A decade of dark sector and light dark matter searches at B-factories

Bertrand Echenard
Caltech
on behalf of the B*A*B*AR* collaboration

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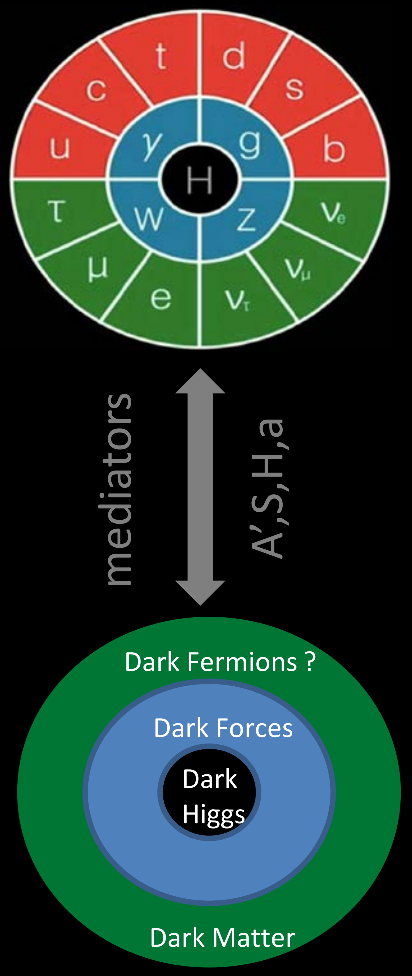
Dark sectors in a nutshell

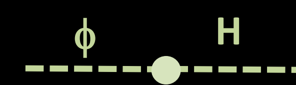
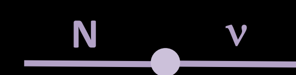
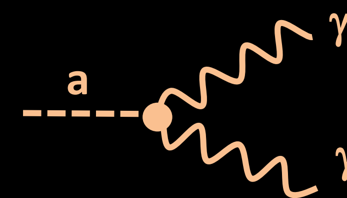
What are dark sectors / hidden sectors

- New particle(s) that don't couple directly to the SM, but…
- …indirect interactions are possible 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



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

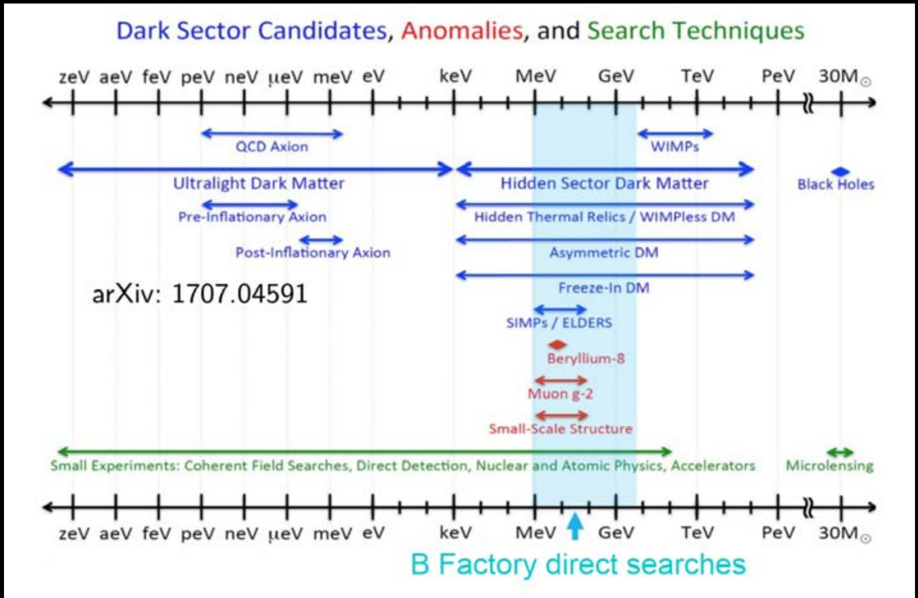
This large variety motivates broad exploration of dark sector
Low energy e^+e^- colliders offer ideal environment to study them

Dark sectors at B-factories

B-factories are well suited to study dark sectors

- Well defined initial e+e- state
- Hermetic detector coverage (almost 4π)
- Good missing energy reconstruction
- Clean displaced vertex identification in $\sim$1mm < $c\tau$ < 10-100cm with $c\tau$ > O(1m) being missing energy
- Excellent PID capaibilties
- 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 B-factories

Extensive "dark sector" program conducted at B*ABAR* and Belle 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"

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

Search for dark bosons

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

Search for leptophobic B boson

$\eta \to \gamma B, B \to \pi^+\pi^-$

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* / Belle

Miho Wakai will review Belle II results

References in supplementary slides

B-factory experiments

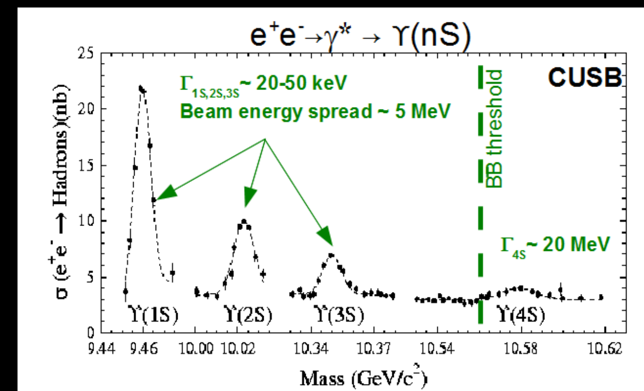
First generation of experiments at e^+e^- asymmetric-energy colliders designed to study *CP* violation in B decays and many other topics (charm, tau, dark sector,…)

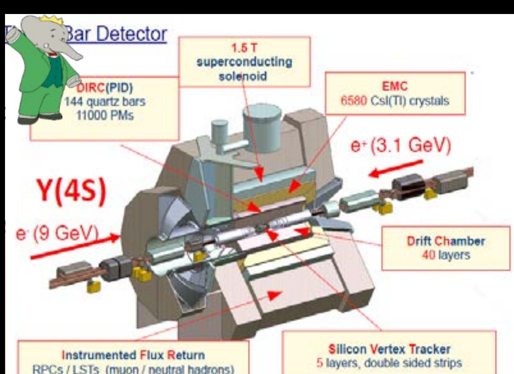
Asymmetric e-/e+ beam energies: 9.0/3.0 GeV (B*A*B*AR*) and 8.0 / 3.5 (Belle)

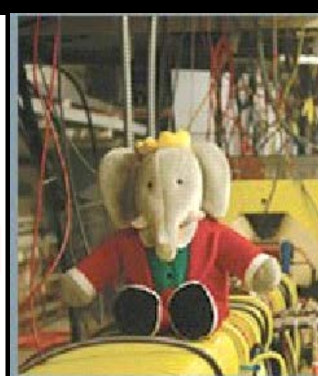
Large instantaneous luminosities > 10^{34} cm^{-2} s^{-1}

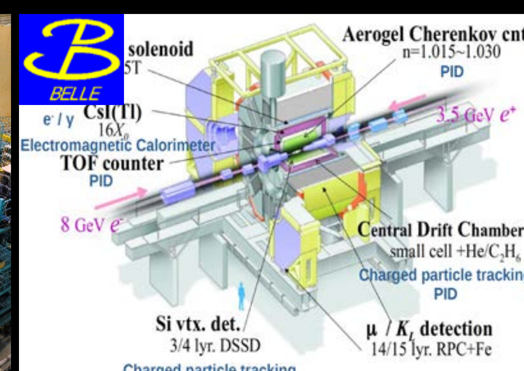
Nominally collected data around the Υ(4S) resonance, then at the Υ(1S), Υ(2S), Υ(3S) and Υ(5S) resonances:

- **B*A*B*AR* @ PEP-II (**1999-2008): $\int Ldt \sim 0.5\ ab^{-1}$
- **Belle @ KEKB** (1999-2010): $\int Ldt \sim 1\ ab^{-1}$









DARK BOSON

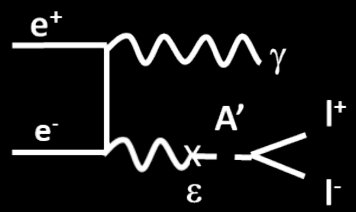
DARK PHOTON & MUONIC DARK FORCE

Dark photon searches

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

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

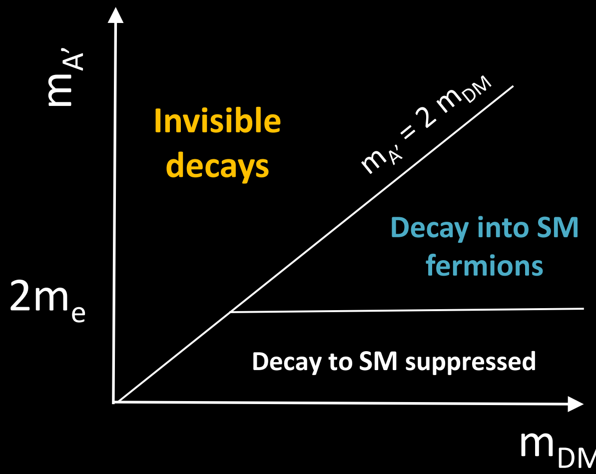
Any process that produces photon can also produce dark photon with a rate reduced by ε^2



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

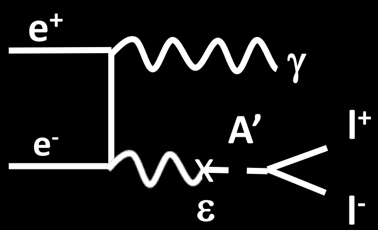


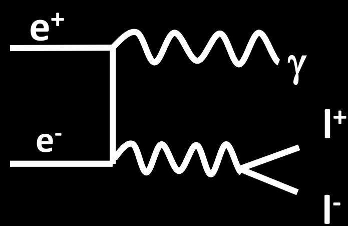
Note that there is no extra factor of ε for visible decays into SM fermions, since the A' has to decay back into leptons/quarks. The mixing strength only controls the decay width (i.e. lifetime), not the rate.

Visible dark photon decays

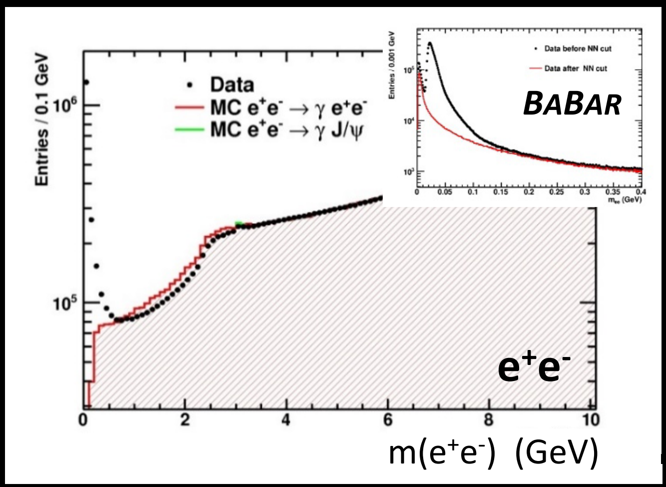
PRL 113 (2014) 201801

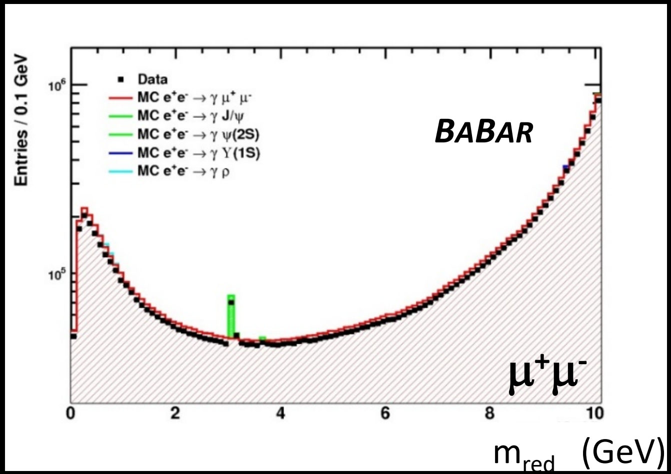
Search for dark photon in $e^+e^- \rightarrow \gamma A'$, $A' \rightarrow e^+e^-, \mu^+\mu^-$





Dilepton mass distributions





Search for a narrow resonance over large QED background:

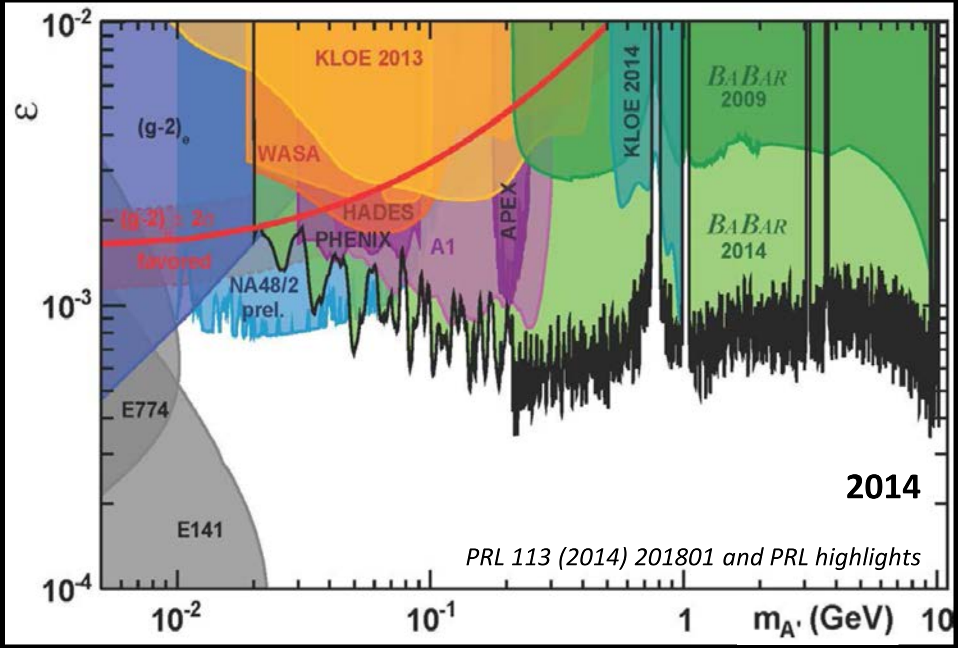
- 2 tracks + 1 photon
- Constrained fit (beam energy + vertex)
- Particle identification (e/mu)
- Kinematic cuts to improve purity
- Quality cuts on tracks and photons

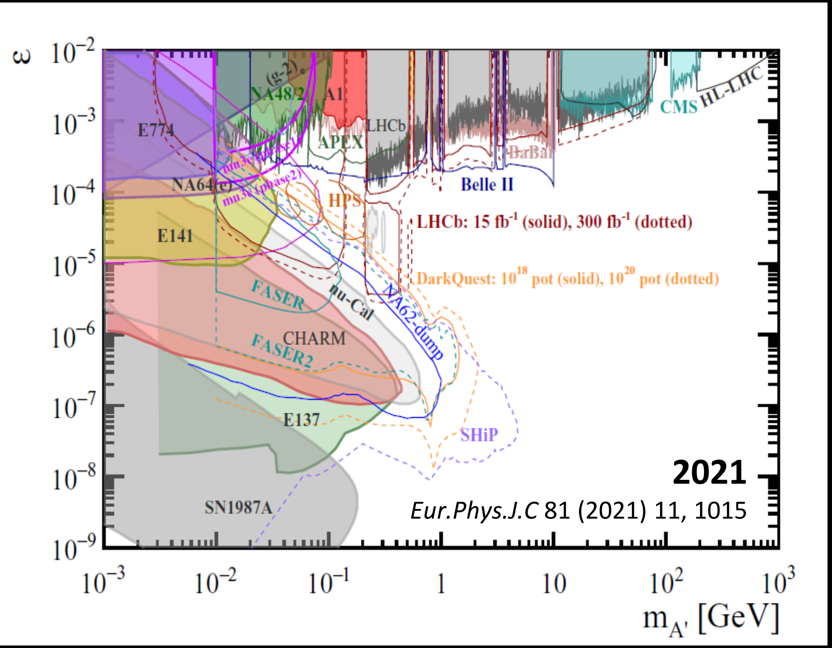
Visible dark photon decays

PRL 113 (2014) 201801

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

Limits on kinetic mixing (90% CL)



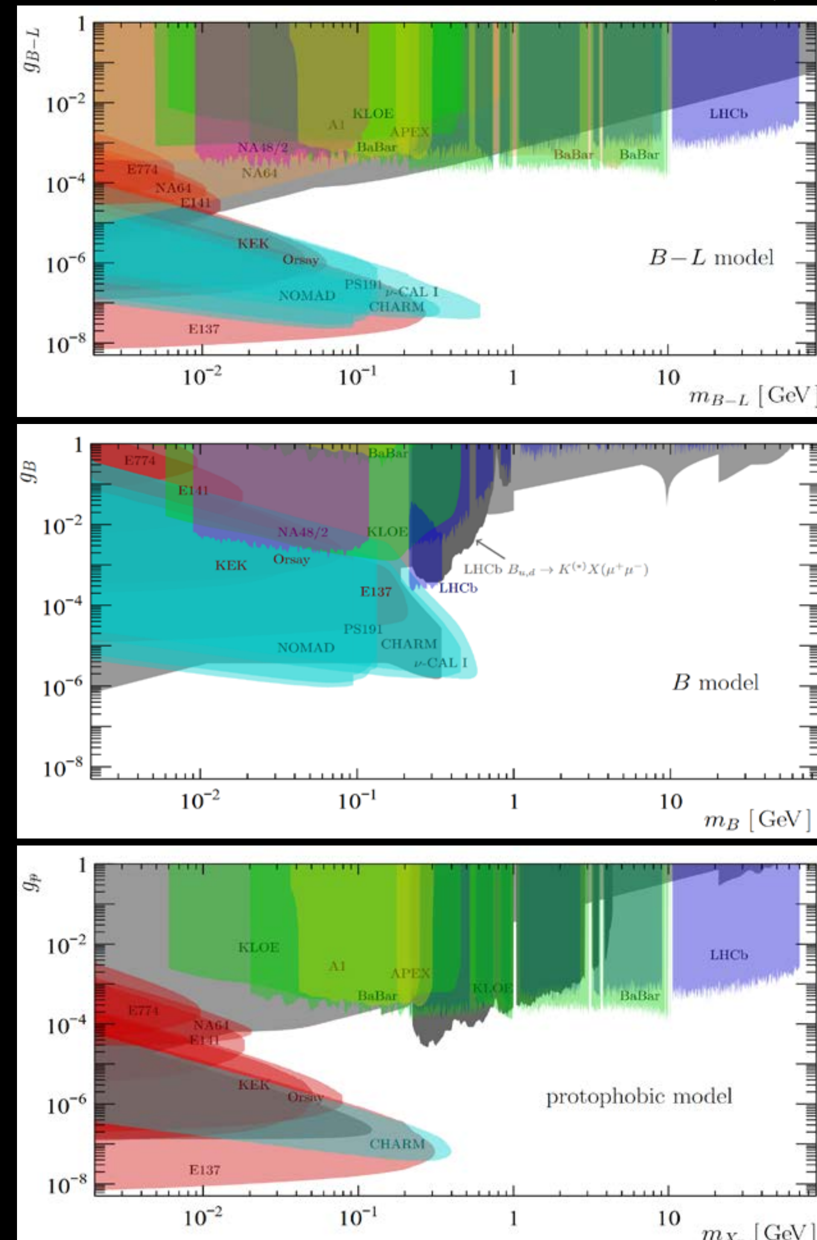


Improved constraints over a large range of masses

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

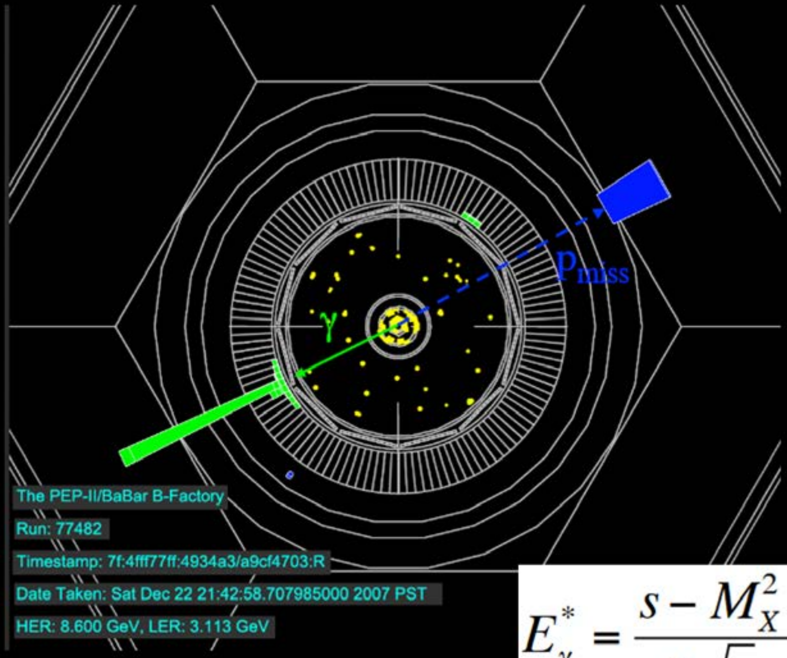
Invisible dark photon decays

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



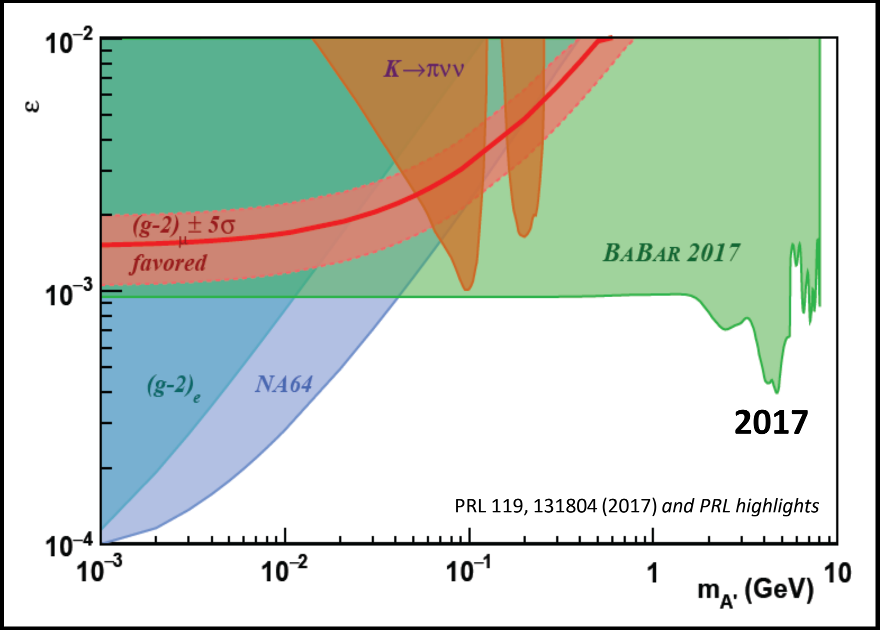
$$E_\gamma^* = \frac{s - M_X^2}{2\sqrt{s}}$$

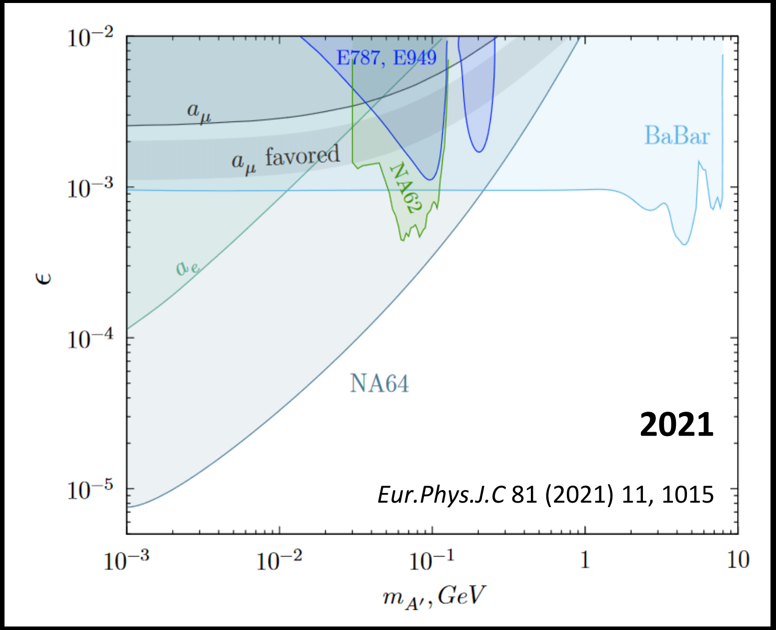
Invisible dark photon decays

PRL 119, 131804 (2017)

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

Limits on kinetic mixing (90% CL)



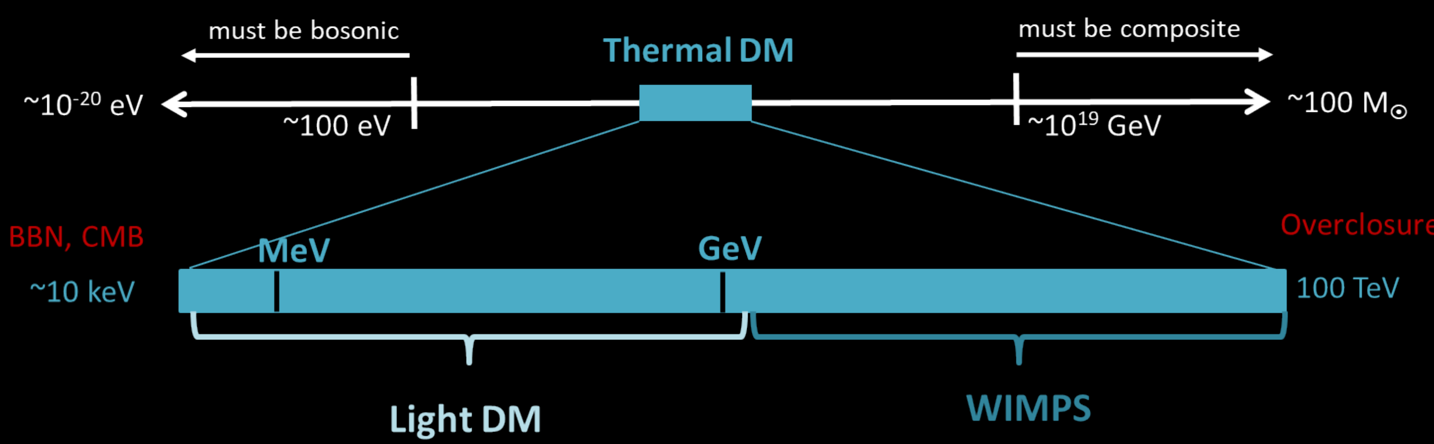


Substantially improve previous limits in high mass region, and exclude purely invisible dark photon as explanation of "g-2" anomaly

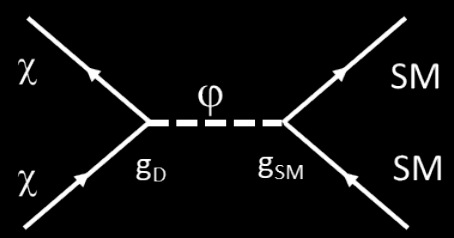
Next generation B-factories should substantially improve at high masses

Thermal freeze-out dark matter with vector portal

Thermal freeze-out dark matter is both predictive and simple, and strongly restricts the range of possible dark matter masses (see Van Tilburg's talk on Monday)



Freeze-out scenario with light dark matter (χ) requires new light mediator (ϕ) to explain the relic density, or dark matter is overproduced



$$<\sigma v>_{relic} \sim \frac{g_D^2\, g_{SM}^2\, m_x^2}{m_\varphi^4} \qquad (m_\varphi \gg m_x)$$

$$m_\varphi^4 \sim \frac{g_D^2\, g_{SM}^2\, m_x^2}{<\sigma v>} \leq \frac{m_x^2}{<\sigma v>} \qquad \text{since } g \leq O(1)$$

Naturally realized in the context of hidden sectors

Thermal freeze-out dark matter with vector portal

Thermal freeze-out DM with vector portal (direct annihilation)

- Light DM can annihilate into SM particles via dark photon mediator $m_{A'} > m_{DM}$

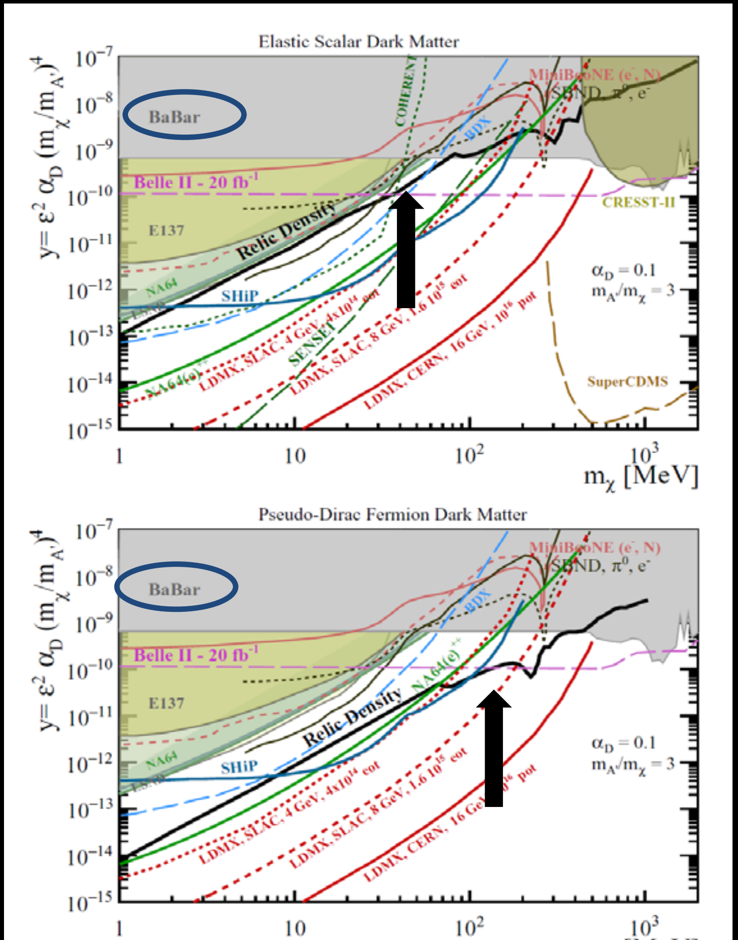
- Thermal relic density uniquely predicted from DM mass and spin:

$$< \sigma v > \sim \alpha_D \varepsilon^2 \frac{m_x^2}{m_A^4} \sim y \frac{1}{m_x^2}$$

Dimensionless variable $y = \alpha_D \, \varepsilon^2 \frac{m_x^4}{m_A^4}$

BABAR is already excluding parameter space for invisible decays above ~100 MeV – GeV depending on the model

Future B-factories will be instrumental in full probing these models



Eur.Phys.J.C 81 (2021) 11, 1015

Muonic dark force

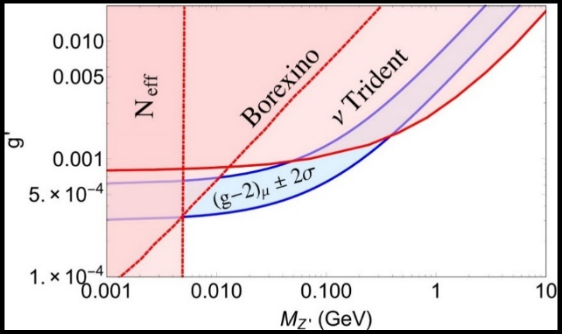
Muonic dark force: a new force coupling only to the second and third generation of leptons with a corresponding gauge boson Z’

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)

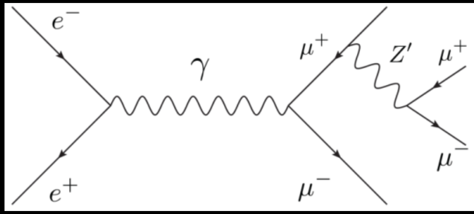
Searches for a muonic dark force at B*A*B*AR*/Belle via Z’-strahlung :

“Current” constraints on Z’

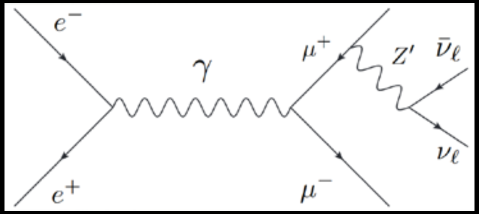


PRD 89 (2014) 113004

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



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

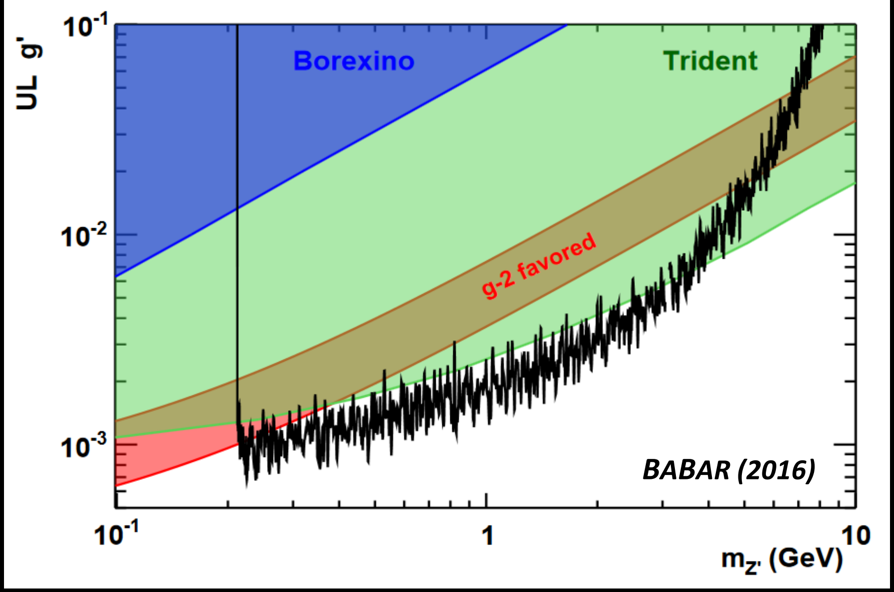


Muonic dark force

BABAR, PRD 94 (2016) 011102
BELLE, submitted to PRD

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

Limits (90% CL) on Z' coupling



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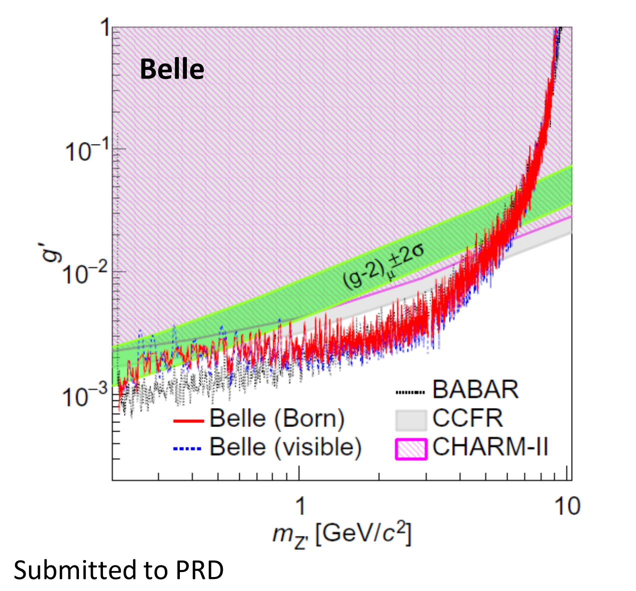


Measurements improve upon previous bounds and further exclude region favored by the g-2 anomaly

Search for invisible Z' decays at Belle-II using 276 pb^{-1} of data

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

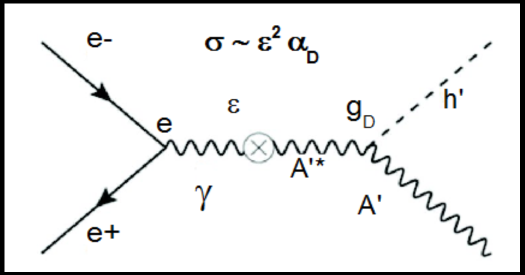
Can be produced via Higgsstrahlung process

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

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

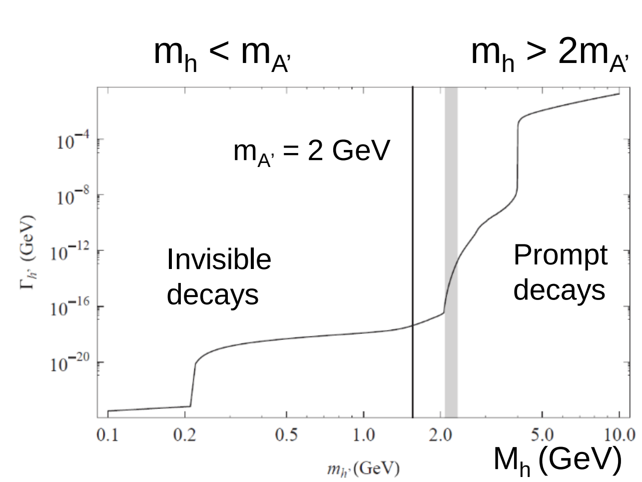
Decay topology depends on the dark Higgs and dark photon masses: either invisible (KLOE) or visible ($h' \rightarrow A' A'$ at B*ABAR*, Belle)

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



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

Dark Higgs decay topology

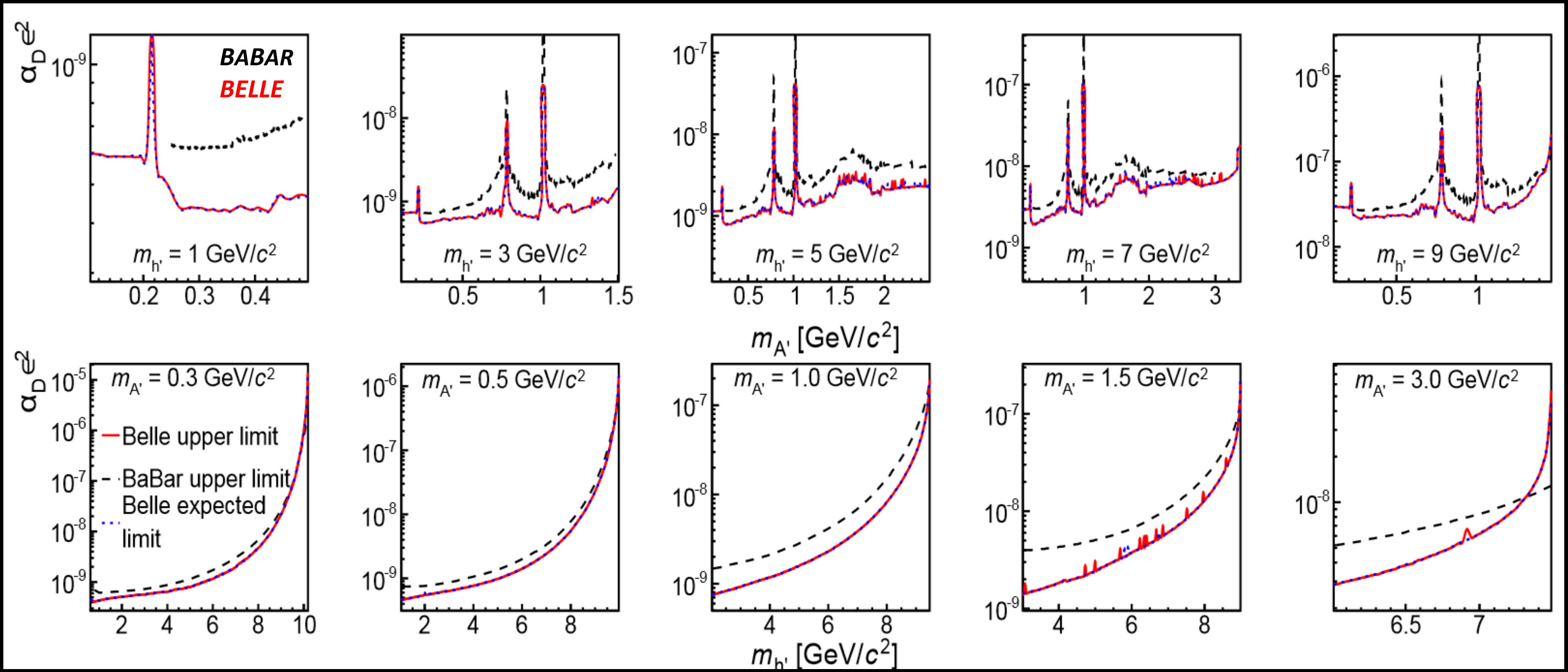


B. Batell et al., PRD 79 (2009) 115008
R. Essig et al., PRD 80 (2009) 015003

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

Leptophilic dark scalar

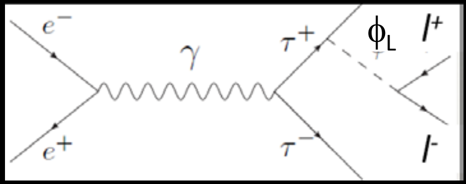
PRL 125 (2020) 181801

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

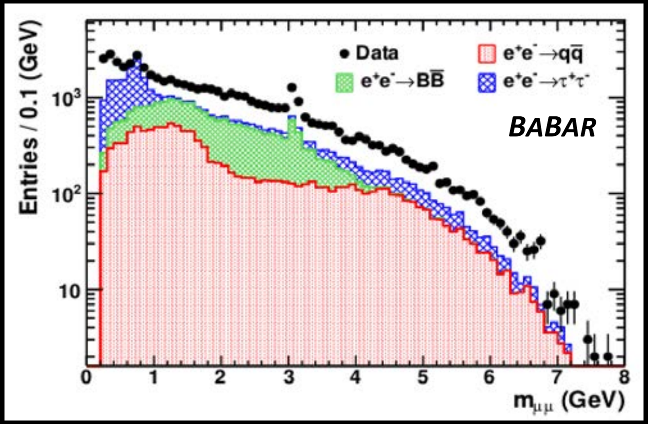


Search for $e^+e^- \to \tau^+\tau^- \phi_L$, $\phi_L \to l^+l^-$ (l=e,μ), final state $\phi_L \to \tau^+\tau^-$ has too many neutrinos to provide competitive constraints

Analysis strategy

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

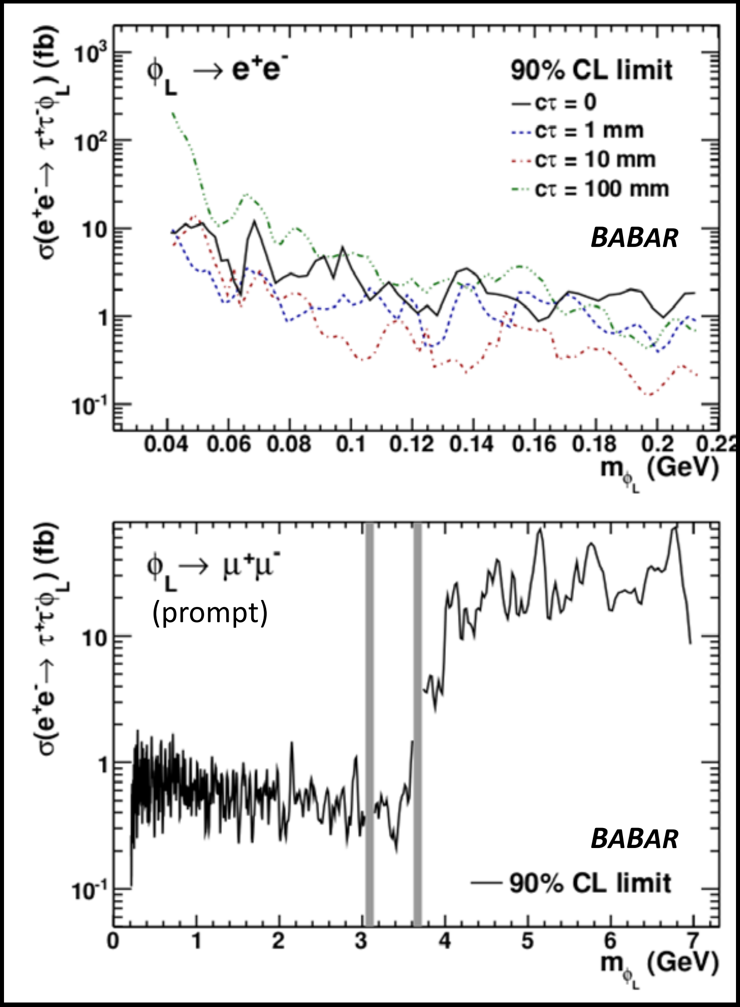
Final dimuon mass distribution

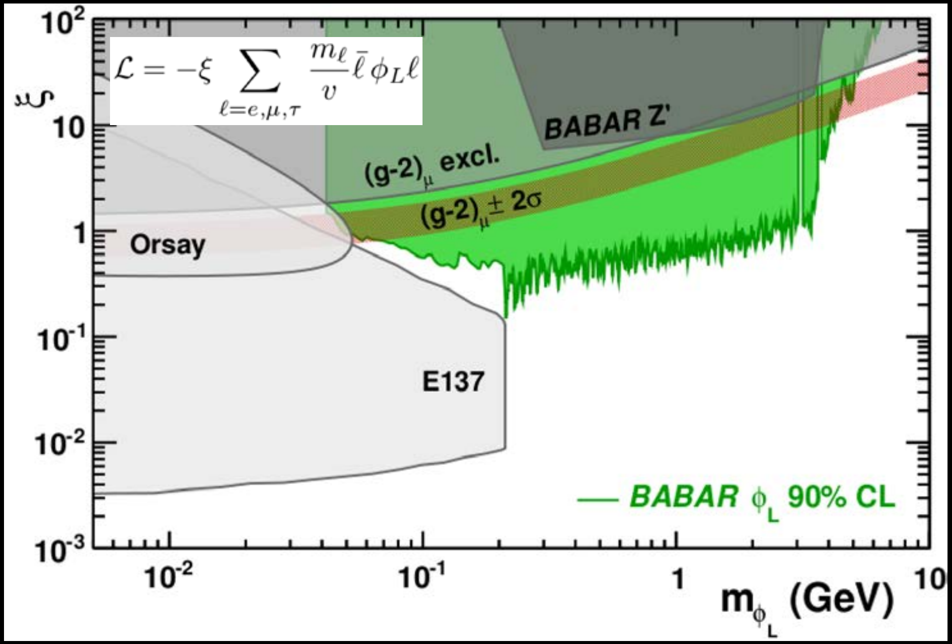


Leptophilic dark scalar

PRL 125 (2020) 181801

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





Significant improvement over previous bounds

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

Belle II should be able to further improve

AXION

AXION-LIKE PARTICLE IN B DECAYS

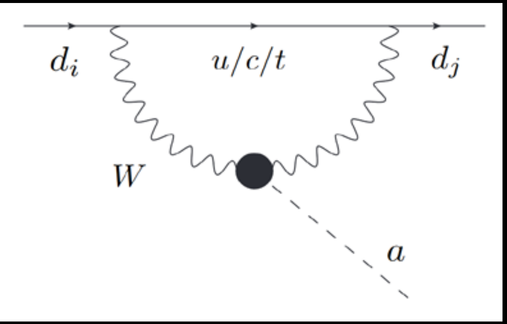
Axion like particle (ALP)

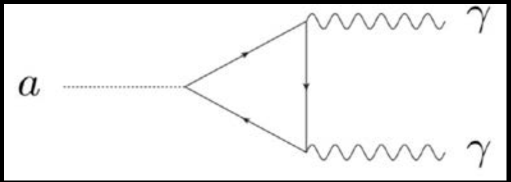
What are axion like particles

- Pseudo-goldstone bosons ubiquitous in BSM physics, coupling predominantly to pair of bosons with non-renormalizable coupling constant $f_a \sim 1/m_a$
- 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 $B \to Ka$, $a \to \gamma\gamma$ 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 $B \to Ka$ decays, exploiting $b \to s$ transition
- Axion lifetime becomes important at low masses and couplings ($\tau \sim 1/m_a^3 g_{aW}^2$) $\to$ long-lived axion

Axion like particle (ALP)

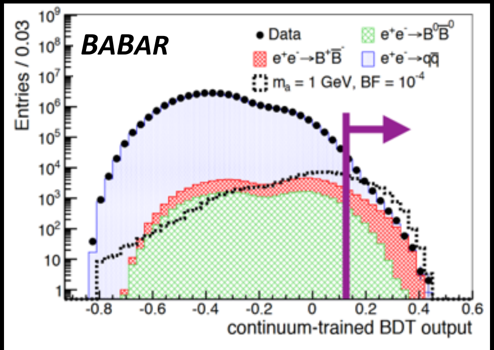
2111.01800, submitted to PRL

Search for di-photon decay of an axion (a) produced in B decays: $B \rightarrow Ka$, $a \rightarrow \gamma\gamma$

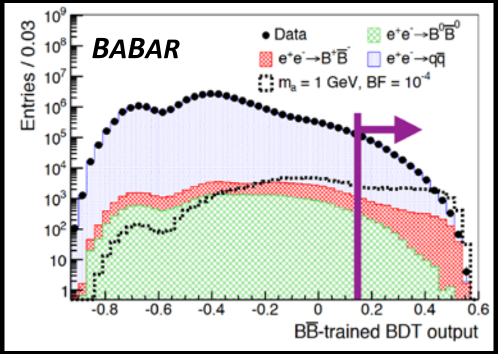
Analysis strategy

- 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 $e^+e^- \rightarrow q\bar{q}$ (q=u,d,s,c) and $e^+e^- \rightarrow B\bar{B}$ backgounds
- Blind analysis, optimize on 8% of dataset and discard from final results

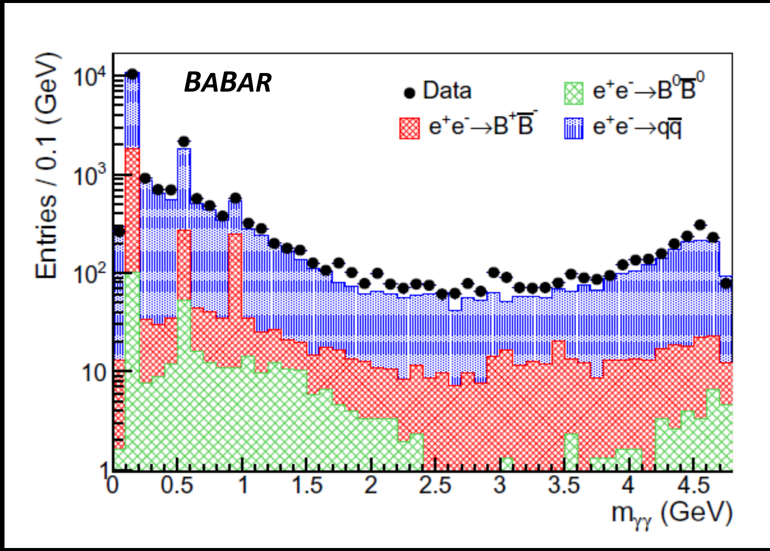
Continuum BDT



B-Bbar BDT



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



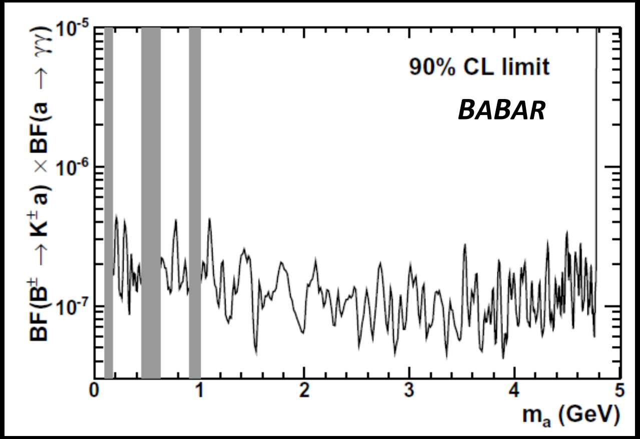
Peaking background at π^0,η,η' masses,
2.6σ excess near the η_c, consistent with $B \rightarrow K\,\eta_c$, $\eta_c \rightarrow \gamma\gamma$

Axion like particle (ALP)

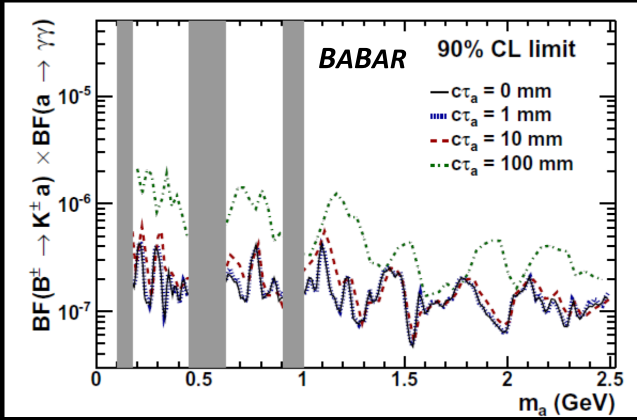
2111.01800, submitted to PRL

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

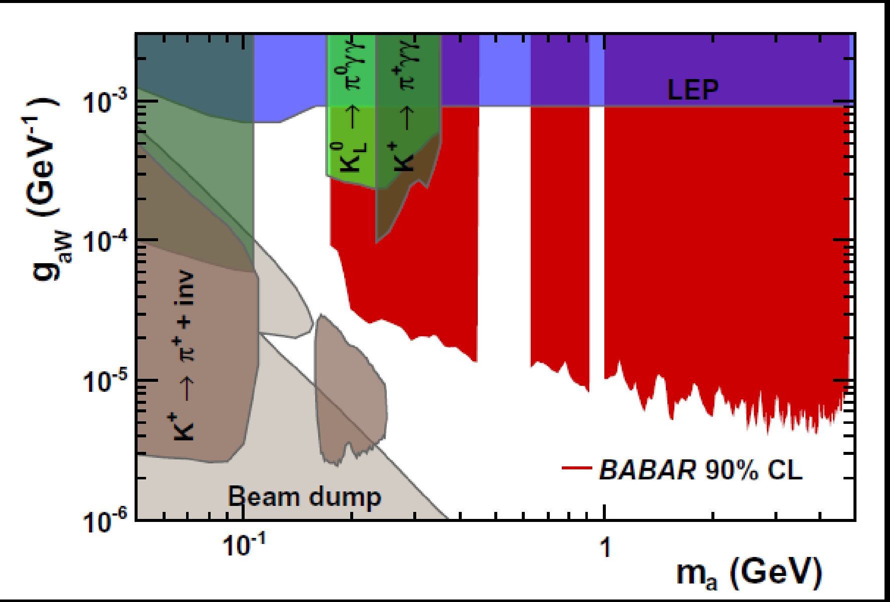
Prompt decays



Displaced decays



90% CL upper limits on coupling g_{aW}



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

See Belle II talk for more axion searches

SELF-INTERACTING DARK MATTER

MINIMAL DARK SECTOR MODEL

Self-interacting dark matter

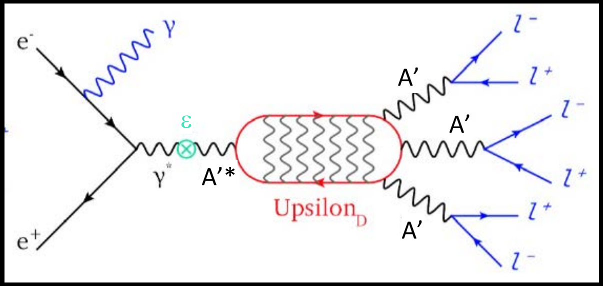
Search for darkonium Υ_D in $e^+e^- \to \gamma\Upsilon_D$, $\Upsilon_D \to A' A' A'$, $A' \to X^+X^-$ $(X=e,\mu,\pi)$

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

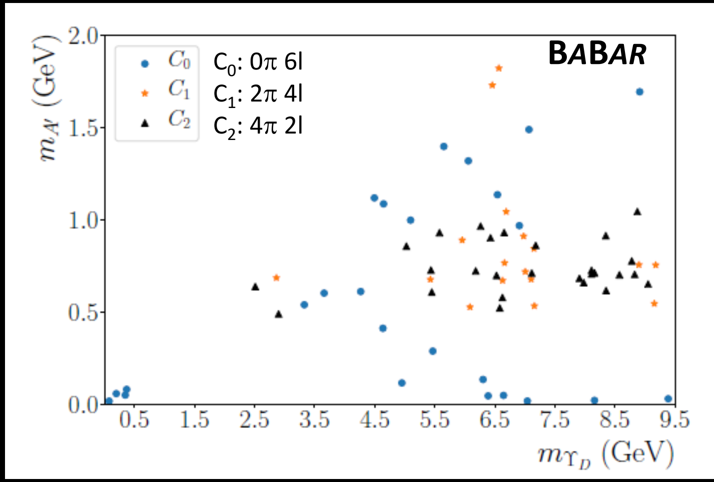
Dark photon lifetime can be large for small values of the kinetic mixing ε and mass $\to$ prompt and displaced vertex analyses



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
- Scan the Υ_D – A' mass plane to extract signal

Final Υ_D candidate sample (prompt)



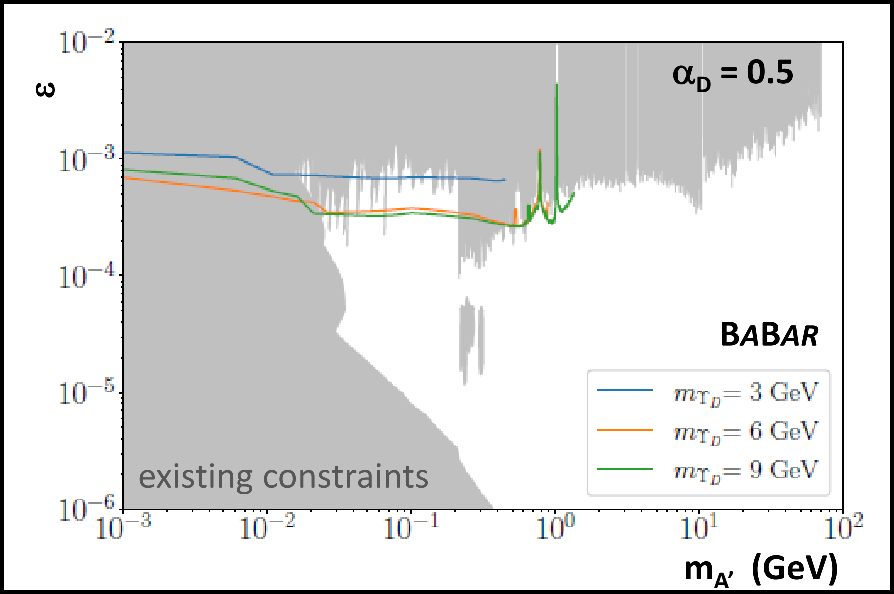
No significant signal is observed

Self-interacting dark matter

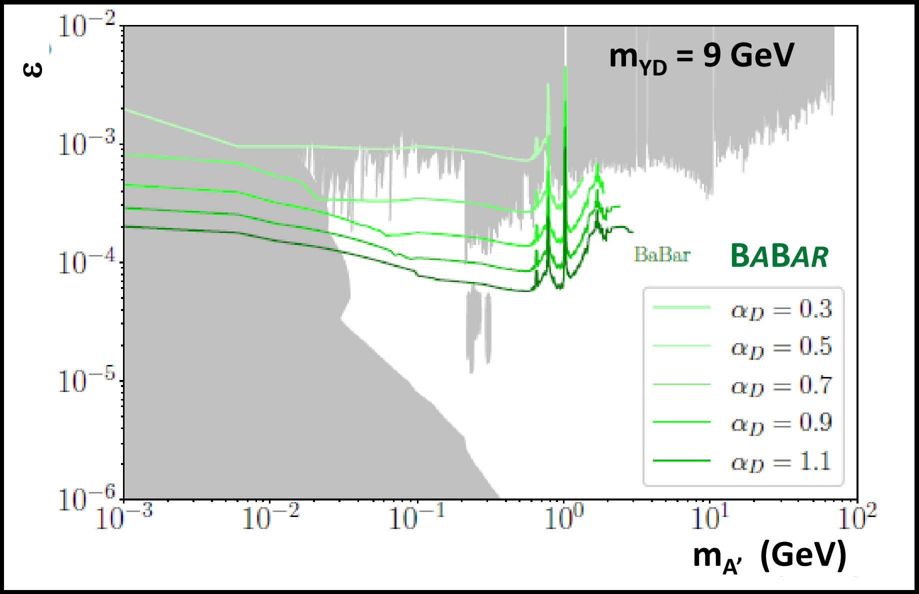
2106.08529, submitted to PRL

Extract 90% CL limit on the kinetic mixing parameter 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

DARK MATTER

SIX-QUARK DARK MATTER

Six-quark dark matter

Search for six-quark state S in $\Upsilon(2S,3S) \to \bar{\Lambda}\bar{\Lambda}S$ decays

A new state of matter and dark matter candidate proposed by G. Farrar (1708.08951):

- 6-quark uuddss state (Q=0, B=2, S=-2, spin zero, flavor singlet)
- tightly bound state
- lifetime is cosmological if mass below 2.05 GeV ($m_\Lambda + m_p$)
- absolutely stable if mass below 1.88 GeV ($2m_p$)

If dark matter consists of nearly equal number of u,d,s quarks, then its formation rate is driven the quark-gluon plasma transition (QGP) to the hadronic phase

Six-quark DM with a mass ~1860-1880 MeV can reproduce the ratio of DM to ordinary matter densities Ω_{DM} / Ω_b within 15%, and predict a total baryon asymmetry in the universe at the level of 10^{-9}, within an order of magnitude of the currently measured value

Search strategy

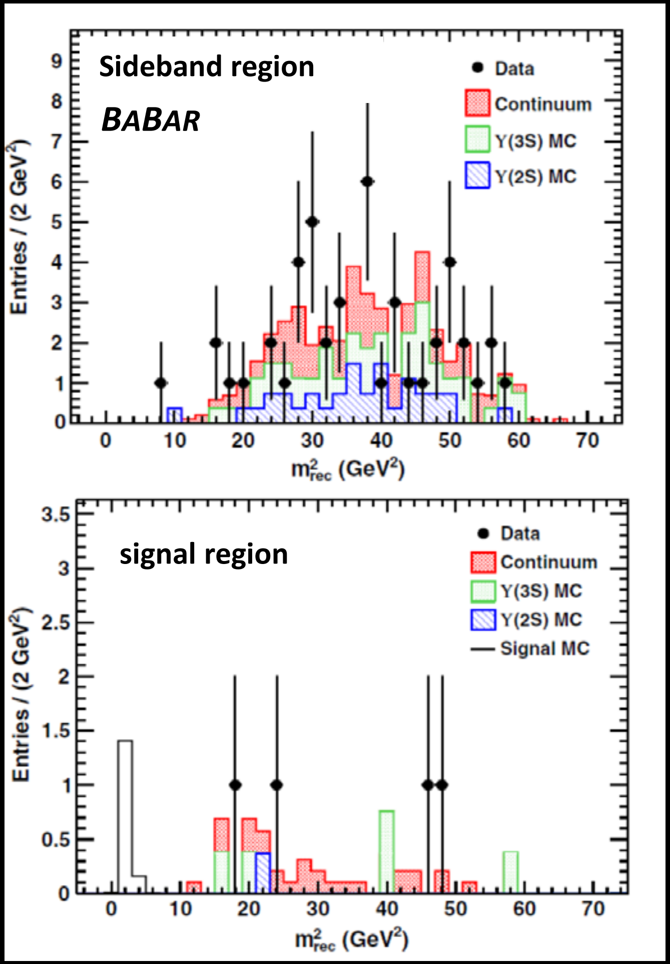
- Search for two same-strangeness Λ decays with missing energy
- Small amount of extra neutral energy in region outside the S direction (E_{extra})
- Search for peak in the recoil mass against the $\Lambda\Lambda$ system

Six-quark dark matter

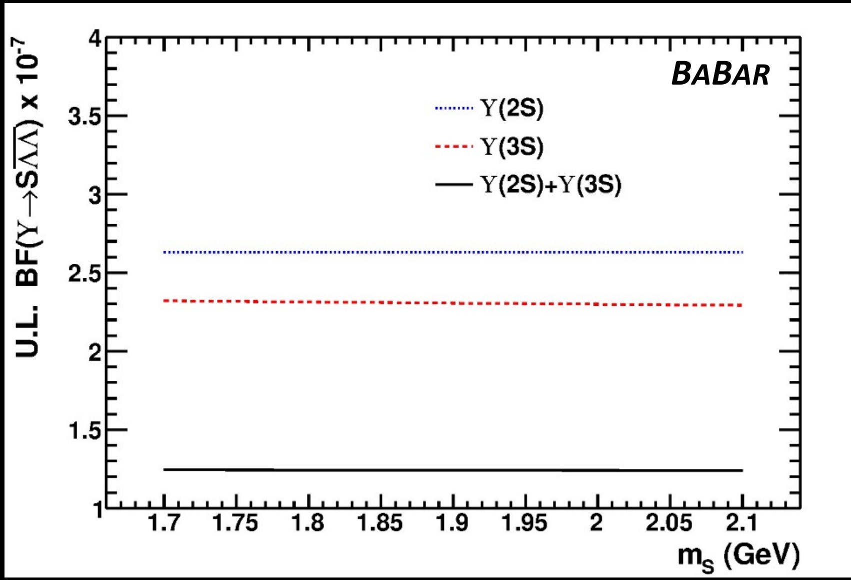
PRL 122 (2019) 072002

Search for six-quark state S in $\Upsilon(2S,3S) \rightarrow \bar{\Lambda}\bar{\Lambda}S$ decays

Recoil mass distribution



Limits on $\Upsilon(nS) \rightarrow \bar{\Lambda}\bar{\Lambda}S$ decay rate



No evidence for six-quark state in Υ(2S,3S) decays, combined limit at the level of $1.2\text{-}1.4 \times 10^{-7}$

EPILOGUE

CONCLUSION

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* / Belle 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 the dark photon in $B^0 \to A'A'$, $A' \to e^+e^-$, $\mu^+\mu^-$, and $\pi^+\pi^-$ decays at Belle, JHEP 04 (2021) 191

Search for muonic dark force

Search for a muonic dark force at BABAR, Phys. Rev. D 94, 011102 (2016)
Search for $Z' \to \mu^+\mu^-$ in the $L\mu-L\tau$ gauge-symmetric model at Belle, arXiv:2109.08596

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 the dark photon and dark Higgs boson at Belle, PRL 114 (2015) 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, submitted to PRL, arxiv:2106.08259

Search for axion-like particle

Search for an Axion-Like Particle in B Meson Decays, submitted to PRL, arXiv:2111.01800

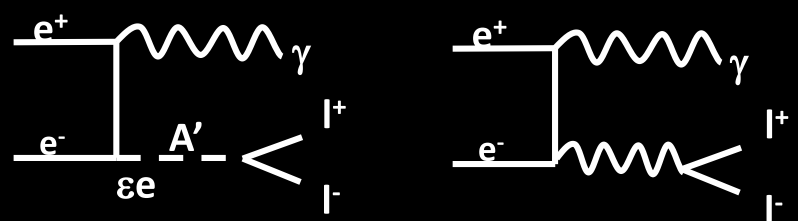
Search for six-quark dark matter

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

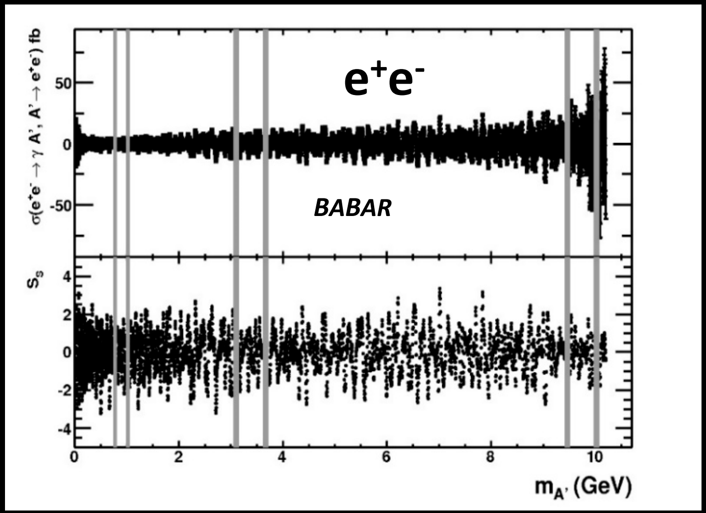
Visible dark photon decays

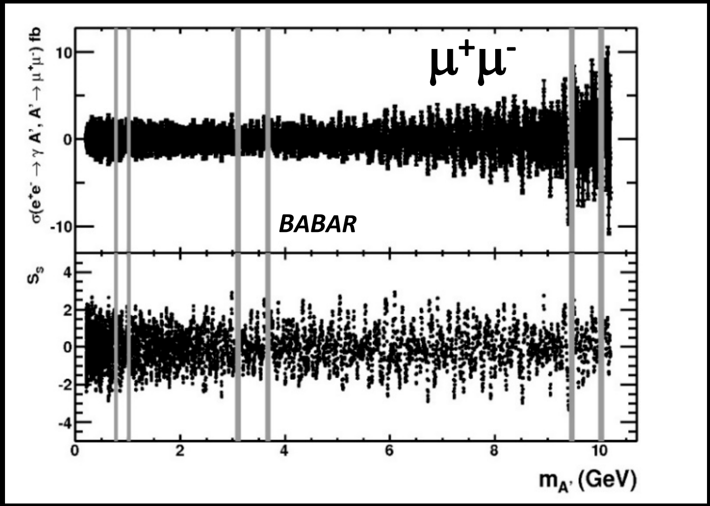
A dark photon can be produced in

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



Signal significance





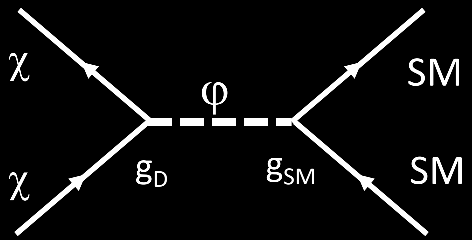
No significant signal found

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

Light thermal dark matter

Freeze-out scenario with light dark matter (χ) requires new light mediator to explain the relic density, or dark matter is overproduced



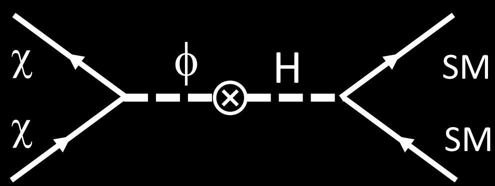
$$< \sigma v >_{relic} \sim \frac{g_D^2\, g_{SM}^2\, m_x^2}{m_\varphi^4} \qquad (m_\varphi \gg m_x)$$

$$m_\varphi^4 \sim \frac{g_D^2\, g_{SM}^2\, m_x^2}{<\sigma v>} \leq \frac{m_x^2}{<\sigma v>} \qquad \text{since } g \leq O(1)$$

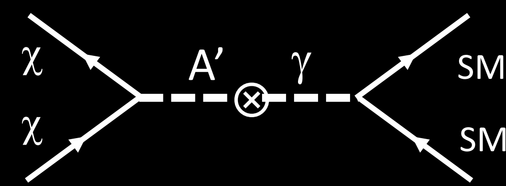
What kind of mediator?

Must be neutral under the SM and renormalizable. Among the simplest choices:

New scalar (ϕ) with Higgs coupling



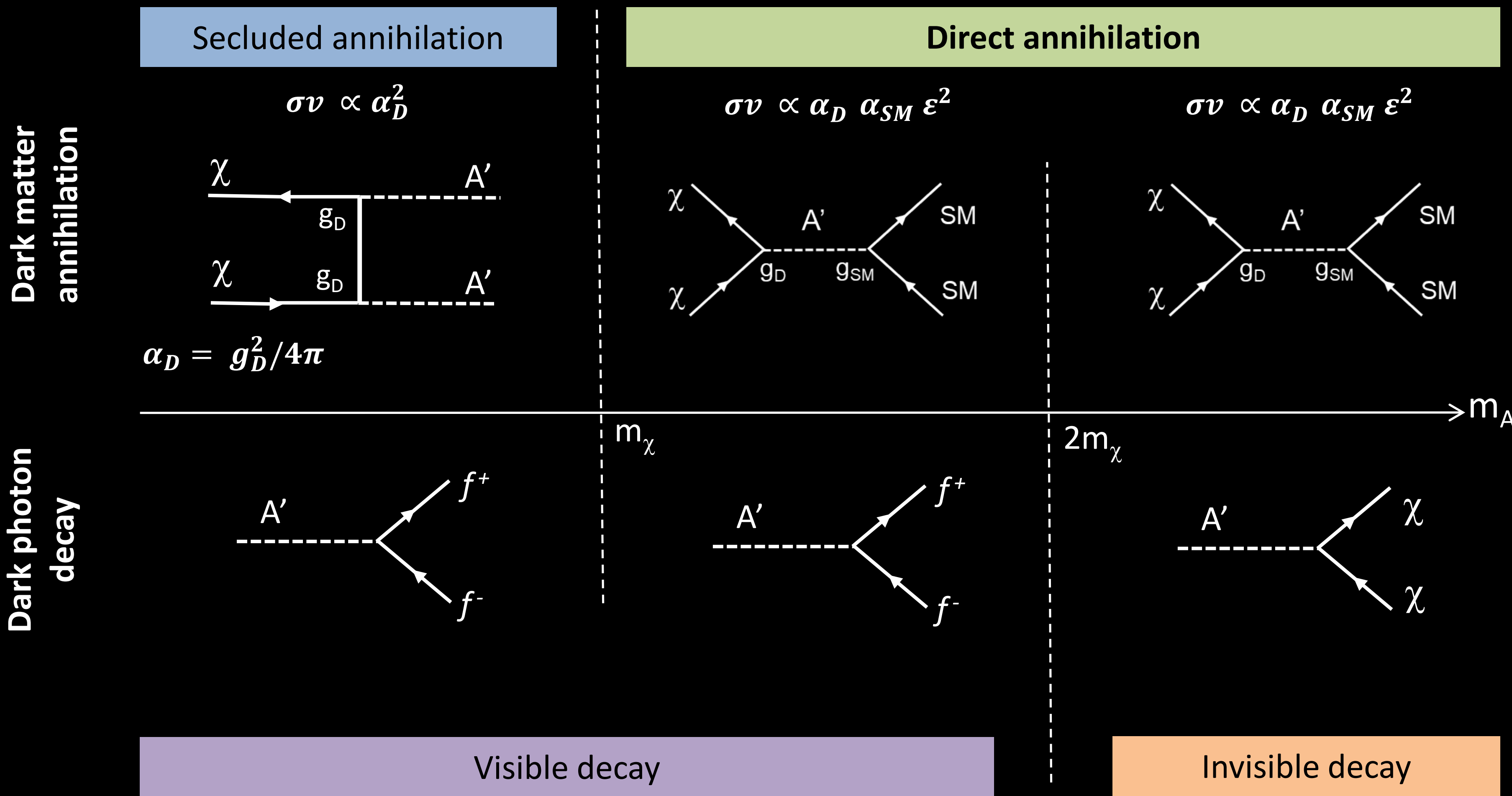
New vector (A') with photon coupling



Naturally realized in the context of dark sectors

Focus on vector portal, much less constrained than the scalar one

Light thermal dark matter



Prompt or displaced decay
Resonance feature

Missing …
… mass
… energy
… momentum

Light thermal dark matter

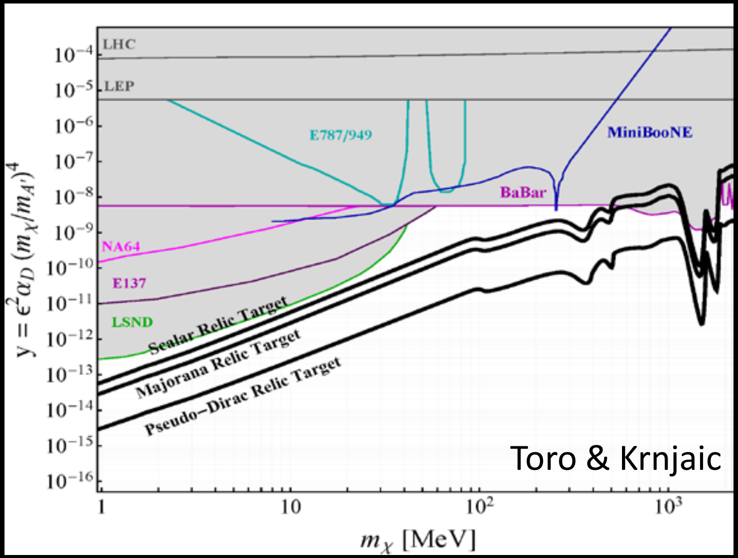
Thermal freeze-out DM with vector portal (direct annihilation)

- Light DM can annihilate into SM particles via dark photon mediator $m_{A'} > m_{DM}$
- Thermal relic density uniquely predicted from DM mass and spin:

$$< \sigma v > \sim \alpha_D \varepsilon^2 \frac{m_x^2}{m_A^4} \sim y \frac{1}{m_x^2}$$

Dimensionless variable $$y = \alpha_D \, \varepsilon^2 \frac{m_x^4}{m_A^4}$$

- Dark matter must be a scalar, Dirac fermion or pseudo-fermion to satisfy CMB constraints



Conservative assumptions (α_D = 0.5 and m_A/m_χ = 3) made for plotting constraints from missing mass / momentum / energy experiments.

Definitive predictions (targets) as a function of mass and particle type !!!

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 $\Upsilon(1S)$ mass for the $\Upsilon(2S)$ and $\Upsilon(3S)$ dataset to reject $\Upsilon(2S,3S) \rightarrow \pi\pi\ \Upsilon(1S)$, $\Upsilon(1S) \rightarrow \mu\mu$
- Kinematic fit imposing beam-energy constraint is finally performed, but no constraints on the χ^2 are applied

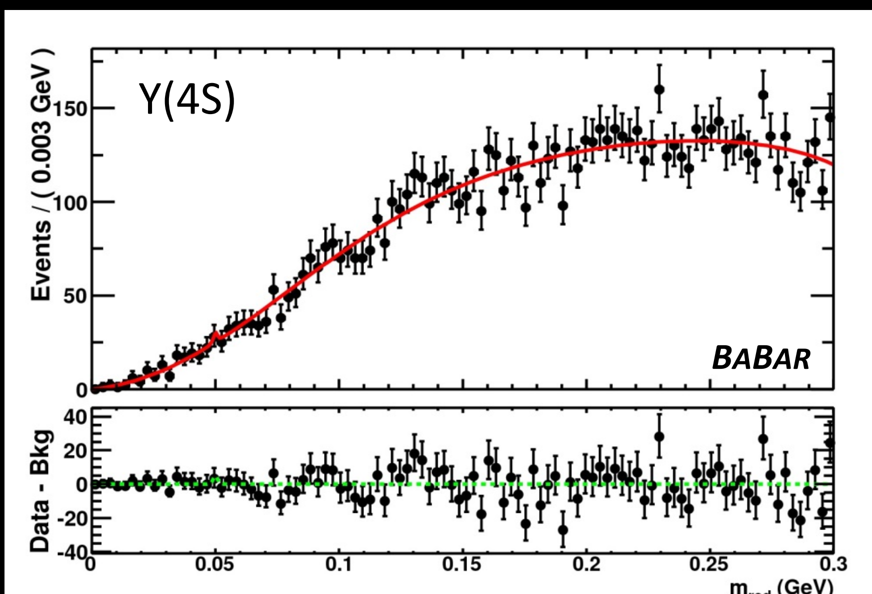
We perform a blind analysis, the selections criteria are optimized on a small subset (5%) of the data, which is subsequently discarded

Muonic dark force

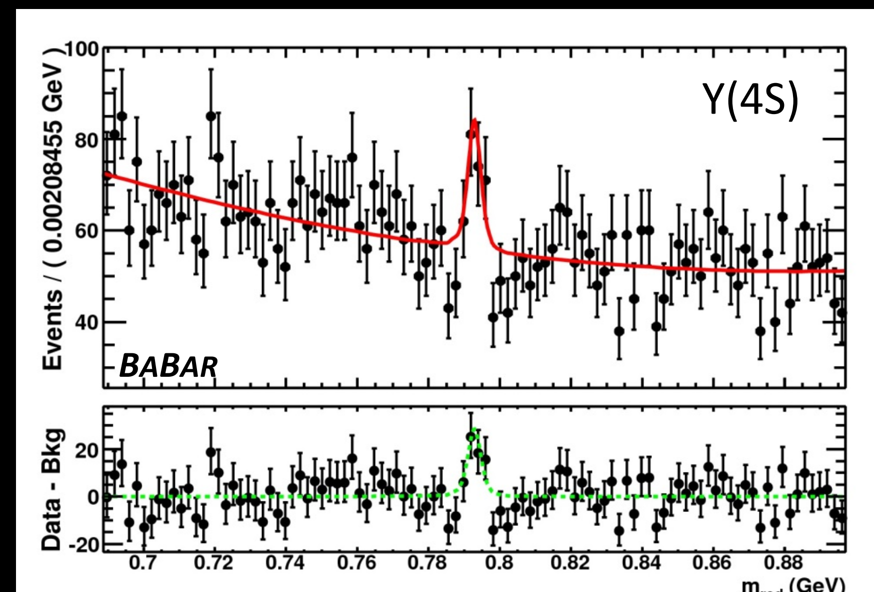
We extract the signal separately for the data at the Υ(4S), Υ(3S) and Υ(2S) by performing a series of fits to the reduced dimuon mass for each sample

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

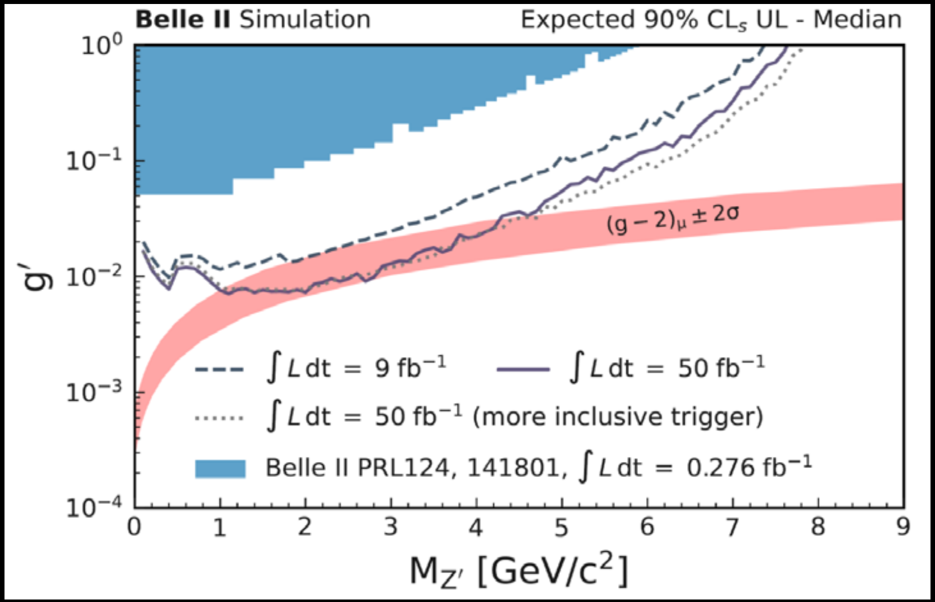


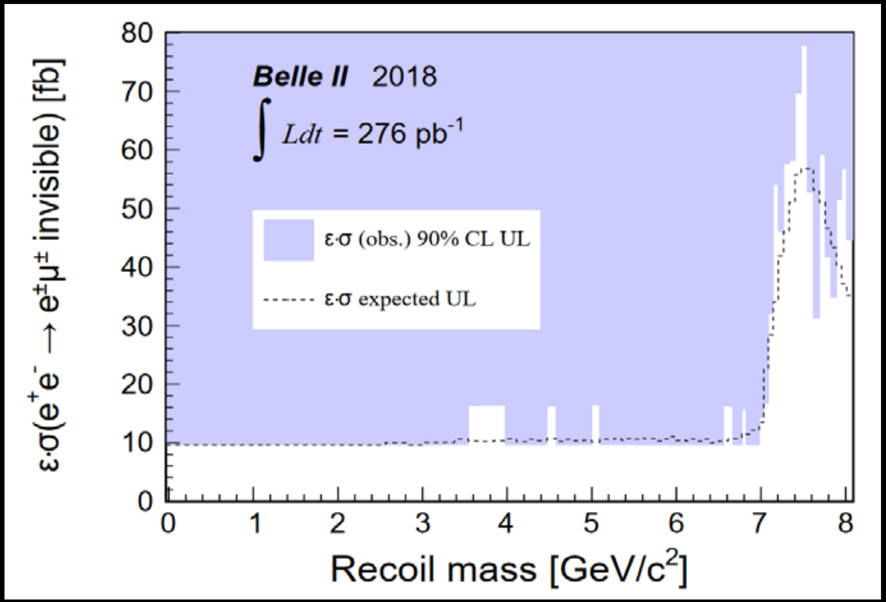
Local /global significance: 4.3σ /1.6σ

Muonic dark force

Search for invisible Z' decays at Belle II

PRL 124 (2020) 141801

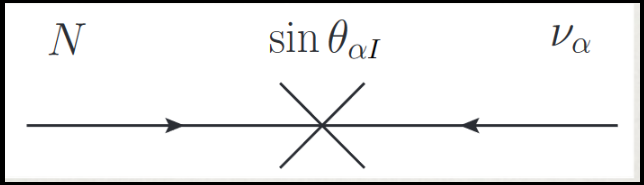




Probing the low mass region is quite challenging at e+e- collideres!

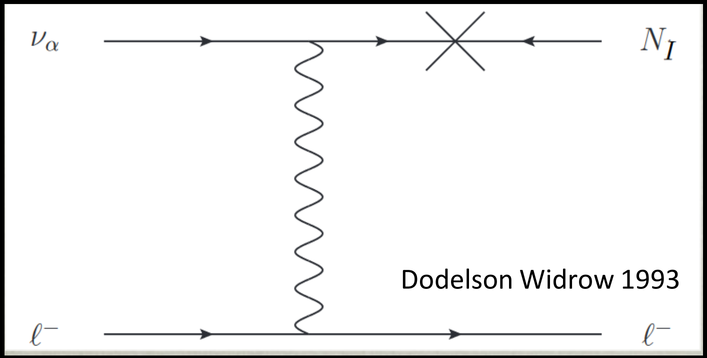
Sterile neutrino dark matter

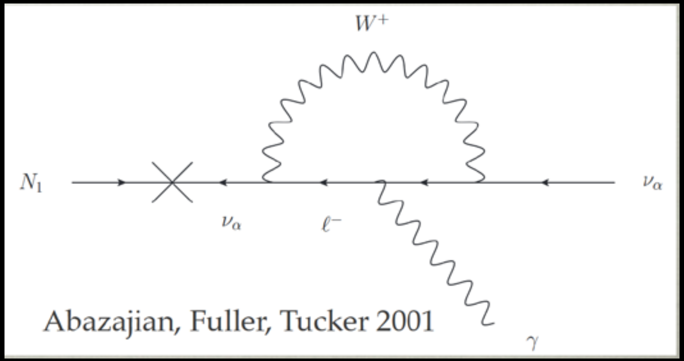
Dark matter model of sterile neutrino N (SM gauge singlet). After EWSB, Standard Model neutrinos get a (small) mass and the SM & sterile neutrino mix



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

Sterile neutrino live and die by this mixing

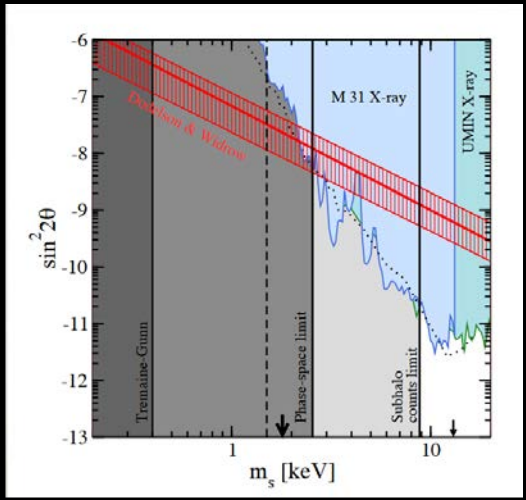




Can the mixing angle be large enough to produce enough sterile neutrinos to account for dark matter and small enough to suppress decays?

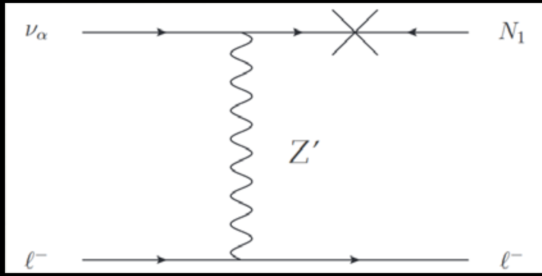
Sterile neutrino dark matter

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



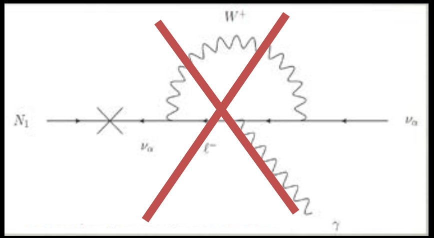
Horiuchi *et al.* 2013

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



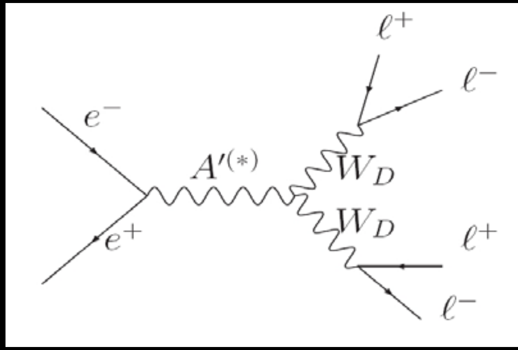
New dark force coupling to 2^{nd} / 3^{rd} generation of leptons ($L\mu$-$L\tau$, anomaly free). The corresponding gauge boson Z' must be light – O(GeV) or less – to avoid constraints from magnetic dipole measurements and provide the correct rate enhancement

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



Dark gauge bosons

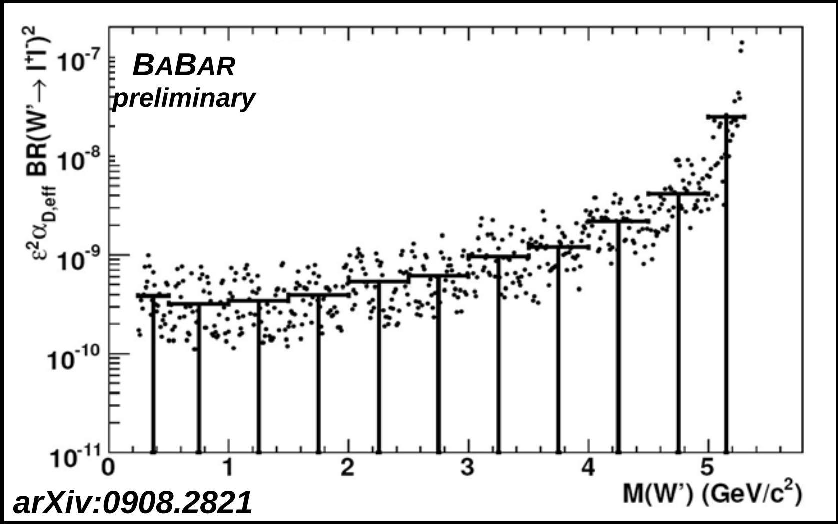
Search for generic dark gauge bosons



- The simplest extension to a non-Abelian case is SU(2)xU(1) with 4 bosons: A', W_D, W_D' and W_D''
- Produce a pair of dark bosons through an off-shell A':

  $e^+e^- \to A'^* \to W_D W_D'$, $W_D^{(')} \to e^+e^-, \mu^+\mu^-$
- Process suppressed only by $\alpha_D\varepsilon^2$ where $\alpha_D = g_D^2 / 4\pi$ is the dark sector coupling constant
- Search for two dileptonic resonances with similar mass
- No signal observed, set limits for product $\alpha_D\varepsilon^2$ at the level of $10^{-10} - 10^{-7}$
- Limits on $\varepsilon^2 < 10^{-7} - 10^{-3}$ assuming α_D= 1/137

Limits on $\alpha_D\varepsilon^2$ x BF($W \to l^+l^-)^2$ for $m_W \approx m_{W'}$



Dark Higgs boson

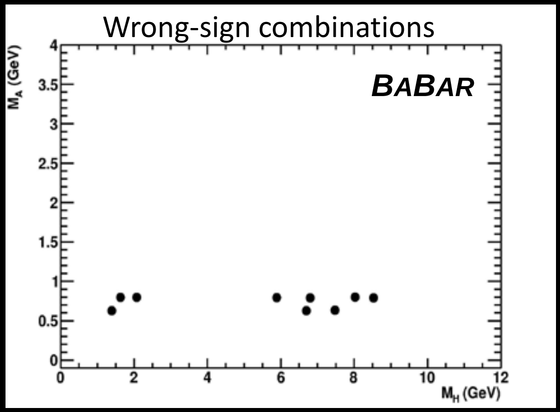
Search for dark Higgs boson h'

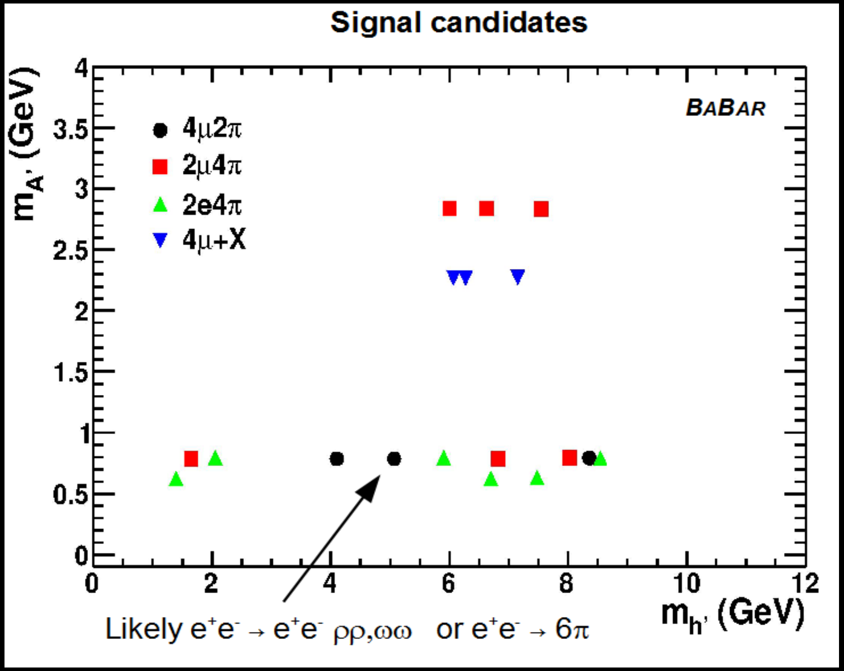
Analysis overview

- 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



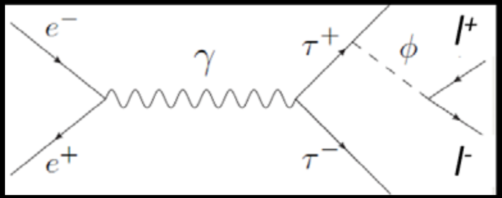


Distribution consistent with pure background hypothesis

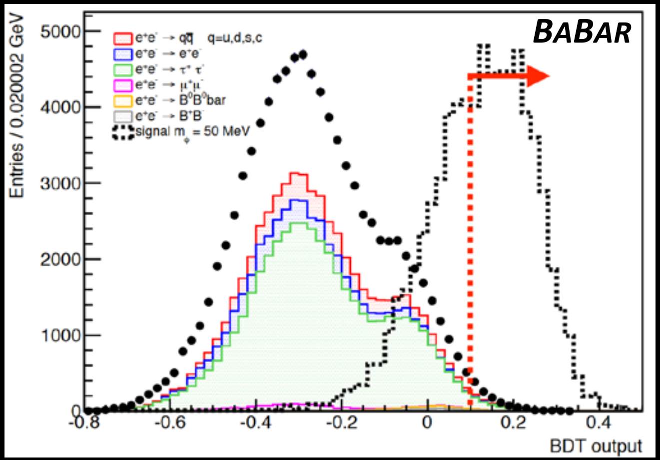
Leptophilic dark scalar

Search for a leptophilic dark scalar ϕ_L

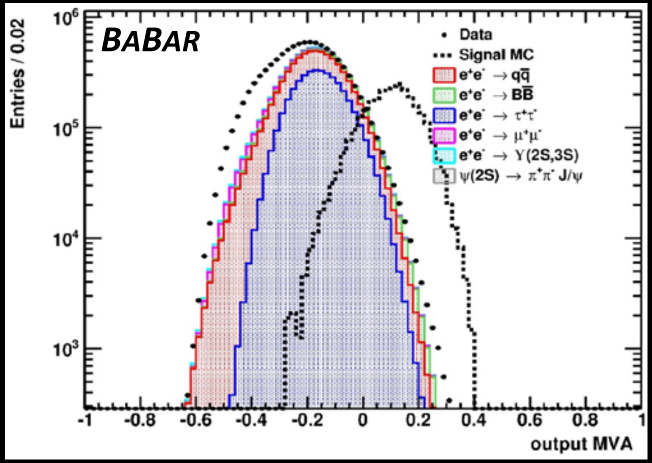
$e^+e^- \rightarrow \tau^+\tau^- \phi_L$, $\phi_L \rightarrow l^+l^-$ (l=e,μ)



Dielectron BDT (prompt)



Dimuon BDT (prompt)



Analysis overview

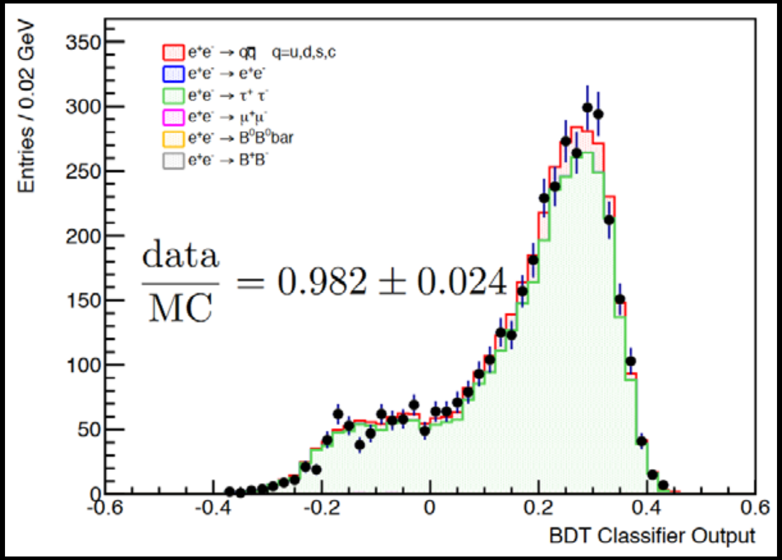
- Consider all 1-prong decays of the tau
- Train BDT to increase signal purity (see backup slide)
- Optimize analysis for each final state and prompt or long-lived ϕ_L
- Data/MC discrepancy due to non-modelled MC components (two-photon, ISR,...) but this discrepancy has very limited impact on the results

Leptophilic dark scalar

Validate efficiency with control samples and derive corresponding corrections

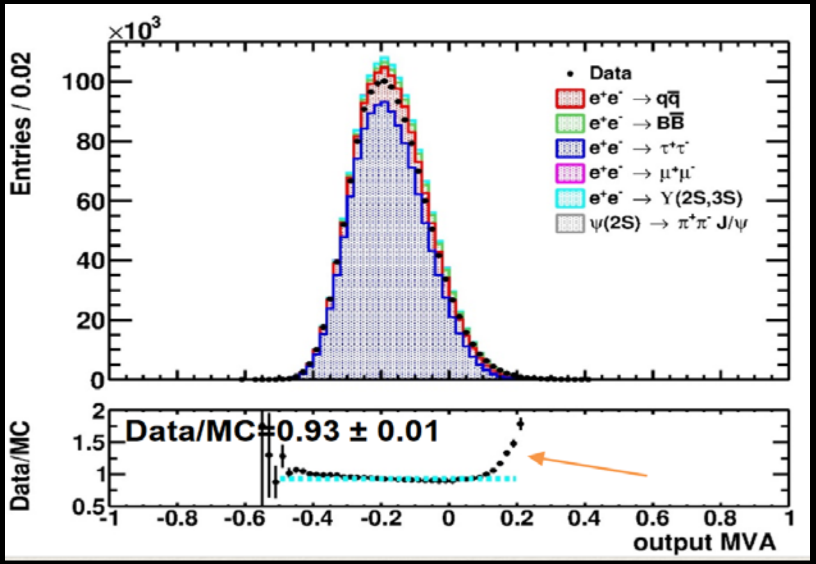
Dielectron

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

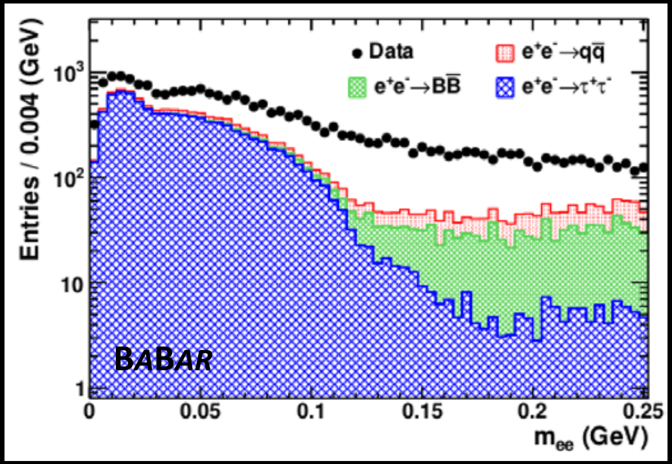


Data globally well reproduced by MC predictions, corrections between 2-7%

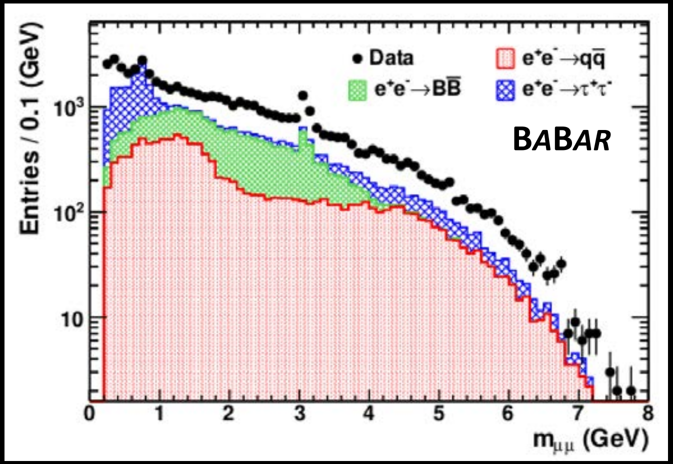
Leptophilic dark scalar

Final mass spectra for each final state and lifetime

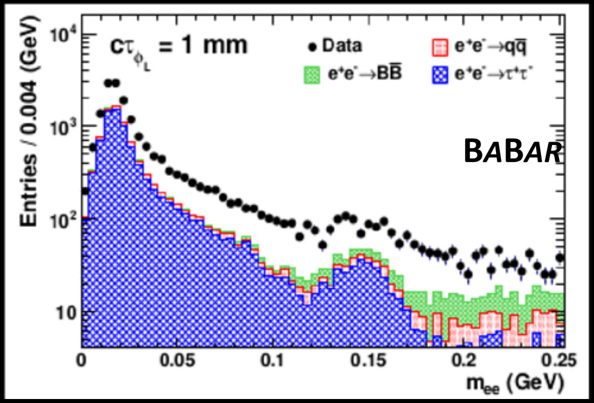
Dielectron (prompt)

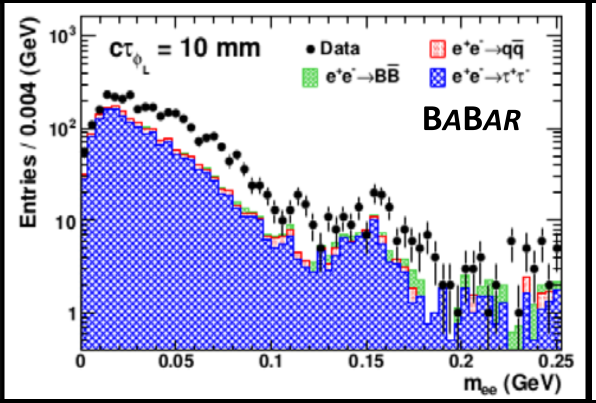


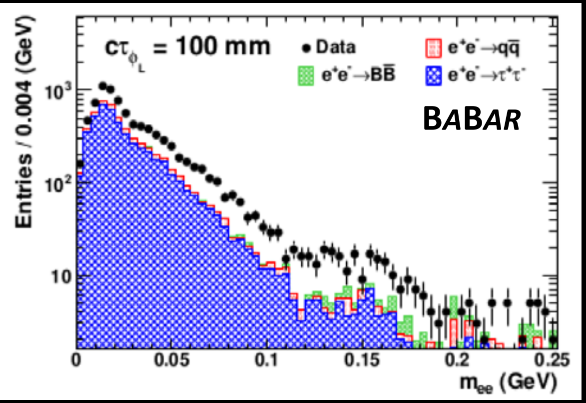
Dimuon (prompt)



Dielectron (displaced)

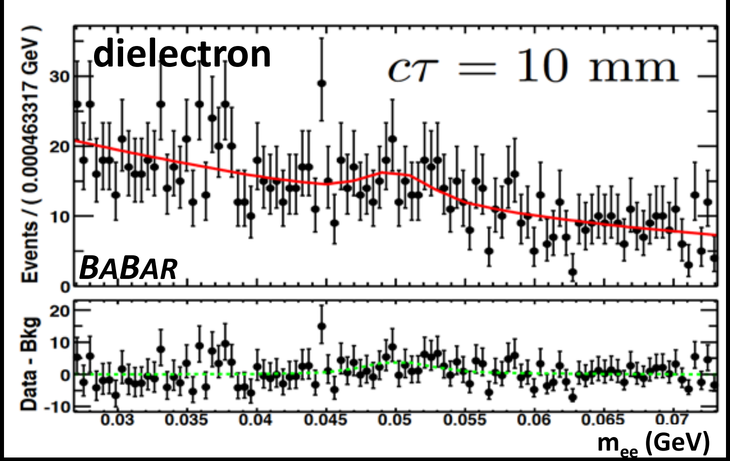


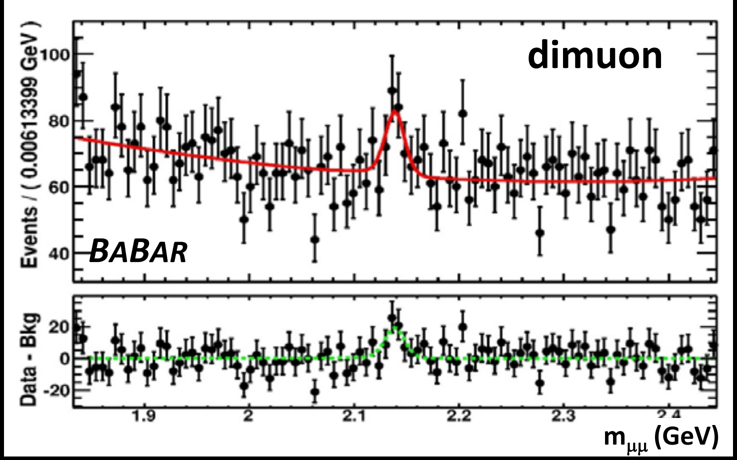




Leptophilic dark scalar

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:

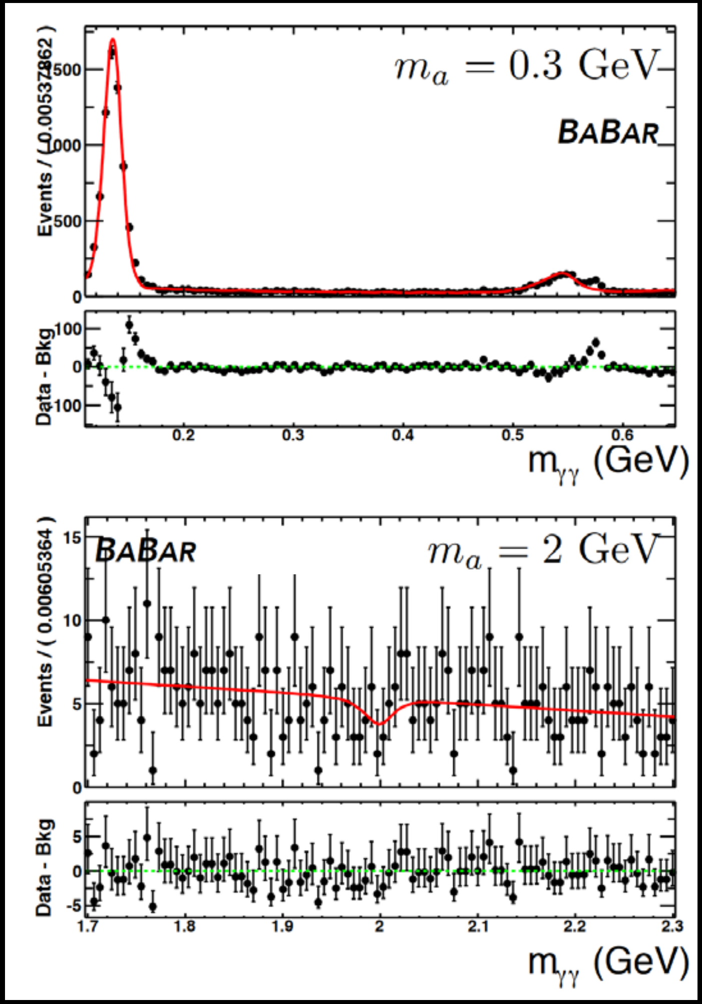
- Signal modeled from signal MC and interpolated between simulated mass points
- Continuum background modelled by second or third order polynomials
- Peaking background (π^0, J/ψ, $\psi(2S)$) modelled from bkg MC

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:

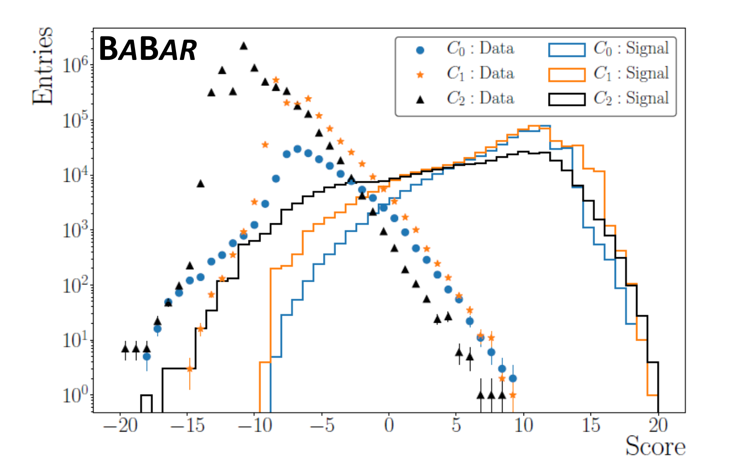
- Signal modeled from signal MC and interpolated between simulated mass points
- Continuum background modelled by first or second order polynomials
- Peaking background modelled from bkg MC

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%

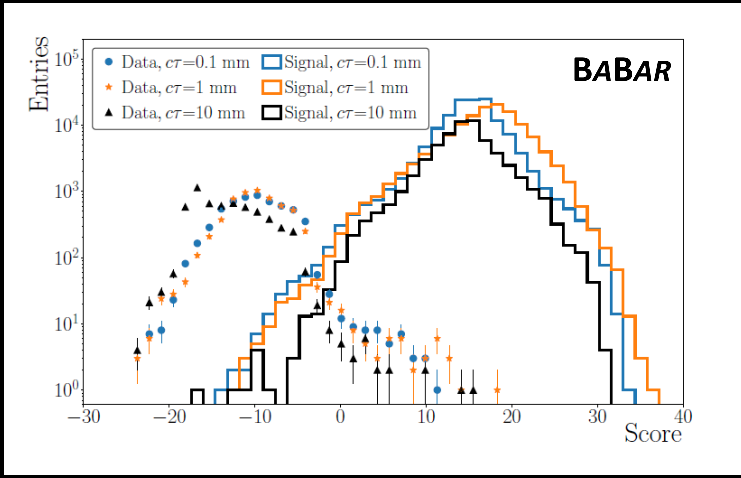
Signal efficiency varies between 2%-33%

Self-interacting dark matter

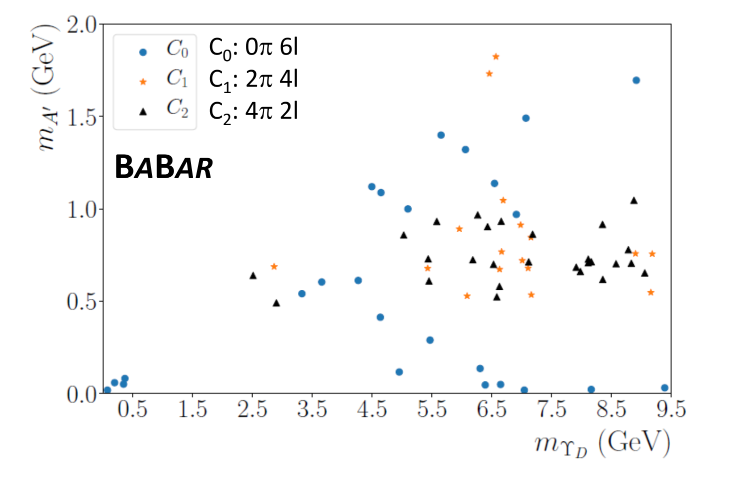
MVA score distributions (prompt)



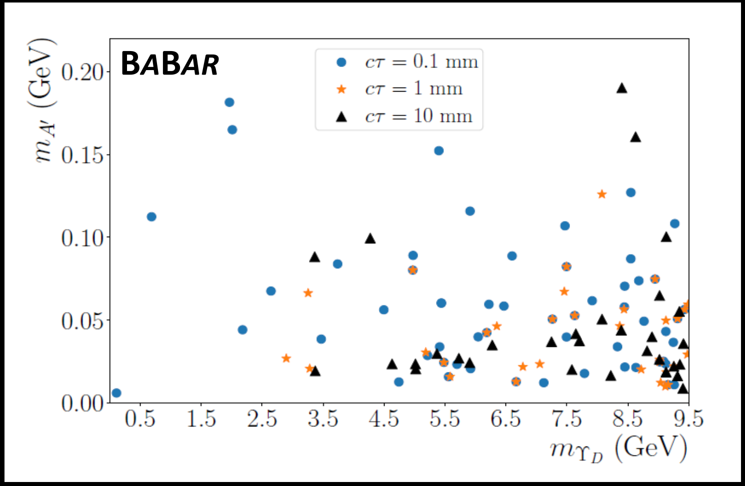
MVA score distributions (displaced)



Final Υ_D candidate sample (prompt)



Final Υ_D candidate sample (displaced)



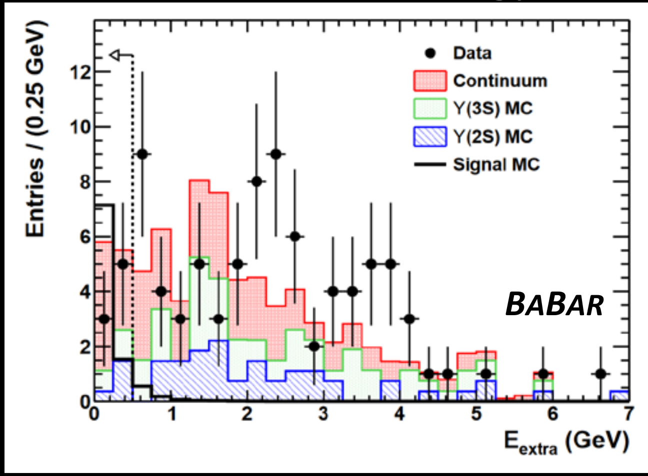
Six-quark dark matter

Search for Υ(2S,3S) → $\overline{\Lambda}\overline{\Lambda}$S

Analysis overview

- Search for two same-strangeness $\Lambda \to p\pi$ decays with missing energy
- Select 4 charged tracks with two (anti-) protons
- Quality cuts on Λ (flight significance > 5σ, point back to IP)
- Kinematic fit to improve mass resolution
- Small amount of extra neutral energy in region outside the S direction (E_{extra})
- Define signal region (E_{extra} < 0.5 GeV) and sideband region (E_{extra} > 0.5 GeV)

Extra neutral energy



pπ mass distribution