Dark Sector Physics at *BABAR*

Steven Robertson
Institute of Particle Physics
&
University of Alberta

On behalf of the *BABAR* Collaboration

INSTITUTE OF PARTICLE PHYSICS

Lake Louise Winter Institute
Chateau Lake Louise, Alberta
Feb 19 – 25, 2023

UNIVERSITY OF ALBERTA

Dark sectors

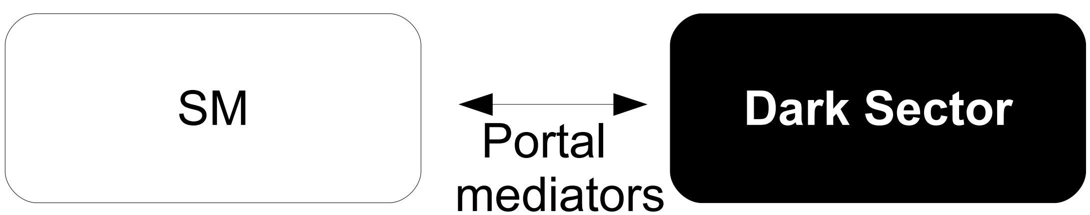
Dark matter may carry charges for non-SM gauge interactions, possibly acquiring mass via dark sector Higgs etc.

- Effective Field Theory (EFT) provides a number of “portals” to access this dark sector:

$$\mathcal{L} = \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{(\mathrm{SM})} \mathcal{O}_l^{(\mathrm{med})} = \mathcal{L}_{\mathrm{portals}} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

$$= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

Vector portal — Higgs portal — Neutrino portal



→ Dark sector can be probed via mixing of the portal mediators with SM particles

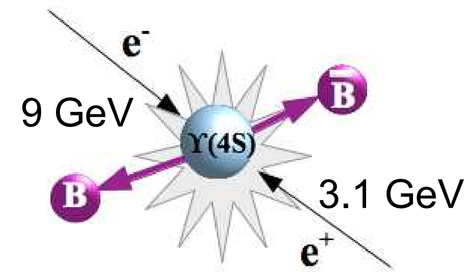
Outline

- Search for an Axion-Like Particle — Phys. Rev. Lett. 128, 131802 (2022).
- Search for B Mesogenesis — arXiv:2302.00208 [hep-ex]
- Search for Darkonium — Phys. Rev. Lett. 128 021802 (2022)

BABAR experiment

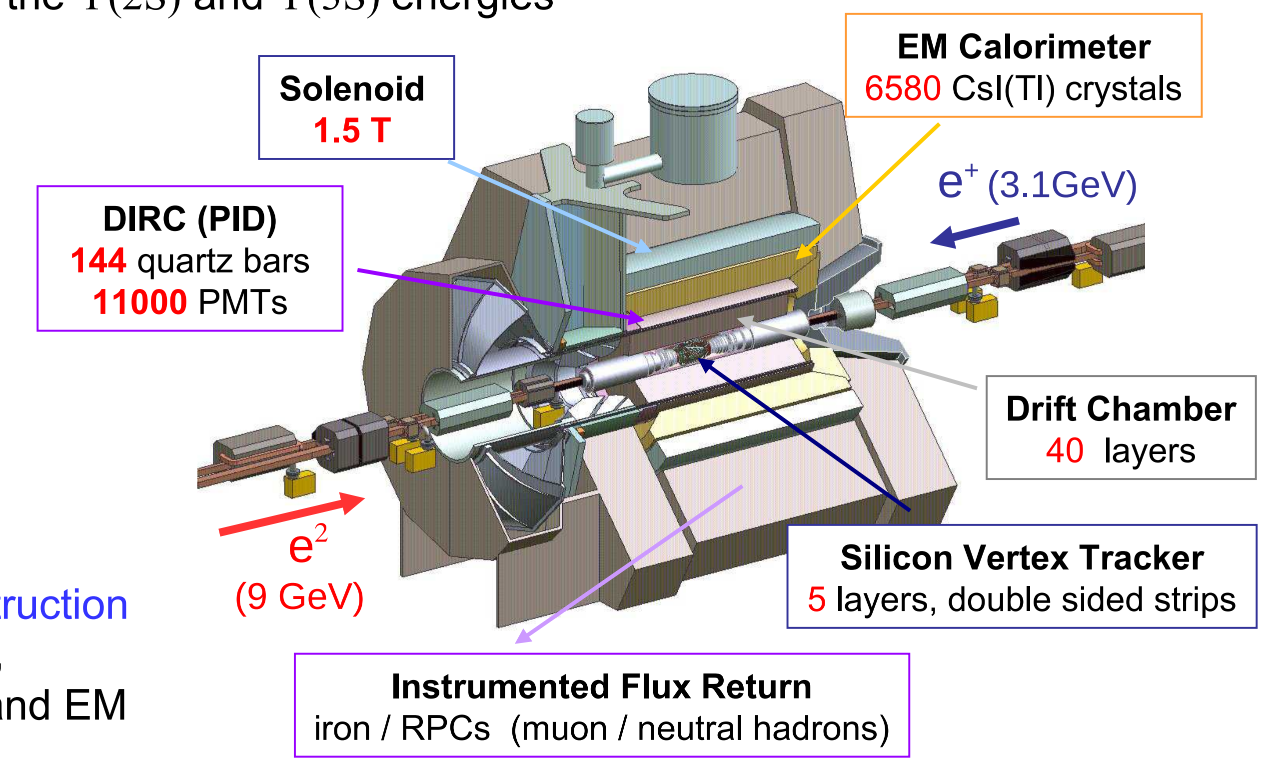
Asymmetric B Factory experiment at the SLAC National Accelerator Laboratory

- *BABAR* collected data from1999 until 2008:
  - **432 fb^{-1} $\Upsilon(4S)$ "on peak"** (~470 x 10^6 $B\bar{B}$ pairs)
  - 53 fb^{-1} non-resonant "off peak"
  - Smaller samples at the $\Upsilon(2S)$ and $\Upsilon(3S)$ energies



Process	σ (nb)
$b\bar{b}$	1.1
$c\bar{c}$	1.3
Light quark $q\bar{q}$	~2.1
$\tau^+\tau^-$	0.9
e^+e^-	~40

Optimized for B vertex reconstruction and momentum measurement, particle identification of K - π and EM calorimetry



Dark sector @ *BABAR*

B factories are extremely well suited to dark sector studies:

- **Clean** e^+e^- environment with relatively **hermetic** detector coverage; good missing energy reconstruction
- Potential to **reconstruct displaced vertices** from long-lived particles in $\sim 1\text{mm} < c\tau < \sim 10\text{cm}$ ($\sim 100\text{cm}$), with $c\tau > \sim 3\text{m}$ being "missing energy"
- **Inclusive trigger** for ($N_{tracks} > 3$) hadronic events, but low-multiplicity searches require dedicated triggers
- **High statistics** "precision frontier" data samples

Dark sector production mechanisms:

- Production of on-shell dark bosons via $\mathbf{e^+e^- \to \gamma\, Z'}$ "**radiative**" and $\mathbf{e^+e^- \to f\, f\, Z'}$ "**-strahlung**" processes
- Light dark sector particles can be produced in **decay**s of B and D mesons

Axion-Like Particles

Many extensions of SM include spontaneously-broken global symmetries, resulting in pseudo-Goldstone bosons known as **Axion-Like Particles (ALPs)**

- Can potentially help resolve issues of naturalness of SM parameters but may also serve as mediators to dark sectors
- ALPs (a) couple primarily to pairs of SM gauge bosons.

coupling

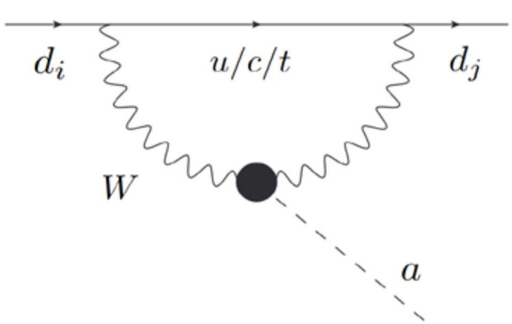
$$\mathcal{L} = -\frac{g_{aW}}{4} a W^b_{\mu\nu} \tilde{W}^{b\mu\nu}$$

$SU(2)_W$ field strength tensor

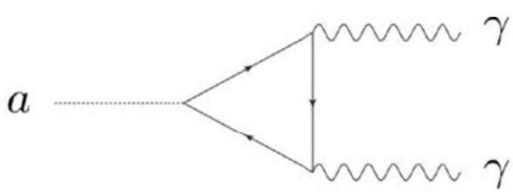
E. Izaguirre et al., PRL 118 (2017) 111802

Can be produced in FCNC B decay processes, specifically $\mathbf{B \to Ka}$

- $\mathbf{a \to \gamma\gamma}$ with nearly 100% BF for $m(a) < m(W)$
- For low axion mass and small coupling, the axion lifetime can become “long”, i.e. non-prompt.



$$\tau \sim 1 / m_a^3 \, g_{aW}^2$$



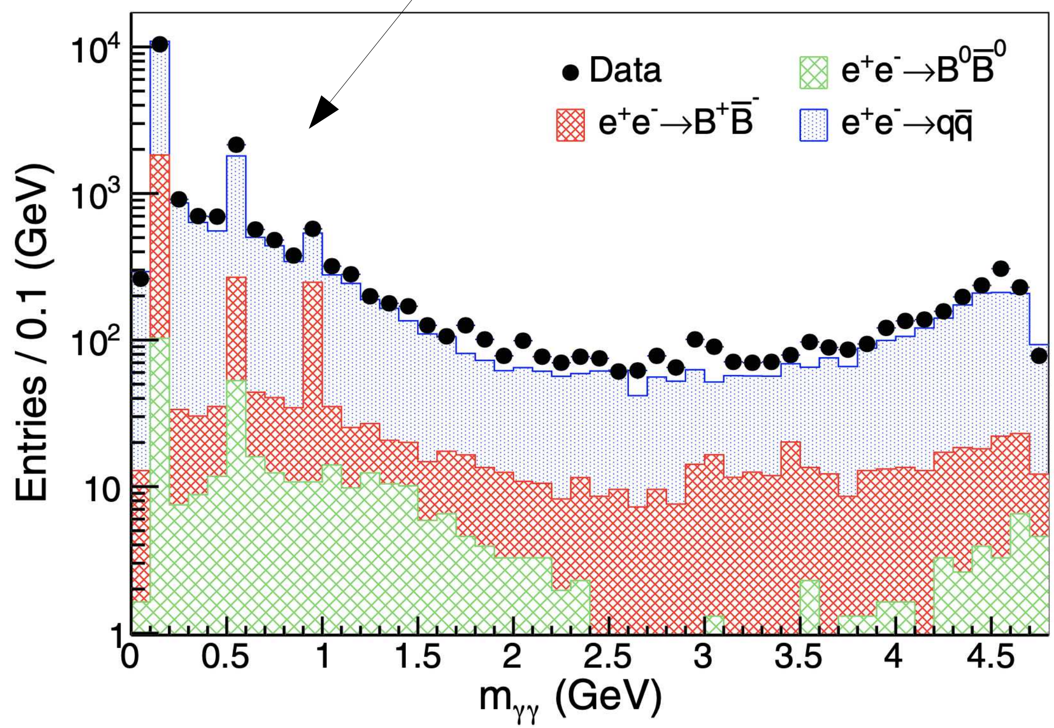
Axion-Like Particles

Phys. Rev. Lett. 128, 131802 (2022)

BABAR searches for ALPs in $B^+ \rightarrow K^+a$ $(a \rightarrow \gamma\gamma)$ in 4.72 x 10^8 $B\bar{B}$ pairs (424 fb^{-1}) collected at the $\Upsilon(4S)$ energy.

- Exclusively reconstruct B meson via well-identified K and photons, then "bump hunt" in the reconstructed $\gamma\gamma$ mass
- Kinematic fit to improve resolution
- Boosted decision trees using kinematic variables from "rest of event" to suppress continuum $e^+e^- \rightarrow qq$ $(q = u,d,s,c)$ and BB backgrounds
- Analysis optimized and validated on 8% of data set (subsequently discarded), then search performed on remainder of (blinded) dataset

peaking contributions from π^0, η, η' η_c



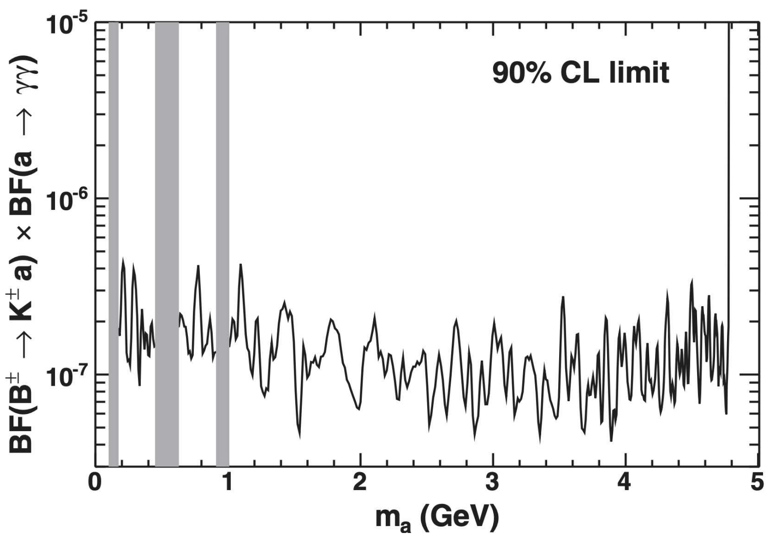
Axion-Like Particles

Phys. Rev. Lett. 128, 131802 (2022)

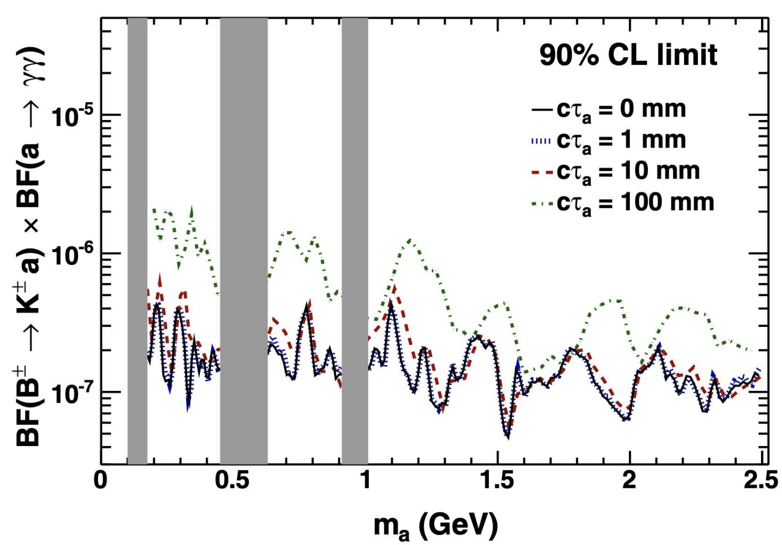
Scan $m_{\gamma\gamma}$ with steps equal to the signal mass resolution (~ 8 – 14 MeV)

- 461 signal mass hypotheses fit with unbinned ML fits to a hypothetical signal peak + smooth background over range of ~24 – 60 σ around each hypothesis

Prompt decay hypothesis



Displaced decay hypothesis

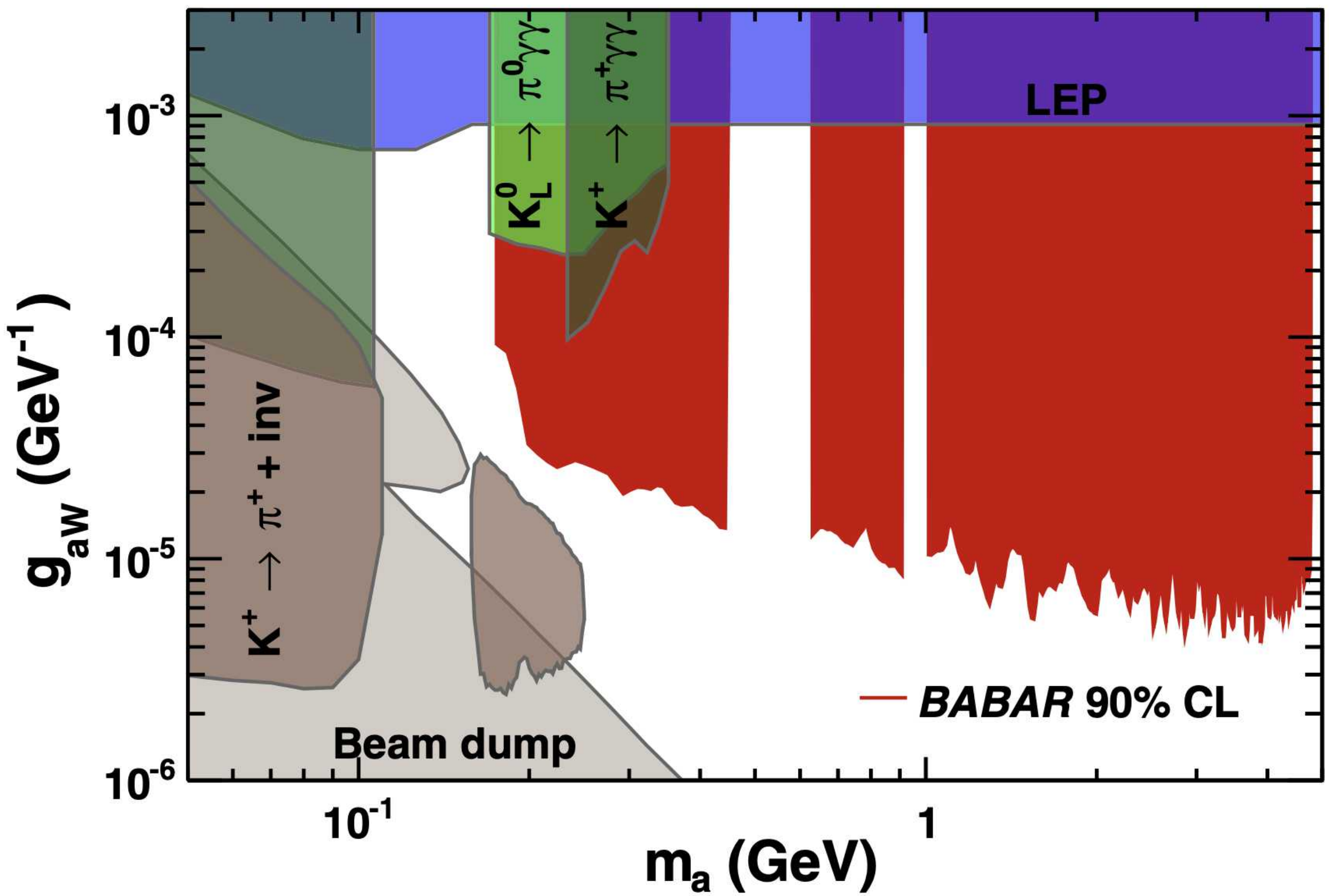


In low mass region ($m_{\gamma\gamma}$ < 2.5 GeV) the signal sensitivity is also assessed for non-prompt signal hypotheses: $c\tau$ = 1, 10, 100mm

- displaced vertex not reconstructed, but ALP resolution degraded
- No significant excess observed

Axion-Like Particles

Phys. Rev. Lett. 128, 131802 (2022)



Set 90% CL exclusion bounds on the ALP coupling g_{aW}

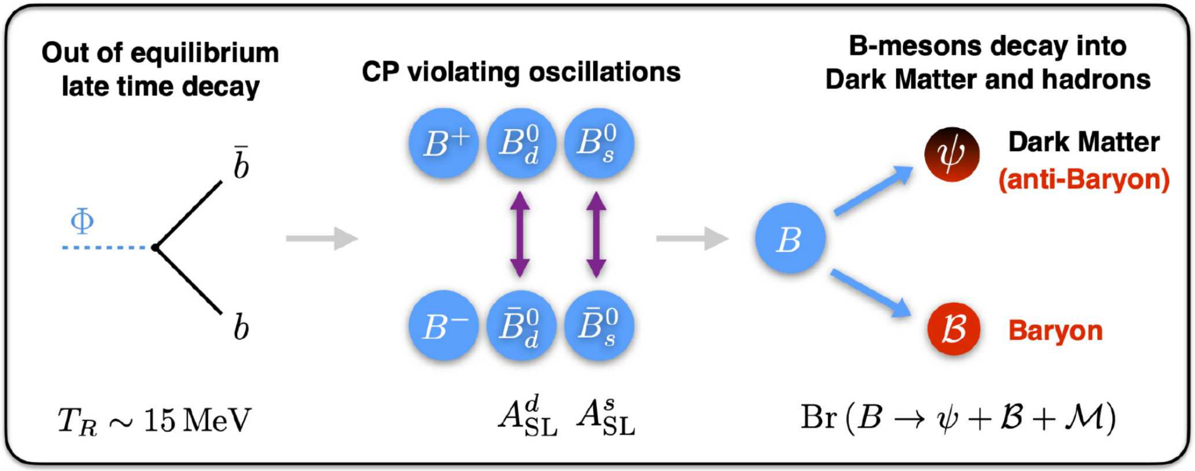
- Improvements of up to two orders of magnitude over previous limits

Search for B Mesogenesis

Mechanism proposed to explain dark matter abundance and Baryon Asymmetry of the Universe (BAU)

- Light dark-sector anti-baryon and a TeV-scale color-triplet bosonic mediator
- BAU results from B meson decays into a a baryon and a dark sector anti-baryon ψ_D (+ light mesons)
- Visible and dark sectors have equal but opposite matter-antimatter asymmetries, but total baryon number is conserved

G. Elor, M. Escudero and A. E. Nelson, Phys. Rev. D 99, 035031 (2019).
G. Alonso-Alvarez, G. Elorand, and M. Escudero, Phys.Rev. D 104, 035028 (2021).

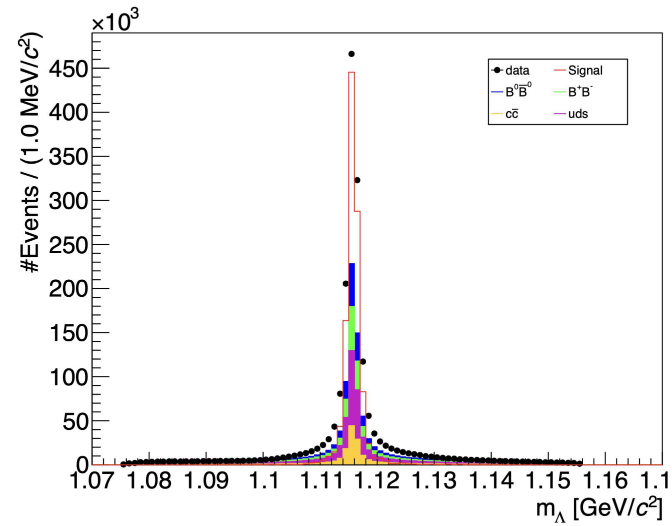


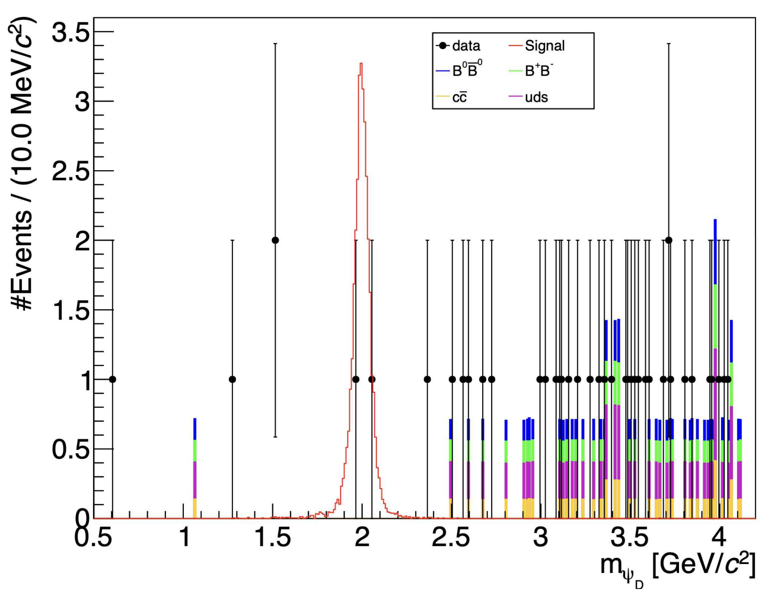
Search for B Mesogenesis

arXiv:2302.00208 [hep-ex]

BABAR search for $B \to \Lambda\, \psi_D$

- Invisibly decaying dark sector ψ_D escapes detection
- Reconstruct accompanying B meson from $\Upsilon(4S) \to B\bar{B}$ and look for signal signature in the remainder of the event
- Kinematic fit of $\Lambda \to p\, \pi$, including displaced vertex significance requirement

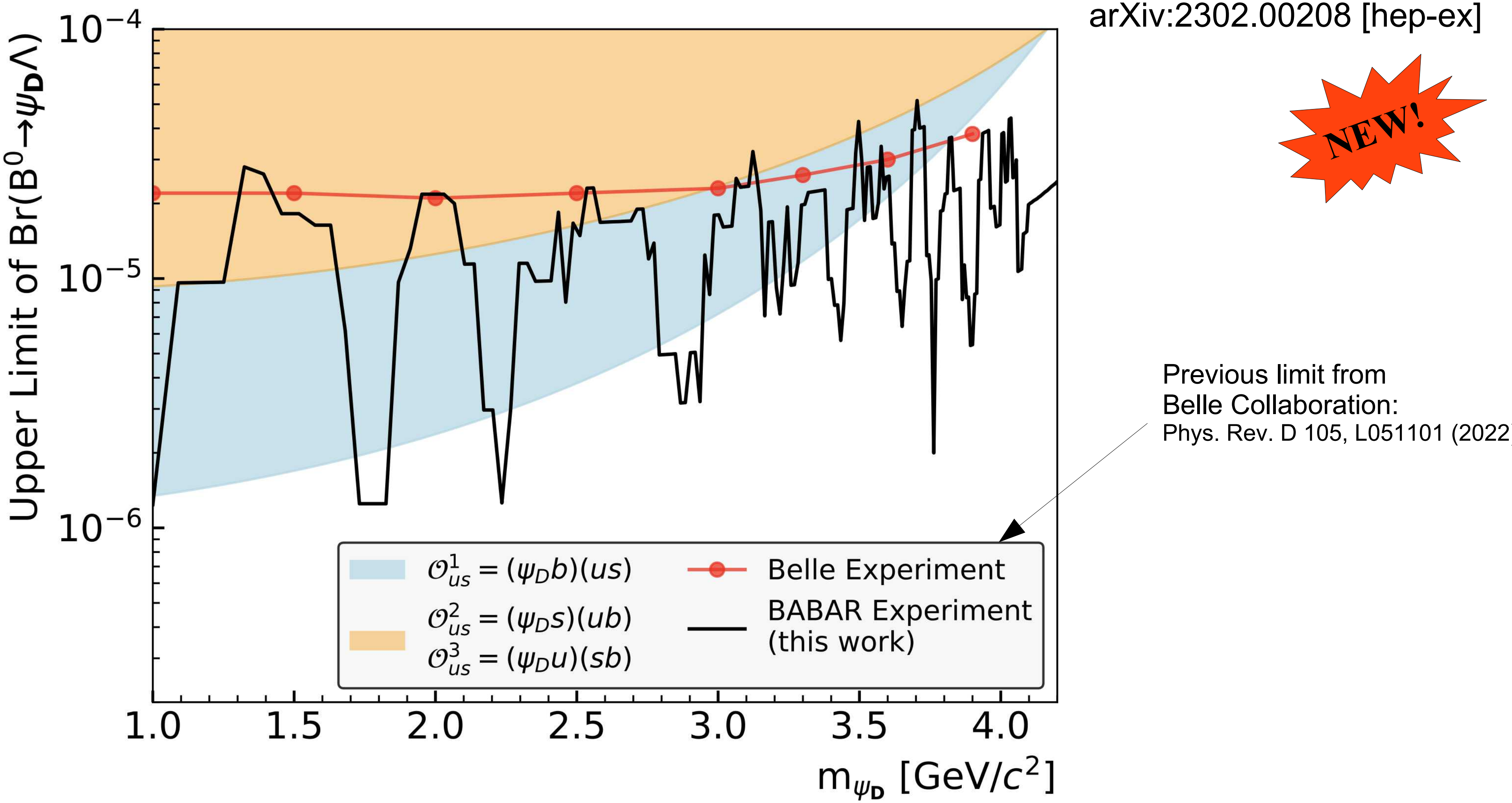




- Reconstruct ψ_D from the missing energy 4-vector
- BDT used to suppress residual combinatorial backgrounds from $q\bar{q}$ and $B\bar{B}$ decays
- Background estimated directly from m_{ψ_D} sideband data
- 193 mass hypotheses tested

Search for B Mesogenesis

arXiv:2302.00208 [hep-ex]



Branching fraction 90% confidence limits obtained at level of $10^{-6} – 10^{-5}$

- Exclude large fraction of parameter space for B mesogenesis

Search for Darkonium

Self-interacting dark matter, i.e. dark matter bound states can arise in simple dark photon models in which the A' couples strongly to the dark matter fermion (χ) via coupling α_D

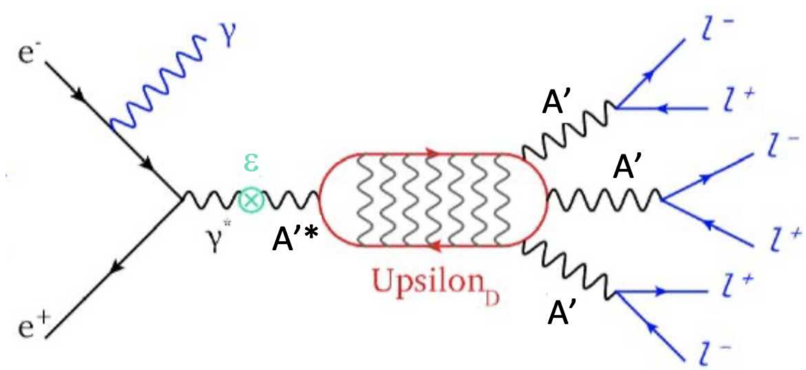
H. An et al., PRL 116 (1026) 151801

- Two lowest bound states are η_D ($J^{PC} = 0^{-+}$) and Υ_D ($J^{PC} = 1^{--}$)
- Dark photon A' mixes with SM photon via kinetic mixing with strength ε

Produced via $e^+e^- \to \gamma\,\Upsilon_D$, with

$$\Upsilon_D \to A'A'A' \quad \text{and} \quad A' \to f\bar{f}\ \ (f = e, \mu, \pi)$$

- Dark photon lifetime can be long for small masses and small kinetic mixing ε hence prompt and displaced vertex signatures
- BABAR search in six-track final state in 514 fb^{-1}



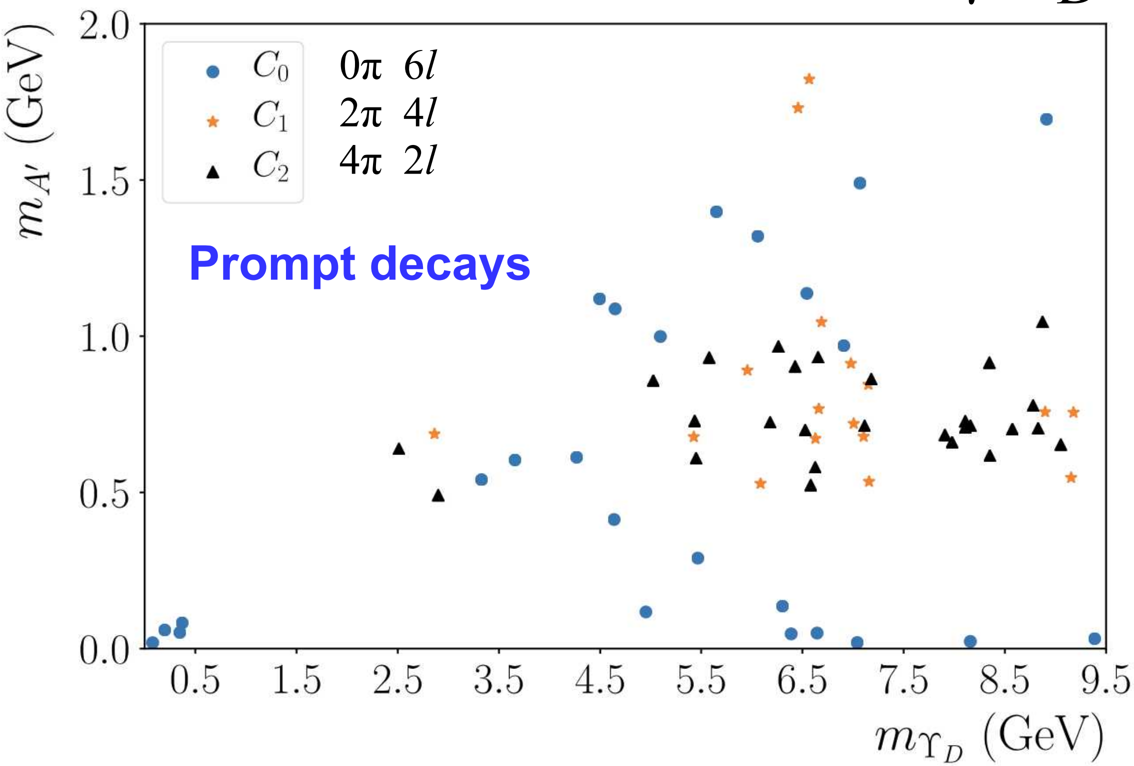
Search for Darkonium

PRL 128, 021802 (2022)

3 pairs of opposite-sign tracks (at least one lepton pair) which should all have same invariant mass

$e^+e^- \rightarrow \gamma \Upsilon_D$

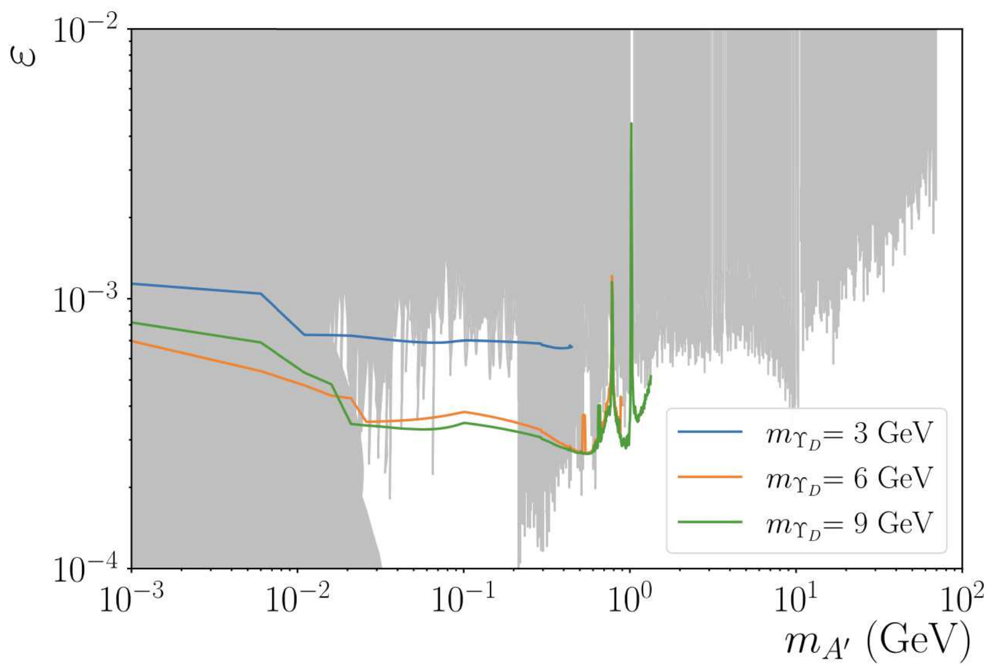
- Reconstruct Υ_D mass
- ISR photon may or may not be detected, but recoil mass against Υ_D should be consistent with zero
- MVA used to suppress backgrounds
- Scan $m(\Upsilon_D)$ - $m(A')$ for evidence of peaks

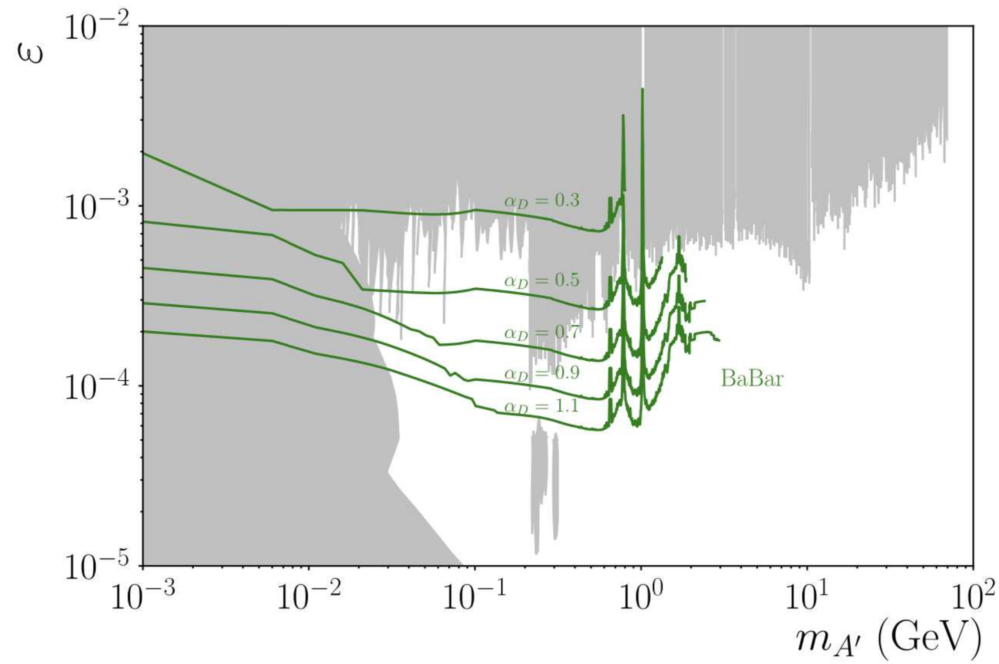


No significant signals observed in either prompt or displaced decay searches

Search for Darkonium

PRL 128, 021802 (2022)





90% C.L. Upper limits placed on the kinetic mixing parameter ε

- As a function of m(A')
- For different values of $m(\Upsilon_D)$ and α_D

Conclusion

BABAR data remains an interesting and important resource for searching for physics beyond the Standard Model

- Clean B factory environment is extremely well suited to searches for light dark sector new physics
- B mesogenesis, darkonium and ALPs searches are the most recent in a long history of dark sector and exotic searches

BABAR papers

Extensive program of searches for physics beyond the Standard Model, and dark sector in particular:

- Search for heavy neutral leptons in τ decays
  arXiv 2207.09575 [hep-ex] (accepted to PRD)
- Lepton universality in Y(3S) decays
  Phys. Rev. Lett .125, 241801 (2020)
- Search for LFV in Y(3S) $\rightarrow$e μ
  Phys. Rev. Lett. 128, 091804 (2022)
- Rare and forbidden D decays
  Phys. Rev. Lett. 124, 071802 (2020)
- Search for LFV in $D^0 \rightarrow X^0$ e μ
  Phys. Rev. D 101, 112003 (2020)
- B mesogenesis
  arXiv:2302.00208 [hep-ex]
- Search for Darkonium
  Phys. Rev. Lett. 128 021802 (2022)
- Axion like particle
  Phys. Rev. Lett. 128, 131802 (2022).
- Dark Leptophilic scalar
  Phys. Rev. Lett. 125,181801 (2020).
- Six quark dark matter
  Phys. Rev. Lett. 122, 072002 (2019).
- Dark photon
  Phys. Rev. Lett. 113, 201801 (2014);
  Phys. Rev. Lett. 119, 131804 (2017).
- Muonic dark force
  Phys. Rev. D 94, 011102 (2016).
- Dark Higgs bosons
  Phys. Rev. Lett. 108, 211801 (2012)

Dark Leptophilic Scalar

Extended Higgs sector with additional light singlets that mix with the Higgs boson (e.g. NMSSM, but more generally singlet-extended scalar sectors)

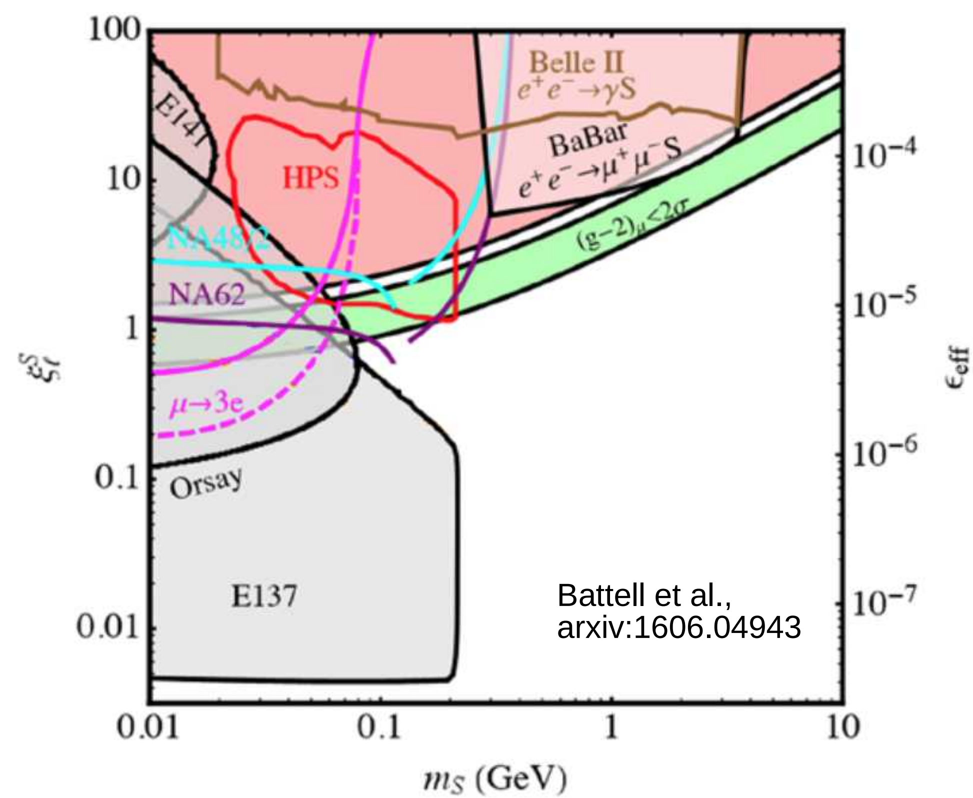
- scalar could mediate interactions between the SM and dark matter
- generic scenarios strongly constrained by heavy flavour FCNC decays (e.g. $B \to K\varphi$, $K \to \varphi\pi$)

If this new scalar interacts predominantly with leptons rather than quarks, then experimental bounds can be evaded

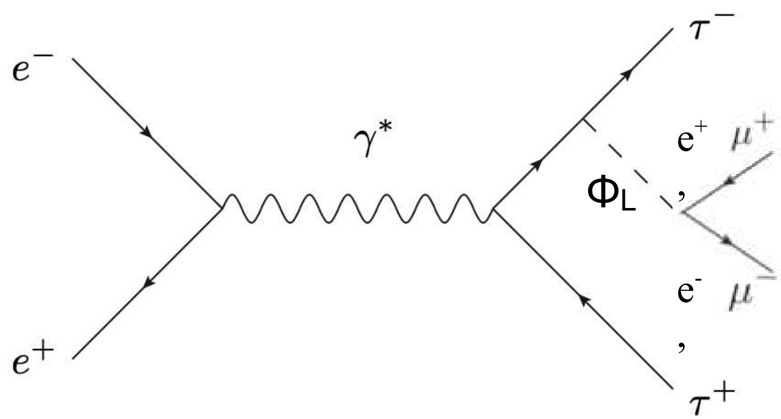
- couplings proportional to mass, hence interact preferentially with heavy-flavour leptons
- such a scalar could explain the g-2 anomaly

Previous BABAR search for muonic dark force provides model-independent constraints

Phys. Rev. D94 011102 (2016)



Dark Leptophilic Scalar



Search for a dark scalar Φ_L which is radiated from a tau lepton

$$\mathcal{L} = -\xi \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} \bar{\ell} \phi_L \ell$$

- Φ_L preferentially decays to kinematically accessible final states (depends on mass)
- For low Φ_L mass and coupling, Φ_L can be non-prompt

Experimental signature is a narrow resonant peak in m($l^+ l^-$) (l = e, μ) with width limited by detector resolution

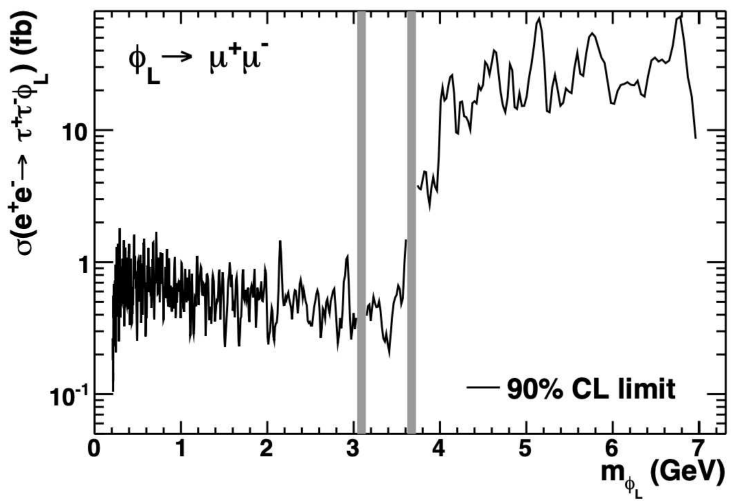
$$e^+e^- \rightarrow \tau^+\tau^- \Phi_L ,$$
$$\Phi_L \rightarrow l^+ l^- \quad (l = e, \mu)$$

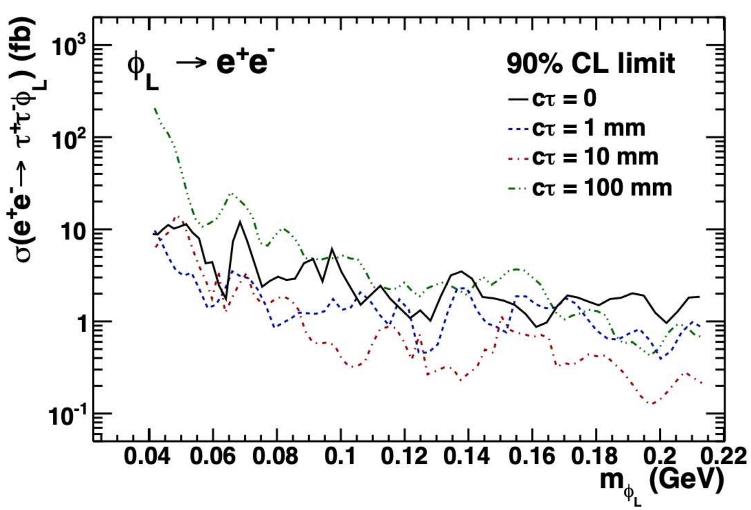
- Consider 1-prong tau final states, i.e. two charged tracks (e, μ, π) accompanied by two oppositely charged leptons
- 4-track topologies (plus additional neutrals)
- For $2m_e < m_\Phi < 2m_\mu$ permit Φ_L to be non-prompt
- Analysis is optimized and validated using a small sample (~5%) of data, which is subsequently discarded

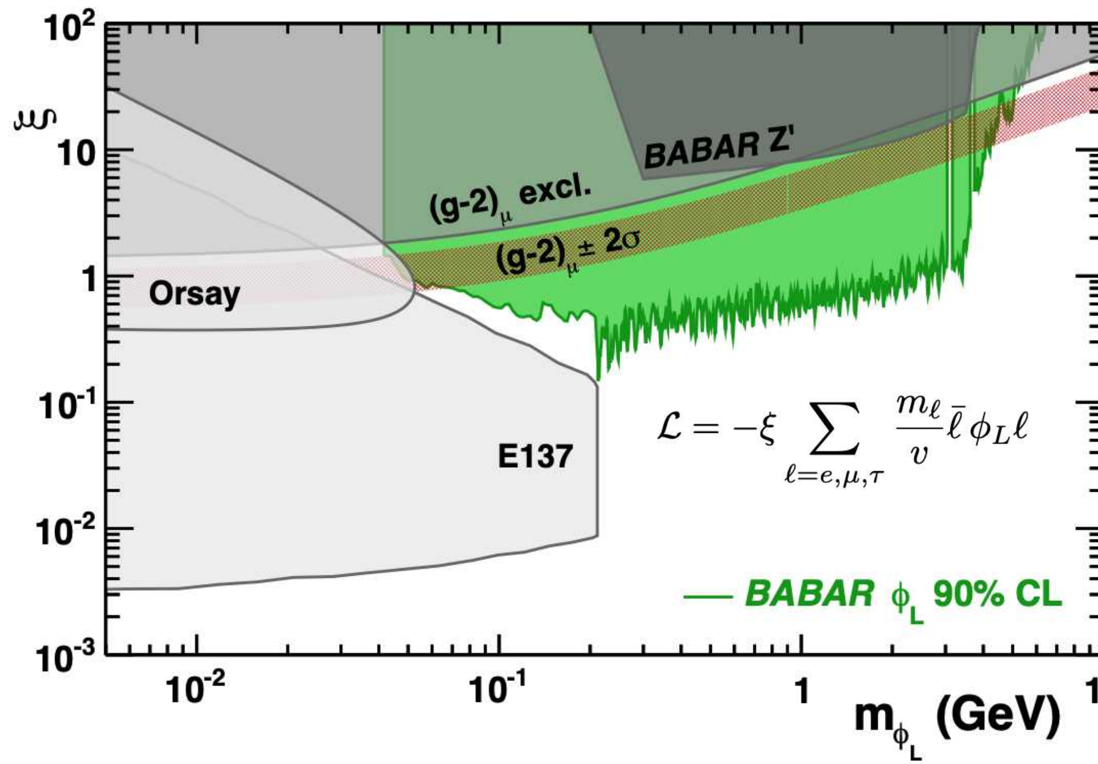
Dark Leptophilic Scalar

Limits on the scalar coupling are derived using an iterative procedure, to account for impact of Φ_L lifetime:

Phys. Rev. Lett. 125, 181801
514 fb^{-1}





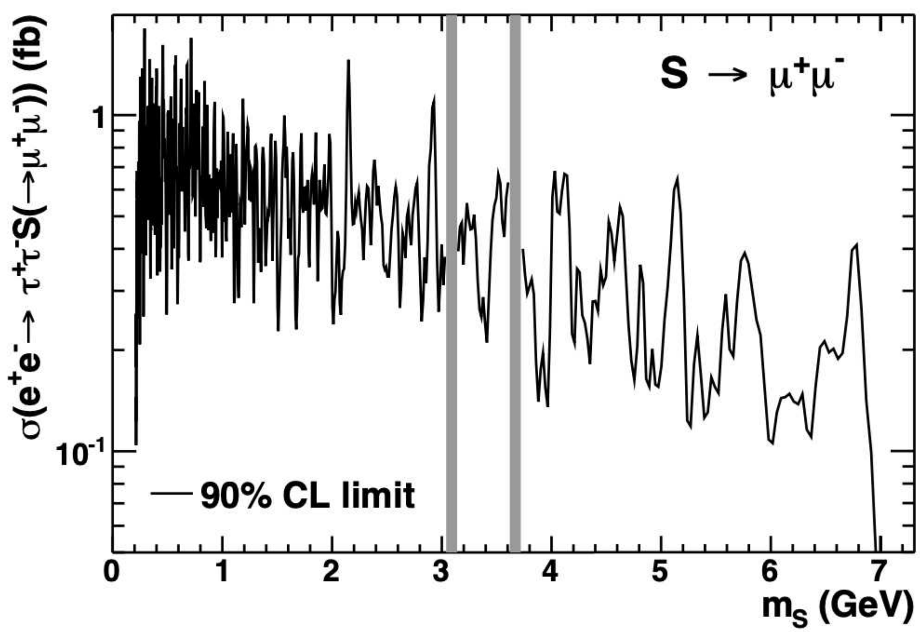


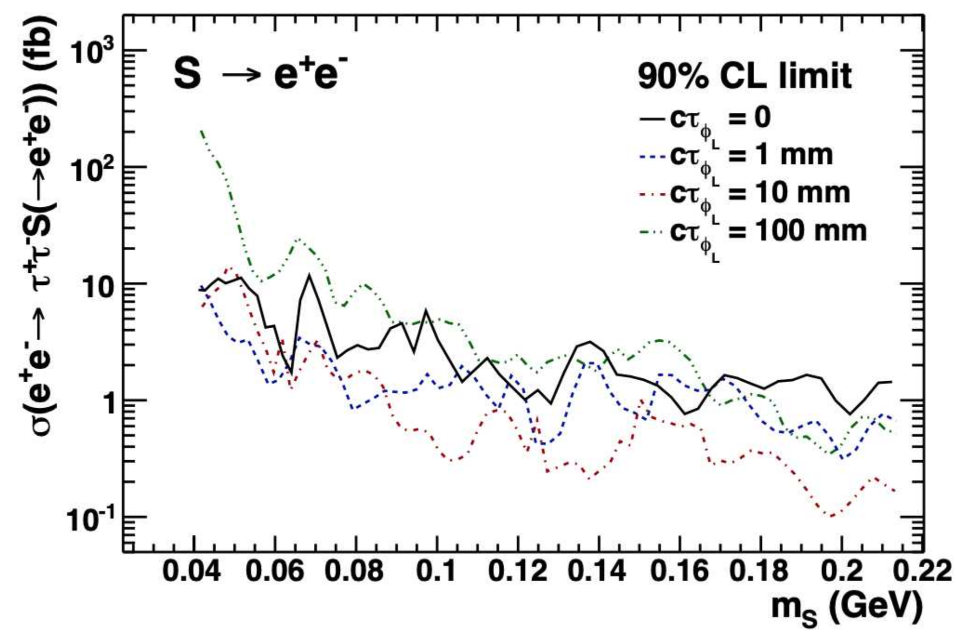
- Limits on ξ for the di-electron channel at the level of ~[0.5 – 1], corresponding to $c\tau_{\Phi L}$ ~ 10mm, and $c\tau_{\Phi L}$ ~ 2mm for di-muon channel
- $(g-2)_\mu$ region mostly excluded below di-tau threshold

Dark Leptophilic Scalar

Phys. Rev. Lett. 125, 181801
514 fb^{-1}

Alternatively, limits can be derived on the production cross section of a scalar S, without model assumptions on other decay modes:



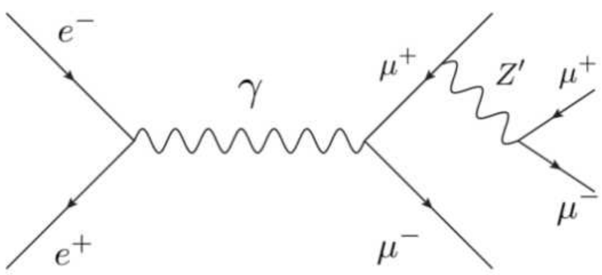


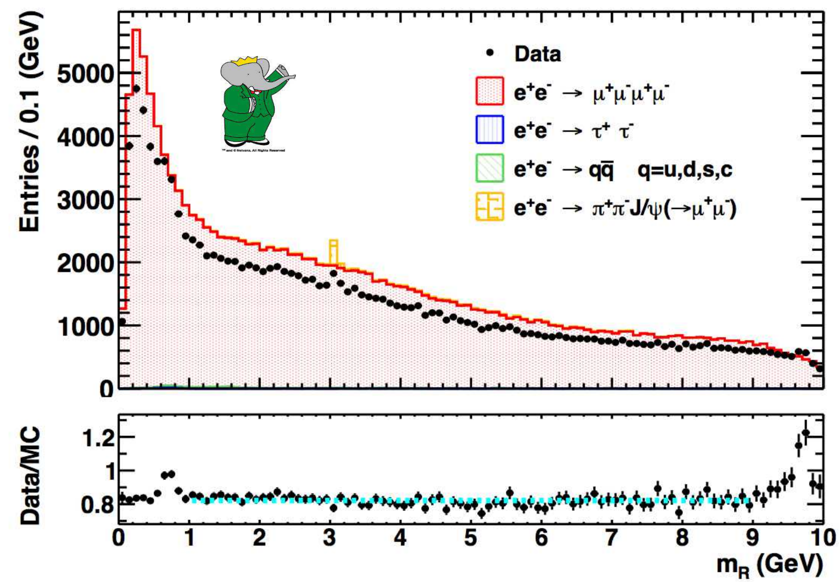
Muonic dark force

Phys. Rev. D94 011102 (2016)

Dark boson Z' which couples only to second and third generation leptons (i.e. SM fields are directly charged under dark force)

He, Joshi, Lew, Volkas, Phys. Rev. D 43, R22 (1991). B. Batell, D. McKeen and M. Pospelov, Phys. Rev. Lett. B.107, 011803 (2011).



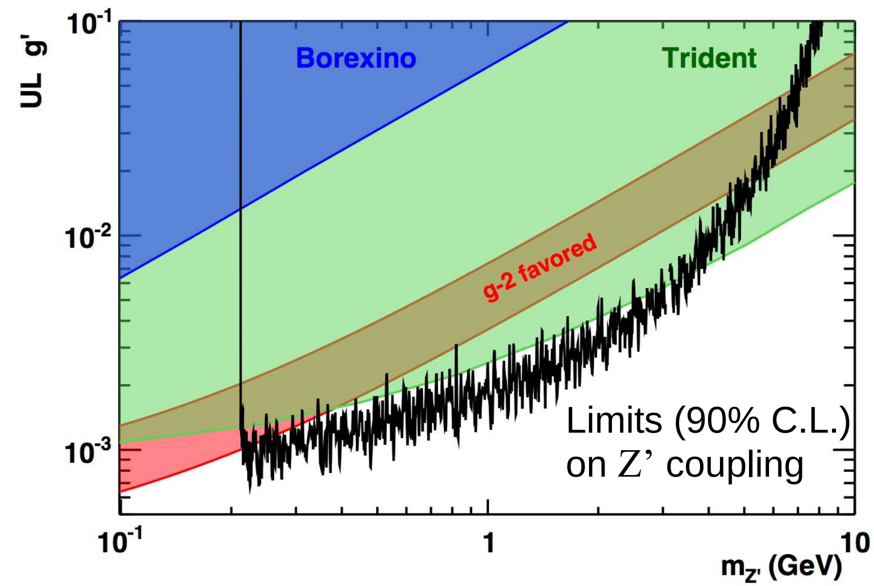


Di-muon reduced mass: $m_R = (m_{\mu\mu}^2 - 4m_\mu^2)^{1/2}$

"Z'-strahlung" production of Z' :

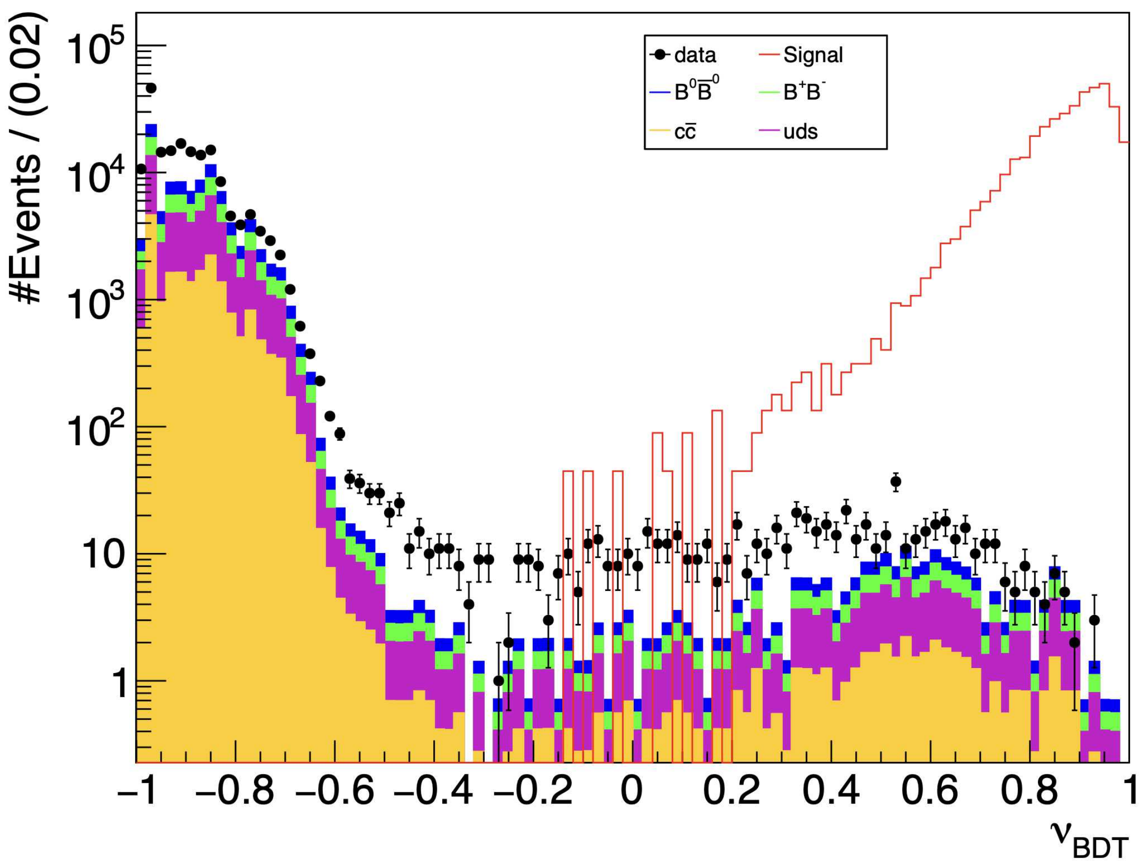
$$e^+e^- \to \mu^+\mu^- Z' \,,\ Z' \to \mu^+\mu^-$$

- Search for a di-muon mass peak in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$
- No signal observed; cross section limits obtained at 90% C.L. at level of ~0.2 fb below $m_{Z'}$ of 10 GeV



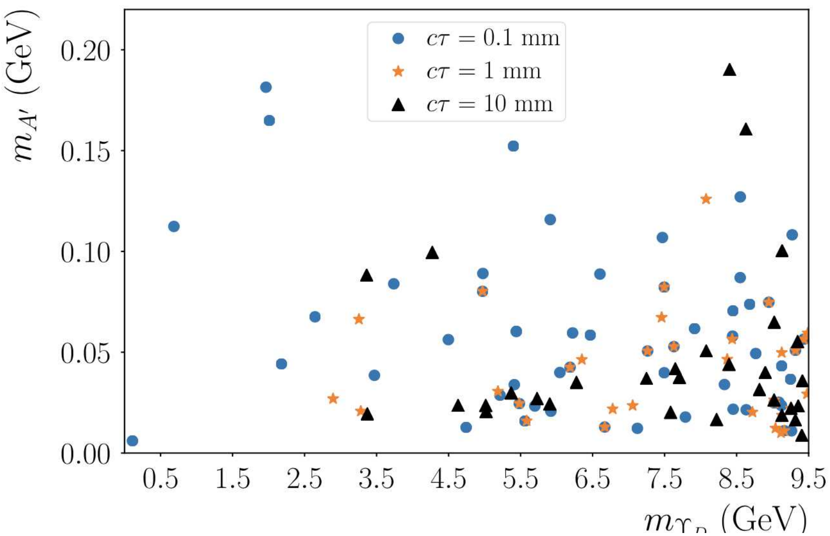
However, no model-specific assumptions in analysis; results are more generally applicable

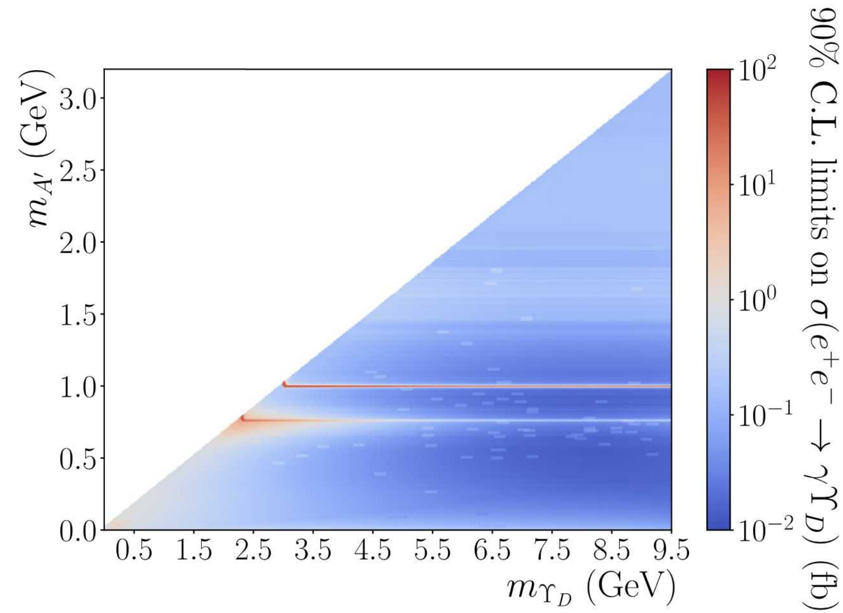
B mesogenisis

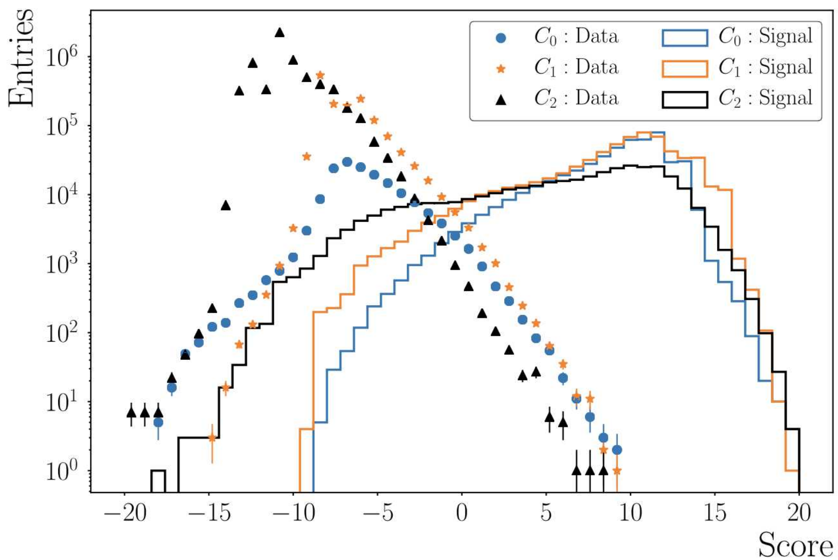


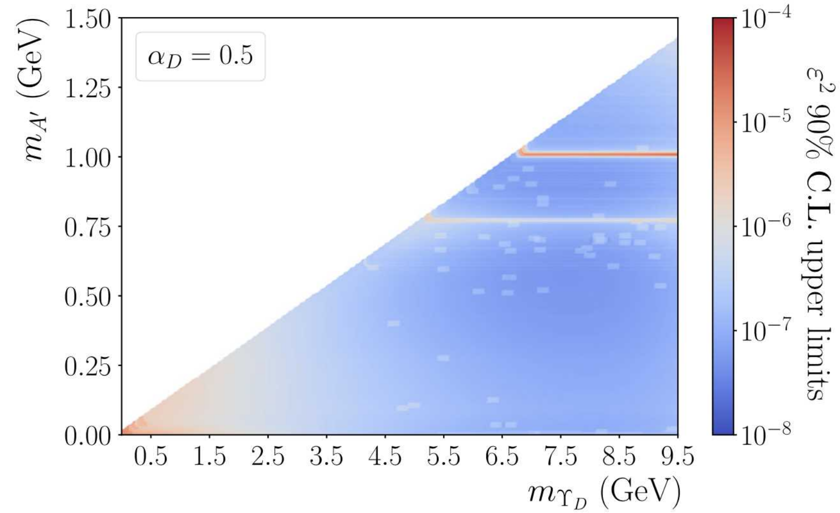
Darkonium

PRL 128, 021802 (2022)









ALP

Yield and local significance

- Grey bands are π^0, η, η' regions excluded from the search