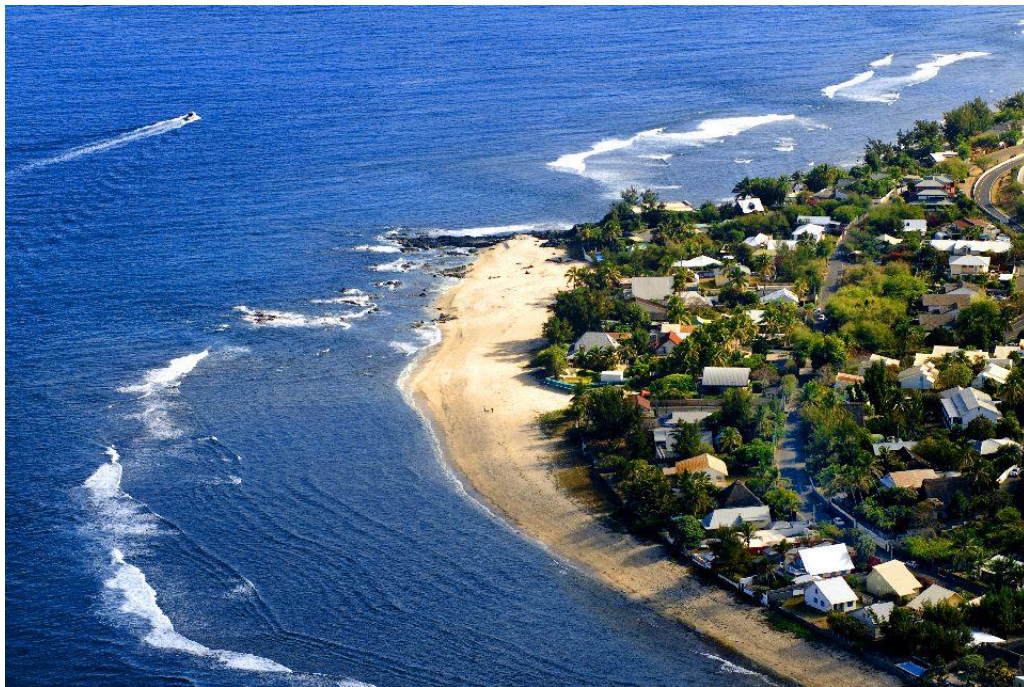


Dark matter searches with the BABAR detector



4th World Summit on
Exploring the Dark Side of
the Universe

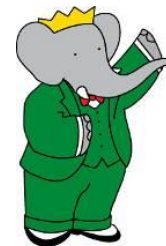
La Réunion, France

November 8, 2022

Georges Vasseur

georges.vasseur@cea.fr

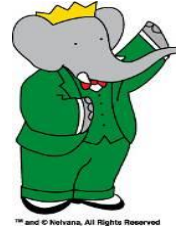
on behalf of the BABAR Collaboration



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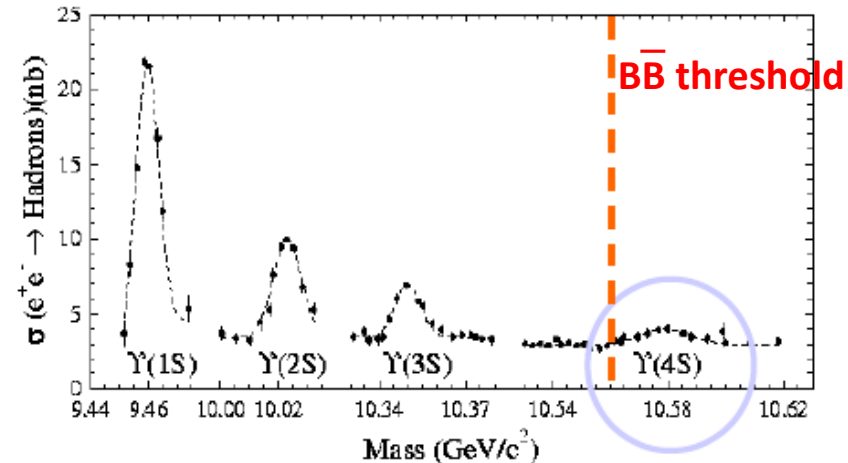
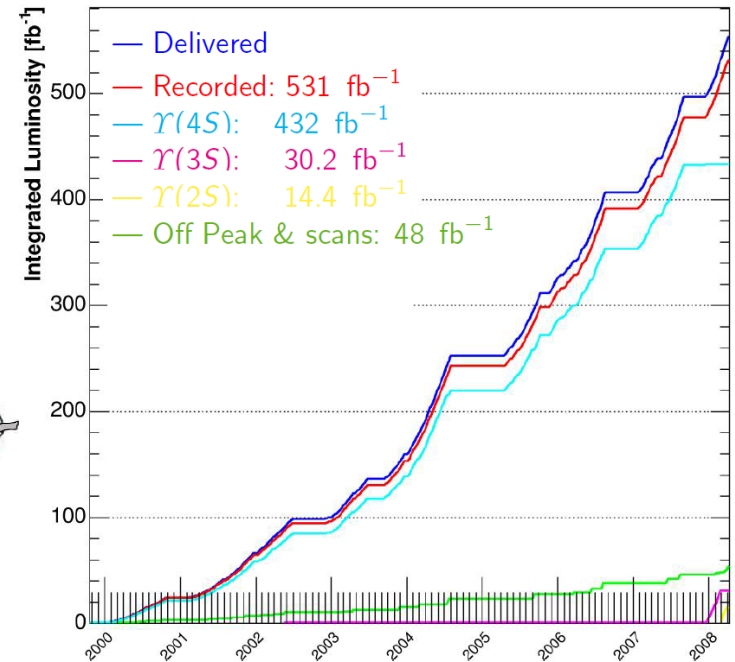
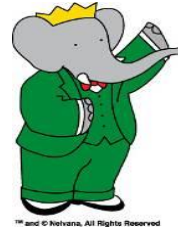
Outline

- The BABAR experiment
- Search for Darkonium
 - Phys. Rev. Lett. 128 (2022) 021802
- Search for a Dark Leptophilic Scalar
 - Phys. Rev. Lett. 125 (2020) 181801
- Search for a Heavy Neutral Lepton
 - arXiv:2207.09575 accepted in Phys. Rev. D
- Search for an Axionlike Particle
 - Phys. Rev. Lett. 128 (2022) 131802



BABAR data sample

- The BABAR experiment
 - At the SLAC PEP-2 high intensity e^+e^- collider
 - Huge quantity of data: 0.5 ab^{-1} over 10 years (1999-2008)
 - Around the Υ resonances ($\sim 10 \text{ GeV}$)
- Main physics topics
 - CP violation
 - Heavy flavour physics



BABAR detector

Cherenkov detector (DIRC)

144 quartz bars and 11000 PMTs

solenoid
1.5T

Electromagnetic calorimeter

6580 CsI(Tl) crystals

e^+ (3.1 GeV)

e^- (9 GeV)

Drift chamber

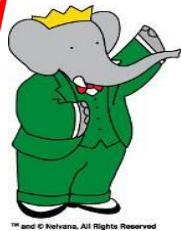
40 layers

Si vertex tracker

5 layers

μ chambers
RPC / LST

- Good vertex separation
- Momentum measurement
- Good particle identification
- Precision calorimetry



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Dark sector searches

- Thanks to:
 - Clean e^+e^- environment
 - Hermetic detector coverage
 - Good missing energy reconstruction
 - Good particle detection and identification
 - Inclusive and dedicated triggers
 - Huge data sample
- BABAR was able to search for manifestations of the dark sector in low energy e^+e^- collisions

Dark matter portals

from B. Echenard, Lake Louise, Feb 2022

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

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

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

γ HNL

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

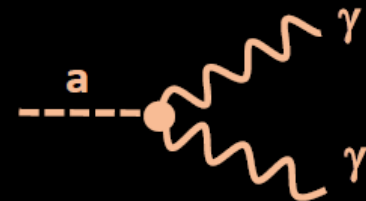


Dim=5

Axion

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

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



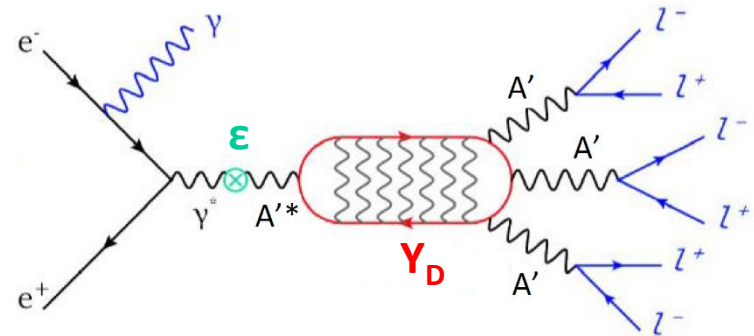
And many variations with slightly different couplings

Darkonium

- Minimal dark sector with a dark photon coupling to a dark fermion and antifermion
- **Bound dark matter fermion pair** for large coupling constant α_D H. An et al., PRL 116 (2016) 151801

- Search for lightest vector darkonium Y_D ($J^{PC} = 1^{--}$)

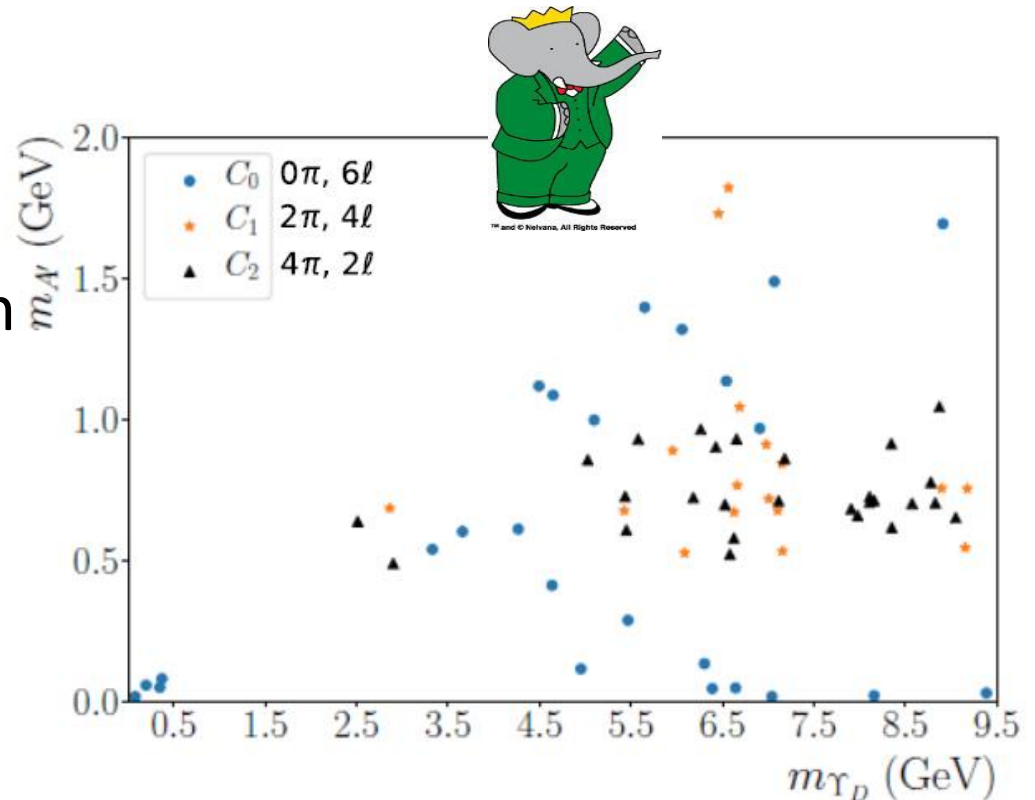
- $e^+ e^- \rightarrow \gamma Y_D$
 - where $Y_D \rightarrow A' A' A'$
 - with $A' \rightarrow X^+ X^-$ ($X = e, \mu, \pi$)



- Dark photon lifetime can be large
 - Prompt analysis and displaced vertex analyses

Darkonium: analysis

- Use 514 fb^{-1} of data
- Select events with 3 lepton or pion pairs with same invariant mass
 - At least 1 lepton pair
- Recoil mass against Y_D compatible with zero
 - ISR photon inside or outside calorimeter acceptance
- Scan $Y_D - A'$ mass plane

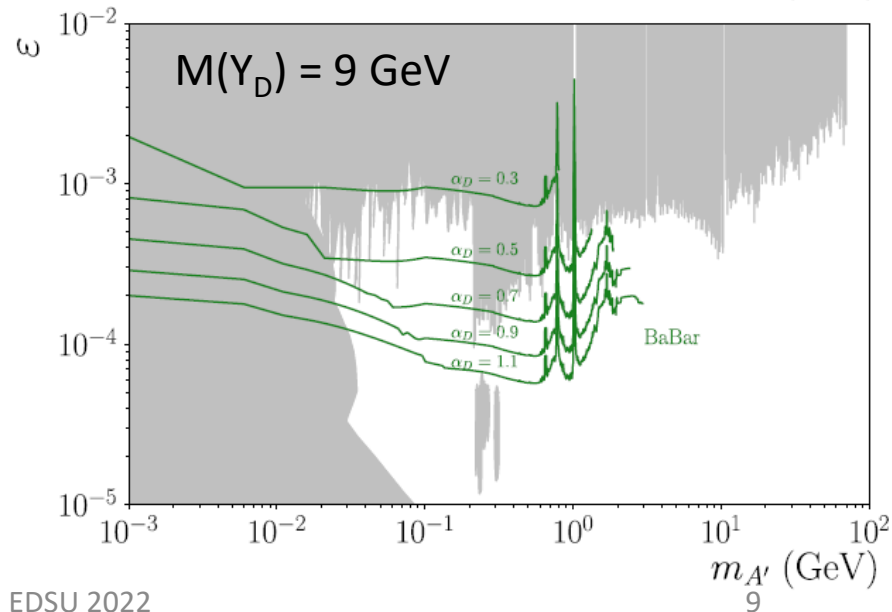
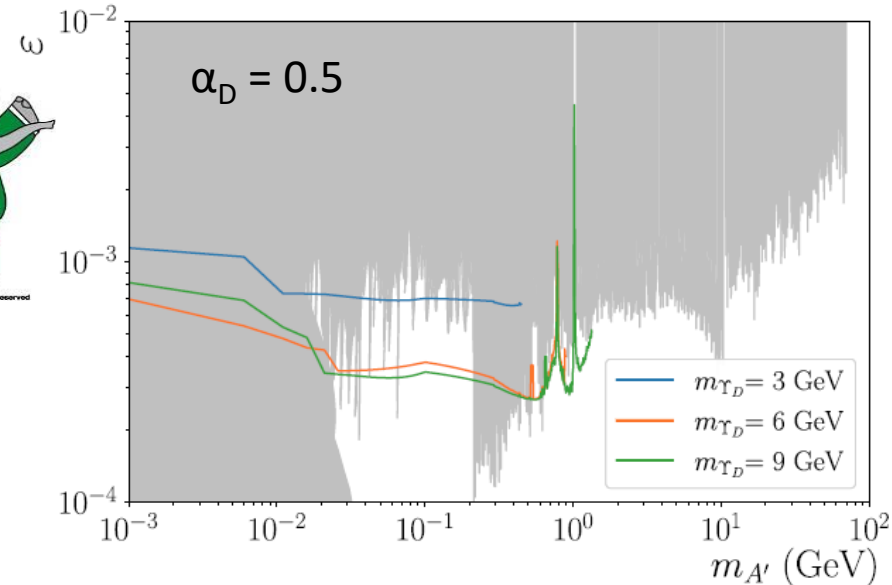
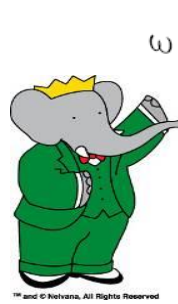


PRL 128 (2022) 021802

Darkonium: results

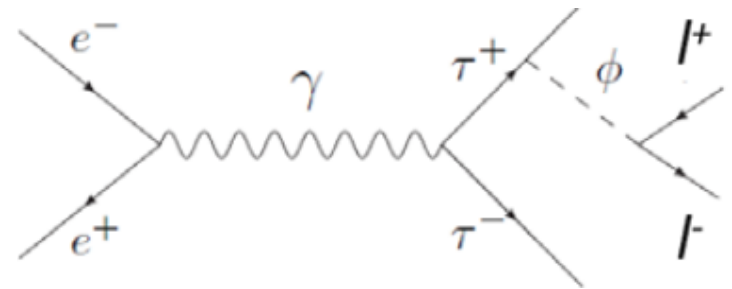
- No significant signal is observed
- Extract 90% CL upper limit on the kinetic mixing parameter ε
 - As a function of $m_{A'}$
 - For different values of α_D and $m(Y_D)$

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Dark leptophilic scalar

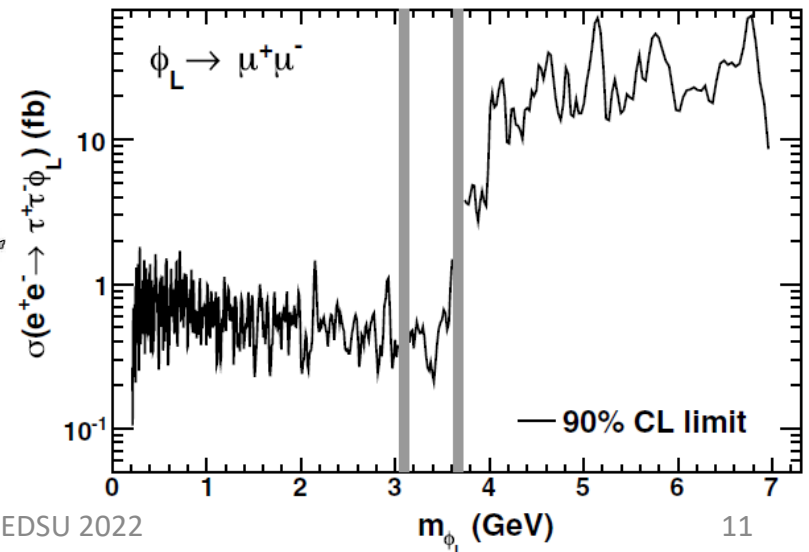
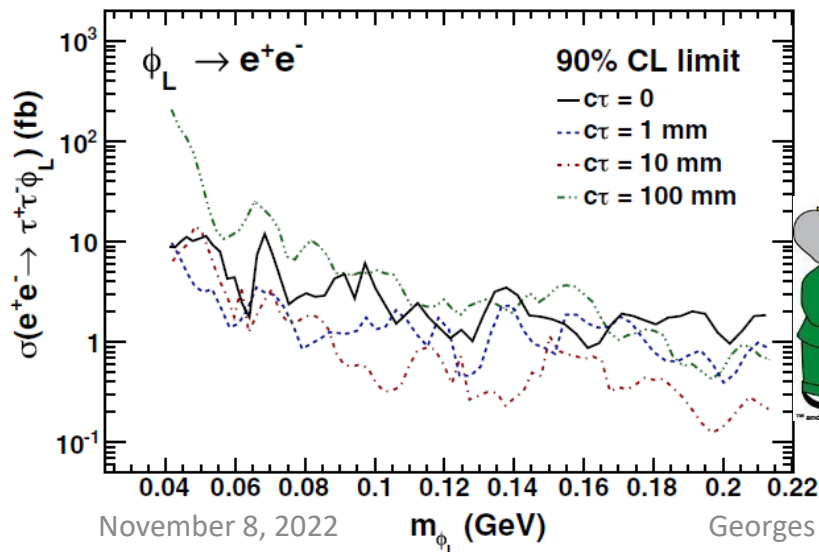
- A dark leptophilic scalar interacting mainly with leptons rather than quarks could:
 - Escape the current constraints
 - Explain the $g-2$ anomaly
- Higgs-like mass proportional coupling implies that:
 - It is produced preferentially with tau leptons
 - It decays mainly to the most massive kinematically accessible lepton-pair
- Search for: $e^+e^- \rightarrow \tau^+\tau^-\phi$
 - with $\phi \rightarrow e^+e^-, \mu^+\mu^-$
 - (Too many neutrinos in $\phi \rightarrow \tau^+\tau^-$)



Dark leptophilic scalar: analysis

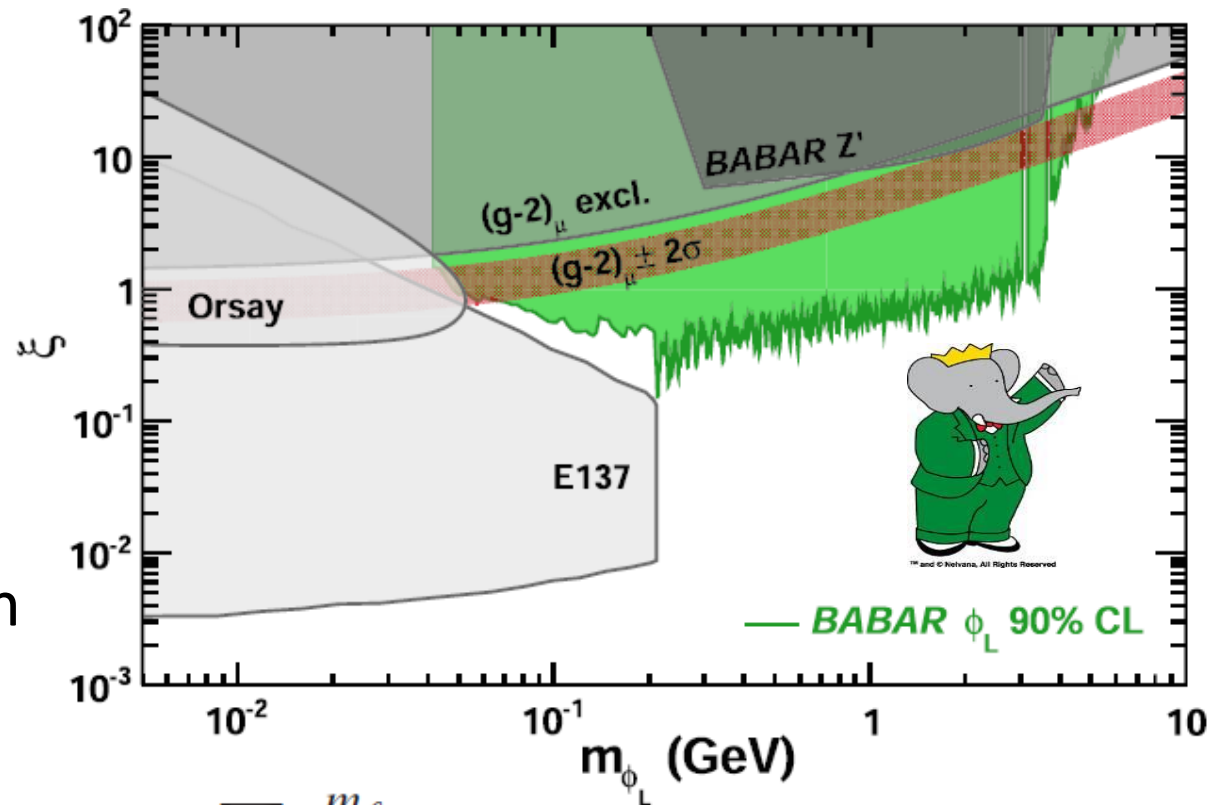
PRL 125 (2020) 181801

- Analysis performed on 514 fb^{-1} of data
- Select events with two 1-prong τ decays + a lepton pair
- Fit peaks in dilepton mass over sliding intervals: no signal
- Compute **90% CL upper limits on production cross section**



Dark leptophilic scalar: result

- Set 90% CL upper limit on coupling strength ξ
- Improve significantly upon current constraints
- Exclude that a dark leptophilic scalar with a mass up to 4 GeV could explain the $g-2$ anomaly

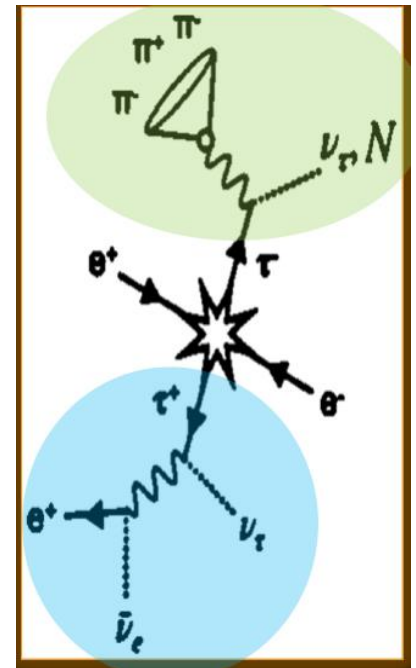


$$\mathcal{L} = -\xi \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} \bar{\ell} \phi_L \ell$$

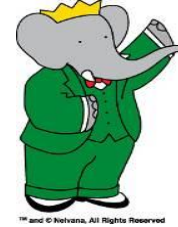
PRL 125 (2020) 181801

Heavy neutral lepton

- Heavy neutral leptons are additional neutrino states ν_n (“sterile neutrinos”)
 - mixing with active neutrinos ν_l with mixing strength $|U_{ln}|^2$
 - U_{ln} element of the extended PMNS matrix
- Model independent search
 - looking only at kinematics
 - For a HNL $N=\nu_4$ mixing with ν_τ
 - Signal side : 3-prong pionic τ decay
 - Tag side : leptonic τ decay

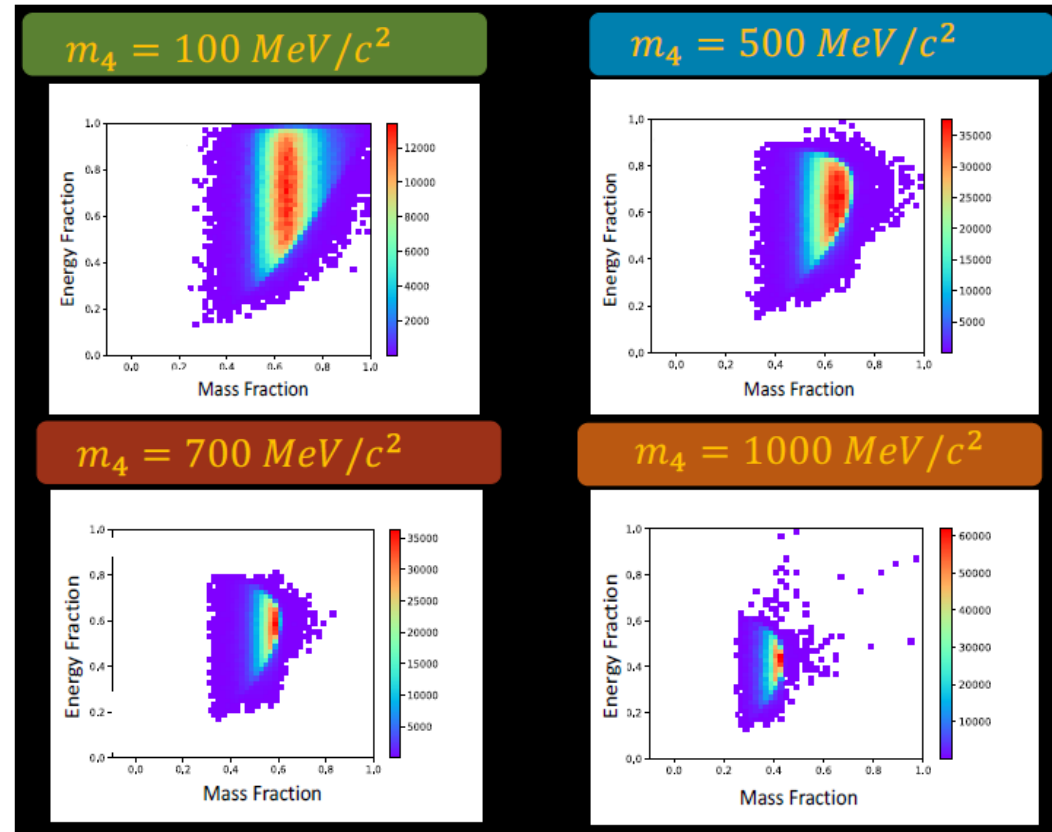


Heavy neutral lepton: analysis



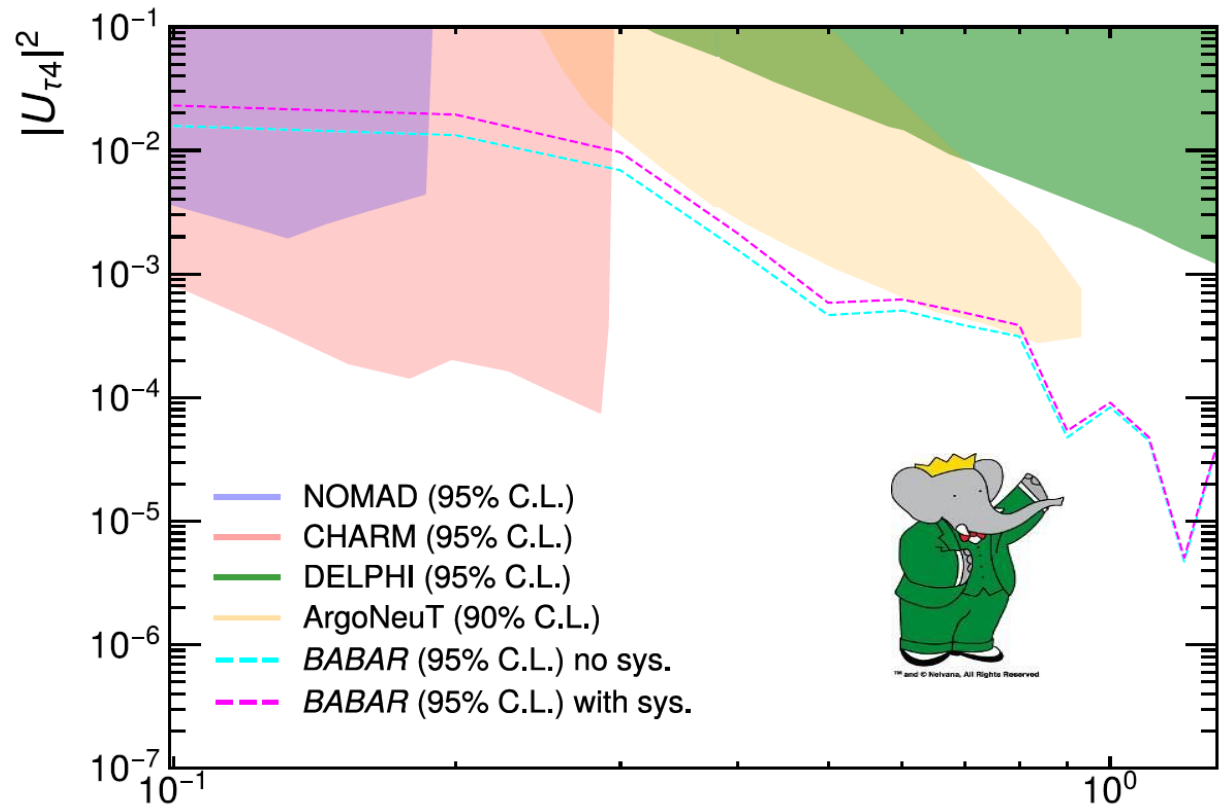
arXiv:2207.09575

- Analysis performed on 424 fb^{-1} of data
- Use both electron and muon tags
- Based on the 2D plots E_h vs m_h : energy and invariant mass of the hadronic system in the 3-prong τ decay
- Likelihood fit



Heavy neutral lepton: result

- No significant signal
- Set 95% CL upper limit on $|U_{\tau 4}|^2$ in the mass range between 0.1 and 1.3 GeV.
- Best sensitivity at large mass.

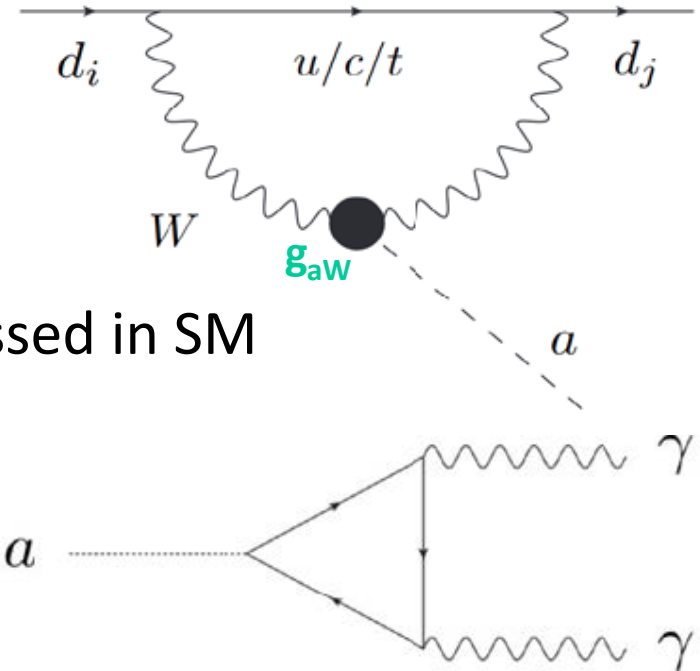


arXiv:2207.09575

Axionlike particle

- Pseudo Goldstone boson a coupling predominantly to pairs of bosons with coupling $f_a \sim 1/m_a$
- Low mass ALP can be both dark matter candidate and dark sector mediator
- Search in $B^\pm \rightarrow K^\pm a$, with $a \rightarrow \gamma\gamma$
 - FCNC, like $b \rightarrow s$, extremely suppressed in SM
 - Perfect place to search for ALP

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

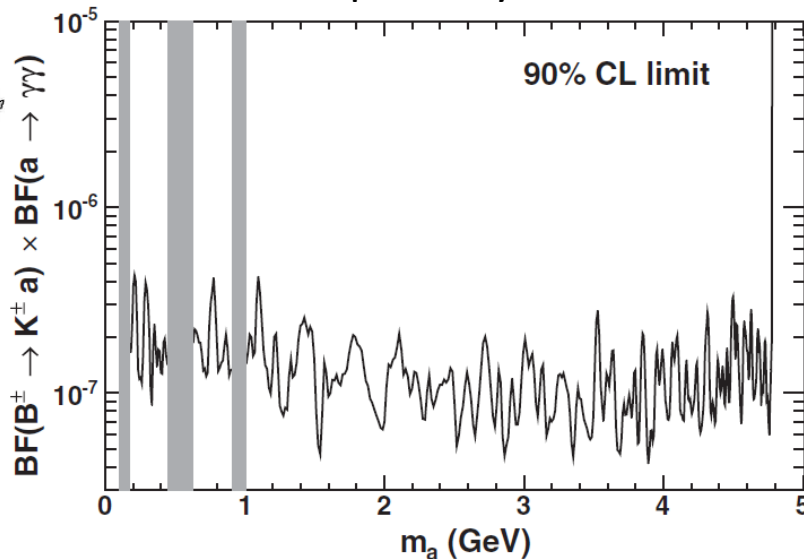


Axionlike particle: analysis

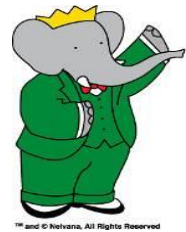
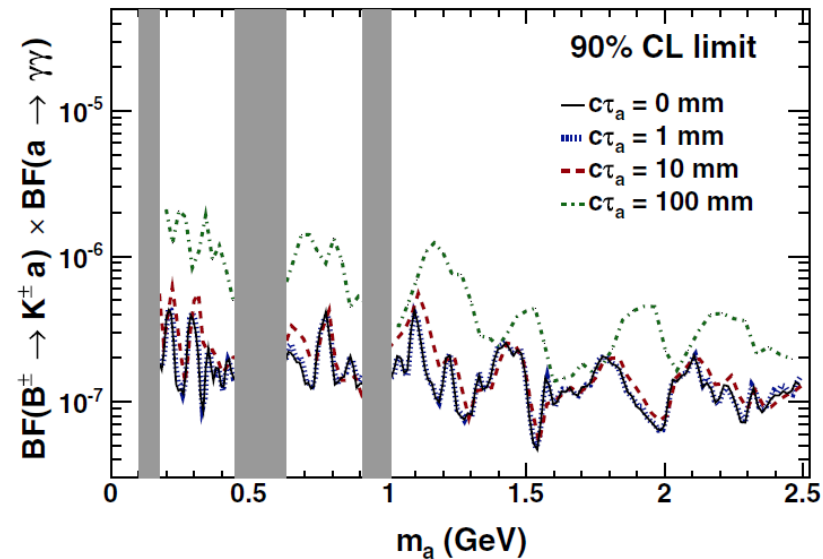
- Performed on 424 fb^{-1} of data at the $\Upsilon(4S)$
- Form B candidate from a well-identified kaon and two photons
- $\tau_a \sim 1/m_a^3 g_{aW}^2$: ALP can be long-lived
 - Analysis for prompt decays and several decay length hypotheses
- Fit m_a peak over smooth background away from π^0 , η and η' known resonances: no significant signal

PRL 128 (2022) 131802

Prompt decays

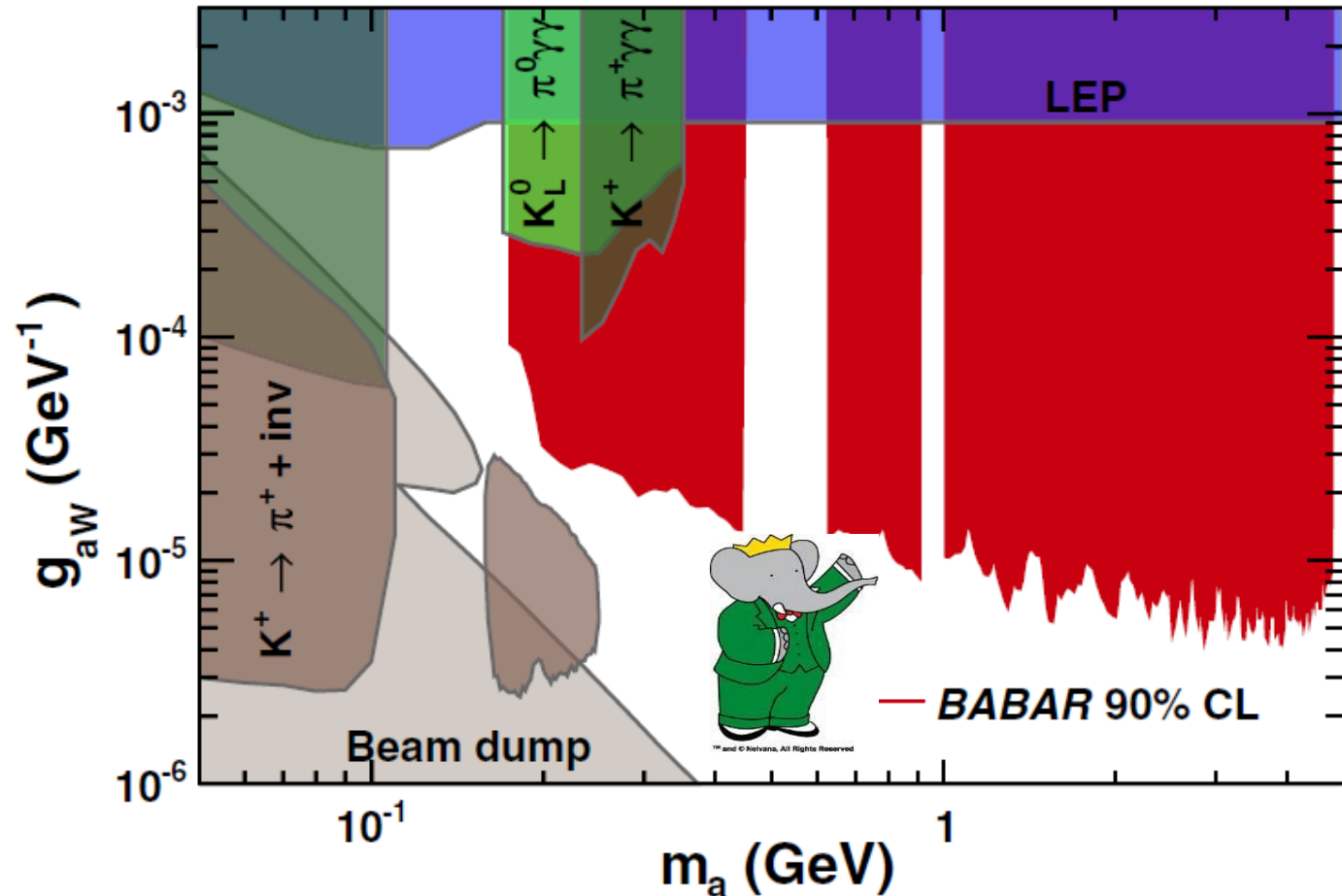


Displaced decays



Axionlike particle: results

- 90% CL upper limit on the aW coupling
- Improvement up to two orders of magnitude over a large mass range



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Summary

- B-factories are able to perform competitive searches for dark sector particles in **low energy e^+e^- annihilations**
- A lot of such analyses from BABAR
 - Still ongoing
- New constraints put on:
 - Darkonium
 - Dark leptophilic scalar
 - Heavy neutral lepton
 - Axionlike particle