Search for muonic dark force at *BABAR*

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on behalf of the *BABAR* collaboration

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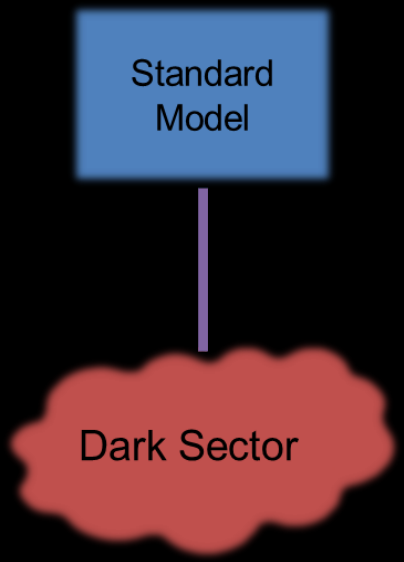
Beyond WIMPS: dark sectors

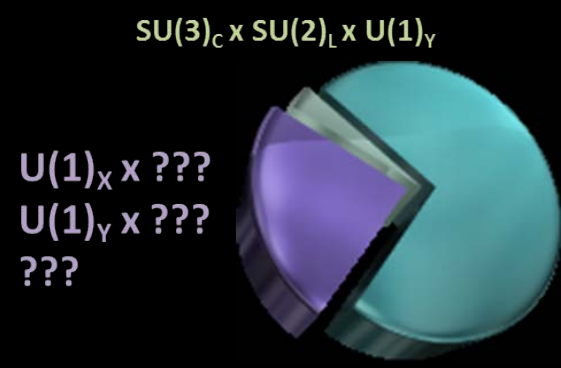
What are dark sectors

- New particles that don't couple directly to the SM.
- Theoretically motivated: string theory and many BSM scenarios include dark sectors with extra U(1).
- Dark photons (A') are the corresponding U(1) gauge bosons, mediating the dark force.



Dark matter could be part of a dark sector

- The SM is not minimal, and there is no reason to believe dark matter should be a single particle .
- Dark sector could have a rich structure, and dark matter could only be a fraction of it.



Dark sectors are also very natural in the context of light (sub-GeV) dark matter, which requires additional low-mass mediators to explain the observed relic density (see US cosmic visions workshop report - arXiv:1707.04591)

Connection to the SM

There are a few interactions allowed by Standard Model symmetries with dimensionless couplings, i.e. *they are sizeable irrespective of their source.*

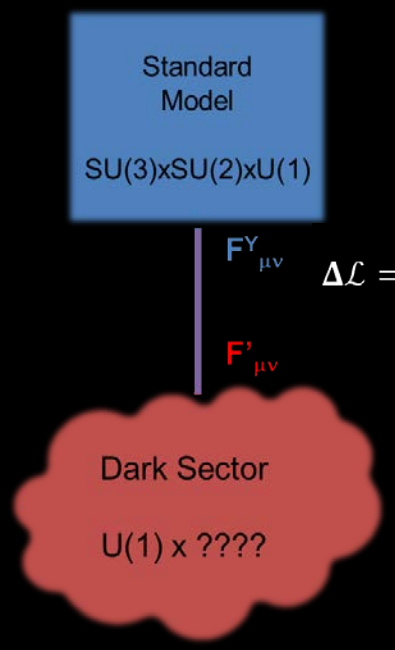
An example: vector portal

- Dark sector with a new gauge group U(1)' and a corresponding gauge boson, the dark photon A'
- Generic interaction with the SM (kinetic mixing)

$$\Delta\mathcal{L} = \frac{\varepsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

with a mixing strength ε.

After EWSB, there is a coupling between the dark photon and the photon, opening a window to the dark sector.



$$\Delta\mathcal{L} = \frac{\varepsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

Holdom, Galison, Manohar

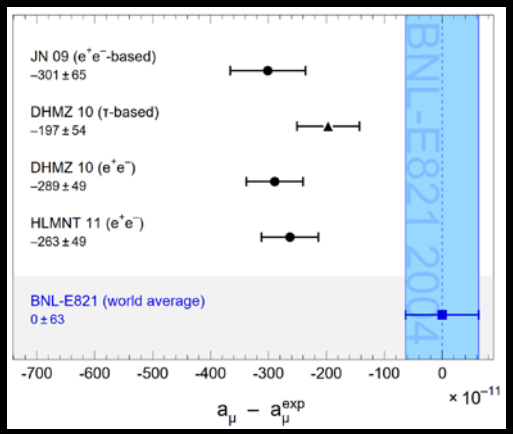
The dark photon is an example of a more generic family of models, where the mediator could couple preferentially to baryonic, leptonic, B-L, Lμ-Lτ or other currents

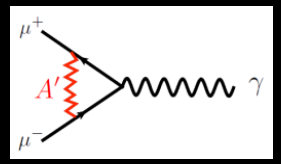
A muonic dark force

Muonic dark force: a new force coupling only to the second and third generation of leptons with a corresponding gauge boson Z' (arXiv:1403.2727).

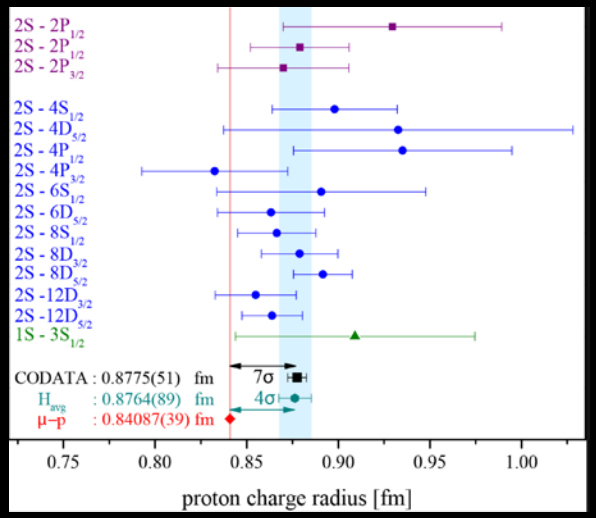
Such a force could explain various anomalies observed in the muon sector ("g-2" discrepancy, proton radius puzzle), and account for dark matter as sterile neutrinos by increasing their cosmological abundance via new interactions with SM neutrinos.

Muon g-2

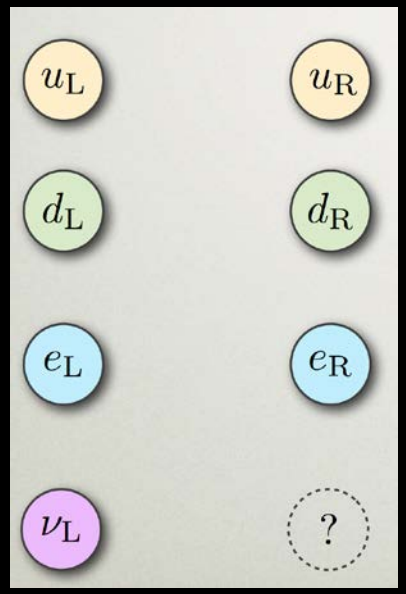




Proton radius



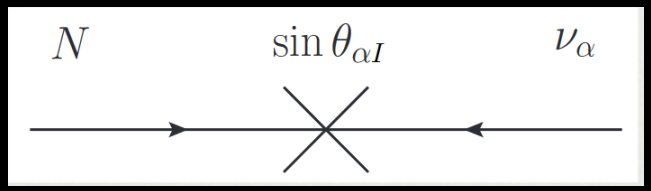
Sterile neutrino



Shuve *et al.*

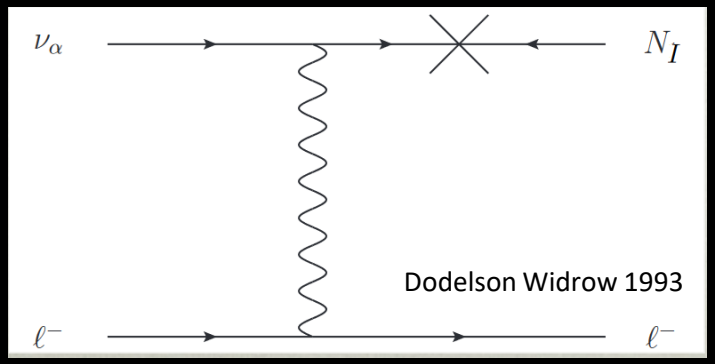
Sterile neutrino dark matter

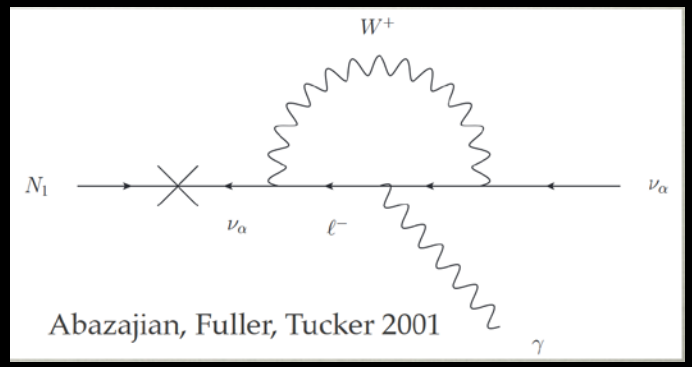
Dark matter model of sterile neutrino N (SM gauge singlet). After EWSB, Standard Model neutrinos get a (small) mass and the SM & sterile neutrino mix.



$$\sin\theta_{\alpha I} = \frac{F_{\alpha I}\langle H\rangle}{M_N}$$

Sterile neutrino live and die by this mixing

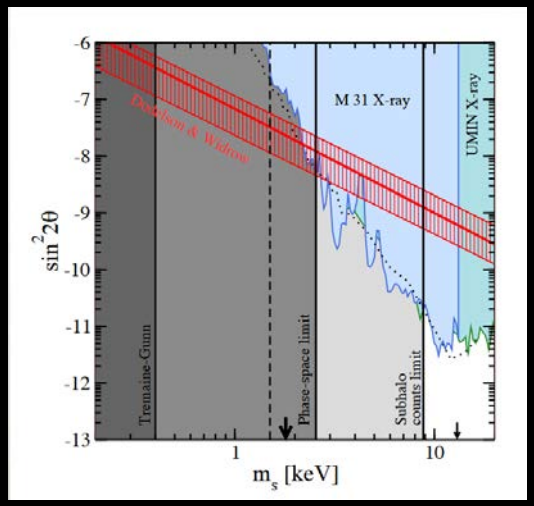




Can the mixing angle be large enough to produce enough sterile neutrinos to account for dark matter and small enough to suppress decays?

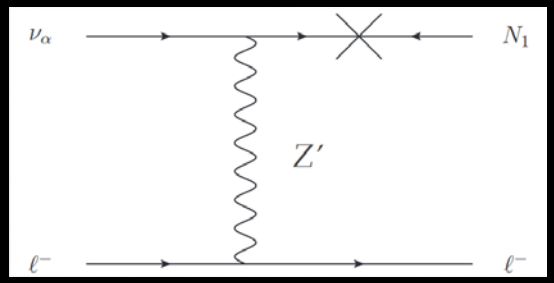
Sterile neutrino dark matter

Constraints from astrophysics (monochromatic x-ray line from N→ γν decays and small scale structures) imply that the mixing angle is too small to produce the observed relic density.

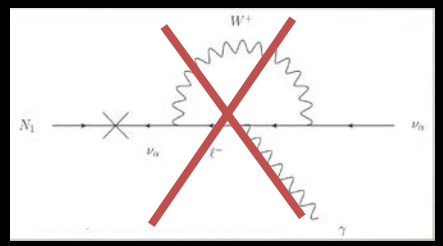


Horiuchi *et al.* 2013

BUT, a new neutral interaction coupling to leptons and neutrinos could boost the sterile N production without increasing the decay.



New dark force coupling to 2nd / 3rd generation of leptons (Lμ-Lτ, anomaly free). The corresponding gauge boson Z' must be light – O(GeV) or less – to avoid constraints from magnetic dipole measurements and provide the correct rate enhancement.



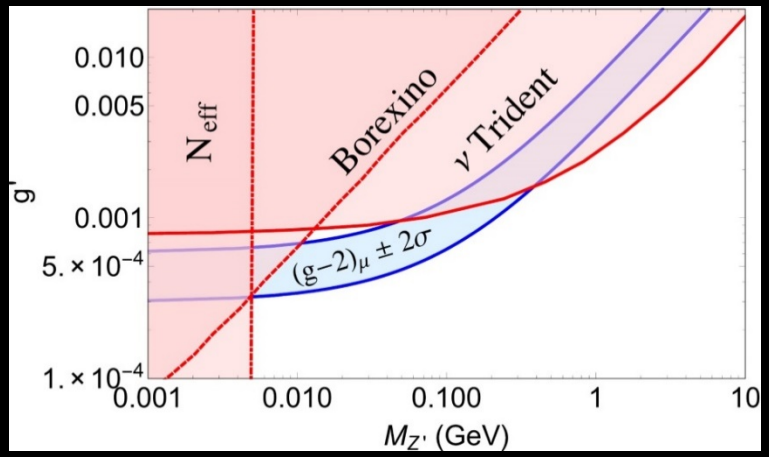
Z' decays to muons, taus and neutrinos when kinematically accessible

Muonic dark force

Some constraints from neutrino physics have already been derived, but they only indirectly probe the existence of Z' (with large systematic uncertainties).

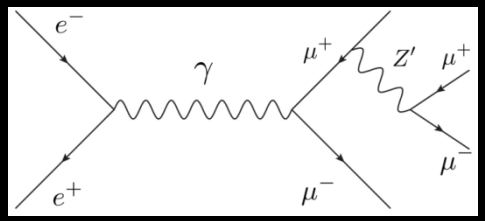
In particular, regions of the parameter space to explain the (g-2) anomaly is still unexplored

Current constraints on Z'

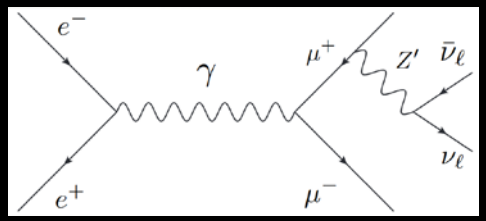


BABAR offers an ideal environment to search for a muonic dark force. We can search for direct Z' production at colliders via Z'-strahlung :

$e^+e^- \to \mu^+\mu^- Z', Z' \to \mu^+\mu^-$



$e^+e^- \to \mu^+\mu^- Z', Z' \to \nu\bar{\nu}$



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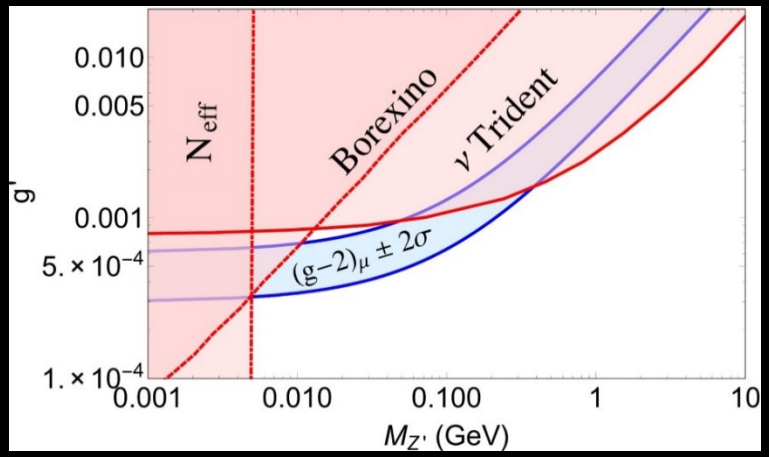

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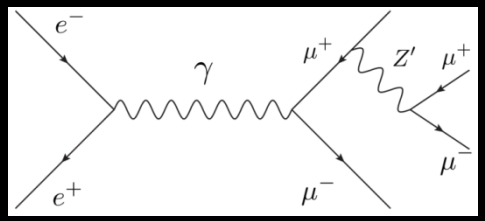

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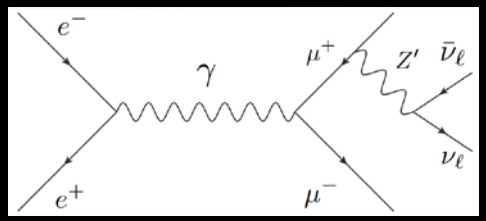
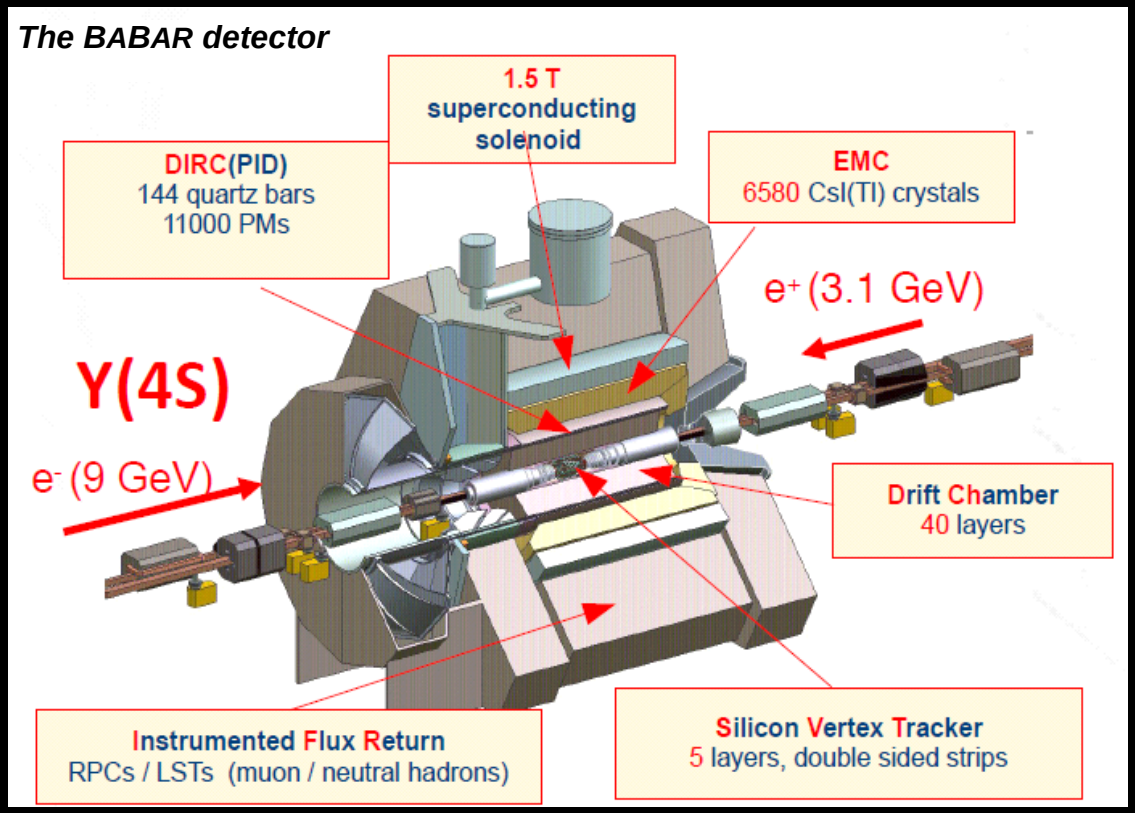
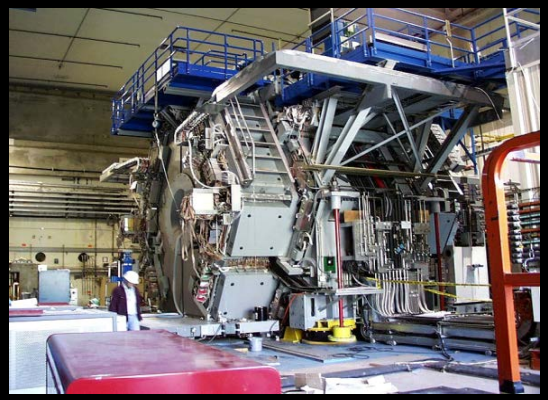


The *BABAR* experiment

BABAR collected around 500 fb^{-1} of data around the ϒ(4S), ϒ(3S) and ϒ(2S) resonance





B-factories offer an ideal environment to search for dark sector particles

Search for muonic dark force

Search for Z' in $e^+e^- \rightarrow \mu^+\mu^- Z'$, $Z' \rightarrow \mu^+\mu^-$ events

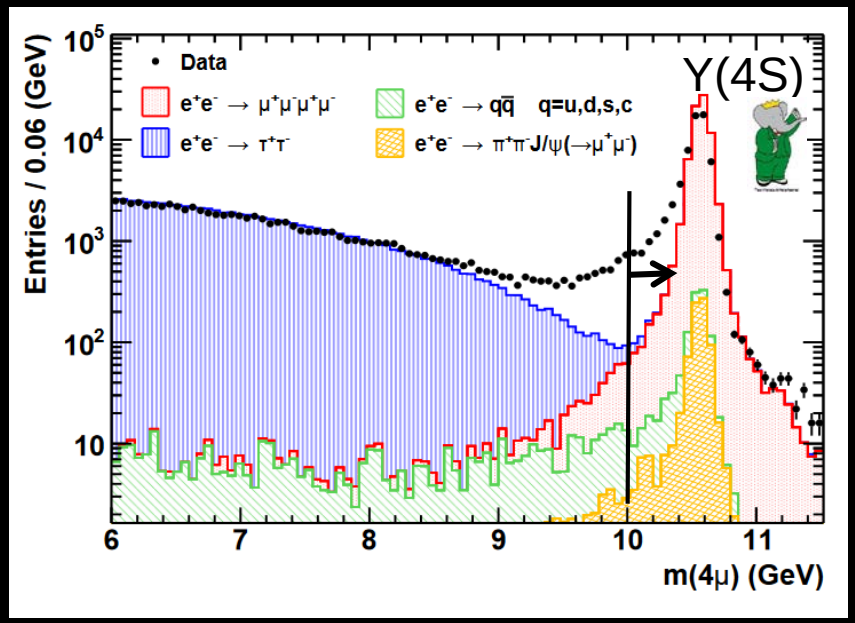
Analysis overview

- Analysis based on 514 fb^{-1} of data collected at Y(4S), Y(3S) and Y(2S)
- Four tracks and no extra neutral energy (E_{extra} < 200 MeV)
- Particle identification: at least 2 same-sign tracks identified as muon
- Four-muon invariant mass within 500 MeV of nominal CM-energy
- Veto events with a dimuon candidate within 10 MeV of the Υ(1S) mass for the Υ(2S) and Υ(3S) dataset to reject $\Upsilon(2S,3S) \rightarrow \pi\pi\, \Upsilon(1S)$, $\Upsilon(1S) \rightarrow \mu\mu$
- Kinematic fit imposing beam-energy constraint is finally performed, but no constraints on the χ^2 are applied (improve mass resolution).

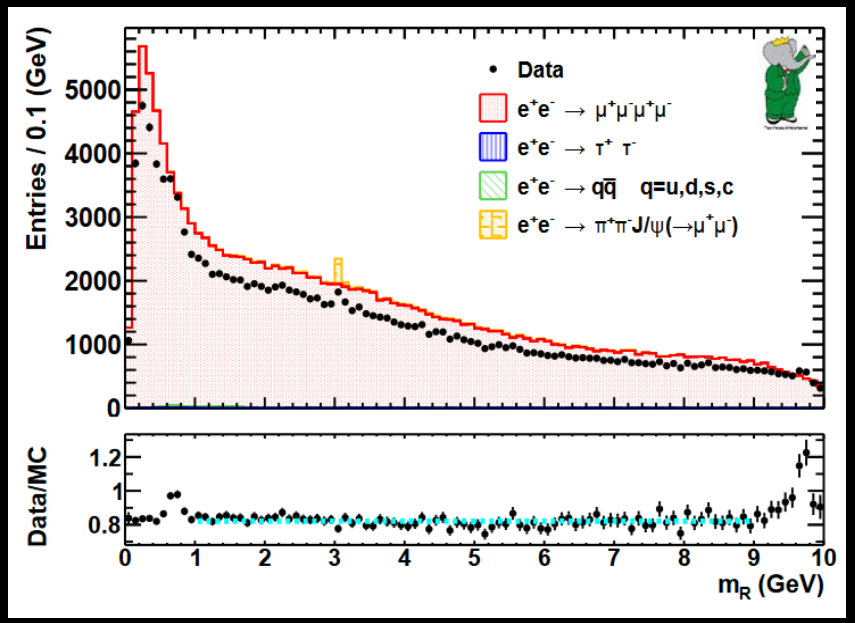
We perform a blind analysis, the selections criteria are optimized on a small subset (5%) of the data, which is subsequently discarded.

Invariant mass spectra

Four-muon invariant mass - Y(4S) dataset



Reduced di-muon mass (2 entries / event)



$m_R = (m_{\mu\mu}^2 - 4\, m_\mu^2)^{1/2}$

Signal region dominated by $e^+e^- \rightarrow 4\mu$ QED background. Discrepancy arises primarily from ISR (absent in MC) and differences in particle identification efficiencies, track reco.,… The ratio data/MC is used to correct the signal efficiency (ISR not included in signal MC)

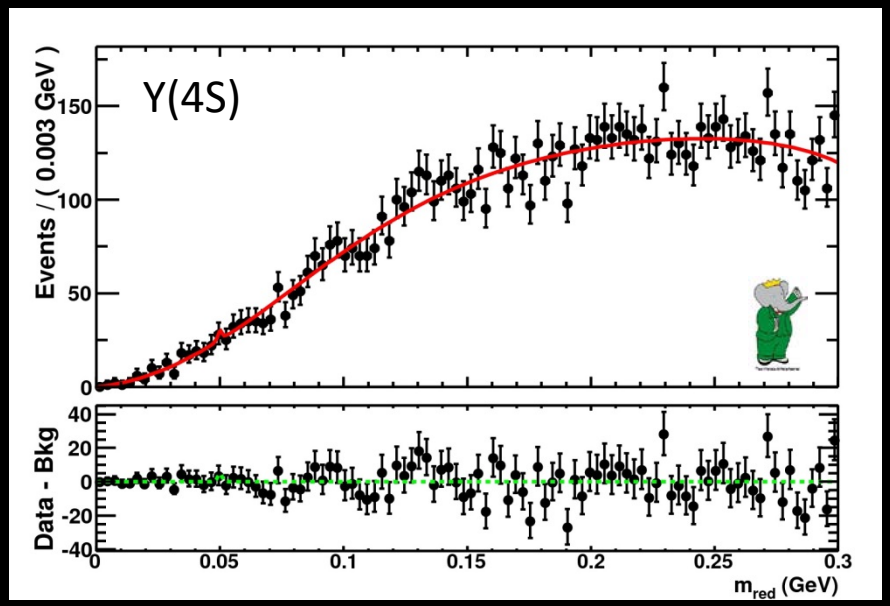
Low 4μ mass region well reproduced by MC predictions. Factoring ISR contribution, the corrections factors derived from this region agree with the ones determined at high masses.

Signal extraction

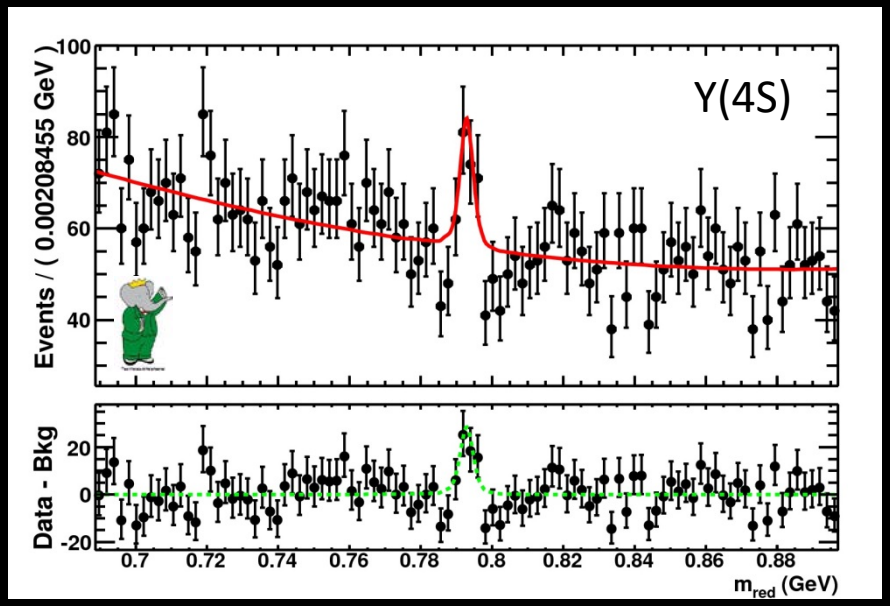
We extract the signal separately for the data at the Y(4S), Y(3S) and Y(2S) by performing a series of fits to the reduced dimuon mass for each sample.

For each mass hypothesis, we fit over a fixed range of 0-0.3 GeV (m_R < 0.2 GeV) or a window corresponding to 50x signal resolution (m_R > 0.2 GeV). A region of ±30 MeV around the J/ψ is excluded.

Fit m_R = 0.05 GeV



Most significant fit m_R = 0.79 GeV



Local /global significance: 4.3σ /1.6σ

Signal extraction

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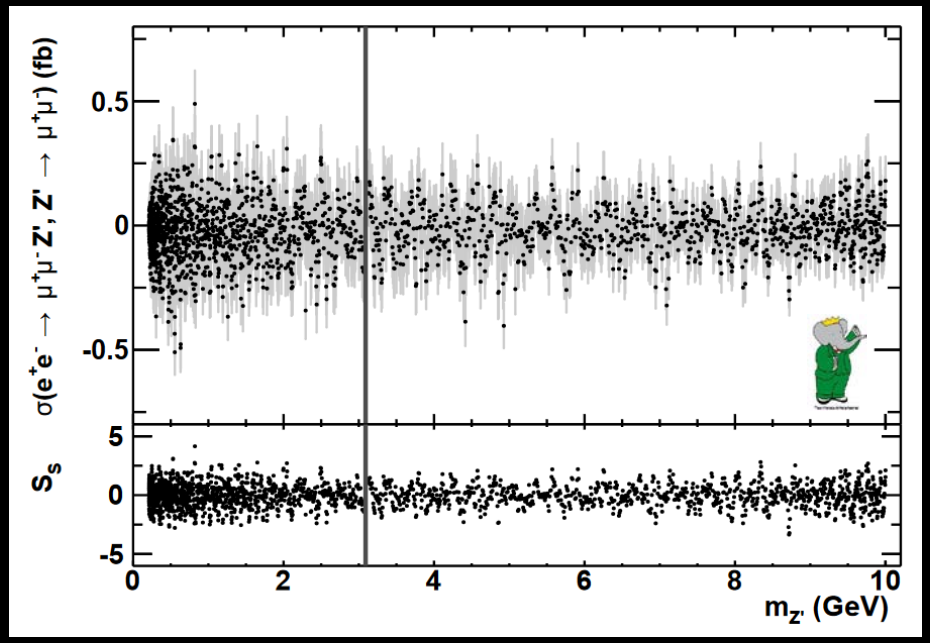
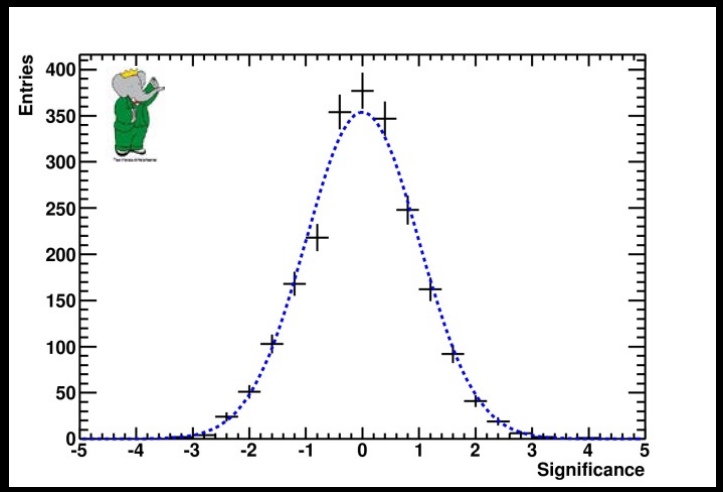
We extract the cross-section separately for the data at the Y(4S), Y(3S) and Y(2S) and combine the results together

Combined cross-section and significance



Significance distribution

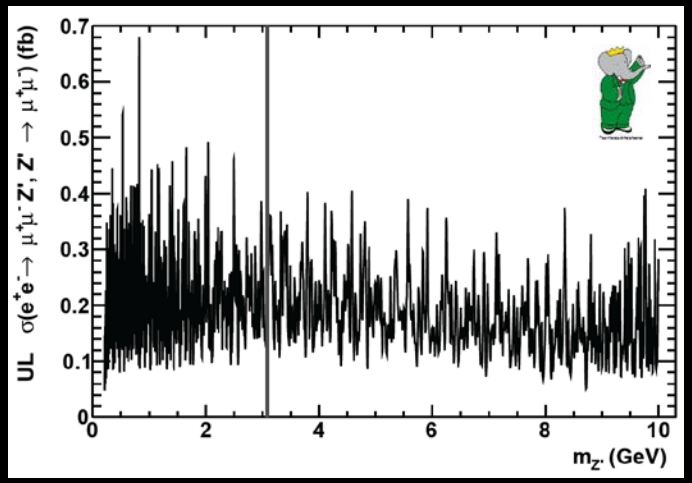


Compatible with null hypothesis

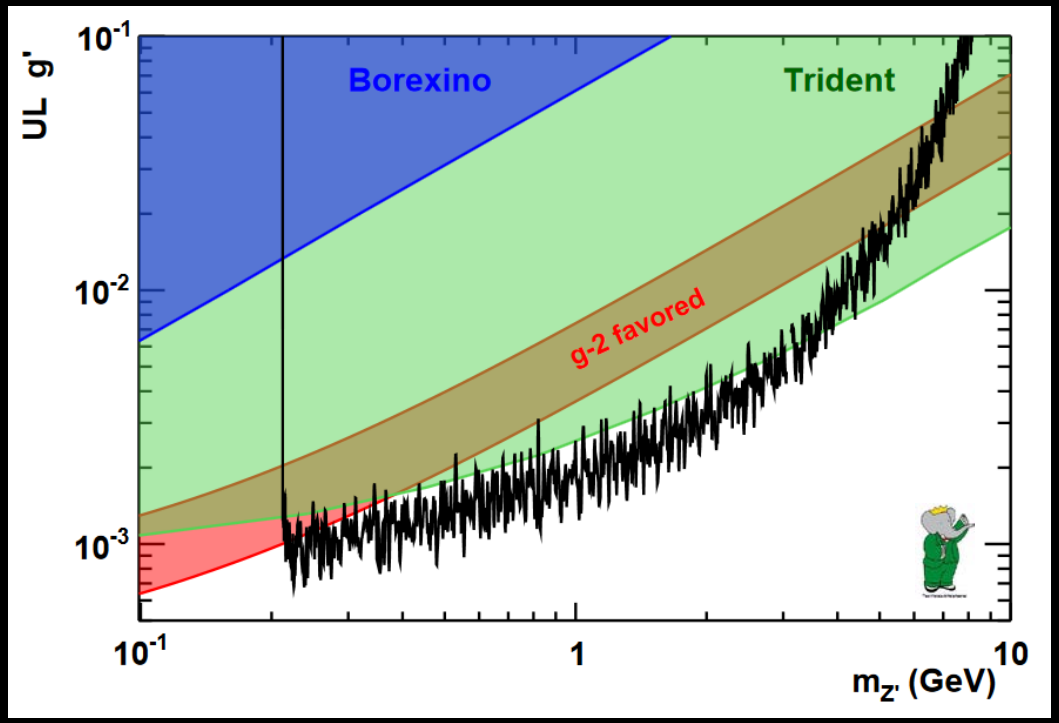
Results

PRD 94 (2016) no.1, 011102

Limit on $\sigma(e^+e^- \rightarrow \mu^+\mu^- Z', Z' \rightarrow \mu^+\mu^-)$



Limits (90% CL) on Z' coupling



Improve the previous constraints from the neutrino experiments and exclude all but a sliver of the region favored by the "g-2" anomaly.

Results

PRD 94 (2016) no.1, 011102

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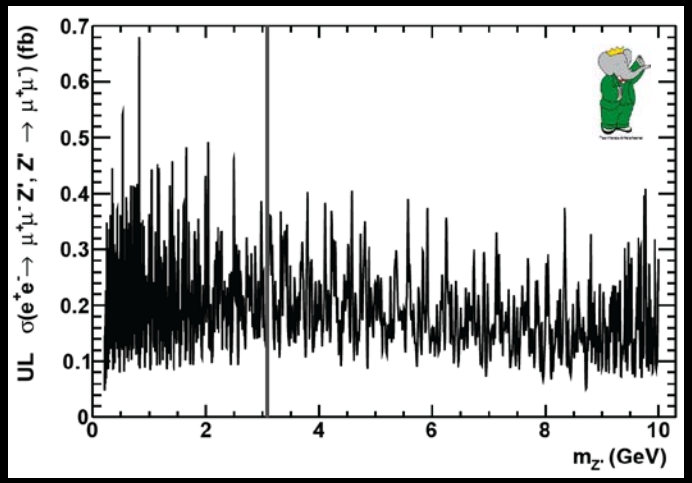

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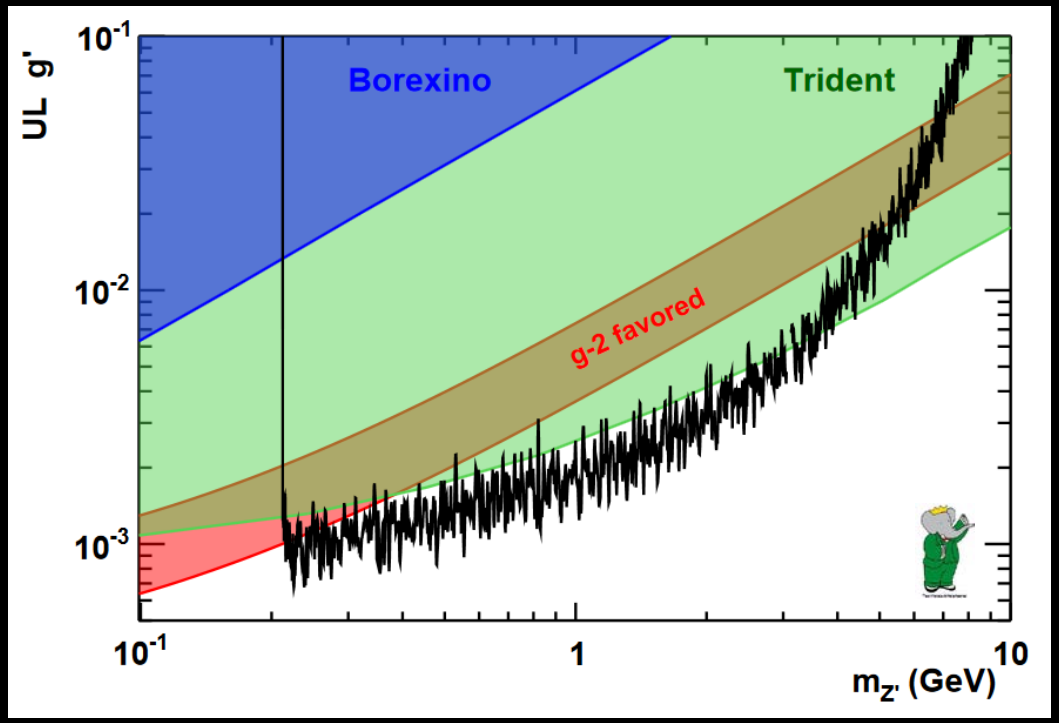


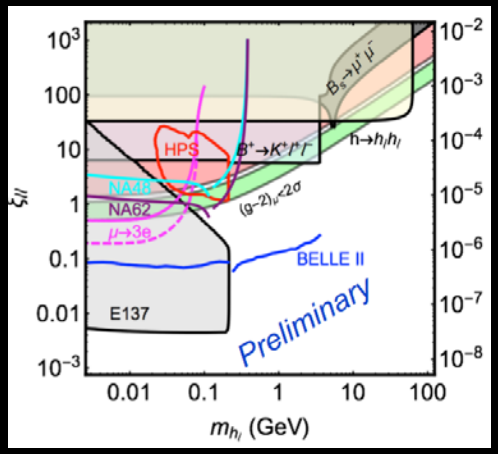
What about $Z' \rightarrow \nu\nu$? It turns out the Z' mass resolution is too low to extract competitive bounds. No luck this time!!!

More to come

On-going searches for dark sector at *BABAR*

Search for dark scalar (ϕ): A light dark scalar could couple to SM fermions via its mixing with the Higgs. Since the couplings are proportional to the mass, the best search strategy is to look for a dimuon resonance in $e^+e^- \to \tau^+\tau^- \phi$, $\phi \to \mu^+\mu^-$, e^+e^- events. *BABAR* could hopefully probe the remaining "g-2" preferred region at low masses.

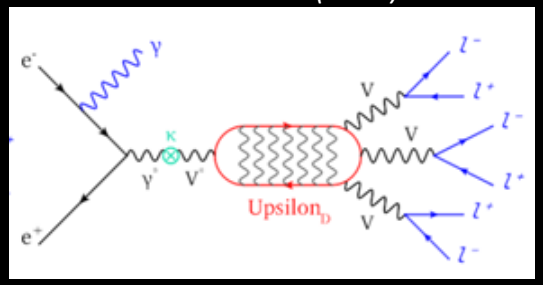
Limits on ϕ coupling



Batell, Lange, McKeen, Pospelov, Ritz

Self-interacting dark matter: if the dark-sector coupling is strong, dark sector bound states (darkonium) could be formed. Such states would leave a striking multi-muon final signature at *BABAR*.

PRL 116 (2016) 151801



And maybe more…

Summary

Light dark sectors have recently emerged as a new possibility for dark matter, and could have a rich phenomenology.

Low-energy, high-intensity colliders offer an ideal environment to probe such possibilities.

BABAR has conducted an extensive program to search for dark sector signatures, and set stringent limits on their existence. A few more searches are in the pipeline

More generally, there are still amazing possibilities at the GeV-scale, and dedicated programs are underway to explore them.