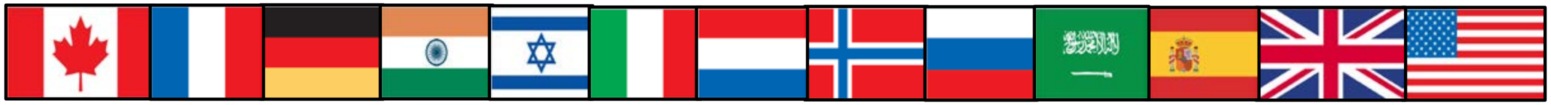
Dark Sector Searches with *BABAR*

David Hitlin
Caltech
for the *BABAR* Collaboration

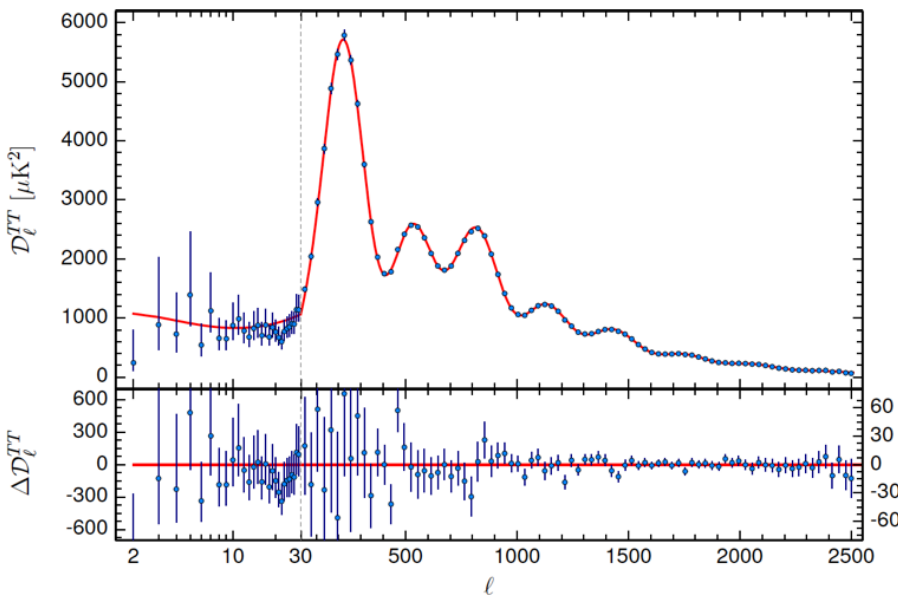
Physics in Collision
September 14, 2018



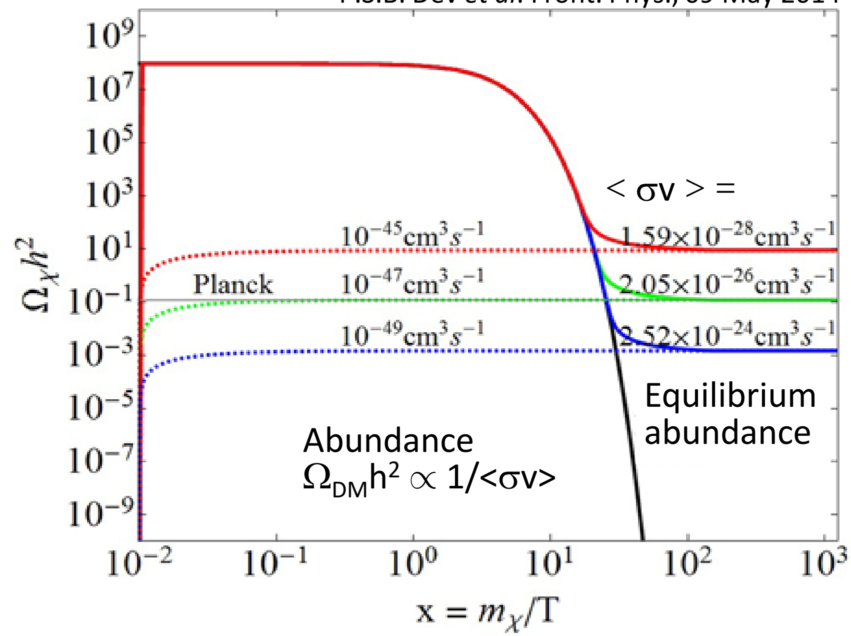
Caltech

Dark matter - the Thermal Relic Target

- Much effort has been expended in searching for a particle physics connection to dark matter



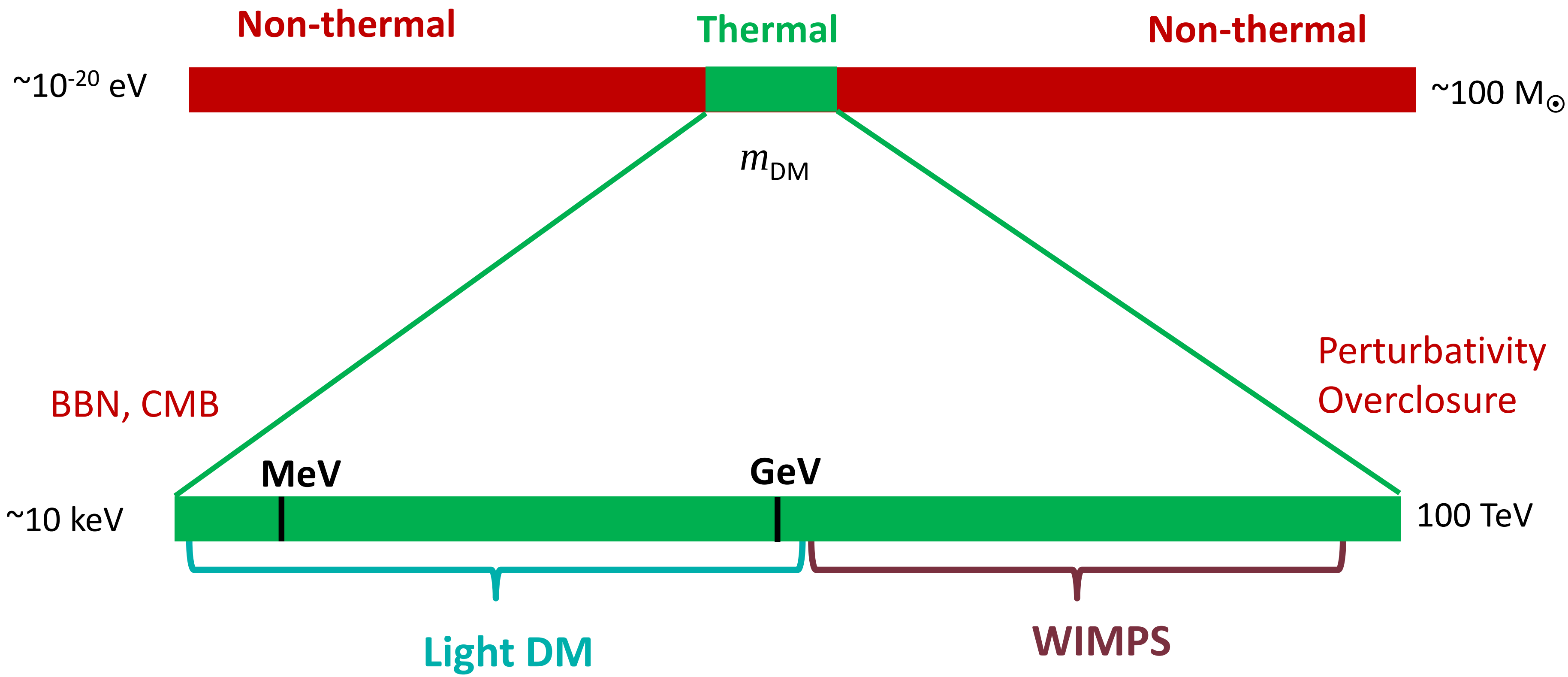
P.S.B. Dev *et al*. Front. Phys., 09 May 2014



- The cosmic microwave background establishes a matter-density target for dark matter
- If dark matter is produced thermally, the observed abundance sets a requirement for the coupling and particle mass

The search range for thermal dark matter

The thermal relic hypothesis restricts the allowed range of DM masses

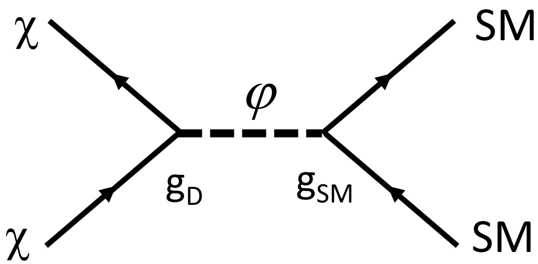


Thermal contact implies a new mediator
Hidden sector light Dark Matter is a well-motivated model

Thermal freeze-out for weak scale masses has driven Dark Matter searches for the last ~30 years

Light thermal dark matter

A freeze-out scenario with light dark matter (χ) requires a new light mediator to explain the relic density in order to avoid overproduction of the dark matter

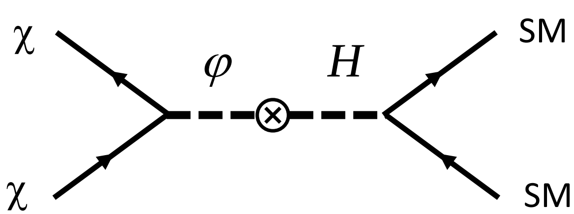


$$< \sigma v >_{relic} \sim \frac{g_D^2 \, g_{SM}^2 \, m_x^2}{m_\varphi^4} \qquad (m_\varphi \gg m_x)$$

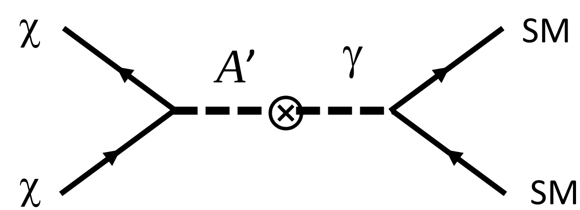
$$m_\varphi^4 \sim \frac{g_D^2 \, g_{SM}^2 \, m_x^2}{<\sigma v>} \leq \frac{m_x^2}{<\sigma v>} \qquad \text{since } g \leq O(1)$$

The mediator must be neutral under the SM and renormalizeable. The simplest choices are:

New scalar (φ) with Higgs coupling



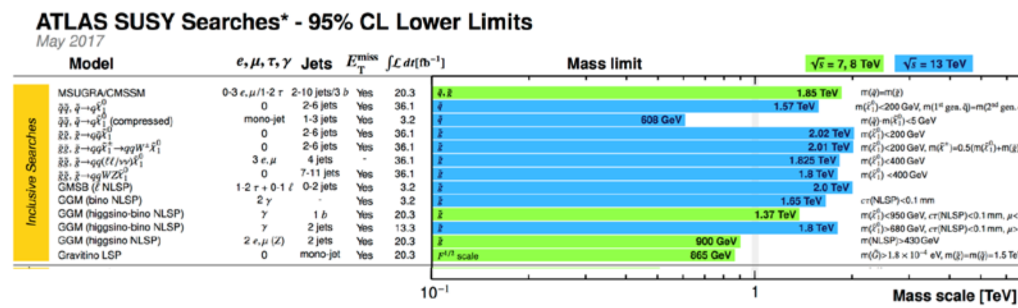
New vector (A') with photon coupling



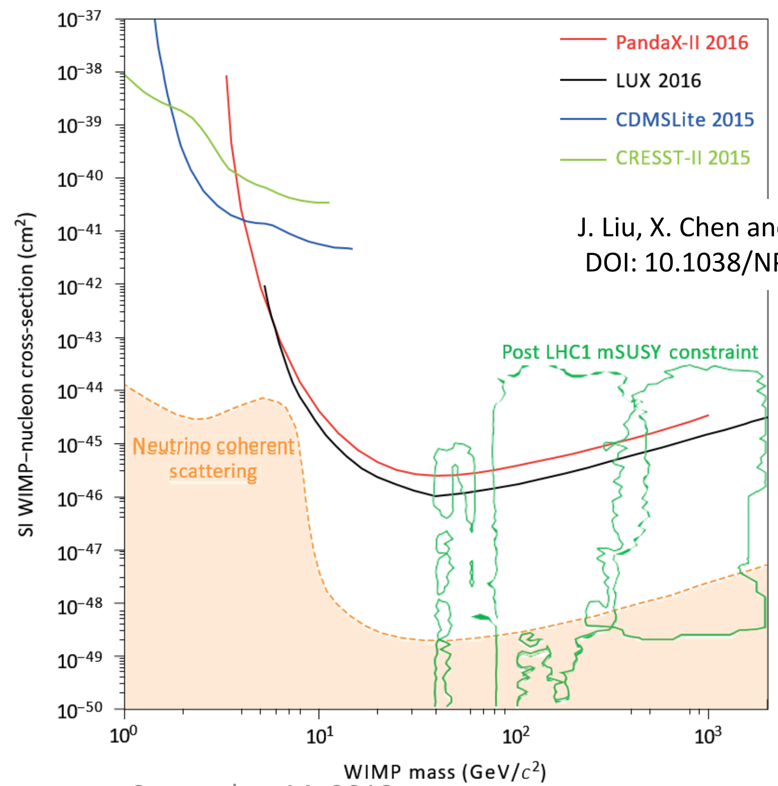
These are naturally realized in the context of hidden sectors

WIMPs, Hidden Sectors, ...

- **WIMP**s provide an attractive realization of the thermal relic scenario
  - Tightly tied to EWSB
  - Identification with the LSP
  - large viable mass range
- However, direct dark matter and LHC searches now highly constrain this scenario



- The lighter mass range is harder to access
  - Provides motivation for pushing direct searches to lower masses
  - Many new ideas in play
  - One of these approaches – **hidden sectors** - naturally accommodates lower masses
  - Hidden sectors are **best studied in accelerator experiments**
  - A combination of collider and fixed target accelerator experiments can fully probe directly annihilating thermal dark matter in the MeV to GeV range



J. Liu, X. Chen and X. Ji,
DOI: 10.1038/NPHYS4039

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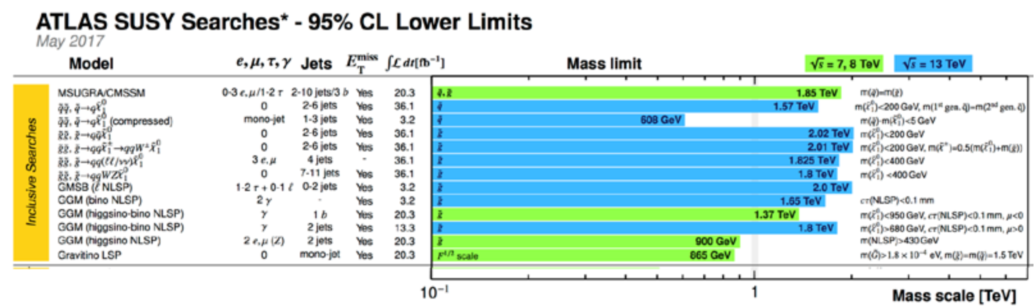

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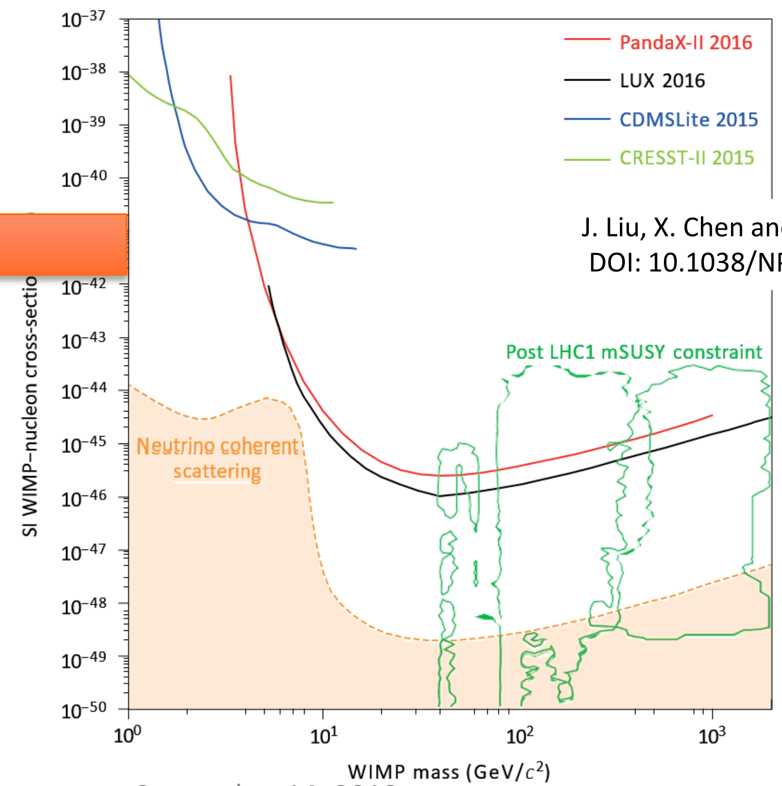

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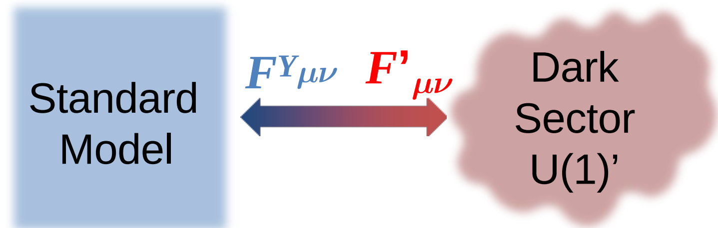
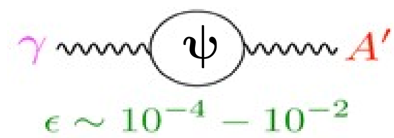
Hidden sectors

- There are several viable new interactions involving a "hidden sector" that respect Standard Model symmetries and have dimensionless couplings, *i.e.* they are sizeable irrespective of their source
- Hidden sectors are generic in many BSM theories
  - Dark matter could be part of a dark sector
- Let's consider the so-called vector portal: a "**Dark Sector**" coupled to the SM via a low-mass spin 1 "dark photon" mediator, the gauge boson of a new U(1) symmetry
- These **dark photons** A' could be in the MeV to GeV mass range and mix with the SM photon with mixing strength ε
- The dark photon could decay to
  - SM fermions if other DM states are inaccessible, producing visible decays
  - a lighter **dark matter** state χ
    - If $m_\chi < m_{A'}/2$, then the dominant decay mode of the A' would then be invisible: $A' \to \chi\bar{\chi}$
- A dark sector could potentially explain the proton charge radius puzzle and the muon g-2 anomaly
- A dark sector is more general than light dark matter



heavy particle ψ with both dark and EM charges.



GUT (2 loops)

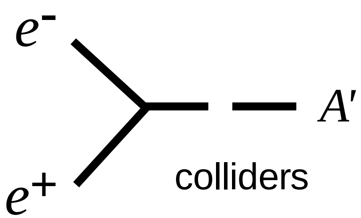
→10^{-7} if both U(1)'s are in unified groups

e.g. Arkani-Hamed & Weiner; Cheung, Ruderman, Wang, Yavin; Morrissey, Poland, Zurek; Essig, Schuster, Toro;

Dark sector searches

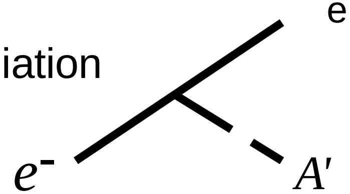
- Dark photons are readily produced in accelerator experiments
  - Photons in any process can be replaced by dark photons (with an extra factor of ε^2)

Annihilation

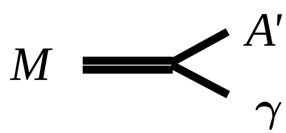


colliders

Radiation

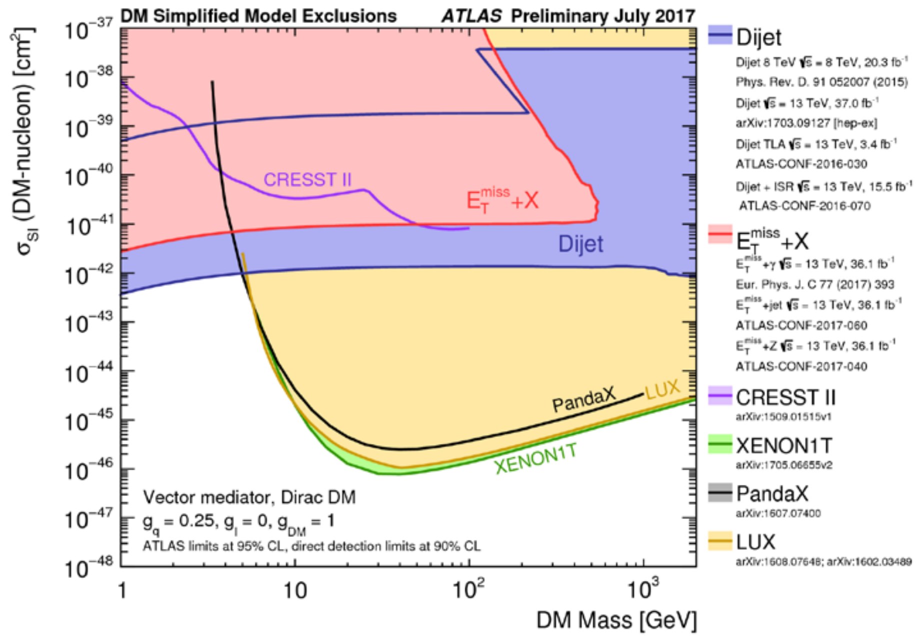


Meson decay

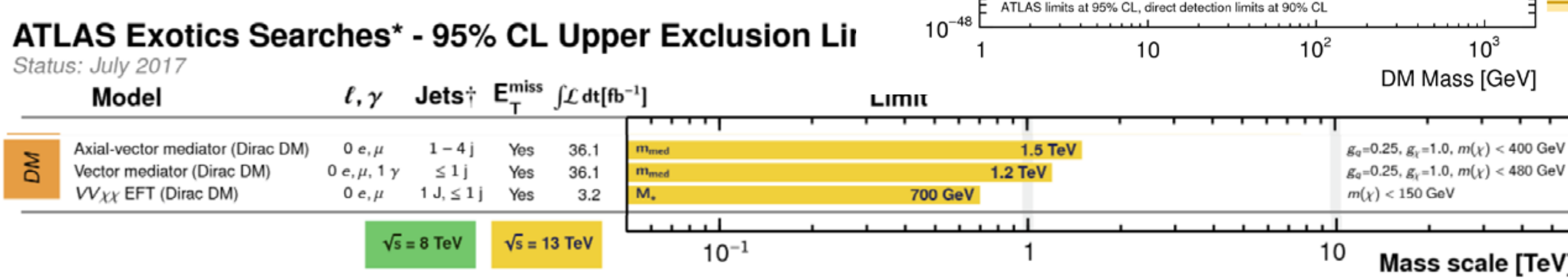


p beam dump, hadron-rich environment (*e.g.* SHIP)

Require high intensity
+ high energy for high mass A'
low energy for low mass A'



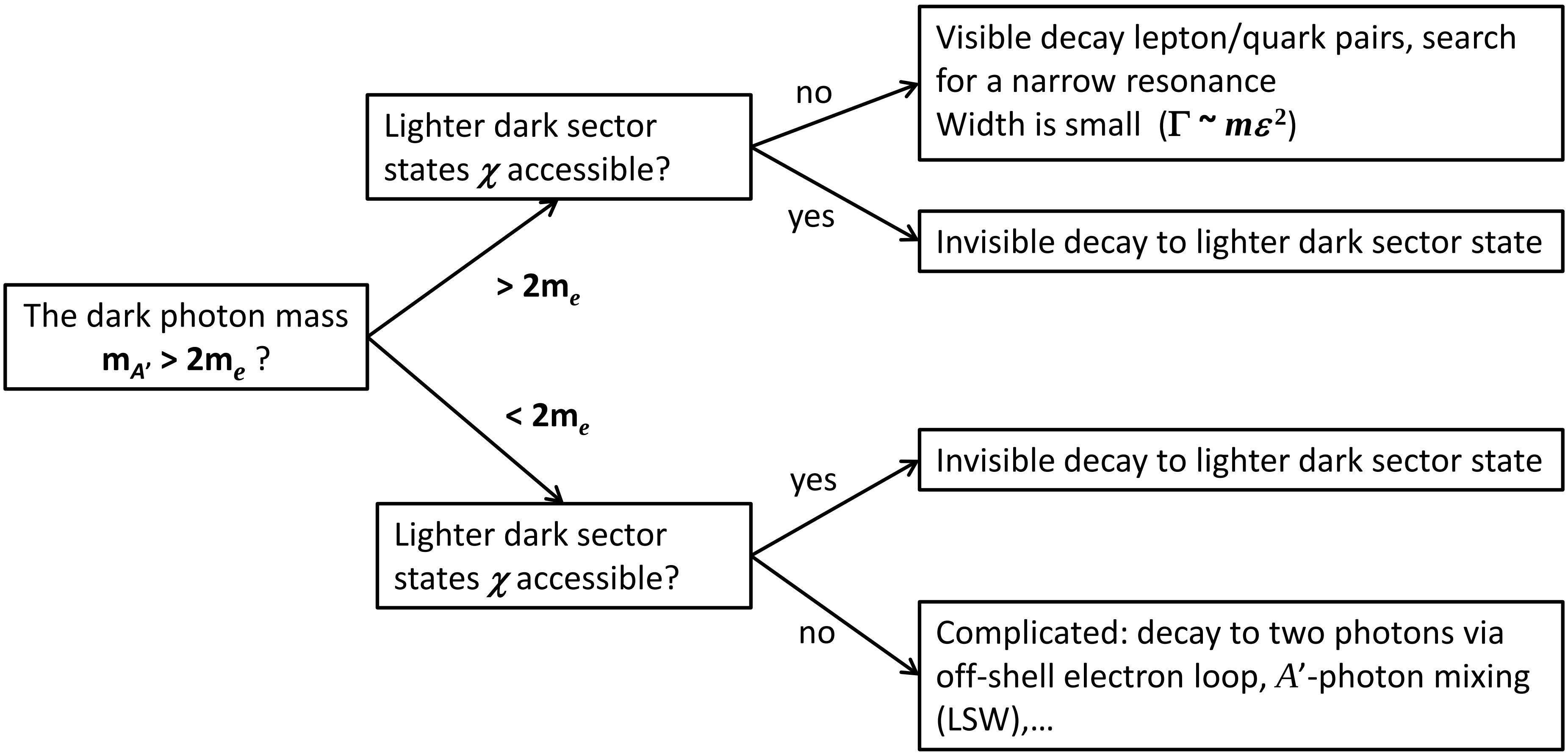
- LHC can explore the high mass regime
  - LHC limits are not very constraining below the GeV regime



The light dark sector at colliders

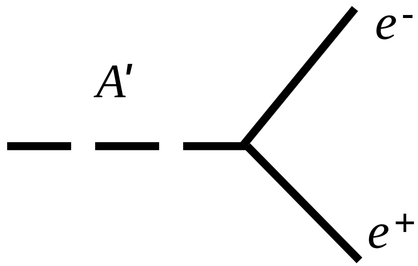
- A (simplified) roadmap

Dark photon decay channels



The MeV – GeV dark sector

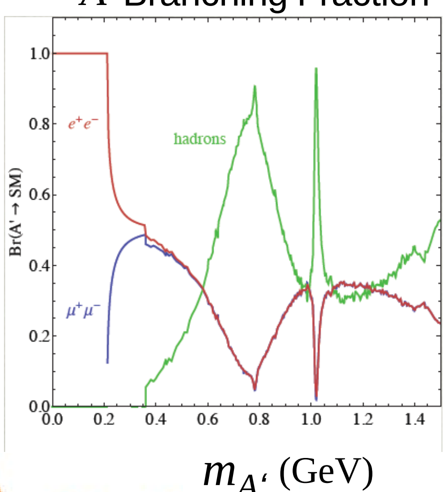
Lepton / quark decays

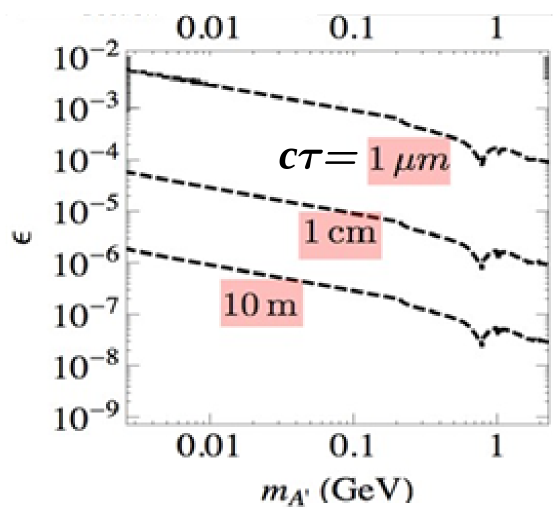


decay via kinetic mixing
$\rightarrow$ small width $\Gamma \sim \alpha m \varepsilon^2$

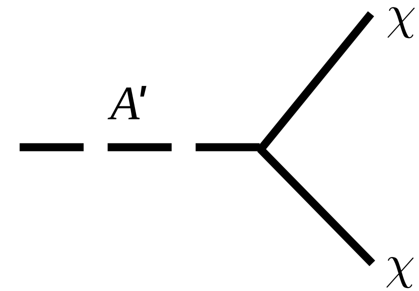
Prompt or displaced decays

A' Branching Fraction





Light dark sector states χ



Not ε suppressed
Dominates if $m_\chi < 2m_{A'}$

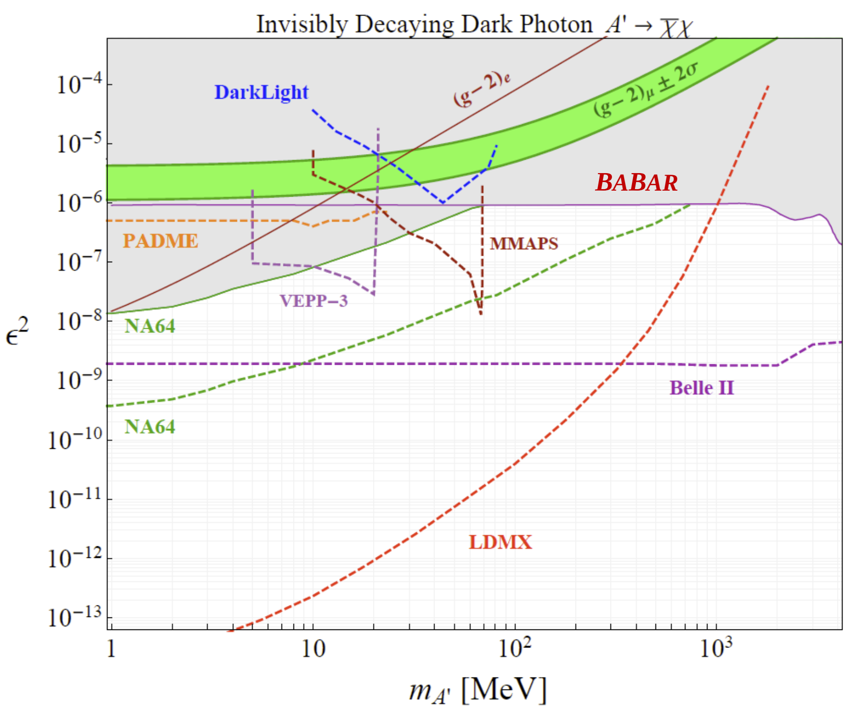
Two cases:
- χ is stable $\Rightarrow$ invisible decays
- χ decays back to SM particles

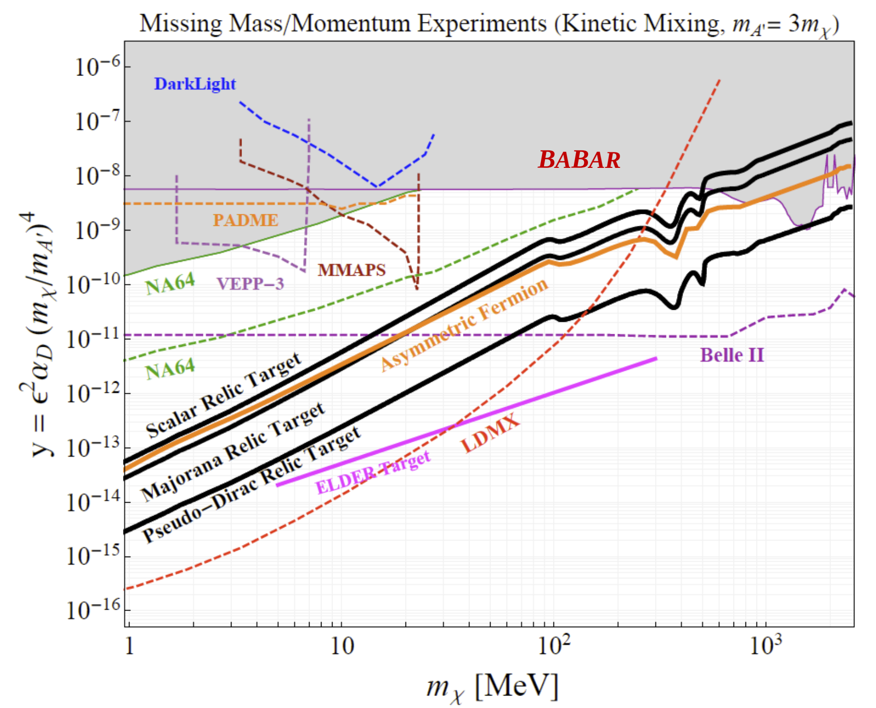
Coupling is often characterized as

$$y = \varepsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}} \right)^4$$

New ideas abound – The Cosmic Visions Workshop

US Cosmic Visions: New Ideas in Dark Matter 2017
Community Report
arXiv:1707.04591v1 [hep-ph] 14 Jul 2017





- The workshop considered WIMP, Hidden Sector and Ultralight Dark Matter and a suite of experiments to extend the sensitivity of direct detection and accelerator-based searches
- I will discuss the *BABAR* contribution to current dark matter/dark photon search limits and add a few words about LDMX, a proposed future experiment to improve low mass sensitivity

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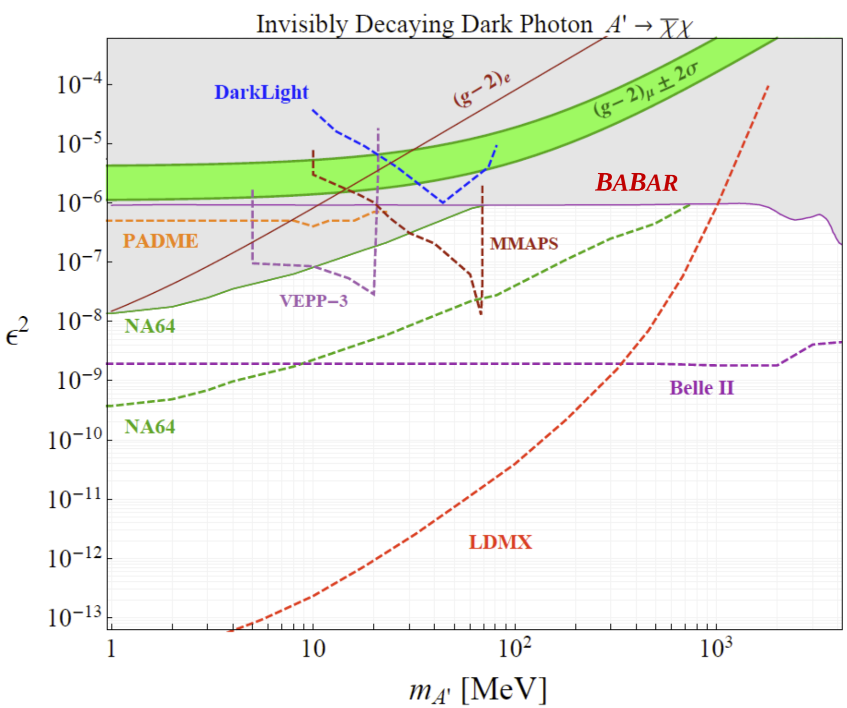
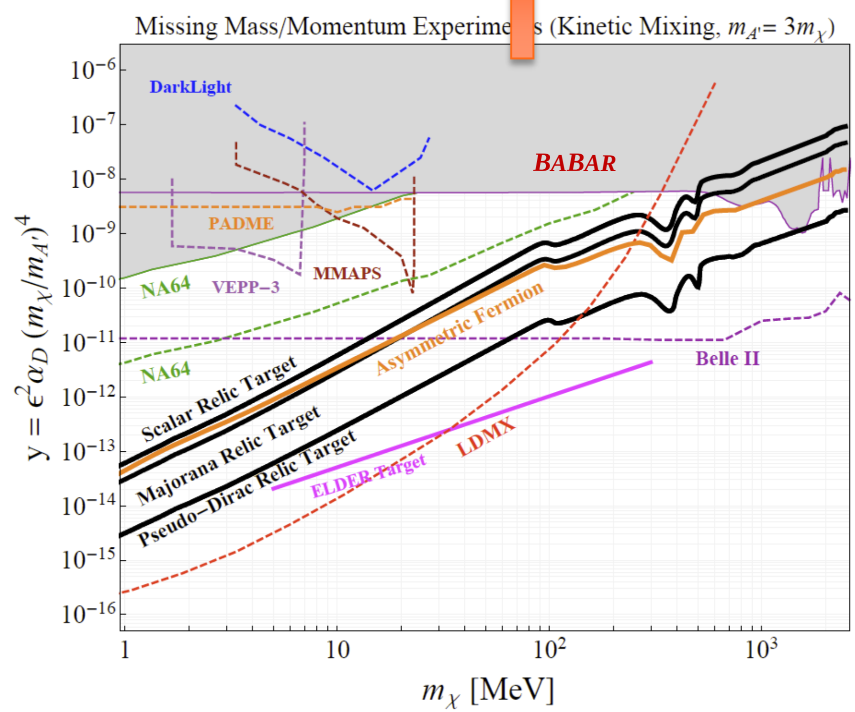
LHC constraints





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Dark sector studies at *BABAR*

BABAR has conducted an extensive Dark Sector search program

Search for dark photon

$e^+e^- \to \gamma A', A' \to e^+e^-, \mu^+\mu^-$

$e^+e^- \to \gamma A', \quad A' \to$ invisible

$\pi^0 \to \gamma\, \ell^+\ell, \eta \to \gamma\, \ell^+\ell^-, \phi \to \eta\, \ell^+\ell^-$

Search for dark Higgs boson

$e^+e^- \to h' A', h' \to A' A'$

Search for dark boson(s)

$e^+e^- \to \gamma A' \to W' W''$

Search for dark hadrons

$e^+e^- \to \pi_D + X, \qquad \pi_D \to e^+e^-, \mu^+\mu^-$

Search for dark scalar (*s*) and dark pseudoscalar (*a*)

$B \to K^{(*)} s \to K^{(*)} \ell^+\ell^-$ / $B \to K^{(*)} a \to K^{(*)} \ell^+\ell^-$

$B \to ss \to 2(\ell^+\ell^-)$

Search for "muonic dark force"

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

Search for leptophilic dark scalar

$e^+e^- \to \tau^+\tau^- h', h' \to \mu^+\mu^-$ (4 leptons + MET)

Search for self-interacting dark matter

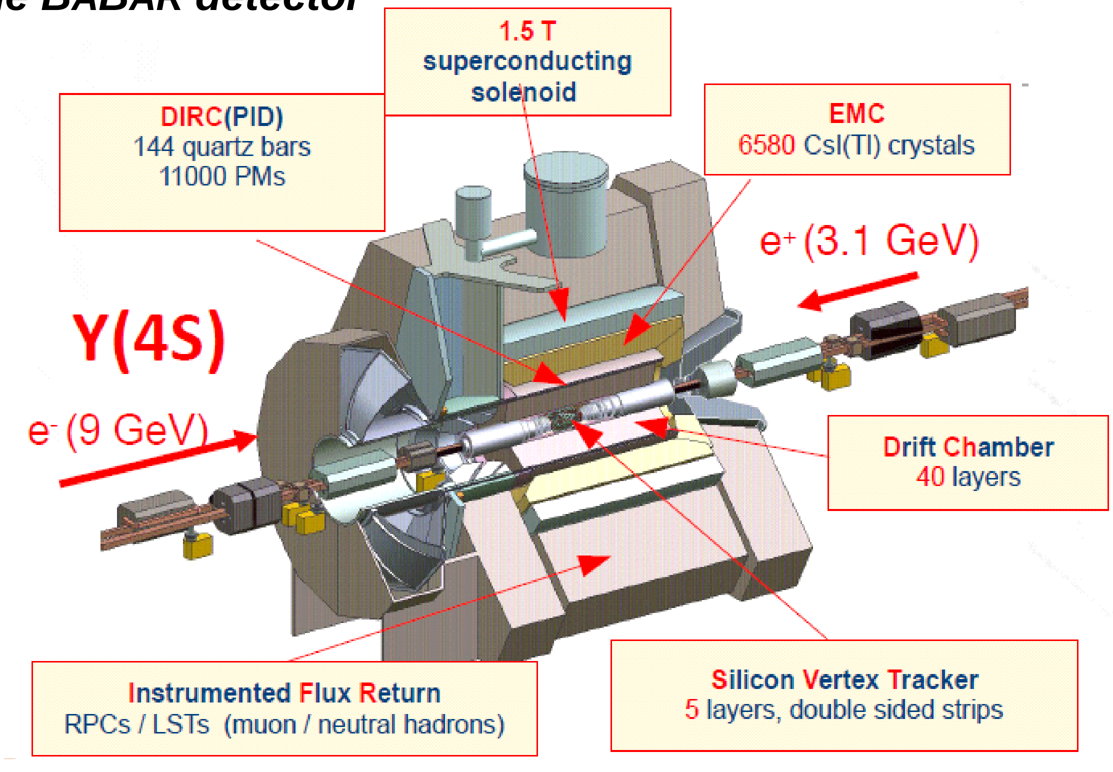
$e^+e^- \to \gamma A' A' A', A' \to \ell^+\ell^-, \pi^+\pi^-$

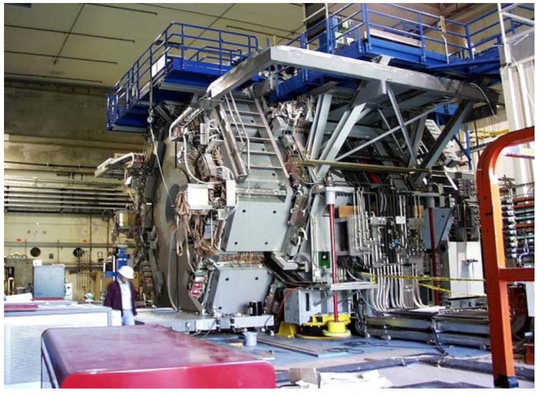
Ongoing / published
Preliminary studies

The *BABAR* experiment

BABAR at PEP-II collected ~ 500 fb^{-1} of data, mainly at and around the $\Upsilon(4S)$, $\Upsilon(3S)$ and $\Upsilon(2S)$ resonances

The BABAR detector

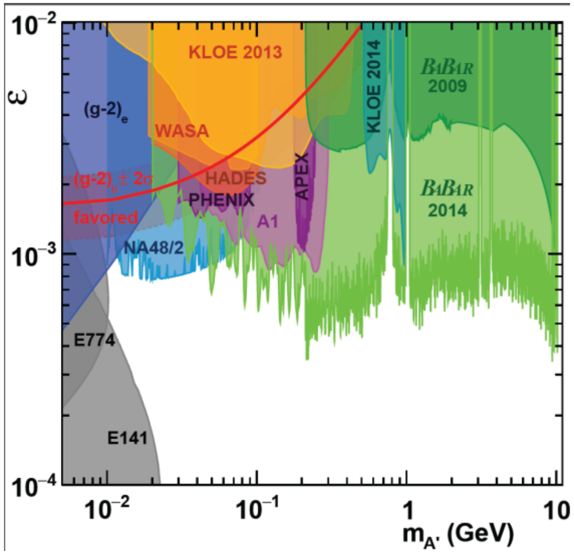


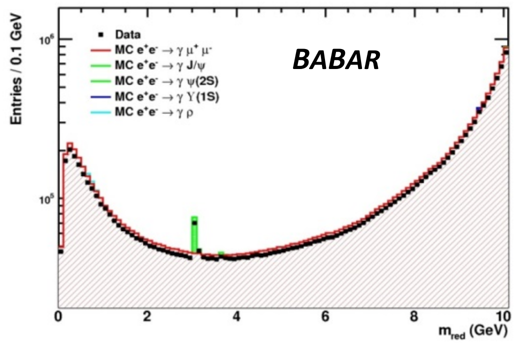


B factories offer an ideal environment to search for ~GeV dark sector particles, provided there is an appropriate trigger, distinct from the usual multiparticle trigger

Some highlights of the *BABAR* program

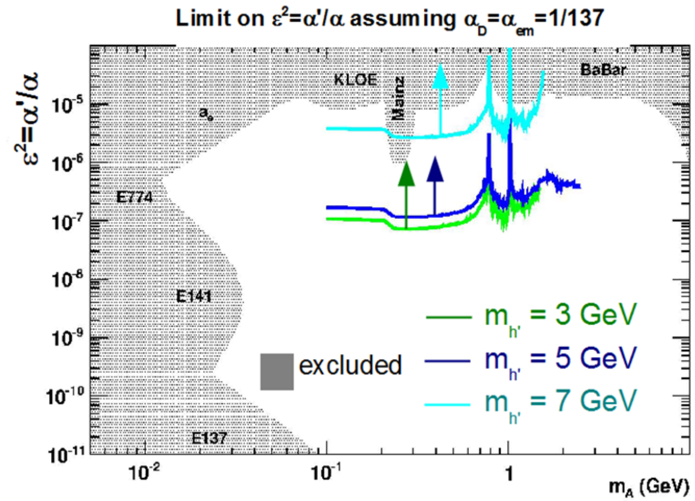
Search for dark photons in $e^+e^- \to \gamma A'$, $A' \to e^+e^-, \mu^+\mu^-$





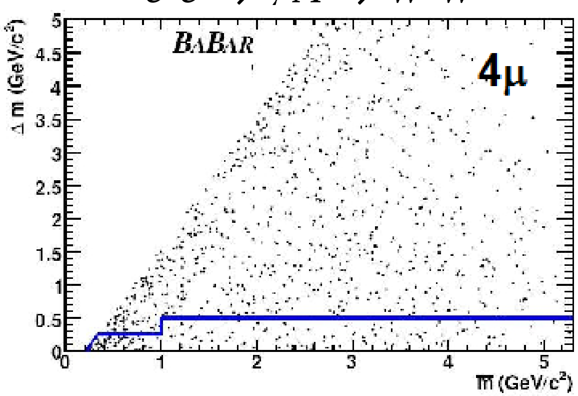
PRL 113 (2014) 201801
PRL viewpoint

Search for dark Higgs bosons in
$e^+e^- \to h'A'$, $h' \to A'A'$



PRL 108 (2012) 211801

Search for dark bosons in
$e^+e^- \to \gamma A' \to W'W'$



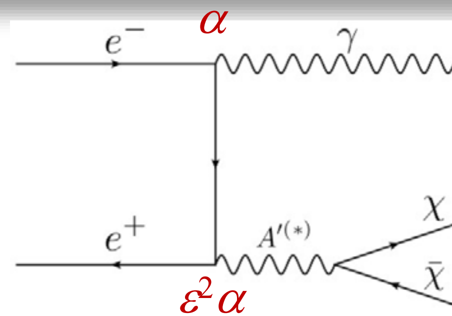
arXiv:0908.2821

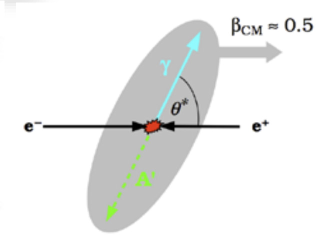
This talk will cover two recent measurements

Search for invisible dark photon decay
Search for muonic dark force

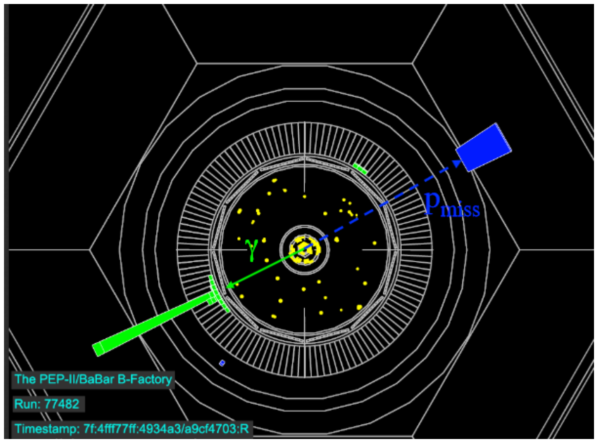
Search for invisible A' decay

- The dark photon will decay invisibly if there are lighter dark sector states
- At e^+e^- colliders, we can search for
  $e^+e^- \to \gamma A'$, $A' \to$ invisible by
  tagging the recoil photon in "single photon" events.





- The signature of the invisible dark photon is a monochromatic photon and missing energy/mass
  $$M_X^2 = s - 2E_\gamma^*\sqrt{s}$$
- Hermeticity is key, but we need to allow some machine background
- The search strategy:
  select a single-photon final state, then look for a bump in missing mass M_X (or E_γ)
- Main backgrounds: $e^+e^- \to \gamma\gamma$ and $e^+e^- \to \gamma e^+e^-$ with particles outside detector acceptance
- *BABAR* collected ~53 fb^{-1} of data with dedicated single photon triggers during its last year of data taking, mostly collected at the $\Upsilon(3S)$ and $\Upsilon(2S)$ energies.



	High Mass	Low Mass
$\Upsilon(4S)$	----	$5.9\,fb^{-1}$
$\Upsilon(3S)$	$20\,fb^{-1}$	$28\,fb^{-1}$
$\Upsilon(2S)$	$14.4\,fb^{-1}$	$14.4\,fb^{-1}$
off-peak	$1.5\,fb^{-1}$	$4.2\,fb^{-1}$
Total	$35.9\,fb^{-1}$	$53\,fb^{-1}$

Phys.Rev.Lett. 119, 131804 (2017)

Single photon trigger + event selection

- Search requires a dedicated single-photon trigger
  - Level-1 Hardware trigger: 1 or more calorimeter clusters with E_{lab} > 0.8 GeV
  - Level-3 Software trigger: Two different software triggers were used

Low M_X -4 GeV² < M_X^2 < 36 GeV²

- Require $E_\gamma^* > 2$ GeV
- No tracks originating from e^+e^- interaction region
- Trigger active for full 53 fb^{-1} data sample

- Dominant background from $e^+e^- \rightarrow \gamma\gamma$ events where a photon escapes detection
- 1 Electromagnetic Calorimeter (EMC) cluster
- Require $E_\gamma^* > 3$ GeV
- No drift chamber tracks with momentum p^* > 1 GeV
- Multivariate discriminator cut

High M_X 24 GeV² < M_X^2 < 69 GeV² $\Upsilon(3S)$; 63.5 GeV² $\Upsilon(2S)$

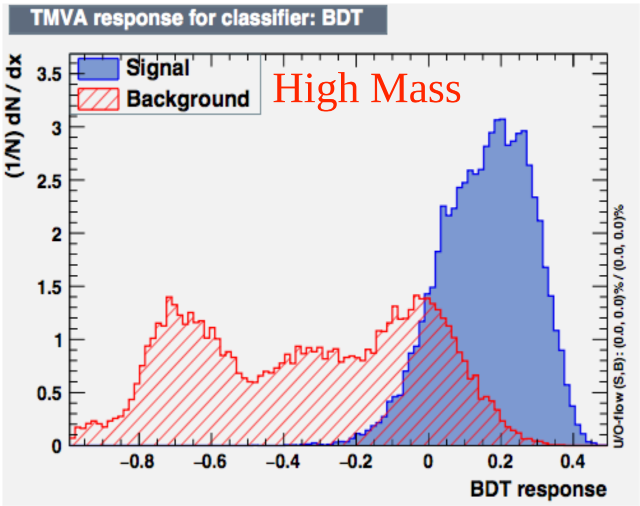
- Require $E_\gamma^* > 1$ GeV
- No tracks originating from e^+e^- interaction region
- Trigger active for 35.9 fb^{-1} subset of 53 fb^{-1} data sample

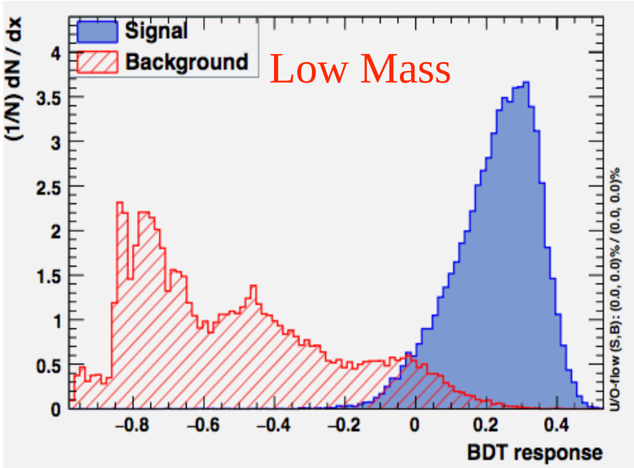
- Dominant background from $e^+e^- \rightarrow e^+e^-\gamma$ events where the e^+ and e^- escape detection
- 1 EMC cluster consistent with an electromagnetic shower
- Require $E_\gamma^* > 1.5$ GeV
- No drift chamber tracks with momentum p^* > 0.1 GeV
- Multivariate discriminator cut

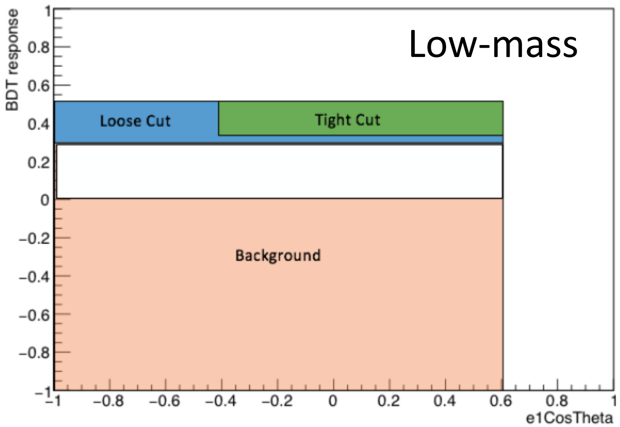
$$E_\gamma^* = \frac{s - M_X^2}{2\sqrt{s}}$$

The BDT discriminator

- Apply additional selection criterion using Boosted Decision Tree (BDT) multivariate discriminator
- The BDT is trained separately for the Low Mass and High Mass samples
- There are 12 discriminating variables including:
  - Shape parameters for the most energetic EMC cluster
  - Total EMC energy without the most energetic cluster
  - $E^*, \theta^*, \Delta\varphi^*(E_1)$ of the second most energetic EMC cluster
  - $E^*, \theta^*, \Delta\varphi^*(E_1)$ of the Instrumented Flux Return (IFR) cluster closest to the missing momentum direction
- BDT is trained using:
  - 25k simulated signal events with uniformly distributed A' masses
  - 25k background events from $\Upsilon(3S)$ data sample





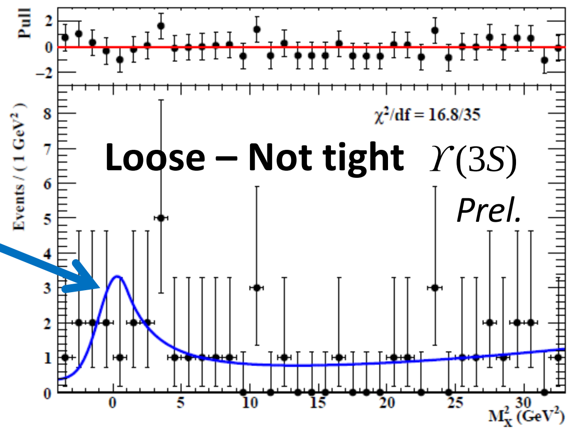


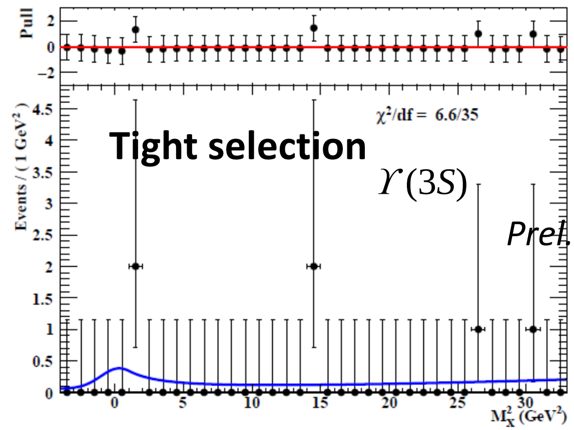
To further reduce the residual peaking contribution from $e^+e^-\rightarrow\gamma\gamma$ events near $M_X \sim 0$, instead of simply relying on the BDT output, we define several signal regions in the bi-dimensional space of BDT output *vs* photon angle

Search for invisible A' decay

Low-mass region: data distributions at $\Upsilon(3S)$

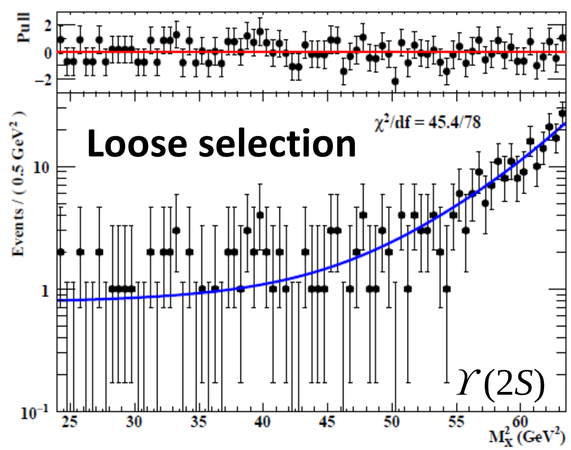
Peaking background $e^+e^- \to \gamma\gamma$ (irreducible)

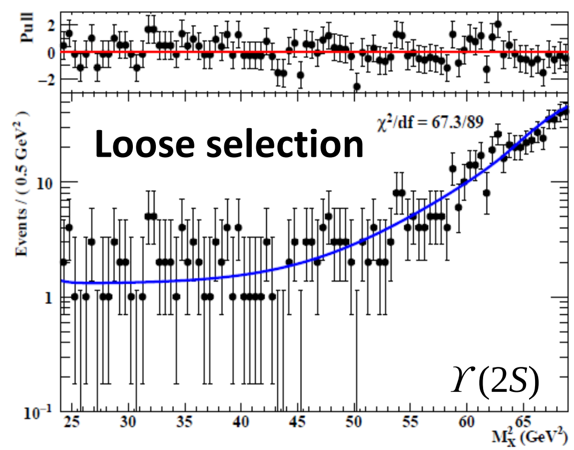




High-mass region: data distributions at $\Upsilon(2S)$

In blue: bkg-only fit



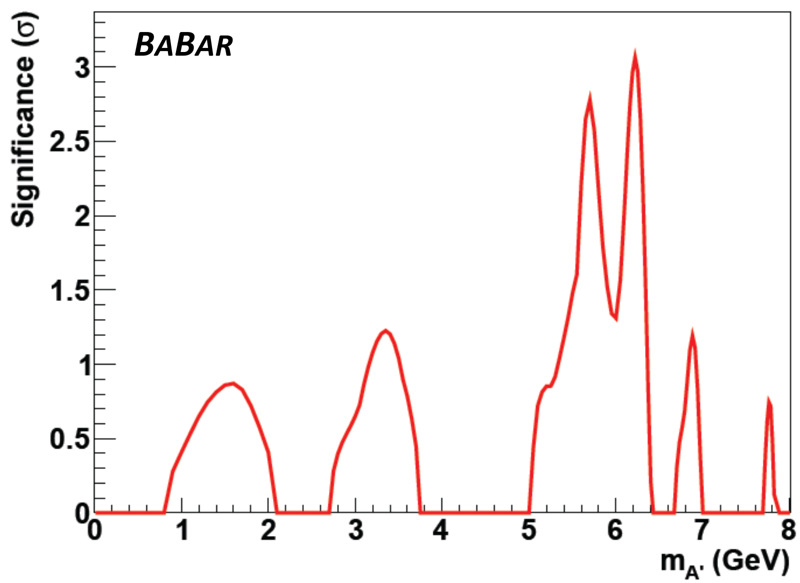


Search for invisible A' decay

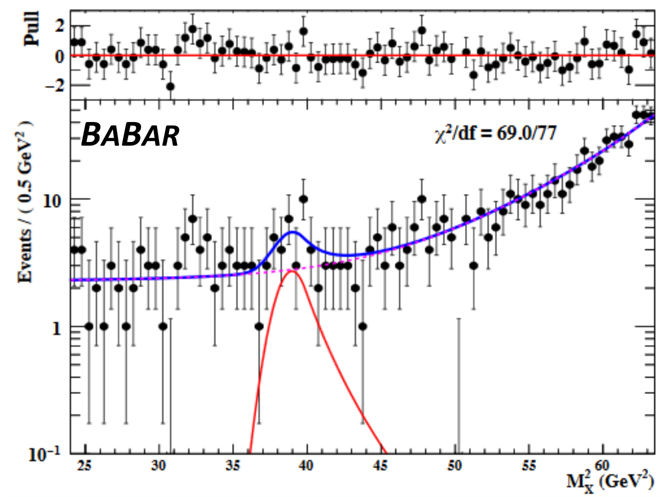
We extract the signal by a simultaneous fit to these independent regions for each beam energy, for a total of 166 mass hypotheses

For each fit, we fix the background shape using the background region, and float the signal yield, peaking and continuum background contributions

Signal significance distribution



Most significant fit m_A = 6.22 GeV



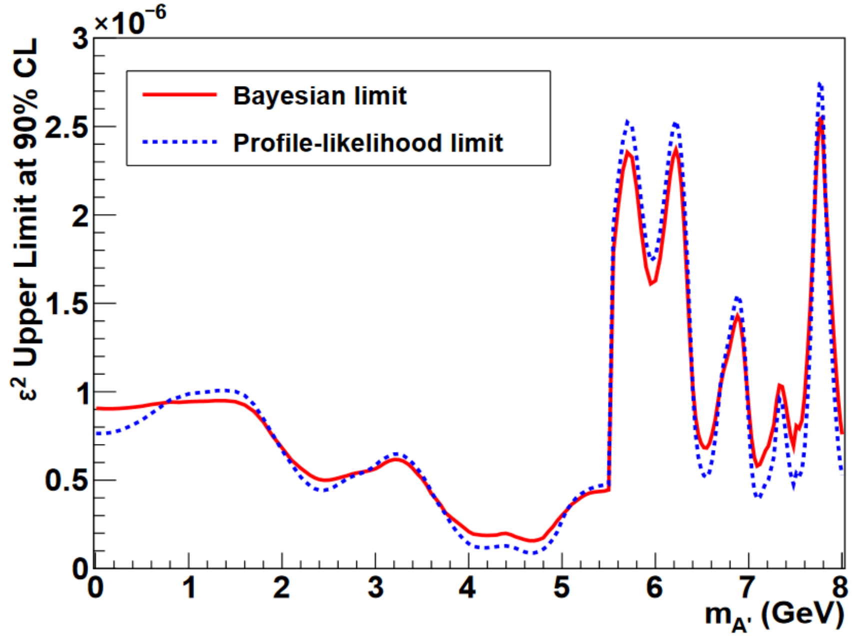
Local (global) significance: 3.1σ (2.6σ)

Global p-value ~ 1%

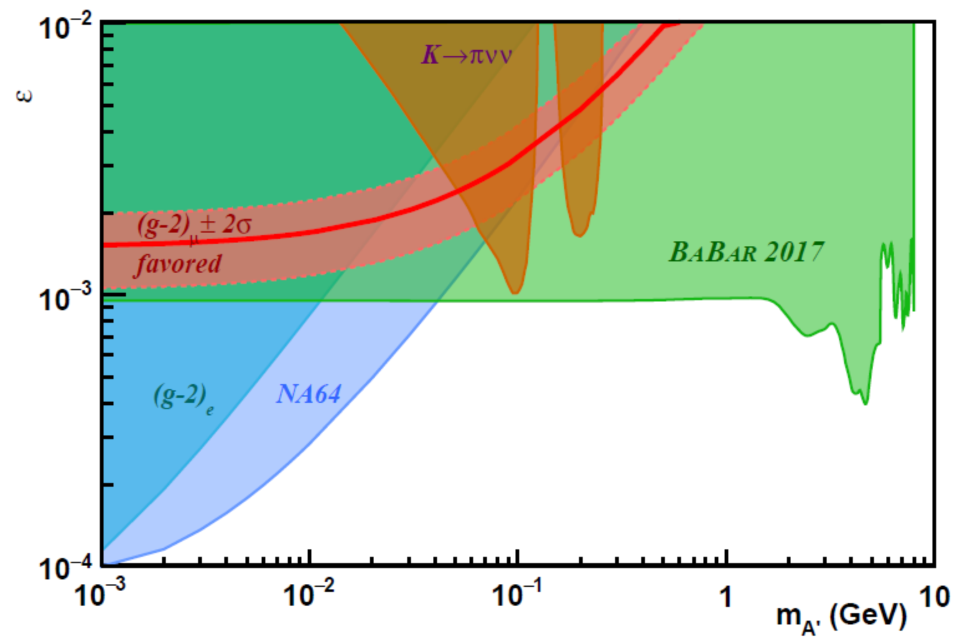
We find no significant signal

Search for invisible A' decay

Limits on mixing parameter ε^2



Limits (90% CL) on mixing parameter



This represents a significant improvement over previous measurements

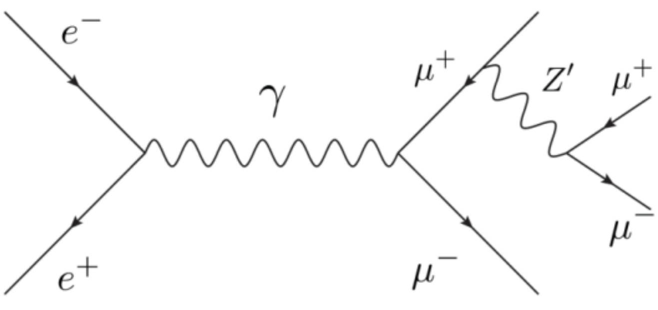
Rules out the entire region preferred by $(g\text{-}2)_\mu$ anomaly

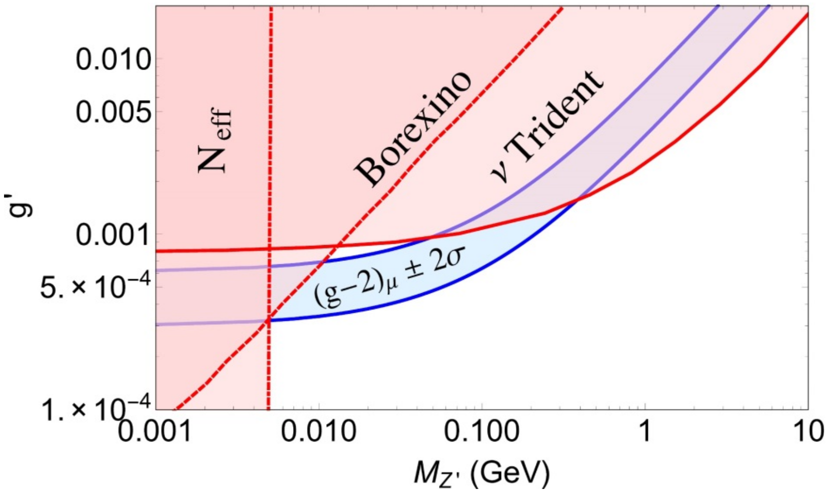
Muonic dark force

- Consider a new dark force that couples only to the second and third generation of leptons with a corresponding gauge boson Z' PRD 94, 011102 (2016)
- 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
- Some constraints from neutrino physics have already been derived, but they only indirectly probe the existence of Z' (with large systematic uncertainties)

We can search for direct Z' production at colliders via Z' bremsstrahlung :

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





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 $\Upsilon(4S)$, $\Upsilon(3S)$ and $\Upsilon(2S)$
- Requirements
  - Four tracks and no extra neutral energy (E_{extra} < 200 MeV)
  - Particle identification: at least 2 same-sign tracks identified as muon
  - Invariant mass of the four μs within 500 MeV of the nominal CM-energy
  - Events having a dimuon candidate within 10 MeV of the $\Upsilon(1S)$ mass for the $\Upsilon(2S)$ and $\Upsilon(3S)$ dataset are vetoed to reject

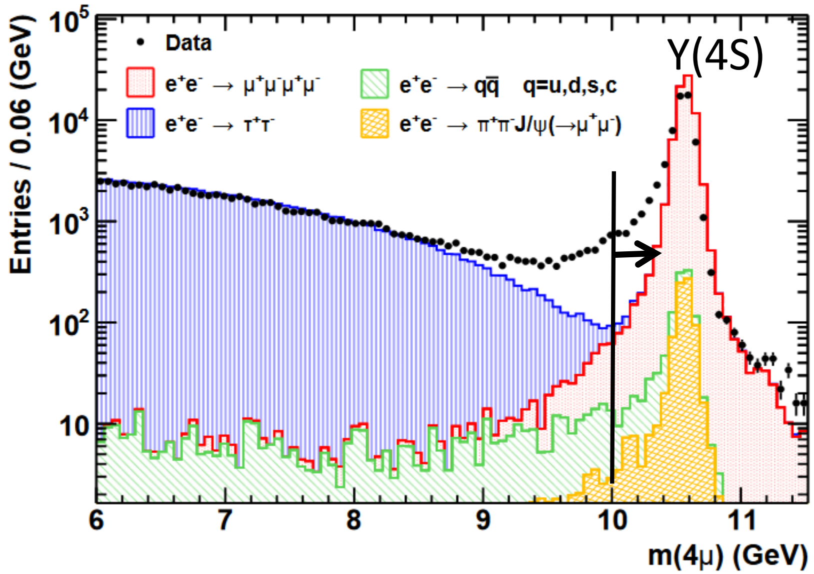
$$\Upsilon(2S,3S) \rightarrow \pi\pi\, \Upsilon(1S),\ \Upsilon(1S) \rightarrow \mu\mu$$

- A kinematic fit imposing the beam-energy constraint is performed, but no constraints on the χ^2 are applied.

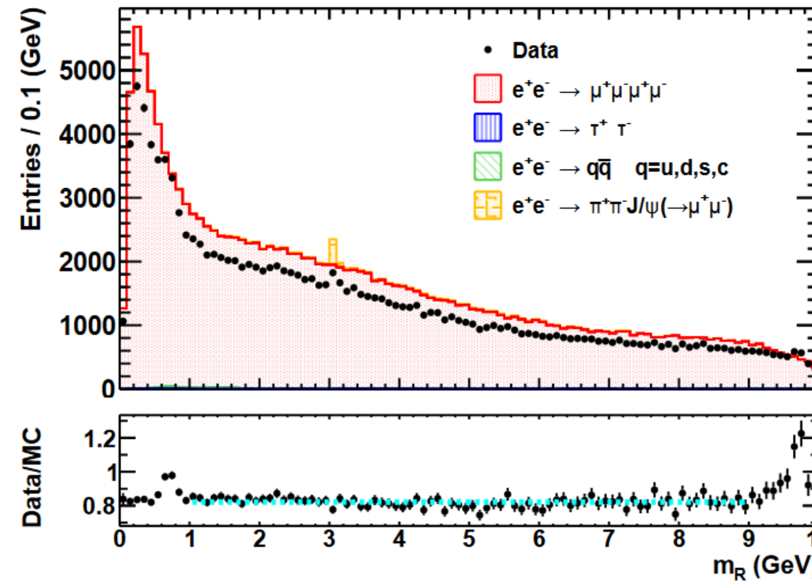
This is a blind analysis, with the selections criteria optimized on a small subset (5%) of the data, which is subsequently discarded

Muonic dark force

Four-muon invariant mass - $\Upsilon(4S)$ dataset



Reduced di-muon mass (2 entries / event)



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

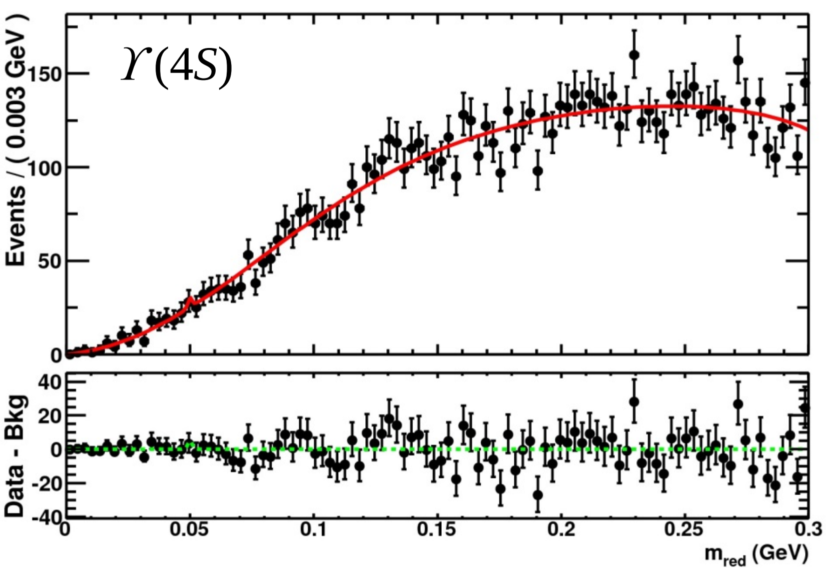
- The signal region is dominated by $e^+e^- \rightarrow 4\mu$ background
- Discrepancies arise primarily from ISR, which is not in the Monte Carlo, as well as from differences in particle identification efficiencies, track reconstruction,…
- The ratio data/MC is used to correct the signal efficiency
- The low 4μ mass region is well-reproduced by the Monte Carlo
- Factoring in the ISR contribution, the correction factors derived from this region agree with those determined at high masses

Muonic dark force

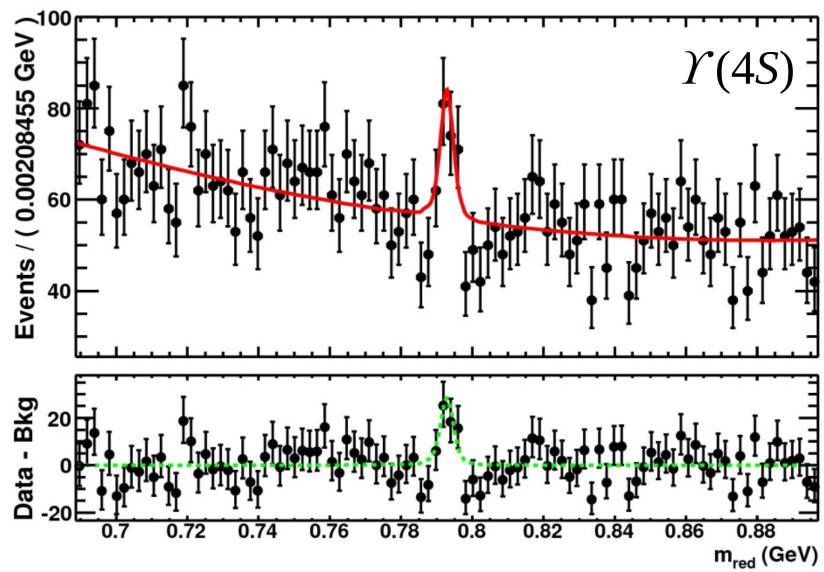
We extract the signal separately for the data at the $\Upsilon(4S)$, $\Upsilon(3S)$ and $\Upsilon(2S)$ by performing a series of fits to the reduced dimuon mass for each sample

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 5σ signal resolution (m_R > 0.2 GeV). A region of $\pm$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

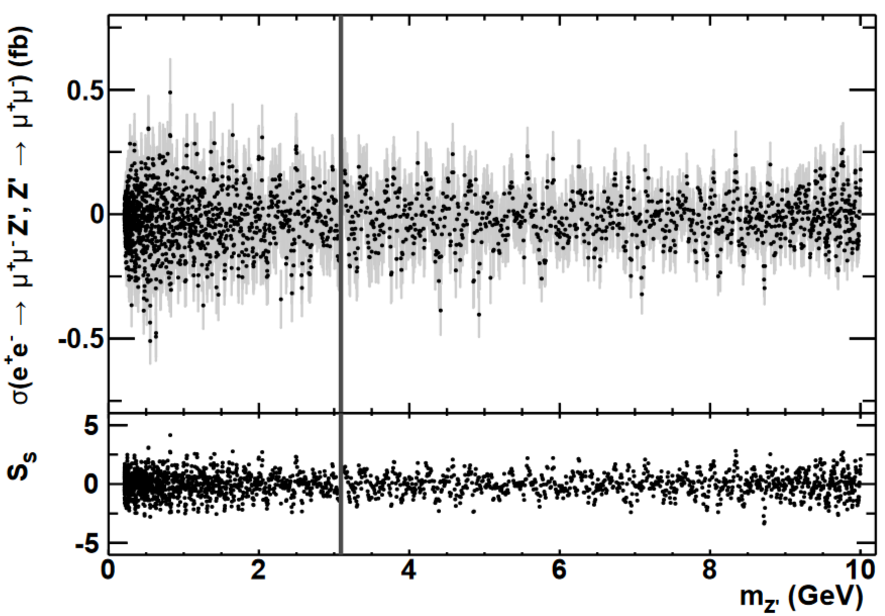
Muonic dark force

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

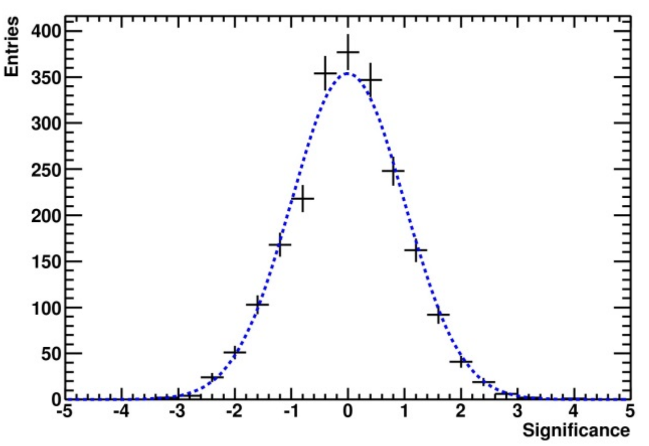
For each mass hypothesis, we fit over a fixed range of 0-0.3 GeV (m_R < 0.2 GeV) or a window corresponding to 5σ signal resolution (m_R > 0.2 GeV). A region of ±30 MeV around the J/ψ is excluded

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

Combined cross-section and significance



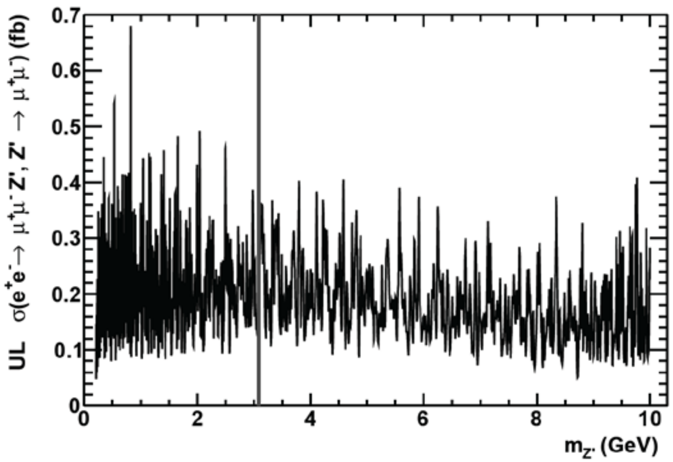
Significance distribution



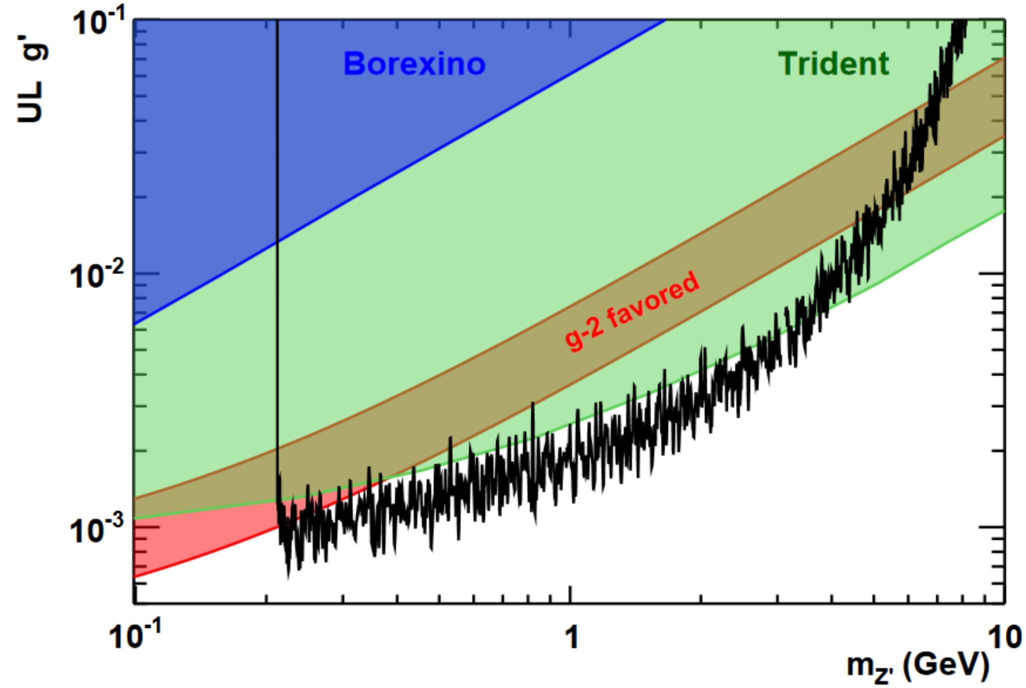
Compatible with null hypothesis

Muonic dark force

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



Limits (90% CL) on Z' coupling



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

More to come…

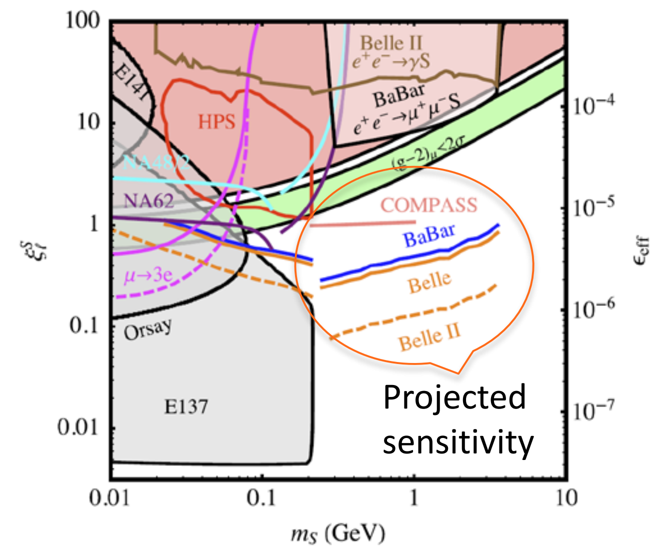
On-going searches for dark sector at *BABAR*

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

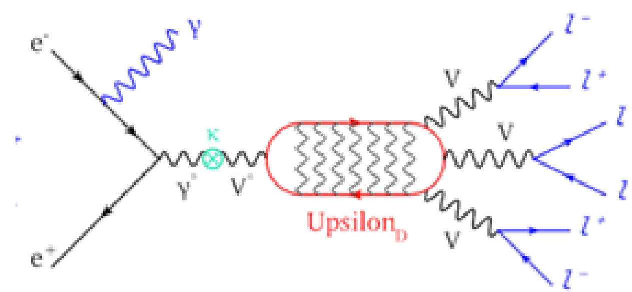
Self-interacting dark matter: if the dark-sector coupling is strong, dark sector bound states (darkonium) could be formed. These states have a striking multi-muon final state signature at *BABAR*.

And hopefully more…

Limits on dark scalar (ϕ) coupling

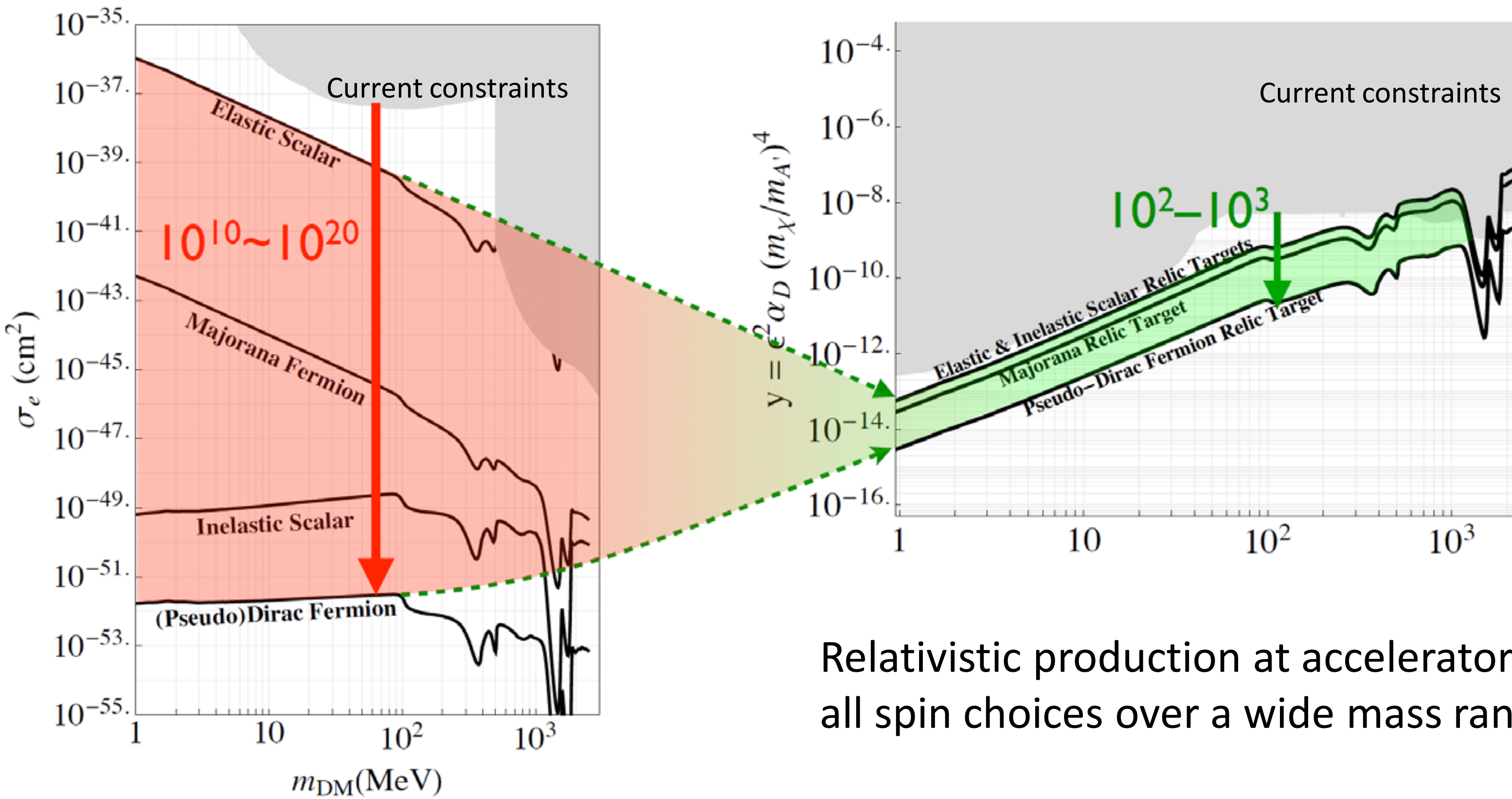


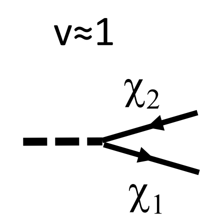
B. Batell, N. Lange, D. McKeen, M. Pospelov, A. Ritz
Phys.Rev. D95, 075003 (2017)



Direct detection and accelerators

Direct detection targets **Accelerator targets**



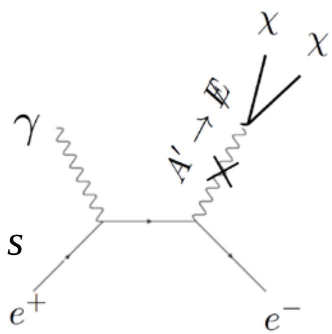


Relativistic production at accelerators probes all spin choices over a wide mass range

- Accelerators are well-positioned to directly probe annihilating thermal LDM
  - Lighter dark sector masses are more difficult to access – the coupling must be much lower, which makes it difficult to produce in a collider
  - Fixed-target configurations are likely the way to get large-enough luminosities

Accelerator approaches

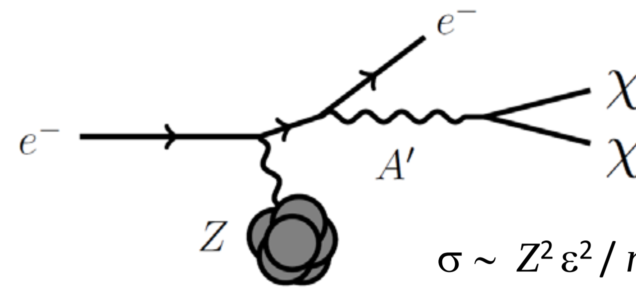
Missing mass



$\sigma \sim \varepsilon^2/s \quad m_A << s$
$\sigma \sim \varepsilon^2/(s - m_A^2) \quad m_A \sim s$

Resonant signal

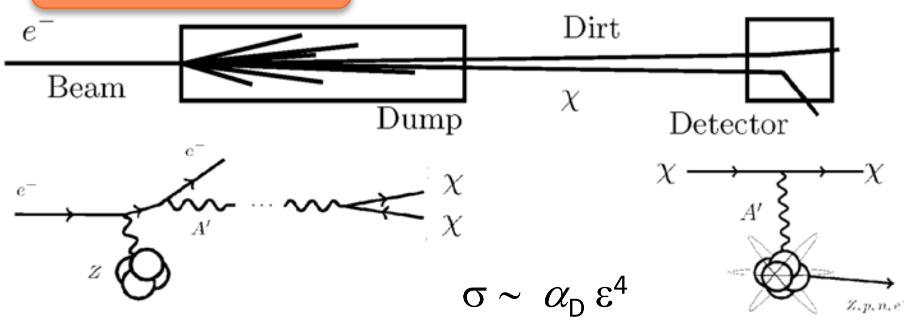
Missing energy / momentum



$\sigma \sim Z^2 \varepsilon^2 / m_A^2$

Large yield at low $m_{A'}$

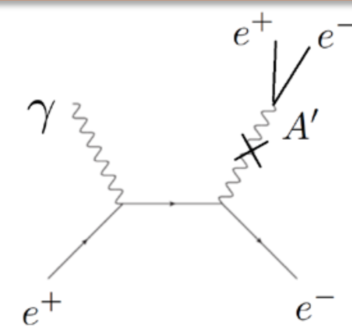
Beam dump



$\sigma \sim \alpha_D \varepsilon^4$

Probes DM interaction twice

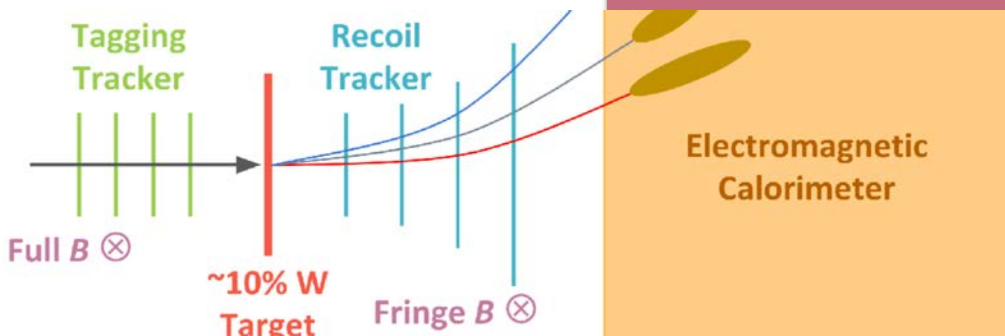
Direct mediator search



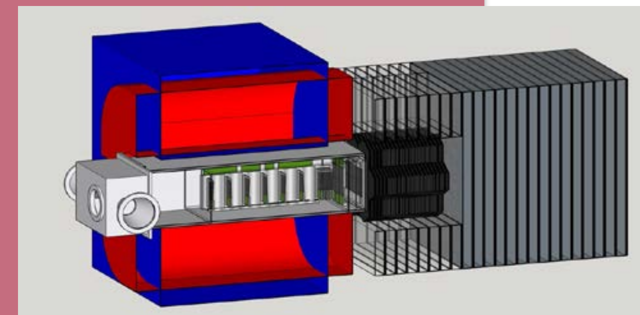
Visible decay $m_{A'} < 2m_\chi$

Accelerator experiments can explore the physics in detail ($\varepsilon, m_{A'}, m_\chi, \alpha_D$), while direct detection is needed to establish cosmological stability

LDMX: a missing momentum design



Hadronic Veto Calorimeter



Beam time structure must allow reconstruction of each individual incident electron event

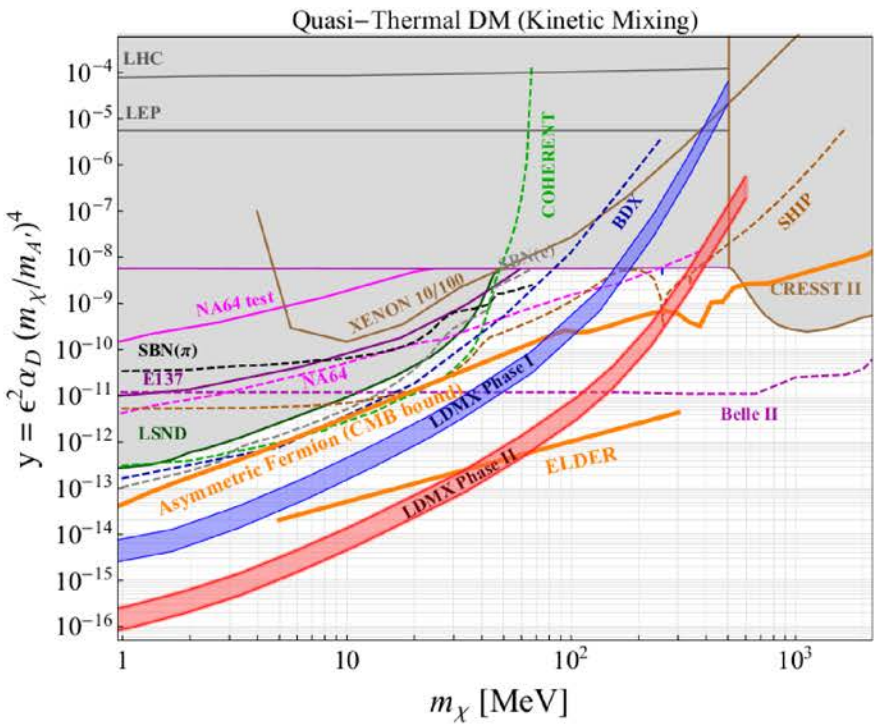
- A multi-GeV, low-current, high repetition rate (CW) (10^{16} EOT/year ≈ $1e^-$ / 3 ns) beam with a large beam spot to spread the occupancy/radiation dose
- Candidate beams: DASEL @ SLAC (4/8 GeV) and CEBAF @ JLab (up to 12 GeV)

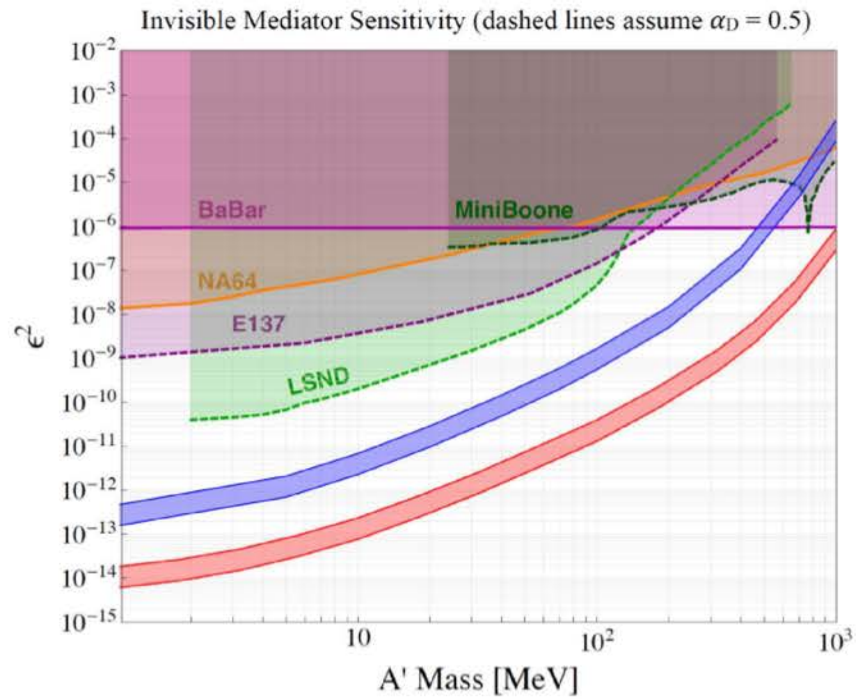
Detector technology with high rate capabilities and high radiation tolerance

- Fast, low mass tagger/recoil tracker with good momentum resolution to tag each electron
- Fast, granular, radiation hard EM calorimeter
- Highly efficient hadronic veto calorimeter

LDMX has will realize these design requirements in two phases:
Phase I with 10^{14} EOT ($1e^-$/25 ns) , and Phase II with 10^{16} EOT ($1e^-$/3 ns)

Sensitivity estimates





LDMX can also explore DM with quasi-thermal origins, *e.g.* asymmetric DM or SIMP/ELDER scenarios, and improve the sensitivity on invisible A' decays

Summary

Light dark sectors having a rich phenomenology have emerged as a fertile new regime for dark matter searches, as the WIMP paradigm is now highly constrained

Low-energy, high-intensity colliders provide a sensitive probe for dark sectors

BABAR has an extensive program to search for dark sector signatures, and set stringent limits on their existence

Belle II will over the next decade improve these collider limits

Extending the search region to the thermal relic limit at low masses requires fixed target accelerator experiments, such as LDMX ……..