Searches for Dark Matter at B-factories

SLAC, CA

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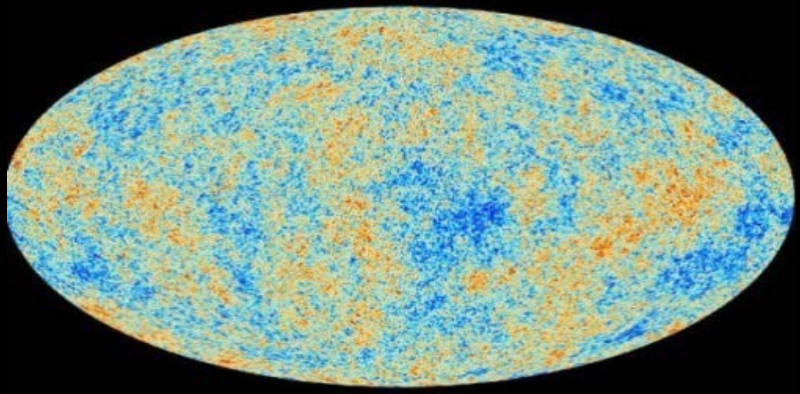
Dark Matter (DM): Evidence

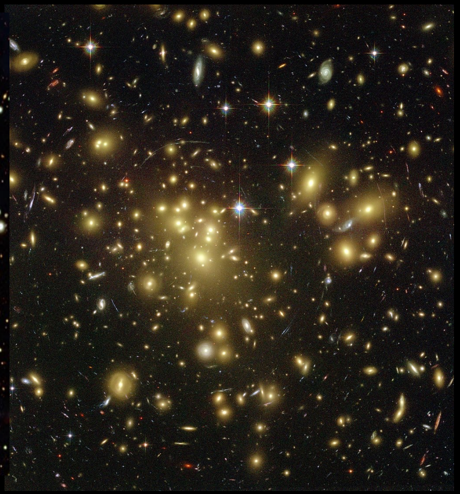
- Much observational evidence for existence of Dark Matter (DM).
- Lambda CDM:
  - 5% Ordinary matter, 27% Dark Matter, 68% Dark Energy.
- But the nature and mass scale of this matter remains unknown.

Cosmic Microwave Background

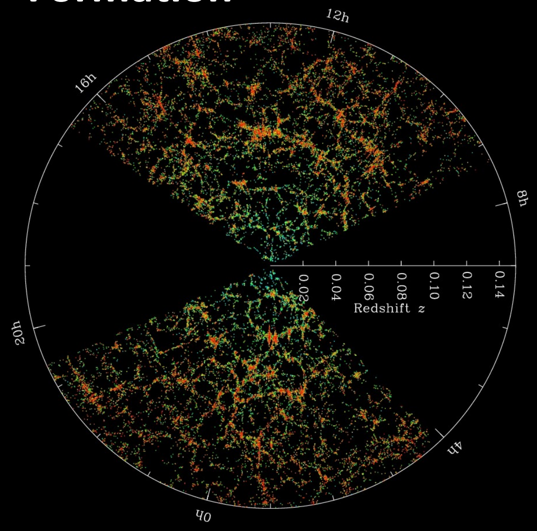


Bullet Cluster

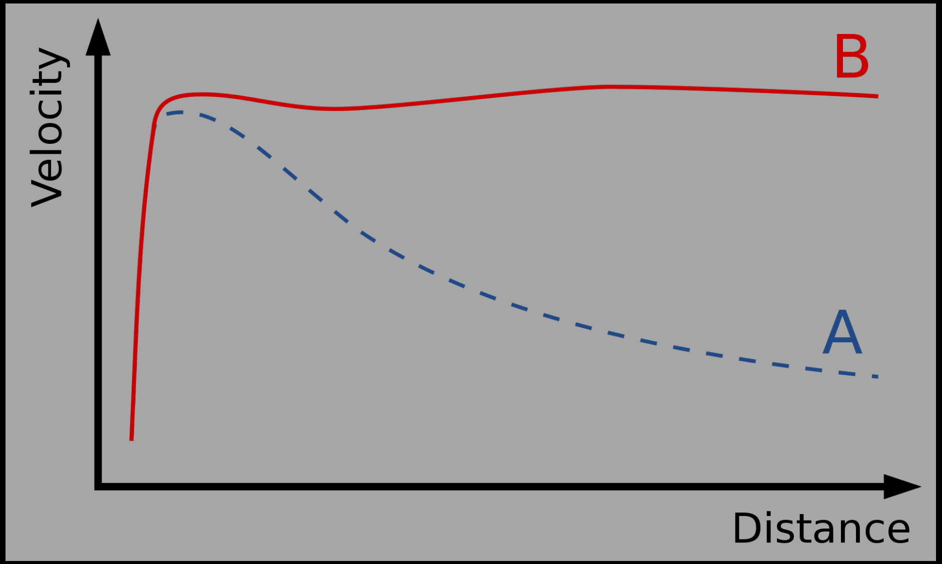
Lensing



Large Scale Structure Formation



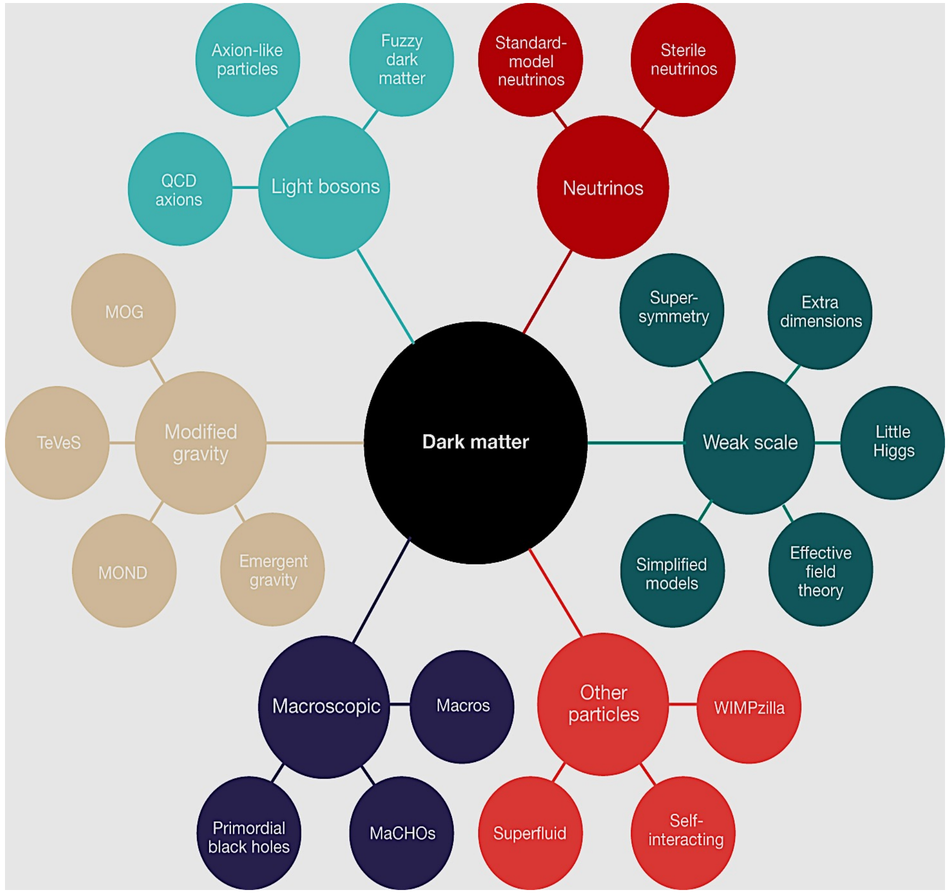
Rotation Curves



Dark Sector "Portals"

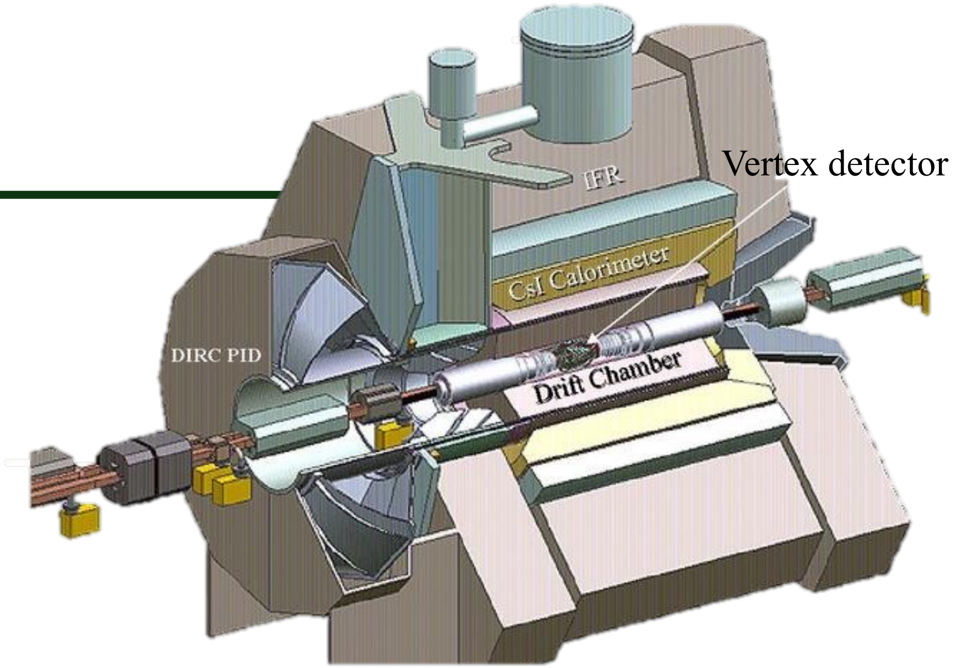
- Known particles and interactions are insufficient to explain cosmological and astrophysical observations of dark matter.
- This motivates the possibility of new hidden sectors that are only feebly coupled to the SM.

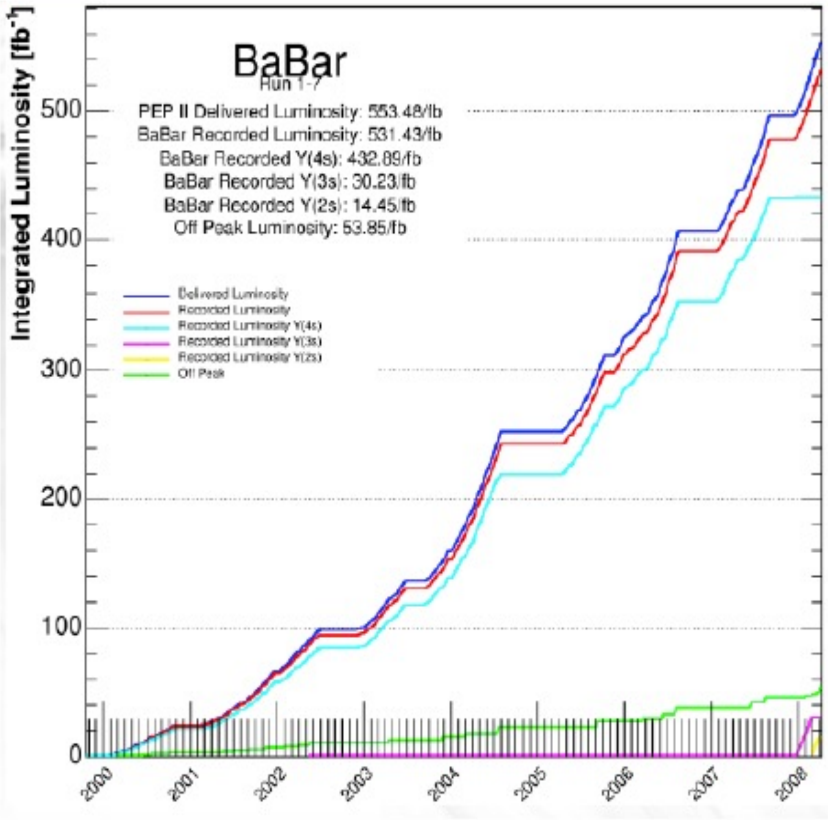
B-factories have provided constraints on models in all 4 types!



The BaBar Experiment

- For overview of experiment: **Nucl. Instrum. Meth. A 729, 615 (2013)**.
- Asymmetric e^+e^- collider with $\sqrt{s}$ = 10.58 GeV/c^2 i.e. Υ(4S) resonance: 9 GeV electrons collide with 3 GeV positrons.
- **Total luminosity: 432 fb^{-1} (4.7 x 10^8 $\bar{B}B$) on peak.**



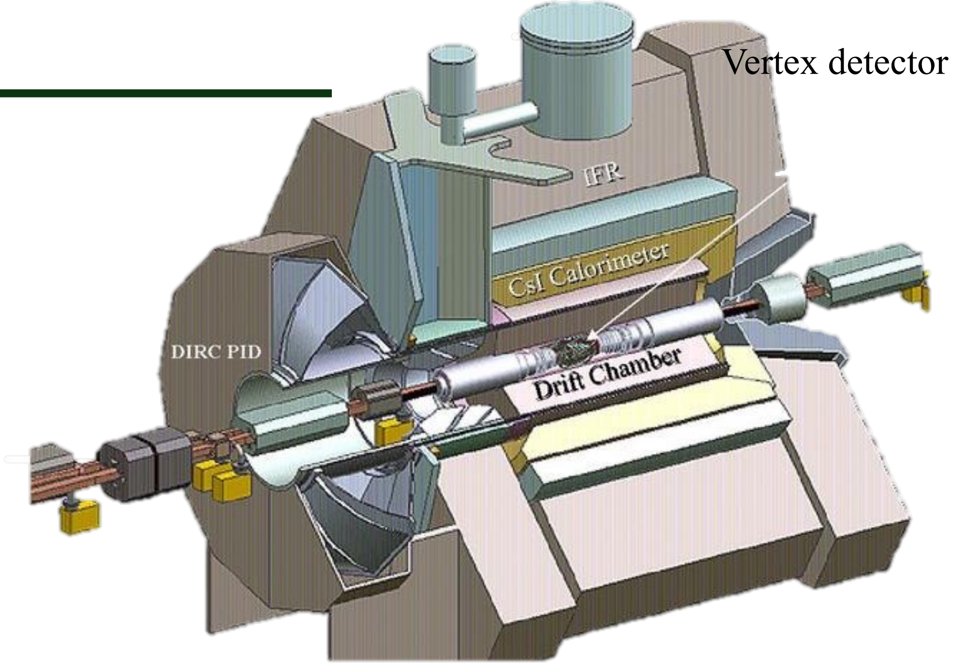


Detectors:

- **Reconstruct tracks:** Silicon Vertex Tracker (SVT) + 40-layer Drift Chamber (DCH), in 1.5-T solenoid.
  - Momentum resolution = 0.47% at 1 GeV/c
- **Measure energy:** Electromagnetic Calorimeter (EMC)
  - Energy resolution = 3% at 1 GeV.
- **PID:**
  - Identify charged pions, kaons and electrons using Ring Imaging Cherenkov detector (DIRC) + ionization loss measurements in the SVT and DCH.
  - Instrumented flux return of solenoid used to identify muons.

Dark Matter & the Dark Sector

- B-factories can perform searches for wide range of mediators with either prompt or intermediate lifetimes;
- They have provided some of the tightest constraints on the dark and hidden sectors:
  - e^+e^- colliders offer a clean environment,
  - excellent particle ID,
  - hermetic detector coverage,
  - precise reconstruction of missing energy,
- **making them excellent facilities for search for dark sector particles.**



I will concentrate on BABAR's contributions, but will note also some additional constraint made by BELLE & BELLE-II.

A Selection of Recent Papers

Extensive program conducted at B-factories over the past decade including the following analyses:

BABAR

- ***Dark Matter and Baryogenesis:*** *Phys.Rev.Lett.* 131 (2023) 20, 201801, *Phys.Rev.D* 107 (2023) 9, 092001
- **Heavy Neutral Leptons in Tau Decays:** *Phys.Rev.D* 107 (2023) 5, 052009
- **Axion Like Particles:** *Phys.Rev.Lett.* 128 (2022) 13, 131802
- **Darkonium:** *Phys.Rev.Lett.* 128 (2022) 2, 021802
- **Dark Leptophilic Scalar:** *Phys.Rev.Lett.* 125 (2020) 18, 181801
- **Invisible Decays of Dark Photons:** *Phys.Rev.Lett.* 119 (2017) 13, 13180
- **Muonic Dark Force:** *Phys Rev D 94 (2016) 011102*

BELLE

- **Heavy Neutral Leptons:** *Phys.Rev.Lett.* 131 (2023) 21, 211802 and *arXiv:2402.02580v1 [hep-ex] 2024*
- **Dark Leptophilic Scalar:** *Phys.Rev.D* 109 (2024) 3, 032002
- **Dark Matter and Baryogenesis:** *Phys. Rev. D 105, L051101 (2022).*

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This talk can cover only a few examples of these analyses in detail!

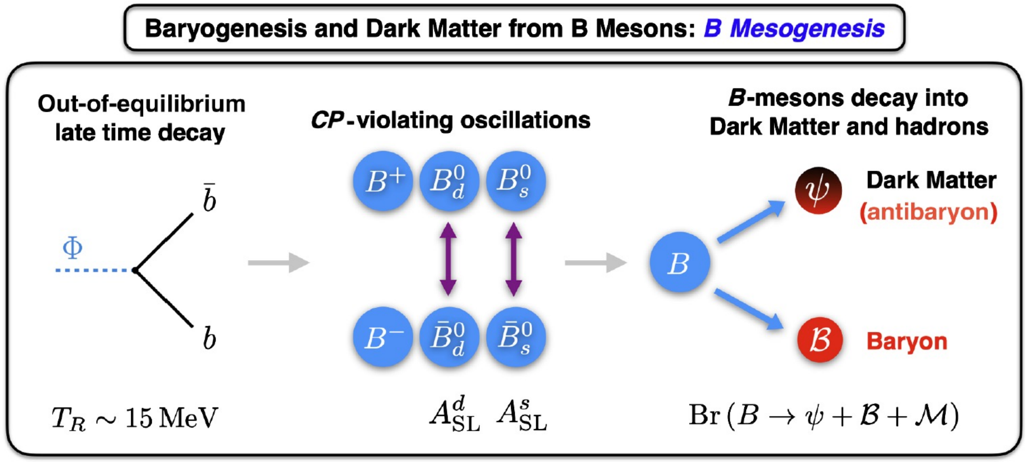
Dark Matter & Baryogenesis

Phys.Rev.Lett. **131 (2023) 20, 201801,** *Phys.Rev.D* **107 (2023) 9, 092001 (BABAR)**
Phys. Rev. D 105, L051101 (2022) (BELLE)

B-Mesogenesis and Dark Matter

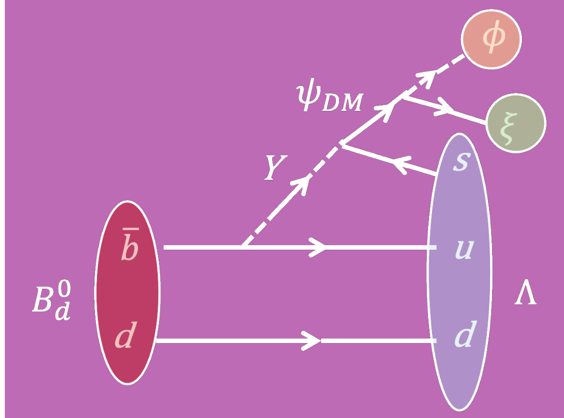
B-Mesogenesis is a scenario proposed to simultaneously explain the baryon asymmetry in the universe (BAU) and the presence of dark matter (DM) via B-meson decays:

- In early universe $b\bar{b}$ pairs hadronize to produce B-mesons;
- B-mesons decay to: baryon ($\mathcal{B}$), dark-sector baryon (ψ_D) and any number of additional mesons ($\mathcal{M}$);
- CP violation from $B^0 - \bar{B}^0$oscillations generates a matter-antimatter asymmetry;
- B^0 decays slightly dominate over $\bar{B}^0$ decays into anti-baryons;
- Net excess of baryon in the visible sector, and an anti-baryon excess in the dark sector;
- ***Baryon number in the whole universe is conserved, but a net excess is present in the visible sector.***



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).

Example:



Φ = heavy scalar field;
ψ_D = dark fermion;
Y = TeV scale mediator;
ξ = Majorana Fermion;
ϕ = scalar baryon.

B-Mesogenesis and Dark Matter

- ψ_D decay into stable dark sector particles producing the relic abundance we see today;
- Kinematic constraints require that the ψ_D mass lies between 0.94 – 4.34 GeV/c^2
- Need to explore channels which have access to all operators $O_{i,j} = (\psi_D\, b)\,(ij)$ $(i = u, c \text{ and } j = d, s)$;
- Flavor constraints imply that only one operator can be active in the early universe, one dominates, not a combination of operators;
- **BABAR has recently published world-leading/first limits on two channels:**

Initial State	Final State	Operators	ΔM (MeV/c^2)	
B^0	$\psi_D + \Lambda$	O_{us}	4163.95	***Phys.Rev.D* 107 (2023) 9, 092001**
B^0	$\psi_D + \Xi_c^0$	O_{cd}	2807.76	
B^0	$\psi_D + \Lambda_c^+ + \pi^-$	O_{cd}	2853.60	
B^+	$\psi_D + p$	O_{ud}	4341.05	***Phys.Rev.Lett.* 131 (2023) 20, 201801**
B^+	$\psi_D + \Sigma^+$	O_{us}	4089.95	
B^+	$\psi_D + \Lambda_c^+$	O_{cd}	2992.86	***Results Coming soon***
B^+	$\psi_D + \Xi_c^+$	O_{cs}	2810.36	

Results

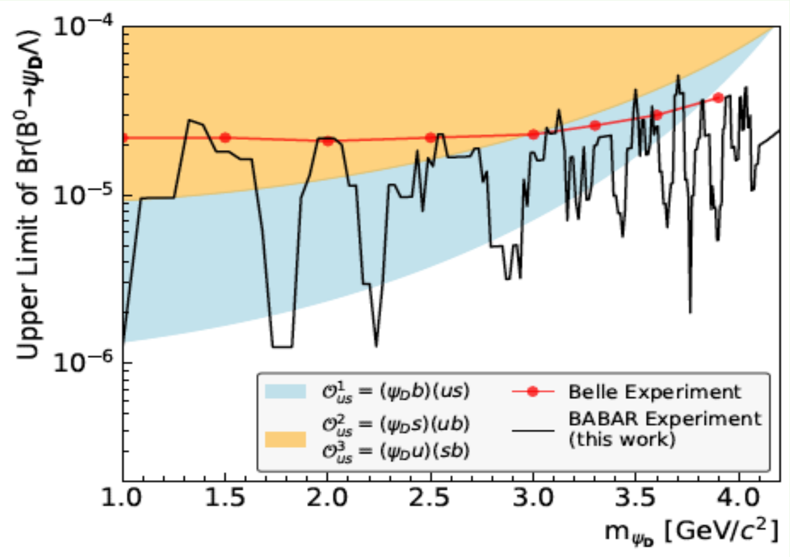
Applied result to a few specific models:

- World-leading result for $B^0 \rightarrow \psi_D + \Lambda$, improving on previous result and further constraining models;
- First direct search for $B^+ \rightarrow \psi_D + p$ places tight constraints on specified model of DM + BAU plus several others;

Parameter space vastly reduced, almost excluded for some operators.

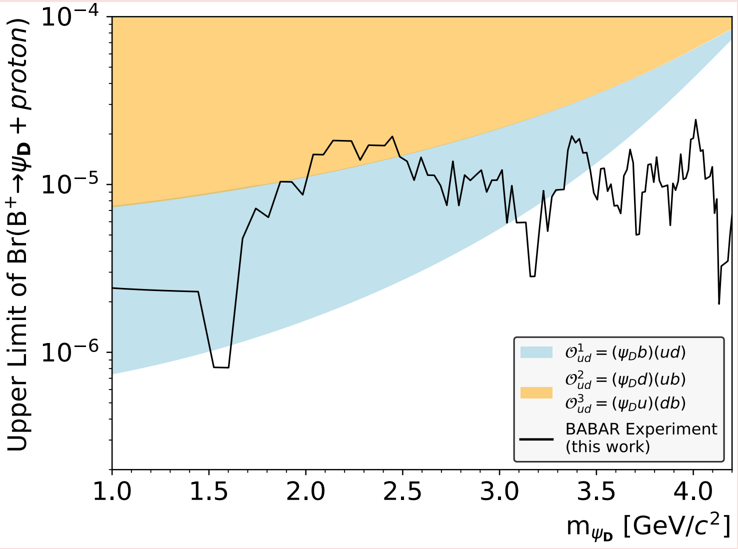
Must explore additional operators to fully exclude this model.

$B^0 \rightarrow \psi_D + \Lambda$



Phys.Rev.D 107 (2023) 9, 092001

$B^+ \rightarrow \psi_D + p$

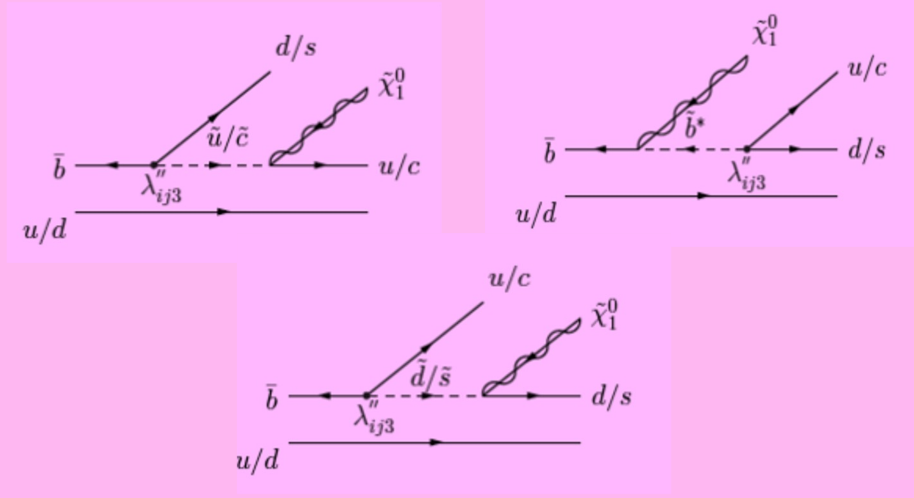


Phys.Rev.Lett. 131 (2023) 20, 201801

Results

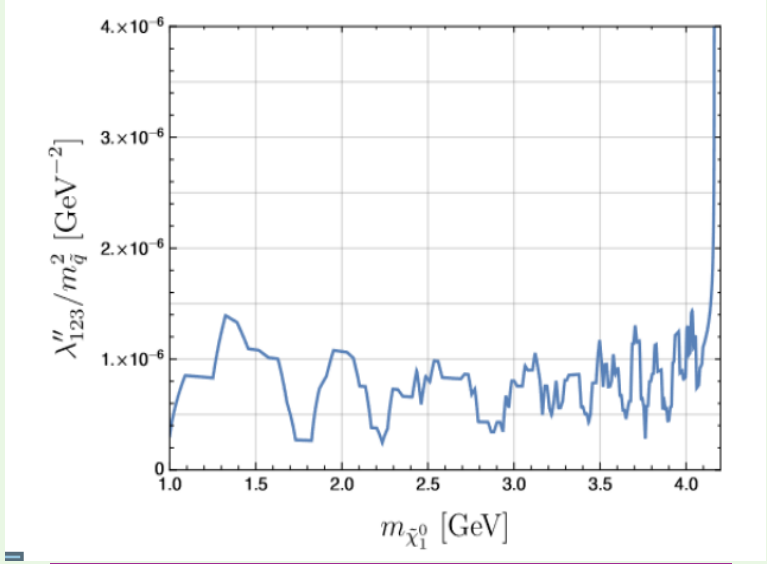
Given that all we are looking for is missing mass in the final state, we could apply our search to any such model:

- Extended search to provide first limit on RPV SUSY model described in **JHEP 2023 (02 224 (2023)).**



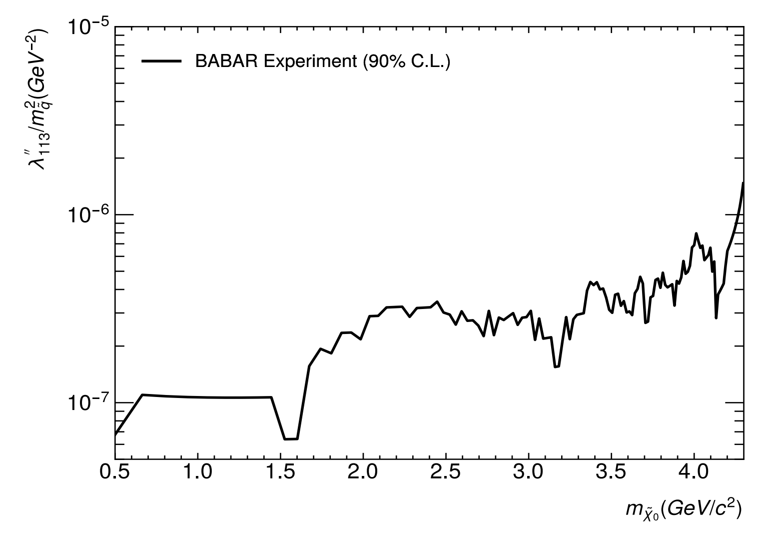
First limits on this SUSY model for both channels

$B^0 \rightarrow \widetilde{\chi_0} + \Lambda$



JHEP 02 (2023) 224

$B^+ \rightarrow \widetilde{\chi_0} + p$



Phys.Rev.Lett. 131 (2023) 20, 201801

Heavy Neutral Leptons

Phys.Rev.D 107 (2023) 5, 052009 (BABAR)

Phys.Rev.Lett. 131 (2023) 21, 211802 and *arXiv:2402.02580v1 [hep-ex] 2024 (BELLE)*

Motivations

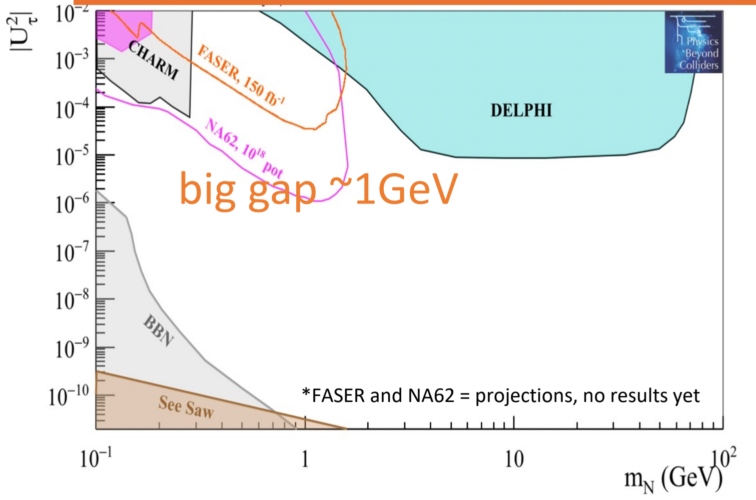
Heavy Neutral Leptons (HNLs) are additional neutrino states. They have mass but are neutral in all respects.

- HNLs are proposed by several beyond Standard Model (BSM) theories to explain three major observational phenomena:
  - **Neutrino oscillations and origins of their mass via seesaw models etc. (Phys. Rev. D 23,165);**
  - **Baryonic asymmetry of Universe (Phys. Rev. Lett. 81, 1359);**
  - **Dark matter candidate (Phys. Lett. B 631, 151–156).**
- *ν*-MSM proposes three keV-GeV scale HNLs.

- Experiments generally quote results in parameter space of elements $|U_{ln}|^2$ .v. HNL mass hypothesis.
- **Tau sector historically less explored…**

Tau Mixing Parameter .v. HNL mass

Journal of Physics G: Nuc. & Part.1075 Phys. 47, 010501 (2019)



$\sigma(e^+e^- \to \tau^+\tau^-) = \mathbf{0.919 \pm 0.003}$ **nb**
Integrated luminosity in runs used **= 424 fb $^{-1}$**
$\to N_{\tau\tau} \sim 4 \times 10^8$ events

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ \vdots & \vdots & \vdots & \ddots & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \vdots \end{pmatrix}.$$

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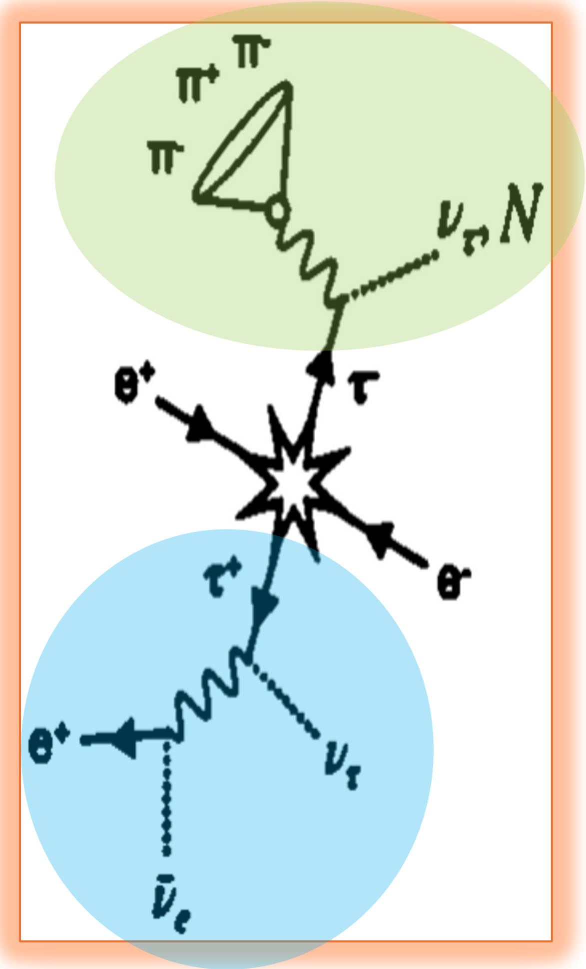
The BaBar Search

$\sigma(e^+e^- \to \tau^+\tau^-) = \mathbf{0.919 \pm 0.003}$ **nb**
Integrated luminosity in runs used **= 424 fb $^{-1}$**
$\to$ **$N_{\tau\tau}$ ~ 4 × 10^8 events**

- ***BaBar*** 2022 analysis used the kinematics of hadronic tau decays based on previous technique (*Phys.Rev.D* 91 (2015) 5, 053006 Kobach and Dobbs).
- Looks only at kinematics, no assumptions on underlying model, except that there must be some small mixing with tau sector:
  - "signal side" : three pronged pionic tau decay ($\tau^- \to \pi^-\pi^-\pi^+\upsilon_\tau$) as it allows access to region $100 < m_4 < 1360$ MeV/c^2 where limits were loose.
  - "tag side" : Second tau decay must be leptonic, due to cleaner environment.

CPT assumed to hold, combining + and – signal sides.



Branching Fractions:
1-prong (electron or muon) $\sim$ **34 %**
3-prong (3 pion) $\sim$ **9%**

Method

Templates for each mass in the form of 2D plots of E_h.v. m_h. Boundary of curved region in this plot characteristic of a massive neutrino.

SM Tau Decay | **BSM Tau Decay**

$$\frac{d\Gamma_{\text{tot}}(\tau^- \to \nu h^-)}{dm_h dE_h} = (1-|U_{\tau 4}|^2)\frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\Big|_{m_\nu=0} + |U_{\tau 4}|^2\frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\Big|_{m_\nu=m_4}.$$

- Model 3-pronged decay as 2-body with outgoing HNL and hadronic system (h).
- Define E_h as reconstructed energy and m_h as the invariant mass of the visible, hadronic products.
- $E_\tau = \frac{E_{cms}}{2}$ in the limit of no ISR. The value of E_h and m_h can exist, in principle, in the ranges:

$$3m_{\pi^\pm} < m_h < m_\tau - m_4$$

and

$$E_\tau - \sqrt{m_4^2 + q_+^2} < E_h < E_\tau - \sqrt{m_4^2 + q_-^2},$$

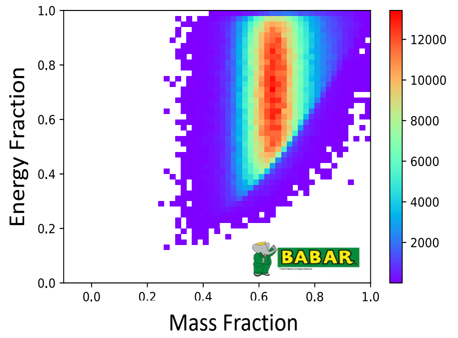
where

$$q_\pm = \frac{m_\tau}{2}\left(\frac{m_h^2 - m_\tau^2 - m_4^2}{m_\tau^2}\right)\sqrt{\frac{E_\tau^2}{m_\tau^2} - 1} \pm \frac{E_\tau}{2}\sqrt{\left(1 - \frac{(m_h+m_4)^2}{m_\tau^2}\right)\left(1 - \frac{(m_h-m_4)^2}{m_\tau^2}\right)};$$

Signal samples made in modified TAUOLA, and passed through G4 + BABAR reco. alg.

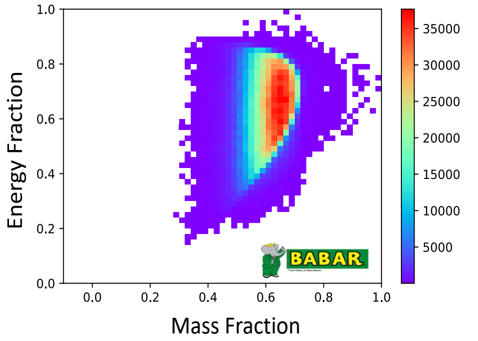
$m_4 = 100\ MeV/c^2$

BABAR-MC



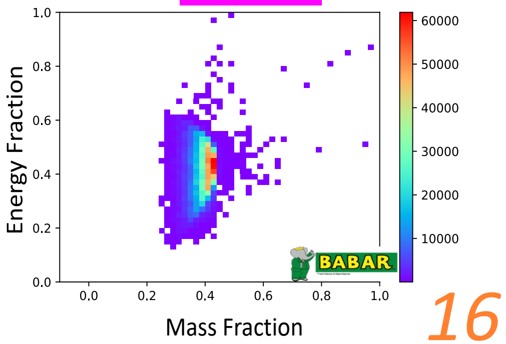
$m_4 = 500\ MeV/c^2$

BABAR-MC



$m_4 = 1000\ MeV/c^2$

BABAR-MC



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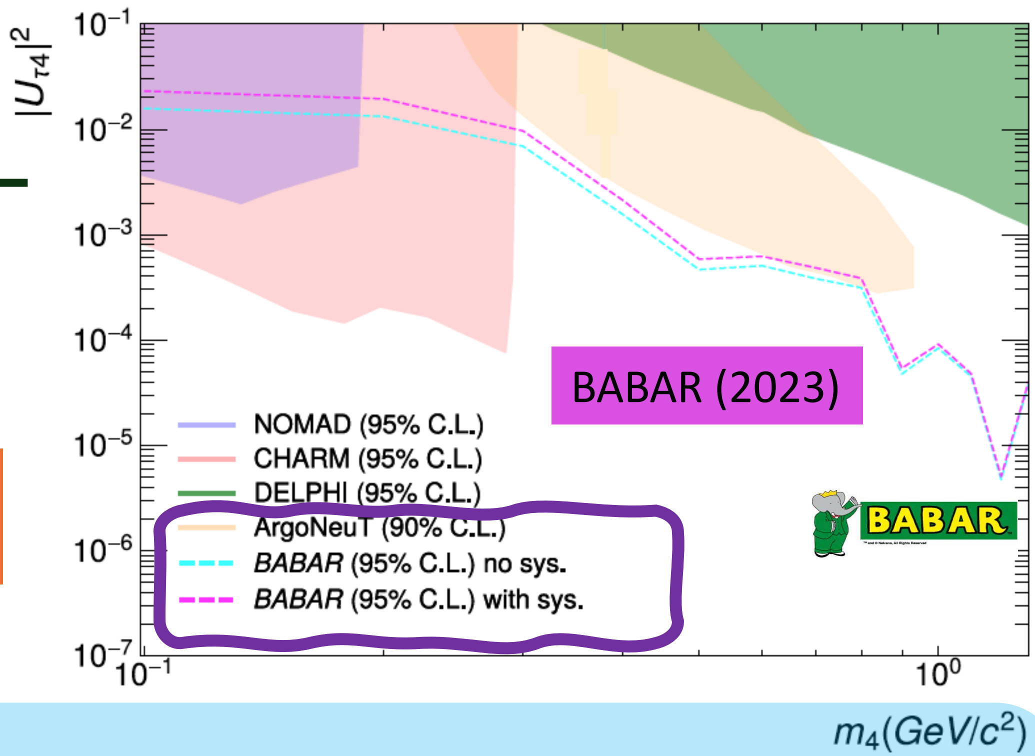
The BABAR Result

Mass [MeV]	No Sys.	With Sys.
100	1.58×10^{-2}	2.31×10^{-2}
200	1.33×10^{-2}	1.95×10^{-2}
300	6.91×10^{-3}	9.67×10^{-3}
400	1.57×10^{-3}	2.14×10^{-3}
500	4.65×10^{-4}	5.85×10^{-4}
600	5.06×10^{-4}	6.22×10^{-4}
700	3.82×10^{-4}	4.85×10^{-4}
800	3.12×10^{-4}	3.58×10^{-4}
900	4.70×10^{-5}	5.28×10^{-5}
1000	8.34×10^{-5}	9.11×10^{-5}
1100	4.49×10^{-5}	4.78×10^{-5}
1200	4.70×10^{-6}	5.04×10^{-6}
1300	3.85×10^{-5}	4.09×10^{-5}

At 95 % C.L

BABAR (2023):
Phys.Rev.D 107 5, 052009



- Binned likelihood fit incorporating nuisance parameters.
- Dominant systematic from modelling uncertainties in hadronic tau decays.
- Presents new upper limits on $|U_{\tau4}|^2$ at 95 % *C.L.* between 100 MeV/c^2 – 1300 MeV/c^2 :
  - **World-leading constraints at time of acceptance for publication.**
- In 2021-2023 there have also been new results in this region from:
  - ArgoNEUT: Phys. Rev. Lett., 127, 121801 (shown)
  - Boiarska et al.: Phys. Rev. D 104, 095019 (indirect use of CHARM electron and muon result)
  - Barouki et al. : SciPost Phys., 13:118, 2022. (BEBC reanalysis)

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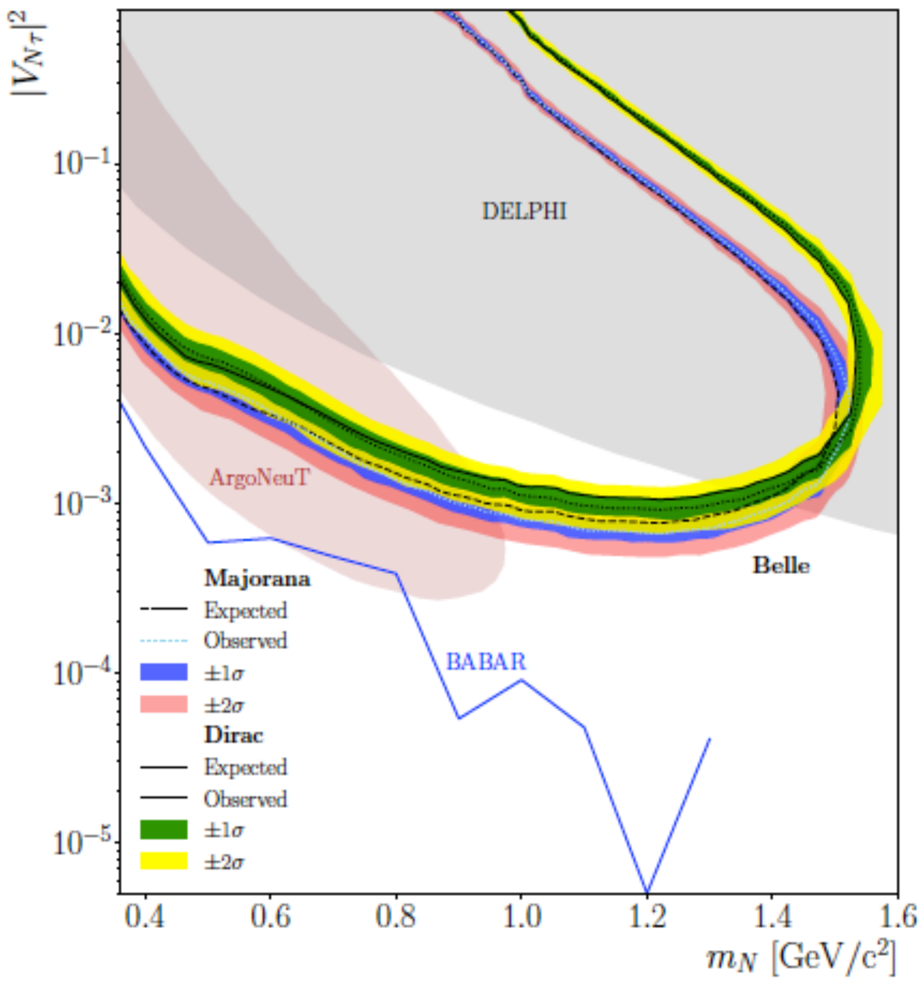
New Belle Result arXiv:2402.02580v1 [hep-ex] 4 Feb 2024

- Search for decay $\tau^- \rightarrow \pi^- N$ followed by $N \rightarrow \mu^-\mu^+\upsilon_\tau$.
- Green and yellow bands show the 1σ and 2σ bands for the expected limits for the Dirac case. The blue and pink bands show the same for the Majorana case.



Axion Like Particles

Phys.Rev.Lett. **128 (2022) 13, 131802 (BABAR)**

Axion-like particles at BABAR

coupling $SU(2)_W$ *field strength tensor*

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

Many BSM theories include spontaneously-broken global symmetries, resulting in Axion-Like Particles (ALPs):

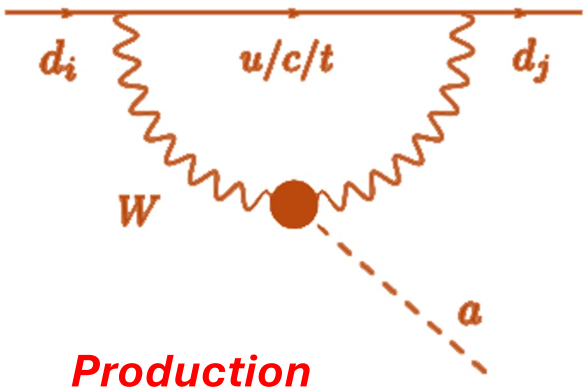
- can help resolve issues of naturalness of SM parameters but may also serve as mediators to dark sectors;
- ALPs (a) couple primarily to pairs of SM gauge bosons.

Can be produced $B^{\pm} \rightarrow K^{\pm}a$:

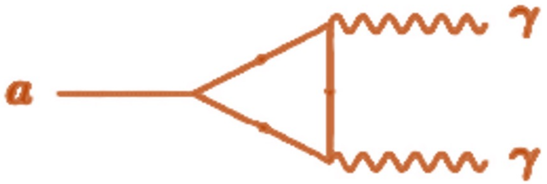
- $a \rightarrow \gamma\gamma$ with nearly 100% BF for $m(a) < m(W)$;
- for low ALP mass and small coupling, the axion lifetime can become "long", i.e. non-prompt:

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

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



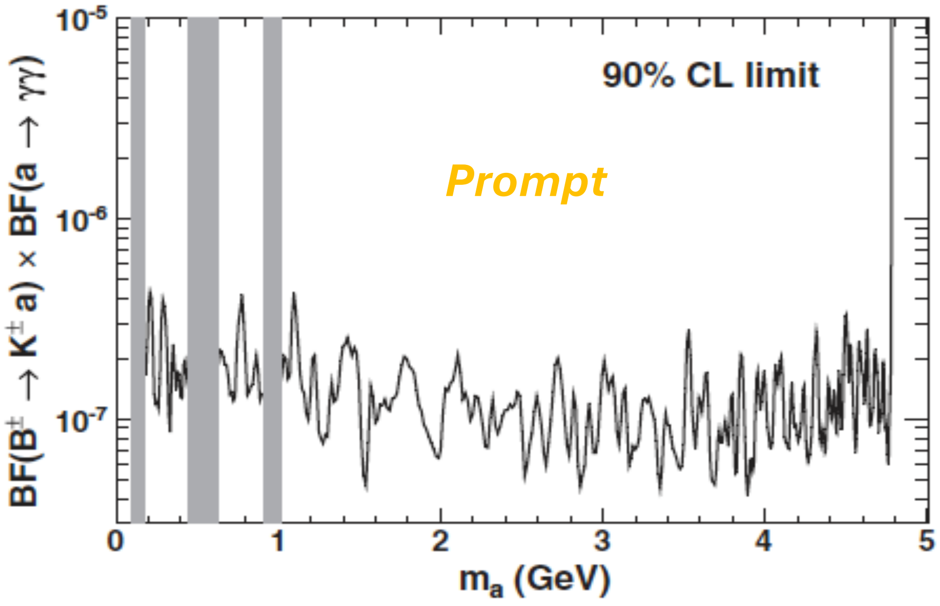
Production

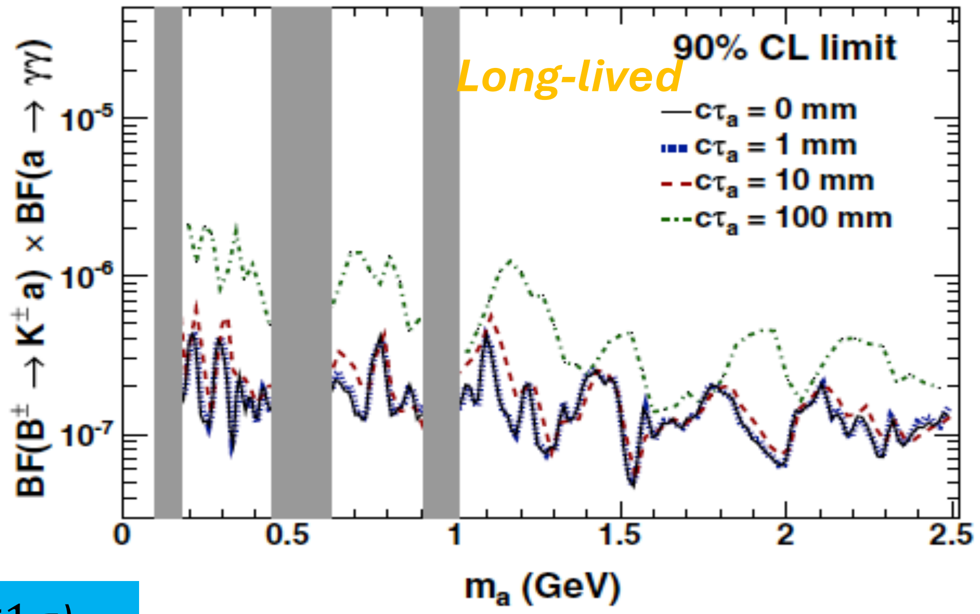


Decay

Analysis Method

- BABAR search for ALPs in $B^{\pm} \to K^{\pm}a$ ($+a \to \gamma\gamma$) in 4.72 x 10^8 $B\bar{B}$ pairs collected at the ϒ(4S) energy.
- Scan $m_{\gamma\gamma}$ with steps equal to the signal mass resolution ($\sim$ 8 – 14 MeV).
- Each signal mass hypothesis fit with unbinned maximum likelihood with a hypothetical signal peak + smooth background.
- 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.
- $c\tau$ dependence is smaller at larger masses because ALP is less boosted, leading to shorter decay length in the detector.



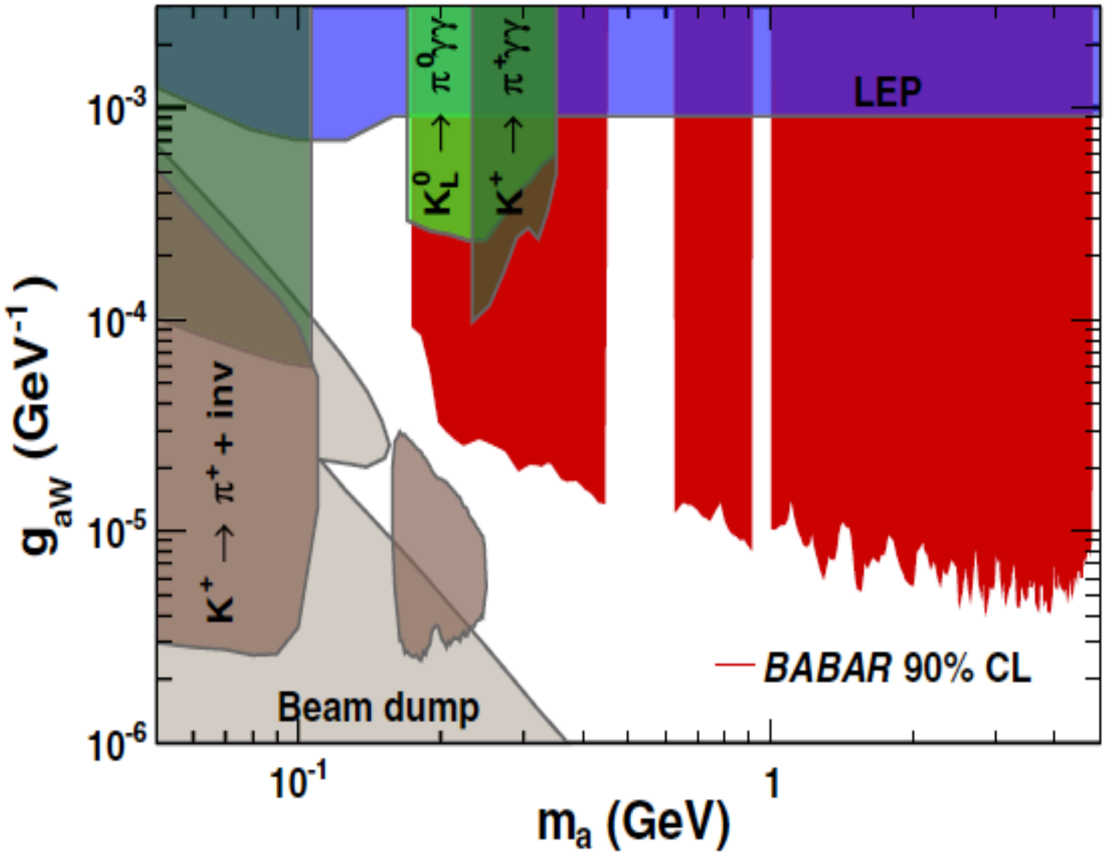


Largest local significance near 1.1GeV (<1σ)

Result

Phys. Rev. Lett. 128.131802 (2022)

- **Results show new limits on g_{aW} at 90% C.L. which vastly improve on previous limits;**
- Combination of results for all mass hypotheses and lifetimes;
- First search for visibly decaying ALPs produced in B meson decays.



Search for Darkonium

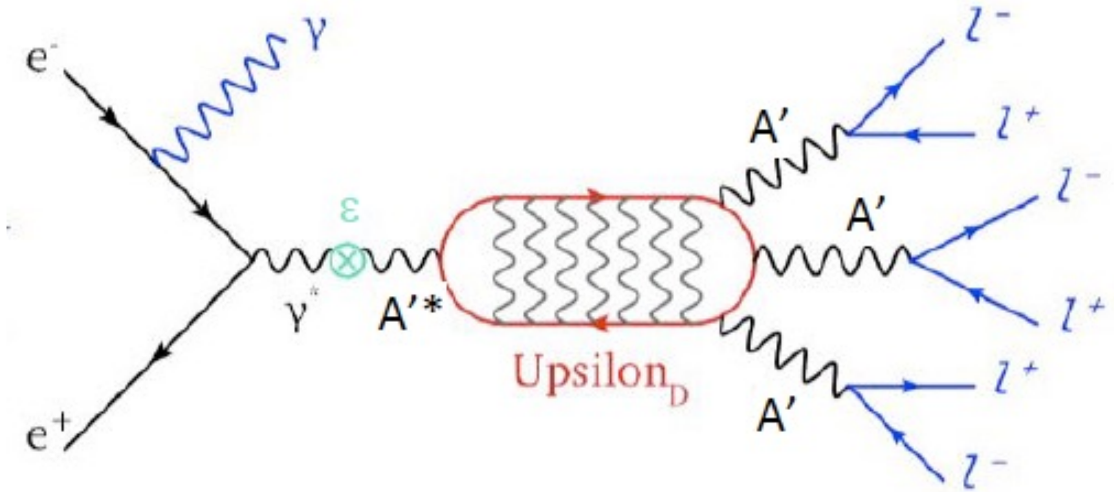
Phys.Rev.Lett. 128 (2022) 2, 021802 (BABAR)

Self-interacting Dark Matter

- **BABAR carried out a search for darkonium Υ_D in $e^+e^- \rightarrow \gamma Y_D, Y_D \rightarrow A'A'A',\ A' \rightarrow X + X\ (X = e\mu\pi)$;**
- 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 formed →darkonium;

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

- Search for the lightest vector darkonium Y_D ($J^{PC}= 1^{--}$). Dark photon lifetime can be large for small values of the kinetic mixing ε and mass → **prompt and displaced vertex analyses!**

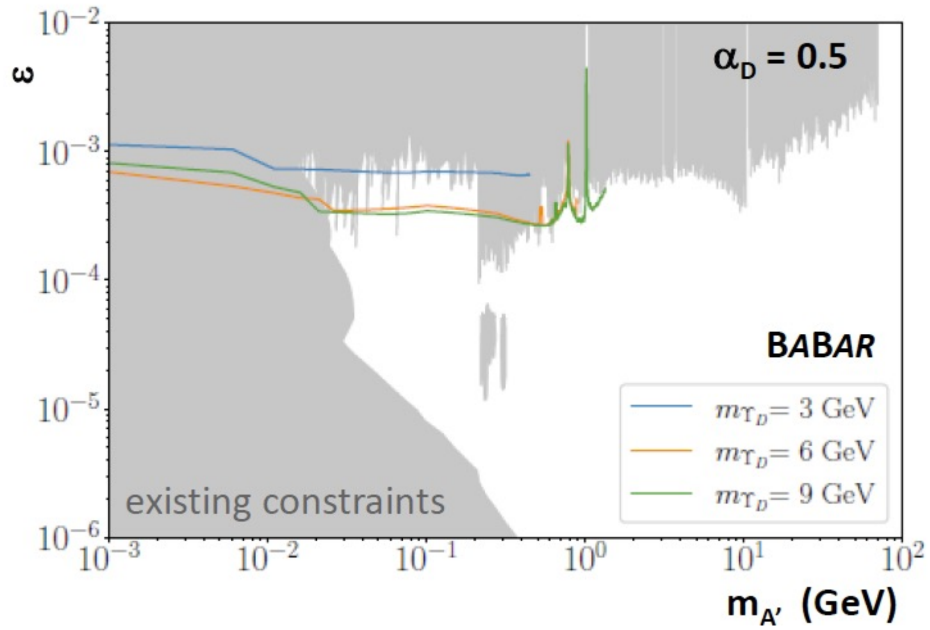


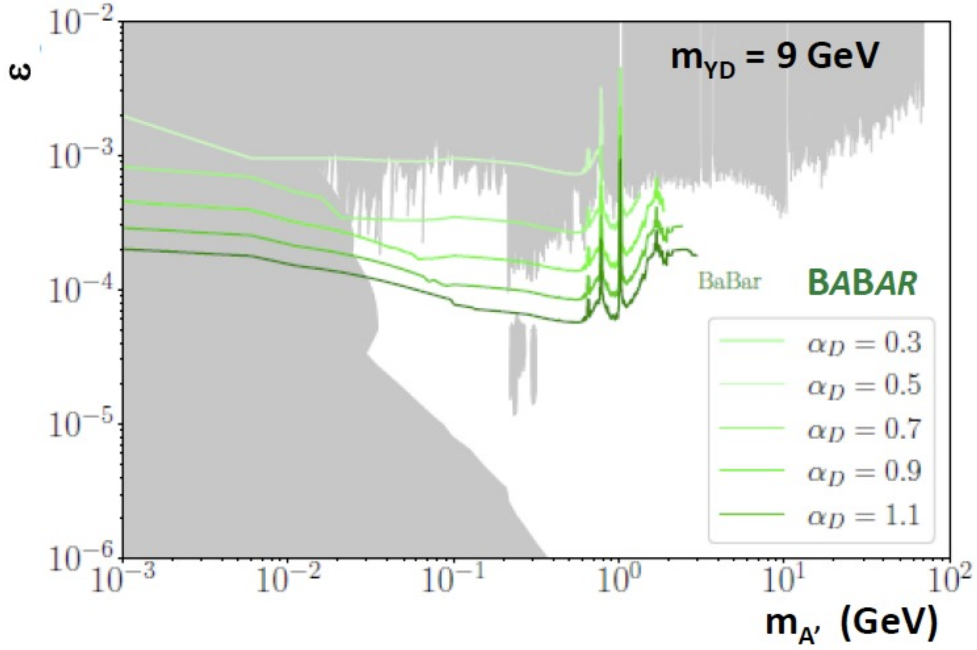
Results

Analysis Method:

- Final states must consist of three pairs of leptons or pions with similar masses (require 2+ leptons);
- Recoil mass against $\boldsymbol{Y_D}$ compatible with photon;
- ISR photon can be emitted inside or outside calorimeter acceptance;
- MVA to improve signal purity;
- Scan the $\boldsymbol{Y_D}$–A’ mass plane to extract signal;
- **Results show 90% CL limit on the kinetic mixing strength ε for different values of α_D and m_{YD}.**

Phys.Rev.Lett. 128 2, 021802 (2022)

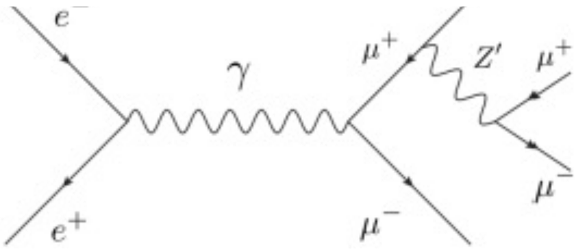




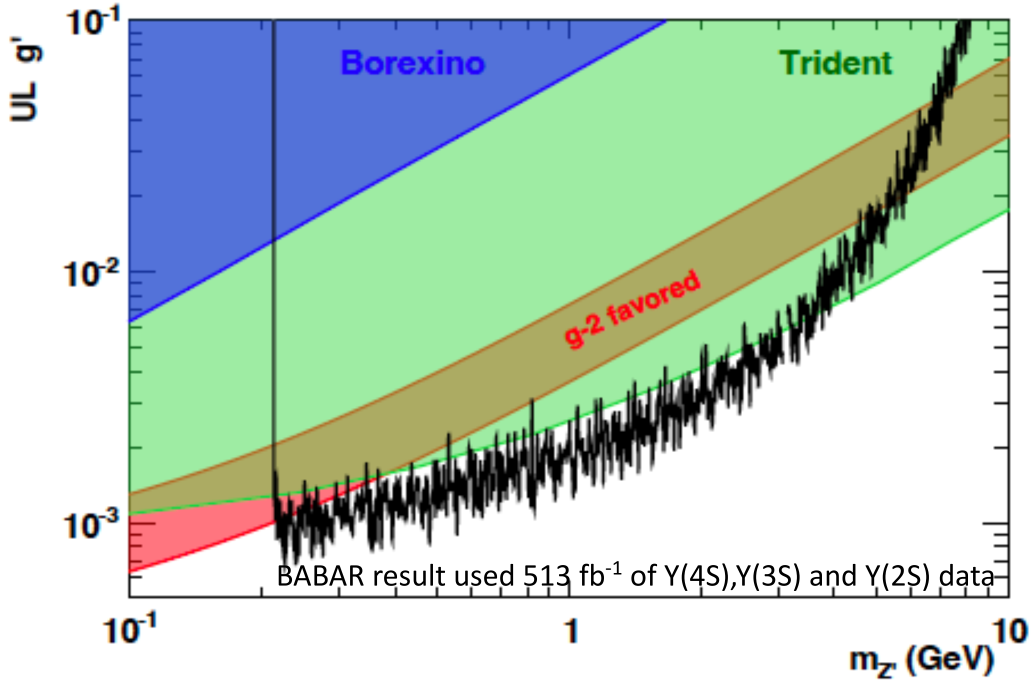
Many Other Results

too many for one talk ….

Muonic Dark Force

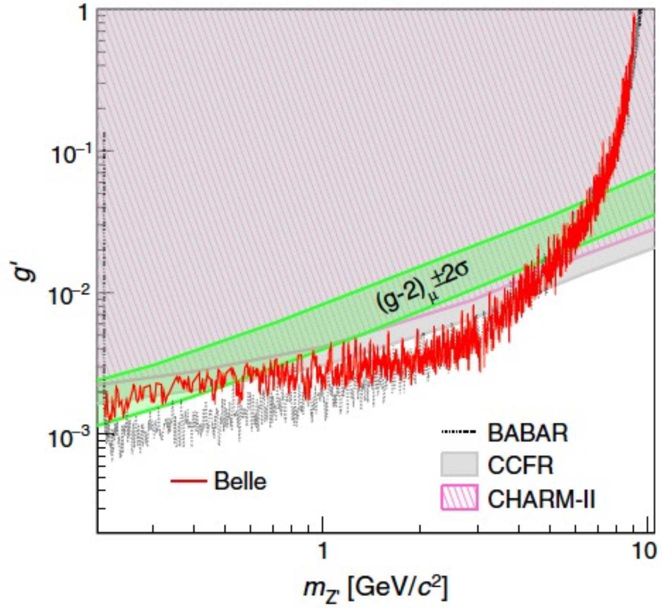


Muonic dark force



Phys. Rev. D 94, 011102 (2016) (BABAR)
Phys. Rev. D 106, 012003 (2022) (BELLE)

- Muonic dark force: a new vector force coupling only to the second and third generation of leptons with a corresponding gauge boson Z';
- Could explain g-2 discrepancy or proton radius puzzle;
- **Results show 90% CL upper limits on the new gauge coupling g' as a function of the Z' mass.**



Caltech

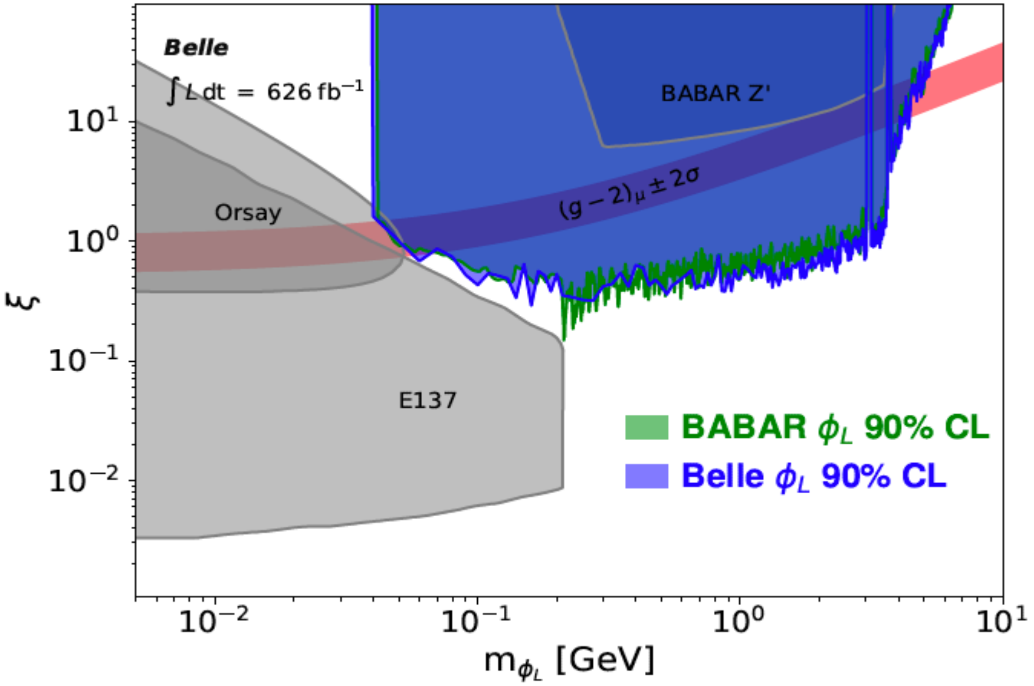
Dark Leptophilic Scalar

- A new light gauge singlet could directly mix with the Higgs boson via the scalar portal;
- New leptophilic scalar interacting mainly with leptons could explain the g-2 anomaly;
- Mass proportional coupling implies that this scalar is produced preferentially via its coupling to the tau;
- Decays mainly to the most massive lepton-pair kinematically accessible:

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

- **Results show 90% C.L upper limits on coupling ξ as a function of dark scalar mass.**

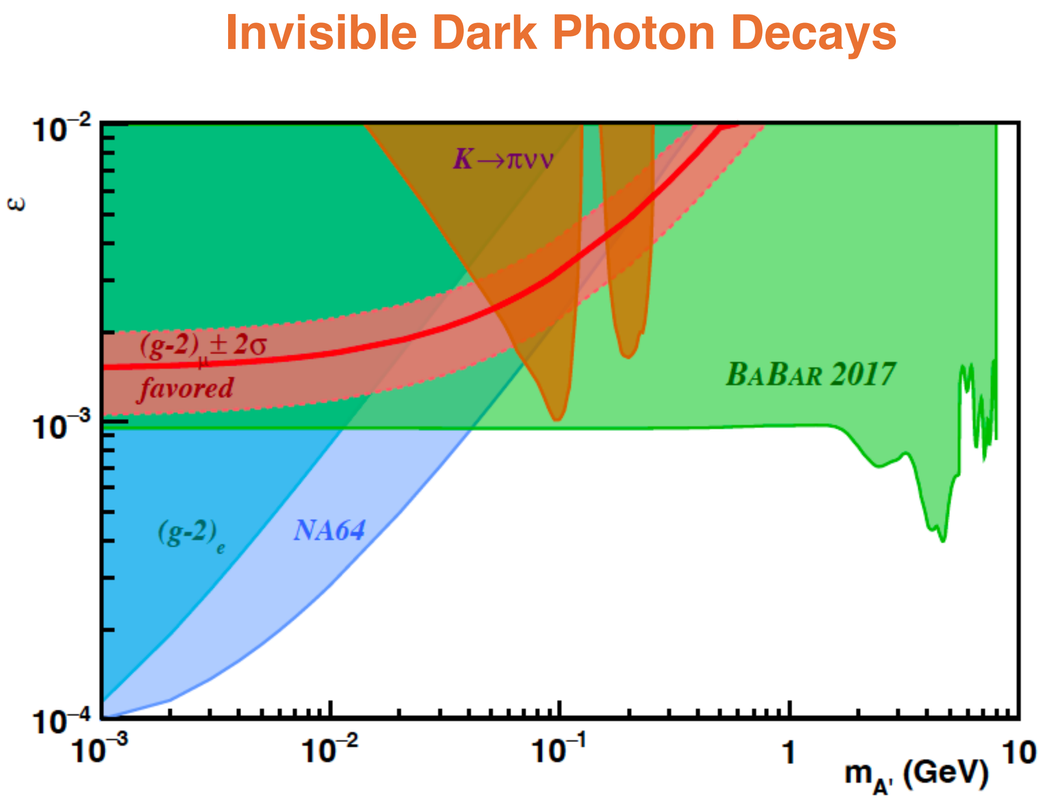
dark leptophilic scalar



Phys.Rev.Lett. 125 (2020) 18, 181801 (BABAR)

Phys. Rev. D 109, 032002 (2024) (BELLE)

Invisible Dark Photon Decays



Phys. Rev. Lett. 119, 131804 (2017) (BABAR)

- Substantially improve previous limits in high mass region, and exclude purely invisible dark photon as explanation of "g-2" anomaly ;
- **Results show 90 % CL upper limits on mixing strength ε as function of A' mass;**
- **Next generation B-factories will substantially improve at high masses.**

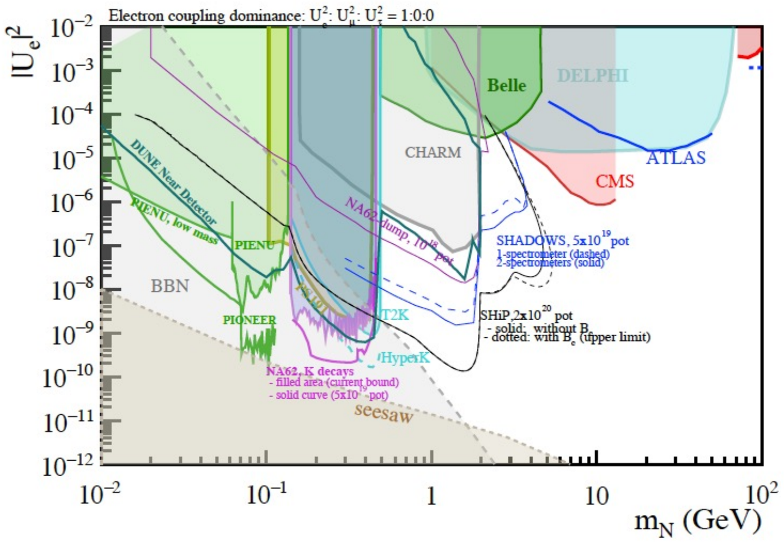
Summary

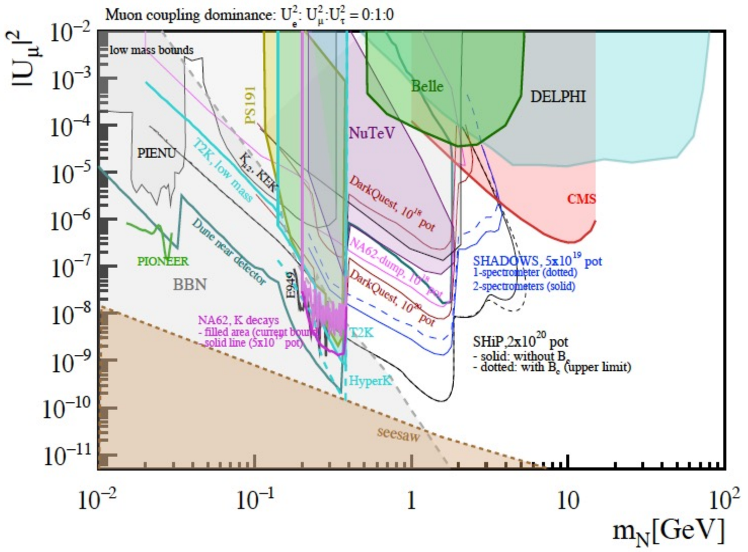
Summary

- Dark sector models are a popular possibility to explain dark matter;
- e^+e^- colliders offer ideal environment to probe these dark sector models for various reasons;
- B*A*B*AR* has specifically conducted an extensive program to search for dark sector signatures and continues to put world-leading limits on many scenarios. Only a selection could be shown today.

There are many unexplored opportunities and improvements still to be made. Dedicated programs continue at BABAR and BELLE & BELLE-II which aims to take large amounts of data in the coming years and make substantial improvements on exploring many of these models.

All Mixings





Phys. Rev. D 87, 071102 (2013) (BELLE)