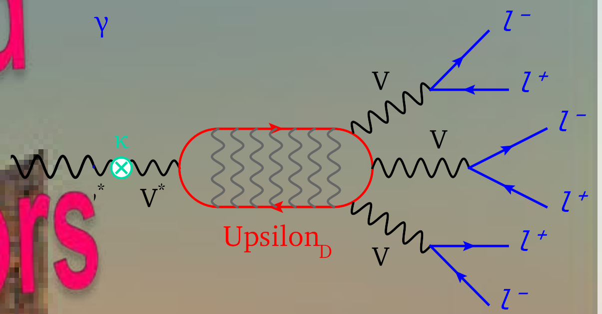
Search for Self-interacting Dark Matter and other Dark Sectors at BABAR



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On behalf of the BABAR collaboration

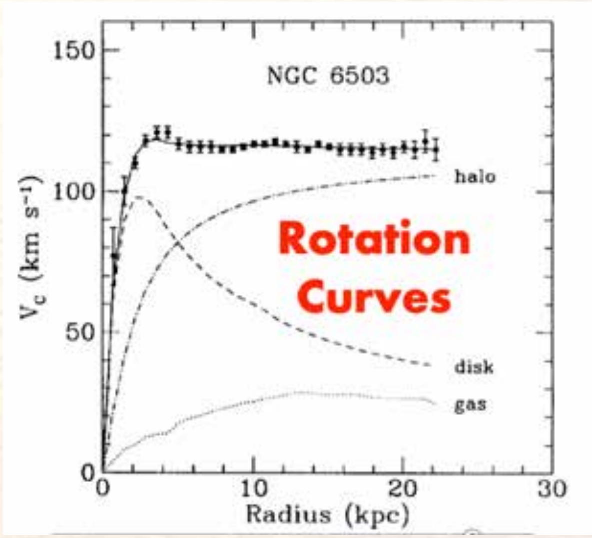
EPS Conference, Hamburg, July 26-30, 2021

Outline

- Introduction
- **Search for self-interacting dark matter (Darkonium)**
- Search for Axion-like Particles (ALP)
- Search for Leptophilic dark matter PRL **125**, 18,181801 (2020)
- Conclusion

Introduction

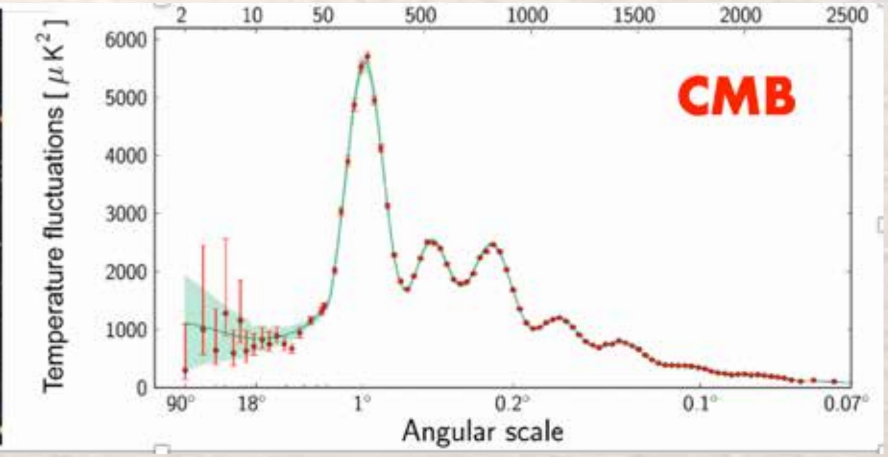
- What is dark matter?
  - New particle(s)?
  - A gravitational effect?
  - Black holes?
  - A combination of all?



- So far, we see only gravitational effects of dark matter

- **No new particles have been observed**

- Searches are ongoing at *B*-factory, LHC and astroparticle physics experiments



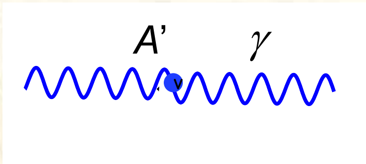
- At *B*-factories explore new domains like self-interacting dark matter, leptophilic dark scalars, dark photons and axion-like particle, which sample lower energies

Link between SM and Dark Matter

- The SM may be connected to the dark sector through so-called portals, these links are the lowest-dimensional operators that may provide coupling of the dark sector to the SM (higher-dimensional operators are mass suppressed)

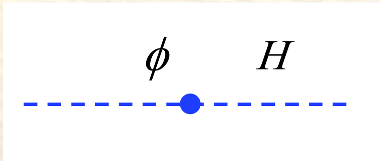
PLB **662**, 53 (2008)

- **Vector**
  $\varepsilon F_Y^{\mu\nu} F'_{\mu\nu}$ (dim. 4)



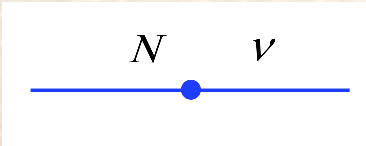
new U(1) symmetry ➔ dark photon, coupling to SM γ/Z via kinetic mixing ε

- **Scalar**
  $H^2\left(\mu\phi + \lambda\phi^2\right)$ (dim. 4)



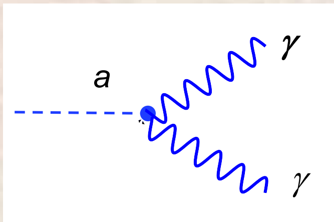
new dark scalar, mixing with Higgs

- **Neutrino**
  $\kappa H \ell N$ (dim. 4)



new heavy neutral lepton, mixing with left-handed SM doublet and Higgs

- **Axion-like**
  $f_a^{-1} F^{\mu\nu} F_{\mu\nu} a$ (dim. 5)



new axion/axion-like particle, coupling to SM gauge and fermion fields

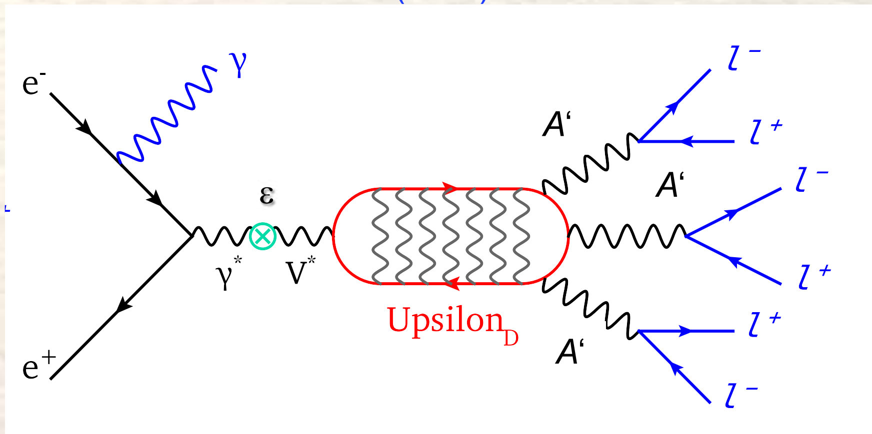
- *B* factories provide tests of vector, scalar and axion-like portals in the lower-mass region

Search for Self-interacting Dark Matter

Search for Self-interacting Dark Matter

- A dark photon *A'* may couple to a dark fermion antifermion pair ($\chi\bar{\chi}$)
- If the *A'*- χ coupling constant α_D is large enough, the $\chi\bar{\chi}$ pair could form a bound state, darkonium

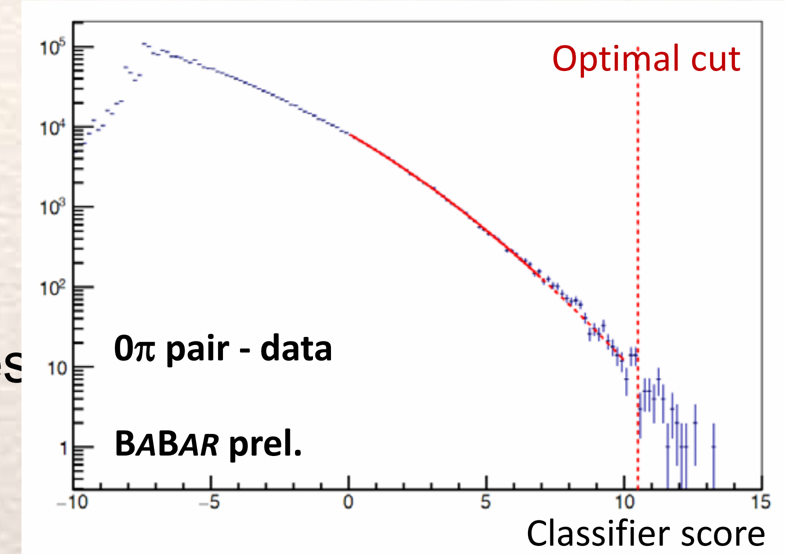
PRL 116 (1026) 151801



- This represents self-interacting dark matter
- The lowest states are $J^{PC}=0^{-+}$ (pseudoscalar) and $J^{PC}=1^{--}$ (vector); in analogy with the SM called η_D and Υ_D
- These states may be produced in $e^+e^-\to A'\eta_D$, $\eta_D\to A'A'$ and $e^+e^-\to\gamma\Upsilon_D$, $\Upsilon_D\to A'A'A'$
- BABAR searched for $e^+e^-\to\gamma\Upsilon_D$, $\Upsilon_D\to A'A'A'$, $A'\to e^+e^-$, $\mu^+\mu^-$, $\pi^+\pi^-$ via γ-*A'* kinetic mixing ε
- Data collected at $\Upsilon(4S)$, $\Upsilon(3S)$, $\Upsilon(2S)$ and off-resonance: $\mathcal{L}_{int}$ = 514 fb^{-1}
- The decay may be either prompt (primary vertex) or delayed (secondary vertex)

Event Selection

- Final state consists of ISR photon plus 6 charged tracks
  - Event must be consistent with ISR, but photon in the calorimeter is not required
  - Require 6 charged tracks, at most 2 $\pi^+\pi^-$ pairs to cut large QCD background
  - Require small extra energy from neutrals in the calorimeter (excluding ISR γ)
  - Recoil against Υ_D must be compatible with ISR photon
- The three dark photon masses must be similar
- For prompt decay consider masses:
  - A': $0.001<m_{A'}<3.16$ GeV/c^2
  - Υ_D: $0.05< m_{\Upsilon D} < 9.5$ GeV/c^2
  - Generate 119 different A' & Υ_D mass hypotheses
- For mass range $m_{A'} < 0.20$ GeV/c^2
  consider flight paths: $c\tau$= 0.1, 1 and 10 mm



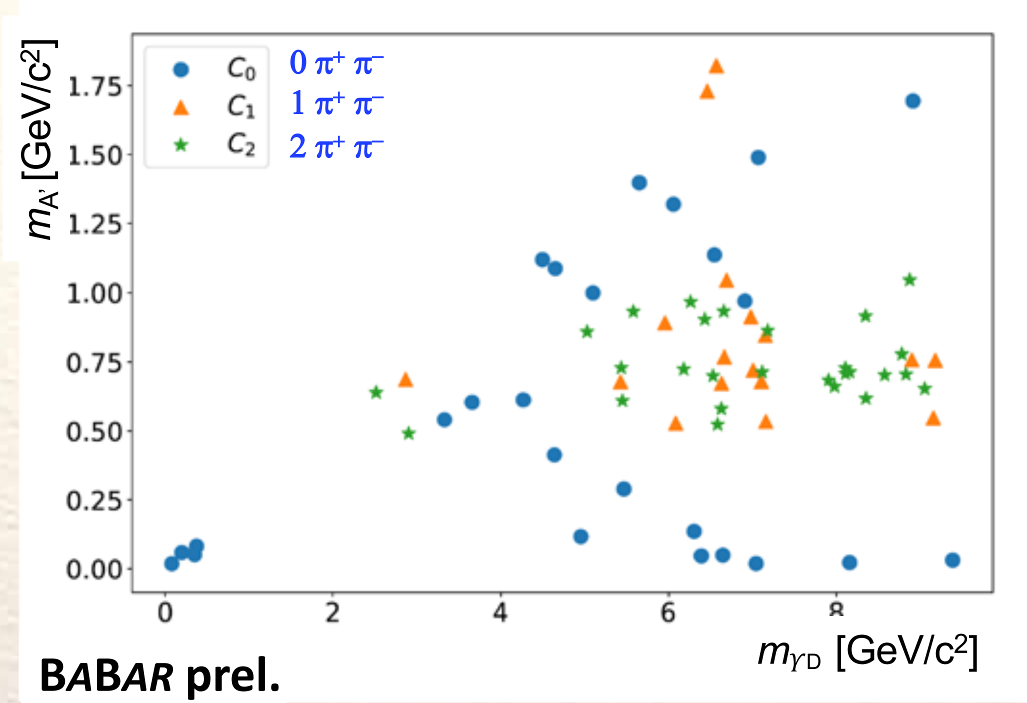
- Dark photon must satisfy bound state condition: $m_{A'} < \alpha_D\ m_{\Upsilon D}/3.36$

PR **A 1**, 155 (1970)

- Classify events into 3 categories: C_0: no $\pi^+\pi^-$, C_1: 1$\pi^+\pi^-$ and C_2: 2$\pi^+\pi^-$
- Train 3 separate MVAs (using 13 input variables) and cut on classifier score

Results for Prompt Decays

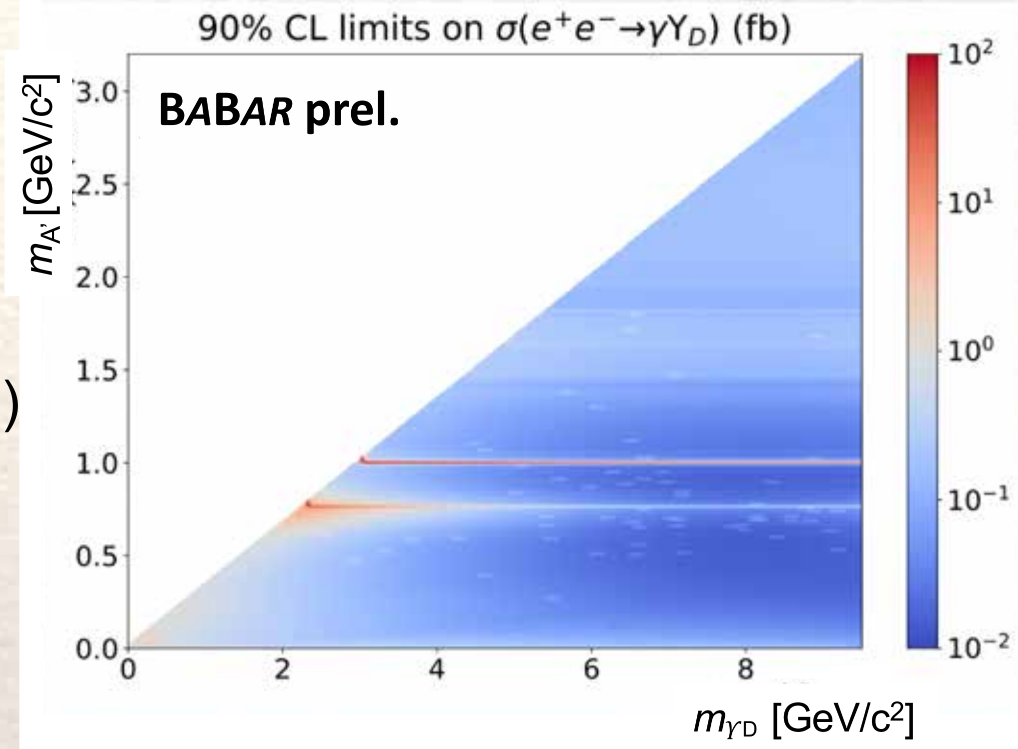
- Combine events of all categories into a single sample
- Define the $(m_{A'}, m_{\Upsilon_D})$ signal region: $(m_{A'} \pm 4\,\sigma_{mA'})$ and $(m_{\Upsilon D} \pm 4\sigma_{m\Upsilon D})$
- Estimate backgrounds in region: $(m_{A'} - 4\sigma_{mA'}, m_{A'} + 4\sigma_{mA})$ and $(m_{\Upsilon D} - 8\sigma_{m\Upsilon D}, m_{\Upsilon D} - 4\sigma_{m\Upsilon D})$ & $(m_{\Upsilon D} + 4\sigma_{m\Upsilon D}, m_{\Upsilon D} + 8\sigma_{m\Upsilon D})$



- See 69 signal events after applying all selection criteria
- The most significant measurements contain 2 events in a signal window

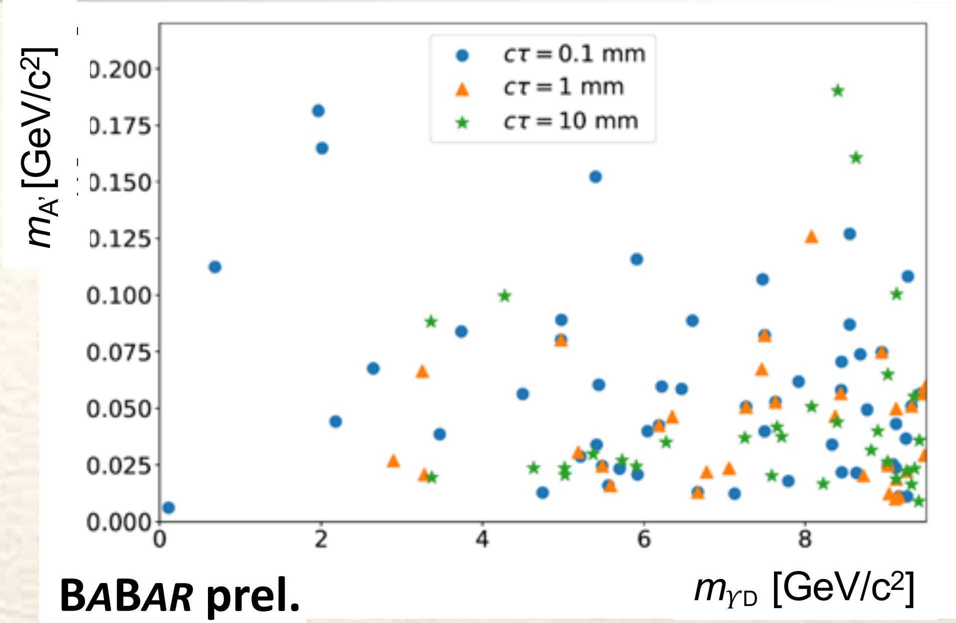
90% CL Upper Limits for Prompt Decays

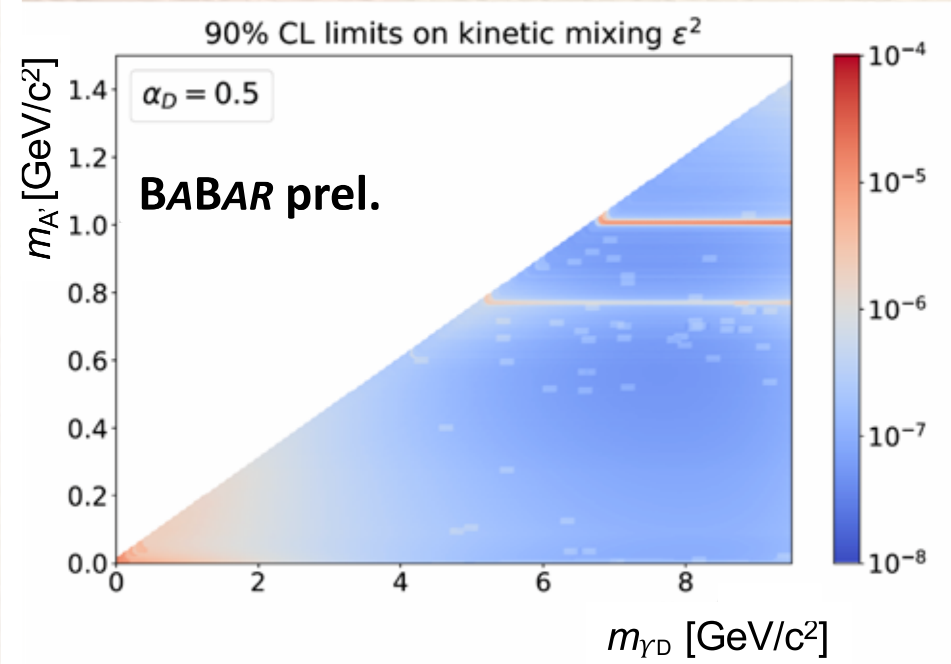
- Scan the ($m_{A'}$, $m_{\Upsilon D}$) plane in steps of the mass resolutions
  - $\sigma_{mA'}$ =1-5 MeV depending on $m_{A'}$
  - σ_{mYD} = 5-35 MeV depending on $m_{\Upsilon D}$
- Set 90% confidence level upper limits on the $e^+e^-\rightarrow\gamma\Upsilon_D$ cross section using a profile likelihood method
- Enhancements near 0.8 GeV/c^2 in m($\pi^+\pi^-$) and 1.0 GeV/c^2 in m(K^+K^-) come from ρ^0 and ϕ decay backgrounds
  ➔increases cross section upper limits to 1-100 fb^{-1}
- No other enhancements are seen
  ➔ 90% CL cross section upper limits are 10^{-2} to1 fb



90% CL Upper Limits on Kinetic Mixing ε

- For low-mass dark photons, lifetime may become longer ➔ search for events with decay vertices of $c\tau$ = 0.1, 1 and 10 mm
- We follow a similar procedure as for the analysis of prompt decays
- We observe 56, 33 and 31 events for $c\tau$ = 0.1, 1 and 10 mm decay lengths, respectively

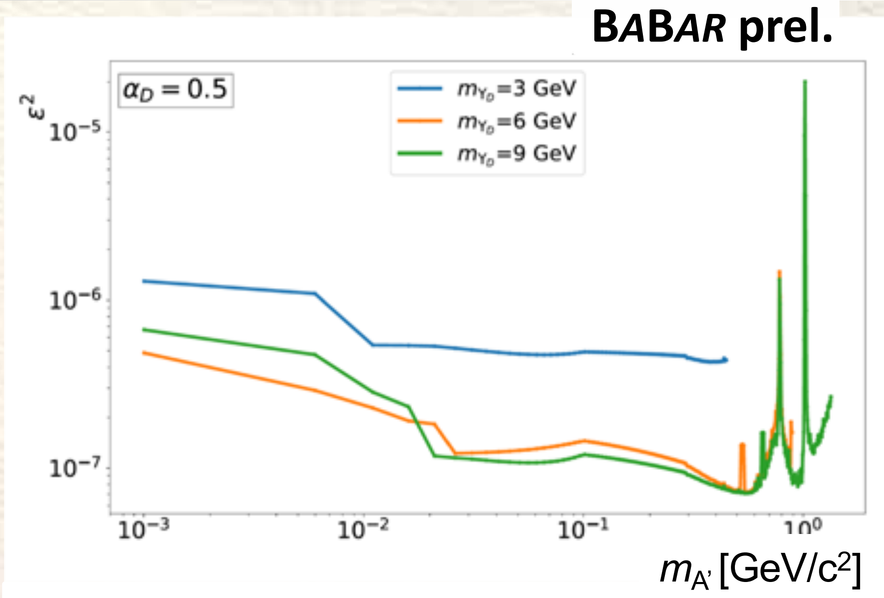


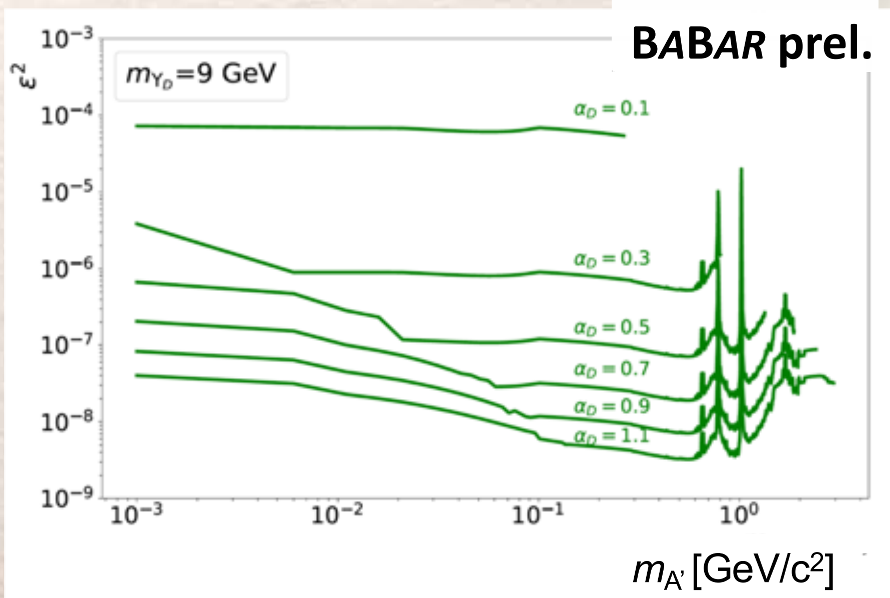


- No significant signal is observed for any lifetime
- We extract 90% CL upper limits on the kinetic mixing parameter ε^2 in an iterative procedure taking lifetime into account
- Dark photon lifetime is independent of α_D ➔set upper limits for different α_D

Constraints on Kinetic Mixing Parameter

- We set different 90% CL upper limits on the kinetic mixing parameter ε^2 as a function of $m_{A'}$ for different values of m_{Y_D} and α_D
- We achieve improved upper limits for larger $m_{A'}$
- We achieve improved upper limits for larger m_{Y_D}
- We achieve improved upper limits for larger α_D
- The lowest value of ε^2 is achieved for $m_{A'} \approx 0.5$ GeV/c^2, m_{Y_D} =9 GeV/c^2 and α_D=1.1
- Belle II will eventually improve these limits

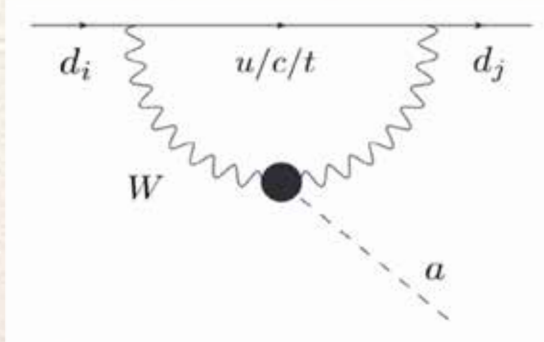




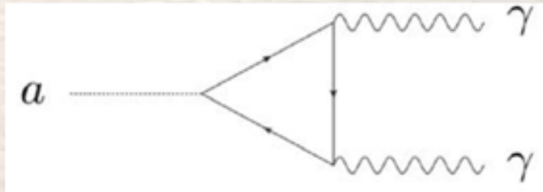
Search for Axion-like Particles

Search for Axion-like Particles (ALPs)

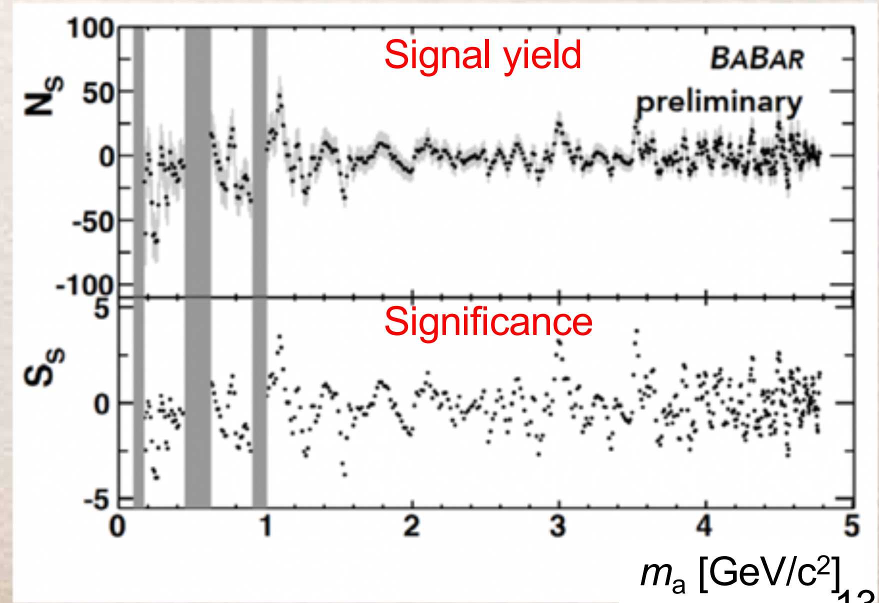
- ALPs (a) are new light pseudoscalars that couple dominantly to gauge bosons
- In the presence of coupling to SU(2) gauge bosons we may get large FCNC production rate since ALP production is at a lower order in EFT than corresponding SM FCNCs



- At small mass/coupling, lifetime may be large (mm - tens cm)
- BABAR has searched for ALPs in $B \to Ka$, $a \to \gamma\gamma$
  - Combine well identified K with two γs to form B candidate
  - Apply kinematic fit to improve axion mass resolution
  - Train 2 BDTs to separate signal from $e^+e^- \to B\bar{B}$ and $e^+e^- \to q\bar{q}$ backgrounds ($q = u, d, s, c$)



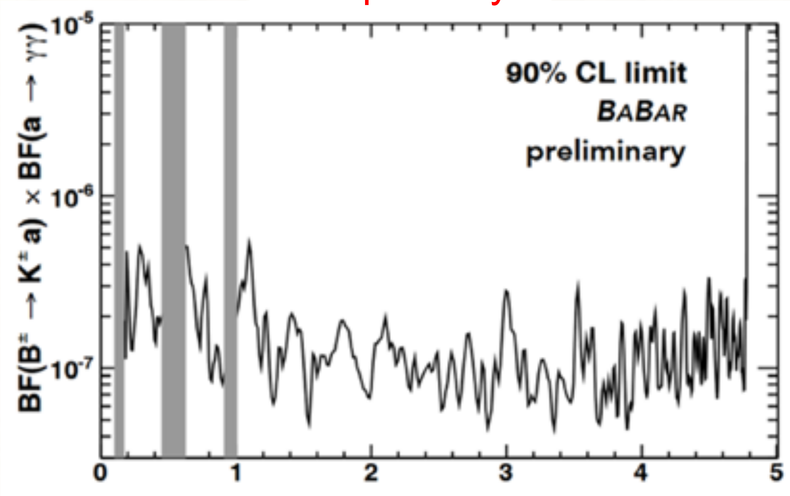
- The $m_{\gamma\gamma}$ spectrum shows peaking backgrounds at π^0, η, and η' masses that we exclude
- Extract signal as a function of axion mass with fits over sliding mass intervals



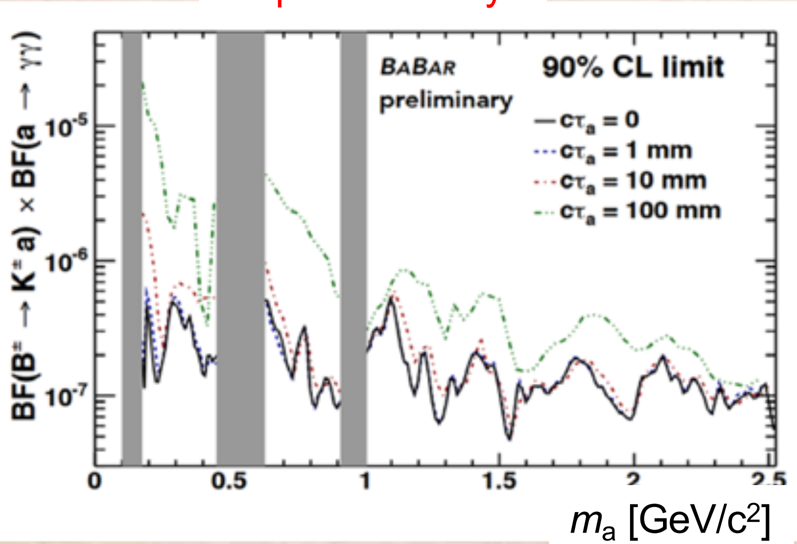
90% CL Upper Limits on ALPs

- See no significant signals
- Set 90% CL upper limits on the branching fraction $B \to Ka$, $a \to \gamma\gamma$ for prompt and displaced decays
- Set 90% CL upper limits on a-W coupling parameter g_{aW} ➔ improvements over two orders of magnitude over a large mass range

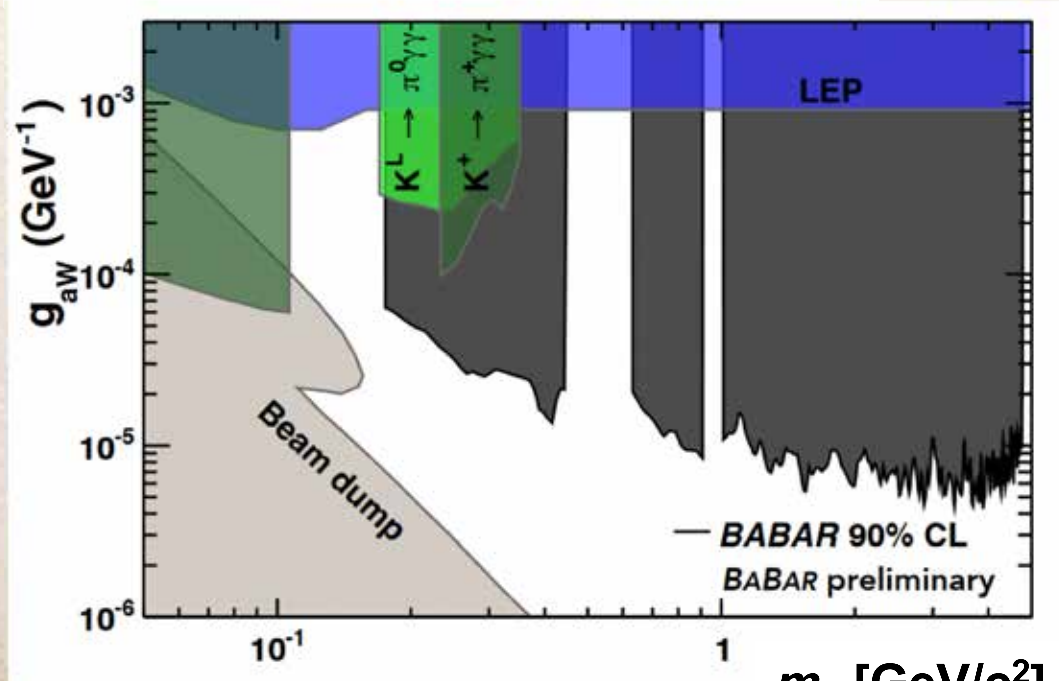
Prompt decays



Displaced decays



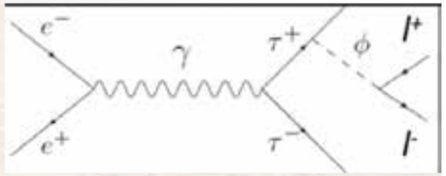
90% CL upper limits on a-W coupling parameter



Search for Leptophilic Dark Scalar

Search for Leptophilic Dark Scalar

- A new light scalar ϕ_L is predicted in BSM models that can mix with the Higgs boson



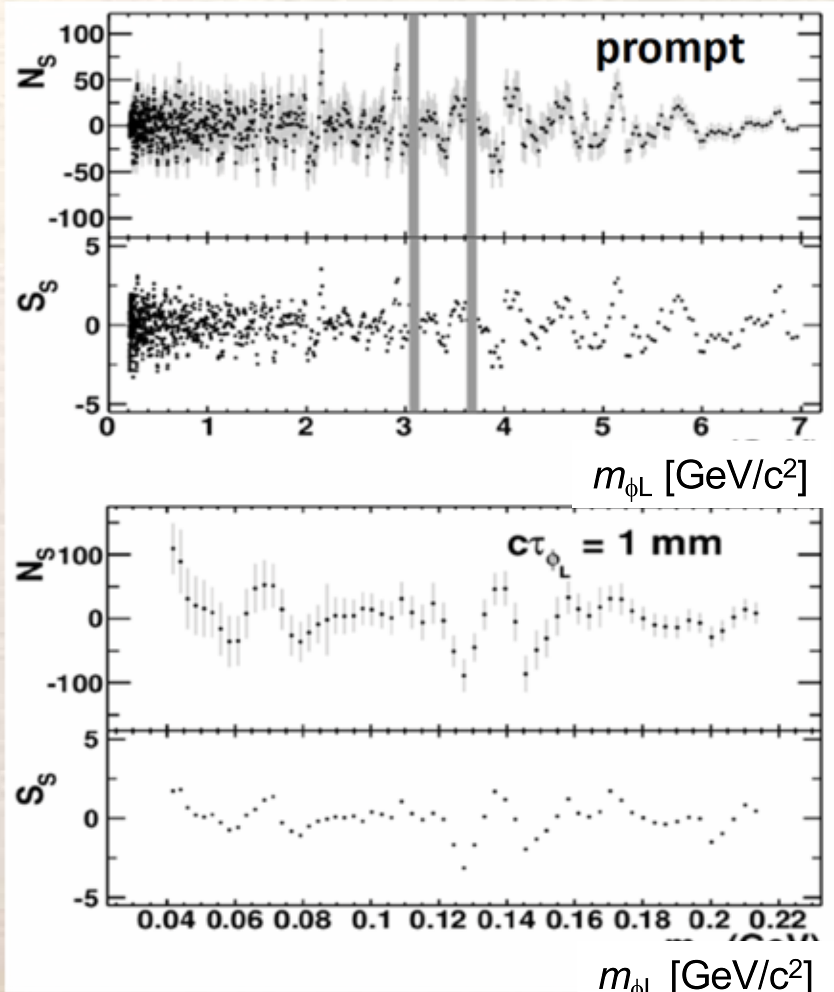
- Experimental constraints disfavor interactions with quarks but interaction to leptons are permitted (leptophilic)

arXiv:2104.03281

- Leptophilic scalar could explain g-2 discrepancy and the KOTO experiment excess in $K_L \to \pi^0 \nu\bar{\nu}$

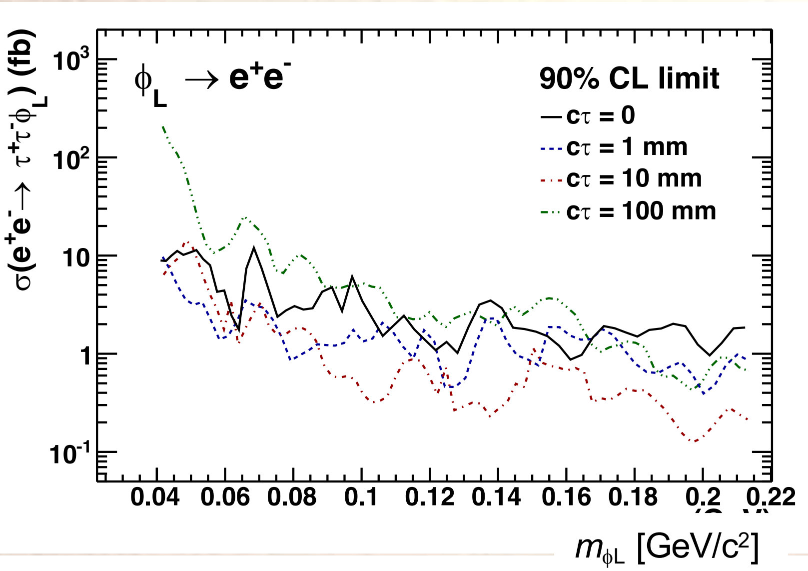
arXiv:2001.06522

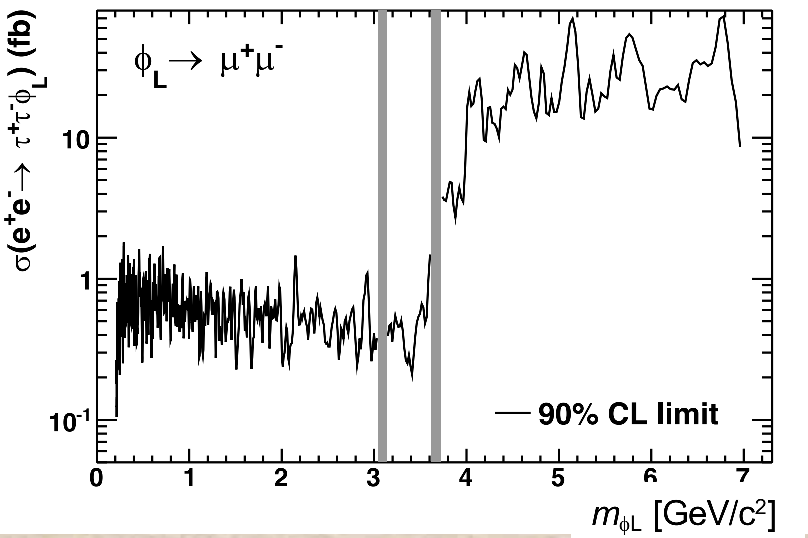
- ϕ_L couples preferentially to τs
- BABAR has searched for $e^+e^- \to \tau^+\tau^- \phi_L$ with $\phi_L \to e^+e^-, \mu^+\mu^-$ ($\mathcal{L}$=514 fb^{-1})
- Consider all τ^+ to one-prong decays
- Optimize analysis for each final state and prompt or long lived ϕ_L using individual BDT selection
- Extract signal as a function of ϕ_L mass with fits over sliding intervals
- Signal efficiency varies between 0.2-26%

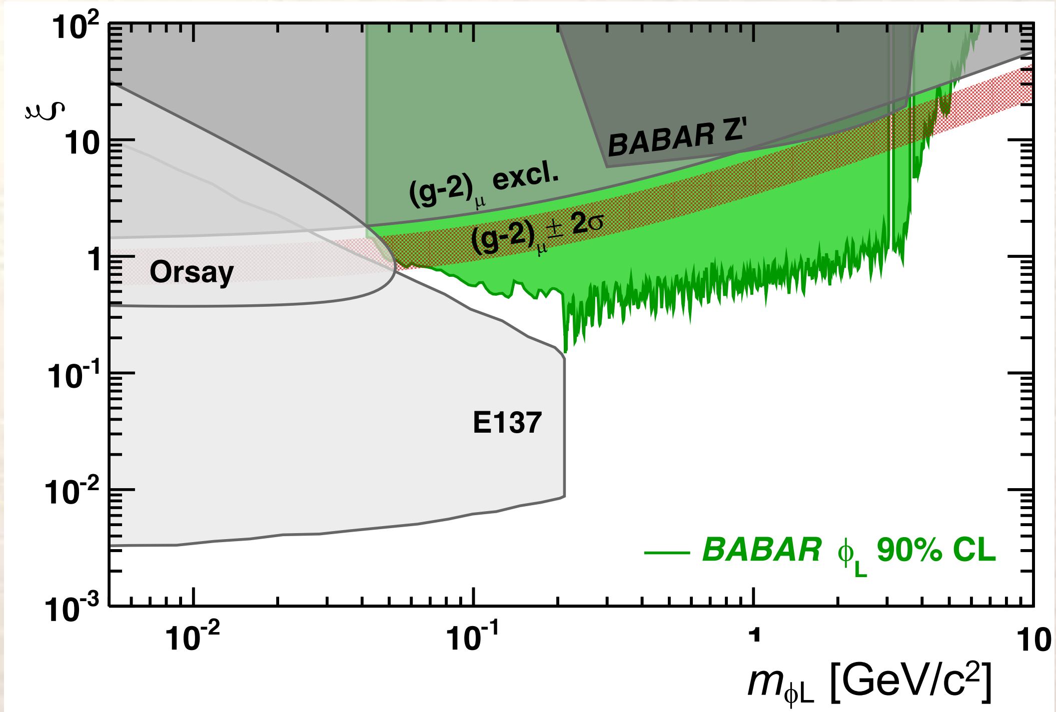


Upper Limits on Leptophilic Dark Sector

- See no signal and extract 90% CL upper limits on the cross sections **$\sigma(e^+e^- \to \tau^+\tau^- \phi_L [\to e^+e^-, \mu^+\mu^-])$**, and the ϕ_L lepton coupling parameter ξ







PRL **125** 18,181801 (2020)

- Significant improvement over previous bounds
- Exclude large g-2 parameter space below $m_{\tau\tau}$
- Belle II will reduce bounds

Conclusions

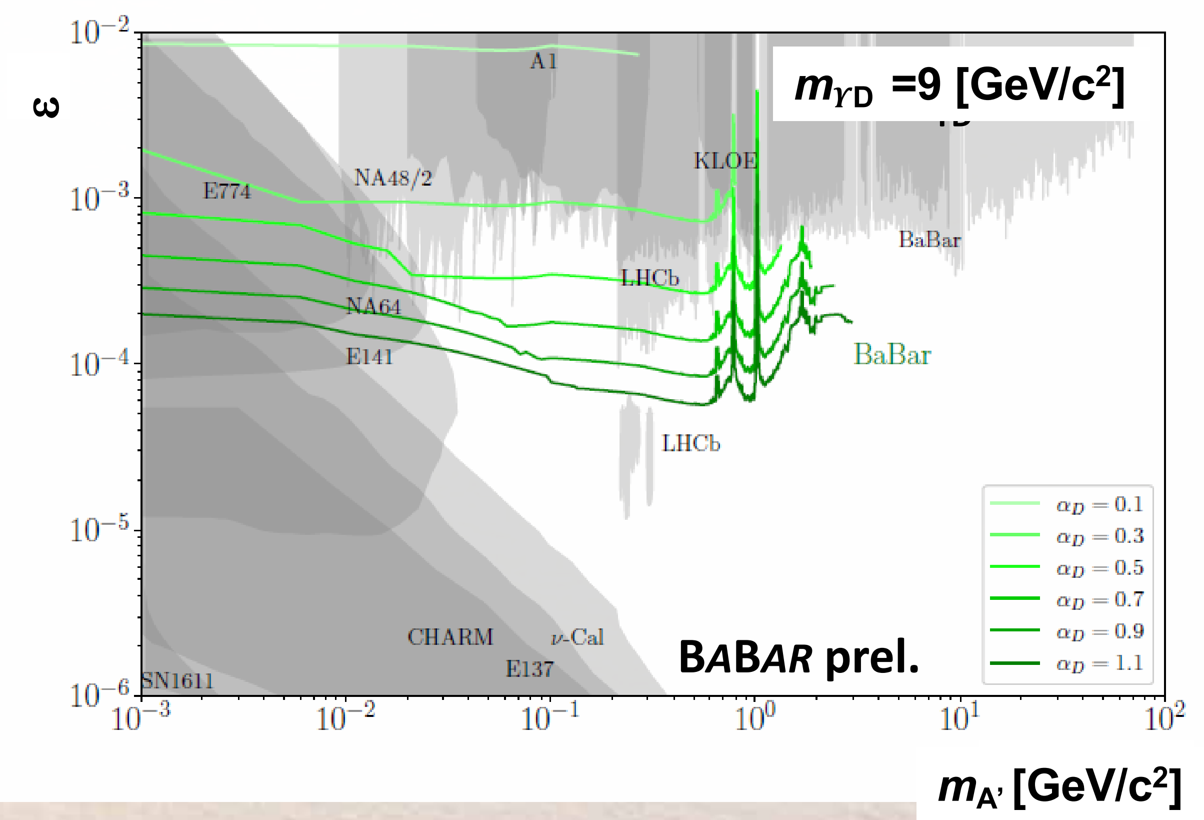
- Present e^+e^- colliders provide a unique opportunity for testing the concepts of dark sectors via portals to the SM at low energies

- BABAR has conducted a rich program to look for dark matter effects and has set many stringent 90% CL upper limits on cross sections and couplings

- The most recent BABAR results include world-leading constraints on self-interacting dark matter, axion-like particles and leptophilic dark scalars

- There are still new analyses ongoing

- In the long run Belle II will improve these limits



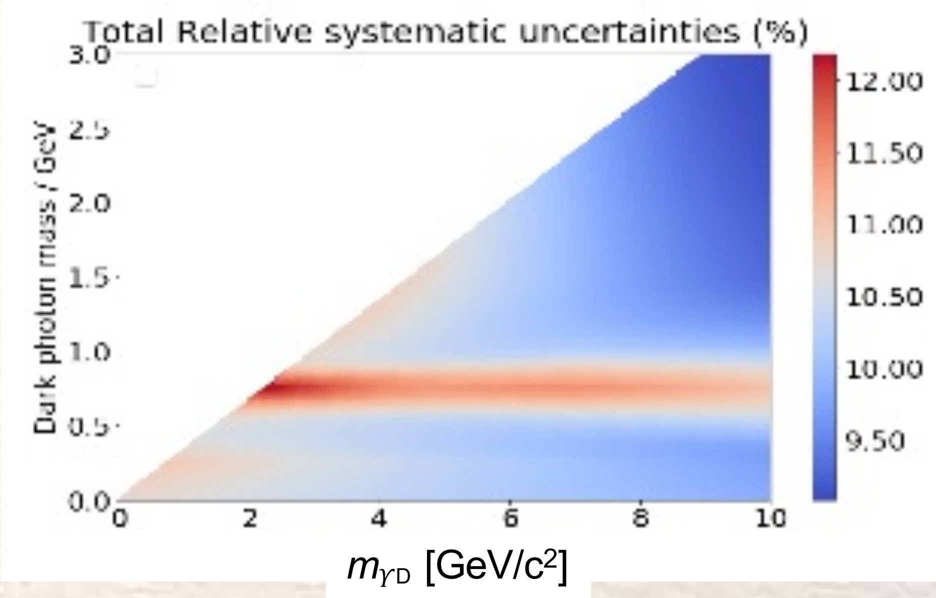
Thank you for your attention

Backup Slides

Systematic Uncertainties

- Monte Carlo statistics: <1%
- Interpolation as a function of ($m_{A'}$, m_{YD}): < 8%
- PID uncertainties (added linearly)
  - muon: 2%
  - pion: 2%
  - electron: 1%

  The final error depends explicitly on the final state
  ➔ C_0: 6-12%, C_1:8-12%, C_2: 10-12%



- Luminosity: 0.6%
- Tracking efficiency: 0.2% per track ➔1.2% in total
- Branching fraction for $A' \rightarrow e^+e^-$, $\mu^+\mu^-$, $\pi^+\pi^-$: <1%
- Combined systematic error depends on ($m_{A'}$, m_{YD}): 9.5-12%

The BABAR Detector

- B*ABA*R collected ~500 fb-1 around the ϒ(4S), ϒ(3S) and ϒ(2S) resonance between 1999 -2008
- Collaboration is still active after more than 10 years of data taking