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

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PASCOS – UC Irvine
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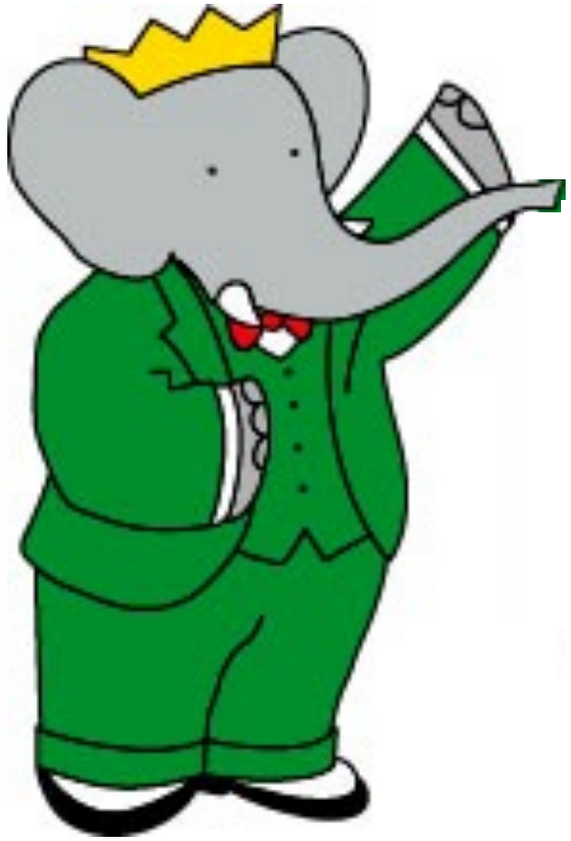
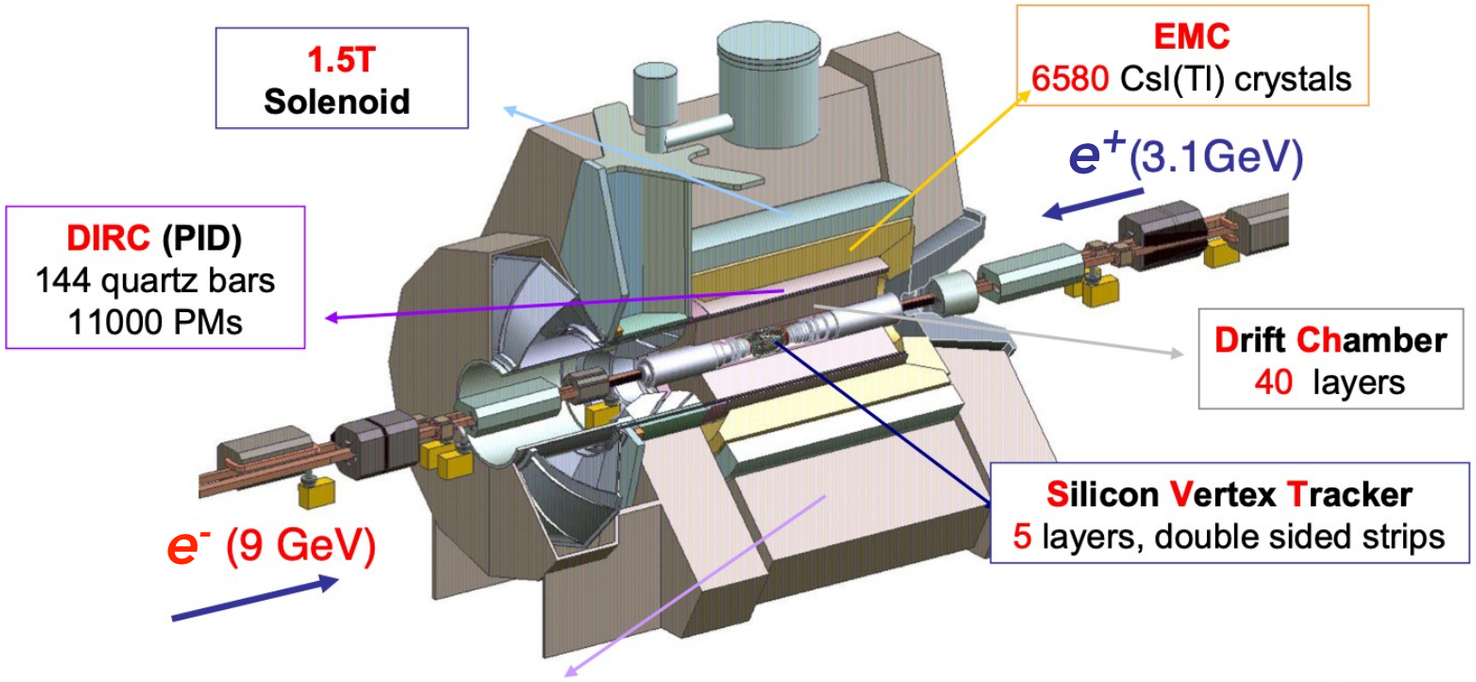
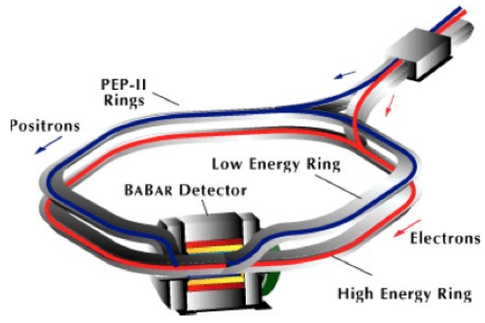


BABAR EXPERIMENT



1999-2008

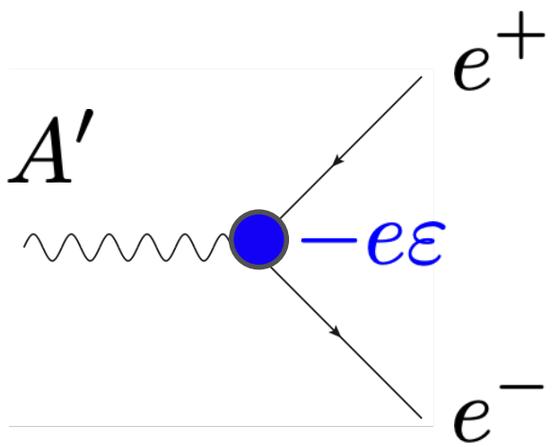


- 432/fb $\Upsilon(4S)$ on-peak ($\sqrt{s} = 10.58$ GeV)
- ~500 million *B* meson pairs
- smaller samples at $\Upsilon(2S)/\Upsilon(3S)$ and off-peak

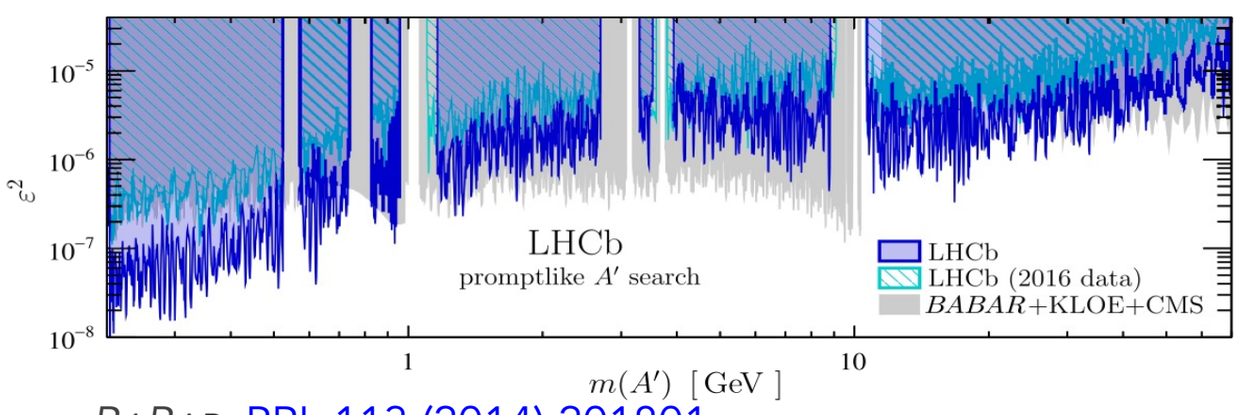
- High luminosity, low backgrounds make *BABAR* an ideal experiment for discovering MeV-GeV scale hidden particles

HIDDEN SECTOR DM

- For thermal dark matter masses below a few GeV, a low-mass mediator is needed for observed abundance
  B. Lee, S. Weinberg, PRL 39, 165 (1977)
- Many searches focus on minimal, predictive "portals", such as a dark photon (A') with kinetic mixing ε

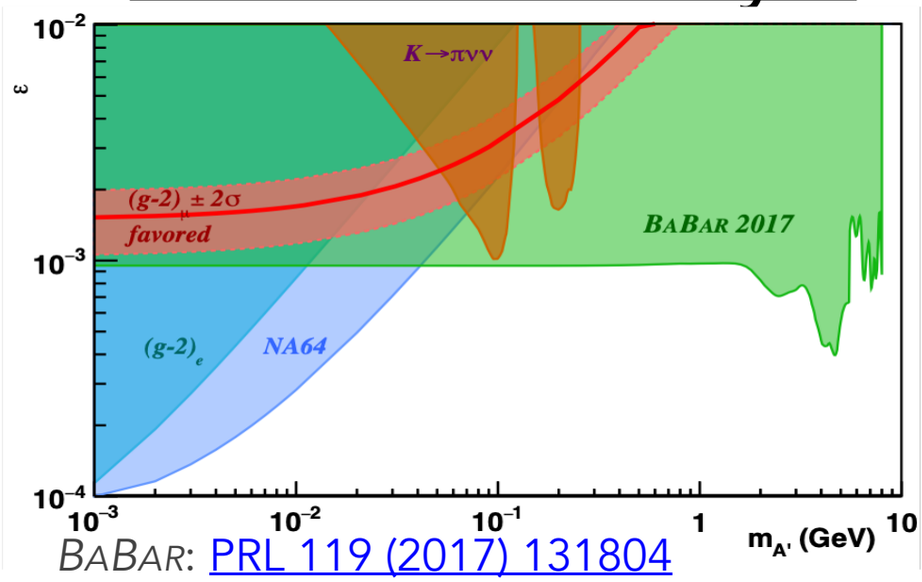


visible decays: $A' \to \ell^+\ell^-$



BABAR: PRL 113 (2014) 201801
LHCb: PRL 124 (2020) 041801

invisible decays:



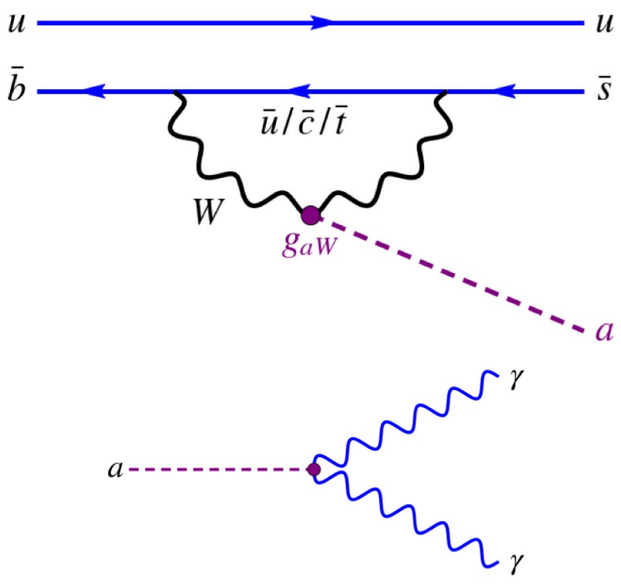
BABAR: PRL 119 (2017) 131804

- However, a richer array of signatures is possible, necessitating new searches

SEARCHES PRESENTED TODAY

Axion-like particles (ALPs)

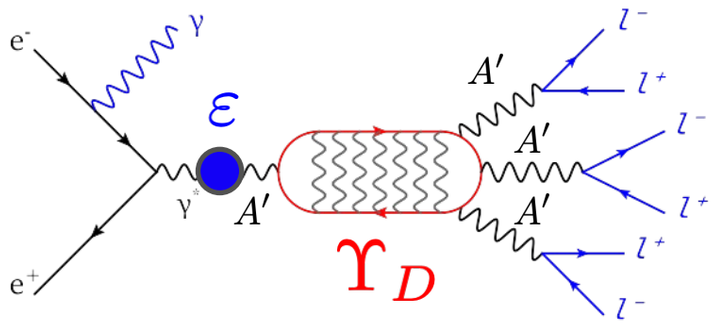
- *B* mesons decay to ALP via coupling to gauge bosons



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

DM bound states

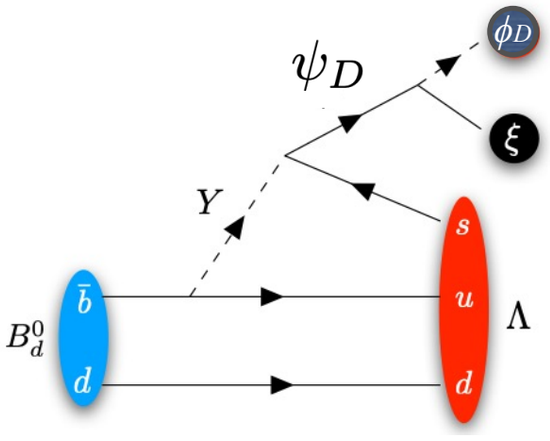
- dark photon + large coupling to DM
- search for DM bound states



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

B-Mesogenesis

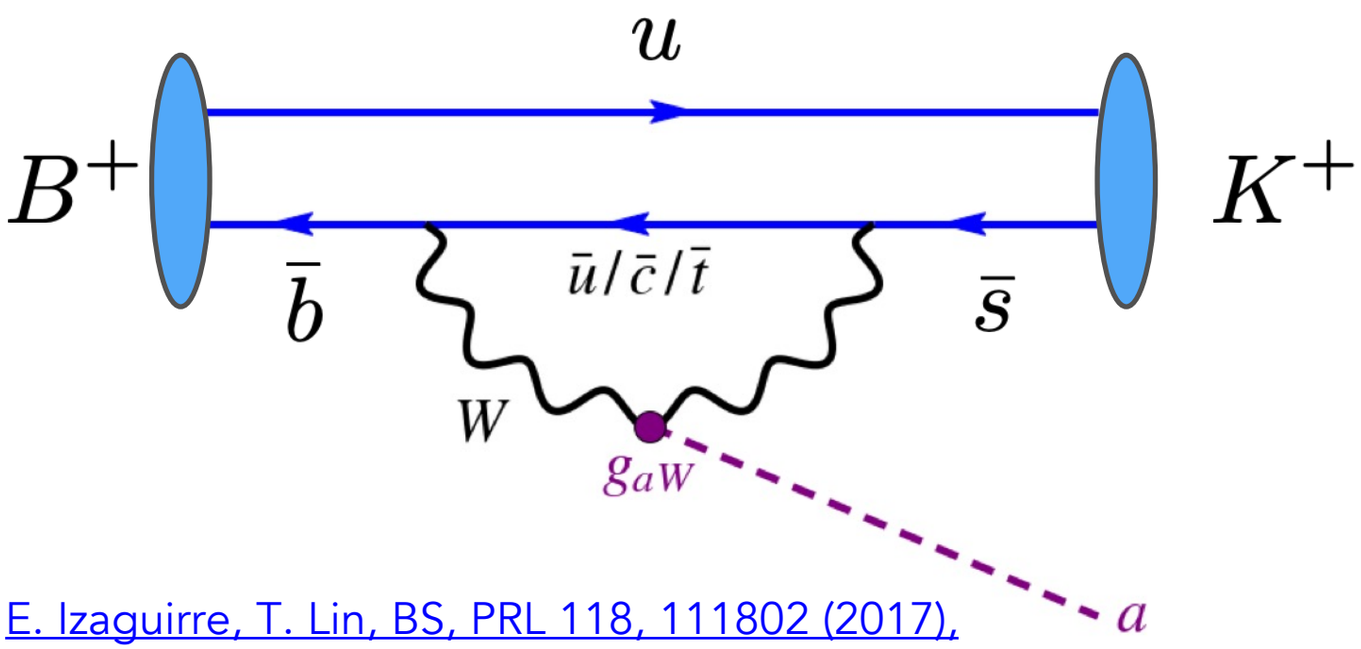
- model of QCD-scale baryogenesis
- *B* mesons decay to baryon + dark baryon



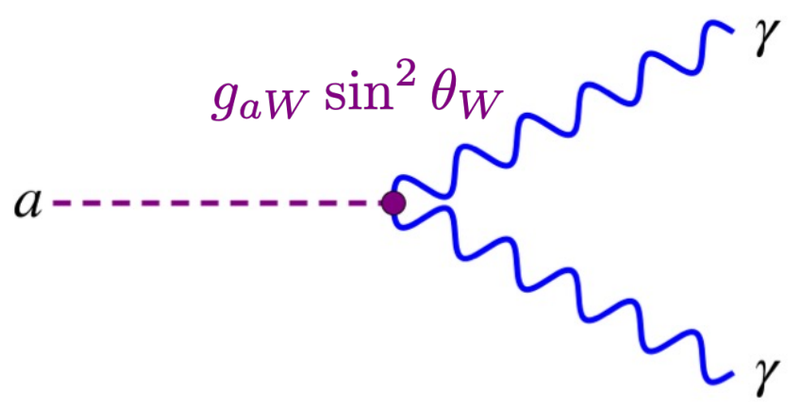
BaBar, PRD 107, 092001 (2023)
BaBar, arXiv:2306.08490 (submitted to PRL)

AXION-LIKE PARTICLES

- **Axion-like particles (ALPs):** pseudoscalars that couple to pairs of gauge bosons
- Ubiquitous in BSM theories, ideal hidden sector mediators
- If ALP couples to SU(2) gauge bosons, it can be produced in rare *B* meson decays:



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

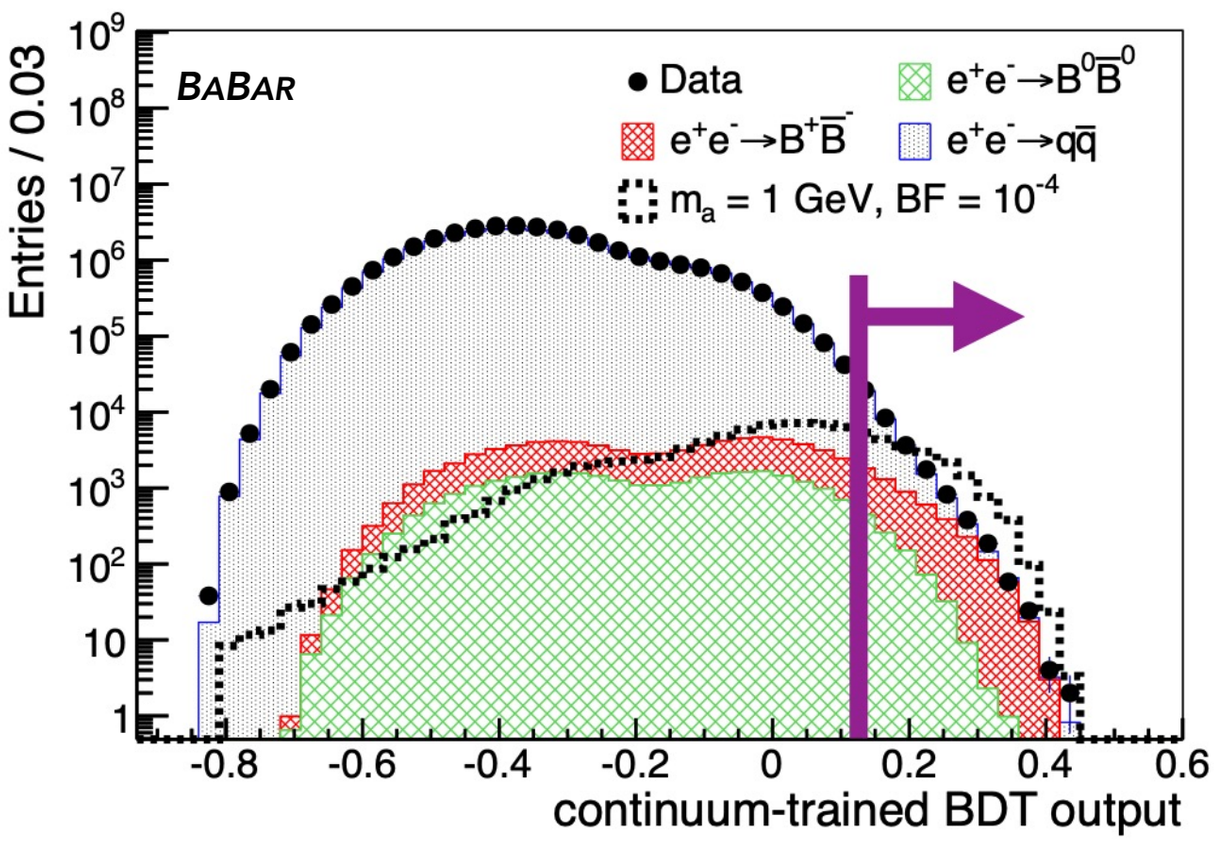


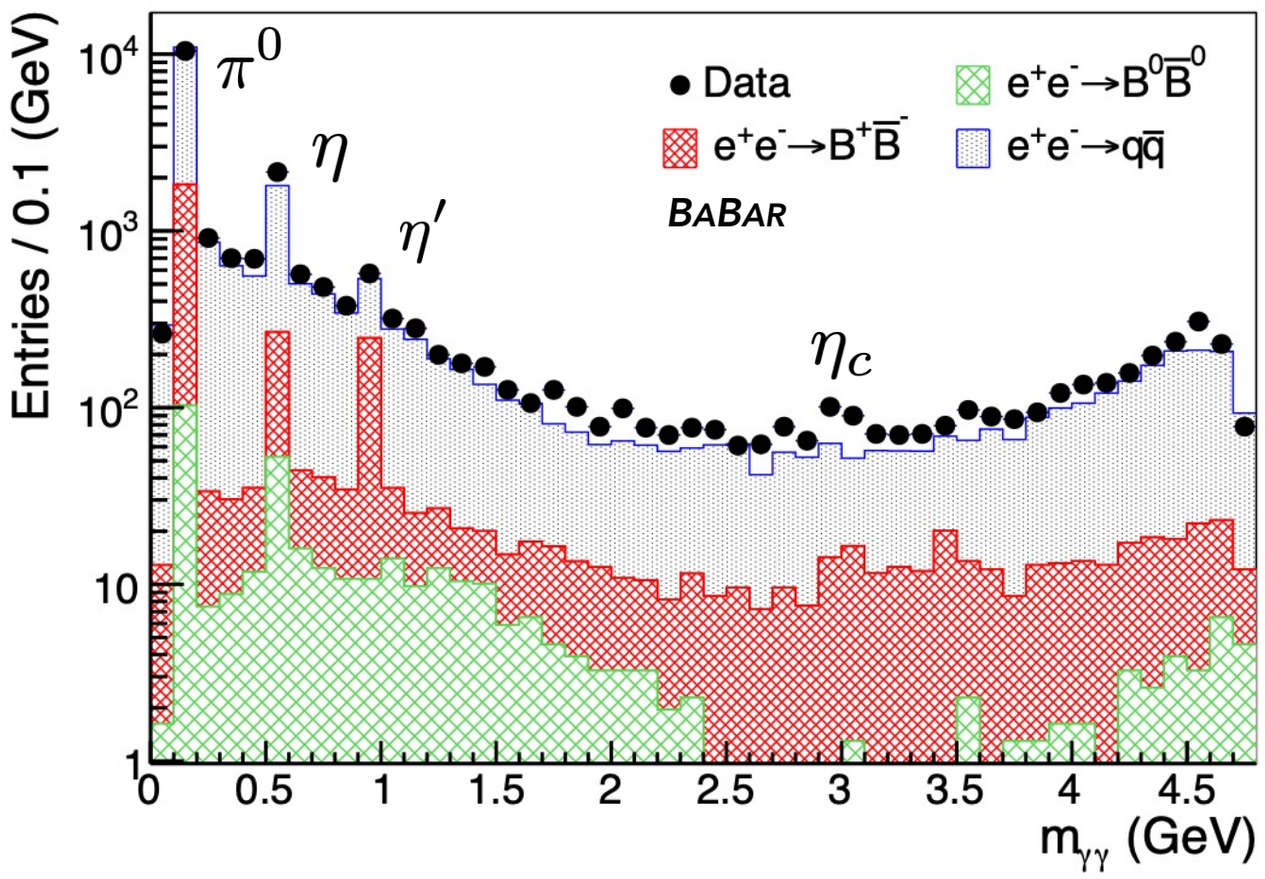
E. Izaguirre, T. Lin, BS, PRL 118, 111802 (2017), arXiv:1611.09355

See also: Belle II search for ALP-fermion coupling, arXiv:2306.02830

AXION-LIKE PARTICLES

- Reconstruct $B^{\pm} \to K^{\pm} a,\ a \to \gamma\gamma$ candidates, look for narrow peak in diphoton mass; assume prompt decays
- Train separate boosted decision trees to reject dominant backgrounds





AXION-LIKE PARTICLES

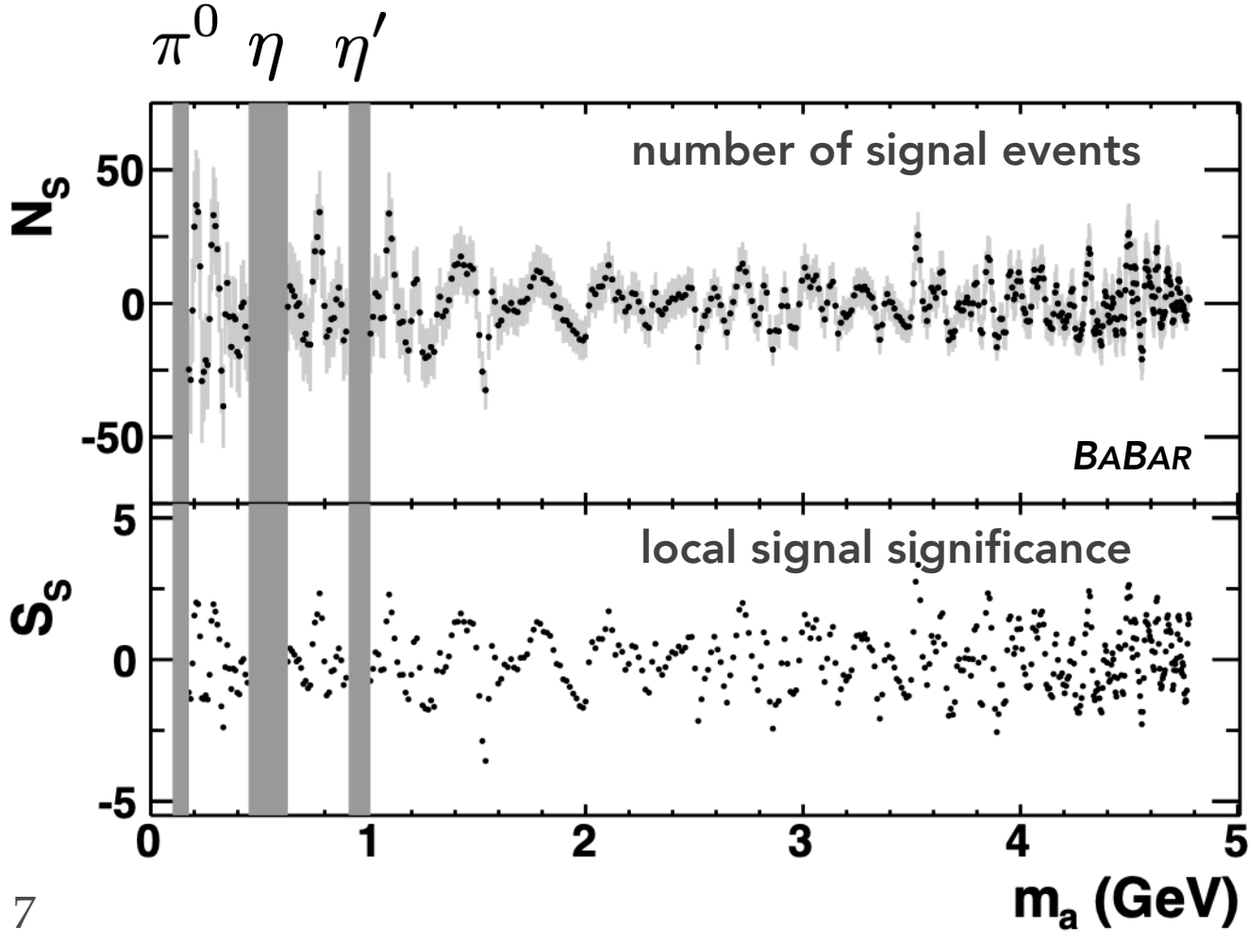
- For each mass hypothesis, fit data in a window whose size is determined by ALP mass. We do not consider signals near η, η'

- Background modeled as a smooth continuum plus a peaking component where relevant

- We see no significant signal

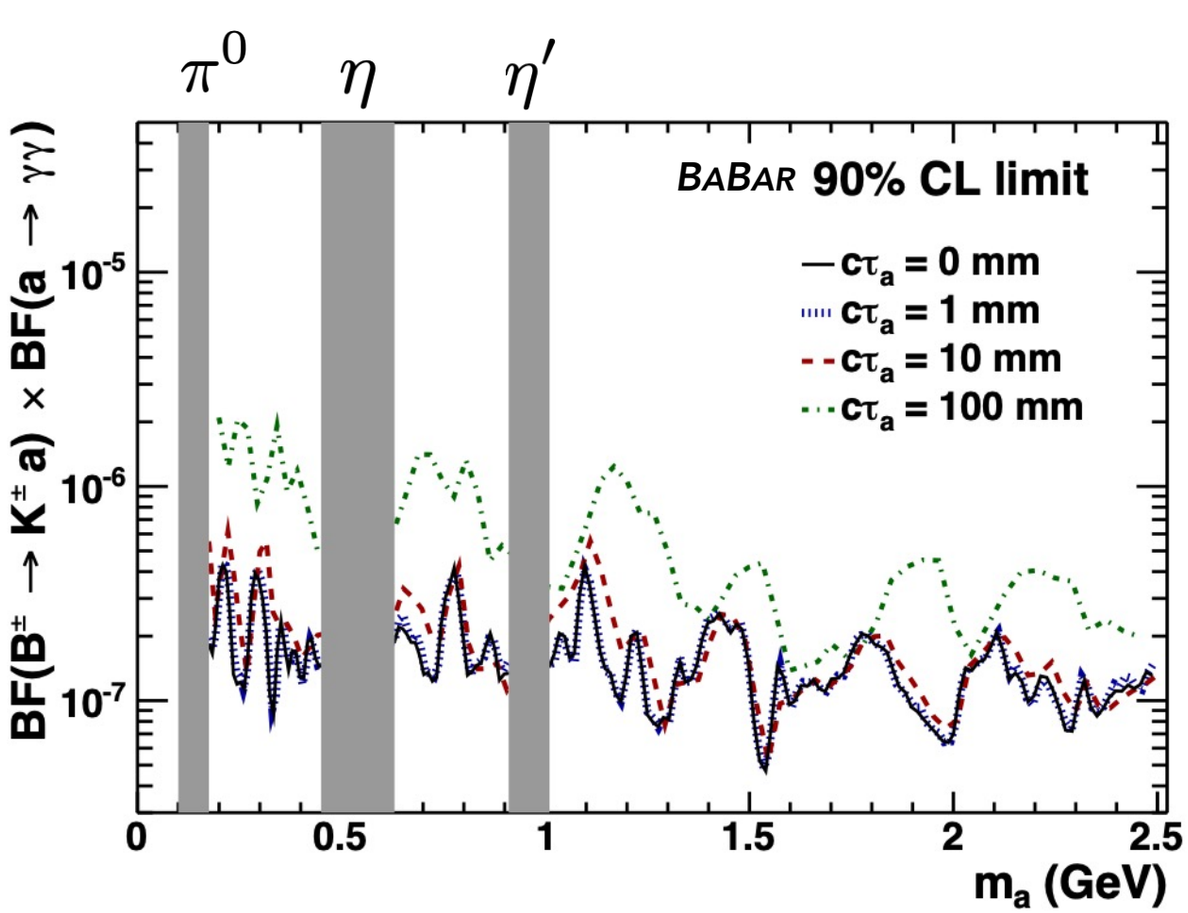
- We find that we are sensitive to ALPs with **finite lifetime**

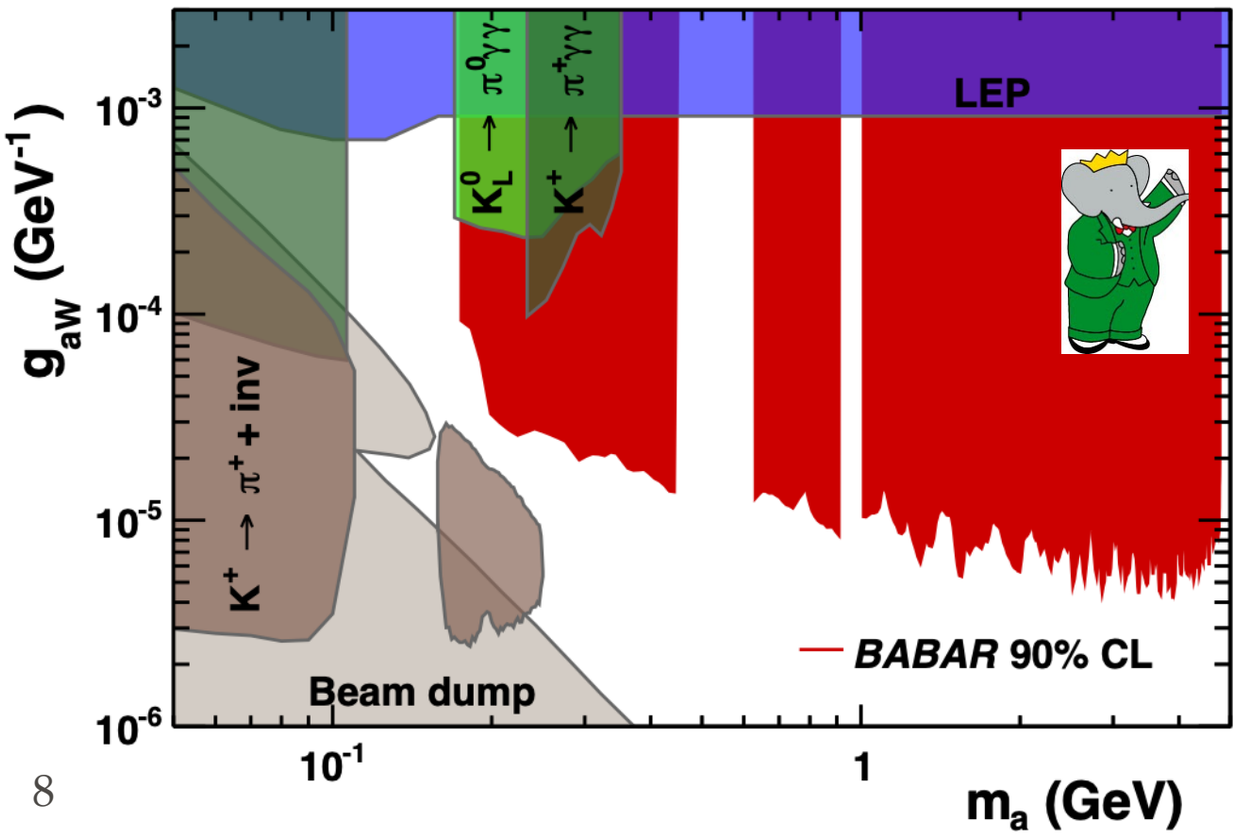
$$\Gamma_a = \frac{g_{aW}^2 \sin^4\theta_W \, m_a^3}{64\pi}$$



AXION-LIKE PARTICLES

- Re-do fits for long-lifetime signals and set 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!**

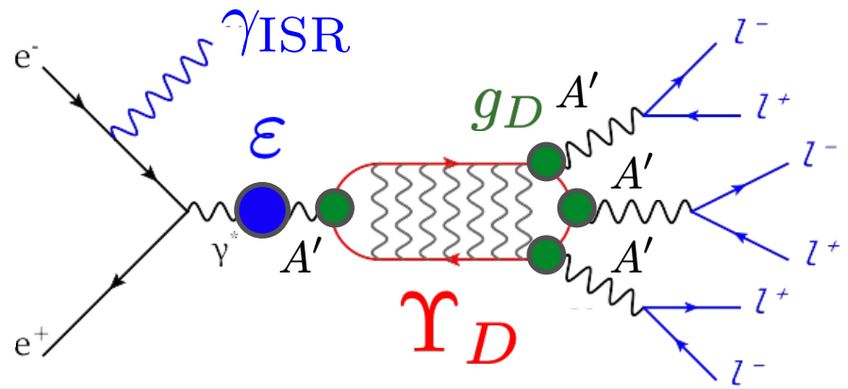




DM BOUND STATE: DARKONIUM

- Consider DM coupled to a dark photon: DM can form bound states (darkonia)!

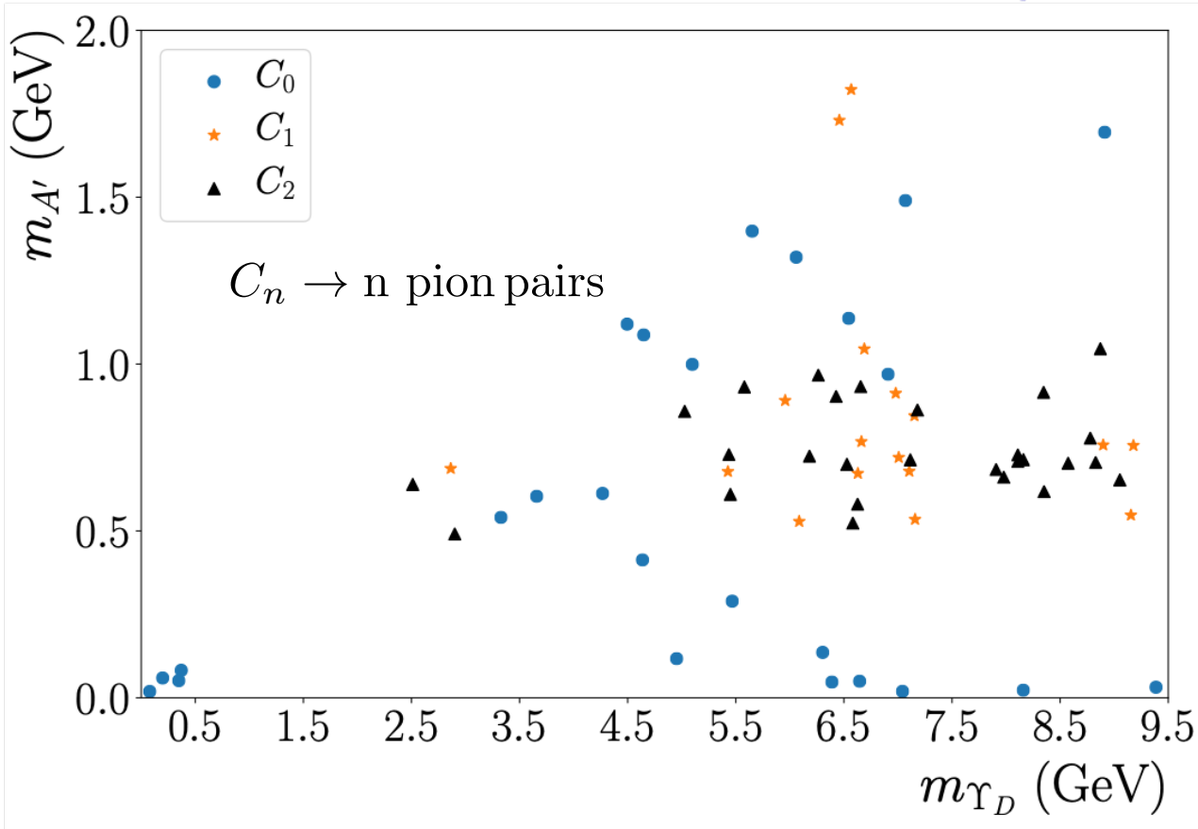
H. An et al., PRL 116, 151801, arXiv:1510.05020



- We search for the lightest vector darkonium, Υ_D

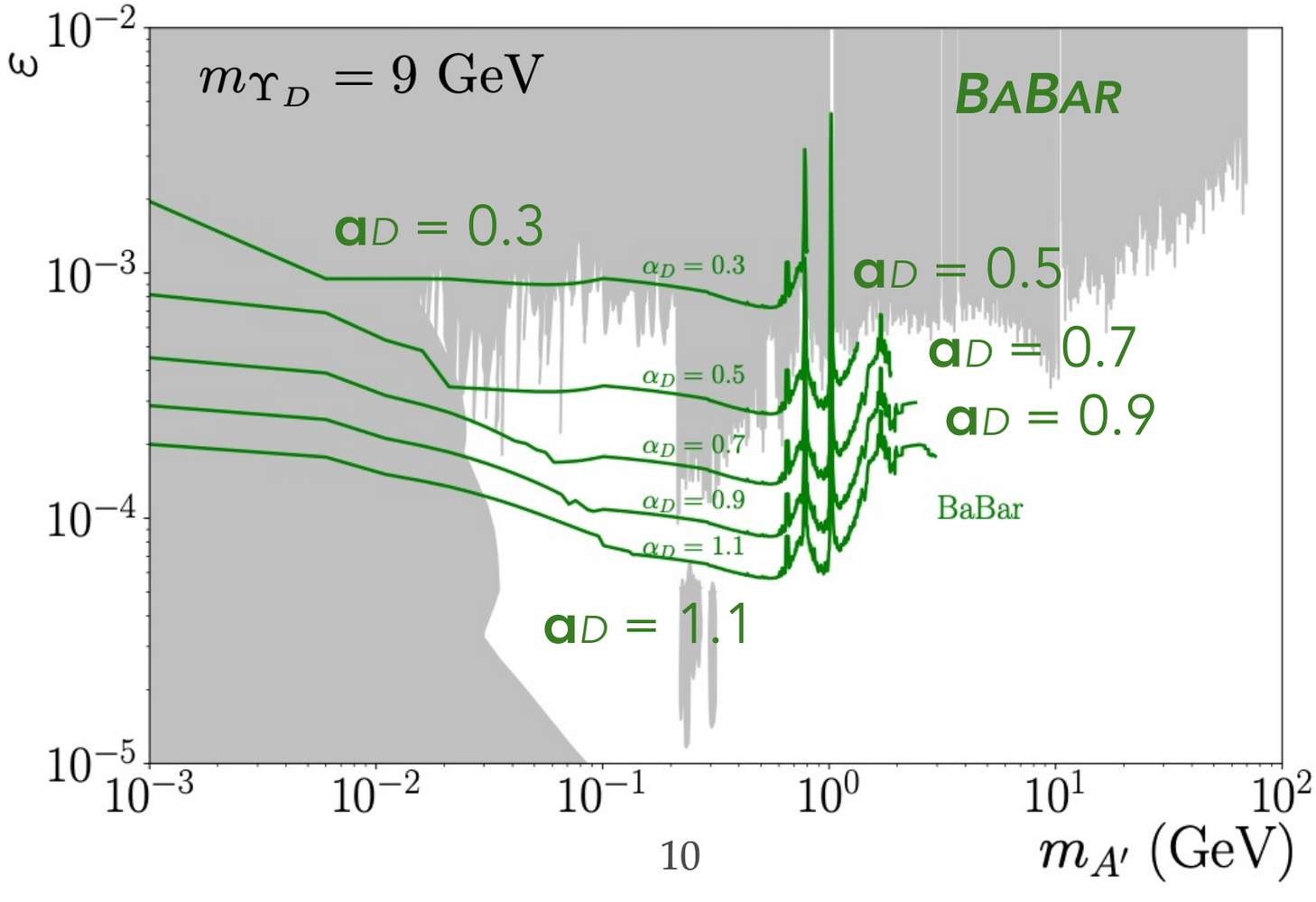
- We reconstruct dark photon decays into $e/\mu/\pi$ pairs of similar mass (min. 1 lepton pair)

- Use multivariate analysis to separate signal from background



DARKONIUM RESULTS

- Repeat analysis for long-lived *A'* decays, including information related to *A'* decay position
- In absence of significant signal, set 90% CL upper limit on kinetic mixing ε as function of DM coupling $\alpha_D \equiv g_D^2/4\pi$



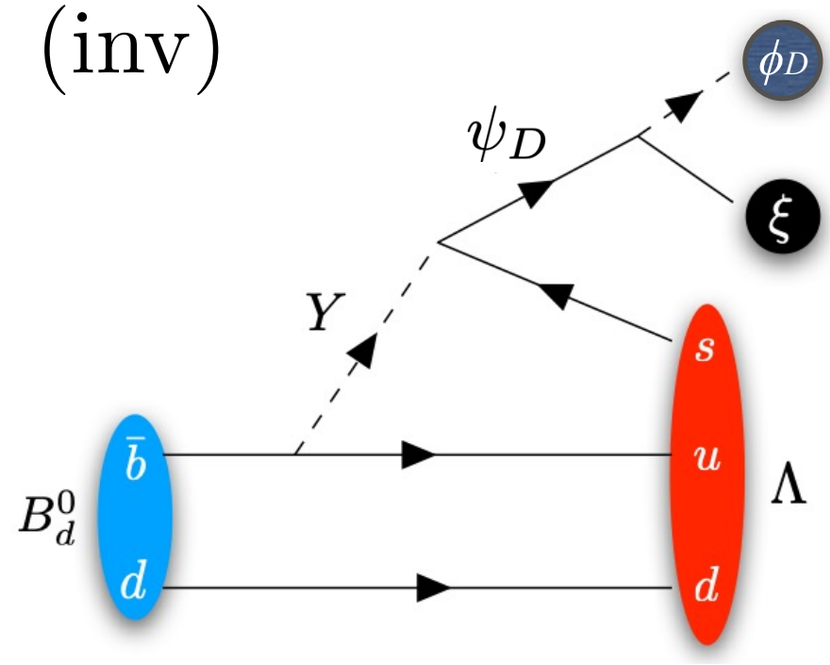
B-MESOGENESIS

- 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); F. Elahi, G. Elor, R. McGehee, PRD 105, 055024 (2022)

- Viable baryogenesis with low reheat temperatures, $T_{\rm RH} \lesssim 100\ {\rm MeV}$

$e.g.,\ B^0 \to \Lambda + \psi_D\ ({\rm inv})$



(dark baryon)

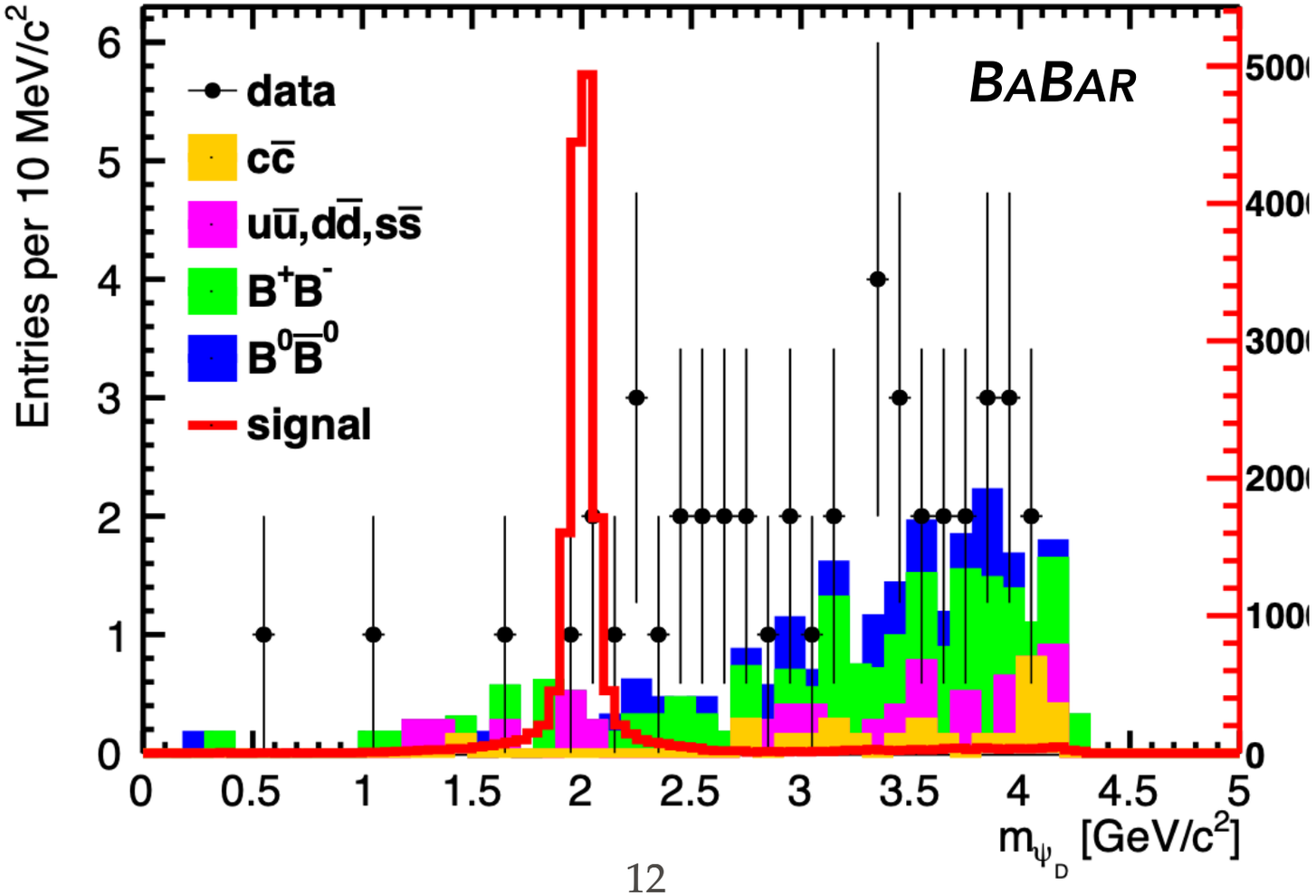
(SM baryon)

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

B-MESOGENESIS

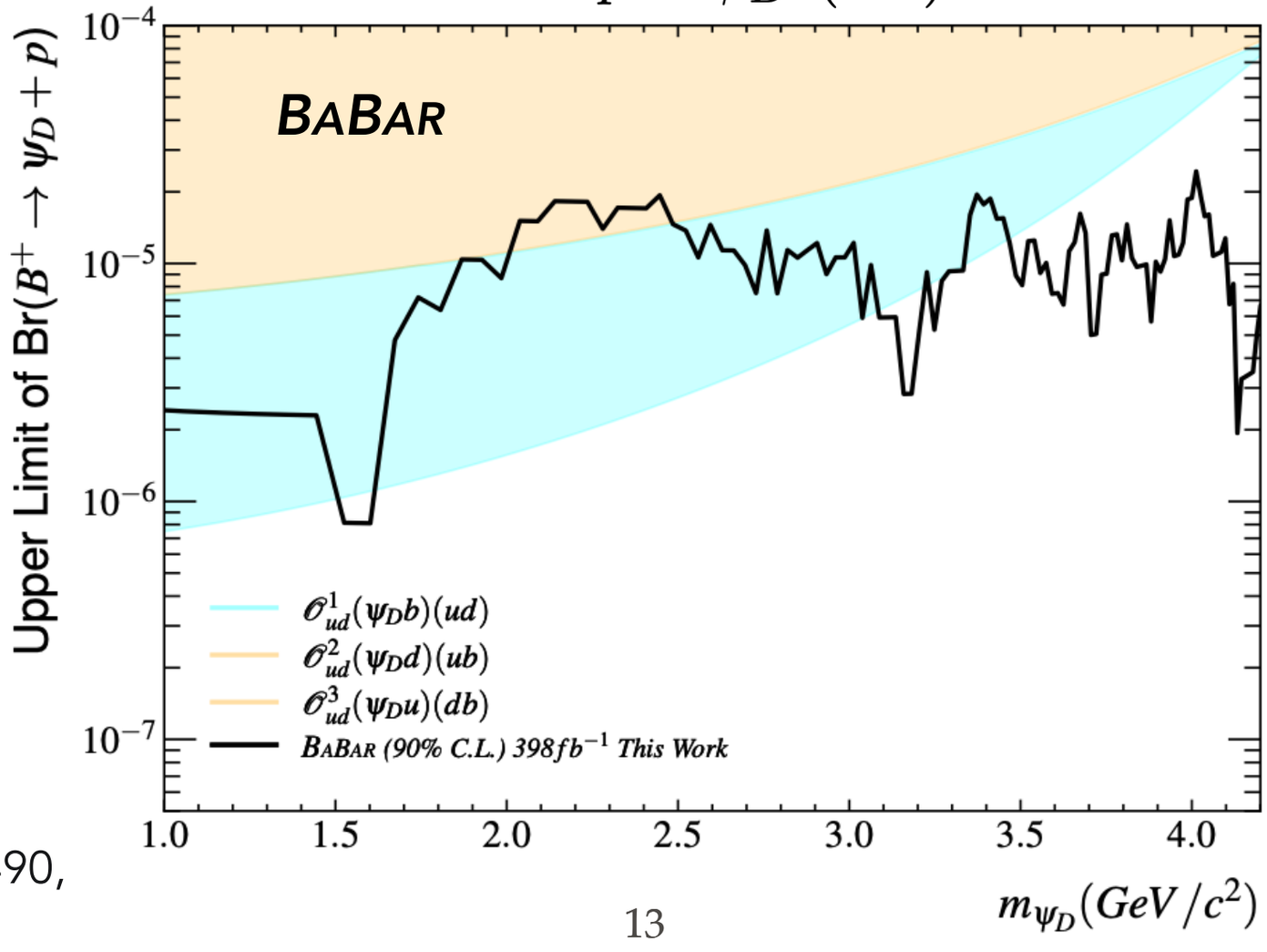
- Fully reconstruct hadronic decay of "tag" *B* meson, search for single SM baryon (Λ or p) + missing mass from signal *B* decay
- Use data to derive MC corrections due to missing decay modes

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



B-MESOGENESIS RESULTS

- No significant signal is seen: set 90% CL limits on signal branching fraction
- Shaded regions are branching fractions predicted from mesogenesis



BABAR, arXiv:2306.08490, submitted to PRL

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

- Presented three recent searches: axionlike particles, DM bound states, and non-thermal models of baryogenesis + DM

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

BACKUP SLIDES

ALP SELECTIONS

- **Preselection:** Reconstruct $B^{\pm}$ candidates from $K^{\pm}$ candidate and two photons
  - Require $$m_{\mathrm{ES}} = \sqrt{\frac{(s/2 + \vec{p}_i \cdot \vec{p}_B)^2}{E_i^2} - p_B^2} > 5.0 \text{ GeV}$$
    $$|\Delta E| = |\sqrt{s}/2 - E_B^{\mathrm{CM}}| < 0.3 \text{ GeV}$$
    - 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 $m_a = 0.175\ \mathrm{GeV}$ to 14 MeV at $m_a = 2\ \mathrm{GeV}$, decreasing back to 2 MeV at $m_a = 4.78\ \mathrm{GeV}$ 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 $m_a = 4.78\ \mathrm{GeV}$ to 33% at $m_a = 2\ \mathrm{GeV}$

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

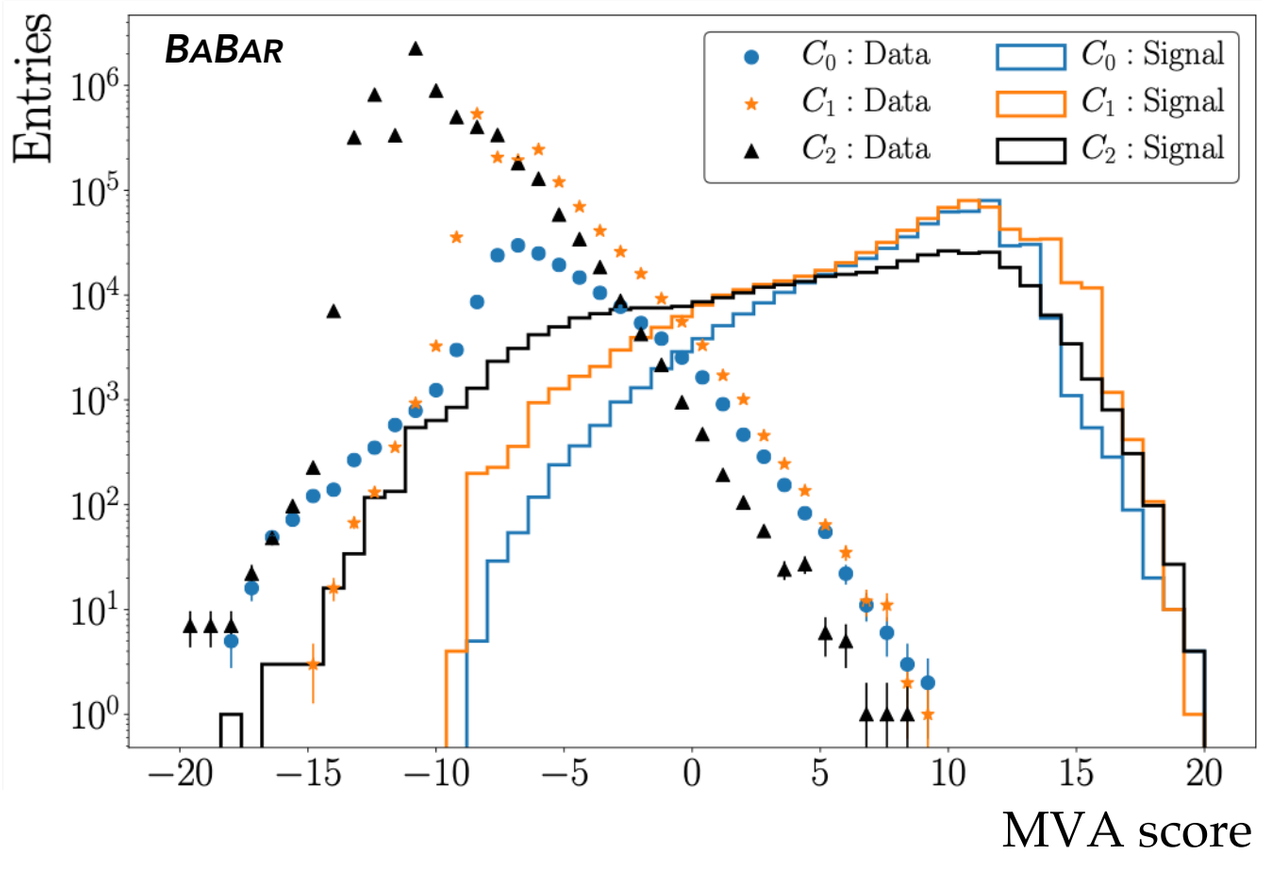
- **Peaking background PDF:** each SM diphoton resonance is modeled as a sum of a signal template and a broader Gaussian distribution with parameters fixed to fits in MC — this component arises from continuum production of $\pi^0/\eta/\eta'$ that is broadened because of kinematic fit

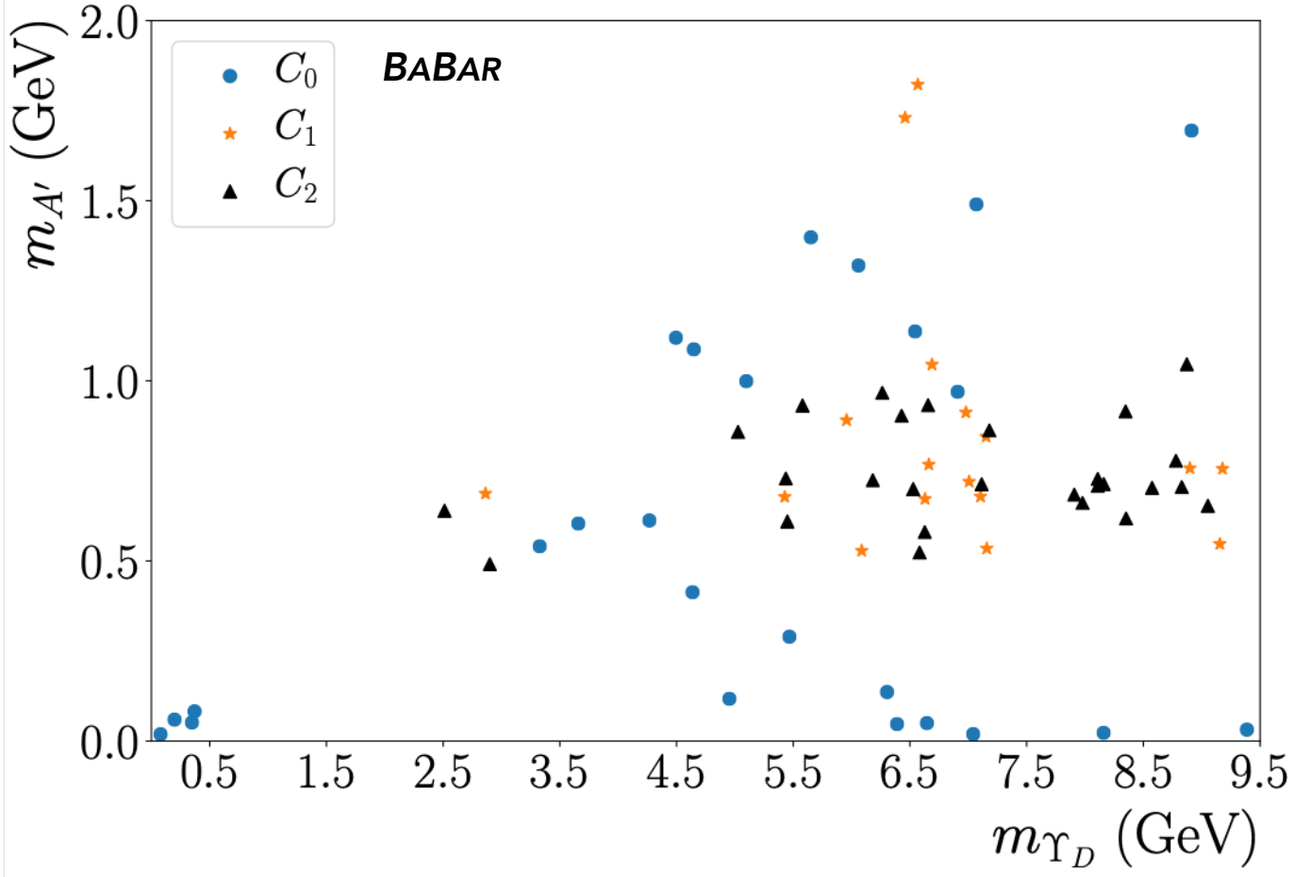
ALP SYSTEMATICS

- 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 RESULTS

- Consider windows 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





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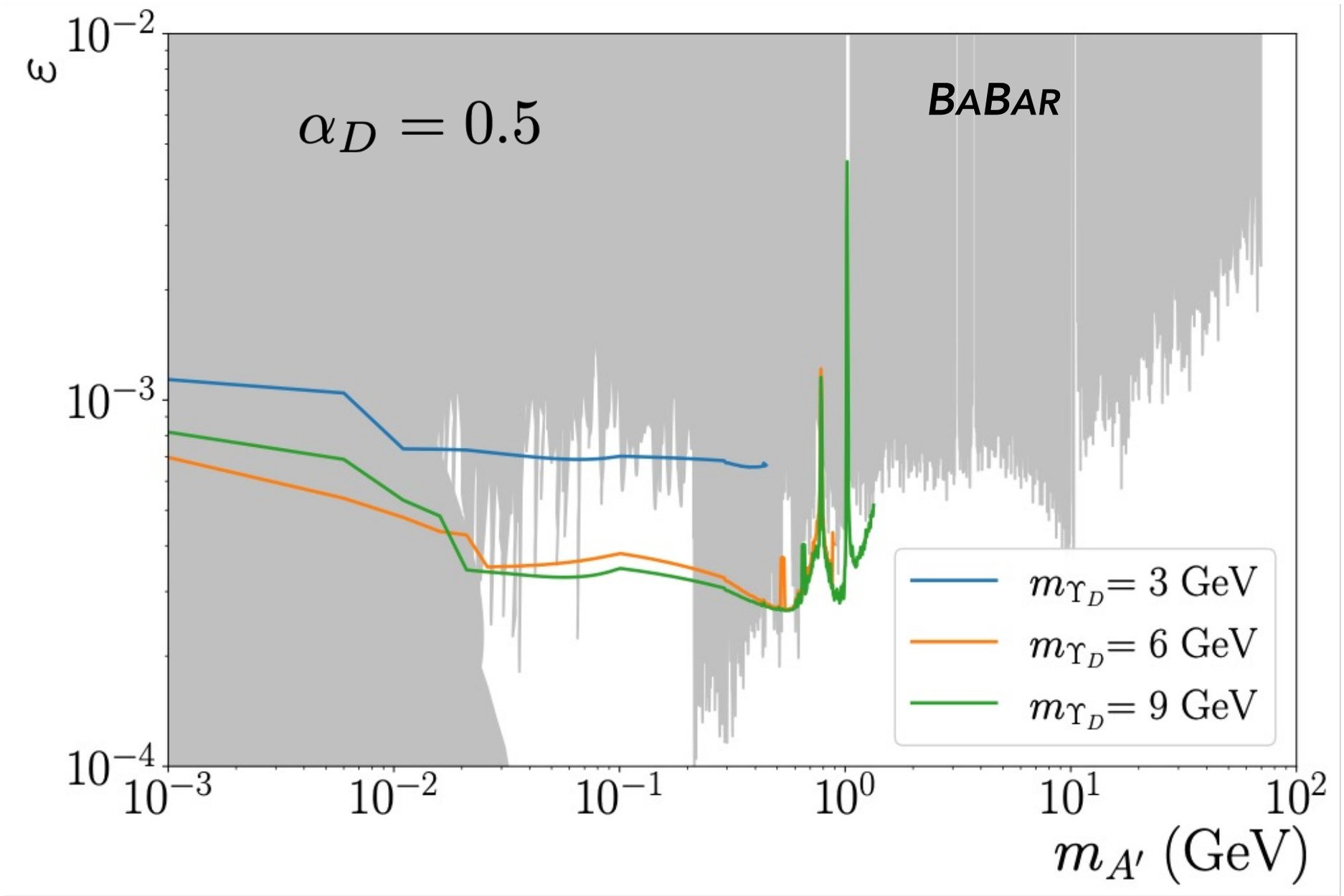
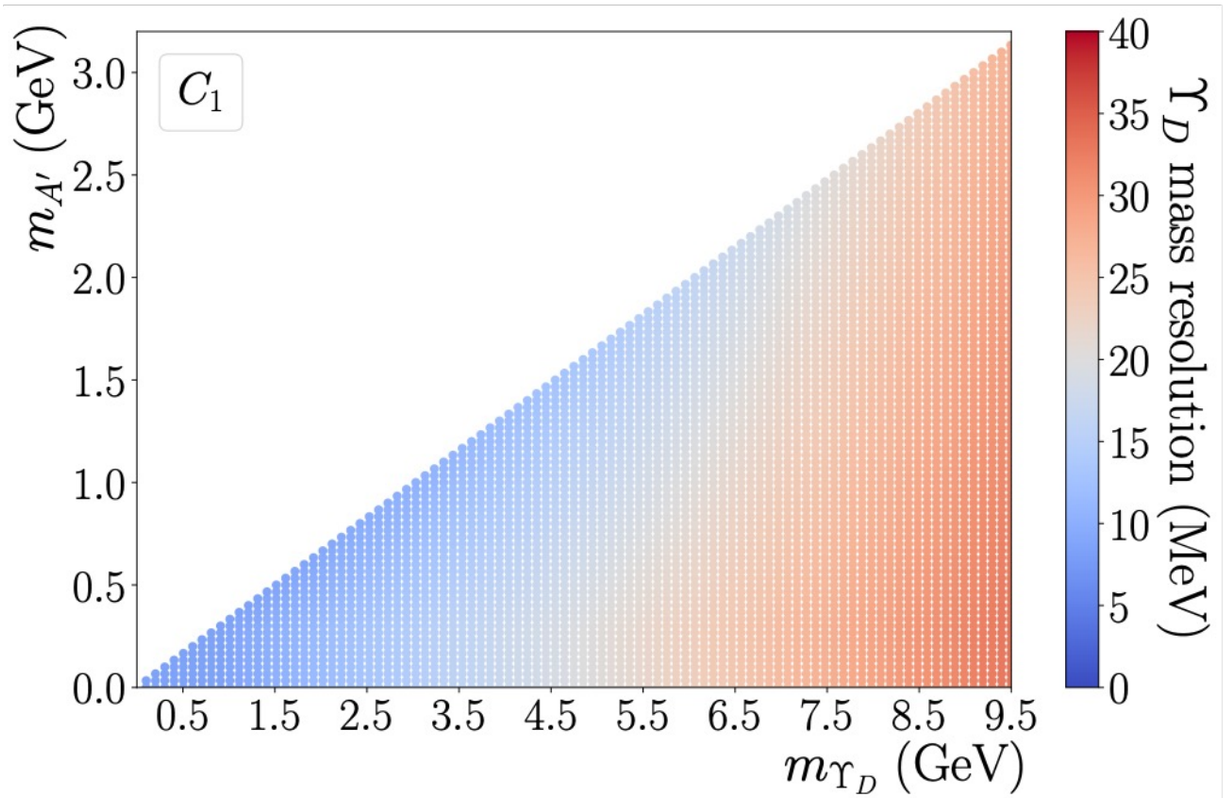
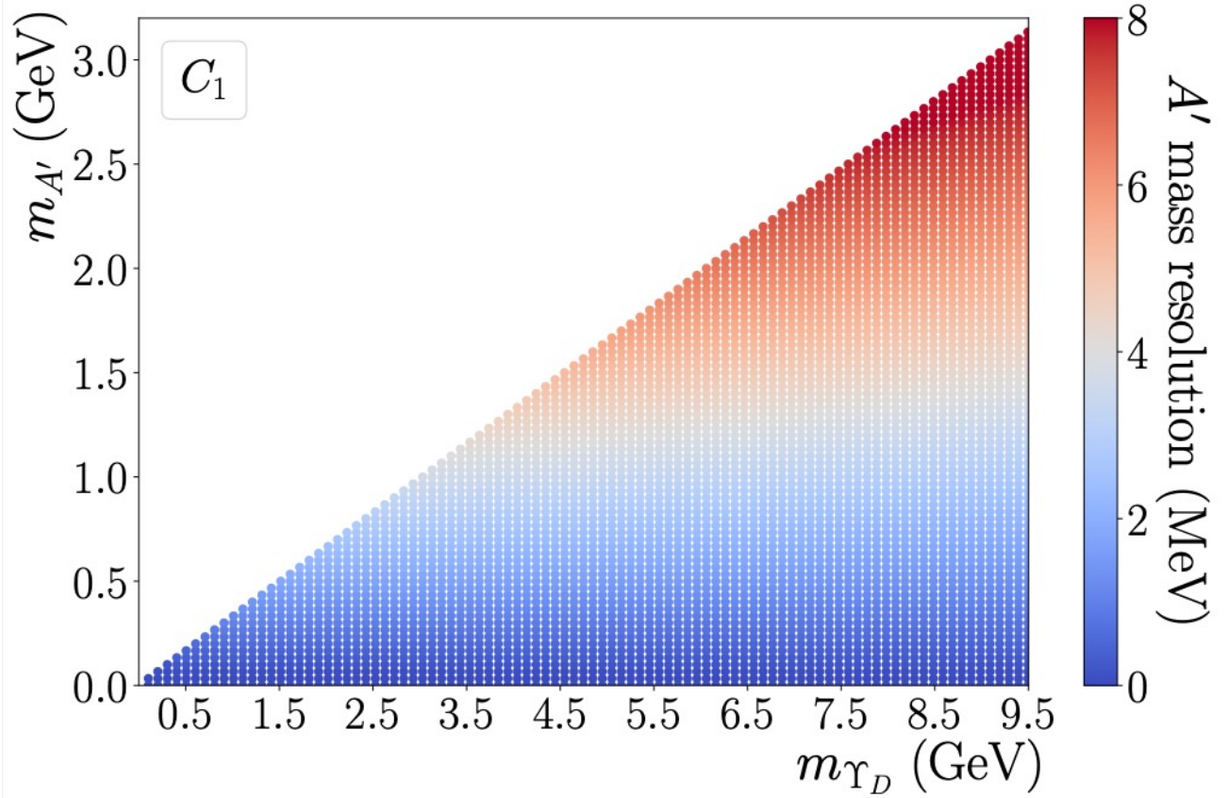
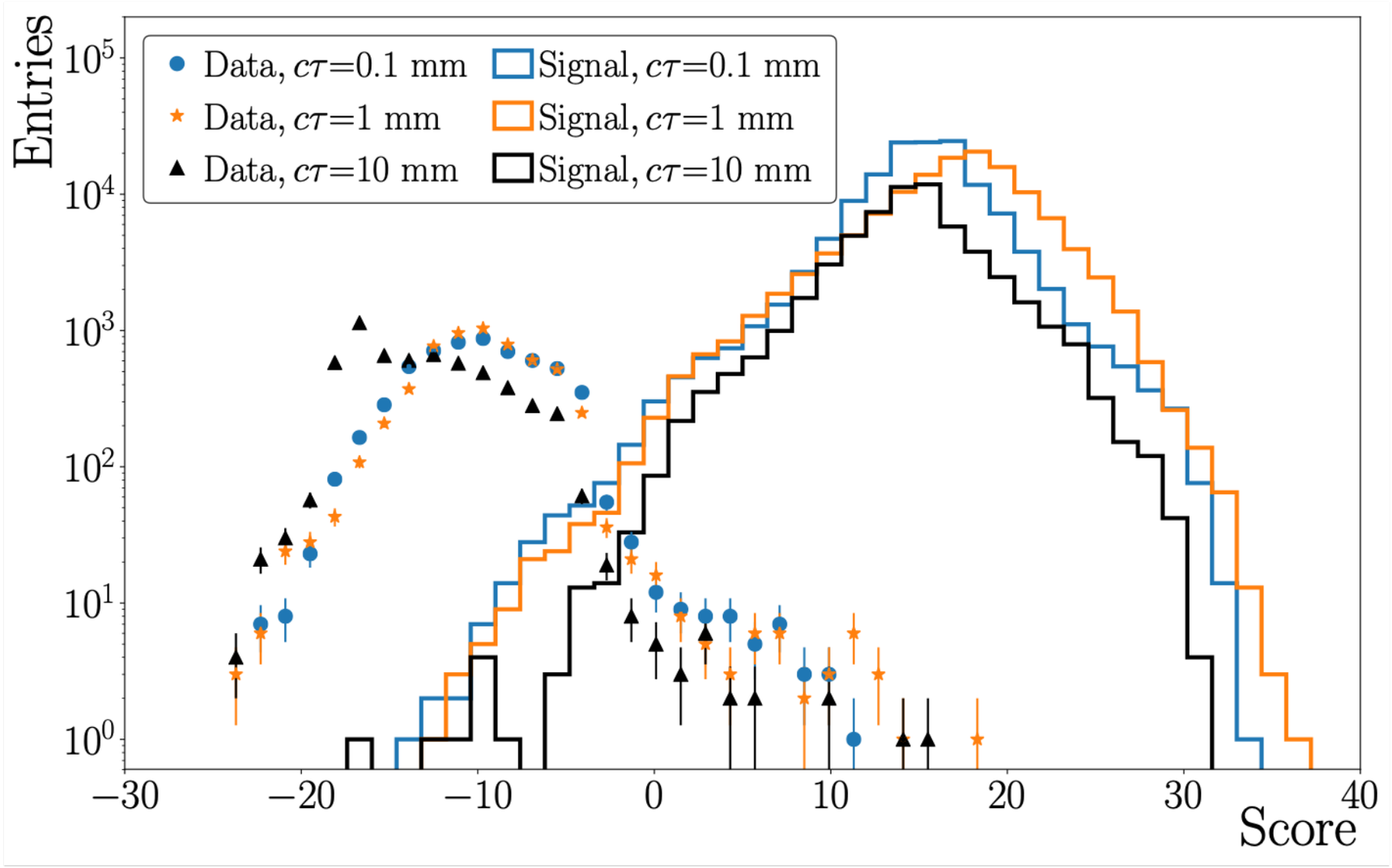


DARKONIUM: RESOLUTION





DARKONIUM: LONG-LIVED A'



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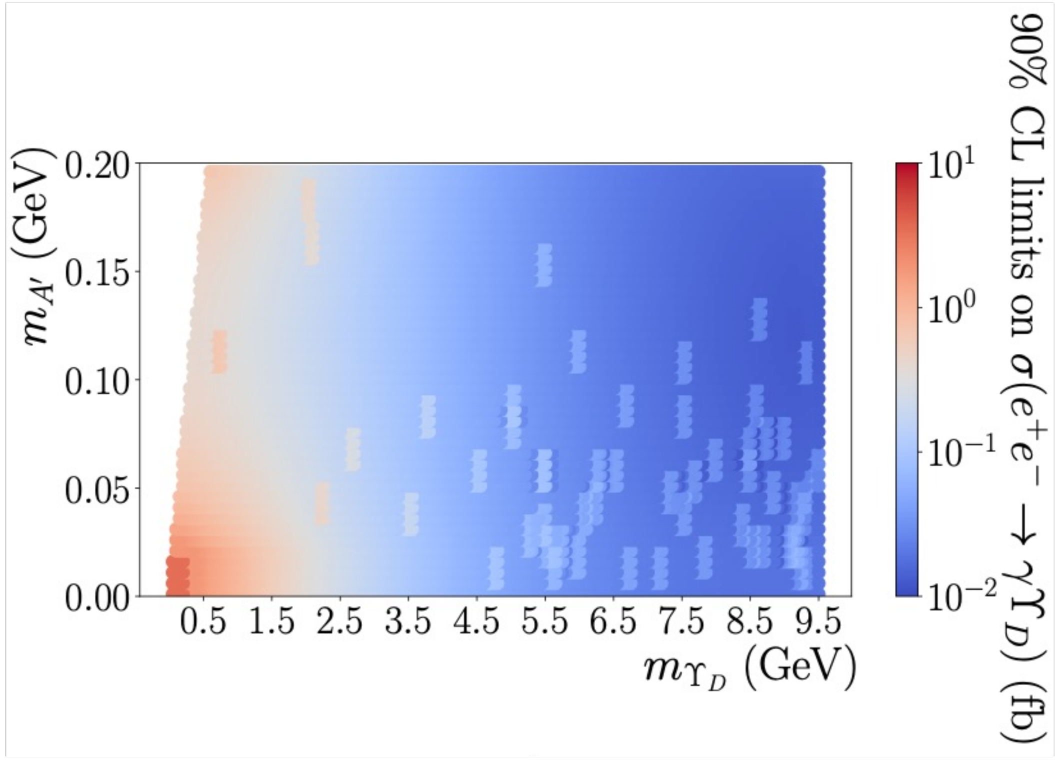
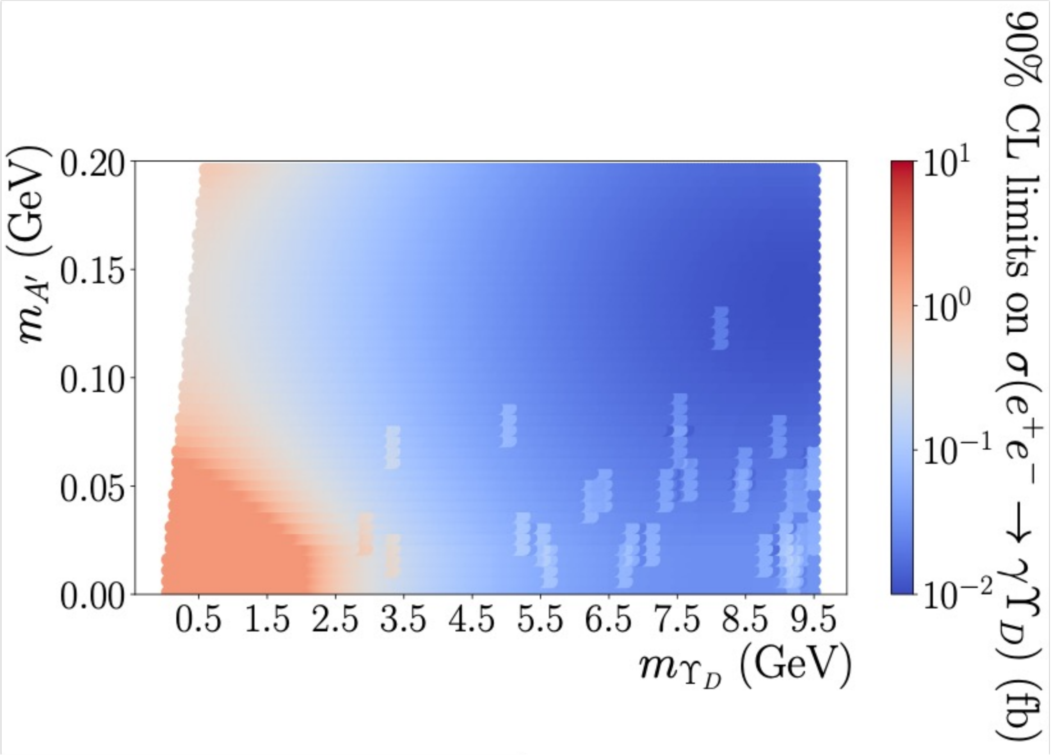
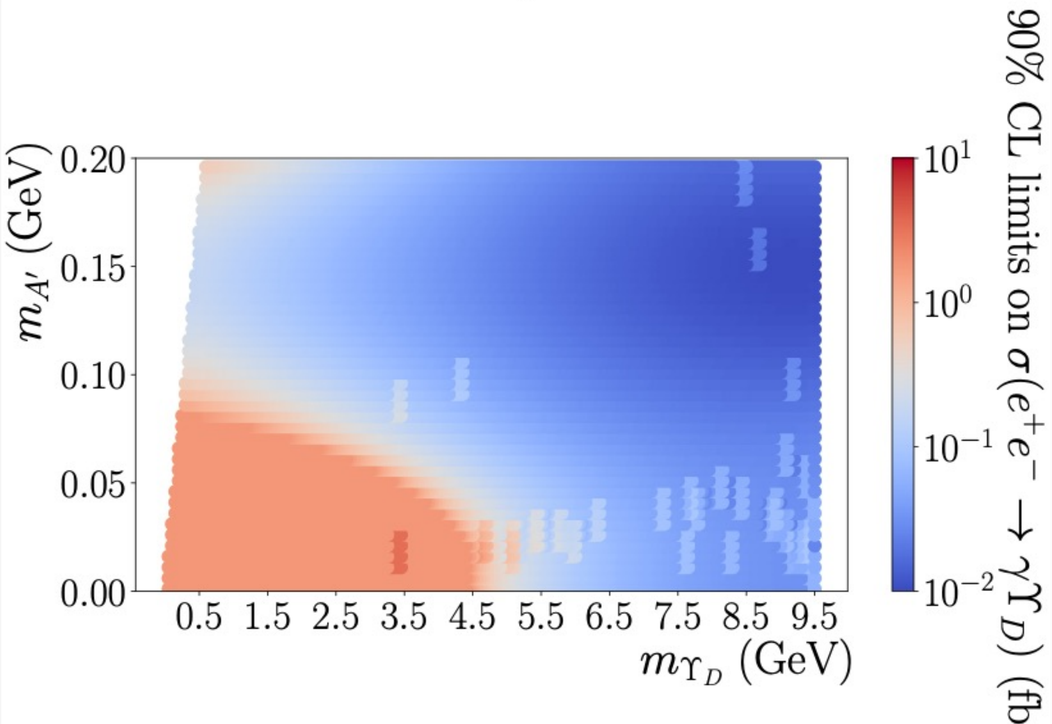




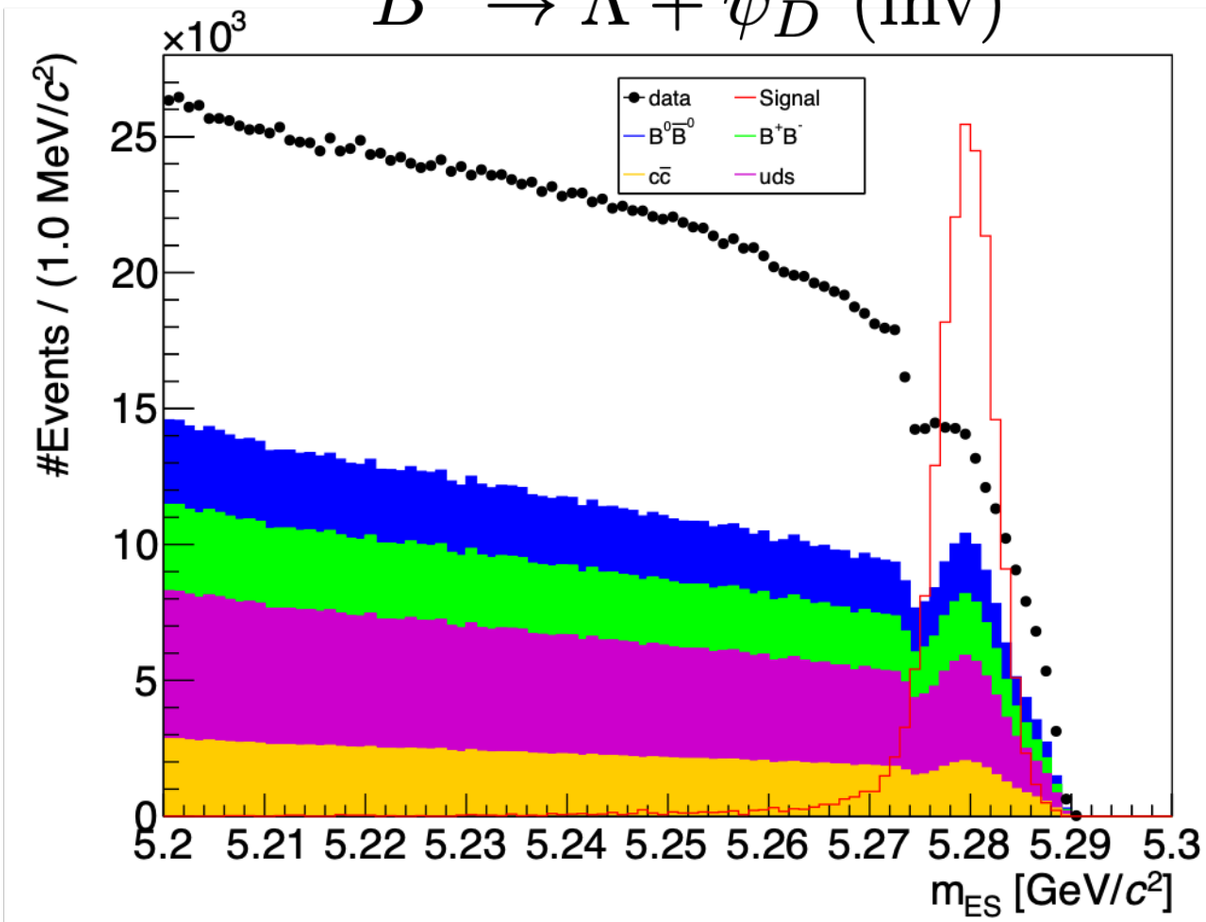


B-MESOGENESIS

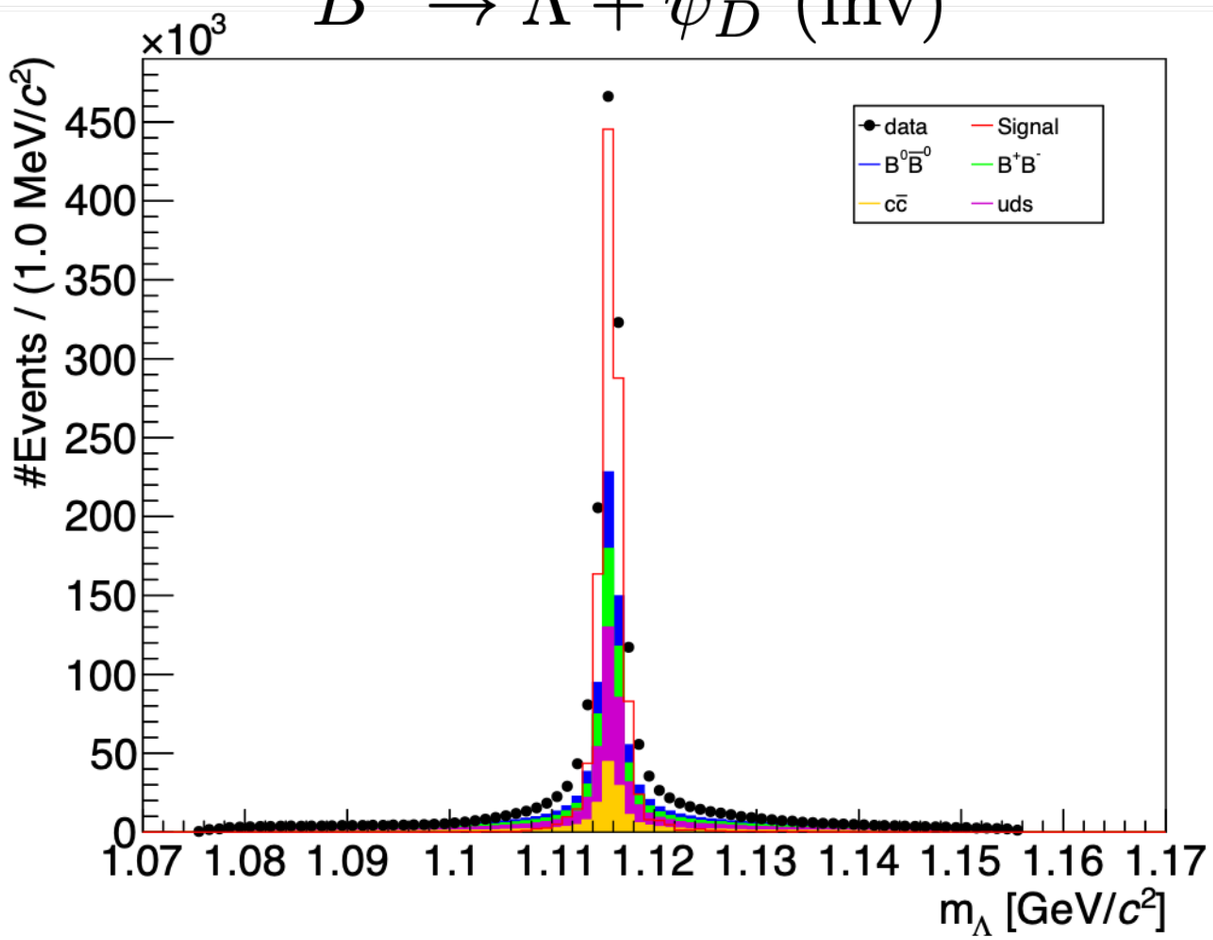
- Select events with: $5.27\ \mathrm{GeV} < m_{ES} < 5.29\ \mathrm{GeV}$

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

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



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

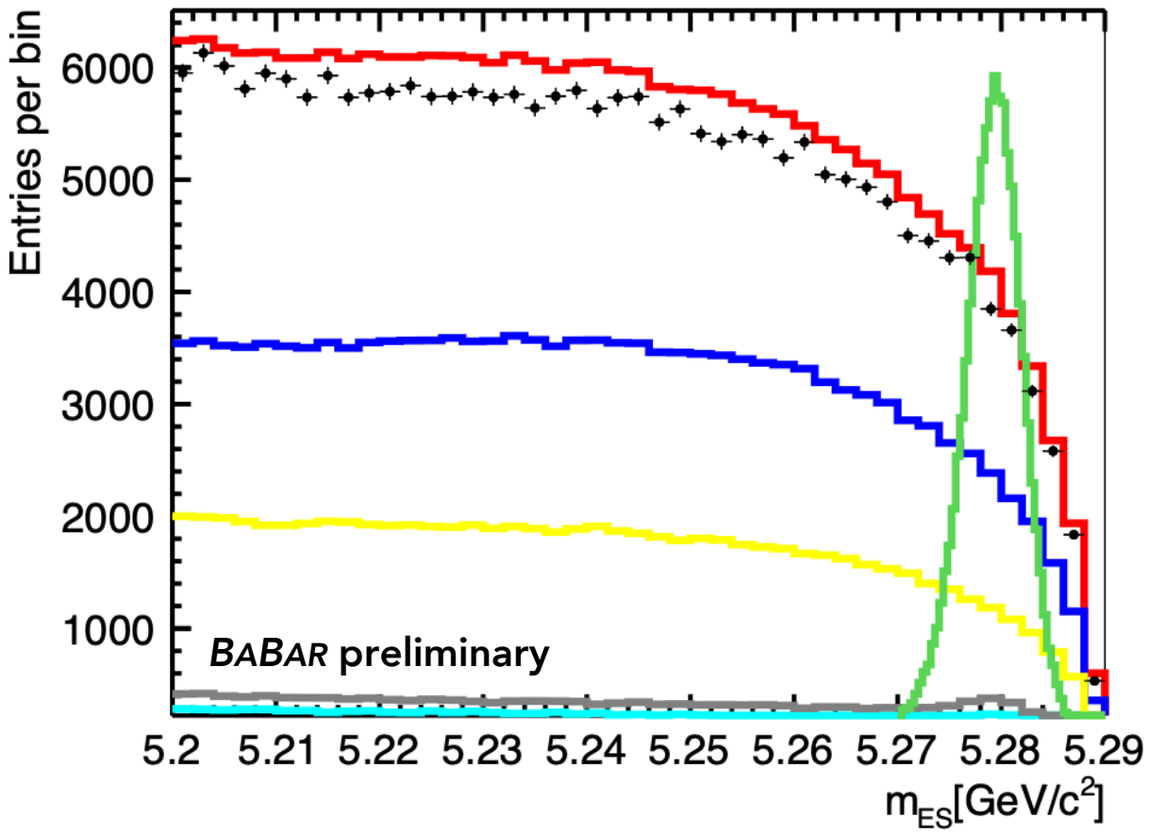


B-MESOGENESIS

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

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

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



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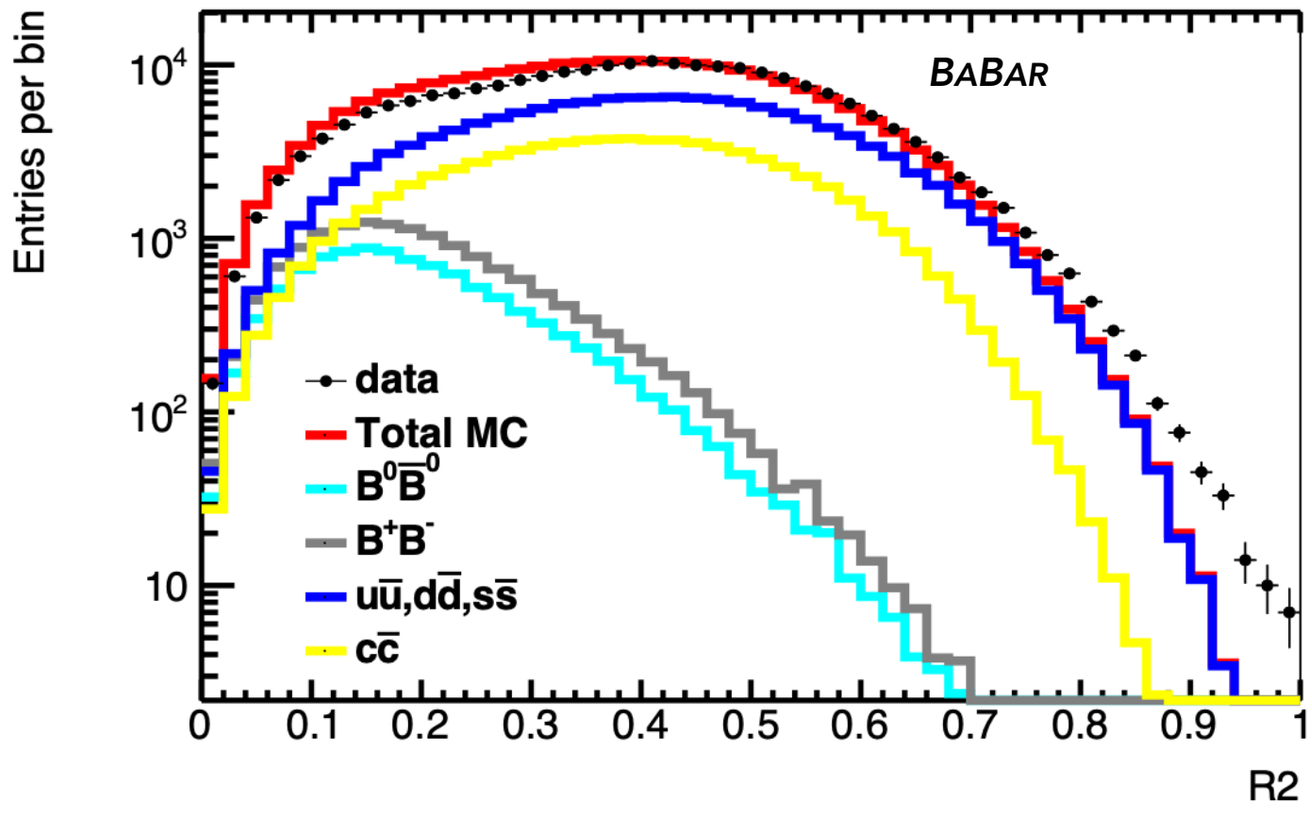
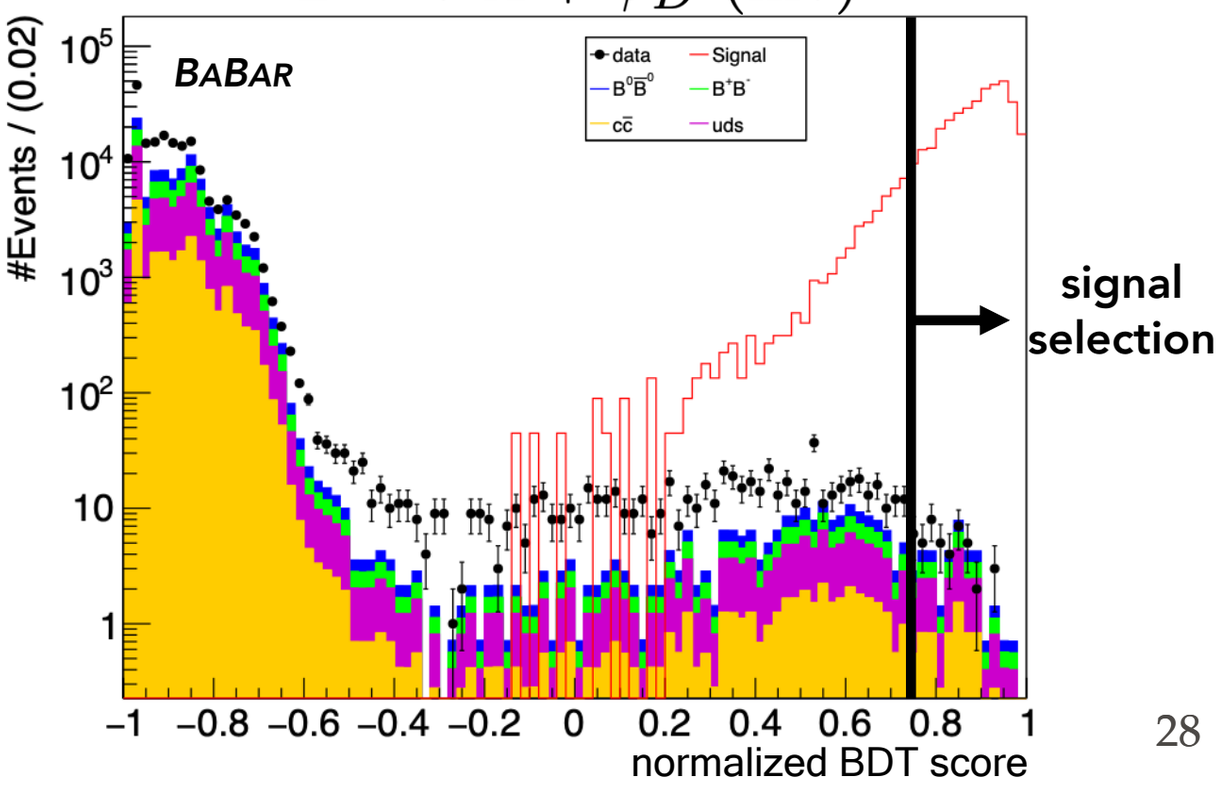


B-MESOGENESIS

- 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)



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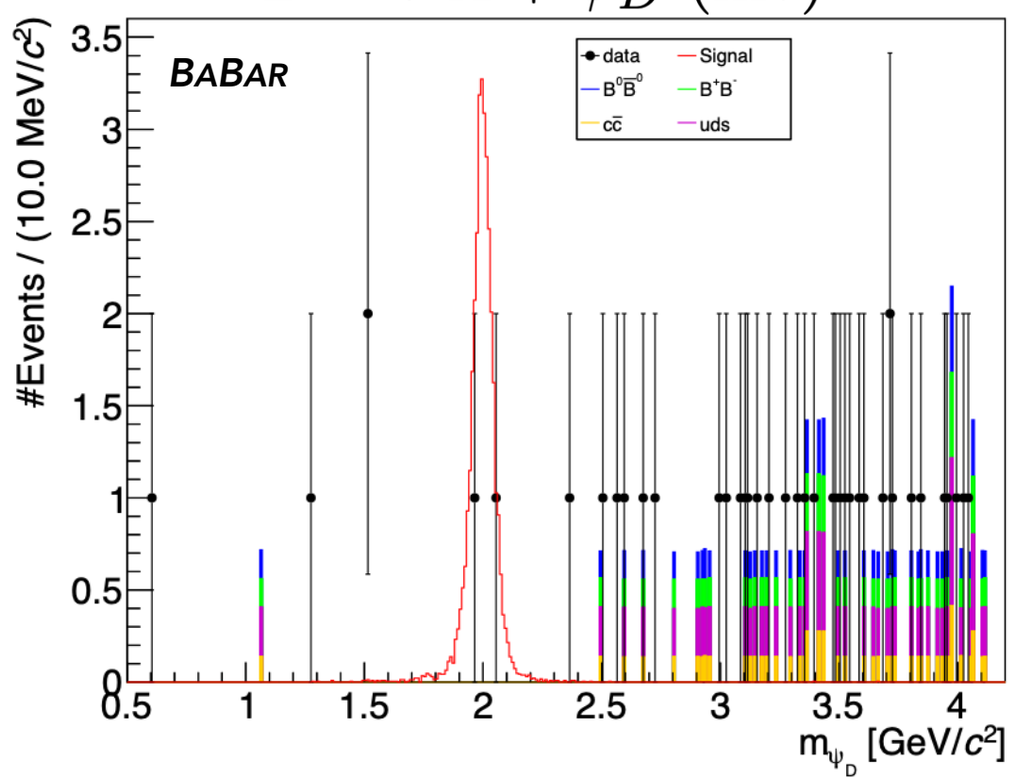

B-MESOGENESIS

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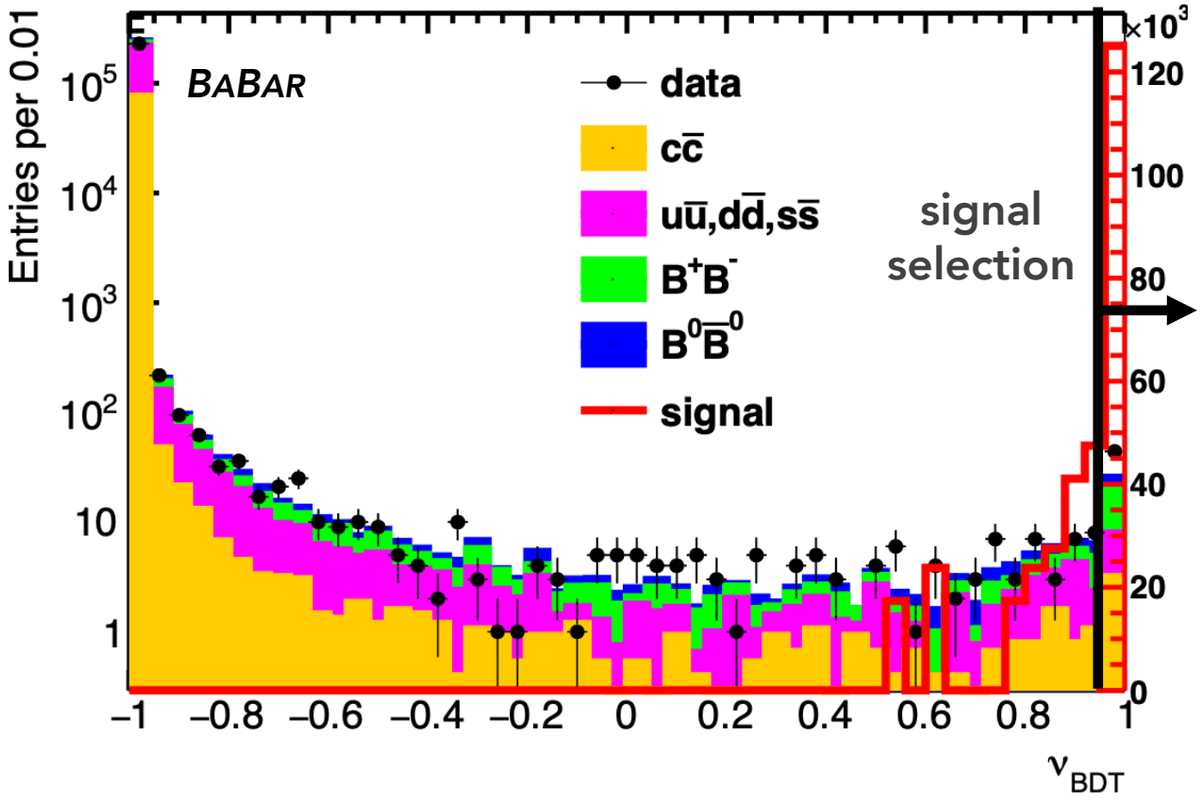

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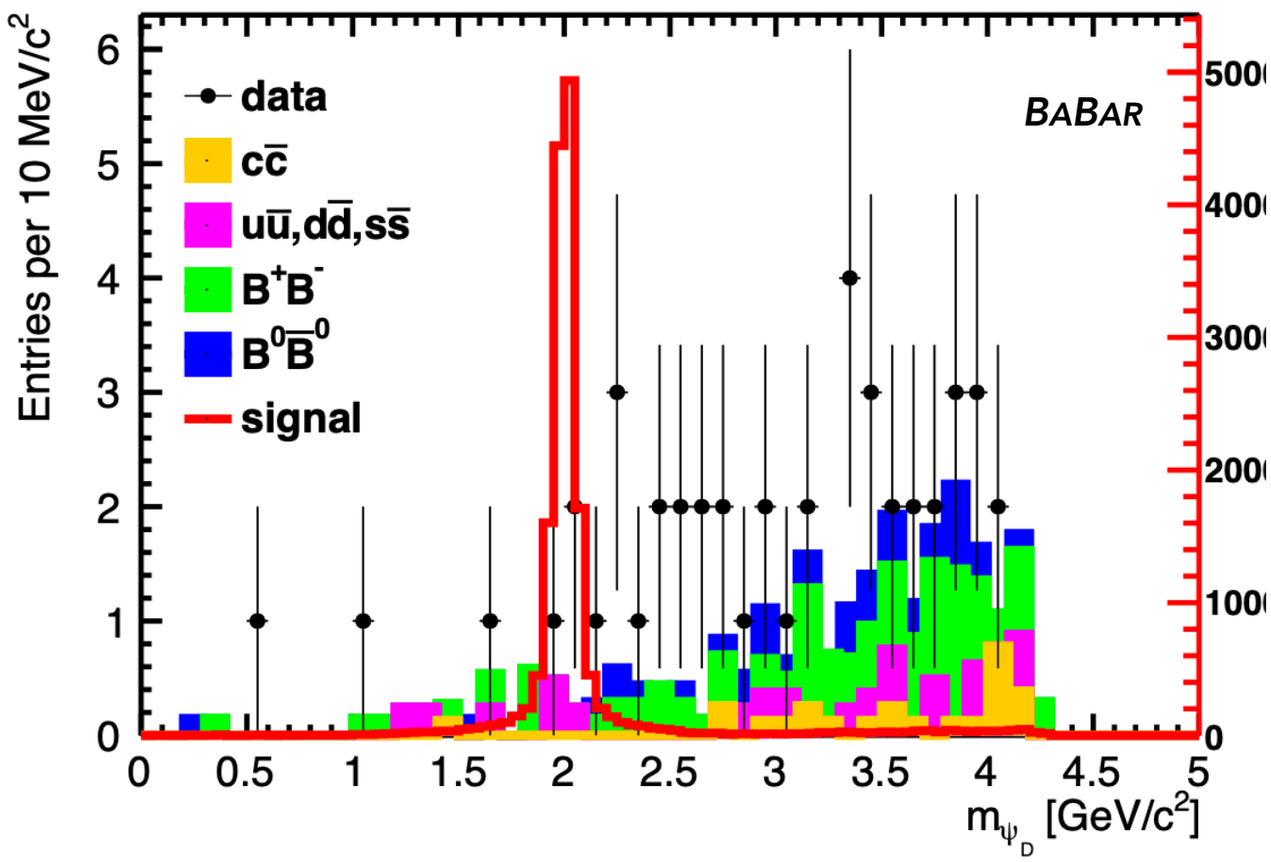
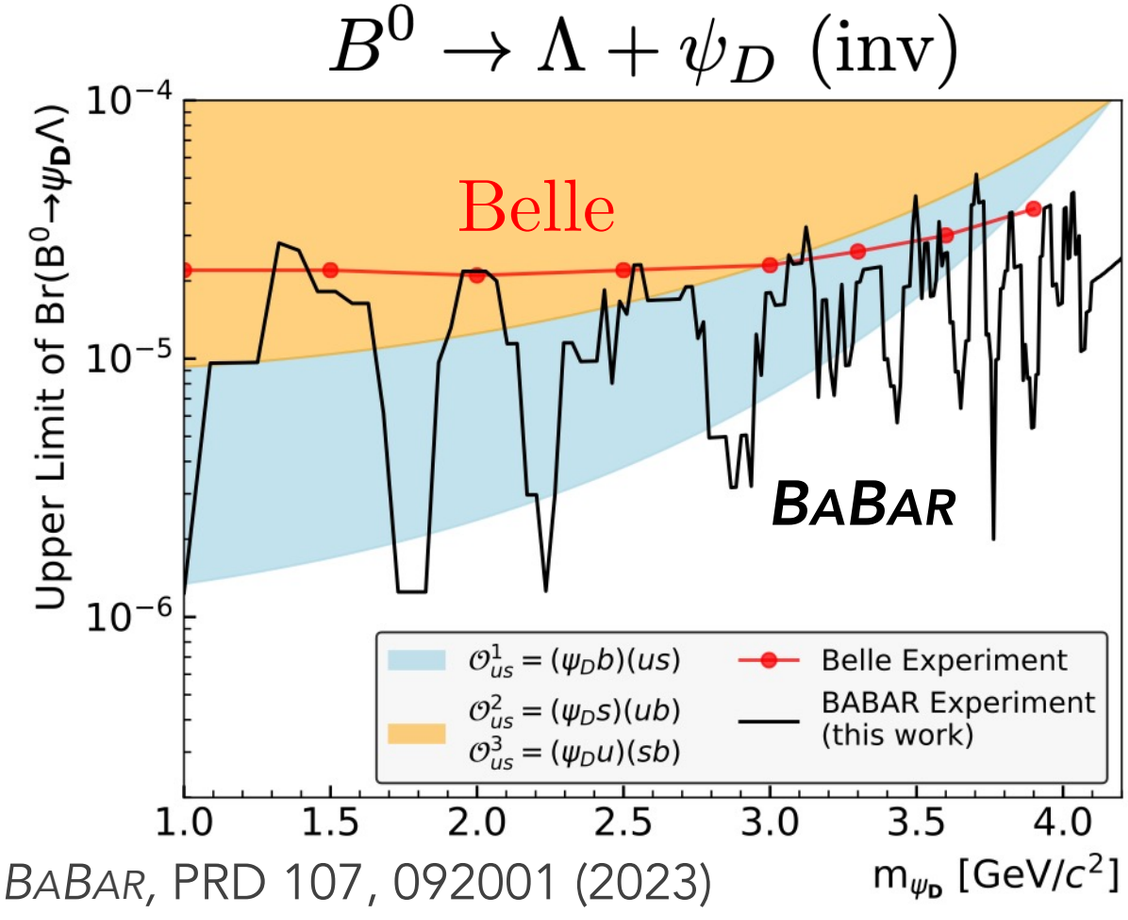
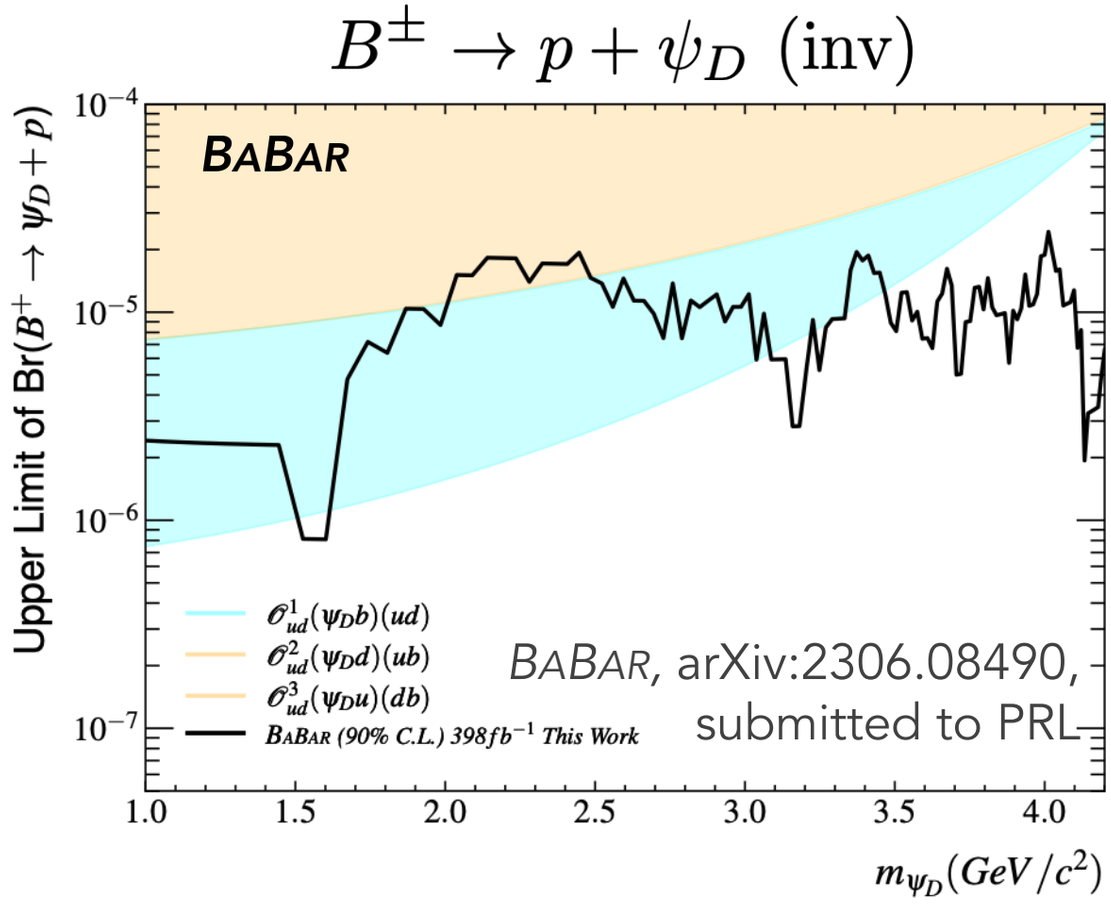


B-MESOGENESIS RESULTS

- 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
- Shaded regions are branching fractions predicted from mesogenesis



BABAR, PRD 107, 092001 (2023)

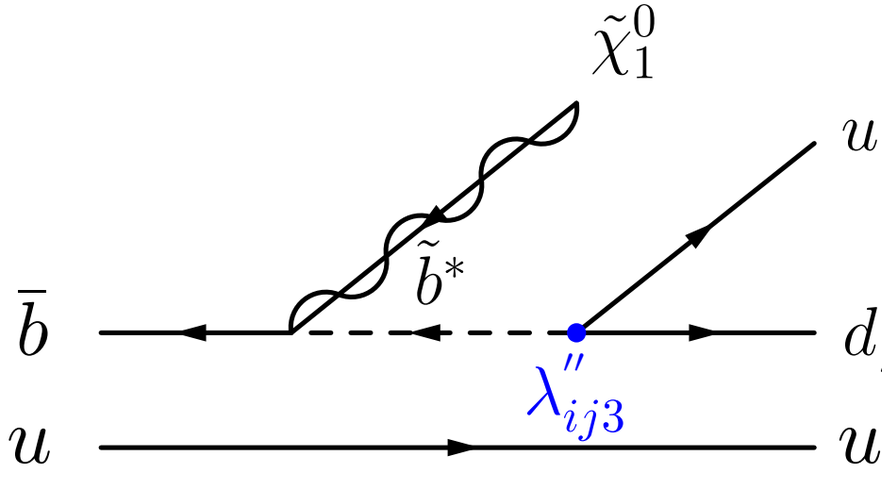


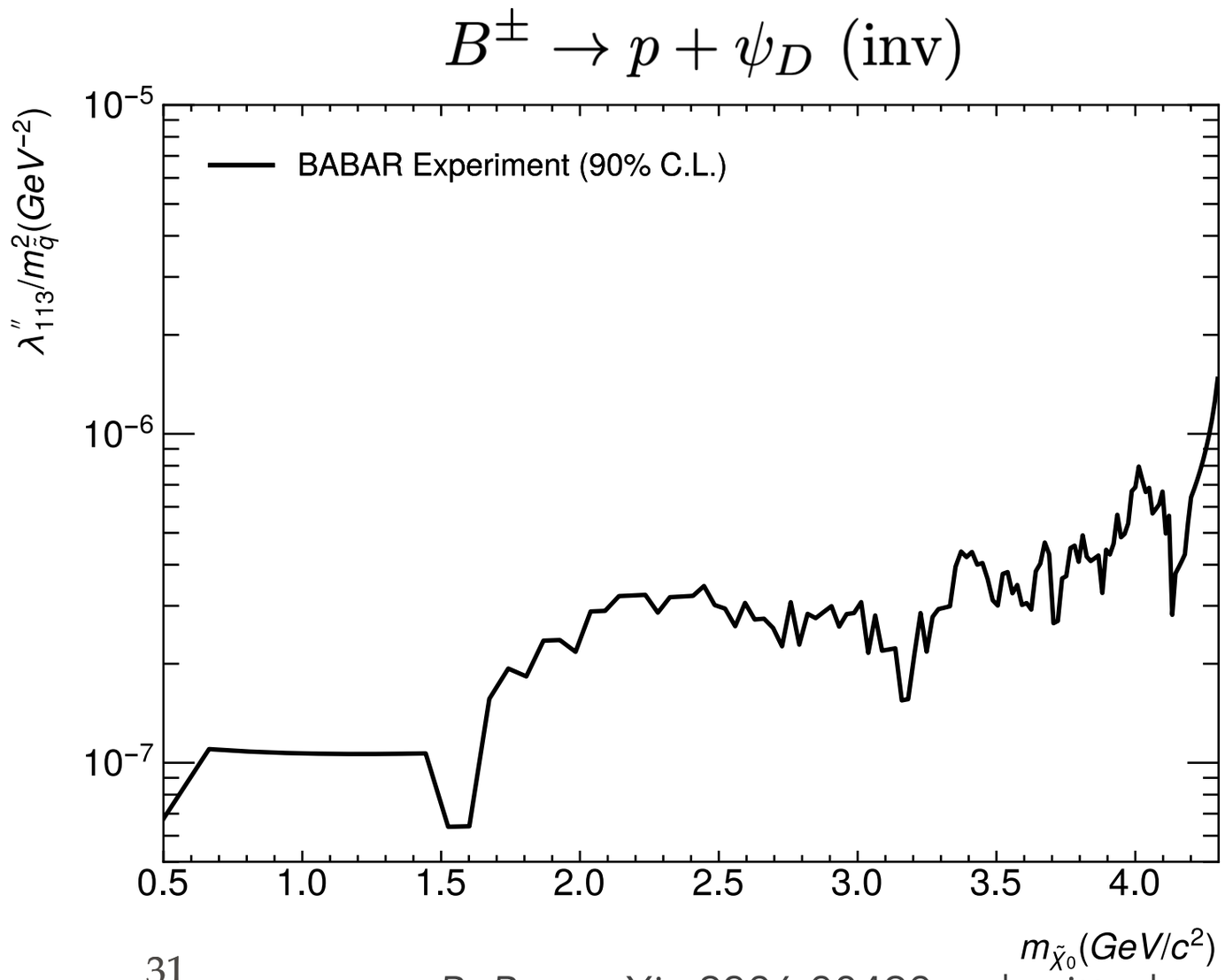
BABAR, arXiv:2306.08490, submitted to PRL

B-MESOGENESIS RESULTS

- The same results can be re-interpreted to constrain R-parity-violating supersymmetry with low-mass neutralinos

C. Dib *et al*, JHEP 02 224 (2023)





BABAR, arXiv:2306.08490, submitted to PRL