Searches for Hidden Sector Particles with BABAR

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Dark matter

What is dark matter?

- New particle(s)?
- A gravitational effect?
- Black holes?
- ..





The existence of dark matter has been supported by astrophysical and cosmological observations. So far, we see only gravitational effects of dark matter.

Dark matter



• Many dark matter candidates have been proposed, including the weakly interacting massive particles (WIMPs), and other alternative models

Hidden sector

- Hidden sector = a collection of particles that do NOT have direct interaction with the Standard Model.
- Theoretically motivated by string theory and other BSM scenarios.
- Hidden sector has its own symmetries, which could be arbitrary complex. Dark matter and other new particles may reside in dark sectors.
- There are portals between the dark sector and SM, acting as indirect interactions: vector (dark photon), scalar (dark Higgs), Neutrino (Sterile neutrino), ...



The BABAR experiment



BABAR collected ~500 fb⁻¹ around the $\Upsilon(4S), \Upsilon(3S)$ and $\Upsilon(2S)$ resonance between 1999 - 2008.

Collaboration is still active more than 10 years after data taken ended!



As of 2008/04/11 00:00



Dark matter searches at BaBar

Hidden sector searches

- Dark Leptophilic Scalar
- Muonic dark forces

Other dark matter searches

• Six-quark dark matter

Many BSM models predict the existence of an extended Higgs sector with new light gauge singlets that can mix with the Higgs boson. Strong experimental constraints on this scenario.

If the new scalar interacts predominantly with leptons rather than quarks, experimental constraints are significantly weakened due to the reduced coupling to electrons.

A leptophilic scalar could explain the g-2 anomaly (1606.04943, 1605.04612) and the more recent KOTO excess (2001.06522).



Mass proportional coupling

- Produced preferentially via its coupling to the tau.
- Decays preferentially to the most massive lepton-pair kinematically accessible
- Long-lived particle for sufficiently low values of coupling constant (mainly below $2m_{\mu}$)

Search for dieletron/dimuon decay of a leptophilic dark scalar (ϕ_L) radiated off a tau lepton:

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





- If decays to muons kinematically allowed, ~100% prompt decays to muon
- If below muon threshold, ~100% displaced decays to electron

Source: Brian, Shuve

Analysis Strategy

- exactly four charged tracks with zero net charge
- reject events with a total visible mass > 9 GeV (Radiative Bhabha, photon conversion)
- cosine of the angle between the momentum of the ϕ_L candidate and that of the nearest track to be less than 0.98
- three or less tracks identified as electrons
- Train BDT to increase signal purity



Data/MC discrepancy due to non-modelled MC components (two-photon, ISR, highmultiplicity QED,...), which has very limited impact on the results.

Extract signal as a function of dark scalar mass with fits over sliding intervals



No significant signal is observed, consistent with the null hypothesis

Extract limit on the production cross-section and the coupling parameter ξ





Probe ϕ_L lifetime $c\tau \sim 10$ cm below dimuon mass.

Significant improvement over previous bounds.

The g-2 region is clearly excluded for almost all masses below the ditau threshold!

Muonic dark force



A new force coupling only to the second and third generation of leptons with a corresponding gauge boson Z' (1401.2459).

Could explain anomalies observed in the muon sector (g-2 discrepancy, proton radius puzzle), and account for dark matter as sterile neutrinos by increasing their cosmological abundance via new interactions with SM neutrinos.

First direct measurement also sensitive to models where neutrino couplings are absent.

Muonic dark force

Search for the muonic dark force (Z') in $e^+e^- \rightarrow \mu^+\mu^- Z'$, $Z' \rightarrow \mu^+\mu^-$

Select events containing two pairs of oppositely- charged tracks, where both positivelycharged or both negatively-charged tracks are identified as muons by particle identification algorithms (PID).

The background at low masses is well reproduced by the simulation, while the $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$ Monte Carlo overestimates the full-energy peak

Extract the signal yield as a function of $m_{Z'}$ by performing a series of unbinned maximum likelihood fits to the reduced dimuon mass spectrum.



Muonic dark force

What is it?

A new dark matter candidate, a *uuddss* 6-quark state (Q=0, B=2, S=-2, spin zero, flavor singlet) proposed by G. Farrar. (arXiv:1708.08951)

Tightly bound state (not hexaquark predicted long ago by Jaffe (PRL 38, 195))

- lifetime is cosmological if mass below 2.05 GeV $(m_{\Lambda} + m_p)$
- if mass below 1.88 GeV $(2m_p)$, absolute stable
- doesn't couple to photons, pions and other mesons.

Connection to dark matter

If dark matter (DM) consists of a nearly equal number of u, d, s quarks, the formation rate is driven by a quark-gluon plasma transition to the hadronic phase

Six-quark DM with a mass ~1860-1880 MeV can reproduce the ratio of DM to ordinary matter densities $\Omega DM / \Omega b$ within 15%.

The total baryon asymmetry in the universe at the level of 10⁻⁹ when including the contribution of DM, within an order of magnitude of the currently measured value.

Search for the reaction $\Upsilon(2S, 3S) \to \overline{\Lambda\Lambda}S, \Lambda \to p\pi$ decay Fully reconstruct both Λ or $\overline{\Lambda}$ in $p\pi$ decay (B=0.64), and calculate recoil mass $m_{rec}^2 = (p_T - p_{\overline{\Lambda}} - p_{\overline{\Lambda}})^2$

Event selection

- Require 4 charged tracks +1 additional track not from interaction point
- Apply loose PID criteria to select (anti-) protons
- Flight significance of each $\Lambda > 5\sigma$

Signal / sideband regions

Examine extra neutral energy in region outside the S direction, i.e. the energy of all photons in the rest of the EM calorimeter, and require $E_{extra} < 500$ MeV.

- Observe zero background events in the signal region in the E_{extra} sideband
- Results in the $E_{extra} < 500$ MeV region show no signal events for zero expected background

No significant signal is observed, and we derive 90% confidence level (CL) upper limits on the $\Upsilon(2S, 3S) \rightarrow \overline{\Lambda}\overline{\Lambda}S$ branching fractions, scanning S masses in the range 0 GeV < $m_{\rm S} < 2.05$ GeV in steps of 50 MeV

Summary

Dark Leptophilic Scalar

- new scalar interacts predominantly with leptons rather than quarks
- $e^+e^- \rightarrow \tau^+\tau^-\phi_L, \ \phi_L \rightarrow l^+l^- \ (l=e,\mu)$

Six-quark dark matter

uuddss 6-quark state S searched from the reaction $\Upsilon(2S, 3S) \rightarrow \overline{\Lambda}\overline{\Lambda}S, \Lambda \rightarrow p\pi$ decay

Muonic dark force

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• A new force coupling only to the second and third generation of leptons

$$e^+e^-
ightarrow \mu^+\mu^- Z^\prime$$
 , $Z^\prime
ightarrow \mu^+\mu^-$

Several dark matter and hidden sector analysis are still ongoing!

Thank you!

Backup slides

mass resolutions

signal efficiencies

*E*extra distribution after preselection shows 92 events of which 8 events satisfy *E*extra < 500 MeV

Kinematic fit of both As to PDG mass and common production point in beam spot