DARK FORCES IN E^+E^- INTERACTIONS

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SuperB workshop & kick-off meeting, June 2011

Dark Sector in a nutshell

Models introducing a new 'dark' force mediated by a new dark gauge boson with a mass around a GeV have been recently proposed to explain the observations of PAMELA, FERMI and DAMA/LIBRA. The dark gauge boson couples to the SM gauge bosons via kinetic mixing. Wimp-like dark matter particles can annihilate into pairs of dark photons, which subsequently decays to lepton pairs (protons are kinematically forbidden).

More generally, a GeV-scale hidden sector *neutral* under the SM can peacefully co-exist with the SM and evade precision constraints. There are a few low-dimension portals that can probe such a hidden sector:

$H^\dagger H\,(AS + \lambda S^2)$	Higgs portal (dim = 3,4)
$\varepsilon\, F^{\mu\nu} B_{\mu\nu}$	Vector Portal (dim = 4)
$Y_N \bar{L} H N$	Neutrino Portal (dim = 4)
$f^{-1} \bar{\psi}\gamma_\mu\gamma_5\psi\partial_\mu a$	Axion Portal (dim=5)

H SM Higgs doublet
$F^{\mu\nu}$ hypercharge field strength
L left-handed lepton doublet
ψ generic fermion

S, N, A_μ', a hidden sector fields

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The vector portal is the main portal for e^+e^- searches

A light hidden sector

- Models of dark matter introduce a new dark sector with a $U(1)_D$ gauge group (and corresponding charge). The corresponding gauge boson has a mass O(GeV) and is usually called a dark photon.

- Interaction with the SM is via the vector portal

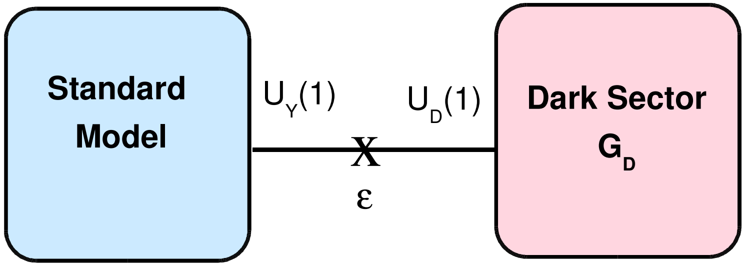
$$\varepsilon F^{\mu\nu} B_{\mu\nu}$$

  For a low mass dark photon, the mixing is essentially with the photon with a mixing strength ε.

- Non-Abelian group introduces additional bosons.

- The boson masses are generated via the Higgs mechanism, adding Higgs(es) to the theory. One can reasonably expect light (GeV-scale) Higgs bosons.

- Dark quarks forming dark hadrons could also be a possibility



$$\Delta\mathcal{L}_{mix} = \varepsilon F^{\mu\nu} B_{\mu\nu}$$

Glossary:

Dark photon:	A_D, A',U,V
Dark photon:	W_D, W'
Dark Higgs:	h_D, h'
Mixing:	ε,κ
	$\alpha' = \alpha\,\varepsilon^2$

$U(1)_D$ structure constant α_D

- Assume there are no light dark fermions, so dark photons have to decay back to SM particles.

  → Amplitude have only power of ε for producing hidden sector particles!

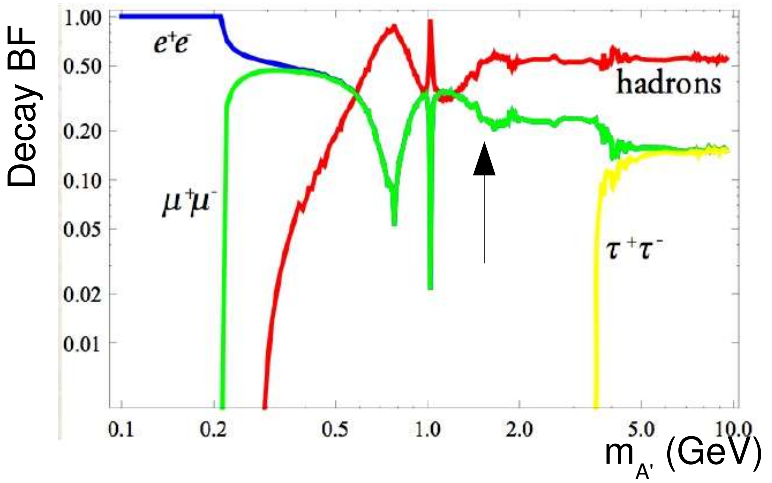
- The photon field can be redefined $A_\mu \rightarrow A_\mu - \varepsilon A_\mu'$, so that SM fermions picks a small $U(1)_D$ charge ~εe, giving rise to so called “millicharged” interaction

- Naturalness arguments seems to favor $\varepsilon \sim 10^{-4} - 10^{-2}$

- The dark photon lifetime is usually small, except for very low mass photons. Expect prompt decays above 0.05 - 0.1 GeV at Super*B*.

- The coupling of the dark photon to SM fermions depends only on the SM electric charge (universal coupling).

PRD 79,115008 (2009)

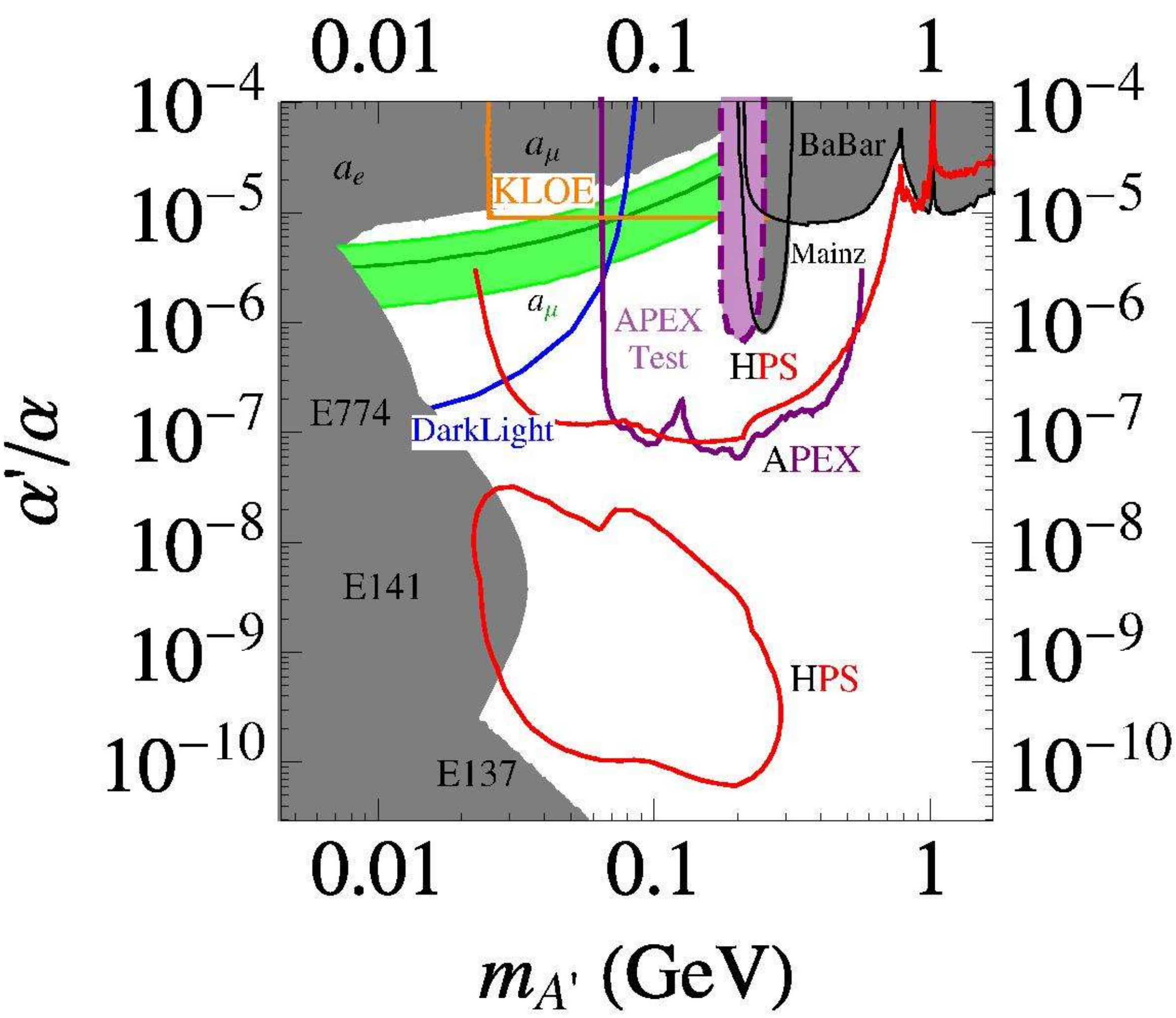


$c\tau\,(A' \rightarrow l^+l^-) \sim 8\times10^{-6}\,(10^{-3}/\varepsilon)^2\,(1\text{ GeV} / M_A)\,(1/N_{eff})$ cm

Decay BF:

$A' \rightarrow$ hadrons / $A' \rightarrow \mu^+\mu^-$ = $e^+e^- \rightarrow$ hadrons / $e^+e^- \rightarrow \mu^+\mu^-$

N.B: Hadron production besides ππ and KK becomes important above ~ 1.2 GeV



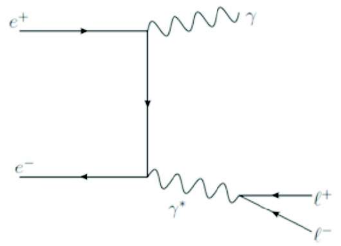
Excluded region

Sensitivity from other experiments

g-2 “favored region”

Dark photon production (2 trks)

$e^+e^- \rightarrow \gamma A_D$, $A_D \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$

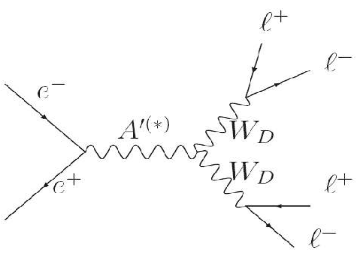


ε^2

Dark boson production (4 trks)

$e^+e^- \rightarrow A^*_D \rightarrow W_D W'_D$, $W^{(')}_D \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$

$e^+e^- \rightarrow \gamma A_D \rightarrow W_D W'_D$

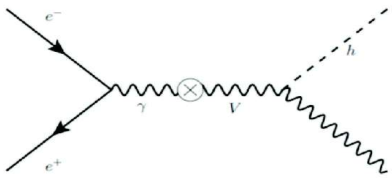


$\alpha_D \varepsilon^2$

Dark Higgs production (Higgs-strahlung) (6 trks)

$e^+e^- \rightarrow H_D A_D$, $H_D \rightarrow A_D A_D$, $A_D \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$

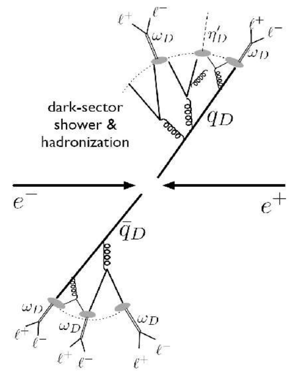
$e^+e^- \rightarrow H_D A_D$, $H_D \rightarrow W_D' W_D''$



$\alpha_D \varepsilon^2$

Dark QCD (6+ trks)

$e^+e^- \rightarrow \pi_D + X$, $\pi_D \rightarrow e^+e^-, \mu^+\mu^-$

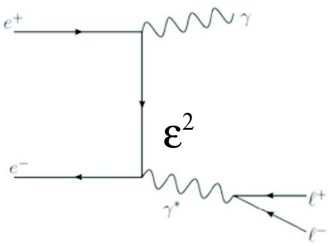


DARK PHOTON

Direct production in e^+e^- collisions, decays to a pair of leptons or pions

Topology:

2 tracks +gamma



PRO:

ε^2 process

good efficiency

CON:

Large background, especially $A_D \rightarrow e^+e^-$ (require photon to clean up)

Trigger efficiency for two tracks (ok if photon detected)

Searches:

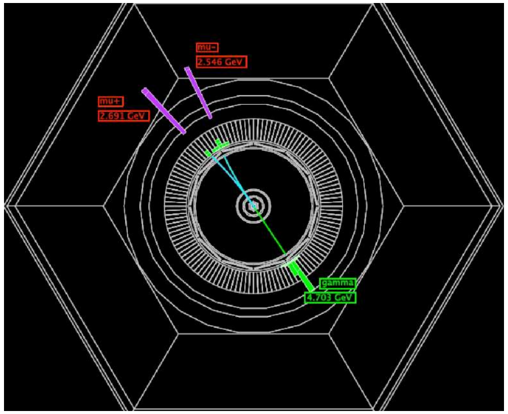
$A_D \rightarrow e^+e^-$ for $m_A < 0.25$ GeV

$A_D \rightarrow \mu^+\mu^-$ for $m_A > 0.25$ GeV

$A_D \rightarrow \pi^+\pi^-$ for the ρ mass region

So far, only one measurement from B*A*B*AR*, reinterpreting the limits from light CP-odd Higgs search in ϒ(2,3S) decays (same topology). About 40 fb^{-1} of data.

Event selection

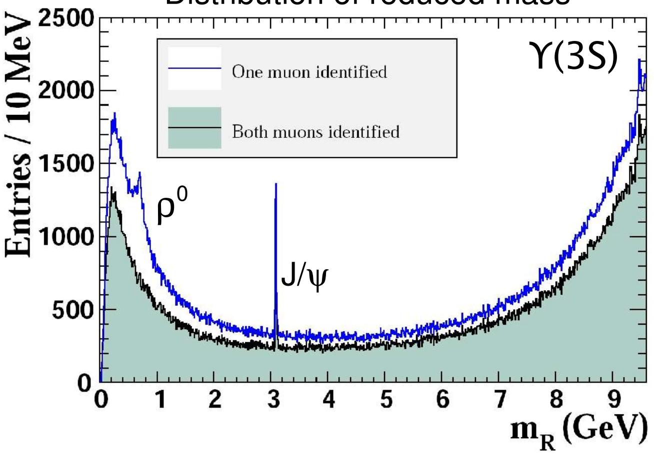


- Fully reconstructed final state, 2 tracks and a photon with $E_\gamma^* > 0.2$ GeV
- Particle Id, one or two tracks must be identified as muon(s)
- Energy and beam spot constraints for ϒ(2,3S) candidate
- Muon pair and photon must be back-to-back in the CM frame

Signal efficiency: ~ 25% - 55% (as fcn of m_R)

Fit procedure

Distribution of reduced mass

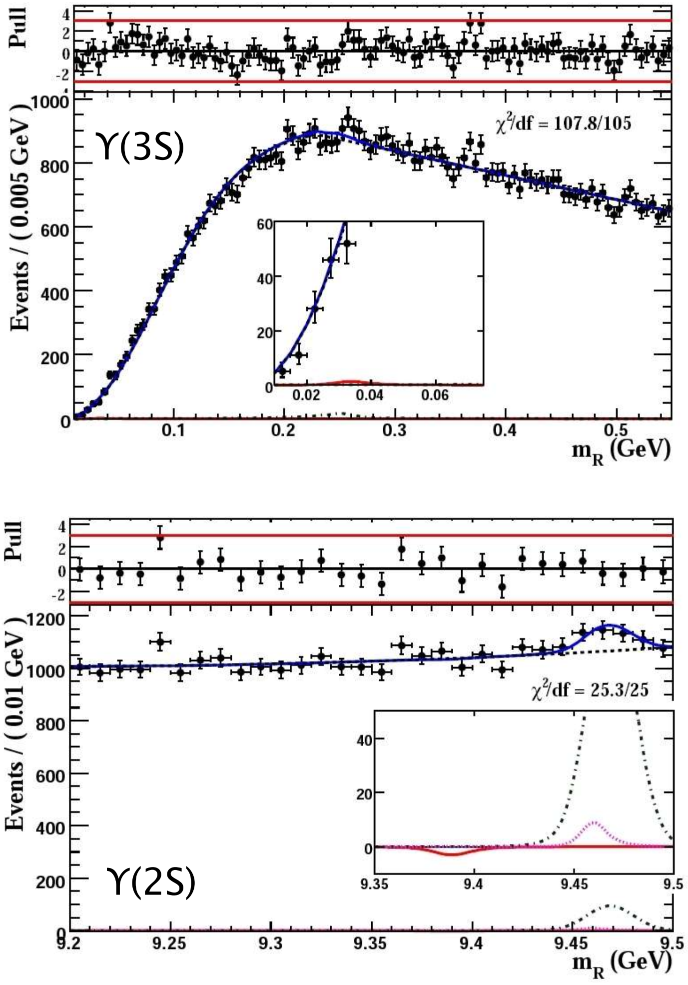


reduced mass $m_r = (m^2_{A0} - 4m_\mu^2)^{1/2}$

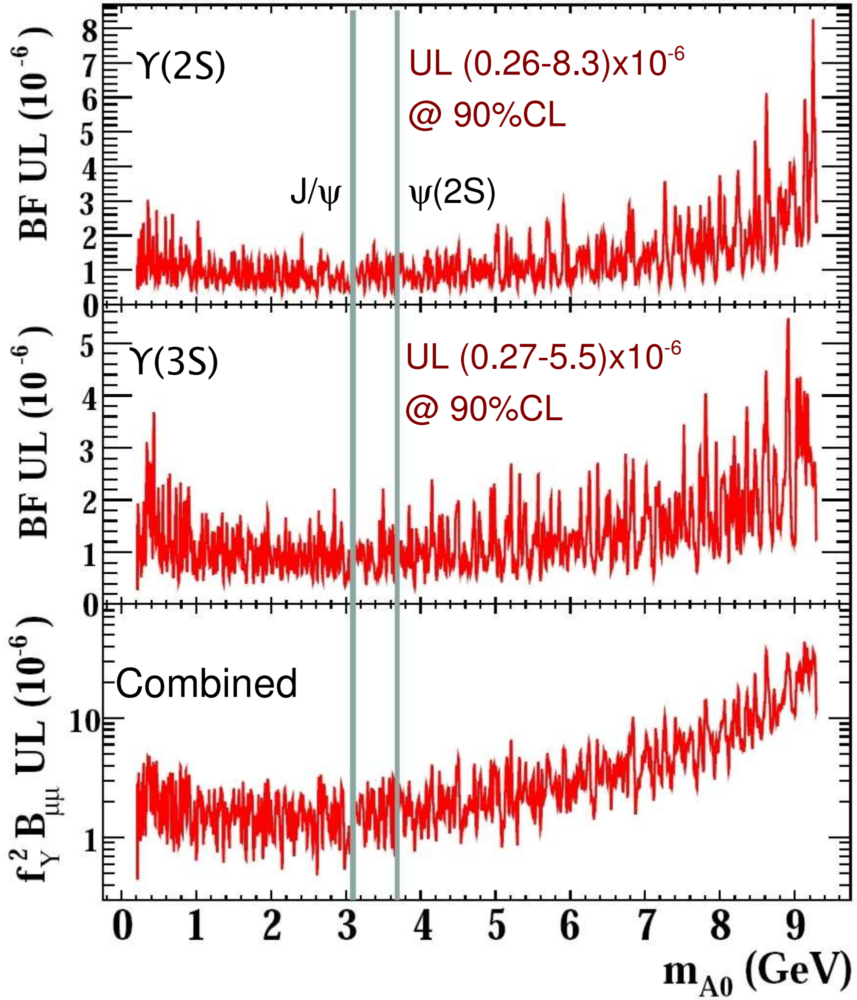
Extended unbinned maximum likelihood fit in 1951 intervals of reduced mass $m_r = (m^2_{A0} - 4^2 m_\mu)^{1/2}$

- Mass range 0.212 – 9.3 GeV
- Step size 2-5 MeV
- Resolution 2-10 MeV

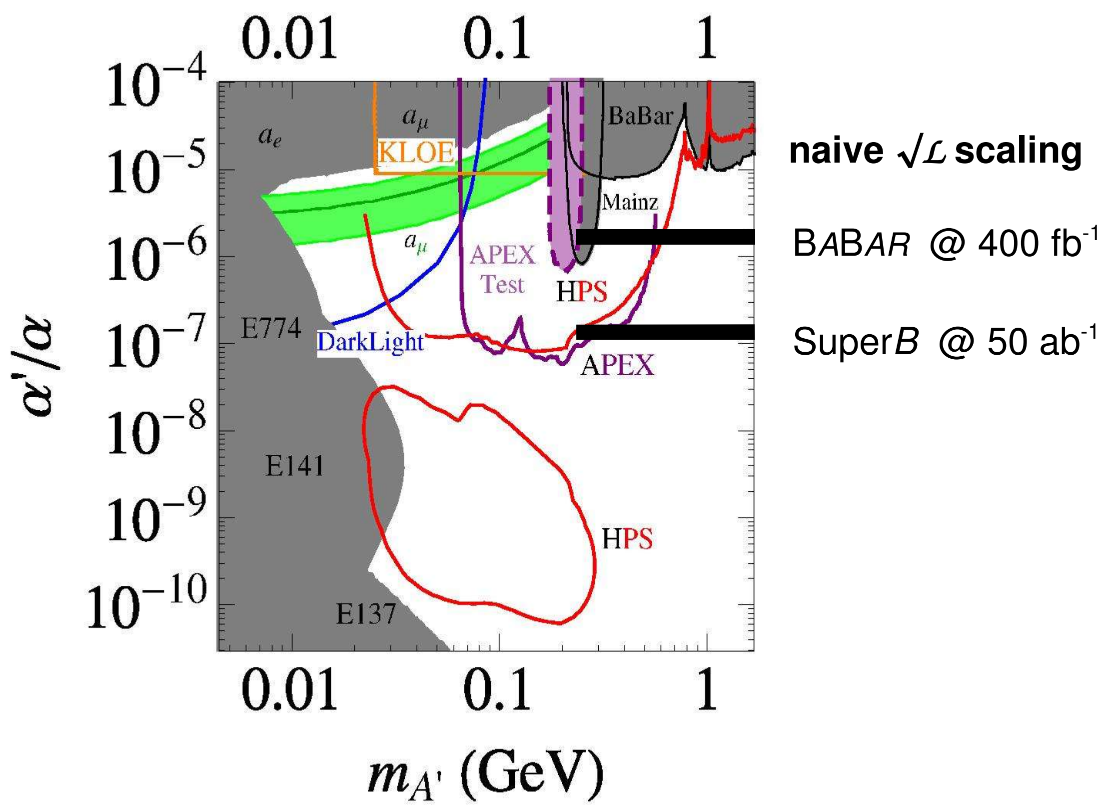
Examples of m_R spectrum fit

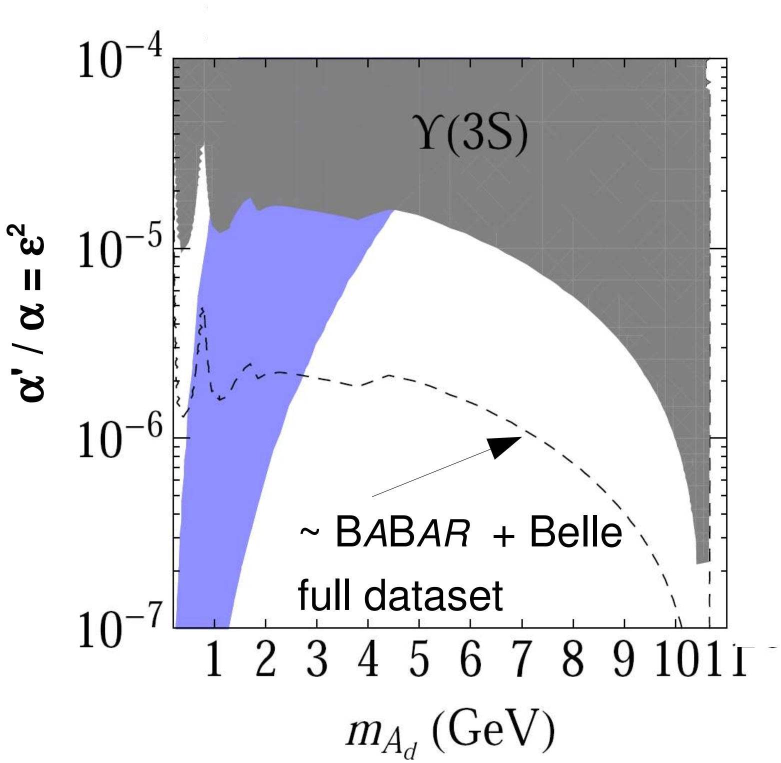


BF(Υ(2,3S)→ γ A^0) x BF(A^0→$\mu^+\mu^-$) upper limits



Constraints on the ratio α' / α = ϵ^2





Ongoing analysis for $e^+e^- \to \gamma A_D$, $A_D \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$ with full dataset

Expect exclusion at the O(10^{-6}) level for low masses and O(10^{-7}-10^{-8}) for highest masses

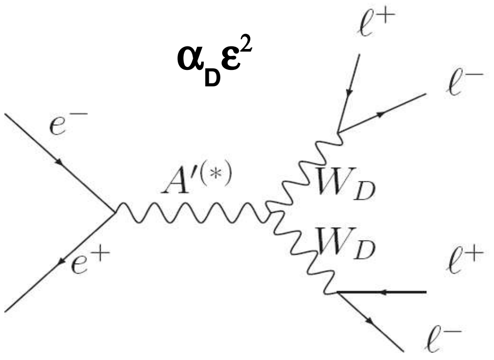
DARK BOSON

The simplest extension to a non-Abelian case is SU(2)xU(1), which has 4 boson: A_D, W_D, W'_D and W''_D.

Dark bosons W_D mix with the photon → can produce a pair of dark boson though an off-shell or on-shell A_D in ISR event.

Topology:

4 tracks (+ ISR gamma)



PRO:

ε^2 process

Relatively small background

CON:

W_D bosons might be too heavy to be produced at low $\sqrt{s}$

Searches:

Dark bosons in 4 leptons final state (arXiv:0908.2821)

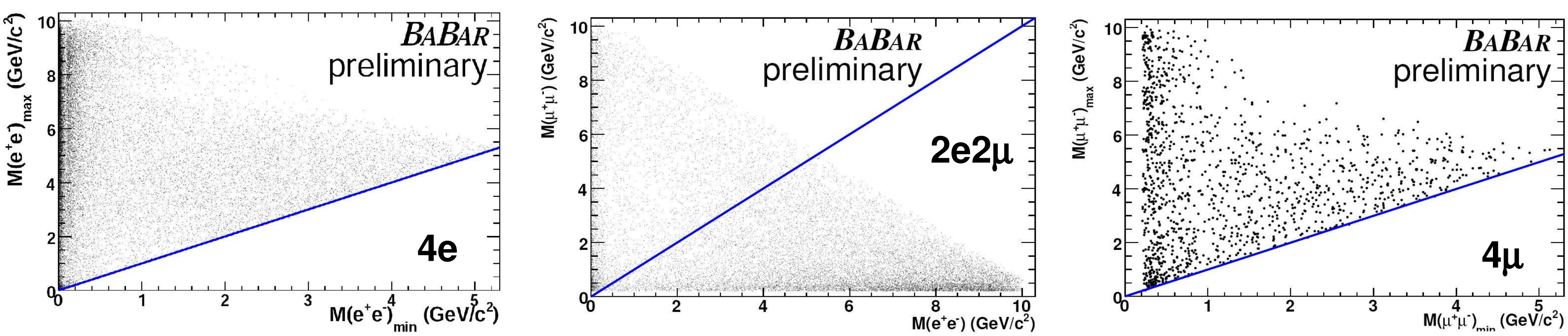
Dark bosons in 4 leptons final state + ISR (on-going)

Search for dark boson production in 4 lepton final states

$$e^+e^- \rightarrow A^*_D \rightarrow W_D W'_D,\ \ W^{(')}_D \rightarrow e^+e^-, \mu^+\mu^-$$

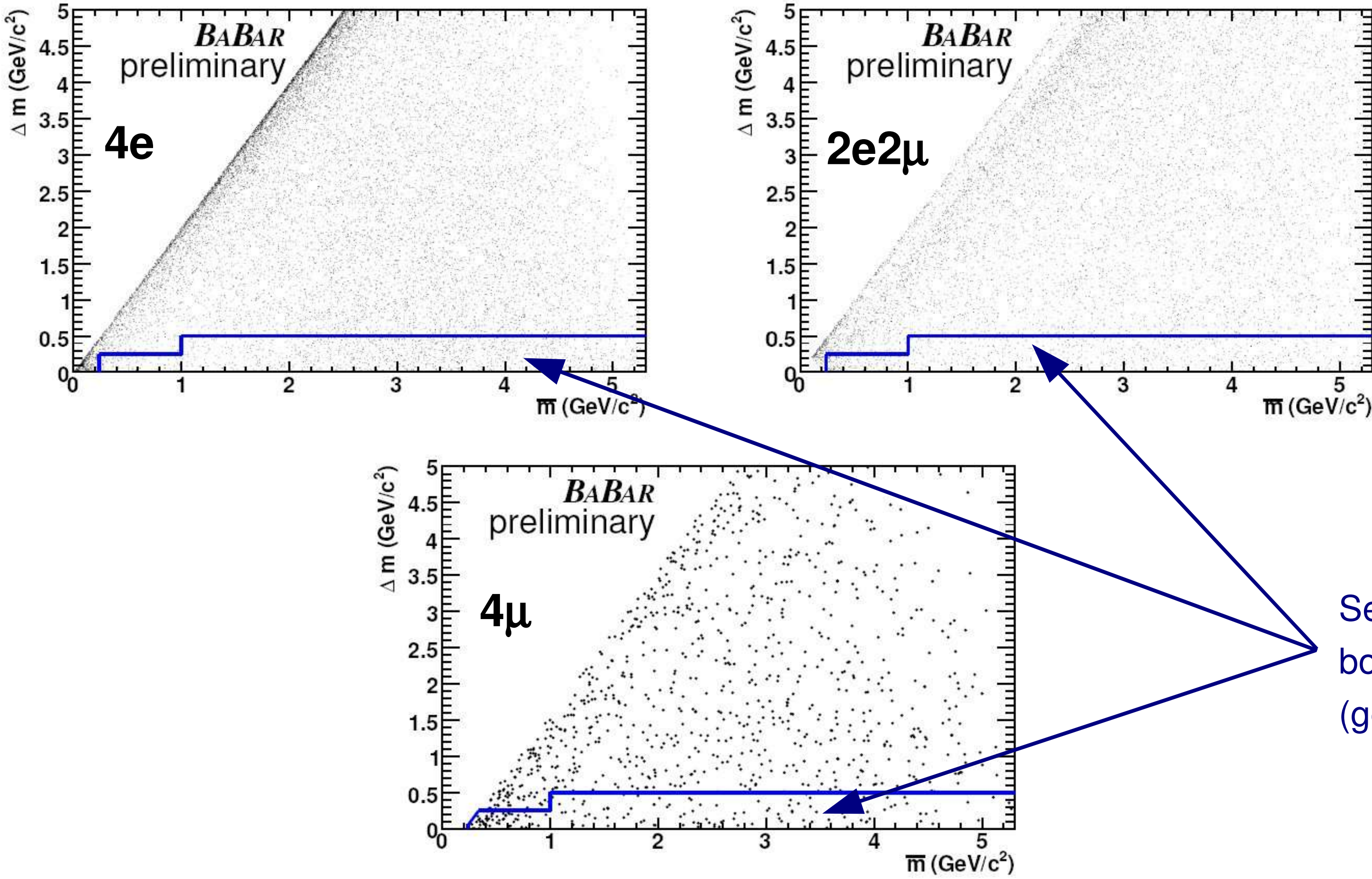
Selection:

- → Reconstruct two pairs of leptons
- → 4 charged tracks, either 4μ, 2μ2e or 4e (PID identified)
- → $M_{4leptons} > 10$ GeV
- → Cosine helicity angle of each lepton pair < 0.95
- → Angle between decay planes > 0.2



Low background in muonic channels

Define: $\overline{m} = (m_{min}+m_{max})/2 \quad \Delta m = (m_{max}-m_{min})|/2$

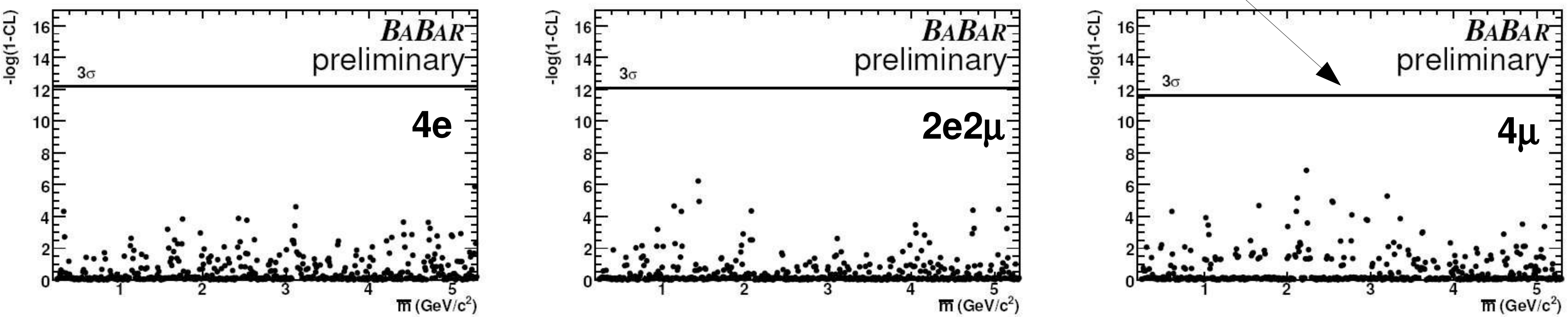


Select events where the two bosons have similar masses (generic case in progress)

Scan mass spectrum for signal (507 points)

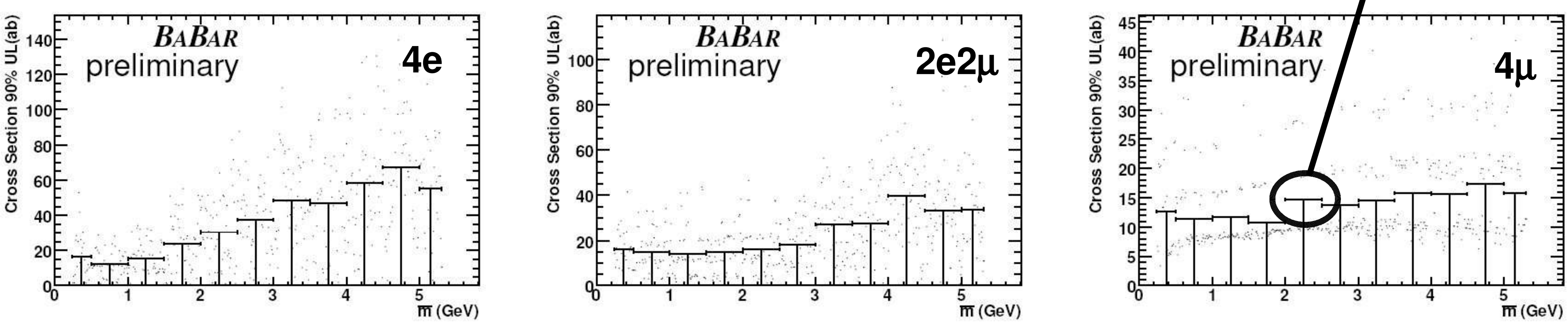
CL distribution

3σ limit, including trial factors



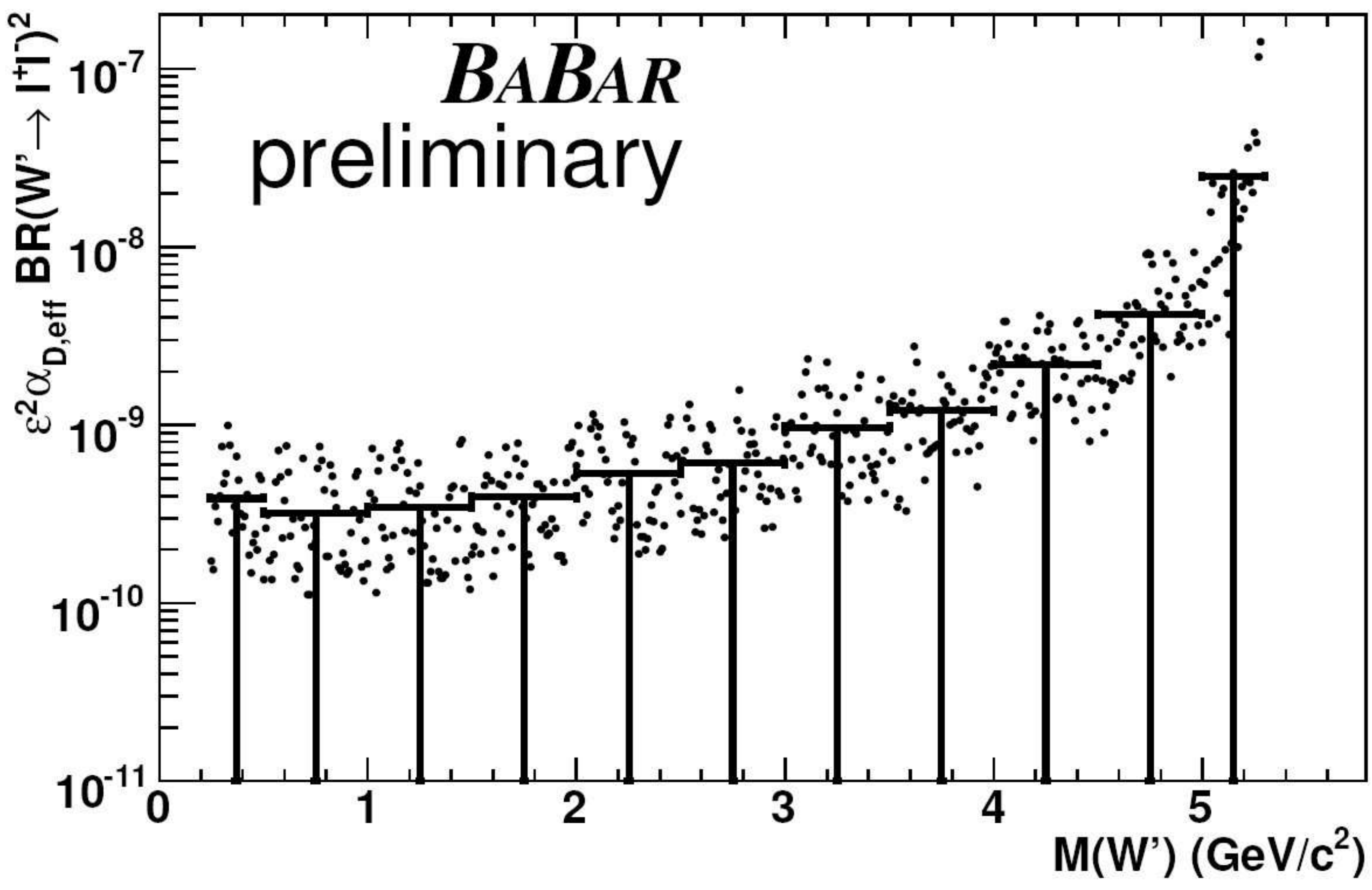
$e^+e^- \to W_D W'_D \to 4l$ cross-section upper limits

Average limit over many bins



Search for dark boson production in 4 lepton final states

Combine upper limits and extract limits on $\alpha_D \varepsilon^2$ x BF($W \rightarrow l^+l^-)^2$



Assuming $\alpha_D = \alpha$

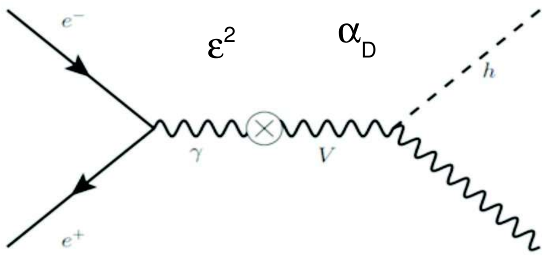
$\varepsilon^2 < 10^{-7} - 10^{-3}$

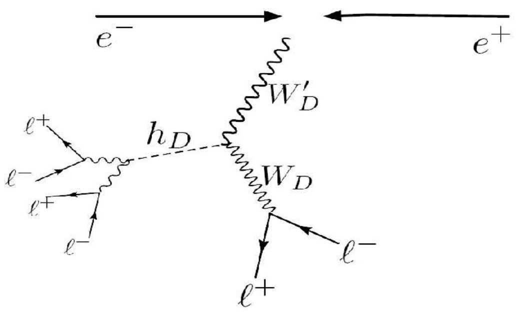
W_D, W_D'
with similar masses

Generic case (any mass difference) as well as on-shell A_D analysis in progress

DARK HIGGS

Since the dark sector is spontaneously broken at about a GeV, it is reasonable to expect that there is a dark Higgs boson at this scale too[1)]. Therefore, we can have dark Higgs'-strahlung, analogous to Higgs-strahlung in the Standard Model, as an interesting channel of production.





TOPOLOGY AND SEARCHES:

depends on the mass scale

PRO:

ε^2 process

almost no background for some decay modes

CON:

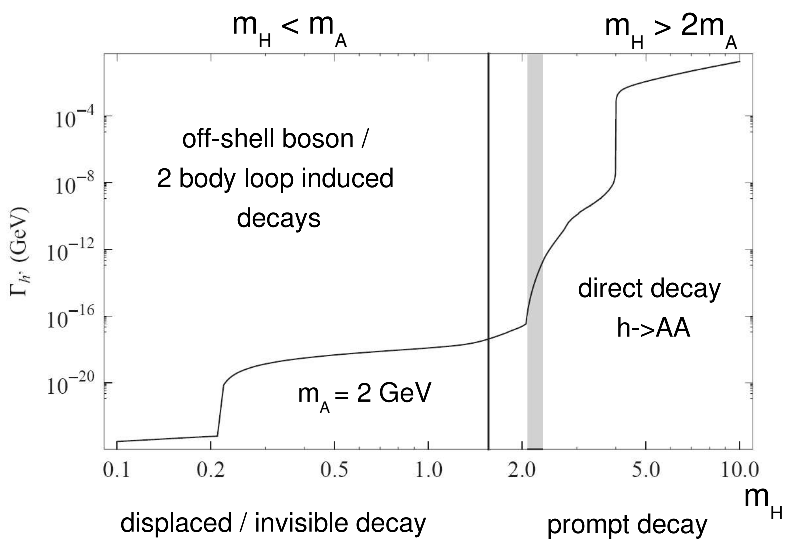
Lower efficiency

Higgs might be too heavy to be produced at low $\sqrt{s}$

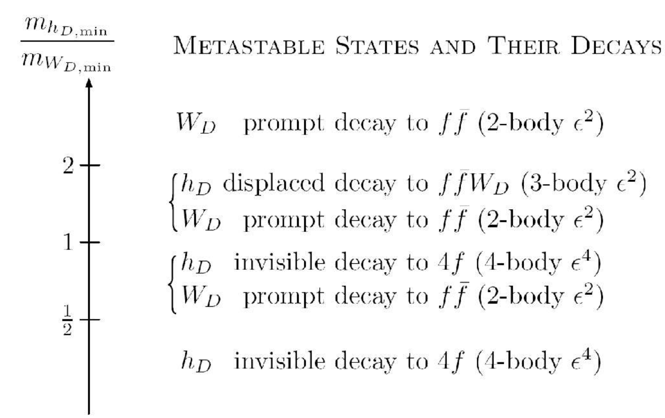
1) See for example: B. Batell, M. Pospelov, and A. Ritz, arXiv:0906.5614. (abelian); R. Essig, P. Schuster, and N. Toro, arXiv:0903.3941. (non-abelian)

Topology: depends on the mass hierarchy

Abelian case : 1 H_D / 1 A_D



Non-Abelian case: 1+ H_D / 1+ W_D



Searches:

6 leptons, 4 leptons + 2 pions, 2 leptons + 4 pions

2 leptons + missing E_T (invisible Higgs)

Quote from a theorist: “Expect anything”

Dark Higgs production

On-going analyses at B*A*B*AR*

1. Abelian case with prompt decays (single A_D), fully reconstructed
   → Three pairs of leptons or pions having the same mass
   → Look for bumps in the Higgs mass vs photon mass plane
   → Almost negligible background (expect a few bkg events)
   → Lower branching fraction at large masses

2. Abelian case with prompt decays (single A_D), partially reconstructed
   → Reconstruct two pairs of leptons, identify the remaining photon as the recoiling system
   → Low background and recover some branching fraction

3. Non-Abelian case with prompt decays, fully reconstructed
   → Three pairs of leptons only
   → Larger background

N.B: The Abelian case works for a single or multiple Higgses.

Expected sensitivity for Abelian searches at B*A*B*AR*:

→ no events are observed (realistic assumption)

→ $0.02 < m_A < 3$ GeV, $1 < m_h < 10$ GeV

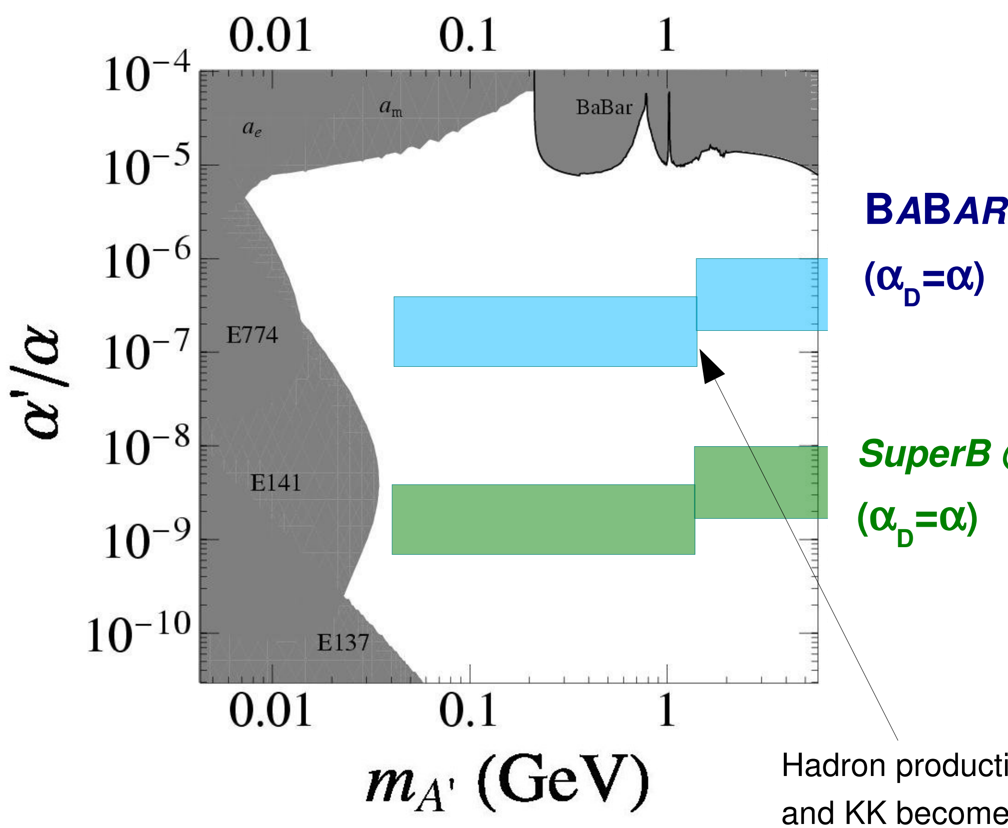
(excluding $\rho, \omega, \phi, J/\psi$ region)

Expected limits, 90% CL

$\sigma(e^+e^- \rightarrow H_D A_D, H_D \rightarrow A_D A_D) < 20 - 60$ ab

$\Rightarrow \alpha_D \varepsilon^2 < O(10^{-9})$

$\Rightarrow \varepsilon^2 < O(10^{-7})$ $(\alpha_D = \alpha)$

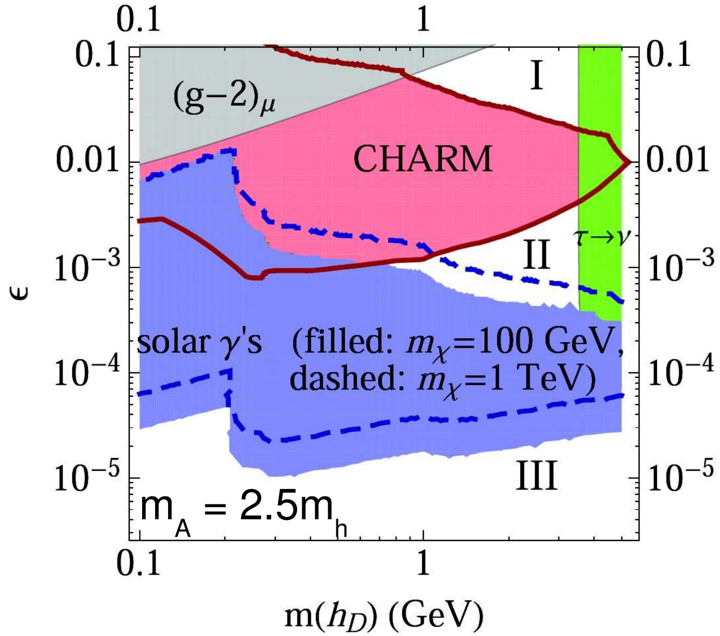


Hadron production besides ππ and KK becomes important above ~ 1.2 GeV

Invisible Higgs decay

For Higgs masses $m_h < m_a$, the dark Higgs has a long lifetime and escapes the detector (the intermediate case $m_a < m_h < 2m_a$ has either displaced or invisible decay).

The signature is: dark photon + missing E_t → 2 leptons + missing E_t. The Higgs mass is identified to the recoiling mass. Expect bump in the Higgs mass vs photon mass plane.



However

Trigger issues (2 trks final state)

Might be excluded from direct search

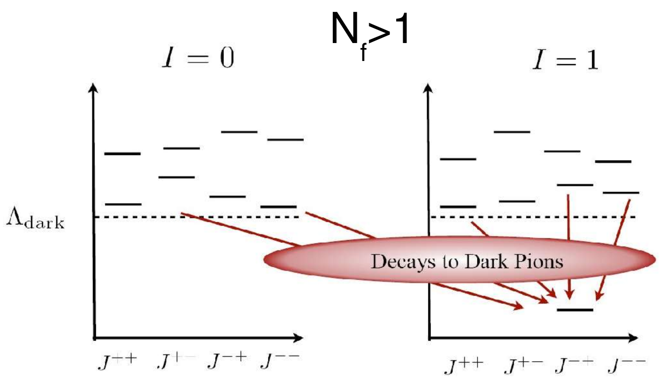
Might not be a priority and done by other experiments

DARK HADRON

Mass spectrum depends on the number of flavors N_f:

$N_f=1$: η'_D ($J^{PC} = 0^{-+}$), ω_D (1^{--}), excited states

$N_f>1$: N_f^2-1 π_D + heavier mesons

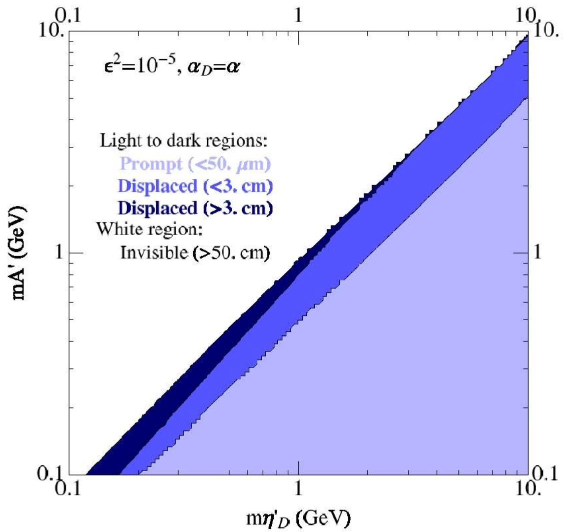


Final state topology:

- η'_D and π_D decays mainly through the anomaly diagram*

  Light A' ($m_{\eta'D} > 2m_A$): prompt decays to 2A'

  Heavy A' ($m_A > m_{\eta'D}$): metastable η'_D with displaced vertex or invisible decay

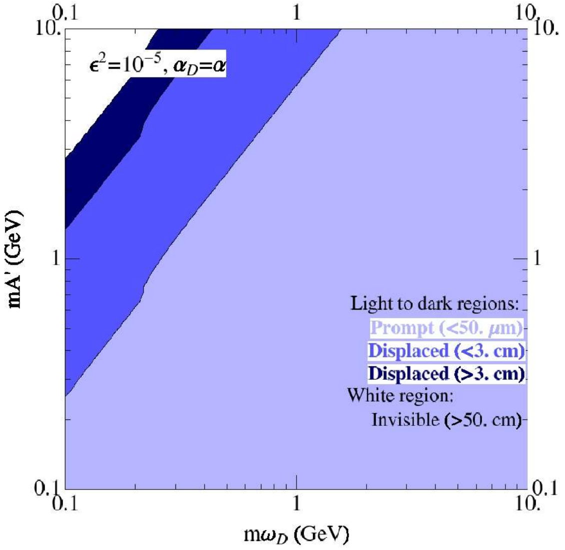


*Kinetic mixing couples the transverse modes between the dark photon and photon ($g^{\mu\nu} - p^\mu p^\nu$), which doesn't couple to the pion (current ~ p^μ)

Mass spectrum depends on the number of flavors N_f:

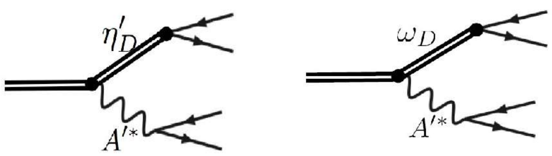
$N_f=1$: η'_D ($J^{PC} = 0^{-+}$), ω_D (1^{--}), excited states

$N_f>1$: N_f^2-1 π_D + heavier mesons



Final state topology:

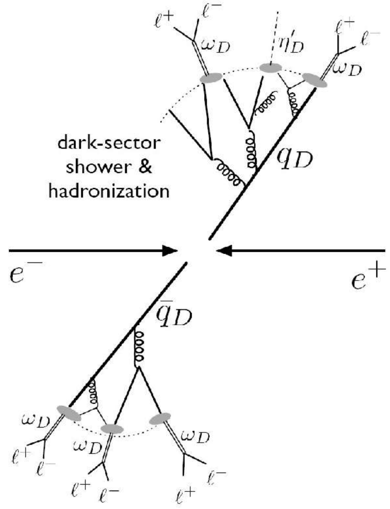
- ω_D can mix to the dark photon and decay as the A'
- heavier states can decay to η'_D / ω_D mesons + A' or π_D



(+ dark baryons / dark exotics / light dark fermions)

e^+e^- → dark hadrons events should produce final states containing many leptons

Dark QCD events have the striking feature of having many leptons in the final state.



Topology:

Many leptons, require 1+ muon to remove background

PRO:

Large efficiency

Low background

Easy to see if there is a signal or not

CON:

Need special MC generator with specific hadronization scheme
to estimate efficiency and give limit

Searches:

On-going search at BaBar, but require more work to get publishable

Interesting topology, but will most likely be ruled out before Super*B* begins

Summary for e^+e^- interactions

The idea of dark sectors is an **interesting possibility really worth investigating**, many on-going analyses at B*A*B*AR* and a few planned experiments at JLab.

B-factories (B*A*B*AR* / Belle) have a **unique opportunity to directly explore** the **1-10 GeV** region and is **quite competitive below 1 GeV**.

B*A*B*AR* might be able to **constraint the ratio α'/α** at the level **$O(10^{-6})$** for direct searches and **$O(10^{-7} – 10^{-8})$** for dark boson and dark Higgs searches.

SuperB could improve these limits with a **factor 10 – 100** depending on the background level. **Sensitivity for dark photon search** should be **at the level of JLab experiments or better, especially above a few hundred MeV**.

Not clear yet what LHC could say, since the production mechanism for hidden sector particles are more complicated and the performance for reconstructing very low mass resonances varies for each experiment. Keep an eye on it....

More information at
http://www.slac.stanford.edu/BFROOT/www/Physics/Analysis/AWG/DarkForce

THANK YOU_D