BABAR Searches for Hidden Sector Particles

Bertrand Echenard
California Institute of Technology

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Dark Sector

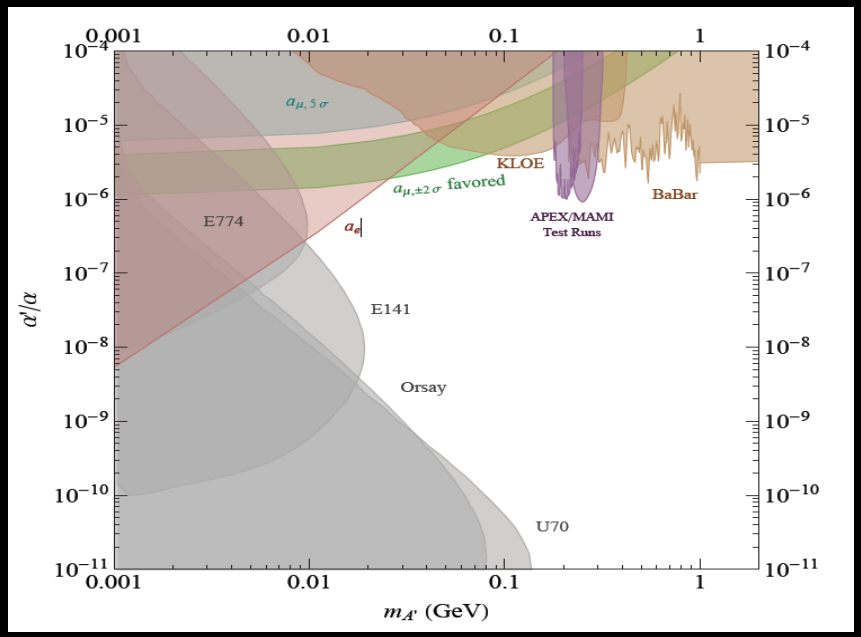
- New dark sector with a $U(1)_D$ gauge group
- New gauge boson: dark photon A' , which could have O(GeV) mass
- Interaction with the SM is via kinetic mixing

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

with a mixing strength ε.

- The dark photon acquires a charge εe, and the coupling of the dark photon to SM fermions is characterized by $\alpha' = \alpha\, \varepsilon^2$
- TeV-scale dark matter particles can annihilate into a pair of gauge bosons, which subsequently decay into SM fermions.

Current limits on ε^2



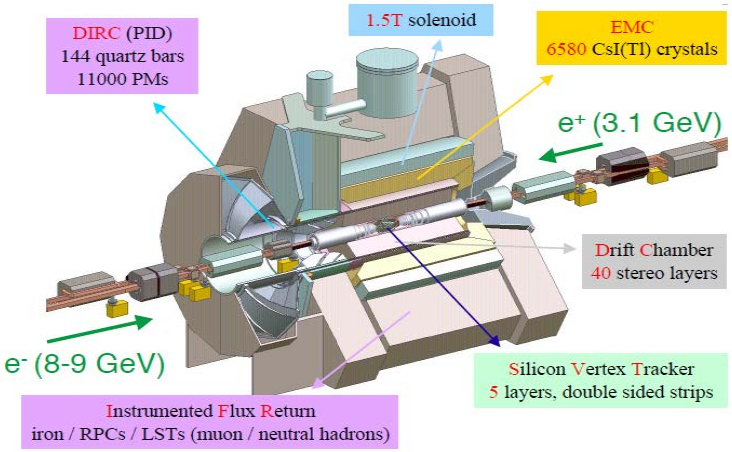
Courtesy: J. Jaros and an unknown theorist(s)

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

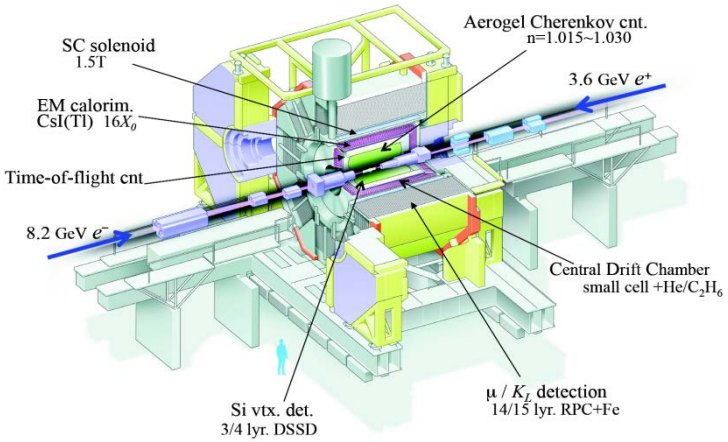
BABAR and Belle experiments

BABAR **/ Belle collected around 550 / 1000 fb^{-1} of e$^+$e$^-$ data around the Υ(4S) resonance**

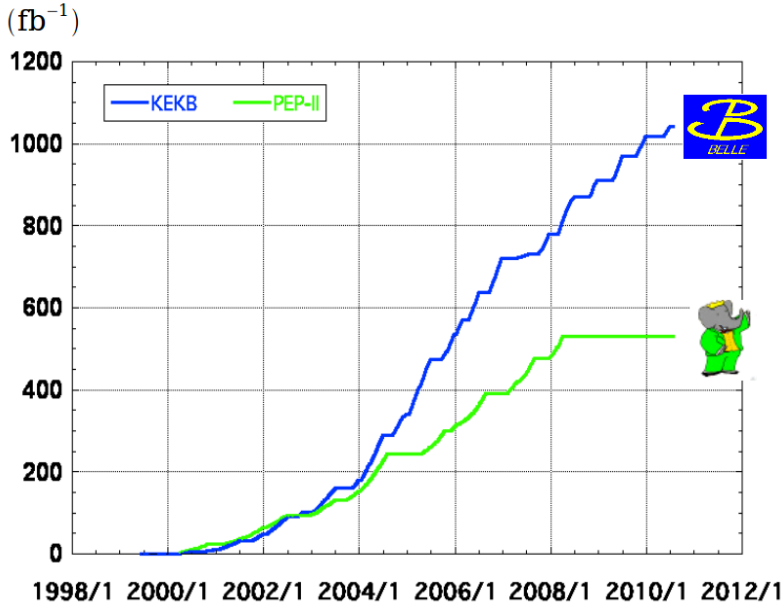
BABAR detector



Belle detector

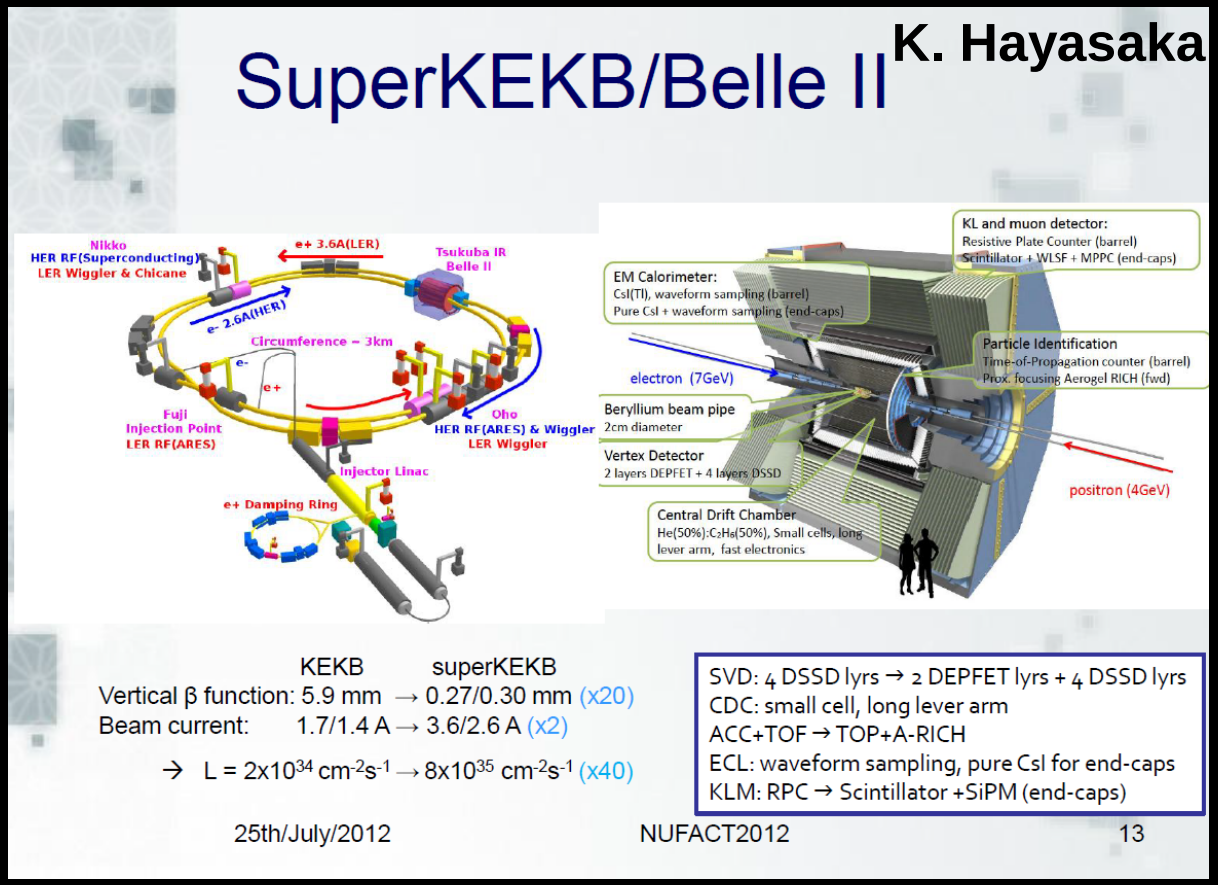


Integrated luminosity of B factories



> 1 ab^{-1}
On resonance:
Υ(5S): 121 fb^{-1}
Υ(4S): 711 fb^{-1}
Υ(3S): 3 fb^{-1}
Υ(2S): 25 fb^{-1}
Υ(1S): 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
Υ(4S): 433 fb^{-1}
Υ(3S): 30 fb^{-1}
Υ(2S): 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}



Should collect about 50 ab^{-1} by 2022

x100 *BABAR* luminosity

→ improve by factor 10-100 current analysis at B-factories depending on background and detector performance

Also Super tau-charm factory proposed at BINP and Frascati (not funded yet).

Larger cross-section for dark photon production (σ~1/s), but lower luminosity,
→ potential results (very) roughly of the same order of those of Belle II.

Possible searches at B-factories

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 Higgs boson

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

Search for dark hadrons

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

Search for dark photon in meson decay

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

Search for dark scalar (s) / pseudoscalar (a)

$B \to K^{(*)}s \to K^{(*)}\, l^+l^-$
$B \to K^{(*)}a \to K^{(*)}\, l^+l^-$
$B \to ss \to 2(l^+l^-)$
$B \to K\, 2(l^+l^-)$
$B \to 4(l^+l^-)$

+ related searches (hidden warped extra dimensions,...)

Can probe hidden structure sector

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Can probe hidden structure sector

Search for dark photon

Search for a single dark photon

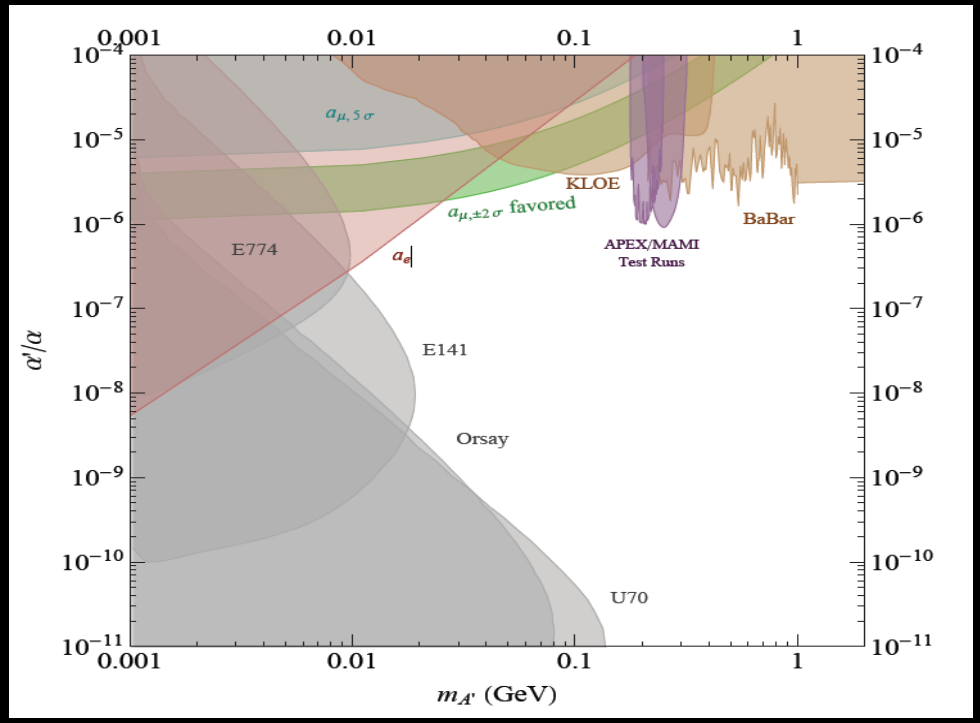
$$e^+e^- \to \gamma\, A' \to \gamma\, l^+l^-,\ \gamma\, q\bar{q}$$

- The simplest case
- Large cross-section
- Large (irreducible) background
- Displaced vertex for low masses and low values of ε^2

No dedicated effort in ~ 1-10 GeV

Luminosity is the key !!!

Projected limits with full *BABAR* dataset for $e^+e^- \to \gamma\, A'$, $A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$



BABAR 40 fb^{-1}

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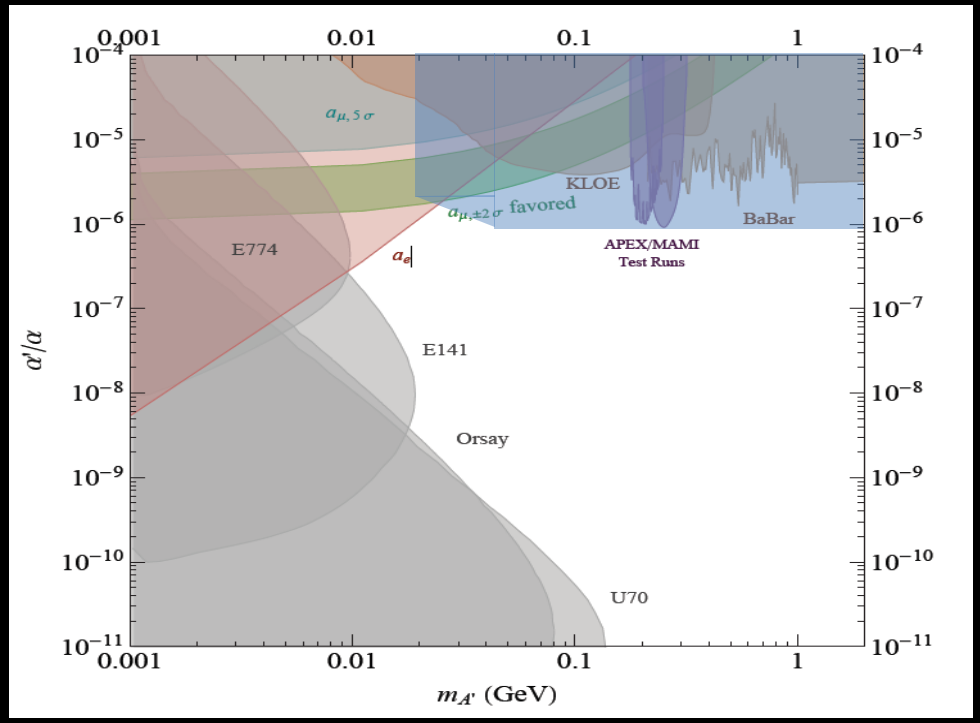

BABAR 40 fb^{-1}
BABAR 500 fb^{-1}

Only an order of magnitude estimate (ripples not shown)

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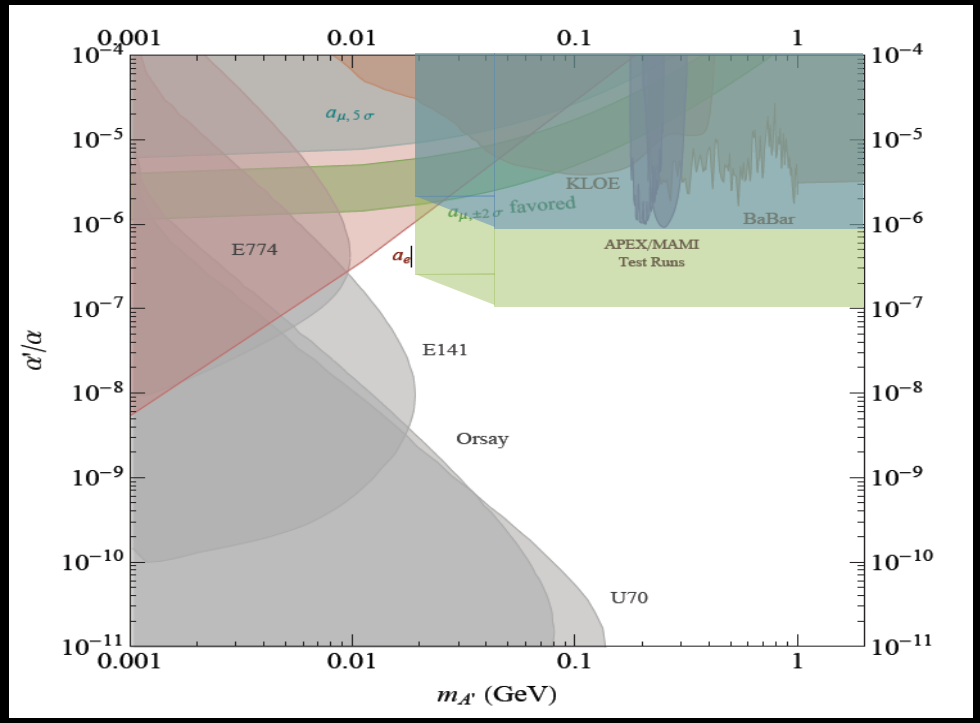
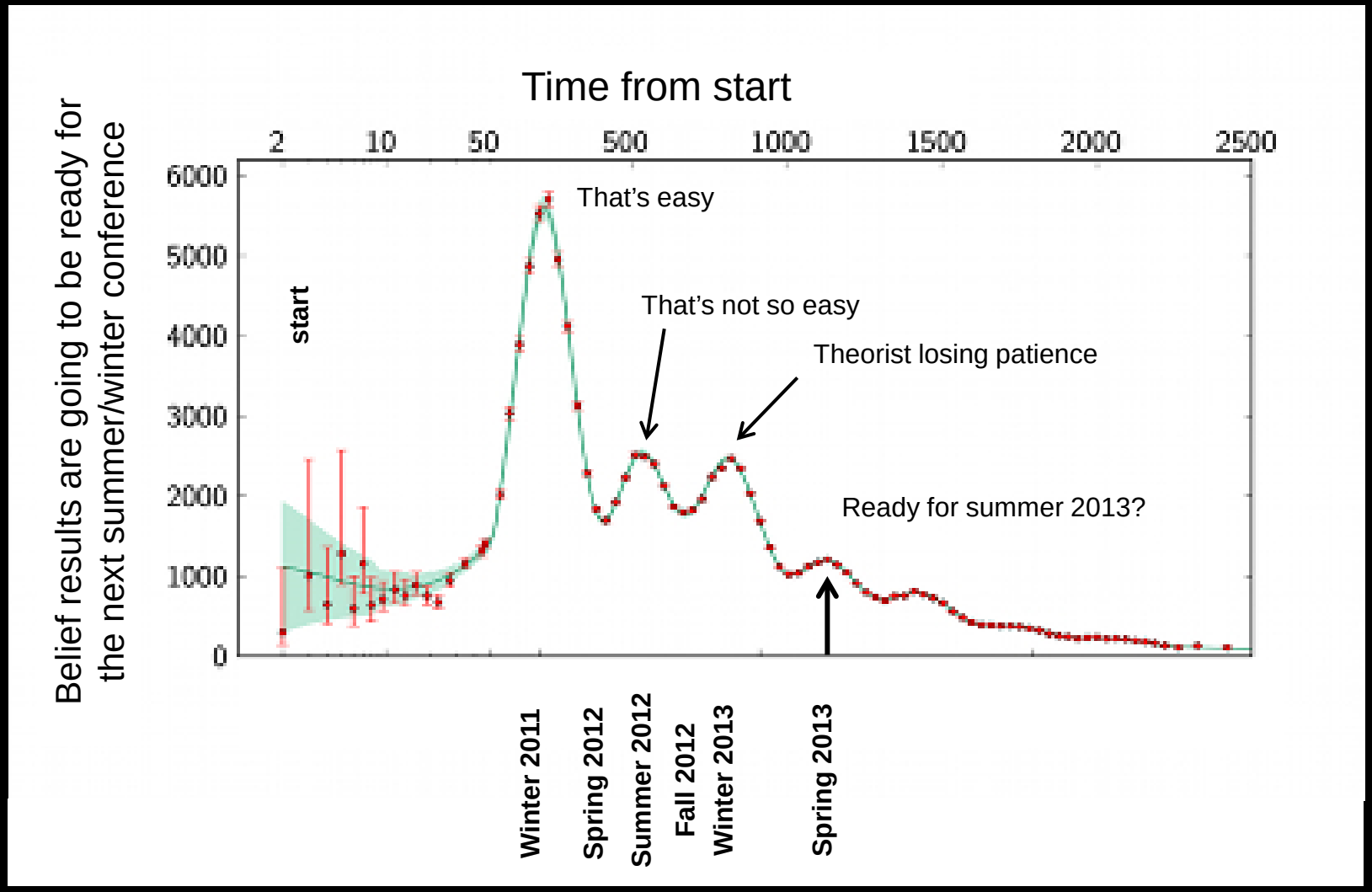


BABAR 40 fb^{-1}
BABAR 500 fb^{-1}
Belle II 50 ab^{-1}

Only an order of magnitude estimate (ripples not shown)

Search for dark photon



Really, really hope to get this done for this summer

Search for dark photon

arxiv:0808.0017

Search for invisible dark photon

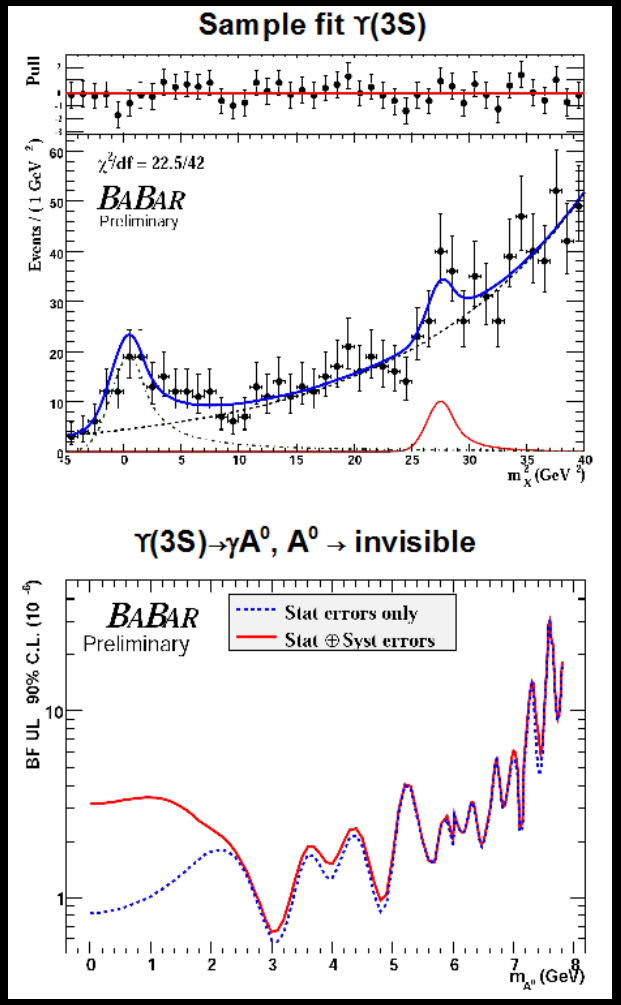
$$e^+e^- \rightarrow \gamma\, A', A' \rightarrow \text{invisible}$$

Several scenarios with dark photon decay to invisible particles (light dark matter for example, see *Cline et al., arXiv 1108.1391*).

Dark photon or similar particle may be long lived and escape detector.

Current measurement if Y(2S,3S) → γ + invisible at *BABAR* could be extended to the dark photon case, limits on ε^2 should be at the level of 10^{-5} - 10^{-4}.

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

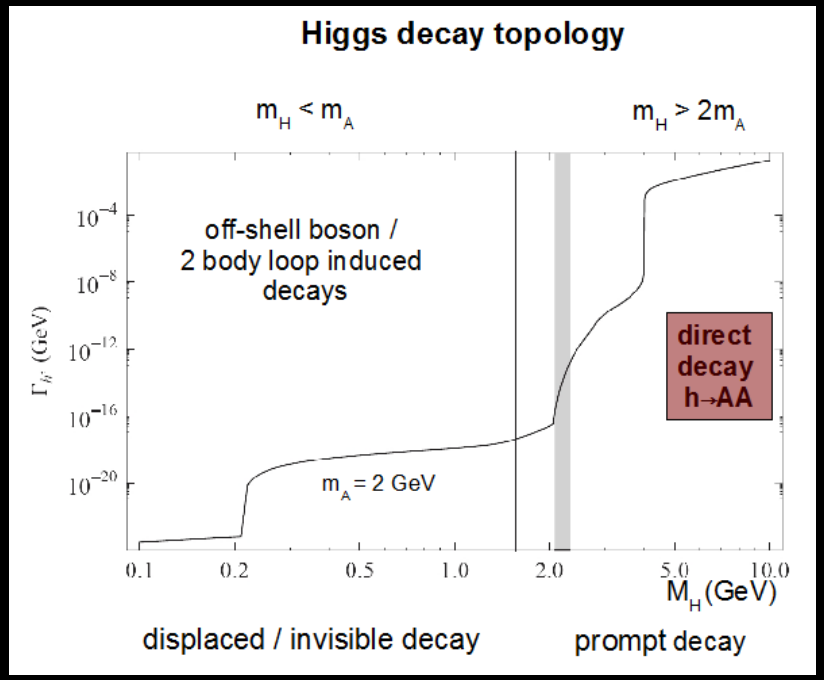


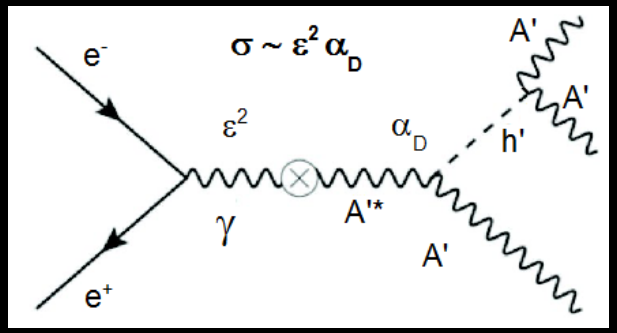
Search for dark Higgs boson

- 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.
- **Dark Higgs mass** could be at the GeV scale
- The Higgsstrahlung process

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

- is very interesting, as it is only suppressed by ε^2 and is expected to have a very small background.





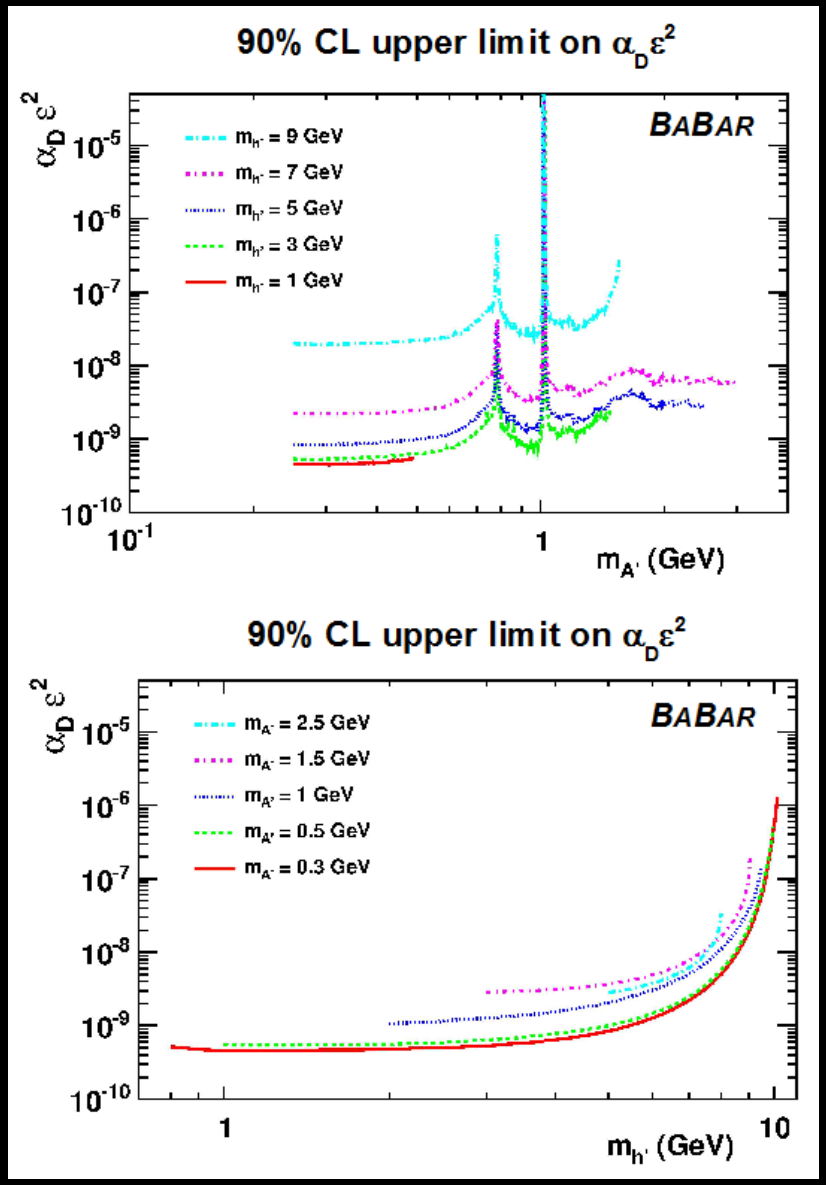
$\alpha_D = g_D^2 / 4\pi$
g_D dark sector gauge coupling

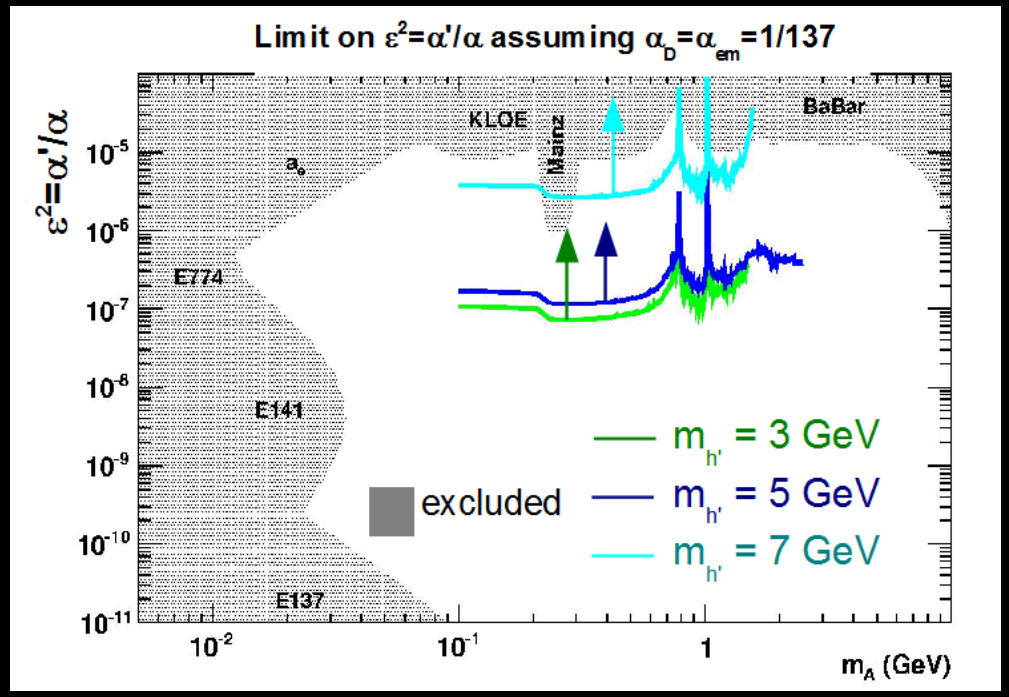
Focus on prompt decays $m_h > 2m_A$

Search for three resonances with similar masses

Search for dark Higgs boson

PRL 108 (2012) 211801





Belle II could improve by a factor 10-100 depending on the background level

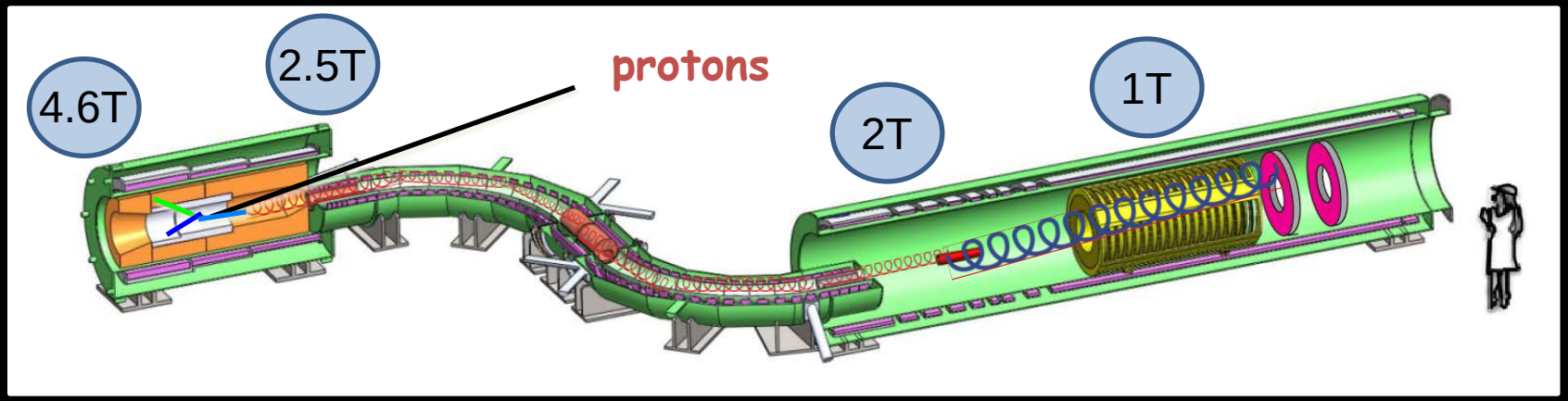
THE CRAZY STUFF

The Mu2e experiment

- The Mu2e experiment will study neutrinoless muon-to-electron conversion in the coulomb field of a nucleus: $\mu N \rightarrow eN$

- Muon-to-electron conversion is a charged lepton flavor violating process, strongly suppressed in the Standard Model.

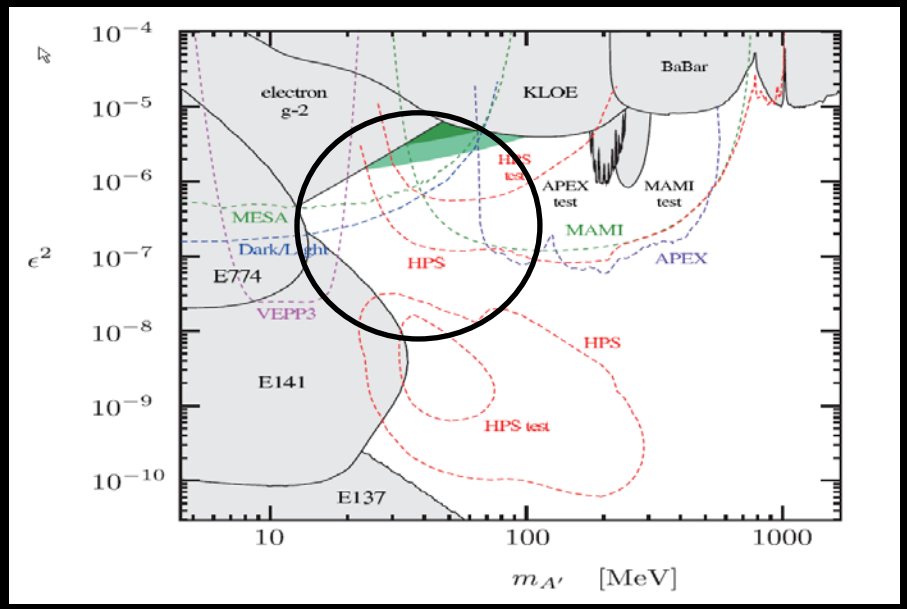
- Observation of CLFV is New Physics



The Mu2e experiment

- Experimental signature is a 105 MeV electron
- Huge amount of photons produced in radiative pion capture $\pi N \rightarrow \gamma N'$, $\gamma \rightarrow e^+e^-$ with energies up to ~100 MeV.

- Can we look for dark photons there, explore the open region between HPS? Many open questions about feasibility (most likely not), but worth a quick study!



Conclusion

- Low-energy e^+e^- colliders provide a unique opportunity to directly explore the 1-10 GeV region and are quite competitive below 1 GeV.

- The new generation of super flavor factories (i.e. Super*KEKB*) might have a sensitivity to dark photon searches similar to that of some dedicated experiments, and cover a larger mass range. Difficult to do better.

- In addition, colliders have the possibility to search for many signatures of a dark sector: dark Higgs boson, non-Abelian sector, dark hadrons and can also explore the scalar and pseudoscalar content.

- Most of the searches performed at *BABAR* should produce results soon. Stay tuned, and we welcome any new idea.

- Might be worth to investigate Mu2e capabilities

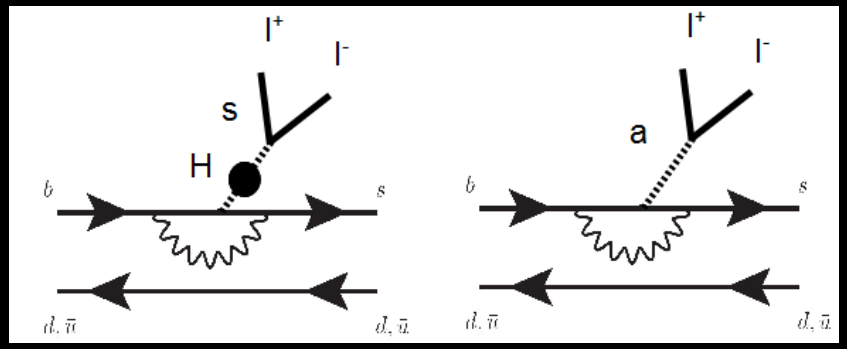
THANK YOU$_D$

EXTRA STUFF

Search for dark scalar / pseudoscalar

Batell et al., PRD 83 (2010) 054005

Scalar (s) and pseudo-scalar (a) content of a dark sector can be probed through the Higgs and axion portals in b → s transitions



Scalar - Higgs mixing angle

Phase-space

Form factor

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

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

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

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

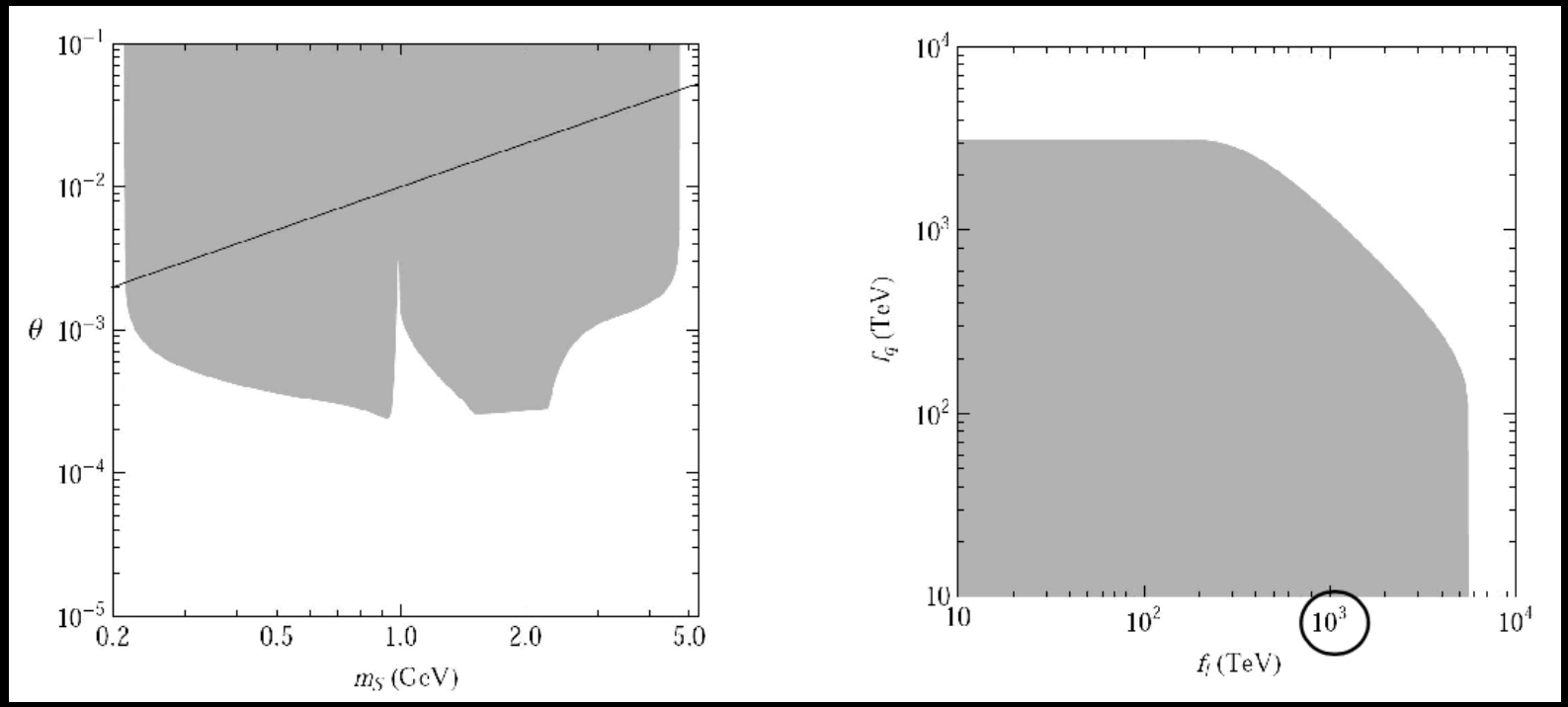
Pseudoscalar - lepton(quark) coupling

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

Search for dark scalar / pseudoscalar

Batell et al., PRD 83 (2010) 054005

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



Limits on pseudo-scalar coupling at the level of thousands of TeV
Belle II could improve by an order of magnitude