Searches for hidden-sector particles with BABAR

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Hidden sectors in a nutshell

What are hidden (dark) sectors

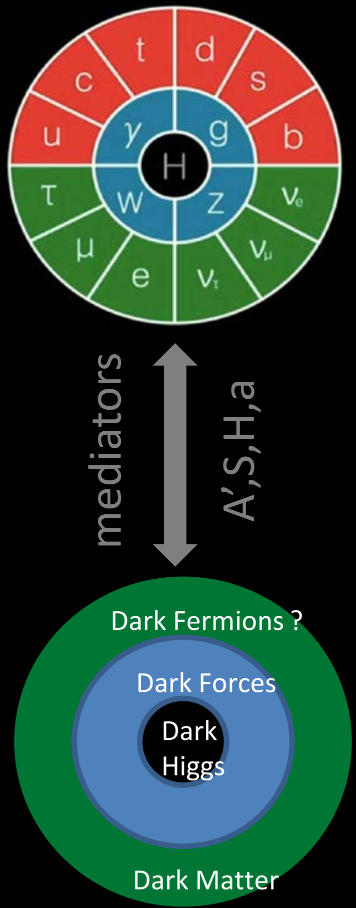
- New particle(s) that don't couple directly to the SM, but indirect interactions couple the two sectors via new mediators - see next slide

- Theoretically motivated: many BSM scenarios (e.g. EWSB) and string theory include dark sectors

- Could have rich structure - SM structure is non-trivial after all

- Realized that MeV-GeV hidden sector have very desirable properties: light dark matter candidate, explanation of CP anomaly (axion), neutrino mass (heavy neutral lepton), …

- Dark matter could reside in the hidden sector, or mediate the SM-HS interactions



Motivates broad exploration of light dark sector – not just limited to dark matter

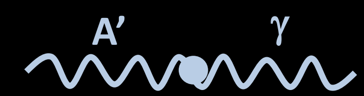
The portals

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

Dim=4

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

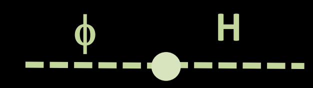
New gauge boson A' (dark photon) mixing with SM photon/Z via kinetic mixing ε



Dim=4

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

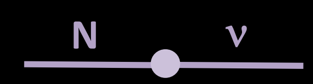
New dark scalar ϕ mixing with SM Higgs



Dim=4

Fermion
yHNL

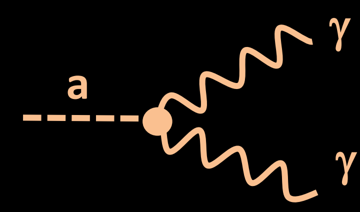
New heavy neutral lepton mixing with left-handed SM doublets and the Higgs boson



Dim=5

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

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



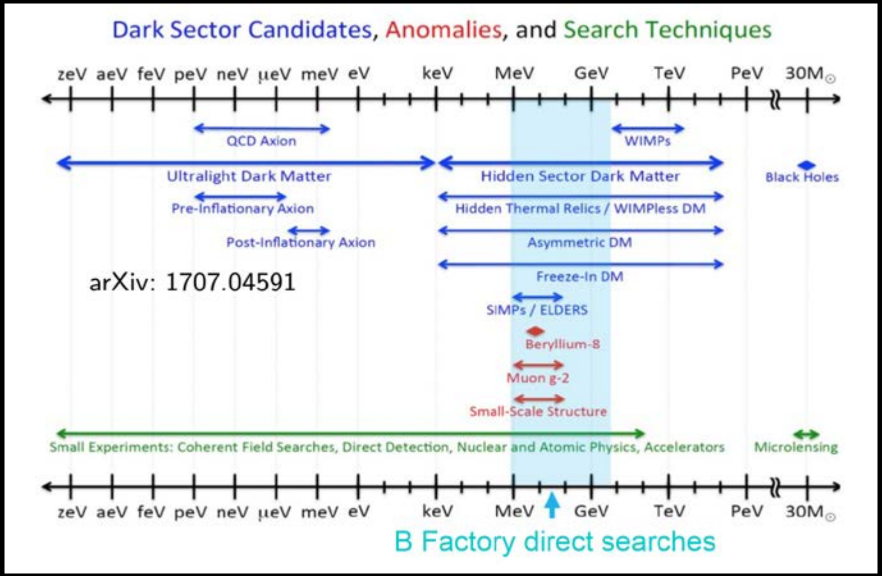
And many variations with slightly different couplings
(note: small variations can have big phenomenological impacts)

Dark sectors at B-factories

B-factories offer a clean environment to study dark sectors

- Well defined initial e+e- state
- Hermetic detector coverage (almost 4π)
- Good missing energy reconstruction
- Clean displaced vertex identification in ~1mm < $c\tau$ < 10-100cm with $c\tau$ > O(1m) being missing energy
- Inclusive trigger for multi-track (N>3) hadronic events, dedicated triggers for low-multiplicity searches

Can probe a wide variety of signatures in the MeV-GeV range, complementing other techniques and experimental approaches



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

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

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

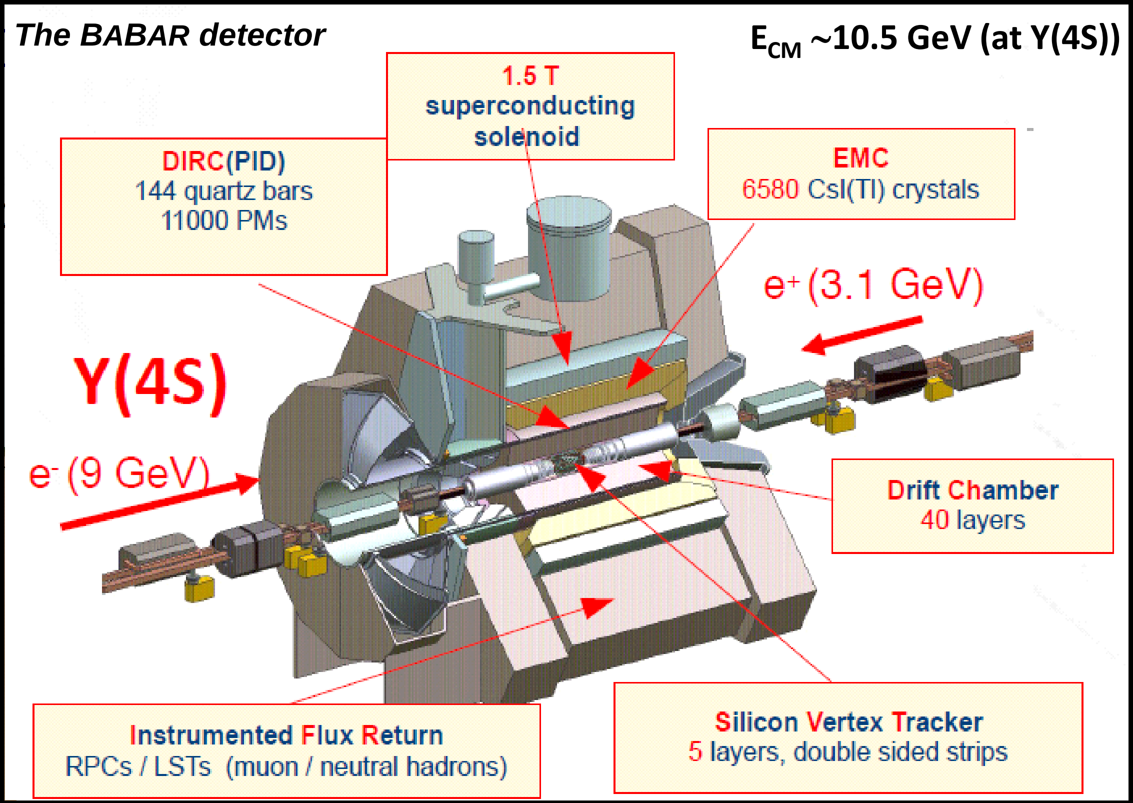
Published

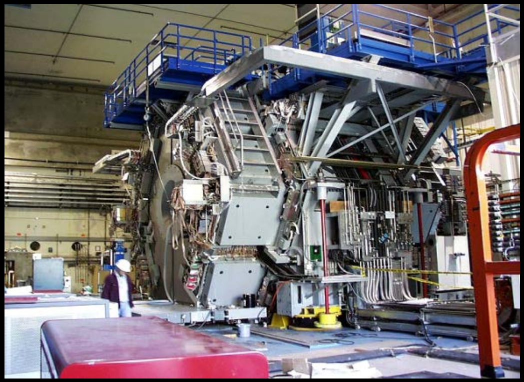
Preliminary

References in supplementary slides

The BABAR experiment

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





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

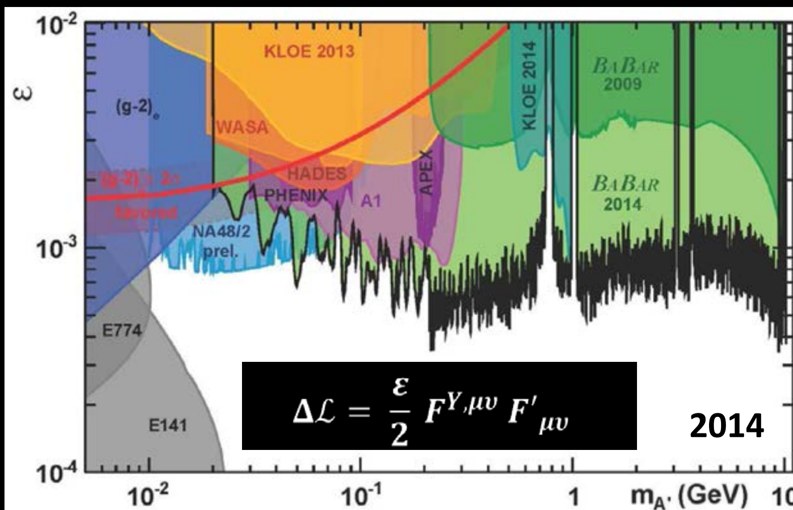
DARK BOSON

DARK PHOTON & MUONIC DARK FORCE

Dark photon searches

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

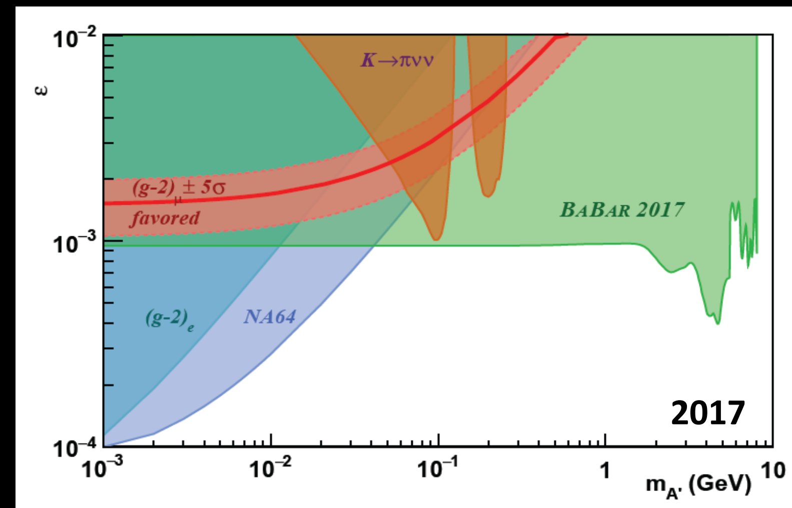
Limits on kinetic mixing parameter



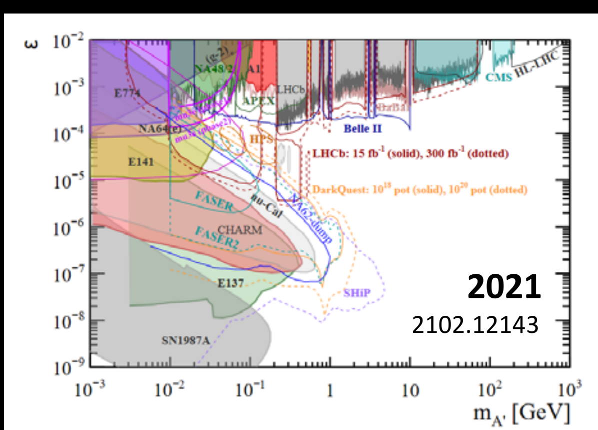
PRL 113 (2014) 201801
PRL viewpoint

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

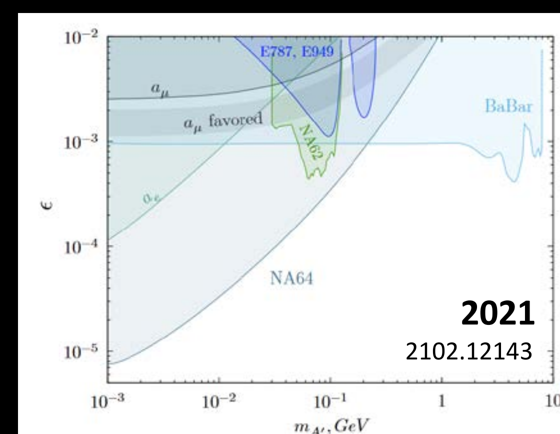
Limits on kinetic mixing parameter



PRL 119 (2017) 131804
PRL highlights

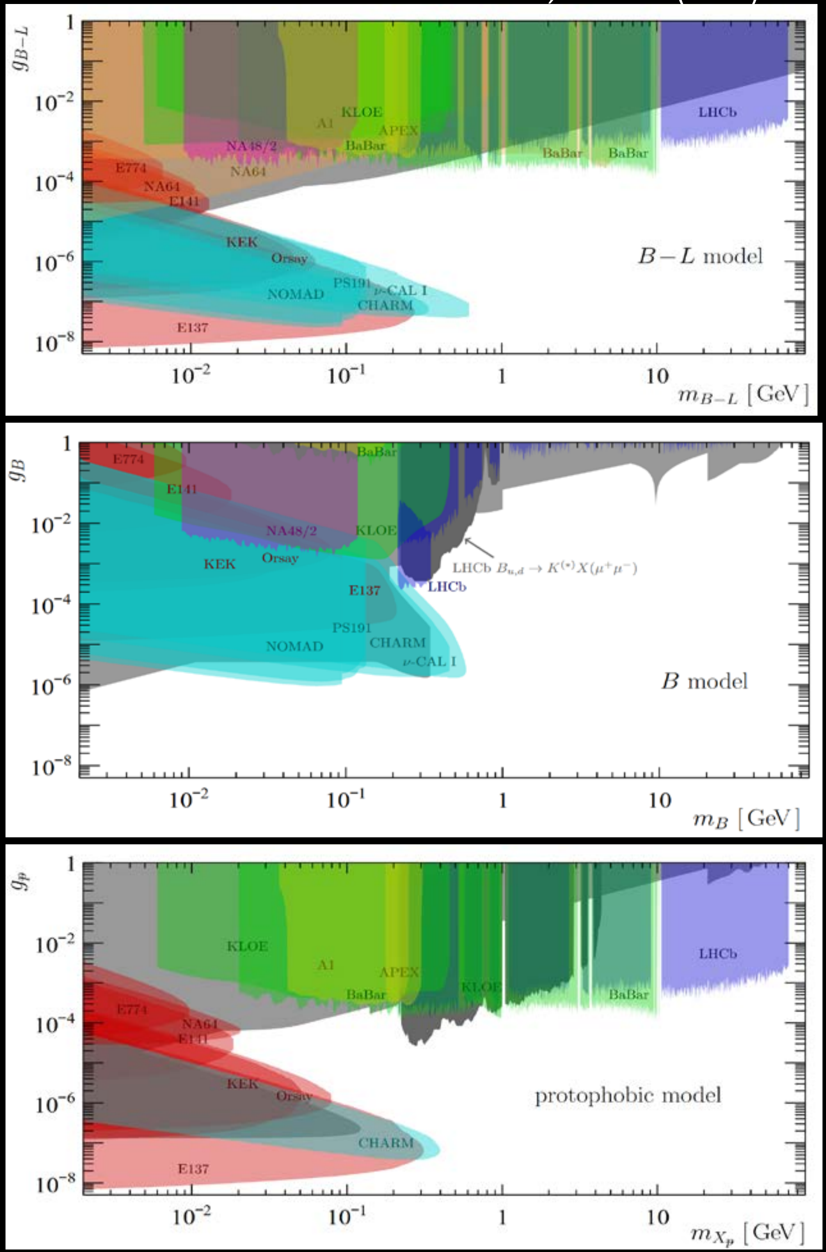


Worldwide program to further probe these possibilities



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 measurement to cover all bases

Muonic dark force

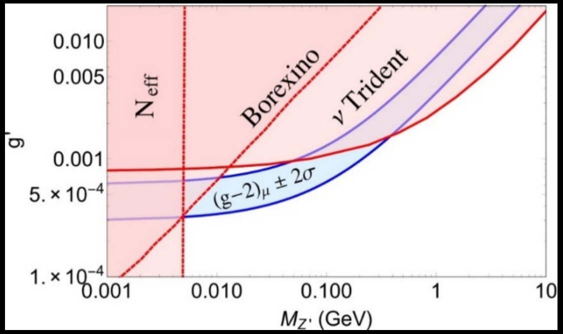
Muonic dark force: a new force coupling only to the second and third generation of leptons with a corresponding gauge boson Z'

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)

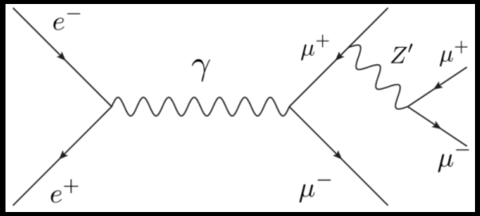
BABAR can directly search for a muonic dark force at colliders via Z'-strahlung :

Current constraints on Z'

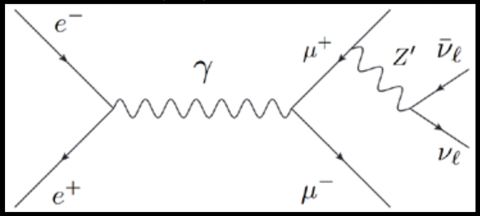


PRD 89 (2014) 113004

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



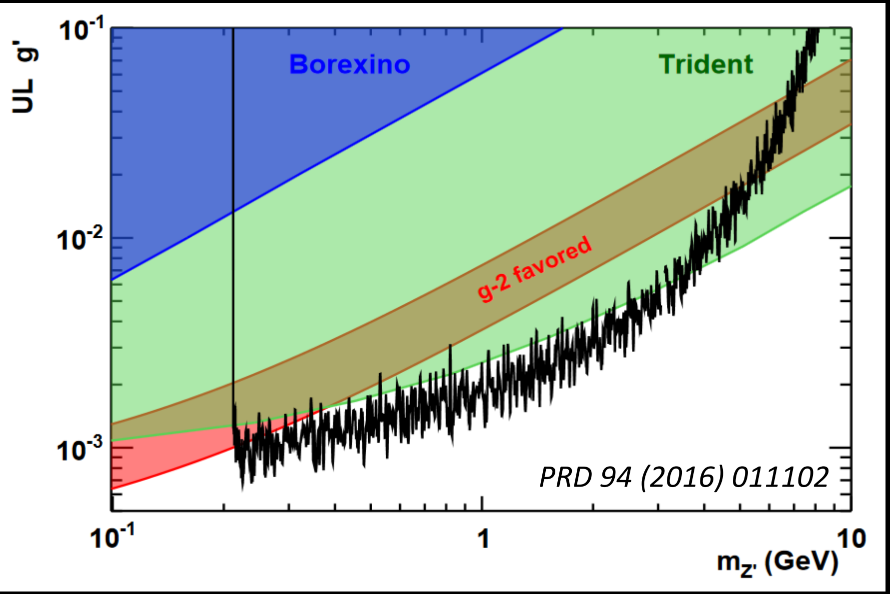
$e^+e^- \to \mu^+\mu^-$ Z', Z' $\to \nu\bar{\nu}$



Muonic dark force

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

Limits (90% CL) on Z’ coupling

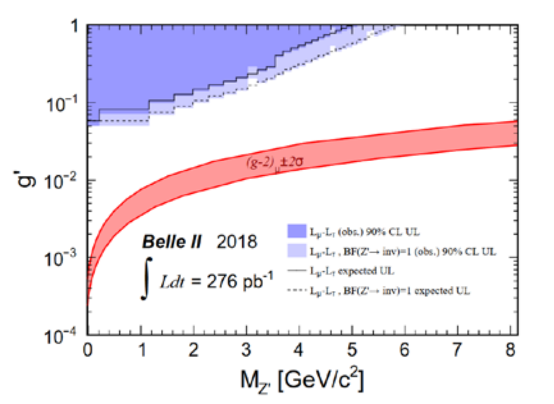


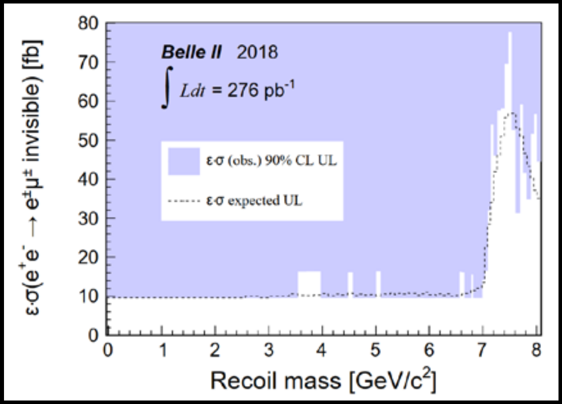
First direct measurement, improves upon previous bounds

Further exclude region favored by the g-2 anomaly

Search for invisible and LFV Z’ decays at Belle II with 276 pb^{-1} of data

PRL 124 (2020) 141801





Full Belle II dataset should be able to significantly improve

DARK SCALAR

DARK HIGGS BOSON & LEPTOPHILIC SCALAR

Dark Higgs boson

Search for dark Higgs boson h'

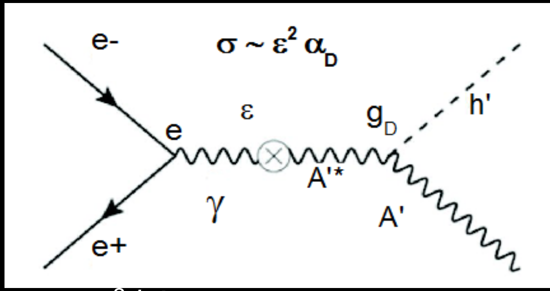
- Dark photon mass is generated via the Higgs mechanism, adding dark Higgs boson(s) to the dark sector content

- Can be produced via Higgsstrahlung process

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

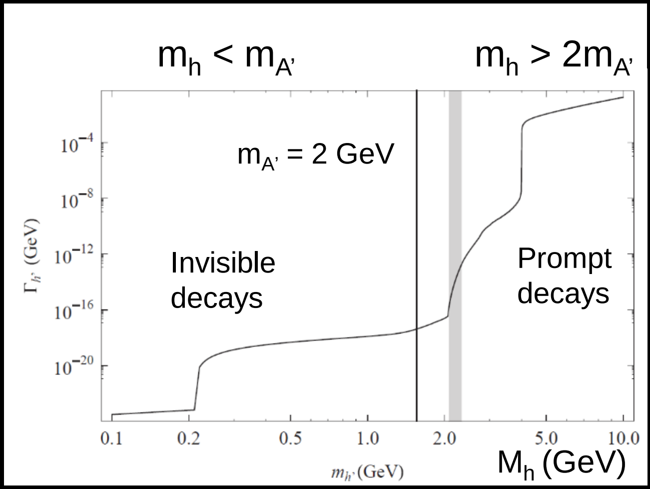
- Process is only suppressed by ε^2 and sensitive to the dark sector coupling constant $\alpha_D = g_D^2 / 4\pi$.

- 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



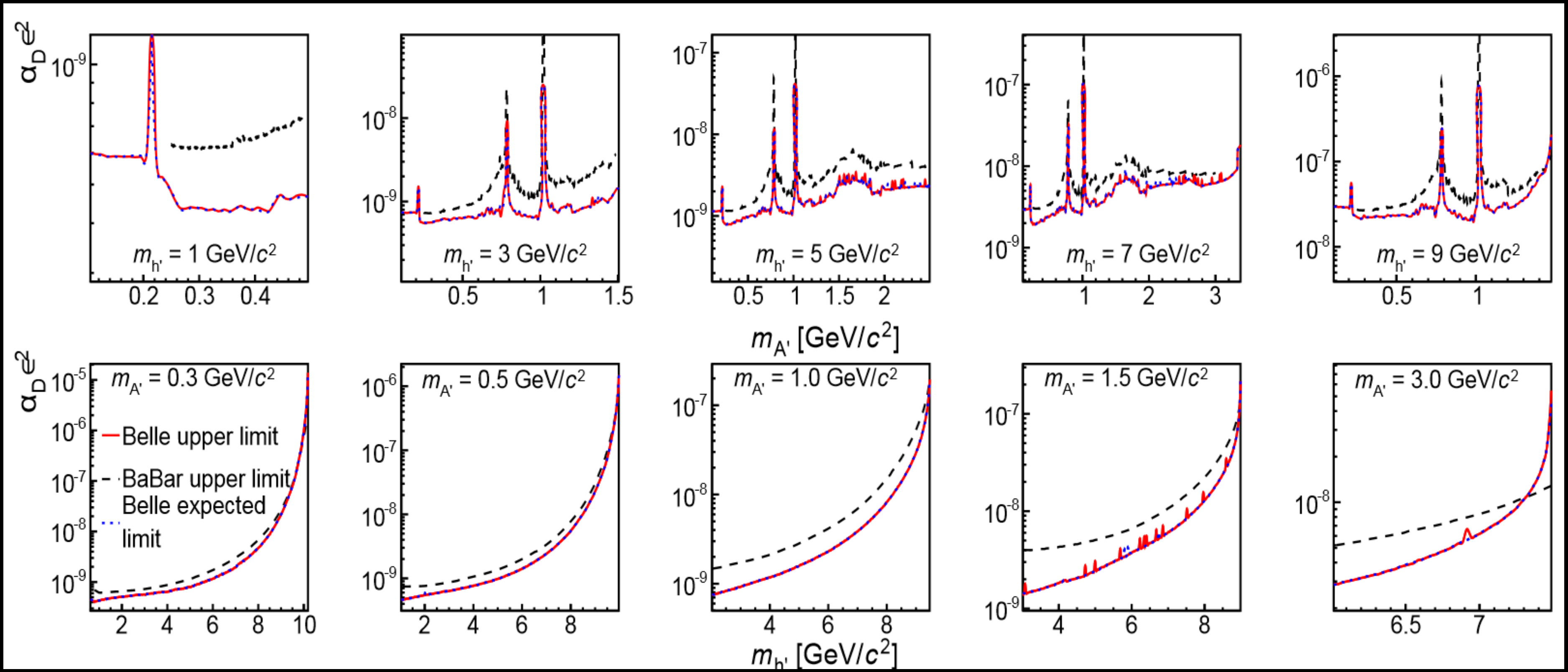
B. Batell et al., PRD 79 (2009) 115008
R. Essig et al., PRD 80 (2009) 015003

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

Dark Higgs boson

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

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



Limits on kinetic mixing ε^2 slightly better than direct production for α_D = 1/137

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

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.

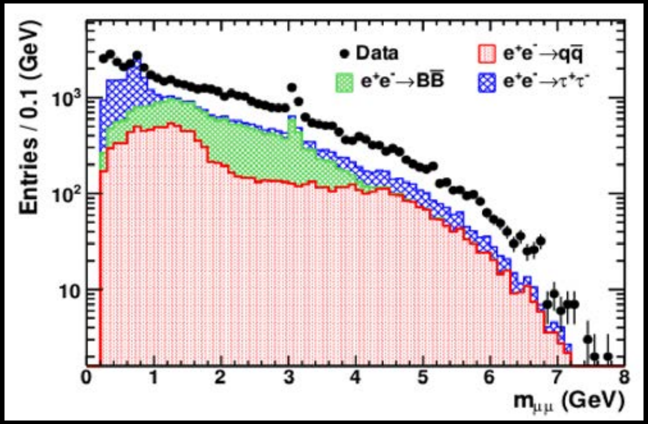
A new leptophilic scalar interacting mainly with leptons rather than quarks could escape the current constraints and explain the g-2 anomaly (1606.04943, 1605.04612) and the KOTO excess (2001.06522)

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

Analysis strategy

- Consider all 1-prong decays of the tau
- Train BDT to increase signal purity
- 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

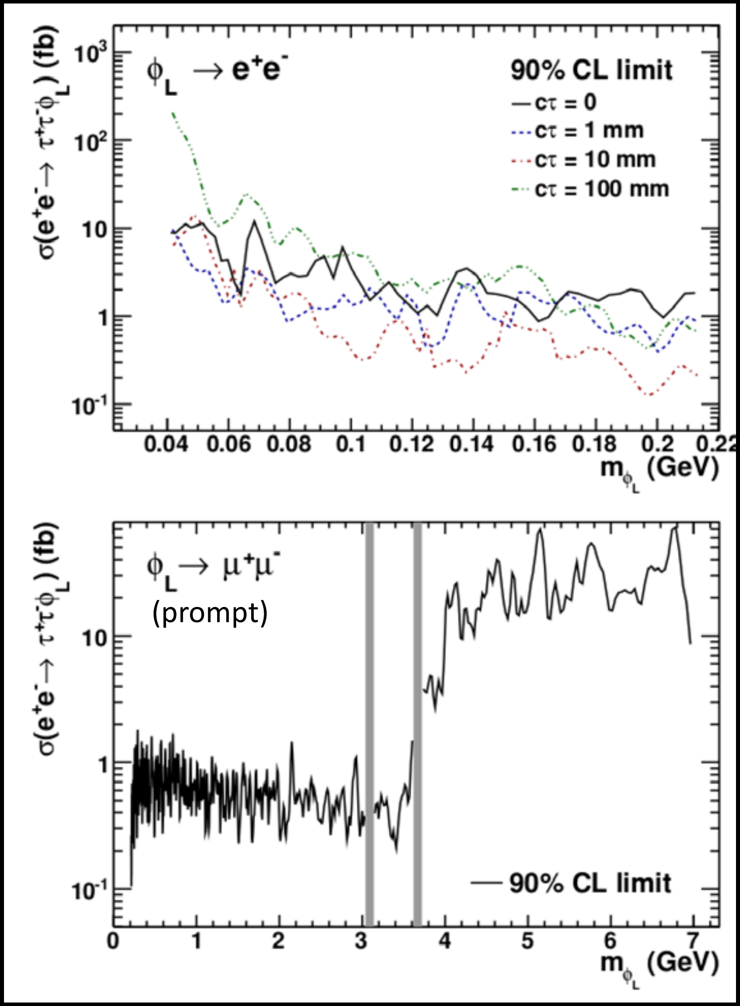
Final dimuon mass distribution

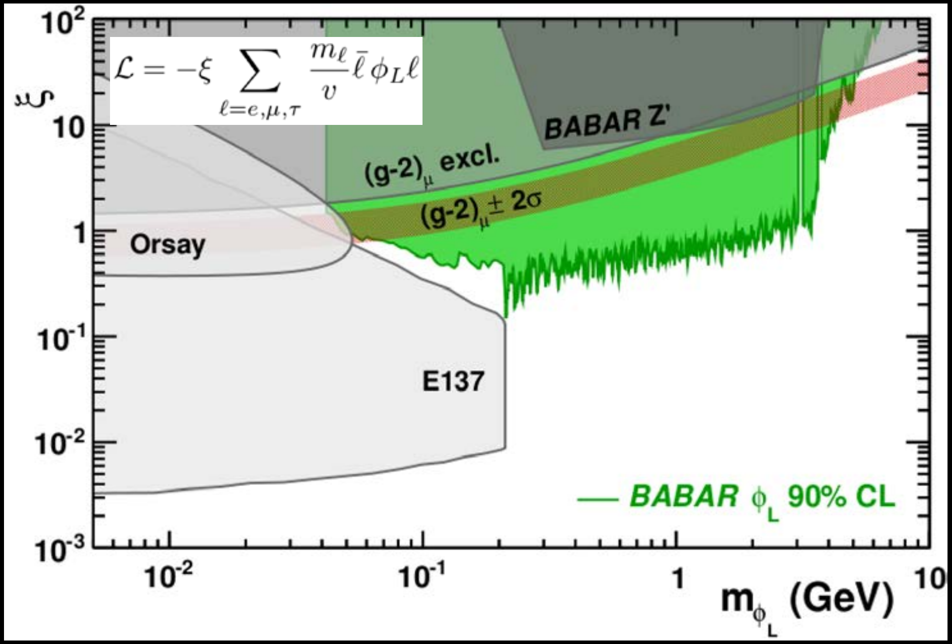


Leptophilic dark scalar

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

PRL 125 (2020) 181801





Significant improvement over previous bounds

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

Belle II should be able to further improve

AXION

AXION-LIKE PARTICLE IN B DECAYS

Axion like particle (ALP)

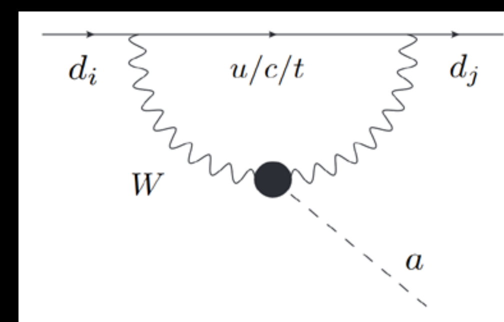
What are axion like particles

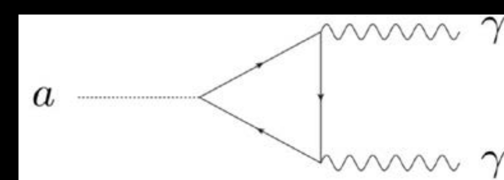
- Pseudo-Goldstone bosons ubiquitous in BSM physics, coupling predominantly to pair of bosons with non-renormalizable coupling constant suppressed by some heavy scale
- Low-mass ALP can mediate dark sector – standard model interactions
- Most searches at low energies focus on photon or gluon couplings 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 lifetime becomes important at low masses and couplings ($\tau \sim 1/m_a^3 g_{aW}^2$) $\rightarrow$ long-lived axion

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





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

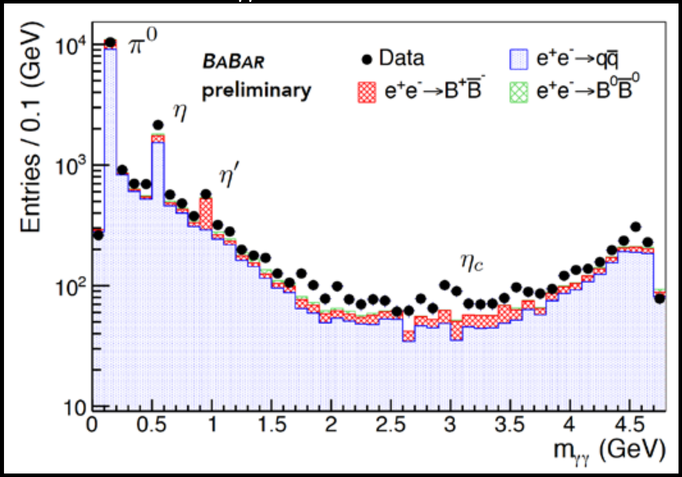
Axion like particle (ALP)

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

Analysis strategy

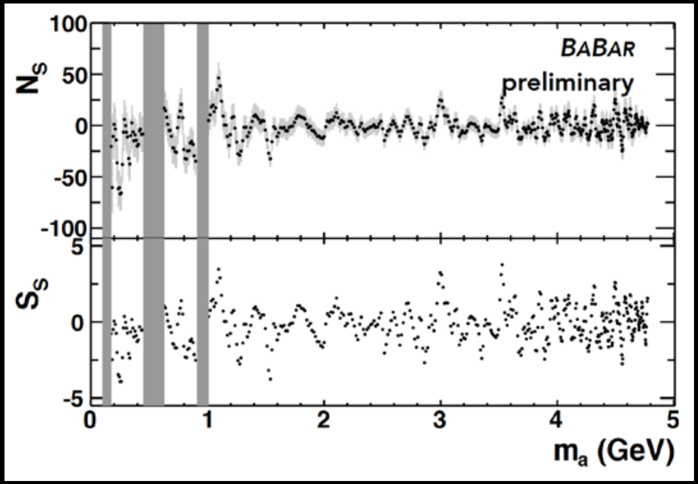
- Combine well-identified K with two photons to form B candidate
- Apply kinematic fit to improve axion mass resolution
- Train 2 BDTs to separate signal from $e^+e^- \to q\bar{q}$ (q=u,d,s,c) and $e^+e^- \to B\bar{B}$ backgounds
- Extract signal as a function of axion mass with fits of a mass peak over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

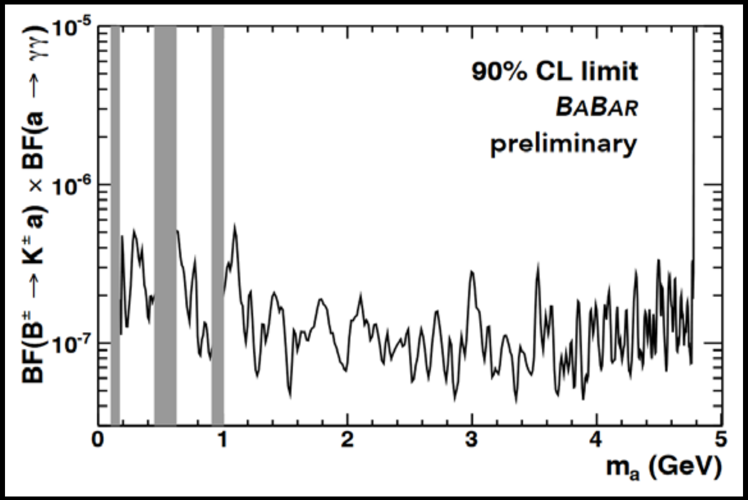


No significant signal is observed

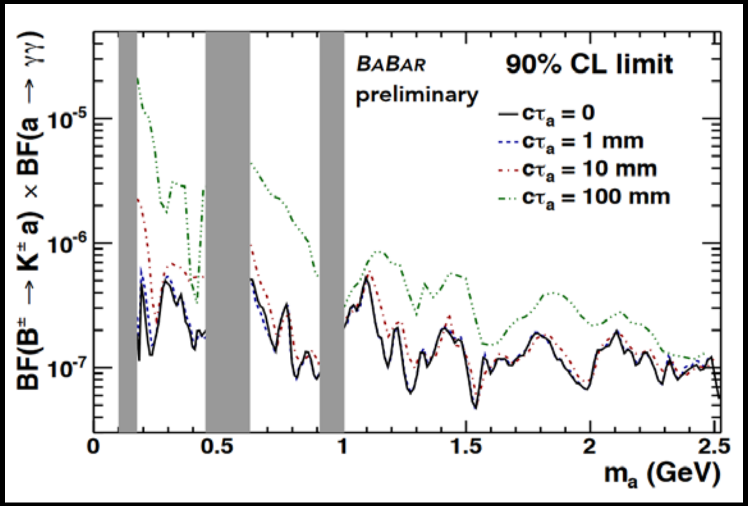
Axion like particle (ALP)

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

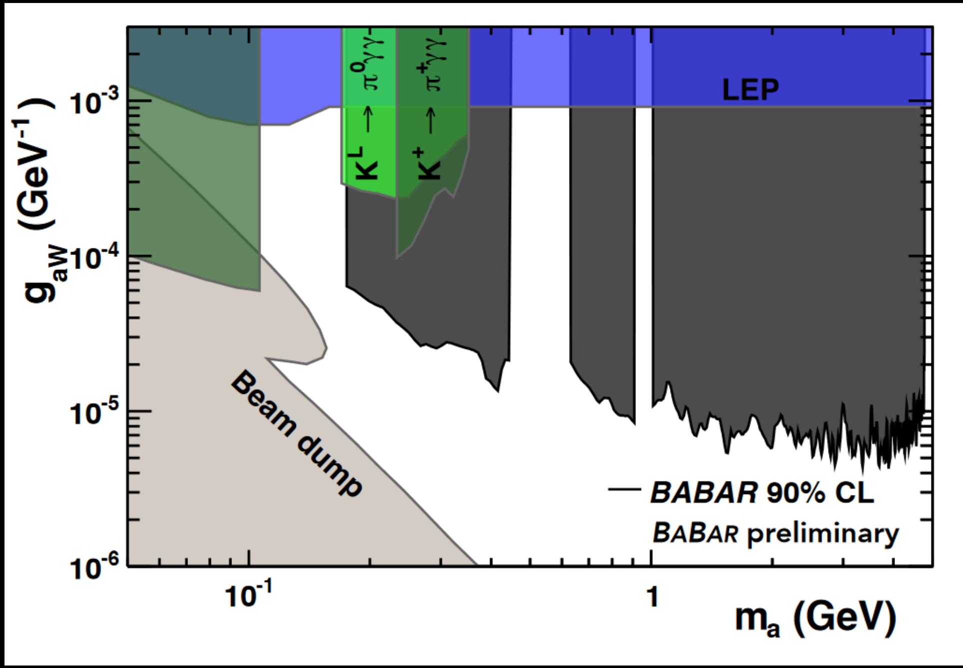
Prompt decays



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

Minimal dark sector model

Self-interacting dark matter

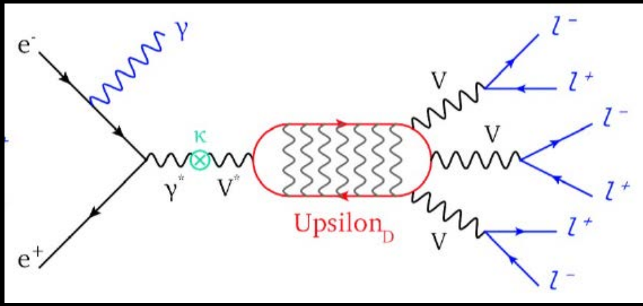
Search for darkonium

- 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 Υ_D ($J^{PC} = 1^{--}$), in analogy with SM
- Can be produced via $e^+e^- \rightarrow A' \eta_D$, $\eta_D \rightarrow A' A'$ and $e^+e^- \rightarrow \gamma\Upsilon_D$, $\Upsilon_D \rightarrow A' A' A'$

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

- 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



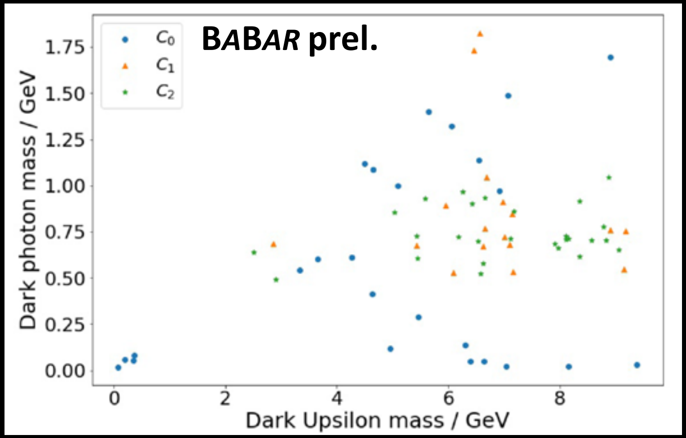
Self-interacting dark matter

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

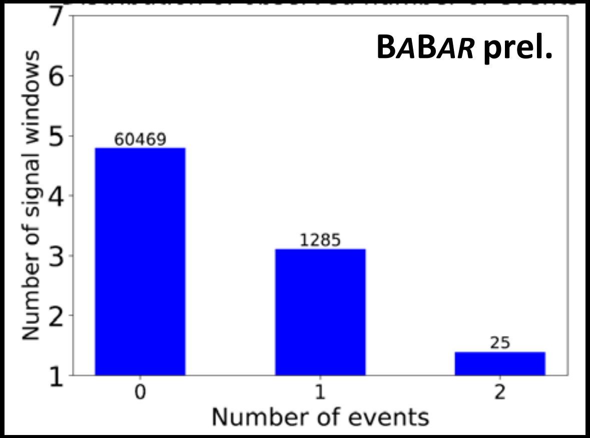
Analysis strategy

- 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)



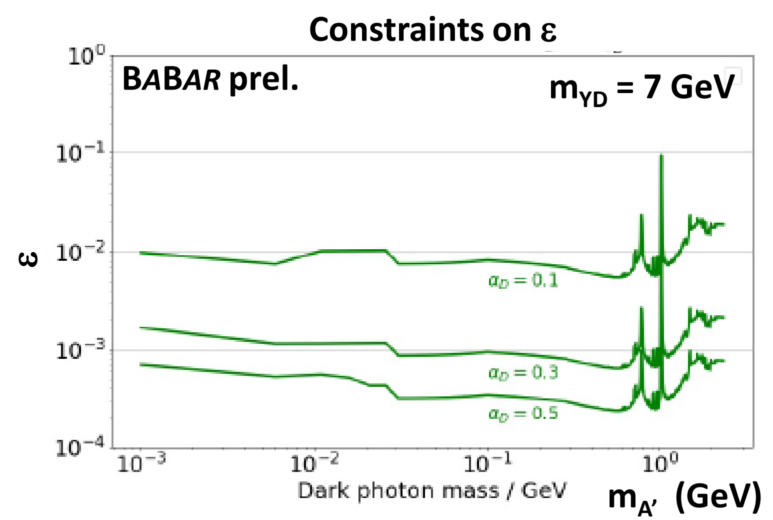
Number of events in signal window (prompt)

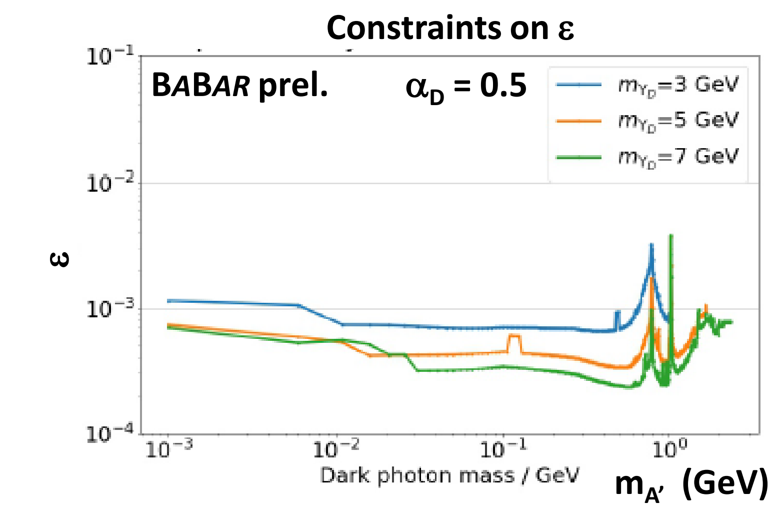


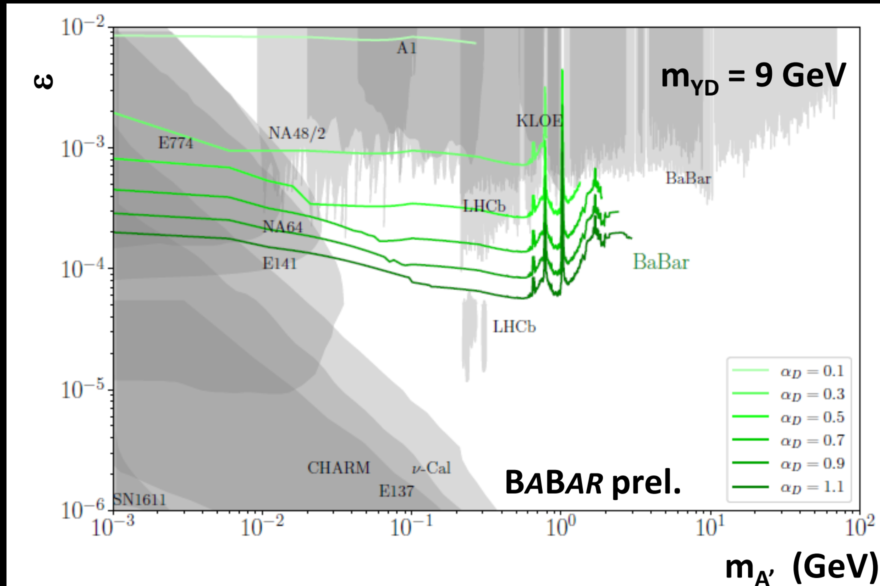
Prompt and displaced vertex analyses compatible with null hypothesis

Self-interacting dark matter

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







2106.08529, submitted to PRL

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

EPILOGUE

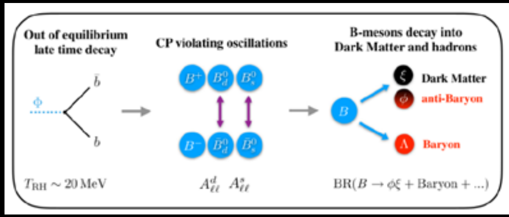
LOOKING FORWARD & CONCLUSION

More to come

On-going searches for dark sector / dark matter at B*A*B*AR*

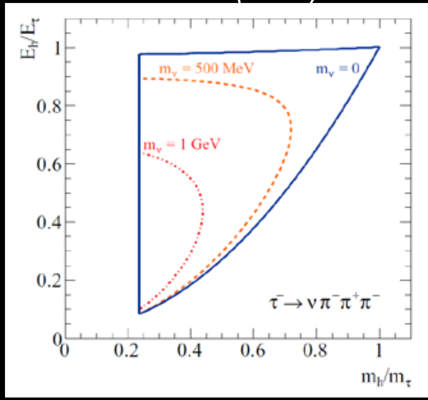
Dark matter and baryogenesis: Search for signature of a new mechanism of baryogenesis and dark matter production in which both the dark matter relic abundance and the baryon asymmetry arise from neutral B meson oscillations and decays

PRD 99 (2019) 035031



Heavy neutral lepton: Search for a heavy neutral lepton in $\tau \to \pi\pi\pi\nu$ decays. The heavy neutral lepton distorts the distribution of the invariant mass and energy of the $\pi\pi\pi$ system

PRD 91 (2015) 053006

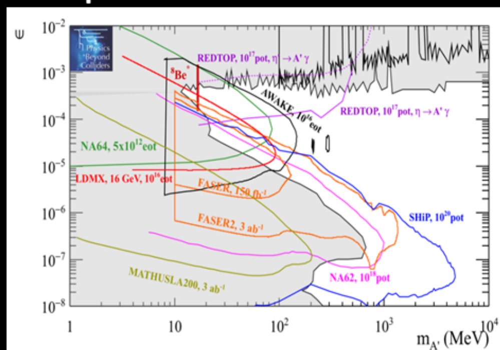


There is always something new to search for....

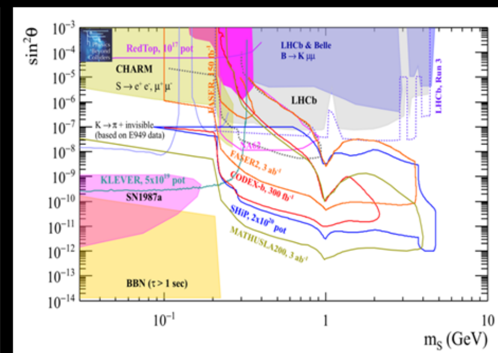
More generally

There is a worldwide effort to search for feebly interacting particles, and B*A*B*AR* is only one of the many experiments involved in these searches

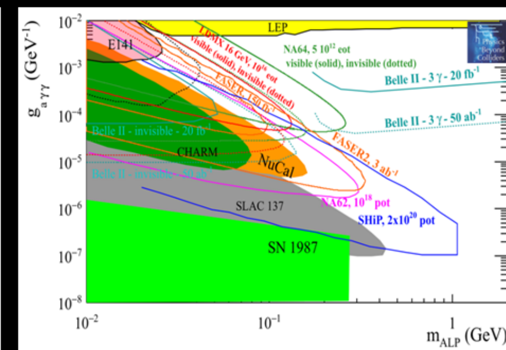
Dark photon



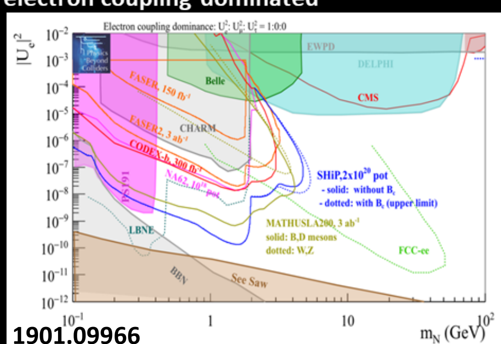
Dark scalar



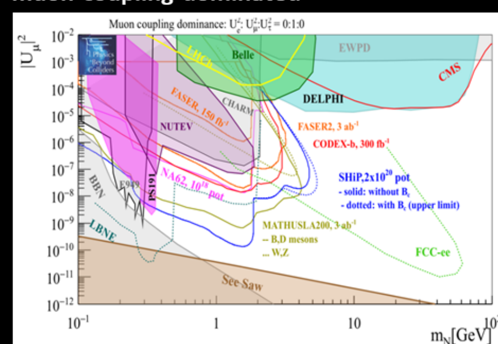
ALP



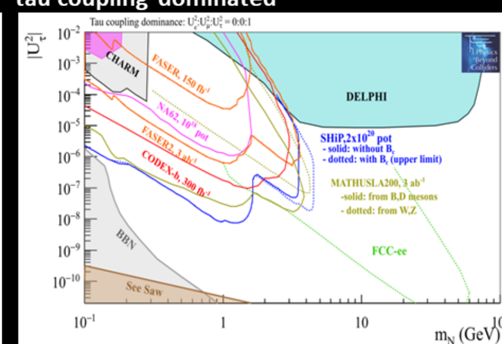
Heavy neutral leptons
electron coupling dominated



Heavy neutral leptons
muon coupling dominated



Heavy neutral leptons
tau coupling dominated



Two recent references (among others)

Physics Beyond Colliders at CERN, arxiv: 1901.09966

FIPs 2020 report, arxiv:2102.12143

Summary

Hidden 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 hidden sectors

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

There is a worldwide effort to explore hidden sectors, and B*A*B*AR* is one of the many experiments involved in these searches

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, Phys. Rev. Lett. 113, 201801 (2014)
Search for Invisible Decays of a Dark Photon Produced in e+e- Collisions at BaBar, Phys. Rev. Lett. 119, 131804 (2017)

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, Phys. Rev. Lett. 108, 211801 (2012)

Search for leptophilic dark scalar

Search for a Dark Leptophilic Scalar in e+e- Collisions, Phys. Rev. Lett. 125, 181801 (2020)

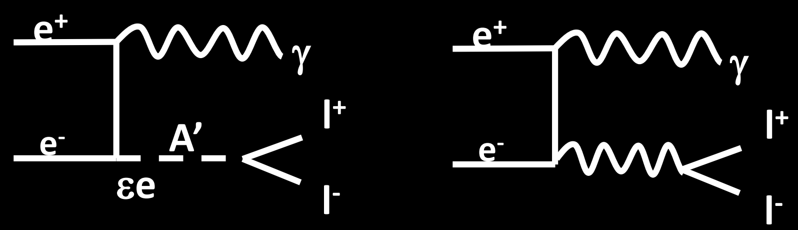
Search for six-quark dark matter

Search for a Stable Six-Quark State at BABAR, Phys. Rev. Lett. 122, 072002 (2019)

Visible dark photon decays

A dark photon can be produced in

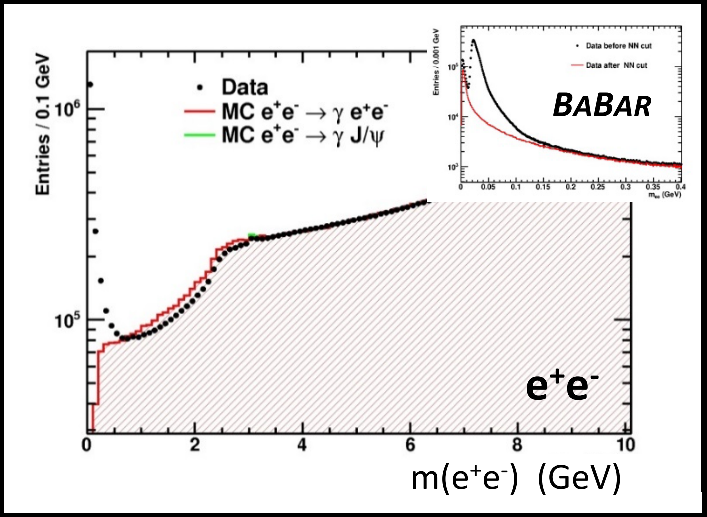
$e^+e^- \rightarrow \gamma A'$, $A' \rightarrow e^+e^-, \mu^+\mu^-$

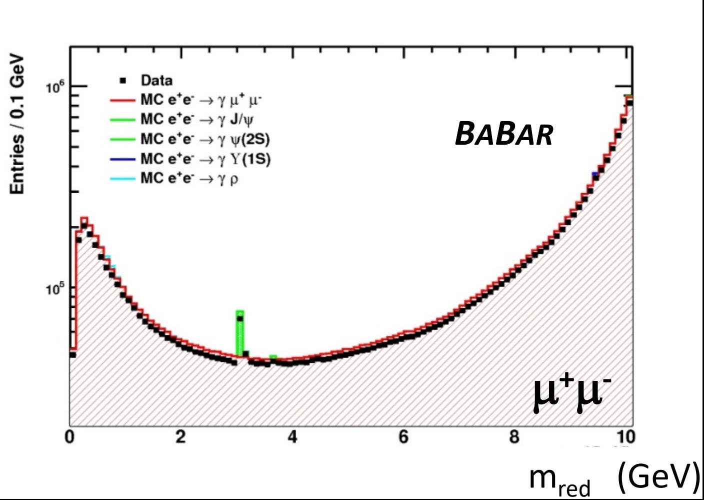


Search for a narrow resonance over large QED background:

- 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

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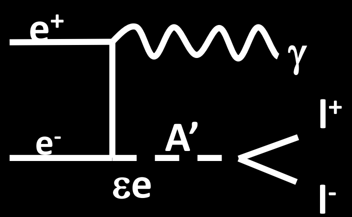

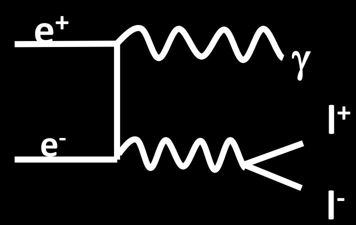

Search for a narrow resonance over large QED background:

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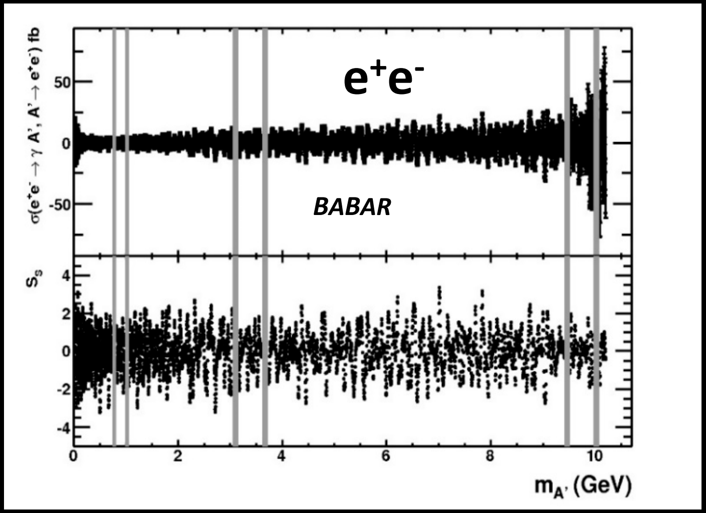
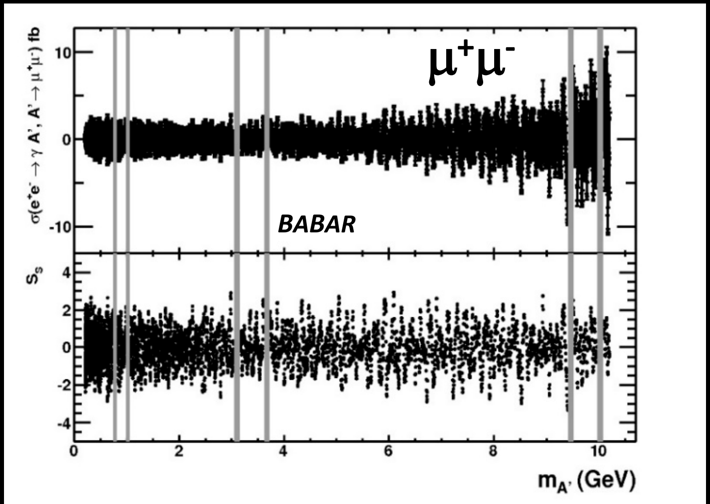
- Kinematic cuts to improve purity
- Quality cuts on tracks and photons

Signal significance





No significant signal found

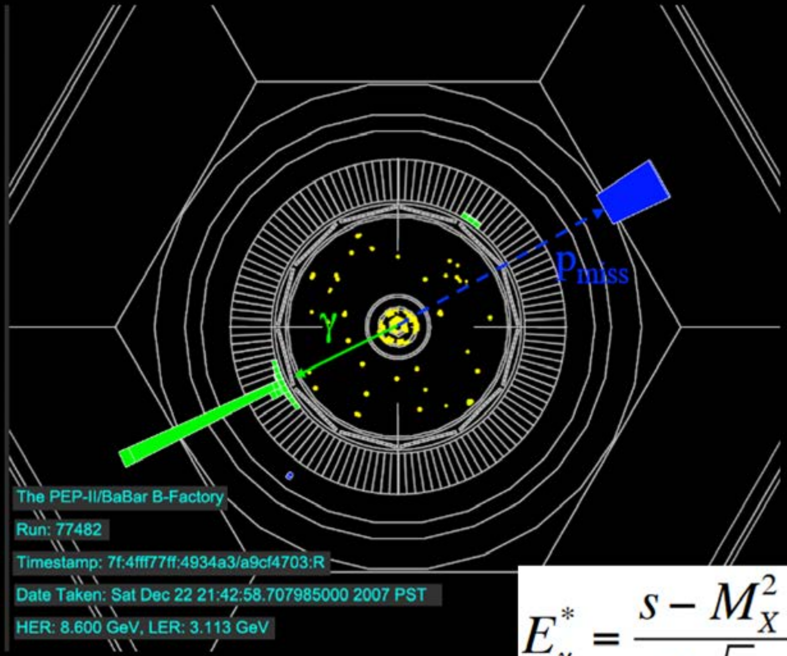
Invisible dark photon decays

At e^+e^- colliders, we can search for $e^+e^- \to \gamma A'$, $A' \to$ invisible by tagging the recoil photon in "single photon" events

BABAR collected ~53 fb^{-1} of data with dedicated single photon triggers during its last year of data taking

Analysis overview

- Missing energy and momentum is best signature
- Hermeticity is key, but need to allow some machine background
- Search strategy: 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 $E_{calorimeter}$, missing mass/energy and muon detector information



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

Muonic dark force

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

Analysis overview

- Analysis based on data collected at Y(4S), Y(3S) and Y(2S)
- Four tracks and no extra neutral energy (E_{extra} < 200 MeV)
- Particle identification: 2 same-sign tracks identified as muon
- Four-muon invariant mass within 500 MeV of nominal CM-energy
- Veto events with a dimuon candidate within 10 MeV of the Υ(1S) mass for the Υ(2S) and Υ(3S) dataset to reject Υ(2S,3S) $\rightarrow \pi\pi$ Υ(1S), Υ(1S) ’ $\mu\mu$
- Kinematic fit imposing beam-energy constraint is finally performed, but no constraints on the χ^2 are applied

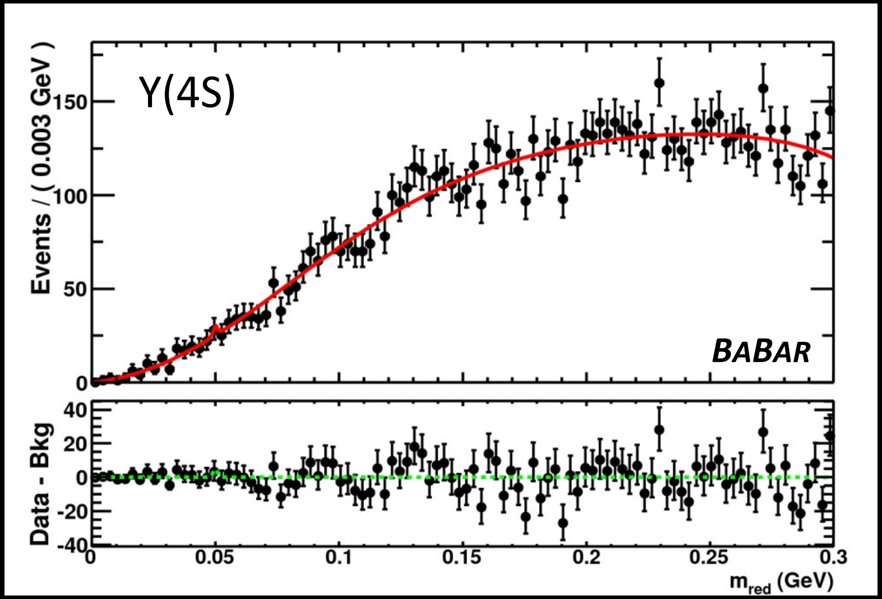
We perform a blind analysis, the selections criteria are optimized on a small subset (5%) of the data, which is subsequently discarded

Muonic dark force

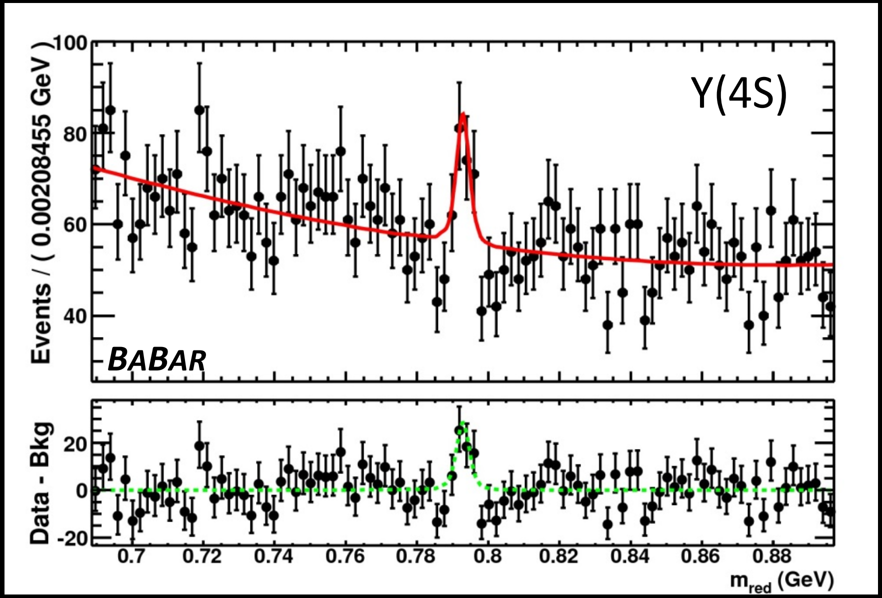
We extract the signal separately for the data at the Υ(4S), Υ(3S) and Υ(2S) by performing a series of fits to the reduced dimuon mass for each sample

For each mass hypothesis, we fit over a fixed range of 0-0.3 GeV (m_R < 0.2 GeV) or a window corresponding to 50 signal resolution (m_R > 0.2 GeV). A region of ± 30 MeV around the J/ψ is excluded

Fit m_R = 0.05 GeV



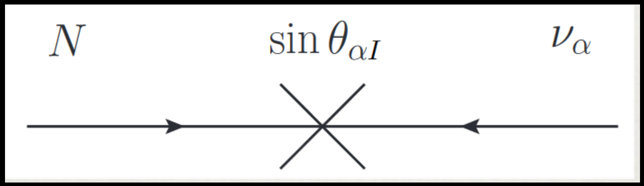
Most significant fit m_R = 0.79 GeV



Local /global significance: 4.3σ /1.6σ

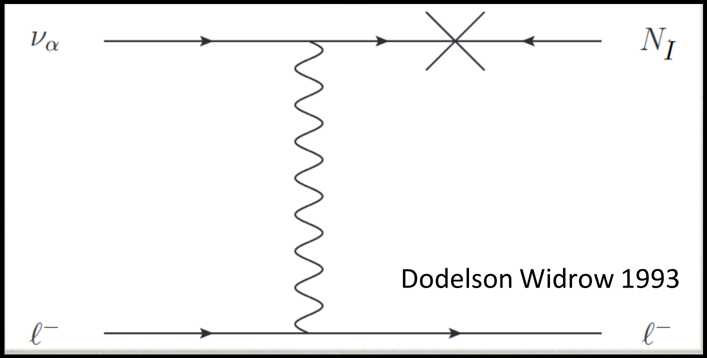
Sterile neutrino dark matter

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

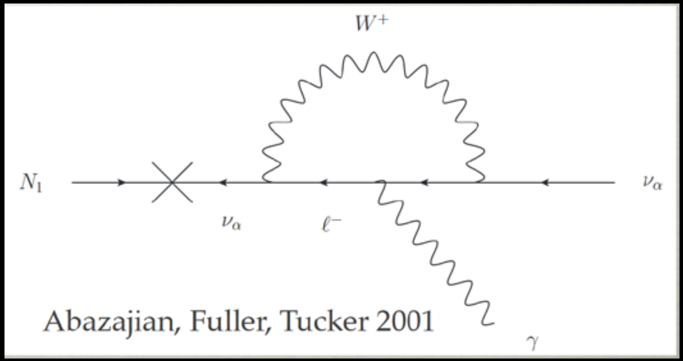


$$\sin\theta_{\alpha I} = \frac{F_{\alpha I}\langle H\rangle}{M_N}$$

Sterile neutrino live and die by this mixing



Dodelson Widrow 1993



Abazajian, Fuller, Tucker 2001

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

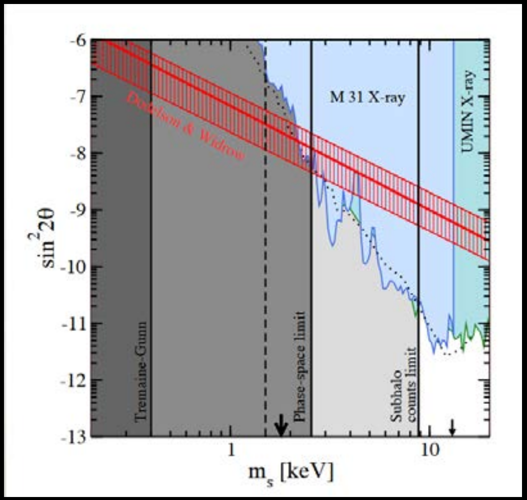
Sterile neutrino dark matter

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

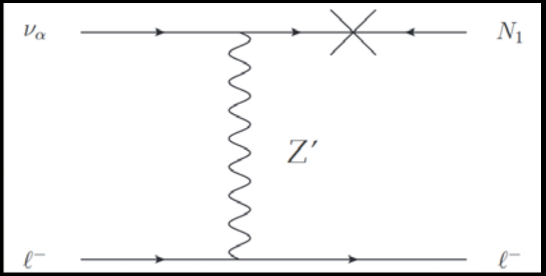
BUT, a new neutral interaction coupling to leptons and neutrinos could boost the sterile N production without increasing the decay

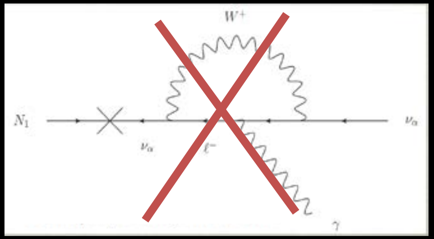
New dark force coupling to 2nd / 3rd generation of leptons ($L\mu$-$L\tau$, anomaly free). The corresponding gauge boson Z’ must be light – O(GeV) or less – to avoid constraints from magnetic dipole measurements and provide the correct rate enhancement

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



Horiuchi *et al.* 2013





Dark Higgs boson

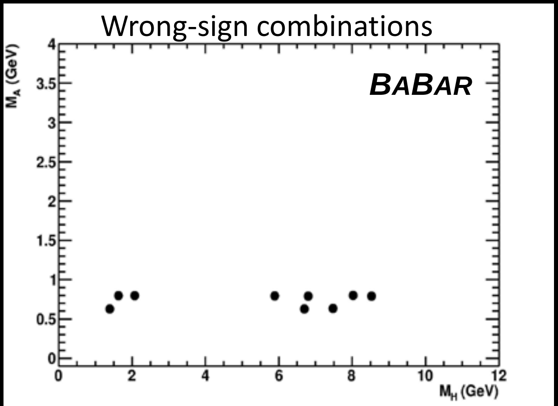
Search for dark Higgs boson h'

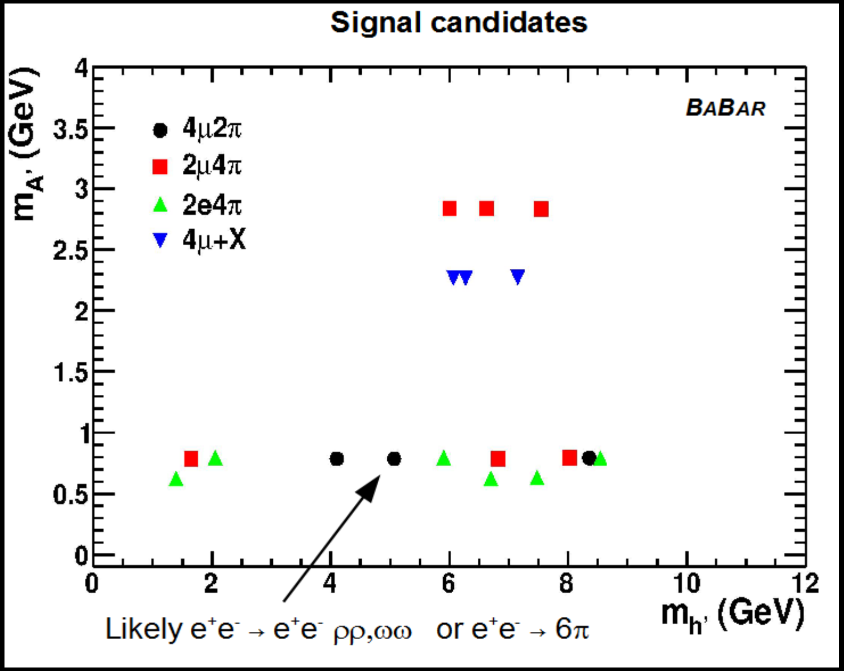
Analysis overview

- Search for events with three dark photons of similar mass, consistent with $e^+e^- \to A' A' A'$ hypothesis
- Six candidates are selected from the full *BABAR* dataset, no event with 6 leptons
- Estimate background from

  - wrong-sign combinations, e.g. $e^+e^- \to (e^+e^+)(e^-e^-)(\mu^+\mu^-)$

  - sidebands from final sample





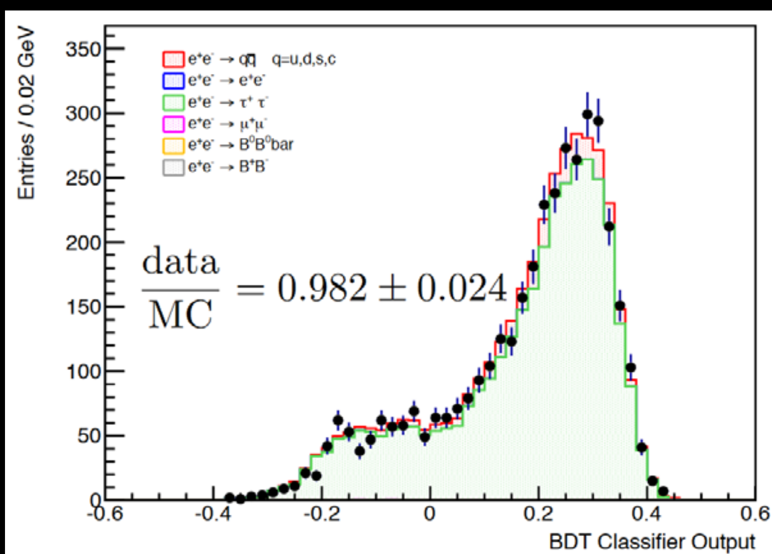
Distribution consistent with pure background hypothesis

Leptophilic dark scalar

Validate efficiency with control samples and derive corresponding corrections

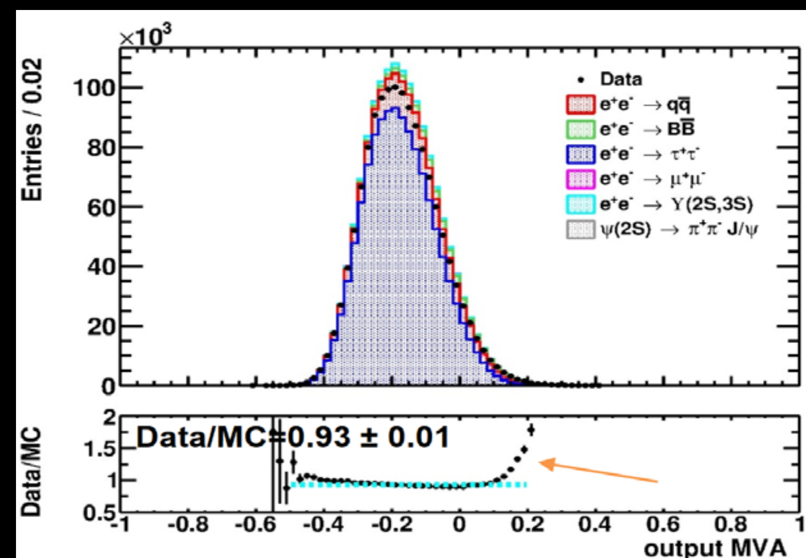
Dielectron

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

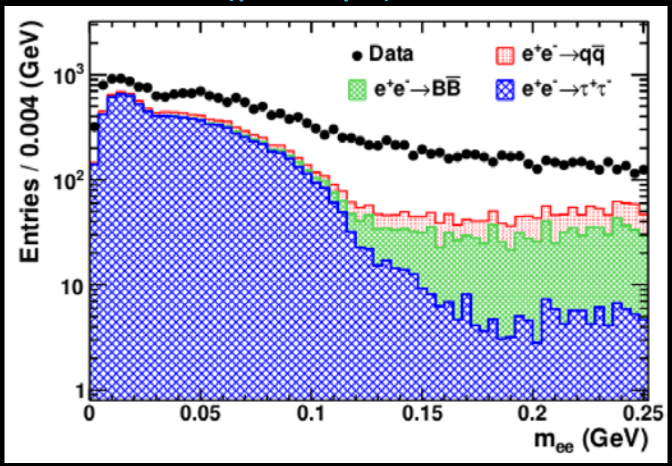


Data globally well reproduced by MC predictions, corrections between 2-7%

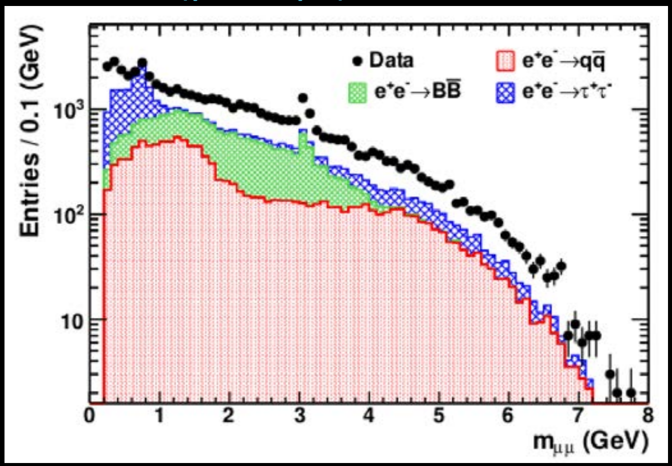
Leptophilic dark scalar

Final mass spectra for each final state and lifetime

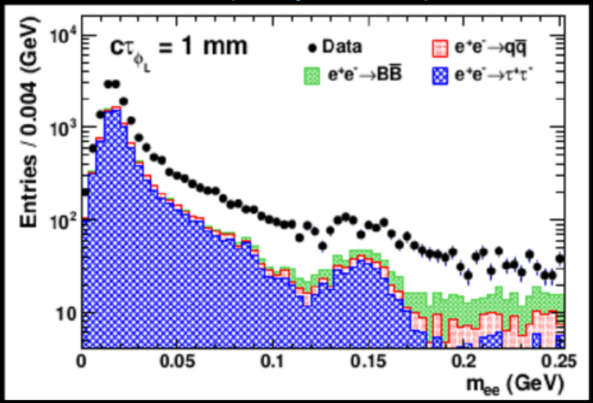
Dielectron (prompt)

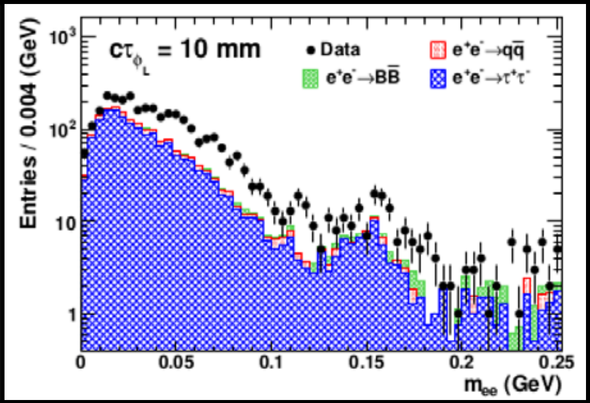


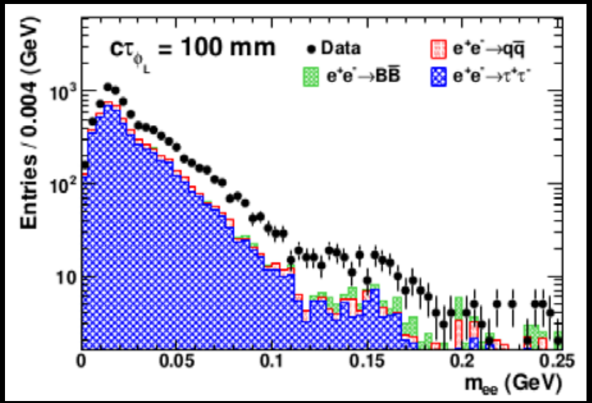
Dimuon (prompt)



Dielectron (displaced)

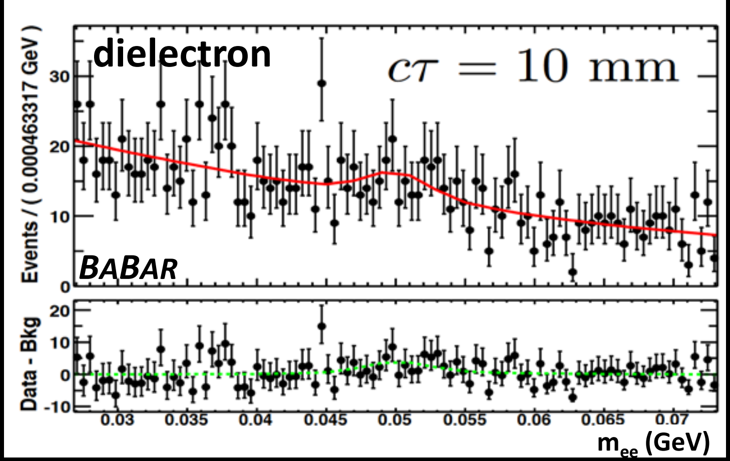


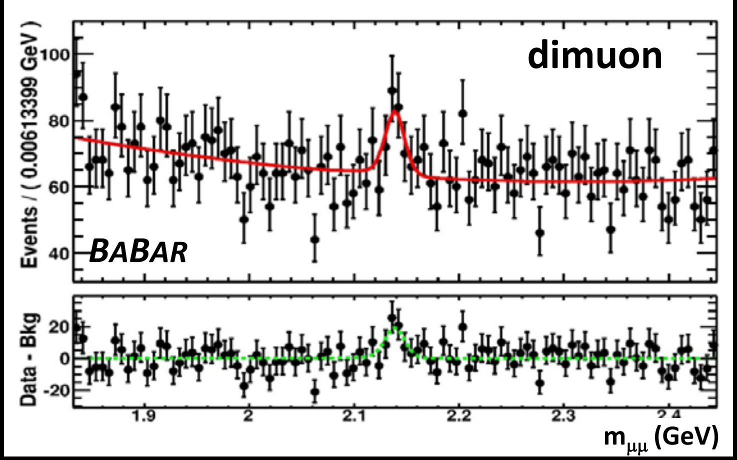




Leptophilic dark scalar

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:

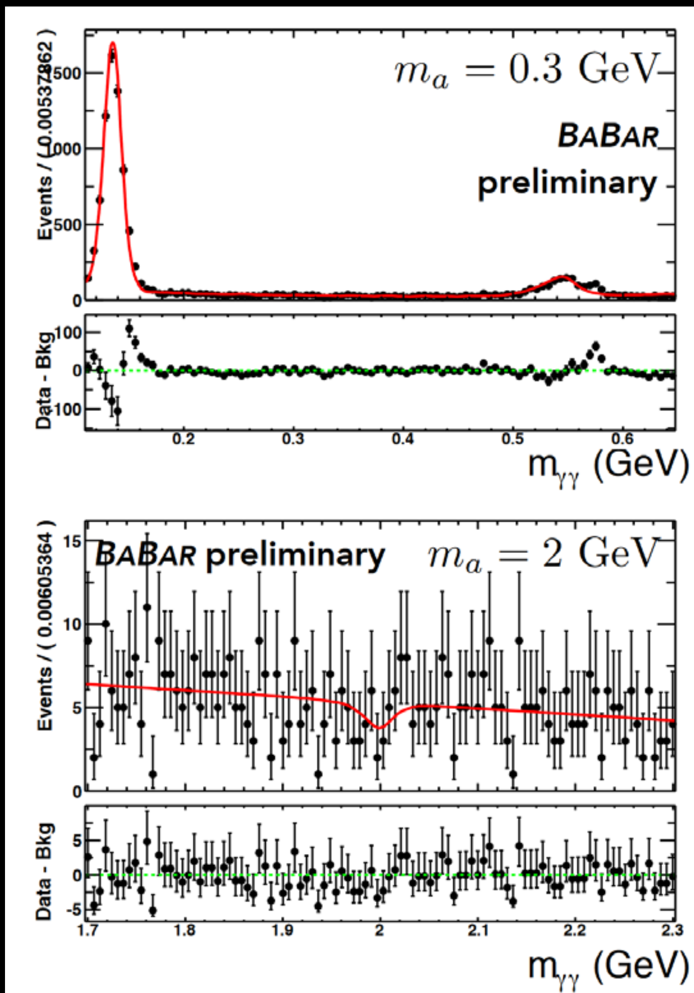
- Signal modeled from signal MC and interpolated between simulated mass points
- Continuum background modelled by second or third order polynomials
- Peaking background (π^0, J/ψ, $\psi(2S)$) modelled from bkg MC

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%