Dark sector searches at BABAR

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on behalf of the BABAR collaboration

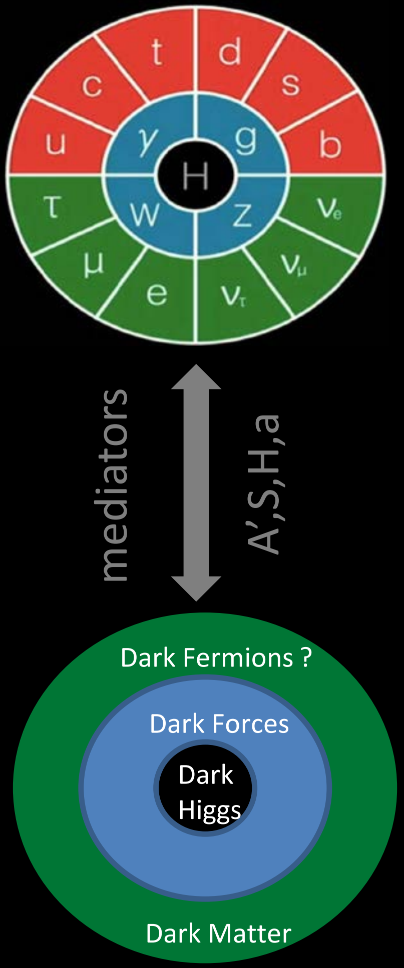
August 2022 – PhiPsi 2022

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!



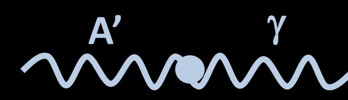
The portals

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

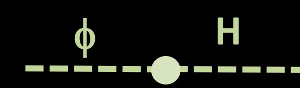
New gauge boson A' (dark photon) mixing with SM photon/Z via kinetic mixing ε



Dim=4

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

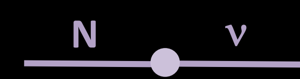
New dark scalar ϕ mixing with SM Higgs



Dim=4

Fermion
yHNL

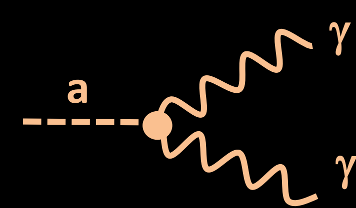
New heavy neutral lepton mixing with left-handed SM doublets and the Higgs boson



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 "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

$B^0 \to A' A', A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$

Search for "muonic dark force"

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

Search for dark 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

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

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

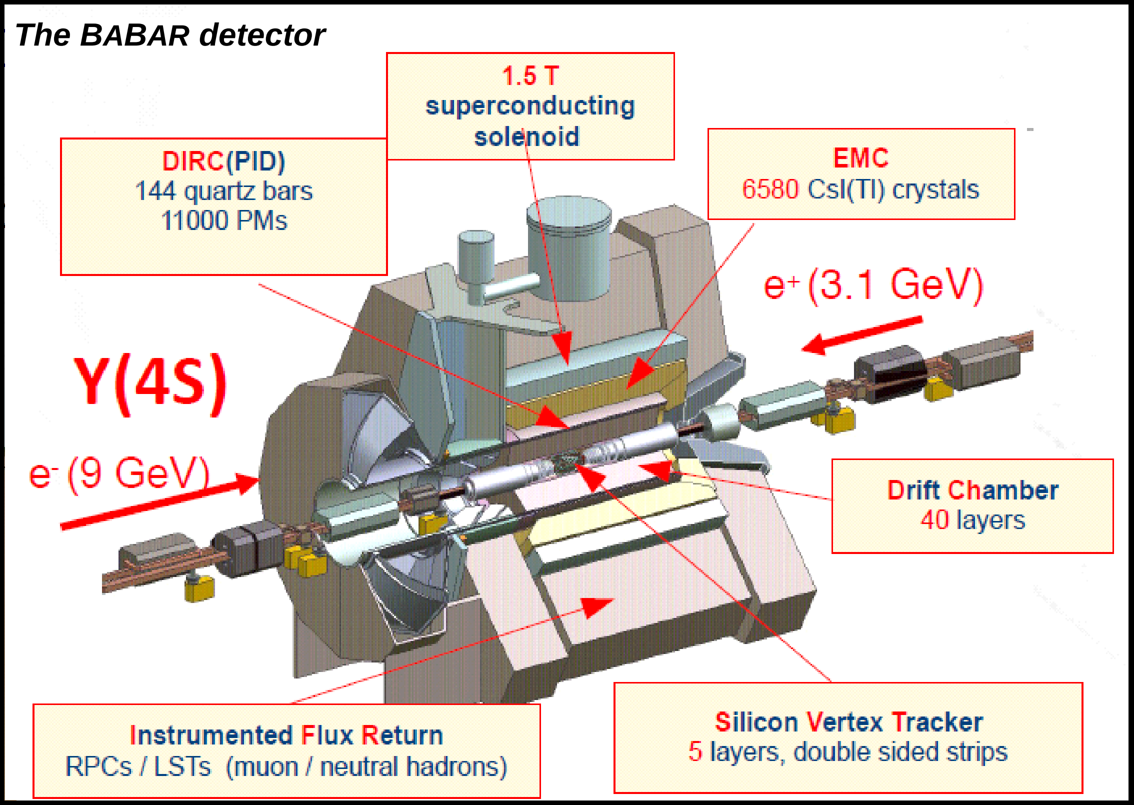
This talk will review key measurements and a selection of the most recent searches at B*ABAR*

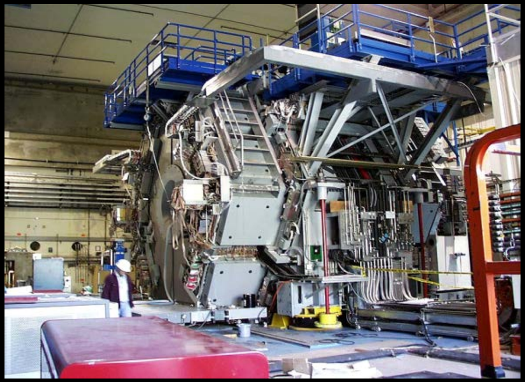
Ngan Nguyen will discuss axion-like particles later

References in supplementary slides

The BABAR experiment

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





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

DARK BOSON

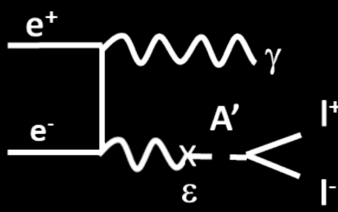
DARK PHOTON & MUONIC DARK FORCE

Dark photon searches

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

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

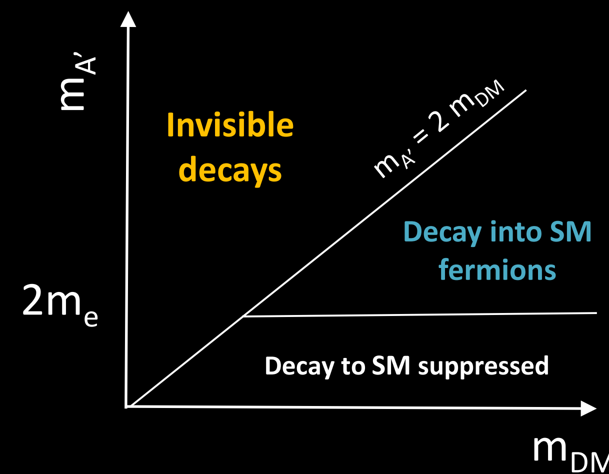
Any process that produces photon can also produce dark photon with a rate reduced by ε^2



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



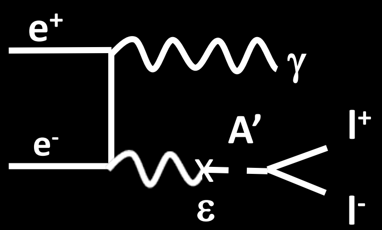
Note that there is no extra factor of ε for visible decays into SM fermions, since the A’ has to decay back into leptons/quarks. The mixing strength only controls the decay width (i.e. lifetime), not the rate. Lifetime can become significant for low A’ masses and small kinetic mixing strength.

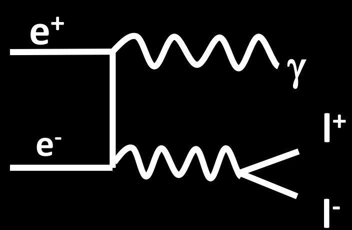
$$\Gamma_{A'} = \frac{1}{3} m_{A'} \varepsilon^2$$

Visible dark photon decays

PRL 113 (2014) 201801

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

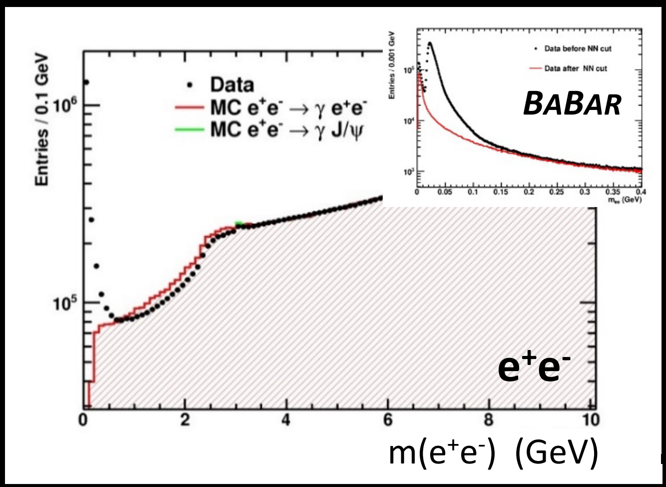


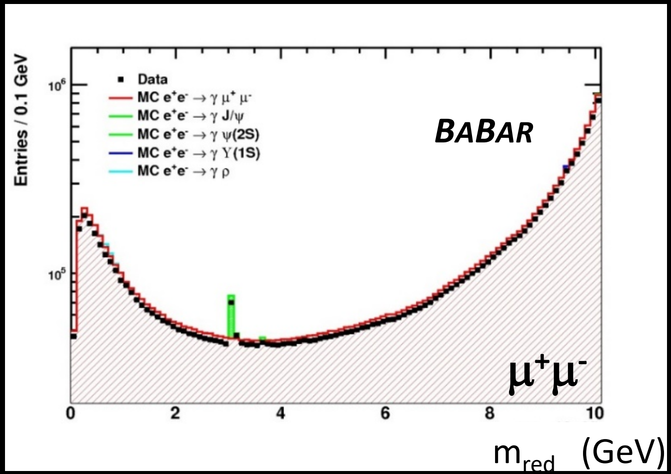


Search for a narrow resonance over large QED background:

- 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



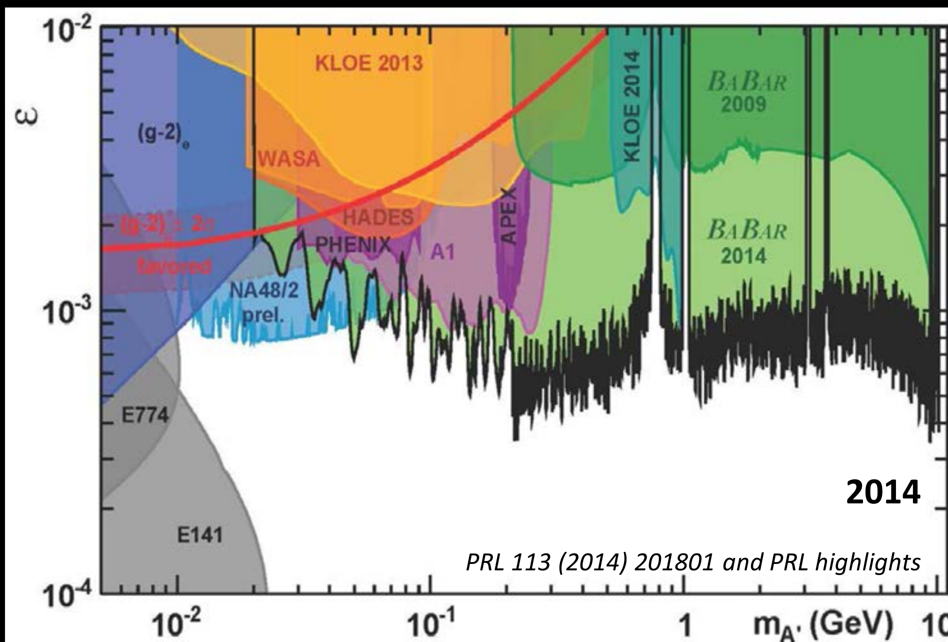


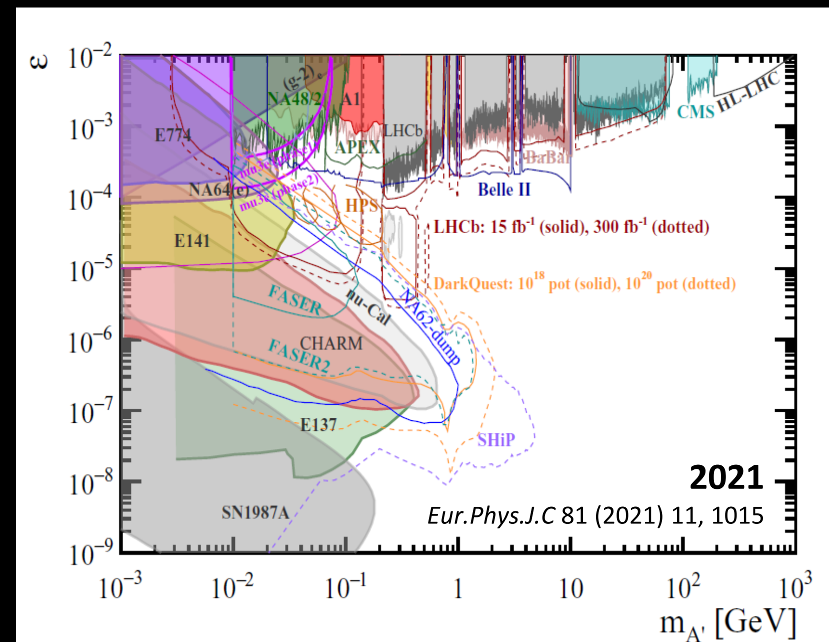
Visible dark photon decays

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)



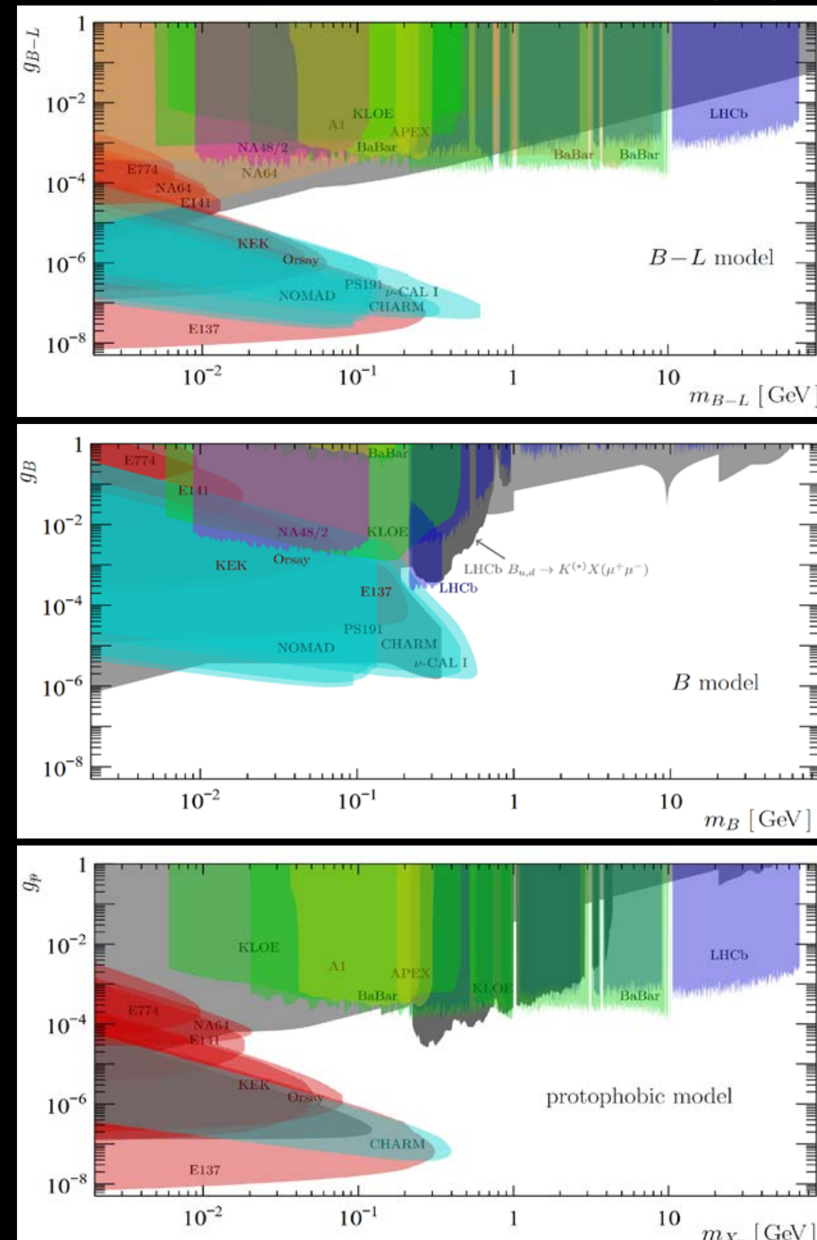


Improved constraints over a large range of masses

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 $i,j=e,\mu,\tau$

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

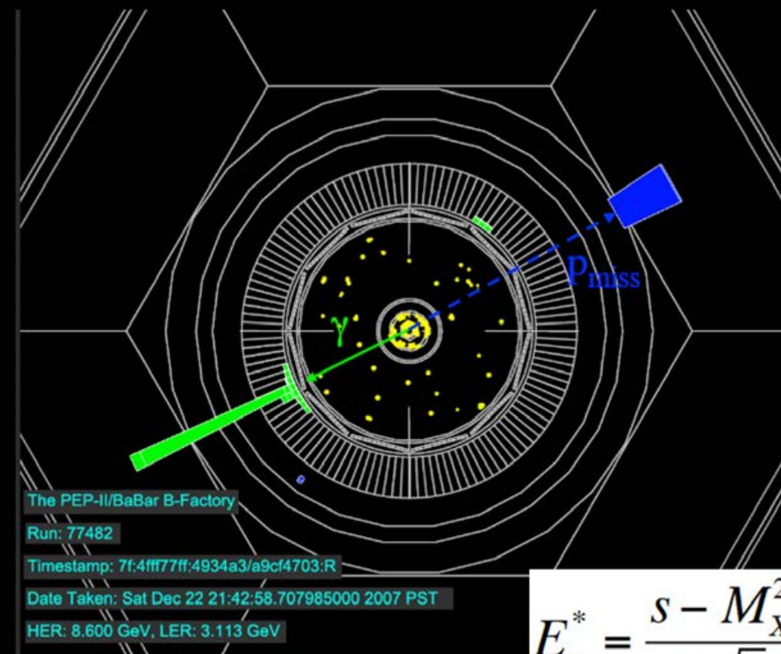
Invisible dark photon decays

PRL 119, 131804 (2017)

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



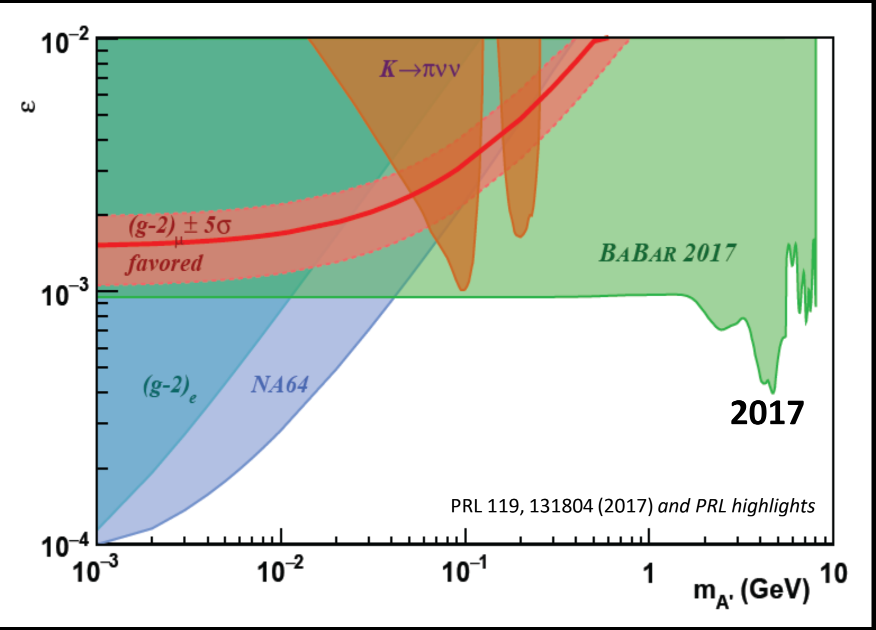
$$E_\gamma^* = \frac{s - M_X^2}{2\sqrt{s}}$$

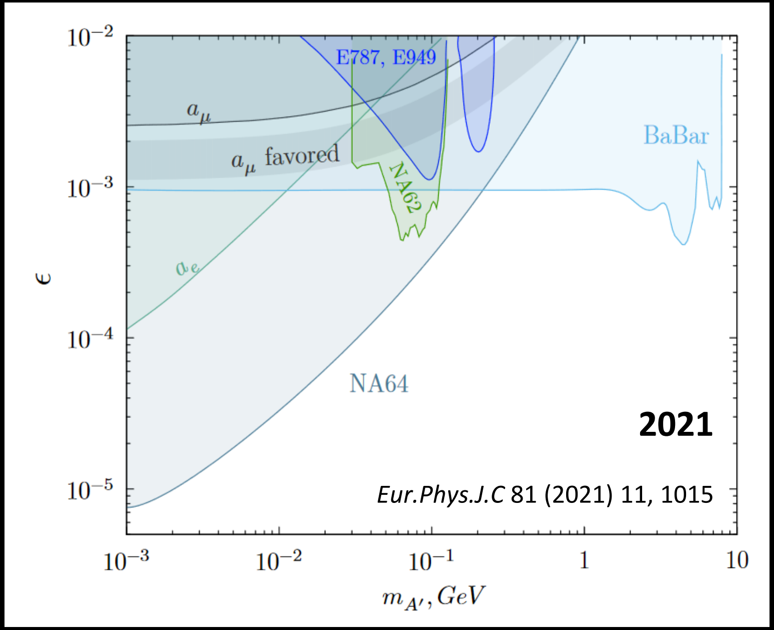
Invisible dark photon decays

PRL 119, 131804 (2017)

Search for $e^+e^- \to \gamma A'$, $A' \to$ 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

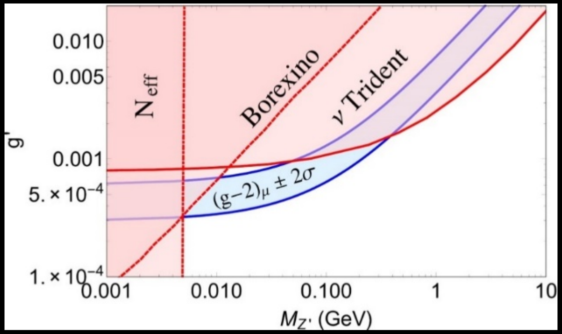
Muonic dark force: a new force coupling only to the second and third generation of leptons with a corresponding gauge boson Z’

Such a force could explain various anomalies observed in the muon sector (“g-2” discrepancy, proton radius puzzle), and account for dark matter as sterile neutrinos by increasing their cosmological abundance via new interactions with SM neutrinos

Some constraints from neutrino physics have already been derived, but they only indirectly probe the existence of Z’ (with large systematics)

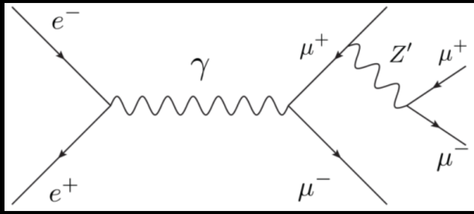
Searches for a muonic dark force at BABAR via Z’-strahlung :

“Current” constraints on Z’

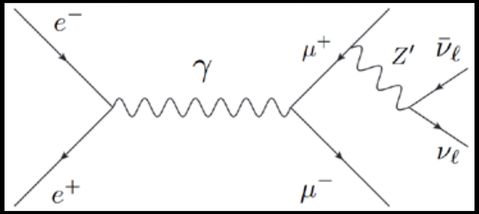


PRD 89 (2014) 113004

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



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

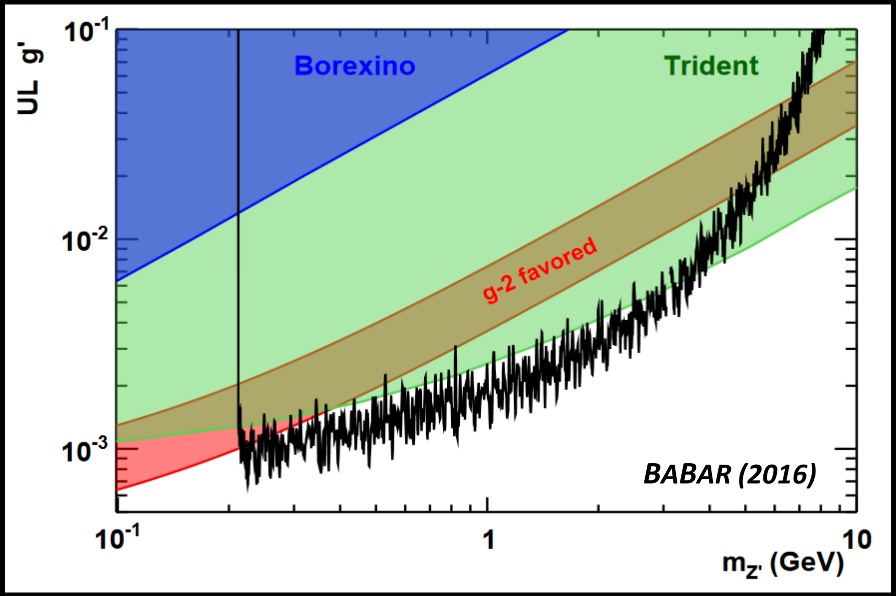


Muonic dark force

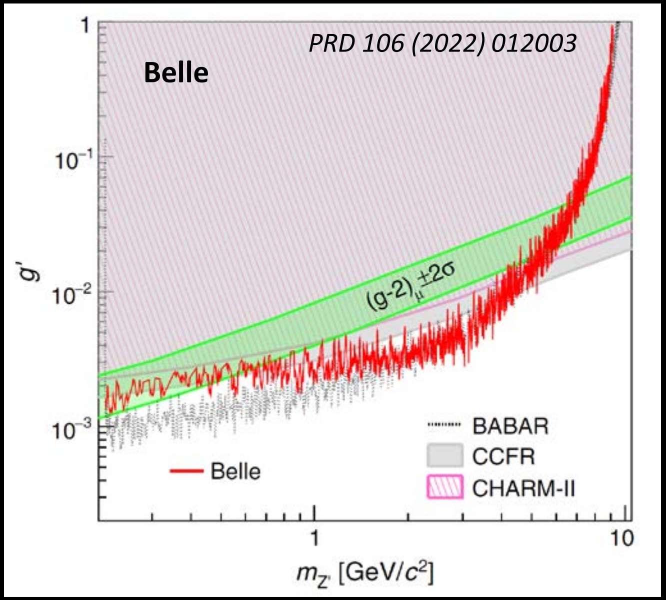
PRD 94 (2016) 011102

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

Also search for invisible Z’ decays at Belle-II

DARK SCALAR

DARK HIGGS BOSON & LEPTOPHILIC SCALAR

Dark Higgs boson

PRL 108 (2012) 211801

Search for dark Higgs boson h'

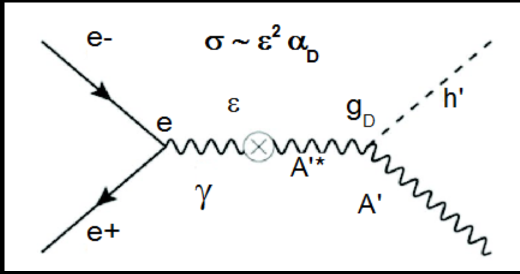
Dark photon mass is generated via the Higgs mechanism, adding dark Higgs boson(s) to the dark sector content

Can be produced via Higgsstrahlung process via $e^+e^- \to A'^* \to h' A'$

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

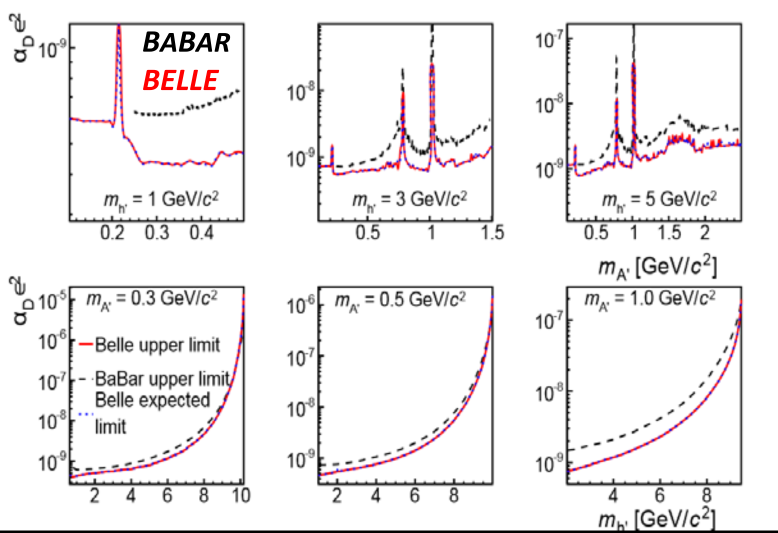
Search for visible h' decays at B*ABAR*:
$e^+e^- \to A'^* \to h' A', h' \to A' A', A' \to l^+l^-, \pi^+\pi^-$

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

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



Belle Collaboration, PRL 114 (2015) 211801
BABAR Collaboration, PRL 108 (2012) 211801

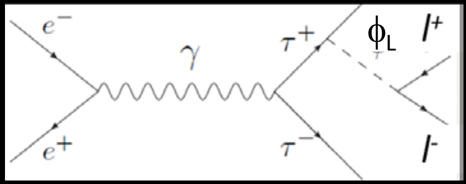
Leptophilic dark scalar

PRL 125 (2020) 181801

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

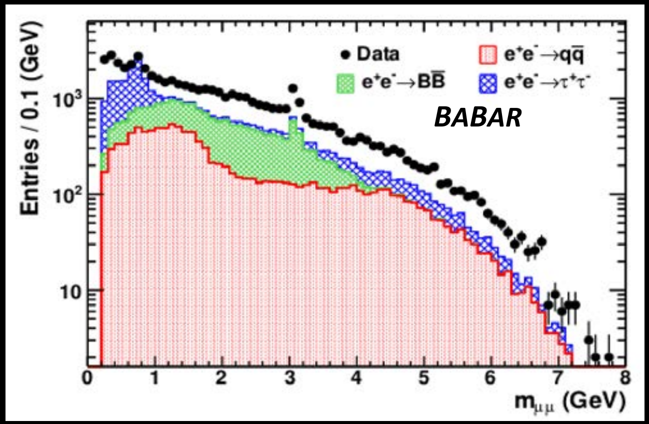
More generally, a new light gauge singlet could directly mix with the Higgs boson via the scalar portal

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

Final dimuon mass distribution

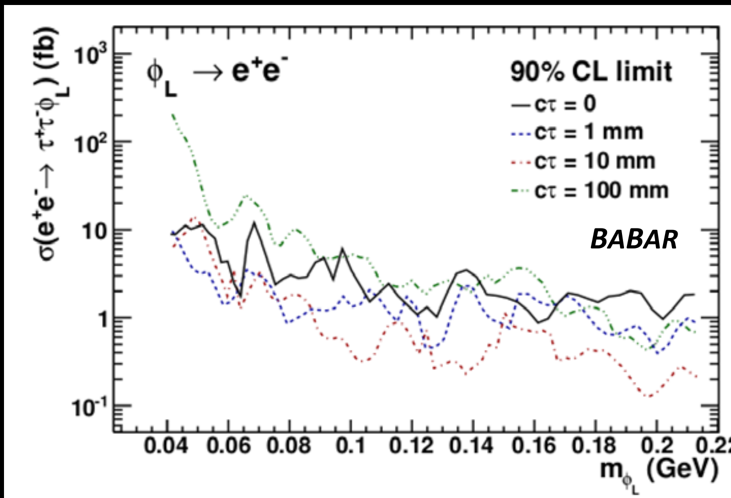


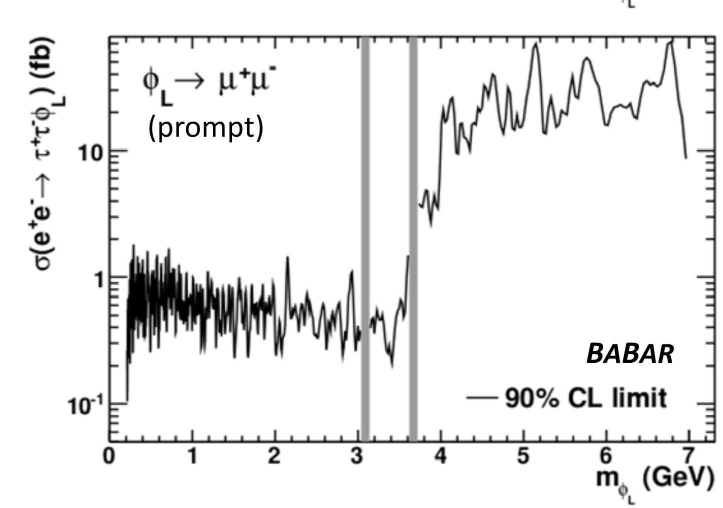
Search for $e^+e^- \to \tau^+\tau^- \phi_L$, $\phi_L \to l^+l^-$ (l=e,μ), final state $\phi_L \to \tau^+\tau^-$ has too many neutrinos to provide competitive constraints

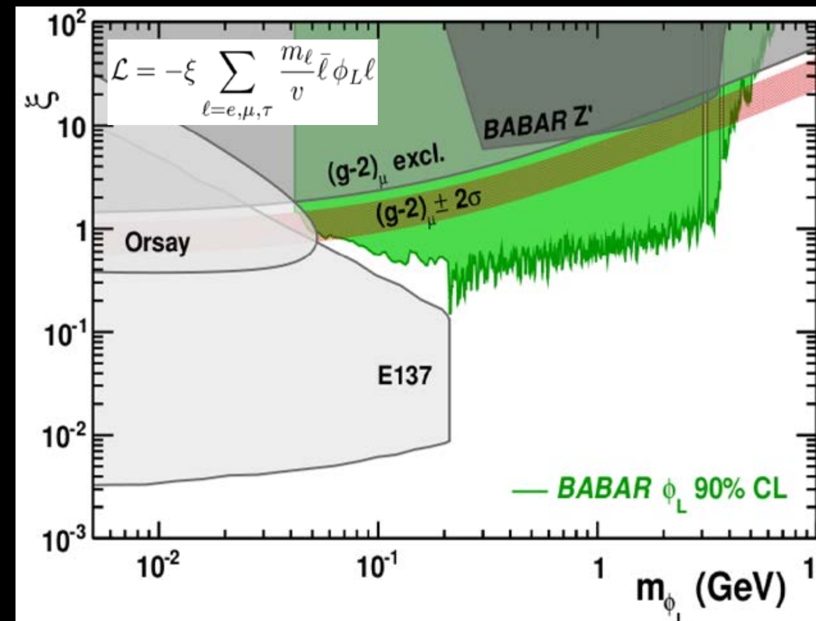
Leptophilic dark scalar

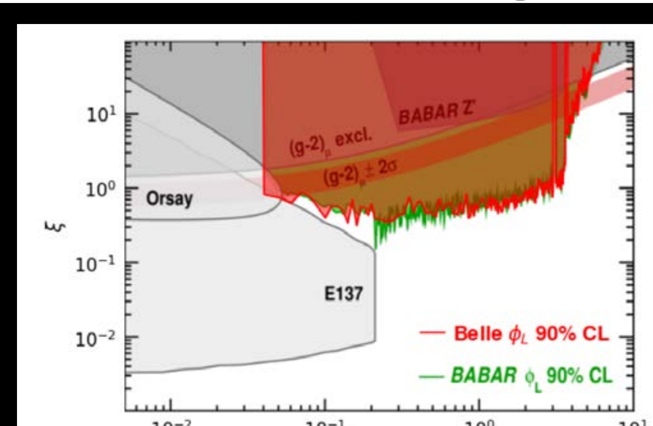
PRL 125 (2020) 181801

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









2207.07476

SELF-INTERACTING DARK MATTER

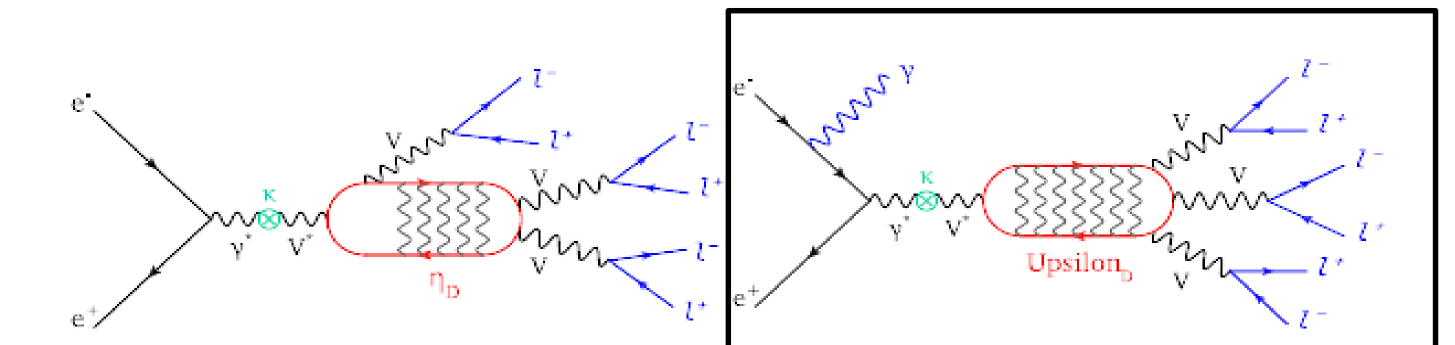
MINIMAL DARK SECTOR MODEL

Self-interacting dark matter

A minimal dark sector scenario

- Dark sector with a dark fermion (χ) 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 ($\chi\overline{\chi}$) could form a bound state $\rightarrow$ darkonium
- The two lowest-energy bound states are denoted η_D ($J^{PC} = 0^{++}$) and Υ_D ($J^{PC} = 1^{--}$), in analogy with SM
- Two main production mechanisms at e^+e^- colliders:

$$e^+e^- \rightarrow A'\,\eta_D,\ \eta_D \rightarrow A'\,A' \text{ and } e^+e^- \rightarrow \gamma\Upsilon_D,\ \Upsilon_D \rightarrow A'\,A'\,A'$$



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

Search overview

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

Analysis overview

- Final state consist of three pairs of oppositely-charged leptons or pions. Events must contain at least an electron or muon pair to reduce the large QCD background.
- 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
- For dark photon masses below 200 MeV, we can probe values of the kinetic mixing strength corresponding to large A' lifetime, leading to displaced vertices

  $\to$ perform analysis for prompt and displaced decays. Displaced analysis is performed for A' lifetimes corresponding to $c\tau$= 0.1mm, 1mm and 10mm, and the results are interpolated between these lifetimes.

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

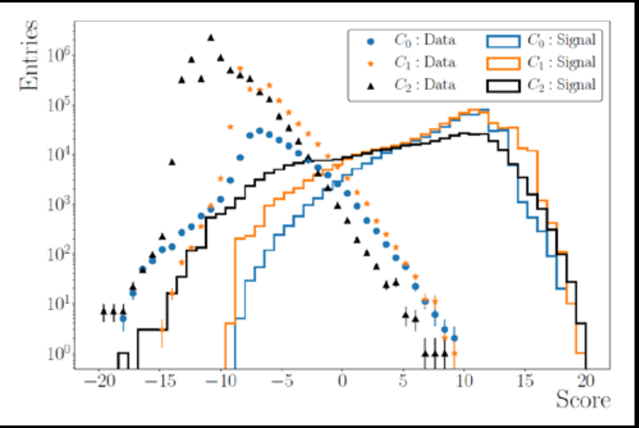
- the mass difference between the A’ candidates
- the mass difference between same-sign pairs
- the quality of the kinematic fit
- combined PID information
- the system recoiling against the Y_D candidate
- the energy of the ISR photon, if emitted inside the calorimeter
- extra neutral energy, excluding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

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

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

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	$1e^+e^-2\pi^+\pi^-$
	$1\mu^+\mu^-2\pi^+\pi^-$

Classifier score (prompt decays)

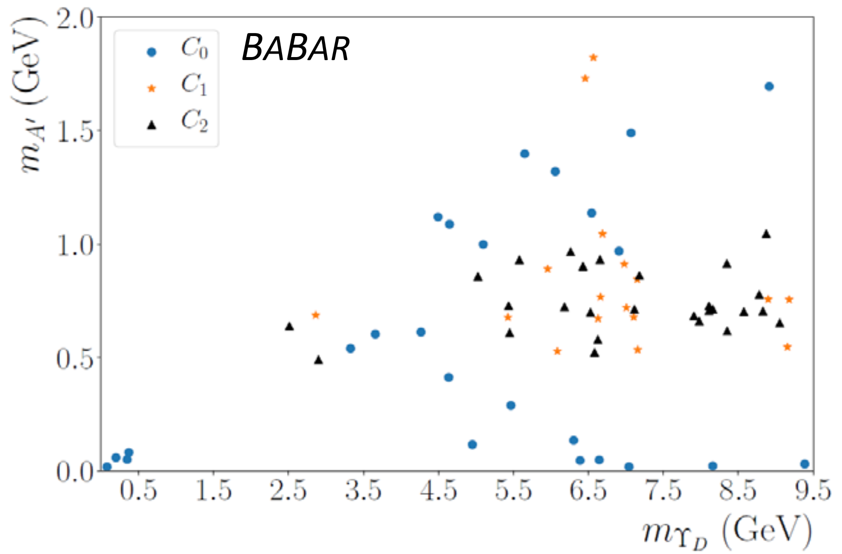


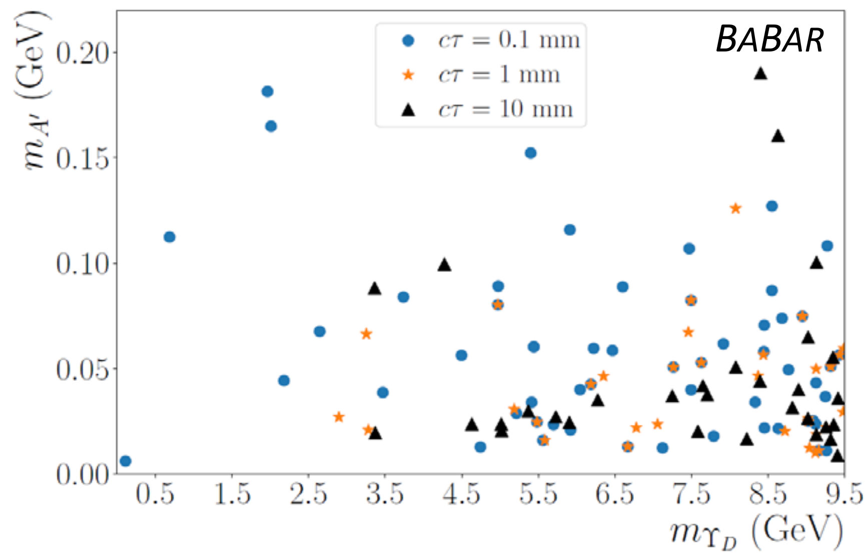
Mass distributions

Dark photon and dark Upsilon mass distributions

Prompt

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





Main backgrounds arise from

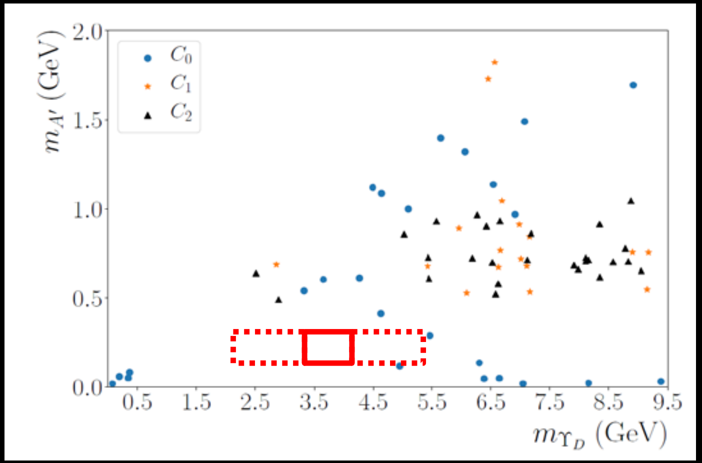
$e^+e^- \to \gamma\gamma\gamma$, $\gamma \to ee$ at low A' masses

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

Signal extraction

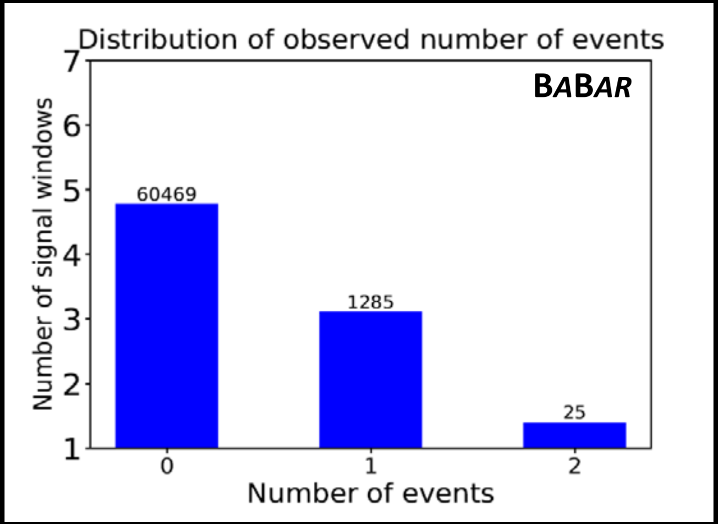
Scan the Υ_D – A' mass plane to extract the signal as a function of the A' and Υ_D masses

- 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

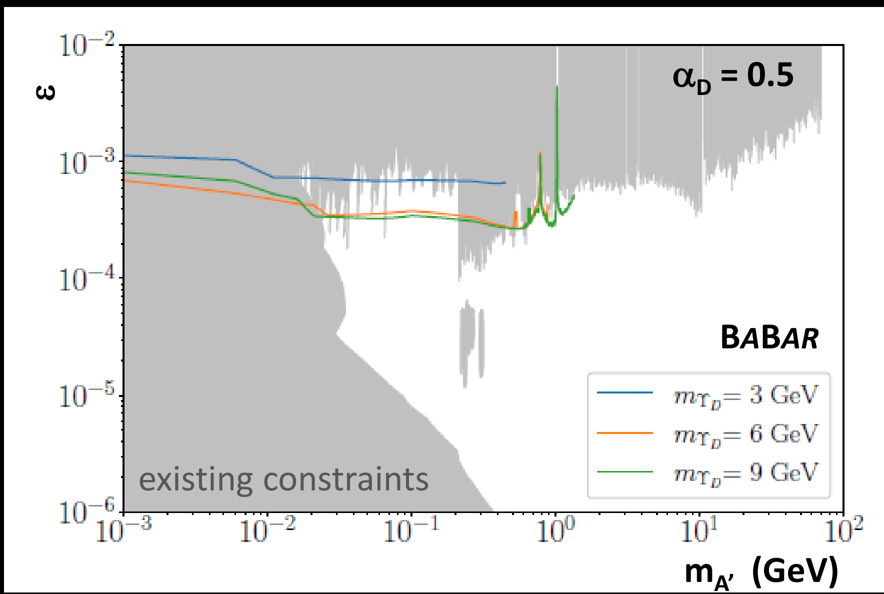
The distributions for displaced decay vertices are also all compatible with the null hypothesis

Self-interacting dark matter

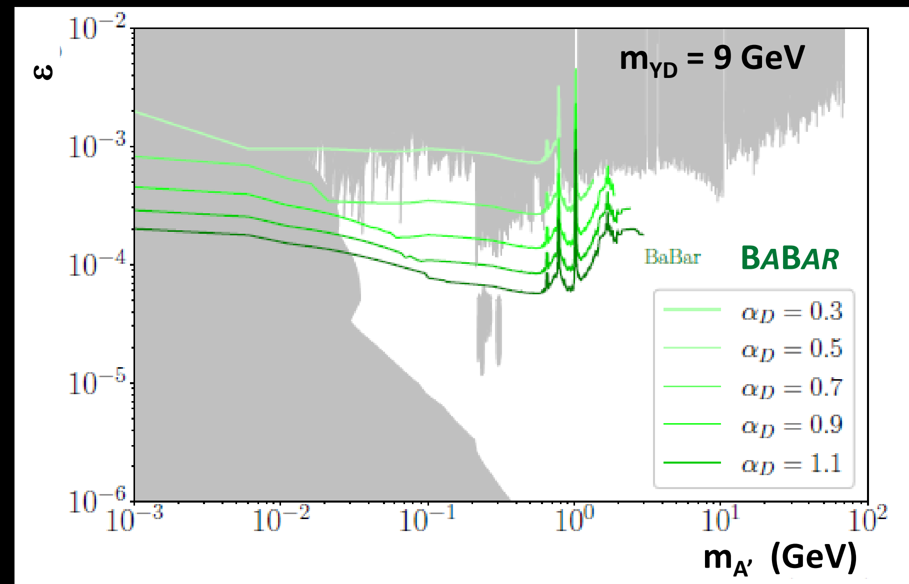
PRL 128 (2022) 021802

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

Constraints on ε for $\alpha_D = 0.5$



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 leptophobic B boson

Search for a dark vector gauge boson decaying to $\pi^+\pi^-$ using $\eta \to \gamma\, \pi^+\pi^-$, PRD 94 (2016) 092006

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

Search for dark Higgs boson h’

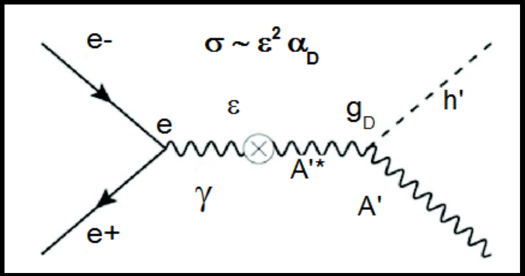
Dark photon mass is generated via the Higgs mechanism, adding dark Higgs boson(s) to the dark sector content

Can be produced via Higgsstrahlung process

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

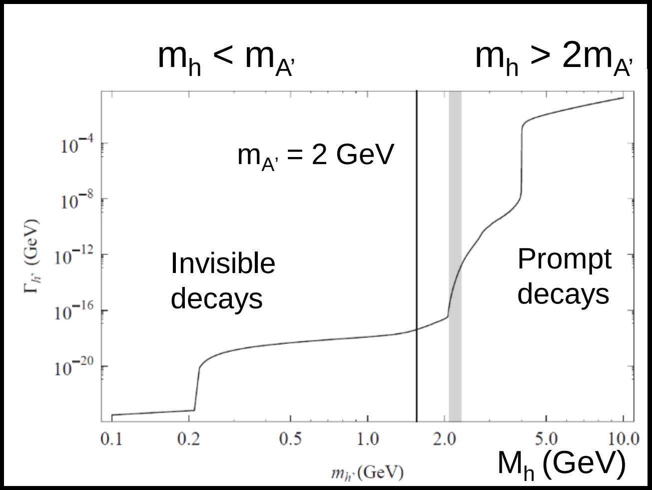
Process is only suppressed by ε^2 and sensitive to the dark sector coupling constant $\alpha_D = g_D^2 / 4\pi$.

Decay topology depends on the dark Higgs and dark photon masses: either invisible (KLOE) or visible ($h' \rightarrow A' A'$ at B*A*B*AR*, Belle)



$\alpha_D = g_D^2 / 4\pi$
g_D is the dark sector gauge coupling

Dark Higgs decay topology



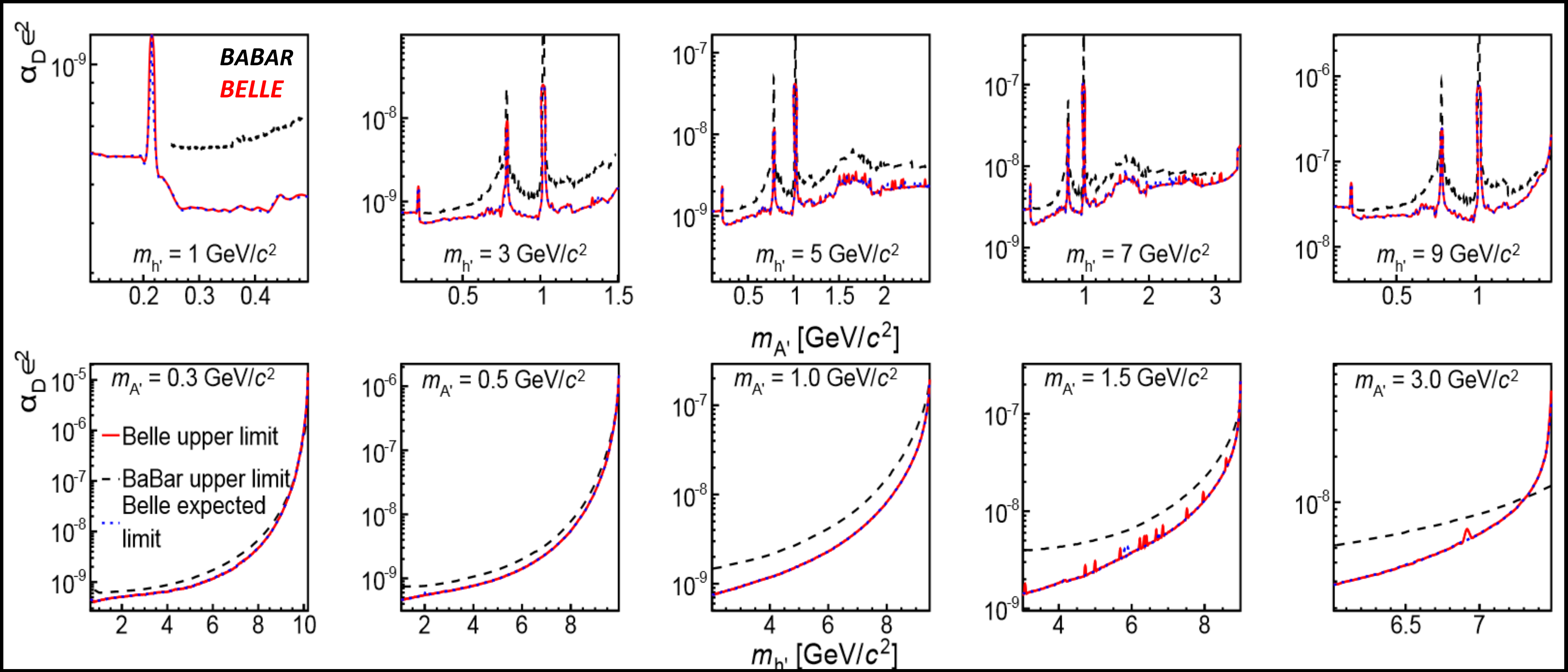
B. Batell et al., PRD 79 (2009) 115008
R. Essig et al., PRD 80 (2009) 015003

> Search for prompt h’ decays at *BABAR / Belle*:
> $e^+e^- \rightarrow A'^* \rightarrow h' A', h' \rightarrow A' A', A' \rightarrow l^+l^-, \pi^+\pi^-$

Dark Higgs boson

Belle Collaboration, PRL 114 (2015) 211801
BABAR Collaboration, PRL 108 (2012) 211801

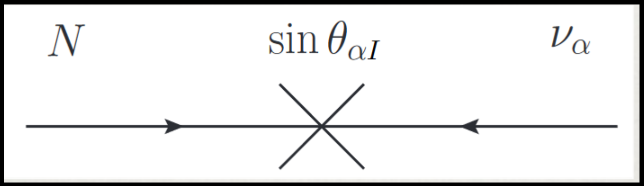
No significant signal observed, set limits on the product $\alpha_D \varepsilon^2$



On-going search for invisible dark Higgs decays at Belle II

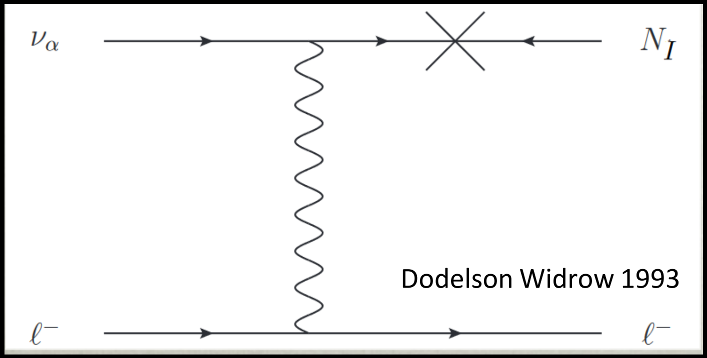
Sterile neutrino dark matter

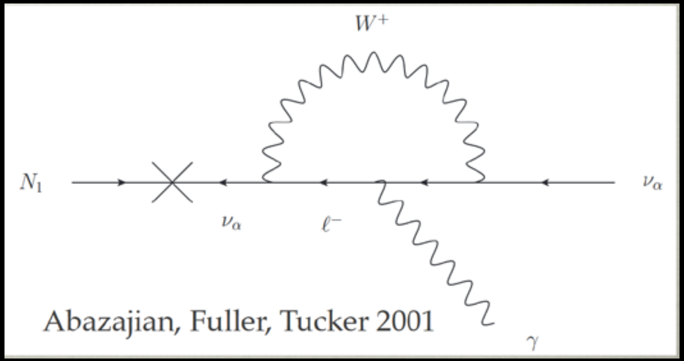
Dark matter model of sterile neutrino N (SM gauge singlet). After EWSB, Standard Model neutrinos get a (small) mass and the SM & sterile neutrino mix



$$\sin\theta_{\alpha I} = \frac{F_{\alpha I}\langle H\rangle}{M_N}$$

Sterile neutrino live and die by this mixing

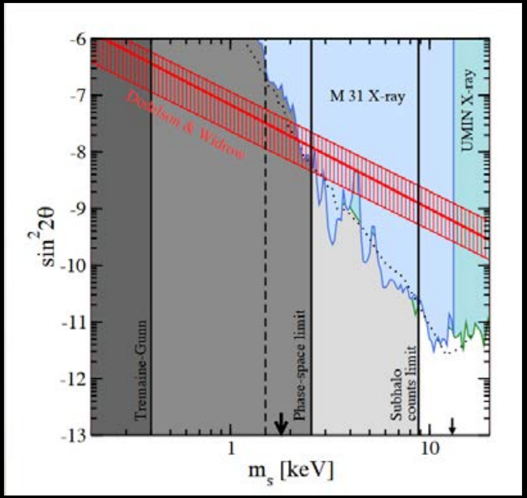




Can the mixing angle be large enough to produce enough sterile neutrinos to account for dark matter and small enough to suppress decays?

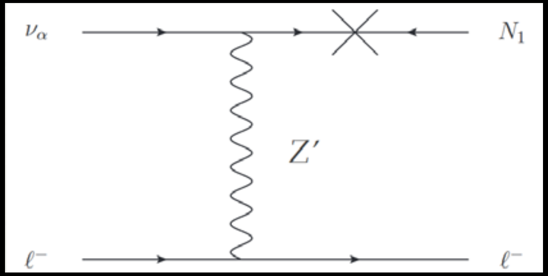
Sterile neutrino dark matter

Constraints from astrophysics (monochromatic x-ray line from N $\rightarrow \gamma\nu$ decays and small scale structures) imply that the mixing angle is too small to produce the observed relic density

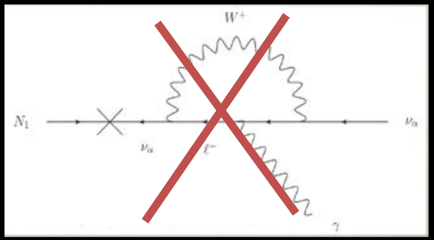


Horiuchi *et al.* 2013

BUT, a new neutral interaction coupling to leptons and neutrinos could boost the sterile N production without increasing the decay



New dark force coupling to 2nd / 3rd generation of leptons (Lμ-Lτ, anomaly free). The corresponding gauge boson Z' must be light – O(GeV) or less – to avoid constraints from magnetic dipole measurements and provide the correct rate enhancement

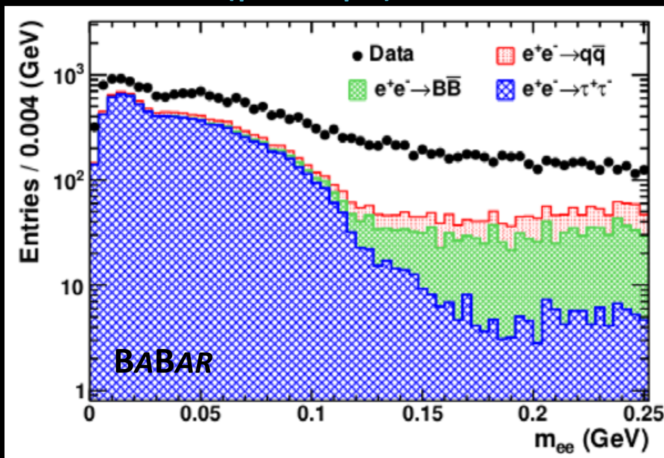


Z' decays to muons, taus and neutrinos when kinematically accessible

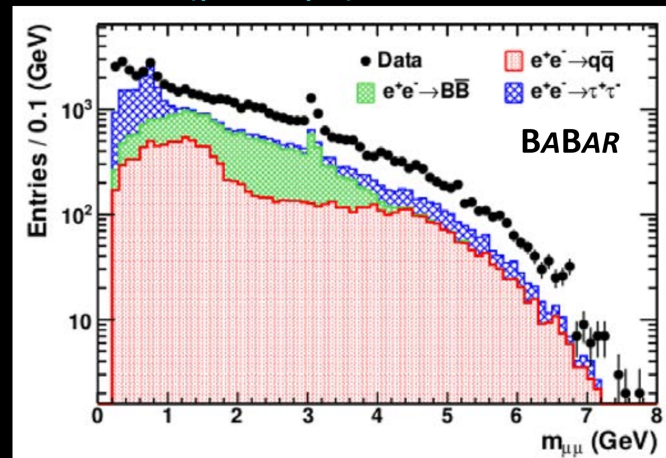
Leptophilic dark scalar

Final mass spectra for each final state and lifetime

Dielectron (prompt)



Dimuon (prompt)



Dielectron (displaced)