Recent Results of Dark Sector Searches with the B*A*B*AR* Experiment

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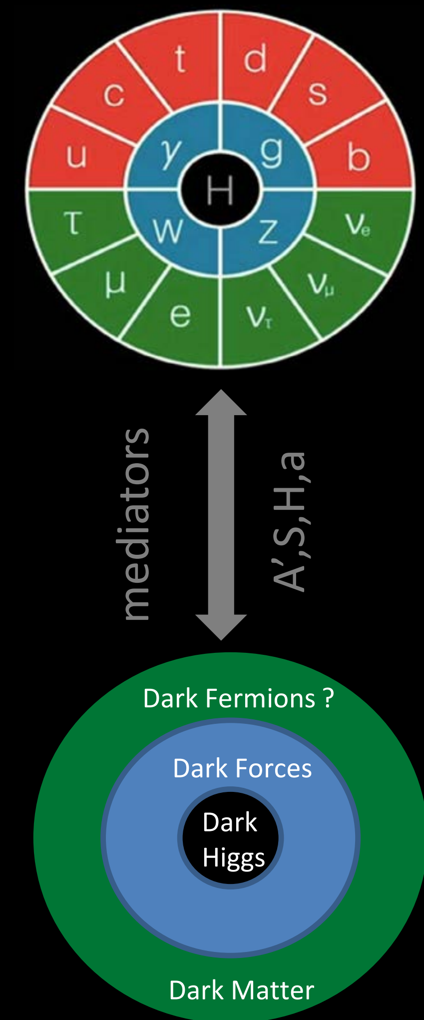
Dark sectors in a nutshell

What are dark sectors / hidden sectors

- New particle(s) that don't couple directly to the SM
- Theoretically motivated: many BSM scenarios (e.g. EWSB) and string theory include dark sectors
- Could have rich structure (SM structure is non-trivial)
- Dark matter could reside inside dark sector



Interaction with the SM through "portals"

Lowest order portals:

- Vector – $\varepsilon F^{\mu\nu} A'_{\mu\nu}$
- Scalar – $H^2 (\mu S + \lambda S^2)$
- Neutrino – $yHLN$
- Axion – $1/f_a(c_1 \mathrm{tr}(G\tilde{G}) + c_2 FF + c_3 \delta_\mu j^\mu)\, a$

Motivates broad exploration of dark sector.
Low energy e^+e^- colliders are offer ideal environment to study them.

Wide program at BABAR

Extensive "dark sector" program conducted at BABAR over the last decade

Search for dark photon

$e^+e^- \to \gamma A'$, $A' \to e^+e^-, \mu^+\mu^-$

$e^+e^- \to \gamma A'$, $A' \to$ invisible

Search for "muonic dark force"

$e^+e^- \to \mu^+\mu^- Z'$, $Z' \to \mu^+\mu^-$

Search for dark bosons

$e^+e^- \to \gamma A' \to W' W''$

Search for dark Higgs boson

$e^+e^- \to h' A'$, $h' \to A' A'$

Search for leptophilic dark scalar

$e^+e^- \to \tau^+\tau^- h'$, $h' \to \mu^+\mu^-$

Search for self-interacting DM

$e^+e^- \to \Upsilon_D \to A'A'A' \to 3X^+X^-$ $(X=l,\pi)$

Search for axion-like particle

$B \to Ka$, $a \to \gamma\gamma$

Search for B-Mesogenesis

$B \to$ Baryon + DM (+mesons)

Exploratory search for dark hadrons

$e^+e^- \to \pi_D + X$, $\pi_D \to e^+e^-, \mu^+\mu^-$

Related searches

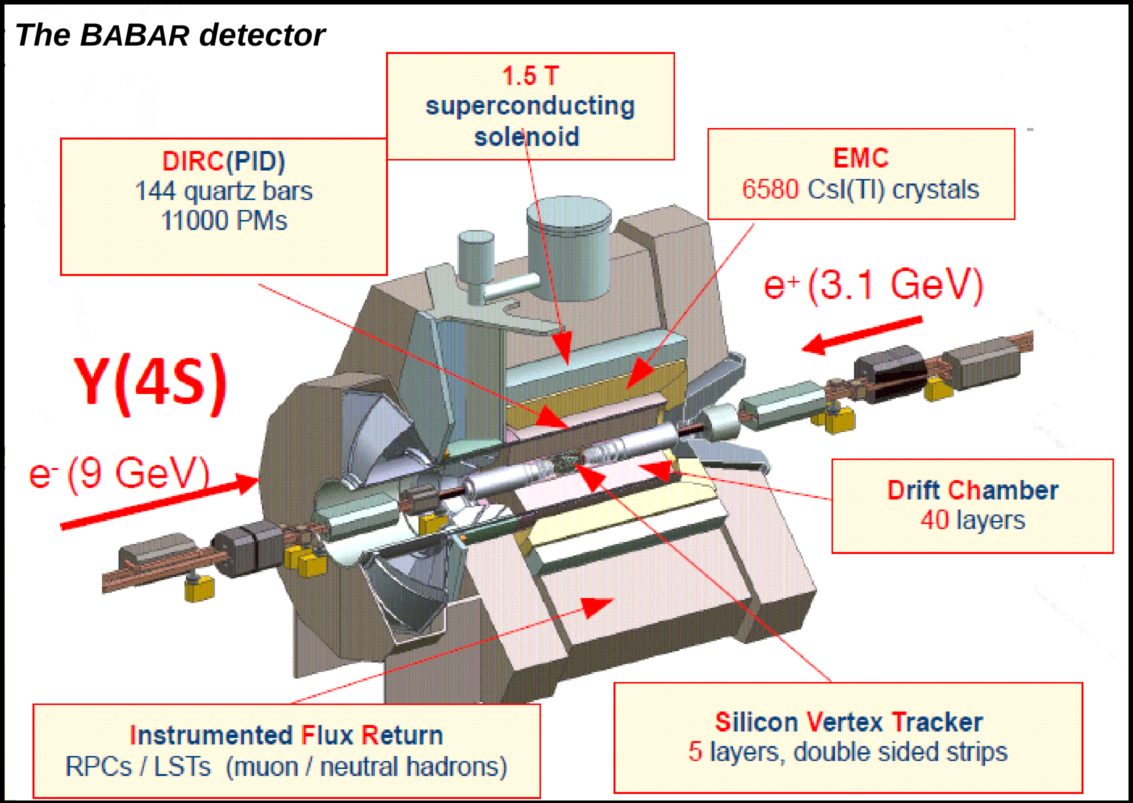
- Search for long-lived particles
- Search for low-mass Higgs boson
- Search for six-quark dark matter

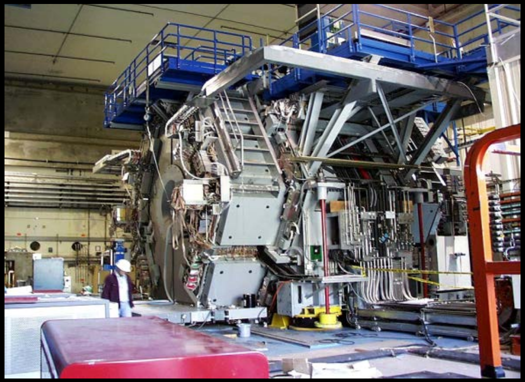
This talk will discuss recent results on leptophilic dark scalar and preliminary results on ALP and self-interaction DM

Published
Preliminary

The BABAR experiment

BABAR collected ~500 fb^{-1} around the Υ(4S), Υ(3S) and Υ(2S) resonance between 1999 - 2008





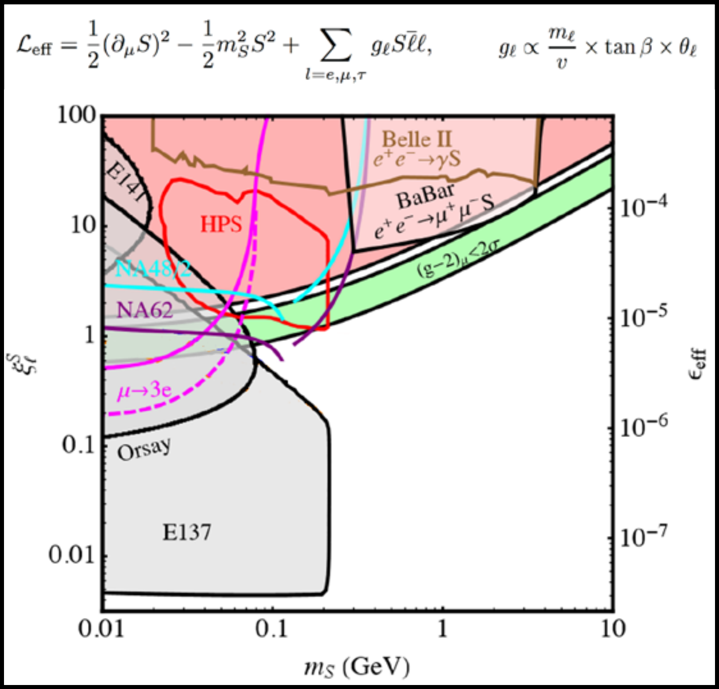
Collaboration is still active more than 10 years after data taking ended !

Leptophilic dark scalar

Many BSM models predict the existence of an extended Higgs sector with new light gauge singlets that can mix with the Higgs boson.

Strong experimental constraints on this scenario, unless the new scalar interacts mainly with leptons rather than quarks, experimental constraints are significantly weakened due to the reduced coupling to electrons

A leptophilic scalar could explain the g-2 anomaly (1606.04943, 1605.04612) and the KOTO excess (2001.06522)



Batell et al., PRD 95 (2017) 075003

Mass proportional coupling

- Produced preferentially via its coupling to the tau
- Decays preferentially to the most massive lepton-pair kinematically accessible
- Long-lived particle for sufficiently low values of coupling constant (mainly below $2m_\mu$)

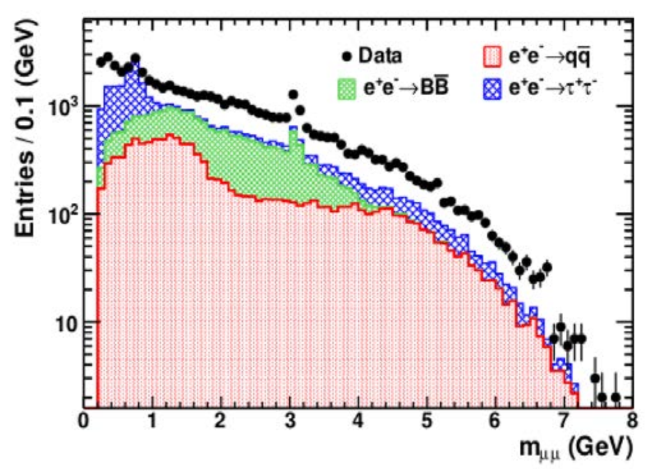
Leptophilic dark scalar

Search for a leptophilic dark scalar ϕ_L in $e^+e^- \rightarrow \tau^+\tau^- \phi_L$, $\phi_L \rightarrow l^+l^-$ (l=e,μ)

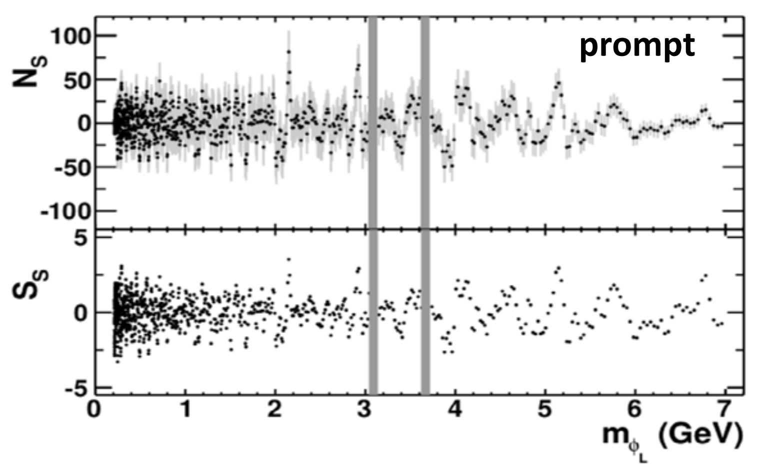
Analysis strategy

- Consider all 1-prong decays of the tau
- Train BDT to increase signal purity (see backup slide)
- Optimize analysis for each final state and prompt or long-lived ϕ_L
- Extract signal as a function of dark scalar mass with fits over sliding intervals

Final dimuon mass distribution



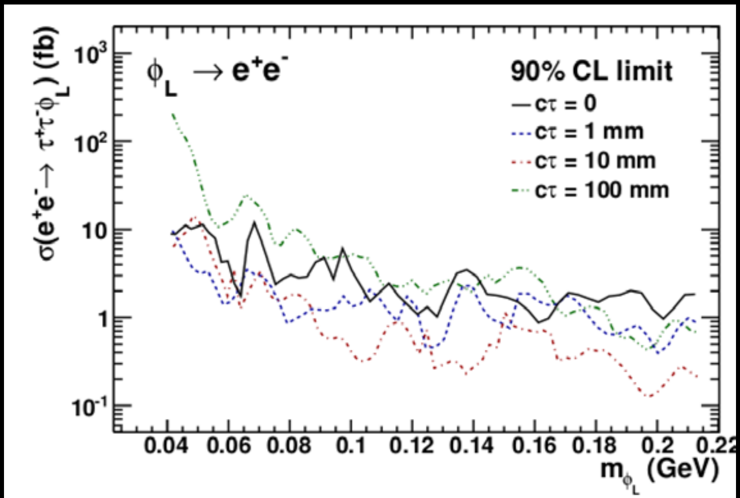
Signal yields and significances

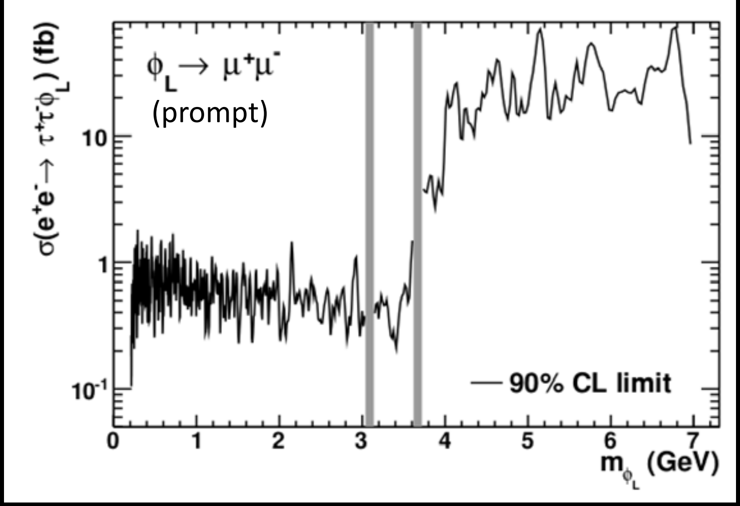


No significant signal, consistent with null hypothesis

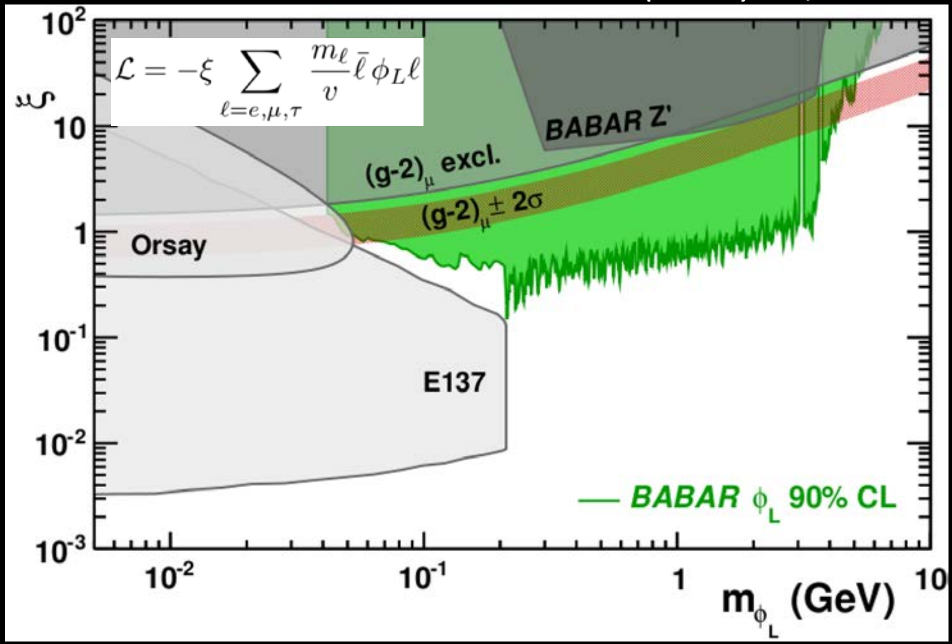
Leptophilic dark scalar

Extract 90% CL limit on the production cross-section and the ϕ_L-lepton coupling parameter ξ





PRL 125 (2020) 18,181801



Significant improvement over previous bounds

The g-2 region is clearly excluded for almost all masses below the ditau threshold!

Belle II should be able to further improve

Axion like particle (ALP)

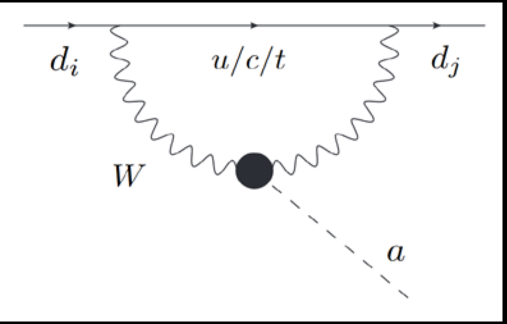
What are axion like particles

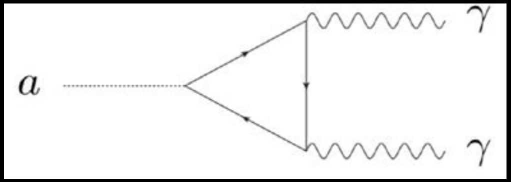
- Pseudo-Goldstone bosons ubiquitous in BSM physics, coupling predominantly to pair of bosons with non-renormalizable coupling constant suppressed by some heavy scale
- Low-mass ALP can mediate dark sector – standard model interactions
- Most searches focus on photon or gluon couplings at low energies as effects from $W^{\pm}$ coupling are suppressed by G_F^2

Search for ALP in $B \rightarrow Ka$, $a \rightarrow \gamma\gamma$ decays

- FCNC are extremely suppressed in the SM, so they are a perfect testbed to search for ALP emission by $W^{\pm}$ boson
- Search for ALP in $B \rightarrow Ka$ decays, exploiting $b \rightarrow s$ transition
- Consider a model in which the axion couples only directly to $W^{\pm}$ bosons (photon coupling via triangle diagram)
- Axion lifetimes becomes important at low masses and couplings ($\tau \sim 1/m_a^3 g_{aW}^2$) $\rightarrow$ long-lived axion

$$\mathcal{L} = (\partial_\mu a)^2 - \frac{1}{2}M_a^2 a^2 - \frac{g_{aW}}{4}\, a\, W^a_{\mu\nu}\tilde{W}^{a\mu\nu}$$





E. Izaguirre et al., PRL 118 (2017) 111802

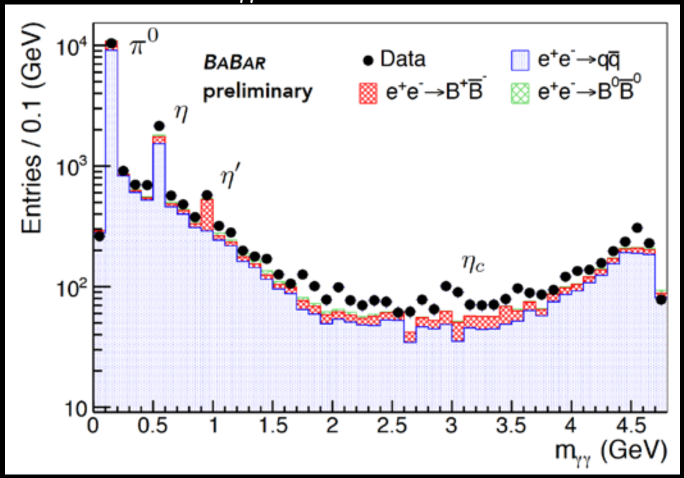
Axion like particle (ALP)

Search for diphoton decay of an axion (a) produced in B decays: $B \to Ka$, $a \to \gamma\gamma$

Analysis strategy

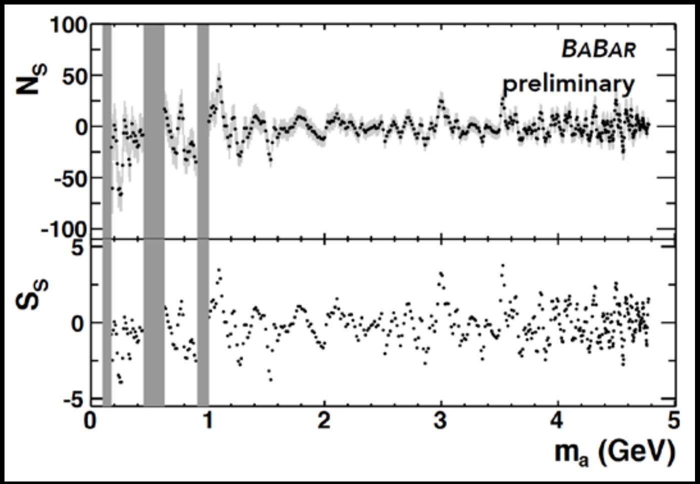
- Combine well-identified K with two photons to form B candidate
- Apply kinematic fit to improve axion mass resolution
- Train 2 BDTs to separate signal from $e^+e^- \to q\bar{q}$ (q=u,d,s,c) and $e^+e^- \to B\bar{B}$ backgounds
- Extract signal as a function of axion mass with fits of a mass peak over smooth background

Final $m_{\gamma\gamma}$ mass distribution



Peaking background at π^0,η,η' masses,
2.6σ excess consistent with $B \to K\,\eta_c$, $\eta_c \to \gamma\gamma$

Signal yields and local significances

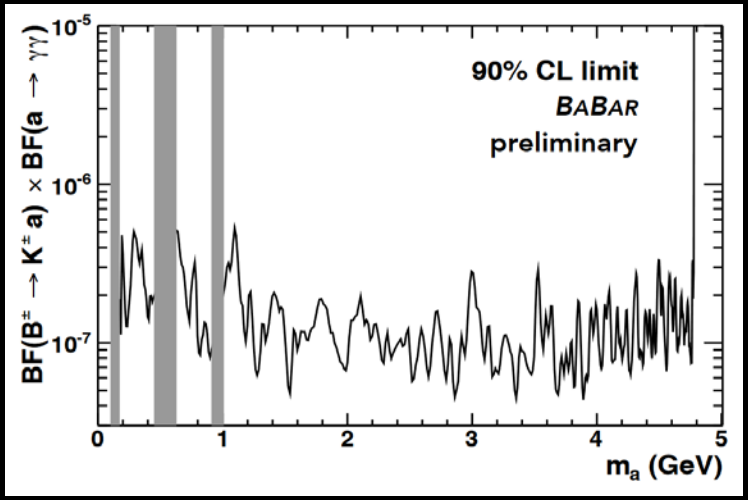


No significant signal is observed

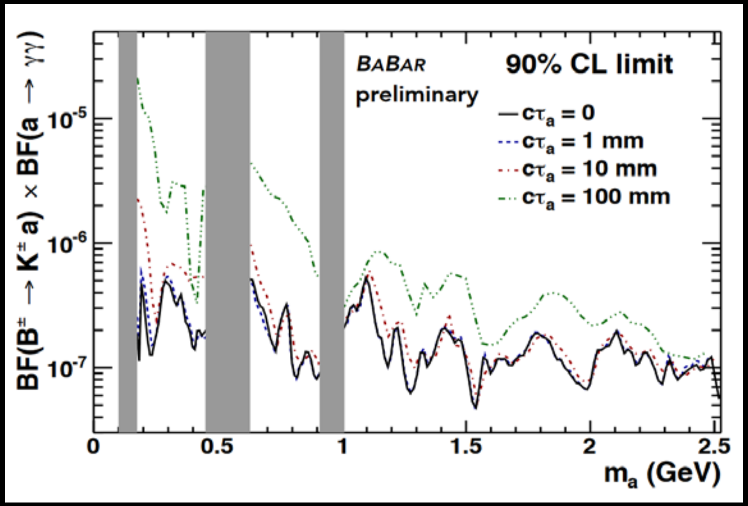
Axion like particle (ALP)

Extract 90% CL limit on the production cross-section and the a-W coupling parameter g_{aW}

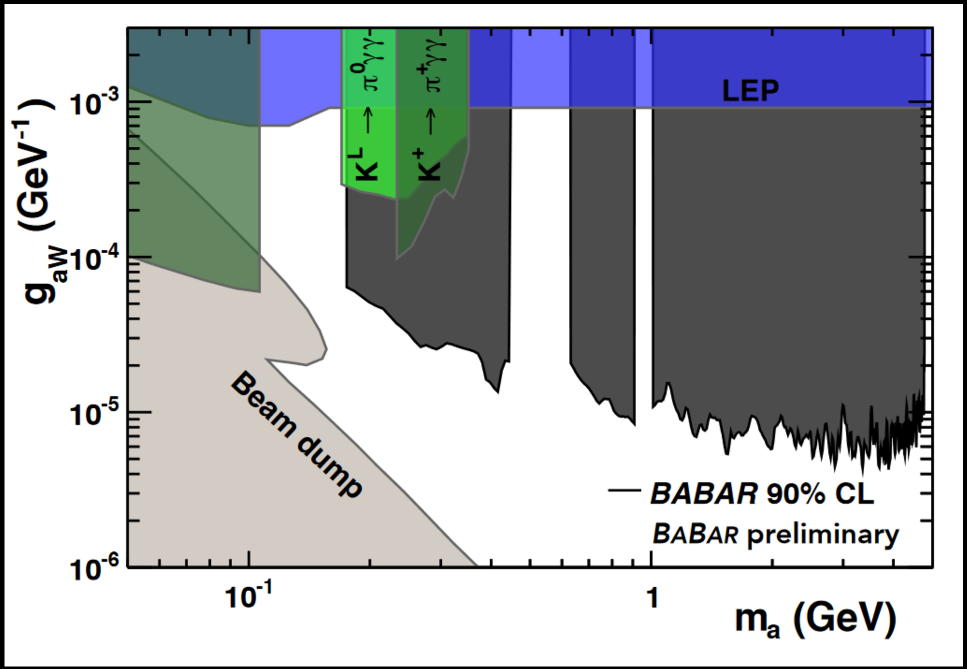
Prompt decays



Displaced decays



90% CL upper limits on coupling g_{aW}



Improvement up to two orders of magnitude over a large mass range

Self-interacting dark matter

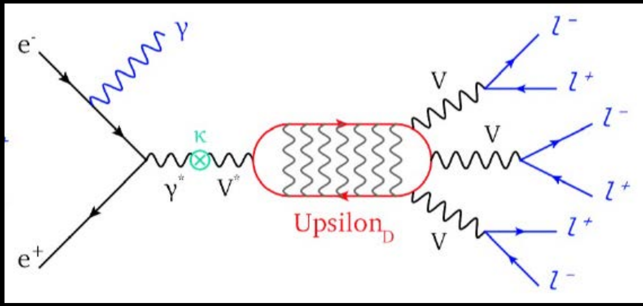
Search for darkonium

- Dark sector with a dark (anti-)fermion coupling to the dark photon
- For sufficiently large values of the dark fermion-dark photon coupling constant α_D, a dark fermion – anti-fermion pair could form a bound state $\rightarrow$ darkonium
- The two lowest energy bound states are denoted η_D ($J^{PC} = 0^{++}$) and Y_D ($J^{PC} = 1^{--}$), in analogy with SM
- Can be produced via $e^+e^- \rightarrow A' \eta_D$, $\eta_D \rightarrow A' A'$ and $e^+e^- \rightarrow \gamma Y_D$, $Y_D \rightarrow A' A' A'$

Search for Y_D in $e^+e^- \rightarrow \gamma Y_D$, $Y_D \rightarrow A' A' A'$, $A' \rightarrow X^+X^-$ ($X=e,\mu,\pi$)

- Dark photon subsequently into pairs of leptons or hadrons
- Dark photon lifetime can be large for small values of the kinetic mixing ε and mass $\rightarrow$ prompt and displaced vertex analyses

H. An et al., PRL 116 (1026) 151801



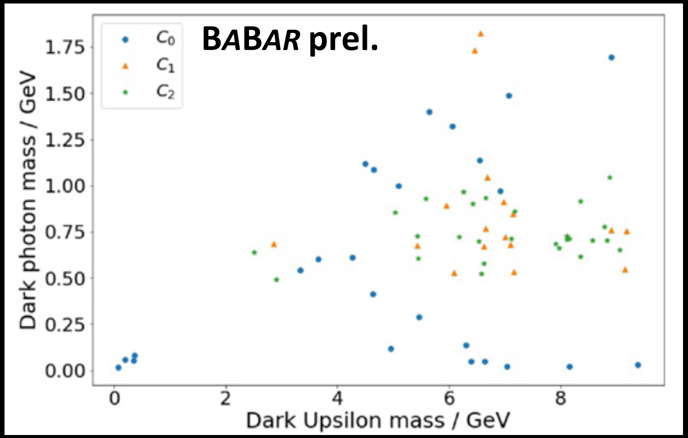
Self-interacting dark matter

Search for Y_D in $e^+e^- \to \gamma Y_D$, $Y_D \to A' A' A'$, $A' \to X^+X^-$ ($X=e,\mu,\pi$)

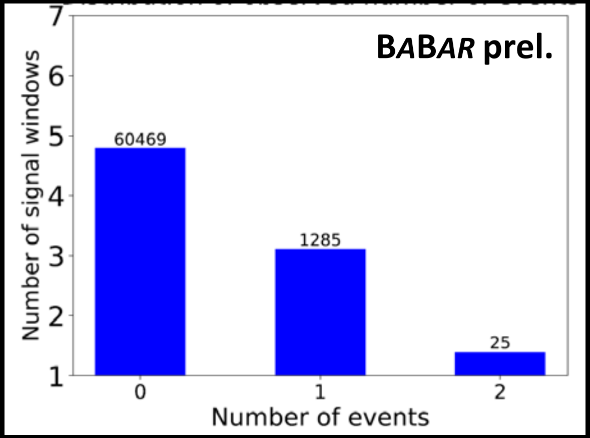
Analysis strategy

- Final states consist of three pairs of leptons or pions, with two or more electrons / muons
- Three dark photons have similar masses
- Recoil mass against Y_D compatible with the photon hypothesis
- Do not require presence of ISR photon in the calorimeter, but it must be compatible with signal hypothesis if emitted inside the calorimeter acceptance
- Scan the Y_D – A' mass plane to extract signal – estimate background with neighboring $m_{A'}$ bins

Final Y_D candidate sample (prompt)



Number of events in signal window (prompt)

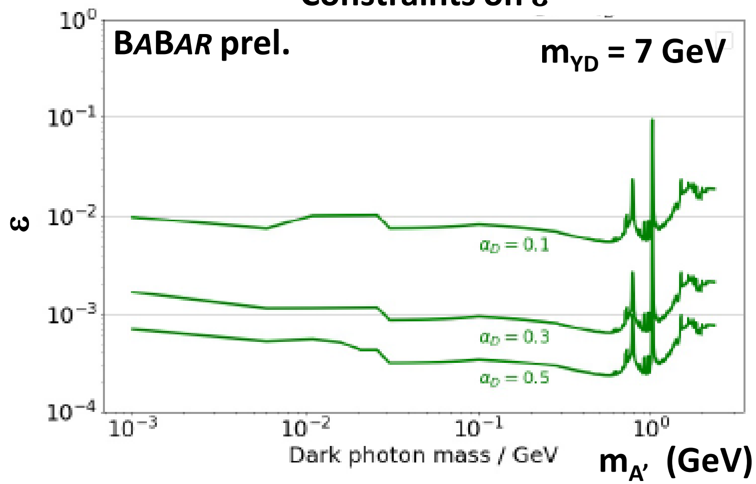


Prompt and displaced vertex analyses compatible with null hypothesis

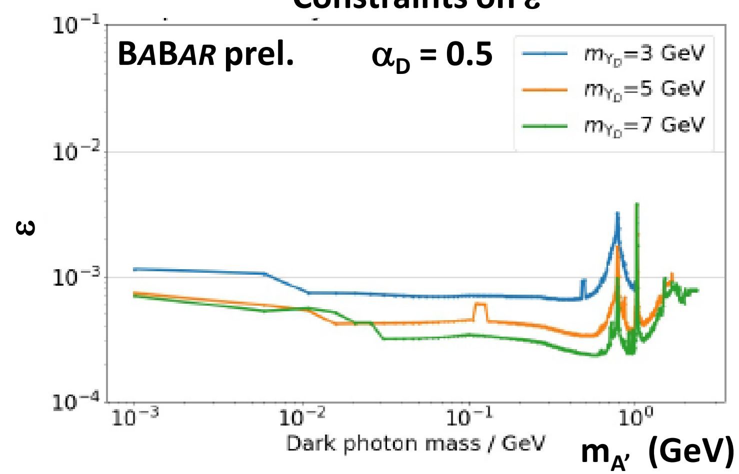
Self-interacting dark matter

Extract 90% CL limit on the kinetic mixing parameter ε for different α_D values

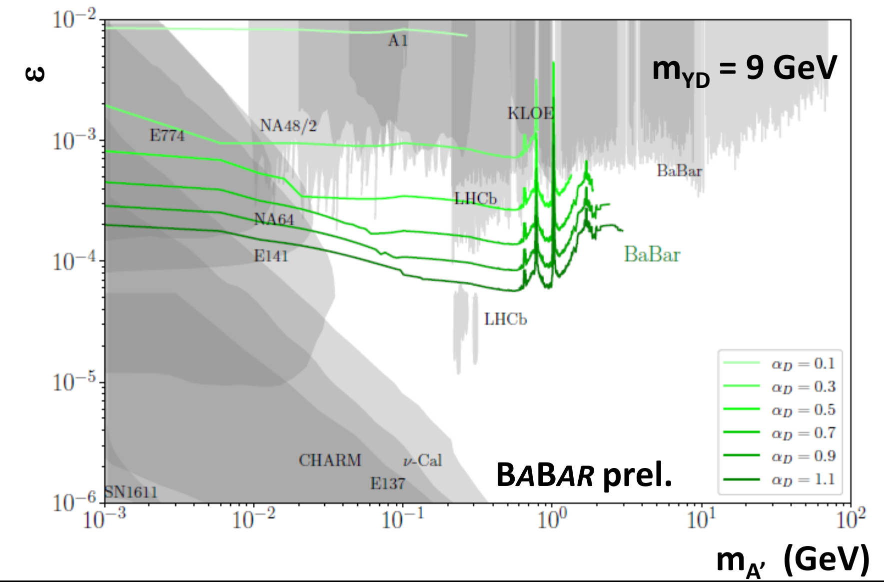
Constraints on ε



Constraints on ε



Constraints on ε for α_D = 0.5



Improve constraints on kinetic mixing for large values of dark sector coupling constant and large Y_D masses

Summary

Dark sectors have emerged as an intriguing possibility to explain dark matter, and more generally to search for light new physics

Low-energy, high-intensity colliders offer an ideal environment to comprehensively probe dark sectors

B*A*B*AR* has conducted an extensive program to search for dark sector signatures, and set stringent limits on their existence

Recently set world leading constraints on leptophilic dark scalar, axion couplings and self-interacting dark matter

There are still amazing possibilities at the GeV-scale, and dedicated programs are underway to explore them

ADDITIONAL MATERIAL

References

Dark photon and other bosons

- Search for a Dark Photon in e+e- Collisions at BaBar, PRL 113 201801 (2014)
- Search for Invisible Decays of a Dark Photon Produced in e+e- Collisions at BaBar, PRL 119 131804(2017)
- Search for a muonic dark force at BABAR, PRD 94 (2016) 011102
- Search for a Narrow Resonance in e+e- to Four Lepton Final States, arxiv:0908.2821

Dark scalar

- Search for Low-Mass Dark-Sector Higgs Bosons, PRL 108 (2012) 211801
- Search for a Dark Leptophilic Scalar in e+e- Collisions, PRL 125 (2020) 181801

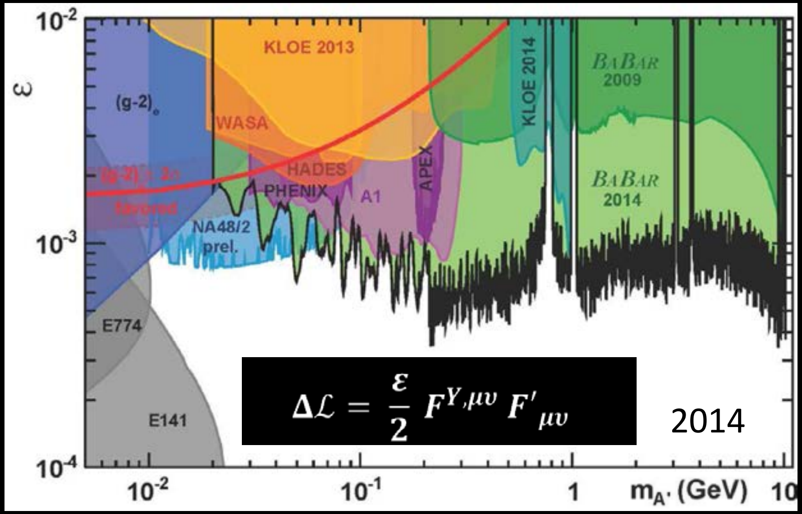
Other DM

- Search for a Stable Six-Quark State at BABAR, PRL 122 (2019) 072002

Dark photon searches

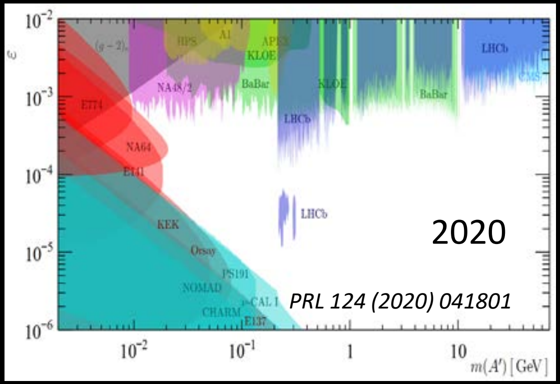
Dark photon (A') search in $e^+e^- \to \gamma A'(\to e^+e^-, \mu^+\mu^-)$

Limits on kinetic mixing parameter



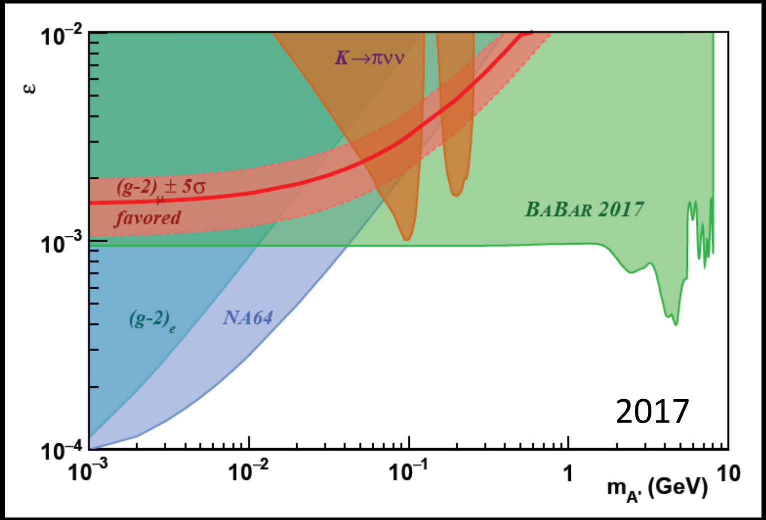
$$\Delta\mathcal{L} = \frac{\varepsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

PRL 113 (2014) 201801
PRL viewpoint



Dark photon (A') search in $e^+e^- \to \gamma A'(\to \text{invisible})$

Limits on kinetic mixing parameter

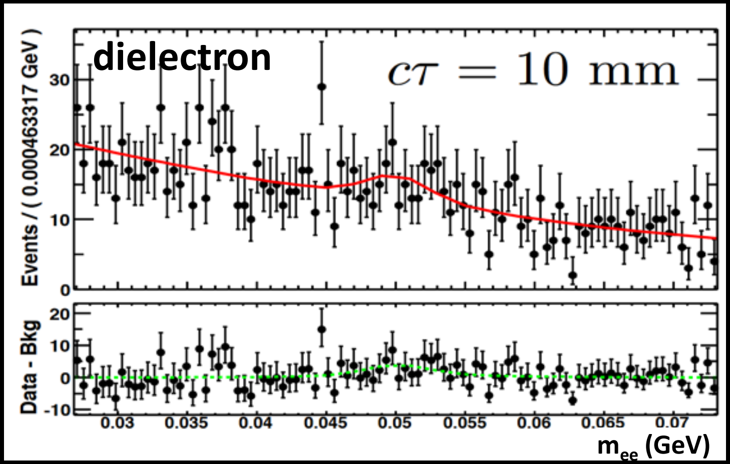


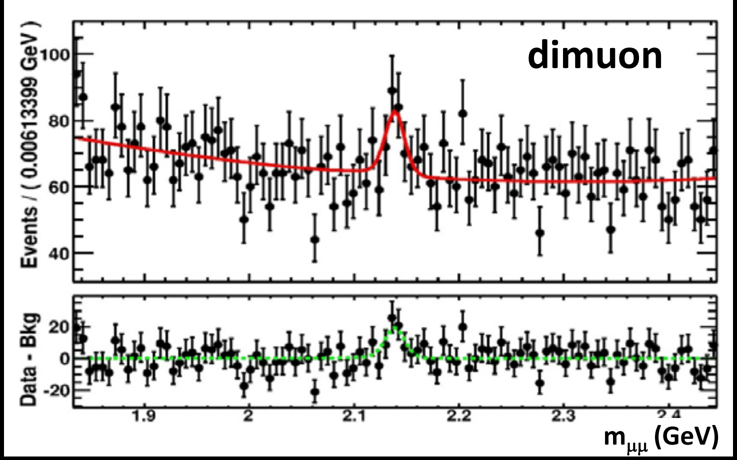
PRL 119 (2017) 131804
PRL highlights

Worldwide program to extend coverage by orders magnitude in the near future

Leptophilic dark scalar

Extract signal as a function of dark scalar mass with fits over sliding intervals (background MC independent)





Fit 966 mass hypotheses, step size taken as signal resolution (1-50 MeV depending on m_ϕ)

Fit includes signal, peaking and continuum background components:

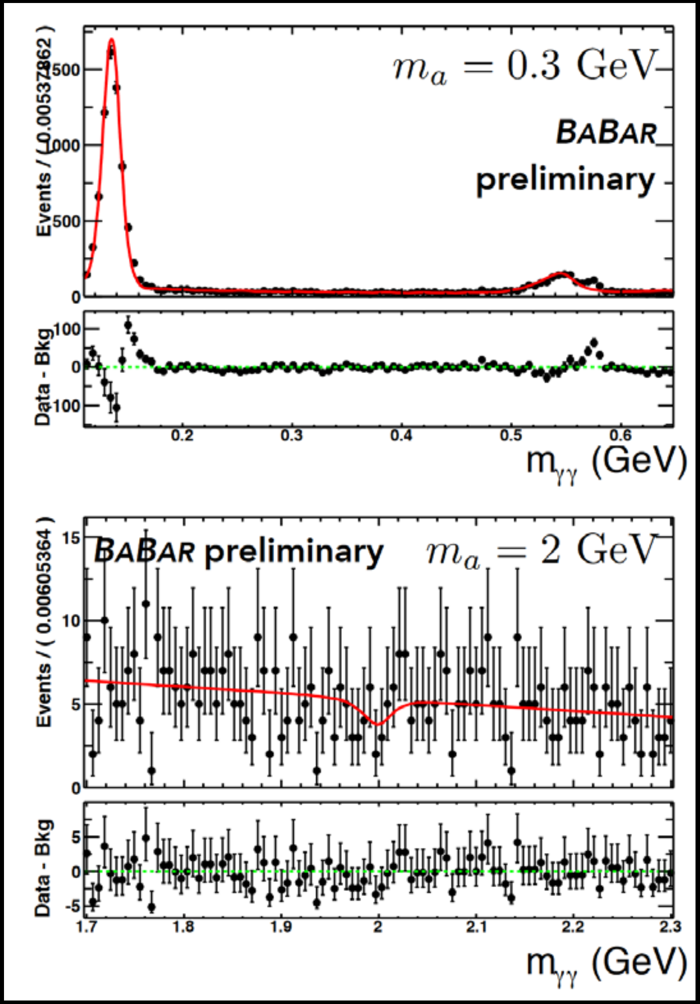
- Signal modeled from signal MC and interpolated between simulated mass points
- Continuum background modelled by second or third order polynomials
- Peaking background (π^0, J/ψ, $\psi(2S)$) modelled from bkg MC

Signal efficiency validated by data/MC comparison of sideband regions. Derive correction factors (2-7%) applied to MC

Signal efficiency varies between 0.2-26%

Axion like particle (ALP)

Extract signal as a function of axion mass with fits over sliding intervals
(prompt decays, background MC independent)



Fit 476 mass hypotheses, step size taken as signal resolution (8-14 MeV)

Fit includes signal, peaking and continuum background components:

- Signal modeled from signal MC and interpolated between simulated mass points
- Continuum background modelled by first or second order polynomials
- Peaking background modelled from bkg MC

Signal MC resolution validated by data/MC comparisons of $B \to K\pi^0$ and $B \to K\eta$, found to be consistent within 3%

Signal efficiency varies between 2%-33%

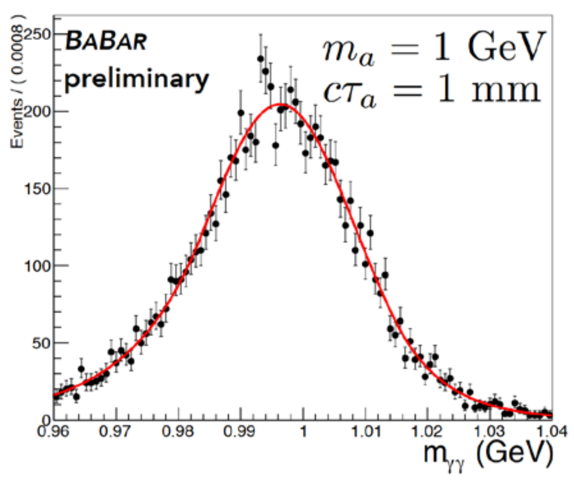
Axion like particle (ALP)

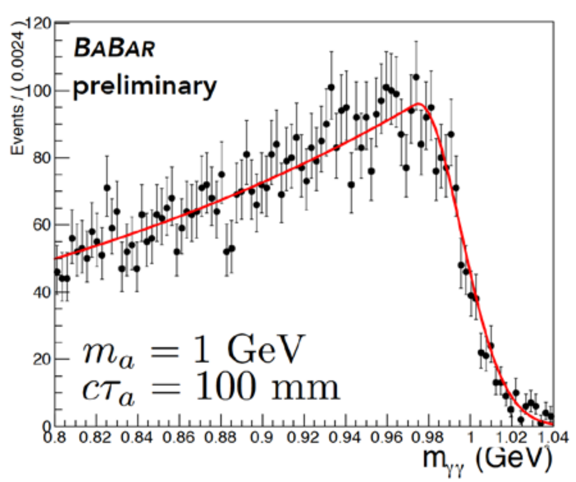
Analysis sufficiently sensitive in the low mass region to probe couplings for which the ALP lifetime becomes non-negligible

The search is optimized for prompt ALP decays, and it is applied without re-optimization to assess the sensitivity to long lived ALPs

Apply same reconstruction / selection for $c\tau_a$ = 1,10,100 mm for m_a < 2.5 GeV

Signal becomes distorted for longer lifetimes $\rightarrow$ signal extraction is more difficult and systematic uncertainties larger.





Leptophilic dark scalar

BDT input variables

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

Ratio of second to zeroth Fox-Wolfram 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.

Axion like particle (ALP)

BDT input variables

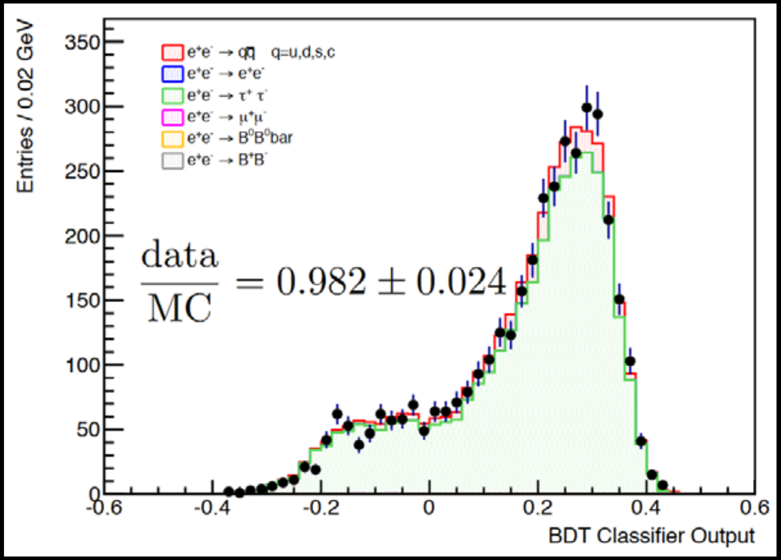
m_{ES}	0.231
Cosine of sphericity angle	0.110
Maximum K PID selector	0.102
Legendre moment of order 2	0.0996
Helicity angle of a daughter photon with highest energy	0.0889
Difference to π^0 mass	0.0882
ΔE (energy difference between E_B^* and E_{beam}^*)	0.0721
Maximum of a daughter energies	0.0653
Invariant mass of all tracks and neutral clusters except $B^\pm \to K^\pm a$ candidate	0.0430
Number of neutral clusters in event	0.0420
Kaon helicity angle	0.0416
Difference to η mass	0.0095
Difference to η' mass	0.0076

Table 3: Variables used in training the BDT, along with the relative importance when trained with uds backgrounds.

Validate efficiency with control samples and derive corresponding corrections

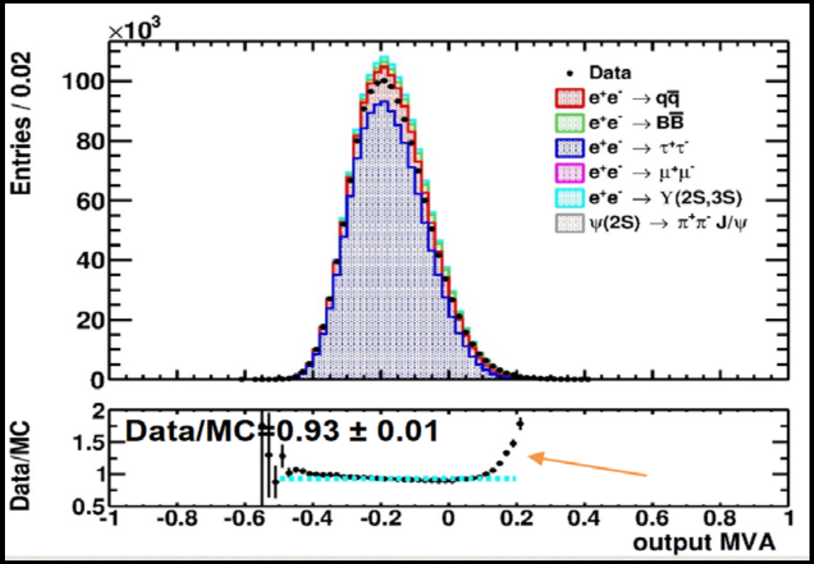
Dielectron

Sample of $K_s \rightarrow \pi^+\pi^-$ in τ decays obtained with a similar selection procedure



Dimuon

BDT response for data with recoil p_T > 2 GeV to suppress non-modelled components

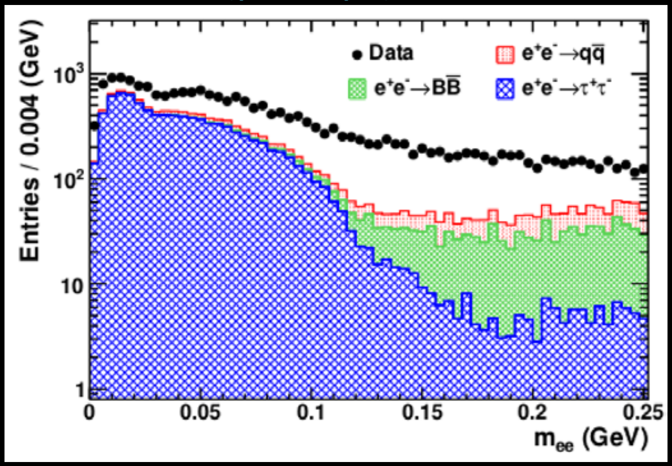


Data globally well reproduced by MC predictions, corrections between 2-7%

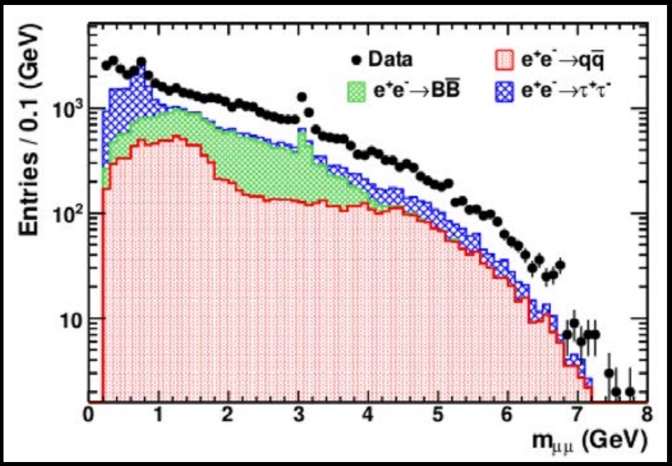
Leptophilic dark scalar

Final mass spectra for each final state and lifetime

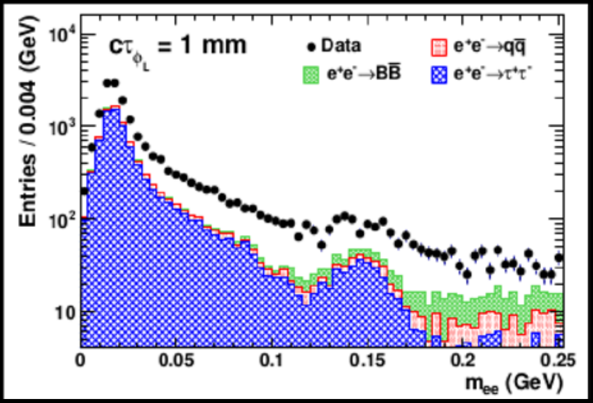
Dielectron (prompt)

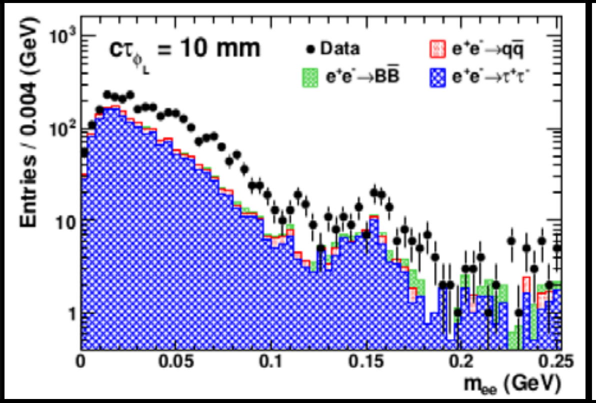


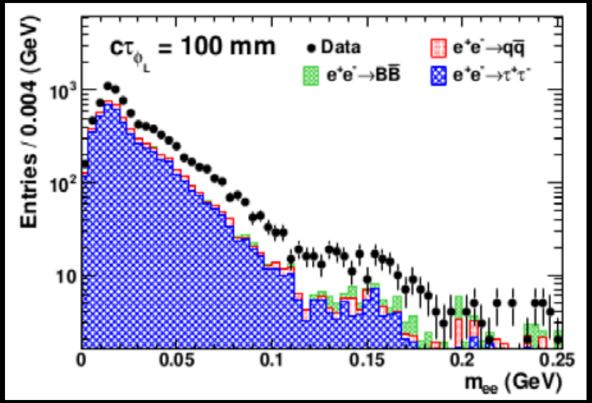
Dimuon (prompt)



Dielectron (displaced)



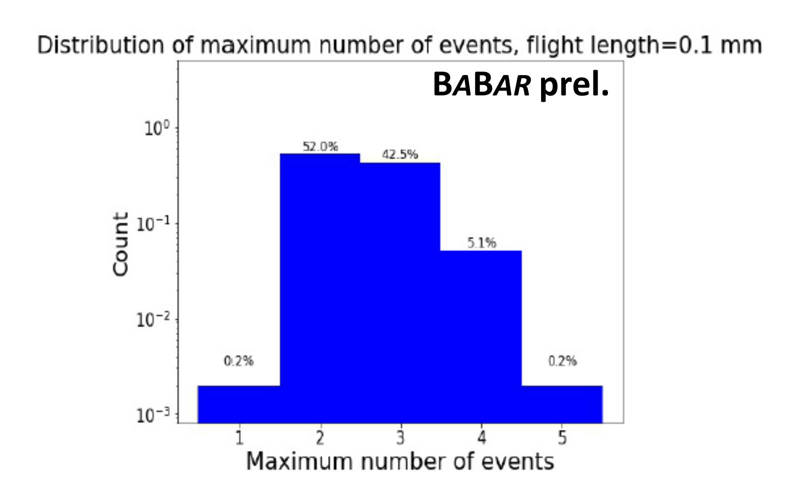


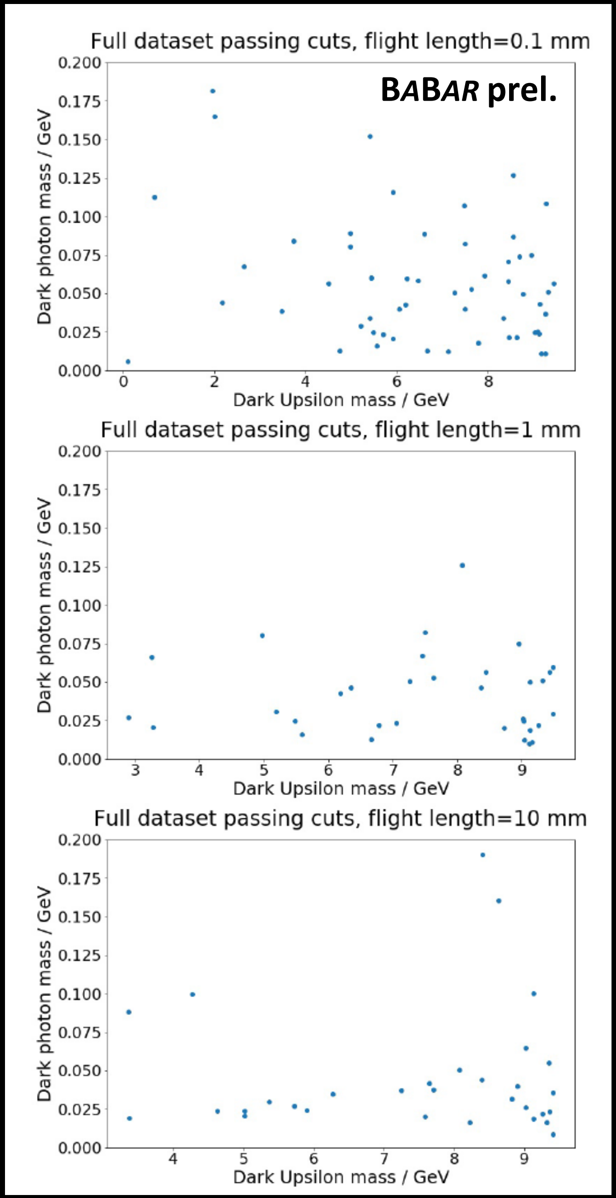


Self-interacting dark matter

Displaced vertices

- Repeat analysis assuming non-zero A' lifetime for $m_{A'} < 0.25$ GeV
- MVA modified to include variables describing the dark photon displaced vertex, but the rest of the analysis is similar
- Extract results for lifetime corresponding to $c\tau_A$ = 1, 10 and 100 mm

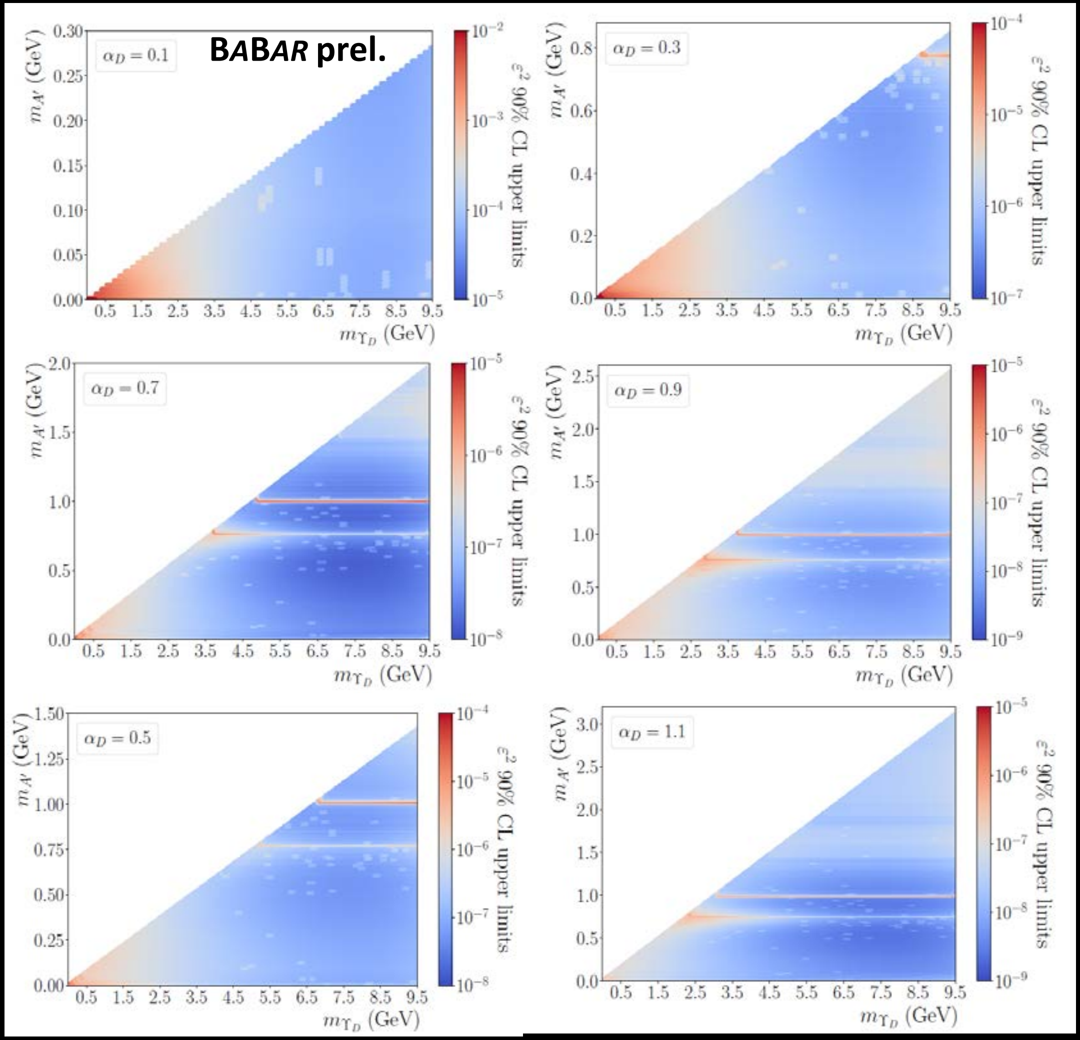




Compatible with null hypothesis for all lifetimes

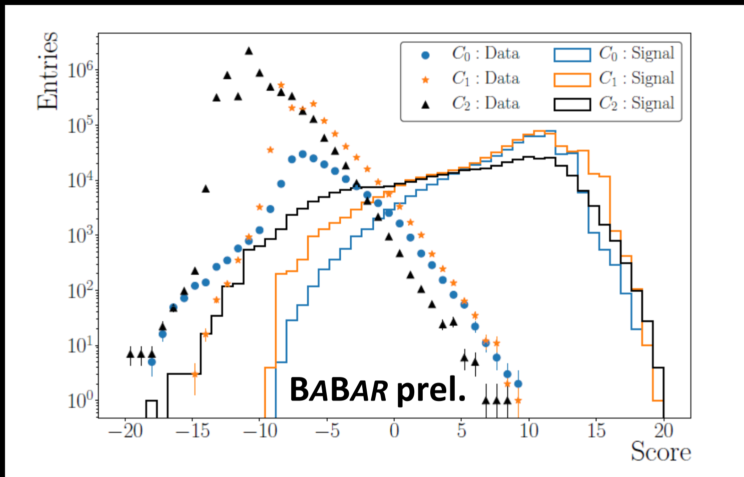
Self-interacting dark matter

Upper limits on the kinetic mixing ε for different values of the dark sector coupling constant α_D

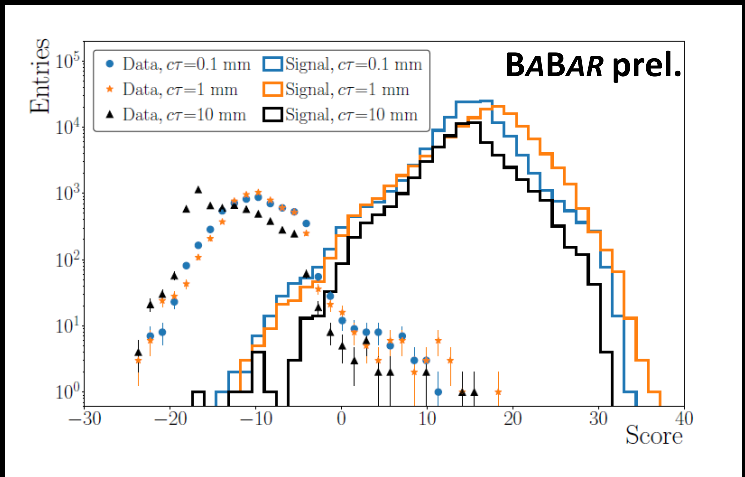


Self-interacting dark matter

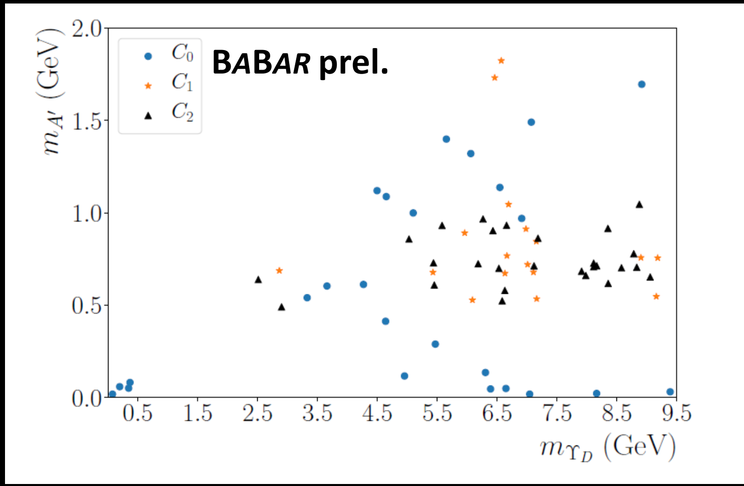
MVA score distributions (prompt)



MVA score distributions (displaced)



Final Υ_D candidate sample (prompt)



Final Υ_D candidate sample (displaced)