Search for dark sectors at *BABAR*

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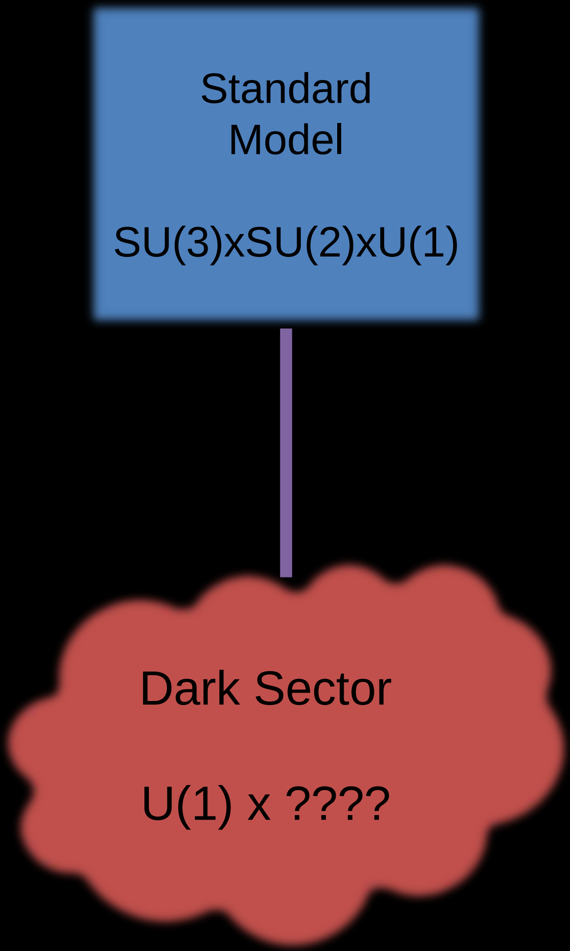
On behalf of the *BABAR* Collaboration

Mini-workshop at Victoria
Victoria – September 2014

A new possibility – dark sectors

- Recent anomalies observed by satellite and terrestrial experiments have motivated dark matter models introducing a new sector with a 'dark' force.
- Dark sector = new particles that do not couple directly to the SM content, but…
- There are "portals" between the dark sector and the SM.
- Implications for astrophysics, cosmology and particle physics.
- In particular, low-energy colliders and fixed target experiments offer an ideal environment to probe these new ideas.



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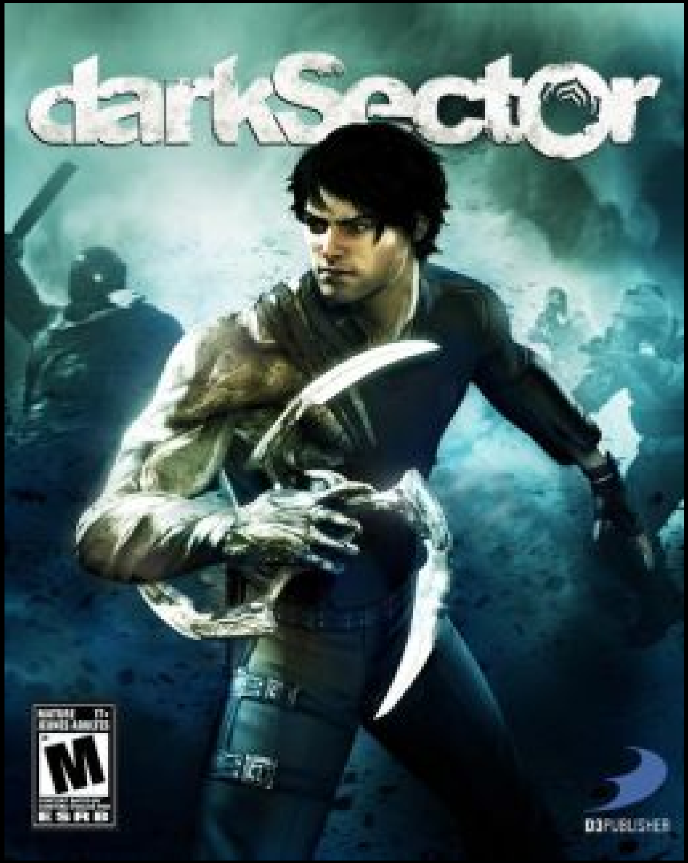


The "portals"

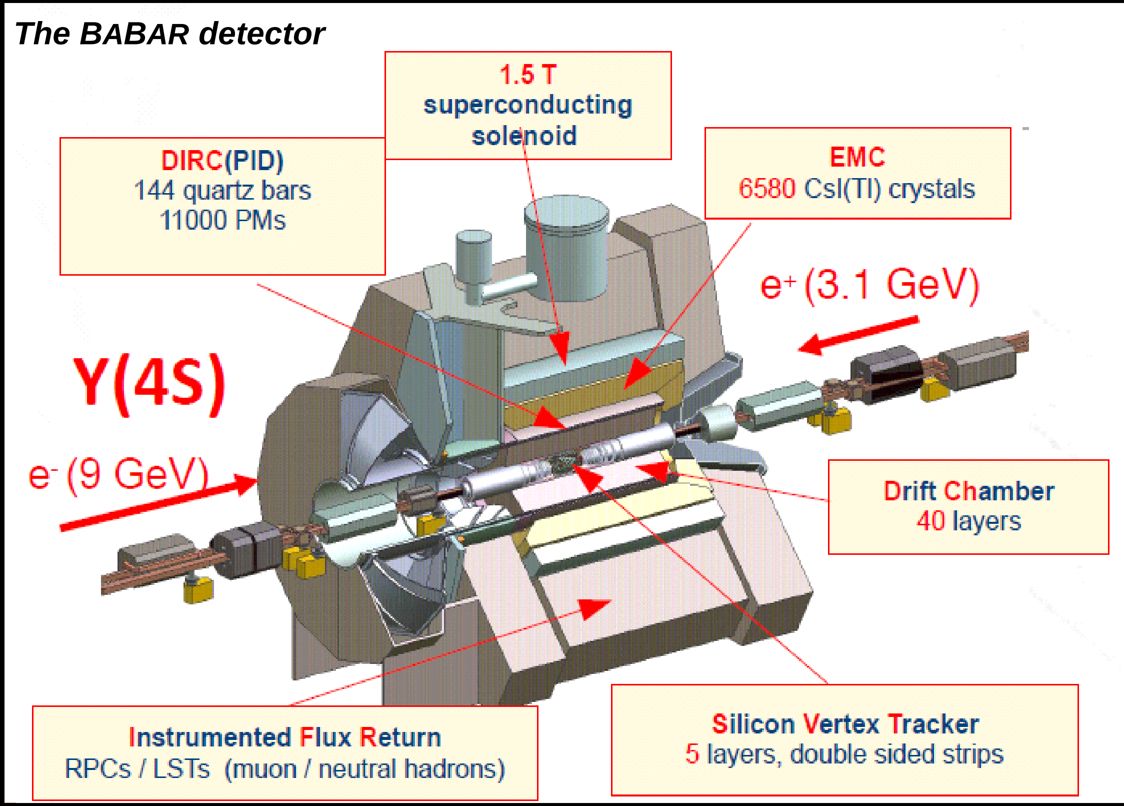
Lowest dimensional operators connection hidden sectors to the SM
(higher dimensional operators are mass suppressed)

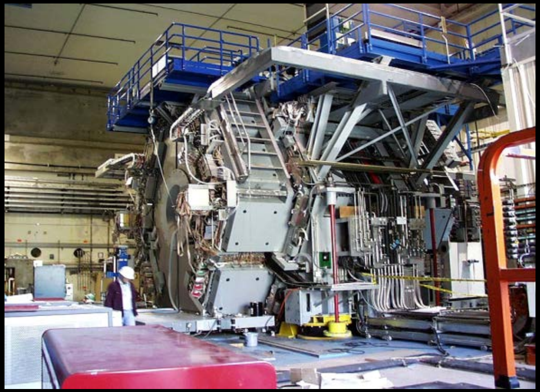
Vector	$\varepsilon F^{Y,\mu\nu} F'_{\mu\nu}$	Hidden photon
Axion	$f_a^{-1} F^{\mu\nu} F_{\mu\nu} a$	Axion / ALP
Scalar	$\lambda H^2 S^2 + \mu H^2 S$	Hidden scalar / exotic Higgs decays
Neutrino	$\kappa(HL)N$	Sterile neutrino

At low-energy scale, light vector portal is the most accessible,
but the scalar portal can also be probed

The *BABAR* experiment @ SLAC (1999 - 2008)

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





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

Possible dark sector searches at *BABAR*

Search for dark photon

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

Search for dark boson(s)

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

Search for dark photon in meson decays

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

Search for dark hadrons

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

Search for dark Higgs boson

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

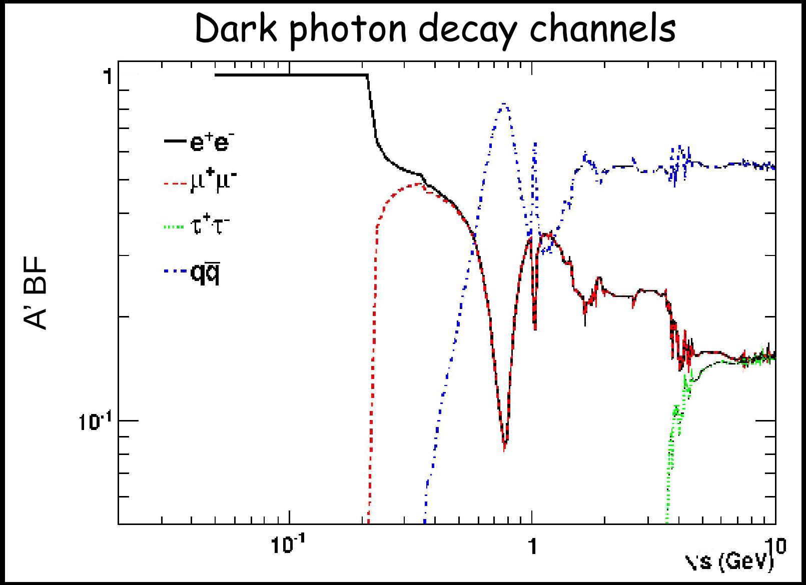
Search for dark scalar (s)

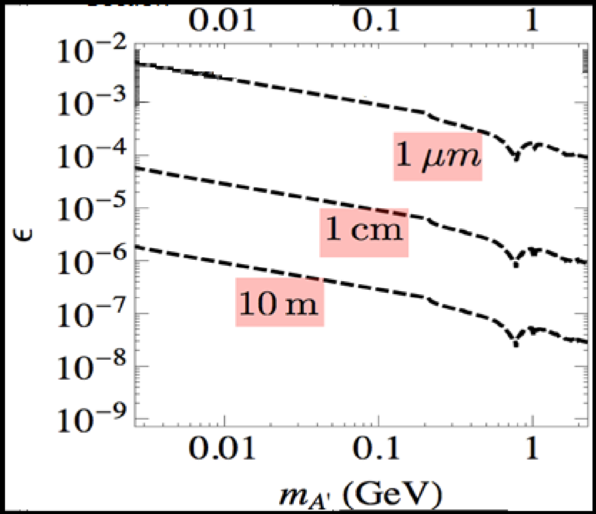
$B \to K^{(*)}s \to K^{(*)}\, l^+l^-$
$B \to Ks \to K\nu\nu$
$Y \to \gamma$ + invisible
$B \to ss \to 2(l^+l^-)$

Possibility to explore the dark sector structure !

Dark photon and particle physics

- Can produce dark photons. In fact, photons in any process can be replaced by dark photons (with an extra factor of ε).
- Decays back to lepton/quark pairs → search for resonances. Lepton contribution dominates at low masses, and is still ~30% at high masses!
- Dark photon width is small (~ $m\varepsilon$) and could be short or long-lived → prompt or displaced decay vertex.
- Potential to probe displaced vertex at Belle II for low masses with enough luminosity?





Dark photon and particle physics

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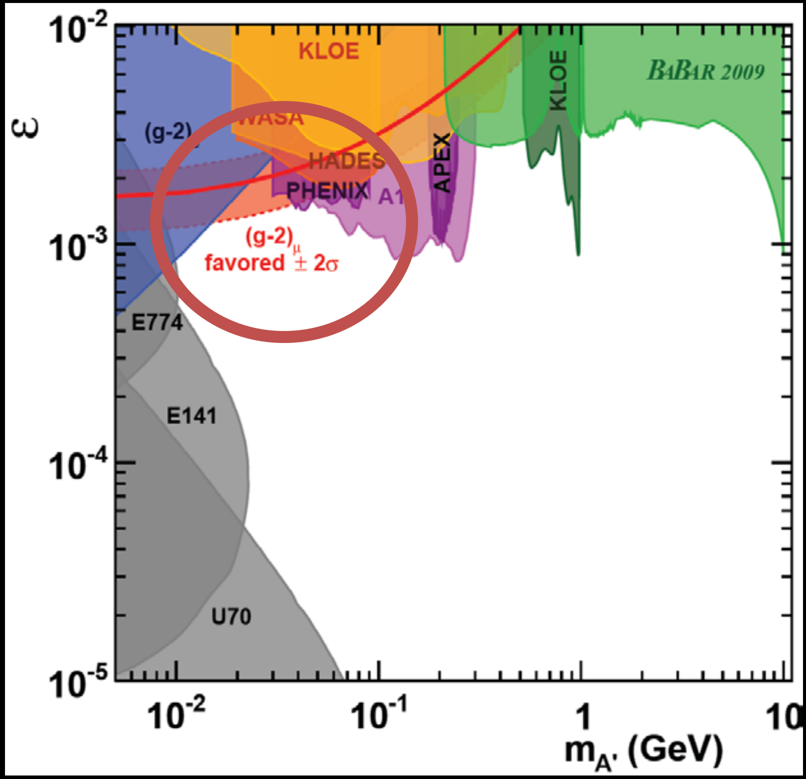
- Dark photon width is small (~ $m\varepsilon$) and could be short or long-lived → prompt or displaced decay vertex.
- Potential to probe displaced vertex at Belle II for low masses?
- Recent constraints still leave a lot of space to explore

Constraints on ε vs. $m_{A'}$



Pospelov;
Bjorken, Essig, Schuster, Toro
Andreas, Niebuhr, Ringwald
Batell, Pospelov, Ritz;
Essig, Harnik, Kaplan, Toro
Blumlein, Brunner;

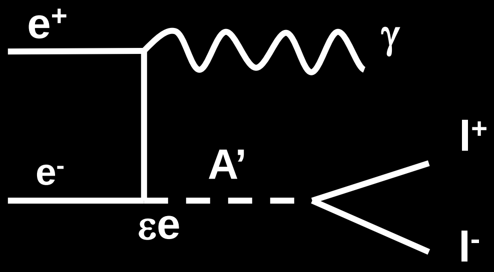
Dent, Ferrer, Krauss
Essig Schuster, Toro, Wojtsekhowski
KLOE, APEX, MAMI/A1 Collab.
Davoudiasl, Lee, Marciano;
Endo, Hamaguchi, Mishima

Low-energy high-luminosity e^+e^- colliders offer a low-background environment to search for MeV/GeV-scale hidden sector (in particular GeV scale) and probe their structure

Direct dark photon production

A dark photon can be produced in

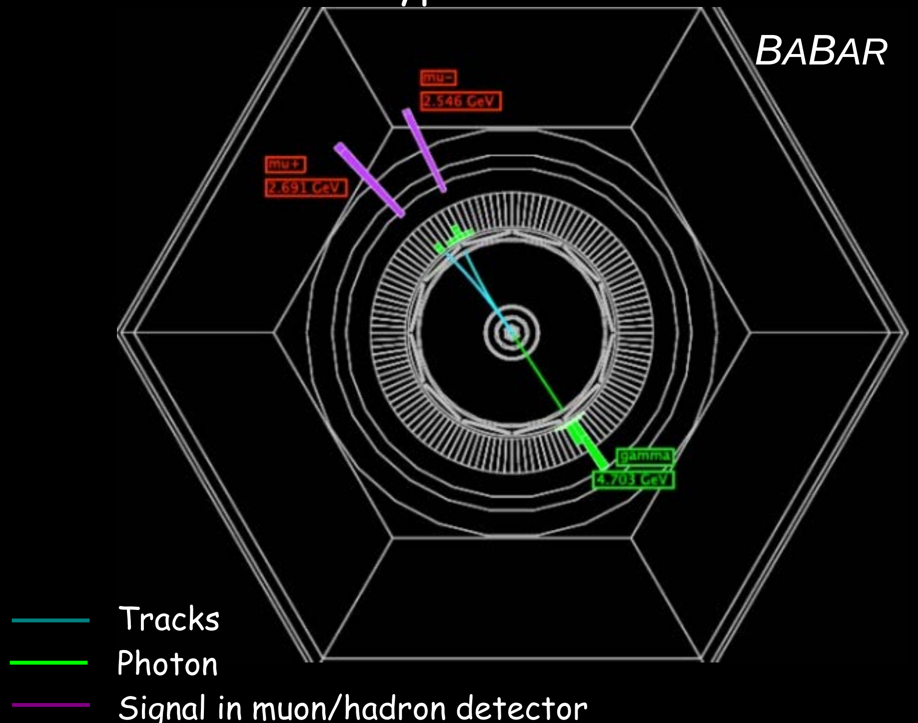
$e^+e^- \rightarrow \gamma A', A' \rightarrow e^+e^-, \mu^+\mu^-$



Event selection

- 2 tracks + 1 photon
- Constrained fit to the beam energy and beam spot
- Particle identification (e/mu)
- Kinematic cuts to improve purity
- Quality cuts on tracks and photons

Typical event

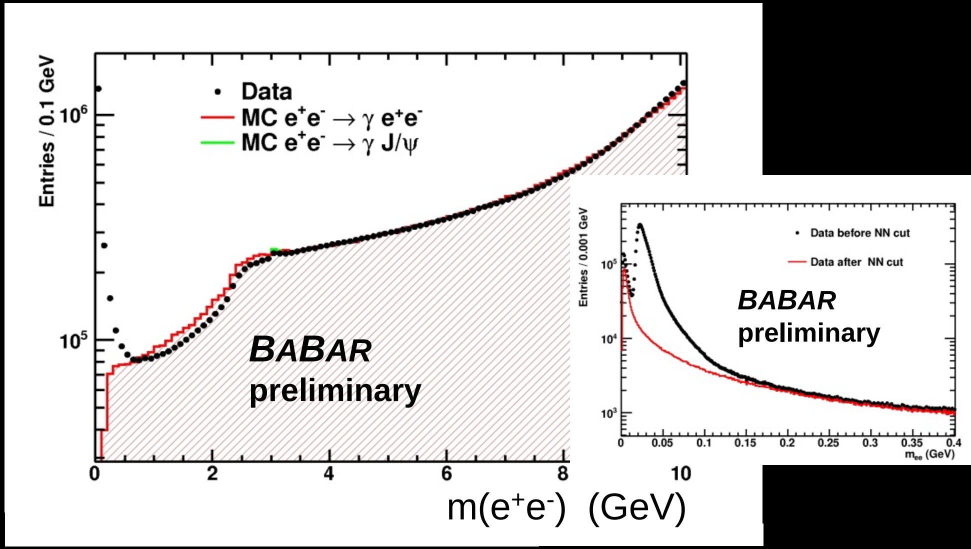


Direct dark photon production

submitted to PRL
arXiv:1406.2980

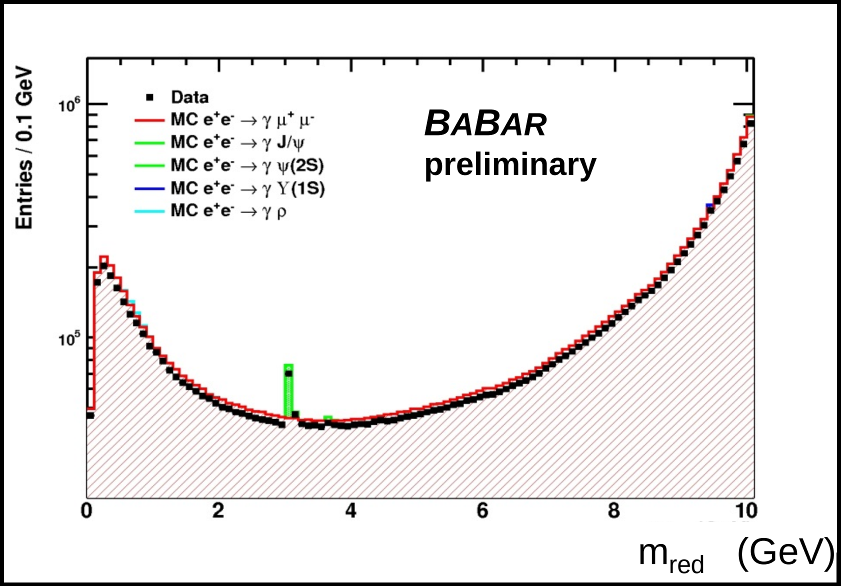
Di-electron mass spectrum

- Globally well reproduced by BHWIDE above 1 GeV, cut-off in the MC (co-linear tracks) affects low mass region. Madgraph reproduces well the low mass region.
- Background from photon conversions suppressed by neural network



Di-muon mass spectrum

- Plot the reduced mass (smoother near threshold): $m_{red} = (m_{\mu\mu}^2 - 4\, m_\mu^2)^{1/2}$
- Globally well reproduced by KK2F, correct for differences in efficiencies

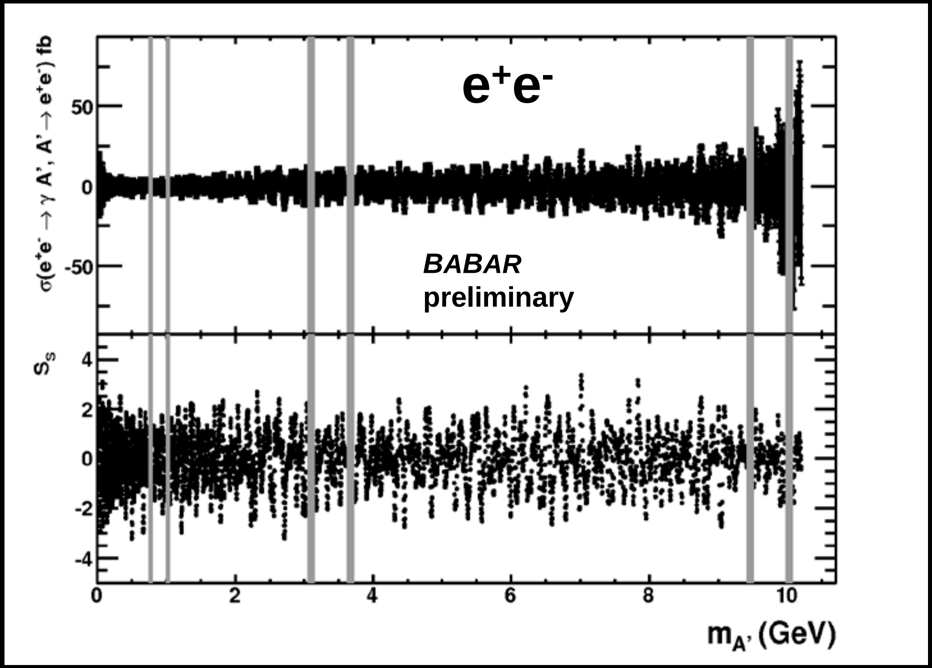


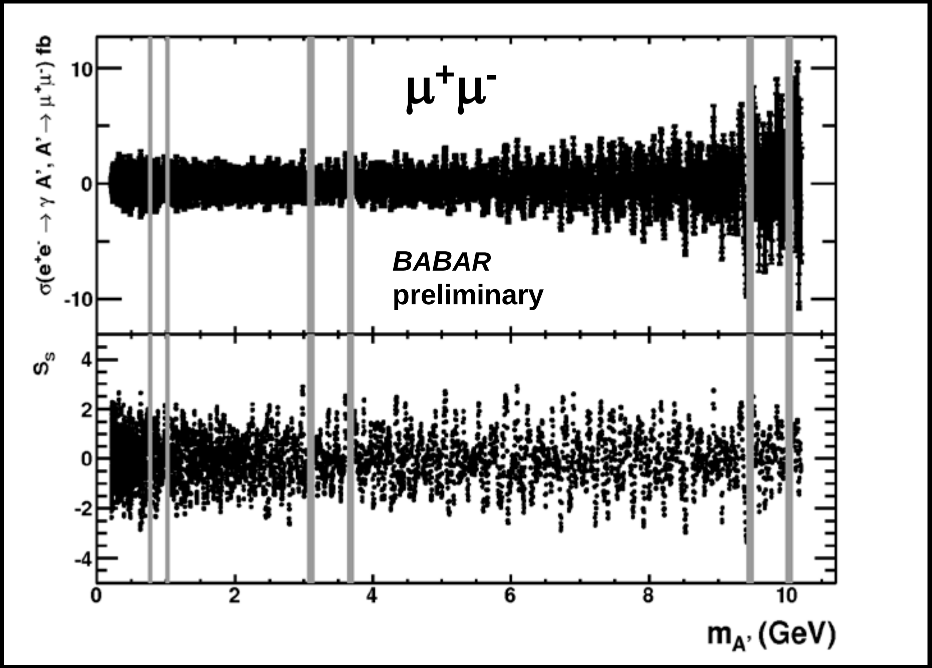
Good data-MC agreement at the J/ψ, $\Psi(2S)$, $\Upsilon(1S)$ resonances

Results – cross sections

submitted to PRL
arXiv:1406.2980

Results on $\sigma(e^+e^- \rightarrow \gamma A', A' \rightarrow l^+l^-)$ for combined Y(2S,3S,4S) datasets



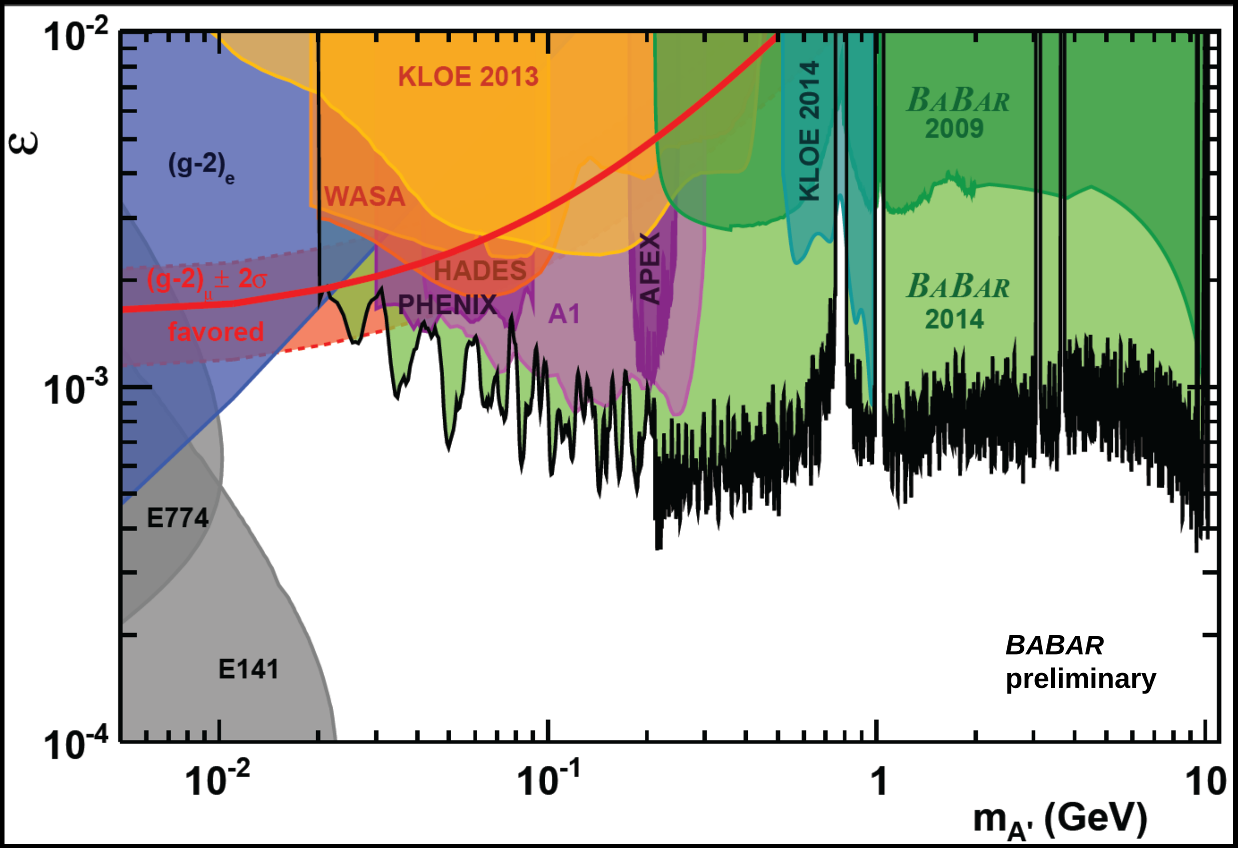


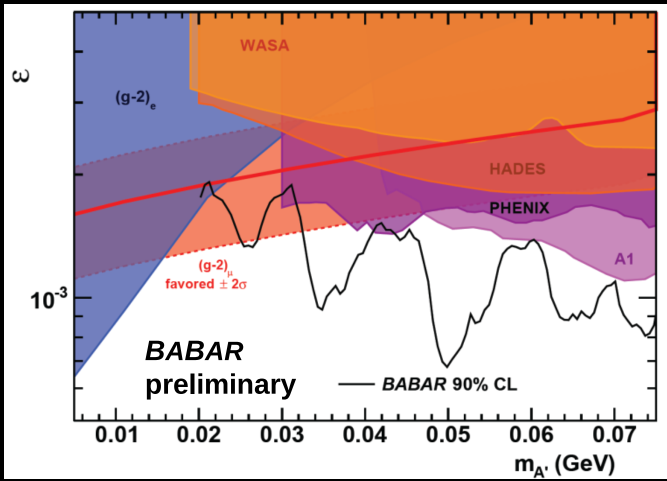
Largest significances:

3.4σ for electrons @ 7.02 GeV $\rightarrow$ 0.6σ with trial factors
2.9σ for muons @ 6.09 GeV $\rightarrow$ 0.1σ with trial factors

Results – dark sector mixing

submitted to PRL
arXiv:1406.2980

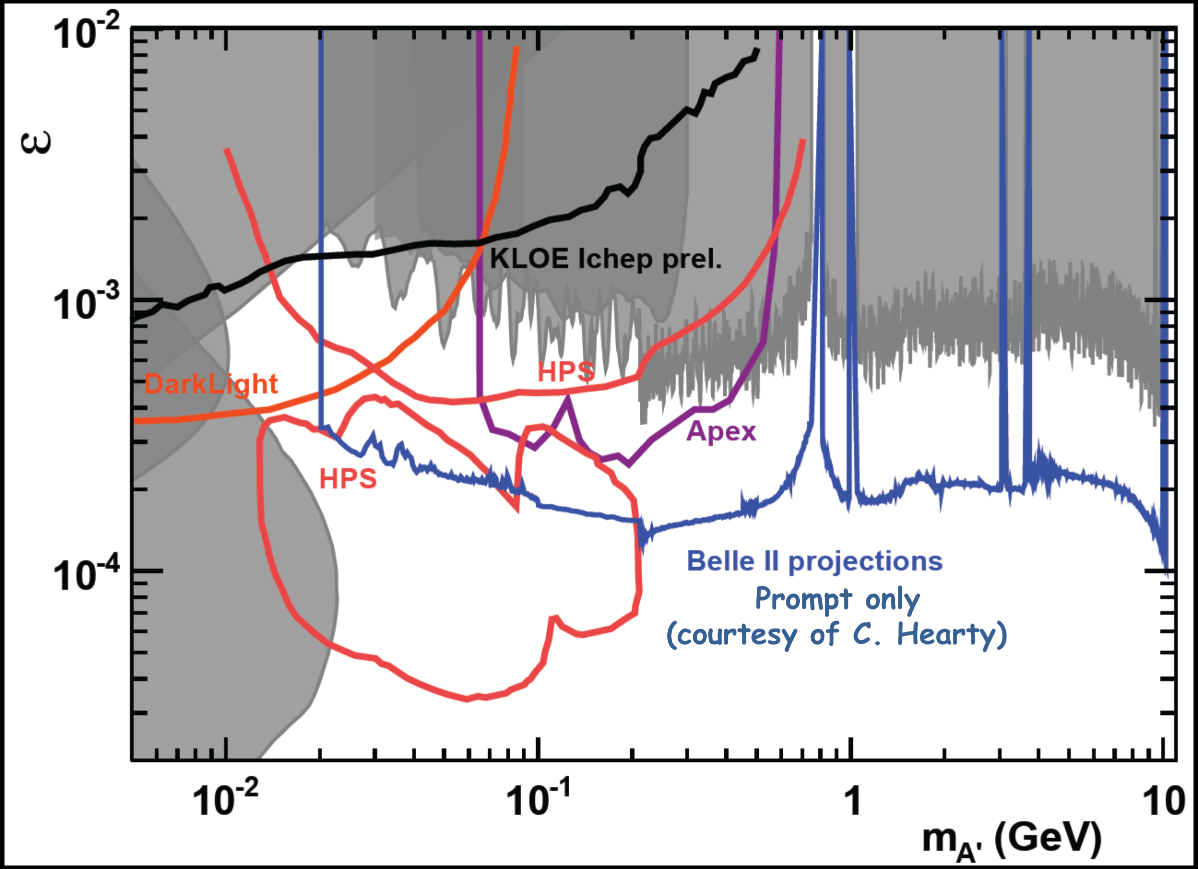




- Exclude a substantial fraction of the remaining region favored by the "g-2" measurement and improve the existing constraints over a wide range of masses.
- An analysis of the $e^+e^- \rightarrow \gamma A'$, $A' \rightarrow \pi^+\pi^-$ final state (not included yet) can further probe the region near the ρ meson.

Results – dark sector mixing

Comparison with expected sensitivity of future experiments



Dedicated experiments will be more sensitive in the low mass region, but B-factories can set the stringent limits above ~500 MeV arxiv:0808.0017

Invisible dark photon decays

- Several scenarios where dark photons decay to invisible final states, e.g lighter dark sector particles (sub-GeV),…

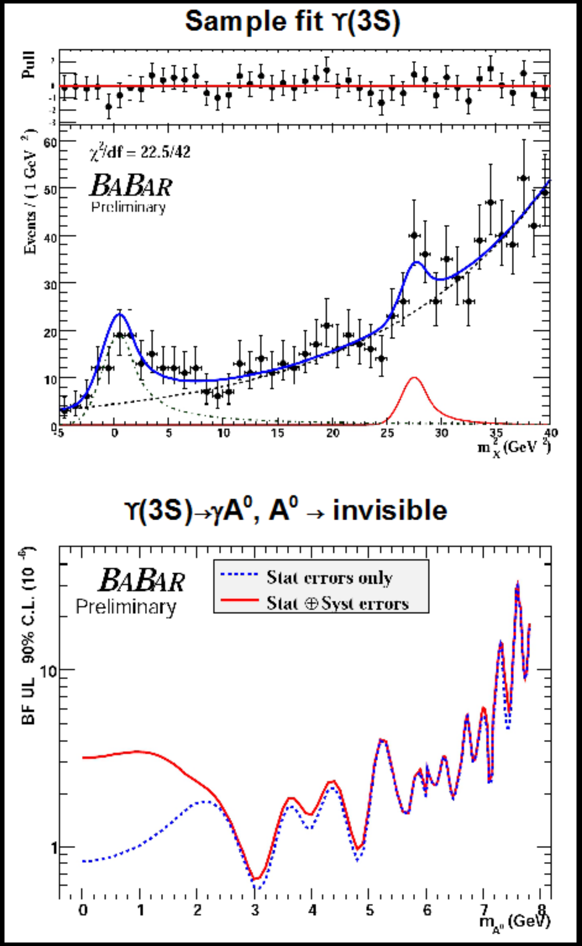
- At e^+e^- colliders, we can search for

$$e^+e^- \to \gamma A' \ , \ \ A' \to \text{invisible}$$

by tagging the recoil photon in "single photon" events.

- Currently only a measurement of
  $\Upsilon(2S,3S) \to \gamma A^0, A^0 \to$ invisible
  at *BABAR* with A^0 a light CP-odd Higgs

$\Upsilon(3S) \to \gamma A^0, A^0 \to$ invisible,
new analysis in progress + extension to A'



Invisible dark photon decays

Invisible dark sector

- Several scenarios where dark photons decay to invisible final states, e.g lighter dark sector particles (sub-GeV),…

- At e^+e^- colliders, we can search for

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- Currently only a measurement of

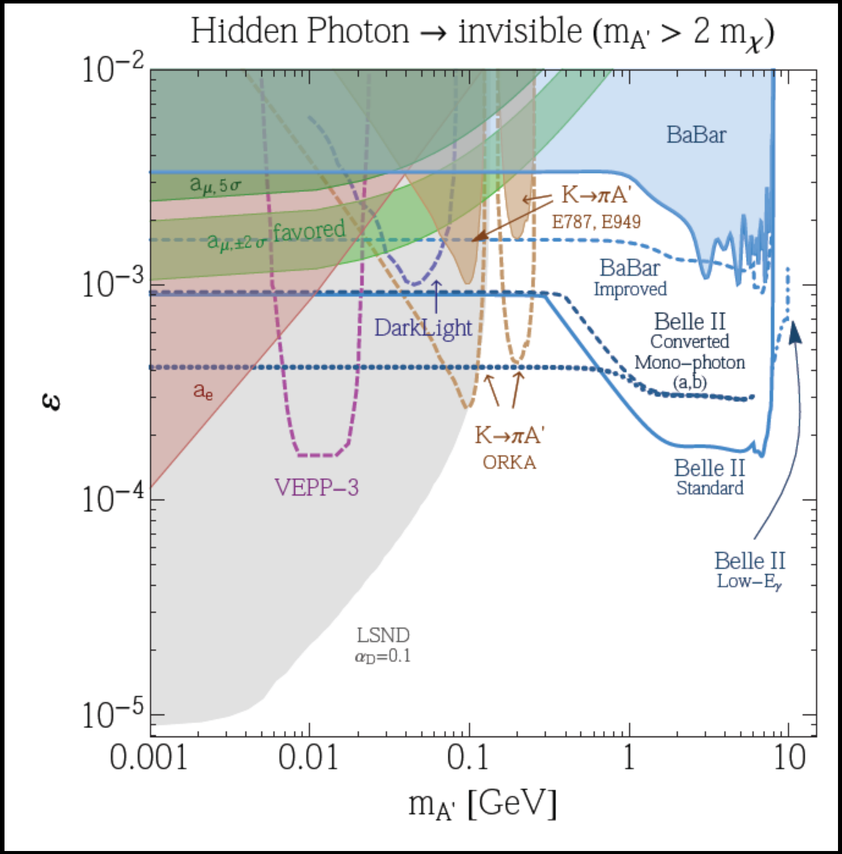
  $$\Upsilon(2S,3S) \to \gamma A^0,\; A^0 \to \text{invisible}$$

  at *BABAR* with A^0 a light CP-odd Higgs

- Analysis extended to full dataset and the dark photon case, expect limits on ε at the level of 10^{-3}.

- Also constraints from (g-2)e, (g-2)μ, $K\to\pi\nu\nu$ decays

Essig *et al.*, arXiv:1309.5084



Major improvement possible with future experiments (e.g. Belle II)

Dark Higgs boson

- Dark photon mass is generated via the Higgs mechanism, adding a dark Higgs boson (h')

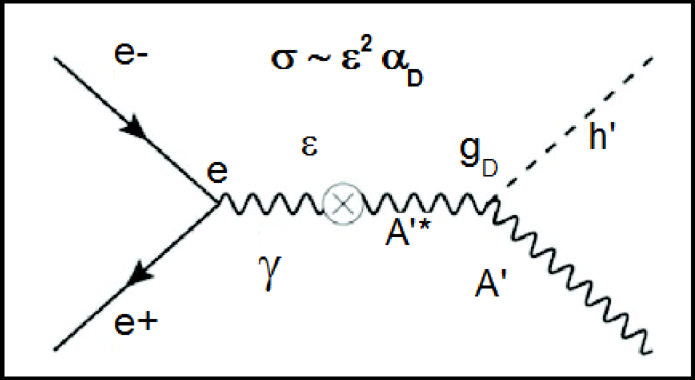
- A minimal scenario has a single dark photon and a single dark Higgs boson.

- The Higgsstrahlung process

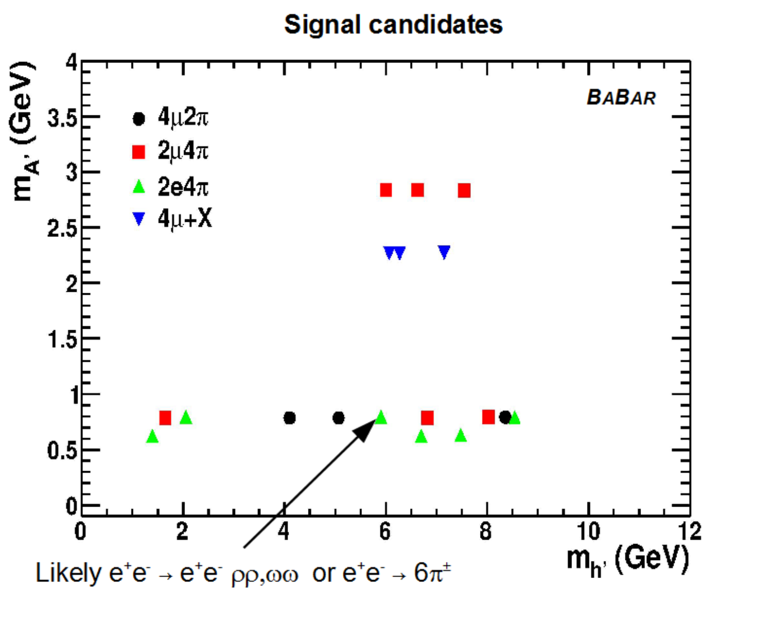
$$e^+e^- \rightarrow A'^* \rightarrow h'\ A'$$

is only suppressed by ε^2 and has low bkg.

- Also sensitive to the dark sector coupling constant $\alpha_D = g_D^2 / 4\pi$



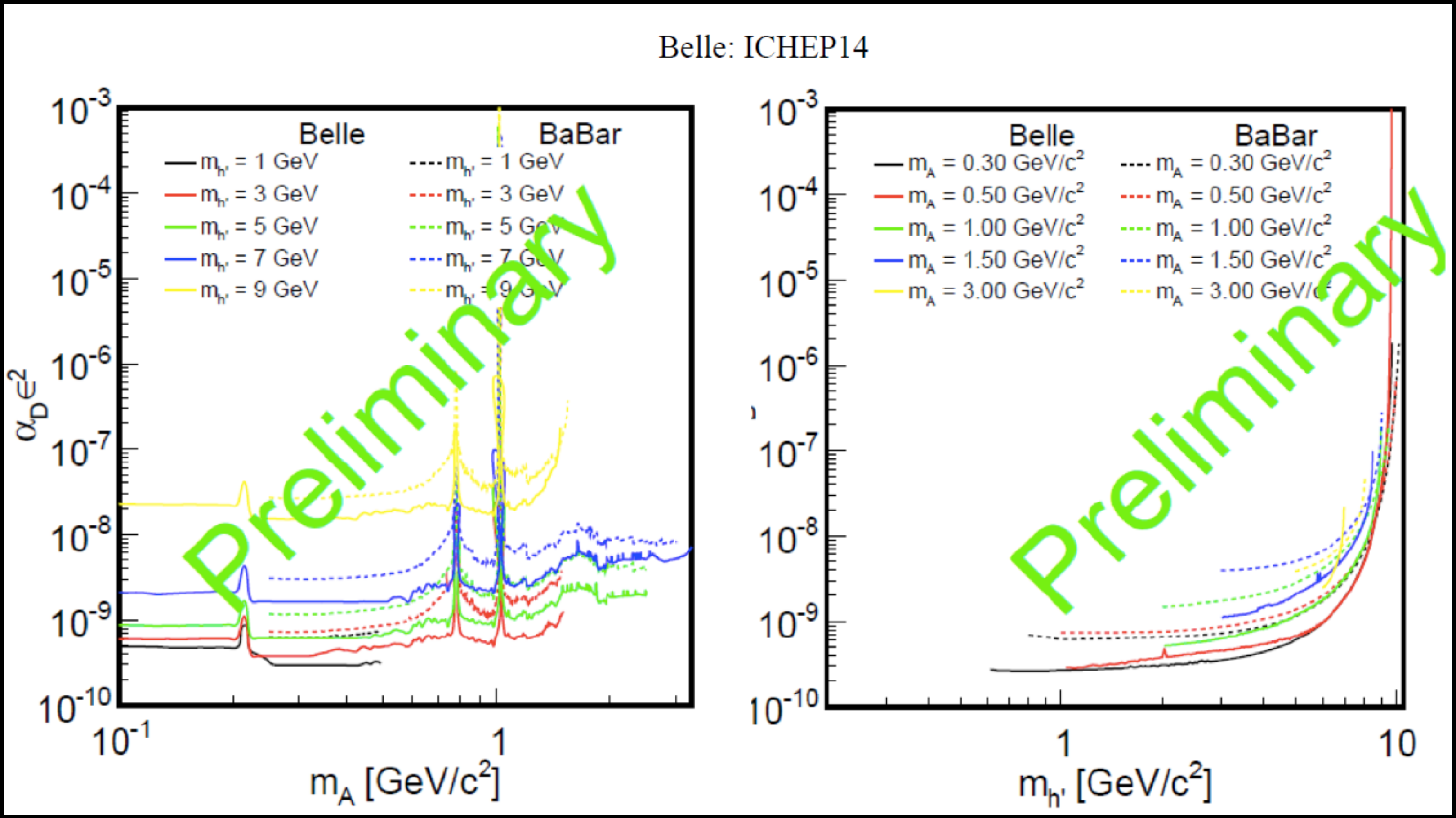
Search for prompt h' decays :
$e^+e^- \rightarrow A'^* \rightarrow h'\ A',\ h' \rightarrow A'\ A'$



See 6 events, all with hadrons (each event is plotted 3 times)

Dark Higgs boson

BABAR: PRL 108 (2012) 211801

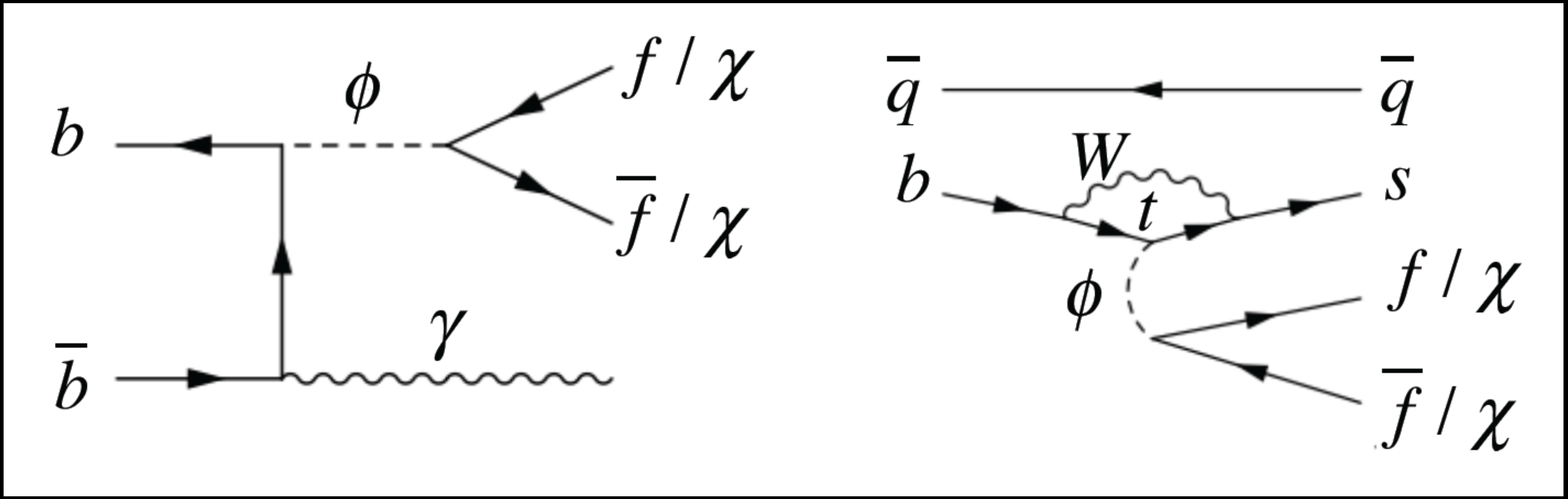


- Assume $\alpha_D = 1/137$, constraints on ε down to a few 10^{-4} (light dark Higgs must exist)
- Almost background free environment, Belle II could improve by factor 100!

Scalar portal

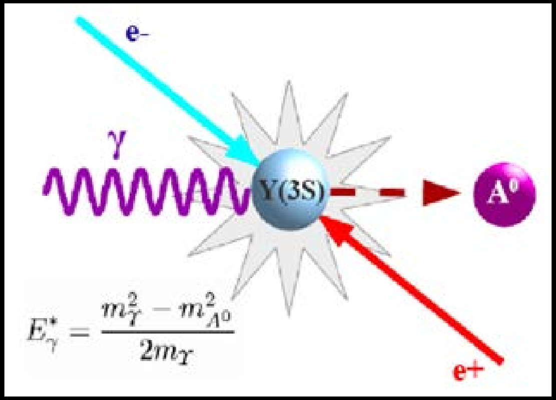
Various scenarios of new scalar (ϕ) that mixes with the SM Higgs, sometimes adding new fermions (χ) as well (e.g. JHEP 1402, 123 (2014); PLB 727, 506 (2013))

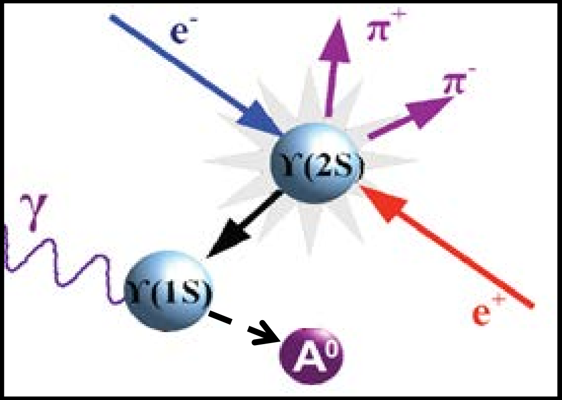
Scalar can be produced in Upsilon or B decays, and decay back to SM fermions or dark sector particles



Signature similar to light CP-odd higgs decays or $B \to K^{(*)} ll$ and $B \to K^{(*)} \nu\nu$ decays

Search for light CP-odd Higgs A^0 predicted in some NMSSM scenarios in Υ decays



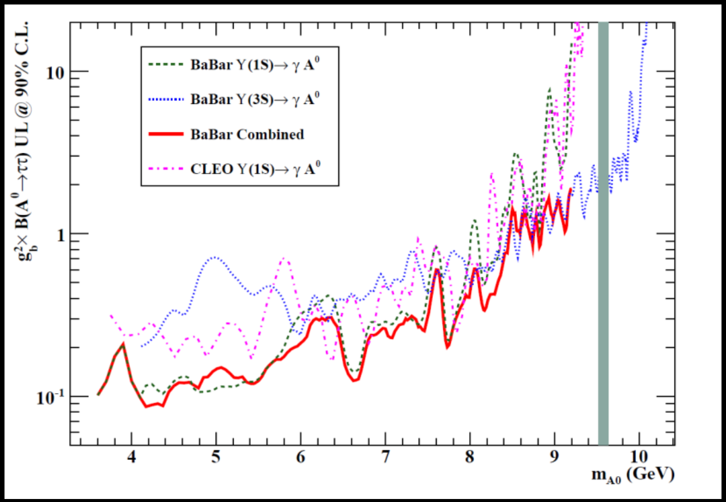


- Search for fully/partially reconstructed A^0 or monochromatic photon in recoil mass
  - **$\Upsilon(2S,3S) \rightarrow \gamma A^0, A^0 \rightarrow \mu^+\mu^-$**
    PRL103 (2009) 081803
  - **$\Upsilon(3S) \rightarrow \gamma A^0, A^0 \rightarrow \tau^+\tau^-$**
    PRL103 (2009) 181801
  - **$\Upsilon(2S,3S) \rightarrow \gamma A^0, A^0 \rightarrow$ hadrons**
    PRL107 (2011) 221803
  - **$\Upsilon(2S,3S) \rightarrow \gamma A^0, A^0 \rightarrow$ invisible**
    arXiv: 0808.0017 + new analysis in progress

- Select $\Upsilon(1S)$ from dipion transition $\Upsilon(2S,3S) \rightarrow \pi^+\pi^- \Upsilon(1S)$
- Search for fully/partially reconstructed A^0 or monochromatic photon in $\Upsilon(1S)$ frame
  - **$\Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow$ invisible**
    PRL107 (2011) 021804
  - **$\Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow \mu^+\mu^-$**
    PRD 87 (2013) 031102
  - **$\Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow \tau^+\tau^-$**
    PRD 88 (2013) 071102
  - **$\Upsilon(1S) \rightarrow A^0, A^0 \rightarrow gg$ or $s\bar{s}$**
    PRD 88 (2013) 031701

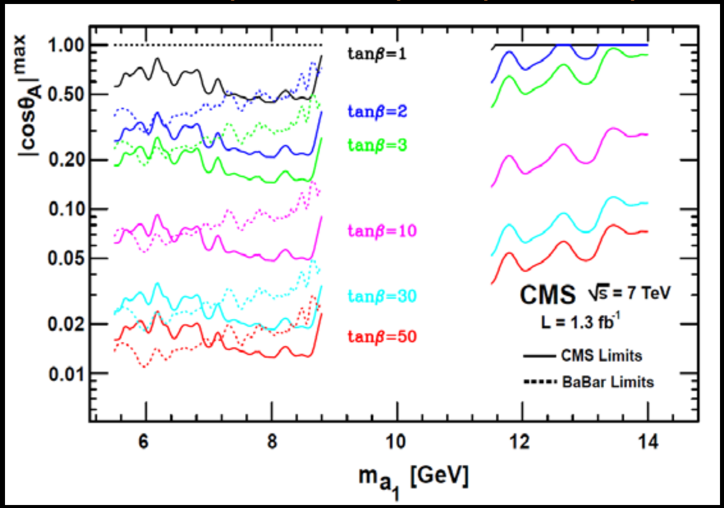
Light CP-odd higgs A^0

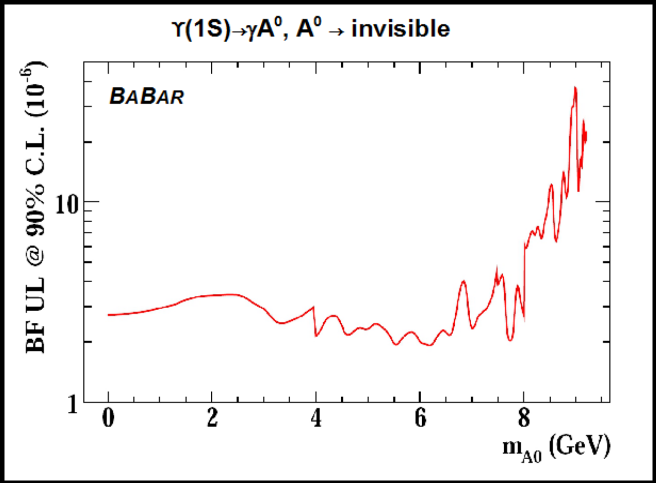
$A^0 \rightarrow \tau^+\tau^-$



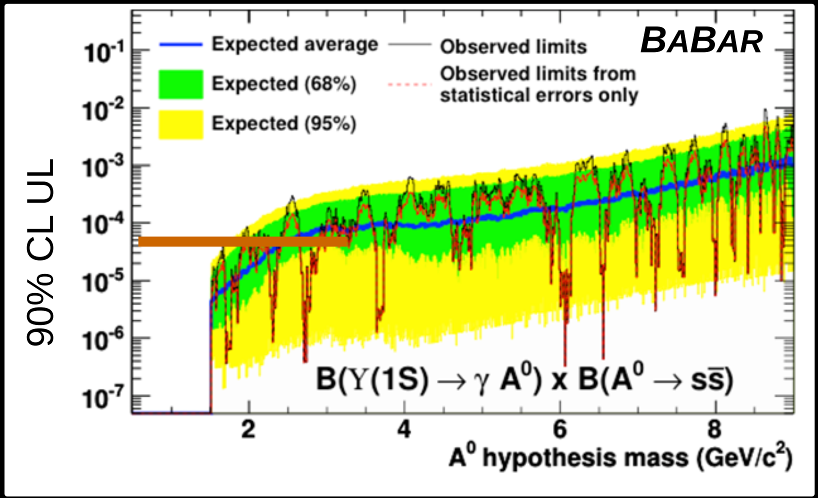
$A^0 \rightarrow \mu^+\mu^-$

CMS (PRL 109 (2012) 121801)





$A^0 \rightarrow s\bar{s}$

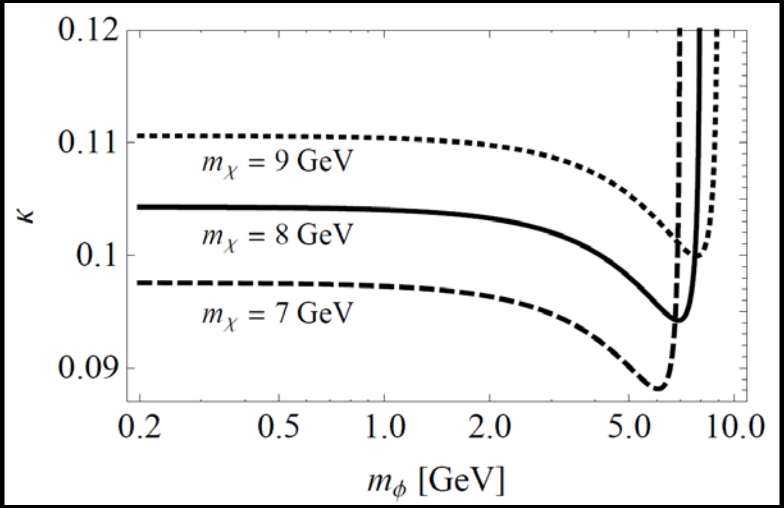


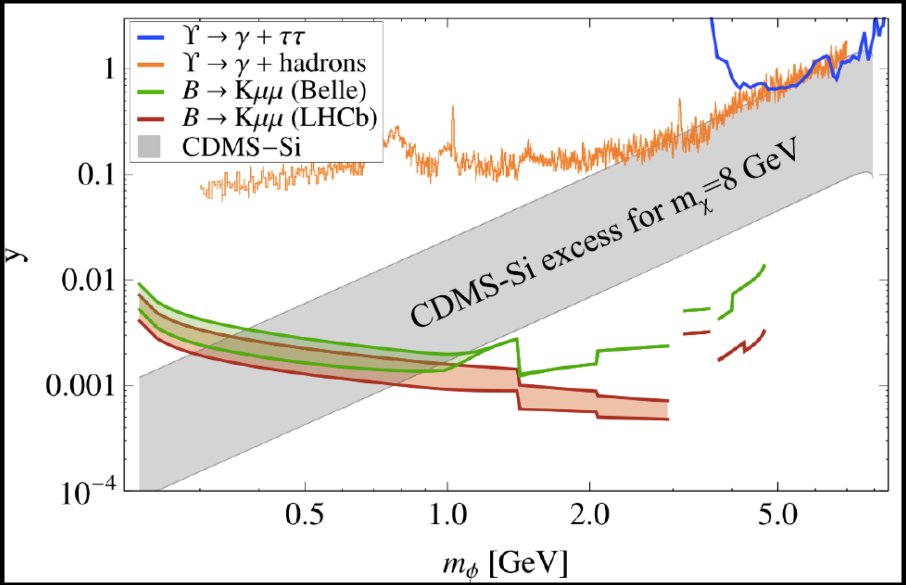
No sign of light CP-odd higgs

Dark matter model with new Majorana fermion (χ) and scalar (ϕ) mediating the DM-SM interaction (PLB 727, 506 (2013)) to explain the CDMS-SI excess.

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{y\, m_f}{v}\,\phi\,\bar{f}f \;-\frac{1}{2}\kappa\phi\bar{\chi}\chi$$

Fix the value of κ to get the correct relic density





Exclude the 1-5 GeV region, expect further improvement at LHC/Belle II

Weinberg's Higgs portal model with new dark scalar and dark Majorana fermion
(PRD 89, 083513 (2014))

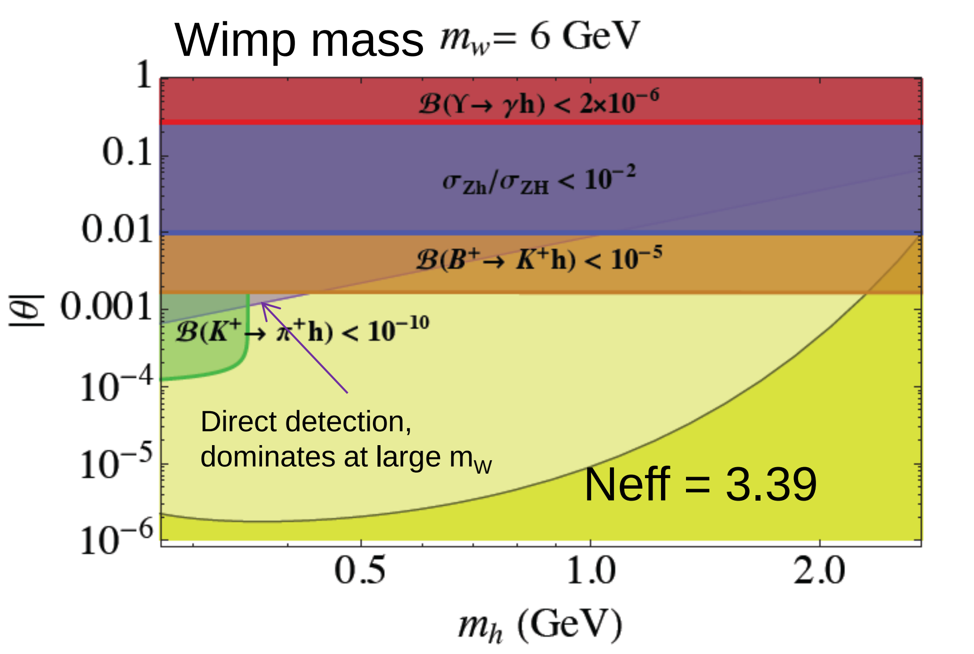
Φ = SM Higgs field

$$\mathscr{L} = \partial_\mu S^\dagger\, \partial^\mu S + \mu^2\, S^\dagger\, S - \lambda (S^\dagger\, S)^2 - \; g_\theta\, (S^\dagger\, S)(\Phi^\dagger\, \Phi) + \mathscr{L}_{\rm SM}$$

$$S = \frac{1}{\sqrt{2}} \left(\langle r \rangle + r(x) \right)\; e^{i\,2\alpha(x)}$$

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} r \\ \phi \end{pmatrix}$$

$$\tan 2\theta = \frac{g_\theta \langle r \rangle \langle \phi \rangle}{\lambda_{\rm SM} \langle \phi \rangle^2 - \lambda \langle r \rangle^2}\,.$$



+ constraints on the relativistic number of d.o.f.

Stringent constraints from B-factories

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$$\mathscr{L} = \partial_\mu S^\dagger\, \partial^\mu S + \mu^2\, S^\dagger\, S - \lambda (S^\dagger\, S)^2 - g_\theta\, (S^\dagger\, S)(\Phi^\dagger\, \Phi) + \mathscr{L}_{\rm SM}$$

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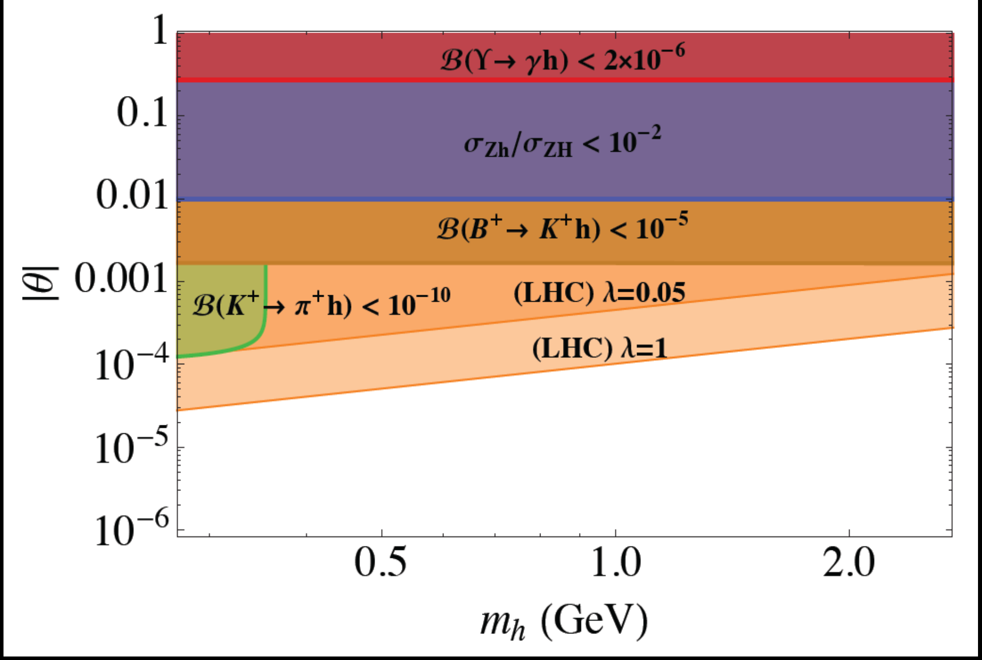


+ constraints on the relativistic number of d.o.f.

LHC can set stringent constraint for large values of λ

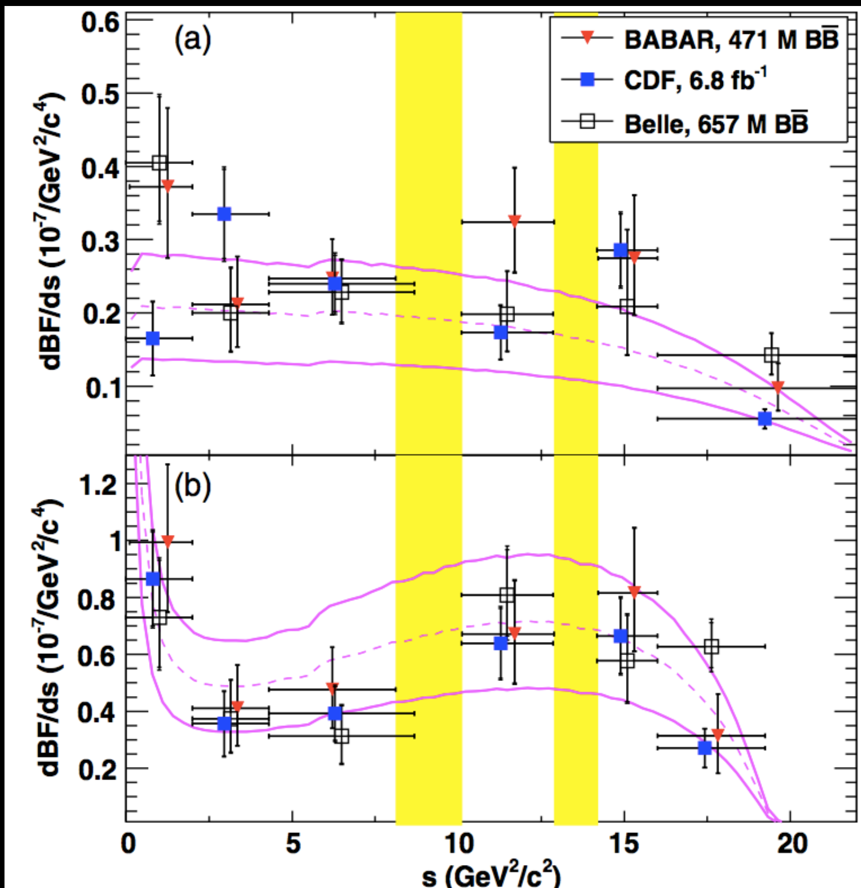
Dark fun

Summary

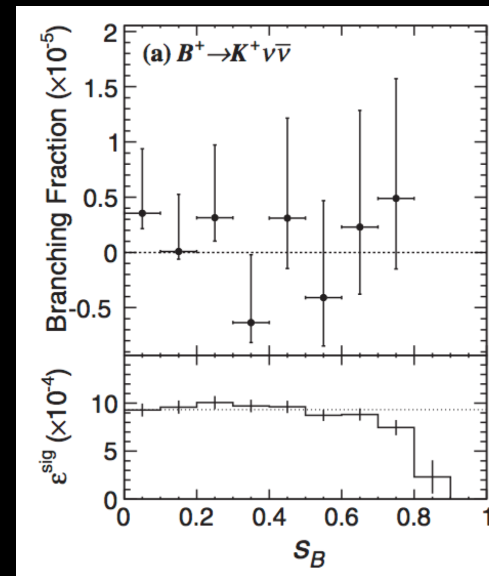
- B-factories offer an ideal environment to search for dark sector: dark photon (visible + invisible), dark Higgs, darkboson,…
- Can probe the structure of dark sector
- Belle II could improve these searches by a factor ~3 – two orders of magnitude, depending on the final state.
- Let me know if you have any interesting idea that could be probed at B-factories…
- Wish list:
  - get once for all a single notation for kinetic mixing, dark photon, dark Higgs,…
  - repository with all the available results (standard plot)
  - Standard tools (MC,…)

Extra material

$B \to Kll$



$B \to K\nu\nu$



Mode	Belle	BABAR
$B^+ \to K^+ \nu\bar{\nu}$	$<5.5 \times 10^{-5}$	$<1.6 \times 10^{-5}$
$B^0 \to K^0_s \nu\bar{\nu}$	$<9.7 \times 10^{-5}$	$<4.9 \times 10^{-5}$
$B^+ \to K^{*+} \nu\bar{\nu}$	$<4.0 \times 10^{-5}$	$<6.4 \times 10^{-5}$
$B^0 \to K^{*0} \nu\bar{\nu}$	$<5.5 \times 10^{-5}$	$<12 \times 10^{-5}$

BABAR PRD 87, 112005 (2013)
Belle PRD 87, 111103 (2013)

BABAR (l^+l^-): PRD 86, 032012 (2012)
Belle (l^+l^-): PRL 103, 171801 (2009)
CDF ($\mu^+\mu^-$): PRL 107, 201802 (2011)

Light scalar model

Batell et al., PRD 83 (2010) 054005

Another model with a single light scalar (S) or pseudo-scalar (a)

Higgs portal	$H^\dagger H\,(AS + \lambda S^2)$
Axion portal	$f_{l,q}^{-1}\,\bar\psi_{l,q}\gamma_\mu\gamma_5\psi_{l,q}\,\partial_\mu a$

Expected limits for *BABAR* on scalar-Higgs mixing angle (θ) and pseudo-scalar couplings ($f_{l,q}$) assuming limits on $BF(B\to K^{(*)}\,l^+l^-)$ for a narrow l^+l^- (pseudo-)scalar at the level of $\sim 10^{-8}$

Scalar - Higgs mixing angle

Form factor

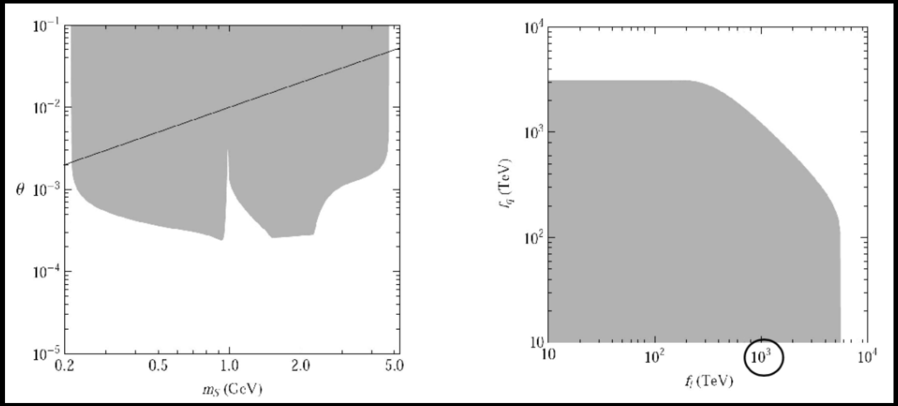
$$\mathrm{Br}_{B\to KS} \simeq 4\times10^{-7}\times\left(\frac{\theta}{10^{-3}}\right)^2 \mathcal{F}_K^2(m_S)\lambda_{KS}^{1/2}$$

$$\mathrm{Br}_{B\to K^*S} \simeq 5\times10^{-7}\times\left(\frac{\theta}{10^{-3}}\right)^2 \mathcal{F}_{K^*}^2(m_S)\lambda_{K^*S}^{3/2}$$

$$\mathrm{Br}_{B\to Ka} \simeq 5\times10^{-6}\times\left(\frac{100\ \mathrm{TeV}}{f_q}\ln\left(\frac{\Lambda_{\mathrm{UV}}}{m_t}\right)\right)^2 \mathcal{F}_K^2(m_a)\lambda_{Ka}^{1/2}$$

$$\mathrm{Br}_{B\to K^*a} \simeq 6\times10^{-6}\times\left(\frac{100\ \mathrm{TeV}}{f_q}\ln\left(\frac{\Lambda_{\mathrm{UV}}}{m_t}\right)\right)^2 \mathcal{F}_{K^*}^2(m_a)\lambda_{K^*a}^{3/2}.$$

Pseudoscalar - lepton(quark) coupling



Limits on pseudo-scalar coupling could be set at O(thousands of TeV)

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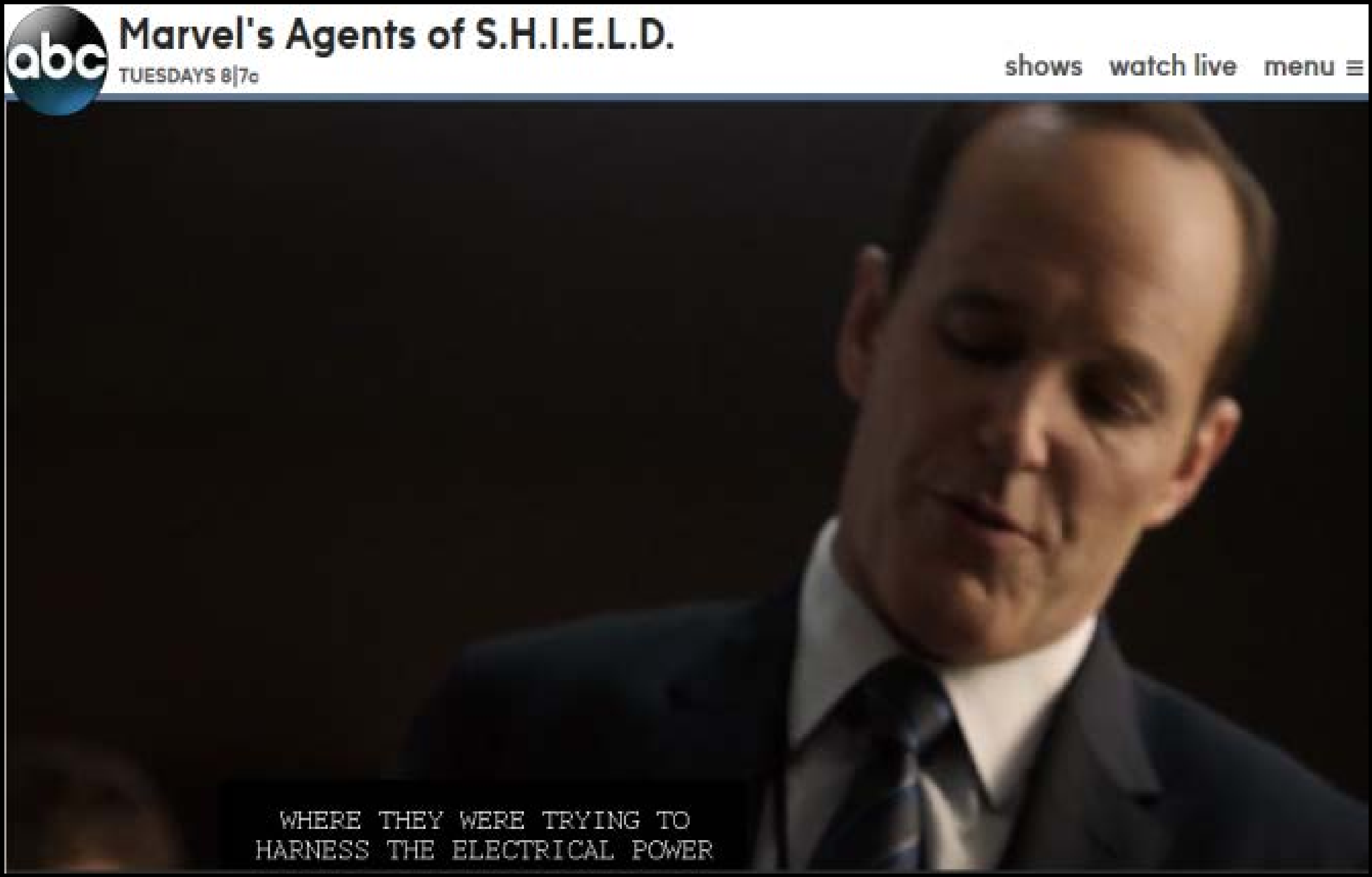
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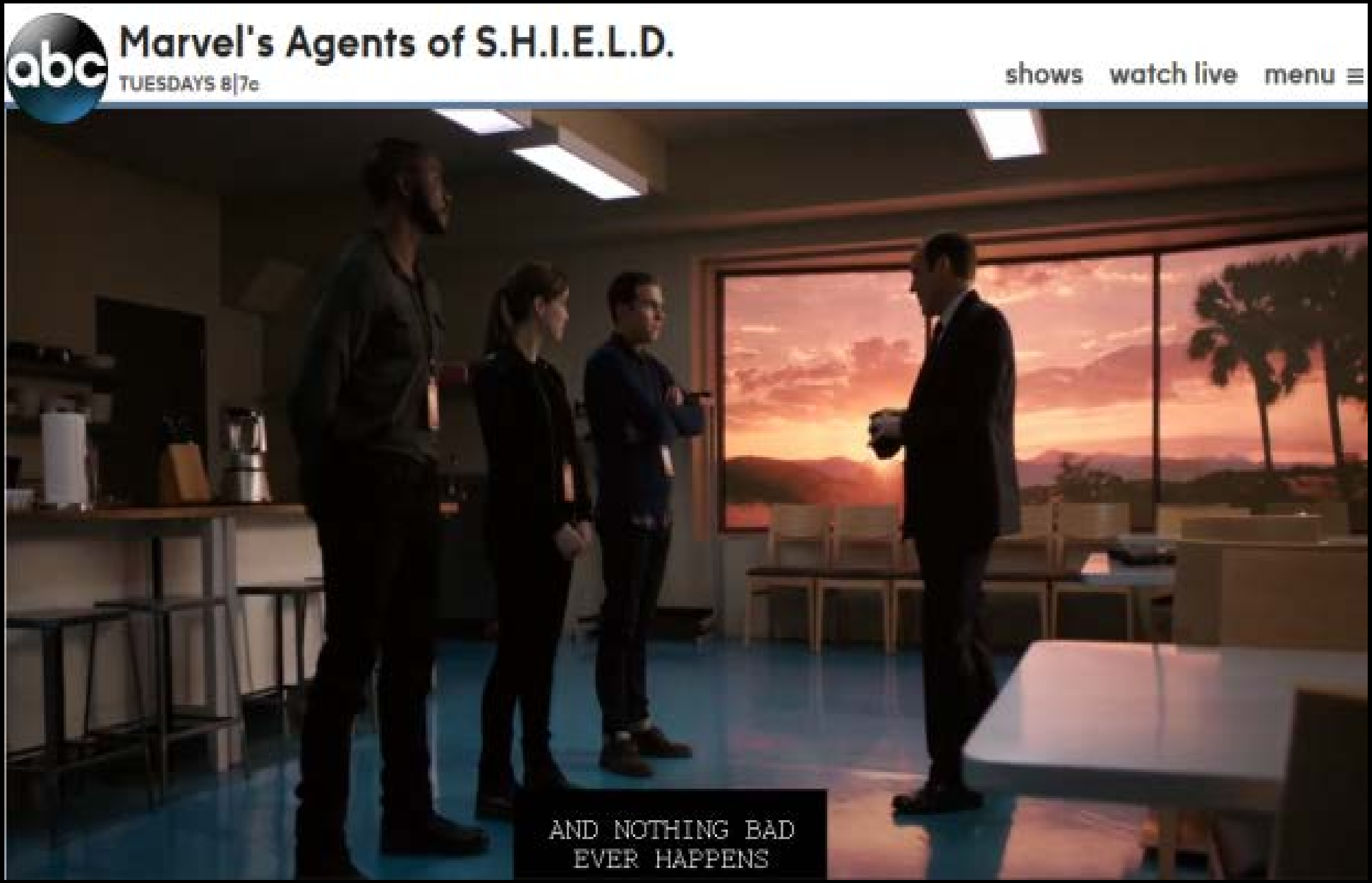
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