

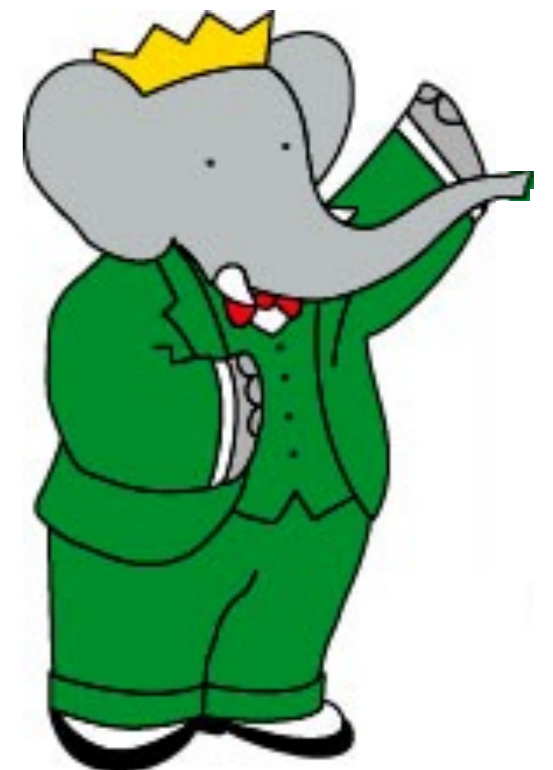
RECENT RESULTS OF DARK SECTOR SEARCHES WITH THE *BABAR* EXPERIMENT

Brian Shuve

on behalf of the BABAR Collaboration

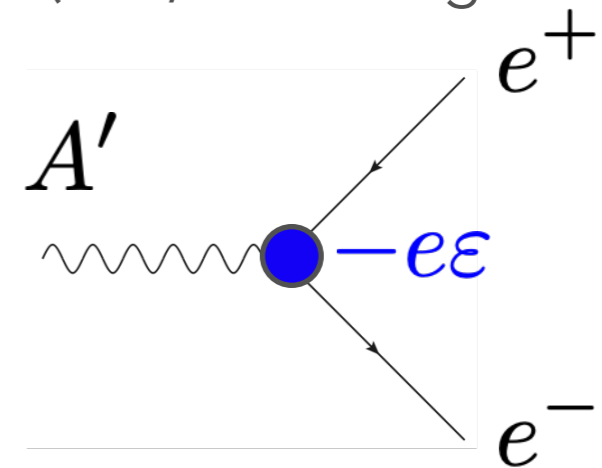
**HARVEY
MUDD
COLLEGE**

6th Colombian Meeting on
High Energy Physics
November 30, 2021



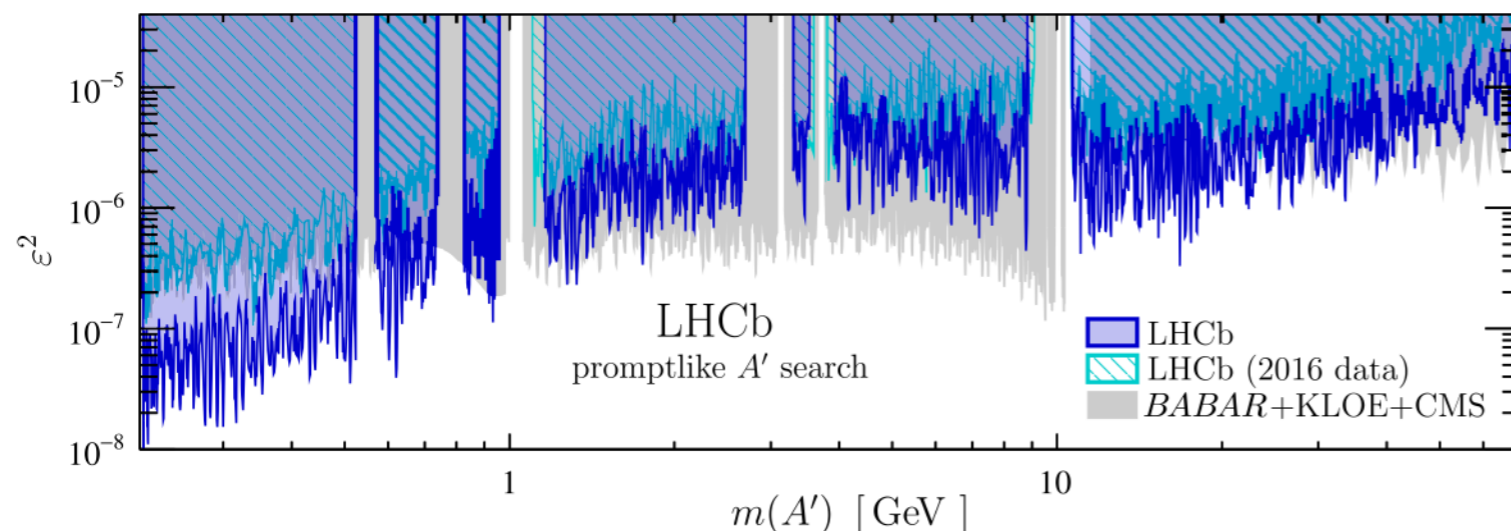
HIDDEN SECTOR DM

- For thermal dark matter masses below a few GeV, a low-mass mediator is needed for observed abundance (Lee, Weinberg 1977 [PRL])
- Many searches focus on minimal, predictive “portals”, such as a dark photon (A')

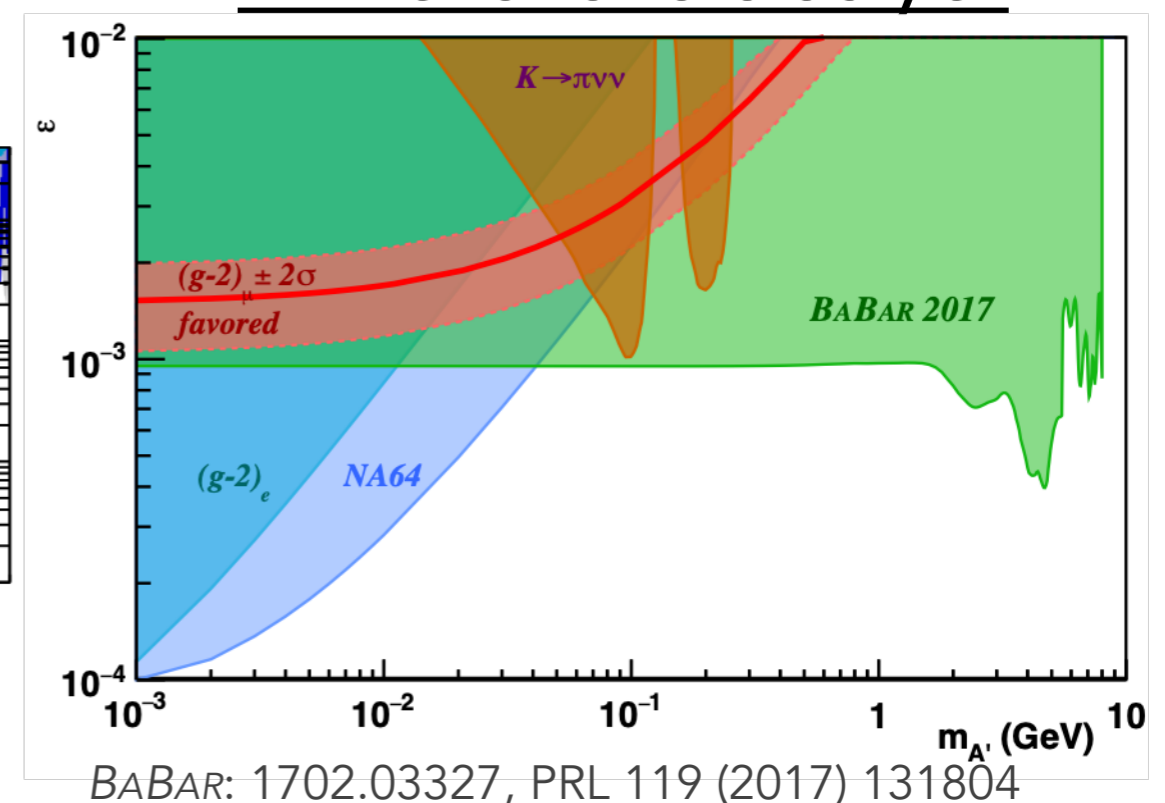


visible decays: $A' \rightarrow \ell^+ \ell^-$

invisible decays:



BABAR: 1406.2980, PRL 113 (2014) 201801
LHCb: 1910.06926, PRL 124 (2020) 041801

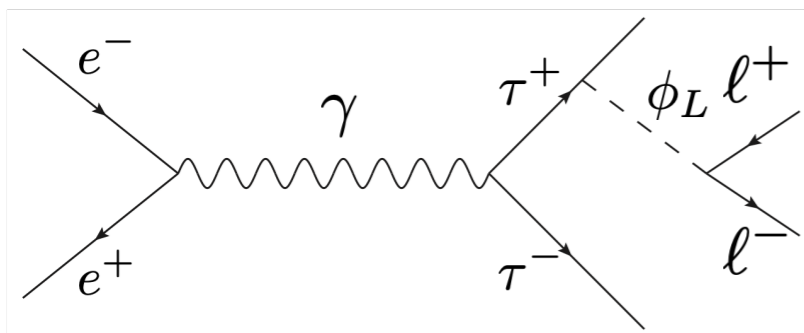


BABAR: 1702.03327, PRL 119 (2017) 131804

BEYOND MINIMAL PORTALS

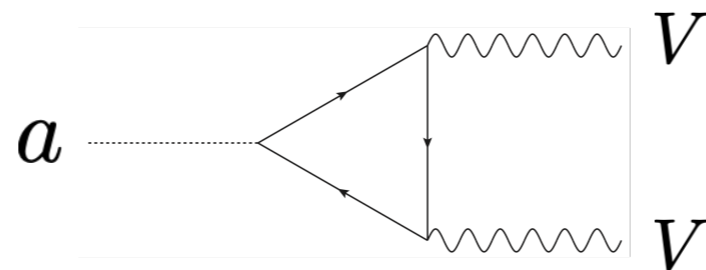
- Hidden sector dynamics can predict signals that differ from canonical portal searches, require new strategies

leptophilic forces



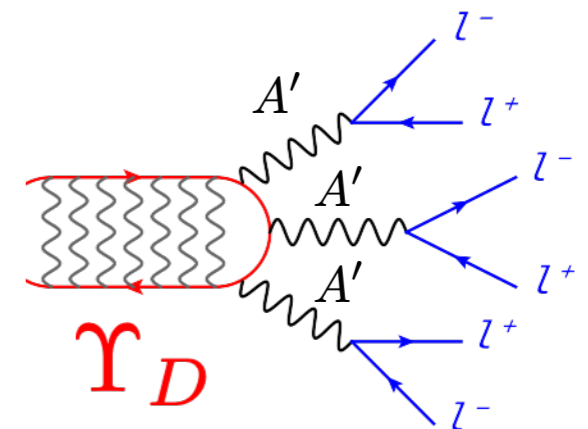
BABAR, 1606.03501, PRD 94 (2016) 011102
BABAR, 2005.01885, PRL 125 (2020) 181801

axionlike particles



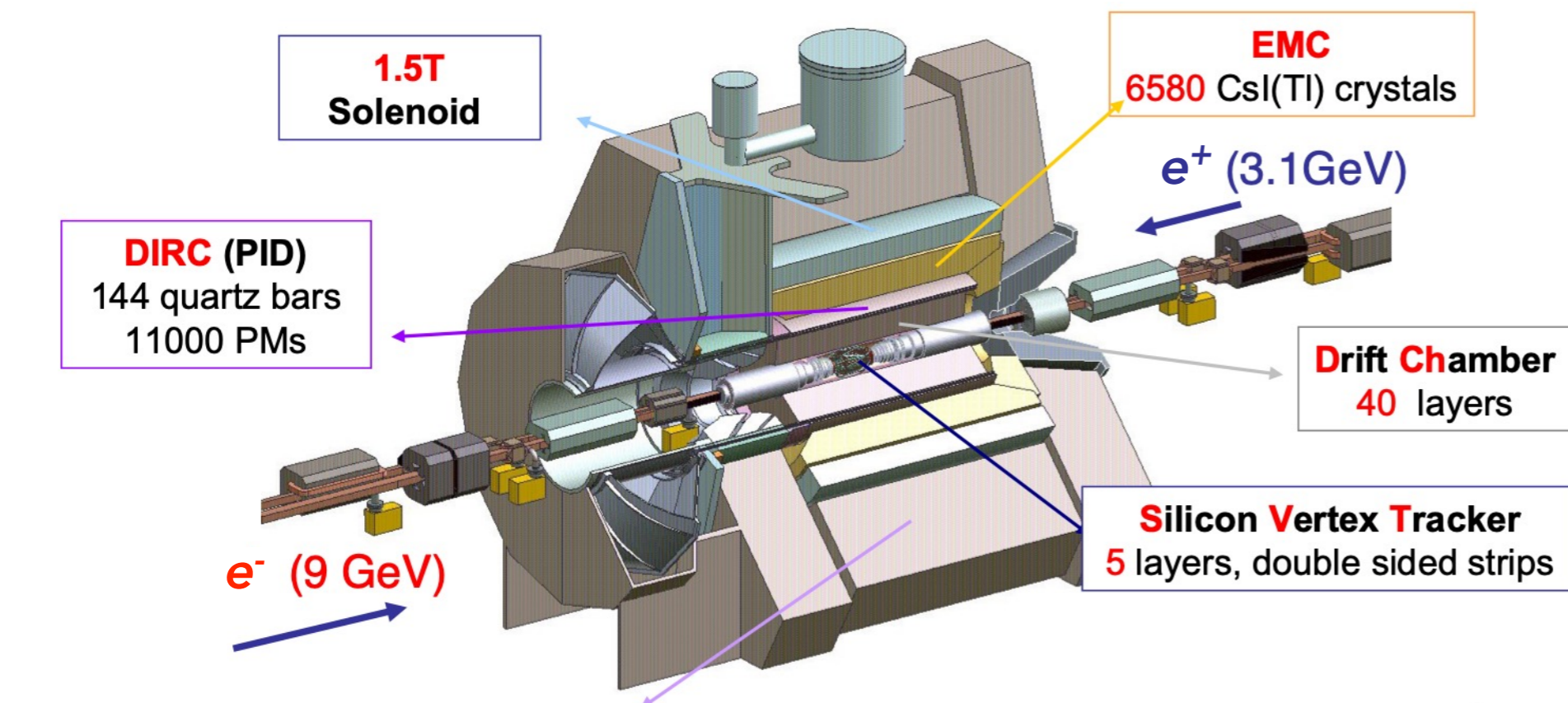
BABAR, 2111.01800

DM bound states

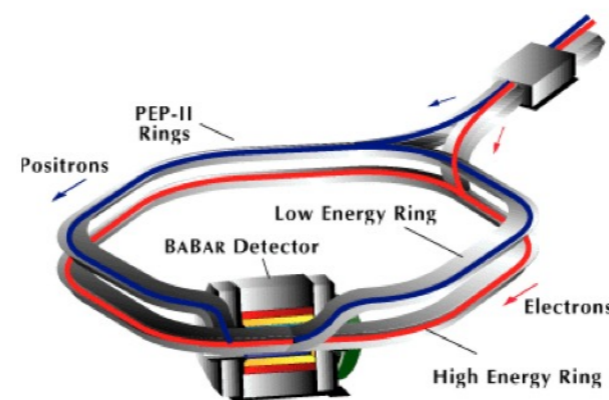


BABAR, 2106.08529

BABAR EXPERIMENT



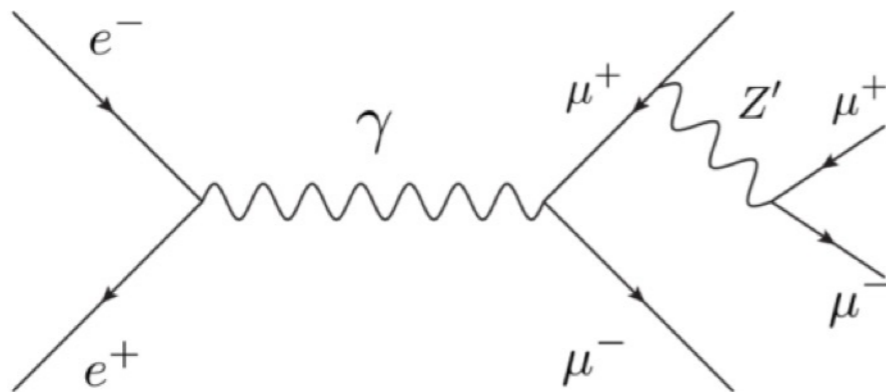
1999-2008



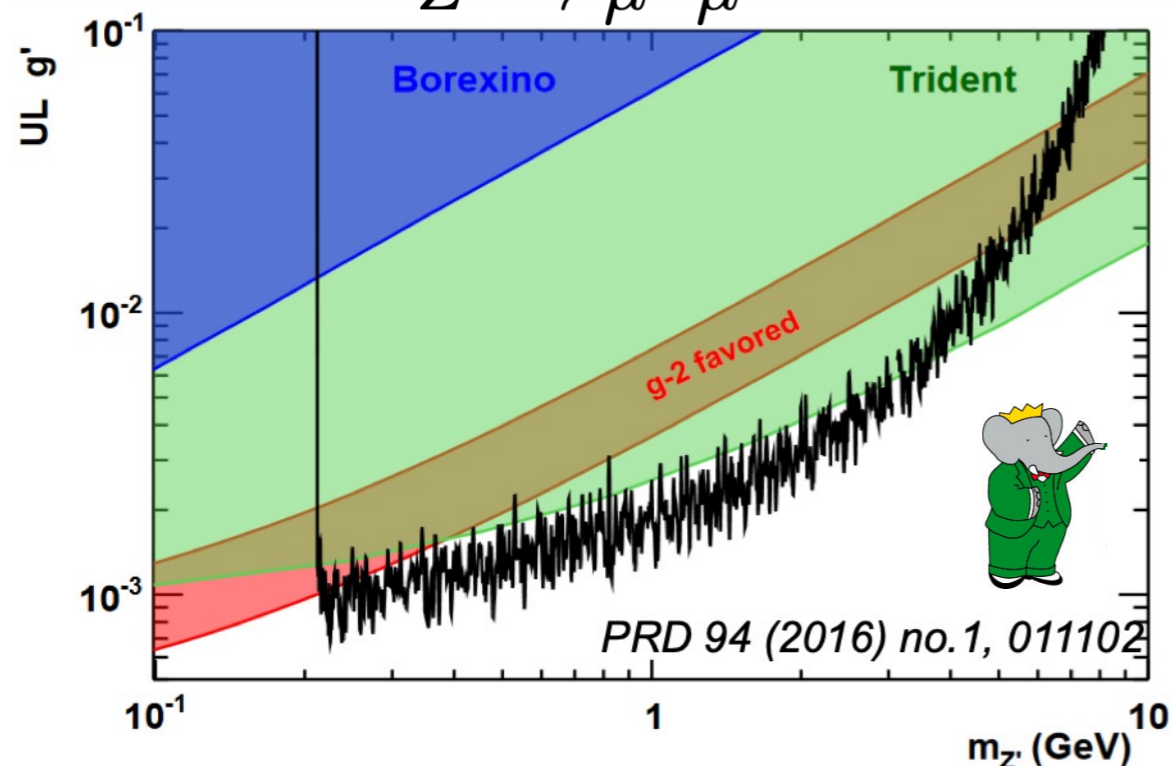
- 432/fb $\Upsilon(4S)$ on resonance
- 53/fb off resonance
- smaller samples at $\Upsilon(2S)/\Upsilon(3S)$

LEPTOPHILIC FORCES

- Mediator couples predominantly to muons or taus, can explain muon $g-2$ while satisfying other constraints

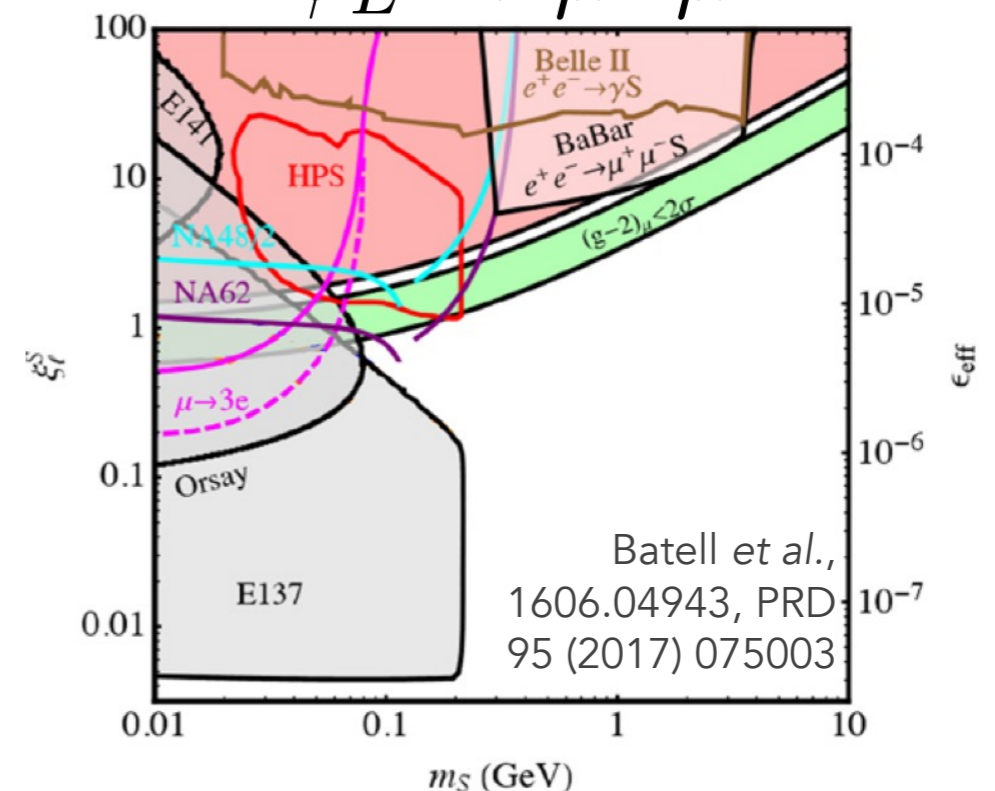


$$Z' \rightarrow \mu^+ \mu^-$$



- Search for dilepton resonance in association with two muons
- BABAR* muonic force searches constrains $m_{Z'} > 2m_\mu$

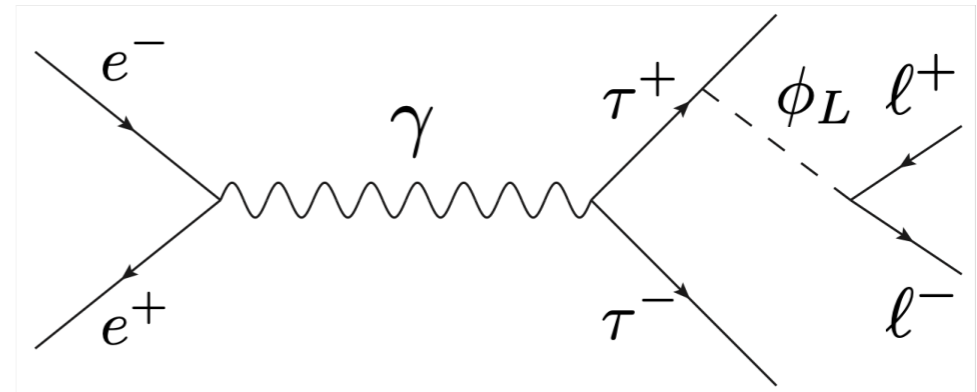
$$\phi_L \rightarrow \mu^+ \mu^-$$



LEPTOPHILIC SCALAR

- In many scalar models, the scalar has **mass-proportional coupling**, so more sensitivity can be obtained through production with taus
- Mediator mostly decays to heaviest accessible lepton

- Prompt decays to muons for $m_{\phi_L} > 2m_\mu$
- Displaced decays to electrons for $m_{\phi_L} < 2m_\mu$



$$g_\ell \propto m_\ell/v$$

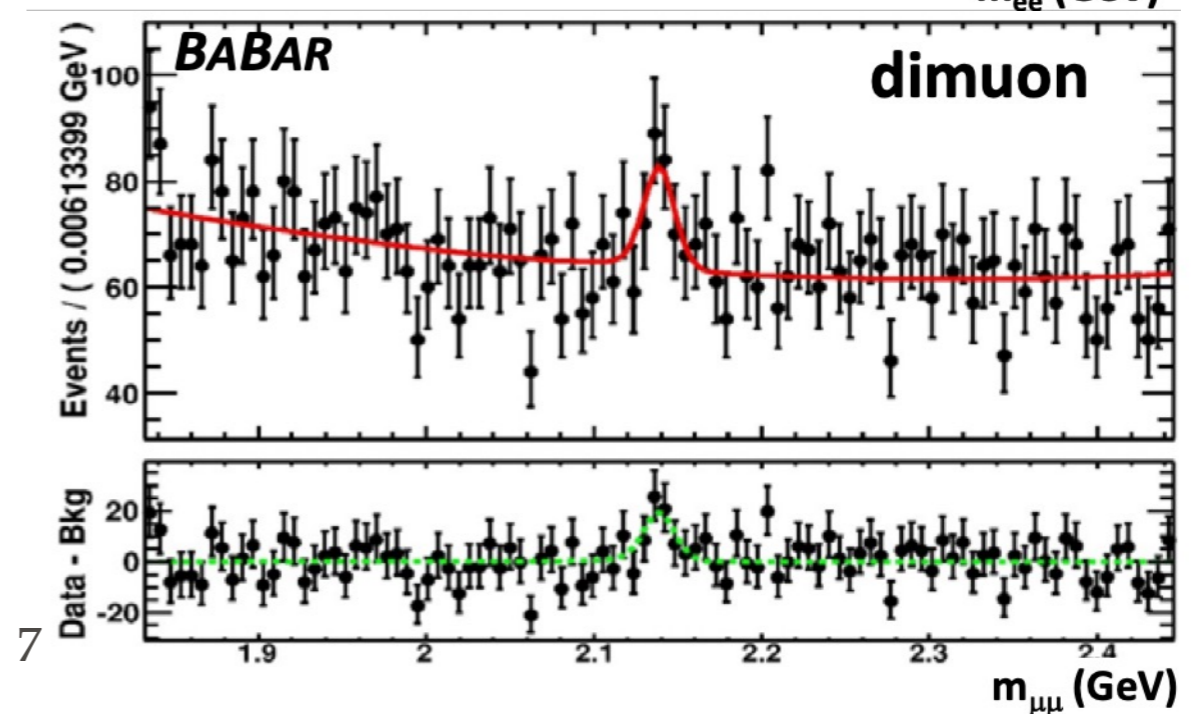
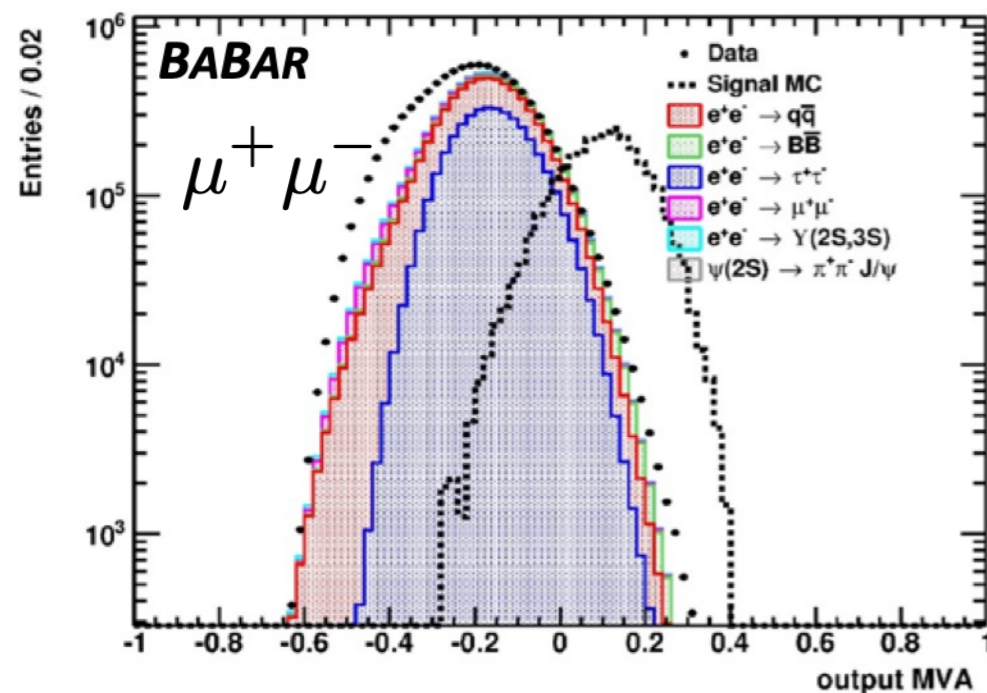
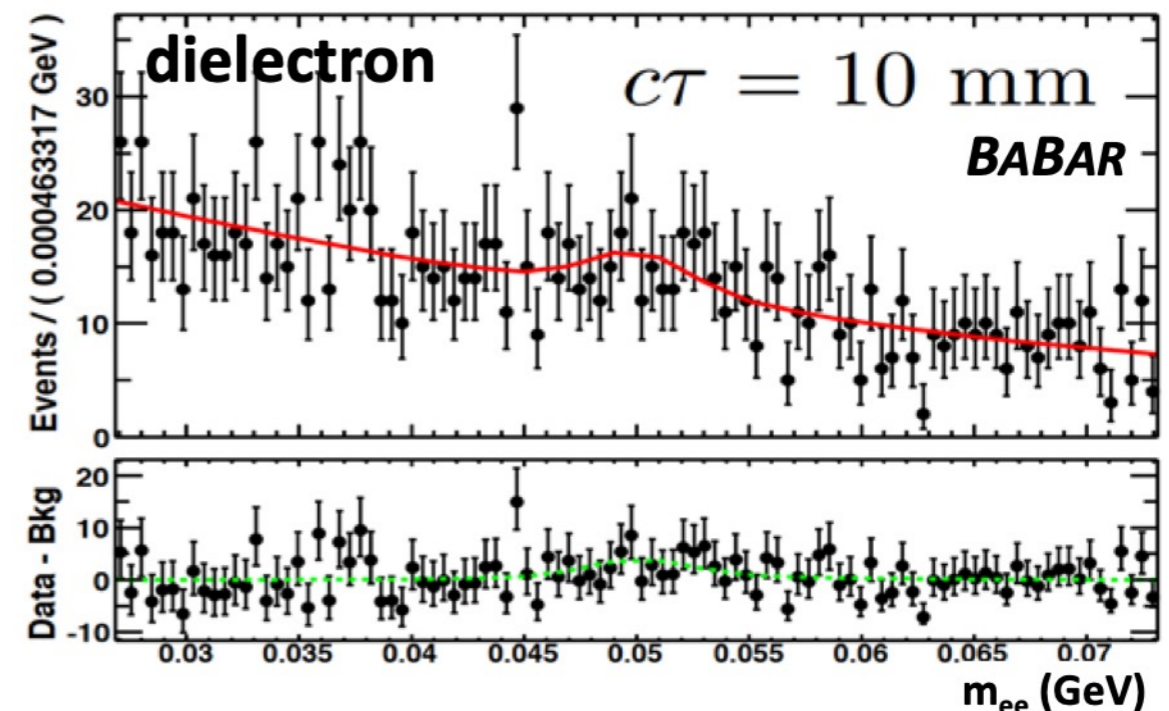
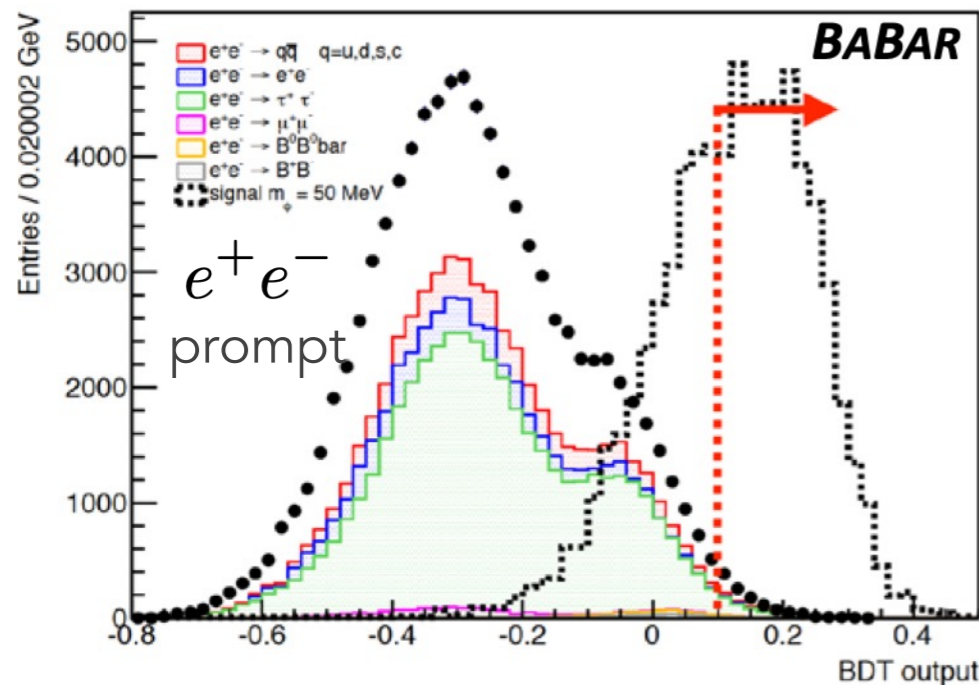
Batell et al., 1606.04943, PRD 95 (2017) 075003
see also Chen et al., 1511.04715, PRD 93 (2016) 035006

- Consider all single-pronged tau decays, trained BDTs for each final state & lifetime to increase signal purity (event shape, vertex information, kinematic observables)

BABAR, 2005.01885, PRL 125 (2020) 181801

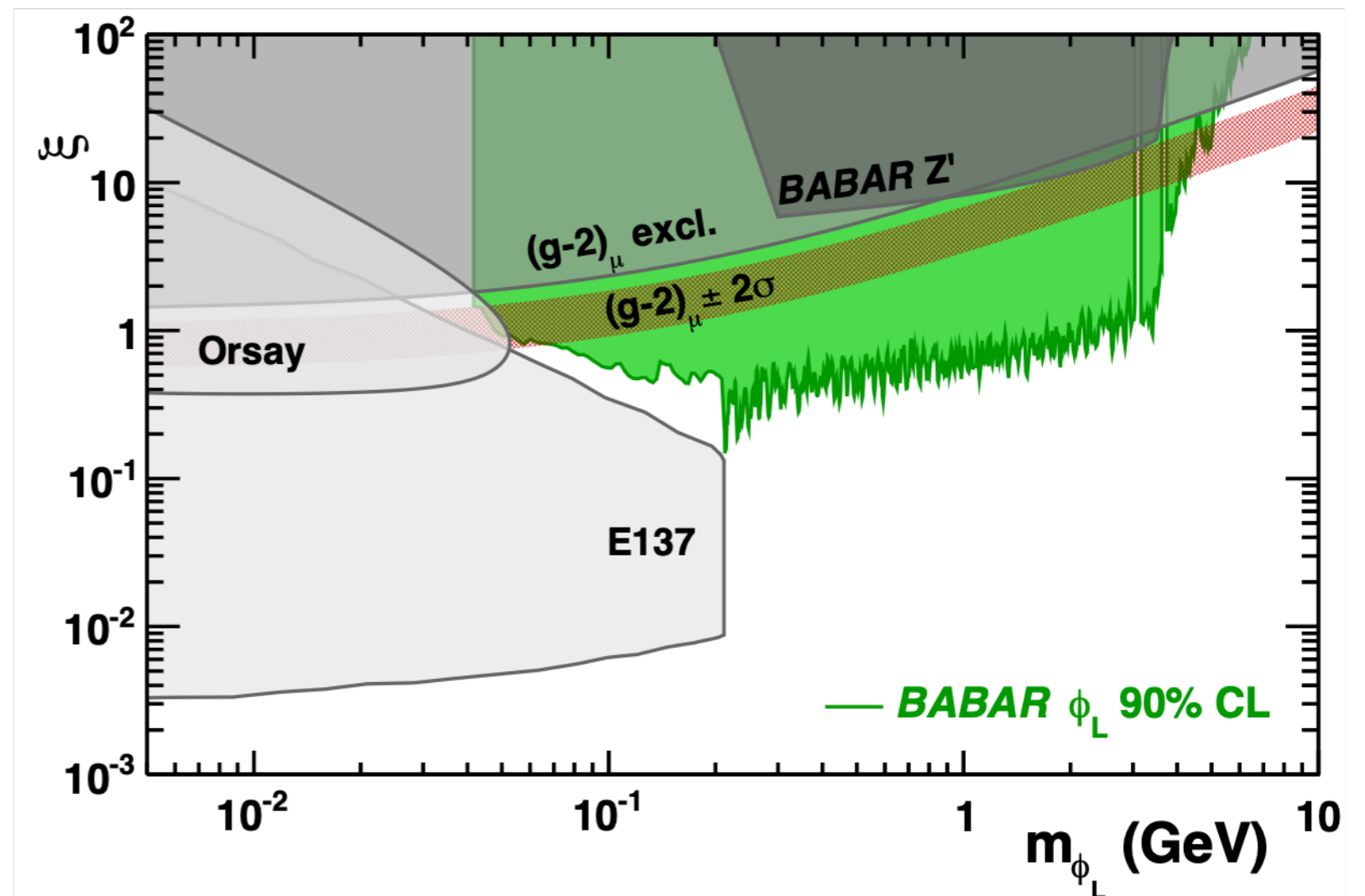
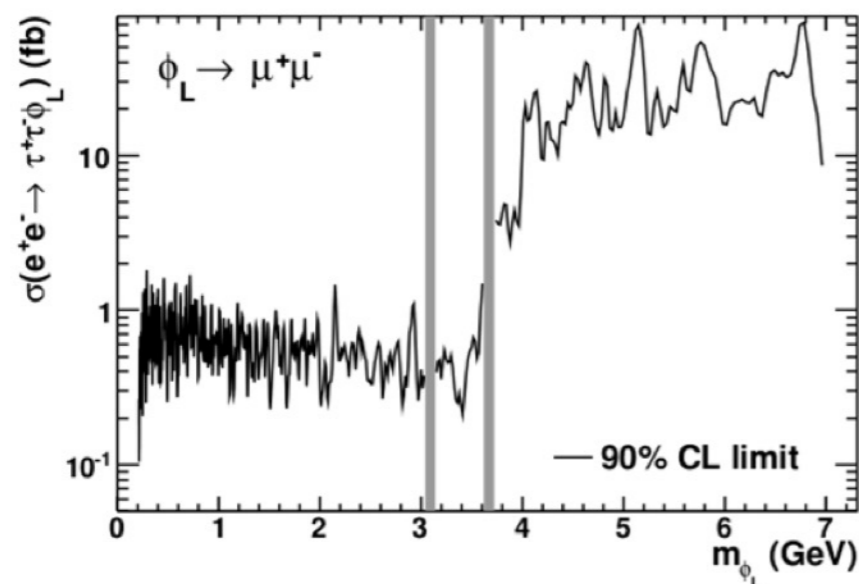
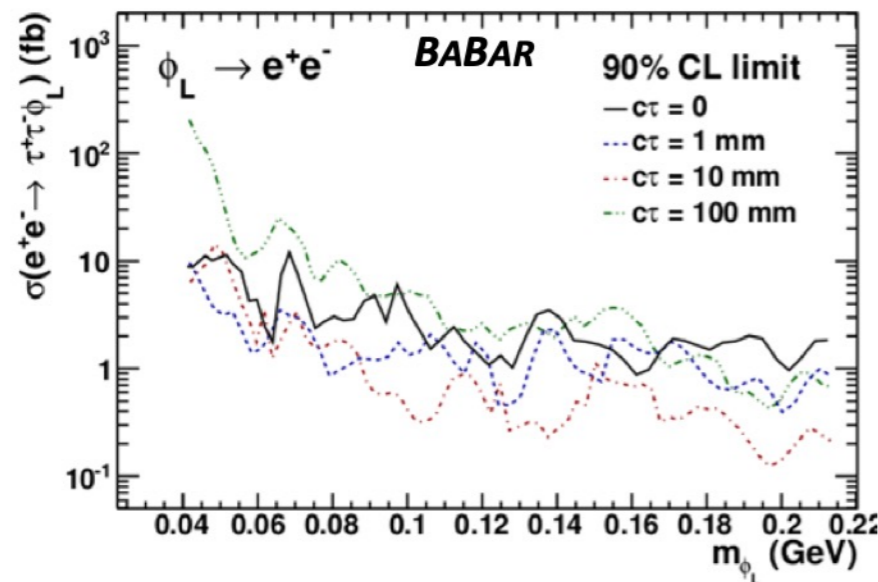
LEPTOPHILIC SCALAR

- Use MC-independent model for background, look for **narrow** peak



LEPTOPHILIC SCALAR

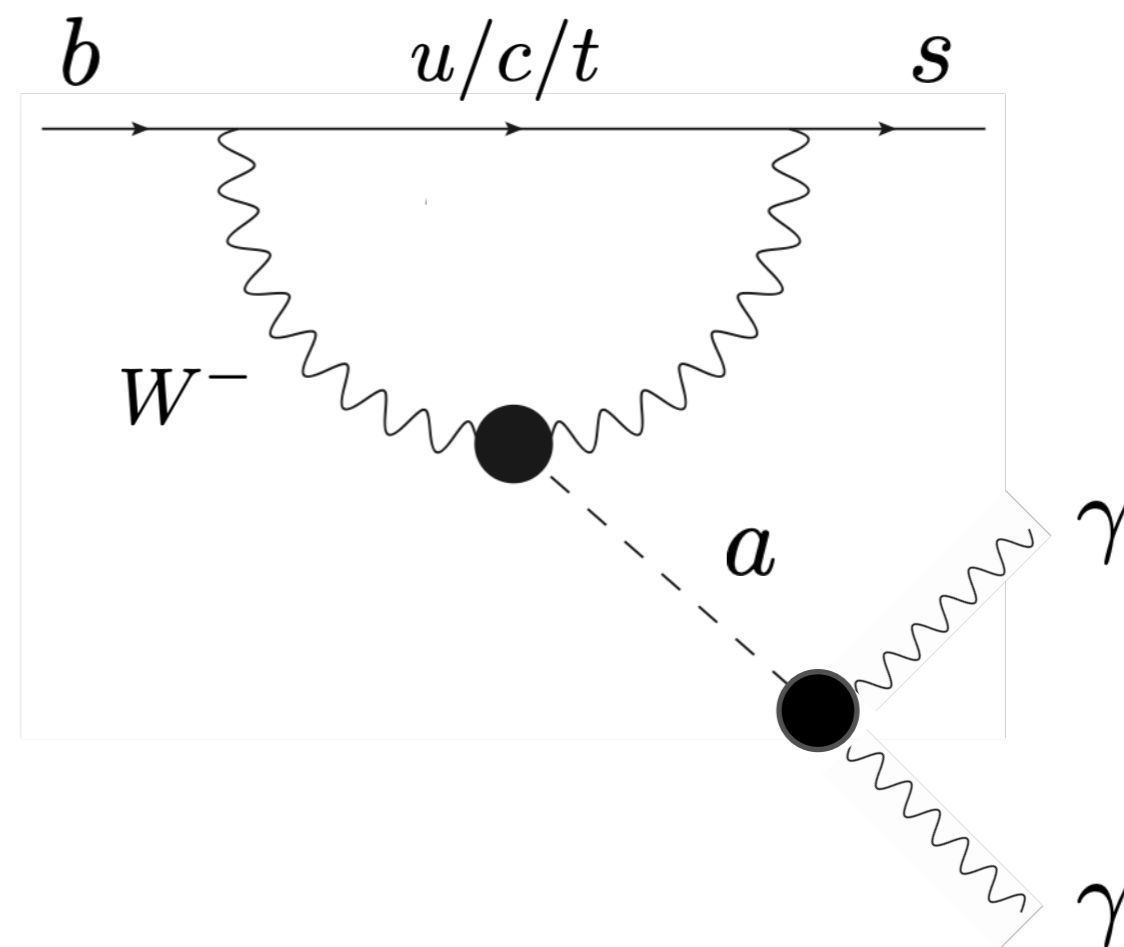
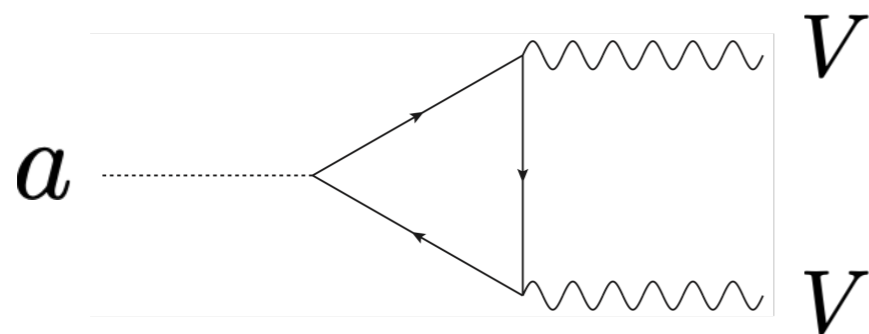
- In the absence of significant signal, we set model-independent 90% CL cross section limits, as well as limits on the leptophilic model coupling



AXIONLIKE PARTICLES

- Another major gap exists when mediators couple predominantly to gauge bosons: **axionlike particles (ALPs)**

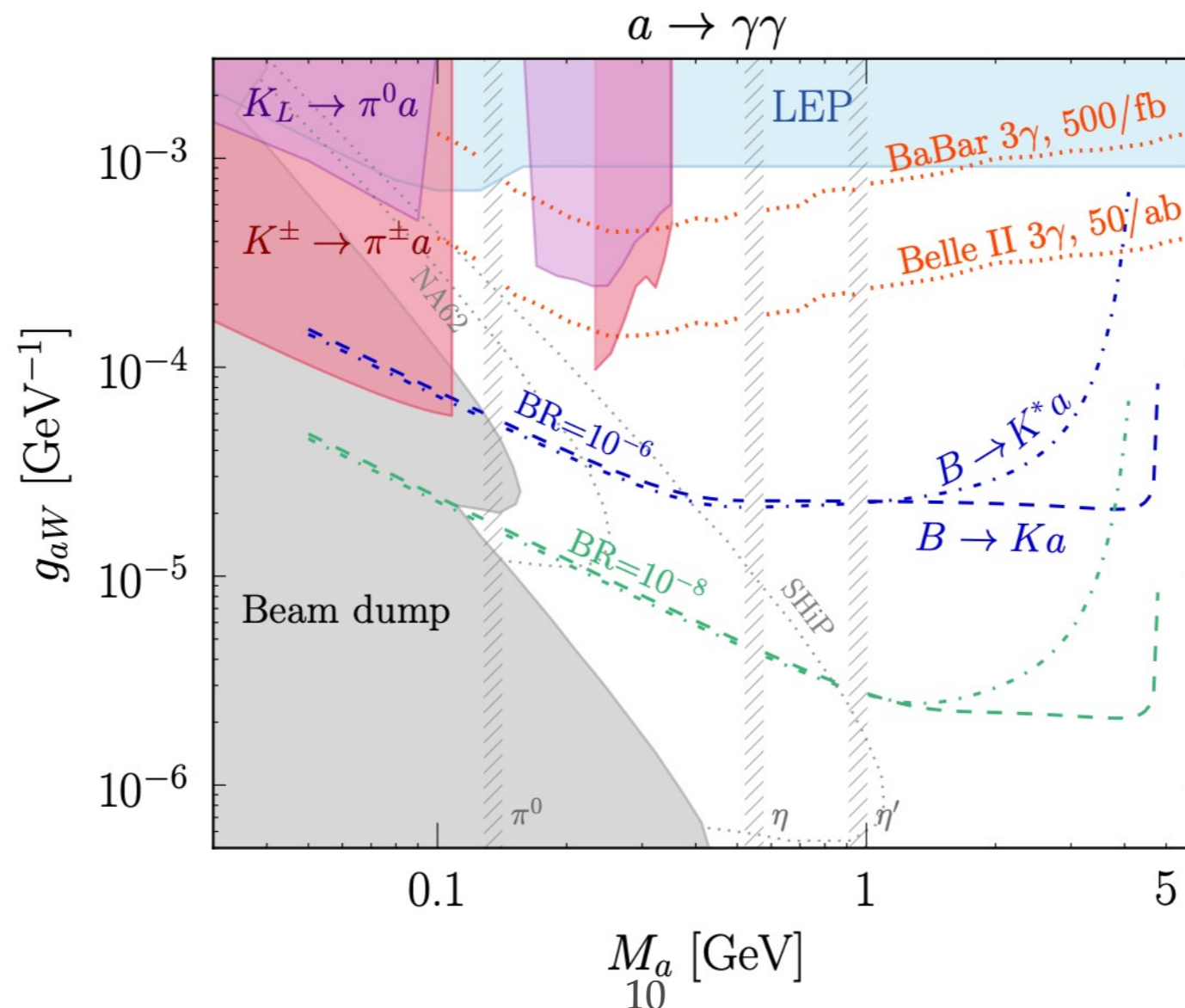
$$\mathcal{L} = -\frac{g_{aV}}{4} a V_{\mu\nu} \tilde{V}^{\mu\nu}$$



- If ALP couples to W bosons, then it can be produced in rare B meson decays: $B^\pm \rightarrow K^\pm a$, $a \rightarrow \gamma\gamma$

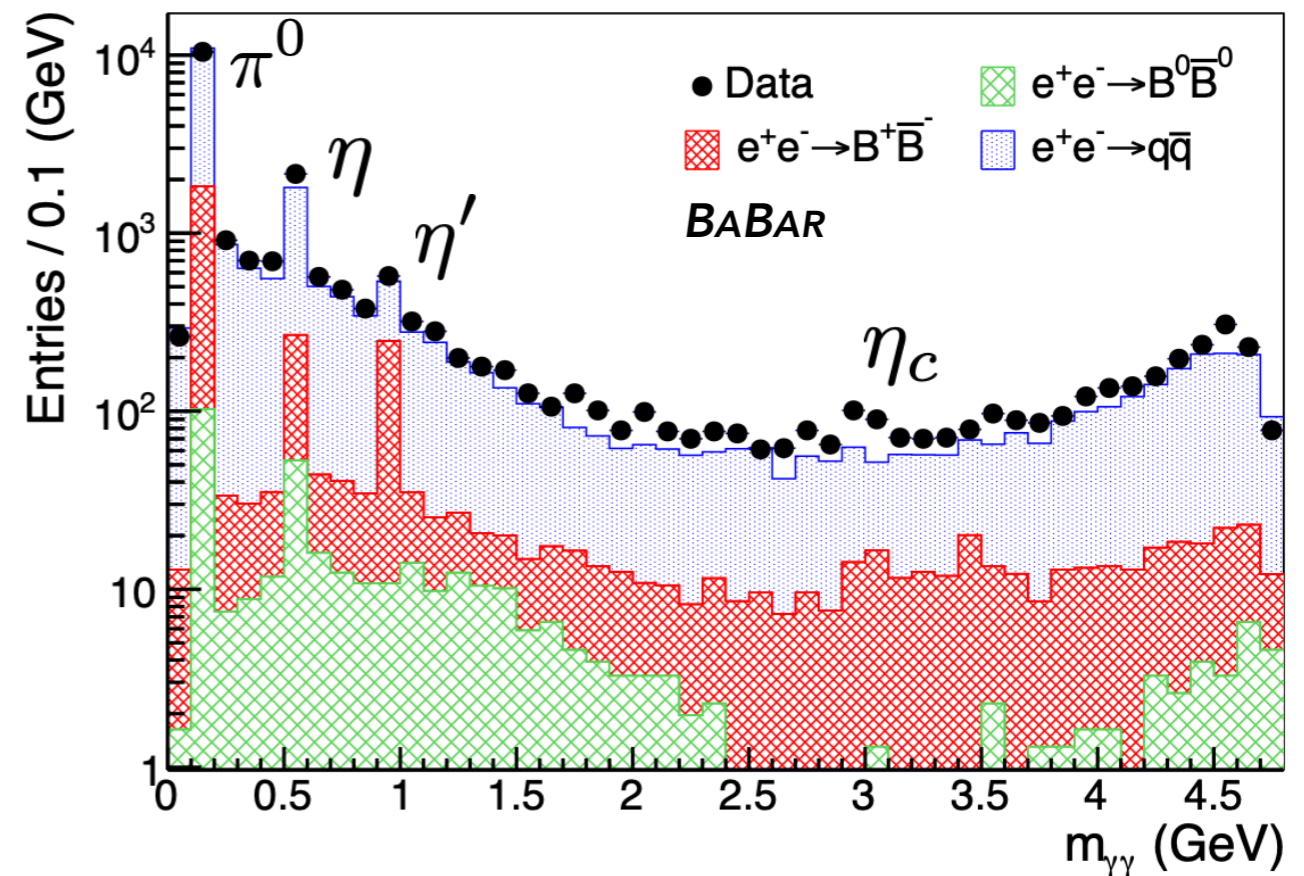
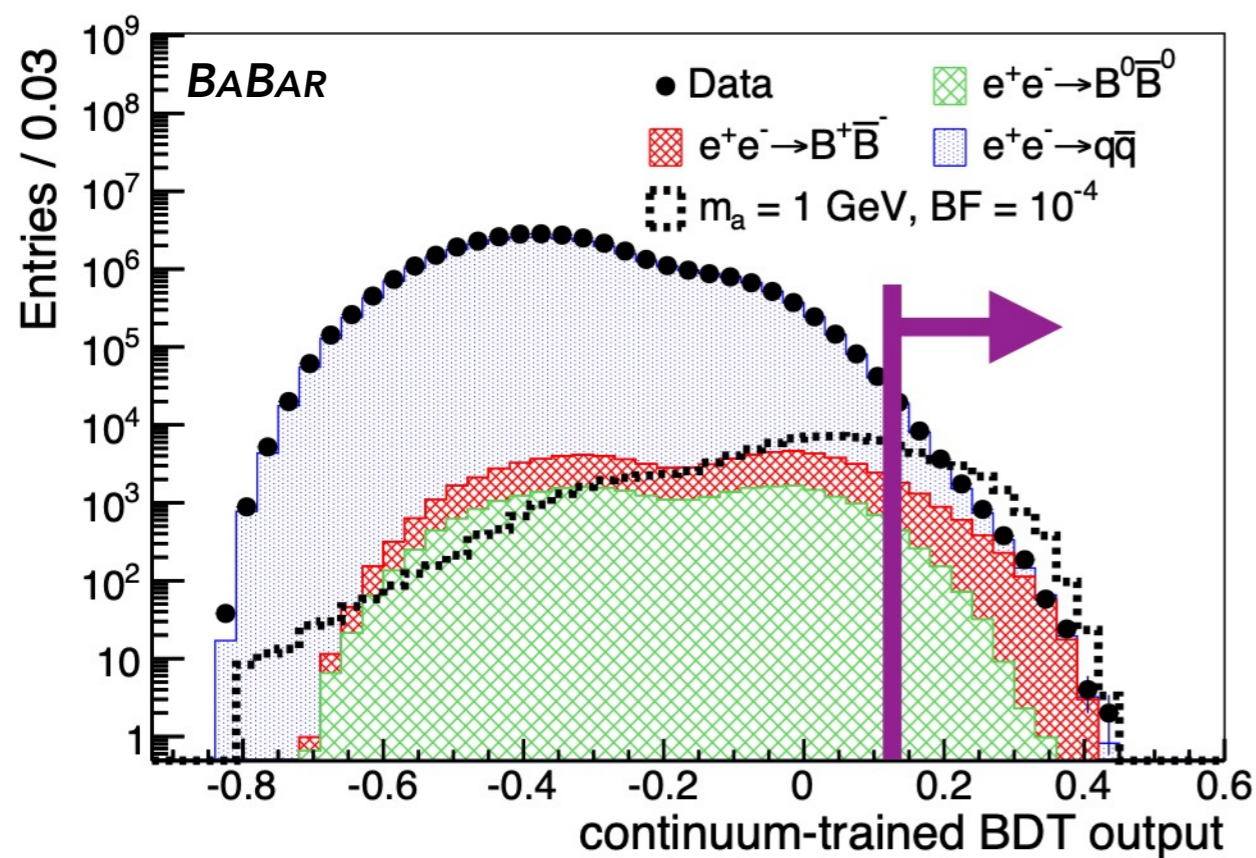
AXIONLIKE PARTICLES

- We consider a model where ALP couples to SU(2) bosons
- The $B^\pm \rightarrow K^\pm a$, $a \rightarrow \gamma\gamma$ mode can give best sensitivity to the model!



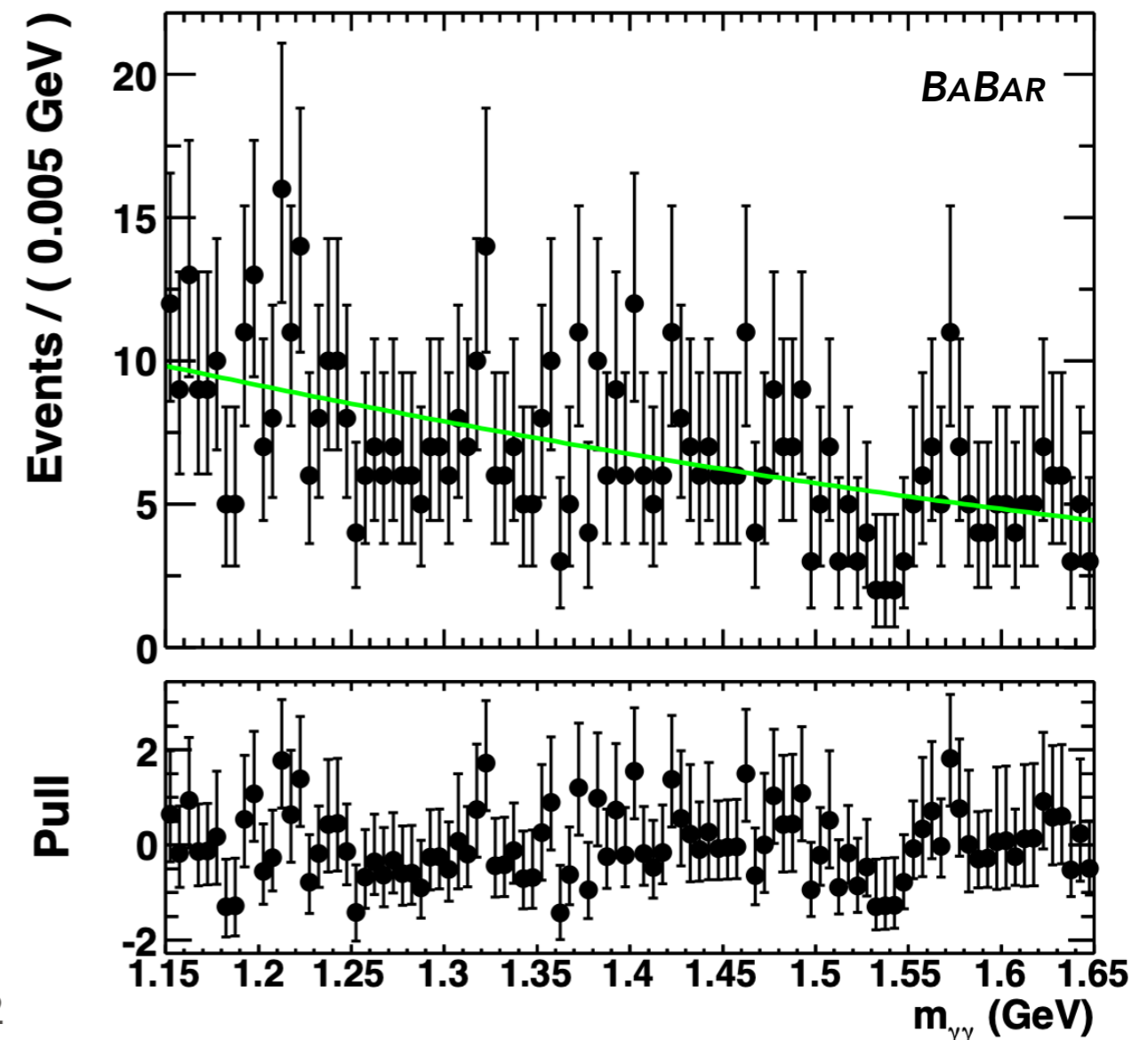
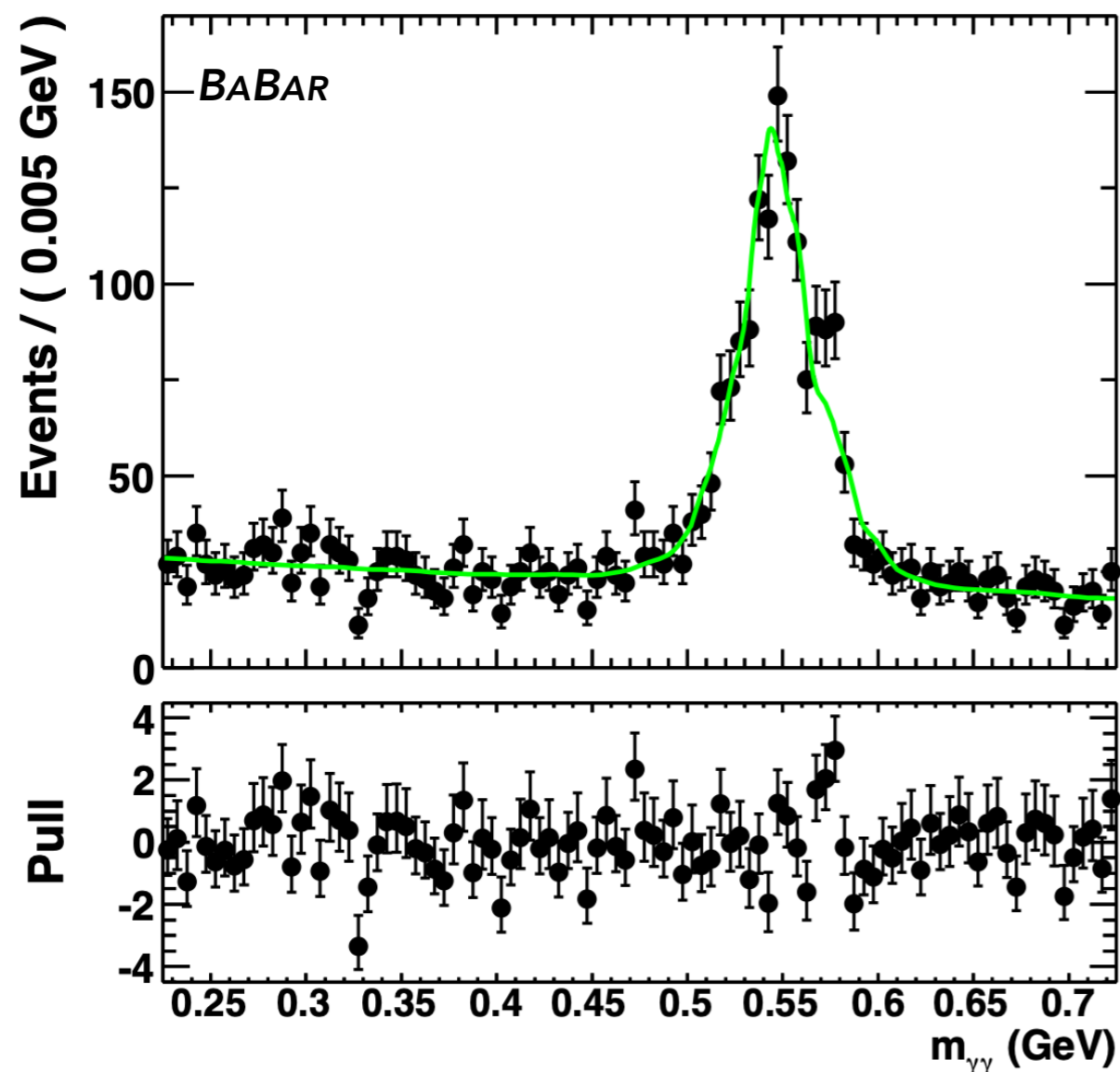
AXIONLIKE PARTICLES

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



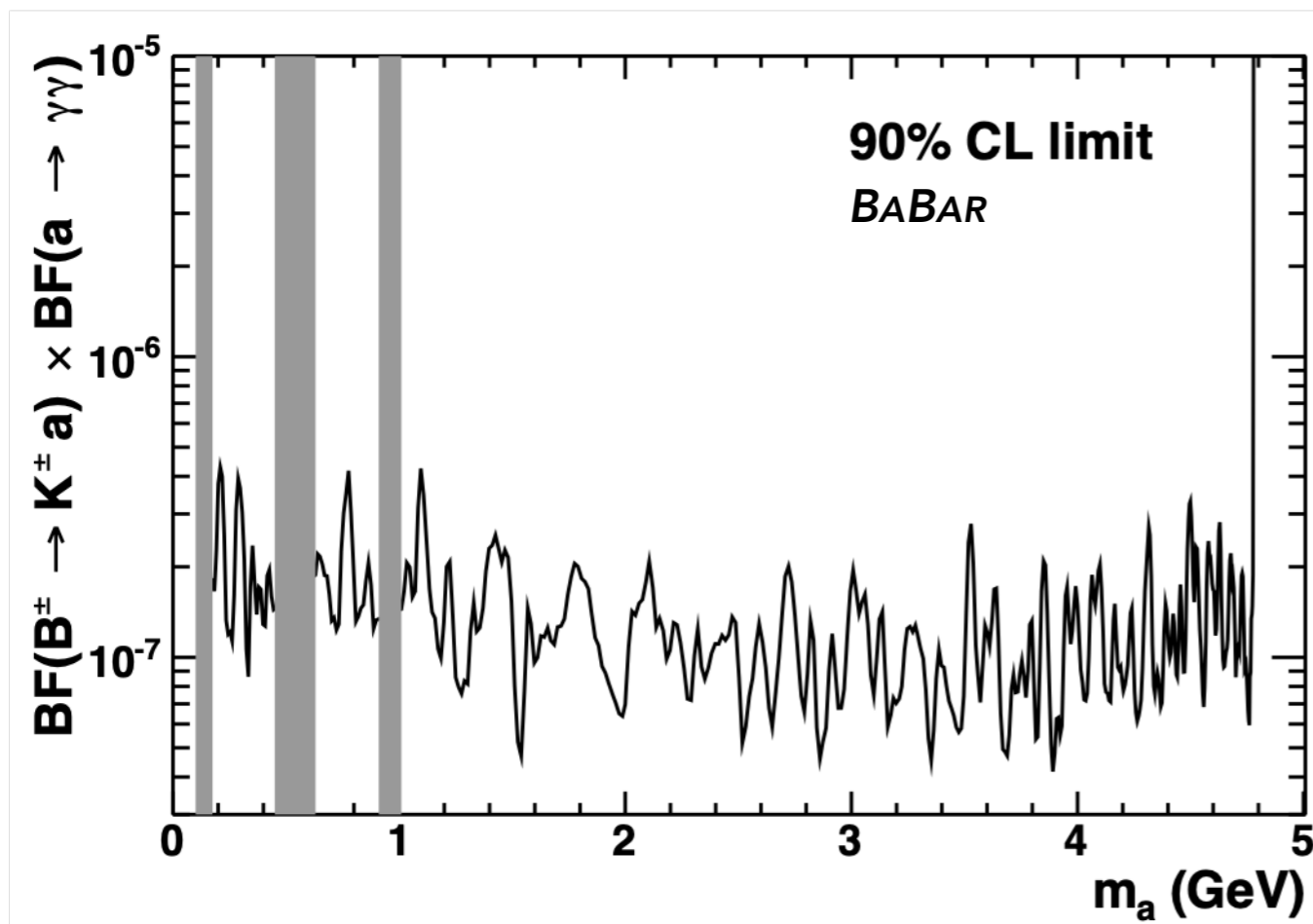
AXIONLIKE PARTICLES

- Peaking components modelled using MC (signal MC used for η_c)
- Continuum components modelled using MC + linear function for masses < 4 GeV, linear function at higher masses

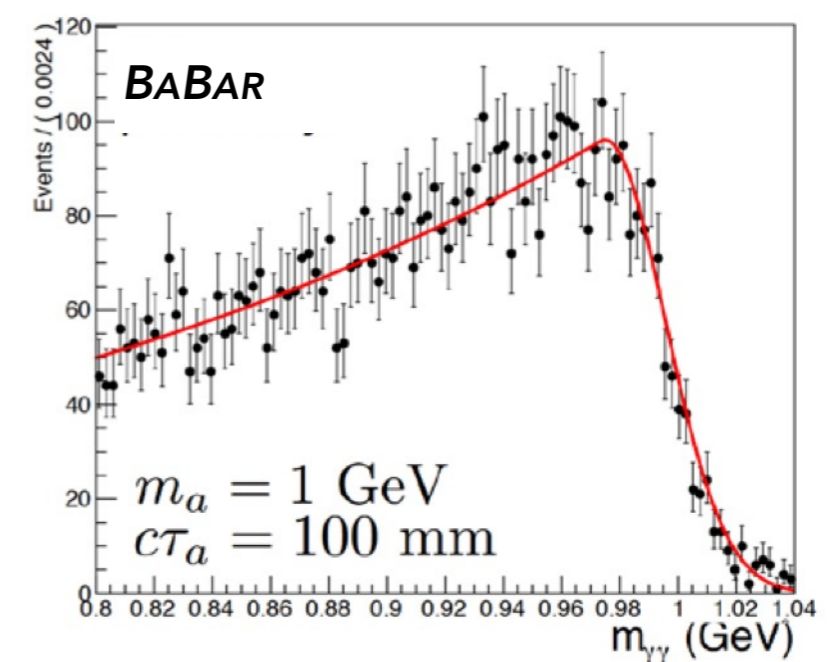


AXIONLIKE PARTICLES

- In the absence of significant signal, Bayesian 90% CL upper limits are derived on $BF(B^\pm \rightarrow K^\pm a, a \rightarrow \gamma\gamma)$ assuming prompt decays

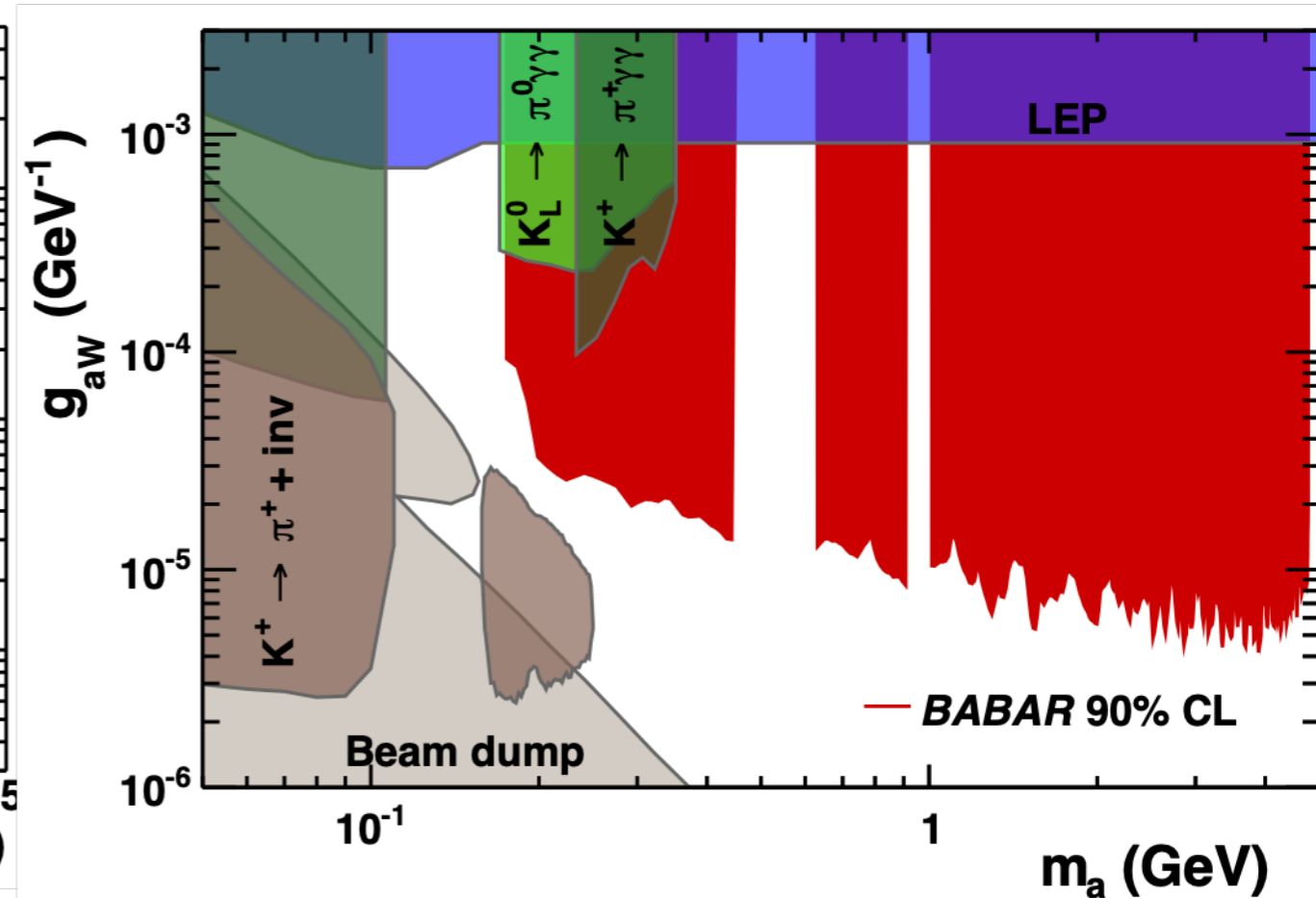
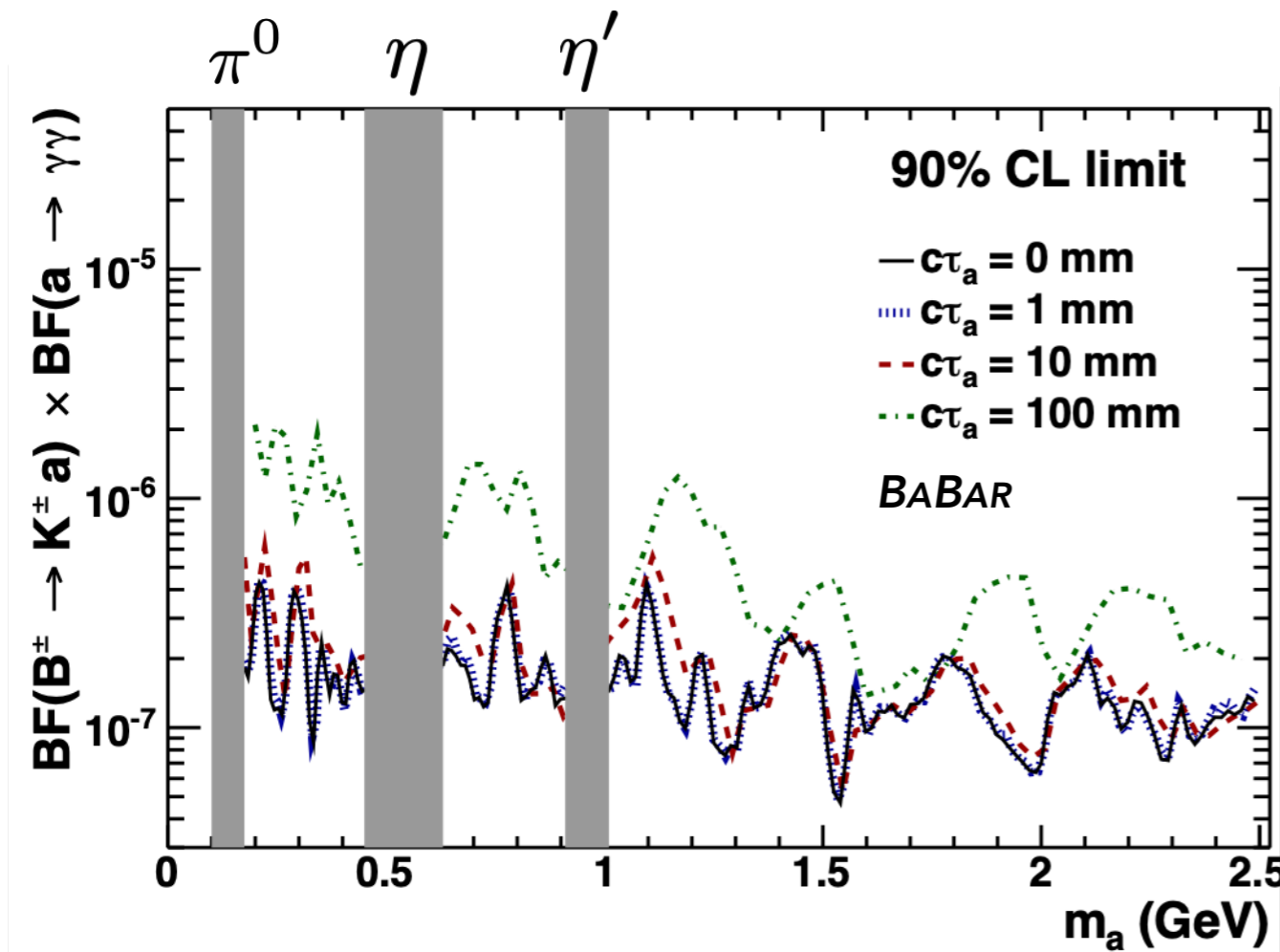


- At longer lifetimes, misreconstruction of displaced photons leads to reduced sensitivity



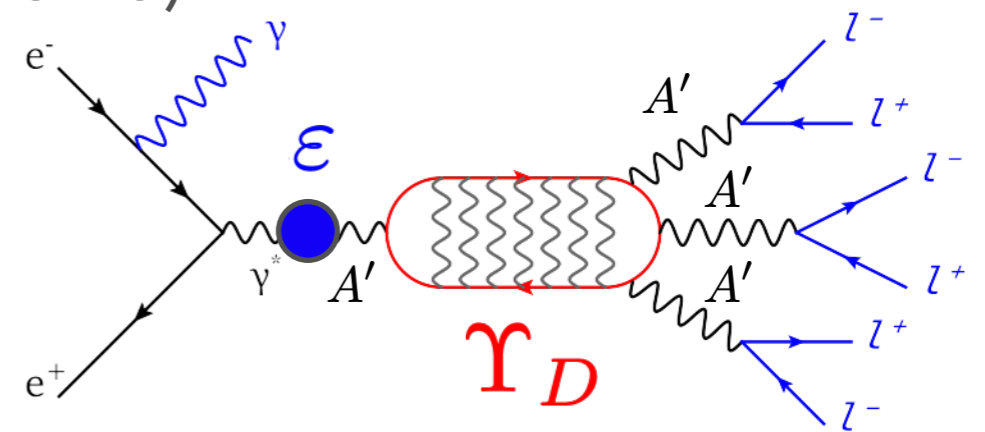
AXIONLIKE PARTICLES

- No significant signal observed; set 90% CL upper limits on branching fraction & ALP coupling



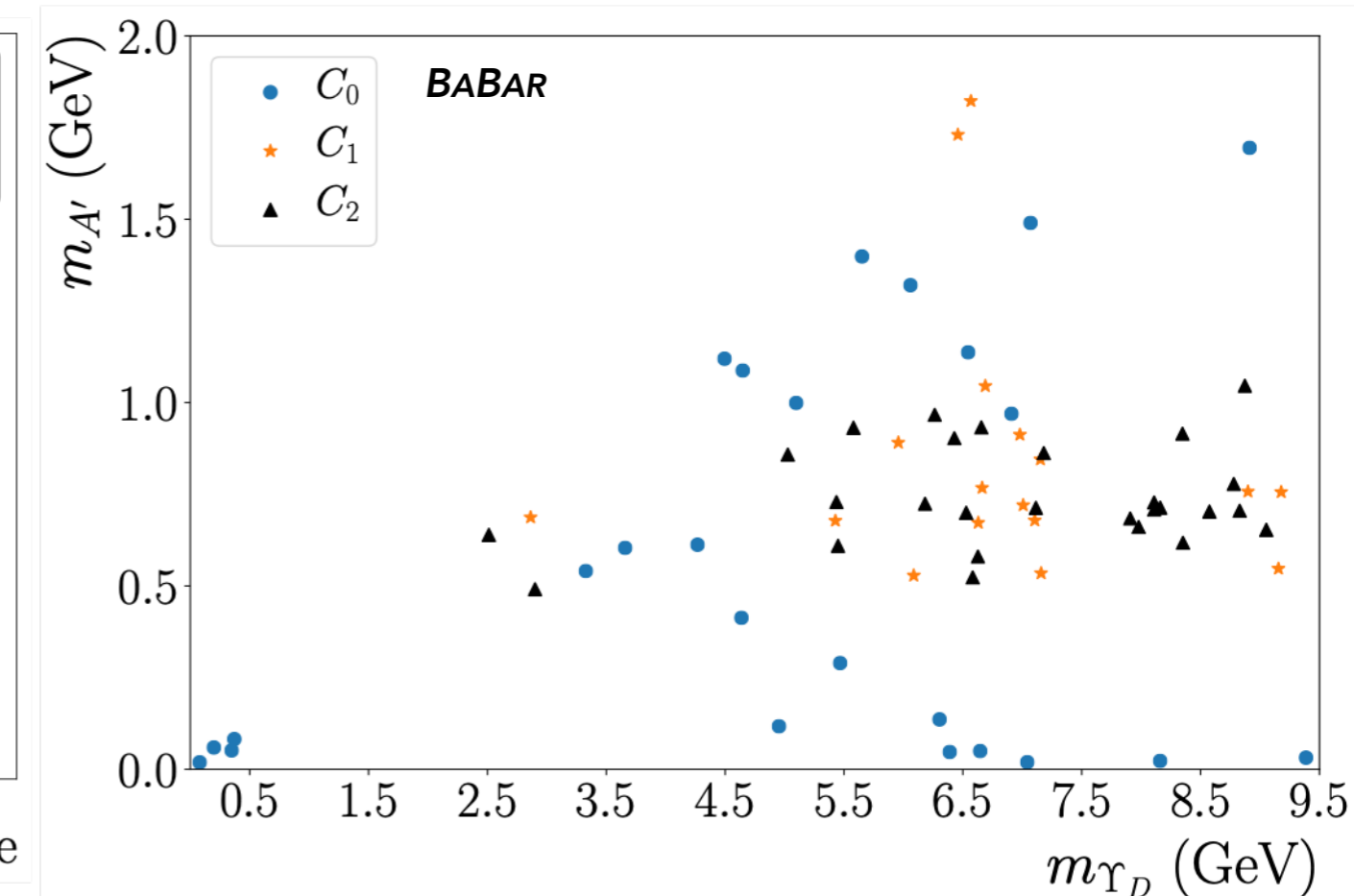
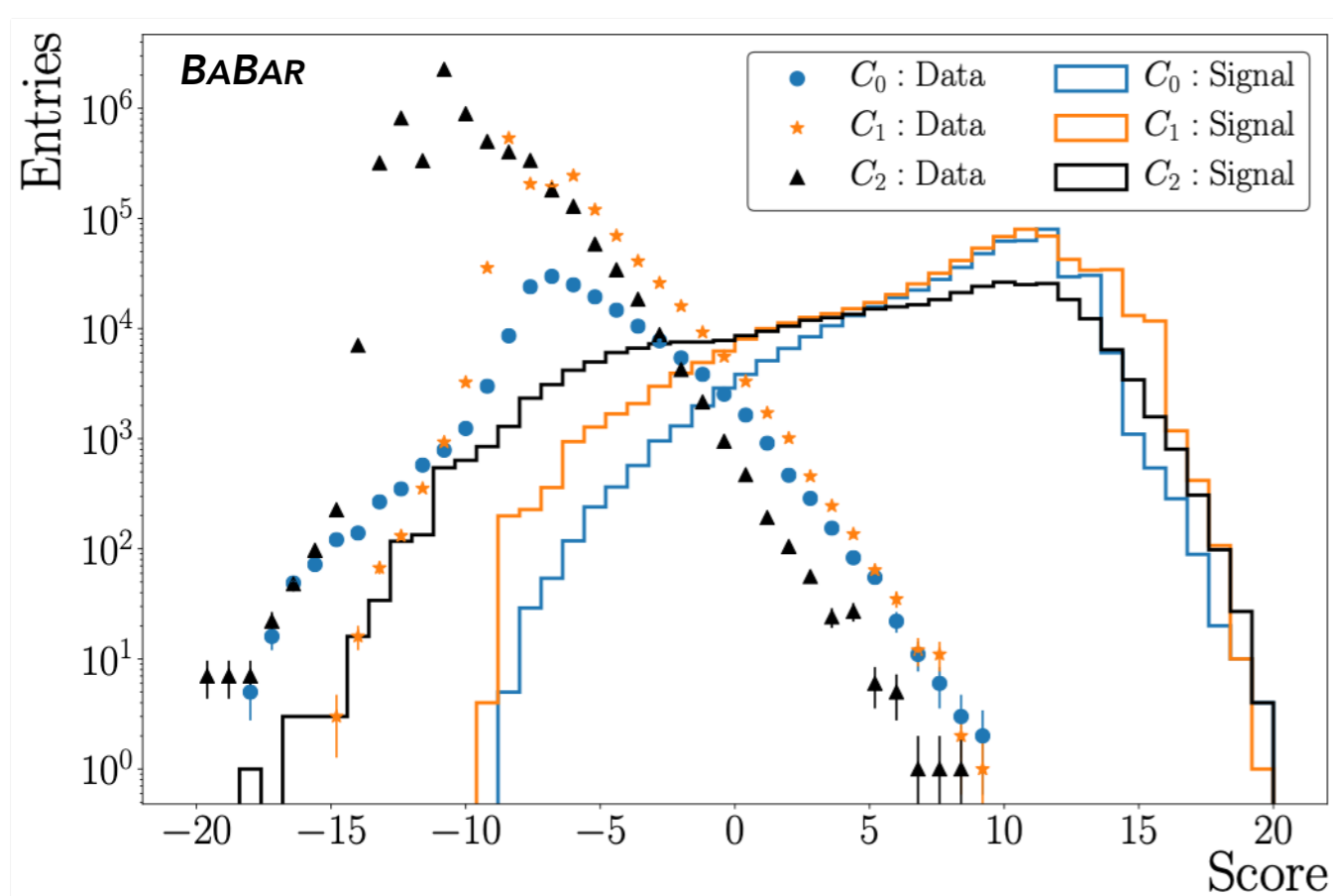
DM BOUND STATE: DARKONIUM

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



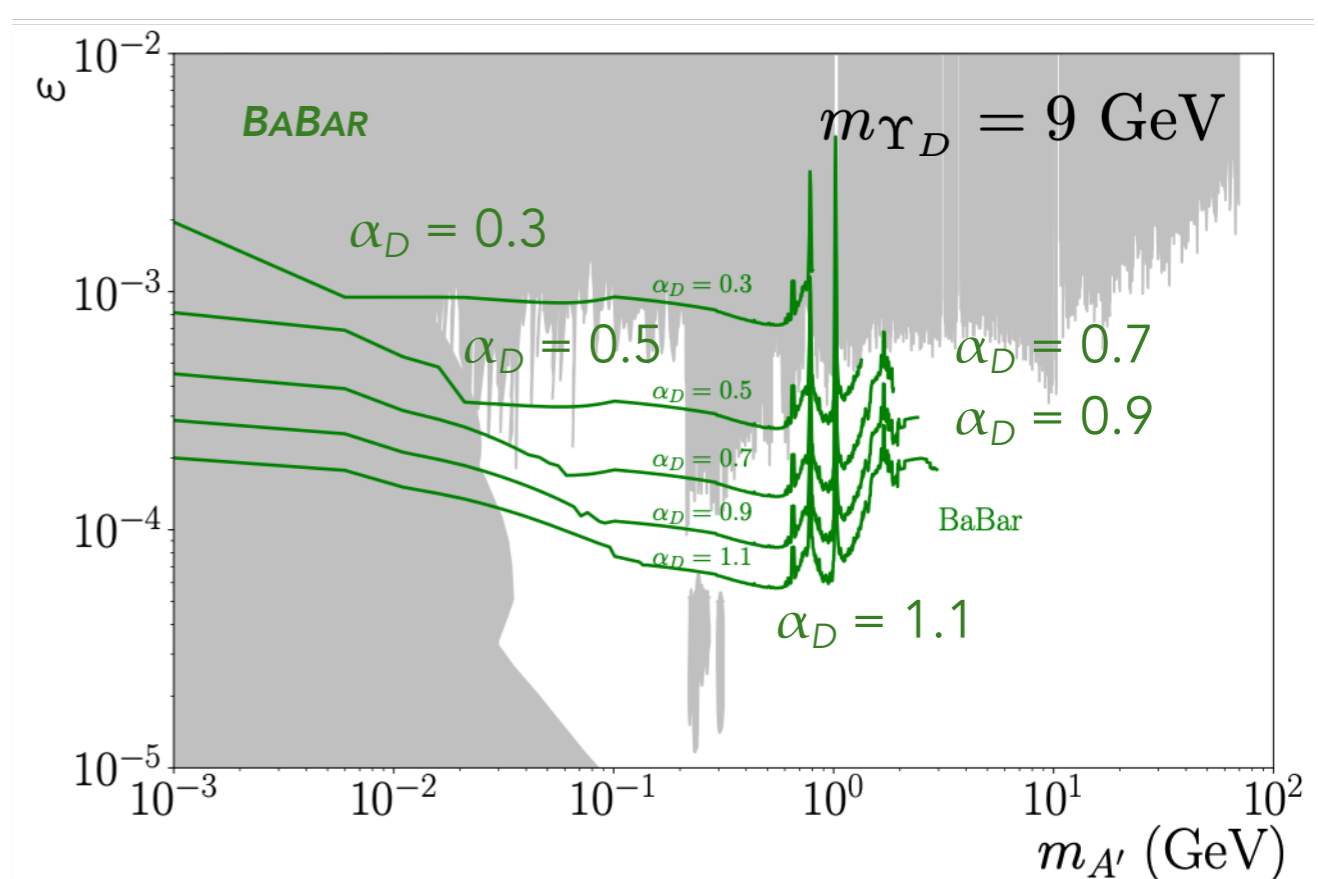
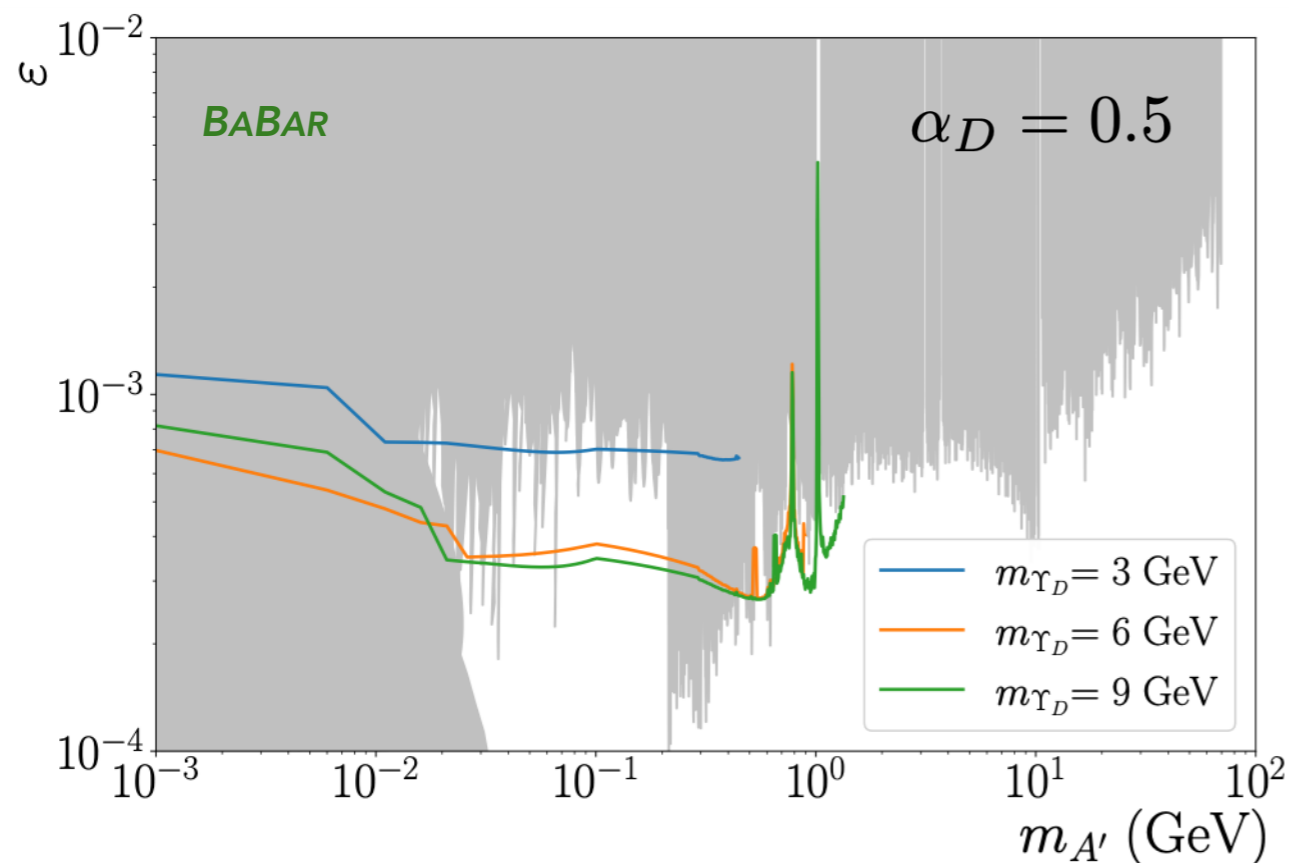
DARKONIUM RESULTS

- C_n sample corresponds to n pion pairs
- Consider window around each mass pair in $m_{\Upsilon_D} - m_{A'}$ plane of width 8x signal resolution, estimate background from adjacent windows



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



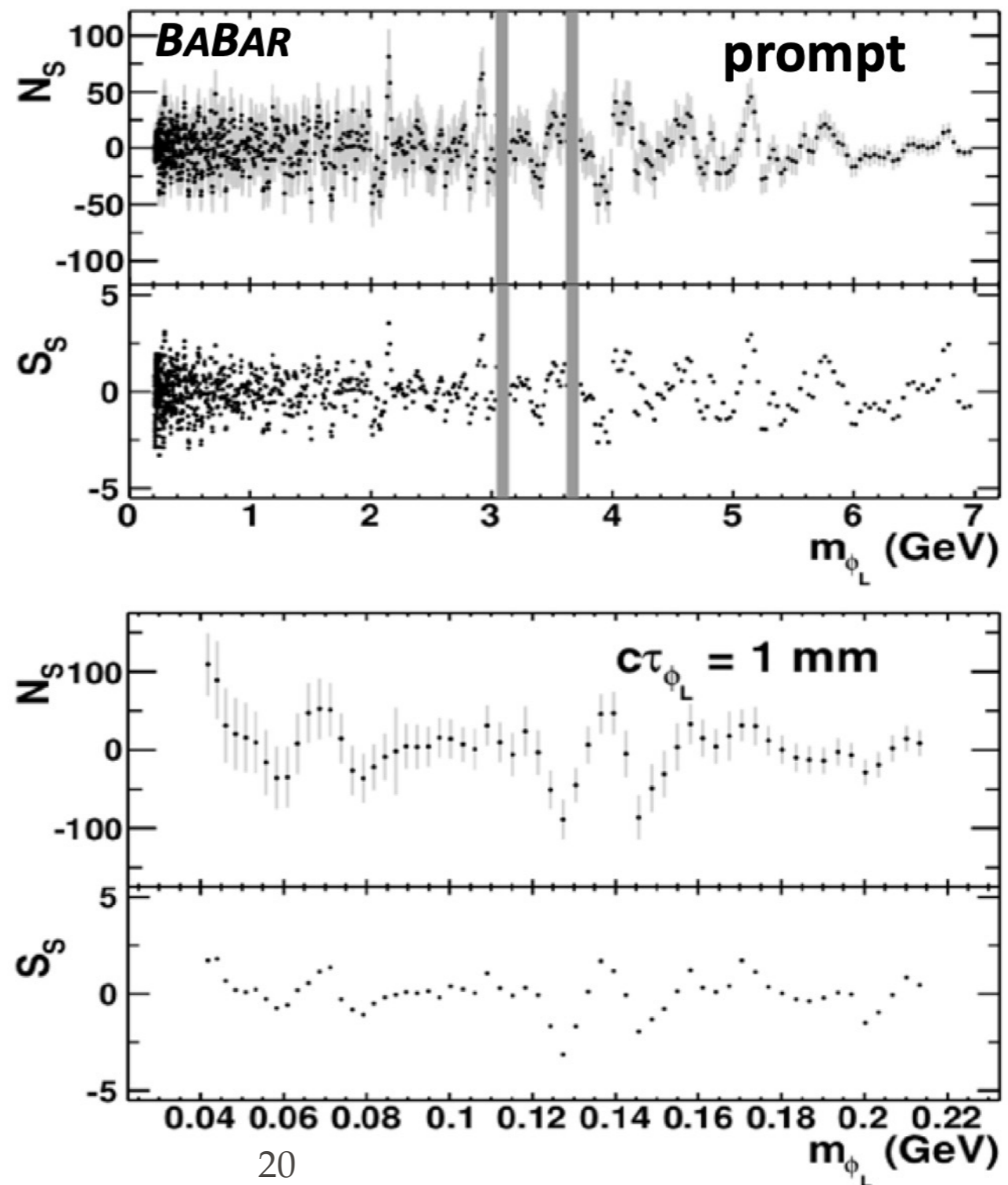
SUMMARY

- 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 leptophilic scalars, axionlike particles, and DM bound states
- There are still models that are essentially untested, and new B factory searches can give significant improvement in sensitivity
- Stay tuned for more searches on the way!

BACKUP SLIDES

DARK LEPTOPHILIC SCALAR

- Signal extraction



DARK LEPTOPHILIC SCALAR

- BDT inputs:

TABLE I: List of variables used as input to the dimuon boosted decision trees.

Ratio of second to zeroth Fox-Wolfman moment of all tracks and neutrals.
Invariant mass of the four track system, assuming the pion (muon) mass for the tracks originating from the tau (ϕ_L) decays.
Invariant mass and transverse momentum of all tracks and neutrals.
Invariant mass squared of the system recoiling against all tracks and neutrals.
Transverse momentum of the system recoiling against all tracks and neutrals.
Number of neutral candidates with an energy greater than 50 MeV.
Invariant masses of the three track systems formed by the ϕ_L and the remaining positively or negatively charged tracks.
Momentum of each track from ϕ_L decays.
Angle between the two tracks produced by the tau decay.
Variable indicating if a track has been identified as a muon or an electron by PID algorithm for each track.

TABLE II: List of variables used as input to the dielectron boosted decision trees.

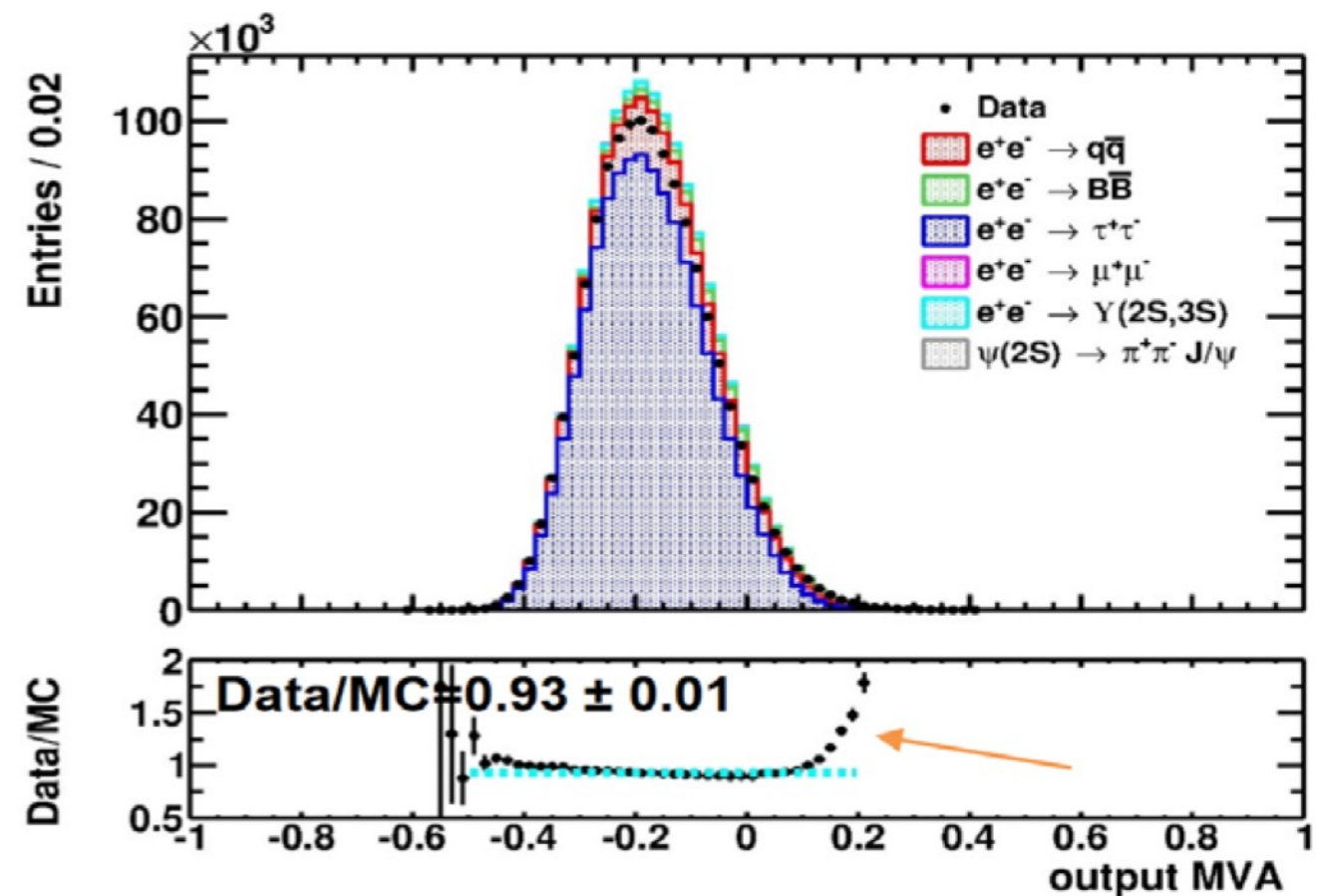
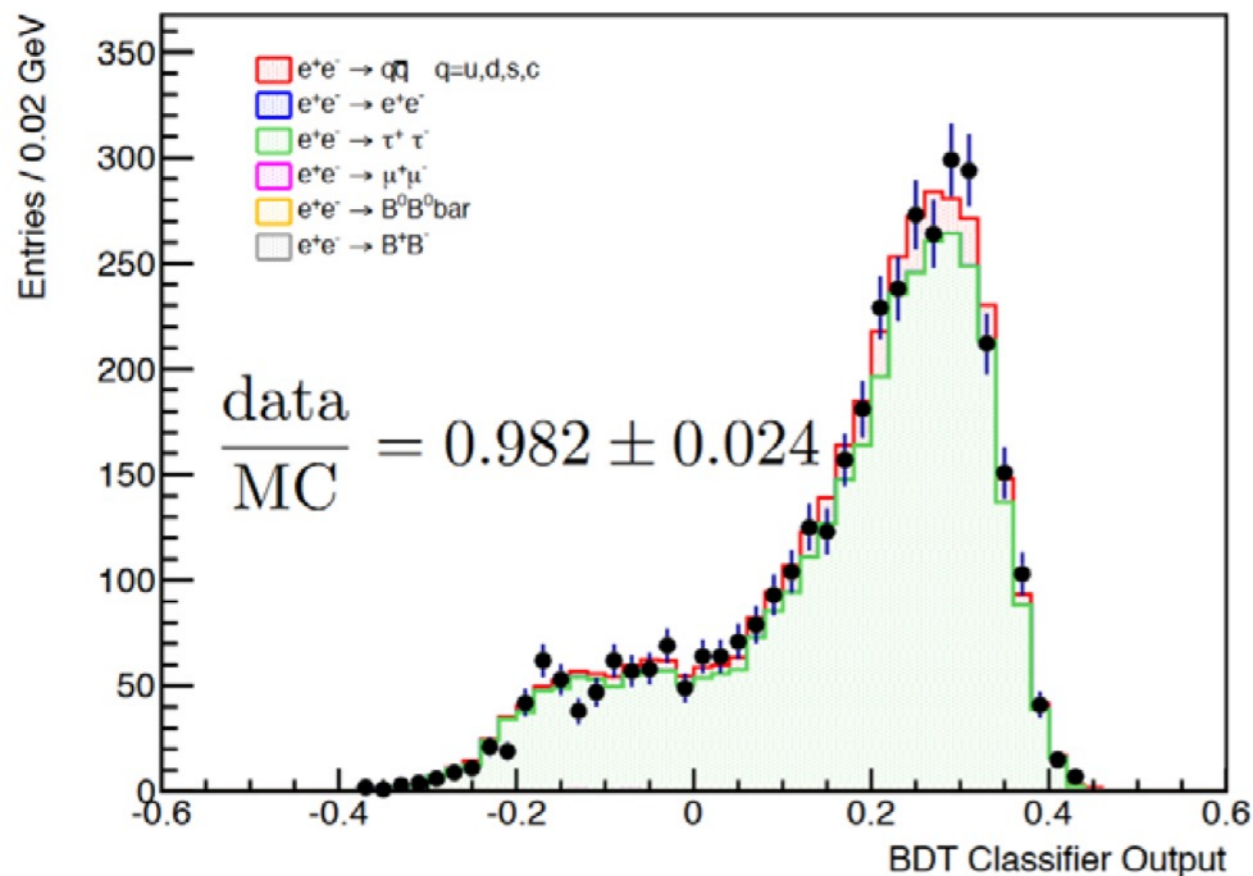
Transverse momentum of the system recoiling against all tracks and neutrals.
Energy of the system recoiling against all tracks and neutrals.
Number of tracks identified as electron candidates by a PID algorithm applied to each track.
Angle between ϕ_L candidate momentum and closest track produced in tau decay.
Angle between ϕ_L candidate momentum and farthest track produced in tau decay.
Angle of ϕ_L candidate relative to the beam in the center-of-mass frame.
Angle between the two tracks produced by the tau decay.
Angle between ϕ_L candidate and nearest neutral candidate with $E > 50$ MeV.
Energy of nearest neutral candidate (with $E > 50$ MeV) to ϕ_L candidate.
Total energy in neutral candidates, each of which has an energy greater than 50 MeV.
Distance between beamspot and ϕ_L candidate vertex.
Uncertainty in the distance between beamspot and ϕ_L candidate decay vertex.
ϕ_L candidate vertex significance, defined by the beamspot-vertex distance divided by its uncertainty.
Angle between the ϕ_L candidate momentum, and line from beamspot to ϕ_L decay vertex.
Distance of closest approach to beamspot of e^- in ϕ_L candidate.
Distance of closest approach to beamspot of e^+ in ϕ_L candidate.
Transverse distance between ϕ_L decay vertex and best-fit common origin of τ candidates and ϕ_L candidate.
χ^2 of the kinematic fit to the ϕ_L and τ candidates constraining their origin to the same production point.
χ^2 of the kinematic fit of the ϕ_L candidate with the constraint that the e^+e^- pair is produced from a photon conversion in detector material.
Dielectron mass for ϕ_L candidate when re-fit with the photon conversion constraint.

DARK LEPTOPHILIC SCALAR

- Signal efficiency validation & correction:

$$\tau^- \rightarrow \pi^- \nu_\tau K_S, K_S \rightarrow \pi^+ \pi^-$$

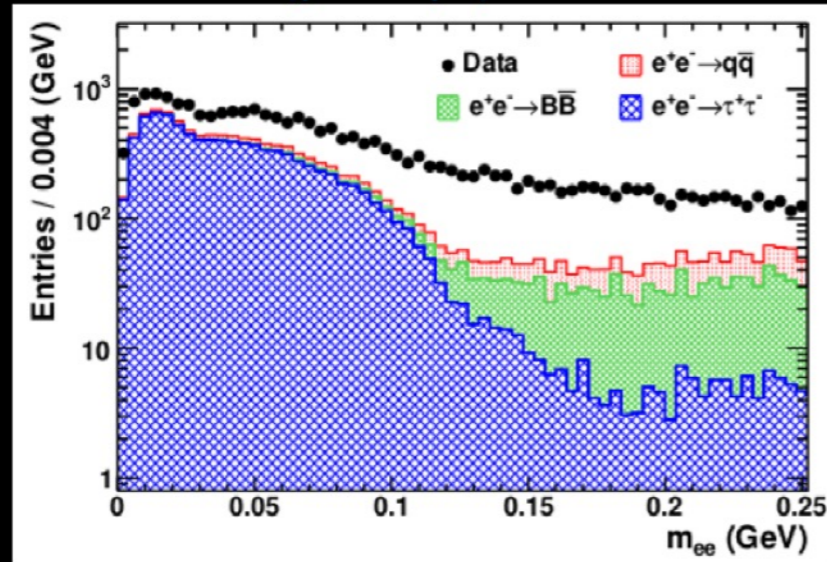
$$p_T^{\text{recoil}} > 2 \text{ GeV}$$



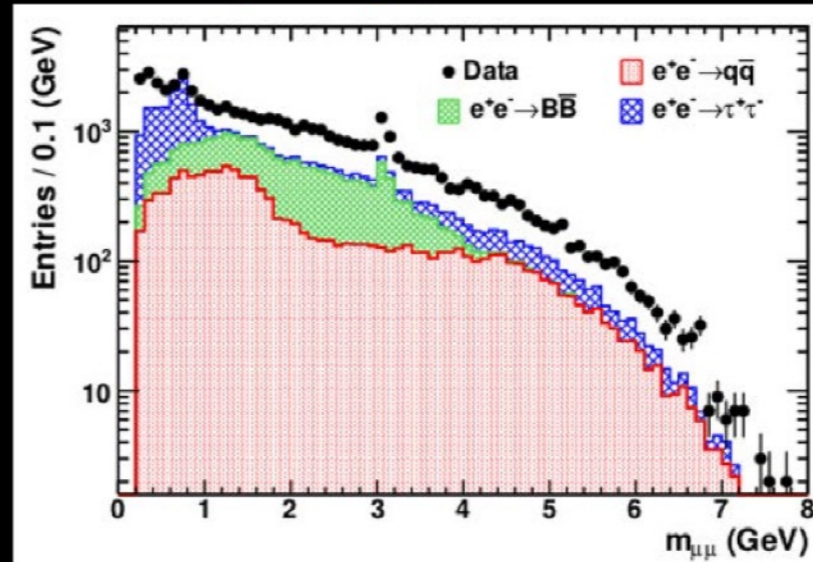
DARK LEPTOPHILIC SCALAR

- Invariant mass distributions:

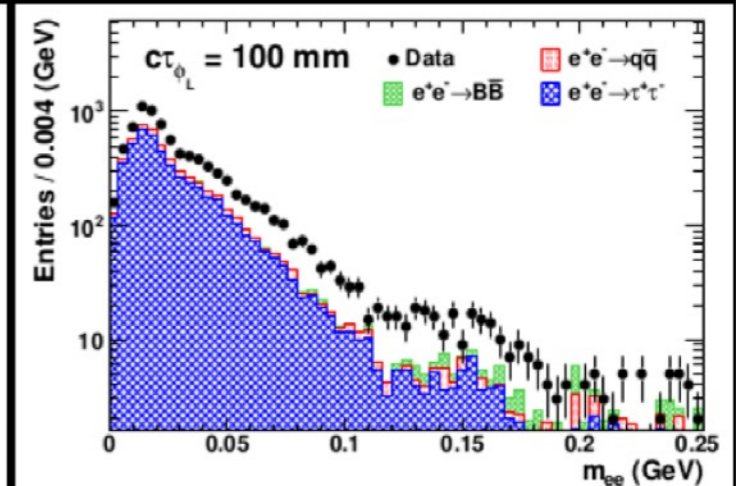
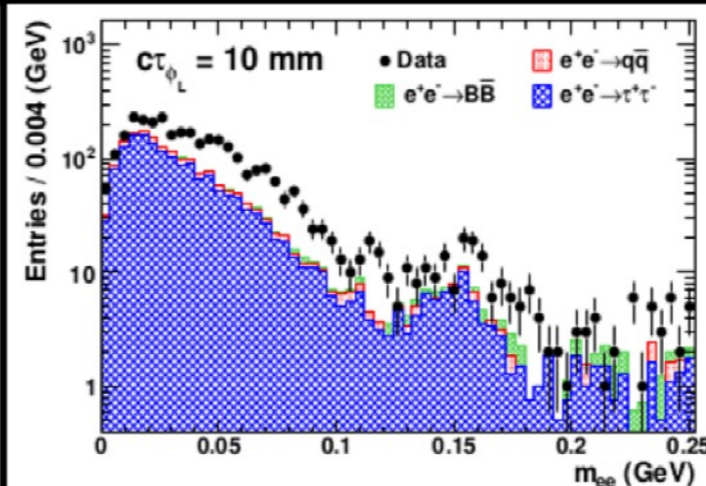
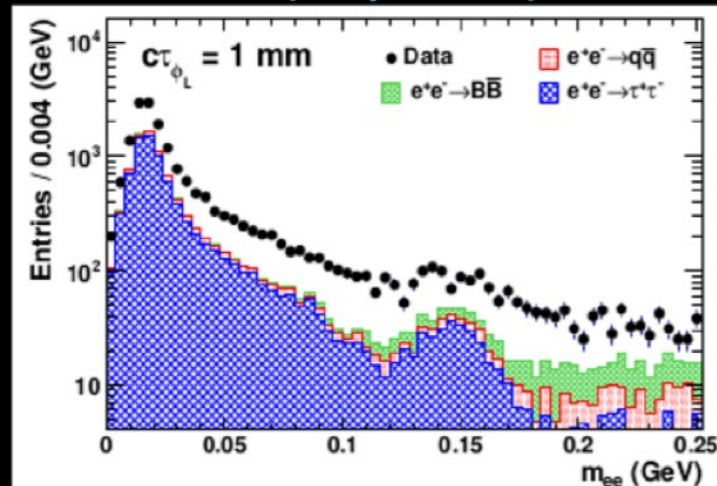
Dielectron (prompt)



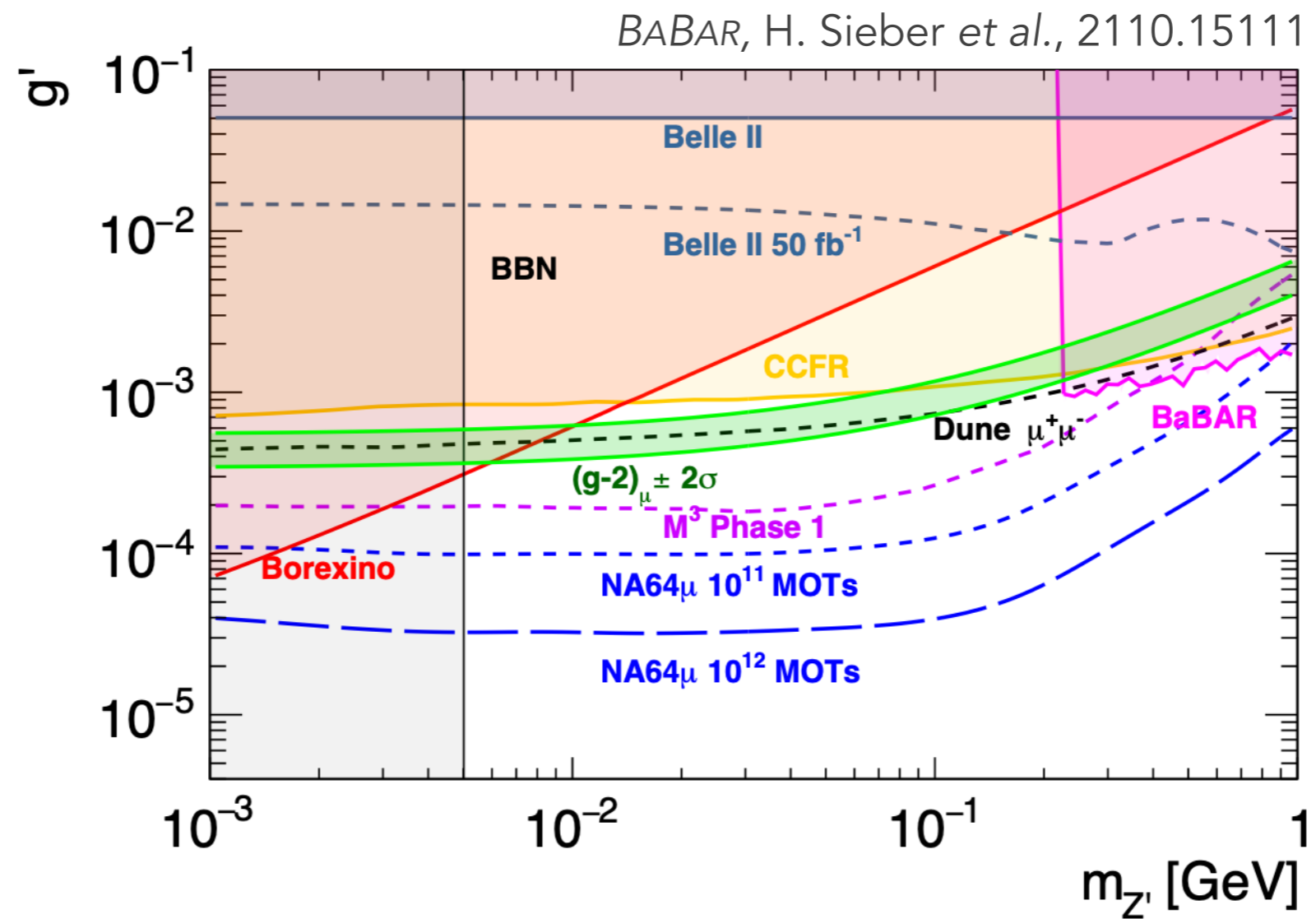
Dimuon (prompt)



Dielectron (displaced)



NA64-MU



ALP SELECTIONS

- **Preselection:** Reconstruct B^\pm candidates from K^\pm candidate and two photons

- Require
$$m_{\text{ES}} = \sqrt{\frac{(s/2 + \vec{p}_i \cdot \vec{p}_B)^2}{E_i^2}} - p_B^2 > 5.0 \text{ GeV}$$

$$|\Delta E| = |\sqrt{s}/2 - E_B^{\text{CM}}| < 0.3 \text{ GeV}$$

- 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:
 - $e^+e^- \rightarrow q\bar{q} \ (q = u, d, s, c)$
 - $\gamma\gamma e^+e^- \rightarrow B^+B^-$

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 $B^\pm \rightarrow K^\pm \pi^0$ and $B^\pm \rightarrow K^\pm \eta$, found to be consistent within 3%
- Signal efficiency derived from MC, ranges from 2% at $m_a = 0.175$ GeV to 33% at $m_a = 4.78$ GeV

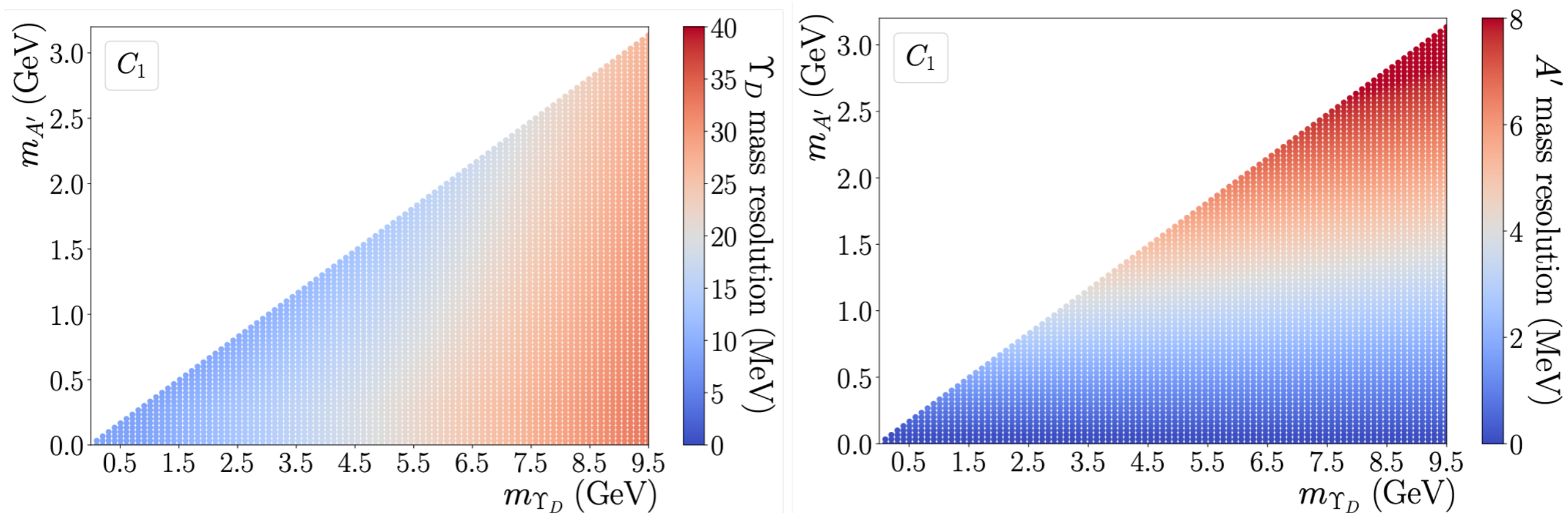
ALP FIT PROPERTIES

- Fits are performed over intervals of length $(30 - 70)\sigma$ depending on ALP mass, restricted to the range $0.11 \text{ GeV} < m_a < 4.8 \text{ GeV}$
- 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 $m_a < 1.35 \text{ GeV}$, 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

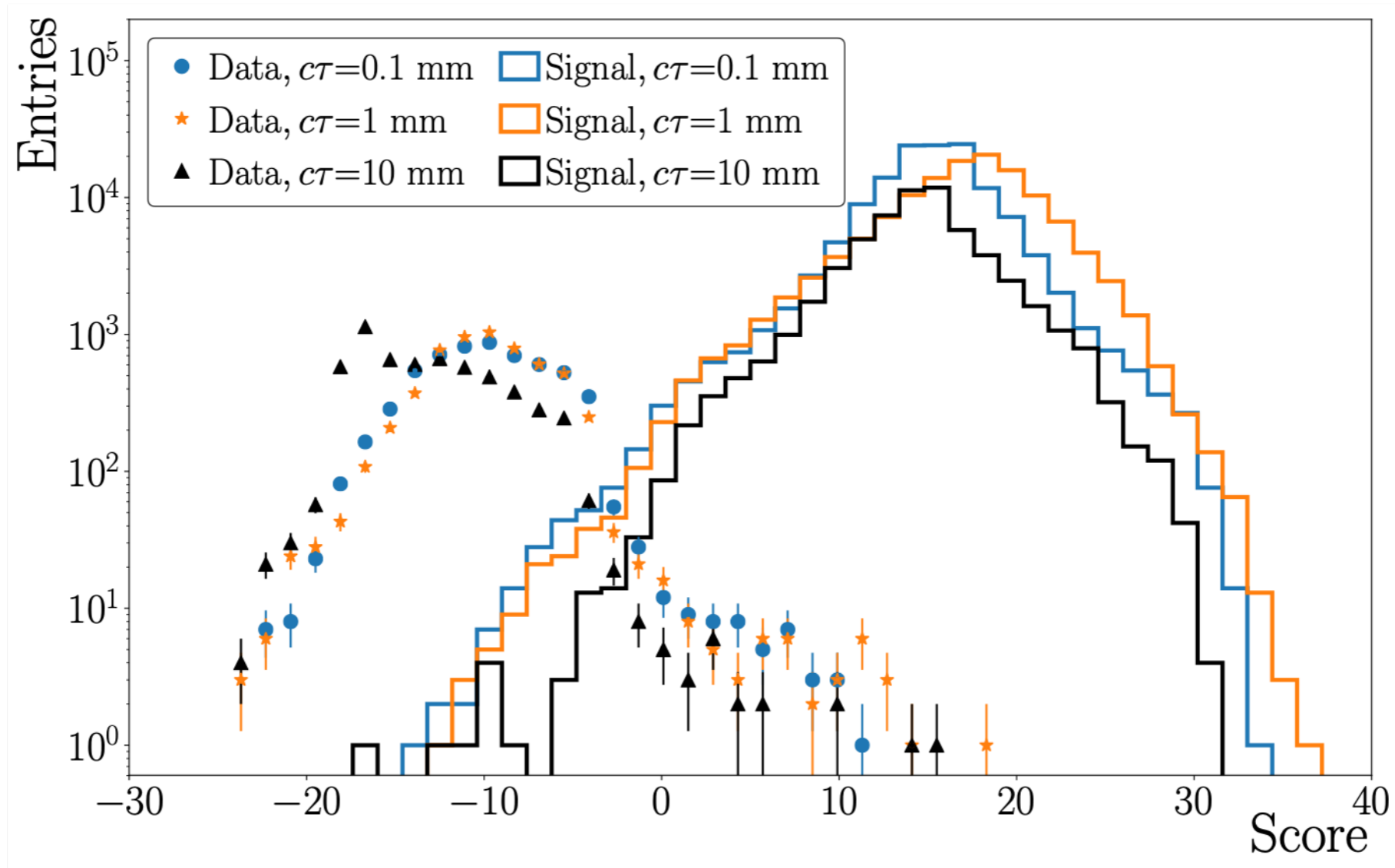
ALP SYSTEMATICS

- Assess uncertainty on signal yield from fit by varying order of polynomial for continuum background (3rd-order for $m_a < 1.35$ 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

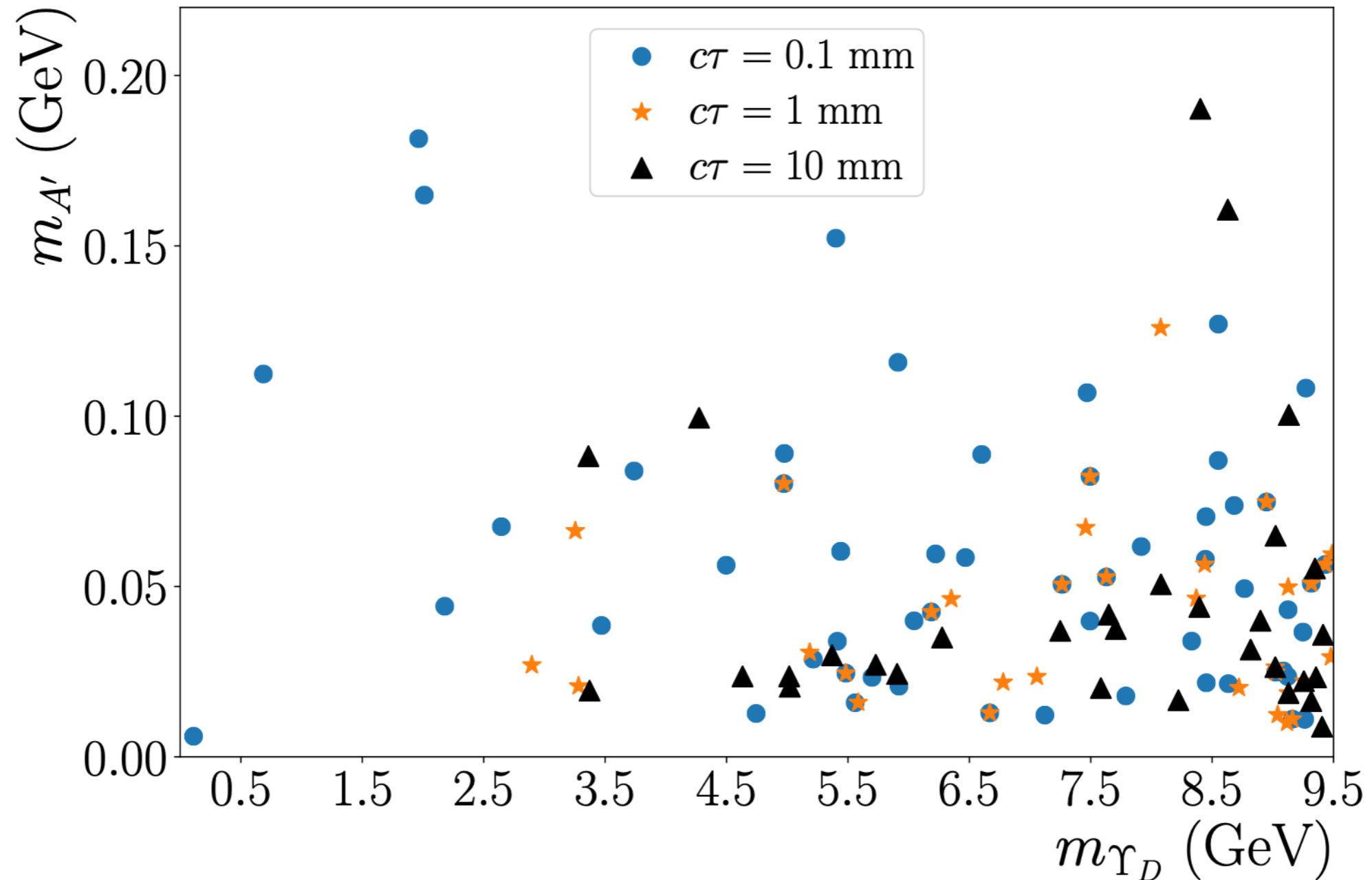
DARKONIUM: RESOLUTION



DARKONIUM: LONG-LIVED A'



DARKONIUM: LONG-LIVED A'



DARKONIUM: LONG-LIVED A'

