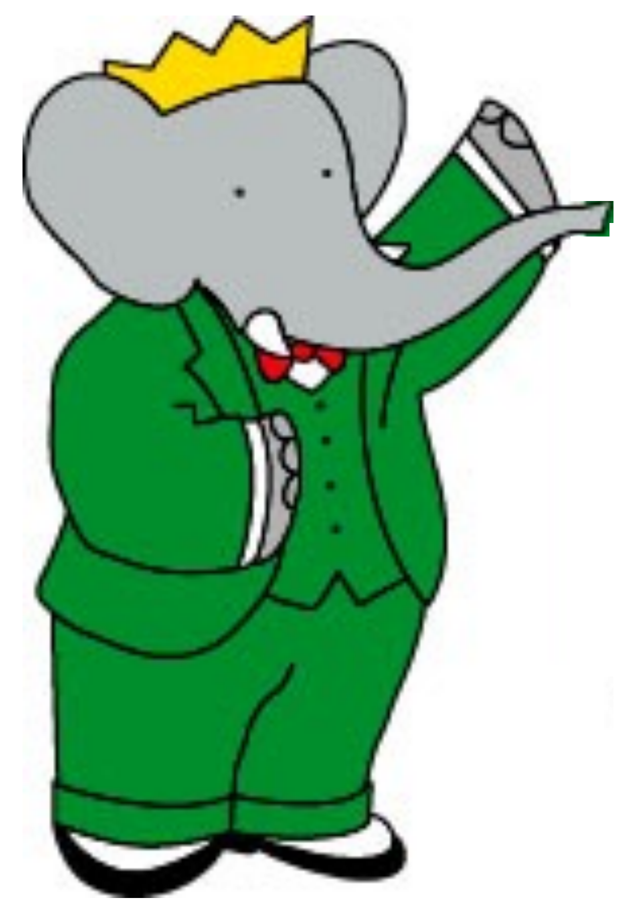
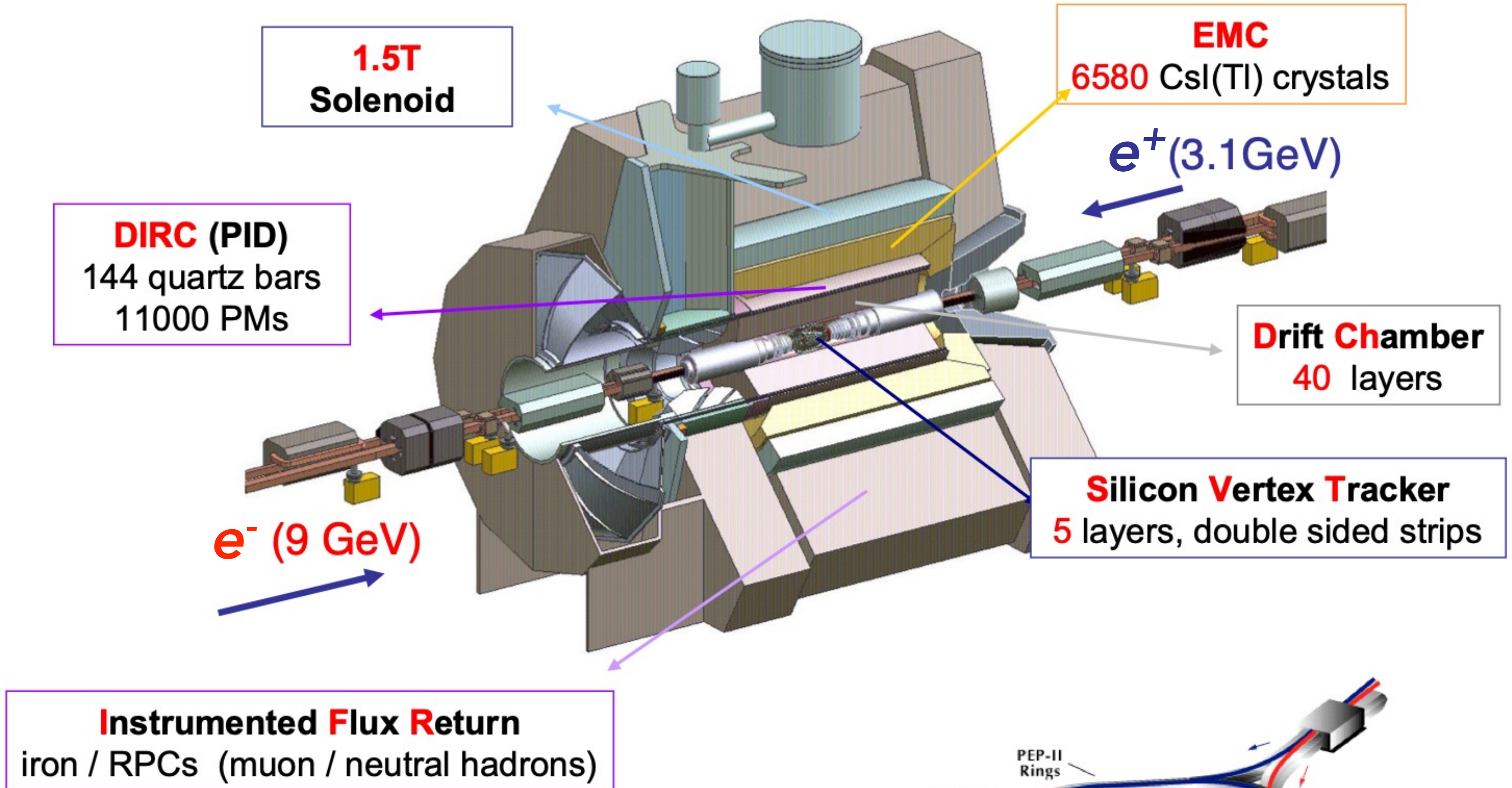
RECENT RESULTS OF DARK SECTOR SEARCHES WITH THE *BABAR* EXPERIMENT

Brian Shuve
on behalf of the BABAR Collaboration
bshuve@g.hmc.edu

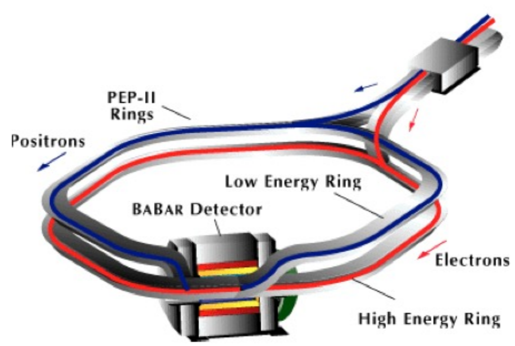
BNL Forum
October 4, 2023



BaBar EXPERIMENT



1999-2008

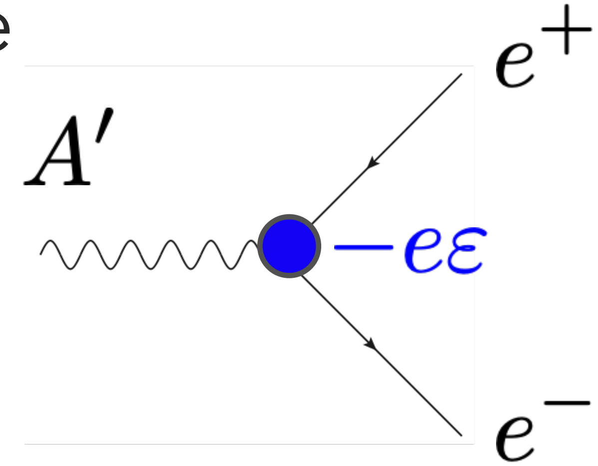


- 432/fb $\Upsilon(4S)$ on-peak ($\sqrt{s} = 10.58$ GeV)
- ~500 million B meson pairs
- smaller samples at $\Upsilon(2S)/\Upsilon(3S)$ and off-peak

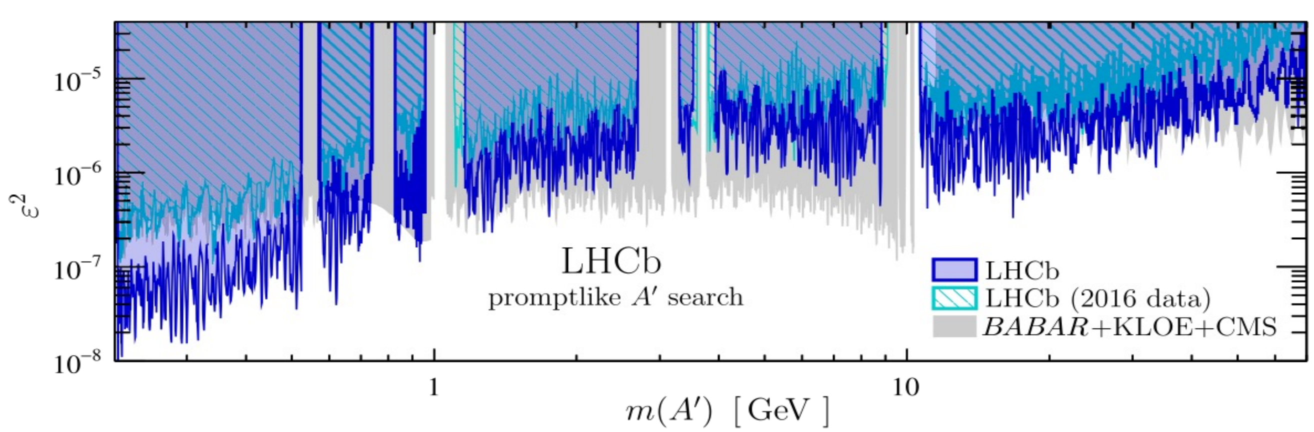
- High luminosity, low backgrounds make *BaBar* an ideal experiment for discovering MeV-GeV scale hidden particles

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

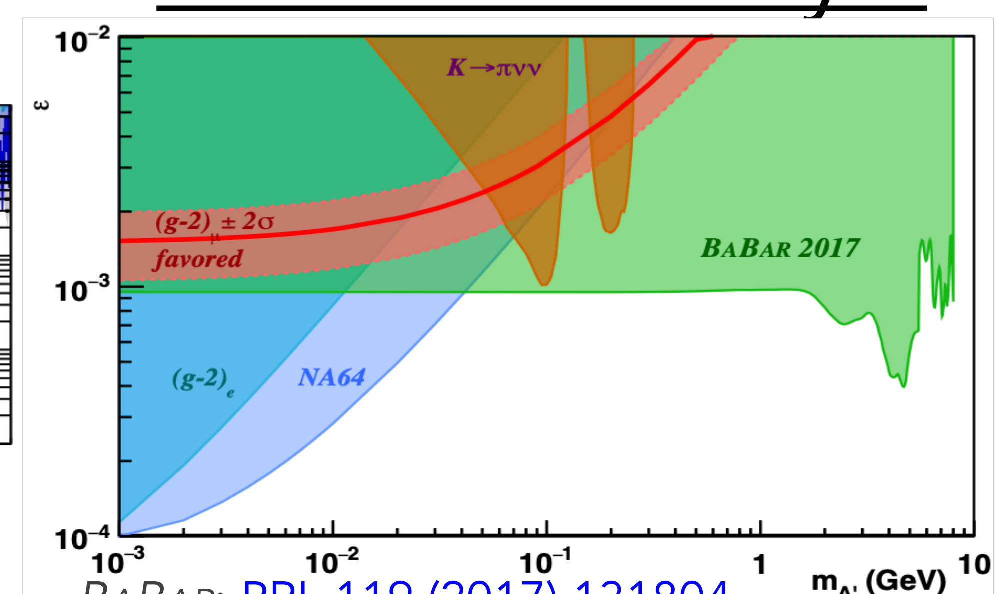


visible decays: $A' \to \ell^+\ell^-$



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

invisible decays:



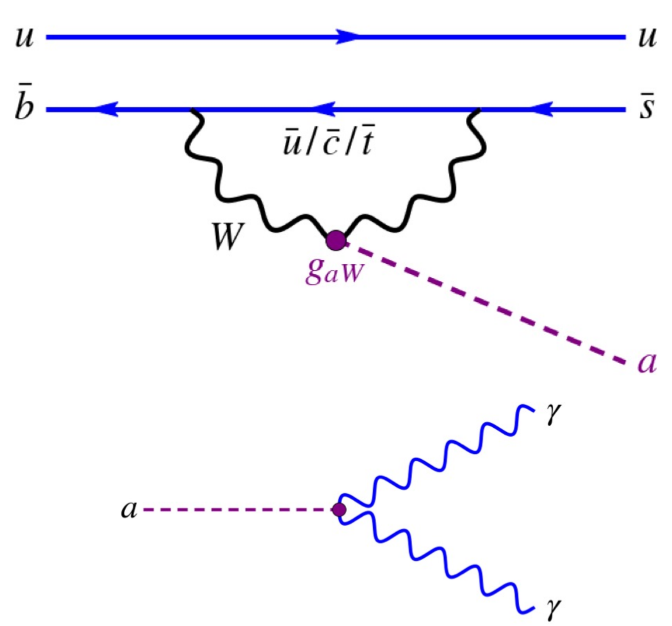
BaBar: PRL 119 (2017) 131804

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

SEARCHES PRESENTED TODAY

Axion-like particles (ALPs)

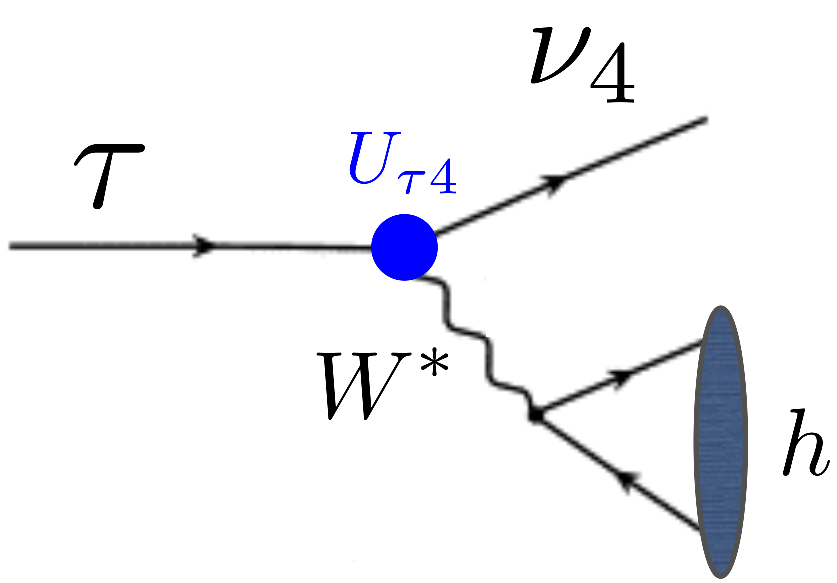
- *B* mesons decay to ALP via coupling to gauge bosons



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

Heavy neutral leptons (HNLs)

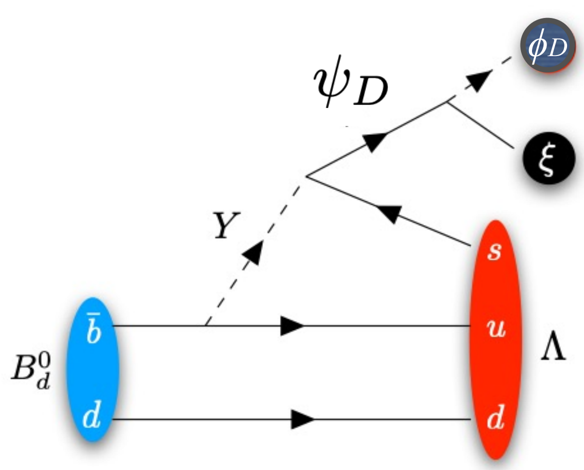
- produced in τ decays
- motivated by neutrino masses, leptogenesis



[BaBar, PRD 107, 052009 (2023), arXiv:2207.09575]

B-Mesogenesis

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

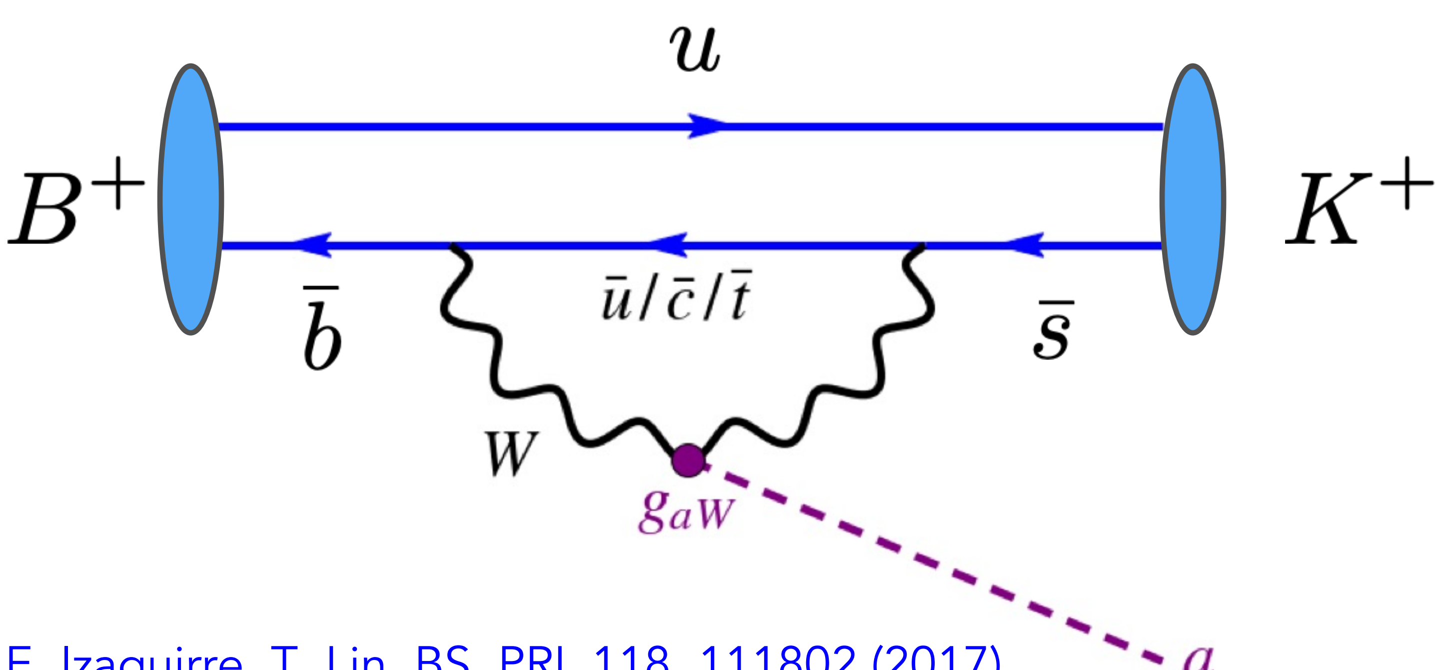


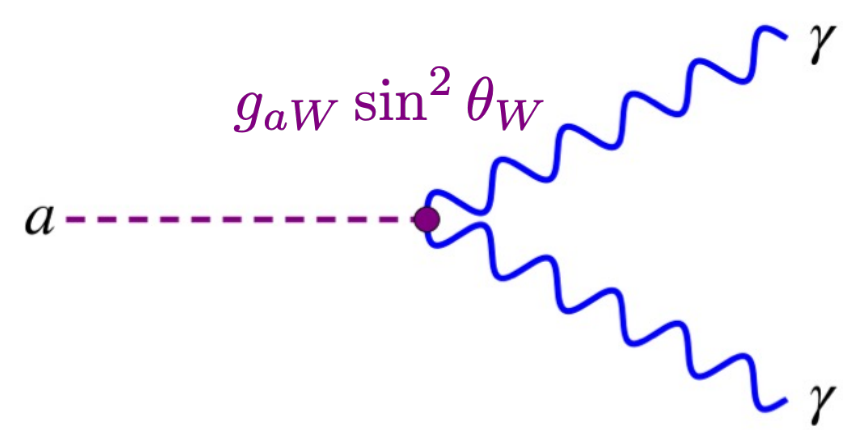
[BaBar, PRD 107, 092001 (2023)]
[BaBar, arXiv:2306.08490] (submitted to PRL)

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:

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



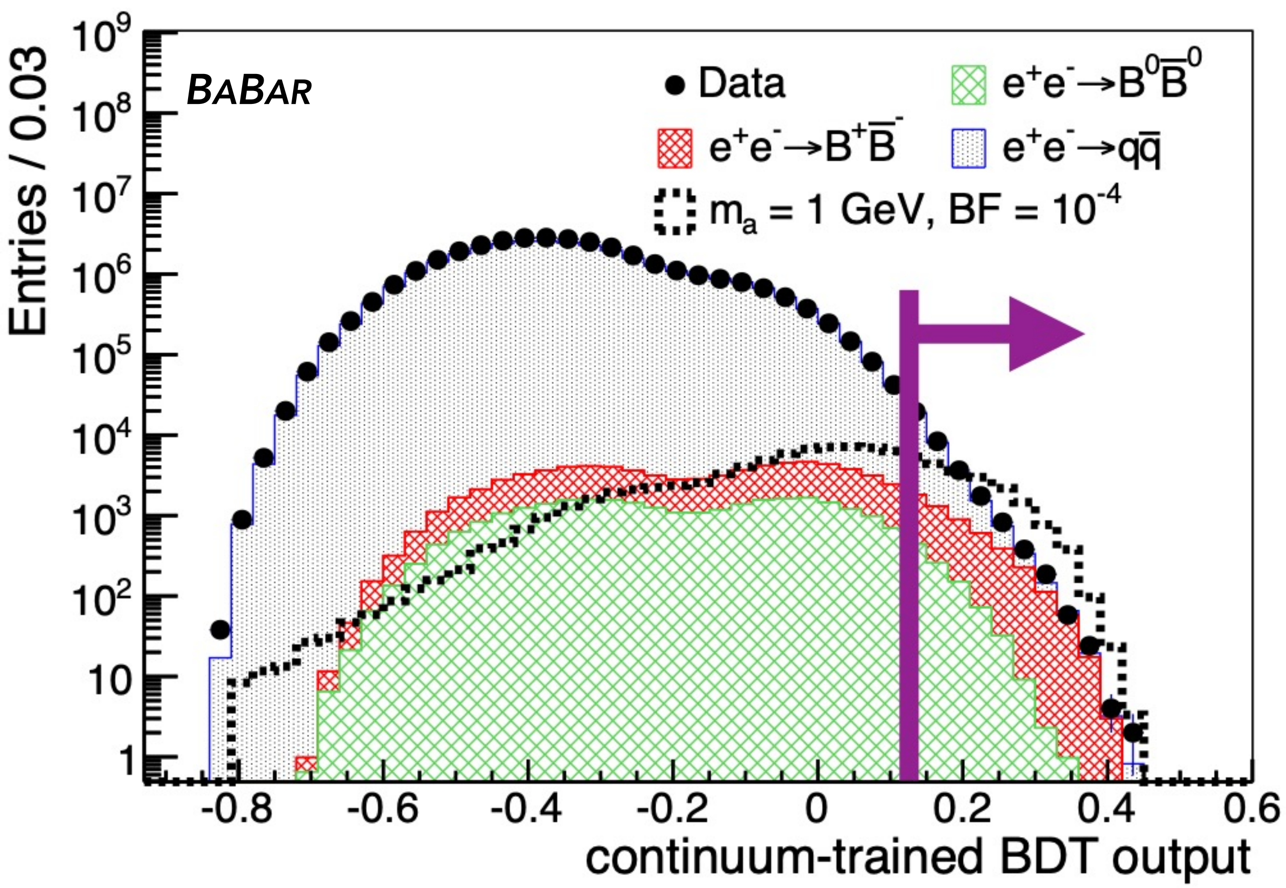


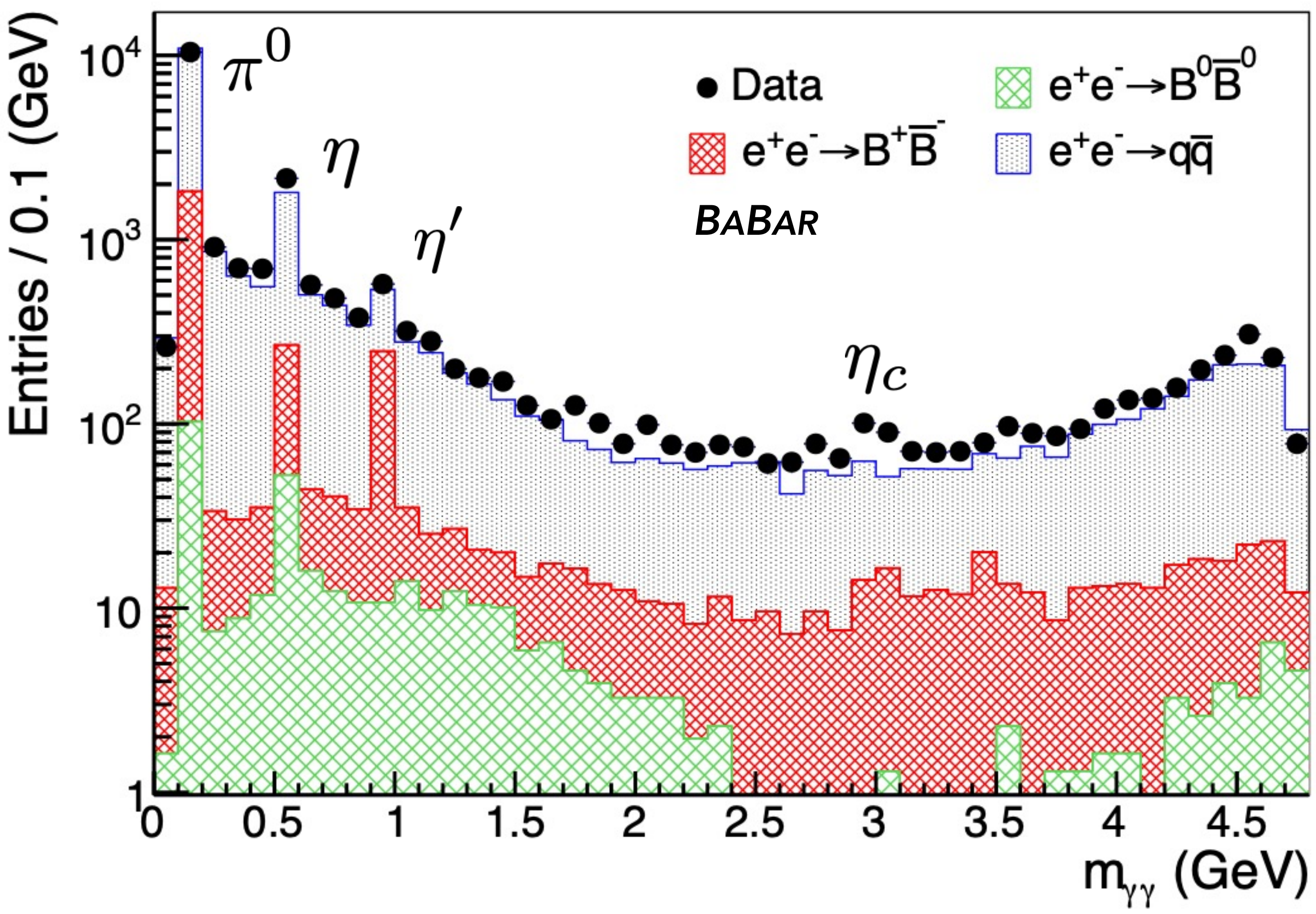
[E. Izaguirre, T. Lin, BS, PRL 118, 111802 (2017), arXiv:1611.09355]

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

AXION-LIKE PARTICLES

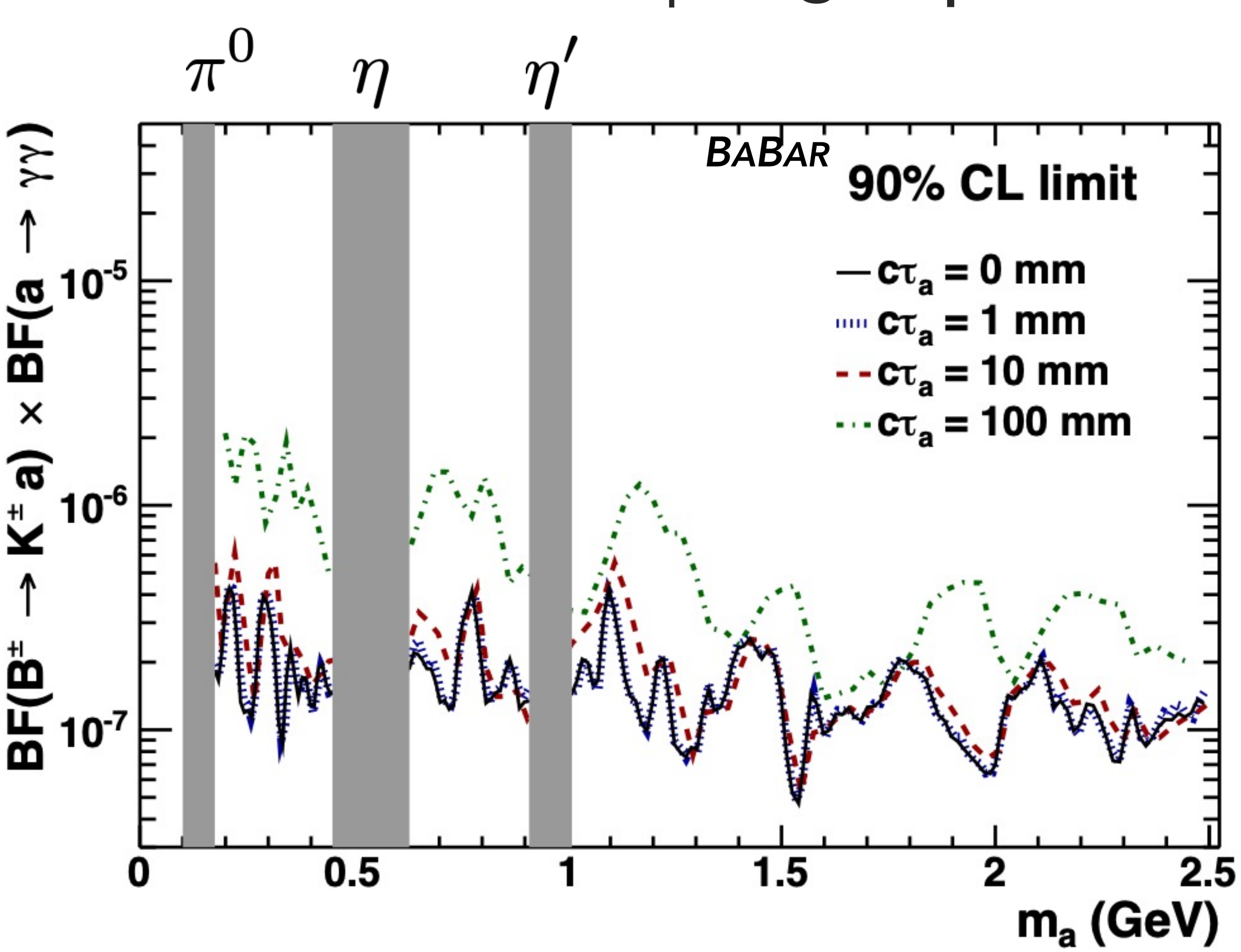
- Reconstruct $B^{\pm} \to K^{\pm}a,\, a \to \gamma\gamma$ candidates, look for narrow peak in diphoton mass; assume prompt decays
- Train separate boosted decision trees to reject dominant backgrounds

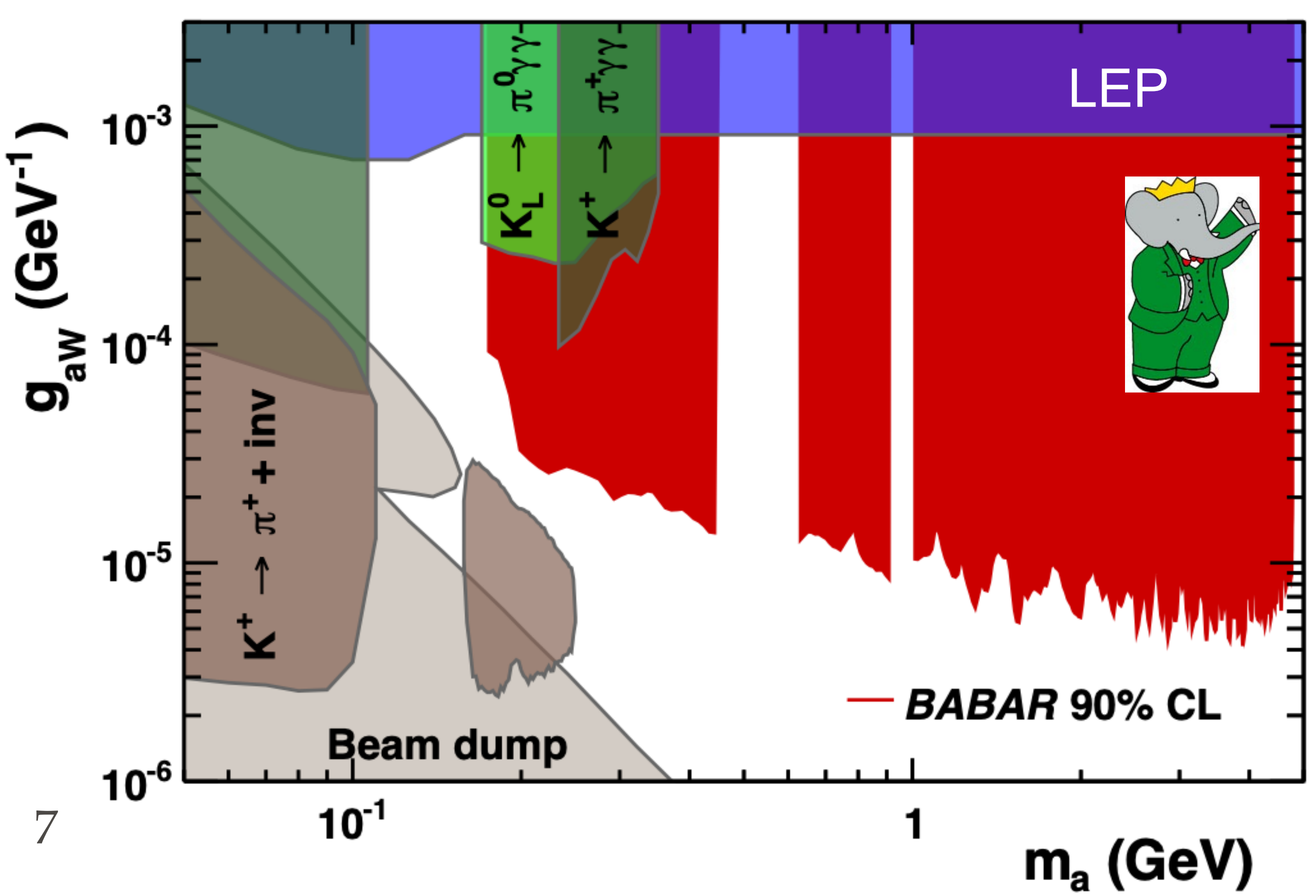




AXION-LIKE PARTICLES

- Search for a narrow diphoton peak over continuum background; use signal template for both prompt & long-lived signals
- Exclude signals in immediate vicinity of SM peaking backgrounds
- No significant signal: set 90% CL limits on signal branching fraction & coupling. **Up to 100x improvement in coupling limits!**



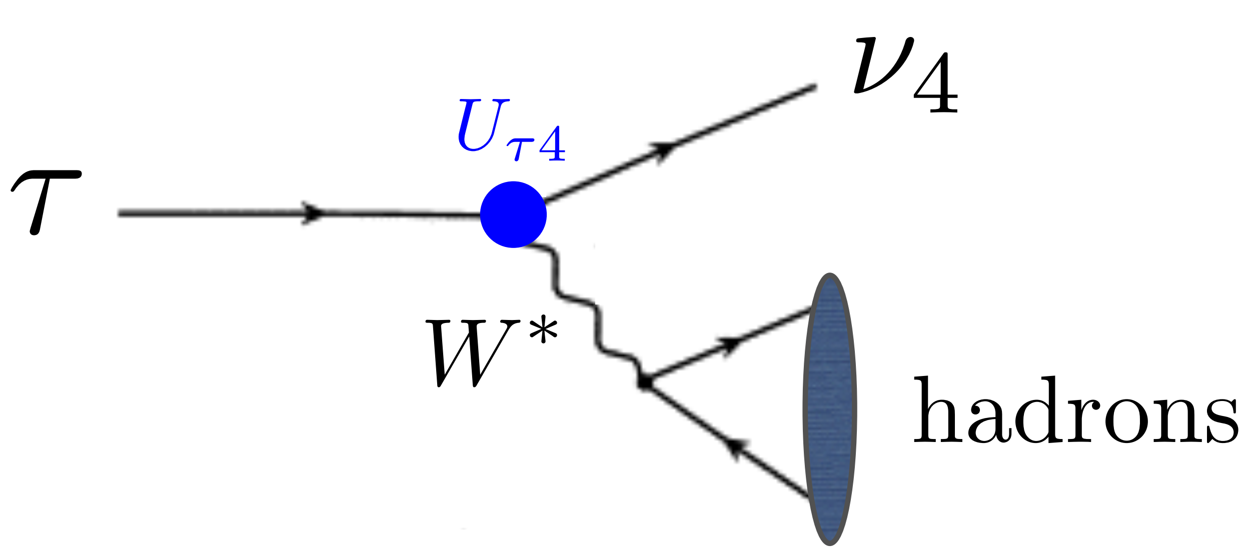


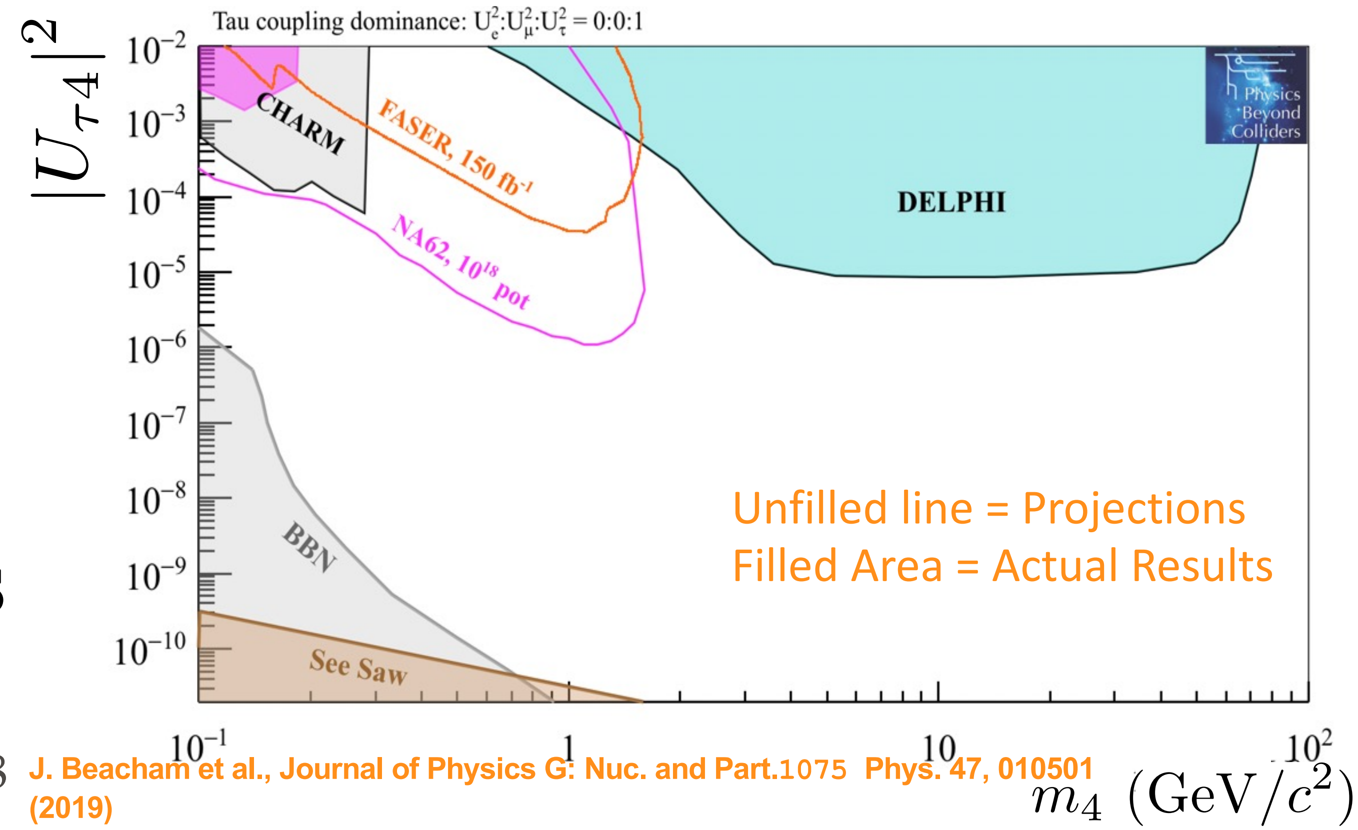
HEAVY NEUTRAL LEPTONS

- Heavy neutral lepton (HNL): right-handed Majorana fermion, singlet under SM. Gives mass to SM neutrinos through seesaw mechanism
- With approx. lepton number symmetry, HNL coupling can be much larger than see-saw prediction: relevant for leptogenesis

e.g., Mohapatra, *PRL* **56** (1986), 561; Shaposhnikov, *Nucl.Phys.B* **763** (2007) 49

- Least constrained HNL is produced through mixing with **SM tau neutrino**: produced in rare tau decays

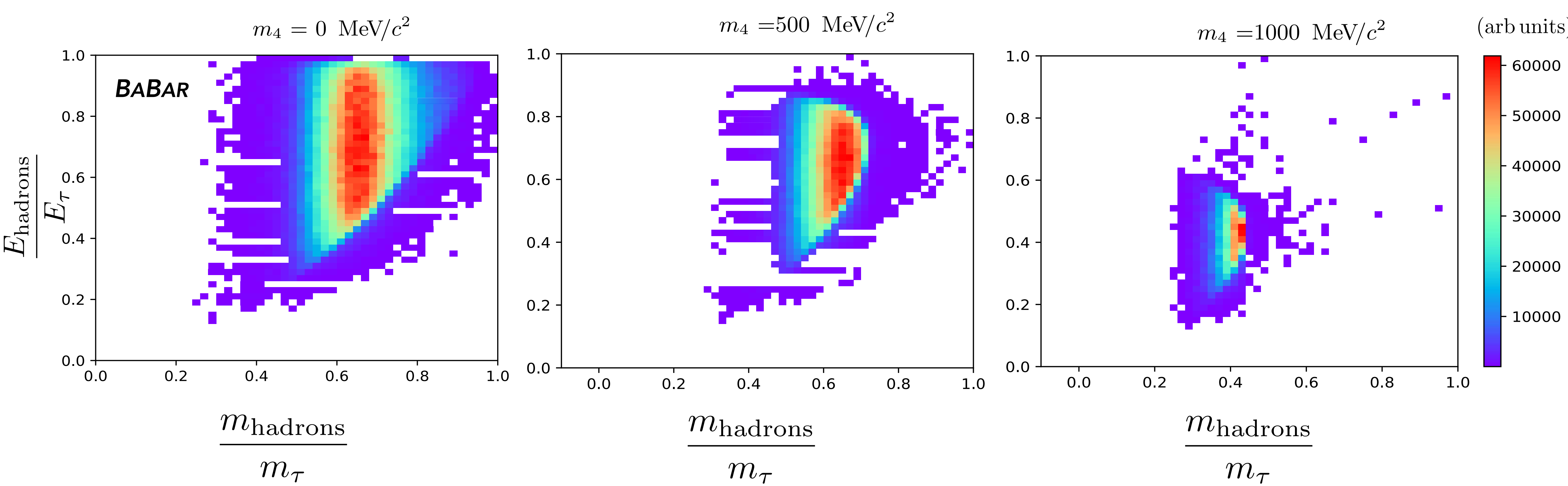




J. Beacham et al., Journal of Physics G: Nuc. and Part.1075 Phys. 47, 010501 (2019)

HNL IN TAU DECAYS

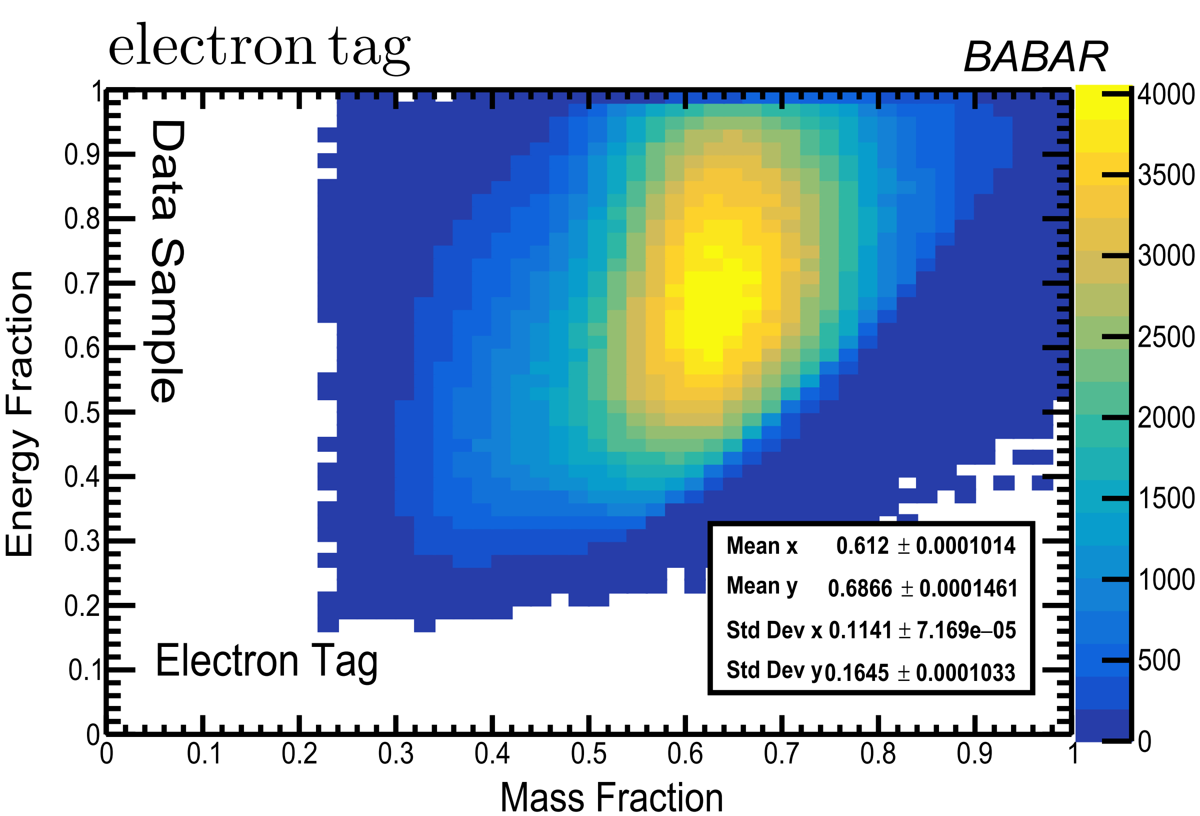
- Consider 3-pronged hadronic tau decays, veto neutrals/K^0_S , other tau in event must decay leptonically; use $\sqrt{s} = 10.58$ GeV dataset
- Use different kinematics of massless SM neutrino vs massive HNL
- Signal & background templates from MC, < 1% non-τ background

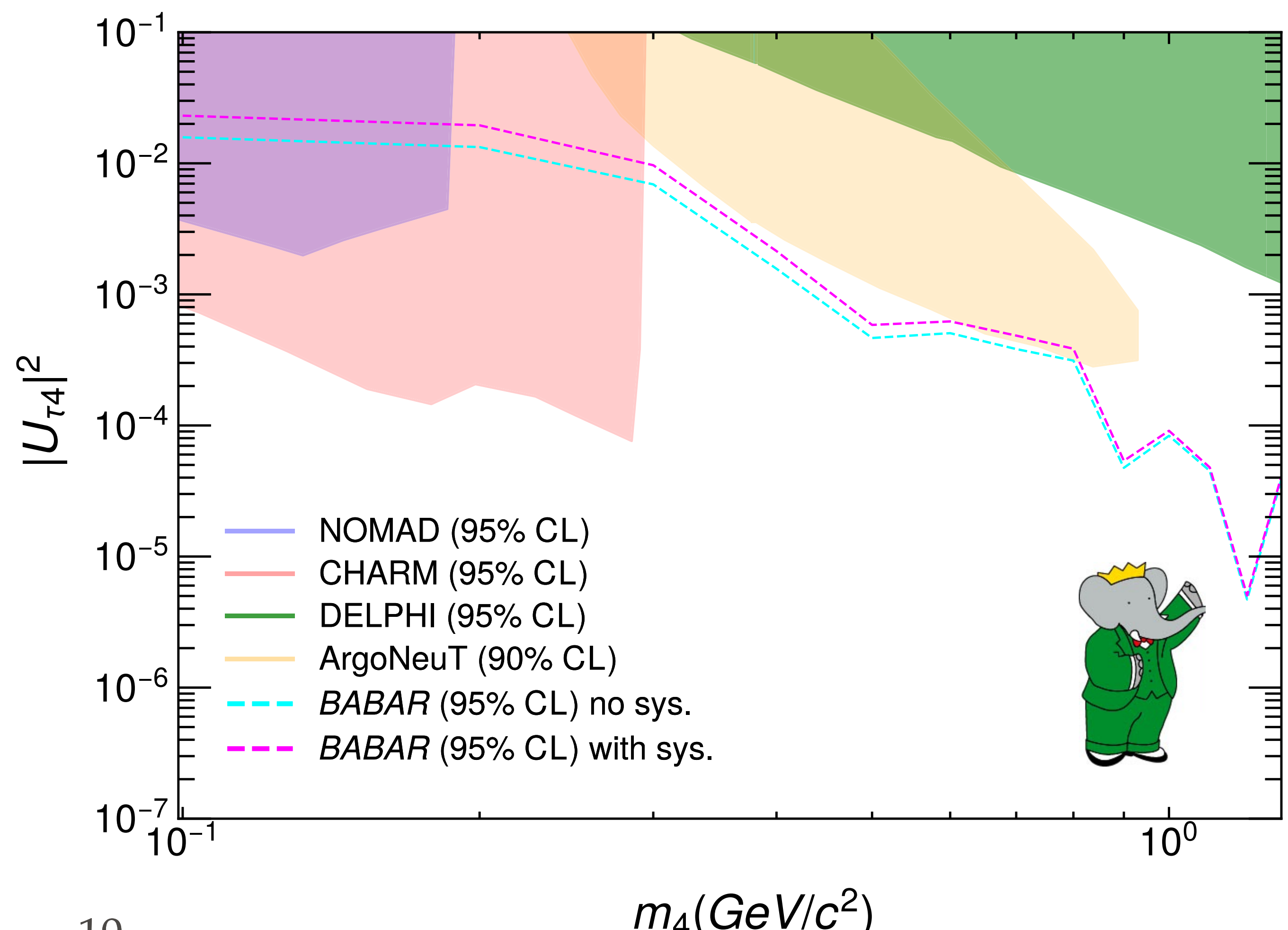


BaBar, *PRD* **107**, 05209 (2023), arXiv:220709575

HNL LIMITS

- Use binned profile likelihood method to set 95% CL limit on $|U_{\tau 4}|^2$
- Dominant systematic comes from uncertainty in a_1 mass and width, which affect τ-decay kinematics. Repeat analysis varying these parameters, take weakest limit (very conservative estimate)



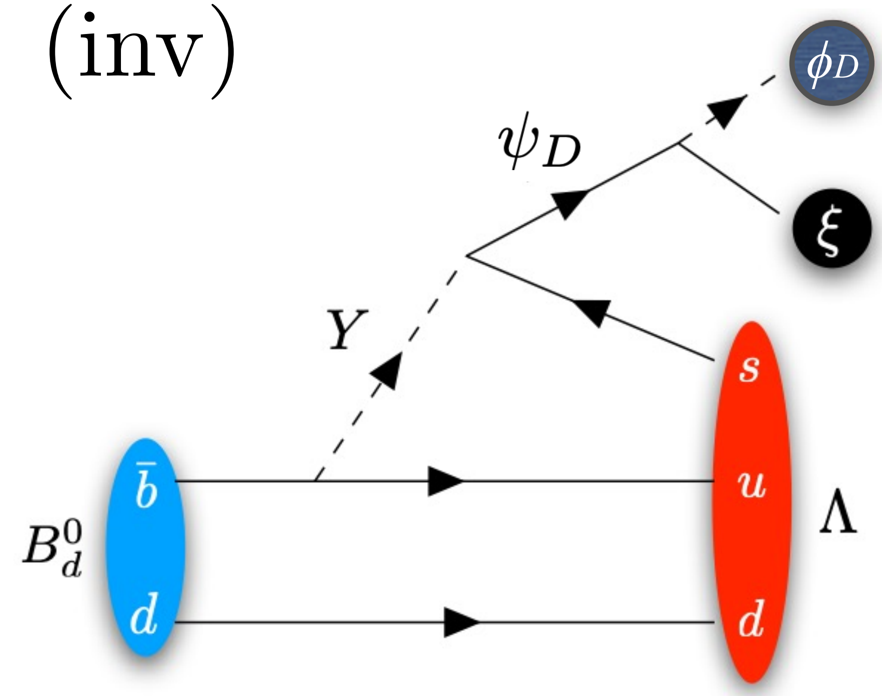


B-MESOGENESIS

- 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, $T_{\mathrm{RH}} \lesssim 100~\mathrm{MeV}$

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

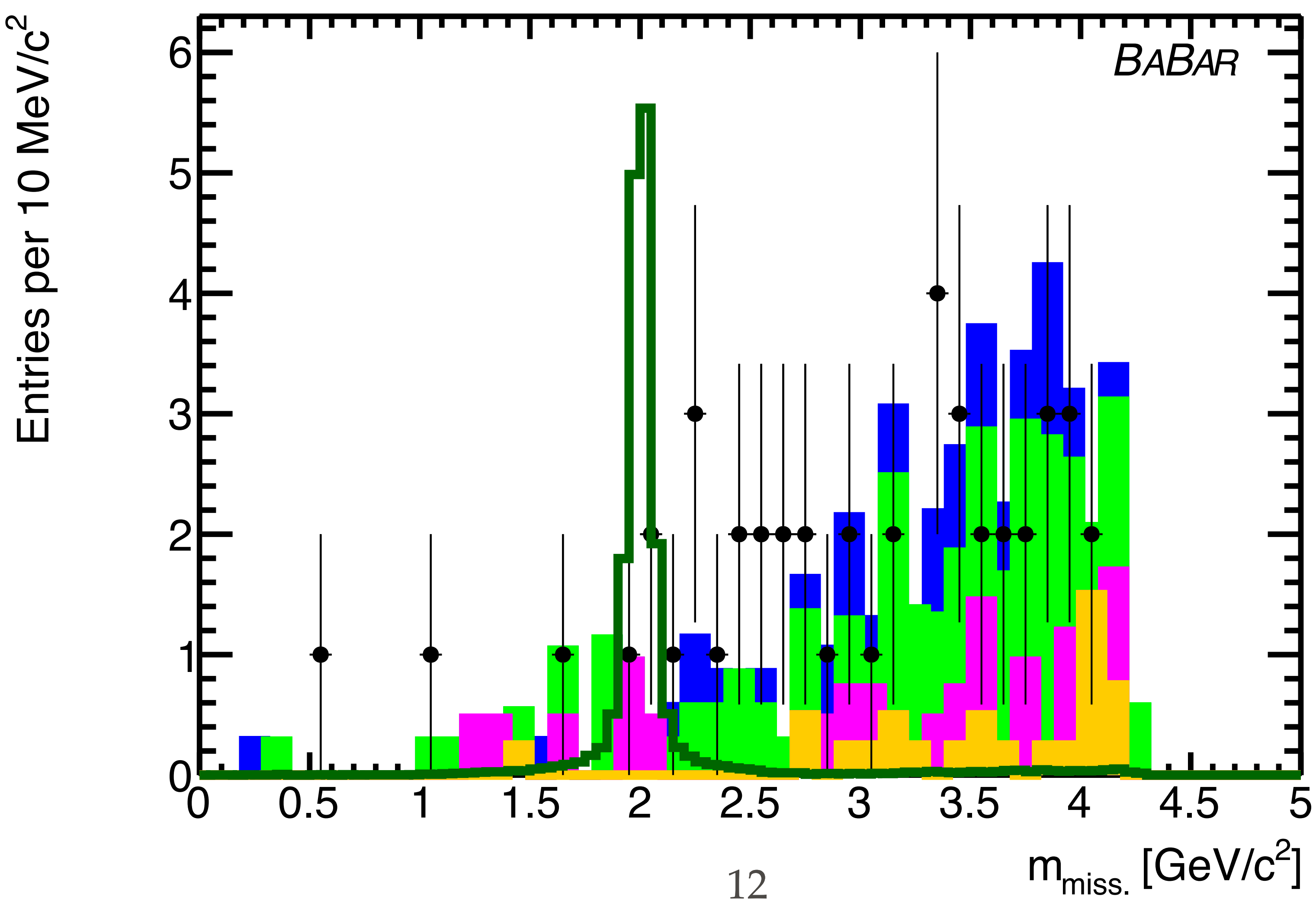


- Signal depends on flavor structure; can also get *e.g.*, $B^{\pm} \to p + \psi_D~(\mathrm{inv})$

B-MESOGENESIS

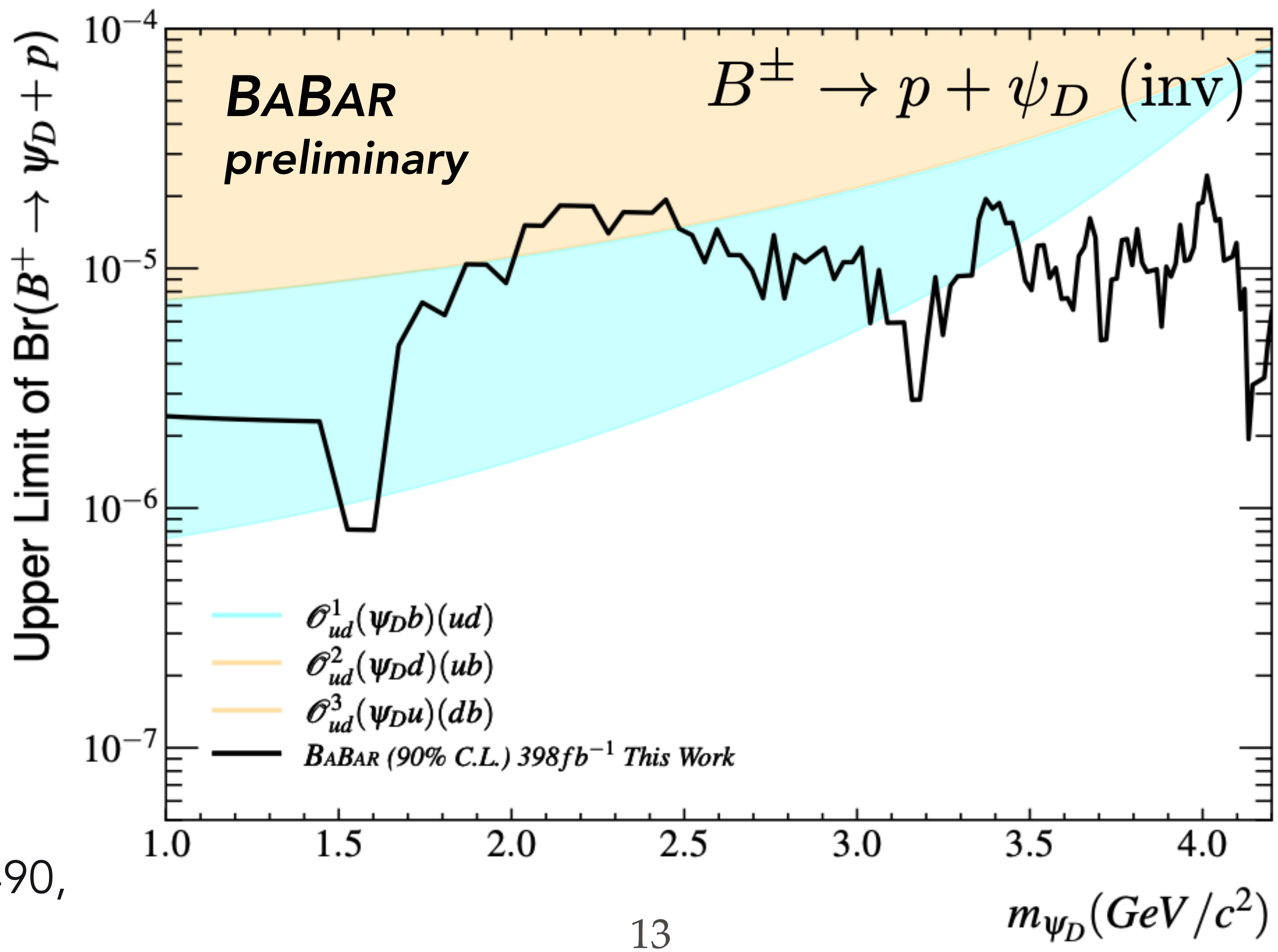
- Fully reconstruct hadronic decay of "tag" *B* meson, search for single SM baryon (Λ or p) + missing mass from signal *B* decay
- Train BDT to separate signal from background

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



B-MESOGENESIS RESULTS

- No significant signal: set 90% CL limits on signal branching fraction
- Shaded regions are branching fractions predicted from mesogenesis
- Additionally constrain R-parity violating supersymmetry scenario



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, heavy neutral leptons, 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 $m_a = 0.175$ GeV to 14 MeV at $m_a = 2$ GeV, decreasing back to 2 MeV at $m_a = 4.78$ 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 $m_a = 4.78$ GeV to 33% at $m_a = 2$ 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

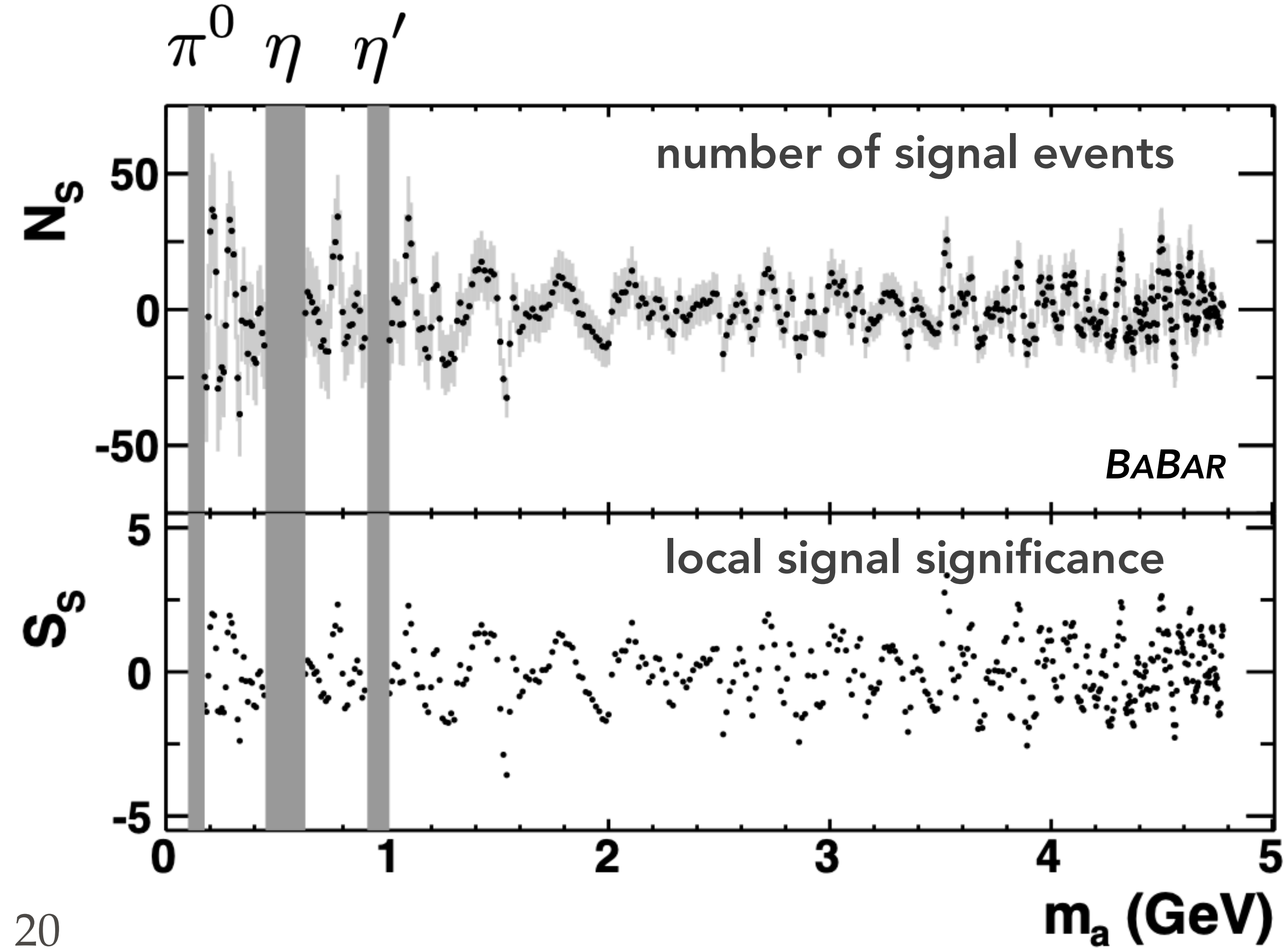
- **Continuum background PDF:** second-order polynomial for $m_a < 1.35\ \mathrm{GeV}$, first-order polynomial at higher masses

- **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

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**

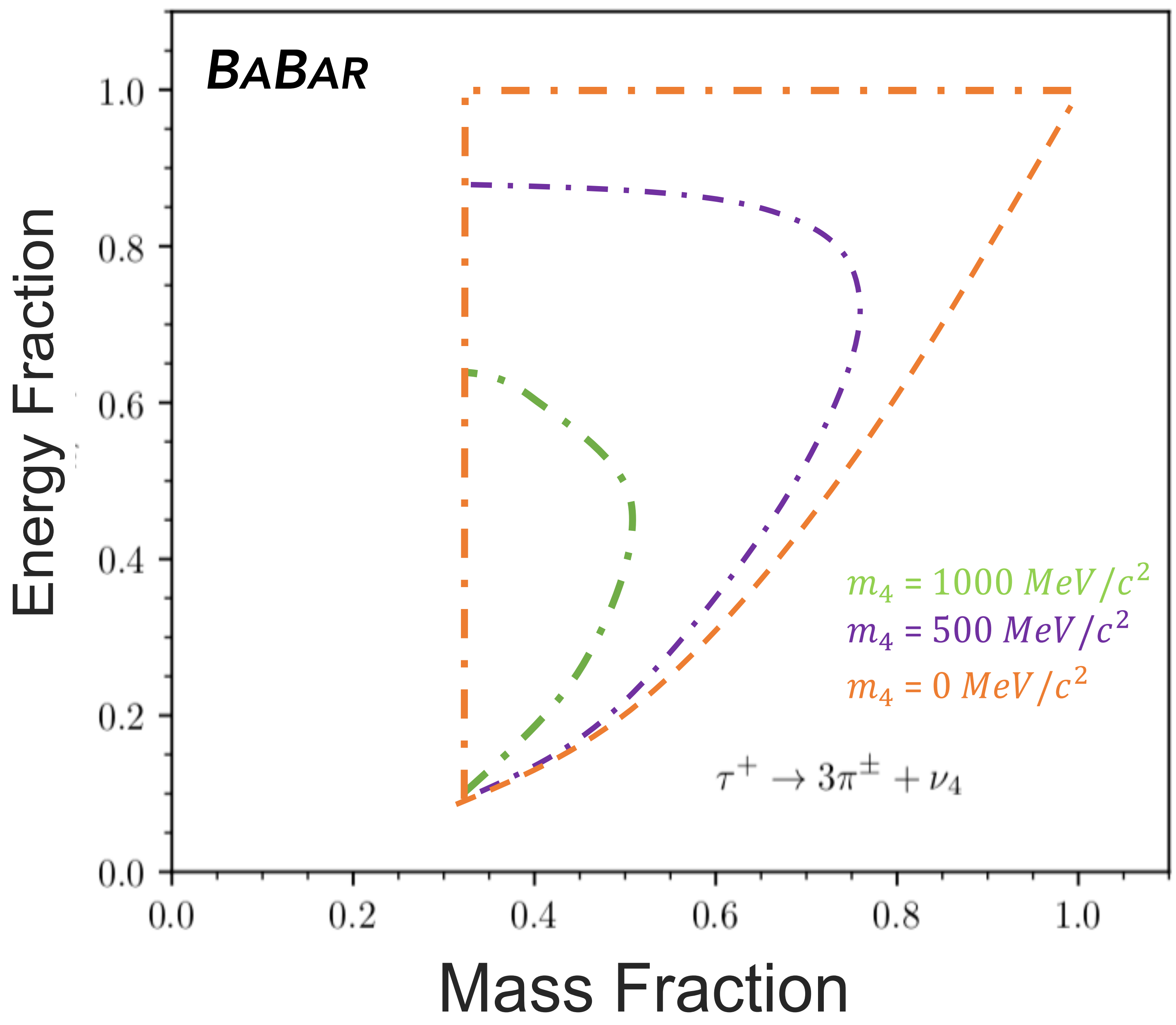
$$\Gamma_a = \frac{g_{aW}^2 \sin^4\theta_W \, m_a^3}{64\pi}$$



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

HNL SIGNAL KINEMATICS



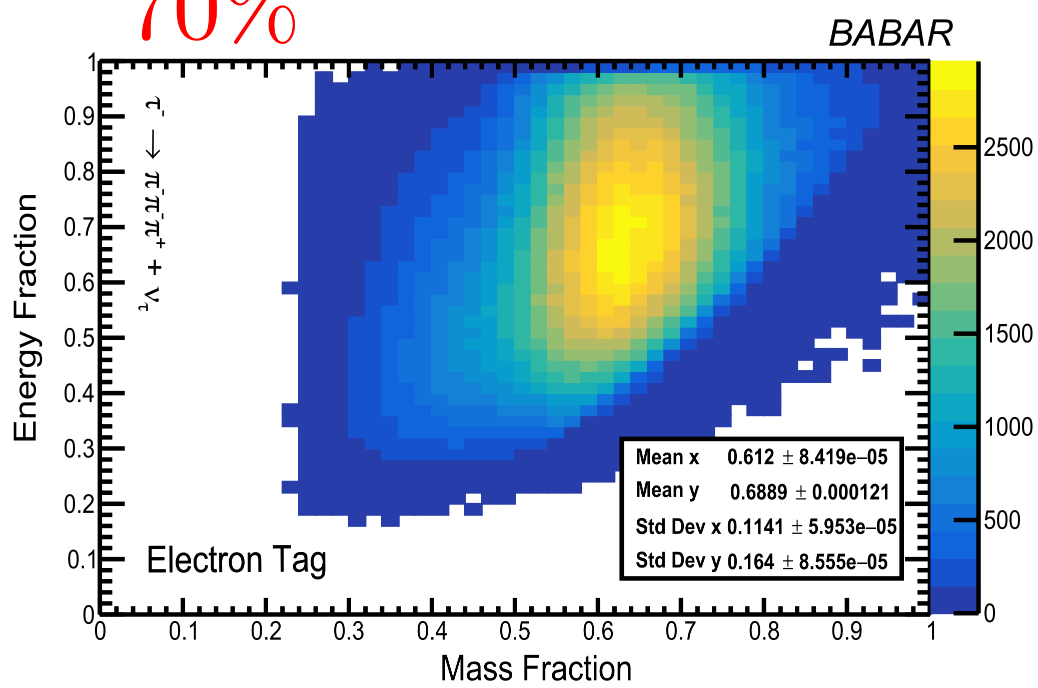
HNL SELECTIONS

Cut	Purpose
Number of tracks	Ensure 1+3 prong topolgy
Total charge on all 4 charged tracks is 0	Charge conservation
$p_{CM}^{miss} > 0.9\% \sqrt{s}$	Suppresses non-tau backgrounds
All tracks: $p_{trans} > 250\text{MeV/c}$	To reach DIRC[1]
All tracks: $-0.76 < \cos(\theta) < 0.9$	Acceptance of DIRC[1]
1 prong: $\frac{2p}{E} < 0.9$	Consistent with tau decay
PID Requirements	Uses Electron and Muon ID algorithms

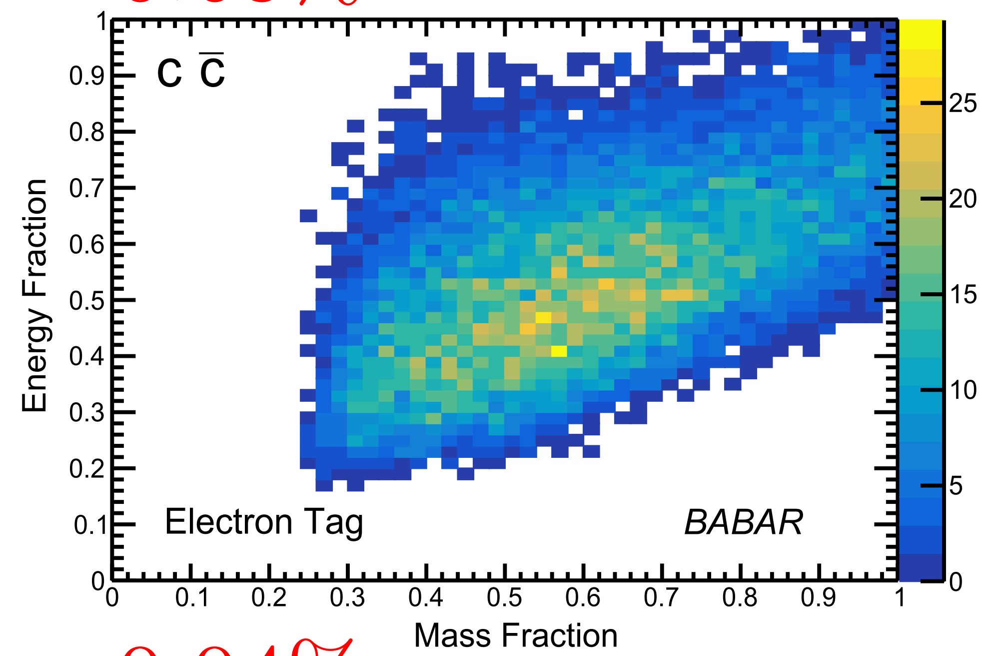
- Events vetoed if tracks consistent with photon conversions
- Neutral clusters are associated with leptons; events vetoed if significant other neutral clusters (>1 GeV/>0.5 GeV on 1-prong side for e/mu, >0.2 GeV on 3-prong side)
- Thrust > 0.85; KS veto based on two-track displaced vertex at KS mass

BACKGROUND DISTRIBUTIONS

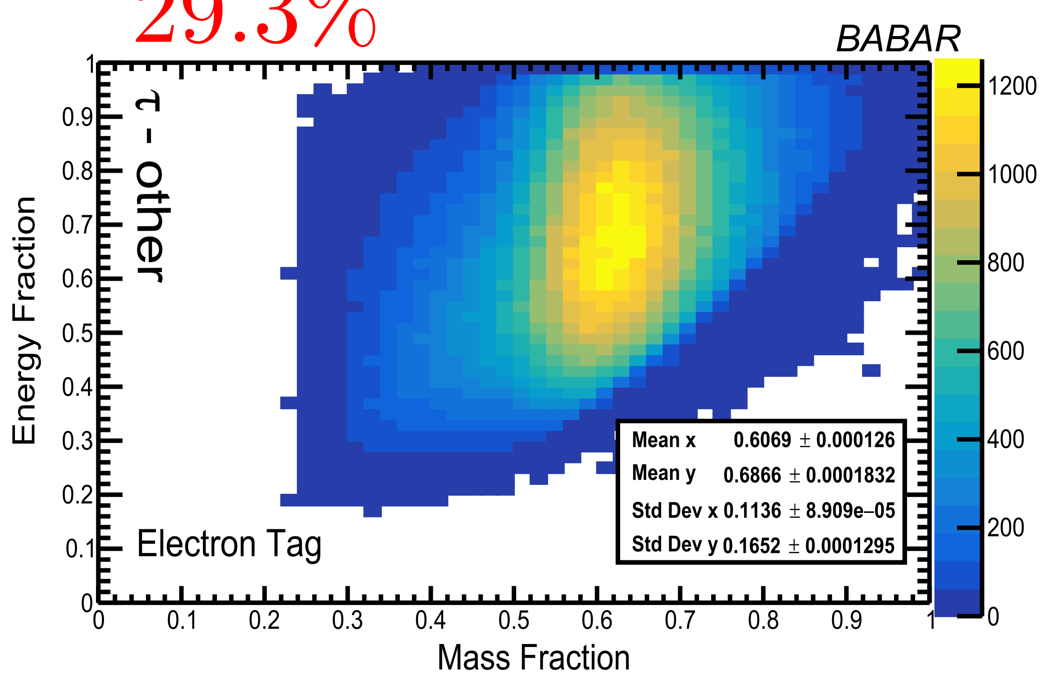
70%



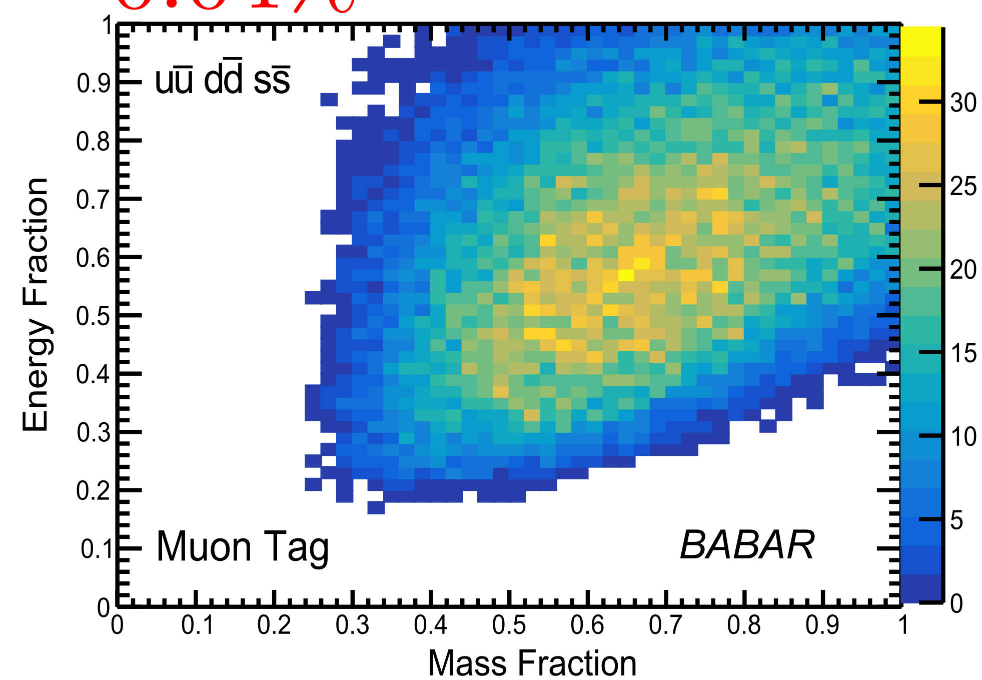
0.63%



29.3%



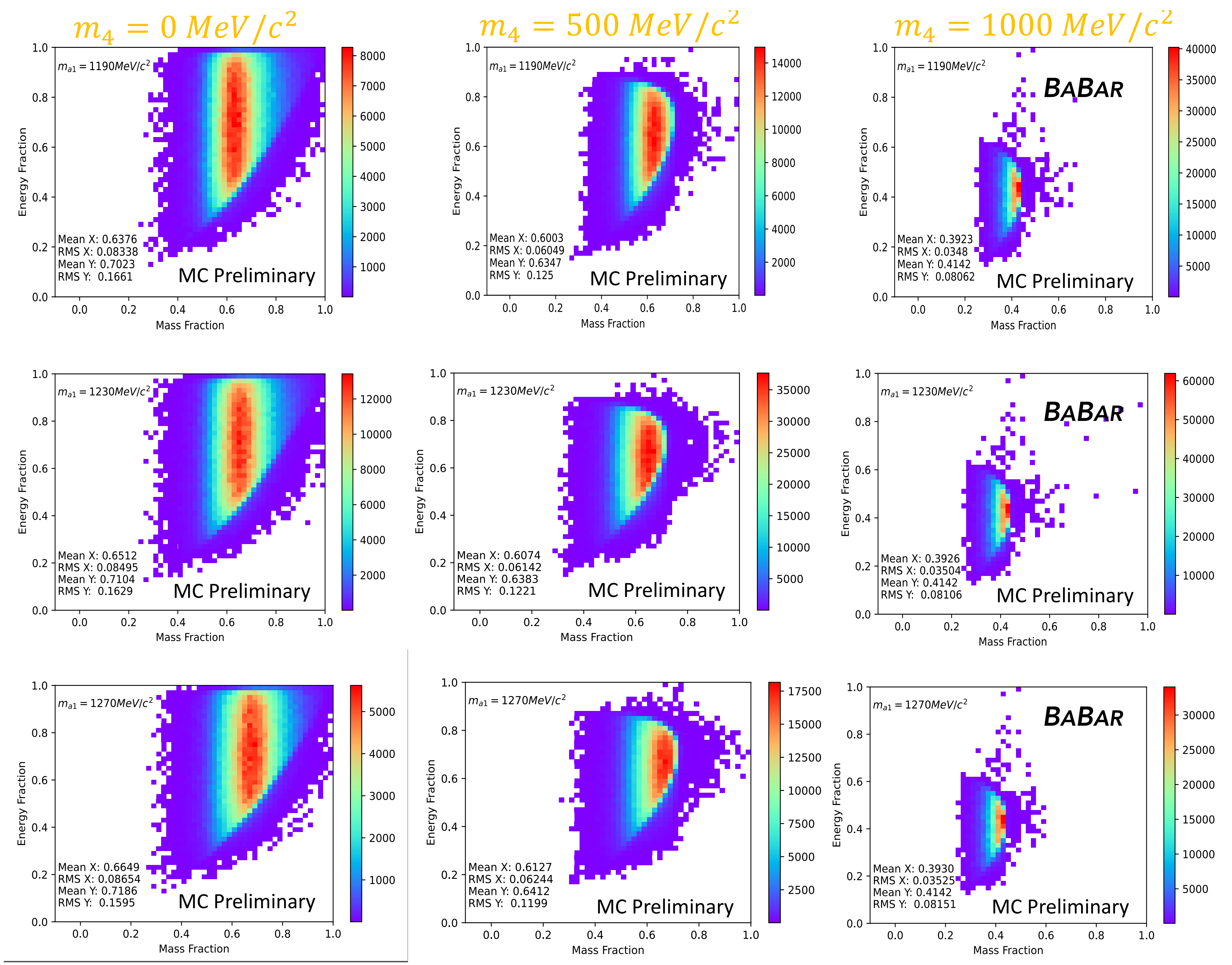
0.04%



BKD NORMALIZATION UNCERTAINTIES

Uncertainty	Contribution
Luminosity	0.44 % [BaBar]
Cross-section	0.31% [Data]
Branching fraction of 1-prong tau decays	Electron : 0.23 % [PDG] Muon: 0.23% [PDG]
Branching fraction of 3−prong tau decays	3 pions : 0.57 % [PDG]
PID Efficiency	Electron : 2 % [BaBar] Muons : 1 % Pions : 3 %
$q\bar{q}$ and Bhabha Contamination	0.3 % [Control region analysis]
Bin Size	< 1% [Alter bins, check results]
Tracking Efficiency	N/A
Detector Modelling	N/A
Tau Mass uncertainty	N/A
Tau Energy	N/A

BKD SHAPE UNCERTAINTIES



$$m_{a_1} = 1230 \pm 40\ \mathrm{MeV}/c^2$$

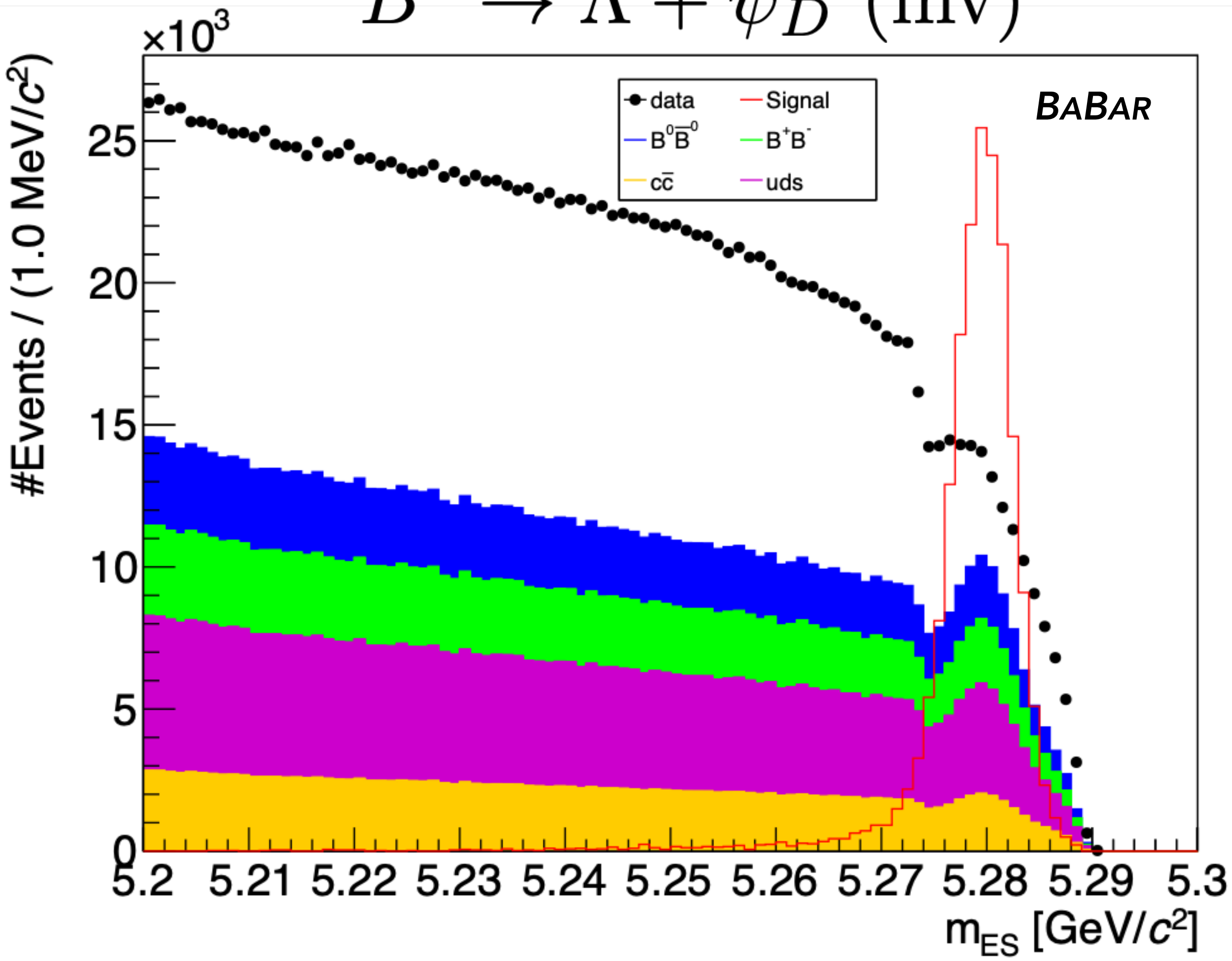
$$\Gamma_{a_1} = 420 \pm 35\ \mathrm{MeV}/c^2$$
$$(\mathrm{conservative}: 250 - 600\ \mathrm{MeV}/c^2)$$

B-MESOGENESIS

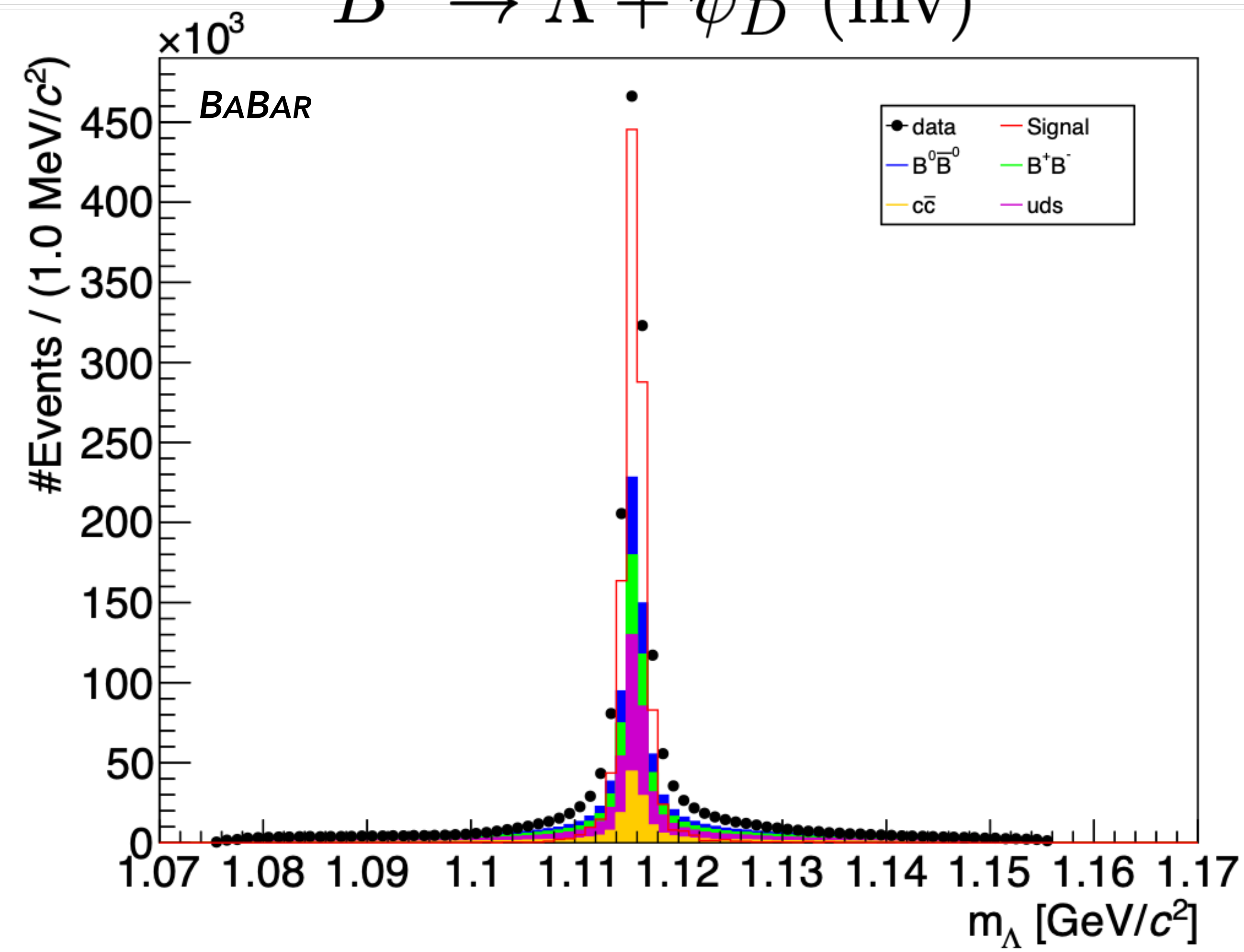
- Select events with: $5.27 \text{ GeV} < m_{ES} < 5.29 \text{ GeV}$

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

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



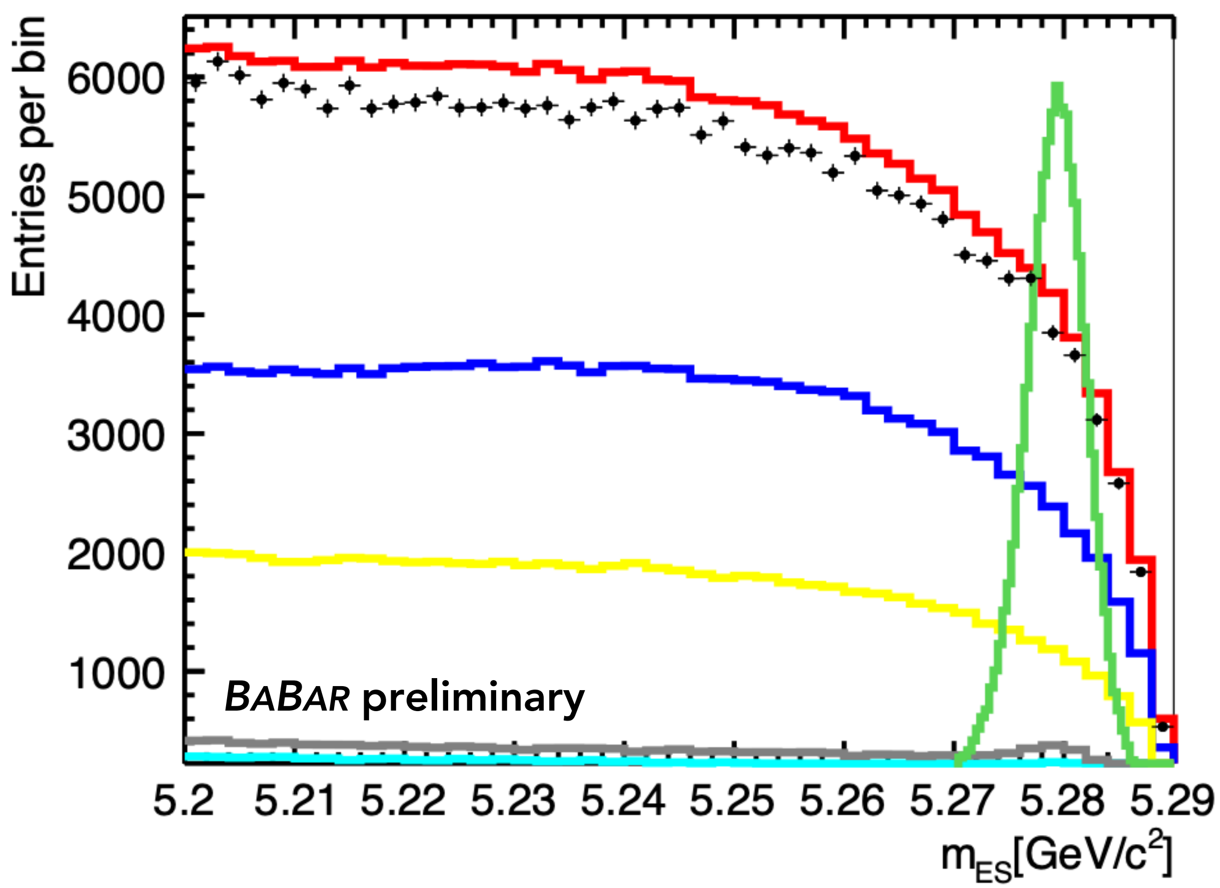
$B^0 \to \Lambda + \psi_D \text{ (inv)}$



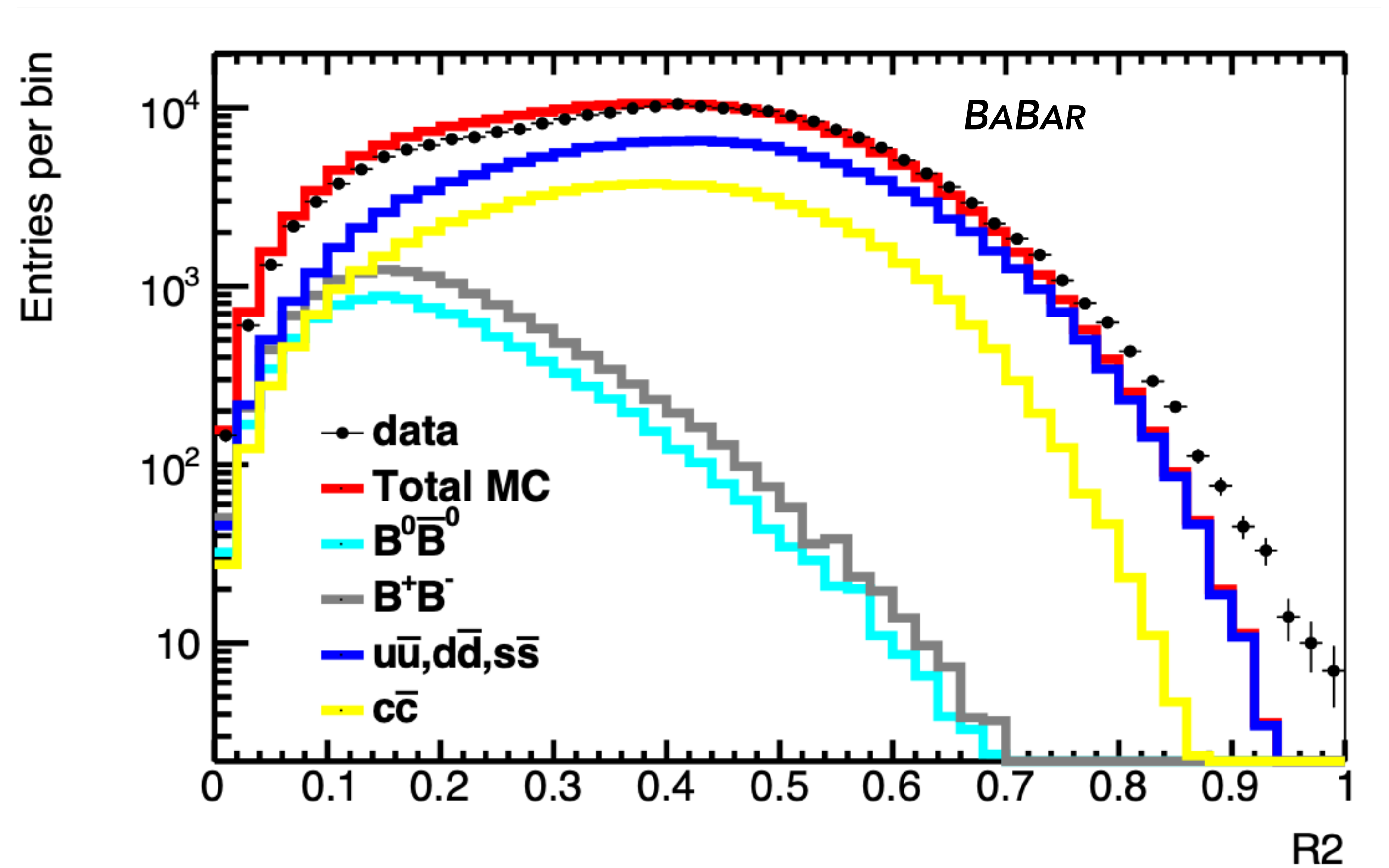
B-MESOGENESIS

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

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



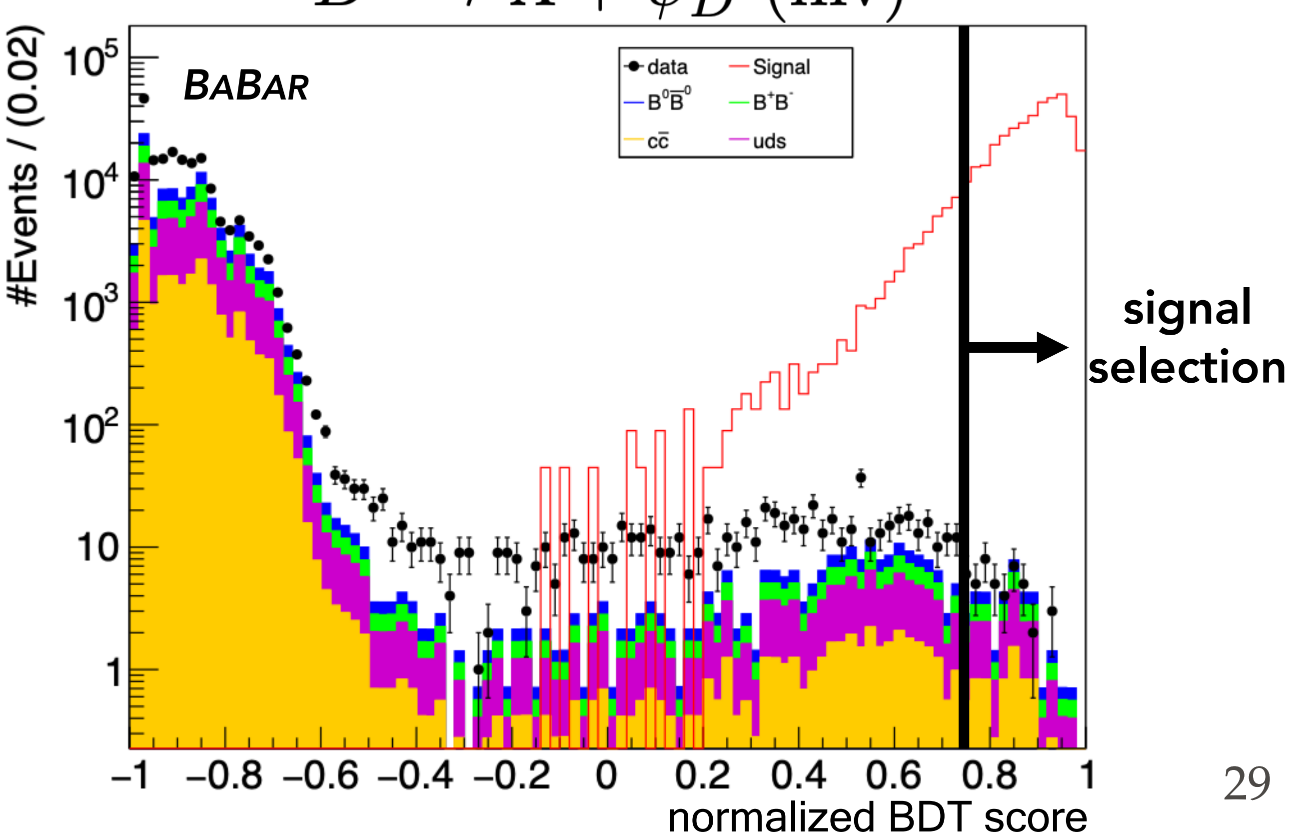
$B^{\pm} \to p + \psi_D\ (\text{inv})$



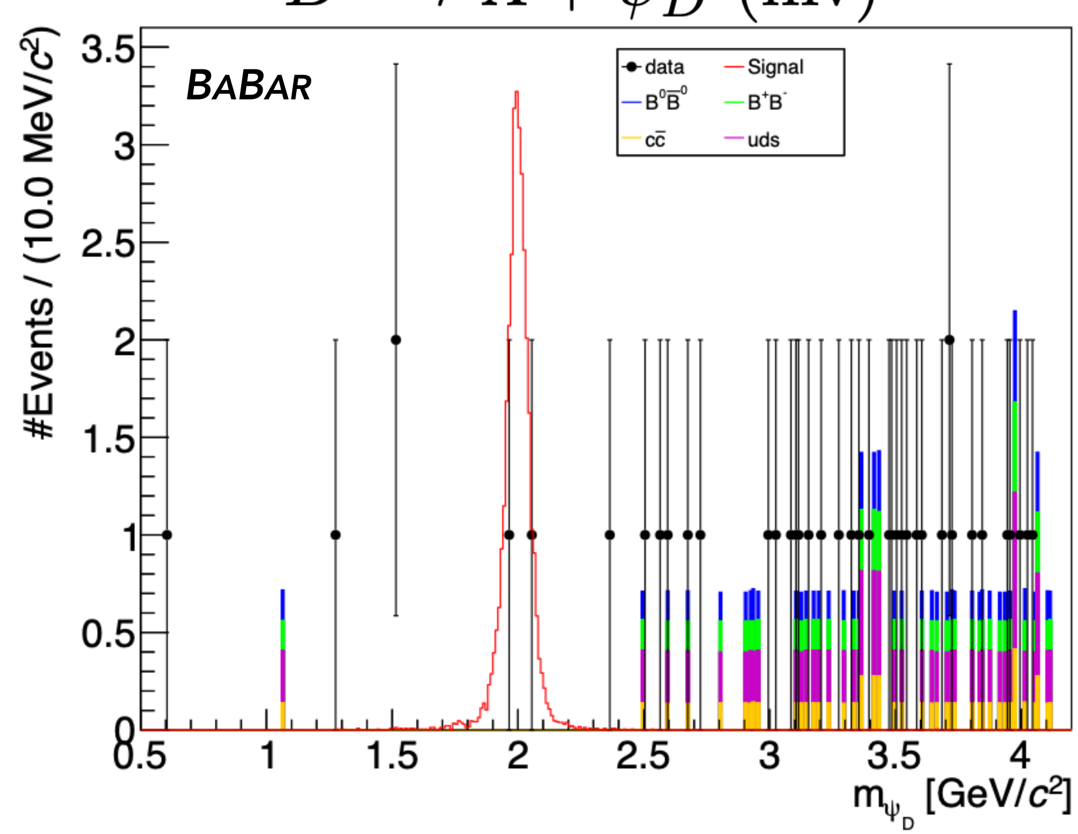
B-MESOGENESIS

- 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)

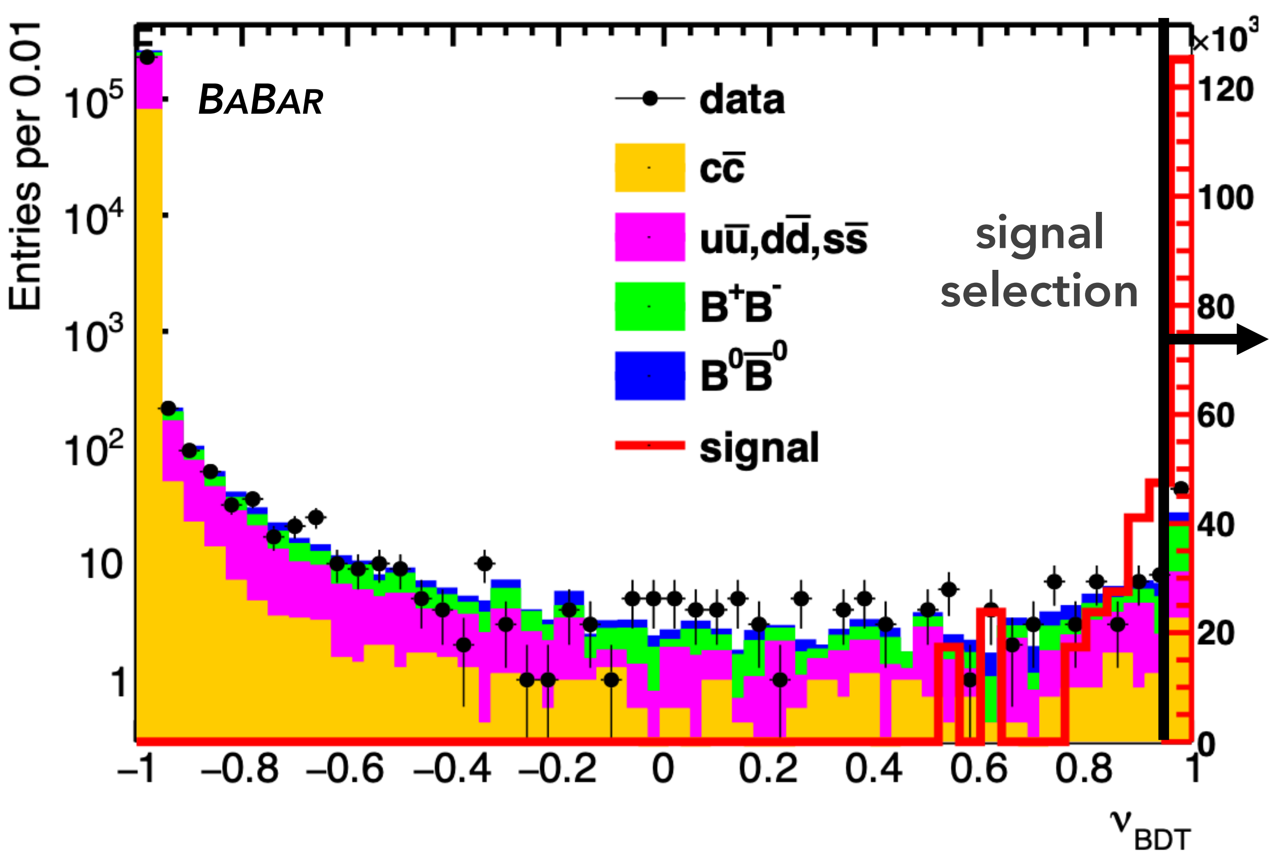


$B^0 \to \Lambda + \psi_D$ (inv)

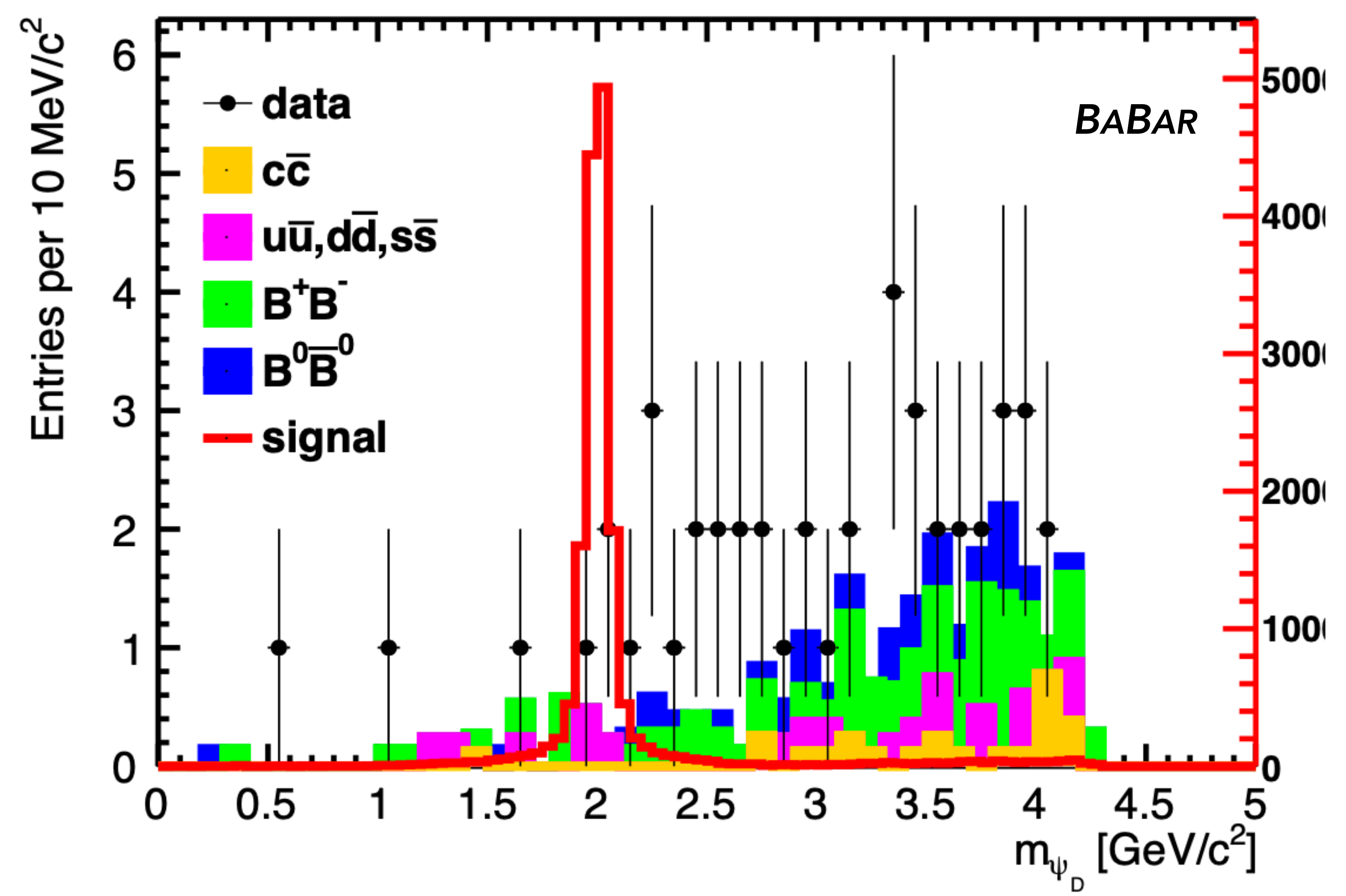


B-MESOGENESIS

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



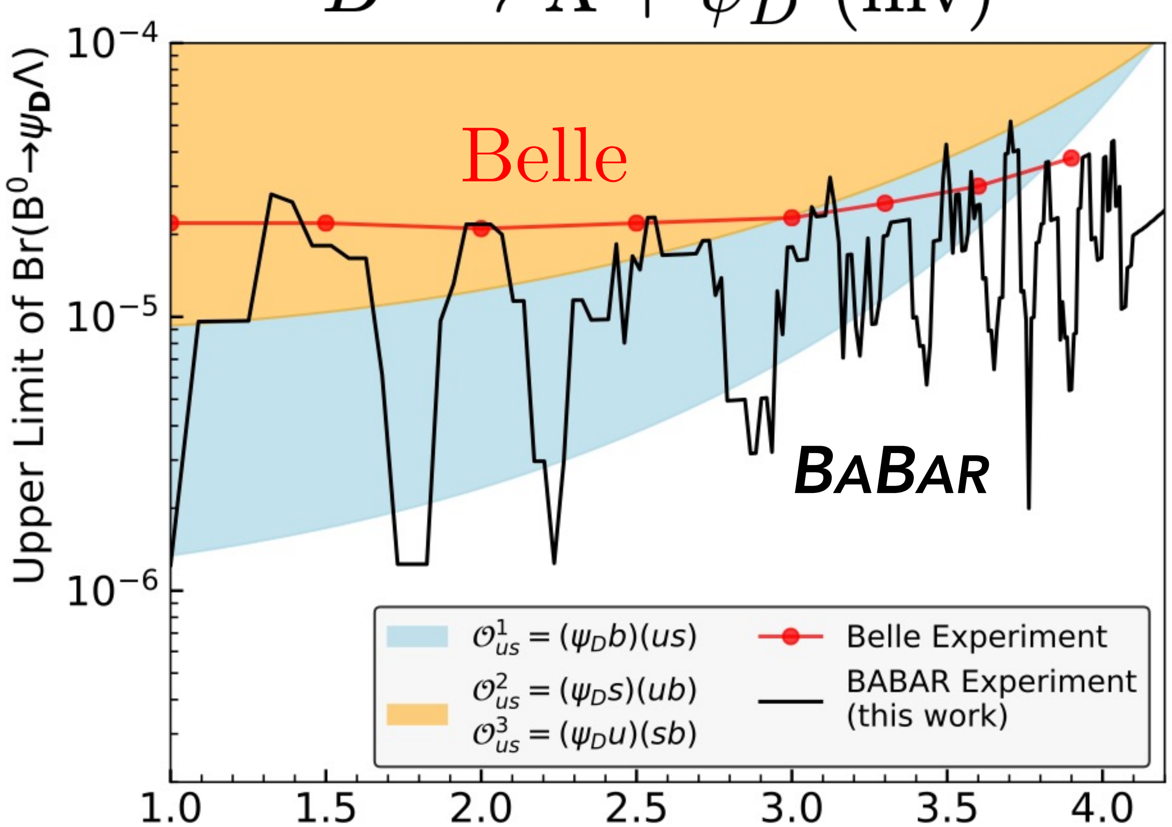
$B^{\pm} \to p + \psi_D \;\; (\mathrm{inv})$



B-MESOGENESIS RESULTS

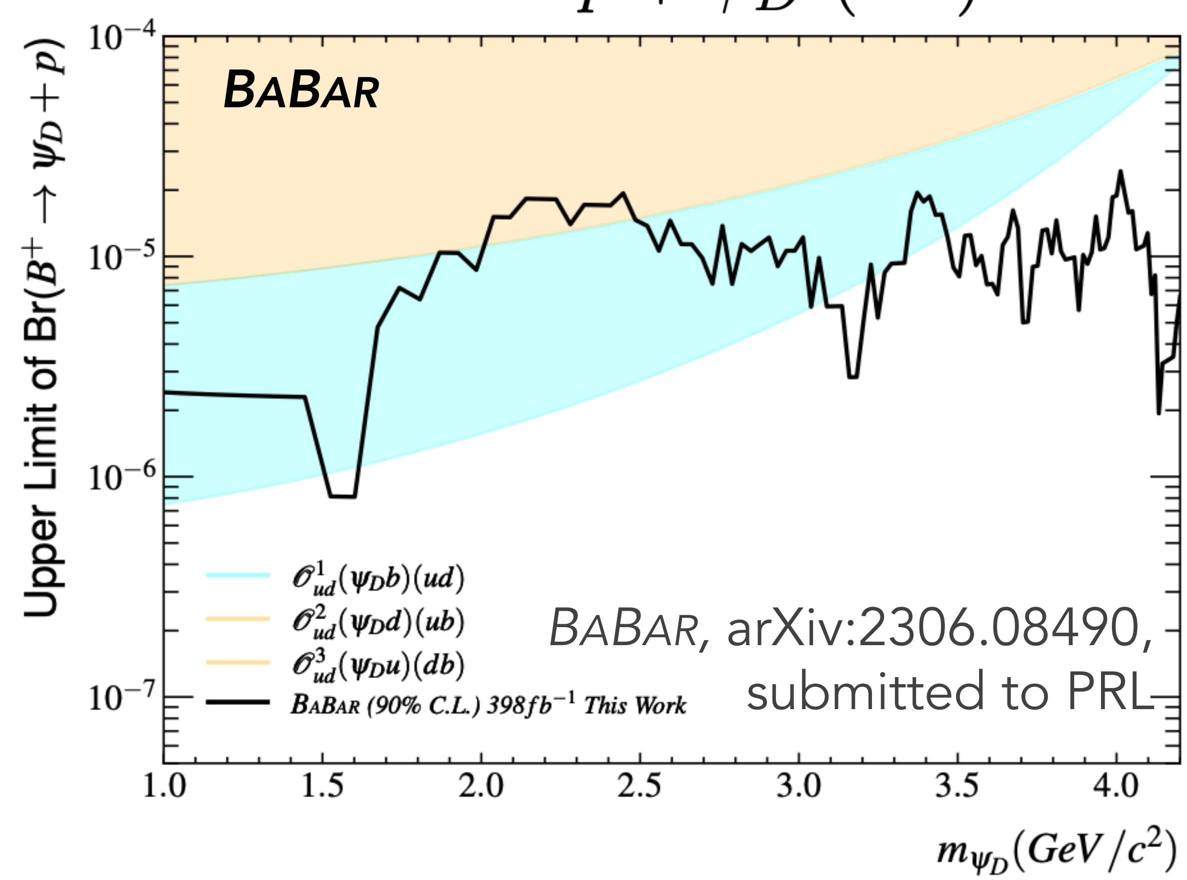
- Scan over ψ_D mass hypotheses: signal region size is 3x signal resolution, background is estimated from adjacent intervals
- No significant signal is seen: set limits on signal branching fraction using profile likelihood method
- Shaded regions are branching fractions predicted from mesogenesis

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



BABAR, PRD 107, 092001 (2023)

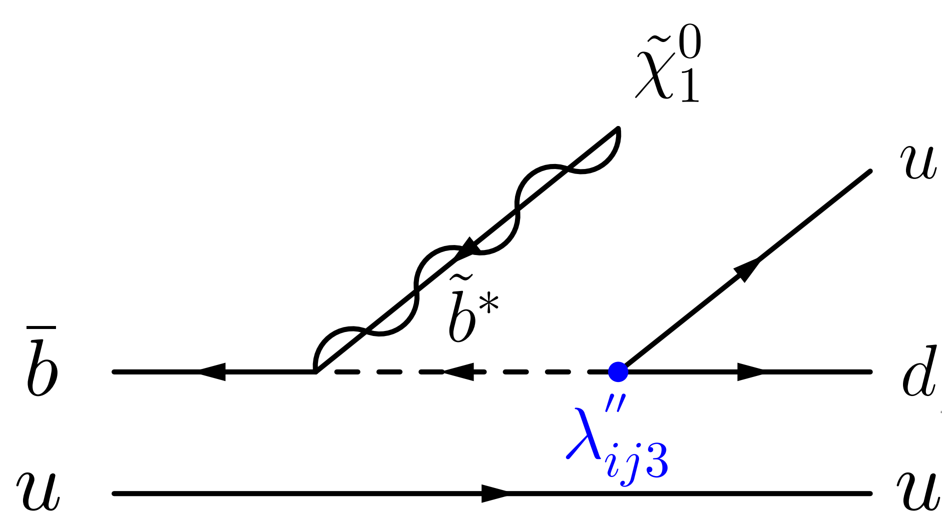
$B^{\pm} \to p + \psi_D$ (inv)

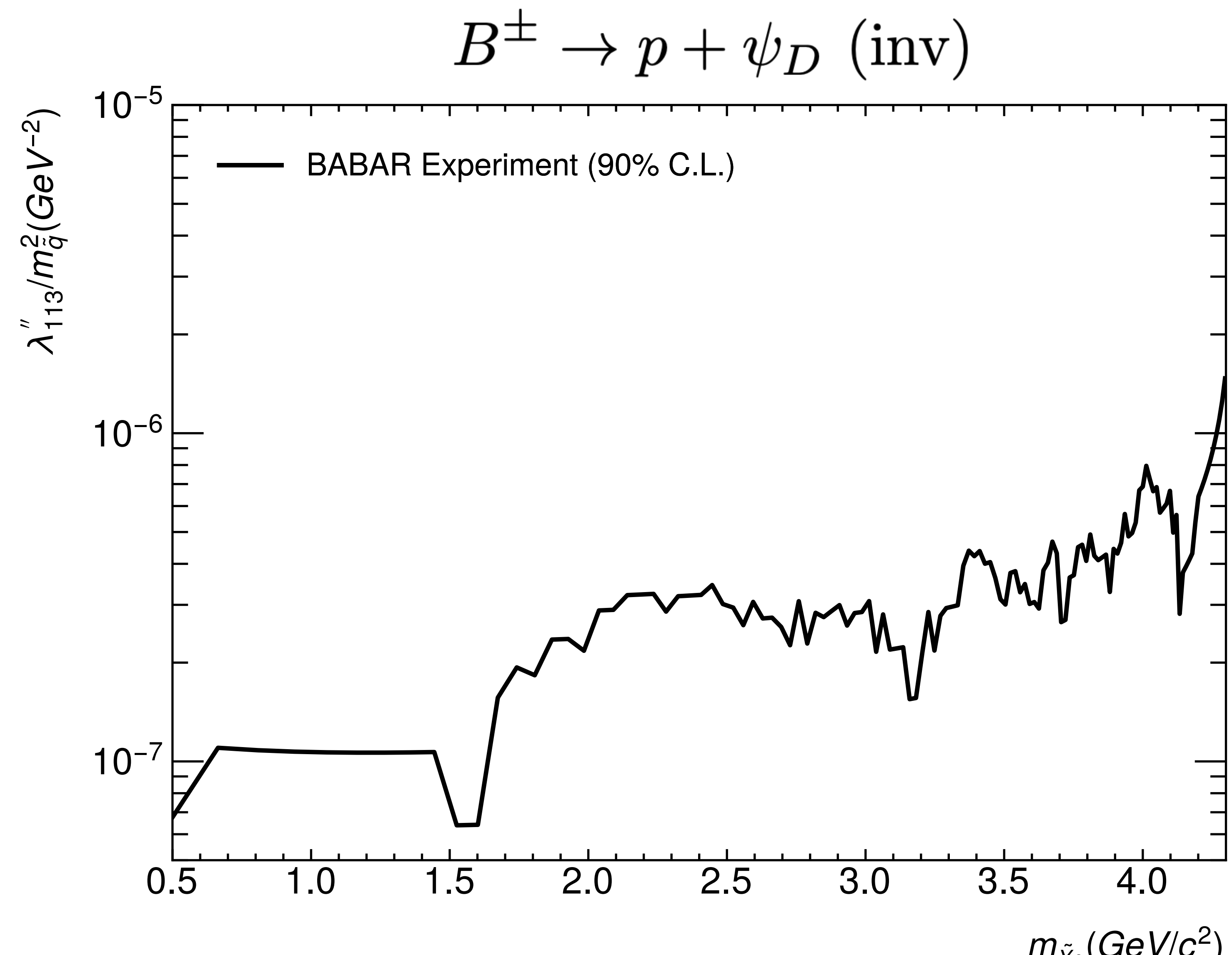


B-MESOGENESIS RESULTS

- 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