PLANK2025 – The 27th International Conference From the Plank Scale to the Weak Scale

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

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Outline

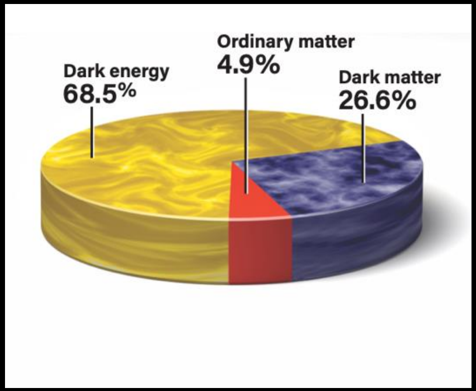
- Introduction
  - Baryogenesis and Dark Matter in B decays
- The Babar Experiment
- BaBar analysis searches for Baryogenesis & Dark matter in B-meson decays
  - $B^+ \to p + \psi_D$ PRL **131**, 201801(2023)
  - $B^0 \to \Lambda + \psi_D$ PRD **107**, 092001(2023)
  - $B^+ \to \Lambda_c + \psi_D$ PRD **111**,L031101(2025)
- Results and Interpretations
- Conclusions

Introduction

Standard Model (SM) is extremely successful theory
- It describes and explains what we observe in nature with extraordinary precision

BUT

There are still several things that we do not understand:
- What is Dark Matter (DM)?
- What is Dark Energy?
- How can we explain the Baryon Asymmetry of the Universe (BAU)?
- Origin of the neutrino mass
- Hierarchy problem
- No quantum theory of gravity



Introduction

Standard Model (SM) is extremely successful theory
- It describes and explains what we observe in nature with extraordinary precision

BUT

There are still several things that we do not understand:
- What is **Dark Matter** (DM)?
  - ➢ Existence of DM is well established from astrophysical evidence, but its nature in still not known
  - ➢ Weakly Interacting Massive Particles (WIMPs) as a favored dark matter candidate, but never observed
  - ➢ Dark sector model:
    - ➢ DM could be not just one new particle, but particles from a whole new "dark sector"
    - ➢ Dark sector particles could couple weakly to ordinary SM particles

Searches for the Dark Sector at BaBar

Collider experiments

- allow for a direct search of DM through decays to SM particles
- electron-positron collider experiments provide particularly clean environments and are well suited for exploring low-energy signatures of New Physics (NP)

No evidence for any dark sector particles from collider experiments

- Stringent limits on dark sector production

It is interesting to consider models that simultaneously generate a baryon asymmetry and produce the DM abundance in the early Universe

Baryogenesis and Dark Matter from B - meson decay

A.D. Sakarov, JETP 5, (1967) 24

Baryon Asymmetry of the Universe (BAU) implies baryogenesis, which requires Sakarov conditions:

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

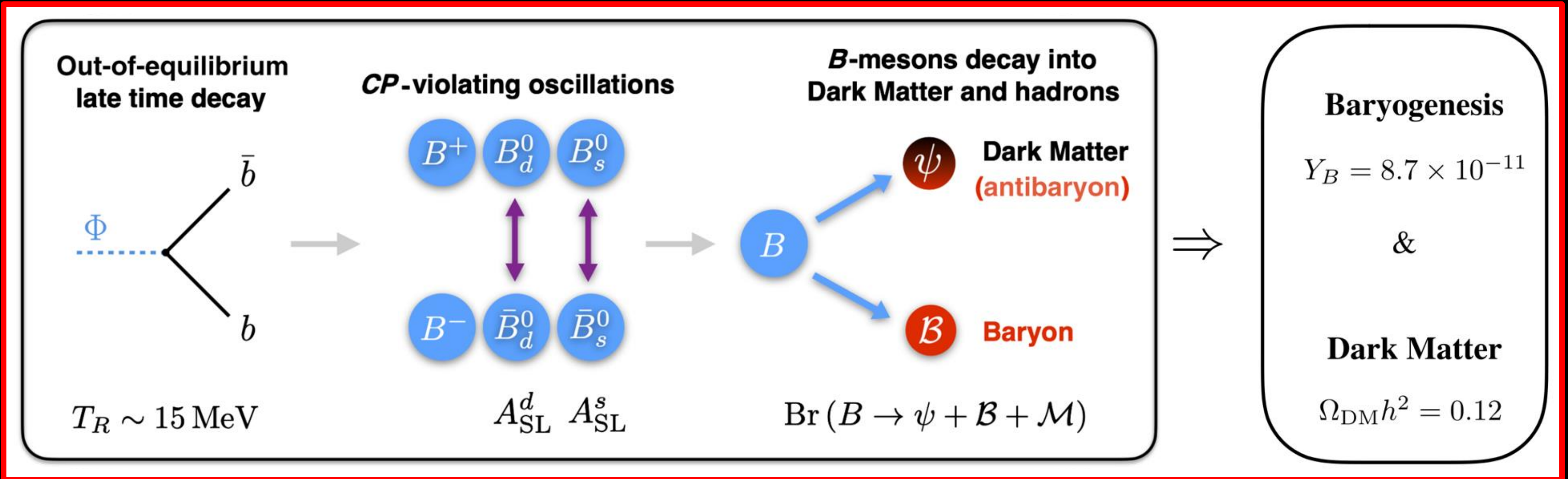
- Conditions are all compatible with SM, but we currently don't have an explanation for the level of baryogenesis required to account for the BAU
- Several New Physics models could introduce necessary ingredients to explain observed level of baryogenesis

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

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

B-mesogenesis

[G. Elor, M. Escudero, A.E. Nelson, PRD **99**, 035031 (2019)](#)
[G. Alonso-Álvarez, G. Elor, M. Escudero, PRD **104**, 035028 (2021)](#)



In the early Universe, a long-lived particle produces b quarks

They hadronize into B mesons and undergo CPV oscillations

B mesons decay into SM and DM particles

PLANK Collaboration, A&A 641, A6 (2020)

- Matter-antimatter asymmetries are generated in the visible and dark sectors with equal but opposite magnitudes: total baryon number is conserved
- The mechanism requires a positive leptonic charge asymmetry in B-meson decays
- New B decay mode into a baryon and missing energy

$$B \to \psi + \mathcal{B} + \mathcal{M}$$

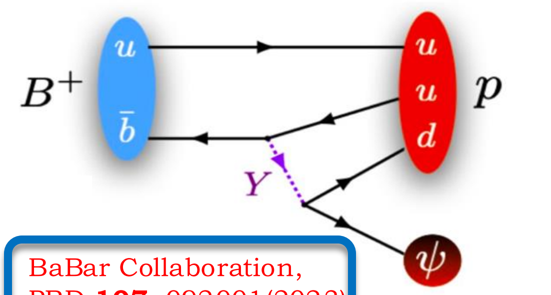
$$Y_B \propto \sum_{q=s,d} A^q_{ll} \times \mathrm{Br}(\mathrm{B} \to \psi + \mathcal{B} + \mathcal{M})$$

Observables testable at current and upcoming collider experiments

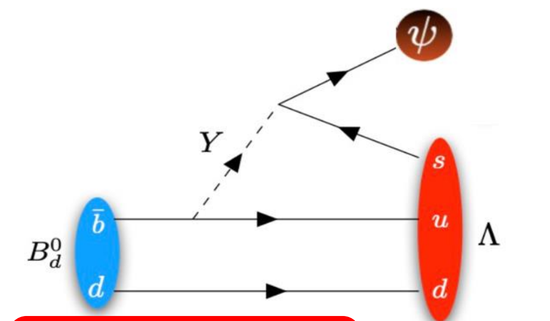
B-mesogenesis: Baryogenesis and DM from B-meson decay

- Kinematic constraints require that the ψ_D mass lies between 0.94 – 4.34 GeV/c^2
- Br > 10^{-4}, and depends on semileptonic asymmetries A_{ll}^{q}
- The type of baryon produced depends on the operator mediating the interaction, leading a variety of final state

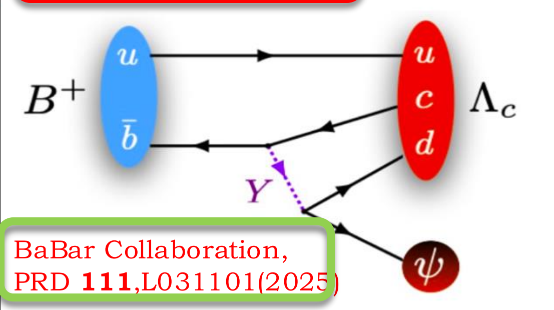
Operator and decay	Initial state	Final state	ΔM (MeV)
$\mathcal{O}_{ud} = \psi b u d$	B_d	$\psi + n(udd)$	4340.1
$\bar{b} \to \psi u d$	B_s	$\psi + \Lambda(uds)$	4251.2
	B^+	$\psi + p(duu)$	4341.0
	Λ_b	$\bar{\psi} + \pi^0$	5484.5
$\mathcal{O}_{us} = \psi b u s$	B_d	$\psi + \Lambda(usd)$	4164.0
$\bar{b}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



BaBar Collaboration, PRD **107**, 092001(2023)



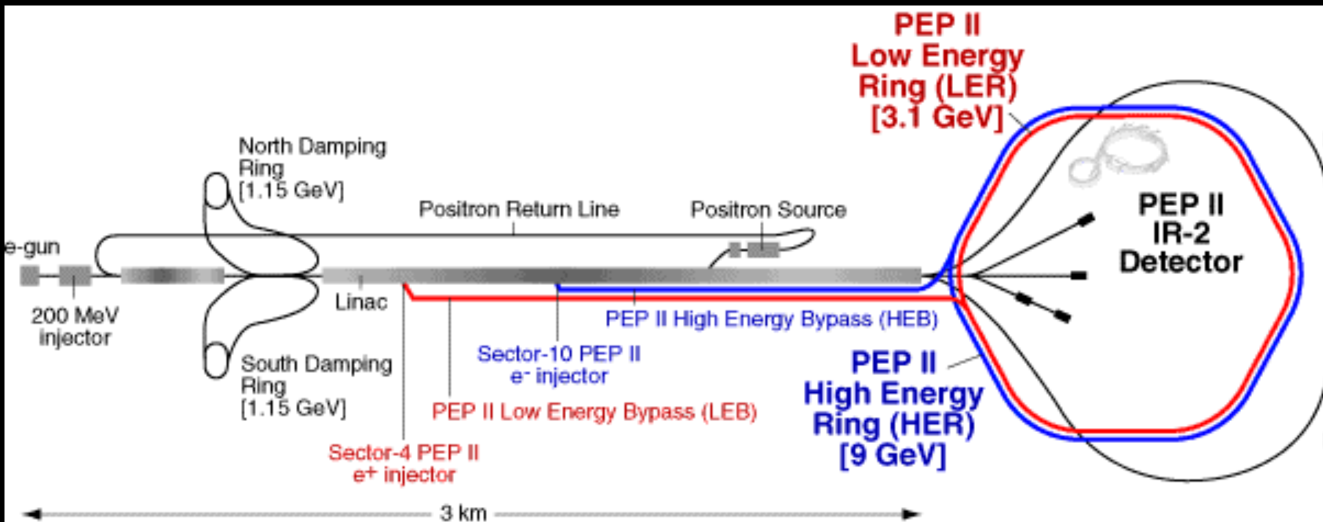
BaBar Collaboration, PRL **131**, 201801(2023)

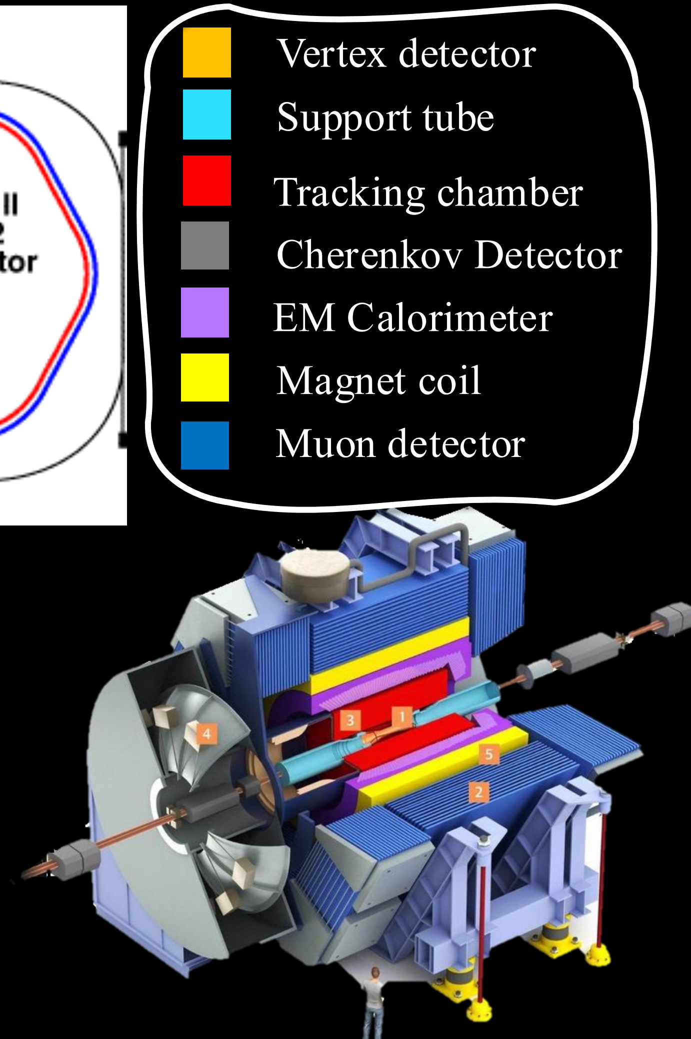


BaBar Collaboration, PRD **111**,L031101(2025)

Φ = heavy scalar field;
ψ_D = dark sector particle;
Y = TeV scale mediator;

PEP-II and the BaBar experiment

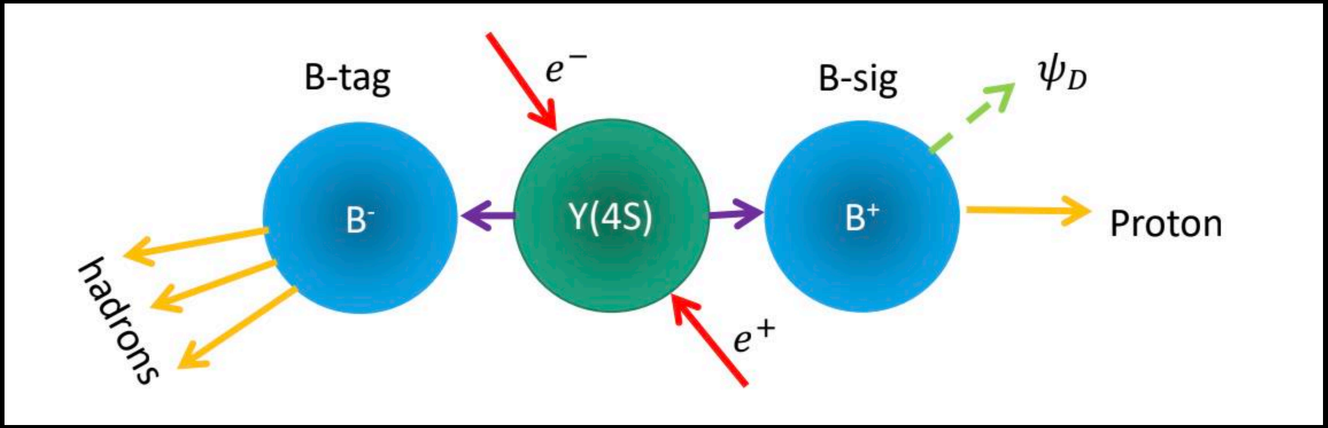




- Asymmetric e^+e^- collider operating at center-of-mass (cms) energy $\sqrt{s}$ close to 10.58 GeV
- Total integrated luminosity of 514 fb^{-1} collected, mostly at the $\Upsilon(4S)$ resonance
    - Initial-State-Radiation (ISR): the emission of a photon in the initial state allows to exploit a lower cms energy range, from threshold to $\sqrt{s}$

Event Reconstruction and Preselection

B-tag: fully reconstructed B in Standard Model decay channel
B-sig: possible signal, search here for missing mass



B-tag selection criteria:

$-0.2\ \mathrm{GeV} < \Delta\mathrm{E} < 0.2\ \mathrm{GeV}$

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

B-sig selection criteria (channel dependent)

N_{BB}~$2\mathrm{x}10^8$ before selection criteria or reconstruction applied

center-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:

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

Analysis Strategy

Simulation

Backgrounds:

- JETSET used to model quark-antiquark
- EvtGen used for $B\bar{B}$

Signal:

- EvtGen used to generate 8 signal mass hypothesis for each channel

Analysis method

- Pass through G4 BABAR model, digitization and full reconstruction. Uses real conditions information and beam background

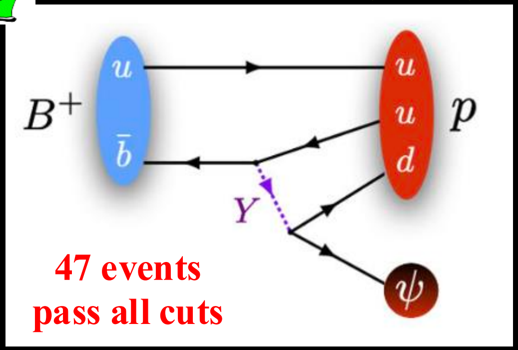
- Use MC to determine signal selection cuts
- Functional forms of fit used to extract selection efficiency and signal resolution for 8 possible masses, and interpolate for any given ψ_D mass
- Scan across the missing-mass distribution with a step size equal to the signal mass resolution
- Perform a profile likelihood fit to determine upper limits on branching fraction for each channels for given mass

Yields determined via data-driven Poisson counting method, with background and signal regions defined from the study of the background and signal MC simulations

Signal Selection

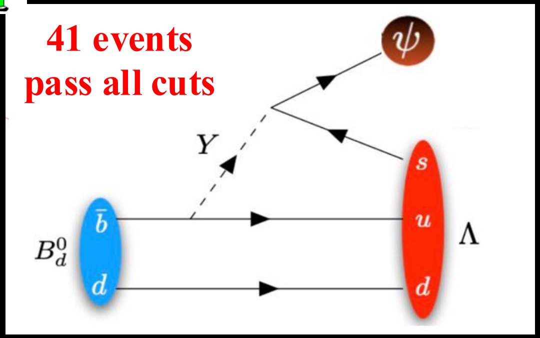
NEW Result

PRL **131**, 201801(2023)



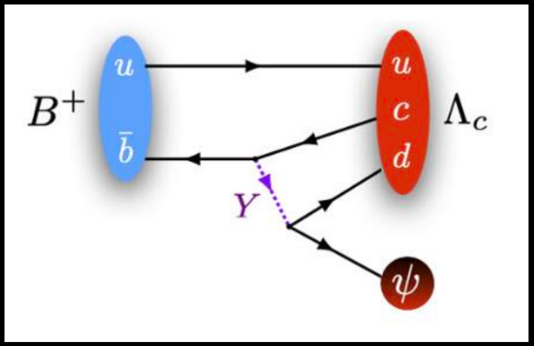
- $\mathcal{O}_{ud}$
- Only one charged track in the signal side
- Proton PID algorithm used to identify proton candidate
- $\upsilon_{BDT} > 0.95$

PRD **107**, 092001(2023)



- $\mathcal{O}_{us}$
- 2 charged tracks required on the signal side
- $\Lambda \to p\pi^-$: PID requirements for π and p
- Λ flight length significance > 1.0
- four-momentum kinematic fit for Λ reconstruction $\chi^2 < 100$
- $\upsilon_{BDT} > 0.75$

PRD **111**,L031101(2025)



- $\mathcal{O}_{cd}$
- 3 charged tracks required on the signal side
- $\Lambda_c^+ \to pK^-\pi^+$: high quality charged tracks plus PID requirements for kaon and proton
- $\upsilon_{BDT} > 0.99$

Further signal and background separation found using a Boosted Decision Tree (BDT) custom to each channel

Further Selections

NEW Result

BDT provides extremely high suppression of remaining backgrounds with little loss of signal efficiency

$B^+ \to \Lambda_c^+ + \psi_D$ ($\mathcal{O}_{cd}$)

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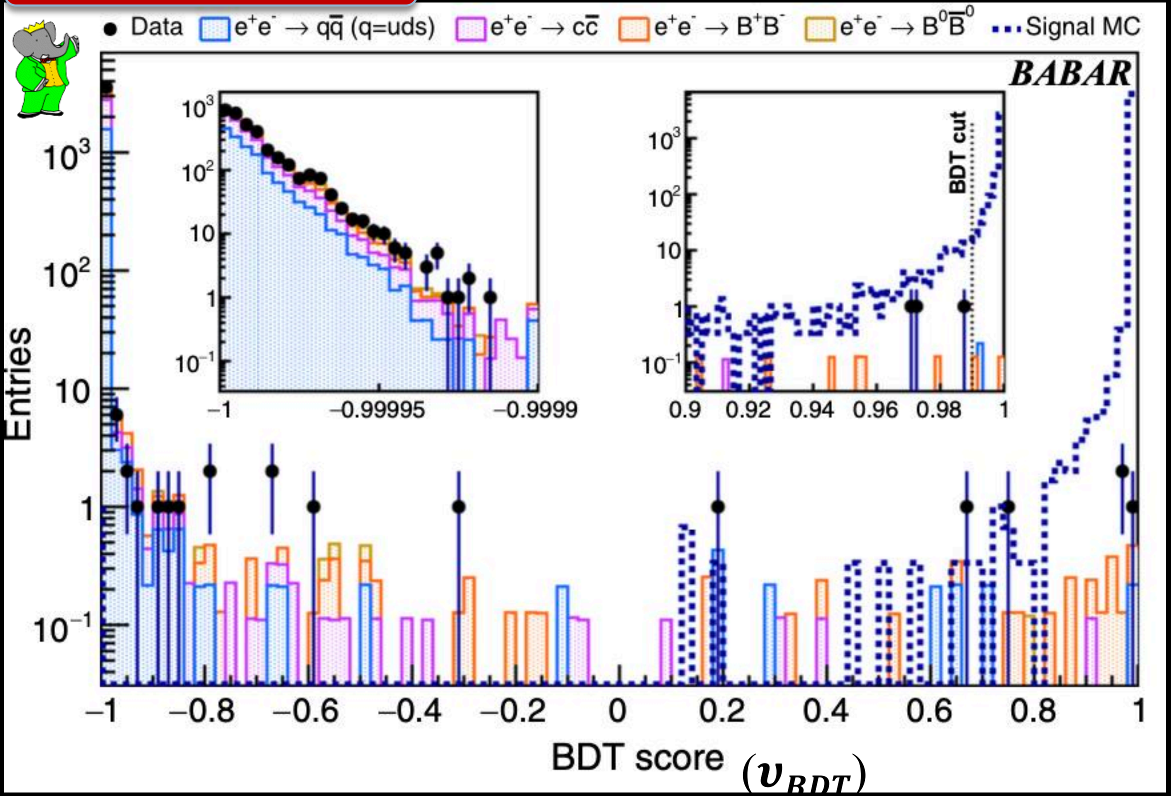


- 14 inputs, based on overall event shape, B_{tag} properties, Λ_c^+ candidate properties, and additional detector activity in the event
- 32 fb^{-1} data sample used for input validation and training, then discarded
- Signal samples spanning full kinematically accessible ψ_D mass range

➢ **Require $\upsilon_{BDT} > 0.99$** ➡ **Provide signal purity > 99%**
0 events pass

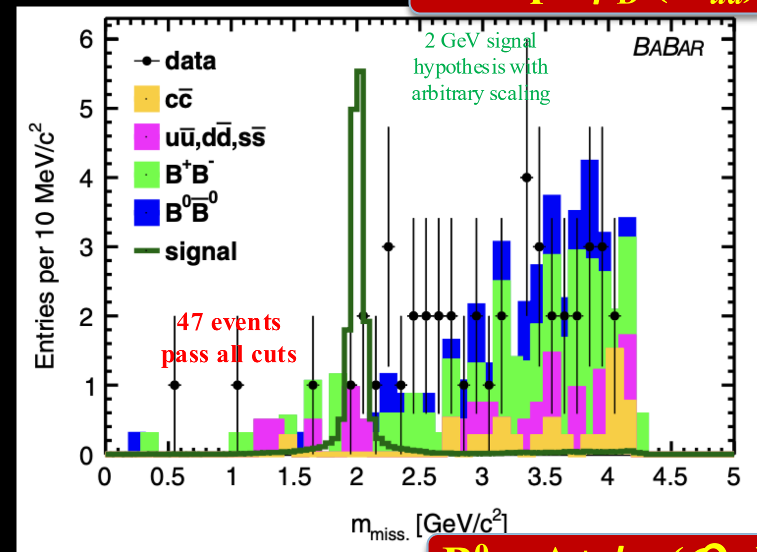
Three events close to signal region were examined and found to be consistent with $q\bar{q}$ continuum production of Λ_c^+

Final Analysis

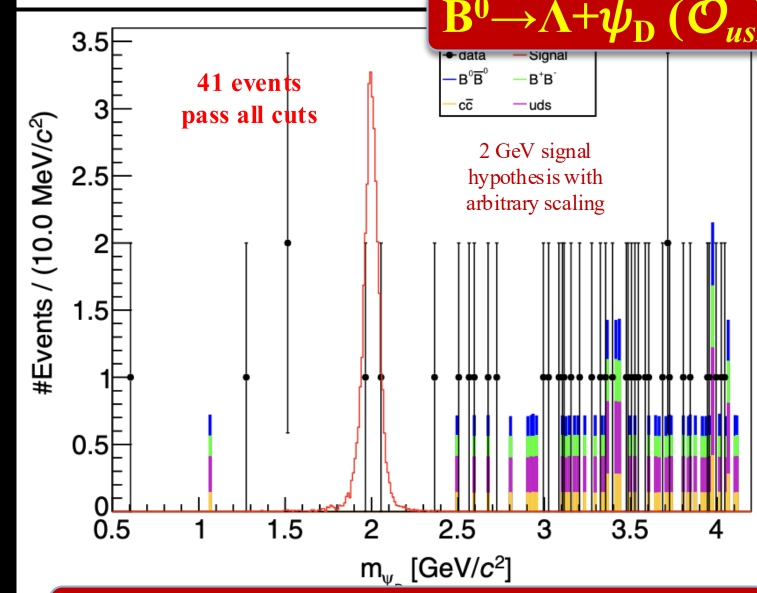
Final analysis proceeds by:

- Reconstructing ψ_D from missing energy 4-vector on signal side
- Extracting the resolution (σ) and efficiency (ε) from fits to MC, and interpolating the results to the full mass range
- scanning across mass range, with step size equivalent to the resolution at that mass
- estimating signal and backgrounds in data using definitions from MC study

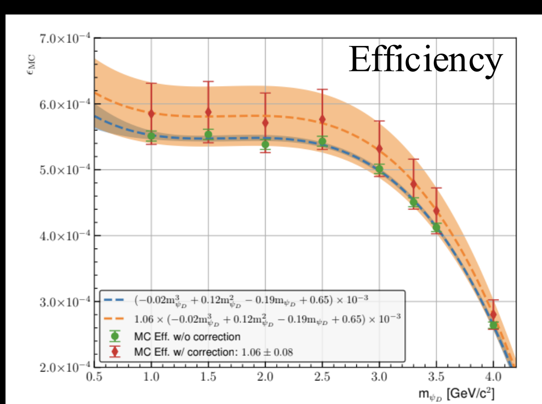
$B^+ \to p + \psi_D\ (\mathcal{O}_{ud})$

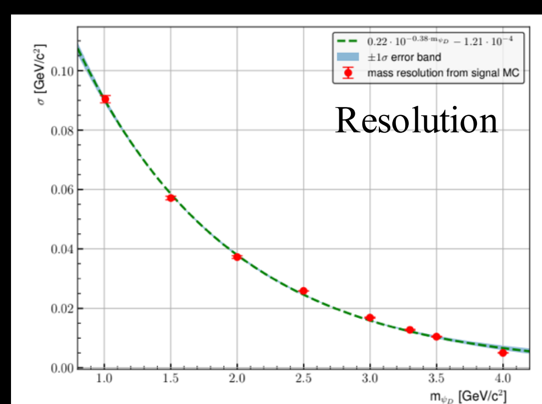


$B^0 \to \Lambda + \psi_D\ (\mathcal{O}_{us})$



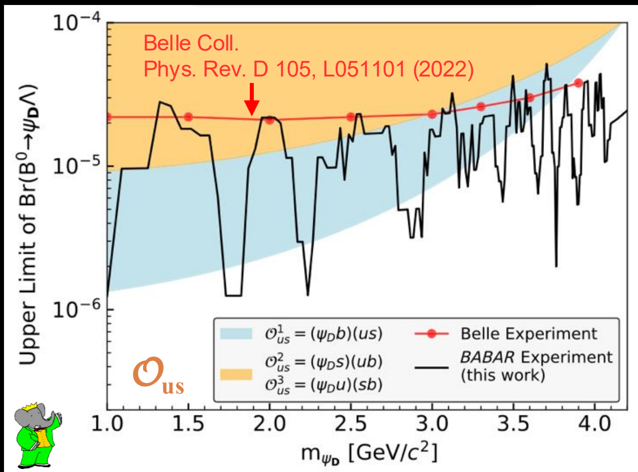
$$m_{\mathrm{miss}} = \sqrt{(E^*_{B_{\mathrm{sig}}} - E^*_p)^2 - |\tilde{p}^*_{B_{\mathrm{sig}}} - \tilde{p}^*_p|^2}$$





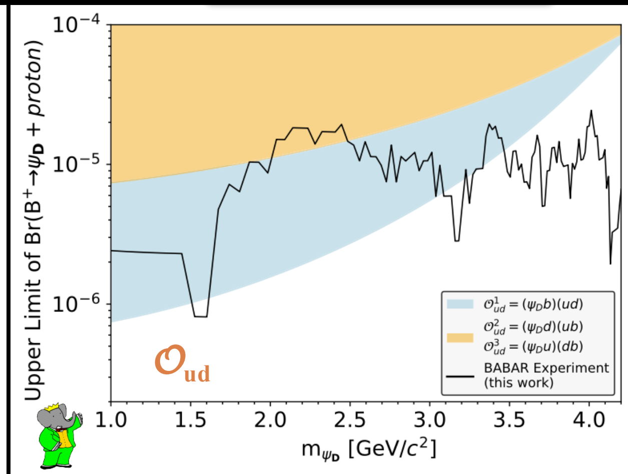
Results

$B^0 \to \Lambda + \psi_D$ ($\mathcal{O}_{us}$)



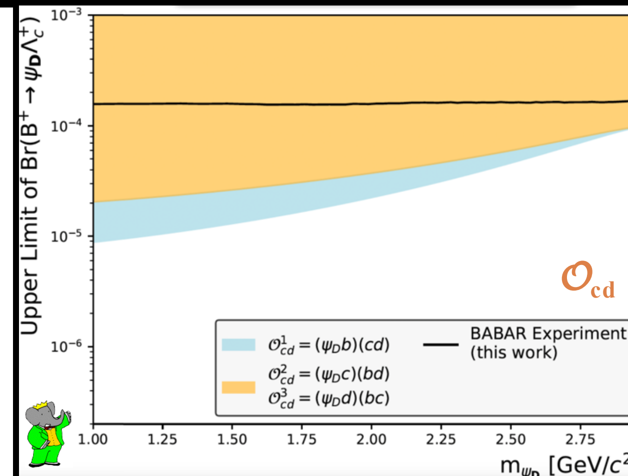
PRD **107**, 092001(2023)

$B^+ \to p + \psi_D$ ($\mathcal{O}_{ud}$)



PRL **131**, 201801(2023)

$B^+ \to \Lambda_C^+ + \psi_D$ ($\mathcal{O}_{cd}$)



PRD **111**, L031101(2025)

- World-leading result for $B^0 \to \Lambda + \psi_D$ ($\mathcal{O}_{us}$), improving on previous result and further constraining model
- First direct search for $B^+ \to p + \psi_D$ ($\mathcal{O}_{ud}$) and $B^+ \to \Lambda_C^+ + \psi_D$ ($\mathcal{O}_{cd}$) place tight constraints on specific model
- Remaining analysis to probe fourth operators $\mathcal{O}_{cs}$

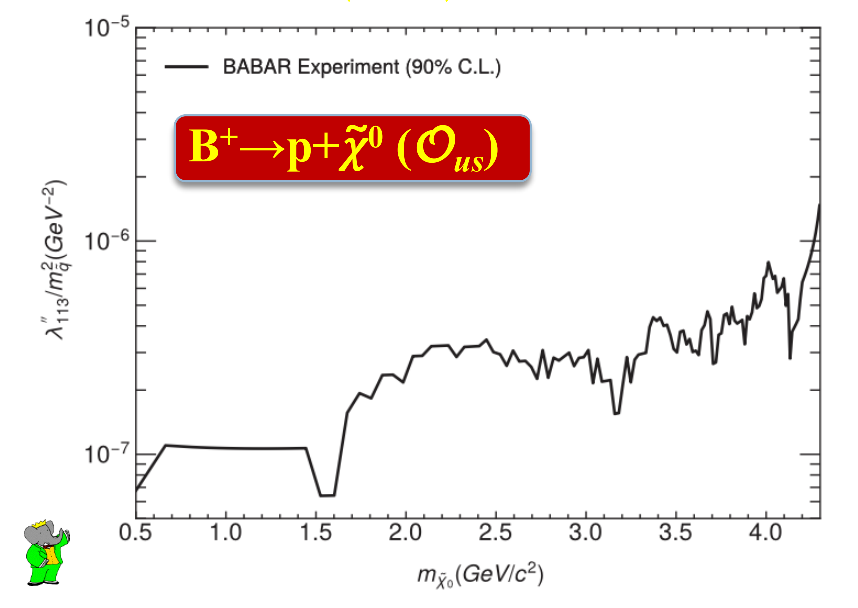
B-mesogenesis parameter space is vastly reduced / almost excluded for some operators.
Need to examine other operators to fully exclude the B-mesogenesis model

Results

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

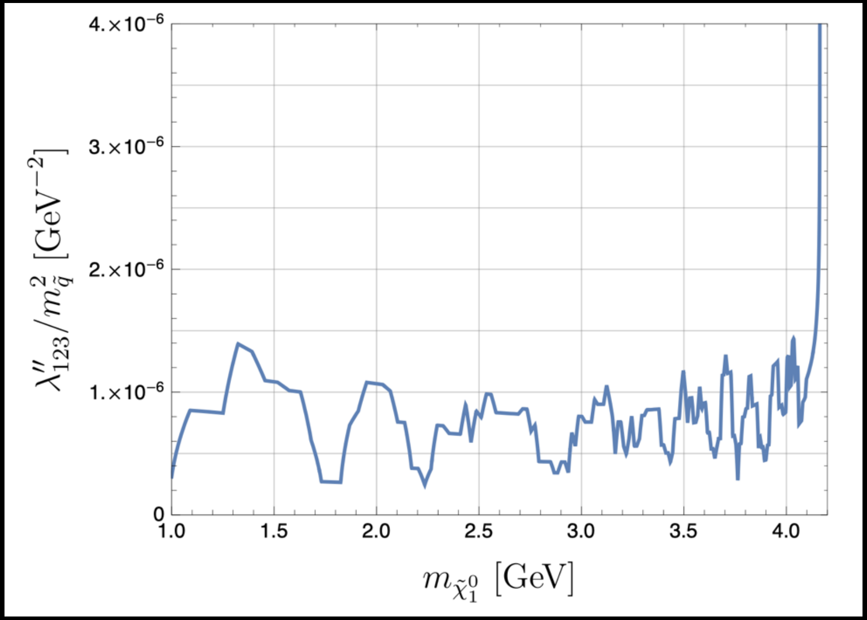
- Extended search to provide first limit on R-Parity Violation (RPV) SUSY model is described in JHEP **02**, (2023) 224

PRL **131**, 201801(2023)



BF upper limits converted to limits on the RPV coupling λ''_{113}

JHEP **02** (2023) 224



Limits on λ''_{123} from BaBar $B^0 \to \Lambda + \psi_D$ results reinterpreted in term of $B^0 \to \Lambda + \tilde{\chi}_1{}^0$

Summary and Conclusions

BaBar has conducted a search for signatures in a model which explains both dark matter and baryogenesis using the full data set available on the $\Upsilon(4S)$ invariant mass

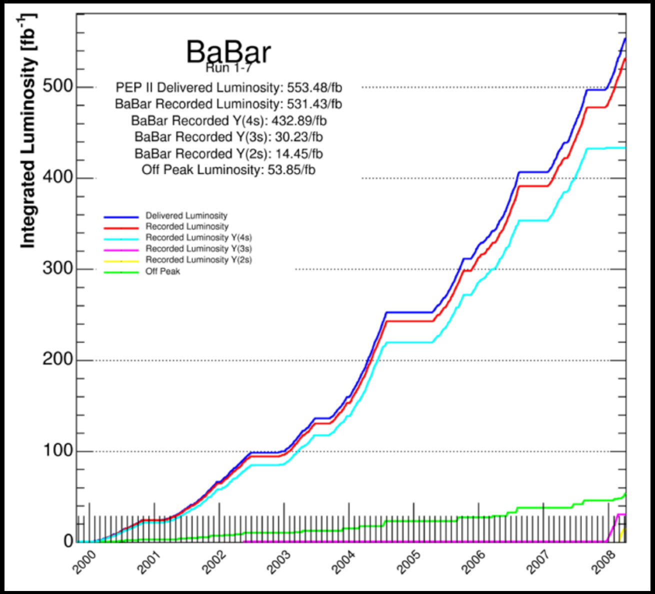
- Improved limits on $B^0 \to \Lambda + \psi_D$ channel
- First direct limits on $B^+ \to p + \psi_D$ and $B^+ \to \Lambda_c^+ + \psi_D$
- Large amounts of parameter space reduced; model not fully excluded until all operators are explored
- Results applied to SUSY model, providing first direct constraints on that model too
  - Results can also apply to other models with missing energy in final state
- Upcoming BaBar analysis with $B^+ \to \Lambda_c \pi + \psi_D$

BABAR still publishing many world-leading results after all these years!!!

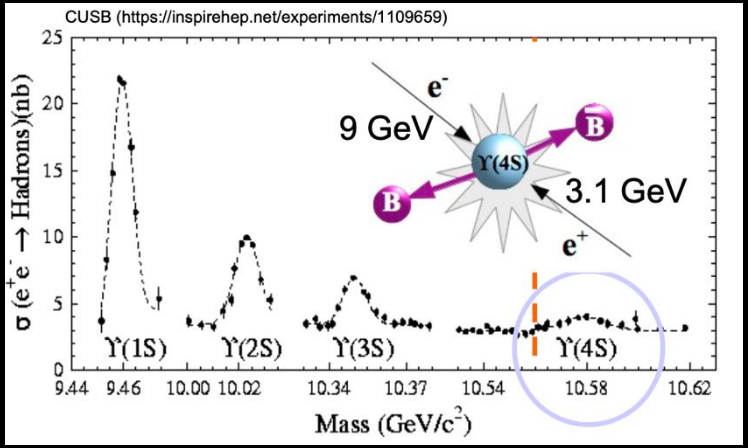
bkslide

BaBar Data Sets

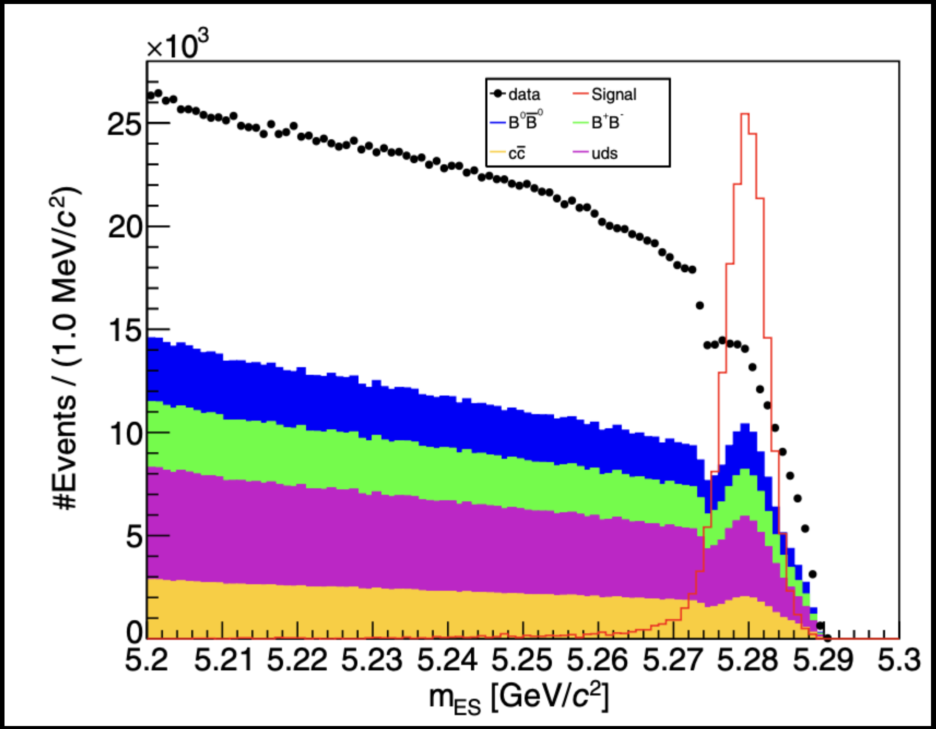
- BaBar collected data from 1999-2008
- 432 fb^{-1} at $\Upsilon(4S)$ ("onpeak") ➔ ~ 470 × 10^6 BB pairs
- 53 fb^{-1} non-resonant data ("offpeak") collected about 40 MeV the $\Upsilon(4S)$ peak
- 122 × 10^6 $\Upsilon(3S)$ decays and 99 × 10^6 $\Upsilon(2S)$ decays collected during last few months of running

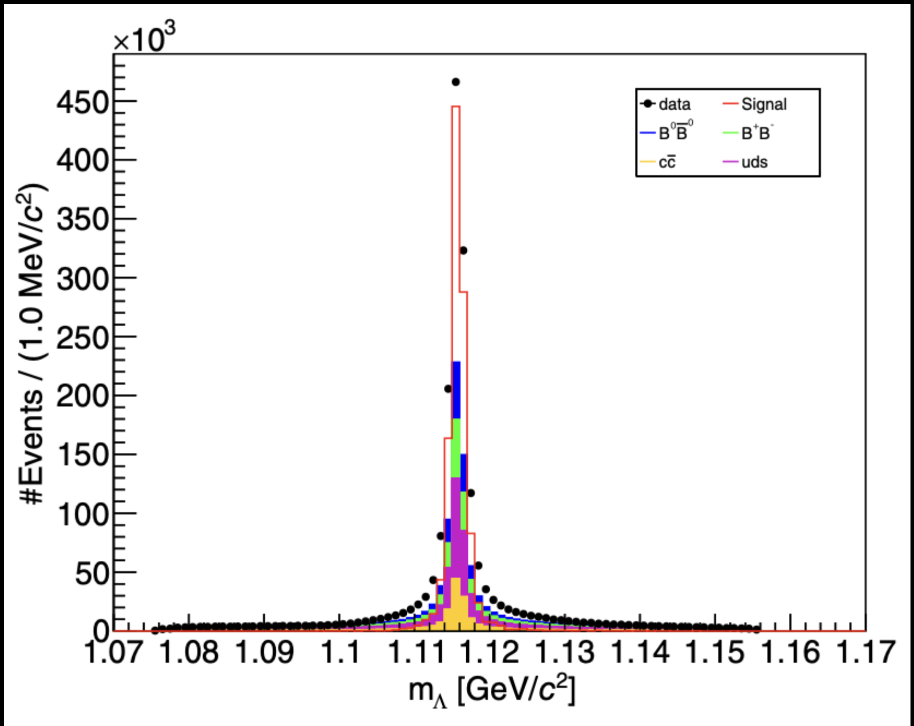


Process	Cross section (nb)
$b\bar{b}$	1.1
$c\bar{c}$	1.3
light quark $q\bar{q}$	~2.1
$\tau^+\tau^-$	0.9
e^+e^-	~40



$\mathcal{B} \rightarrow \Lambda \psi_{\mathcal{D}}$

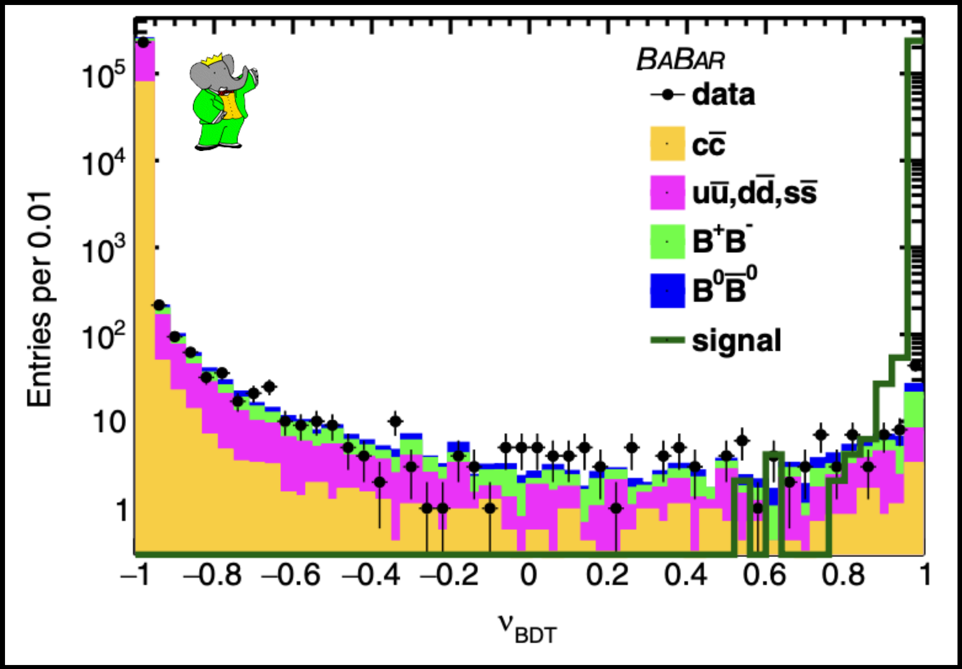




Further Selections

$B^+ \to p + \psi_D$ $(\mathcal{O}_{us})$

PRL **131**, 201801(2023)

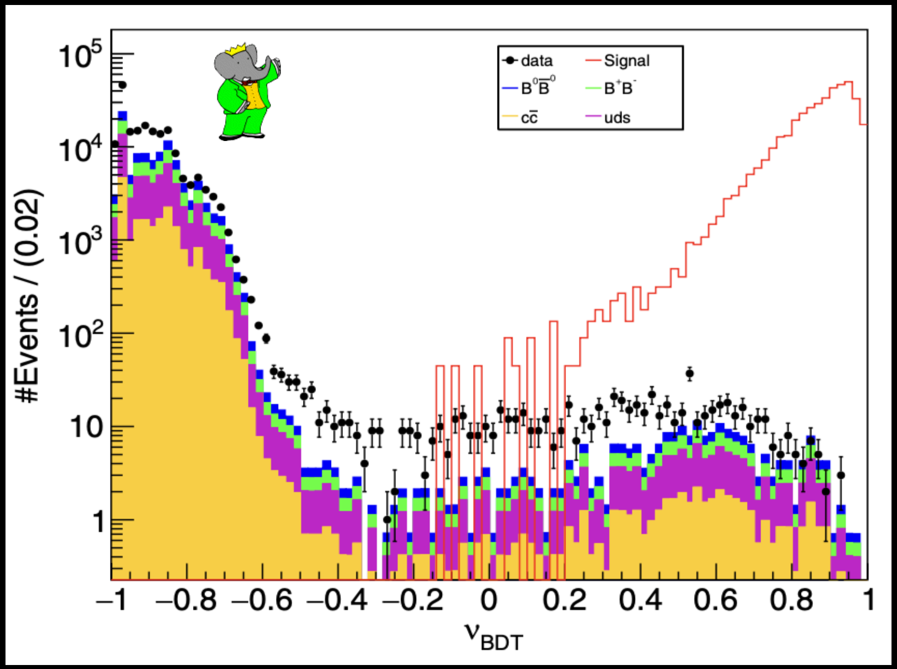


- Require $\upsilon_{BDT} > 0.95$

Provide signal purity > 99%
47 events pass all cuts

$B^0 \to \Lambda + \psi_D$ $(\mathcal{O}_{us})$

PRD **107**, 092001(2023)



- Require $\upsilon_{BDT} > 0.75$

Provide signal purity > 99%
41 events pass all cuts