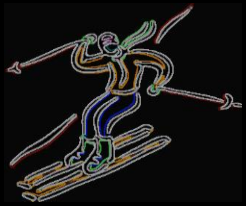
Search for *B*-mesogenesis at B*A*B*AR*

Bertrand Echenard
echenard@caltech.edu
on behalf of the B*A*B*AR* collaboration

Lake Louise Winter Institute 2024

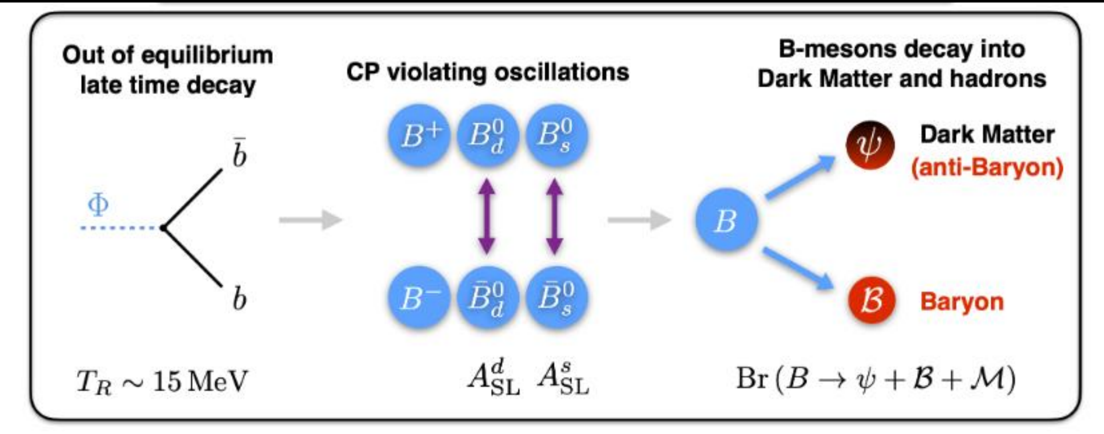


B-mesogenesis in a nutshell

B-mesogenesis* is a scenario proposed to simultaneously explain the baryon asymmetry in the universe and the presence of dark matter via *B*-meson decays

In a nutshell:

- Introduce a new heavy, weakly coupled scalars produced in the early universe (Φ), a dark sector baryon (ψ_D), and a few more dark sector particles
- Heavy scalars decay into a $b\bar{b}$ pairs, a fraction of which hadronizes into *B* mesons
- Neutral *B*-mesons undergo CP-violating oscillations and decay into baryons ($\mathcal{B}$), dark-sector anti-baryons (ψ_D), and any number of additional mesons ($\mathcal{M}$)
- Because of CP violation, the $B \to \mathcal{B} + \psi_D + \mathcal{M}$ decays slightly dominate over the $\overline{B} \to \overline{\mathcal{B}} + \overline{\psi}_D + \overline{\mathcal{M}}$ decays



* Elor, Escudero, Nelson, PRD 99, 035031 (2019); Alonzo-Alvarez, Escudero, Elor, PRD 104, 035028 (2021)

B-mesogenesis in a nutshell

B-mesogenesis* is a scenario proposed to simultaneously explain the baryon asymmetry in the universe and the presence of dark matter via *B*-meson decays

In a nutshell:

- Introduce a new heavy, weakly coupled scalars produced in the early universe (Φ), a dark sector baryon (ψ_D), and a few more dark sector particles
- Heavy scalars decay into a $b\bar{b}$ pairs, a fraction of which hadronizes into *B* mesons
- Neutral *B*-mesons undergo CP-violating oscillations and decay into baryons ($\mathcal{B}$), dark-sector anti-baryons (ψ_D), and any number of additional mesons ($\mathcal{M}$)
- Because of CP violation, the $B \to \mathcal{B} + \psi_D + \mathcal{M}$ decays slightly dominate over the $\overline{B} \to \overline{\mathcal{B}} + \overline{\psi}_D + \overline{\mathcal{M}}$ decays
- As a result, there is a net excess of baryon in the visible sector, and an anti-baryon excess of the same magnitude in the dark sector – *baryon number in the whole universe is conserved, but a net excess is present in the visible sector*
- The ψ_D decays into other stable dark sector states, and *their present-day abundance can reproduce the observed dark matter density.* Kinematic constraints require that the ψ_D mass lies between 0.94 – 4.34 GeV.

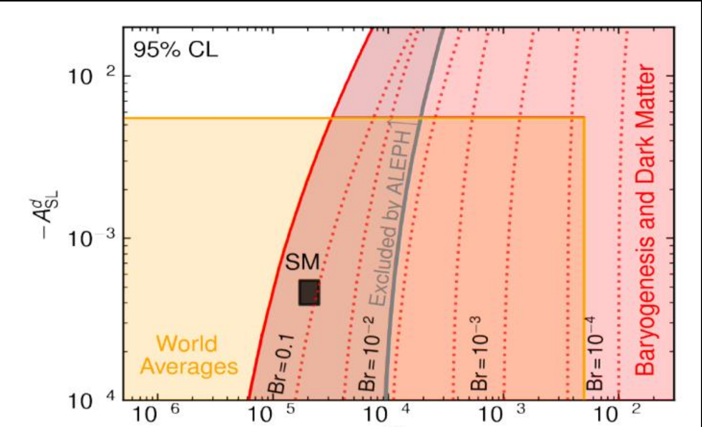
* Elor, Escudero, Nelson, PRD 99, 035031 (2019); Alonzo-Alvarez, Escudero, Elor, PRD 104, 035028 (2021)

B-mesogenesis in a nutshell

This scenario requires a large (inclusive) branching fraction $B \to \mathcal{B} + \psi_D + \mathcal{M}$, greater than ~$10^{-4}$, depending on the semi-leptonic asymmetries $A_{SL}^{d,s}$

- Testable at experimental facilities, but exclusive channels have lower branching fractions (see next slide)

$$Y_{\mathcal{B}} \simeq 8.7 \times 10^{-11} \, \frac{\mathrm{Br}(B \to \psi \, \mathcal{B} \, \mathcal{M})}{10^{-3}} \sum_q \alpha_q \, \frac{A_{\mathrm{SL}}^q}{10^{-3}} \, ,$$



PRD 104, 035028 (2021)

The type of baryon produced depends on the operator mediating the interaction, leading to many final states

- Need to explore all channels to fully test this mechanism as a single operator could be sufficient for successful B-mesogenesis

Operator and Decay	Initial State	Final State	ΔM (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
	Λ_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
	Λ_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
	Λ_b	$\bar{\psi} + \bar{D}^0$	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
	Λ_b	$\bar{\psi} + D^- + K^+$	3256.2

PRD 104, 035028 (2021)

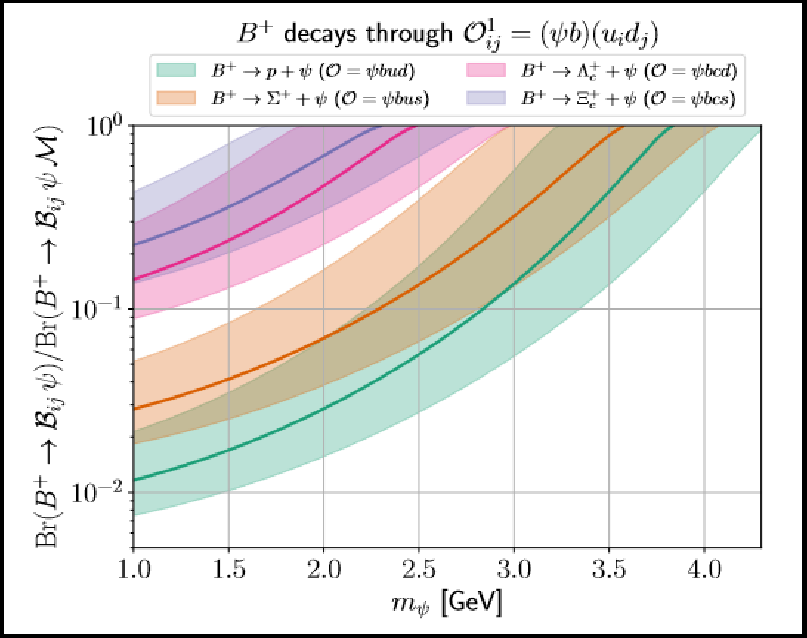
B-factories well suited to probe these possibilities. B*ABAR* searched for the following exclusive reactions:

- $B^0 \to \Lambda + \psi_D$
- $B^+ \to p + \psi_D$
- $B^+ \to \Lambda_c^+ + \psi_D$ (on-going)

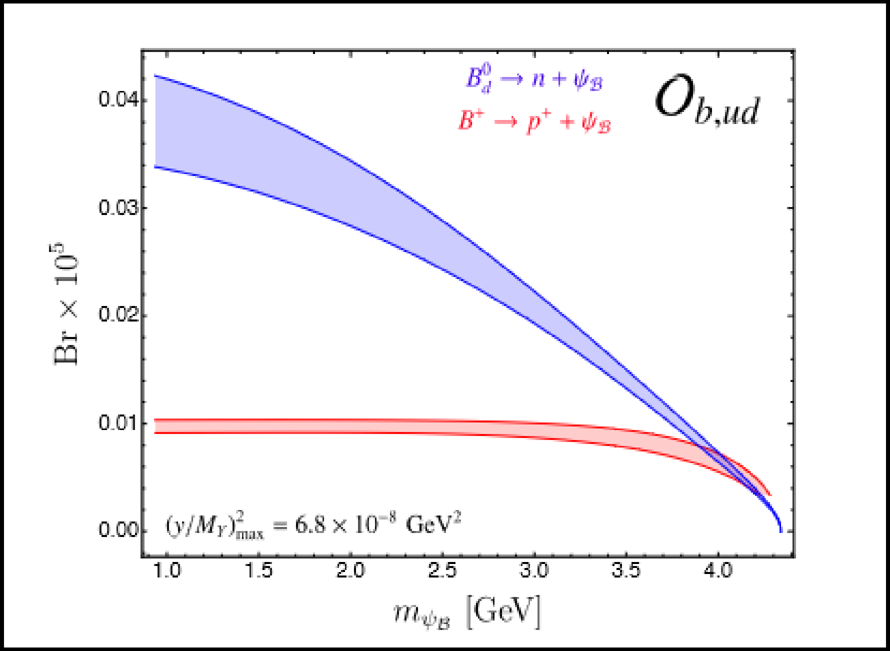
B-mesogenesis in a nutshell

Estimates of the exclusive branching fraction $B \rightarrow \mathcal{B} + \psi_D$ required for *B*-mesogenesis have been calculated using phase space considerations (Escudero *et al.*) or QCD Light Cone Sum Rules (Guerrera *et al*, Boushmelev and Wald)

Alonzo-Alvarez, Escudero, Elor, PRD 104, 035028 (2021)



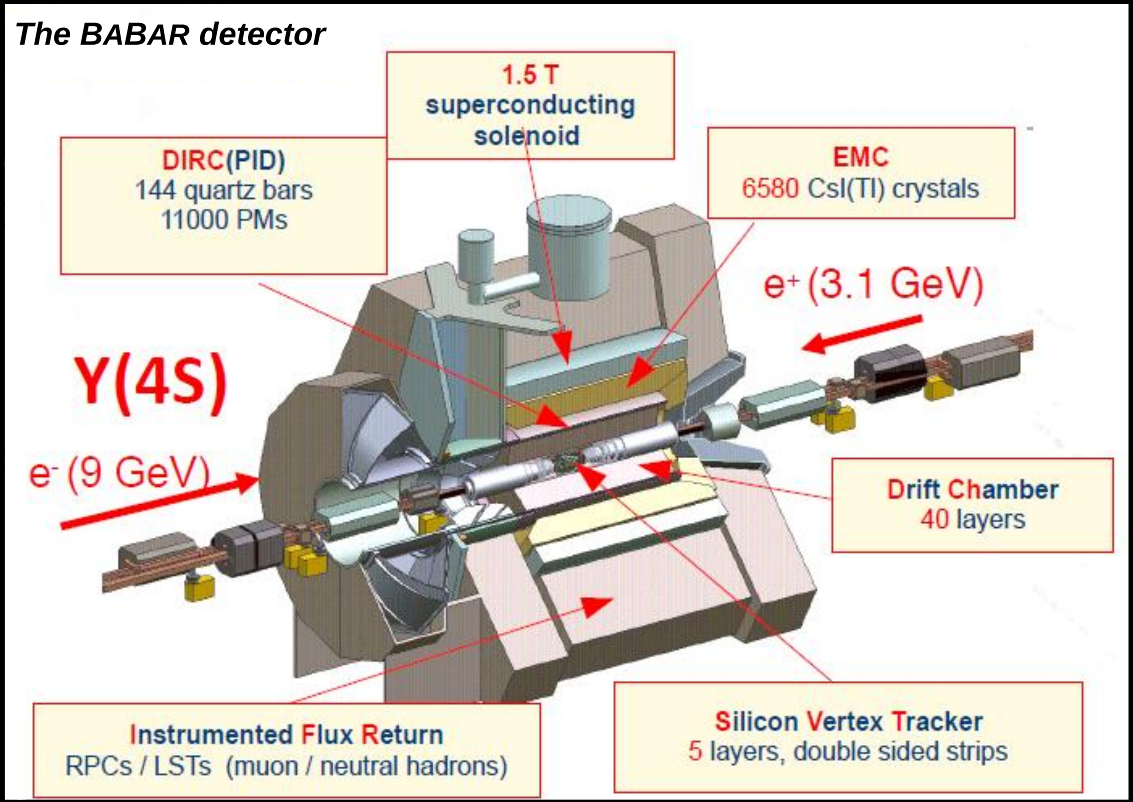
Guerrera et al, JHEP02(2023)100



Exclusive BF at the level of $10^{-7} - 10^{-4}$ required for *B*-mesogenesis, depending on the mass and calculations (predictions can vary by an order of magnitude!)

The B*A*B*AR* experiment

B*A*B*AR* collected ~500 fb^{-1} around the ϒ(4S), ϒ(3S) and ϒ(2S) resonance between 1999 - 2008



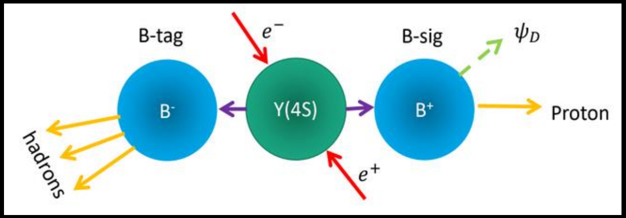
Collaboration is still active more than 15 years after data taking ended !

Analysis overview

Search for $B^+ \to p + \psi_D$ and $B^0 \to \Lambda + \psi_D$

Produce a pair of *B*-mesons in $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ collisions with a "signal B" and a "tag *B*"

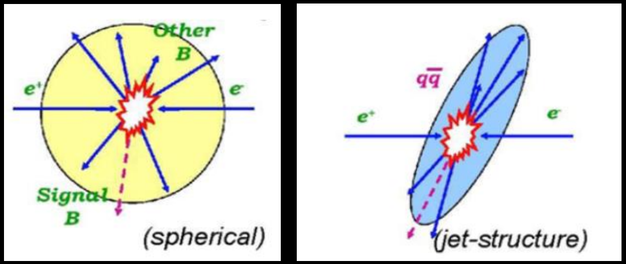
- Search based on full hadronic *B*-tag decays

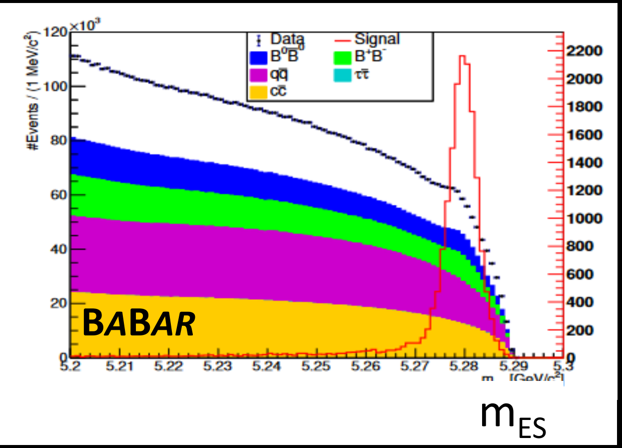


Reconstruct the *B*-tag by combining seed D$^{(*)}$ and J/ψ mesons with up to five kaons or pions

- Dominant backgrounds are $e^+e^- \to q\overline{q}$ ($q = u, d, s, c$), exhibiting a jet-like topology, whereas $e^+e^- \to B\overline{B}$ events are more "spherical"
- Separate and suppress continuum background using kinematic and event shape variables
- Two kinematic variables are commonly used:

$$m_{ES} = \sqrt{E_{beam}^2 - p_B^2} \quad \text{and} \quad \Delta E = E_{Beam} - E_B$$





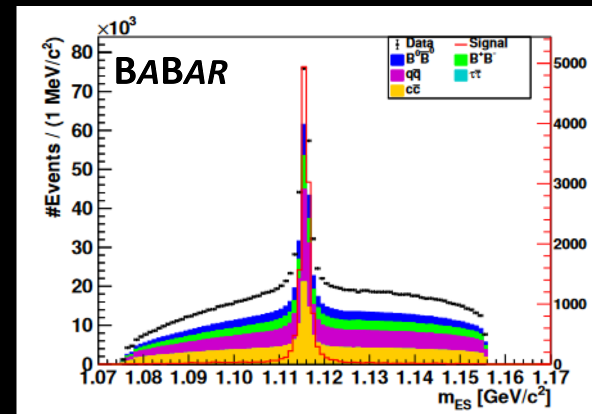
Analysis overview

Search for $B^+ \to p + \psi_D$ and $B^0 \to \Lambda + \psi_D$

Reconstruct signal B decays

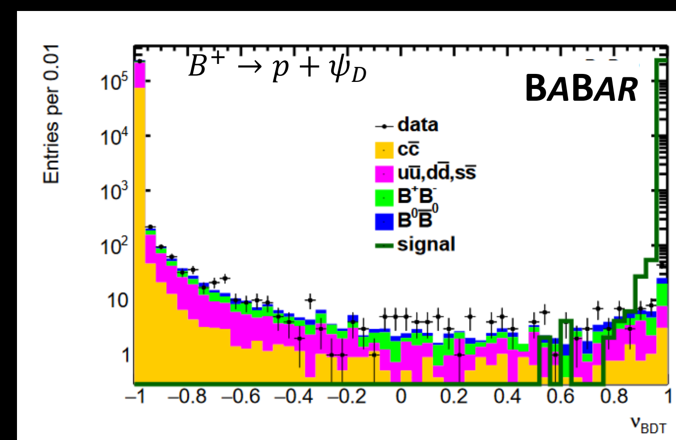
- Assign all remaining particles to the signal *B* candidate
- Require only 1 (2) track(s) for the proton (Λ) channel
- Reconstruct $\Lambda \to p\pi^+$ decays from the signal-side tracks
- Charge of signal candidate must be compatible with signal hypothesis
- Identify ψ_D as system recoiling against the baryon

pπ mass after loose tag B selection



Multivariate selection

- Train Boosted Decision Trees (BDTs) to improve the signal purity using MC samples with a mix of ψ_D masses
- Variables include *B*-tag kinematic, purity, and shape variables; extra neutral energy (signal side); number of π^0 (signal side); direction of the missing momentum vector; quality of the secondary Λ vertex,…
- Blind analysis, finalize selection criteria before looking at the final ψ_D mass distributions

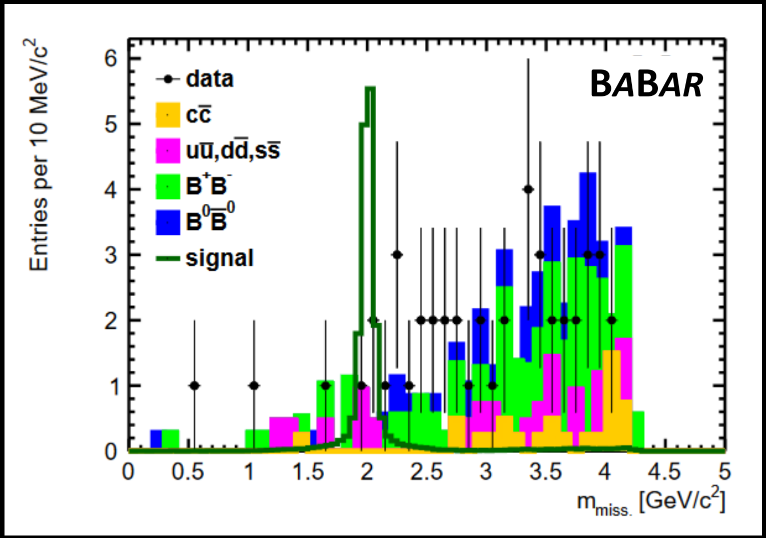


Signal extraction

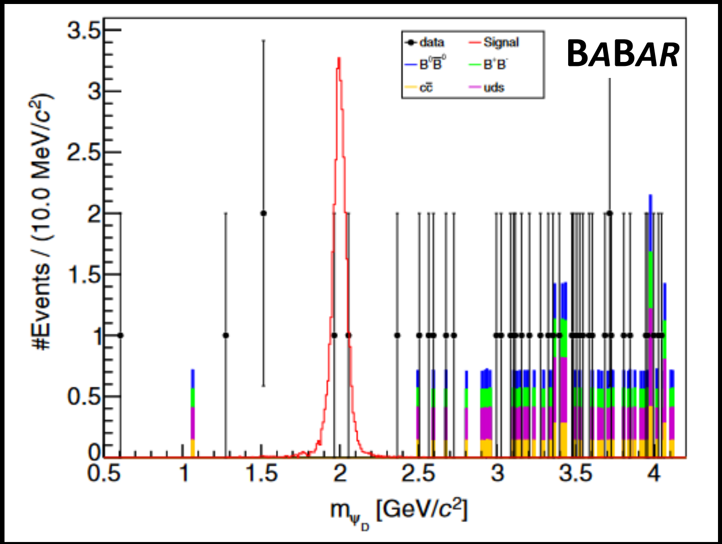
Extract the signal by scanning the missing mass in the signal B frame

- Signal yield determined by counting the number of events in a window of ±5σ (±3σ) centered around the ψ_D mass for the proton (lambda) final state
- Background yield estimated using sidebands of ±5σ (±3σ) around the signal region
- Evaluate signal resolution from fits to signal MC samples as a function of the ψ_D mass
- Scan in steps of the signal resolution

$B^+ \rightarrow p + \psi_D$



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



No significant signal is observed in each final state

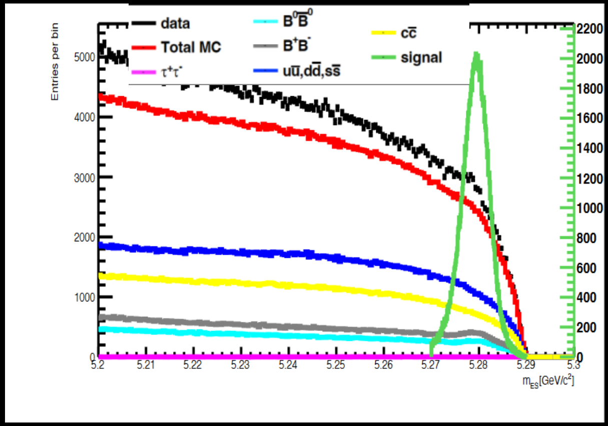
Efficiency and corrections

Known discrepancies between data and MC are taken into account by applying global correction factors

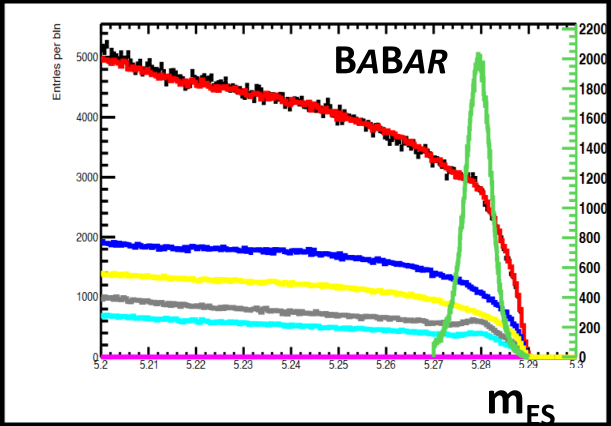
For $B^+ \rightarrow p + \psi_D$, select "pure" bkg sample using B-tag shape variables to correct the $e^+e^- \rightarrow q\overline{q}$ contributions, then scale the $e^+e^- \rightarrow B\overline{B}$ component (assuming mode-independent scaling factors)

For $B^0 \rightarrow \Lambda + \psi_D$, apply a similar strategy on the BDT output distribution obtained with a looser selection

$\boldsymbol{B^+ \rightarrow p + \psi_D}$ **- no correction**



$\boldsymbol{B^+ \rightarrow p + \psi_D}$ **- with correction**



Proton
$f_{qq} = 1.05 \pm 0.03 \quad (R_2 > 0.7)$
$f_{BB} = 0.85 \pm 0.07 \quad (R_2 < 0.7)$

Lambda
$f_{qq} = 1.34 \pm 0.10 \quad (BDT > -0.5)$
$f_{BB} = 1.06 \pm 0.08 \quad (BDT < -0.5)$

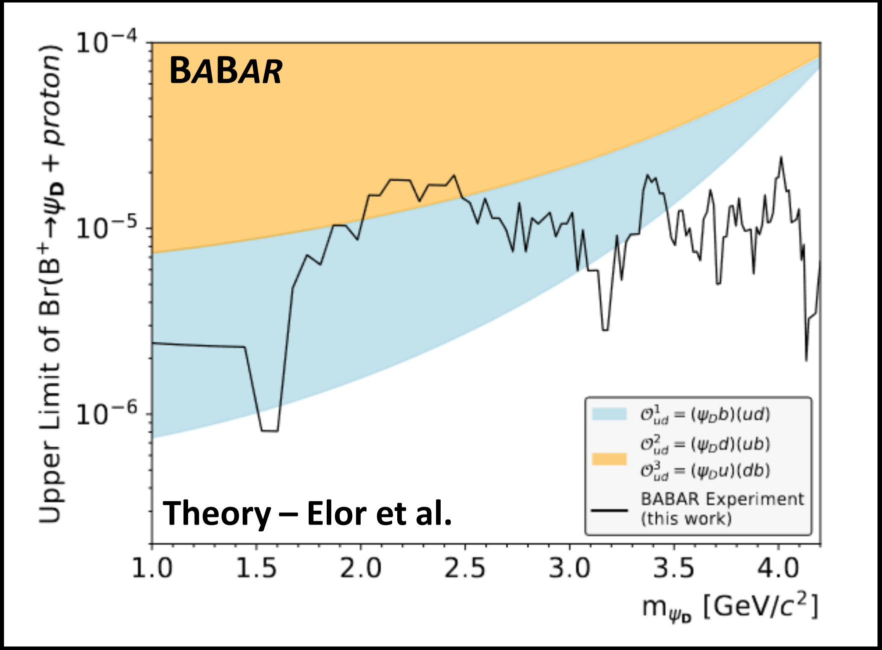
Overall signal efficiency ranges between 0.06% - 0.15% (0.02% - 0.06%) for the proton (lambda) channel, dominated by the efficiency to reconstruct the full hadronic B-tag

Uncertainty on efficiency correction is the largest systematic uncertainty (limited impact on results)

Results

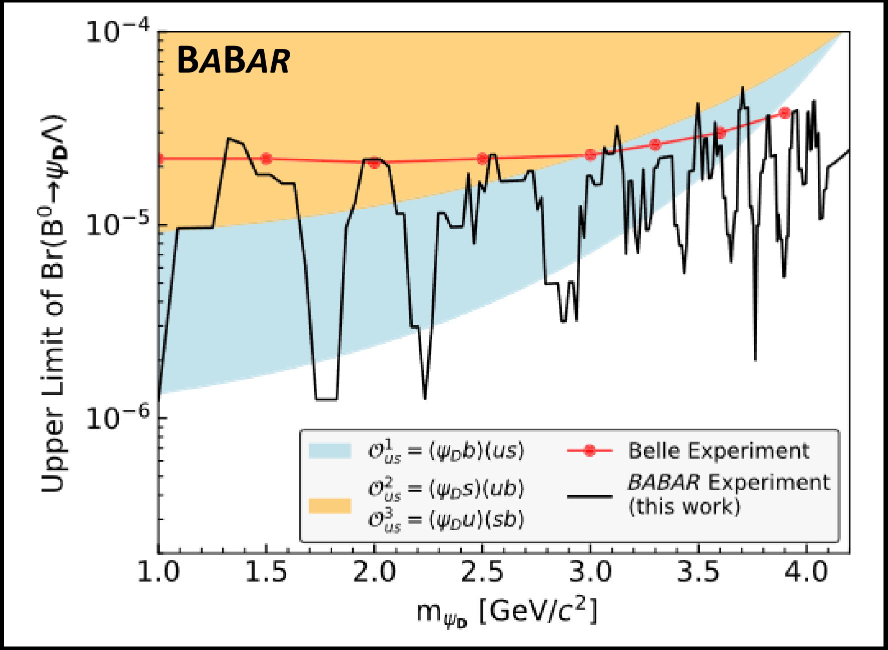
Use profile likelihood approach to derive 90% CL upper limit on the branching fractions

$B^+ \rightarrow p + \psi_D$



PRL 131 (2023) 201801

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



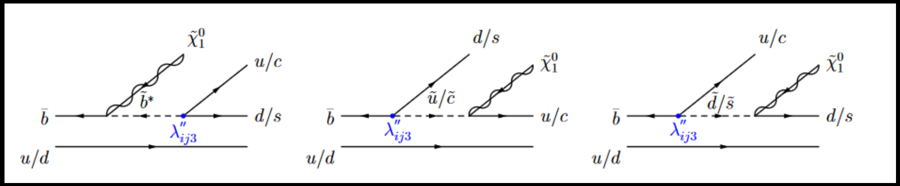
PRD 107 (2023) 092001

Limits at the level of 10^{-6} – 10^{-5}, improving upon previous constraints and excluding a large fraction of the favored parameter space

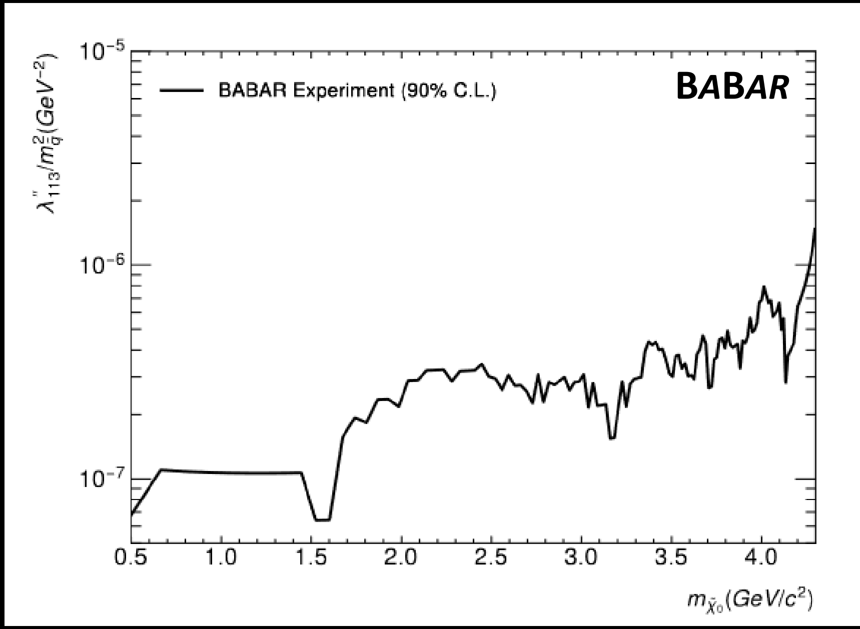
Belle-II should be able to fully explore these scenarios with their full datasets

Bonus time

These searches can be re-interpreted as constraints on couplings in a R-parity violating SUSY scenario with a GeV-scale lightest neutralino $\tilde{\chi}_1^0$ (JHEP 02 (2023) 224)

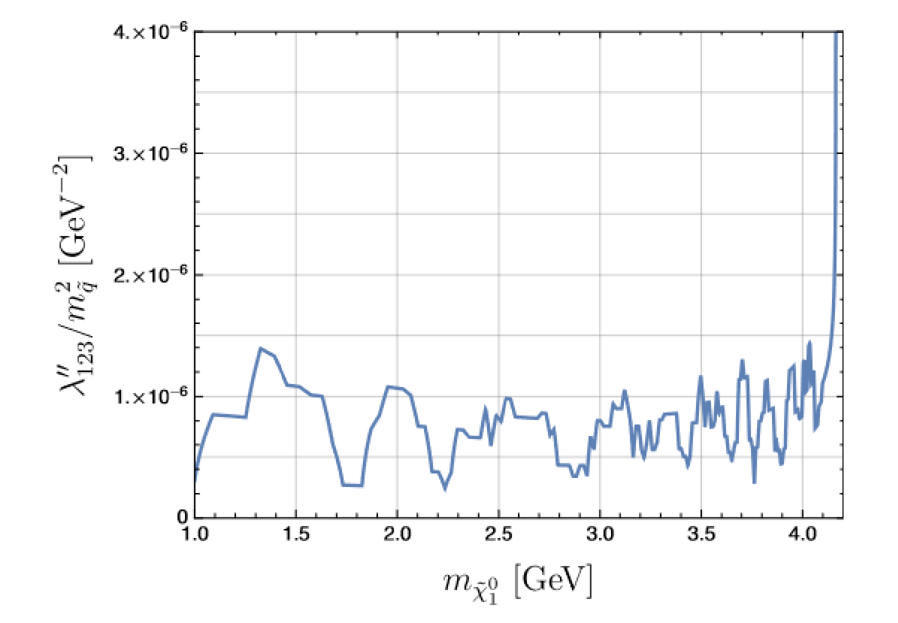


$B^+ \rightarrow p + invisible$



PRL 131 (2023) 201801

$B^0 \rightarrow \Lambda + invisible$



JHEP 02 (2023) 224

Conclusion

B-mesogenesis is a mechanism that can simultaneously explain the baryon asymmetry in the universe and the presence of dark matter

B-factories offer ideal environment to test this scenario, including measurements of $B \rightarrow \mathcal{B} + invisible$ decays

B*A*B*AR* has improved bounds on $B^0 \rightarrow \Lambda + invisible$ decays and provided the first measurement of $B^+ \rightarrow p + invisible$ decays, setting strong constraints on the *B*-mesogenesis parameter space

Belle-II and LHC experiments should be able to fully explore this model

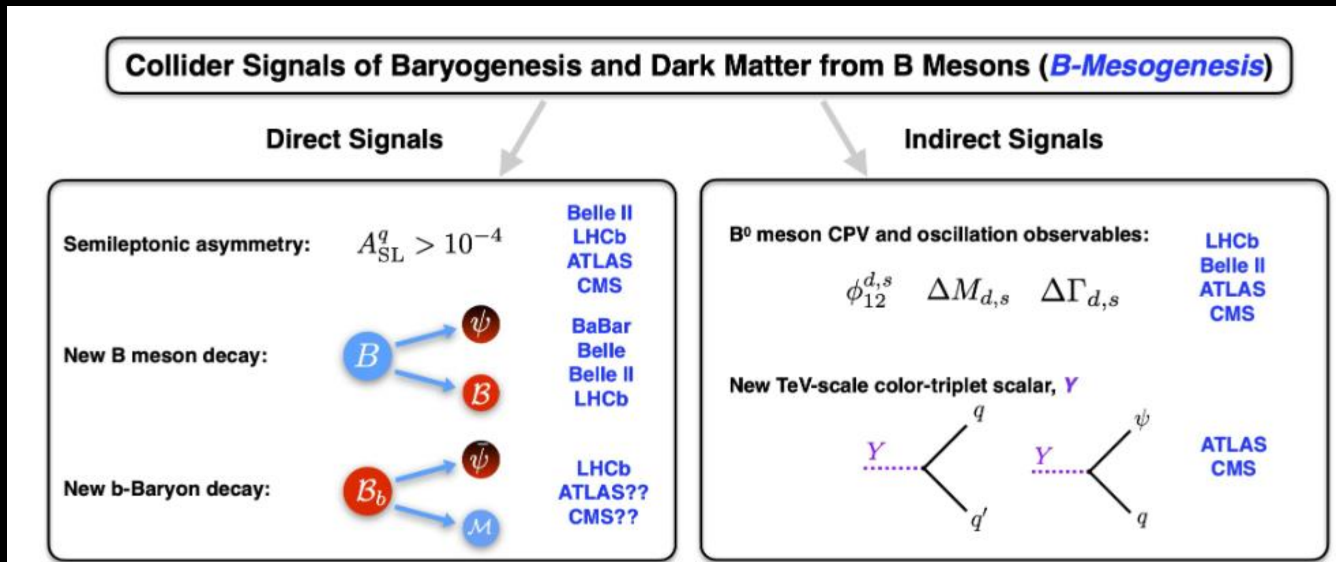
There could still be amazing physics hidden at the GeV-scale, and low-energy, high-intensity colliders are great tools to explore them

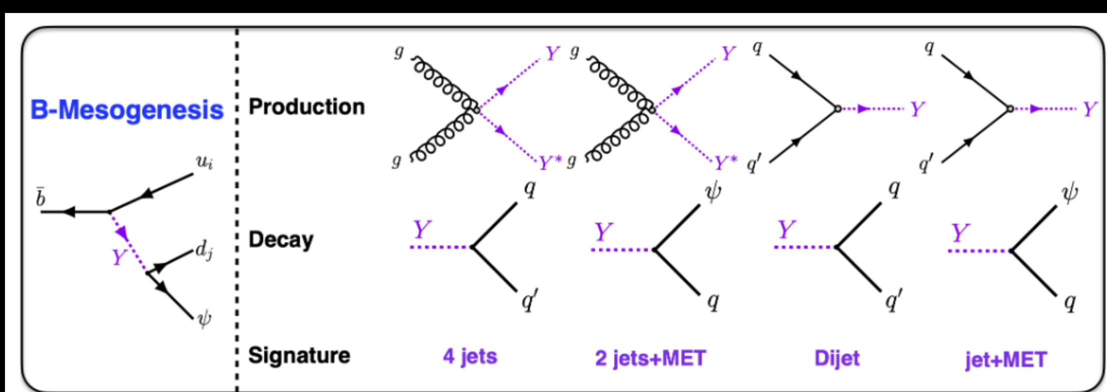
THANK YOU

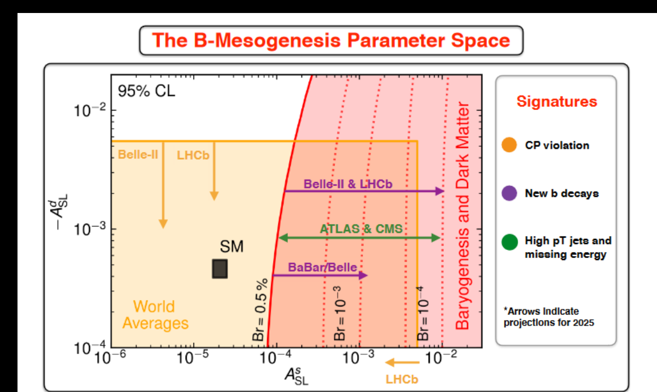
Additional material

B-mesogenesis

Summary of the collider implications of the *B*-mesogenesis mechanism



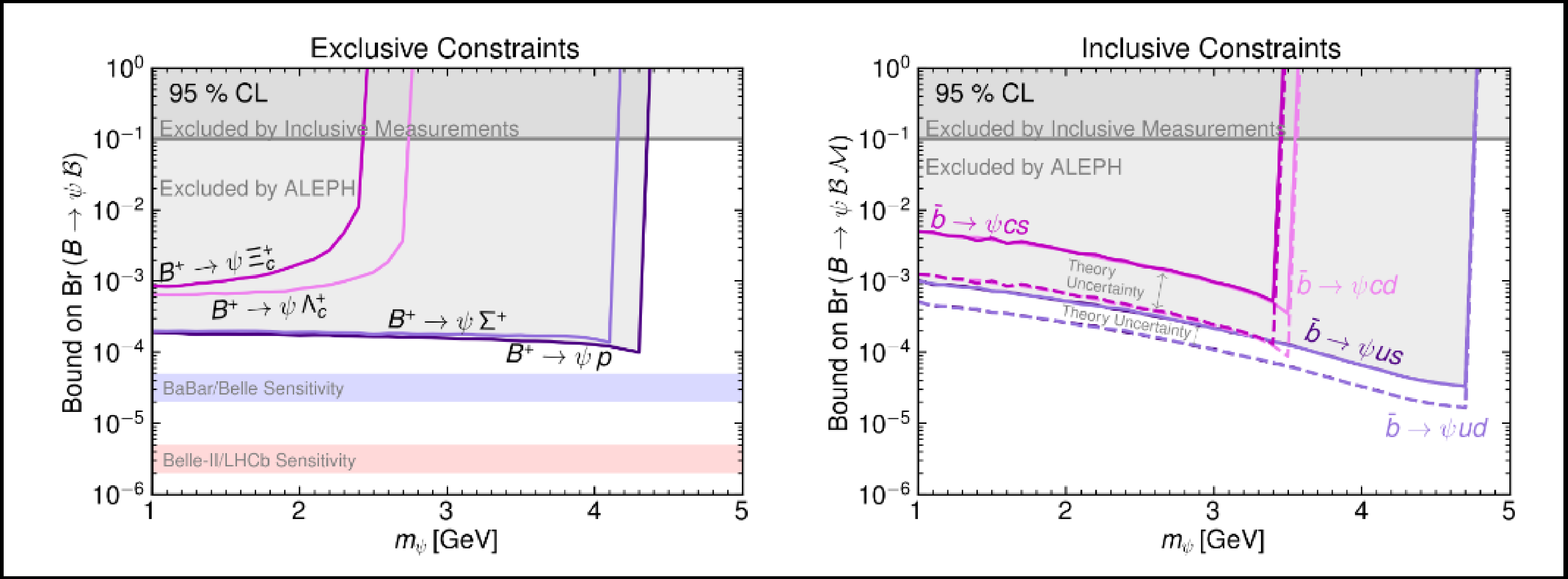




PRD 104, 035028 (2021)

B-mesogenesis

Constraints derived from measurement of $Z \to b\bar{b}$ decays with large missing energy at ALEPH*



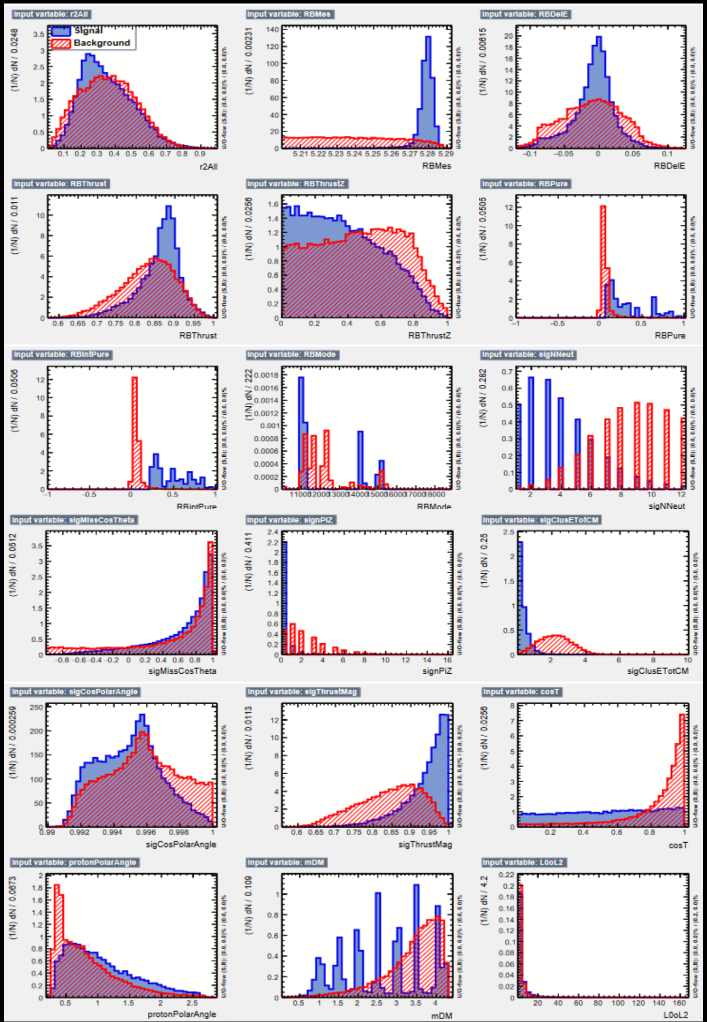
PRD 104, 035028 (2021)

* *Eur.Phys.J.C19:213-227,2001*

Multivariate analysis

The following variables are used in the BDT for the $B^+ \to p + invisible$ channel

- the hadronic decay channel of B-meson tag
- the fraction of B-tag mesons that are correctly reconstructed for a given decay mode
- the integrated purity of the tag decay mode
- the difference of beam energy and the reconstructed B-tag energy
- recoil B-meson mass distribution
- the B-tag thrust axis is defined as the axis which maximizes the longitudinal momenta of all the particles for B-tag reconstruction
- number of neutral particles in the signal side
- the number of π^0 candidates on the signal side
- the polar angle of the missing momentum vector recoiling against the B-tag meson and the signal candidate
- the total extra neutral energy on the signal side in the center-of-mass frame
- the ratio of the second to zeroth Fox-Wolfram moment for all tracks and neutral clusters
- the cosine of the thrust vector



Multivariate analysis

The following variables are used in the BDT for the $B^0 \to \Lambda + invisible$ channel

- the hadronic decay channel of B-tag meson
- the fraction of B-tag mesons that are correctly reconstructed for a given decay mode
- the integrated purity of the tag decay mode
- the difference of beam energy and the reconstructed B-tag energy
- recoil B-meson mass distribution
- the B-tag thrust axis is defined as the axis which maximizes the longitudinal momenta of all the particles for B-tag reconstruction
- number and net charge of the charged
- tracks in the signal B-sig meson side
- three momenta of the signal B-sig candidate
- number of neutral particles in the signal side
- the number of π^0 candidates on the signal side
- the total extra neutral energy on the signal side in the center-of-mass frame
- the polar angle of the missing momentum vector recoiling against the B-tag meson and the signal candidate
- The significance of the Λ decay length
- The χ^2 of the Λ fit