Dark sector searches at B*A*B*AR*

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on behalf of the B*A*B*AR* collaboration

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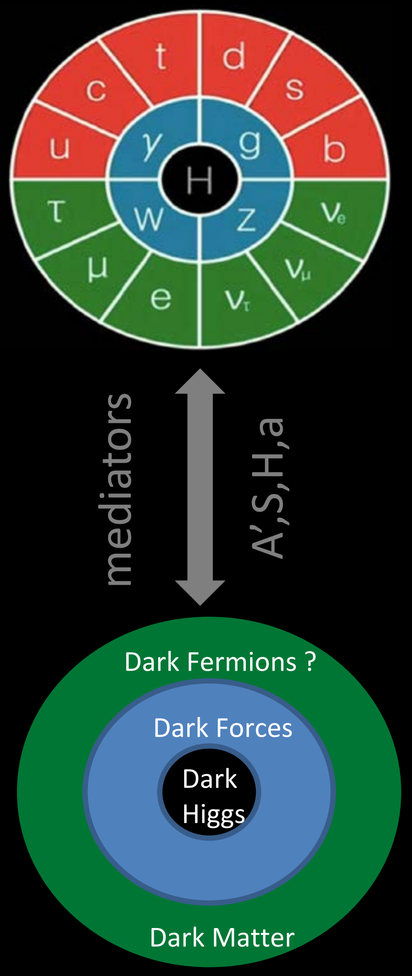
Lake Buena Vista, Florida

Dark sectors in a nutshell

What are dark sectors / hidden sectors

- New particle(s) that don't couple directly to the SM, but…
- …they can couple indirectly through so-called portals – see next slides
- Theoretically motivated: many BSM scenarios (e.g. EWSB) and string theory include dark sectors
- Dark matter could reside inside dark sector. Thermal dark matter below a ~GeV requires a new light mediator (Lee, Weinberg 1977 [PRL]), which is naturally realized in dark sector models
- Dark sector structure could be rich - the SM is non-trivial, and there is no reason for the dark sector to be simple

A whole new world to explore!



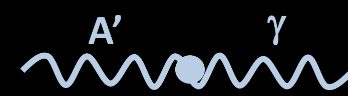
The portals

There are a few indirect interactions allowed by Standard Model symmetries between the dark sector and the SM – the “portals”. The lowest dimensional portals include:

Dim=4

Vector
$\varepsilon B^{\mu\nu} A'_{\mu\nu}$

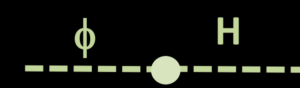
New gauge boson A’ (dark photon) mixing with SM photon/Z via kinetic mixing ε



Dim=4

Scalar
$H^2 (\mu\phi + \lambda\phi^2)$

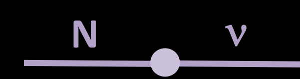
New dark scalar ϕ mixing with SM Higgs



Dim=4

Fermion
yHNL

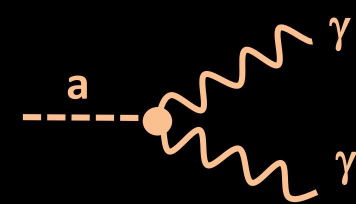
New heavy neutral lepton mixing with left-handed SM doublets and the Higgs boson



Dim=5

Axion
$1/f_a(c_1 \mathrm{tr}(G\tilde{G}) + c_2 F\tilde{F} + c_3 \partial_\mu j^\mu)\ a$

New axion / axion-like particle coupling to gauge and fermion fields



And many variations with slightly different couplings

This large variety motivates broad exploration
Low energy e^+e^- colliders offer ideal environment to study them

Wide program at B-factories

Extensive (and pioneering) "dark sector" program conducted at B*ABAR* 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 gauge bosons

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

Search for dark Higgs boson

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

Search for leptophilic dark scalar

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

Search for self-interacting DM

$e^+e^- \to \Upsilon_D \to A'A'A'$

Search for axion-like particle

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

Related searches

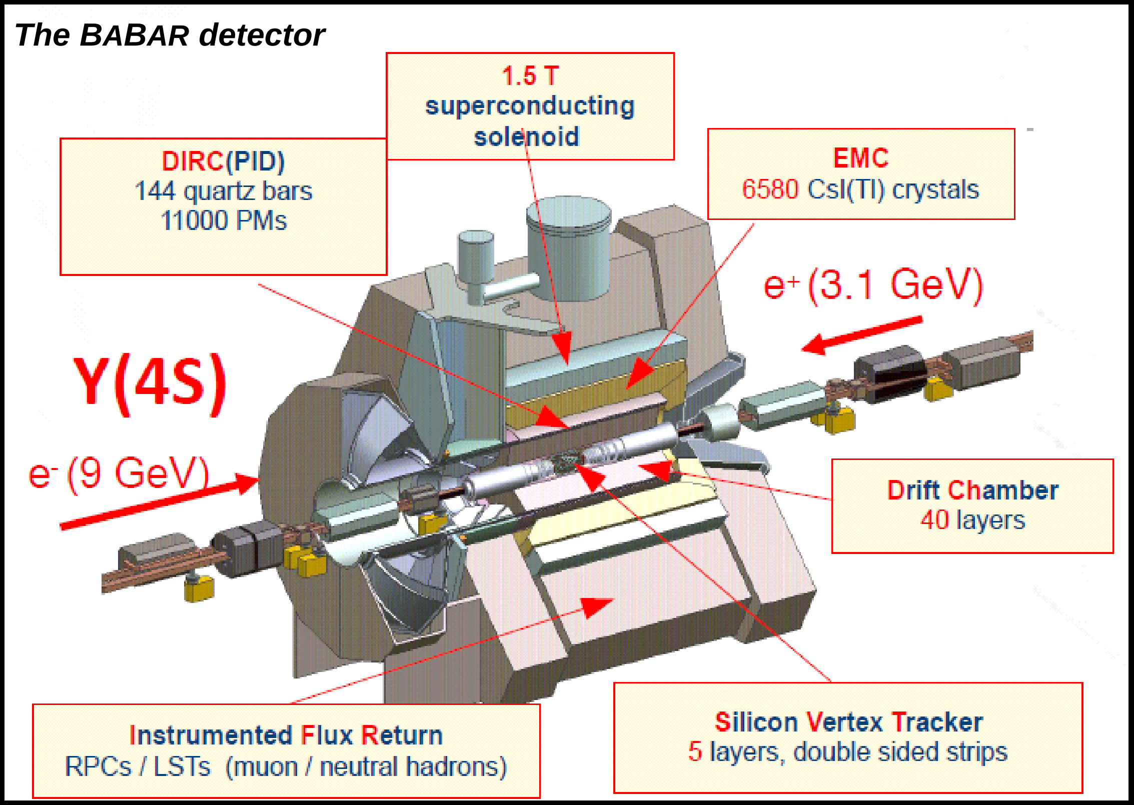
- Search for long-lived particles
- Search for low-mass Higgs boson
- Search for six-quark dark matter

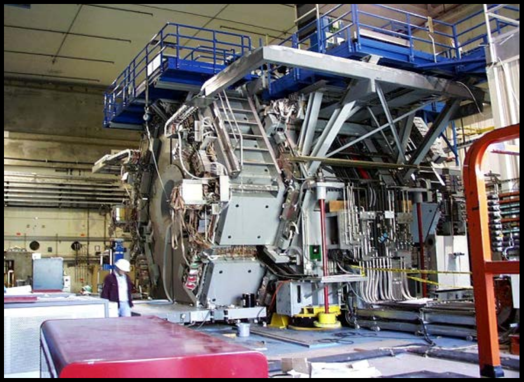
This talk will review key measurements and a selection of the most recent searches at B*ABAR*

References in supplementary slides

The B*A*B*AR* experiment

B*A*B*AR* 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 !

DARK BOSON

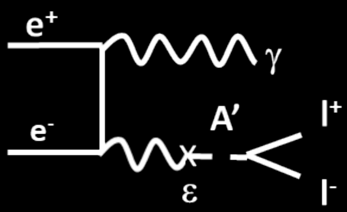
DARK PHOTON & MUONIC DARK FORCE

Dark photon searches

Dark photons: a new massive gauge boson (A') coupling to the SM photon / Z through kinetic mixing with strength ε

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

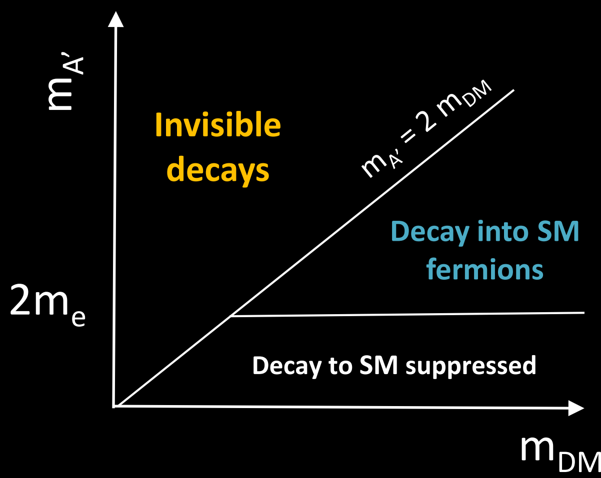
Any process that produces photon can also produce dark photon with a rate reduced by ε^2



Dark photon decay depends on the dark sector structure:

$m_{A'} > m_{DM/2}$
invisible decays into DM if dark sector state exists

$m_{A'} < m_{DM/2}$
$m_{A'} > 2m_{e}$: visible decay into SM fermions
$m_{A'} < 2m_{e}$: decays into photons via loops, A'-γ mixing

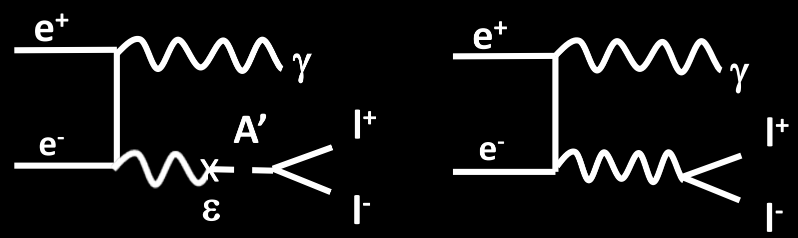


Note that there is no extra factor of ε for visible decays into SM fermions, since the A' has to decay back into leptons/quarks. The mixing strength only controls the decay width (i.e. lifetime), not the decay rate. Lifetime can become significant for low A' masses and small kinetic mixing strength.

$$\Gamma_{A'} = \frac{1}{3} m_{A'} \varepsilon^2$$

Visible dark photon decays

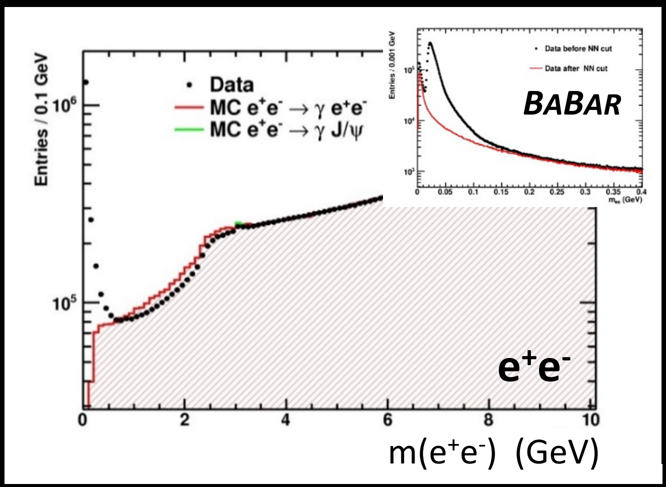
Search for dark photon in $e^+e^- \rightarrow \gamma A', A' \rightarrow e^+e^-, \mu^+\mu^-$

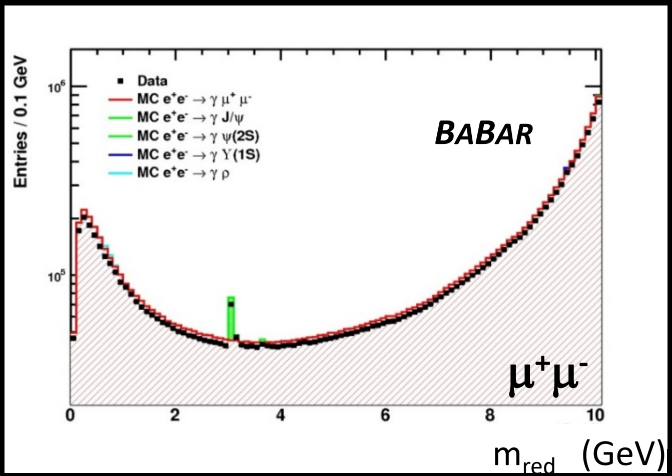


Search for a narrow resonance over large QED background:

- 2 tracks + 1 photon
- Constrained fit (beam energy + vertex)
- Particle identification (e/mu)
- Kinematic cuts to improve purity
- Quality cuts on tracks and photons

Dilepton mass distributions



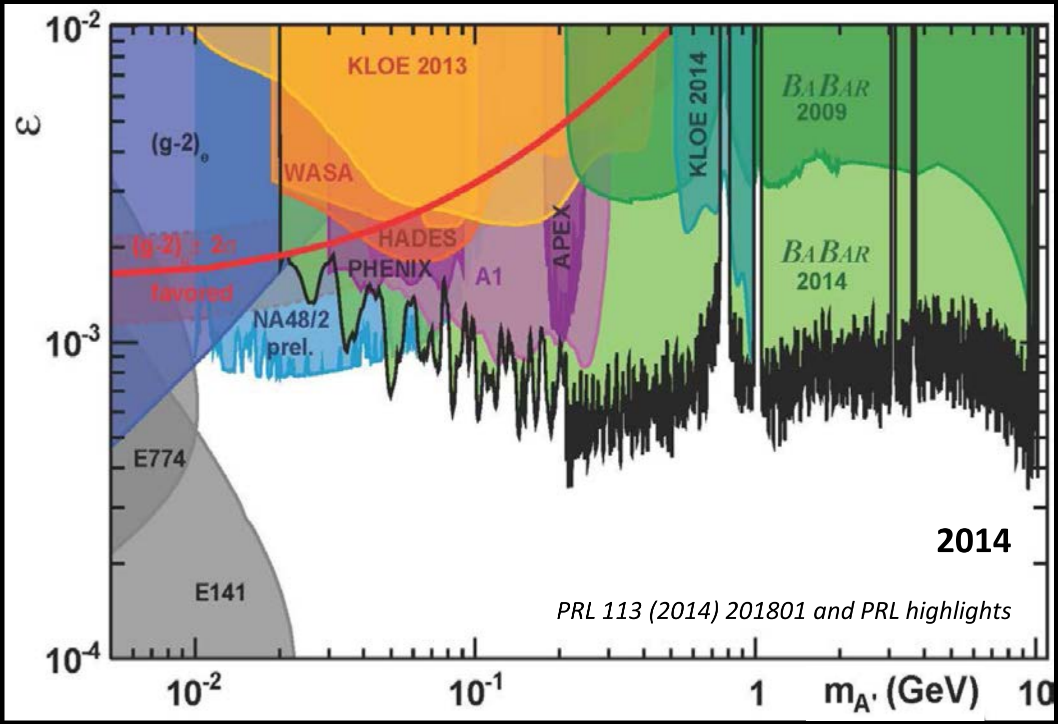


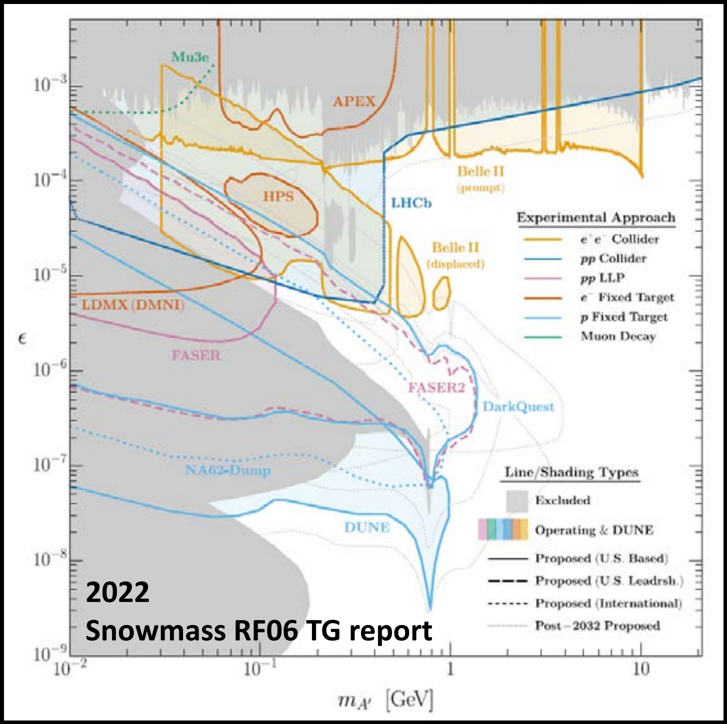
Visible dark photon decays

PRL 113 (2014) 201801

Search for dark photon in $e^+e^- \to \gamma A'$, $A' \to e^+e^-$, $\mu^+\mu^-$

Limits on the kinetic mixing ε (90% CL)



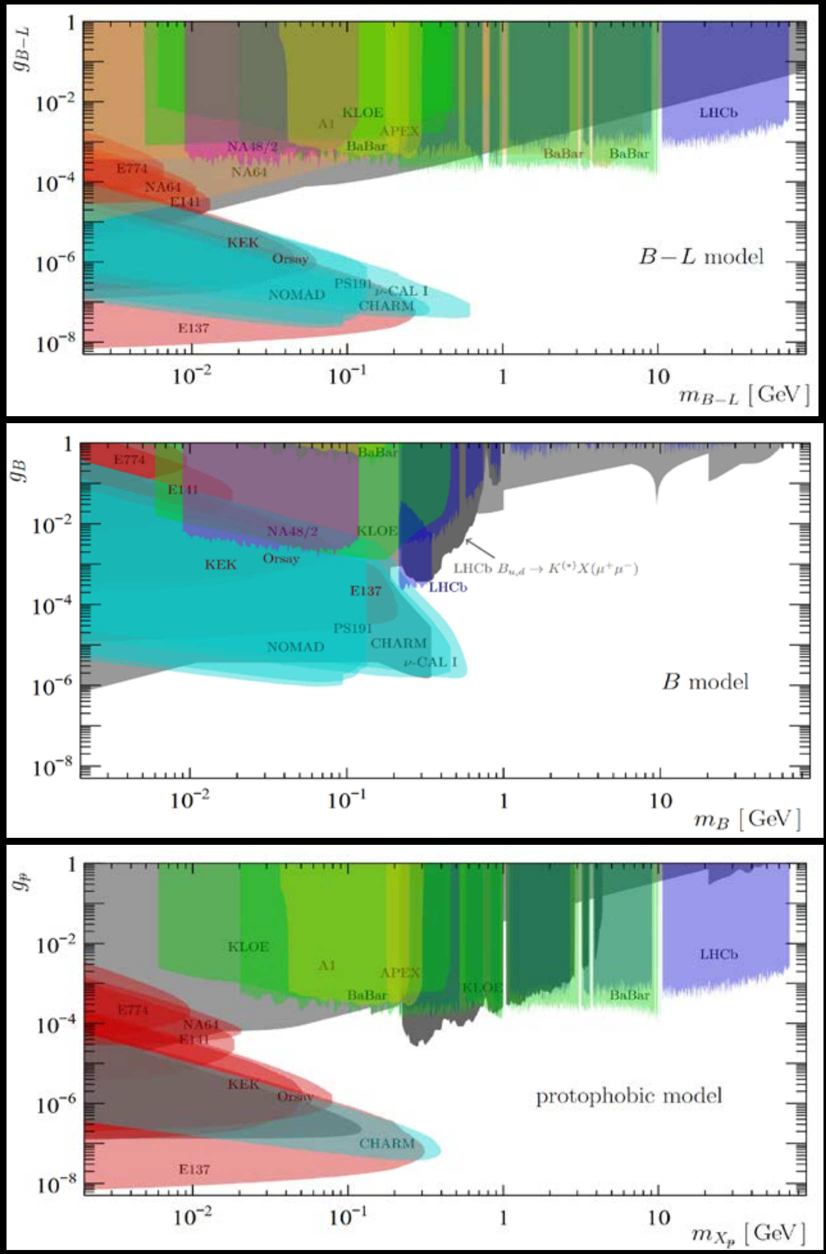


Improved constraints over a large range of masses

Worldwide program to extend coverage (especially in the low mass region)

Visible dark photon decays

Ilten et al., JHEP 06 (2018) 004



Alternative dark photon couplings

Extensions of these portals can be constructed by gauging accidental symmetries of the SM or individual flavor numbers, e.g.

- vector coupling to B−L current
- a leptophobic B boson coupling directly to baryon number
- vector mediating protophobic force
- Vector coupling to L_i-L_j $\quad i,j=e,\mu,\tau$

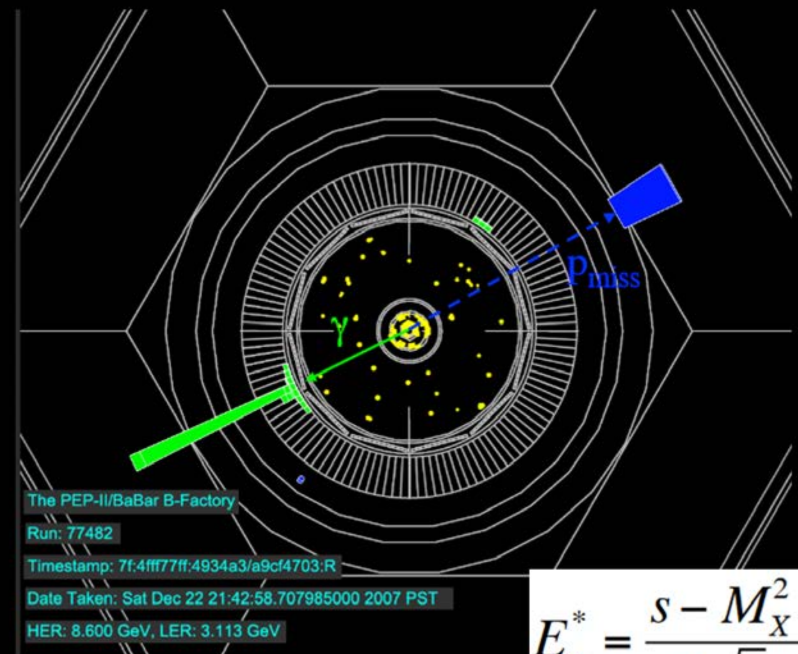
Constraints can be significantly weakened depending on the model $\rightarrow$ need multiple measurements to cover all bases

Invisible dark photon decays

Search for $e^+e^- \to \gamma A'$, $A' \to$ invisible in "single photon" events

Analysis overview

- Based on ~53 fb^{-1} of data with dedicated single photon triggers during its last year of data taking
- Select single-photon final state, then look for a bump in missing mass m_X (or $E\gamma$)
- Main backgrounds: $e^+e^- \to \gamma\gamma$ and $e^+e^- \to \gamma\, e^+e^-$ with particles outside detector acceptance
- Selection variable categories: photon quality, #tracks, extra E_{cal}, missing mass/energy, and muon detector information

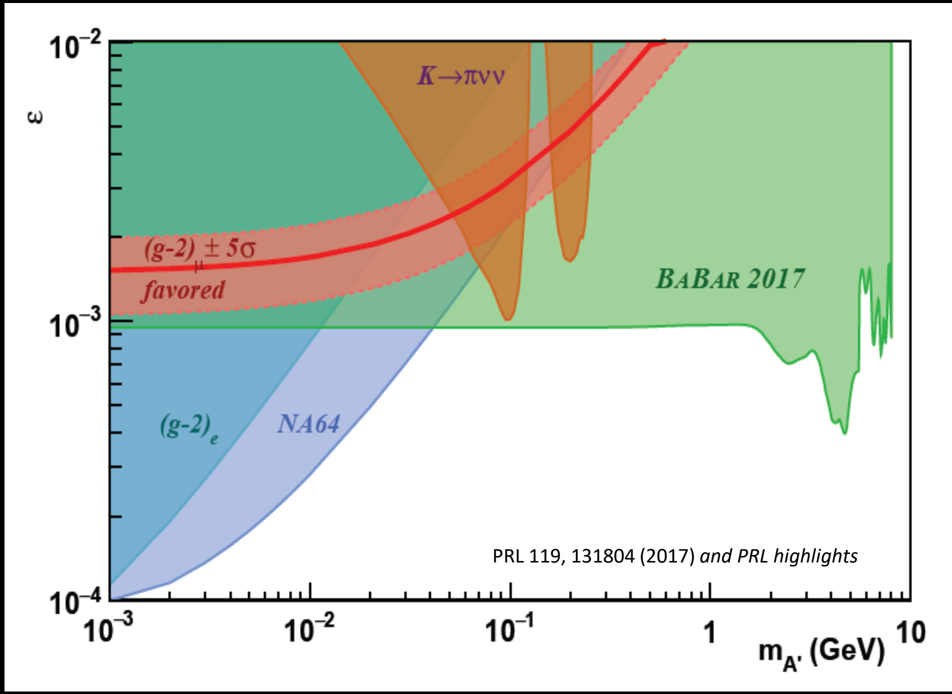


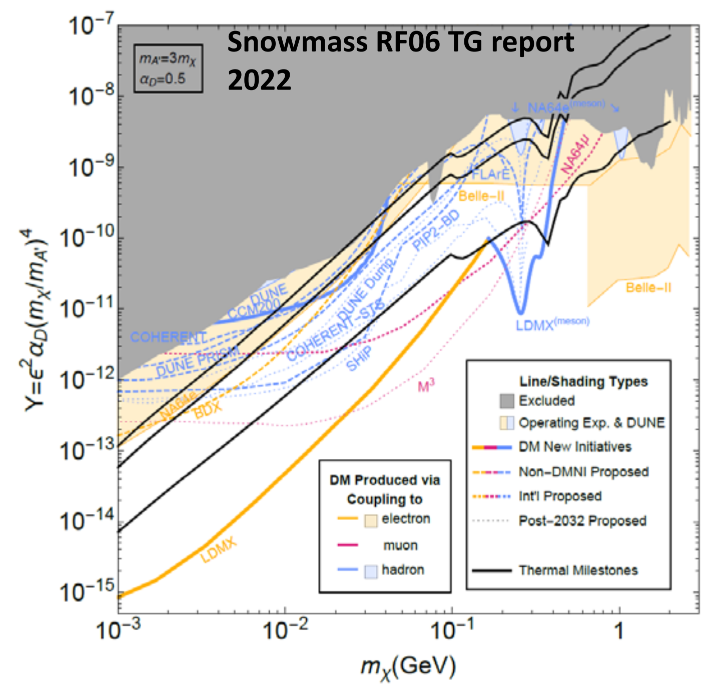
$$E^*_\gamma = \frac{s - M_X^2}{2\sqrt{s}}$$

PRL 119, 131804 (2017)

Search for $e^+e^- \rightarrow \gamma A'$, $A' \rightarrow$ invisible in "single photon" events

Limits on the kinetic mixing ε (90% CL)





Substantially improve previous limits in high mass region, and exclude purely invisible dark photon as explanation of "g-2" anomaly

Next generation B-factories should substantially improve at high masses

Muonic dark force

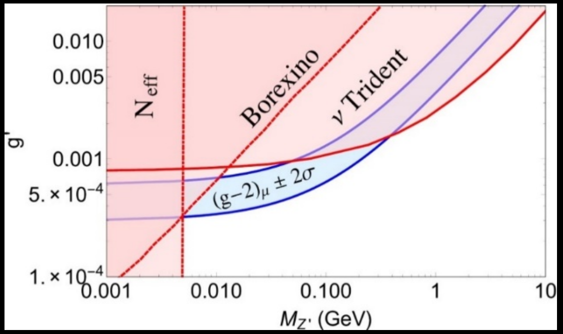
Muonic dark force: a new force coupling only to the second and third generation of leptons with a corresponding gauge boson Z’

Such a force could explain various anomalies observed in the muon sector (“g-2” discrepancy, proton radius puzzle)

At the time, some constraints from neutrino physics had already been derived, but they only indirectly probed the existence of Z’ (with large systematics)

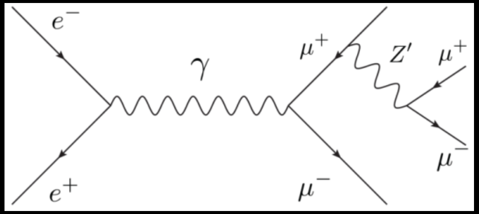
Searches for a muonic dark force at B*A*B*AR* via Z’-strahlung :

Constraints on Z’ circa 2014

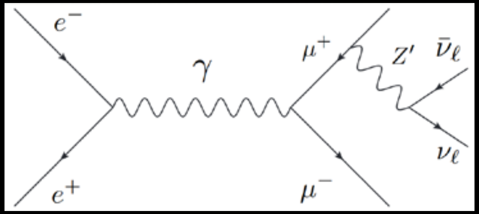


PRD 89 (2014) 113004

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



$e^+e^- \to \mu^+\mu^- Z', Z' \to \nu\overline{\nu}$

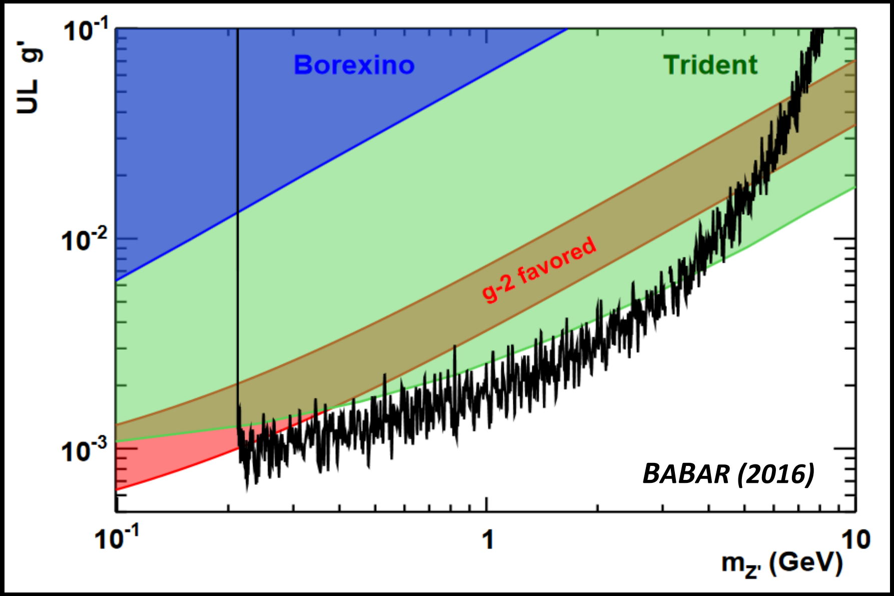


Muonic dark force

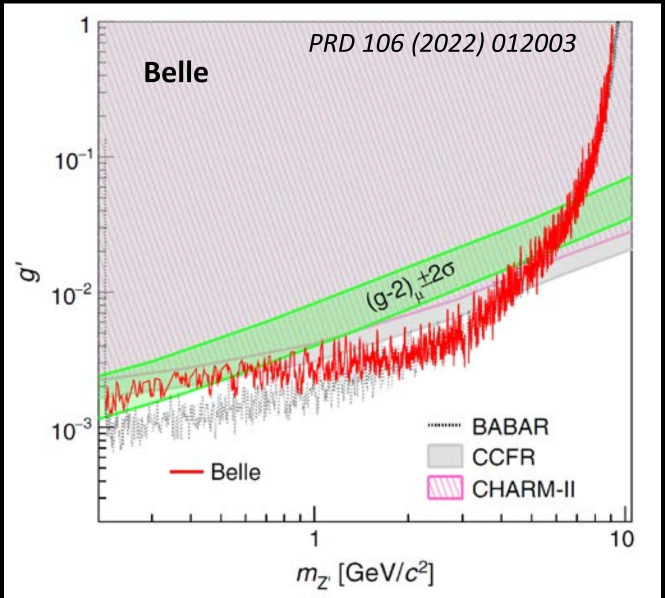
PRD 94 (2016) 011102

Search for Z’ in $e^+e^- \to \mu^+\mu^- Z’, Z’ \to \mu^+\mu^-$

Limits (90% CL) on Z’ coupling



Limits (90% CL) on Z’ coupling



Measurements improve upon previous bounds and further exclude region favored by the g-2 anomaly

Several searches for Z’ decays are currently performed at Belle-II

DARK SCALAR

DARK HIGGS BOSON & LEPTOPHILIC SCALAR

PRL 108 (2012) 211801

Search for dark Higgs boson h'

Dark photon mass is generated via the Higgs mechanism, adding dark Higgs boson(s) to the dark sector content

Can be produced via Higgsstrahlung process via

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

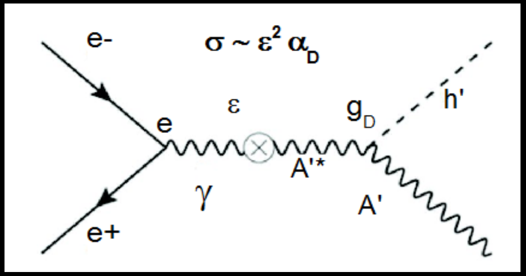
(sensitive to dark sector coupling constant α_D)

Decay topology depends on the dark Higgs and dark photon masses: either invisible or visible

Search for visible h' decays at B*A*B*AR*:

$$\mathbf{e^+e^- \to A'^* \to h' A', h' \to A' A', A' \to l^+l^-, \pi^+\pi^-}$$

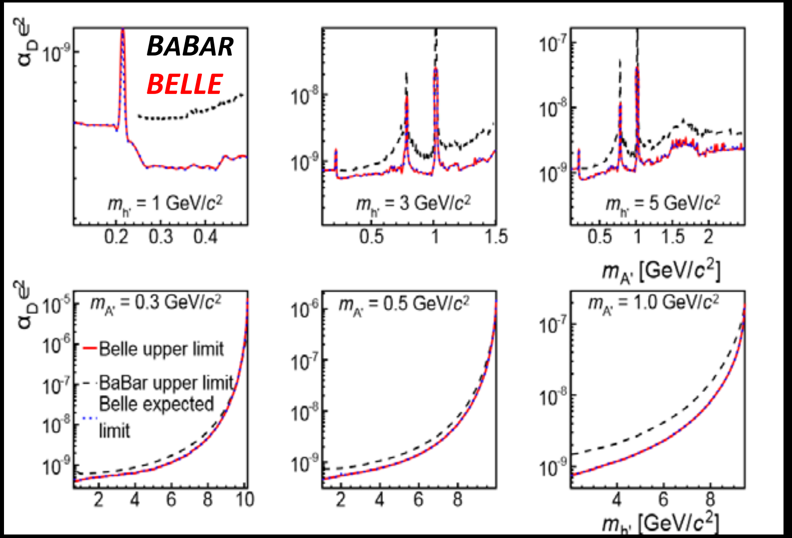
No significant signal observed, set limits on the product $\alpha_D\varepsilon^2$ at the level of 10^{-10}-10^{-5}



$\alpha_D = g_D^2 / 4\pi$

g_D is the dark sector gauge coupling

$$\mathbf{e^+e^- \to A'^* \to h' A', h' \to A' A', A' \to l^+l^-, \pi^+\pi^-}$$



Belle Collaboration, PRL 114 (2015) 211801

BABAR Collaboration, PRL 108 (2012) 211801

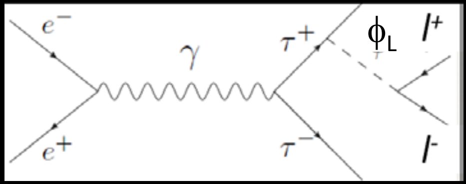
Leptophilic dark scalar

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

More generally, a new light gauge singlet could directly mix with the Higgs boson via the scalar portal

A new leptophilic scalar interacting mainly with leptons rather than quarks could escape the current constraints and explain the g-2 anomaly (1606.04943, 1605.04612) and the KOTO excess (2001.06522)

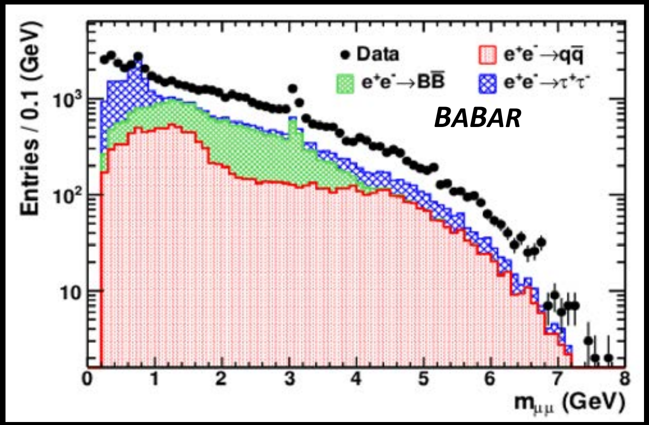
Mass proportional coupling implies that this scalar is produced preferentially via its coupling to the tau, and decays mainly to the most massive lepton-pair kinematically accessible



Search for **$e^+e^- \to \tau^+\tau^- \phi_L$, $\phi_L \to l^+l^-$ (l=e,μ)**

(the final state $\phi_L \to \tau^+\tau^-$ has too many neutrinos to provide competitive constraints)

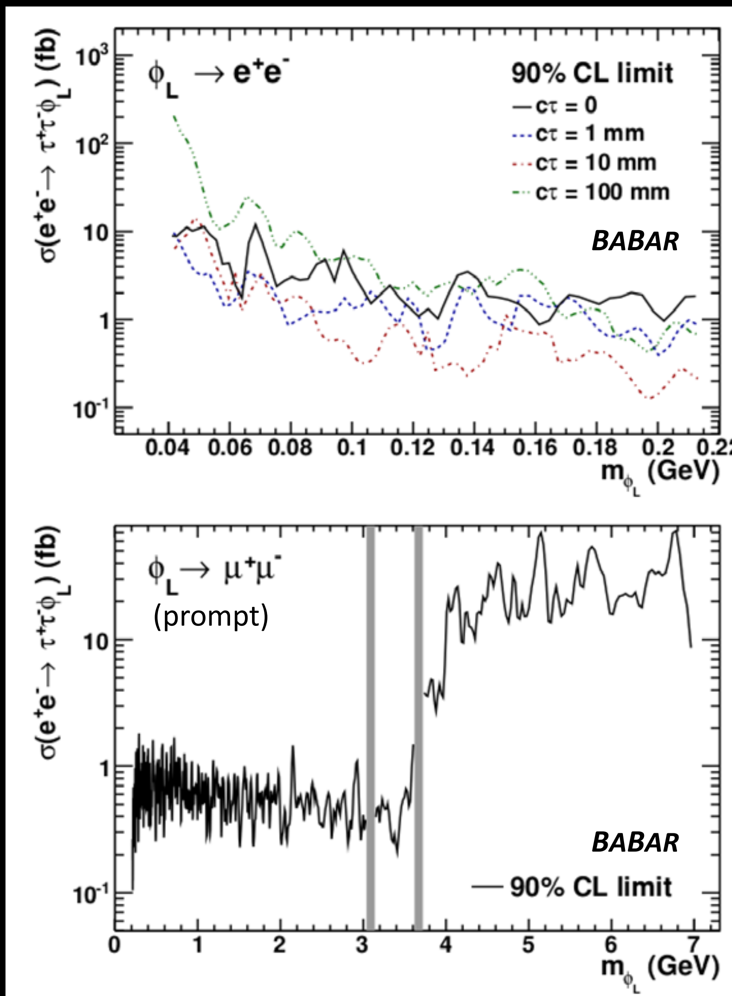
Final dimuon mass distribution

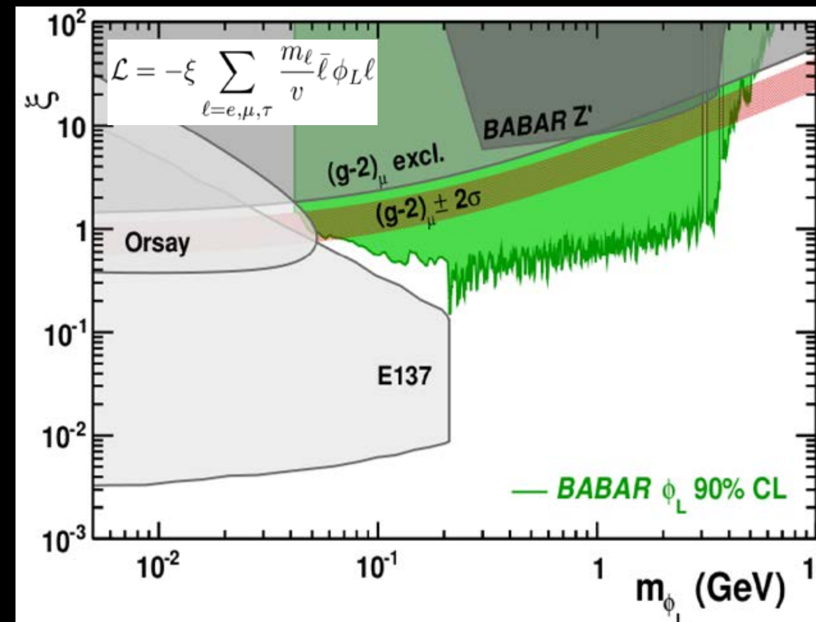


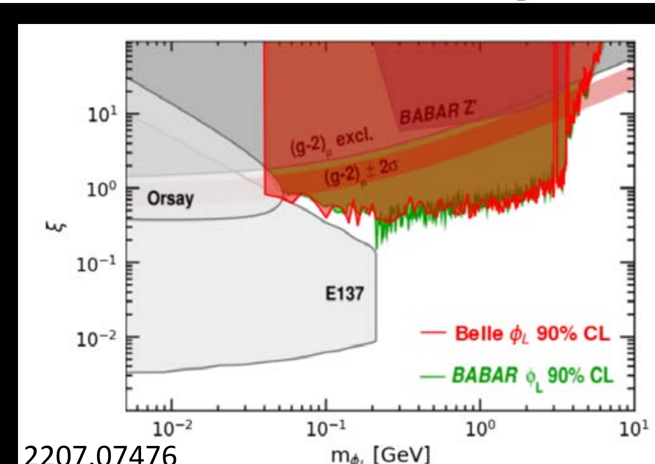
Leptophilic dark scalar

PRL 125 (2020) 181801

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







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AXION

AXION-LIKE PARTICLE IN B DECAYS

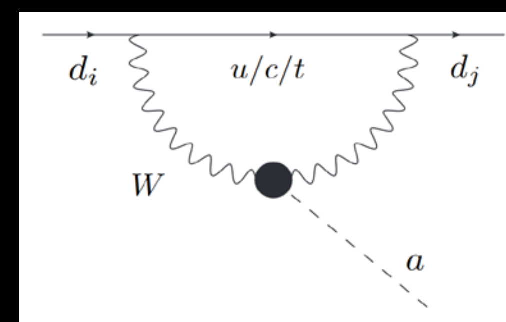
Axion like particle (ALP)

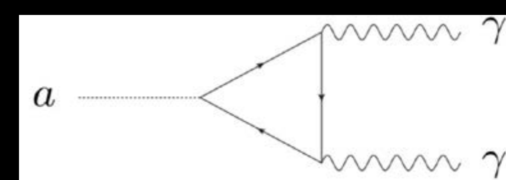
What are axion like particles

- Pseudo-goldstone bosons ubiquitous in BSM physics, coupling predominantly to pair of bosons with non-renormalizable coupling constant $f_a \sim 1/m_a$
- Low-mass ALP can be both dark matter candidate and dark sector mediator
- Most searches focus on photon or gluon couplings at low energies as effects from $W^{\pm}$ coupling are suppressed by G_F^2

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

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





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
- Axion lifetime becomes important at low masses and couplings ($\tau \sim 1/m_a^3 g_{aW}^2$) $\rightarrow$ long-lived axion

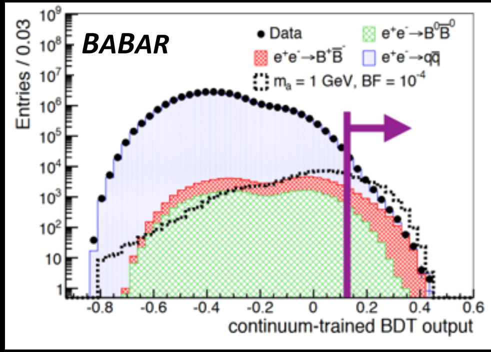
Axion like particle (ALP)

Search for ALP (a) in B decays: $B \to Ka$, $a \to \gamma\gamma$

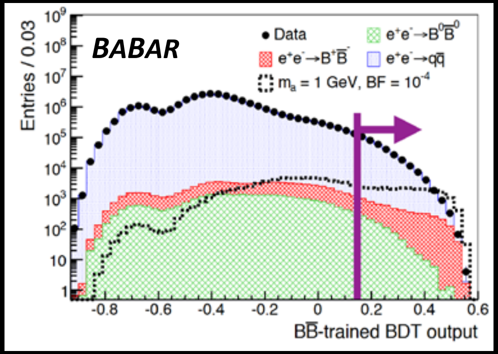
Analysis strategy

- 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
- Blind analysis, optimize on 8% of dataset and discard from final results

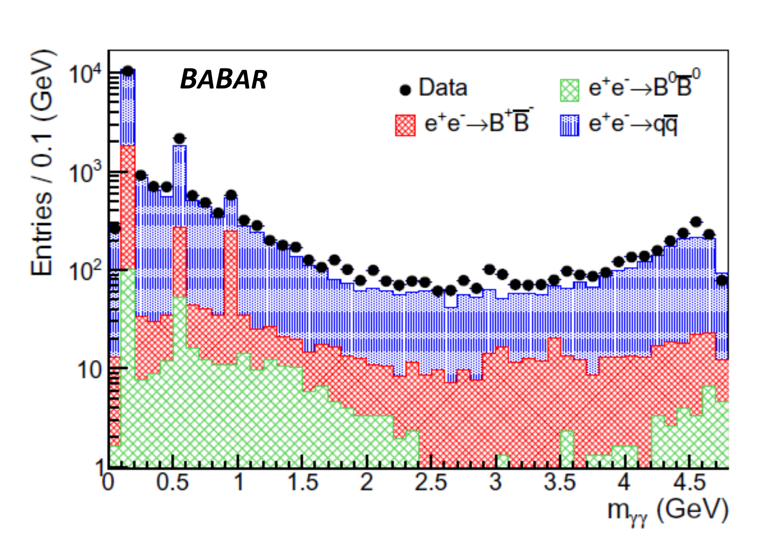
Continuum BDT



B-Bbar BDT



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



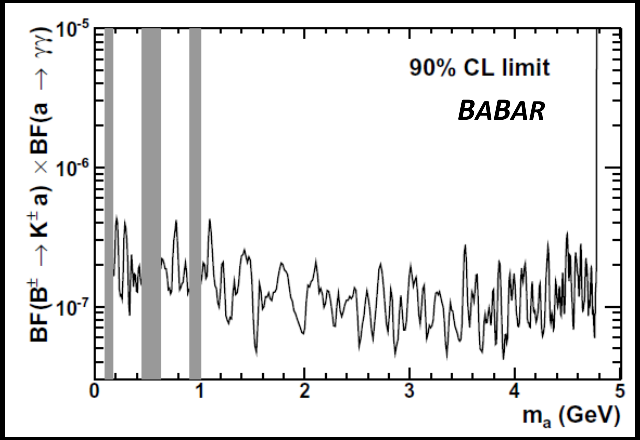
Peaking background at π^0,η,η' masses,
2.6σ excess near the η_c, consistent with $B \to K\,\eta_c$, $\eta_c \to \gamma\gamma$

Axion like particle (ALP)

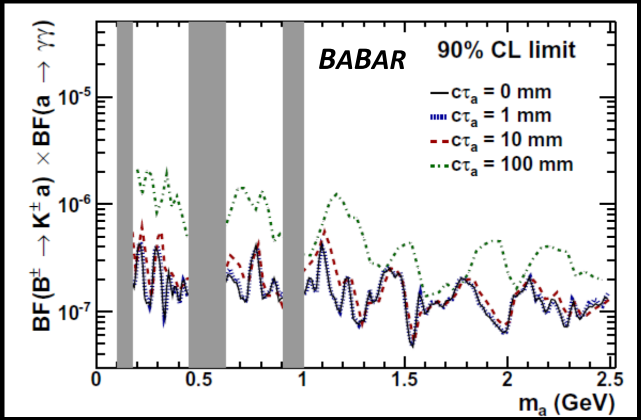
PRL 128 (2022) 131802

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

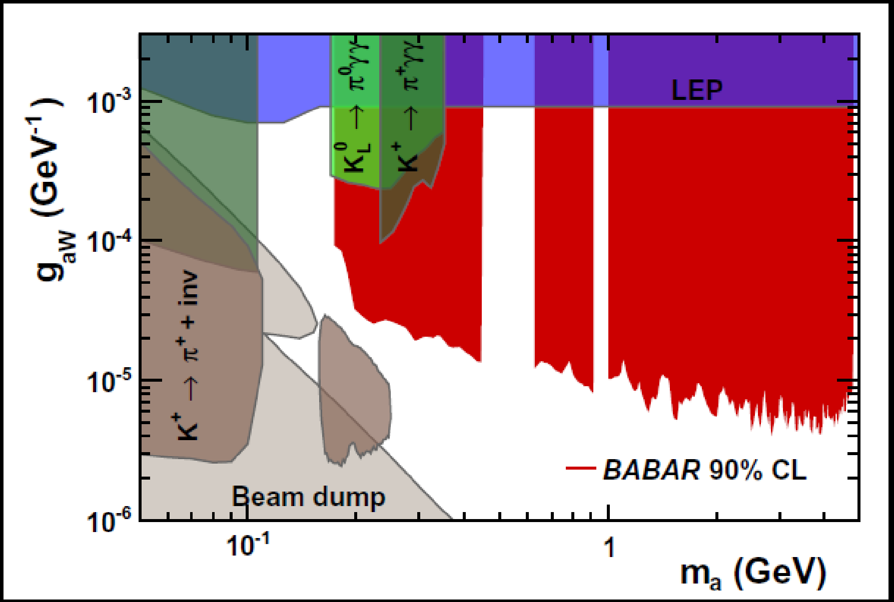
Prompt decays



Displaced decays



90% CL upper limits on coupling g_{aW}



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

On-going searches at Belle II for other axion and ALP decays

SELF-INTERACTING DARK MATTER

MINIMAL DARK SECTOR MODEL

Self-interacting dark matter

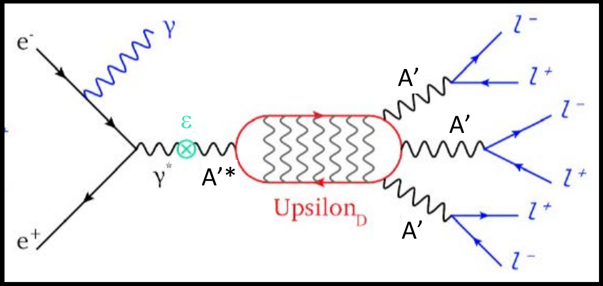
Search for darkonium Υ_D in $e^+e^- \to \gamma\Upsilon_D$, $\Upsilon_D \to A'\,A'\,A'$, $A' \to X^+X^-$ ($X=e,\mu,\pi$)

Minimal dark sector model with a dark (anti-)fermion coupling to the dark photon

For large values of the dark sector coupling constant α_D, a DM bound state can be form $\to$ darkonia (H. An et al., PRL 116 (1026) 151801)

Search for the lightest vector darkonium Υ_D ($J^{PC} = 1^{--}$) in $e^+e^- \to \gamma\Upsilon_D$, $\Upsilon_D \to A'\,A'\,A'$, $A' \to X^+X^-$ ($X=e,\mu,\pi$)

Dark photon lifetime can be large for small values of the kinetic mixing ε and mass $\to$ prompt and displaced vertex analyses

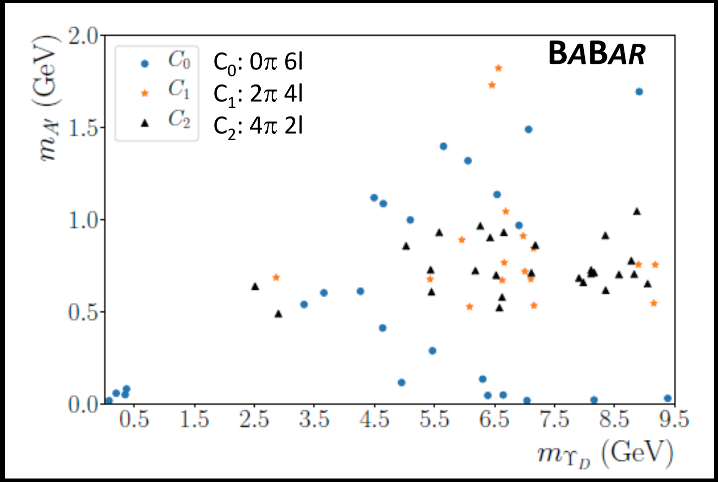


Analysis strategy

- Final states consist of three pairs of leptons or pions with similar masses (require 2+ leptons)
- Recoil mass against Υ_D compatible with photon
- ISR photon can be emitted inside or outside calorimeter acceptance
- MVA to improve signal purity
- Scan the Υ_D – A' mass plane to extract signal

No significant signal is observed

Final Υ_D candidate sample (prompt)

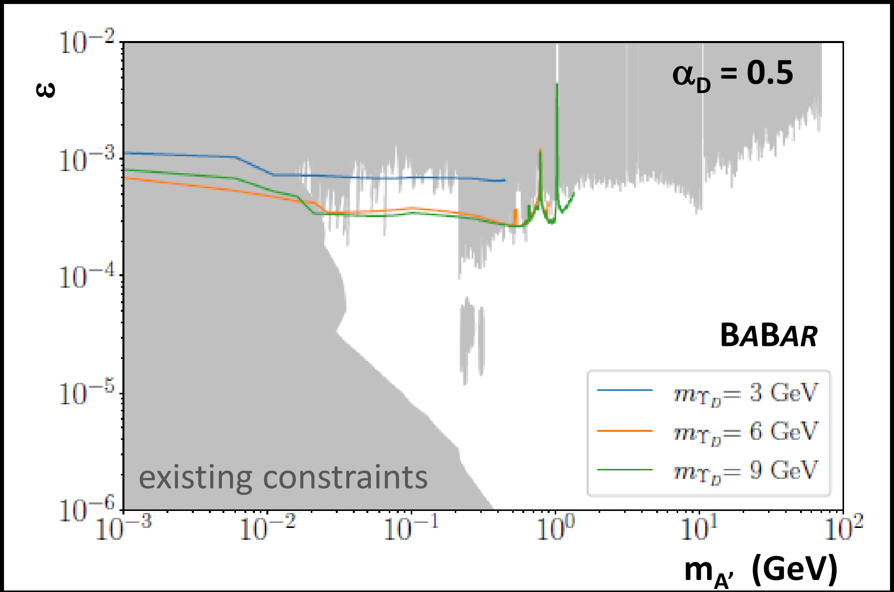


Self-interacting dark matter

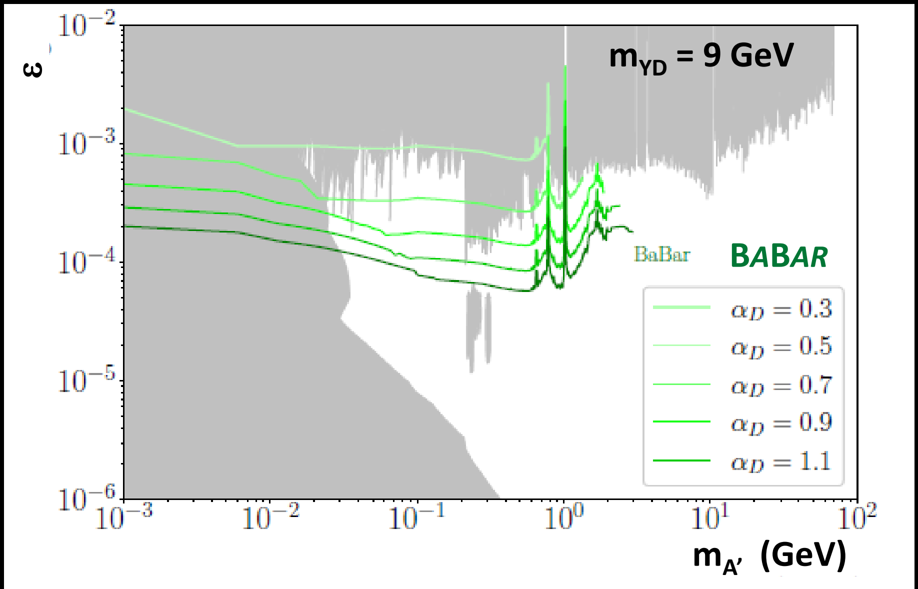
PRL 128 (2022) 021802

Extract 90% CL limit on the kinetic mixing strength ε for different values of α_D and m_{YD}

Constraints on ε for α_D = 0.5



Constraints on ε for m_{YD} = 9 GeV



Improve existing 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 probe these possibilities

B*A*B*AR* has conducted an extensive program to search for dark sector signatures, and continues to put world-leading limits on many scenarios, such as 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

Useful references

Search for dark photon

Search for a Dark Photon in e+e- Collisions at BaBar, PRL 113 (2014) 201801

Search for Invisible Decays of a Dark Photon Produced in e+e- Collisions at BaBar, PRL 119 (2017) 131804

Search for muonic dark force

Search for a muonic dark force at BABAR, Phys. Rev. D 94, 011102 (2016)

Search for dark bosons

Search for a Narrow Resonance in e+e- to Four Lepton Final States, arXiv:0908.2821

Search for dark Higgs boson

Search for Low-Mass Dark-Sector Higgs Bosons, PRL 108 (2012) 211801

Search for leptophilic dark scalar

Search for a Dark Leptophilic Scalar in e+e- Collisions, PRL 125, 181801 (2020)

Search for darkonium

Search for Darkonium in e+e- collisions, PRL 128 (2022) 021802, arxiv:2106.08259

Search for axion-like particle

Search for an Axion-Like Particle in B Meson Decays, PRL 128 (2022), 131802, arXiv:2111.01800

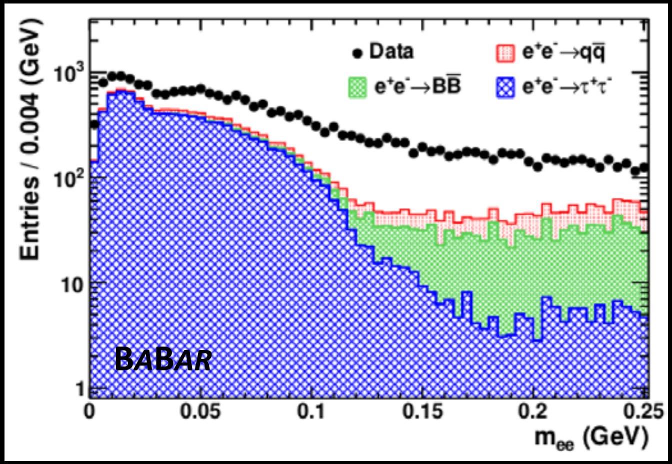
Search for six-quark dark matter

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

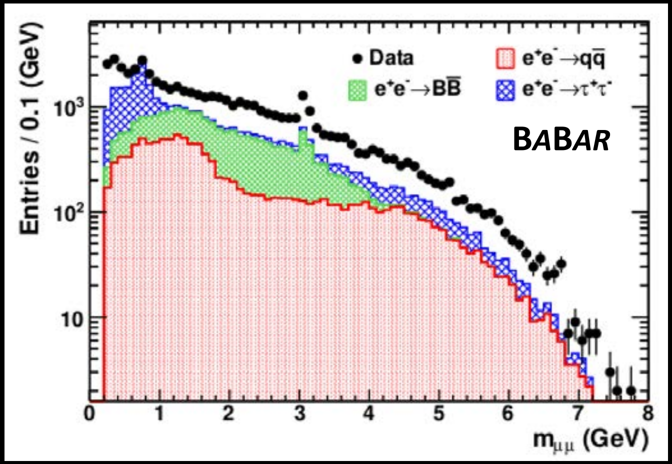
Leptophilic dark scalar

Final mass spectra for each final state and lifetime

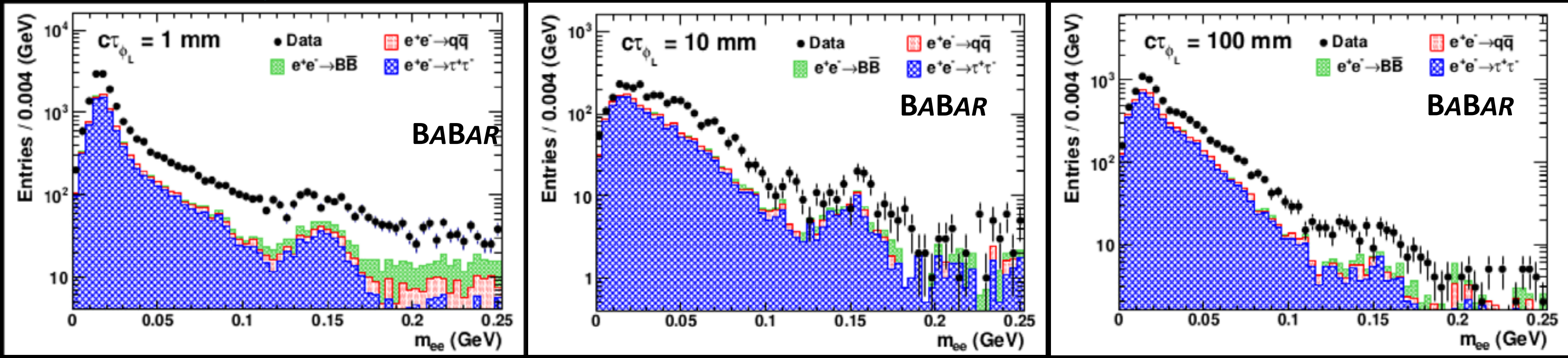
Dielectron (prompt)



Dimuon (prompt)



Dielectron (displaced)



Event selection

Select event with 3 pairs of oppositely charged tracks with at least a lepton pair

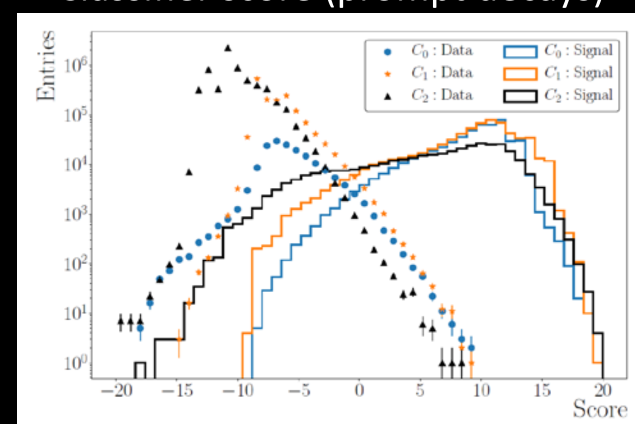
Train a multivariate classifier to improve signal purity

- the mass difference between the A' candidates
- the mass difference between same-sign pairs
- the quality of the kinematic fit
- combined PID information
- the system recoiling against the Y_D candidate
- the energy of the ISR photon, if emitted inside the calorimeter
- extra neutral energy, excluding the ISR photon
- angles between the A' candidates
- decay length of A' candidates

Category	Final state
C_0	$3e^+e^-$ $2e^+e^-1\mu^+\mu^-$ $1e^+e^-2\mu^+\mu^-$ $3\mu^+\mu^-$
C_1	$2e^+e^-1\pi^+\pi^-$ $2\mu^+\mu^-1\pi^+\pi^-$ $1e^+e^-1\mu^+\mu^-1\pi^+\pi^-$
C_2	$1e^+e^-2\pi^+\pi^-$ $1\mu^+\mu^-2\pi^+\pi^-$

Categorize events according to the number of pion pairs in the final state: C_0, C_1 and C_2.

Classifier score (prompt decays)



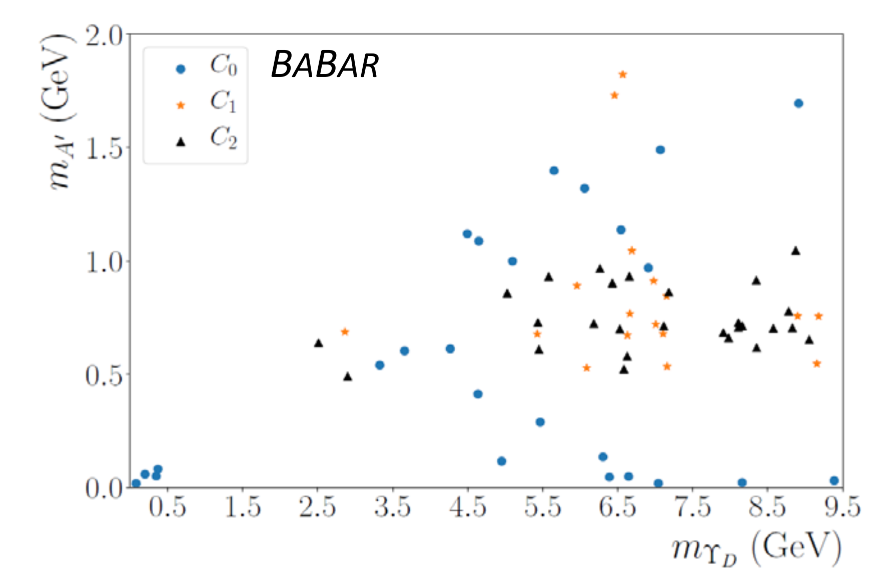
Train a classifier for prompt decays and displaced vertices for each cτ value, and optimize cut on each classifier score independently

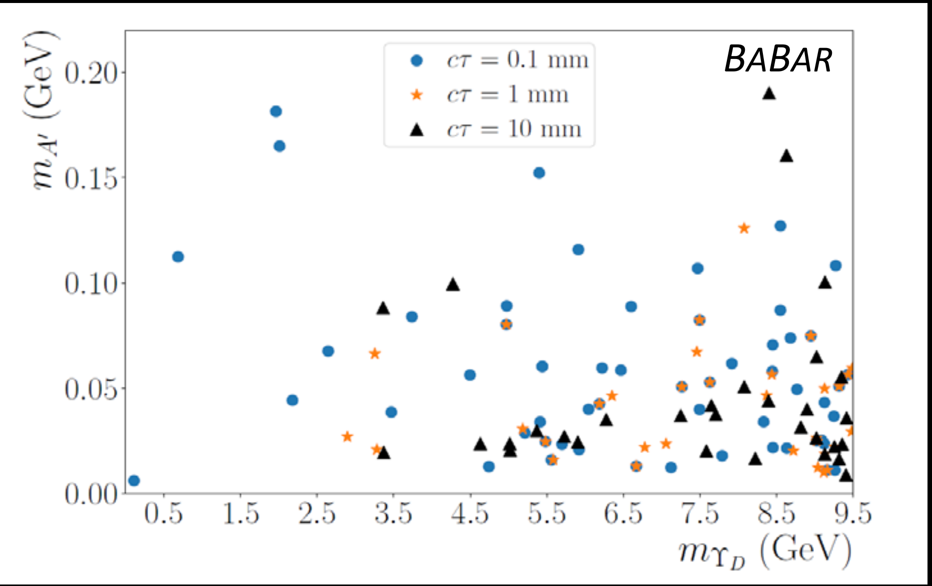
Mass distributions

Dark photon and dark Upsilon mass distributions

Prompt

Displaced ($m_{A'}$ < 200 MeV)





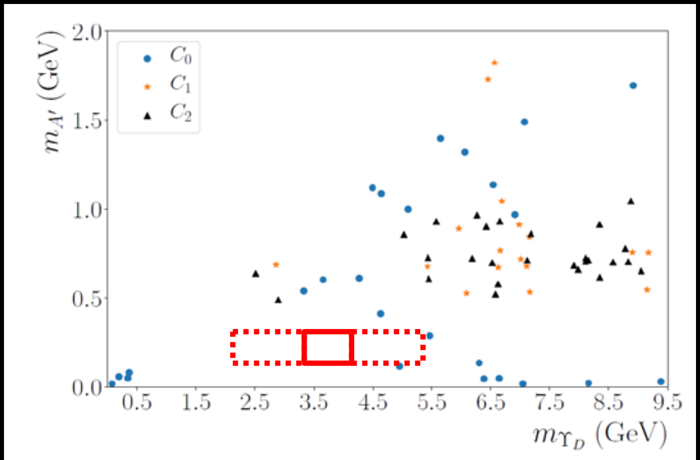
Main backgrounds arise from

- $e^+e^- \to \gamma\gamma\gamma$, $\gamma \to ee$ at low A' masses
- $e^+e^- \to q\bar{q}$ at higher A' masses, with hints of ρ and ω mesons in multi-pion events

Signal extraction

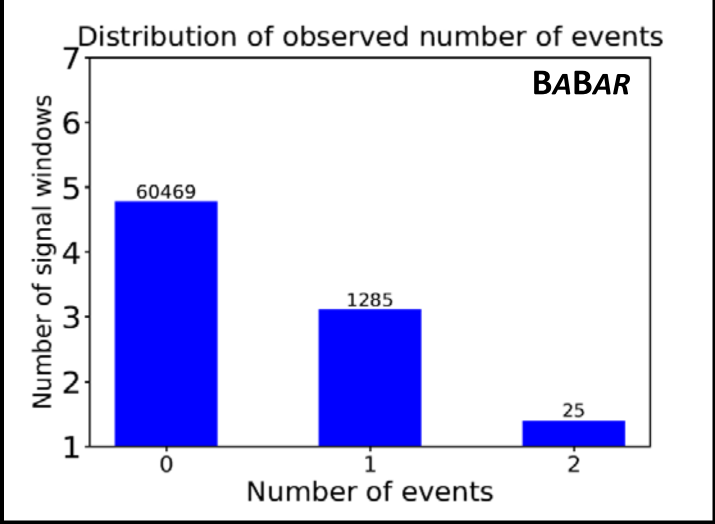
Scan the Υ_D – A' mass plane to extract the signal as a function of the A' and Υ_D masses

- Combine all channels together
- Estimate background with neighboring $m_{A'}$ bins to include possible structure in bkg
- Scan step is (A',Υ_D) mass resolution (~3 MeV, ~20 MeV)



Use sideband data to estimate the probability of observing N events in any of the scanned windows for the background-only hypothesis (bootstrap method)

Number of events in signal windows (prompt decays)



For prompt decays, the probability of observing 2 events in any window for the background is 29%

→ no significant signal

The distributions for displaced decay vertices are also all compatible with the null hypothesis