Title: Uncovering Low-Mass Hidden Sectors at Colliders

Date: Nov 16, 2018 01:00 PM

URL: http://pirsa.org/18110039

Abstract: Hidden sectors are motivated by a range of phenomena unexplained by the Standard Model, such as dark matter, neutrino masses, and the baryon asymmetry. Hidden sector particles below the weak scale can be copiously produced at high-energy and intensity-frontier experiments, but may have evaded detection with current searches.
I will discuss new searches I am doing with the BaBar collaboration that are probing unexplored, well-motivated territory for hidden sectors. I will also show how signatures such as displaced vertices motivate comprehensive, complementary searches at low- and high-energy experiments.

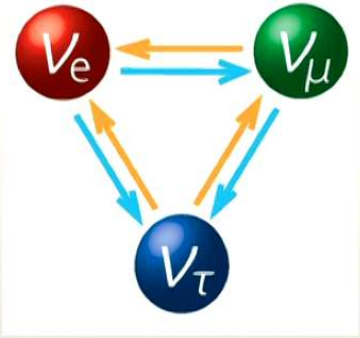
UNCOVERING SIGNALS OF A HIDDEN SECTOR

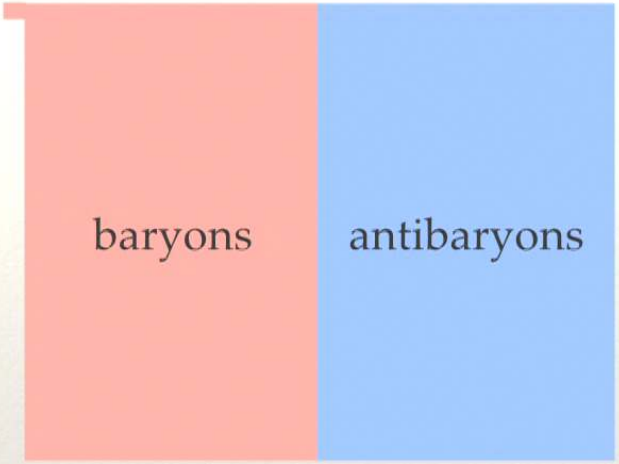
Brian Shuve

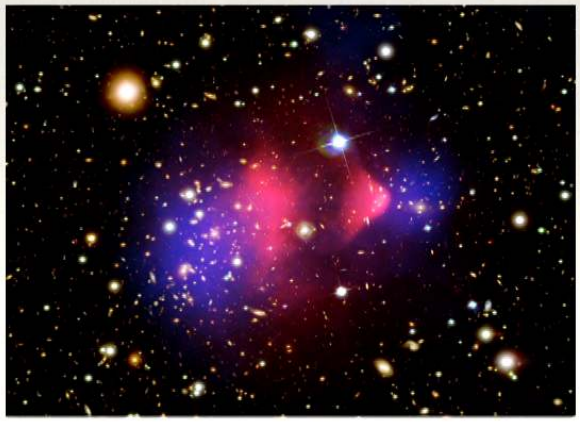
HARVEY MUDD COLLEGE

UCR

EVIDENCE FOR HIDDEN SECTORS



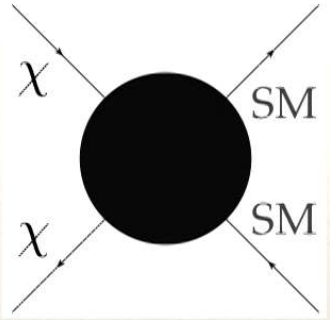


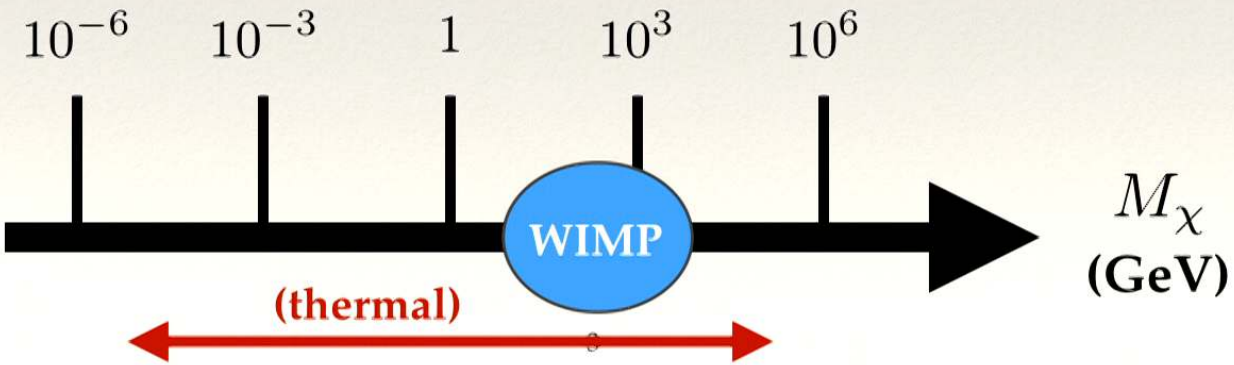


- No **definitive** mass scale for new physics

2

EXAMPLE: THERMAL DARK MATTER

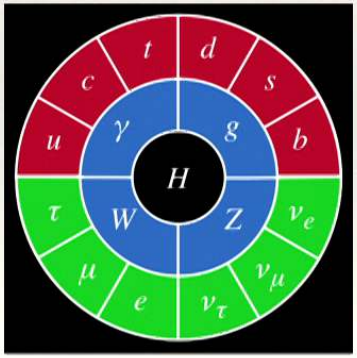




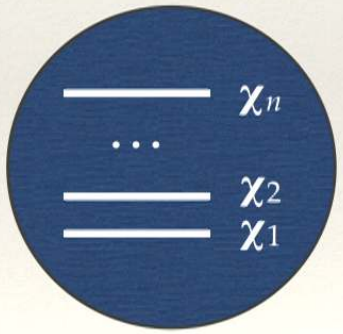
EXAMPLE: THERMAL DARK MATTER

- For dark matter masses below a few GeV, the "weak"/Higgs portals can't give large enough annihilation rate

Lee, Weinberg 1977

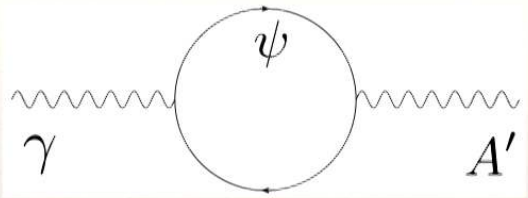


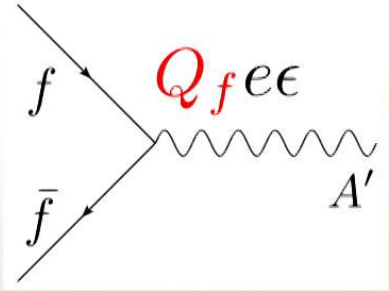
$$\frac{\alpha_{a\chi}\alpha_{a\mathrm{SM}}}{M_\chi^2} \sim \frac{10^{-9}}{\mathrm{GeV}^2}$$



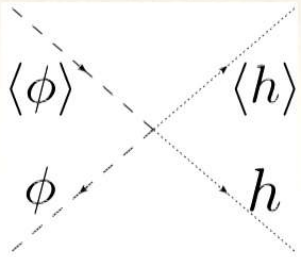
MINIMAL HIDDEN SECTORS

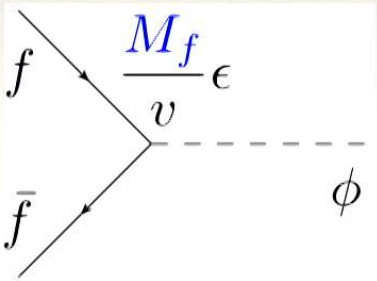
Dark Photon: new kinetically-mixed vector boson





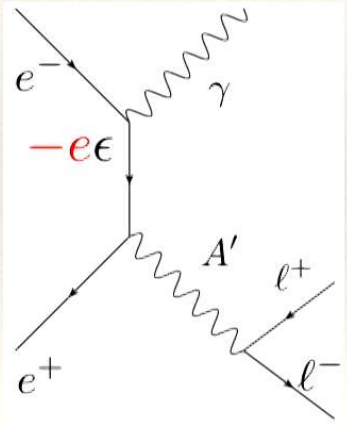
Dark Scalar: new scalar that mixes with Higgs boson

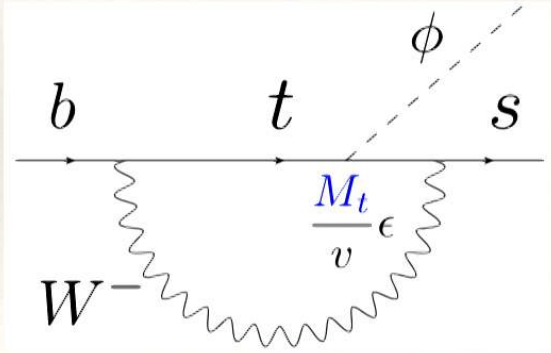




MINIMAL HIDDEN SECTORS

These new couplings provide production portals for new particles, affect SM particle properties

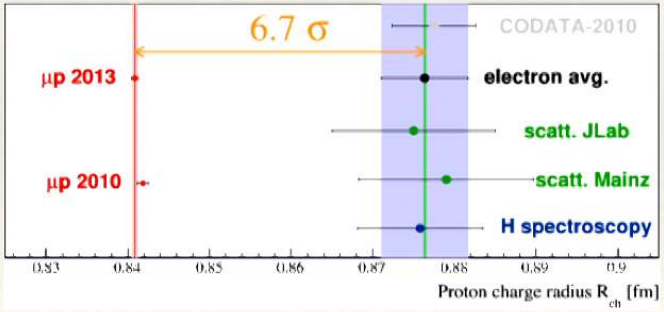




MINIMAL HIDDEN SECTORS

What have we found so far?

$$\frac{1}{2}(g-2)_\mu^{(\mathrm{obs})} - \frac{1}{2}(g-2)_\mu^{(\mathrm{SM})} = 302 \times 10^{-11}$$



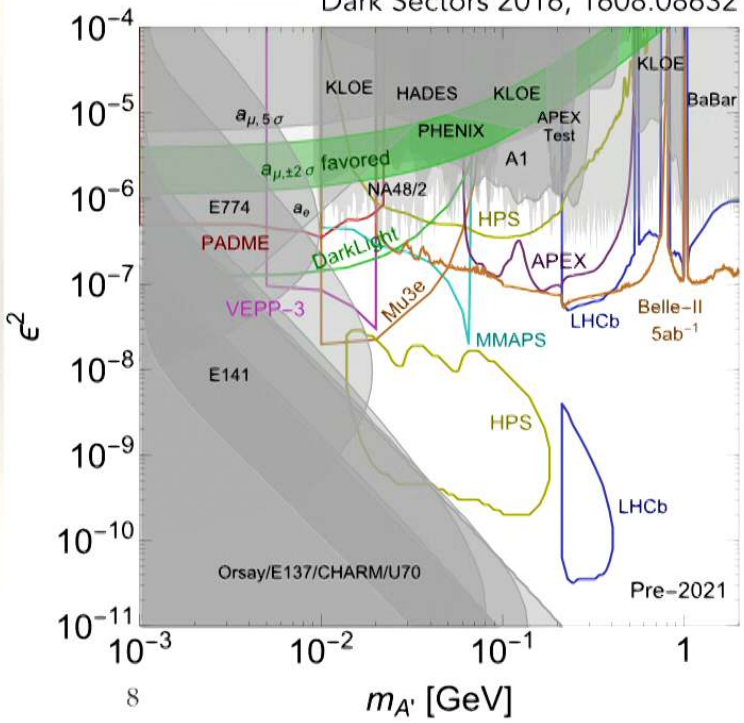
Flavour anomalies: $B \to K^* \mu^+ \mu^-$, *R*(*K*), *R*(*D*), etc.

MINIMAL HIDDEN SECTORS

What have we (not) found so far?

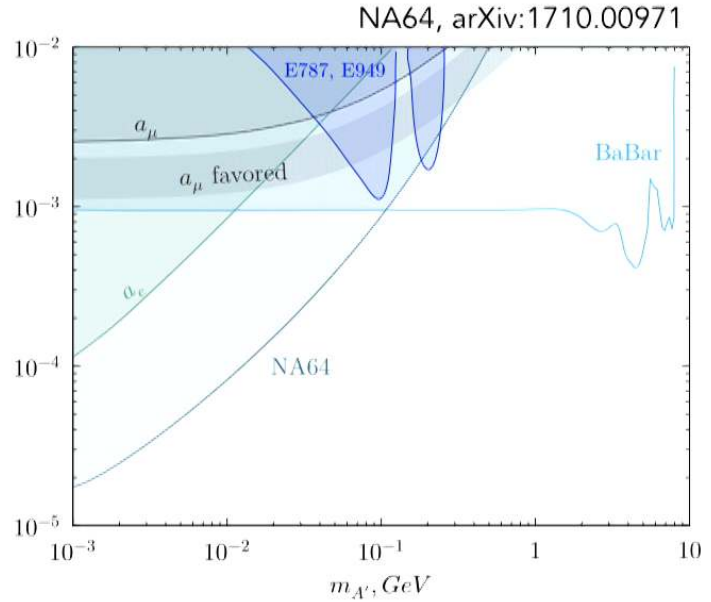
visible

Dark Sectors 2016, 1608.08632



invisible

NA64, arXiv:1710.00971



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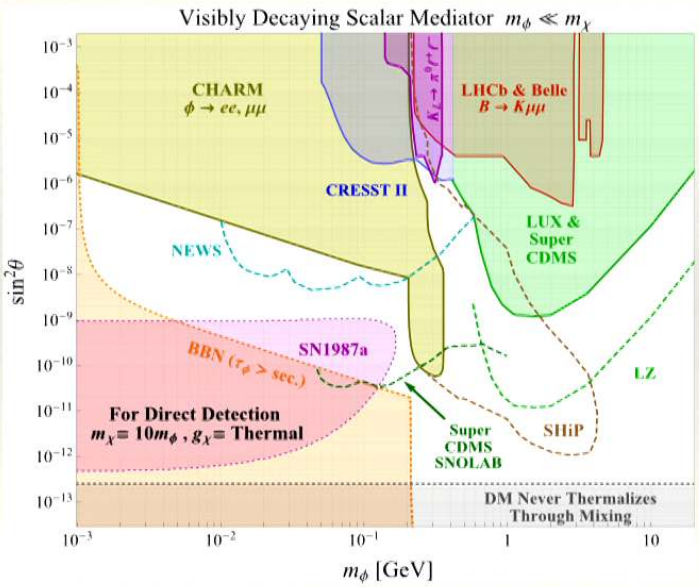
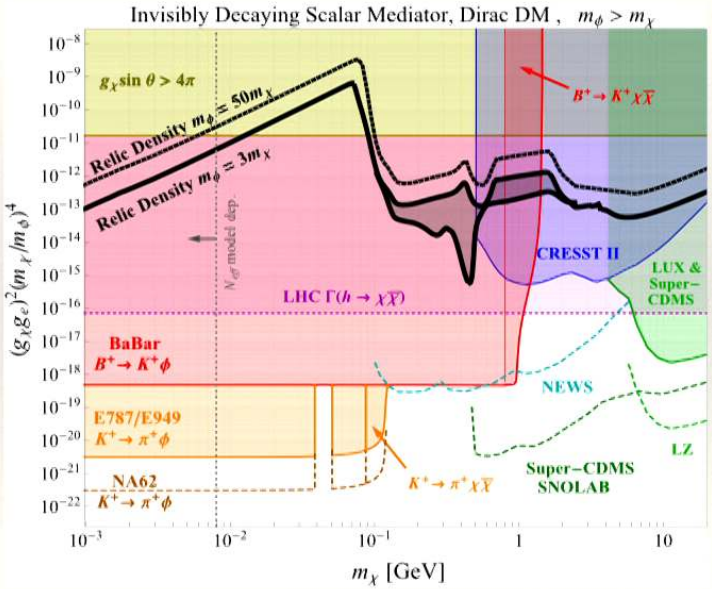


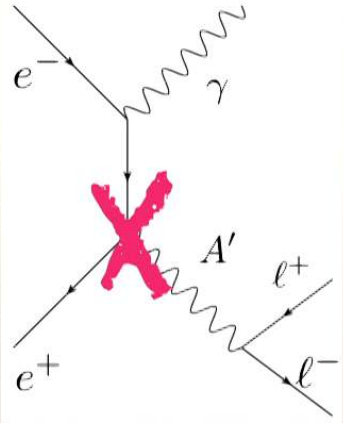
invisible

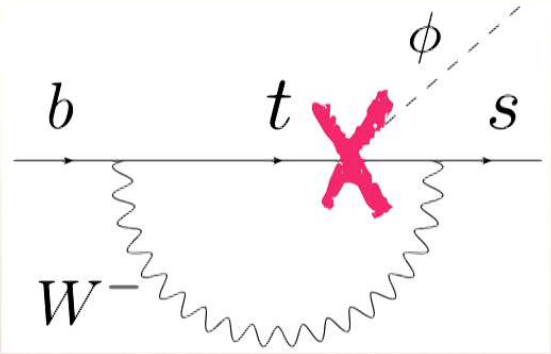


Krnjaic, 2015

BEYOND MINIMALITY

However, searches don't apply if assumptions are broken





- **Leptophilic gauge boson** (gauged $L_\mu - L_\tau$ or RH muon)

  X. He *et al.*, 1991; Batell, McKeen, Pospelov 1103.0721

- **Leptophilic scalar** Chen *et* al., 1511.004715; Batell *et al.*, 1606.04943
- Only couplings to **gauge bosons** (axion-like particles)
- …

This motivates new searches and signatures to close the gaps!

- **New Experimental Results & Search Ideas with *BABAR***
  - Search for a new leptophilic forces
    BS w/ *BABAR* collaboration, arXiv:1606.03501 & ongoing work
  - Seach for axionlike particles
    E. Izaguirre, T. Lin, and BS, arXiv:1611.09355
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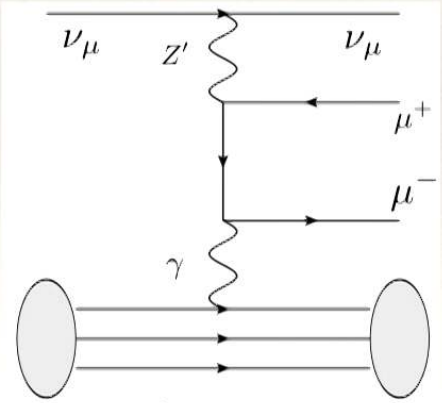
  - Long-lived particle searches with *B*-factories

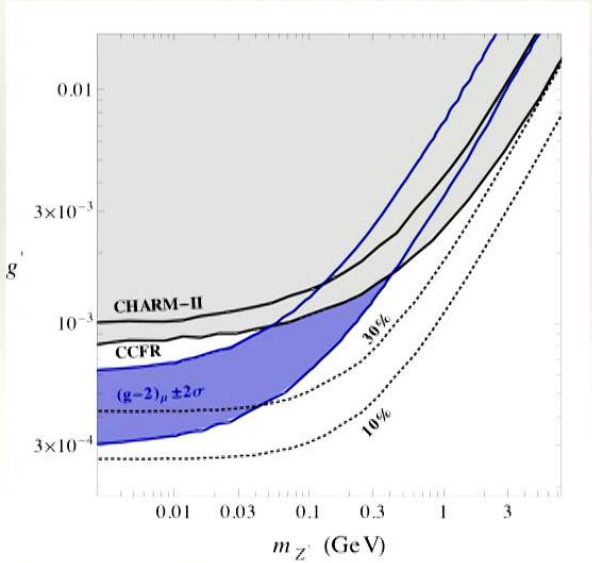
- **Hidden sectors at the LHC in rare *Z* decays**
  N. Blinov, E. Izaguirre and BS, arXiv:1710.07635

DARK MUONIC FORCE

- If we want a model-independent probe of new physics coupled to muons, we want to avoid making assumptions about couplings to electrons and quarks
- *E.g.*, gauged $L_\mu - L_\tau$ with coupling to μ, τ, ν_μ, ν_τ



Altmannshofer *et al.*, 1406.2332;
Magill, Plestid 1612.05642, …



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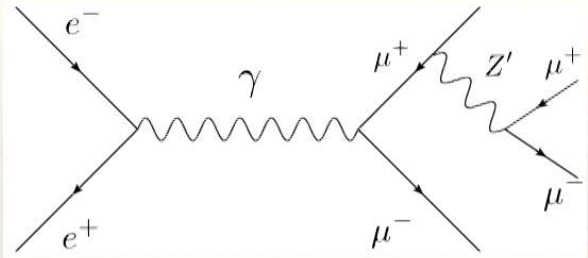
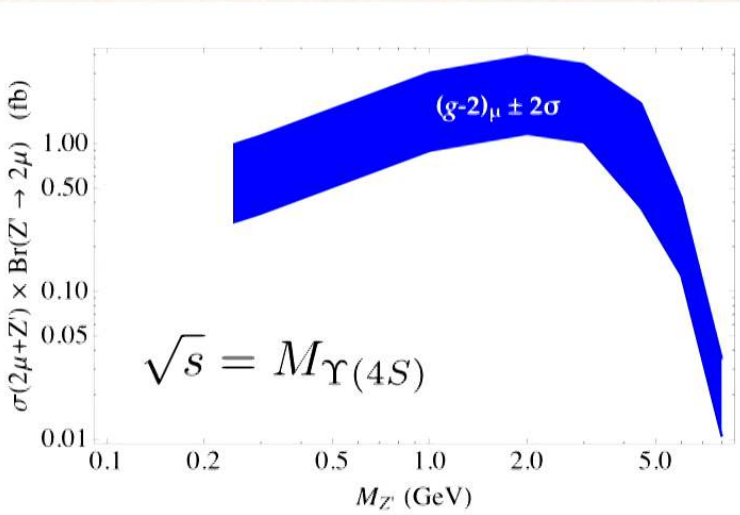
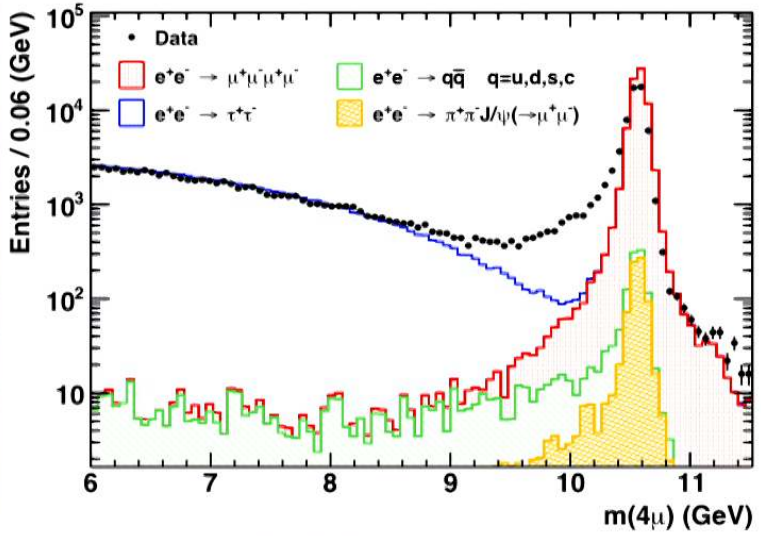


- *BABAR*: 514/fb total luminosity



DARK MUONIC FORCE @ *BABAR*

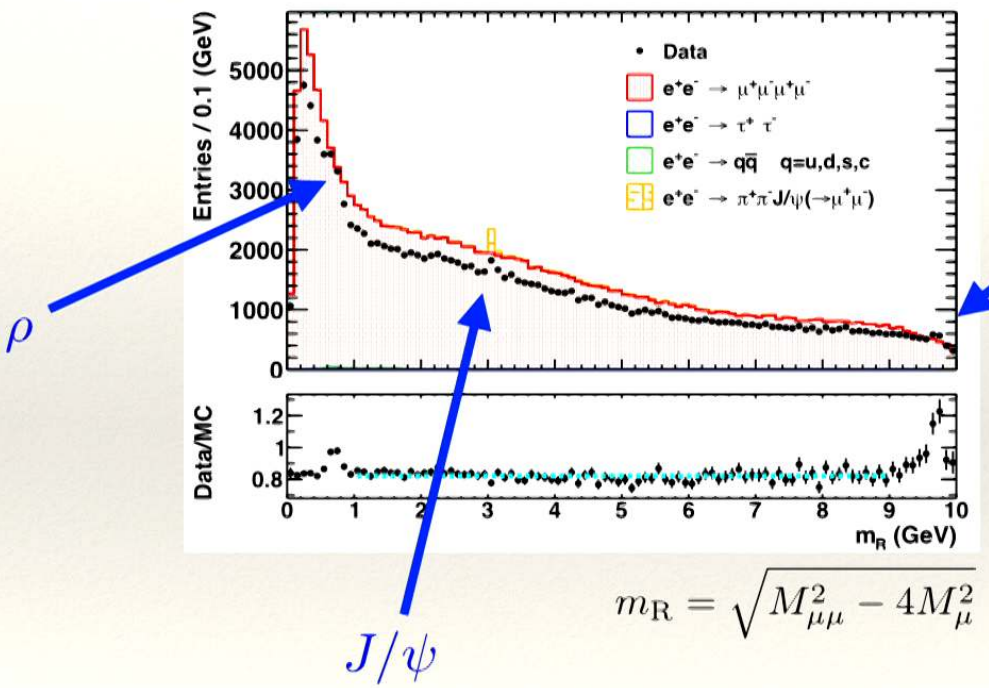
- Striking signature with **4 muons summing to beam energy**
- Dominant background is QED



BS with *BABAR*, arXiv:1606.03501

- ISR not included in signal or bkd MC, corrections applied
- Apply particle ID selection only to *same-sign* muons to increase efficiency

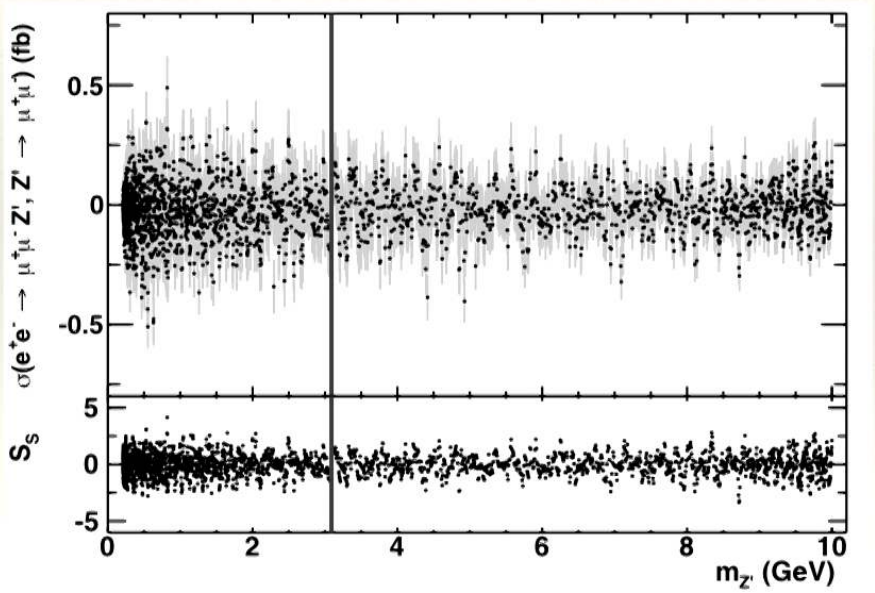
DARK MUONIC FORCE @ *BABAR*

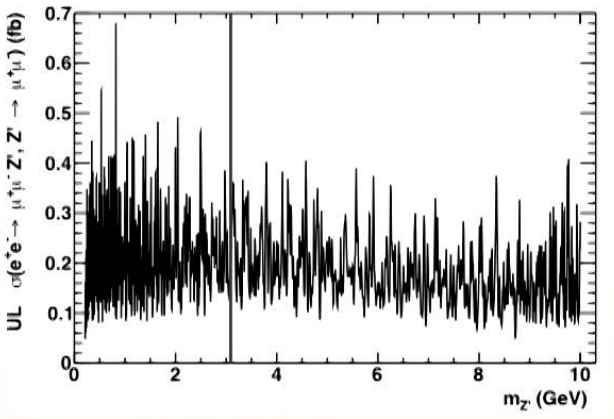


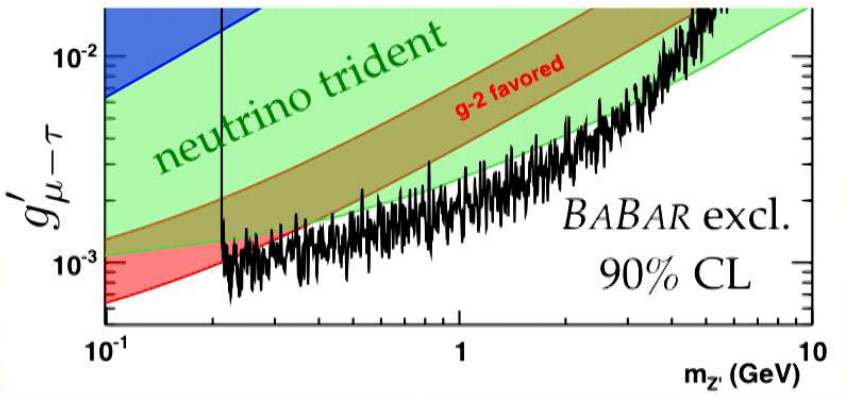
- Typical mass resolution is O(few MeV), mask region around J/Ψ

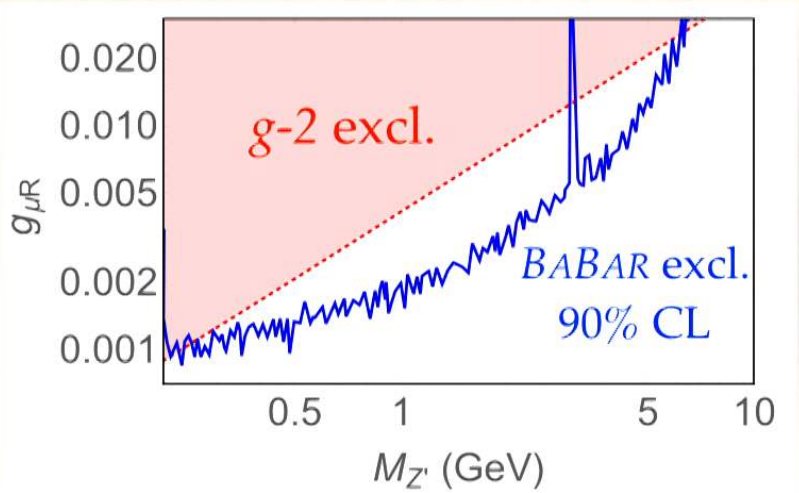
DARK MUONIC FORCE RESULTS

- Fit mass spectrum with background only and signal+background
- Signal spectrum extracted from MC and validated on J/Ψ
- Dominated by statistical uncertainties except very near threshold







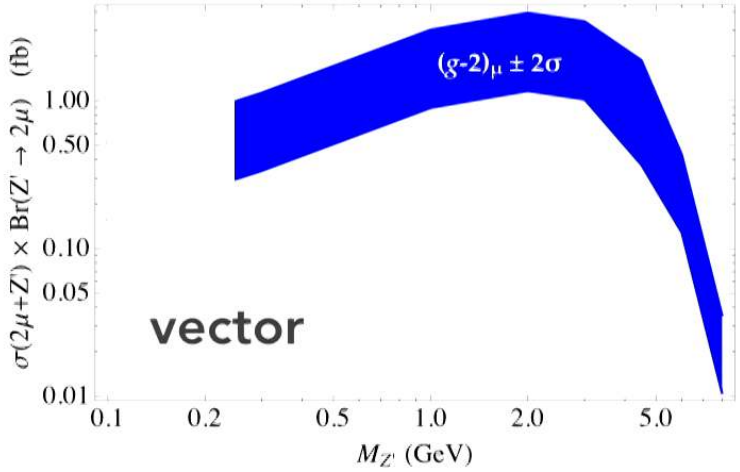


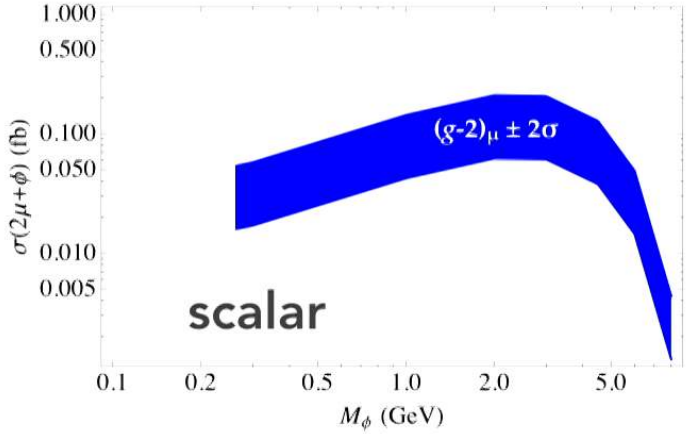
- Constrains some models of flavor anomalies!

Bishara, Haisch, Monni 2017 & private comm.

DARK MUONIC FORCE - SCALAR

- What if the force mediator is a scalar?

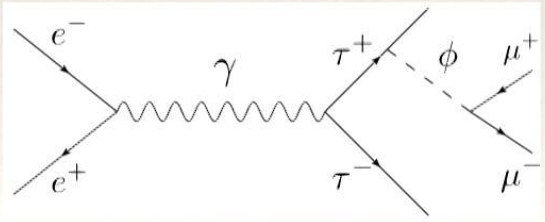


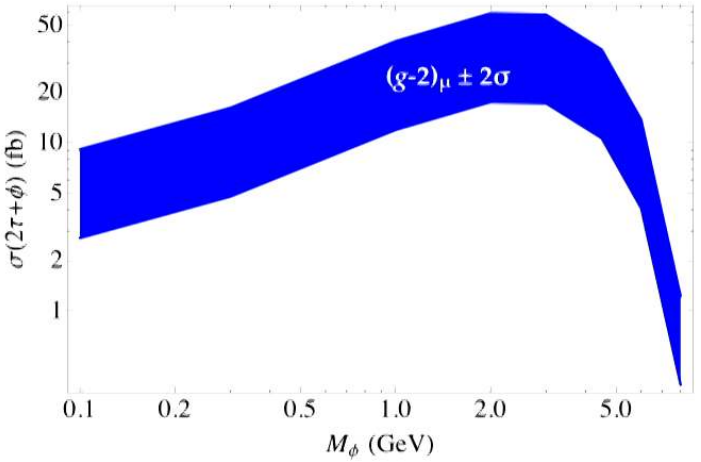


DARK MUONIC FORCE - SCALAR

- However, scalar couplings typically larger to taus:

$$\mathcal{L} = \frac{M_\ell}{v}\,\xi_\ell\,\phi\bar{\ell}\ell$$

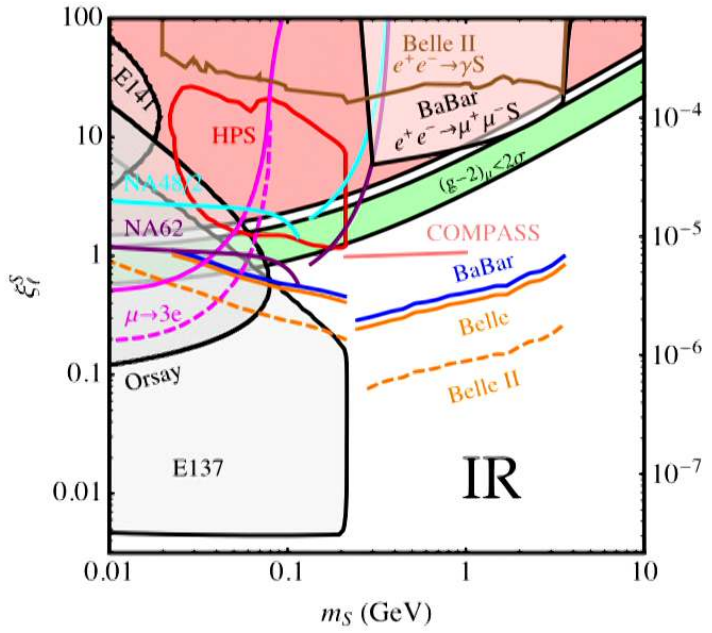




DARK MUONIC FORCE - SCALAR

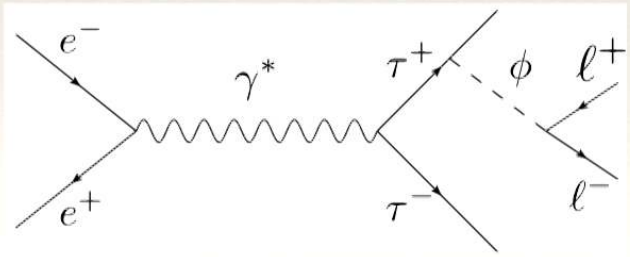
- Example of UV complete model: leptophilic 2HDM+singlet

Batell *et al.*, 1606.04943



DARK MUONIC FORCE - SCALAR

- Ongoing search at *BABAR* with Bertrand Echenard
  - Dilepton resonance in association with single-track tau decays and large missing momentum
  - If decay to muons kinematically forbidden, get long-lived particle with displaced decays to e+e-



- Use multivariate approach to suppress backgrounds
- Currently in internal review - stay tuned!

OVERVIEW

- **New Experimental Results & Search Ideas with *BABAR***
  - Search for a new leptophilic forces
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  - Seach for axionlike particles
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- **Hidden sectors at the LHC in rare *Z* decays**
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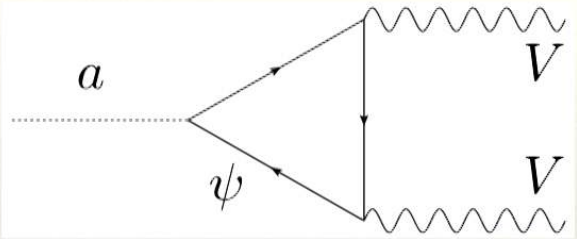
AXION-LIKE PARTICLES

(Pseudo)-Goldstone bosons of anomalous global symmetry w.r.t. SM gauge interactions



$$\mathcal{L} \sim g_{aV}\, a\, V_{\mu\nu} \tilde{V}^{\mu\nu}$$

$$g_{aV} \sim \frac{N\, T(\psi)\, \alpha_V}{4\pi M_{\text{heavy}}}$$

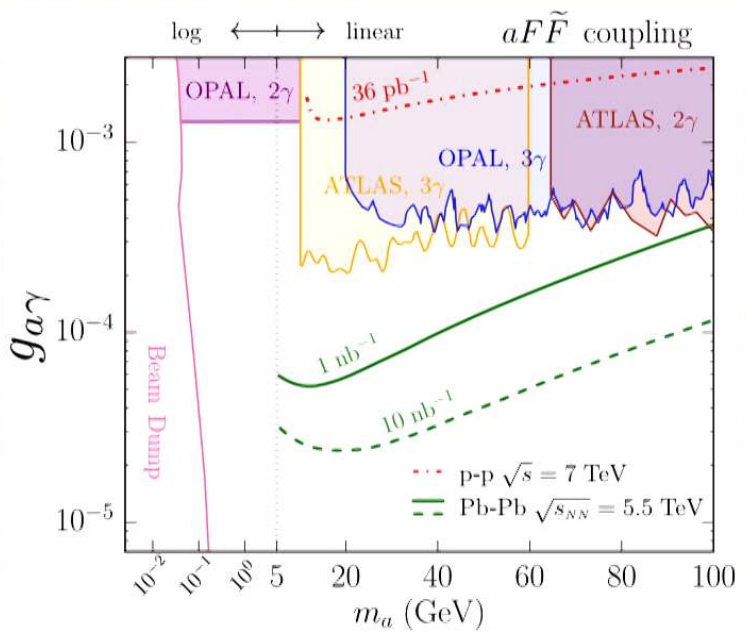
- May couple to fermions at same order, but depends on mixing of PQ scalar with Higgs etc. & similar pheno to dark scalar
- We focus on couplings to gauge bosons

AXION-LIKE PARTICLES

- Get primarily **diboson decays** of ALP

$$\mathcal{L} = \frac{g_{a\gamma}}{4} a\, F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$g_{aV} \sim \frac{\alpha_V}{M_{\text{heavy}}}$$



Knapen *et al.*, 1607.07501

AXION-LIKE PARTICLES

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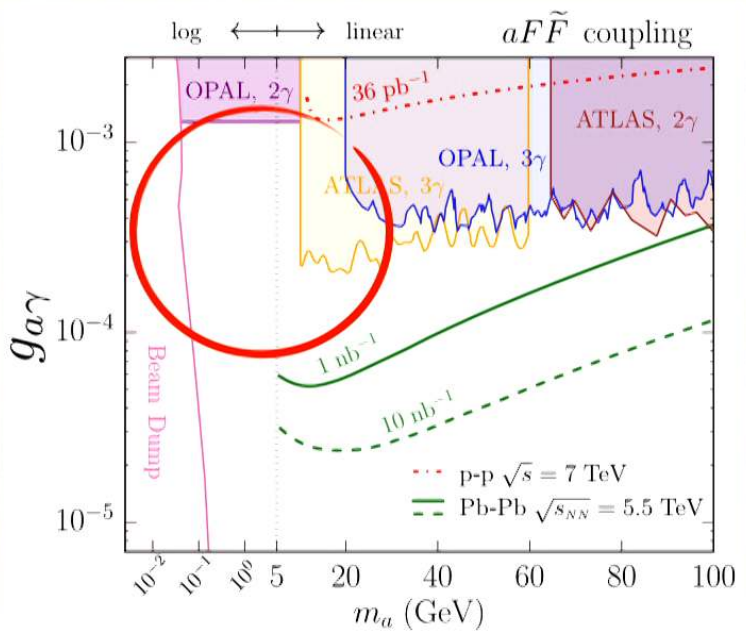
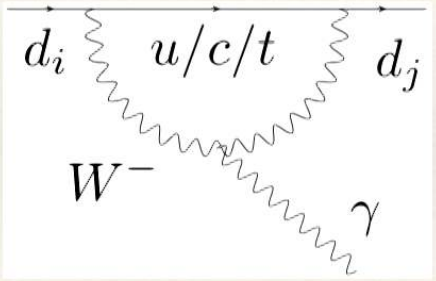


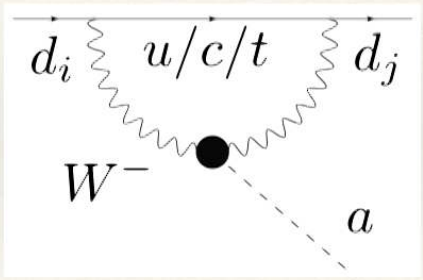
Knapen *et al.*, 1607.07501

AXION-LIKE PARTICLES

- If ALP couples to W boson, can be emitted in flavour-changing processes!

E. Izaguirre, T. Lin, and BS, arXiv:1611.09355



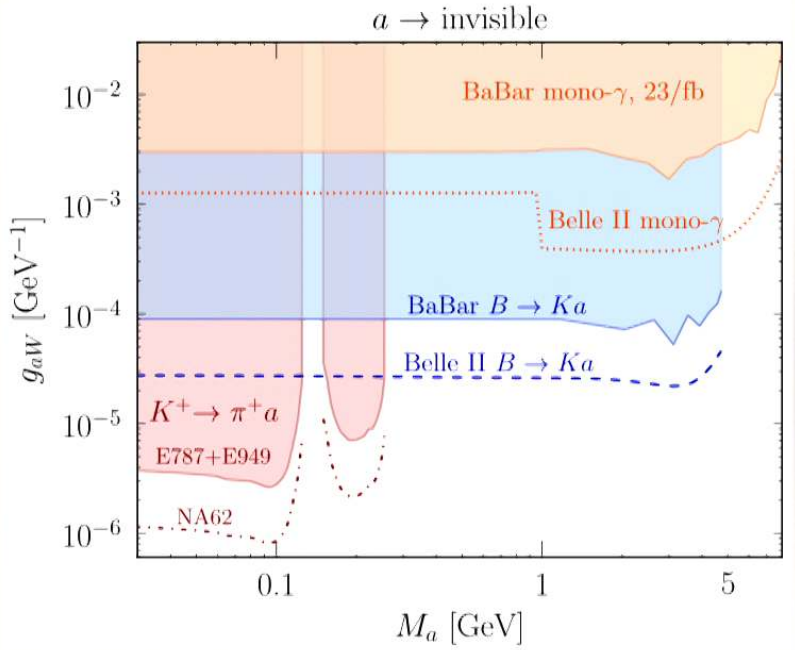


- ALP emitted in processes like $B^\pm \to K^\pm a,\ a \to \gamma\gamma$

E. Izaguirre, T. Lin, and BS, arXiv:1611.09355

ALP PROSPECTS

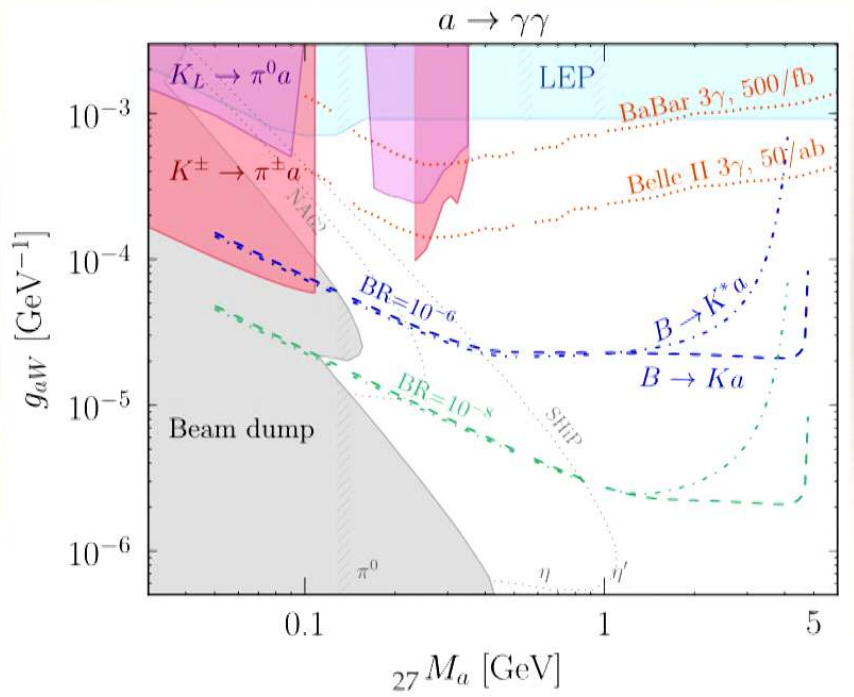
- Strongest constraints on invisible ALP decay



E. Izaguirre, T. Lin, and BS, arXiv:1611.09355

ALP PROSPECTS

- No searches yet for $B \to K^{(*)} a,\ a \to \gamma\gamma$
- However, $B \to K^{(*)} \pi^0$ measured at 10^{-6} level



LONG-LIVED PARTICLES

- What else could we be missing?
- A generic prediction of hidden sectors are **long-lived particles** with $c\tau \gtrsim 1 \text{ mm}$
- *B*-factories have excellent vertex resolution to identify *B* decay vertices
- Right now, there are only a couple LLP searches at *BABAR* (and Belle)
    - Single LLP undergoing 2-body decay to leptons or mesons
    - Dark leptophilic scalar
    - Majorana neutrino produced in (semi)leptonic *B* decays

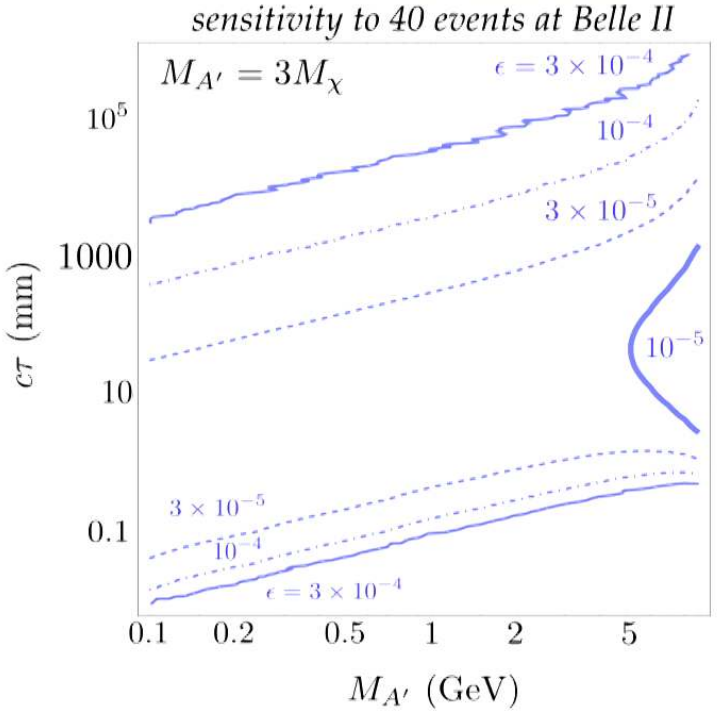
30

LONG-LIVED PARTICLES

- At higher-energy colliders, more **inclusive** searches done to extend sensitivity!

- What are the prospects for discovering LLP coupled via dark photon or a similar portal?

- Require decays within 0.5-30 cm of interaction point in transverse plane



LONG-LIVED PARTICLES

- Ongoing work with N. Blinov:

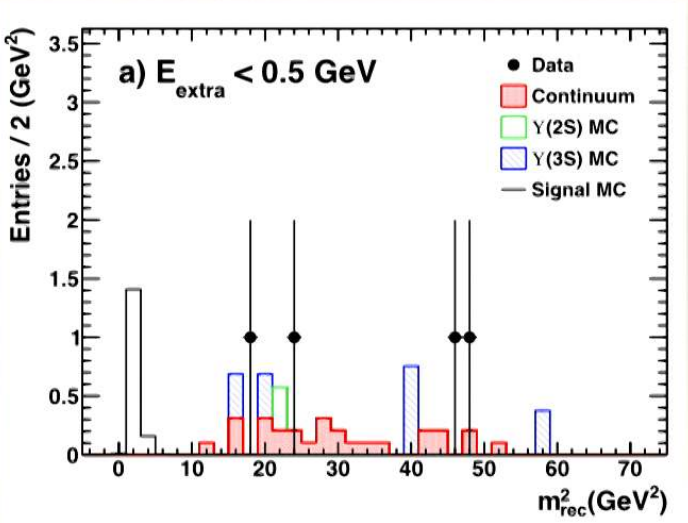
- Determination of a minimal set of production+decay modes for LLPs at low-energy e+e- colliders

- Proposal of a simple set of inclusive searches LLPs to dramatically improve our sensitivity in the low-mass range

LONG-LIVED PARTICLES

- New, more exotic ideas are already being explored
- Ex: production of exotic, meta-stable 6-quark state *S* in $\Upsilon \to S\bar{\Lambda}\bar{\Lambda}$

- *S* would be stable on collider scales if it is < 2 GeV
- Recent search gives limits on production BF < 1.4 x 10^{-7}



BABAR, arXiv:1810.04724

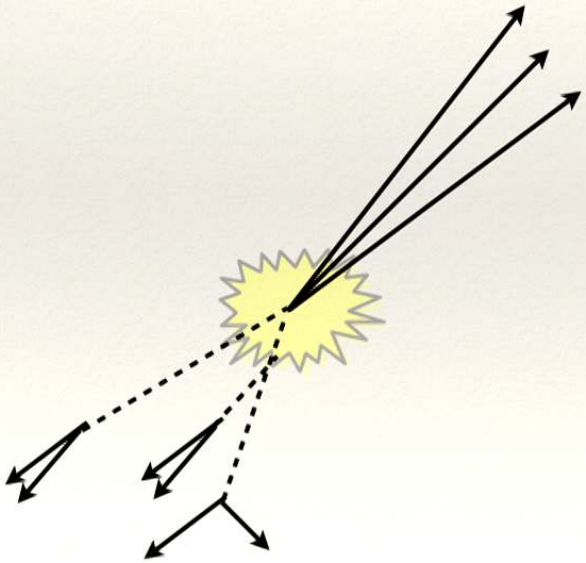
OVERVIEW

- **New Experimental Results & Search Ideas with *BABAR***
  - Search for a new leptophilic forces
    BS w/ *BABAR* collaboration, arXiv:1606.03501 & ongoing work
  - Seach for axionlike particles
    E. Izaguirre, T. Lin, and BS, arXiv:1611.09355
    BS w/ *BABAR* collaboration, ongoing work
  - Long-lived particle searches with *B*-factories

- **Hidden sectors at the LHC in rare *Z* decays**
  N. Blinov, E. Izaguirre and BS, arXiv:1710.07635

HIDDEN SECTORS AT THE LHC

- If new particles too heavy, LHC is only choice!
- As before, only simplest examples covered by current searches

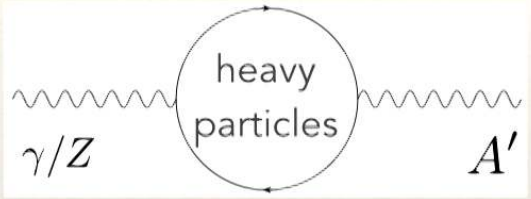


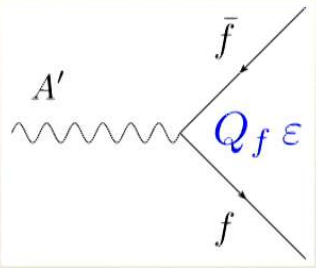
- Additional challenge: how to pass trigger?
- High multiplicities of soft particles from decay of hidden-sector particles

HIDDEN U(1) MODEL

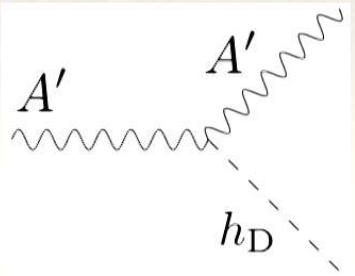
- A simple example of a hidden sector has a dark Higgsed gauge interaction

Holdom, Phys.Lett. 166B (1986) 196-198





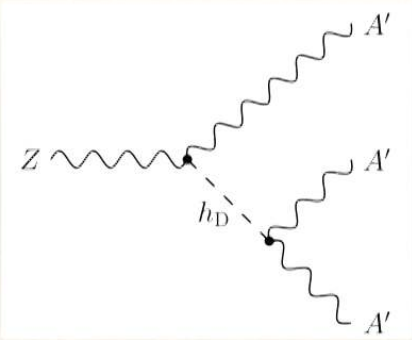
- The presence of a dark mass generation mechanism also give rise to interactions



Blinov, Izaguirre, Shuve, arXiv:1710.07635

HIDDEN U(1) AT THE LHC

- Even in such a simple model, we get new & interesting signals
- Get up to 6 leptons with many resonances, but they are soft!



$$\Gamma(Z \to A' h_{\rm D}) \approx \frac{1}{12} \alpha_{\rm D}\, \varepsilon^2\, \tan^2\theta_{\rm W}\, m_Z$$
$$(m_{A'},\, m_{h_{\rm D}} \ll m_Z)$$

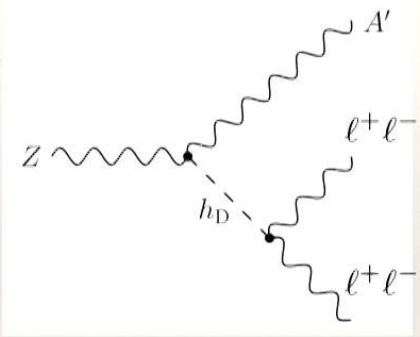
- This is a direct test of the dark mass generation mechanism!
- Similar searches at *B*-factories are incredibly powerful

Batell, Pospelov, Ritz, arXiv:0911.4938

Blinov, Izaguirre, Shuve, arXiv:1710.07635

HIDDEN U(1) AT THE LHC

- To improve signal efficiency, we look at leptonic decays of dark Higgs, inclusive decays of other dark photon



- 4 isolated leptons above threshold
- Veto events with dilepton reconstructing Z or any $m_{4\ell} > 95$ GeV

- Dominant background is $pp \to 4\ell + X$

CMS, arXiv:1709.05406

- Can perform resonance search in 4-lepton mass

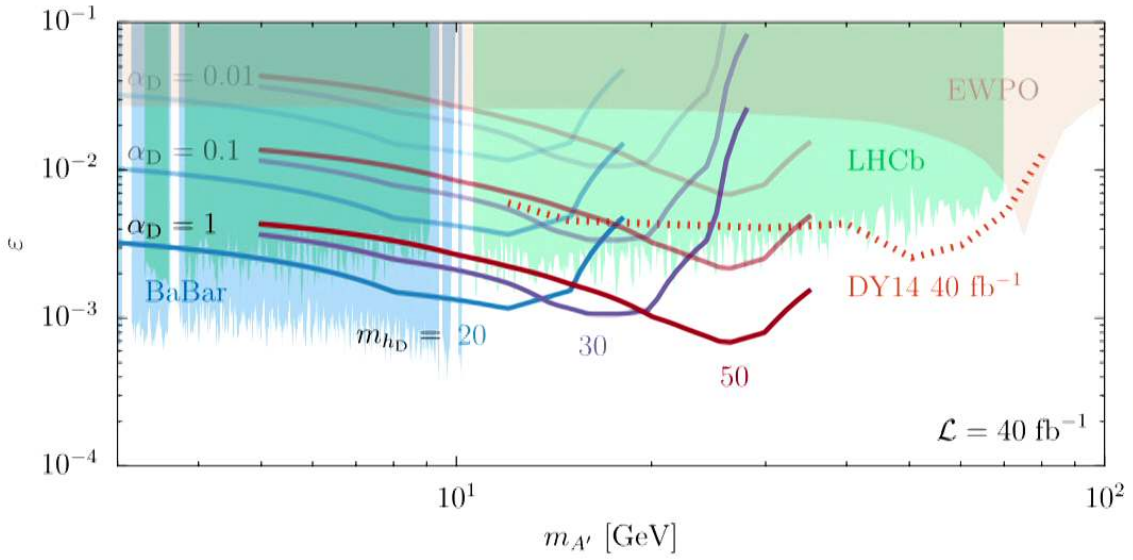
$$\Delta m_{4\ell} = 0.13 \text{ GeV} + 0.065 m_{4\ell}$$

CMS, arXiv:1210.7619

Blinov, Izaguirre, Shuve, arXiv:1710.07635

PROJECTIONS: 4 LEPTON

- Projected 95% CL sensitivity with 40/fb luminosity, 13 TeV

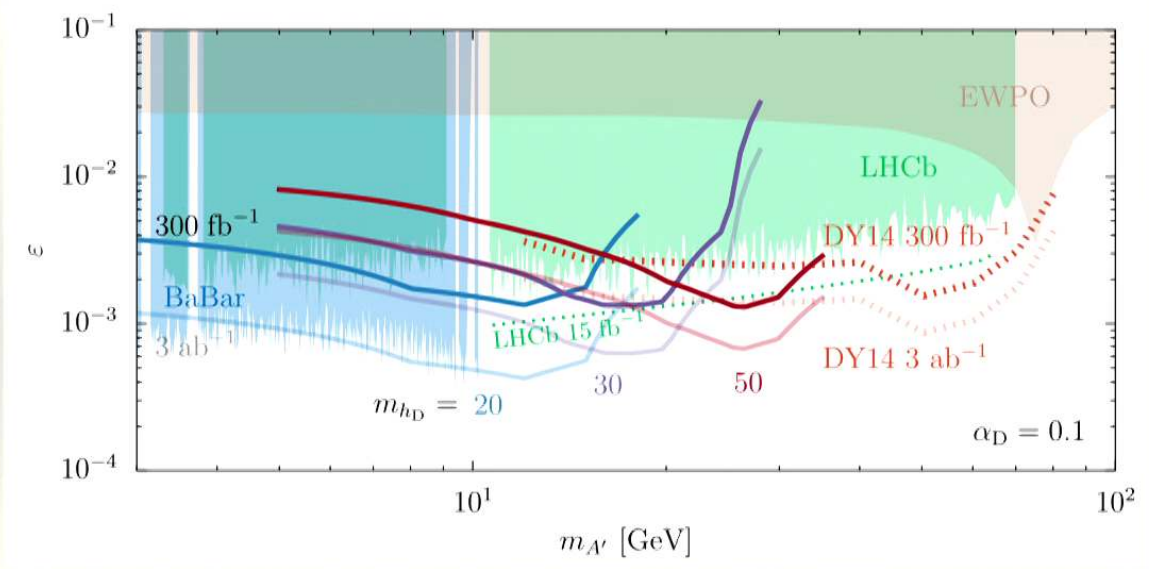


this summer: search in CMS open data with Anna Barth (HMC '21), Andrés Cook (HMC '21)

Blinov, Izaguirre, Shuve, arXiv:1710.07635

PROJECTIONS: 4 LEPTON

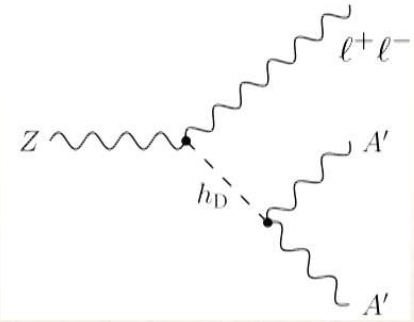
- For the future…



- But the sensitivity degrades significantly if thresholds increase

Blinov, Izaguirre, Shuve, arXiv:1710.07635

HIDDEN U(1) AT THE LHC

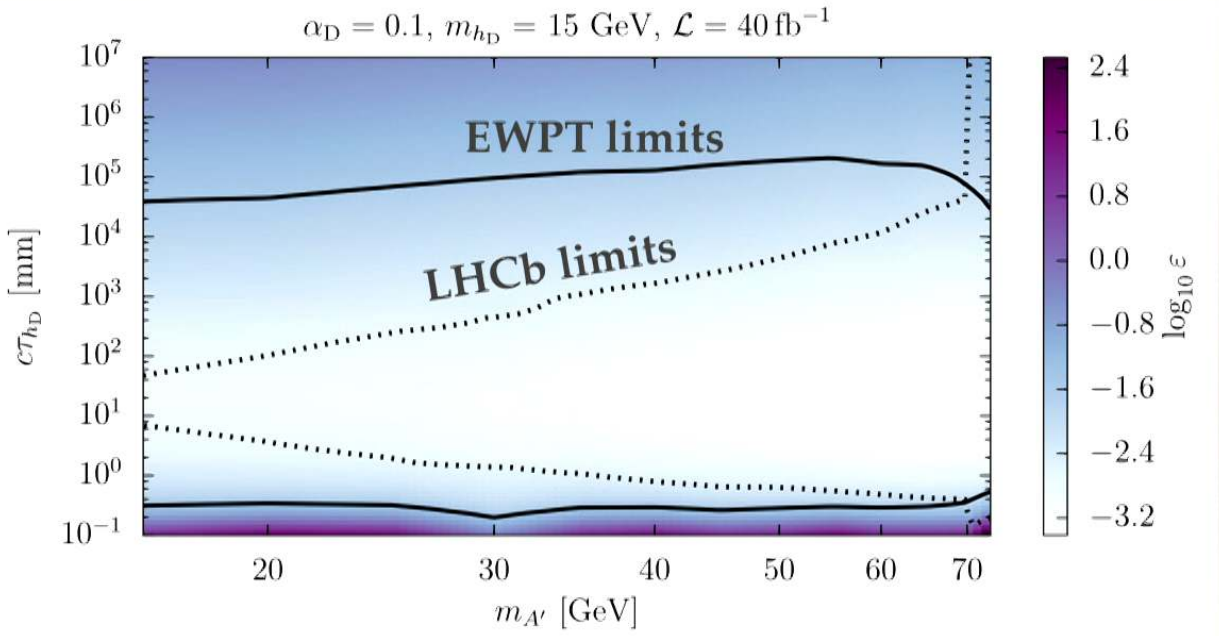


- If dark Higgs cannot decay on-shell to dark photon, it can be long lived!
- Signature: **prompt** dilepton resonance + displaced vertex!

- We apply a dilepton trigger, assume a 50% vertex reconstruction efficiency
- Plot sensitivity for **ten signal events**

Blinov, Izaguirre, Shuve, arXiv:1710.07635

PROJECTIONS: DISPLACED



LHC-LLP COMMUNITY

- Many other gaps in coverage for hidden sectors at LHC, especially long-lived particles (LLPs)
- LLP searches are hard to do and dependent on detector effects in ways that prompt searches are not
- We need coordination to prioritize searches, efficiently cover signature space, & coherently present results
- Co-editing white paper that brings together contributions from members of theory community, ATLAS, CMS, LHCb:

LHC-LLP COMMUNITY

Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider

ed. J. Beacham, B. Shuve

- Library of simplified models to comprehensively cover LLP signatures
- Summary of experimental signatures, gaps in coverage, and new ideas for searches
- Summary of backgrounds for LLP searches
- Opportunities and challenges for LLPs with upgraded detectors
- Challenges of reinterpreting LLP search results and recommendations for presentation of results
- Discussion of dark showers & high multiplicities of LLPs

SUMMARY

- Excellent progress in searching for hidden phenomena beyond the SM
- There is still a huge uncharted territory in even minor extensions of the simplest hidden sectors
- Need comprehensive search strategies to make sure gaps are covered in both low- and high-energy experiments