RECENT RESULTS OF DARK SECTOR SEARCHES WITH THE *BaBar* EXPERIMENT

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on behalf of the BaBar Collaboration

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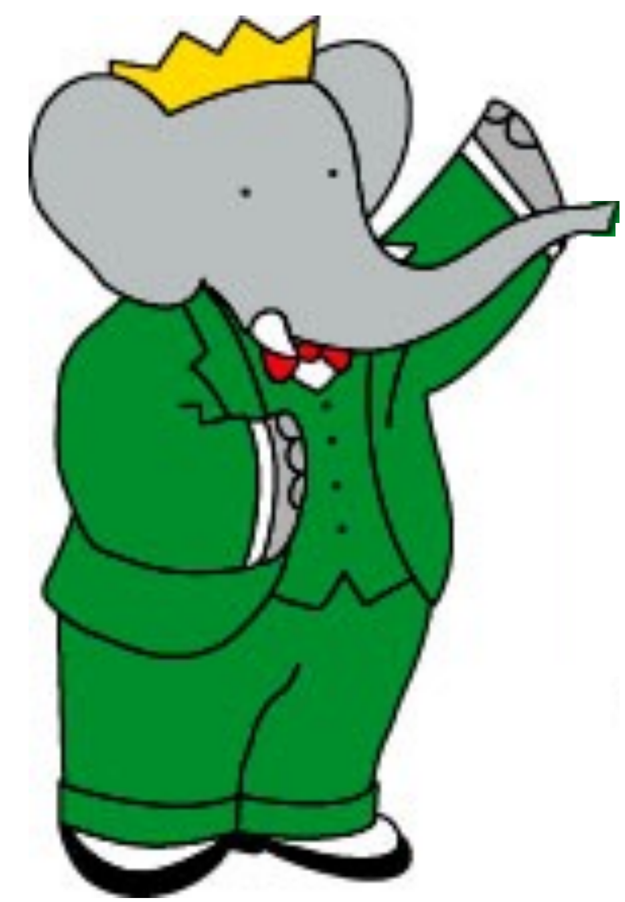
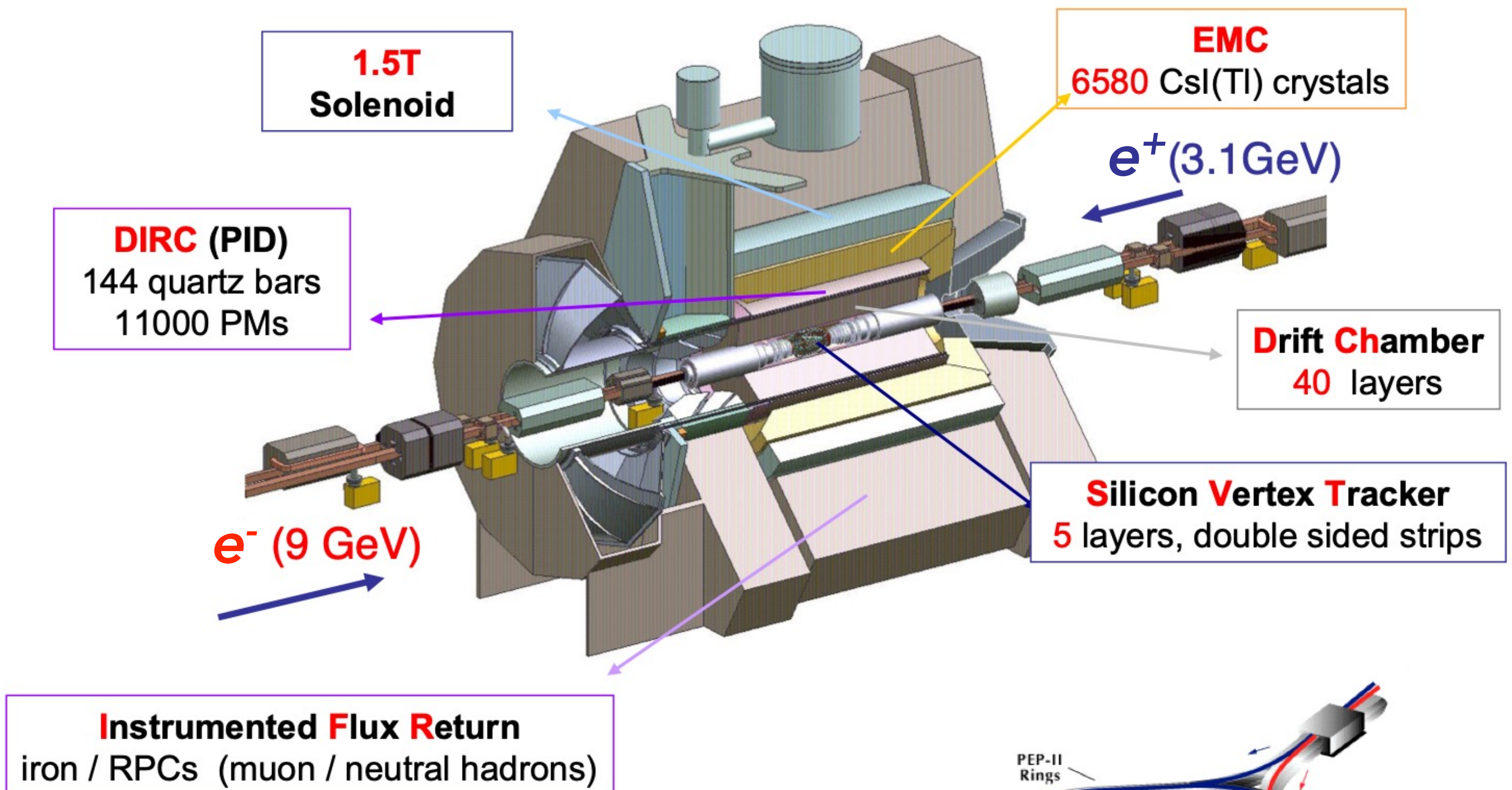


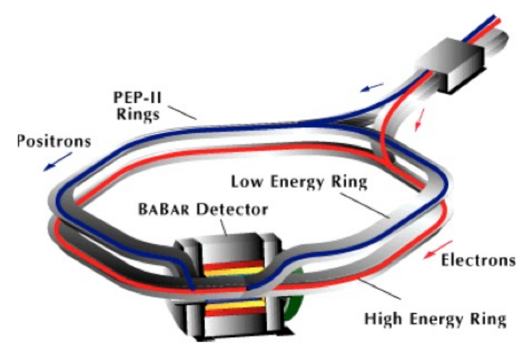
UCLA DM

March 30, 2023

BaBar EXPERIMENT



1999-2008



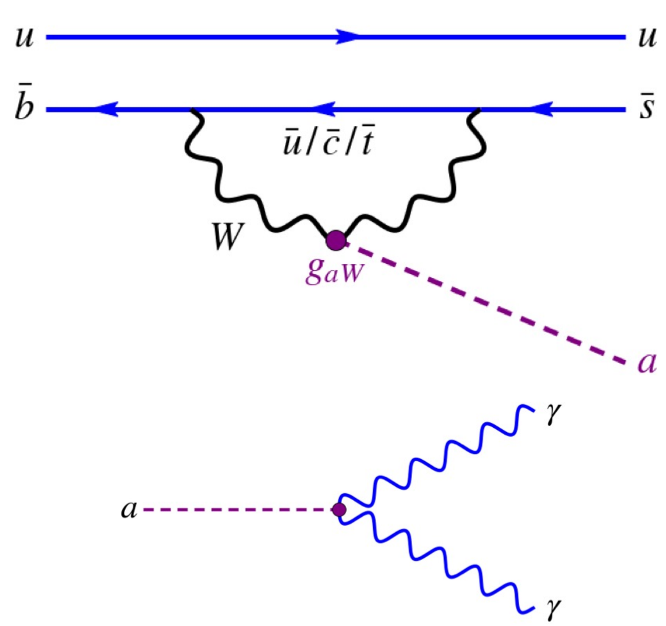
- 432/fb $\Upsilon(4S)$ on-peak ($\sqrt{s} = 10.56$ GeV)
- 472 million *B* meson pairs
- smaller samples at $\Upsilon(2S)/\Upsilon(3S)$ and off-peak

- Large luminosity, low backgrounds make *BaBar* an ideal experiment for discovering MeV-GeV scale hidden particles; collider searches can discover particles that may not show up in direct/indirect detection

RESULTS PRESENTED TODAY

Axionlike particles (ALPs)

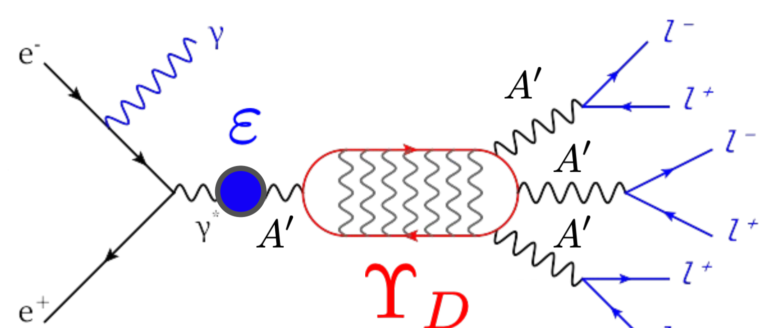
- *B* mesons decay to ALP via coupling to gauge bosons



BaBar, PRL 128, 131802 (2022), arXiv:2111.01800

Self-interacting DM

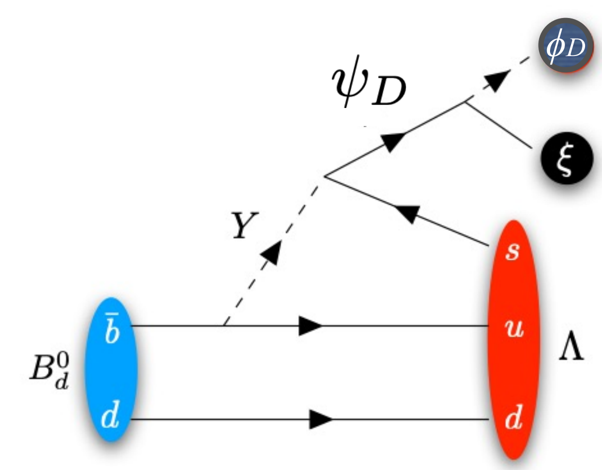
- dark photon + large coupling to DM
- search for DM bound states



BaBar, PRL 128, 021802 (2022), arXiv:2106.08529

B-Mesogenesis

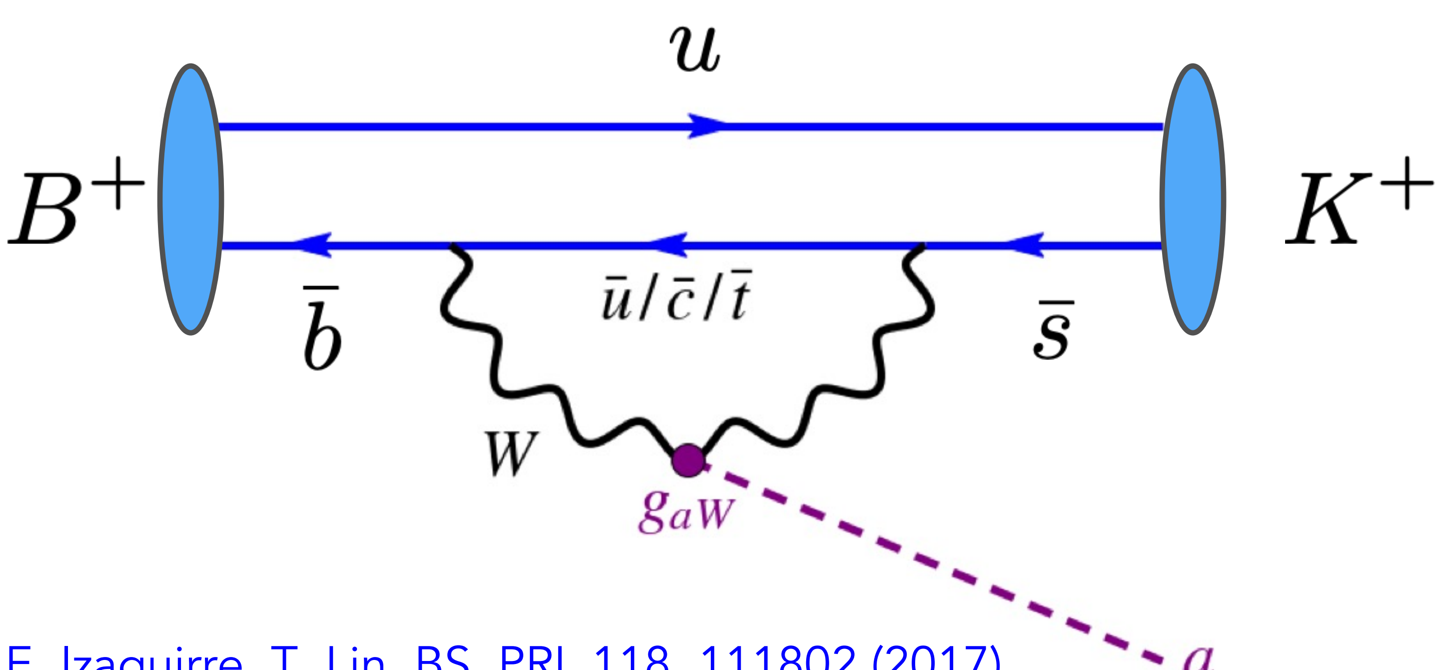
- model of QCD-scale baryogenesis
- *B* mesons decay to baryon + dark baryon



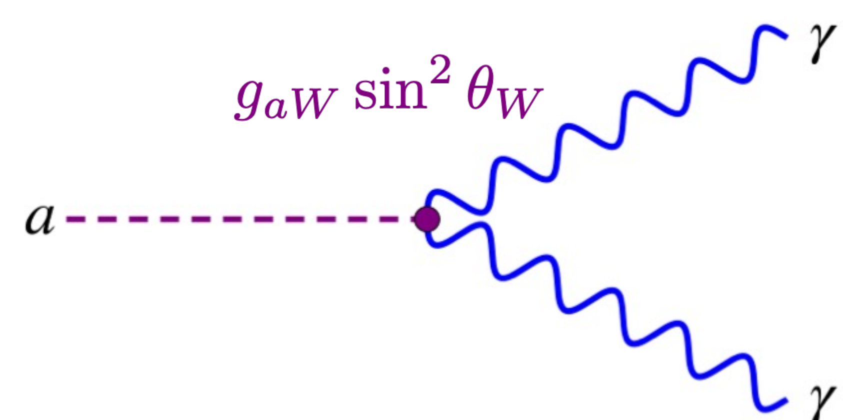
BaBar, arXiv:2302.00208 + new preliminary result

AXIONLIKE PARTICLES

- **Axionlike particles (ALPs):** pseudoscalars that couple to pairs of gauge bosons
- Ubiquitous in BSM theories, naturally light and with suppressed interaction strengths - ideal candidates for hidden sector mediators
- If ALP couples to SU(2) gauge bosons, then it can be produced in rare *B* meson decays: $B^{\pm} \to K^{\pm} a,\ a \to \gamma\gamma$



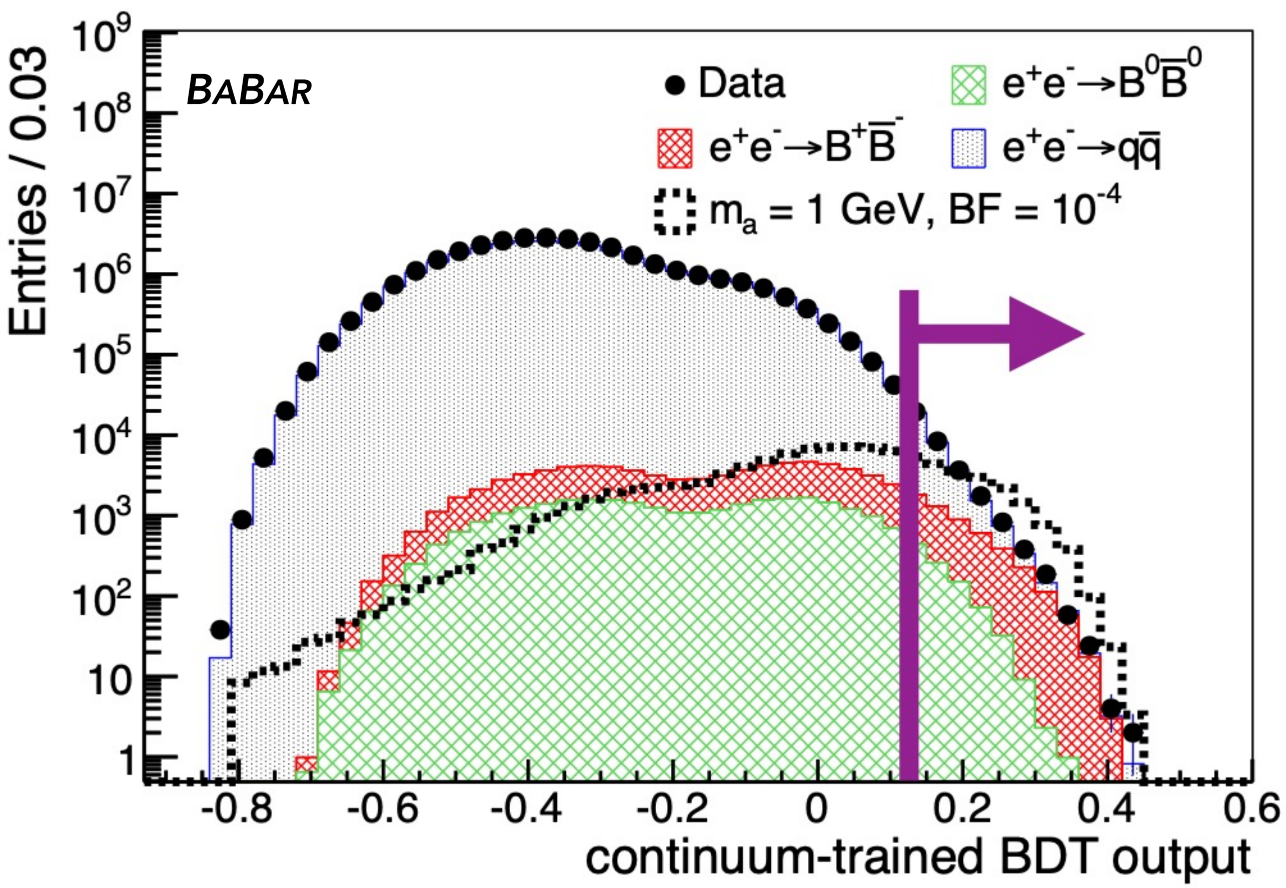
$$\mathcal{L} = -\frac{g_{aW}}{4} a\, W_{\mu\nu} \tilde{W}^{\mu\nu}$$

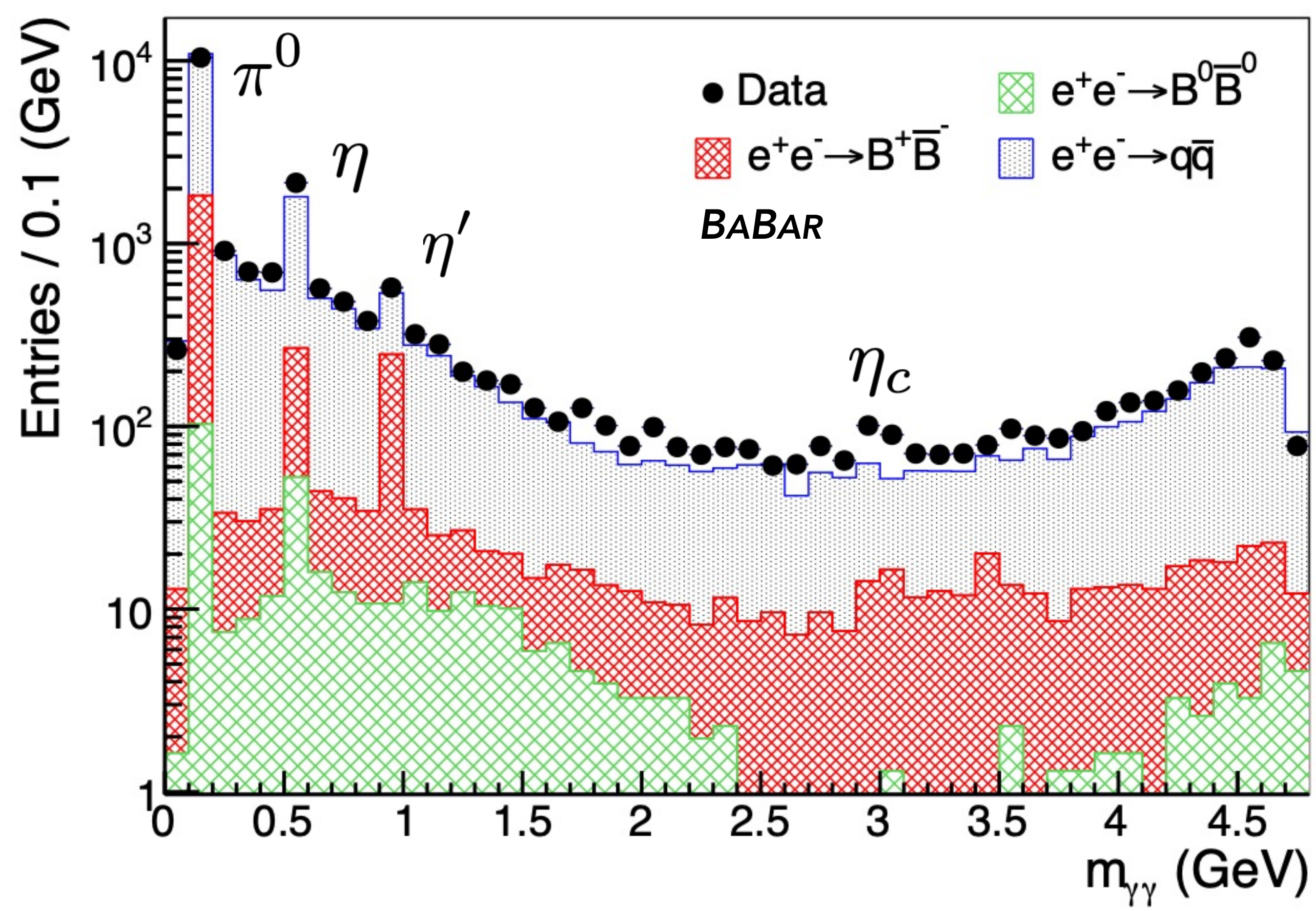


[E. Izaguirre, T. Lin, BS, PRL 118, 111802 (2017), arXiv:1611.09355]

AXIONLIKE PARTICLES

- Reconstruct $B^{\pm} \to K^{\pm} a,\ a \to \gamma\gamma$ candidates with a kinematic fit to improve resolution, look for narrow peak (~8-30 MeV) in diphoton mass; assume prompt decays
- Train BDTs to reject dominant backgrounds (light-quark + B-meson)



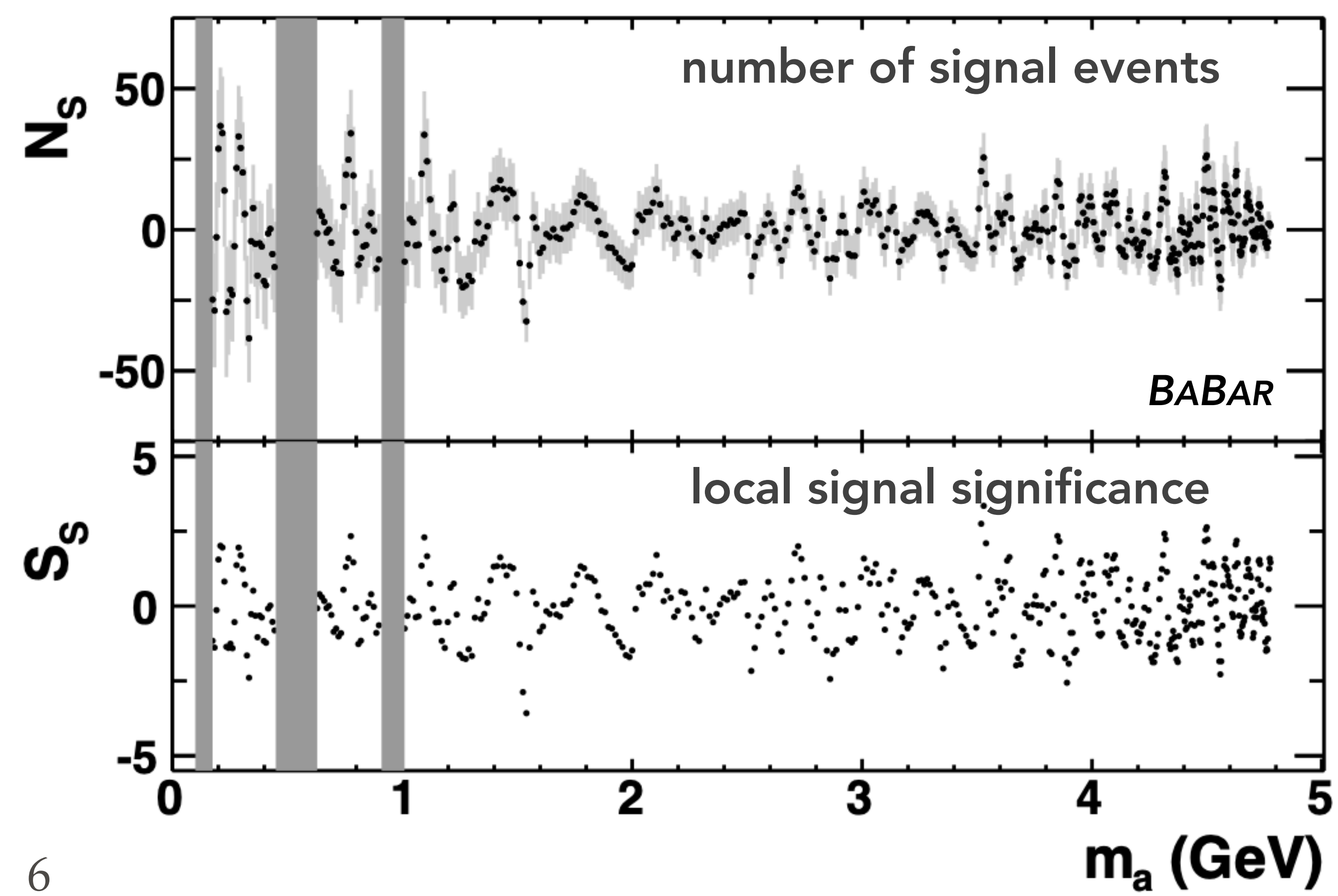


AXIONLIKE PARTICLES

- Fit data for 461 signal mass hypotheses with step size equal to signal resolution $\sigma_{\gamma\gamma}$. We do not consider signals near η, η'
- Fit intervals have sizes $(24-60)\sigma_{\gamma\gamma}$. We include peaking component where relevant, continuum modeled with a smooth function (either modeled from MC or a linear function, depending on ALP mass)

- We see no significant signal
- In setting limits on coupling, we find that we are probing ALPs with **finite lifetime**

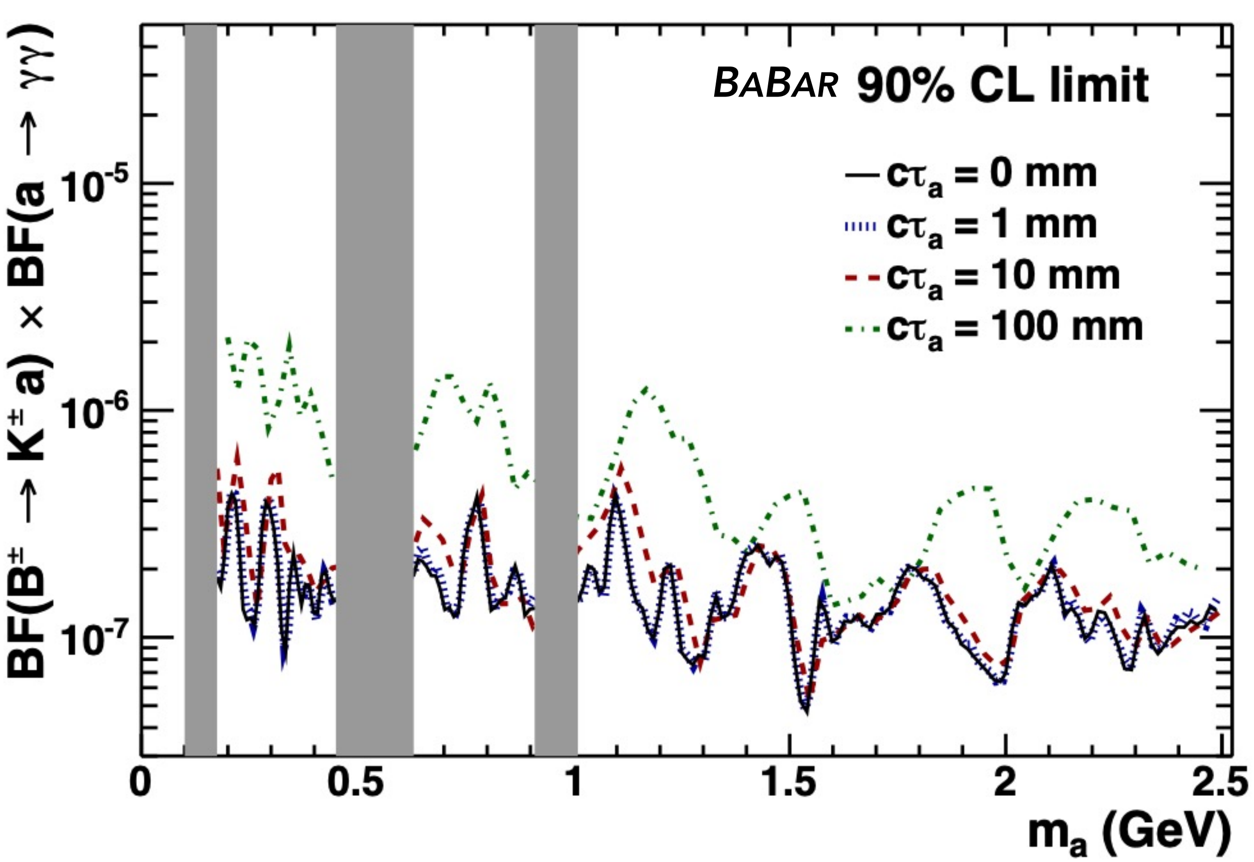
$$\Gamma_a = \frac{g_{aW}^2 \sin^4\theta_W \, m_a^3}{64\pi}$$

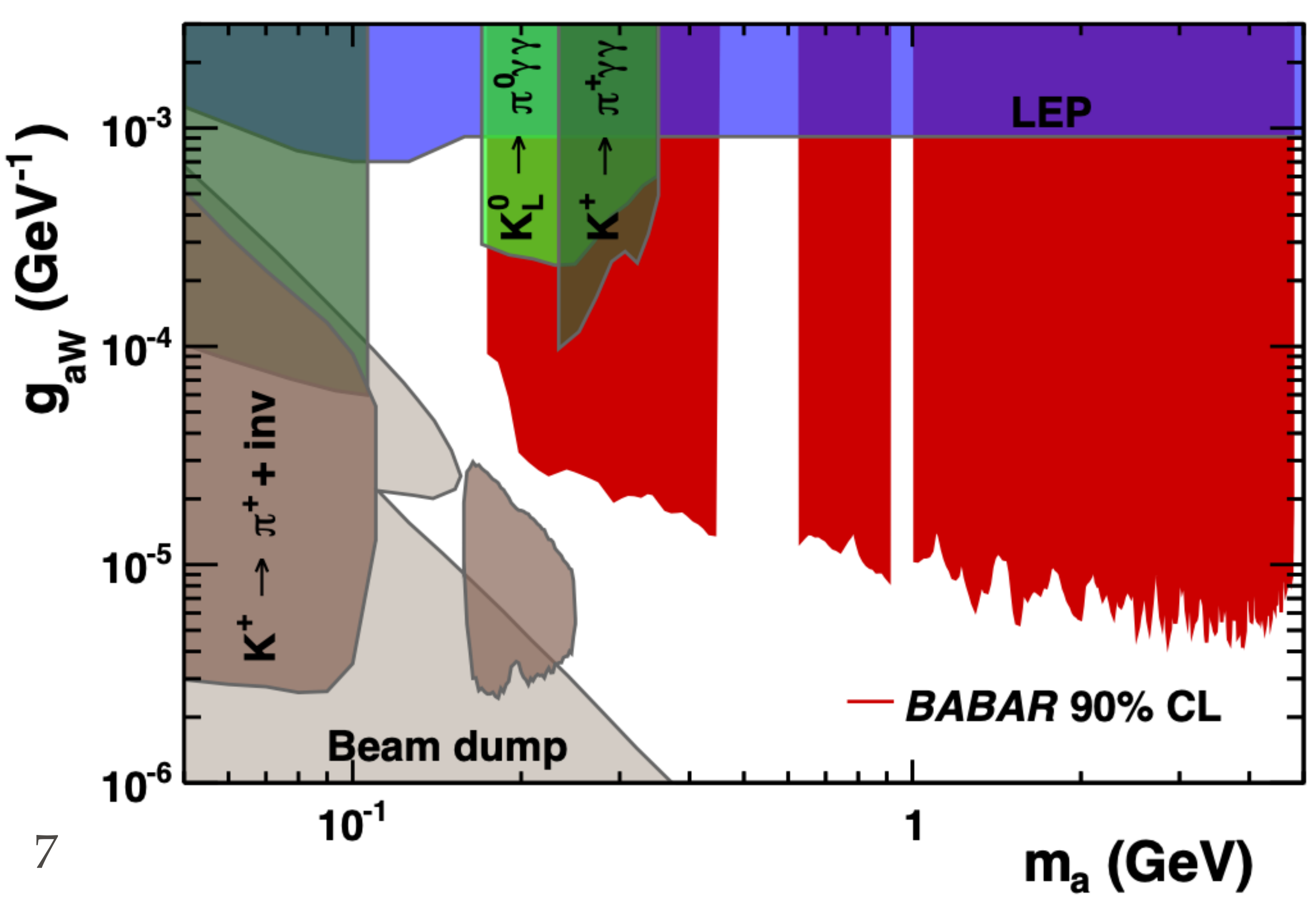


AXIONLIKE PARTICLES

- We assess efficiencies for long-lifetime signals and set Bayesian 90% CL limits on the signal branching fraction as functions of ALP mass and lifetime

- These are converted to limits on the coupling: **improve on previous limits by up to two orders of magnitude!**



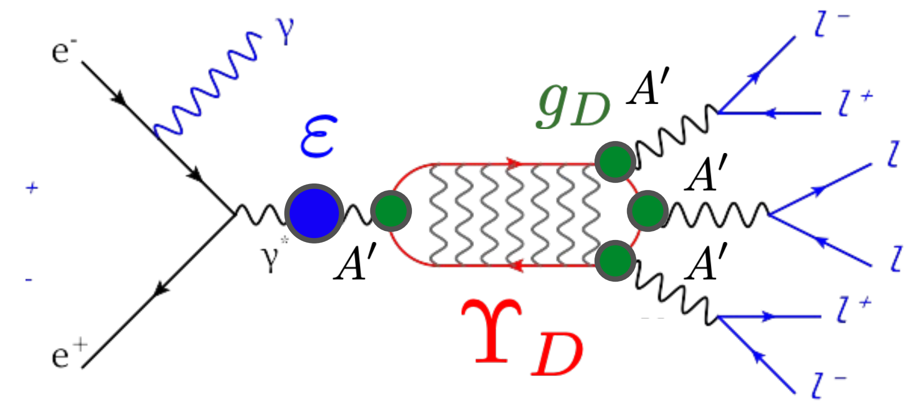


DM BOUND STATE: DARKONIUM

- Consider a DM coupled to dark photon: if coupling in hidden sector is large, can form DM bound states (darkonia)!

H. An et al., PRL 116, 151801, arXiv:1510.05020

- We search for the lightest vector darkonium, Υ_D, which decays into 3 dark photons, A'



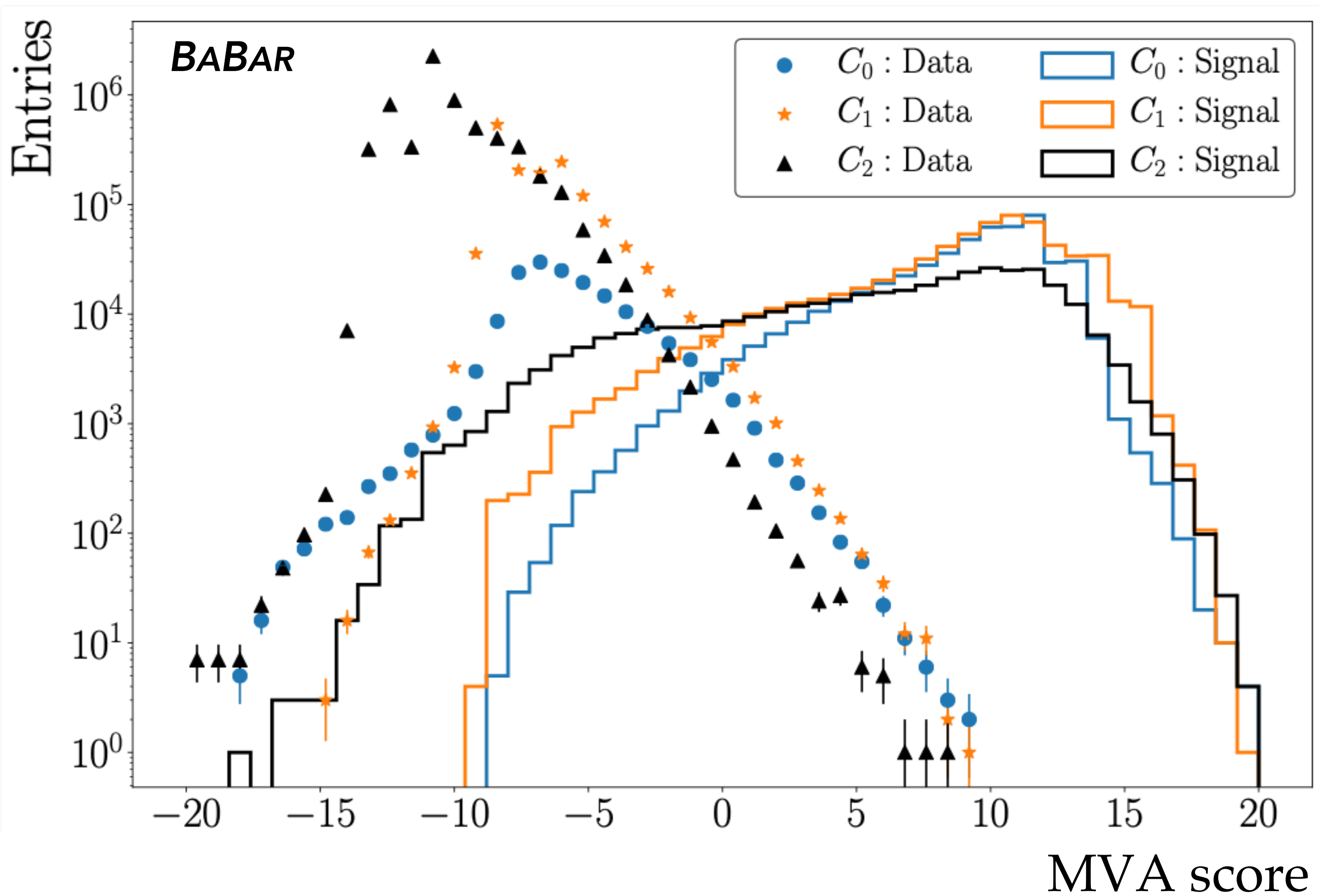
- We reconstruct dark photon decays into electron, muon, or pion pairs of similar mass, with at least one lepton pair

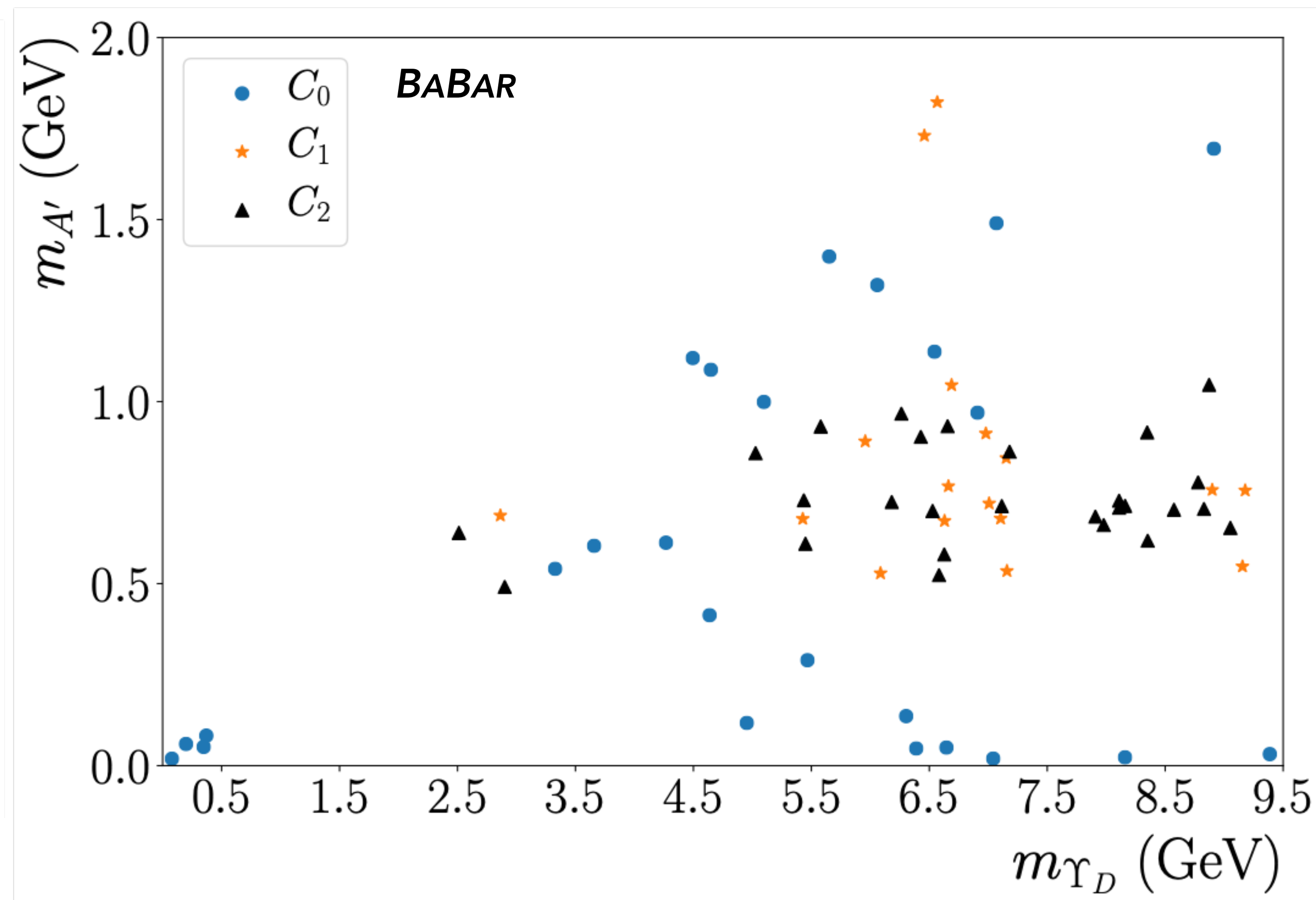
- Reconstructed Υ_D must be consistent with recoil off massless photon, should see photon if emitted in detector acceptance

- Train MVAs to further improve signal purity for different final states

DARKONIUM RESULTS

- Consider window around each mass in the $\Upsilon_D - A'$ plane of width 8x signal resolution, estimate background from adjacent windows
- C$_n$ sample corresponds to *n* pion pairs

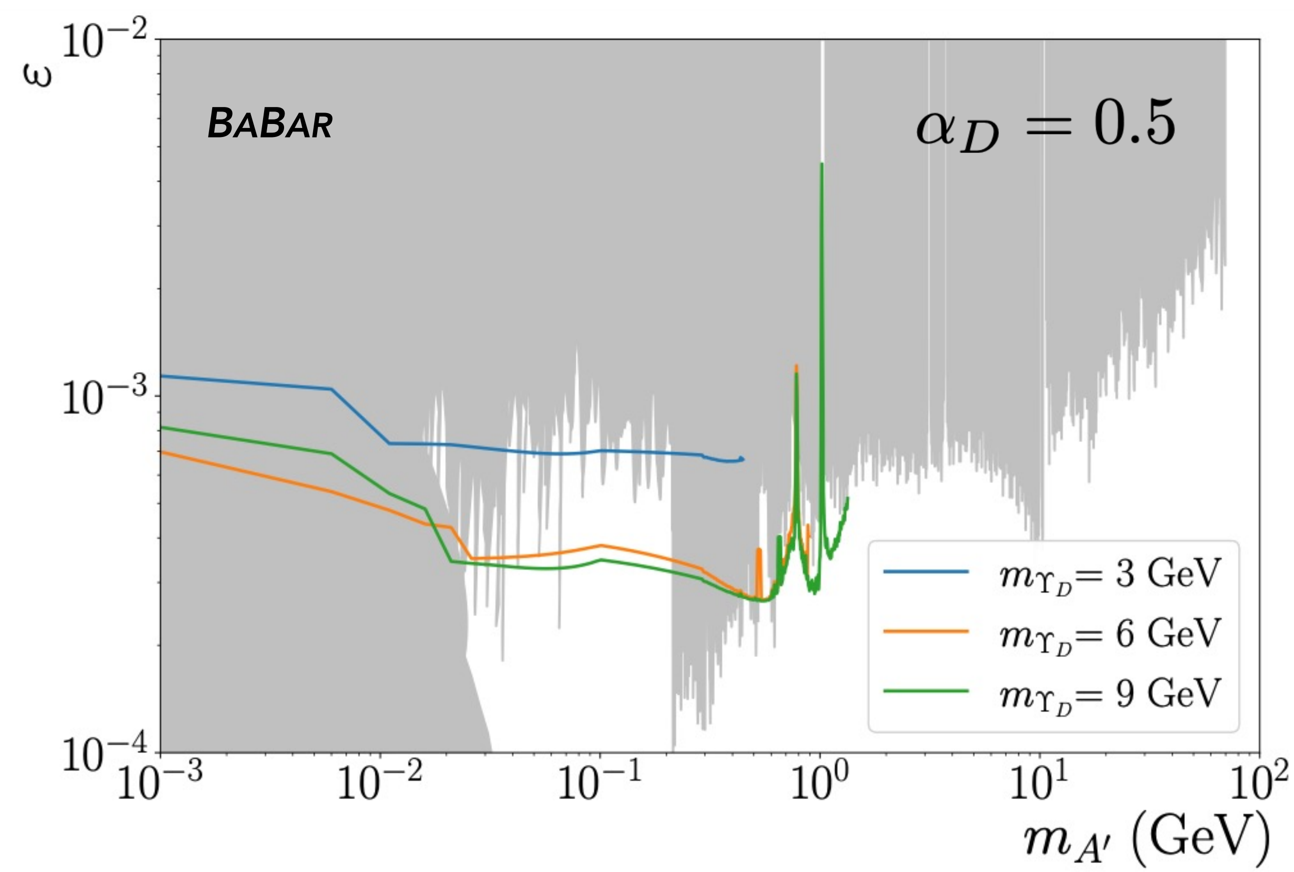


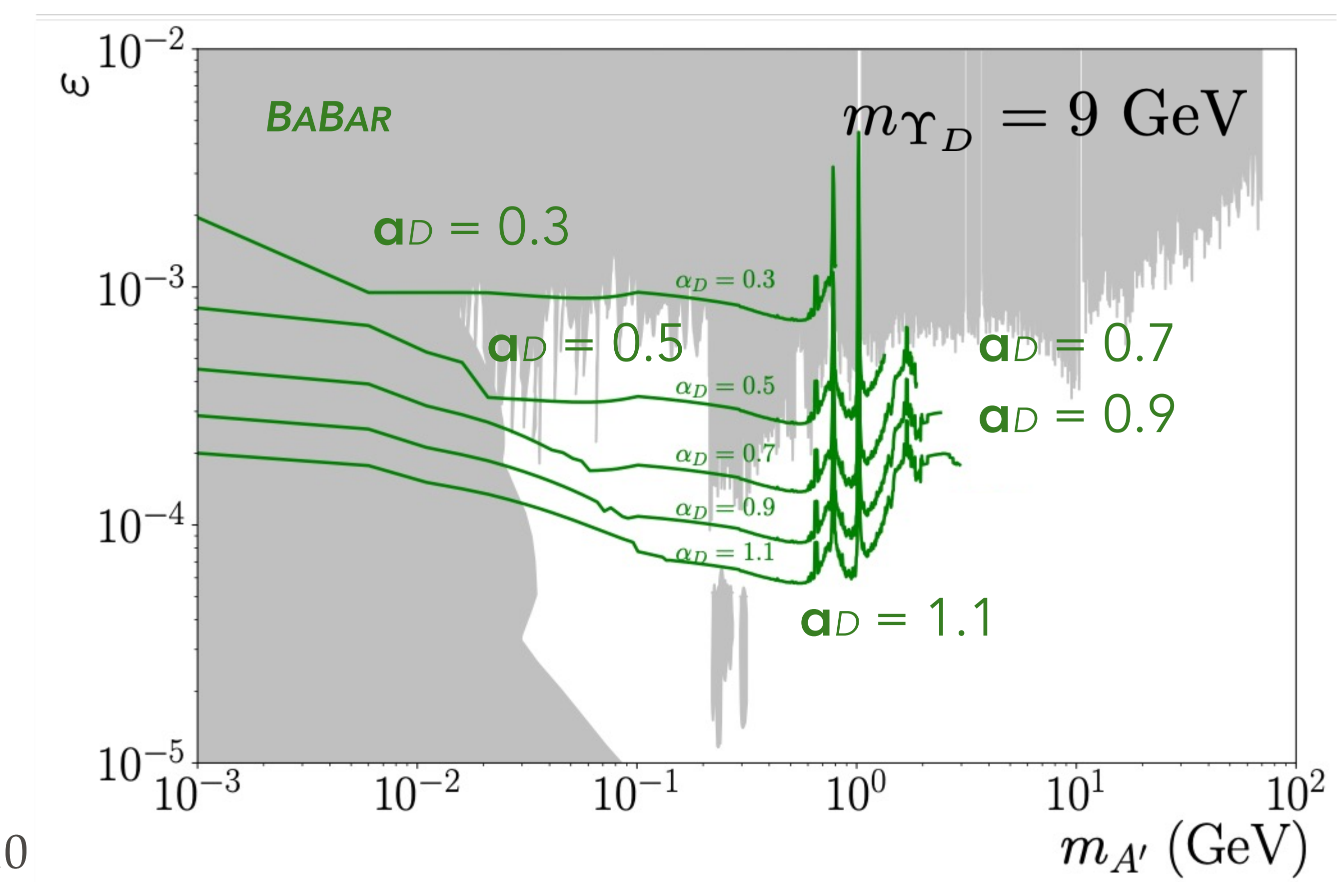


DARKONIUM RESULTS

- Repeat analysis for displaced A' decays, including flight distance and significance in variables used to train MVA
- In absence of significant signal, use profile likelihood method to set 90% CL upper limit on kinetic mixing ε as function of DM coupling

$$\alpha_D \equiv \frac{g_D^2}{4\pi}$$



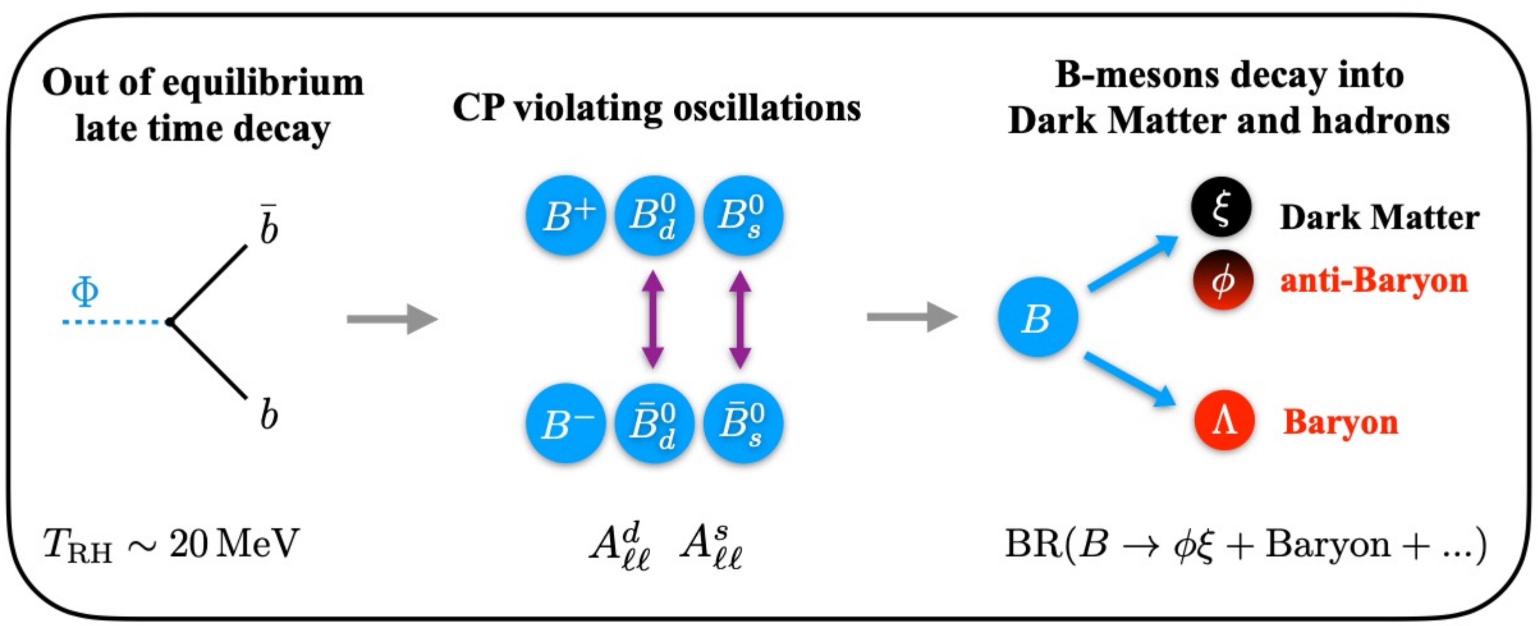


B-MESOGENESIS

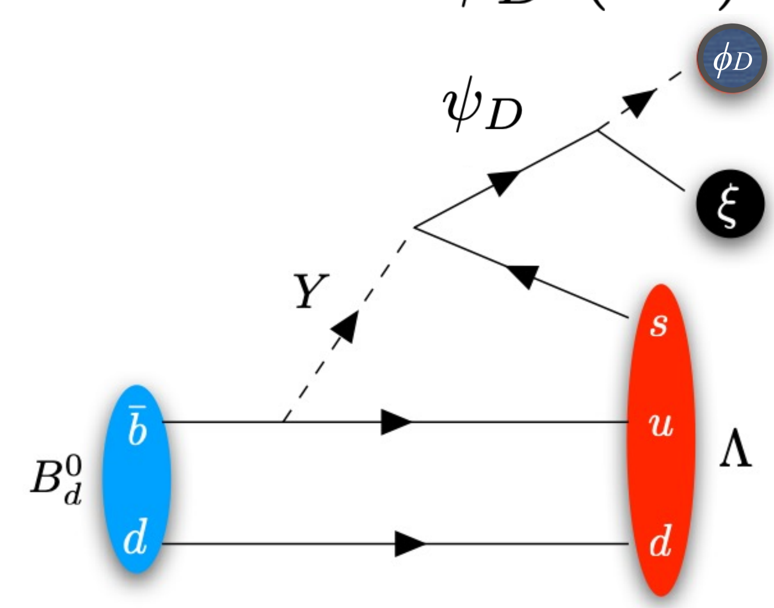
- Mechanism for baryogenesis & DM where regular + dark baryon asymmetries produced in CPV decays of *B* mesons

[G. Elor, M. Escudero, A. Nelson, PRD 99, 035031 (2019), arXiv:1810.00880](https://arxiv.org/abs/1810.00880)

- Rare example of viable baryogenesis mechanism in models with low reheat temperatures ($T_{\rm RH} \lesssim 100$ MeV)



$$B^0 \to \Lambda + \psi_D \text{ (inv)}$$

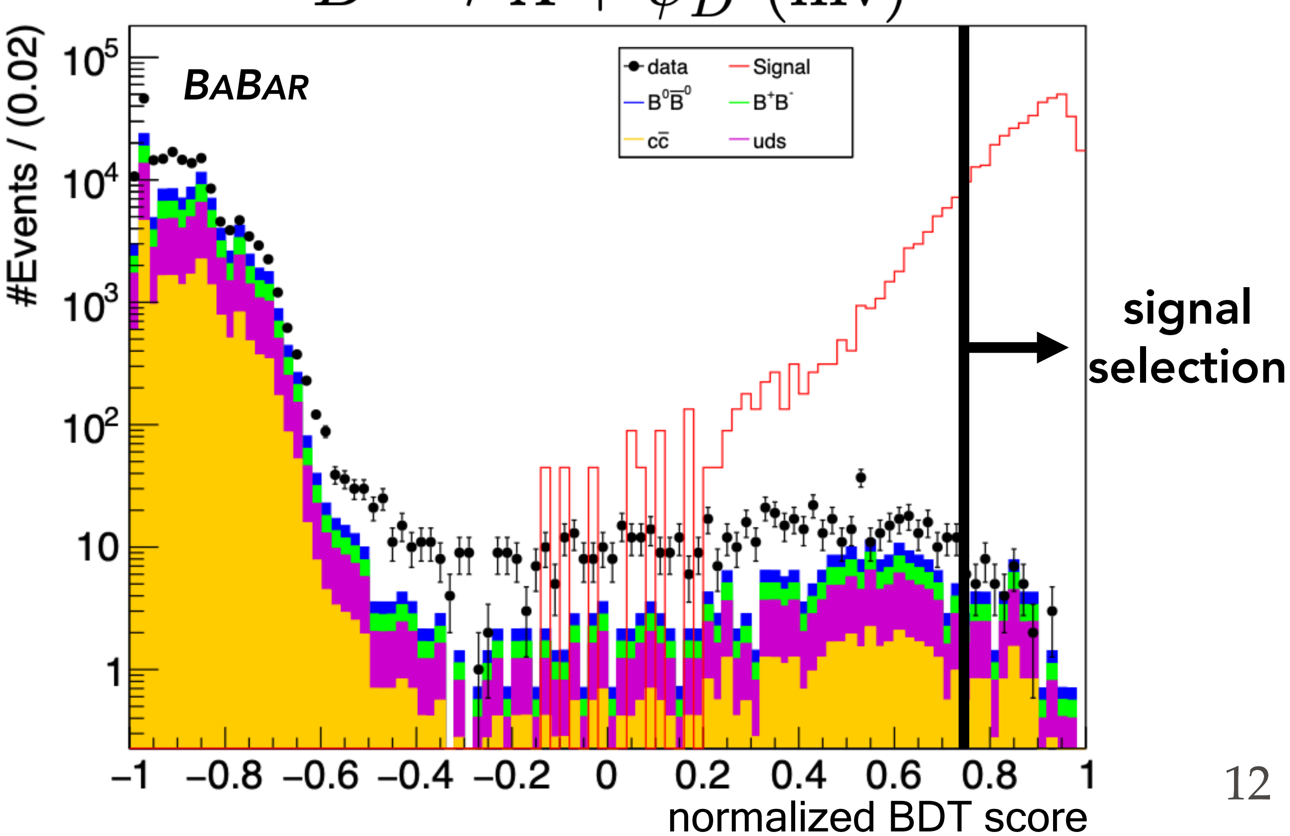


- Signal depends on flavor structure; can also get *e.g.*, $B^{\pm} \to p + \psi_D$ (inv)

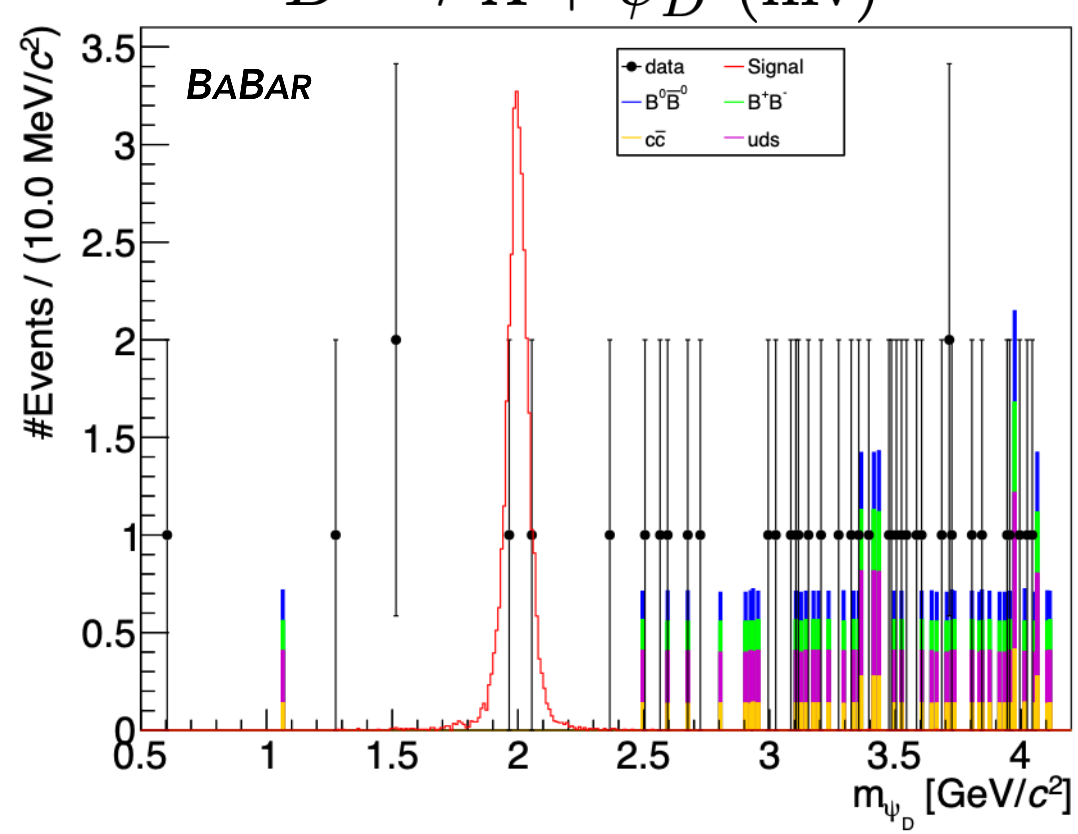
B-MESOGENESIS

- Fully reconstruct hadronic decay of "tag" *B* meson, search for single SM baryon (Λ or p) + missing mass from signal *B* decay
- Train BDT using kinematic & purity observables that distinguish tagged *B* from continuum QCD events, as well as kinematic observables for signal *B*
- Derive data/MC rescaling factors using side bands

$B^0 \to \Lambda + \psi_D$ (inv)



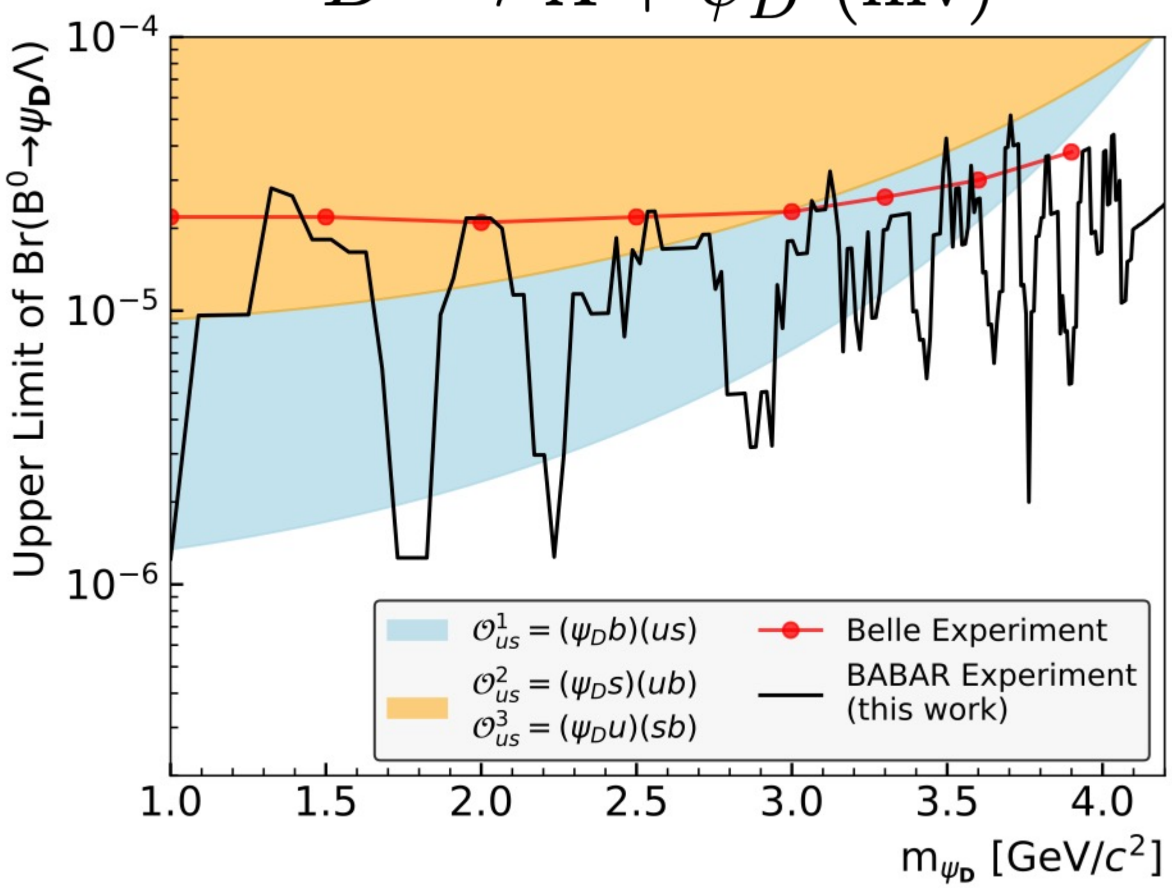
$B^0 \to \Lambda + \psi_D$ (inv)



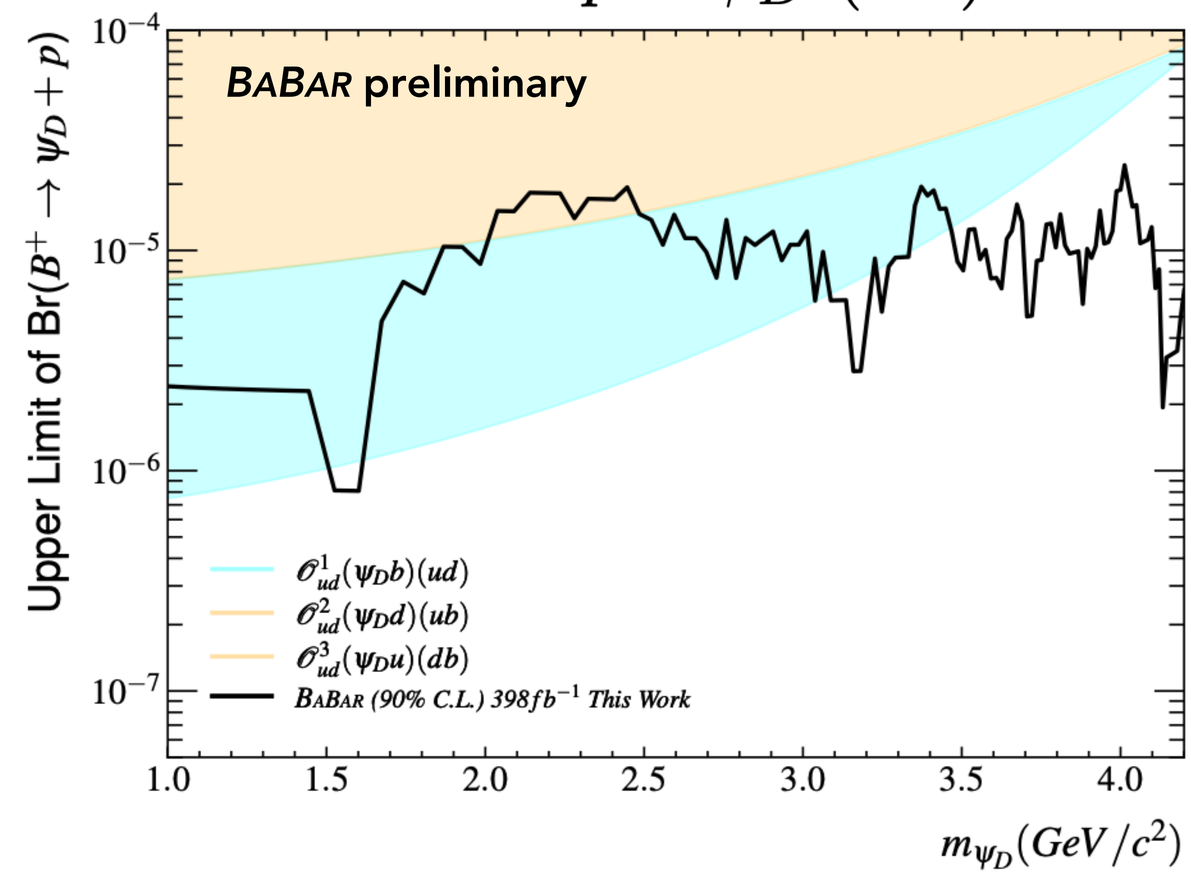
B-MESOGENESIS RESULTS

- Scan over ψ_D mass hypotheses: signal region size is 3x signal resolution, background is estimated from adjacent intervals
- No significant signal is seen: set limits on signal branching fraction using profile likelihood method (also set limits on RPV SUSY model)
- Shaded regions are branching fractions predicted from mesogenesis

$B^0 \to \Lambda + \psi_D$ (inv)



$B^\pm \to p + \psi_D$ (inv)



SUMMARY

- *B* factories are among the best experiments to search for GeV-scale hidden sectors

- Many years after it stopped running, *BaBar* continues to put out new and world-leading hidden-sector results, including recent searches for axionlike particles, DM bound states, and non-thermal models of baryogenesis + DM

- There are still models that are essentially untested, and new searches at *BaBar* and Belle II can significantly improve sensitivity

- Stay tuned for more searches on the way!

BACKUP SLIDES

ALP SELECTIONS

- **Preselection:** Reconstruct $B^{\pm}$ candidates from $K^{\pm}$ candidate and two photons
  - Require $$m_{\mathrm{ES}} = \sqrt{\frac{(s/2 + \vec{p}_i \cdot \vec{p}_B)^2}{E_i^2} - p_B^2} > 5.0\ \mathrm{GeV}$$
    $$|\Delta E| = |\sqrt{s}/2 - E_B^{\mathrm{CM}}| < 0.3\ \mathrm{GeV}$$
  - Perform kinematic fit requiring photon and kaon to originate from beamspot, constrain mass to $m_{B^{\pm}}$ and energy to beam energy

- **Train 2 Boosted Decision Trees:** each is trained on MC for one of the two predominant backgrounds:
  $$e^+e^- \to q\bar{q}\ (q = u, d, s, c)$$
  $$e^+e^- \to B^+B^-$$

ALP SELECTIONS

- 13 BDT training observables:
  - m_{ES}
  - ΔE
  - cosine of angle between sphericity axes of $B^{\pm}$ candidate and rest of event (ROE)
  - PID info for kaon candidate
  - 2nd Legendre moment of ROE, calculated relative to $B^{\pm}$ thrust axis
  - helicity angle of most energetic photon, and of kaon
  - energy of most energetic photon in a candidate
  - invariant mass of ROE
  - multiplicity of neutral clusters
  - invariant mass of diphoton pair, with 1 photon in $B^{\pm}$ candidate and 1 photon in ROE, closest to each of π^0, η, η'

ALP SIGNAL EXTRACTION

- Perform unbinned maximum likelihood fits for signal peak over smooth background
- 476 mass hypotheses, step size between adjacent mass hypotheses is given by the signal resolution, σ
- σ is determined by fitting a double-sided Crystal Ball function to signal MC at various masses, interpolating for intermediate values
- Resolution ranges from 8 MeV at $m_a = 0.175 \text{ GeV}$ to 14 MeV at $m_a = 2 \text{ GeV}$, decreasing back to 2 MeV at $m_a = 4.78 \text{ GeV}$ as a result of the kinematic fit
- Signal MC resolution is validated by data/MC comparisons of $B^{\pm} \to K^{\pm}\pi^0$ and $B^{\pm} \to K^{\pm}\eta$, found to be consistent within 3%
- Signal efficiency derived from MC, ranges from 2% at $m_a = 4.78 \text{ GeV}$ to 33% at $m_a = 2 \text{ GeV}$

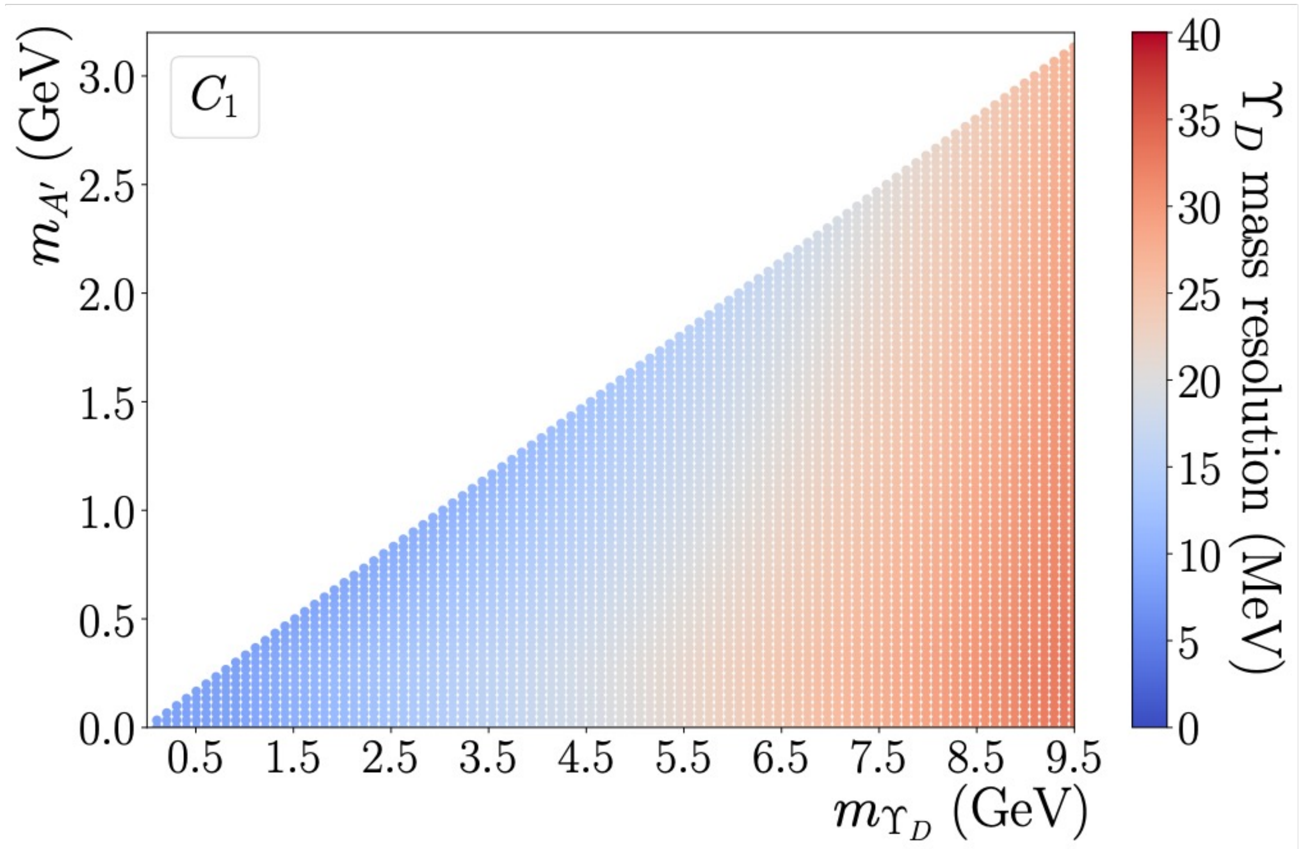
ALP FIT PROPERTIES

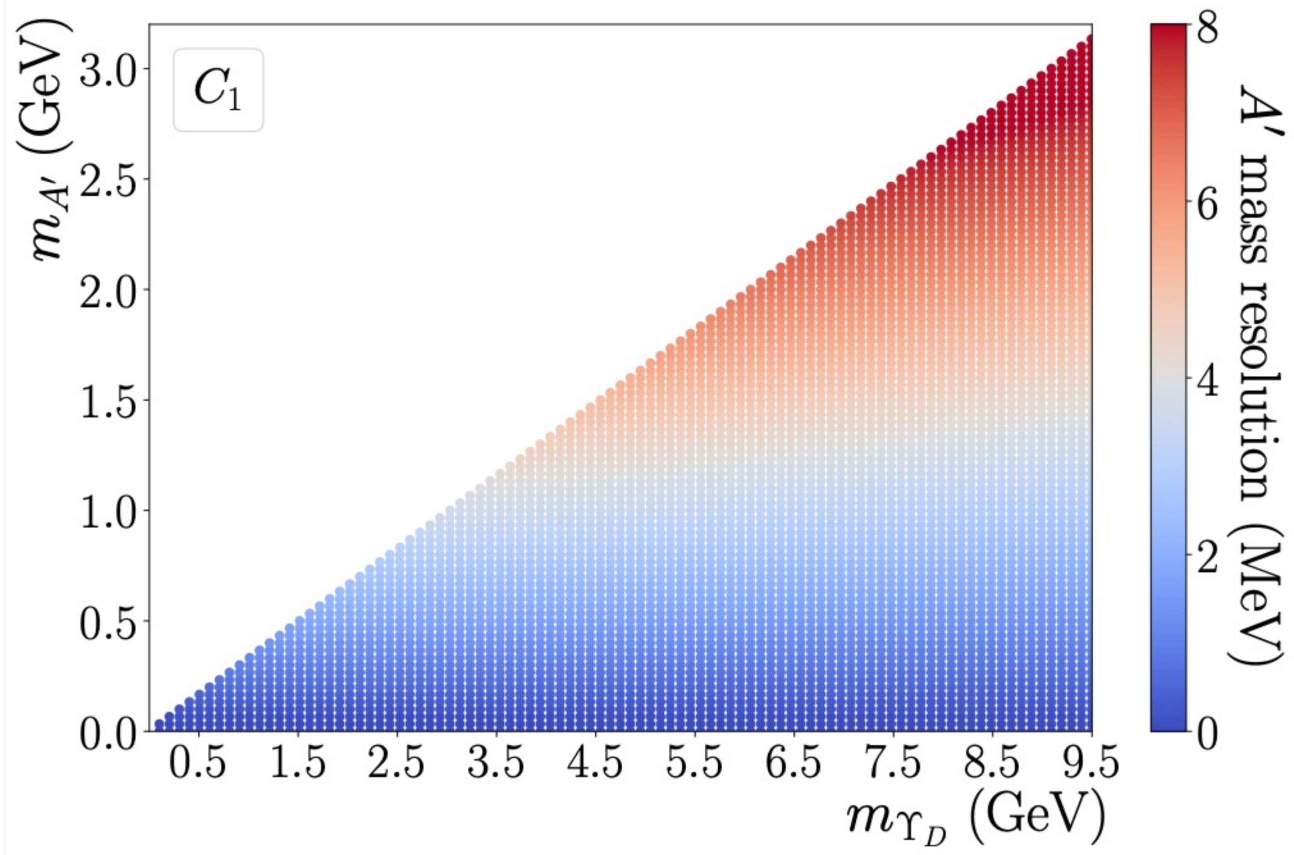
- Fits are performed over intervals of length $(30-70)\sigma$ depending on ALP mass, restricted to the range $0.11\ \mathrm{GeV} < m_a < 4.8\ \mathrm{GeV}$
- Likelihood function includes contributions from signal, continuum background, peaking background
- **Signal PDF:** modeled from signal MC and interpolated between simulated mass points
- **Continuum background PDF:** second-order polynomial for $m_a < 1.35\ \mathrm{GeV}$, first-order polynomial at higher masses
- **Peaking background PDF:** each SM diphoton resonance is modeled as a sum of a signal template and a broader Gaussian distribution with parameters fixed to fits in MC — this component arises from continuum production of $\pi^0/\eta/\eta'$ that is broadened because of kinematic fit

ALP SYSTEMATICS

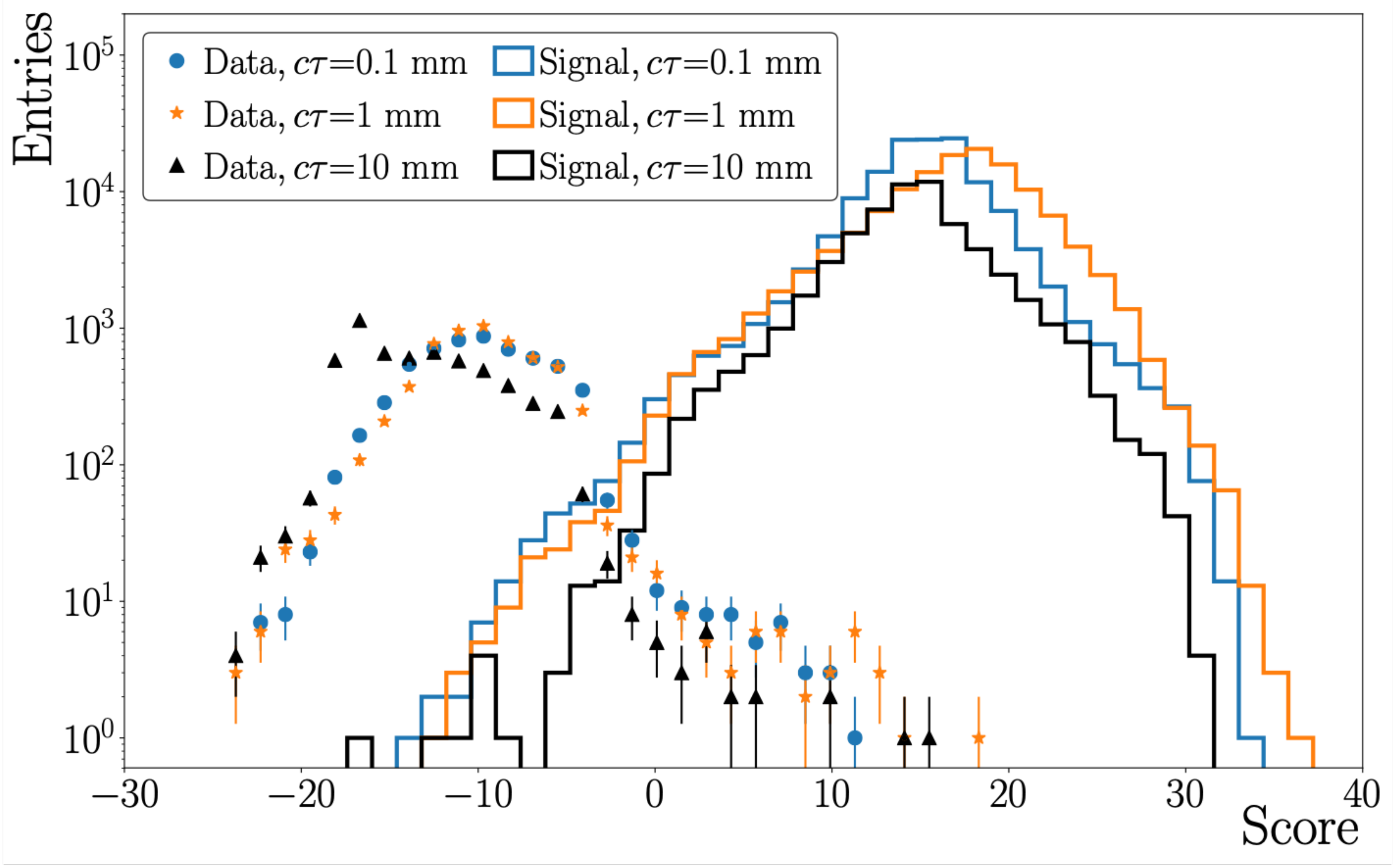
- Assess uncertainty on signal yield from fit by varying order of polynomial for continuum background (3rd-order for $m_a < 1.35\ \mathrm{GeV}$, constant at higher mass), varying shape of peaking background within uncertainties, and using next-nearest neighbor for interpolating signal shape
  - Dominates total uncertainty for some masses in vicinity of π^0/η
- Systematic uncertainty on signal yield from varying signal shape width within uncertainty is on average 3% of statistical uncertainty
- 6% systematic uncertainty on signal efficiency, derived from data/MC ratio in vicinity of η'
- Other systematic effects negligible by comparison, including on limited signal MC statistics, luminosity

DARKONIUM: RESOLUTION

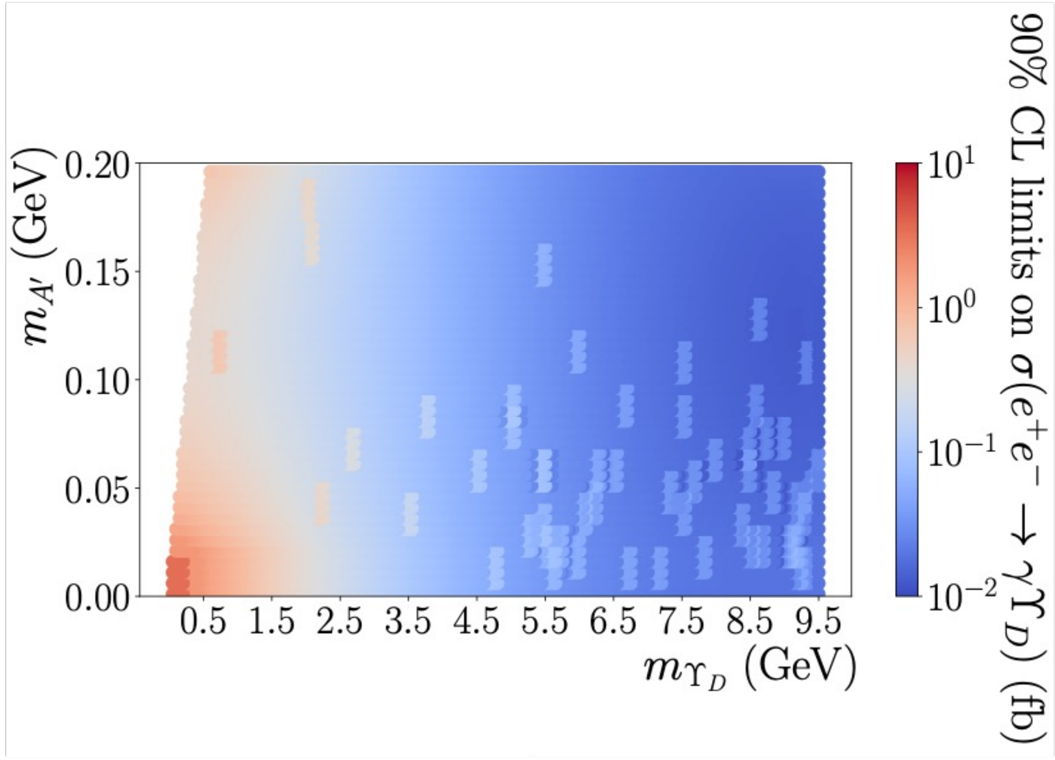


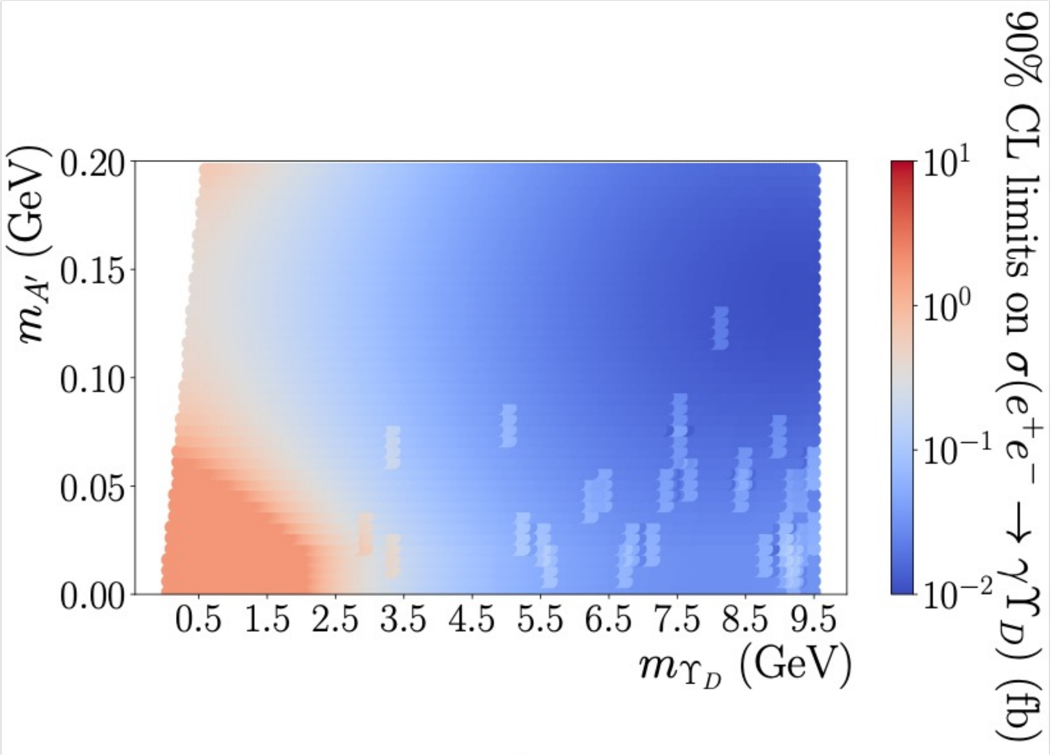


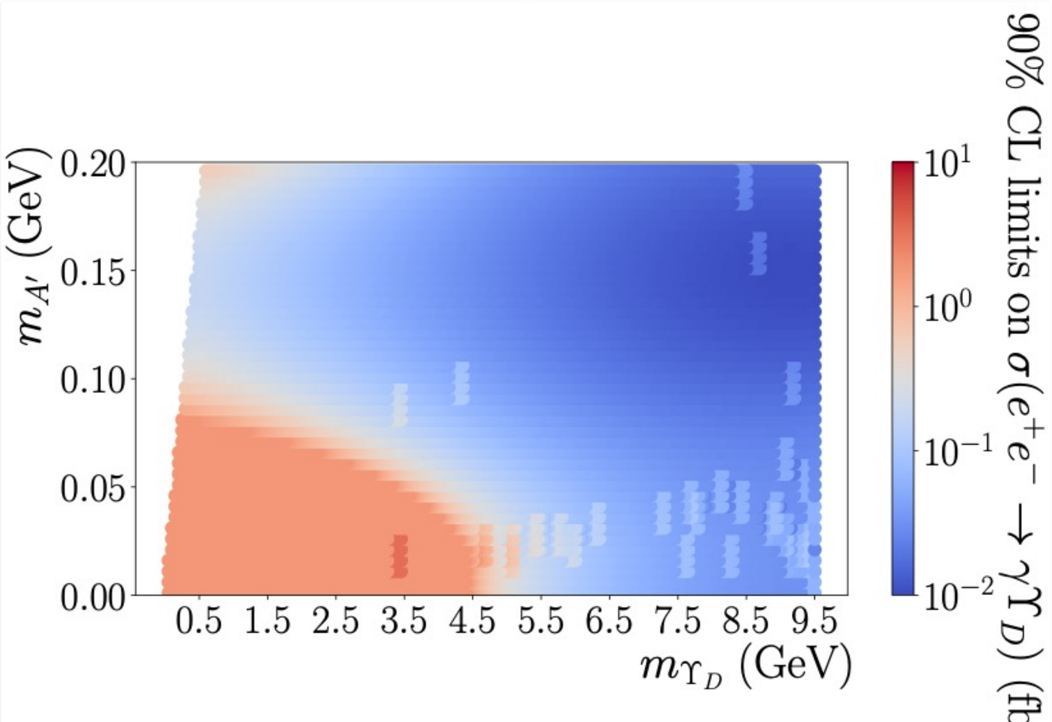
DARKONIUM: LONG-LIVED A′



DARKONIUM: LONG-LIVED A'



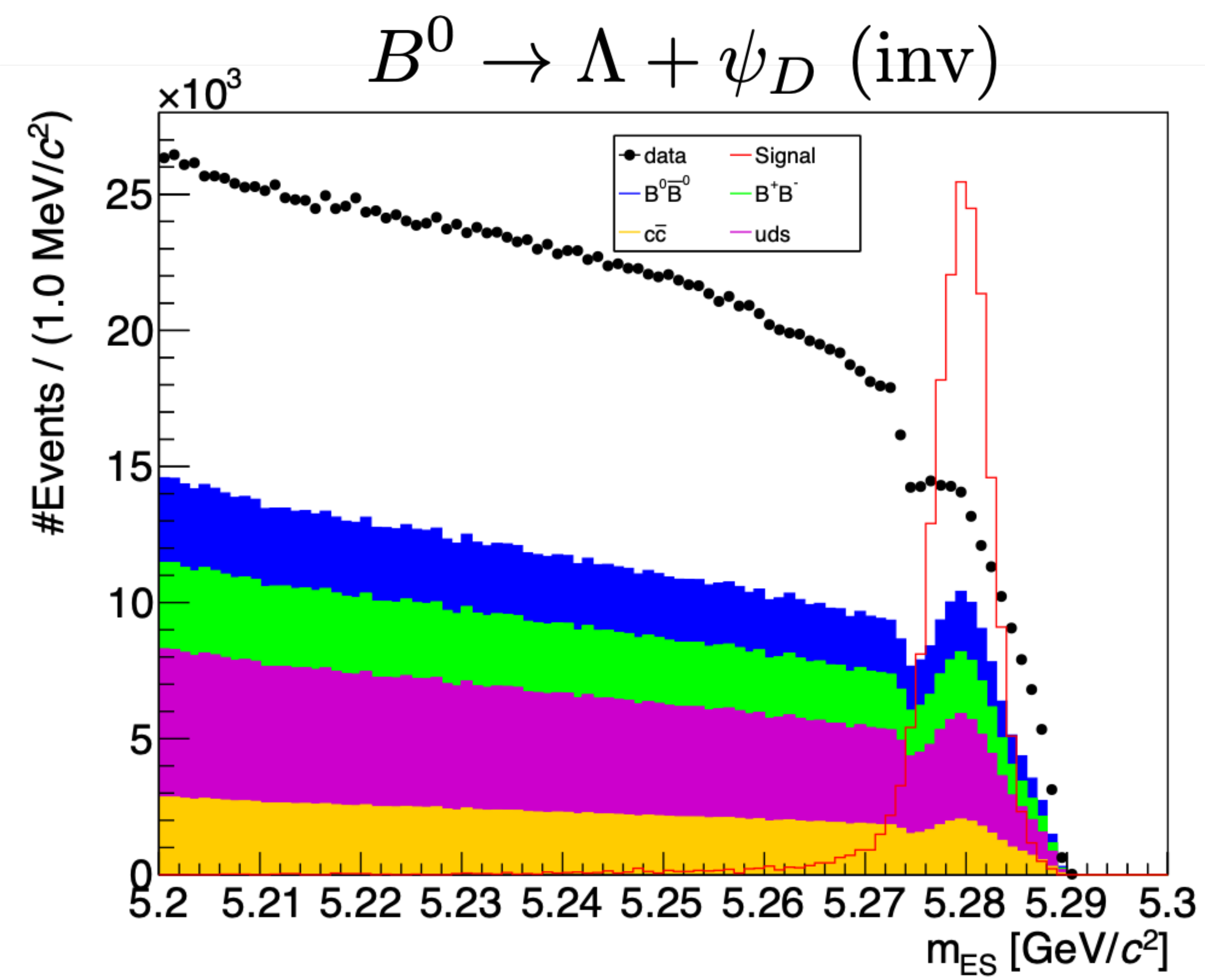


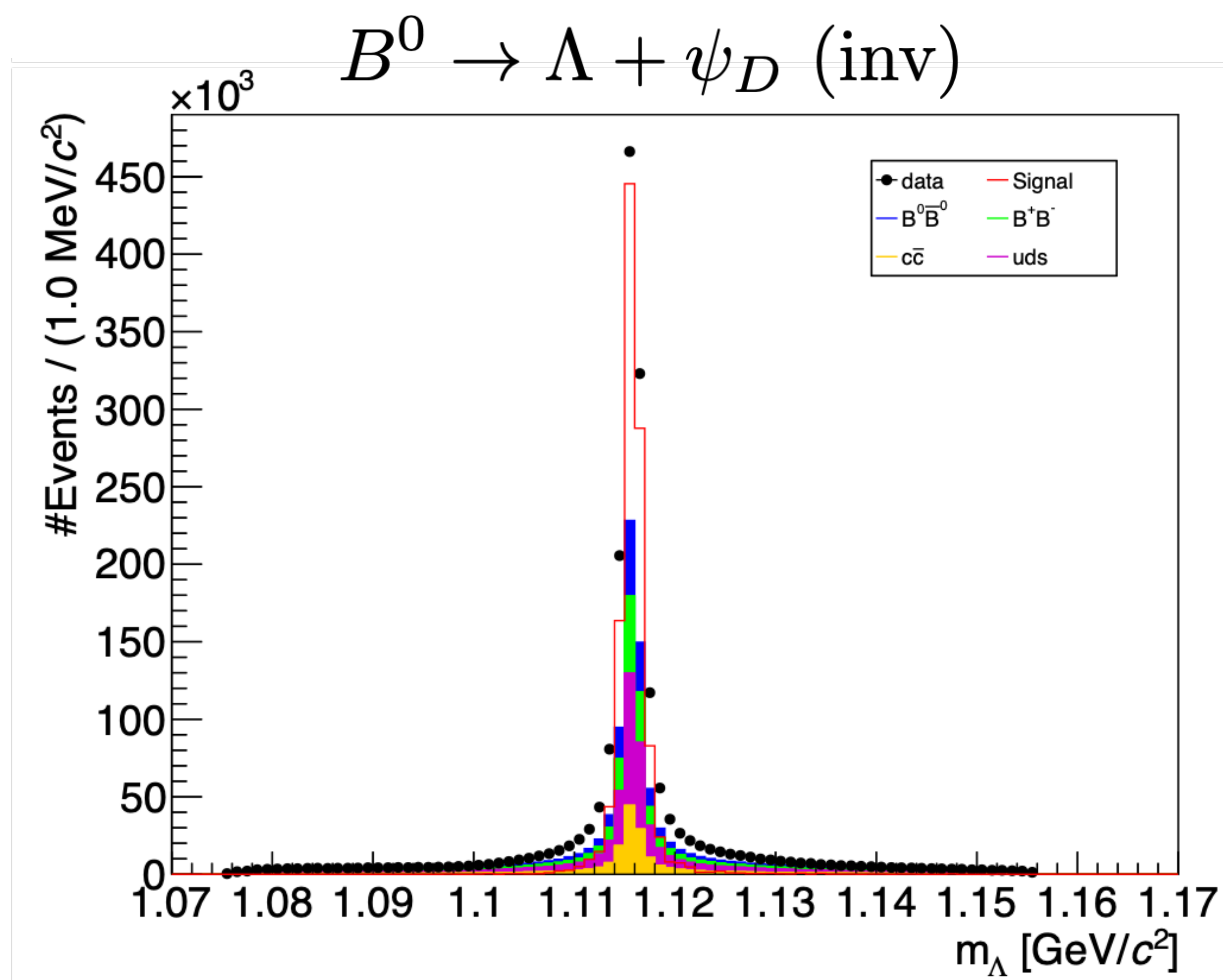


B-MESOGENESIS

- Select events with: $5.27 \text{ GeV} < m_{ES} < 5.29 \text{ GeV}$

$$1.110 \text{ GeV}/c^2 < m_\Lambda < 1.121 \text{ GeV}/c^2$$

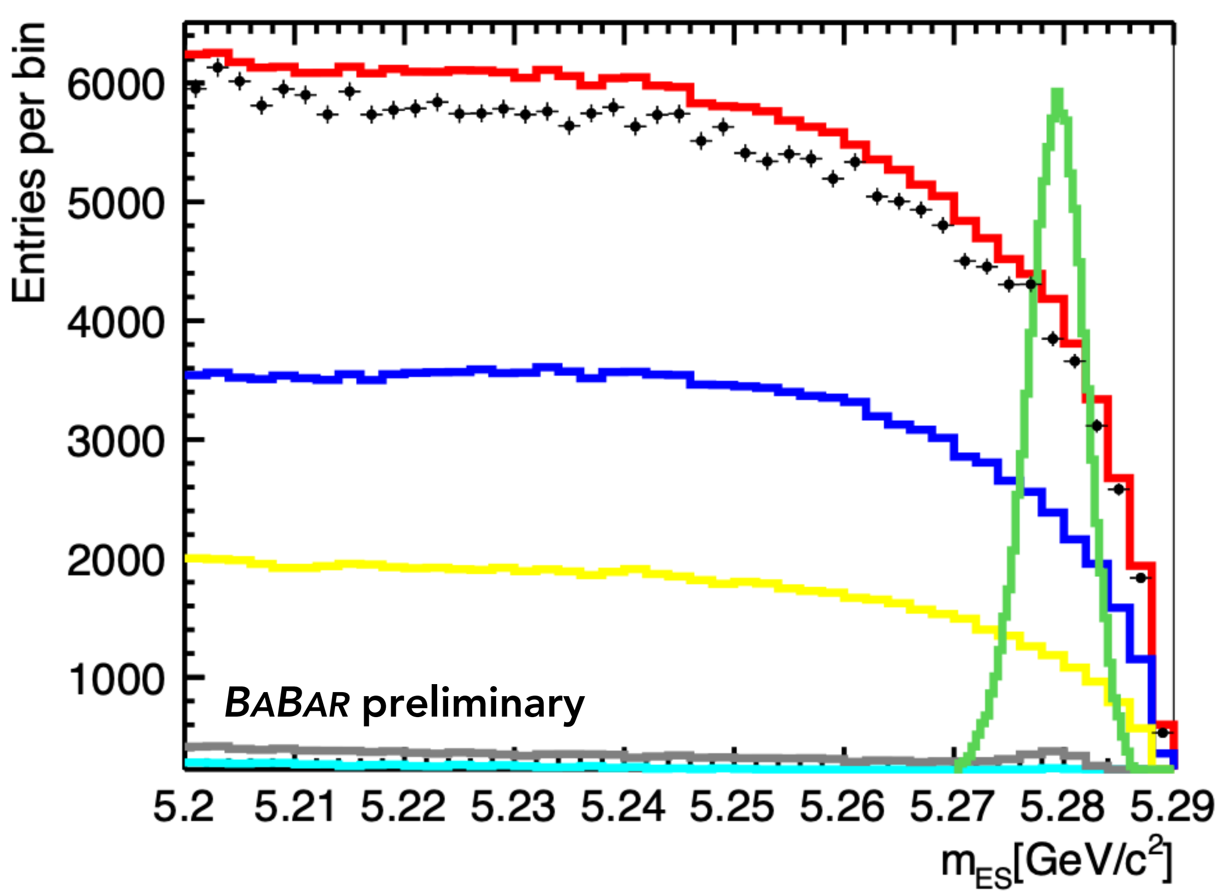




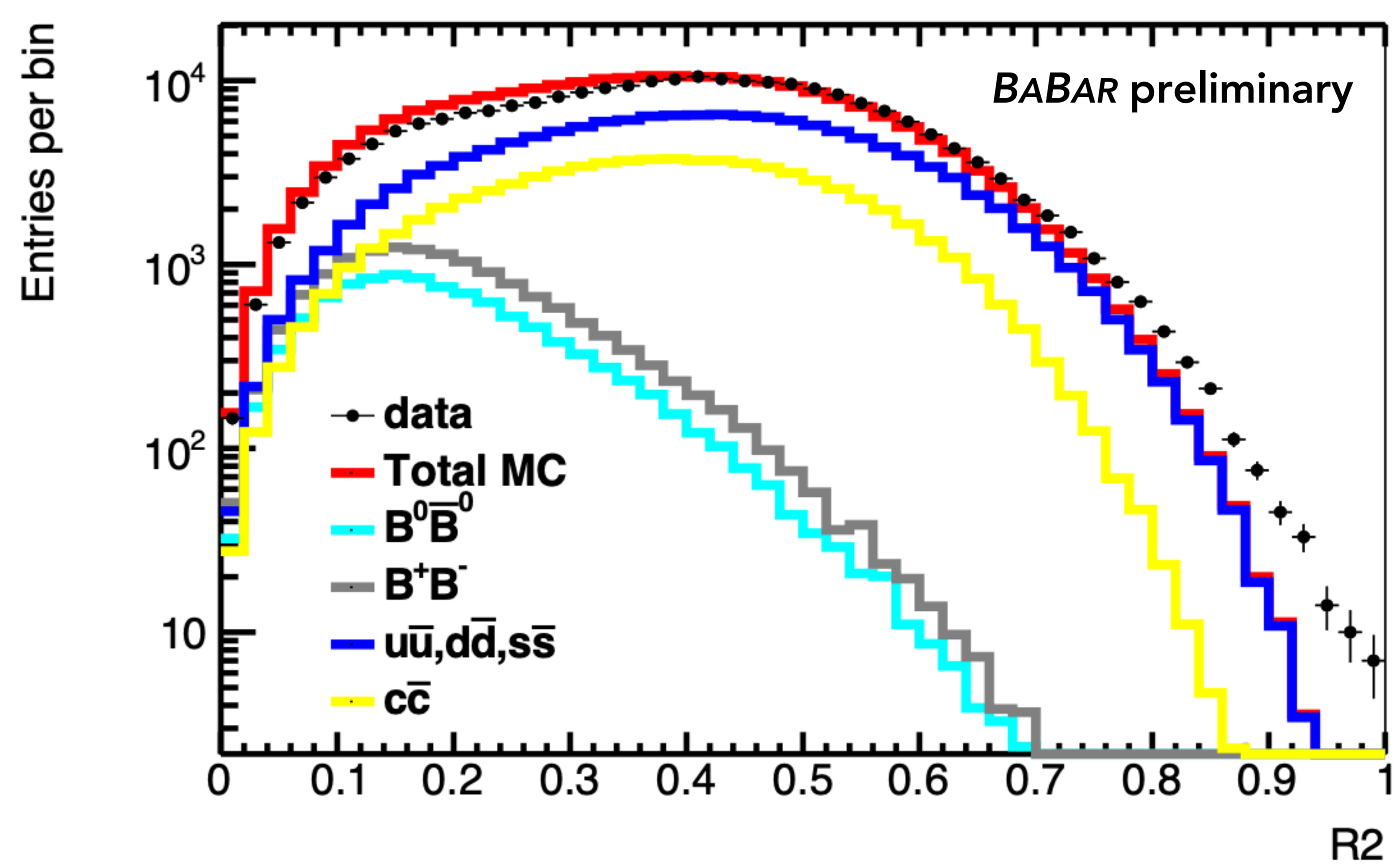
B-MESOGENESIS

- Select events with: $5.27\ \mathrm{GeV} < m_{ES} < 5.29\ \mathrm{GeV}$
  $|\Delta E| < 0.2\ \mathrm{GeV}$

$B^{\pm} \to p + \psi_D\ (\mathrm{inv})$

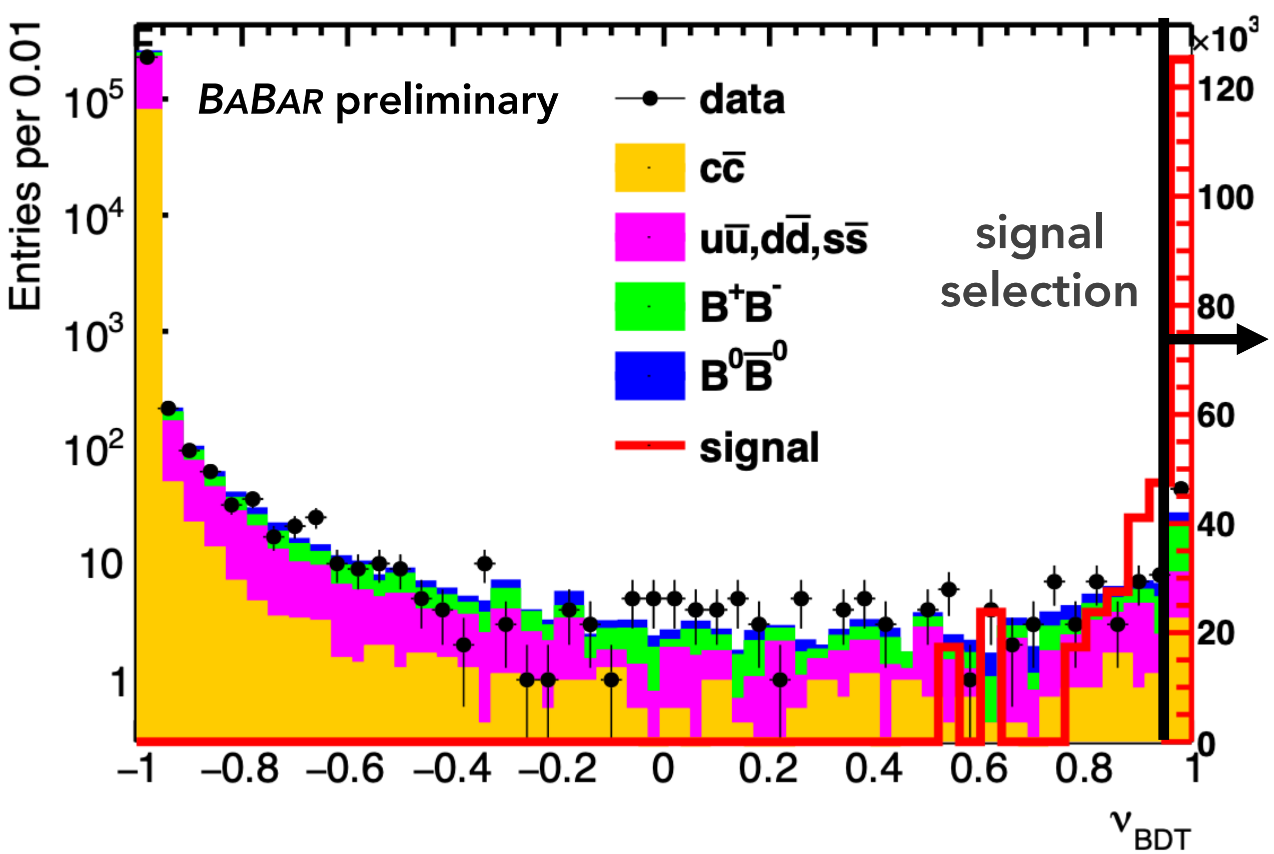


$B^{\pm} \to p + \psi_D\ (\mathrm{inv})$

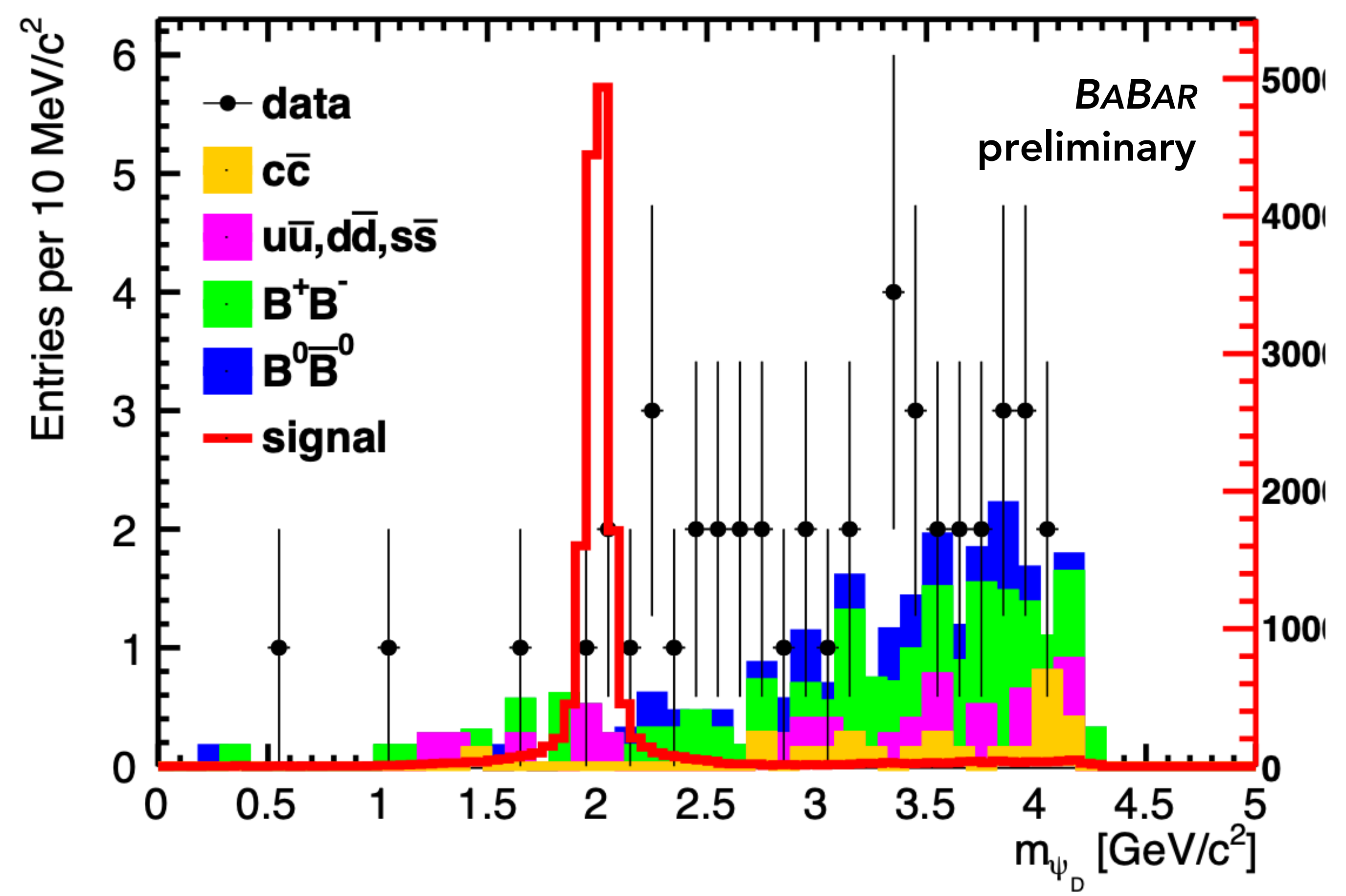


B-MESOGENESIS

$B^{\pm} \to p + \psi_D \ \text{(inv)}$

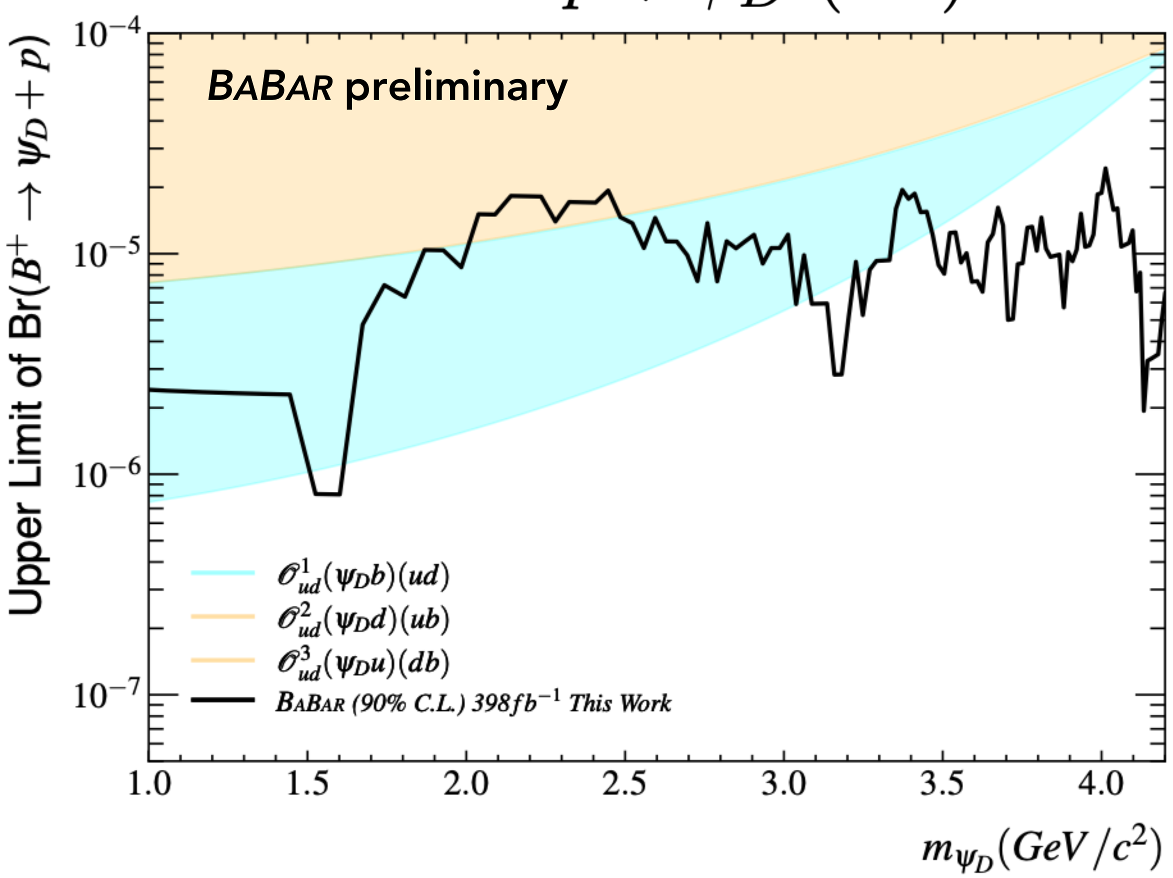


$B^{\pm} \to p + \psi_D \ \text{(inv)}$



B-MESOGENESIS

$B^{\pm} \to p + \psi_D$ (inv)



$B^{\pm} \to p + \tilde{\chi}_0$ (RPV)