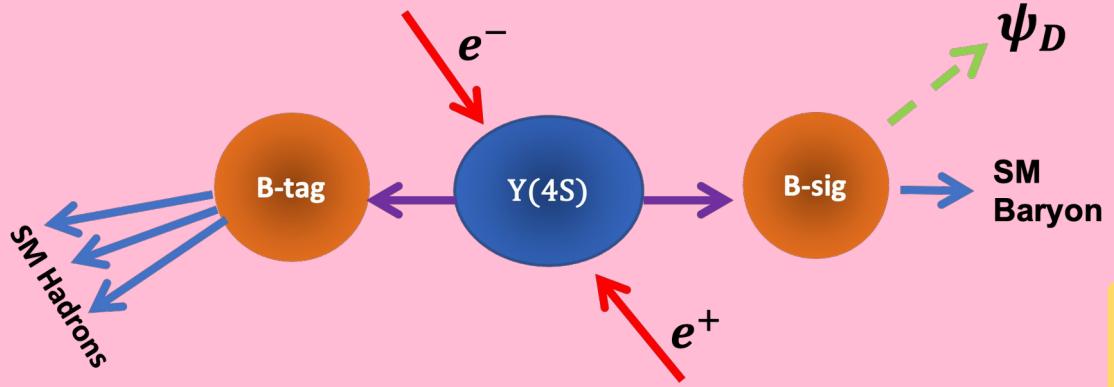
Hadronic recoil tagging method used to reconstruct event.

- **B-tag** = Fully reconstructed Standard Model decay mode;
- **B-sig** = Potential for signal, search here for missing mass.

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

centre-of-mass energy within range of the CM beam energy: $\Delta E = E_{beam} - E_{B_{tag}}$

energy substituted mass in range close to B mass: $m_{ES} = \sqrt{E_{beam}^2 - p_{B_{tag}}^2}$

Method

In the final analysis, yields were found via a data-driven Poisson counting method, with background and signal regions defined from the study of the background and signal MC simulations.

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.

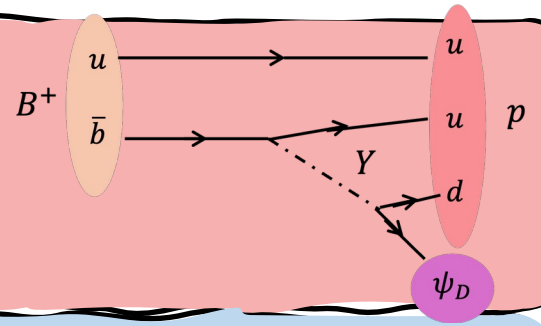
Scanning method:

- 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 ψ_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 Selections

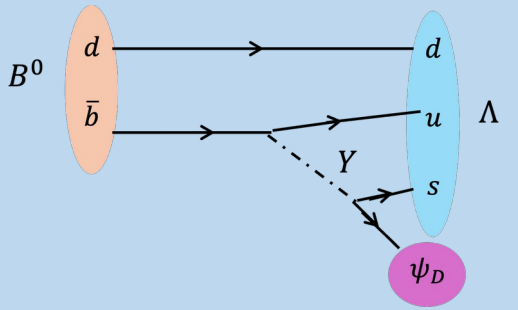
$B^+ \rightarrow \psi_D + p$ (O_{ud})

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



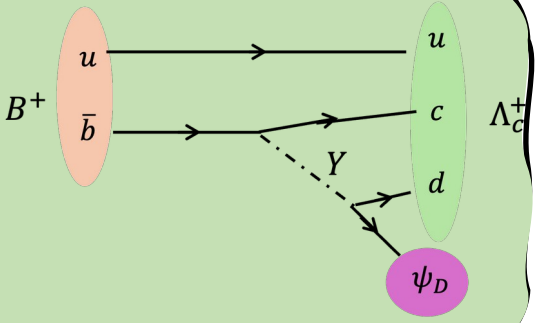
$B^0 \rightarrow \psi_D + \Lambda$ (O_{us})

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



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

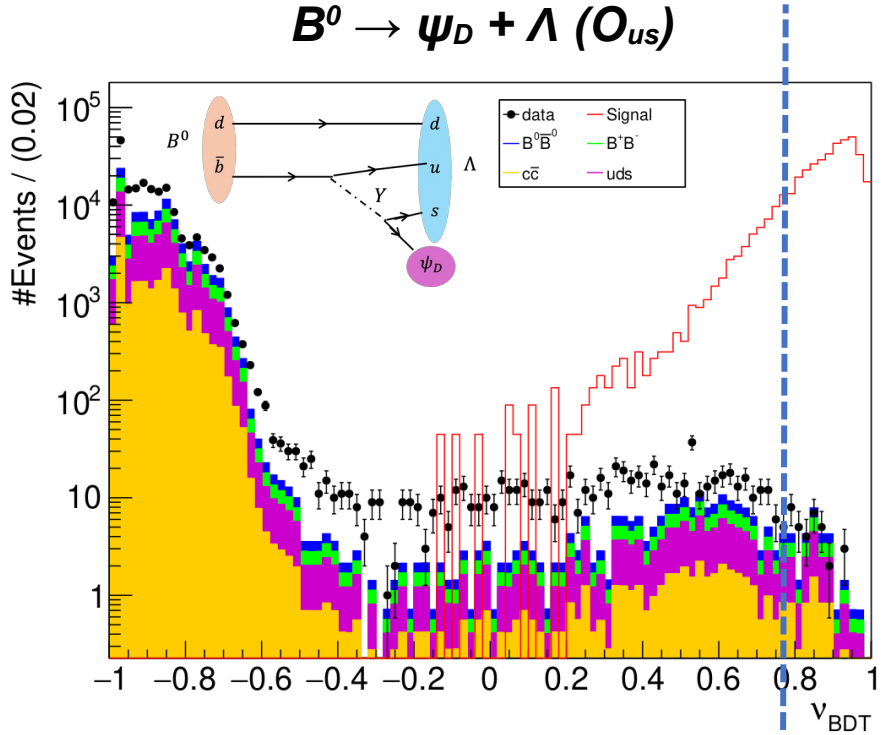
- one Λ_c^+ candidate (only) in the signal side;
- $\Lambda_c^+ \rightarrow pK^-\pi^+$ reconstructed, so three charged tracks required on the signal side;
- high quality charged tracks plus PID requirements for kaon and proton.



BDT Selection (1)

Further signal and background separation obtained using a custom Boosted Decision Tree for each channel. BDT inputs related to B_{tag} quality, event shape variables, and signal side information (e.g. E_{extra})

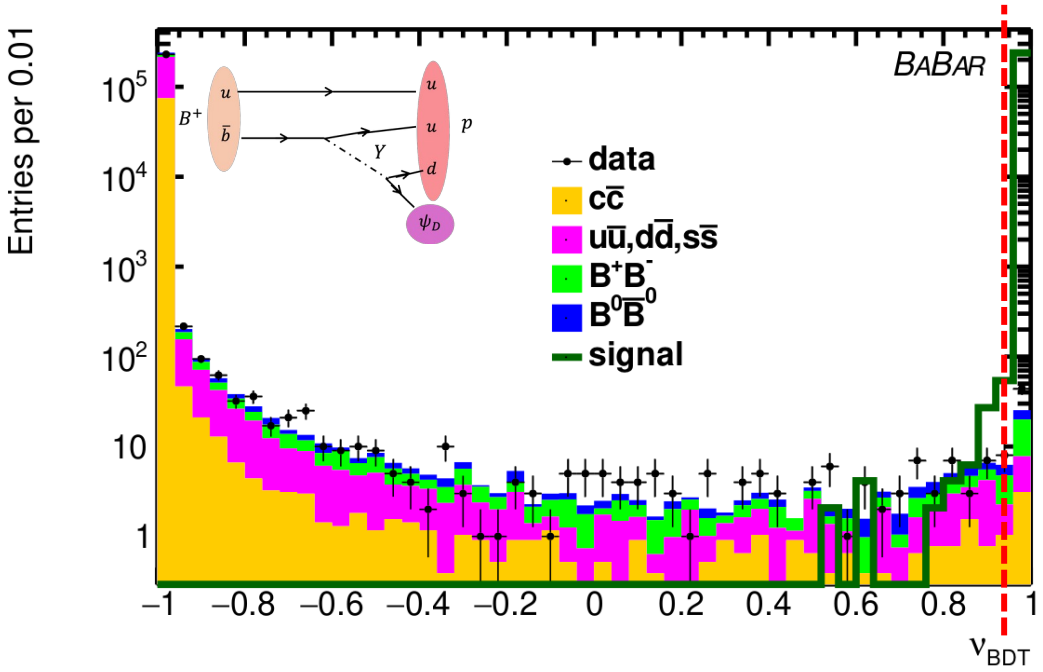
$B^0 \rightarrow \psi_D + \Lambda$ (O_{us})



***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})



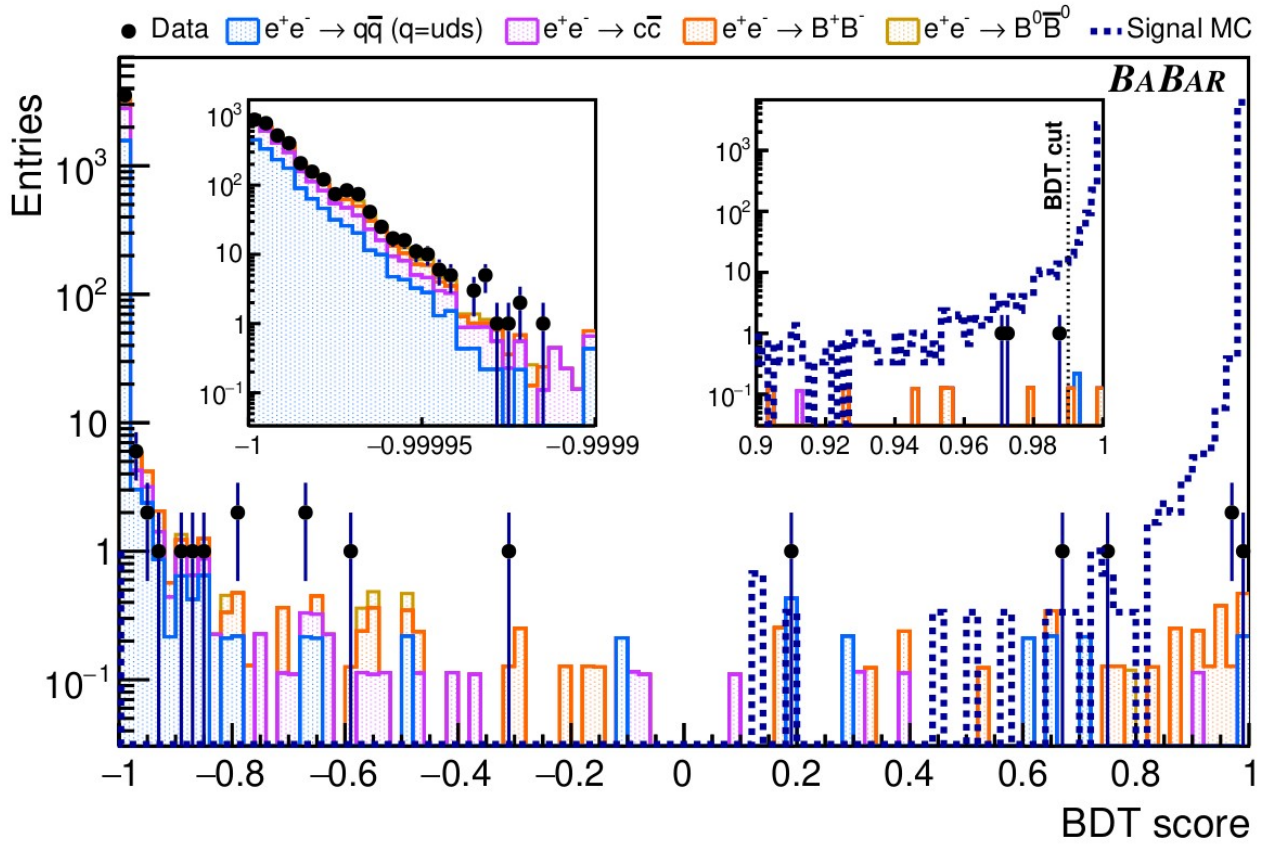
***Phys.Rev.Lett.* 131 (2023) 201801**

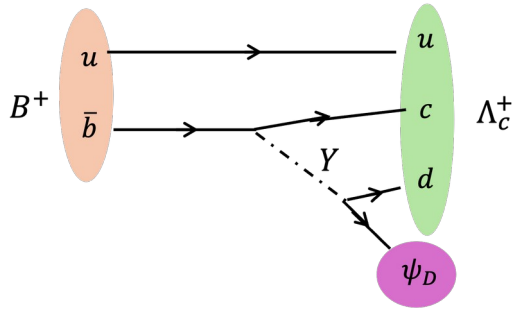
Require $\nu_{BDT} > 0.95$
Provides signal purity > 99%
47 events pass

BDT Selection (2)

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

Limit determination

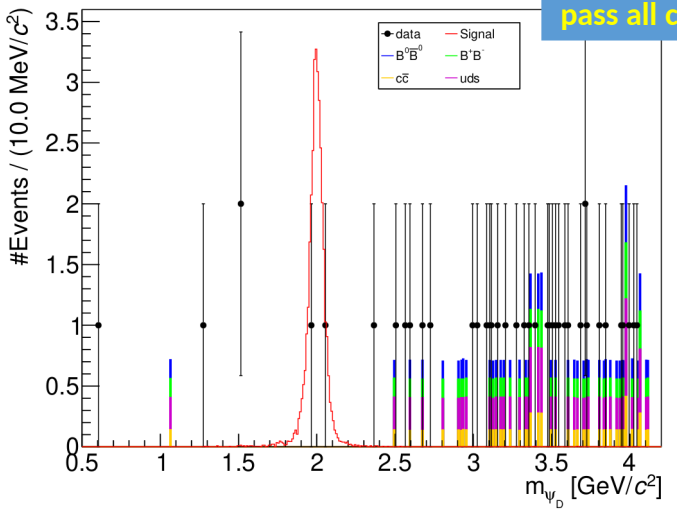
Final analysis proceeds by:

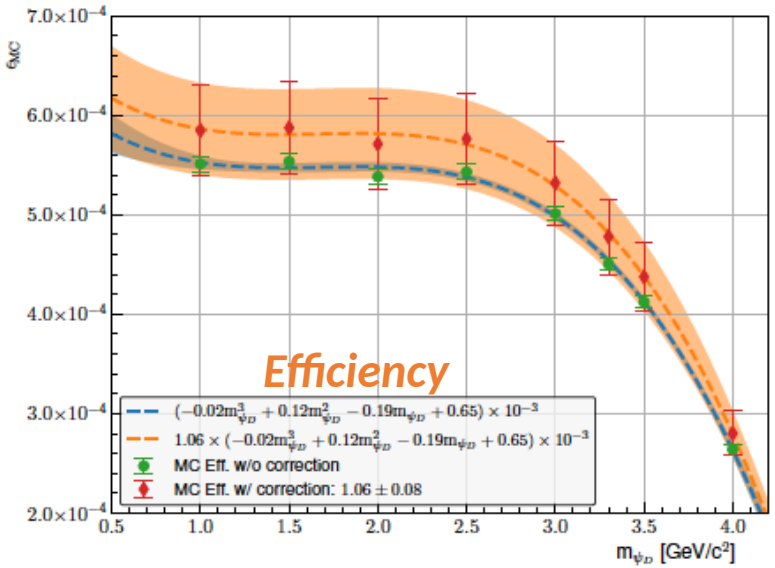
- reconstructing ψ_D from missing energy 4-vector on signal side;
- scanning across mass range, with step size equivalent to σ at that mass;
- extracting resolution (σ) and efficiency (ε) from MC;
- estimating signal and backgrounds in data using definitions from MC study.

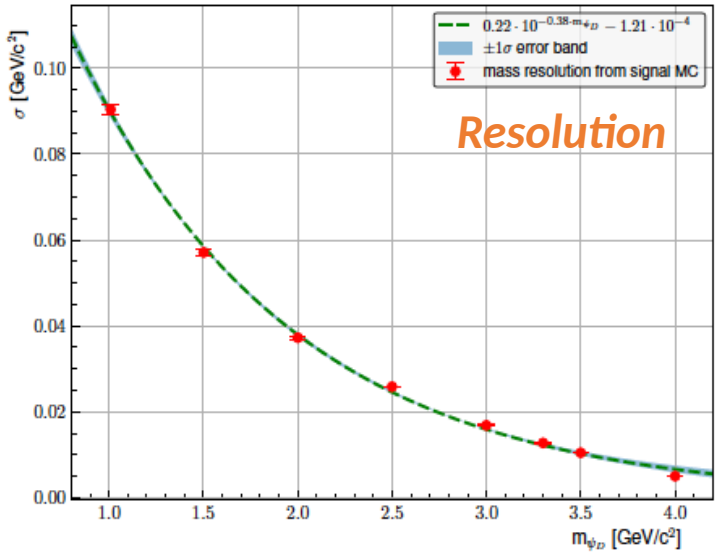
Profile likelihood method is then used to obtain upper limits on BSM branching fractions.

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

41 events pass all cuts



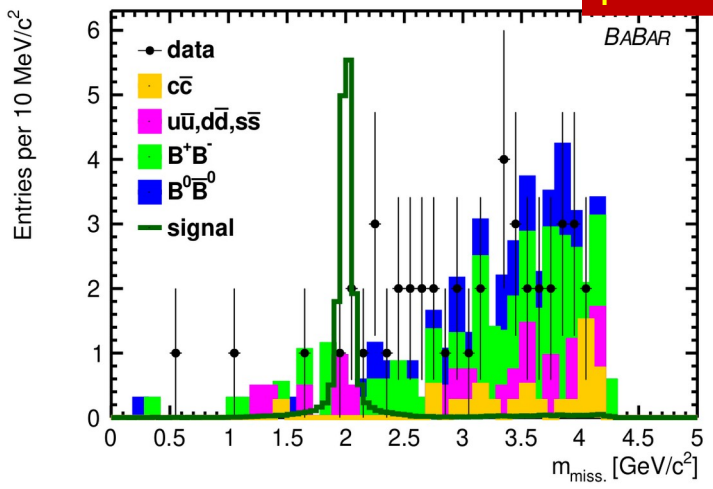




Examples for $B^0 \to \psi_D + \Lambda$ (O_{us})

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

47 events pass all cuts



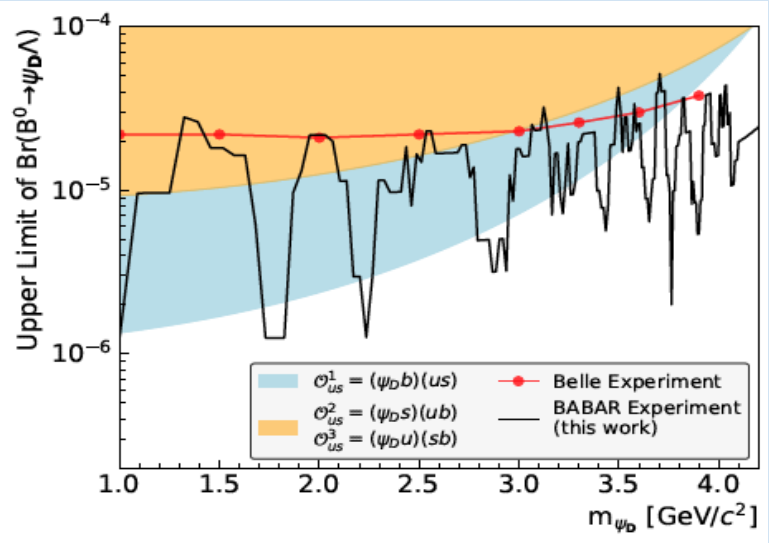
$$m_{\mathrm{miss}}c^2 = \sqrt{(E^*_{B_{\mathrm{sig}}} - E^*_{\mathrm{p}})^2 - |\vec{\mathrm{p}}^*_{B_{\mathrm{sig}}} - \vec{\mathrm{p}}^*_{\mathrm{p}}|^2 c^2}$$

Results

Parameter space vastly reduced, almost excluded for some operators.
Final operator O_{cs} must be probed to fully explore this model.

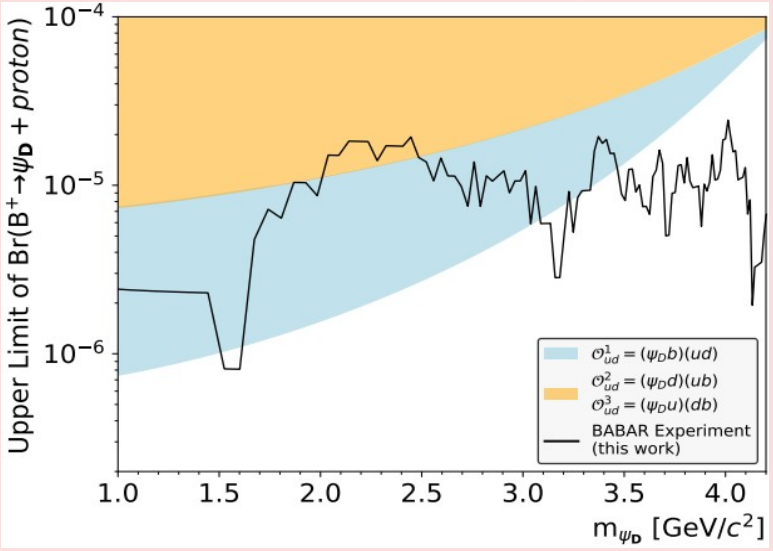
- World-leading result for $B^0 \to \psi_D + \Lambda$ (O_{us}), improving on previous result and further constraining model;
- First direct searches for $B^+ \to \psi_D + p$ (O_{ud}) and $B^+ \to \psi_D + \Lambda_c^+$ (O_{cd}), placing tight constraints on mesogenesis model;
- Work in progress to probe fourth operator (O_{cs}) – BaBar still not finished yet!

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



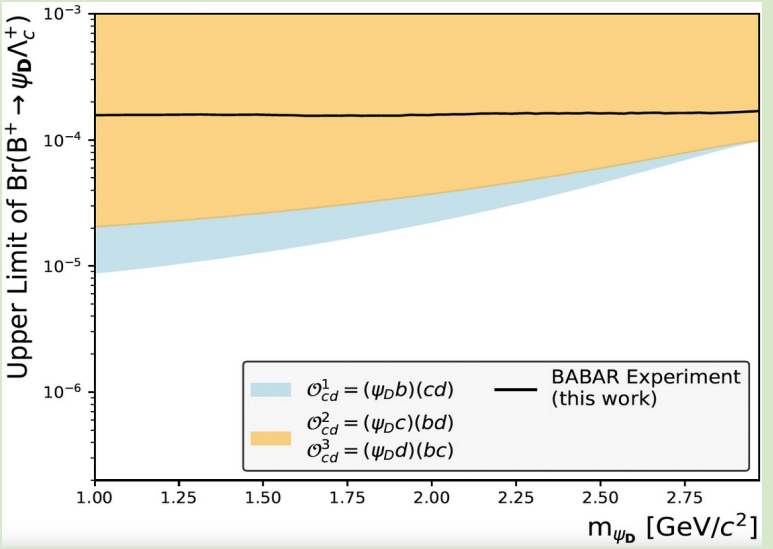
Phys.Rev.D 107 (2023) 092001

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



Phys.Rev.Lett. 131 (2023) 201801

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



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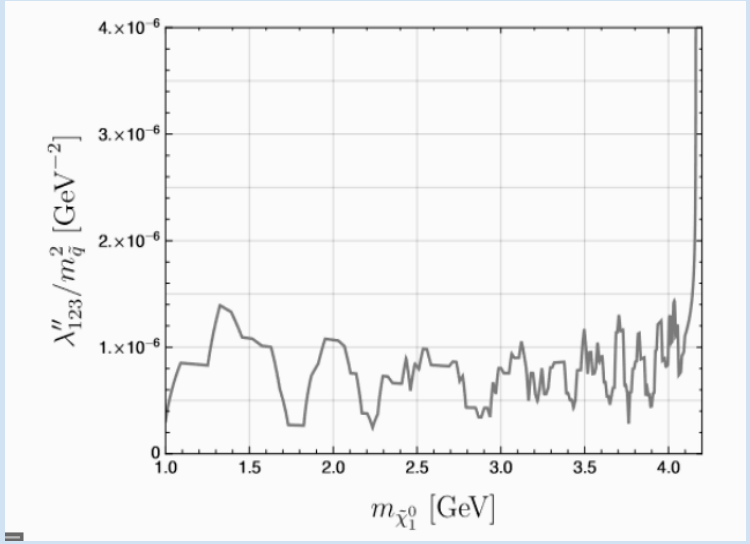
Reinterpretation

The signal signature is missing mass in the final state, so results can be interpreted in any model that produces such a signal, e.g.

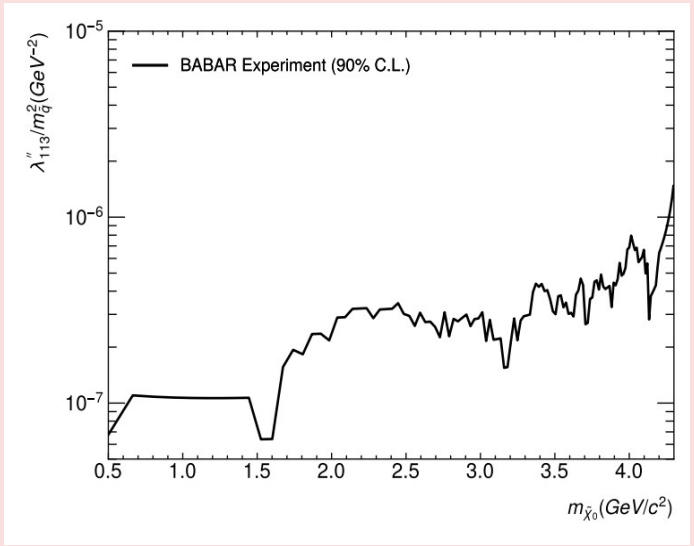
- Our results provide first limit on RPV SUSY model described in **JHEP 02 (2023) 224.**

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

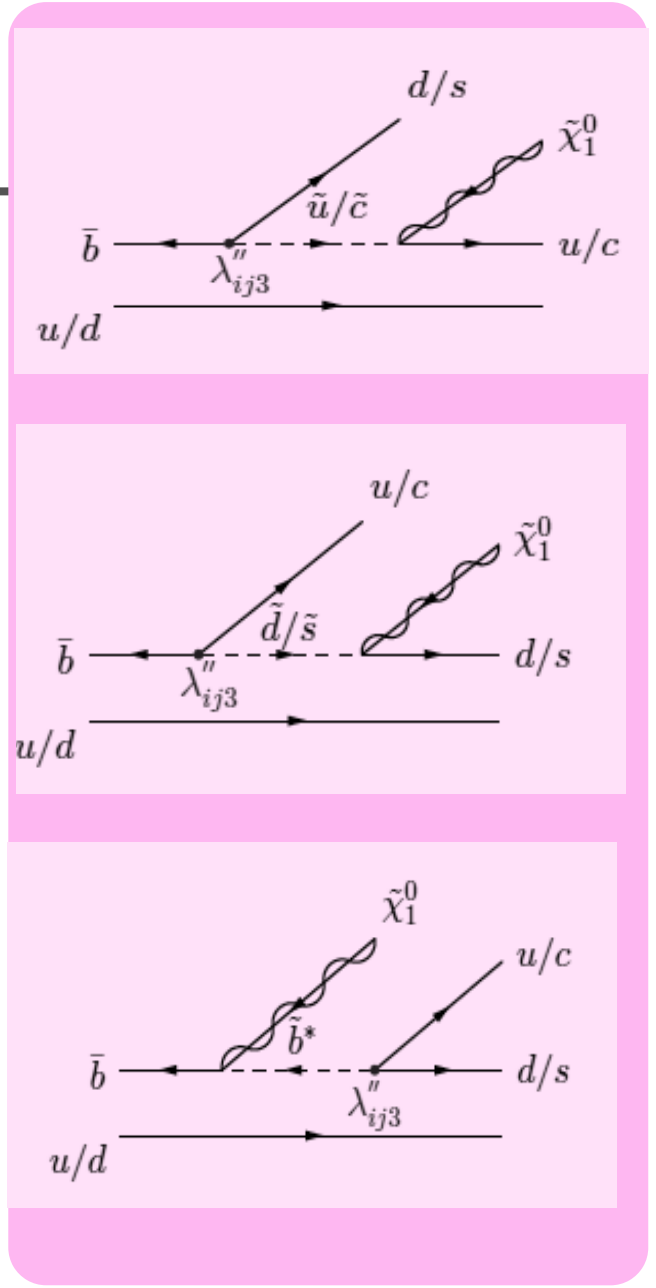


JHEP 02 (2023) 224 (Dib et al)

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



Phys.Rev.Lett. 131 (2023) 201801



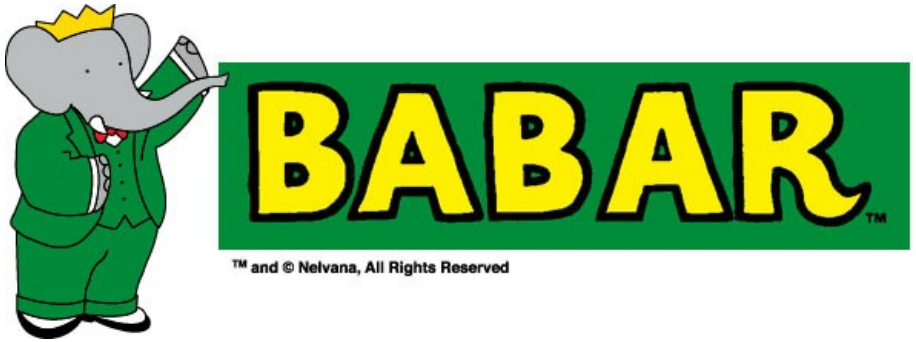
Summary

Results presented constrain mesogenesis models proposed to explaining DM + BAU:

- Used 398 fb^{-1} of data (4 x 10^8 $B\overline{B}$ pairs)
- Scanning method allowed improved limits on $B^0 \rightarrow \psi_D + \Lambda$ channel;
- First direct limits for $B^+ \rightarrow \psi_D + p$ and $B^+ \rightarrow \psi_D + \Lambda_c^+$ channels;
- Large amounts of parameter space excluded, but haven't explored all operators yet;
- Results can be reinterpreted in the context of other models producing same experimental signature
  - already done for RPV SUSY model, providing first direct constraints on that model;
  - can also be applied to e.g. *Phys Rev. D* 105, 055024 Elahi *et al*, arXiv:2412.14947 Lenz *et al*).

***BABAR* still publishing world-leading results after all these years, and not finished yet!**

- https://inspirehep.net/experiments/1108553?ui-citation-summary=true



Back-up

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

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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.	**χ^2** - of the fit applied to the Λ_c^+ 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_c^+ 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

Systematics ($B^+ \to \psi_D + \Lambda_c^+$)

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- Systematic uncertainties in ϵ_{sig} arise from
  - the B_{tag} correction factor $f_{B\bar{B}}$, 4.7%
  - $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (6.24 \pm 0.28)\%$, i.e. 4.5%
  - limited MC statistics, 1.2%
- Knowledge of the integrated luminosity, 0.6%
- Systematic uncertainties on the background level incorporated as nuisance parameter in limit setting procedure
  - i.e. absorbed into statistical uncertainty

BDT ($B^+ \to \psi_D + \Lambda_c^+$)