New physics searches from the *BABAR* experiment

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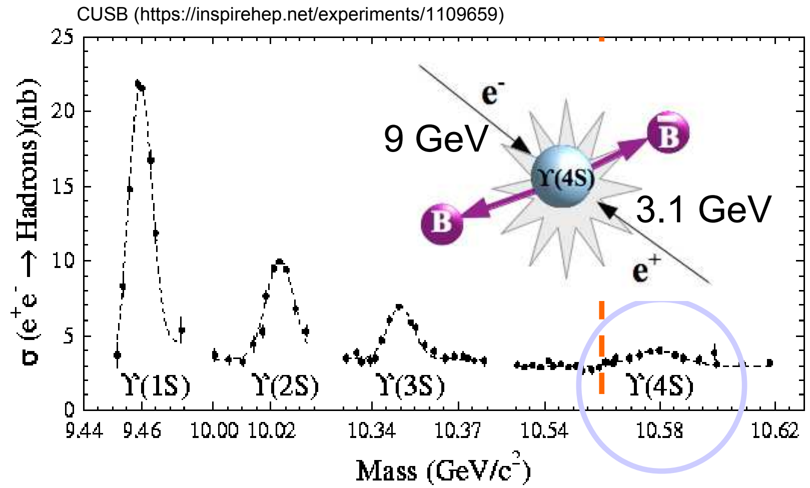
Outline

- Search for Darkonium
- Search for an Axion-Like Particle
- Search for B baryogenesis
- Search for heavy neutral leptons
- Search for LFV in $\Upsilon(3S) \to e^{+}\mu^{-}$

BABAR experiment

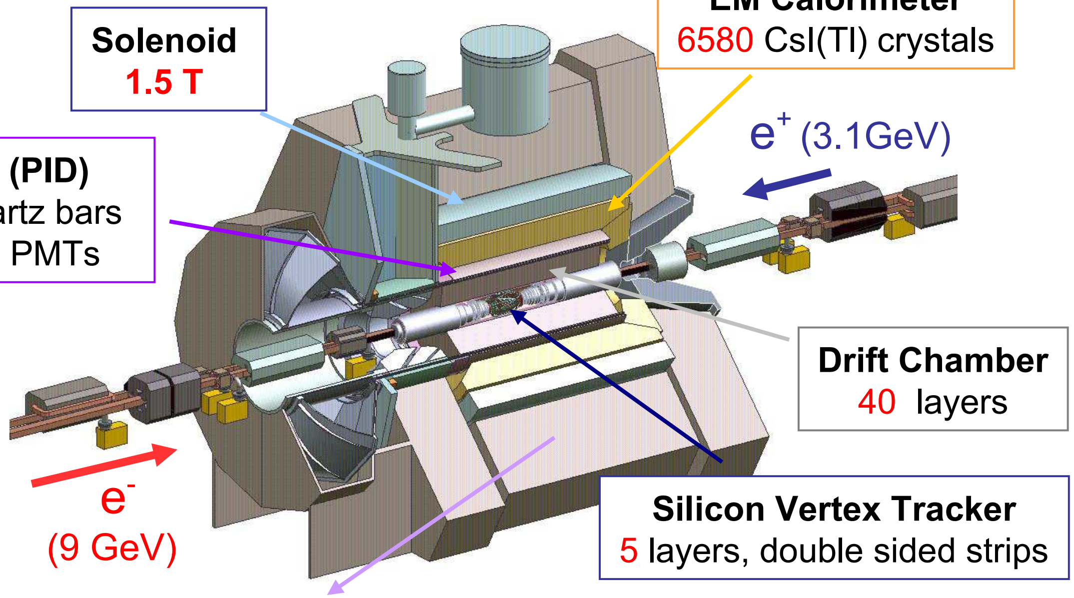
Asymmetric B Factory experiment at the SLAC National Accelerator Laboratory

- *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



Optimized for tracking and B vertex reconstruction, K - π particle identification, precision calorimetry, and μ ID

- **Clean** environment with large solid-angle detector coverage and good missing energy reconstruction
- **Inclusive trigger** (N_{tracks}>3) as well as dedicated low-multiplicity triggers



Dark sectors

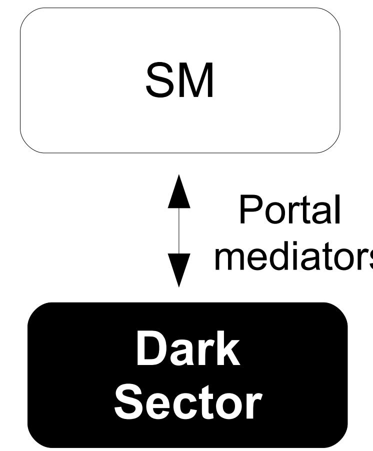
Dark matter may carry charges for non-SM gauge interactions, possibly acquiring mass via dark sector Higgs etc.

- 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

At *BABAR*:

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

Some *BABAR* dark sector results:

- Dark Leptophilic scalar: Phys. Rev. Lett. 125,181801 (2020)
- Dark photon: Phys. Rev. Lett. 113, 201801 (2014); Phys. Rev. Lett. 119, 131804 (2017)
- Six quark dark matter: Phys. Rev. Lett. 122, 072002 (2019)
- Muonic dark force: Phys. Rev. D 94, 011102 (2016)
- Dark Higgs bosons: Phys. Rev. Lett. 108, 211801 (2012)

Search for Darkonium

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

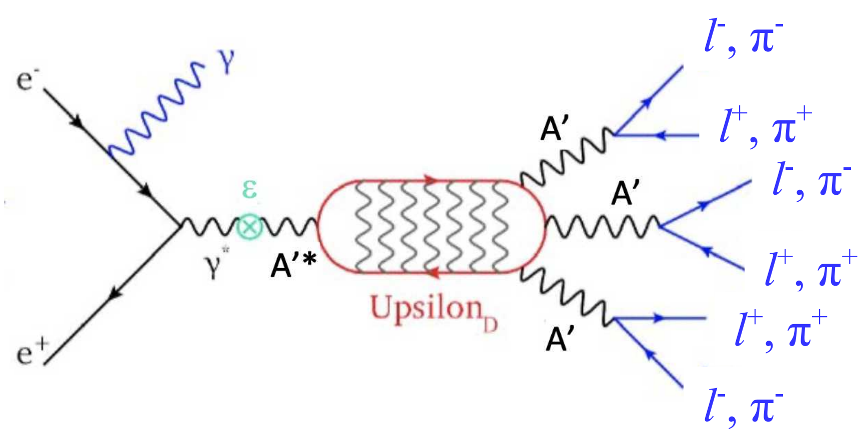
H. An et al., PRL 116 (1026) 151801

- Lowest bound states: 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}

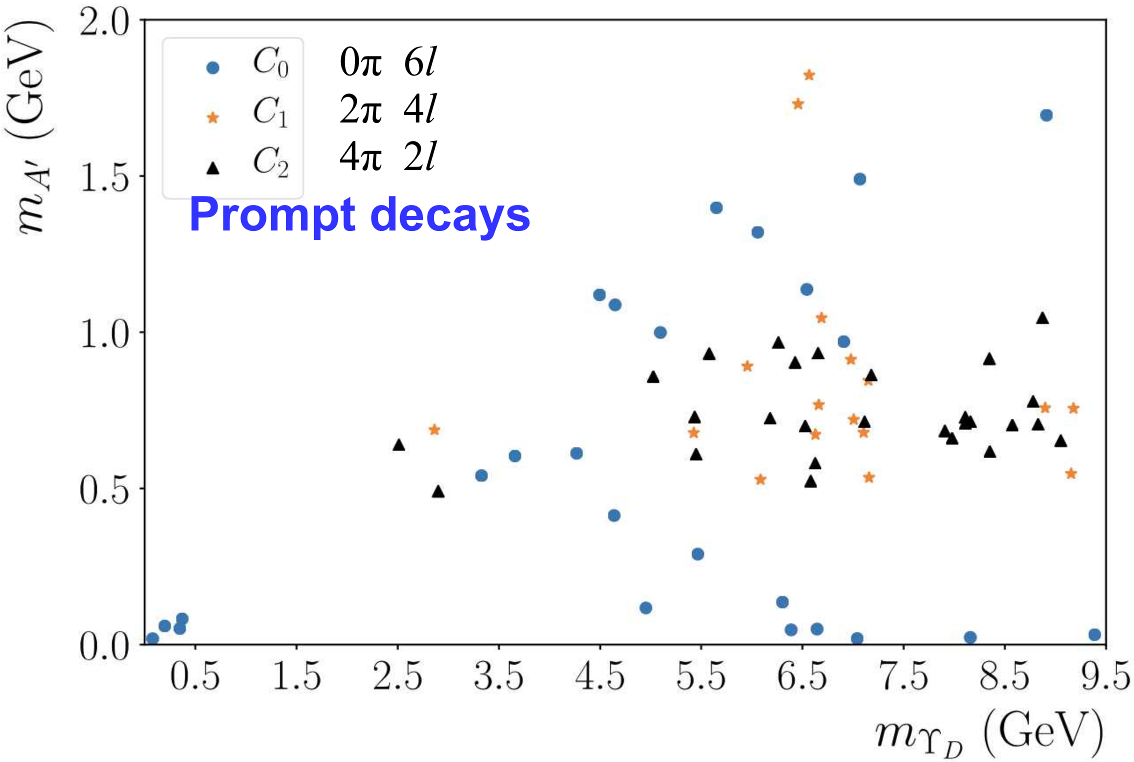
Search for Darkonium

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

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

- The Υ_D mass can be reconstructed from the combination of all six tracks
- 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
- In low mass $m(A') < 0.2$ GeV region, consider also displaced vertex hypotheses with $c\tau = 0.1, 1, 10$ mm

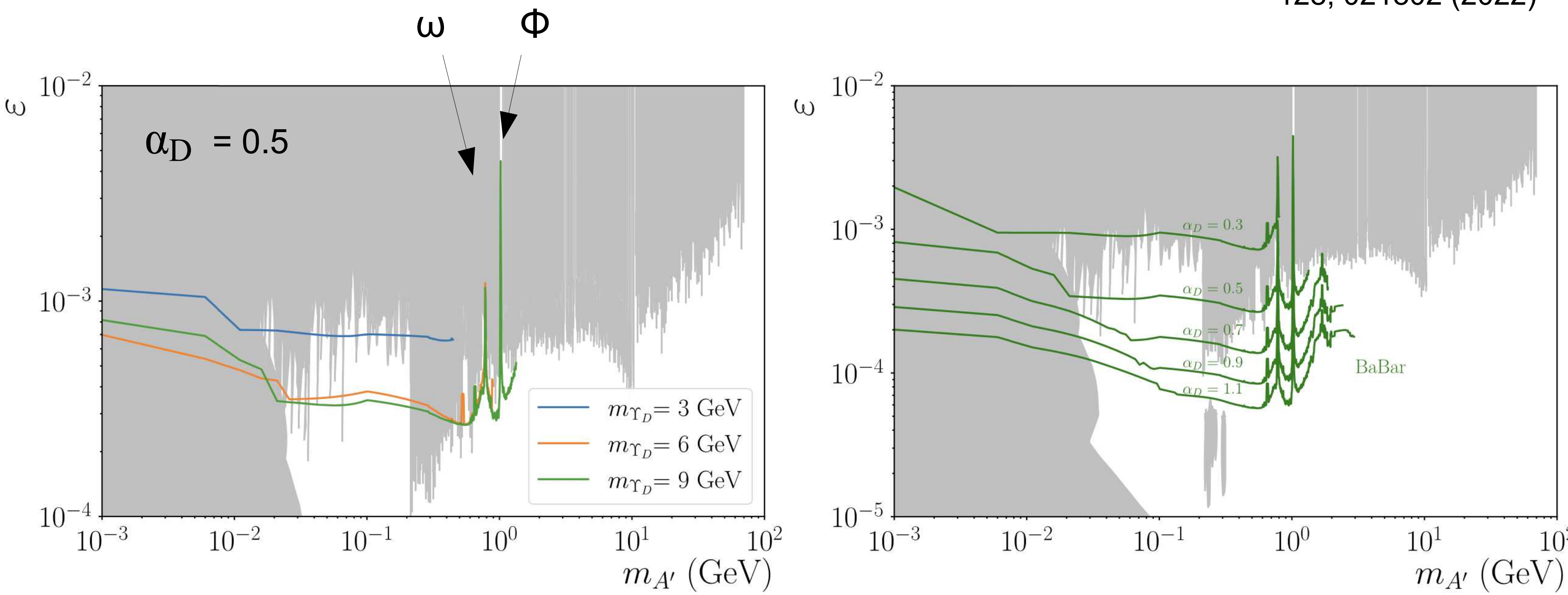
$e^+e^- \to \gamma\, \Upsilon_D$



No significant signals observed in either prompt or displaced decay searches

Search for Darkonium

Phys. Rev. Lett.
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

Axion-Like Particles

Pseudo-Goldstone bosons known as **Axion-Like Particles (ALPs)** appear in many extensions of SM with spontaneously-broken global symmetries

- 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

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

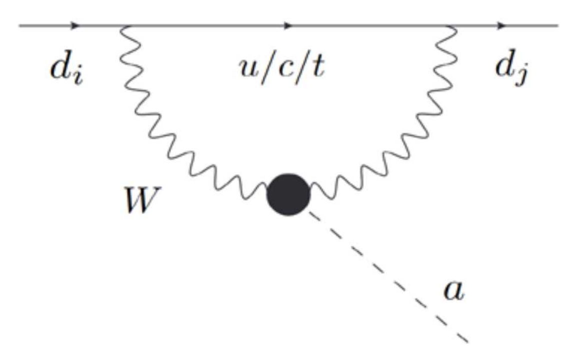
$SU(2)_W$ field strength tensor

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

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

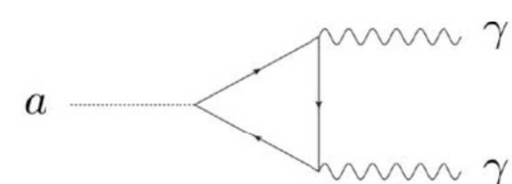
- $a \to \gamma\gamma$ with nearly 100% BF for $m(a) < m(W)$
- For low axion mass and small coupling, the axion lifetime can become "long", i.e. non-prompt.

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



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

- Exclusively reconstruct signal B meson via well-identified K and photons, then "bump hunt" in the reconstructed $\gamma\gamma$ mass

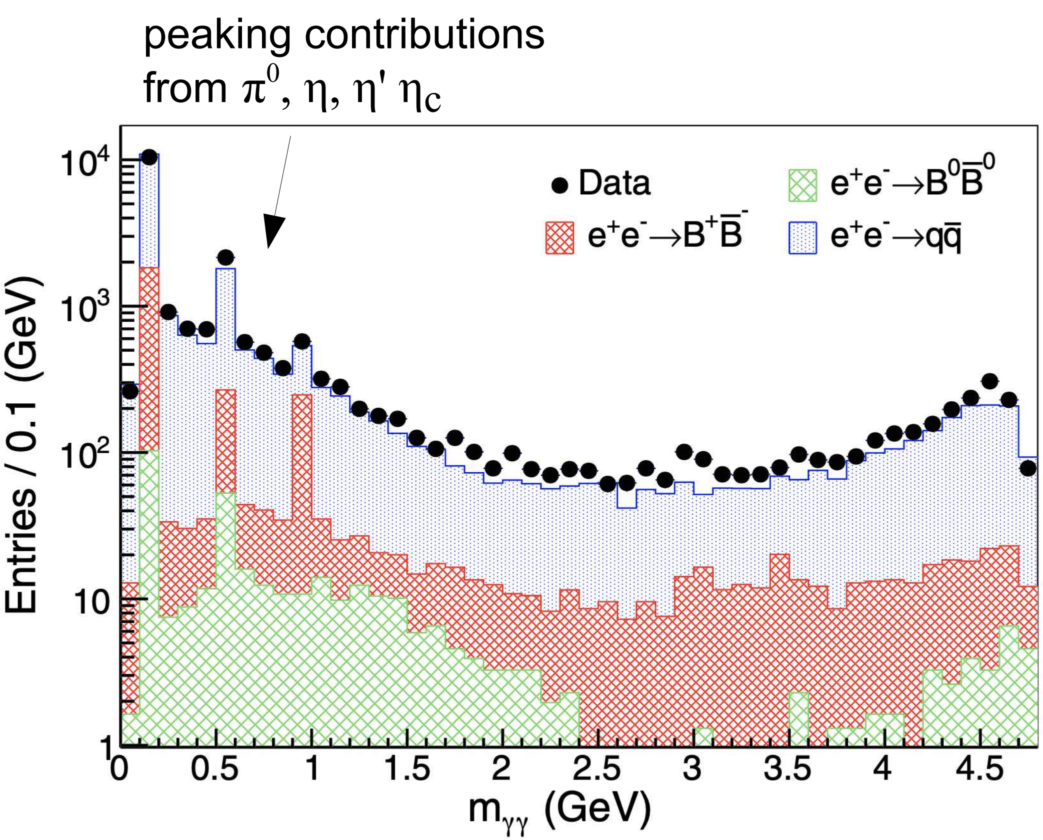


Axion-Like Particles

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

Reconstruct $K + \gamma\gamma$ final state including kinematic fit to improve resolution

- Continuum $e^+e^- \rightarrow q\bar{q}$ $(q = u,d,s,c)$ and BB backgrounds suppressed using boosted decision trees based on kinematic variables from the "rest of the event"
- Analysis optimized and validated on 8% of data set (subsequently discarded), then search performed on remainder of (blinded) dataset



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

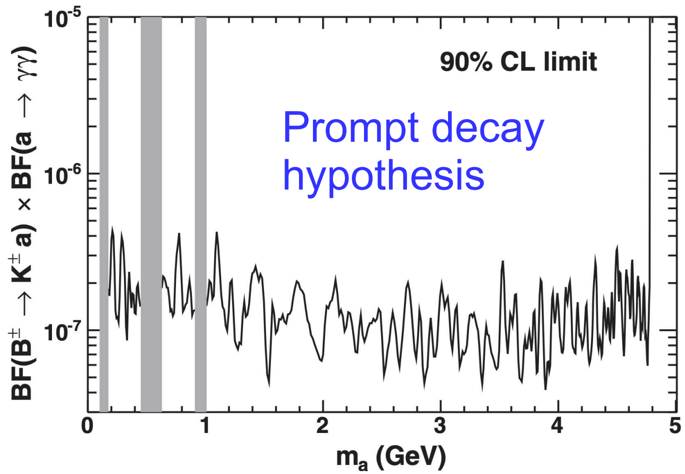
- Fit with unbinned ML fits to a hypothetical signal peak + smooth background
- Peaking contributions from known SM particles taken into account
- 461 signal mass hypotheses over range of ~24 – 60 σ around each hypothesis

Axion-Like Particles

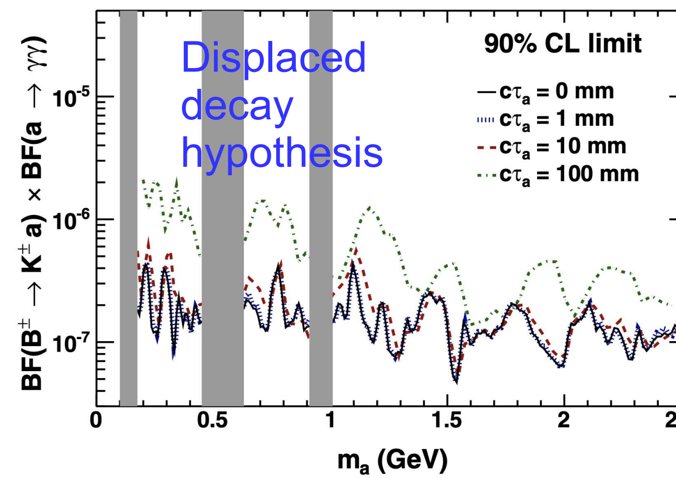
Phys. Rev. Lett. 128, 131802 (2022)

No evidence of signal found at any of the tested mass hypotheses

- Interpret as bounds on $B \rightarrow Ka(\rightarrow \gamma\gamma)$

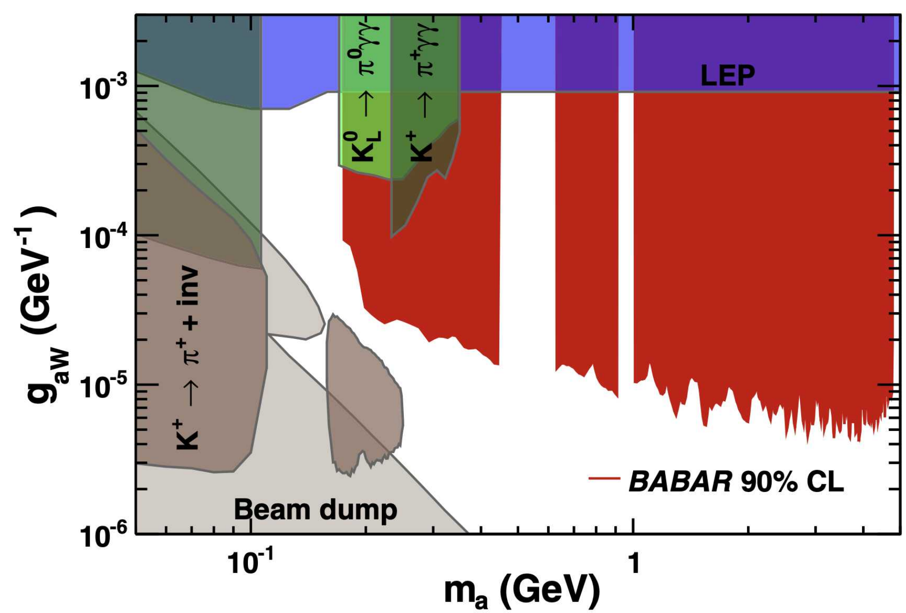


In low mass region ($m_{\gamma\gamma}$ < 2.5 GeV) the signal sensitivity is also assessed for non-prompt signal hypotheses:
$c\tau$ = 1, 10, 100mm



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

- Exclude regions around known SM particle masses (π^0, η, η')
- Improvements of up to two orders of magnitude over existing limits

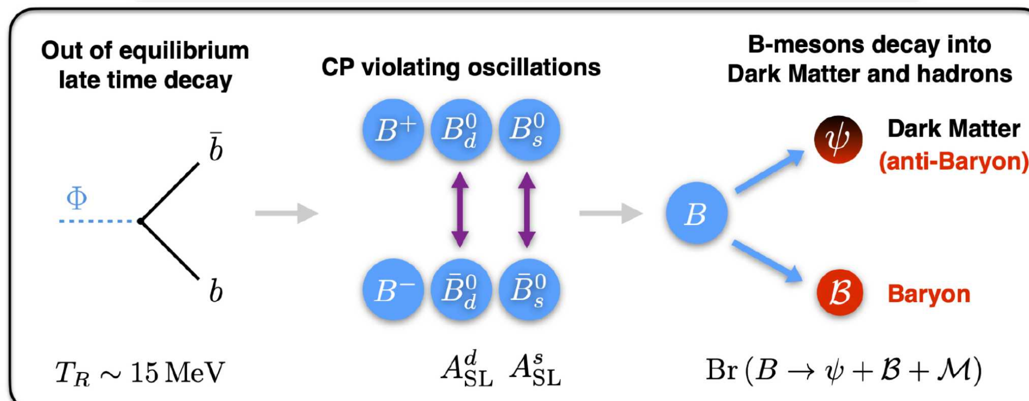


Search for B Baryogenesis

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 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

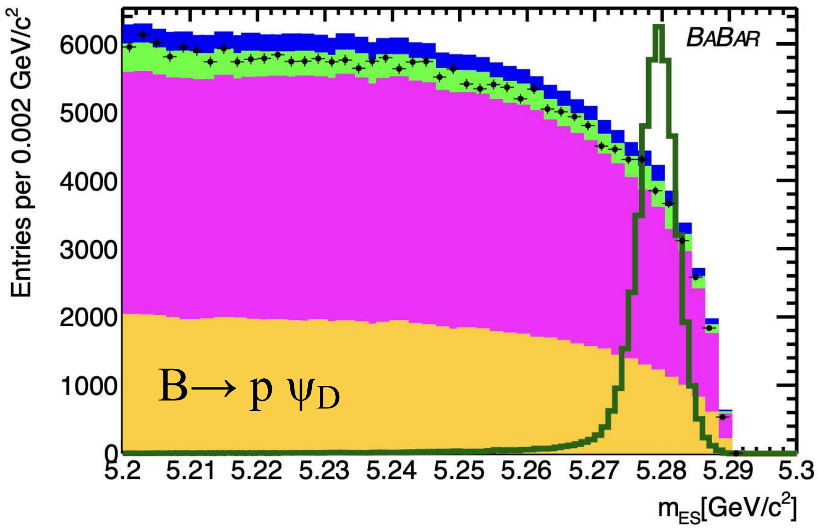
G. Elor, M. Escudero and A. E. Nelson, Phys. Rev. D 99, 035031 (2019).
G. Alonso-Alvarez, G. Elorand, and M. Escudero, Phys.Rev. D 104, 035028 (2021).



Two recent BABAR searches for baryonic final states:

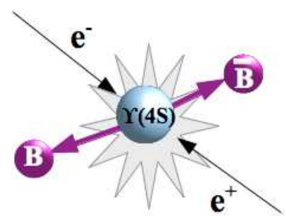
- $B \to \Lambda\, \psi_D$ — Phys. Rev. D 107, 092001 (2023)
- $B \to p\, \psi_D$ — arXiv:2306.08490 [hep-ex]

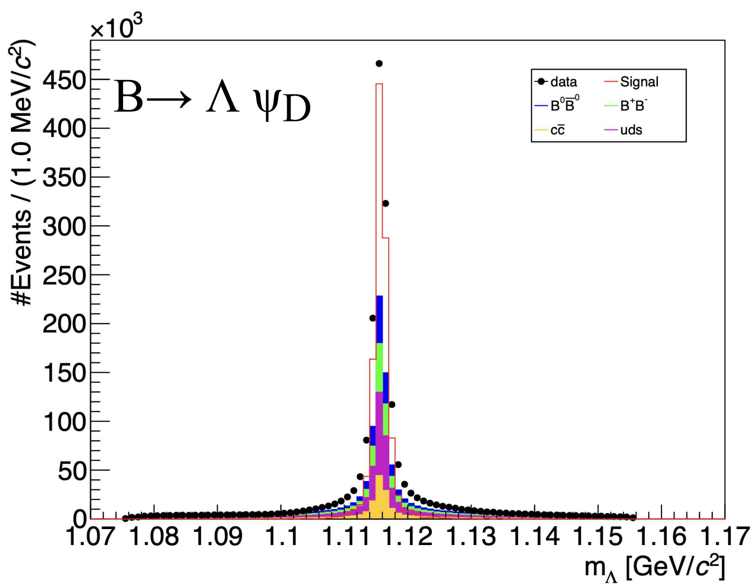
Search for B Baryogenesis



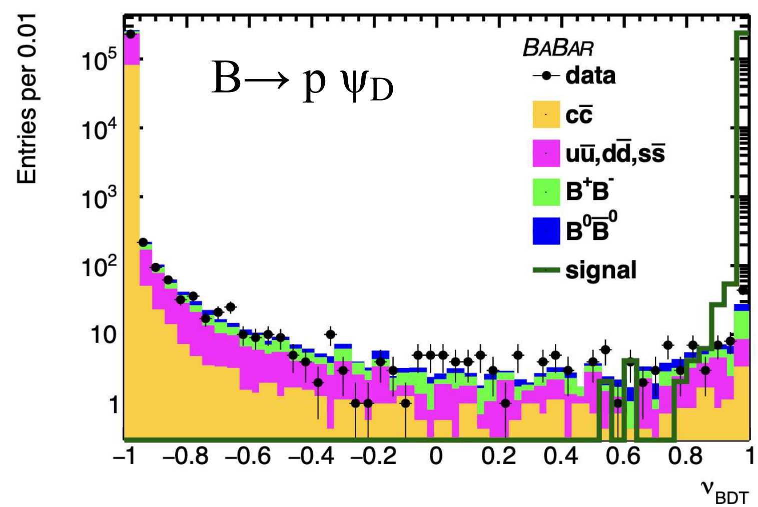
$B \to \Lambda\, \psi_D$ and $B \to p\, \psi_D$ final states:

- The dark sector ψ_D escapes undetected
- Reconstruct accompanying B meson from $\Upsilon(4S) \to B\bar{B}$ and look for signal signature in the remainder of the event:
  - proton (and no additional tracks), or
  - reconstruct $\Lambda \to p\, \pi$, including displaced vertex significance requirement and kinematic fit





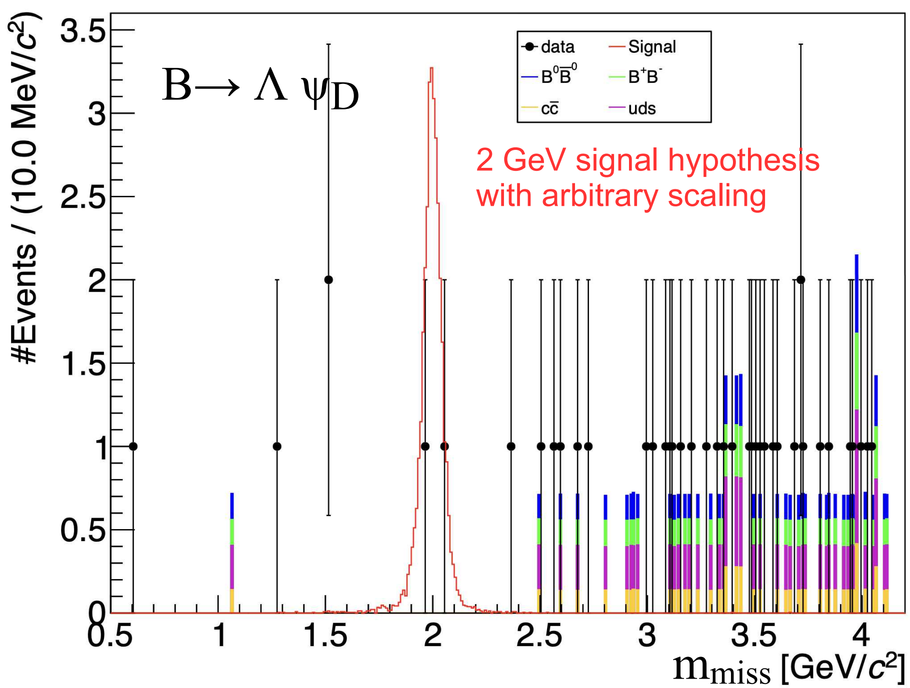
Boosted decision tree to suppress continuum backgrounds based on event shape and kinematic variables

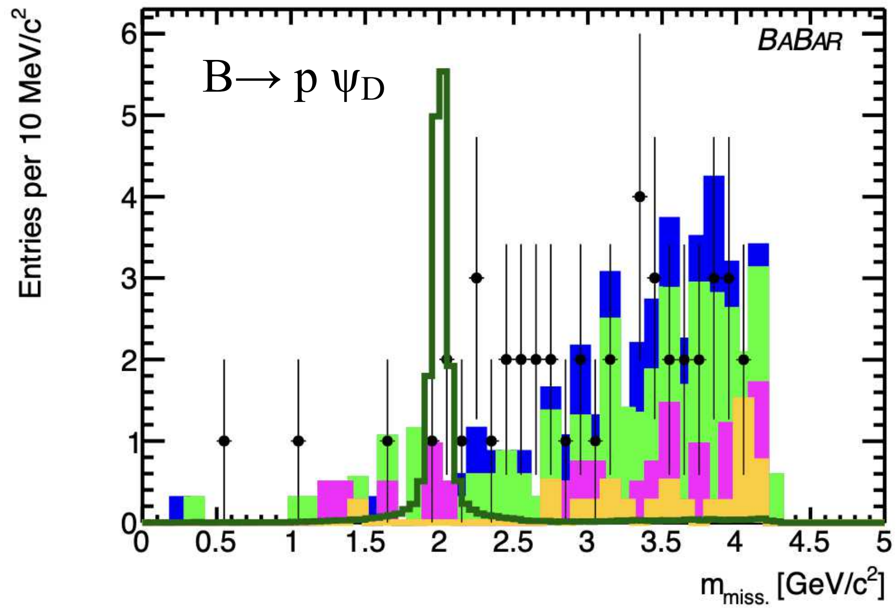


Search for B Baryogenesis

Missing energy 4-vector of “recoil” against the p or Λ yields the ψ_D invariant mass

- For $B \to p\,\psi_D$, m_{miss} resolution varies from ~110 MeV/c^2 (low mass) to ~11 MeV/c^2 (high mass)
- Background estimated directly from m_{miss} sideband data



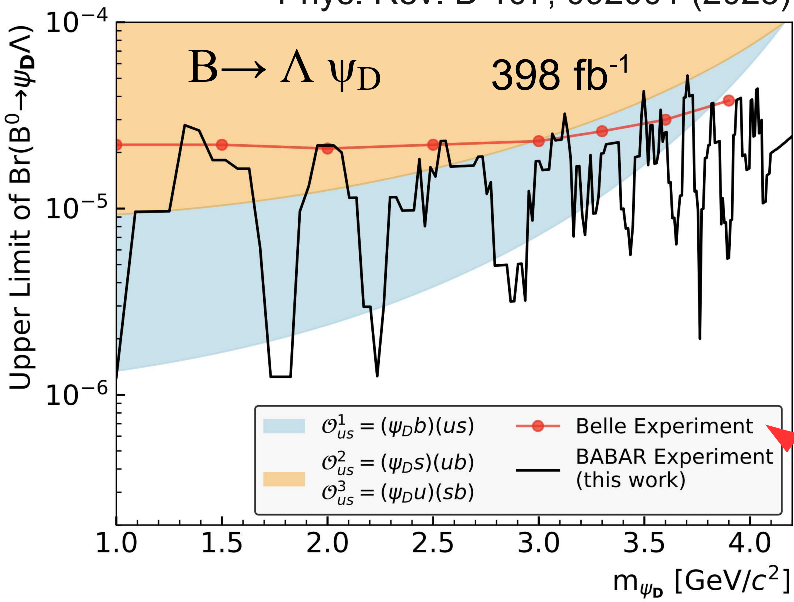


$$m_{miss}c^2 = \sqrt{(E^*_{B_{sig}} - E^*_p)^2 - |\vec{p}^{\,*}_{B_{sig}} - \vec{p}^{\,*}_p|^2 c^2}$$

- Scan the recoil m_{miss} distribution in steps of $\sigma(m_{miss})$ for evidence of a narrow signal peak above a smoothly varying background
- For $B \to p\,\psi_D$, a total of 127 mass hypotheses are tested (193 for $B \to \Lambda\,\psi_D$)

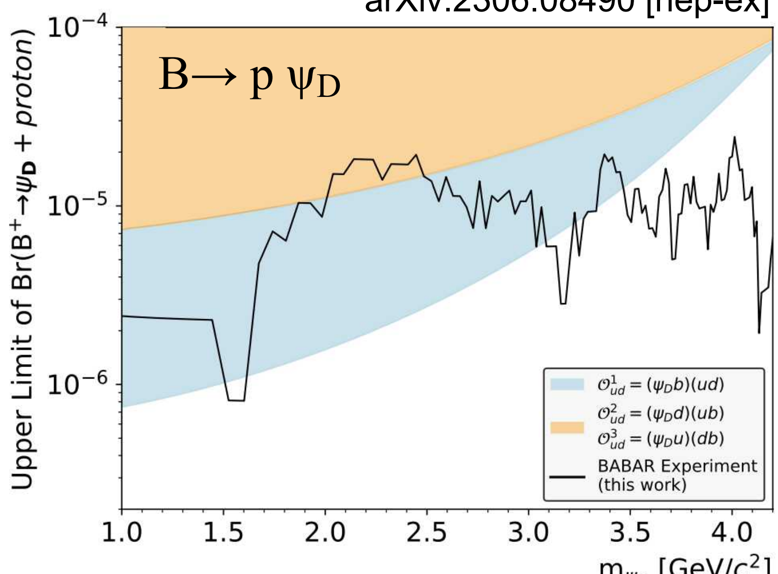
Search for B Baryogenesis

Phys. Rev. D 107, 092001 (2023)



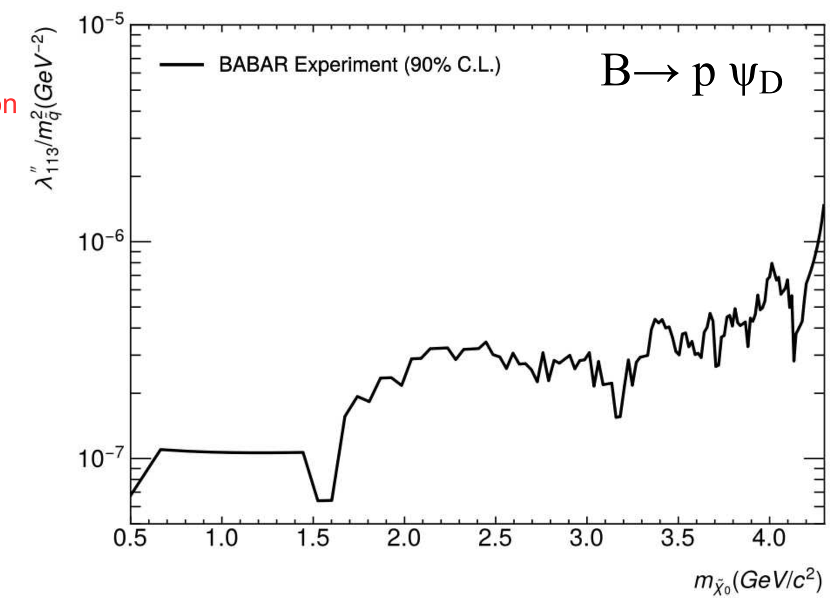
Belle Collaboration Phys. Rev. D 105, L051101 (2022).

arXiv:2306.08490 [hep-ex]



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

- Probes effective operators $O_{i,j} = (\psi_D b)(q_i q_j)$ with q_i = u,c and q_j = d,s
- Results exclude a large fraction of the model parameter space



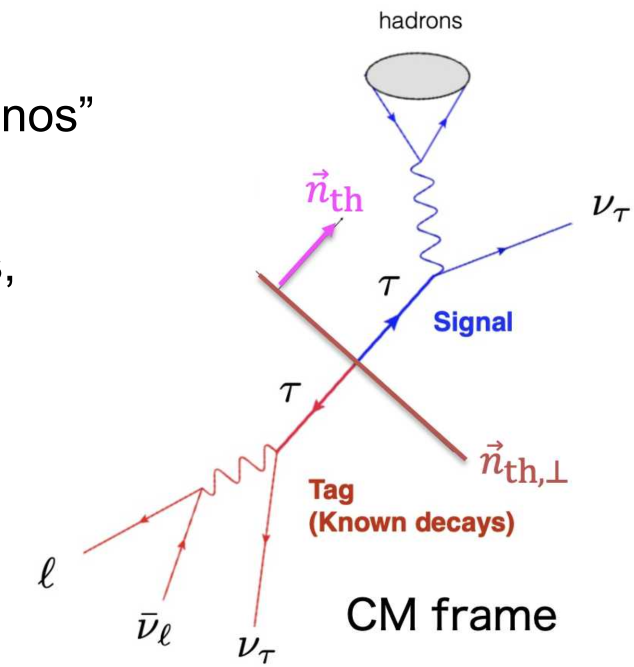
- Can alternatively be interpreted as limits on RPV coupling λ''_{113} assuming $B \rightarrow \chi_0 p$ in RPV SUSY model C. O. Dib et al., JHEP 2023 (02 224 (2023))

Heavy neutral leptons

Phys. Rev. D 107 5, 052009

Heavy neutral leptons (HNL) have no ordinary weak interactions, except those induced by mixing

- Singlets under all gauge interactions, aka “sterile neutrinos”
- ν-MSM (neutrino minimal SM) predicts 3 right-handed Majorana GeV-scale HNL explains neutrino oscillations, the BAU and provide a dark matter candidate
- Can also explain various anomalies at short baseline experiments



Mixing with first and second generation is tightly constrained, but limits on $|U_{\tau 4}|^2$ are weaker

- Extended PMNS matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_L \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{L1} & U_{L2} & U_{L3} & U_{L4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

- $\tau^+\tau^-$ pairs are produced at BABAR in $e^+e^- \to \tau^+\tau^-$ with relatively high boost, resulting in “jetty” topology, with the decay daughters cleanly separated into two “hemispheres”
- “Tag and probe” to cleanly and inclusively select τ signal candidate sample

Heavy neutral leptons

Phys. Rev. D 107 5, 052009

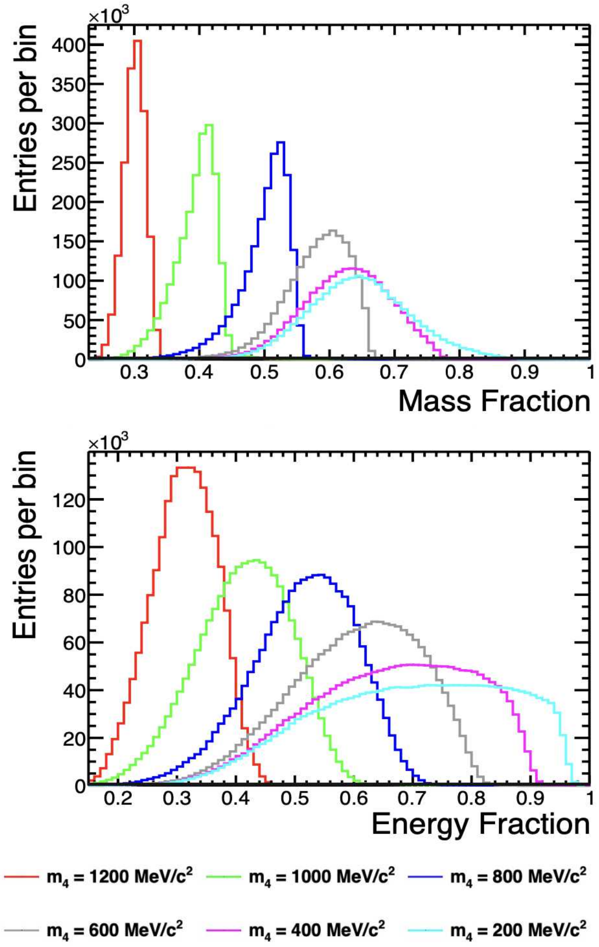
Search method based on kinematics of $\tau \to 3\pi\nu$ decays
(ALEPH neutrino mass measurement method) Eur. Phys. J.1137C 2, 395

- Treat 3-prong tau decay as 2-body process:

$$\tau^- \to h^-(E_h, \vec{p}_h) + \nu(E_\nu, \vec{p}_\nu)$$

- As HNL mass increases the phase space of the hadronic system is reduced in the $(E_h\,,\, m_h)$ plane

$$\left.\frac{\mathrm{d}\Gamma(\tau^- \to \nu h^-)}{\mathrm{d}m_h \mathrm{d}E_h}\right|_{\mathrm{Total}} = |U_{\tau 4}|^2 \left.\frac{\mathrm{d}\Gamma(\tau^- \to \nu h^-)}{\mathrm{d}m_h \mathrm{d}E_h}\right|_{\mathrm{HNL}} + (1 - |U_{\tau 4}|^2) \left.\frac{\mathrm{d}\Gamma(\tau^- \to \nu h^-)}{\mathrm{d}m_h \mathrm{d}E_h}\right|_{\mathrm{SM}}$$



Modelling of hadronic tau decays in TAUOLA is a dominant source of systematics

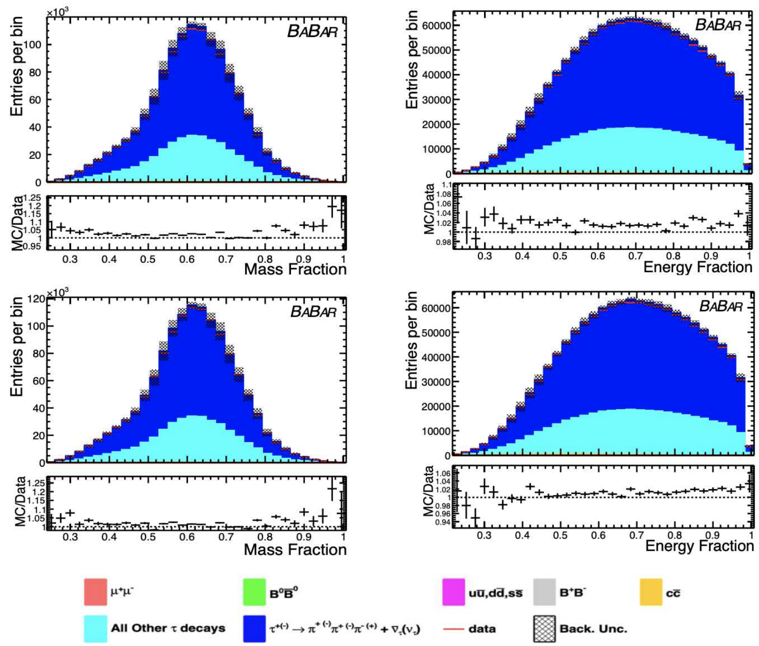
- $\tau \to \pi\pi\pi\nu$ is mediated by the a_1 resonance 97% of the time

Backgrounds from:

- SM tau decays misidentified as $\tau \to 3\pi\nu$ decays (usually due to additional π^0's)
- Non-tau SM sources (including $B\bar{B}$, $q\bar{q}$ and $e^+e^- \to \mu^+\mu^-$)

Heavy neutral leptons

Phys. Rev. D 107 5, 052009

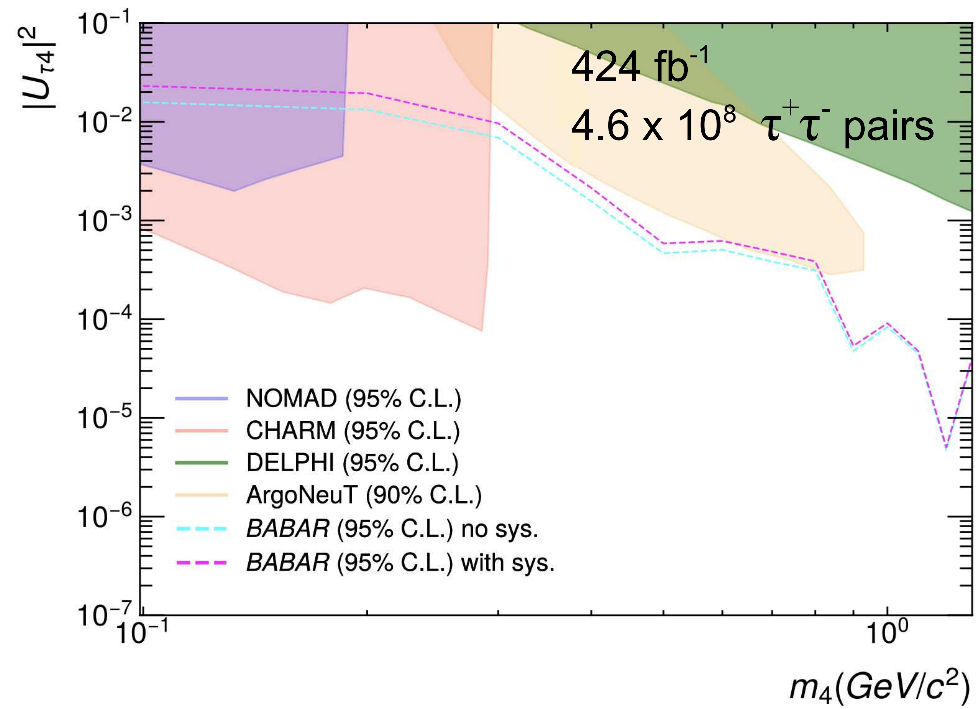


Perform a binned likelihood fit in (E_h, m_h) plane, separately for e and μ, and for l^+ and l^-

- Template fit of SM+HNL kinematic distributions, weighted by $|U_{\tau4}|^2$
- HNL templates derived from 26 simulated signal samples [100MeV - 1300MeV]

Search sensitive to the mass range $300 < m_4 < 1360$ MeV/c^2 (i.e. up to the kinematic endpoint)

- Limits on $|U_{\tau4}|^2$ obtained at level of $10^{-2} < |U_{\tau4}|^2 < 10^{-6}$
- Maximum sensitivity for large HNL mass, where kinematics differ greatly from SM



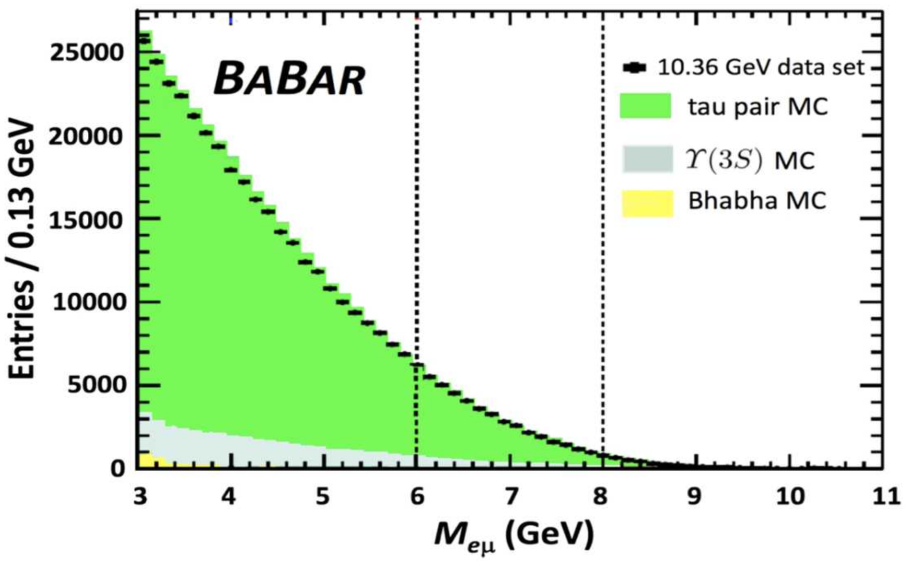
LFV in $\Upsilon(3S) \rightarrow e^+\mu^-$

Phys. Rev. Lett. 128, 091804 (2022)

Charged lepton flavour not explicitly conserved in SM

- Violated at loop level via neutrino mixing at rates far below experimental sensitivity
- Charged LFV would be clear sign of new physics

Previous searches for LFT in $b\bar{b}$ bounds states in $e^+\tau^-$ and $\mu^+\tau^-$ but not in $e^+\mu^-$



BABAR search for $\Upsilon(3S) \rightarrow e^+\mu^-$ in 27 fb^{-1} of data, corresponding to 118 x 10^6 $\Upsilon(3S)$ events

$\Upsilon(4S)$ data, and "offpeak"

data samples collected ~40 MeV below the $\Upsilon(3S)$ and $\Upsilon(4S)$

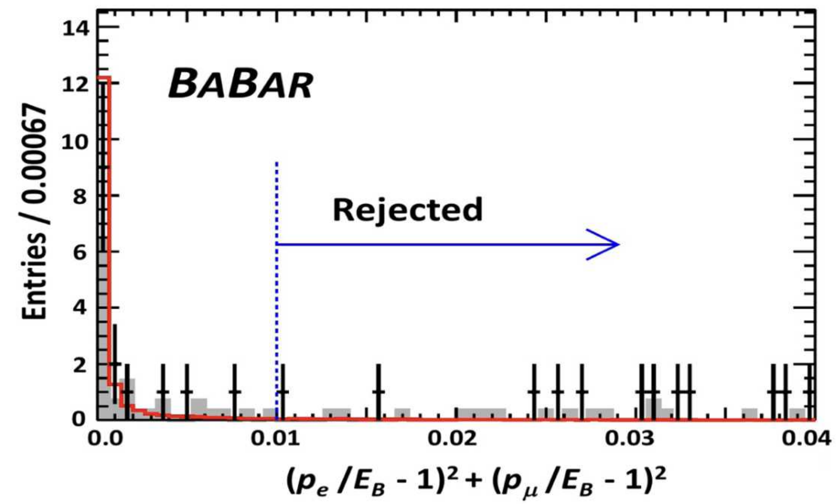
0.93 fb^{-1} of $\Upsilon(3S)$ data used for analysis validation, then discarded

- Signature is exactly 2 back-to-back tracks with opposite charge, and satisfying e,μ particle ID
- Backgrounds originate from
  - $e^+e^- \rightarrow \mu^+\mu^- (\gamma)$ and $e^+e^- \rightarrow e^+e^- (\gamma)$
  - $e^+e^- \rightarrow \tau^+\tau^-$ with leptonic τ decays
  - generic $\Upsilon(3S) \rightarrow f^+f^-$ with particle mis-identification

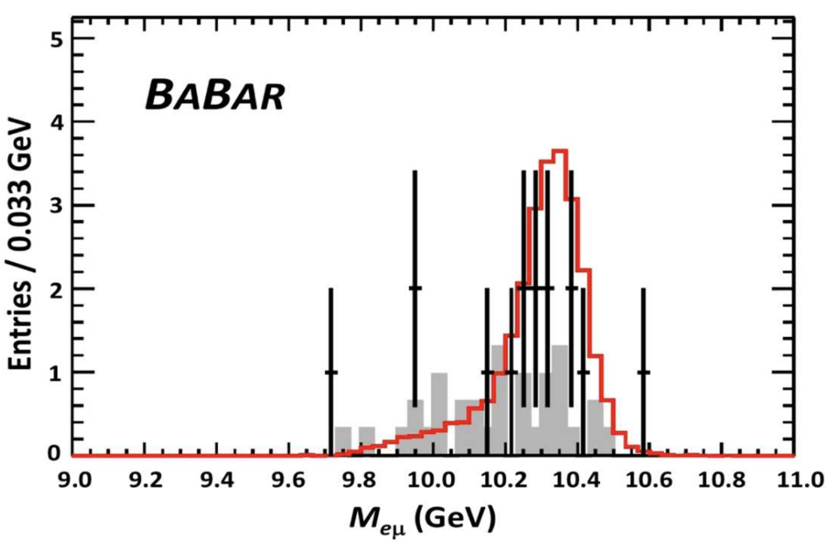
LFV in $\Upsilon(3S) \to e^+\mu^-$

Phys. Rev. Lett. 128, 091804 (2022)

- Kinematic requirements strongly suppress $\tau^+\tau^-$, $\mu^+\mu^-$, radiative Bhabha and 2-photon-mediated processes
  - 12.2 ± 2.1 background events expected from continuum
- No simulated $\Upsilon(3S)$ background events survive the selection
  - uncertainty of 0.9 events evaluated by loosening selection requirements



- 23.4 ± 0.8 % signal efficiency



Observe 15 events in signal region, consistent with background expectation

Branching fraction central value:

$$\mathcal{B}[\Upsilon(3S) \to e^\pm \mu^\mp] = [1.0 \pm 1.4(\text{stat}) \pm 0.8(\text{syst})] \times 10^{-7}$$

Branching fraction limit:

$$\mathcal{B}[\Upsilon(3S) \to e^\pm \mu^\mp] < 3.6 \times 10^{-7} \text{ @ } 90\% \text{ C.L.}$$

$\Lambda_{NP}/g_{NP}^2 > 80$ TeV

Conclusion

- Clean B factory environment is extremely well suited to searches for light dark sector signatures, as well as precision probes of new physics
- *BABAR* data remains an interesting and important resource for searching for physics beyond the Standard Model

Darkonium: Phys. Rev. Lett. 128, 021802 (2022)

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

B barygenesis: Phys. Rev. D 107, 092001 (2023) and arXiv:2306.08490 [hep-ex]

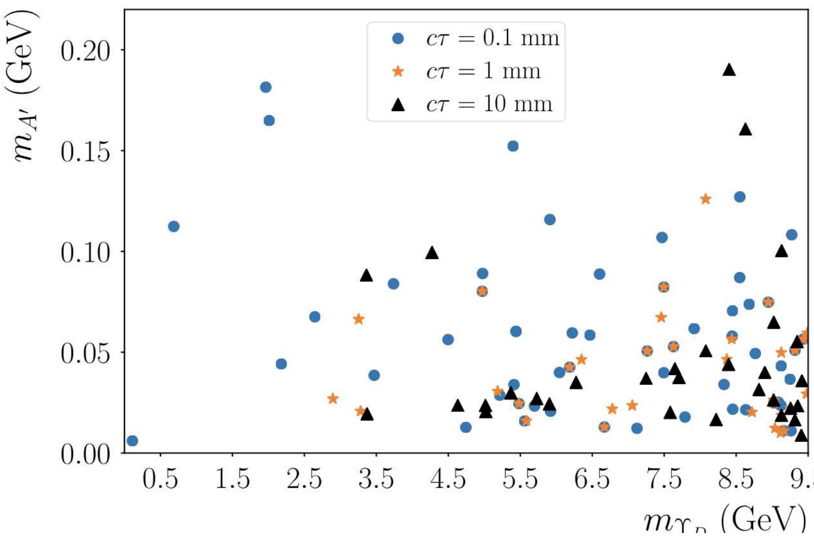
HNL: Phys. Rev. D 107 5, 052009

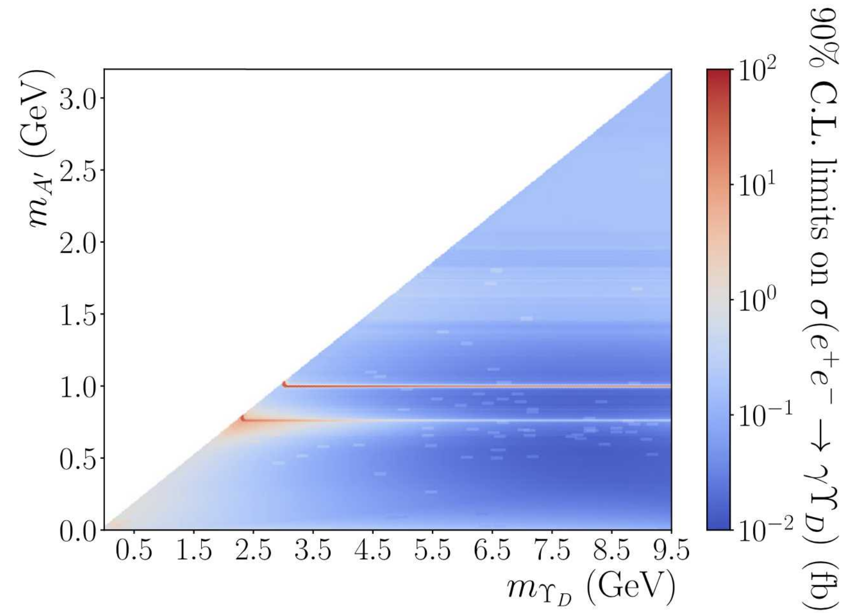
LFV in Ups(3S): Phys. Rev. Lett. 128, 091804 (2022)

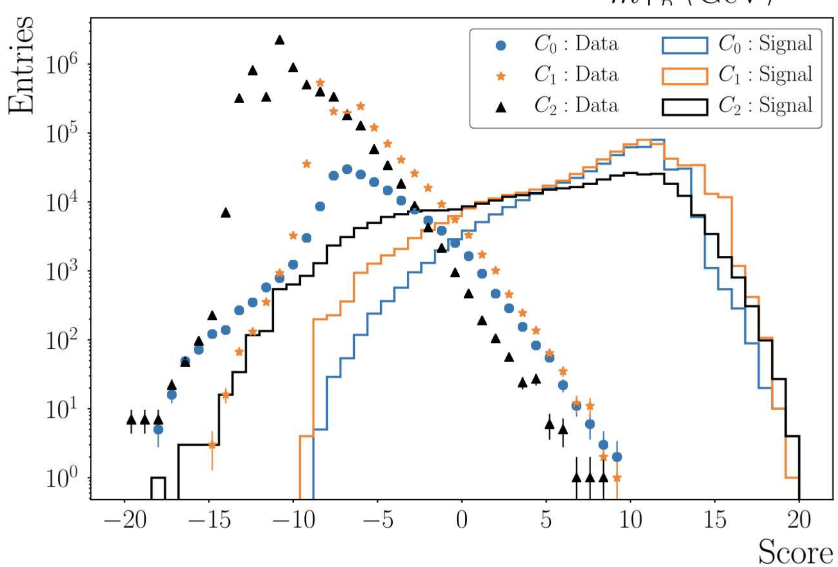
Extra Material

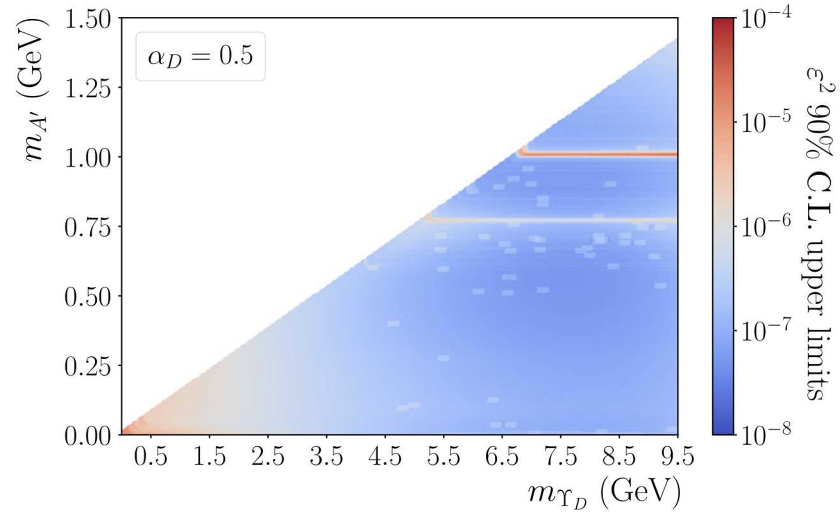
Darkonium

PRL 128, 021802 (2022)





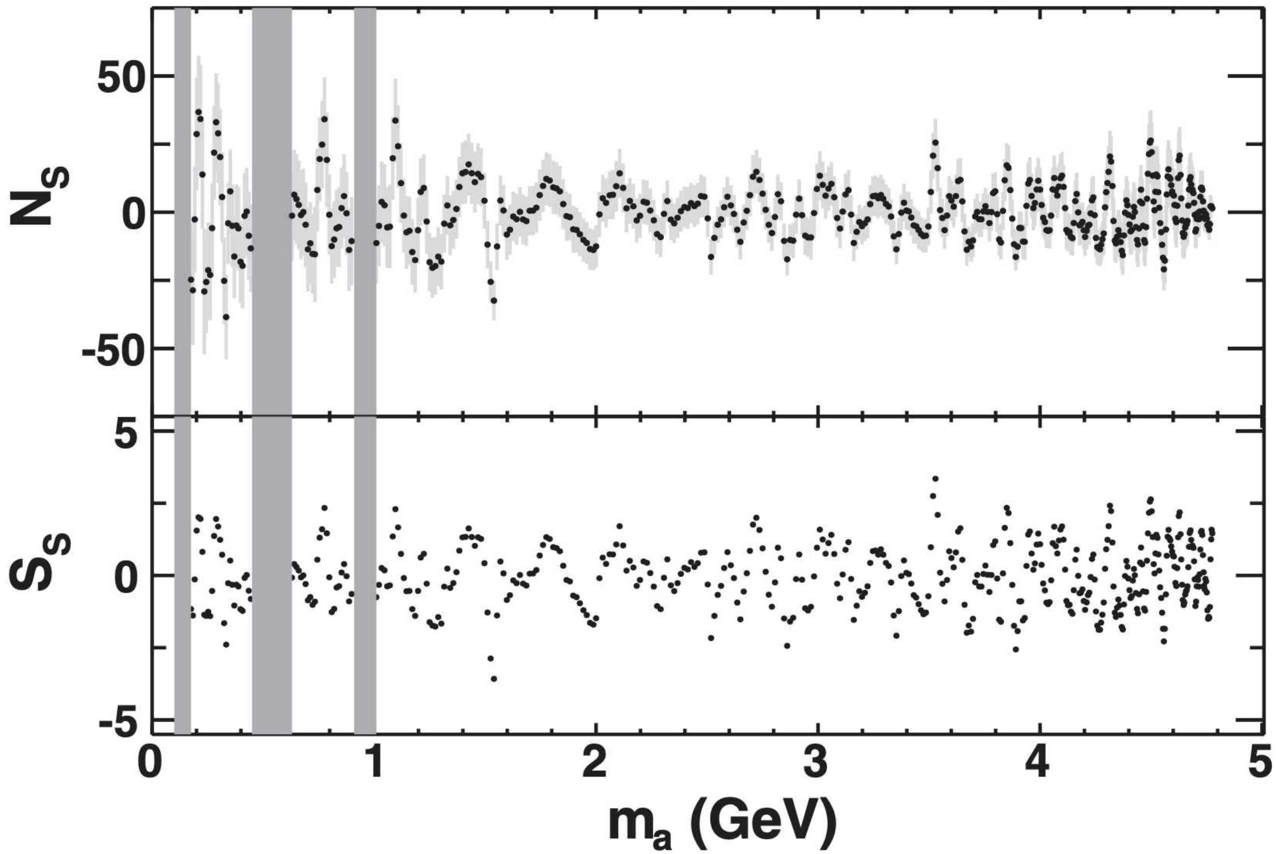




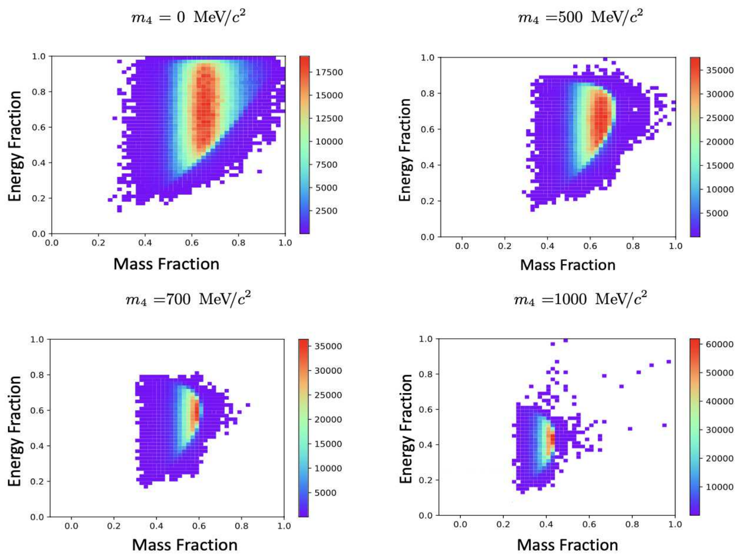
ALP

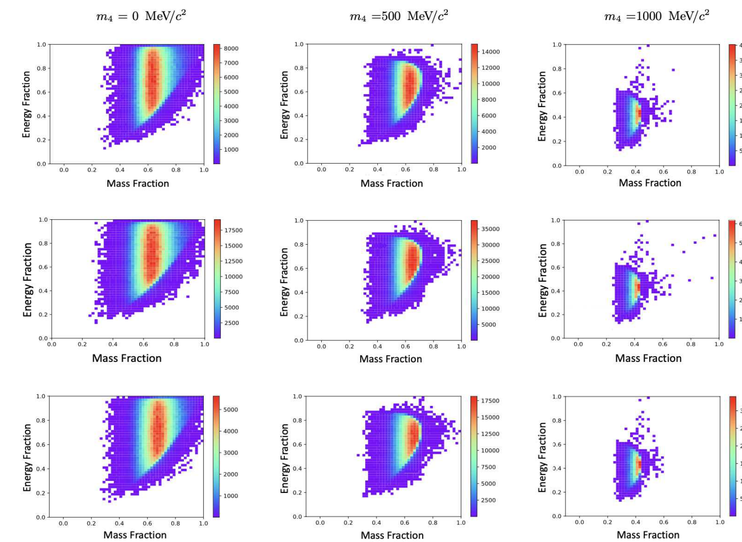
Yield and local significance

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

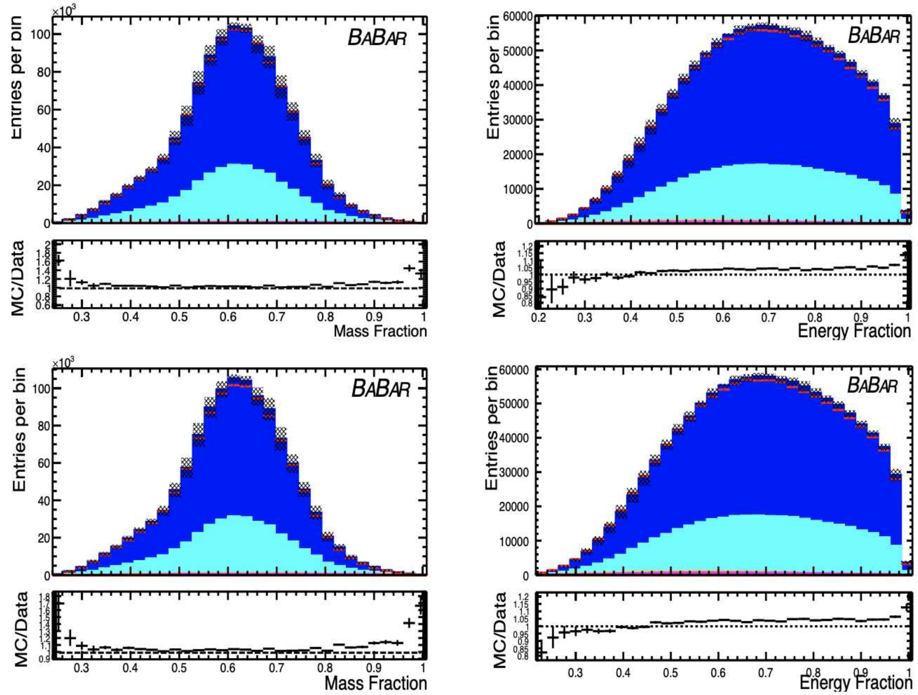


Heavy neutral leptons





Muon



Uncertainty	Yield Change (±)
Luminosity	0.44%
$\sigma(ee \to \tau\tau)$	0.31%
Branching Fractions (1 prong)	e: 0.22%
	μ: 0.22%
Branching Fractions (3 prong)	3π: 0.57%
PID Efficiency	e: 2%
	μ: 1%
	π: 3%
Bhabha Contamination	0.2%
$q\bar{q}$ Contamination (data)	0.1%
Tracking Efficiency	negligible
Detector Modeling	negligible
Beam Energy	negligible
Tau Mass	negligible