Searches for Dark Matter and Baryogenesis at *BaBar*

ICHEP 2024
Prague

By Sophie Charlotte Middleton

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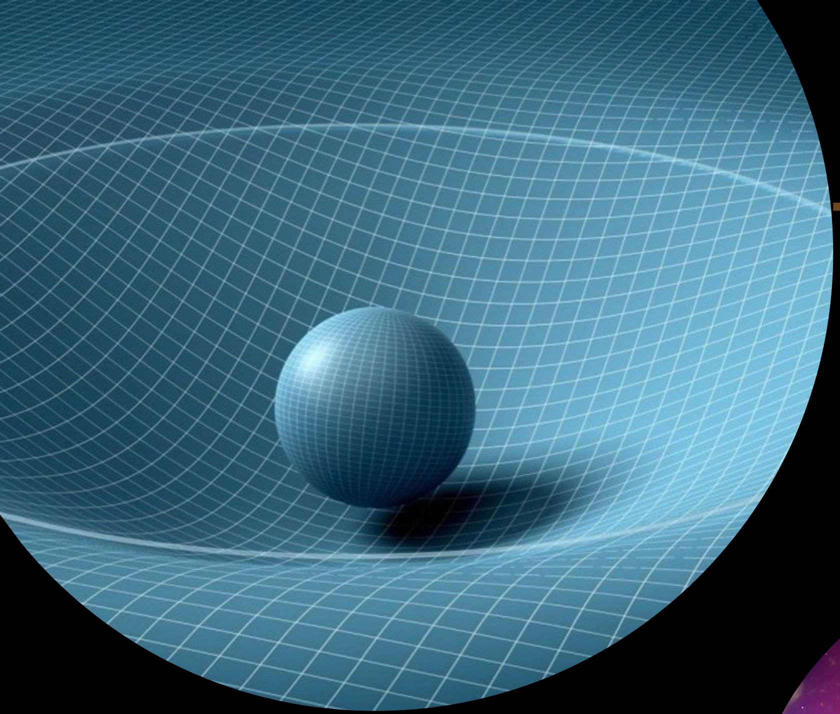
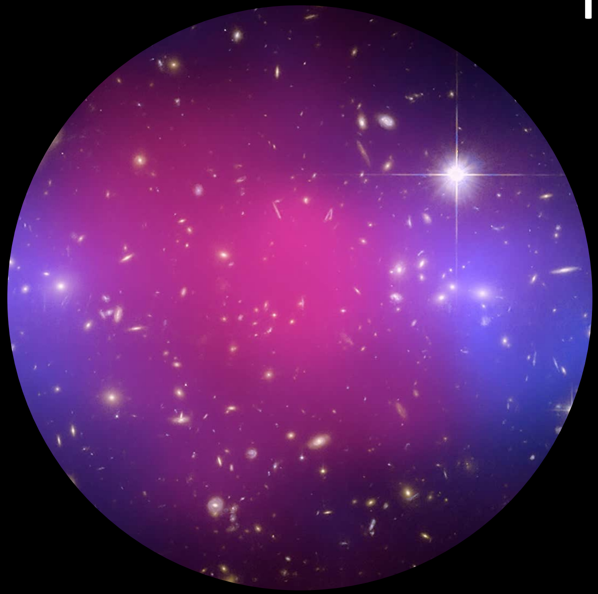
July 2024



Beyond the Standard Model

The Standard Model (SM) is capable of successfully describing nature to good precision.



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- **Baryon Asymmetry in the Universe (BAU);**
- **Nature of Dark Matter;**
- **Existence of Dark Energy;**
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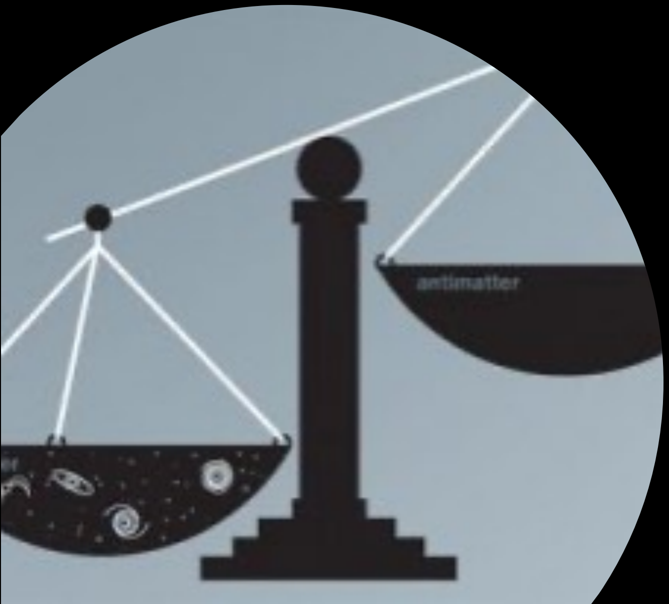
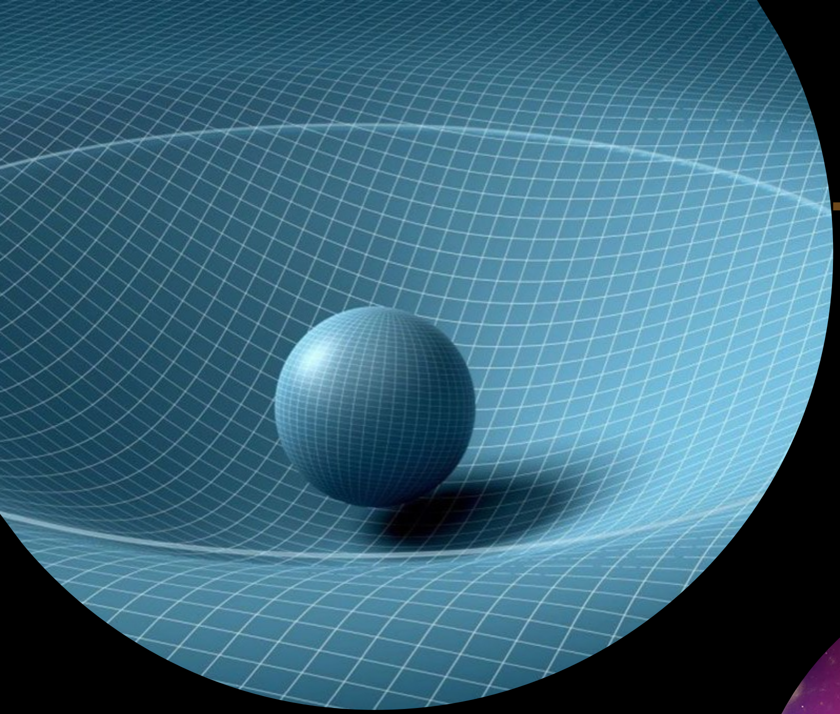
- **Fine Tuning Requirements (e.g. Higgs mass);**
- **Gravity at the Quantum Scale.**





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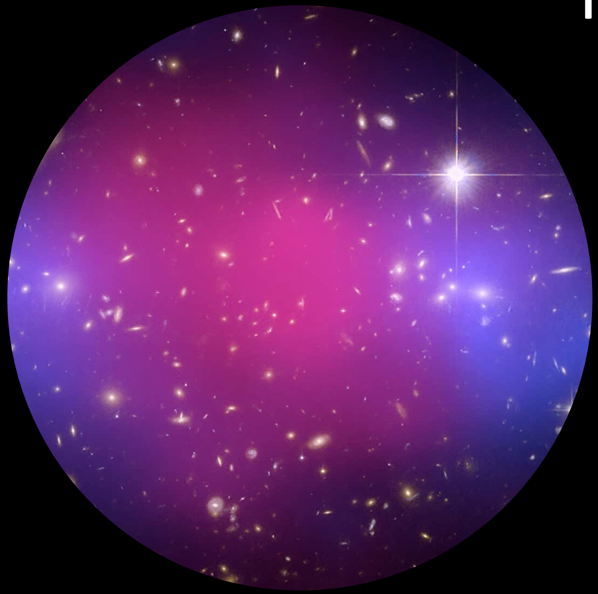

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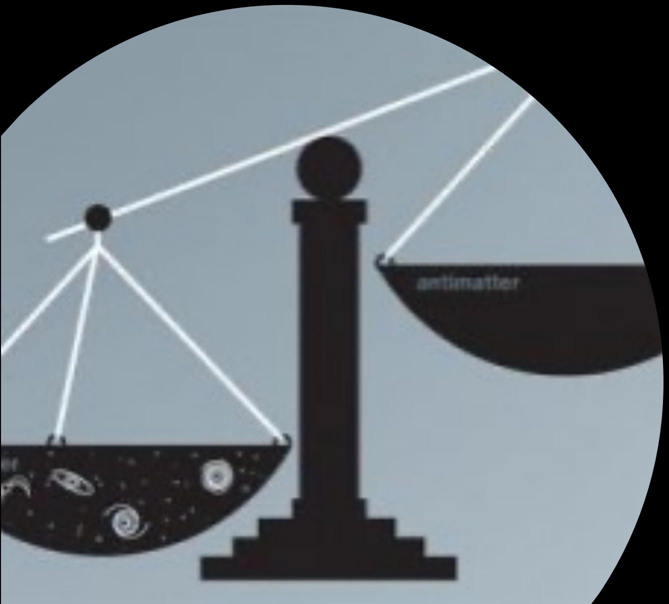

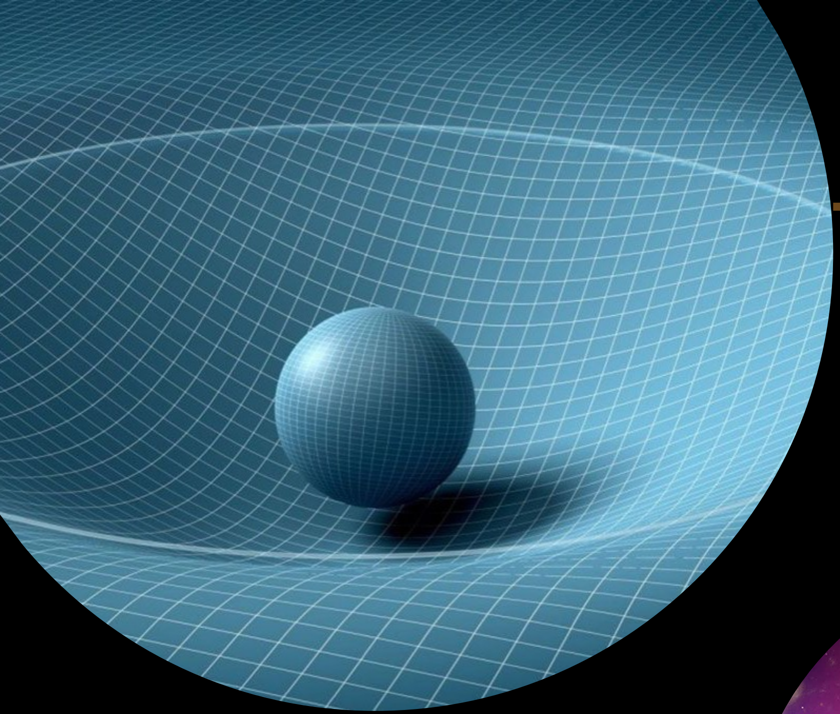

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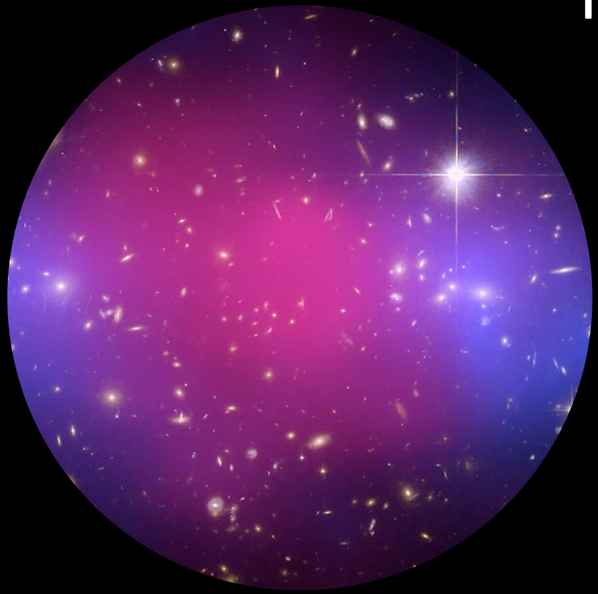

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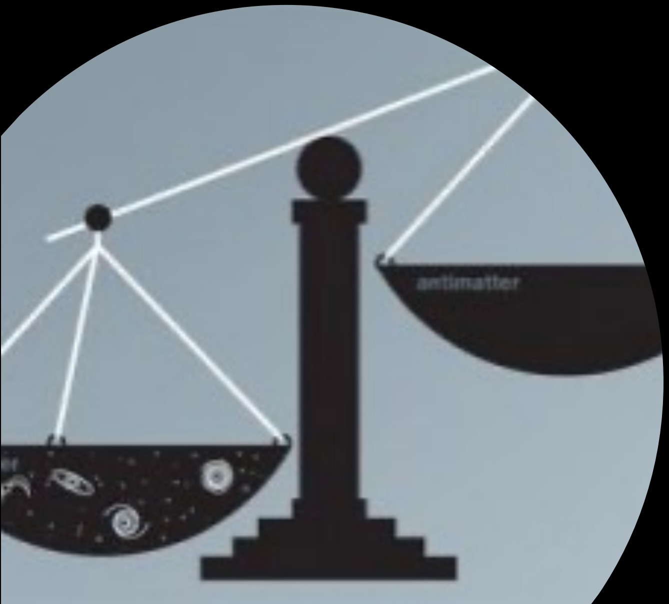
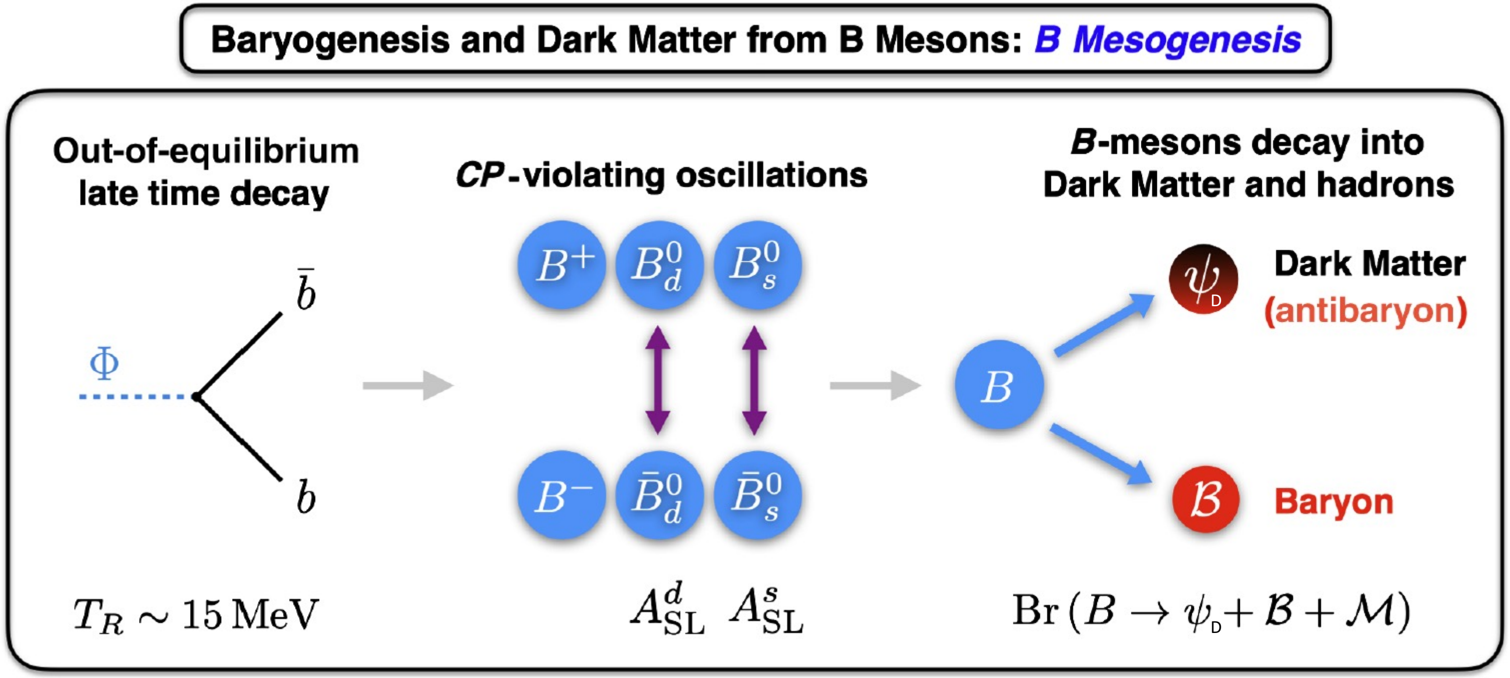


B-Mesogenesis and Dark Matter

B-Mesogenesis can simultaneously explain Baryon Asymmetry in the Universe (BAU) and Dark Matter (DM):

- B-mesons decay to: SM baryon ($\mathcal{B}$), dark-sector baryon (ψ_D) and any number of SM mesons ($\mathcal{M}$);
- CP violation from $B^0 - \bar{B}^0$oscillations generates a matter-antimatter asymmetry;
- B^0 decays slightly dominate over $\bar{B}^0$ decays into anti-baryons;
- Net excess of baryon in the visible sector, and an anti-baryon excess in the dark sector;
- ***Baryon number in the whole universe is conserved, but a net excess is present in the visible sector.***



G. Elor, M. Escudero and A. E. Nelson,
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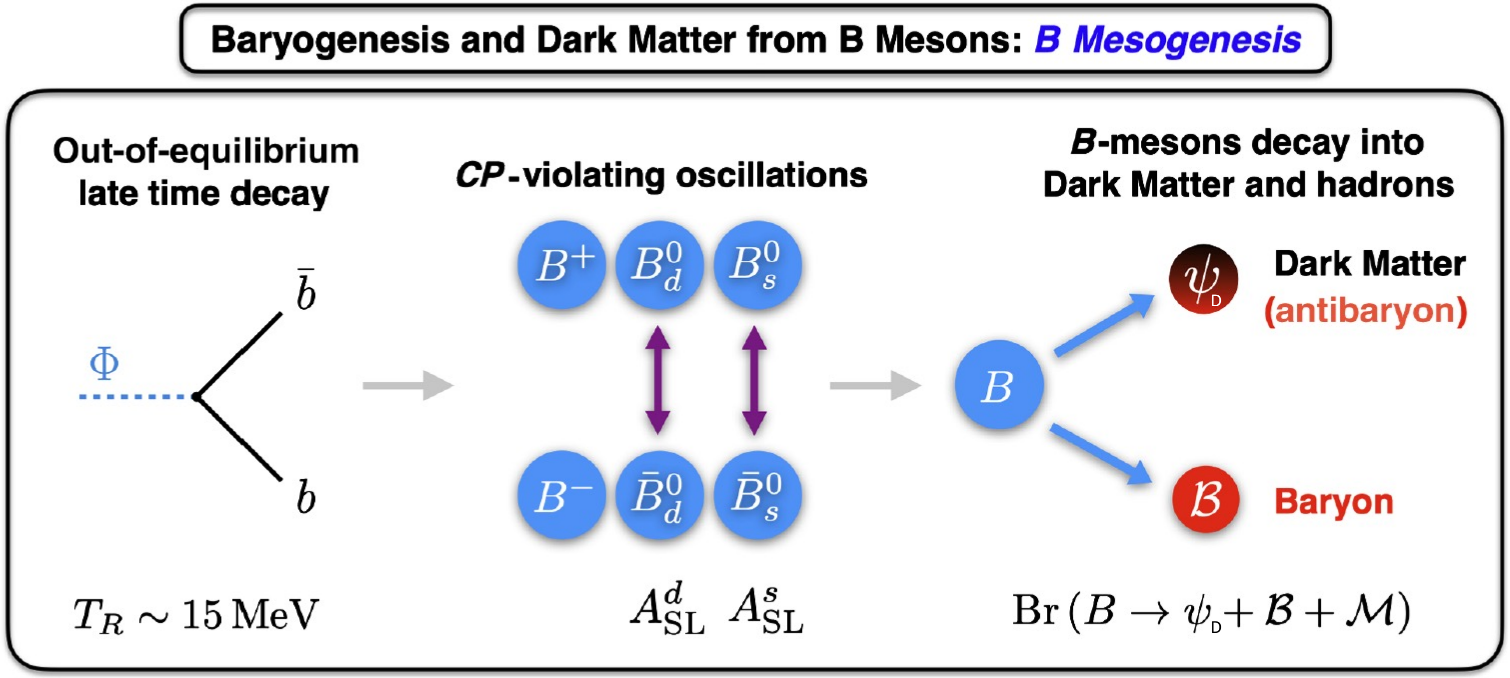
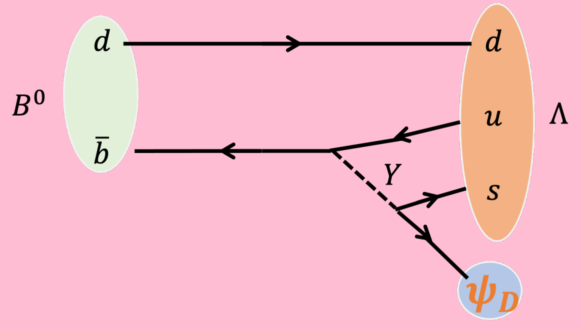


An example:



ψ_D = dark antibaryon;
Y = TeV scale mediator.

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B-Mesogenesis and Dark Matter

- ψ_D decay into stable dark sector particles producing the relic abundance we see today;
- 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 $\mathrm{O}_{i,j} = (\psi_D\ b)\ (q_i q_j)\ (i = u, c\ and\ \ j = d, s)$;
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Initial State	Final State	Operators	ΔM (MeV/c^2)
B^0	$\psi_D + \Lambda$	O_{us}	4163.95
B^0	$\psi_D + \Xi_c^0$	O_{cd}	2807.76
B^0	$\psi_D + \Lambda_c^+ + \pi^-$	O_{cd}	2853.60
B^+	$\psi_D + p$	O_{ud}	4341.05
B^+	$\psi_D + \Sigma^+$	O_{us}	4089.95
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BaBar Results

***Phys.Rev.D* 107 (2023) 9, 092001**

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***Phys.Rev.D* 107 (2023) 9, 092001**

***Phys.Rev.Lett.* 131 (2023) 20, 201801**

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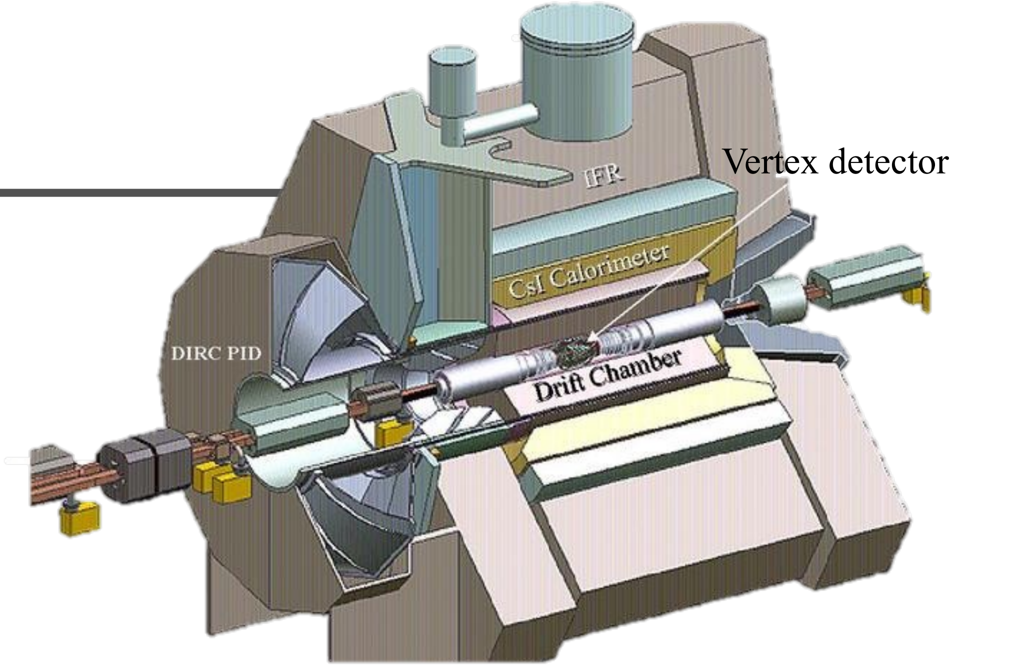
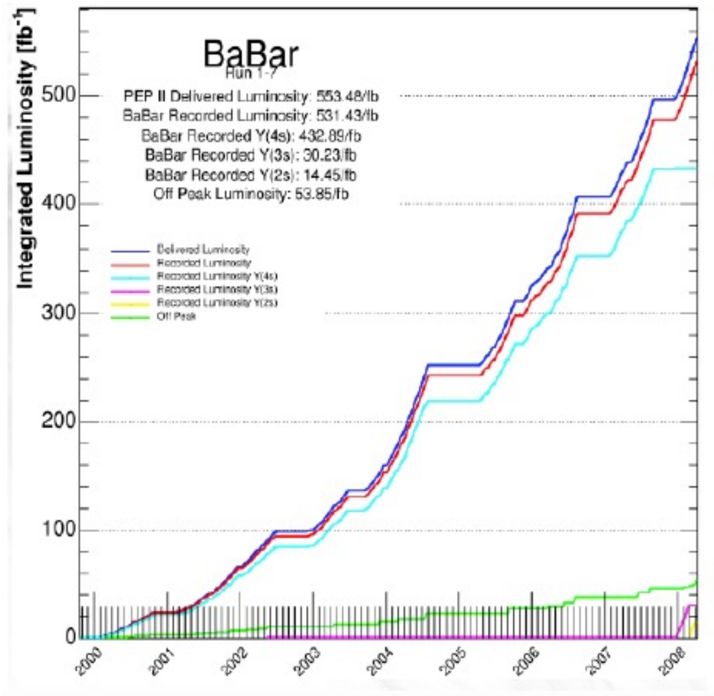
The *BABAR* Experiment



- For overview of experiment: **Nucl. Instrum. Meth. A 729, 615 (2013)**.
- Asymmetric e^+e^- collider with $\sqrt{s}$ = 10.58 GeV/c^2 i.e. Υ(4S) resonance: 9 GeV electrons collide with 3 GeV positrons.
- **Total luminosity: 431 fb^{-1} (4.7 x 10^8 $\overline{B}B$) on peak.**



Detectors:

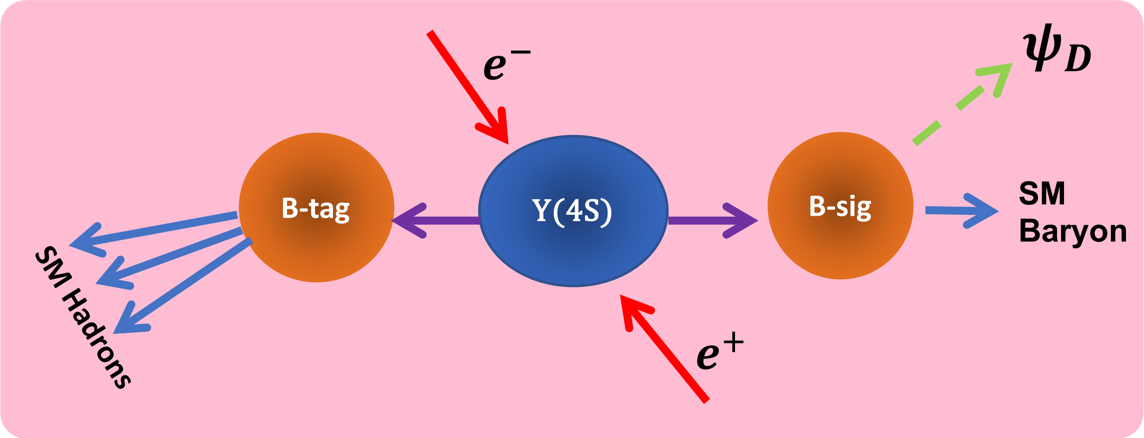
- **Reconstruct tracks:** Silicon Vertex Tracker (SVT) + 40-layer Drift Chamber (DCH), in 1.5-T solenoid.
  - Momentum resolution = 0.47% at 1 GeV/c
- **Measure energy:** Electromagnetic Calorimeter (EMC)
  - Energy resolution = 3% at 1 GeV.
- **PID:**
  - Identify charged pions, kaons and electrons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

Method: Event Reconstruction & Pre-selection

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.

398 fb^{-1} used in final analysis



- **B-tag** candidate must have:

$-0.2\text{GeV} < \Delta E < 0.2\text{GeV},$ centre-of-mass energy within range of the CM beam energy: $\Delta E = E_{beam} - E_{B_{tag}}$

$5.2\text{GeV}/c^2 < m_{ES} < 5.3\text{GeV}/c^2,$ centre-of-mass energy within range of the CM beam energy: $m_{ES} = \sqrt{E^2_{beam} - p^2_{B_{tag}}}$

Method: Signal & Background

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:

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

Signal:
- Used EvtGen to simulate events for 8 signal masses for each channel;

Analysis Method:
- Samples passed through full reconstruction and determine efficiency and resolution was determined and fit;
- Functional forms of fit used to extract resolution and efficiency for any given ψ_D mass – scan across entire mass range.

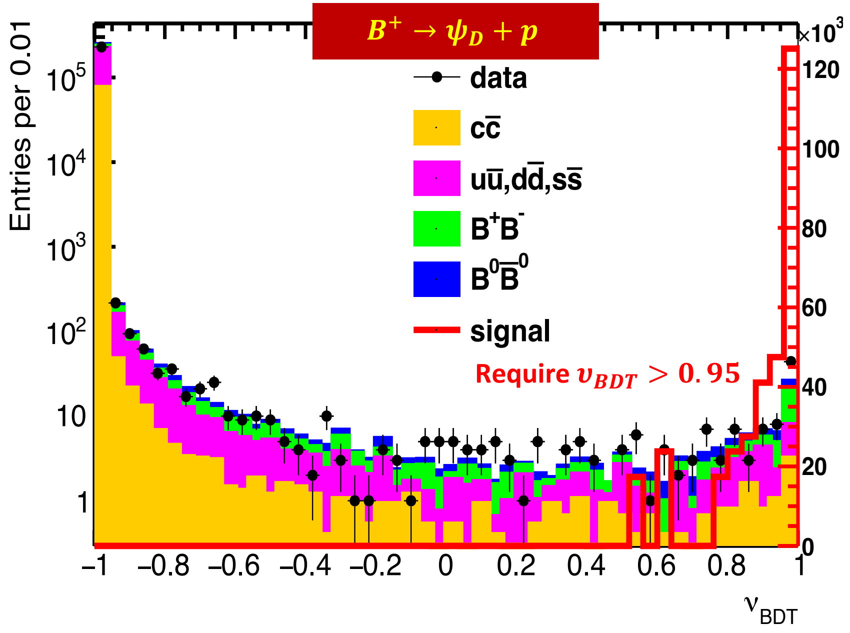
Method: Further Selections

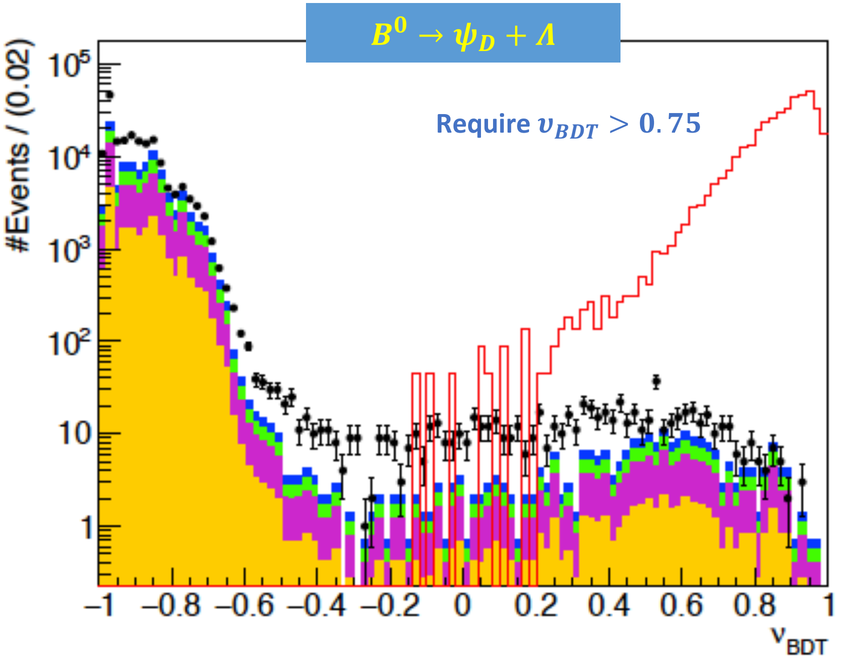
Further signal selections are channel dependent:

- **For the p channel:**
  - *BABAR* proton PID can be used to identify proton candidate;
  - signal side must have + charge and only one charged particle.

- **For the Λ channel:**
  - one Λ candidate in the B-sig;
  - $\Lambda \rightarrow p\pi$ selected, so two charged tracks required on the signal side;
  - significance of the Λ decay length (α_Λ) > 1.0;
  - four-momentum kinematic fit χ^2 of Λ reconstruction $\leq$100.

- **For both cases further signal and background separation found using a Boosted Decision Tree custom to each channel.**
  - p cut at υ_{BDT}> 0.95 results in signal purity > 99 %;
  - Λ cut at υ_{BDT}> 0.75 results in signal purity > 99 %.





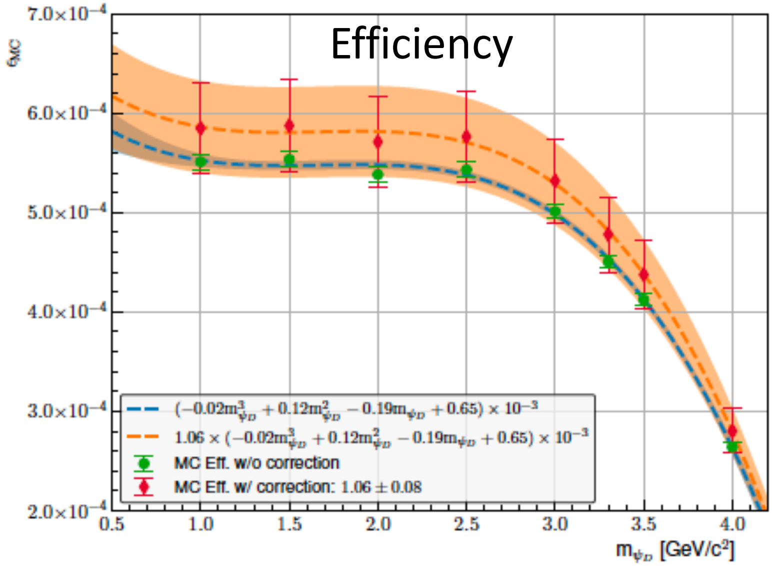
Caltech

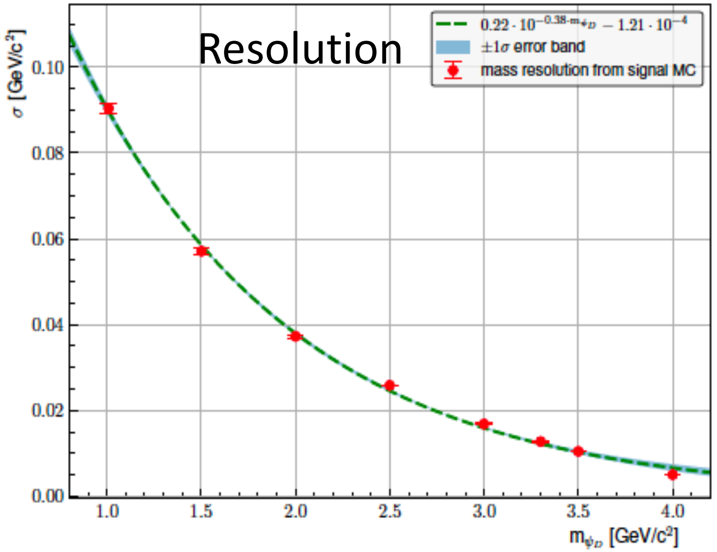
Method: Final Analysis

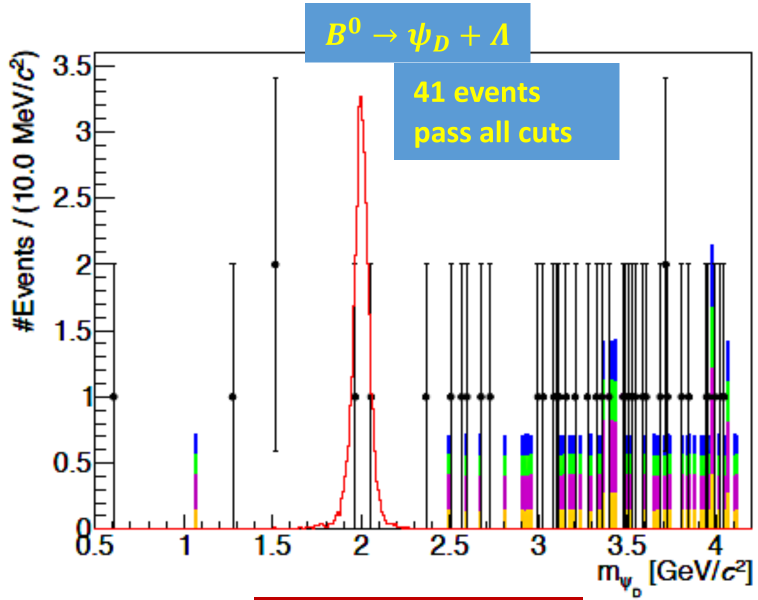
Final analysis proceeds by:

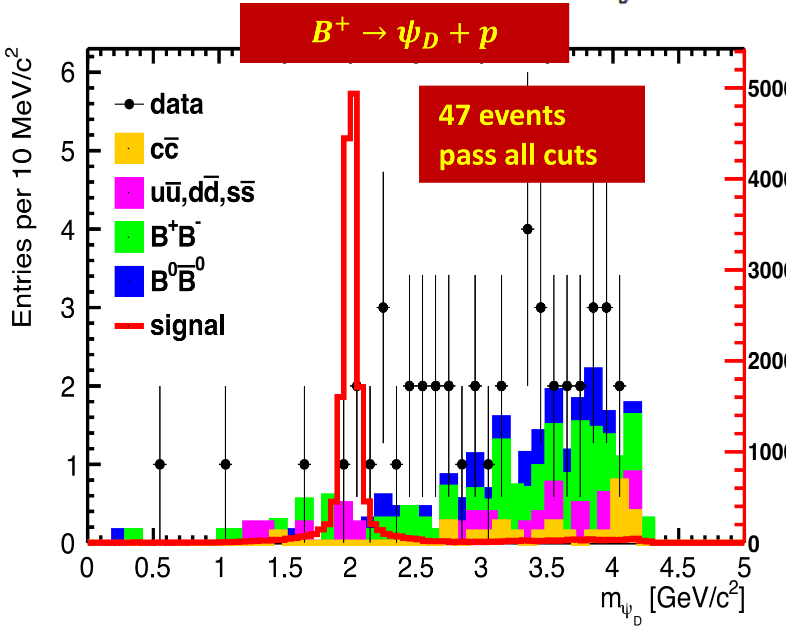
- reconstructing ψ_D from missing energy 4-vector on signal side;
- scanning across mass range, with step size equivalent to σ at that mass;
- extracting resolution (σ) and efficiency (ε_{MC}) from fits to MC;
- estimating signal and backgrounds in data using definitions from MC study.

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









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

Results

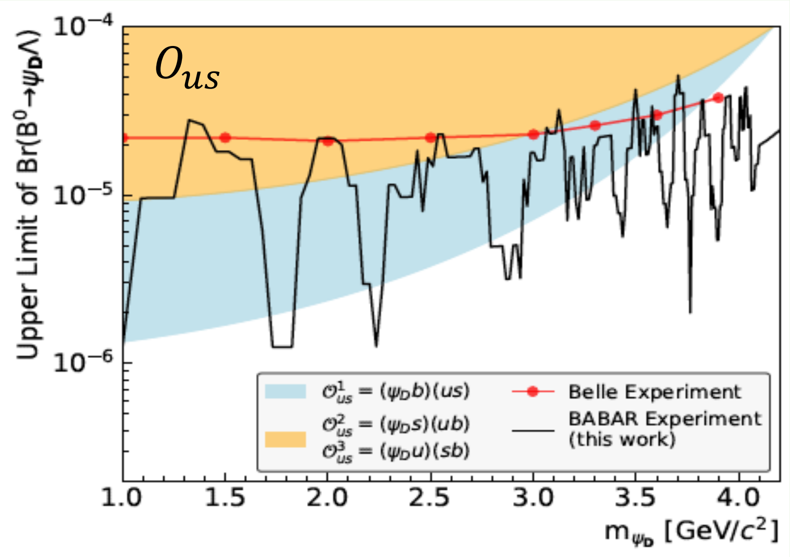
Applied result to a few specific models:

- World-leading result for $B^0 \to \psi_D + \Lambda$, improving on previous result and further constraining model;
- First direct search for $B^+ \to \psi_D + p$ places tight constraints on specified model.

Parameter space vastly reduced, almost excluded for some operators.

Must explore additional operators to fully explore this model.

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



Phys.Rev.D 107 (2023) 9, 092001

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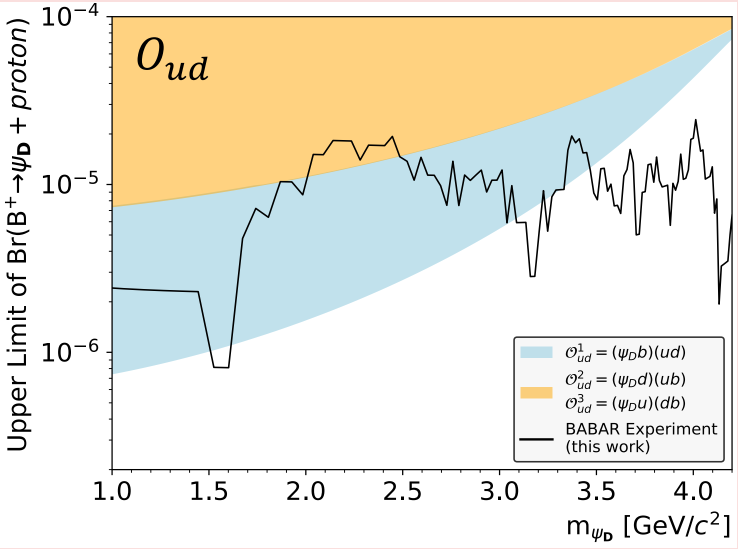


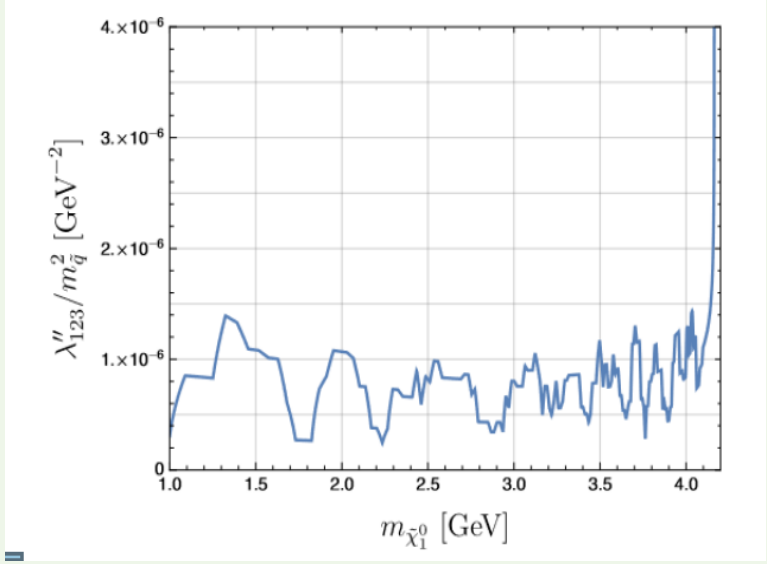
Phys.Rev.Lett. 131 (2023) 20, 201801

Results

Given that all we are looking for is missing mass in the final state, we could apply our search to any such model:

- Extended search to provide first limit on RPV SUSY model described in **JHEP 2023 (02 224 (2023)).**
- First limits on this SUSY model for both channels.

$B^0 \rightarrow \widetilde{\chi}_0 + \Lambda$



JHEP 02 (2023) 224 (Dib et al)

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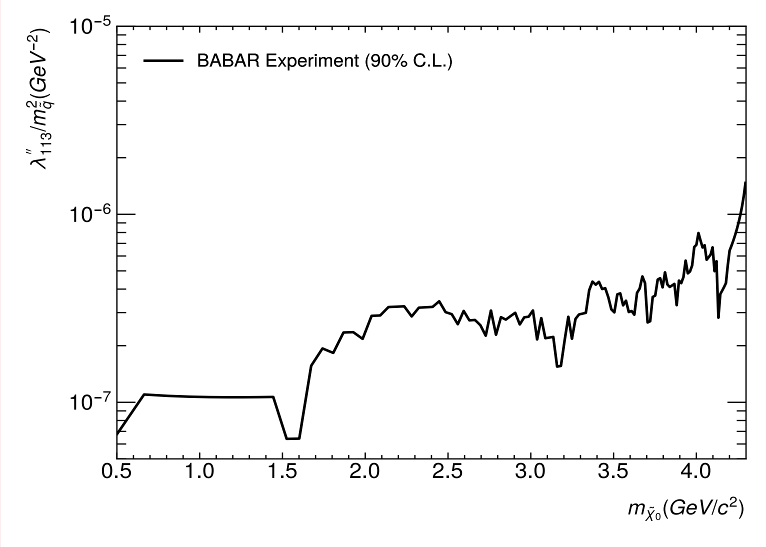

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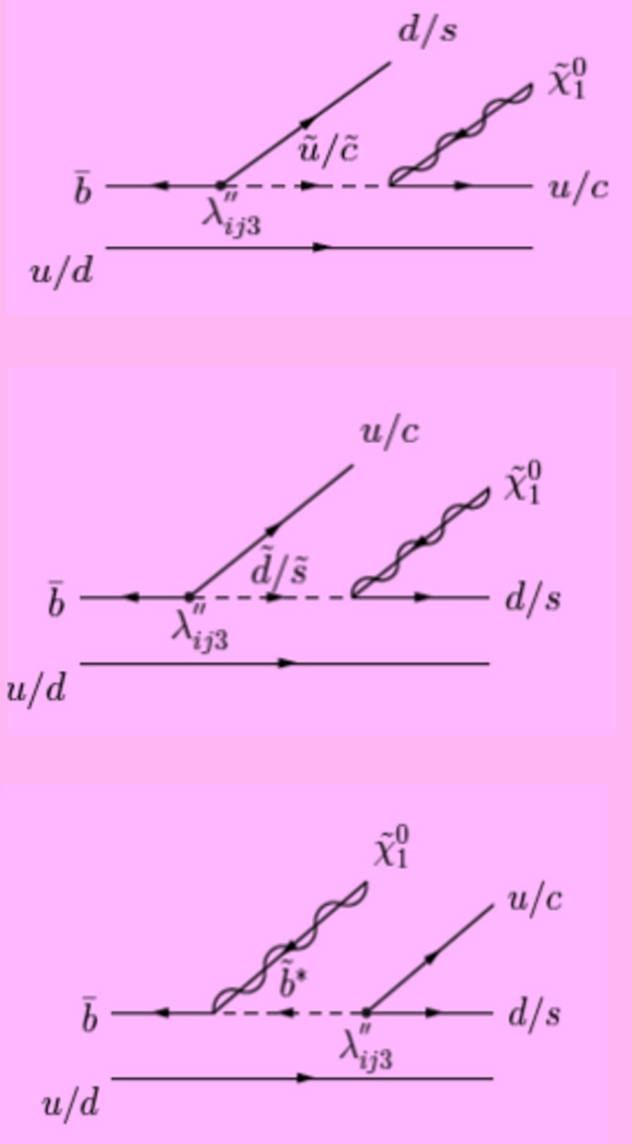


Summary

Results presented in search for model explaining DM + BAU:

- *BaBar* has 398 fb^{-1} of $B\bar{B}$ data – making it an excellent way to explore this model;
- Scanning method allowed improved limits on $B^0 \to \psi_D + \Lambda$ channel;
- First direct limits for $B^+ \to \psi_D + p$ channel;
- *BaBar* soon to publish third analysis: $B^+ \to \psi_D + \Lambda_c^+$;
- 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 e.g. those invoking charged B-Mesogenesis (*Phys Rev. D* 105, 055024 (2022)).

Thank You for Listening,

Any Questions?

Back-up

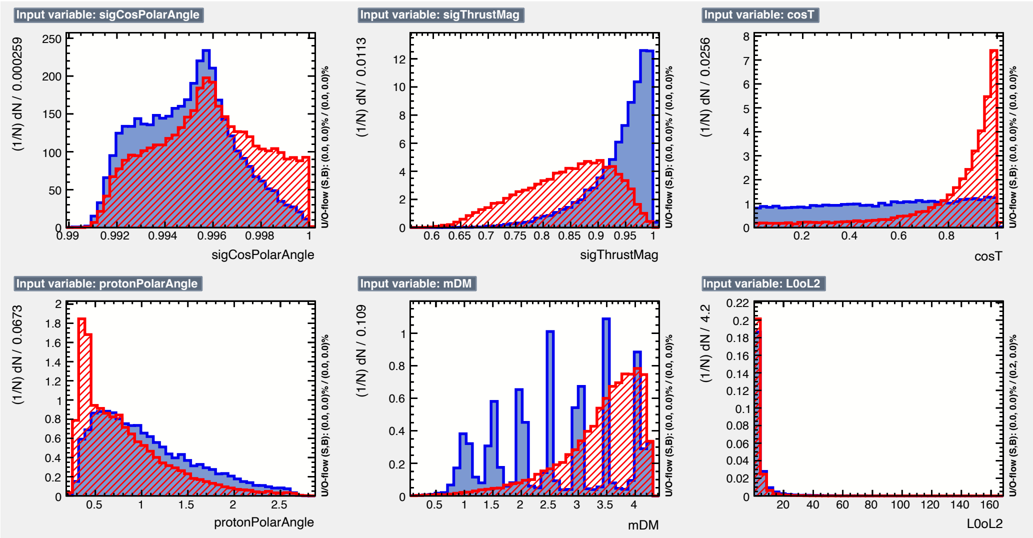
Extra things which didn't fit

MVA: Proton

The set of quantities input into out MVA:

- 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 pi0 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

MVA: Proton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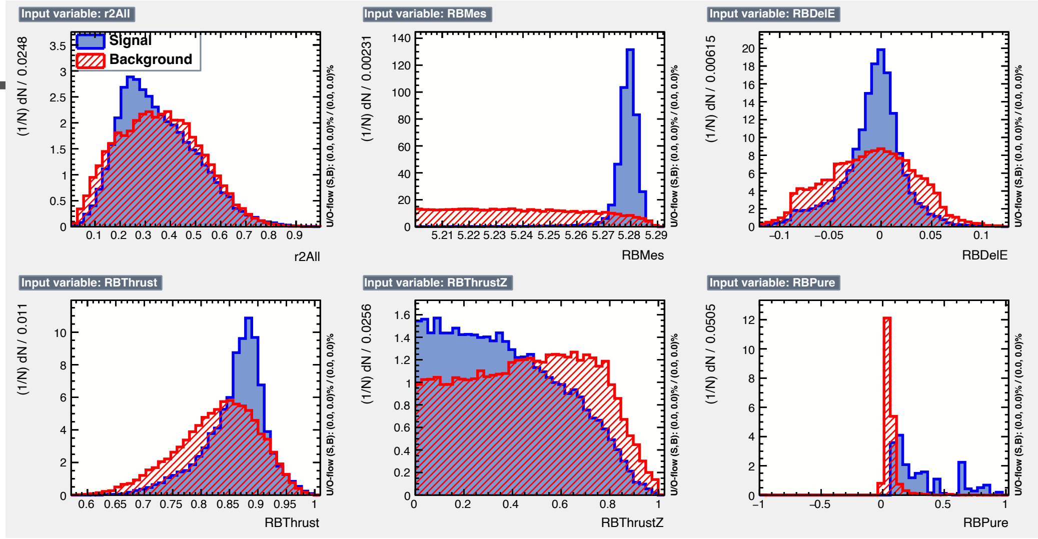
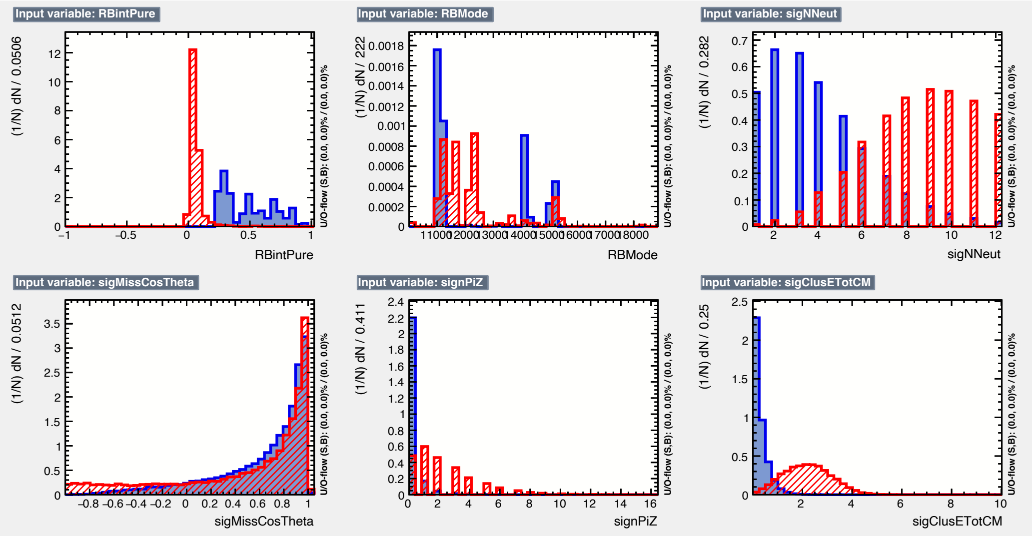
sigCosPolarAngle
Input variable: sigThrustMag
sigThrustMag
Input variable: cosT
cosT
Input variable: protonPolarAngle
protonPolarAngle
Input variable: mDM
mDM
Input variable: L0oL2
L0oL2


Input variable: r2All
Signal
Background
r2All
Input variable: RBMes
RBMes
Input variable: RBDelE
RBDelE
Input variable: RBThrust
RBThrust
Input variable: RBThrustZ
RBThrustZ
Input variable: RBPure
RBPure


Input variable: RBIntPure
RBIntPure
Input variable: RBMode
RBMode
Input variable: sigNNeut
sigNNeut
Input variable: sigMissCosTheta
sigMissCosTheta
Input variable: signPiZ
signPiZ
Input variable: sigClusETotCM
sigClusETotCM

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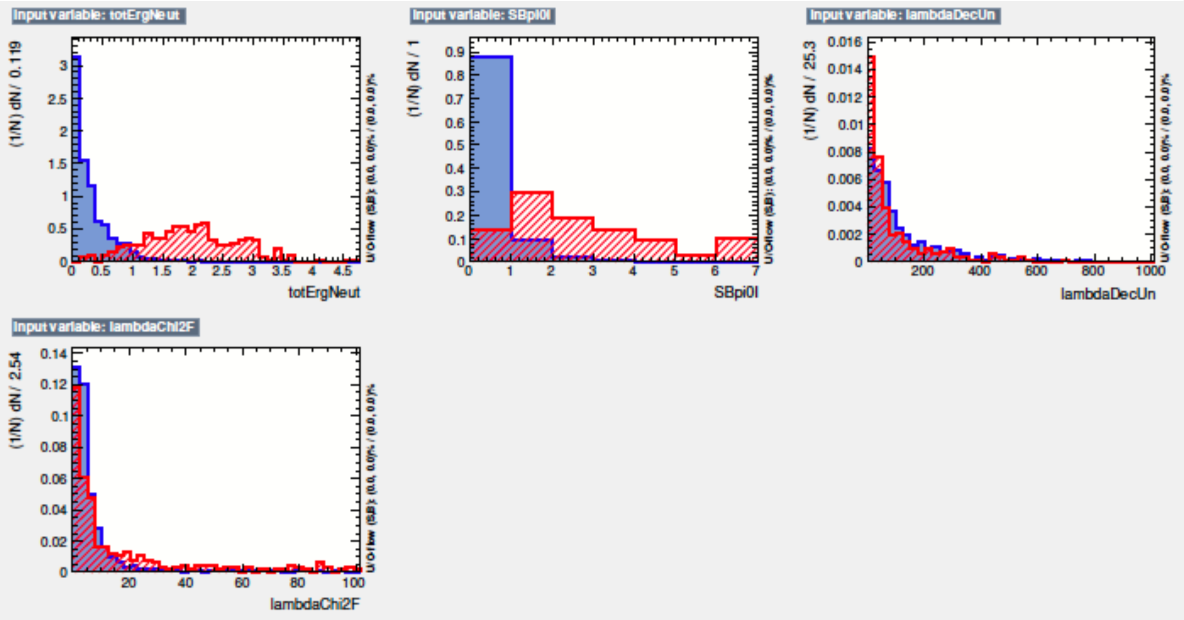
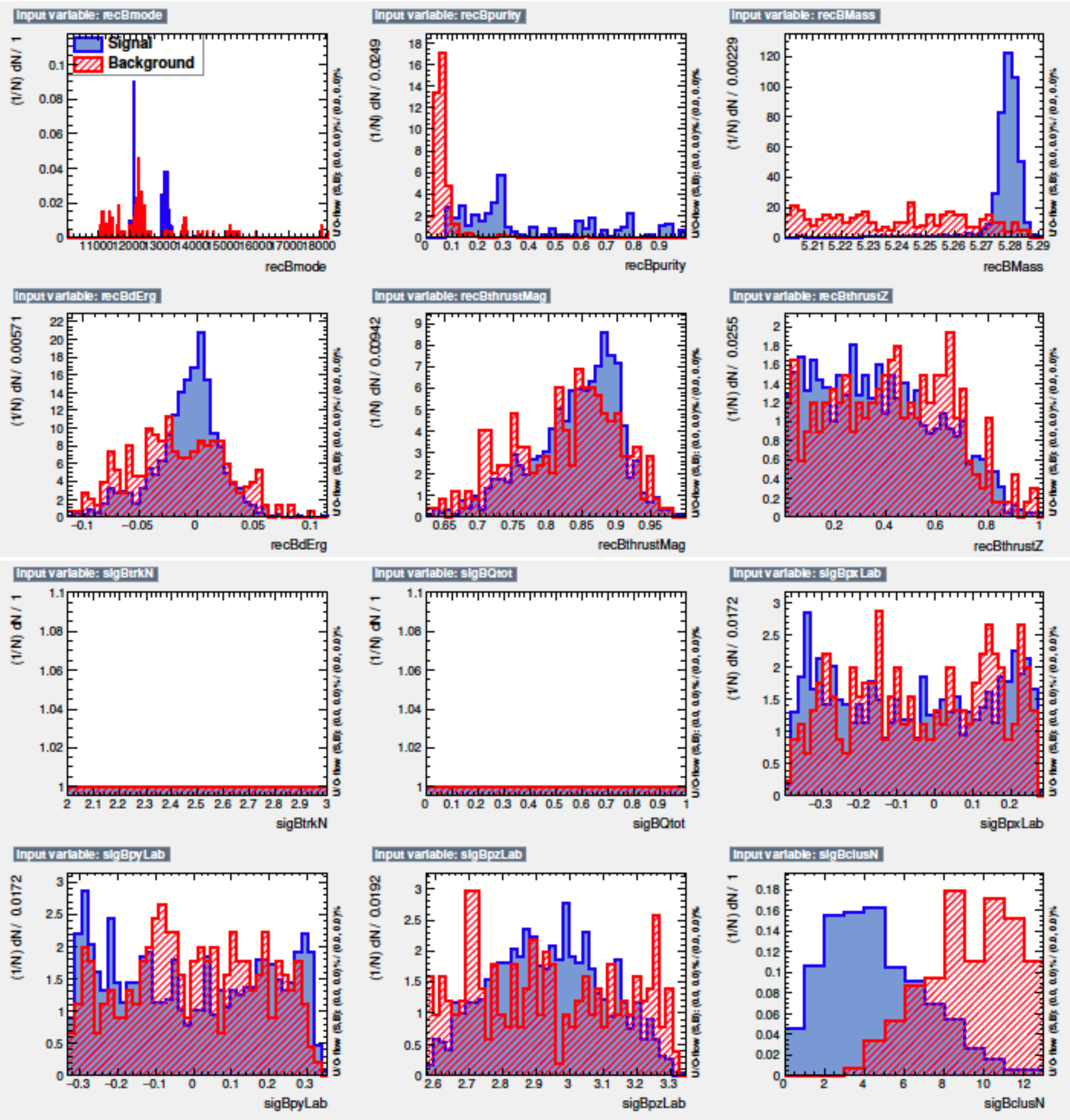
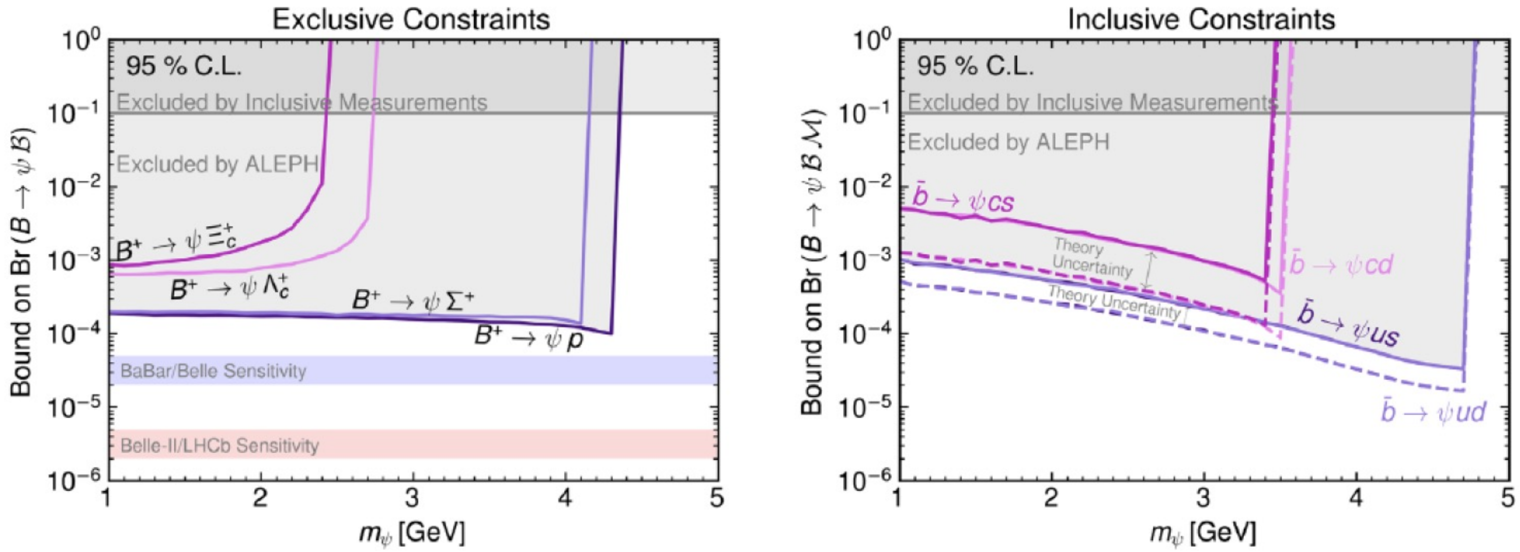
- number and net charge of the charged
- tracks in the signal B-sig meson side
- three momenta of the signal B-sig candidate
- number of neutral particles in the signal side
- the number of pi0 candidates on the signal side
- the total extra neutral energy on the signal side in the center-of-mass frame
- the polar angle of the missing momentum vector recoiling against the B-tag meson and the signal candidate
- The significance of the Lambda decay length
- The chi-2 of the Lambda fit

MVA: Lambda


Input variable: totErgNeut
(1/N) dN / 0.119
totErgNeut
Input variable: SBpi0l
(1/N) dN / 1
SBpi0l
Input variable: lambdaDecUn
(1/N) dN / 25.3
lambdaDecUn
Input variable: lambdaChi2F
(1/N) dN / 2.54
lambdaChi2F


Input variable: recBmode
Signal
Background
(1/N) dN / 1
recBmode
Input variable: recBpurity
(1/N) dN / 0.0249
recBpurity
Input variable: recBMass
(1/N) dN / 0.00229
recBMass
Input variable: recBdErg
(1/N) dN / 0.00571
recBdErg
Input variable: recBthrustMag
(1/N) dN / 0.00942
recBthrustMag
Input variable: recBthrustZ
(1/N) dN / 0.0255
recBthrustZ
Input variable: sigBtrkN
(1/N) dN / 1
sigBtrkN
Input variable: sigBQtot
(1/N) dN / 1
sigBQtot
Input variable: sigBpxLab
(1/N) dN / 0.0172
sigBpxLab
Input variable: sigBpyLab
(1/N) dN / 0.0172
sigBpyLab
Input variable: sigBpzLab
(1/N) dN / 0.0192
sigBpzLab
Input variable: sigBclusN
(1/N) dN / 1
sigBclusN

ALEPH Indirect Constraints



Asymmetry

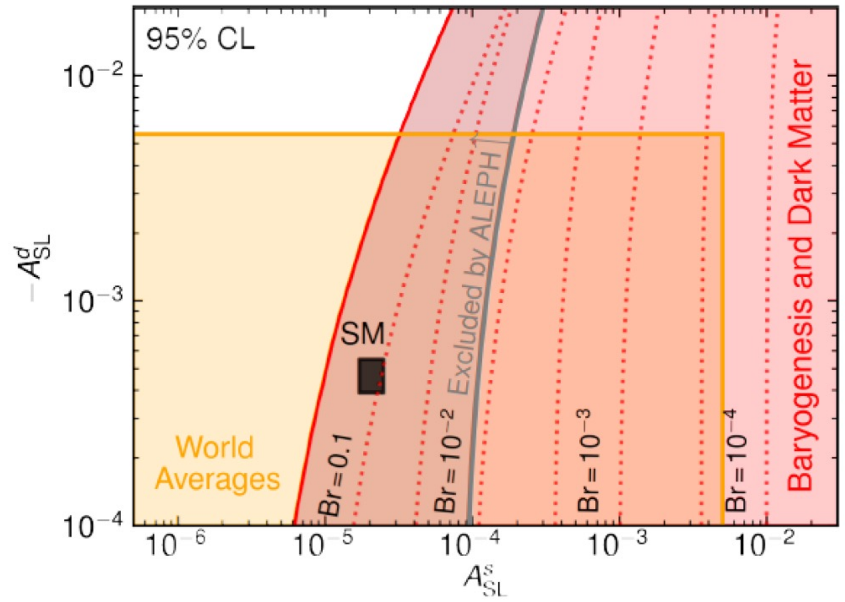


FIG. 3. Contour lines for the minimum $B \to \mathcal{B} + \psi_{DM} + \mathcal{M}$ branching ratio required for baryogenesis and dark matter generation as a function of the semi-leptonic asymmetries $\mathcal{A}_{SL}^{q}$ in B_q^0 decays. The red contours show the relevant parameter space in which baryogenesis can successfully occur. The black rectangle corresponds to the SM prediction for A_{SL}^{q}, and the current world average is shown as the orange contour. The grey line corresponds to the region $BR(B \to \mathcal{B} + \psi_{DM} + \mathcal{M}) > 0.5\%$, disfavored by a search for ALEPH [5]. This figure is taken from Ref. [1].

New Particles

Field	Spin	Q_{EM}	Baryon no.	$\mathbb{Z}_2$	Mass
Φ	0	0	0	+1	$11 - 100\,\text{GeV}$
Y	0	$-1/3$	$-2/3$	+1	$\mathcal{O}(\text{TeV})$
ψ	1/2	0	-1	+1	$\mathcal{O}(\text{GeV})$
ξ	1/2	0	0	-1	$\mathcal{O}(\text{GeV})$
ϕ	0	0	-1	-1	$\mathcal{O}(\text{GeV})$

TABLE I. Summary of the additional fields (both in the UV and effective theory), their charges and properties required in our model.