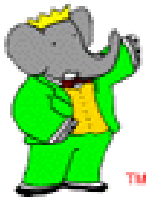
Search for Dark Photons at $B\bar{B}$ colliders

J. Chauveau

LPNHE-UPMC

On behalf of the BaBar Collaboration



P. Fayet Fest, December 8-9, 2016 -- ENS, Paris



- P. Fayet, NPB 78 (1974), 14, *A gauge theory of weak and electromagnetic interactions with spontaneous parity breaking.*
- P. Fayet, NPB 90 (1975), 104, *Supergauge invariant extensions of the Higgs mechanism and a model for the electron and its neutrino.*
- P. Fayet, PLB 69 (1977), 489, *Spontaneously broken supersymmetric theories of weak, electromagnetic and strong interactions.*
- P. Fayet, PLB 95 (1980), 285, *Effects of the spin-1 partner of the goldstino (gravitino) on neutral current phenomenology.*
- P. Fayet, NPB 187 (1981), 184, *A la recherche d'un nouveau boson de spin un.*
- P. Fayet, NPB 347 (1990), 743, *Extra U(1) and new forces*
- P. Fayet, PLB 260 (1991), 213,
- P. Fayet, PRD 74 (2006), 054034, *Constraints on light dark matter and U bosons, from* ψ, $\Upsilon, K^+, \pi^0, \eta$ *and* η' *decays.*
- P. Fayet, PRD 75 (2007), 115017, *U-boson production in* e^+e^- *annihilations,* ψ *and* Υ *decays, and light dark matter.*
- P. Fayet, PLB 75 (2009), 267, *U(1)$_A$ symmetries in two-doublet models, U bosons or light scalars, and* $\psi$and Υ decays.
- P. Fayet, PRD 81 (2010), 054025, *Invisible* Υ *decays into light dark matter.*
- P. Fayet, arXiv:1611:05357v1, *The light U boson as the mediator of a new force coupled to a combination of Q, B, L and dark matter*

Introduction

- The ***U*** boson invented long ago by Pierre is much more general than the Dark Photon.
- Still, experiments (here e^+e^- in the Υ region) have looked for related objects. I overview the searches at the B-factories* of:
  - The Dark Photon ***A'***,
  - The light Brout-Englert-Higgs (B-E-H) boson A^0 in Υ decays,
- which appear as facets of the ***U*** boson construction
  - ➢ The Dark Photon ***A'***,
  - ➢ Invisible axion-like particle ***a***, or A^0
  - (don't cover Light Dark Matter (LDM) aspects addressed by others, nor the parity violating effects in atoms).
- Perspectives.

(*) Many other searches e.g. at CLEO, PEP-1, DORIS, KLOE.

Dark Photon searches

Most experimental presentations motivate the dark photon as follows.

- New Physics phenomenology include a hidden sector of non-standard particles.
- Messengers (portals) of new non-gravitational forces are to be searched.
- Simple extensions of the SM incorporate a new U(1) force. (PF1, PF2)
- A (too simple) case: a dark photon via kinetic mixing (BH)

$$\Delta L \; \alpha \; \varepsilon \; F^{\mu\nu} F'_{\mu\nu}$$

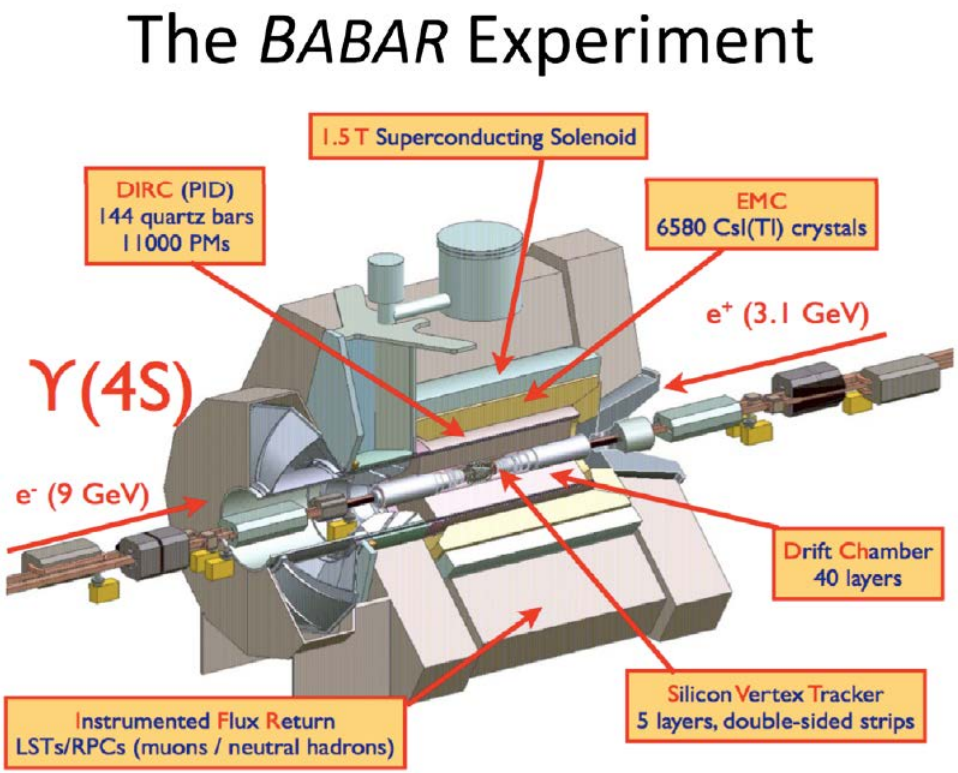
  - A new particle with reduced photon coupling.
  - Can be massive (some prejudice for the MeV – GeV region testable at accelerators like e+e- colliders in the Υ region).
  - can decay with sizable (or not) lifetime.

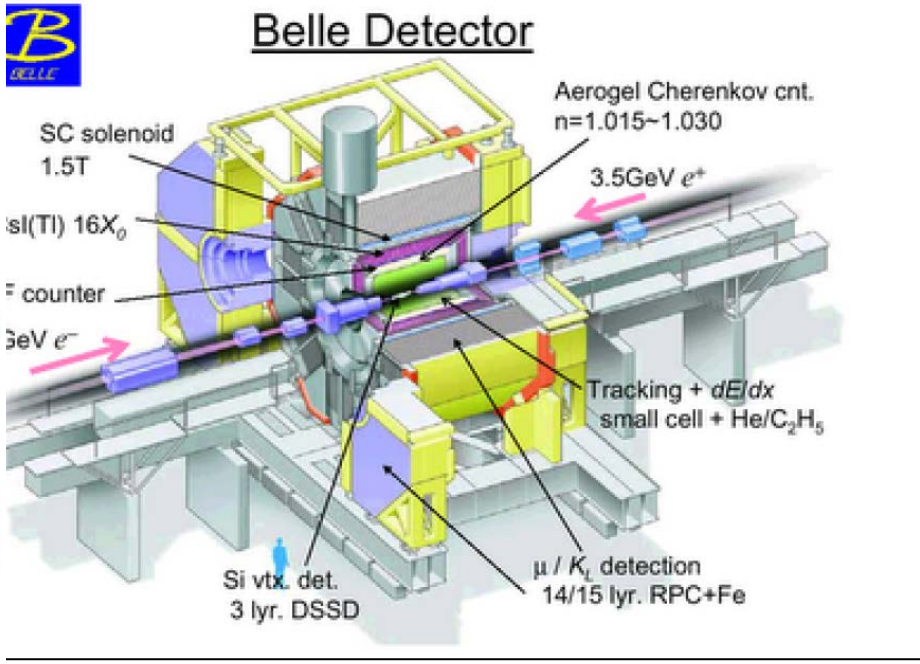
- (PF1) P. Fayet, PLB 95 (1980), 285, *Effects of the spin-1 partner of the goldstino (gravitino) on neutral current phenomenology.*
- (PF2) P. Fayet, NPB 187 (1981), 184, *A la recherche d'un nouveau boson de spin un.*
- (BH) B. Holdom, PLB 166 (1986), 196, *Two U(1)'s and ε charge shifts*.

Experiments

Nucl.Instrum.Meth. A479 (2002)
Nucl.Instrum.Meth.A729 615 (2013)

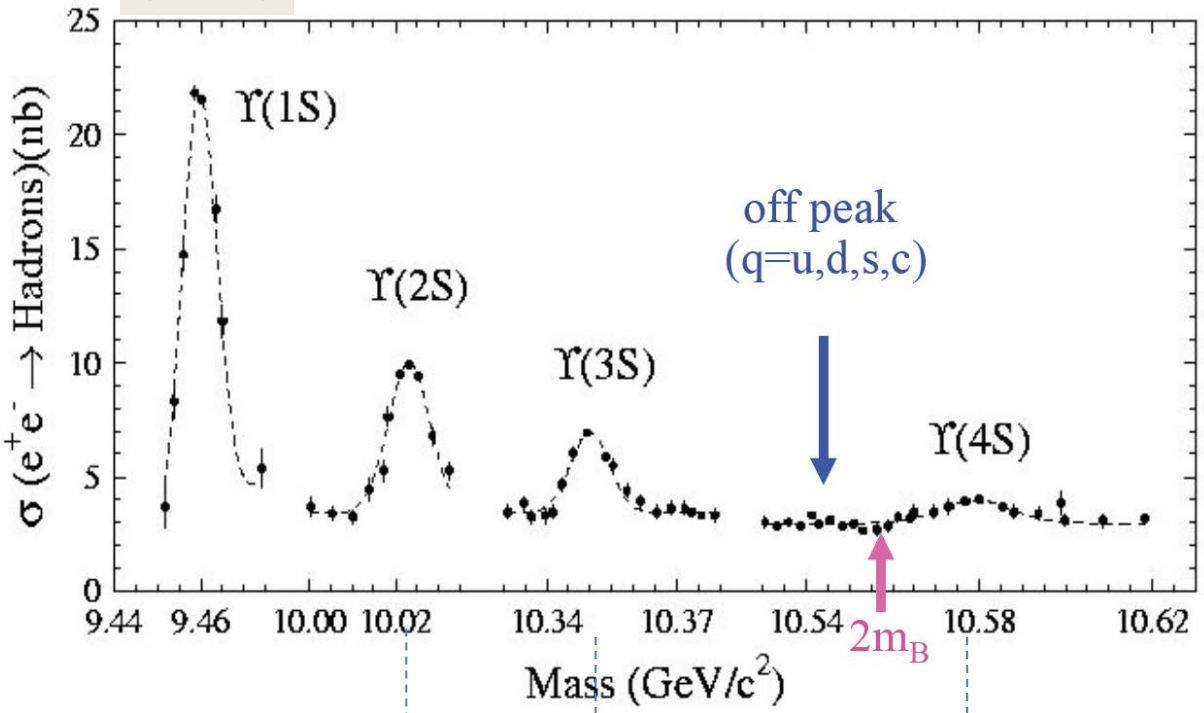


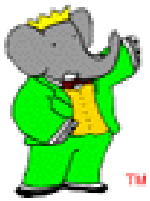




BaBar Datasets

(CUSB)





18 M ← 99 M ← 122 M — 471 M events

+ 5 M ←

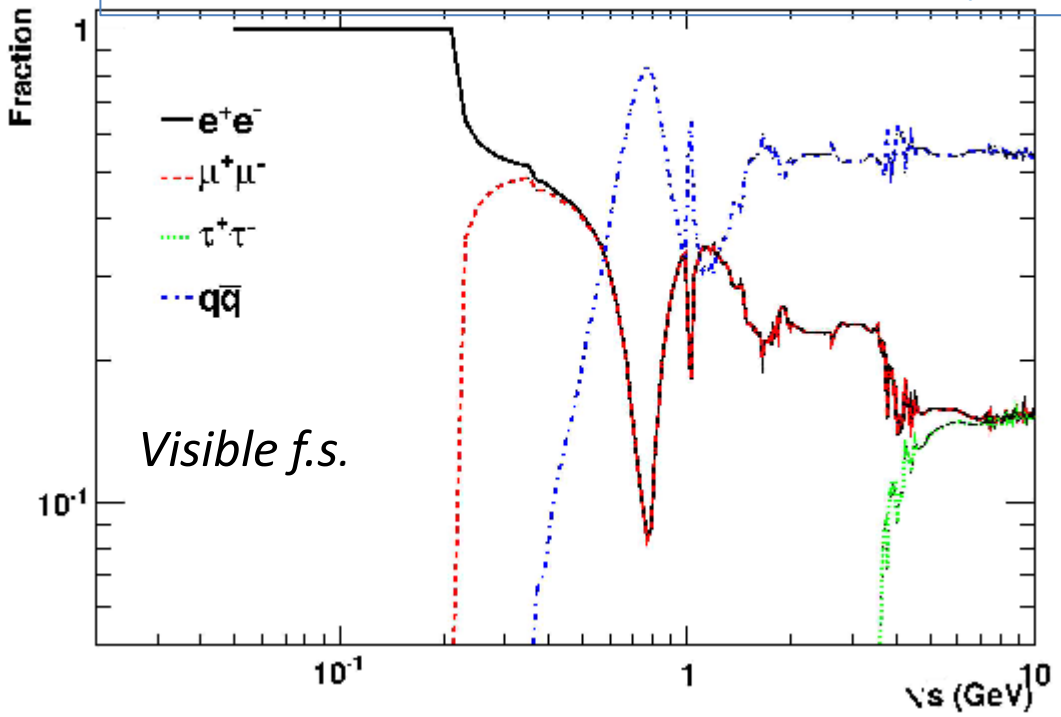
ππ transitions

- A' search on full data sample 514 fb^{-1} (of 531.34 fb^{-1})
- A^0 search on the narrow resonances
  - inclusive
  - tagged

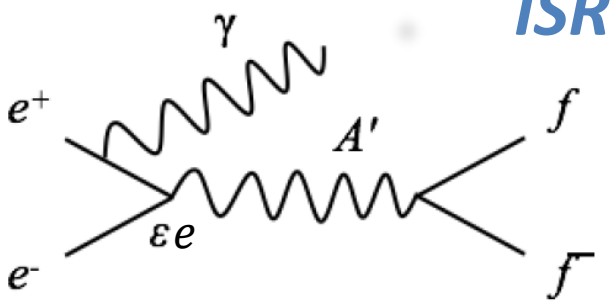
Dark photon (*visible*)

- photon → A'; $\alpha \rightarrow \varepsilon^2\alpha$. A' narrow
- look for narrow resonance produced in e^+e^-, decaying to 2 leptons A' → e^+e^-, $\mu^+\mu^-$

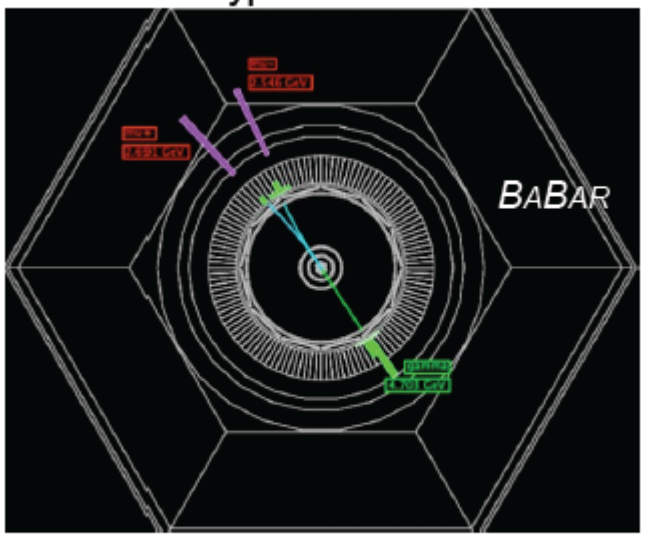
R. Batell, M. Pospelov, A. Ritz, PRD 79 115008 (2009)



ISR

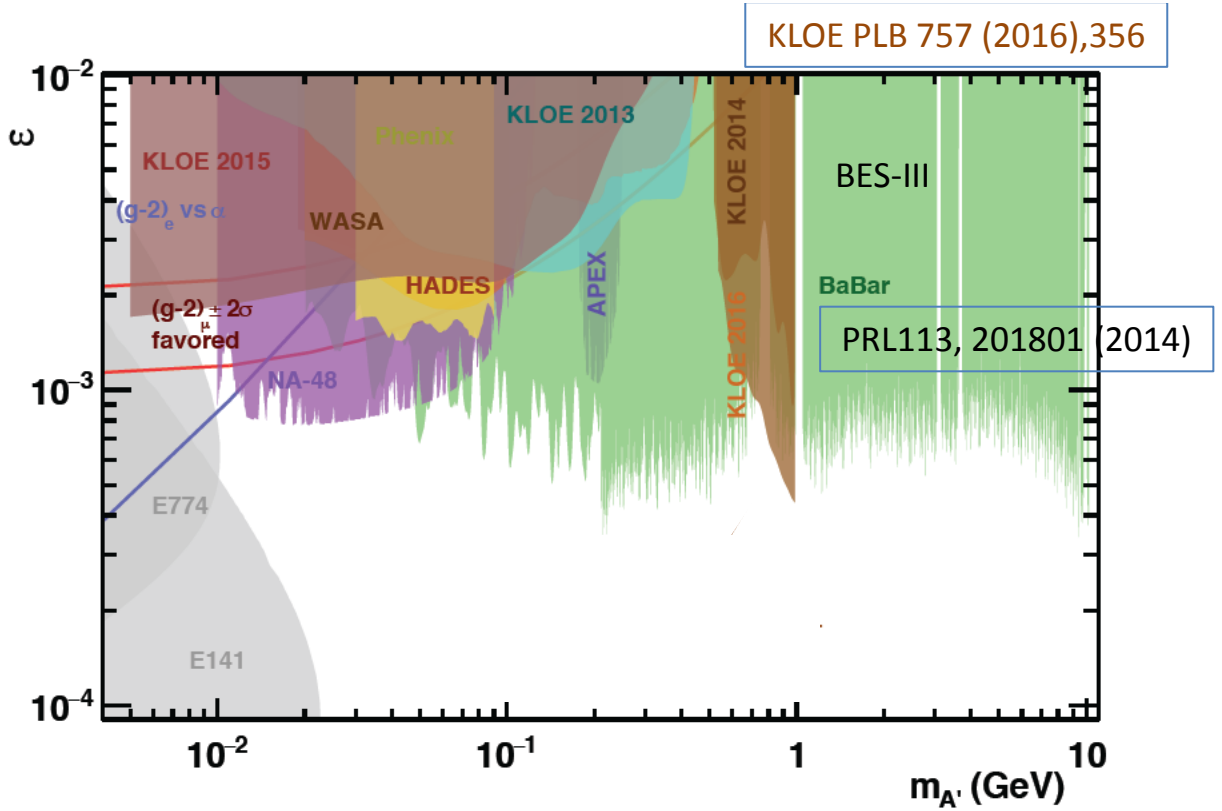


Typical event

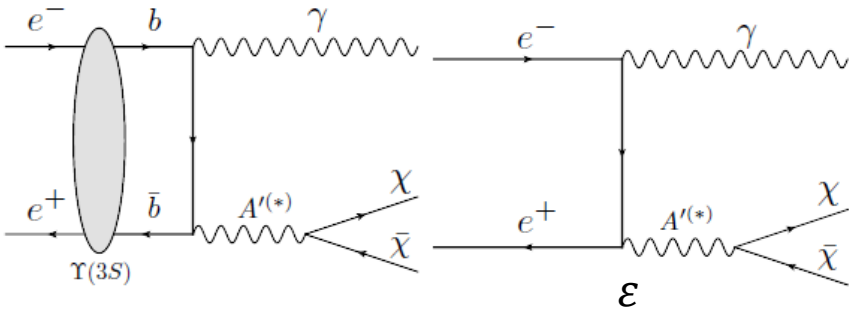


Tracks
Photon
Signal in muon/hadron detector

Dark Photon (visible) FPCP 2016

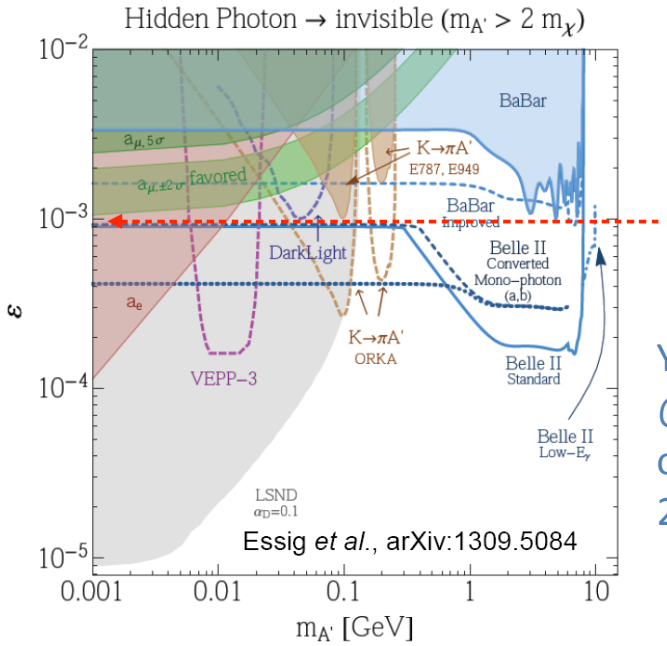


Dark photon (invisible)



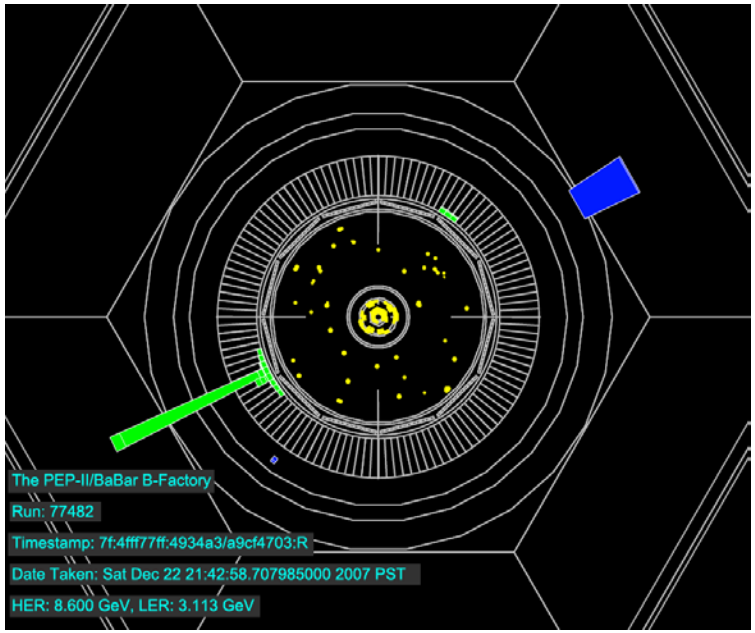
- At $\Upsilon(3S)$ ArXiv 0808.0017
- Requires single photon trigger
- Updated analysis in progress
- Promising for Belle-II

$\Upsilon(3S)$ **ISR**



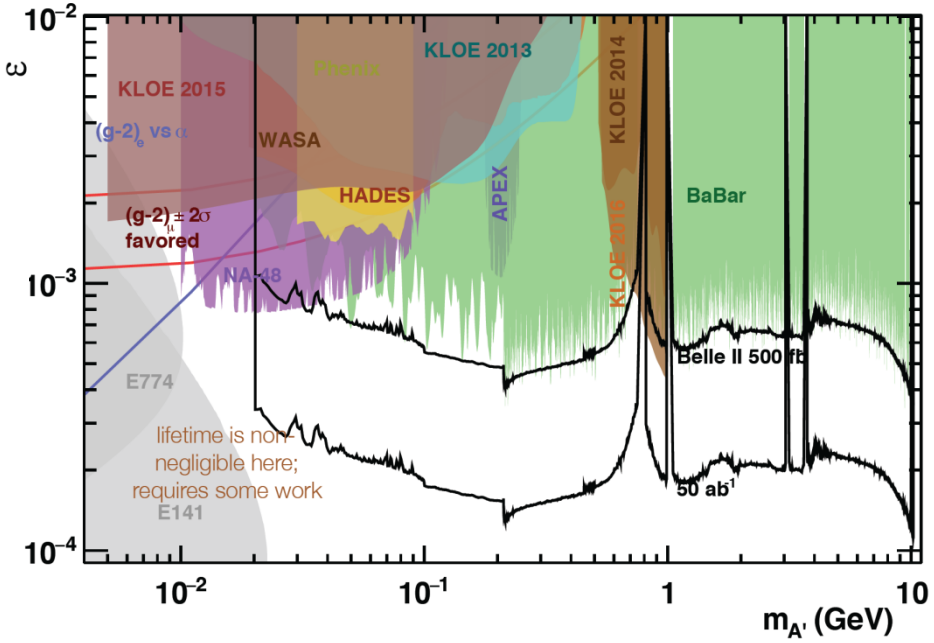
10^{-3} should be possible with updated analysis

Y. Kolomensky @BNL Workshop on dark interactions 2016/10/05

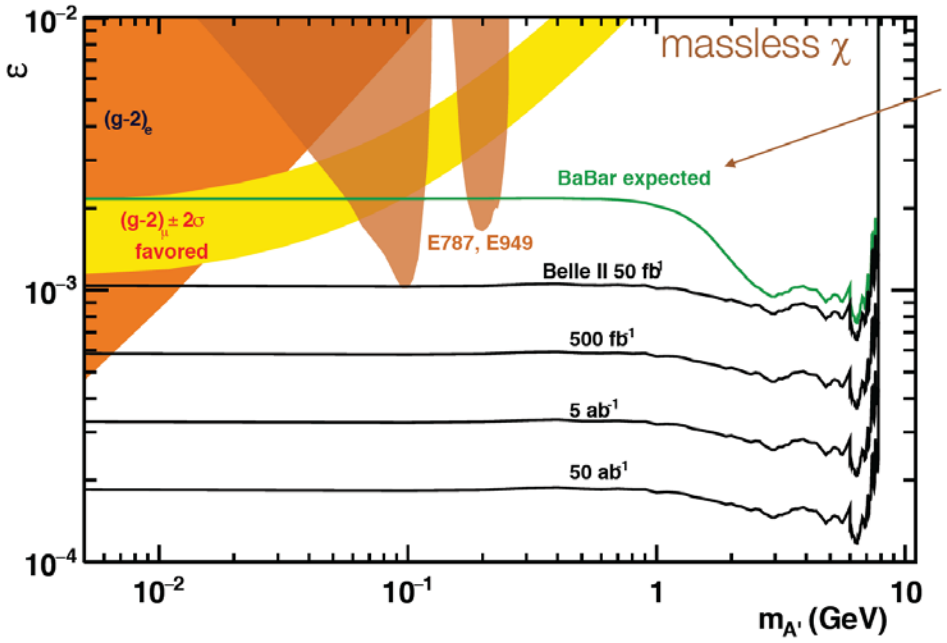


Dark Photon: projected Belle II sensitivity

visible



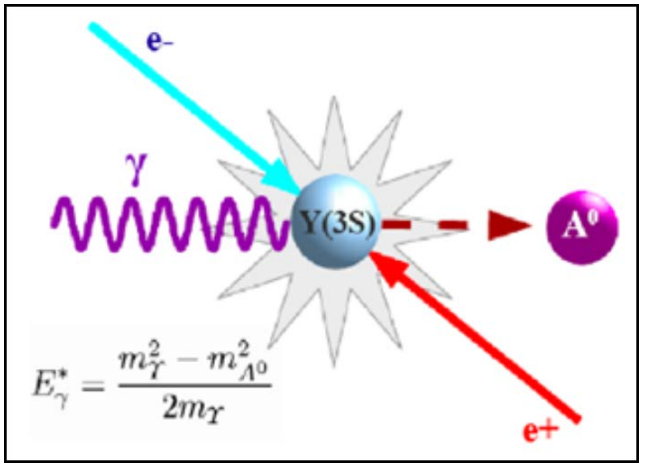
invisible

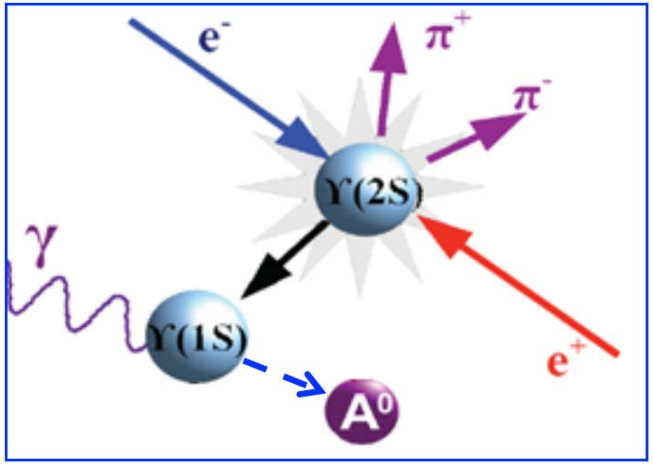


C. Hearty | Light Higgs, Dark Sector | FPCP2016

A^0, A' Searches at BABAR in Υ decays

$Y(3S) \rightarrow \gamma A^0, A^0 \rightarrow$ **invisible**	arXiv:0808.0017 [hep-ex]
$Y(3S) \rightarrow \gamma A^0, A^0 \rightarrow \tau^+\tau^-$	PRL 103, 181801 (2009)
$Y(2S, 3S) \rightarrow \gamma A^0, A^0 \rightarrow \mu^+\mu^-$	PRL 103, 081801 (2009)
$Y(2S, 3S) \rightarrow \gamma A^0, A^0 \rightarrow$ hadrons	PRL 107, 221801 (2011)
$Y(1S) \rightarrow$ **invisible**	PRL 103, 251801 (2009)
$Y(1S) \rightarrow \gamma +$ **invisible**	PRL 107, 021804 (2011)
$Y(1S) \rightarrow \gamma A^0, A^0 \rightarrow \mu^+\mu^-$	PRD 87, 031102 (2013)
$Y(1S) \rightarrow \gamma A^0, A^0 \rightarrow \tau^+\tau^-$	PRD 88, 031102 (2013)
$Y(1S) \rightarrow \gamma A^0, A^0 \rightarrow g\bar{g}, s\bar{s}$	PRD 88, 031701 (2013)
$Y(1S) \rightarrow \gamma A^0, A^0 \rightarrow c\bar{c}$	PRD 91, 071102 (2015)





$\Upsilon \rightarrow \chi\chi$ or $\gamma\chi\chi$ (LDM)

CP-odd Higgs A^0 in NMSSM

- $\Upsilon \rightarrow \gamma A^0$, $A^0 \rightarrow f\bar{f}$, gg
- $A^0 = \cos\theta_A A_{MSSM} + \sin\theta_A A_{singlet}$
- Predicted BF depend on

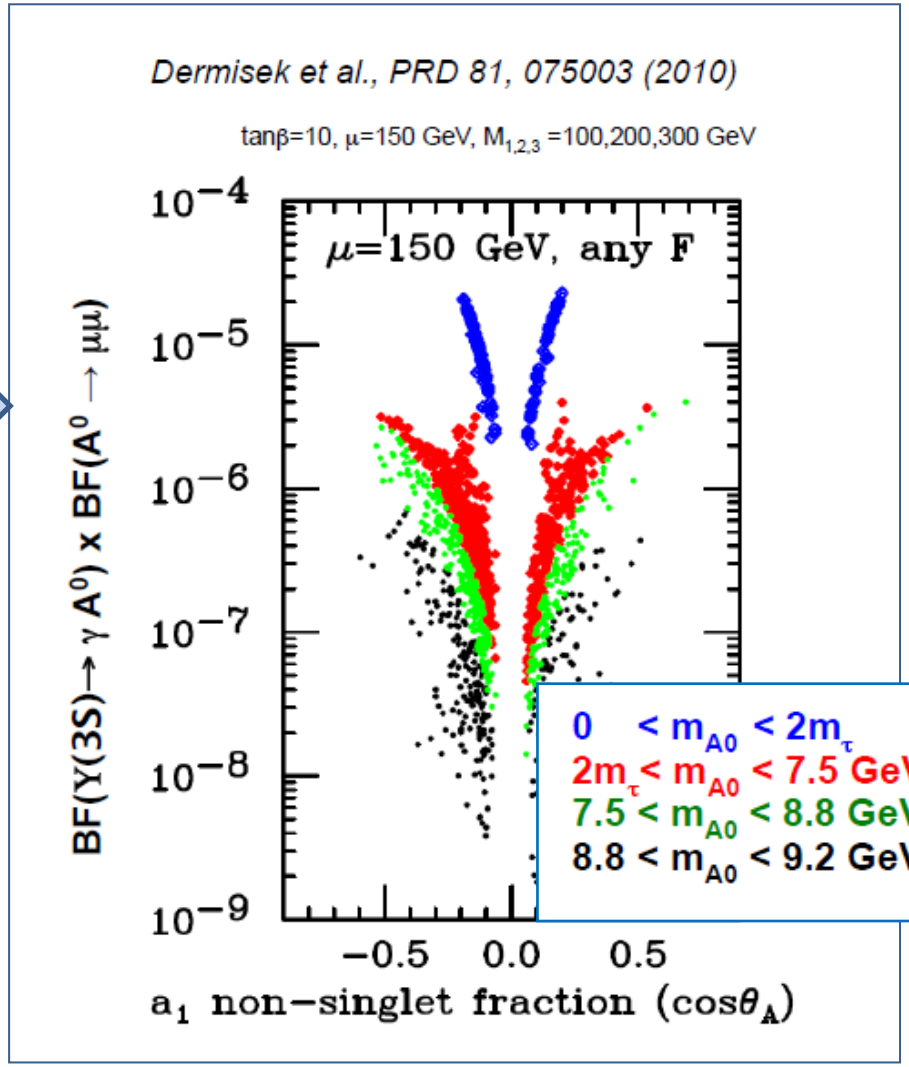
  $\cos\theta_A$, $\tan\beta$, m_{A0}

  ➢ Scans of e.g.

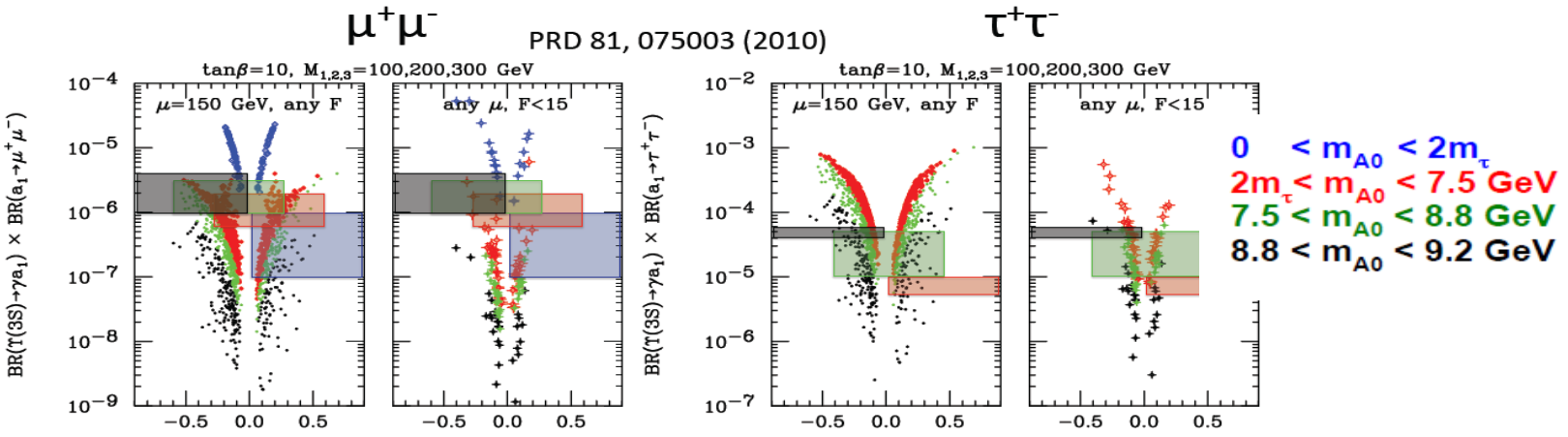
  $BF(\Upsilon \rightarrow A^0)\, BF(A^0 \rightarrow \mu^+\mu^-)$
- Rate accessible to BABAR

$$BR(A^0 \rightarrow f\bar{f}) \propto \cos^2\theta_A m_f^2 / \tan^2\beta \quad \text{up-type fermions}$$
$$BR(A^0 \rightarrow f\bar{f}) \propto \cos^2\theta_A m_f^2 \tan^2\beta \quad \text{down-type fermions}$$

	Low tanβ	High tanβ
Low mass	gg	ss
High mass	cc	ττ



CP-odd Higgs A^0



arXiv: 1209.1143 (B. Echenard)

Mode	Mass range (GeV)	BF upper limit (90% CL)
$\Upsilon(2S,3S) \to \gamma A^0, A^0 \to \mu^+\mu^-$	$0.21 < m_A < 9.3$	$(0.3 - 8.3) \times 10^{-6}$
$\Upsilon(3S) \to \gamma A^0, A^0 \to \tau^+\tau^-$	$4.0 < m_A < 10.1$	$(1.5 - 16) \times 10^{-5}$
$\Upsilon(2S,3S) \to \gamma A^0, A^0 \to$ hadrons	$0.3 < m_A < 7.0$	$(0.1 - 8) \times 10^{-5}$
$\Upsilon(1S) \to \gamma A^0, A^0 \to \chi\bar{\chi}$	$m_\chi < 4.5$ GeV	$(0.5 - 24) \times 10^{-5}$
$\Upsilon(1S) \to \gamma A^0, A^0 \to$ invisible	$m_A < 9.2$ GeV	$(1.9 - 37) \times 10^{-6}$
$\Upsilon(3S) \to \gamma A^0, A^0 \to$ invisible	$m_A < 9.2$ GeV	$(0.7 - 31) \times 10^{-6}$
1S	$c\bar{c}$	$4.0 < m_A < 9.2$	$(0.74 - 24) \times 10^{-4}$
1S	gg	$0.5 < m_A < 9.0$	$10^{-6} - 10^{-2}$
1S	$s\bar{s}$	$1.5 < m_A < 9.0$	$10^{-5} - 10^{-3}$



MONSIEUR JOURDAIN

Par ma foi, il y a plus de quarante ans que je dis de la prose sans que j'en susse rien, et je vous suis le plus obligé du monde de m'avoir appris cela.

The U Boson by Pierre (1)

P. Fayet NPB 187 (1981), 184
P. Fayet NPB 347 (1990), 743,
…,
P. Fayet arXiv:1611.05357

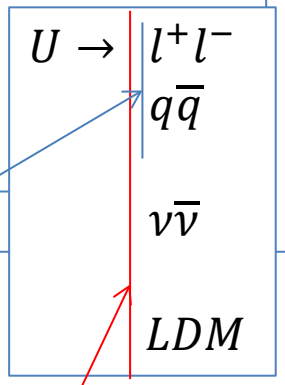
A new interaction: simple case = a new *U(1)*

systematic exploration of $SU(3) \times SU(2) \times U(1) \times U(1)'$

? which $U(1)'$ may be gauged ?

? which mass for a new gauge boson ***U***?

which couplings (~gravity, ~QED, ~Weak NC)?



- generalized weak boson mixing (3×3): W_3, B, $C \rightarrow Z$, γ, ***U***
- Conserved charge $Q_U = \mathbf{Q} + \lambda_B B + \lambda_{L_i} L_i + \lambda_d F_d$

  U coupling constant to SM particles $g''cos\xi cos^2\theta \equiv e\, tan\chi = \boldsymbol{e\varepsilon}$,
- 1HDM (+possible singlet): pure vector coupling

  Specific case (if $J_C \propto J_Y$) *hidden photon* (visible A') or the Dark Photon if $Q_d \neq 0$, possibly to light dark matter LDM particles.

  But more generally ***U*** may also couple to B, L maybe $(B - L)$ as in GUT.
- 2HDM (+possible singlet): V and A couplings are possible :

➢ ***U*** as an invisible axion-like ***a*** in Υ decay: $a = cos\vartheta_A \boldsymbol{A^0} + \sin\vartheta_A\ S$.

kinetic mixing

The U Boson by Pierre (2)

Equivalence theorem, ***U*** as an invisible axion-like ***a*** in Υ decay :

$$Br(\Upsilon \to \gamma U) \simeq Br(\Upsilon \to \gamma A).$$

The same experiment can look at ***U*** (invisible dark photon) or ***A^0*** (light pseudoscalar Higgs) in Υ decays.

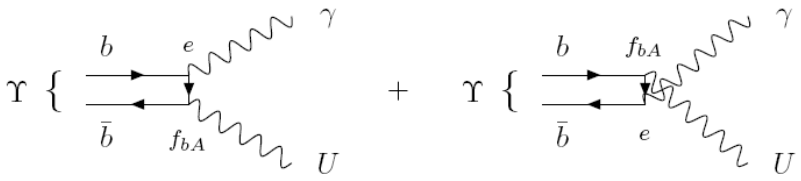


Figure 1: $\Upsilon \to \gamma U$ *decay induced by the axial coupling* f_{bA} *. For a light* U *the total amplitude is essentially the same as for a spin-0* a *with pseudoscalar coupling* $f_{bP} = f_{bA} \frac{2 m_b}{m_U}$.

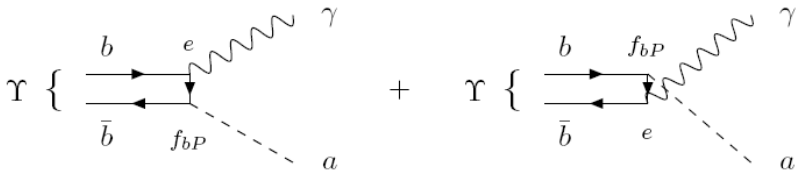
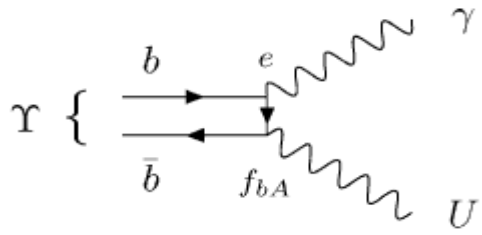


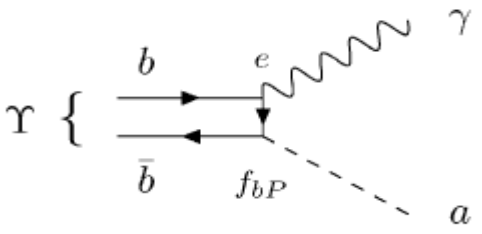
Figure 2: *Production of a spin-0 pseudoscalar in* $\Upsilon \to \gamma a$.

ϒ constraints(1)

Physics Letters B 675 (2009) 267–271



$$f_{q,l\,A} \simeq \underbrace{2^{-\frac{3}{4}} G_F^{\frac{1}{2}}\, m_U}_{2\times 10^{-6} m_U\,(\mathrm{MeV})} \begin{cases} rx = \cos\zeta \cot\beta \\ \quad \text{for } u, c, t \text{ quarks}, \\ r/x = \cos\zeta \tan\beta \\ \quad \text{for } d, s, b \text{ quarks and } e, \mu, \tau \text{ leptons}. \end{cases}$$



$$f_{q,l\,P} \simeq \underbrace{2^{\frac{1}{4}} G_F^{\frac{1}{2}} m_{q,l}}_{4\times 10^{-6} m_{q,l}\,(\mathrm{MeV})} \begin{cases} rx = \cos\zeta \cot\beta \\ \quad \text{for } u, c, t \text{ quarks}, \\ r/x = \cos\zeta \tan\beta \\ \quad \text{for } d, s, b \text{ quarks and } e, \mu, \tau \text{ leptons}. \end{cases}$$

$\zeta \equiv \vartheta_A$ ↑

$\Upsilon \to \gamma(U/A^0 \to \mu\mu)$ limit$< 4 \times 10^{-6} \Rightarrow$

- $\sqrt{B_{\mu\mu}}\,|f_{bA}| < 4 \times 10^{-7}\, m_U\ (MeV)$,
- $\sqrt{B_{\mu\mu}}\,|f_{bP}| < 4 \times 10^{-3}$.
- Doublet fraction $cos^2\vartheta_A < \frac{4\%}{tan^2\beta\, B_{\mu\mu}}$.

$BR(A^0 \to f\bar{f}) \propto \cos^2\theta_A m_f^2 / \tan^2\beta$ up-type fermions

$BR(A^0 \to f\bar{f}) \propto \cos^2\theta_A m_f^2 \tan^2\beta$ down-type fermions

	Low tanβ	High tanβ
Low mass	gg	ss
High mass	cc	ττ

Υ constraints (2)

Physics Letters B 675 (2009) 267–271

P. FAYET

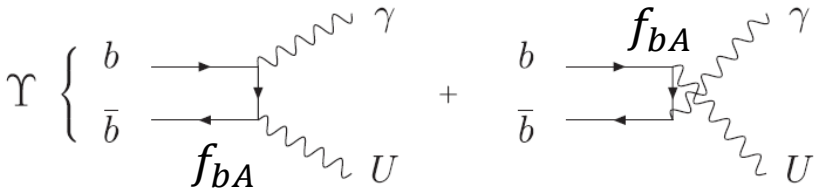


FIG. 5. The decay $\Upsilon \to \gamma U$ [5,21] induced by the axial coupling f_{bA} of the b quark.

$\Upsilon \to \gamma\chi\chi$ axial coupling f_{bA}

$\Upsilon \to \gamma(U/A^0)_{inv}$ limit$< 4 \times 10^{-6} \Rightarrow$

- $\sqrt{B_{inv}}\,|f_{bA}| < 4 \times 10^{-7}\, m_U\ (MeV)$,
- $\sqrt{B_{inv}}\,|f_{bP}| < 4 \times 10^{-3}$.
- Doublet fraction $cos^2\vartheta_A < \frac{4\%}{tan^2\beta\, B_{inv}}$.

PHYSICAL REVIEW D **81,** 054025 (2010)

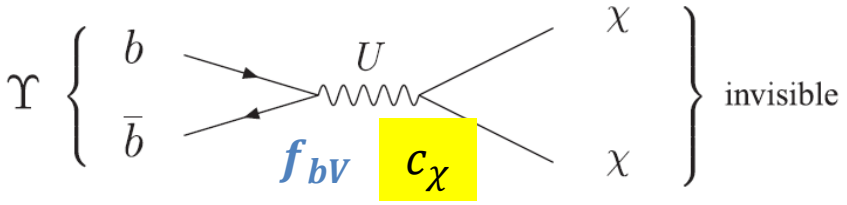


FIG. 6. Υ decay into light dark matter particles, induced by a U boson [5] with vector couplings to b [3,4]. This applies to spin-0 or spin-$\frac{1}{2}$ Majorana or Dirac particles [11,12], $\Upsilon \to \varphi\bar{\varphi}$, $\chi\chi$, or $\chi\bar{\chi}$. The amplitude is $\propto c_\chi f_{bV}/(m_\Upsilon{}^2 - m_U^2)$, compared to $e^2/(3m_\Upsilon^2)$ for $\Upsilon \to e^+e^-$.

$\Upsilon \to \chi\chi$ vector coupling f_{bV}

With BaBar limit: $Br(\Upsilon \to inv) < 3 \times 10^{-4} \Rightarrow$

- (Majorana $\Upsilon \to \chi\chi$) $|c_\chi f_{bV}| < 5 \times 10^{-3}$ for $2m_\chi, m_U < 2\ GeV$
- (Dirac $\Upsilon \to \chi\bar{\chi}$) 3.5×10^{-3}.

Emergence of dark sector research

A blooming field

- experiments
- Workshops
  - SLAC in April 2016 arXiv 1608.08632v1
  - CERN Physics Beyond Colliders (2016-18)
  - CERN-EPFL-Korea Theory Institute, Feb 2017



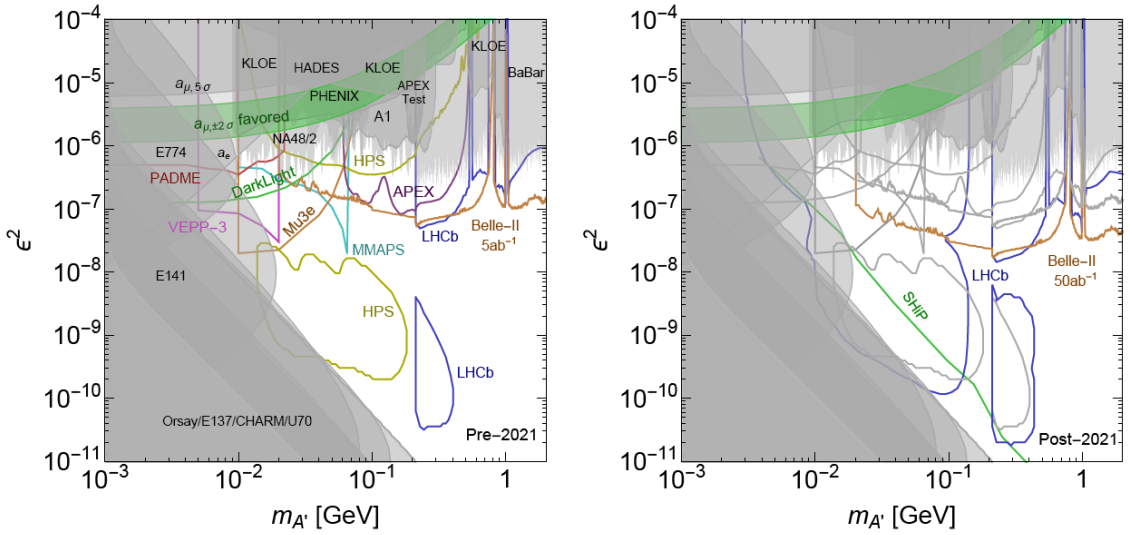




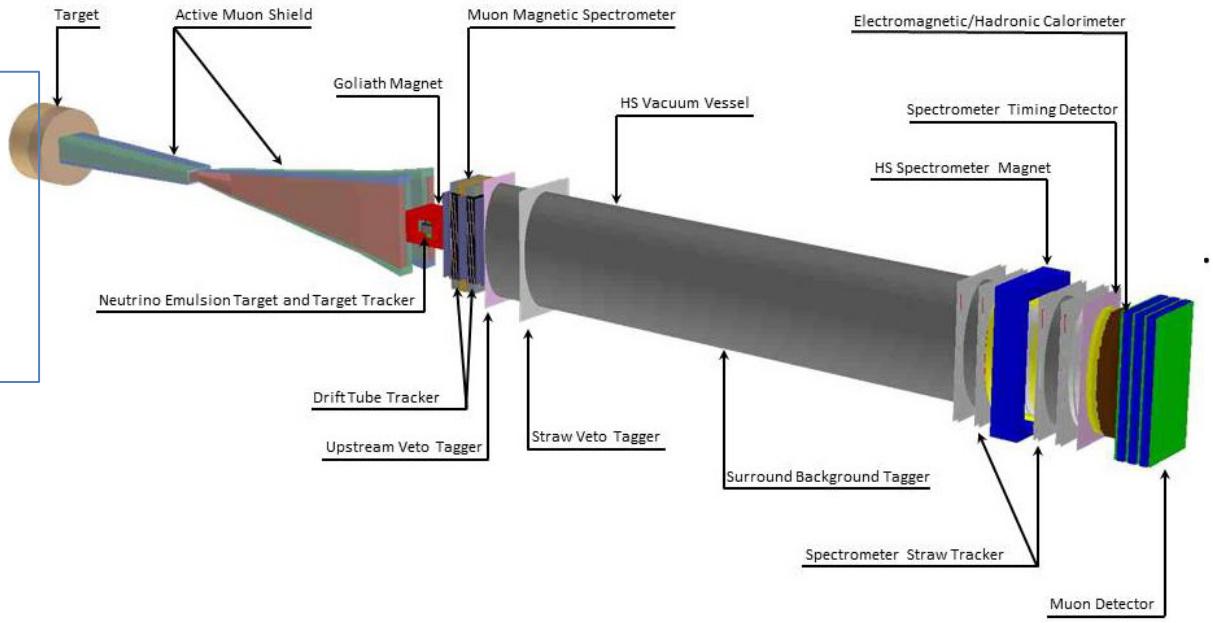
FIG. 4: Sensitivity to A' for exclusive experiments seeking visible decay modes $A' \to \ell^+\ell^-$. **Left:**

Dark Photon search at SHiP

Proton beam dump

A' produced in

- Meson decay (π^0, η,η', ω)
- Bremstrahlung
- Direct QCD qq or $qg \rightarrow V$



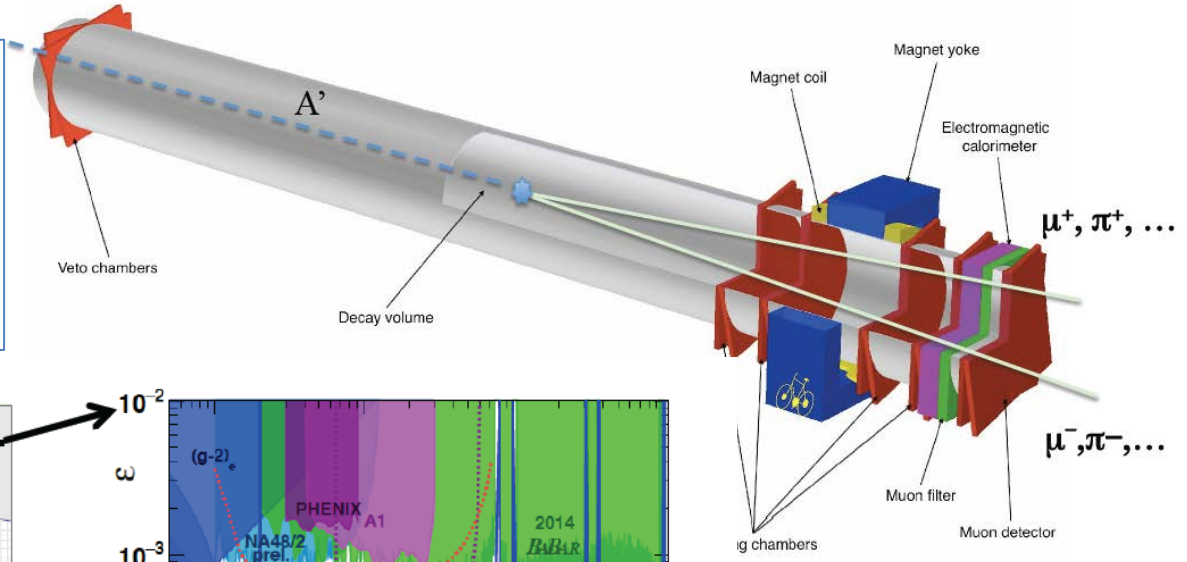
G. Lanfranchi at WORKSHOP ON DARK SECTORS 2016

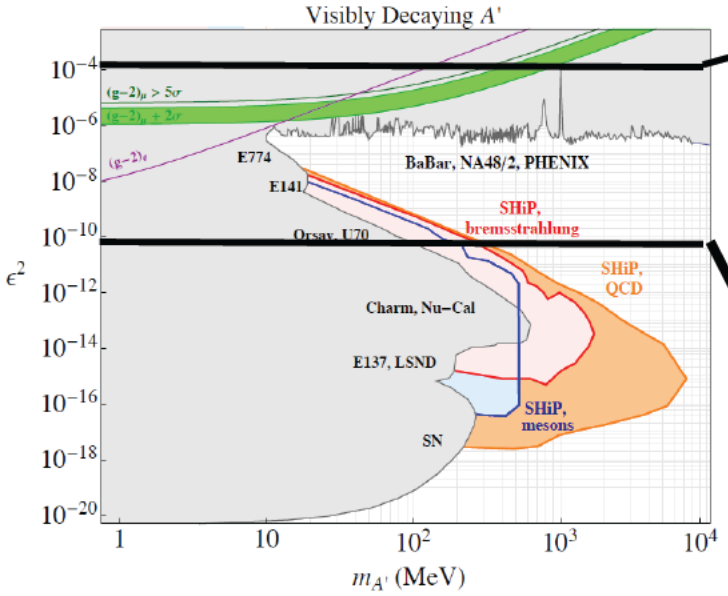
Dark Photon search at SHiP

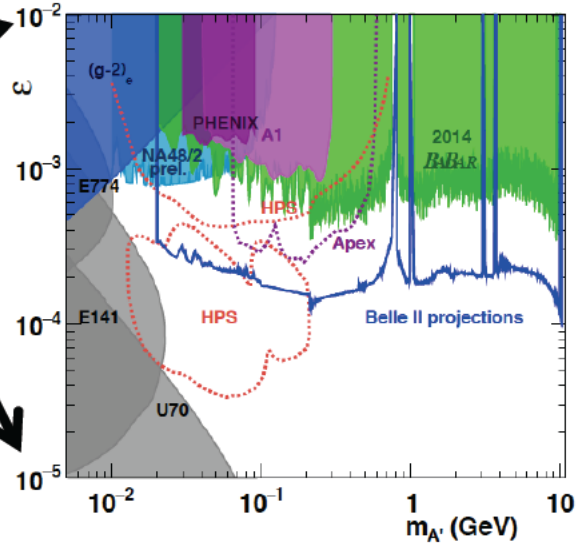
Proton beam dump

A' produced in

- Meson decay (π^0, η,η', ω)
- Bremstrahlung
- Direct QCD qq or $qg \rightarrow V$







SHiP also looks at

- ν_R in ν decays,
- Axion-like particles,
- new scalars,
- Light SUSY,
- LDM.

G. Lanfranchi at WORKSHOP ON DARK SECTORS 2016

Summary and outlook

- The New Physics may well be at low scale.
- Pierre's U boson very inspirational for experiments:
  - Much more general than the dark photon,
  - Connects with light higgs A^0,
  - invisible decays,
  - Light dark matter.
- A blooming experimental field.
- (Over)due recognition to the pioneer!


We need *U*

Extra

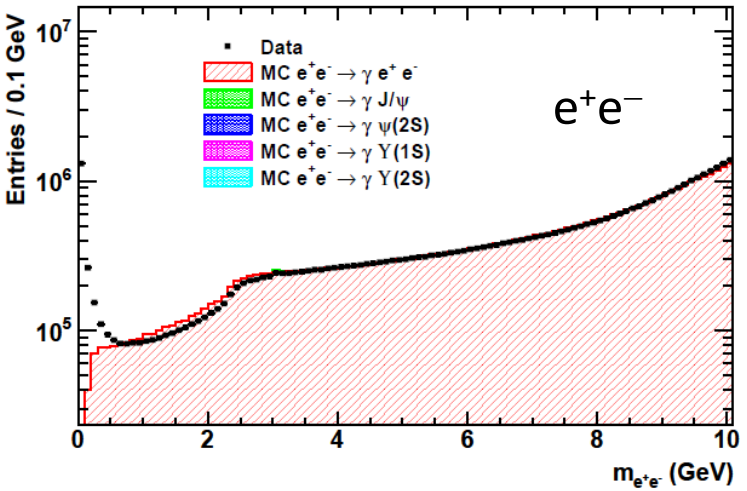
A′ → e^+e^-, $\mu^+\mu^-$

PRL113, 201801 (2014)



Event selection

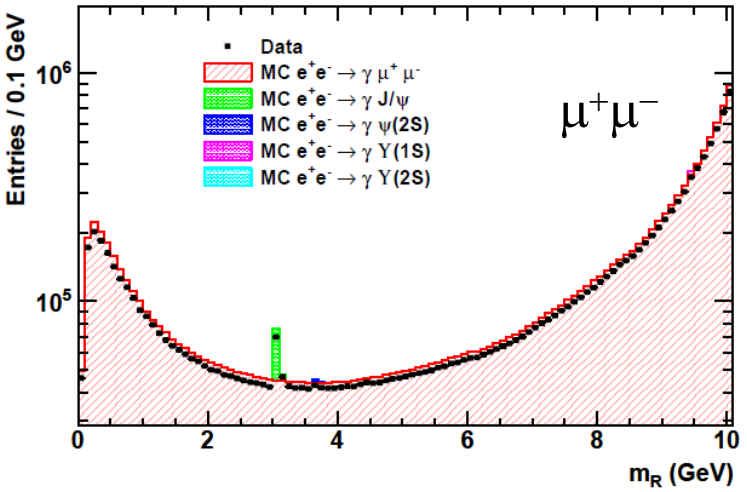
- 2 tracks + 1 photon with E_{cm}>200 MeV
- 1 (e) or 2 (e,μ) track(s) positively identified
- Kinematic+ geometric fit
- MVA to remove conversions (e)



Measurement (blind analysis)

- Final sample with radiative Bhabha's + μμγ + narrow resonances
  - Correction to model the remaining conversions
- Extract cross section with fits over sliding windows covering

0.02 (e), 0.212 (μ) < $m_{A'}$ < 10.2 GeV

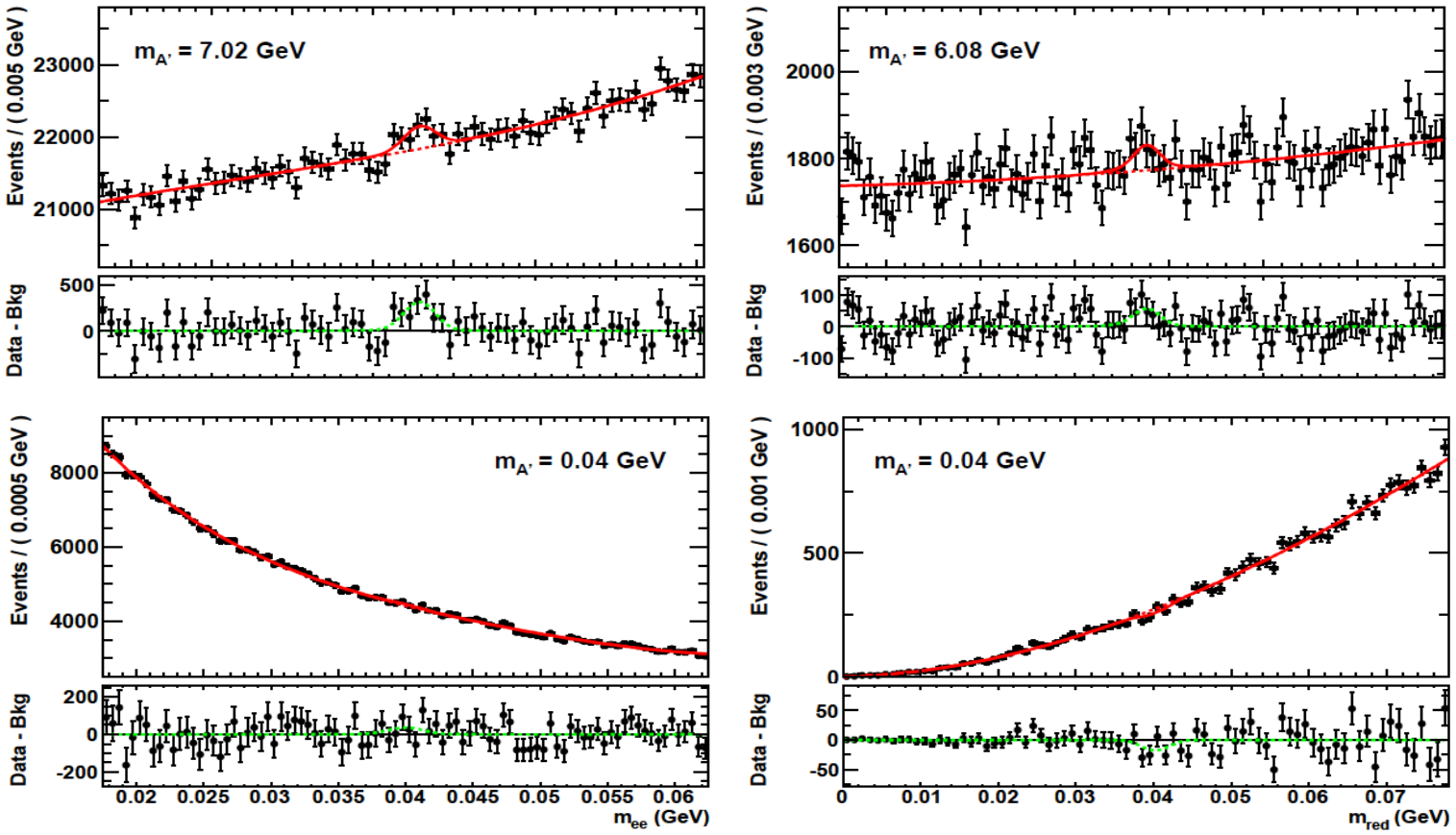


$A' \rightarrow e^+e^-, \mu^+\mu^-$

PRL113, 201801 (2014)

Fit window size >> signal width, << total mass range. Hence, we can use a polynomial background shape to obtain an optimal signal to background ratio.

A few scan points:



A′ → e^+e^-, $\mu^+\mu^-$

PRL113, 201801 (2014)

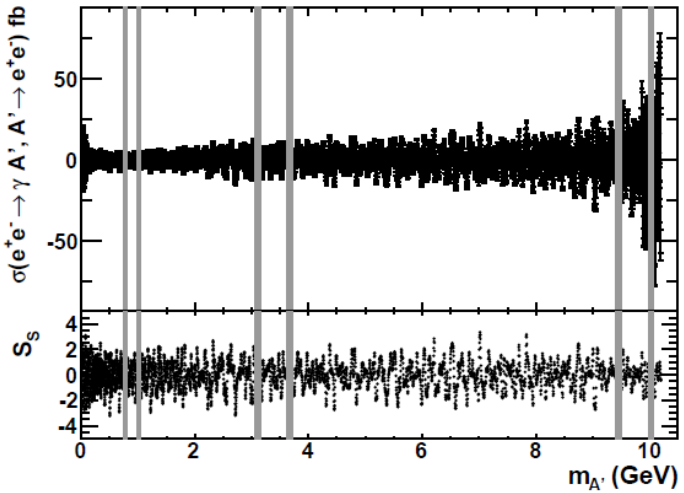


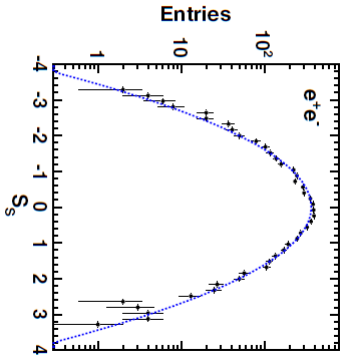
- Highest fluctuations

  - 3.4 σ (e) M=7.02 GeV
  - 2.9 σ (μ) M=6.09 GeV
    p-values=0.57, 0.94
    including trial factors.

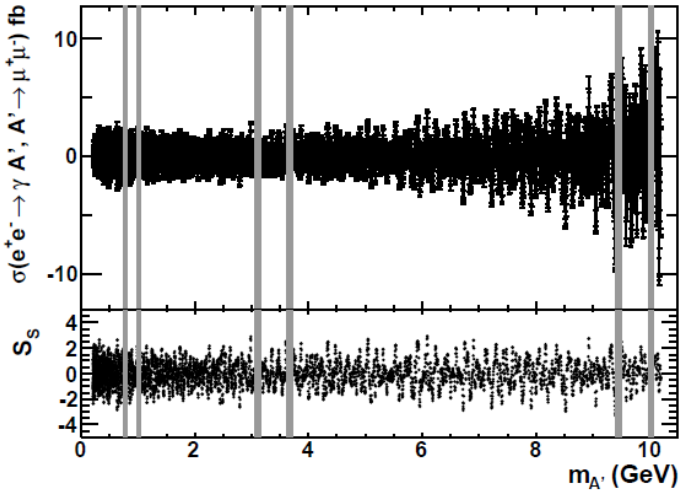
- Bayesian 90% C.L. upper limits ~ 1 to 10 fb

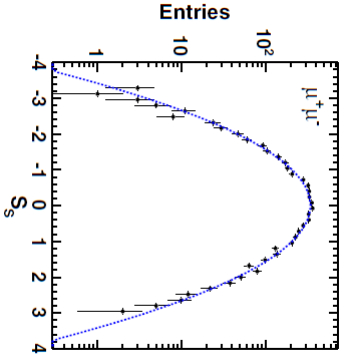
- used to derive 90% u.l. on ε.





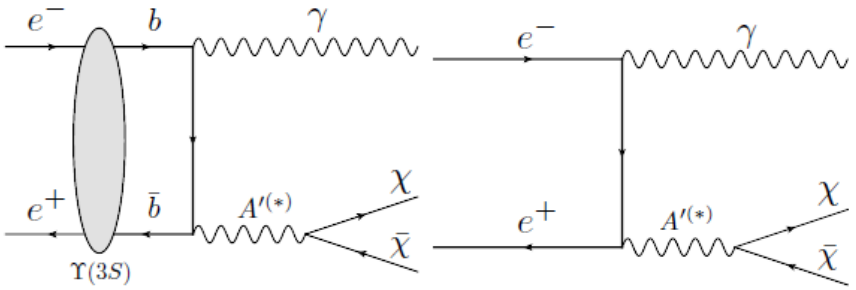
5704 trials



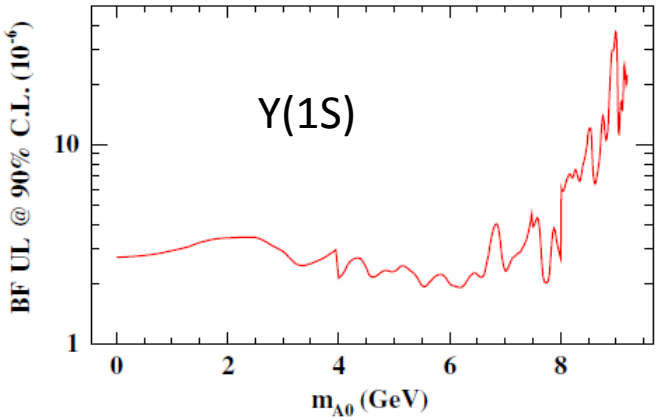


5370 trials

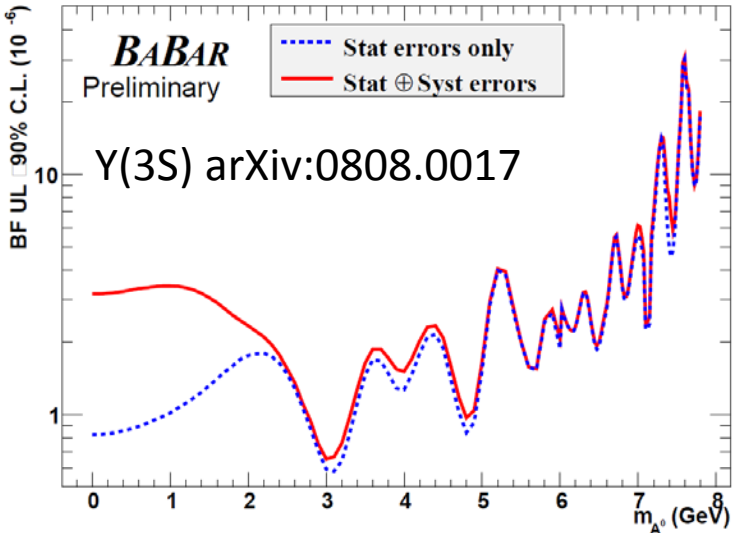
A^0,A'→ invisibles



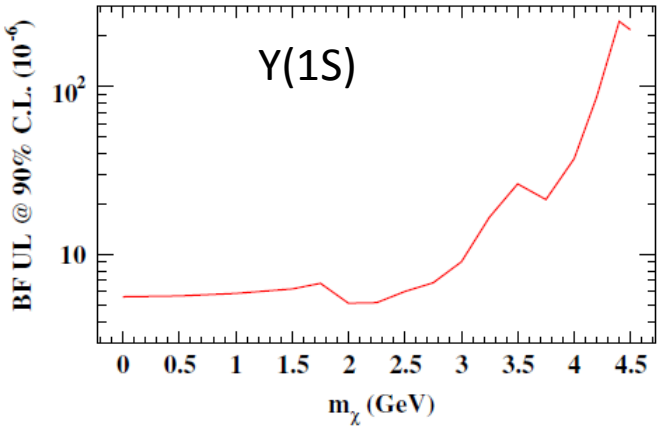
PRL 107, 021804 (2011)



90% C.L. upper limits on
$\mathcal{B}(\Upsilon(1S)\to\gamma A^0)\times\mathcal{B}$ ($A^0\to$invisible)



90% C.L. upper limits on
$\mathcal{B}(\Upsilon(3S)\to\gamma A^0)\times\mathcal{B}$ ($A^0\to$invisible)

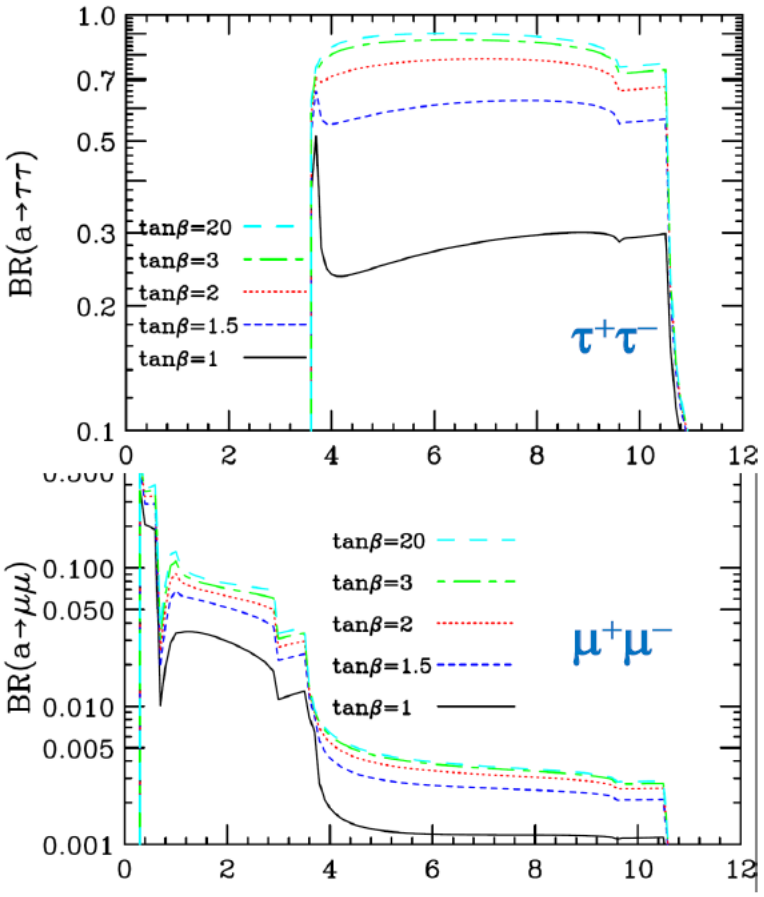


90% C.L. upper limits for $\mathcal{B}(\Upsilon(1S)\to\gamma\chi\bar{\chi})$

A^0 branching fractions

sensitive to m_A, tanβ, fermion masses

Dermisek et al., PRD81, 075003 (2010) Γ_{inv}=0 assumed



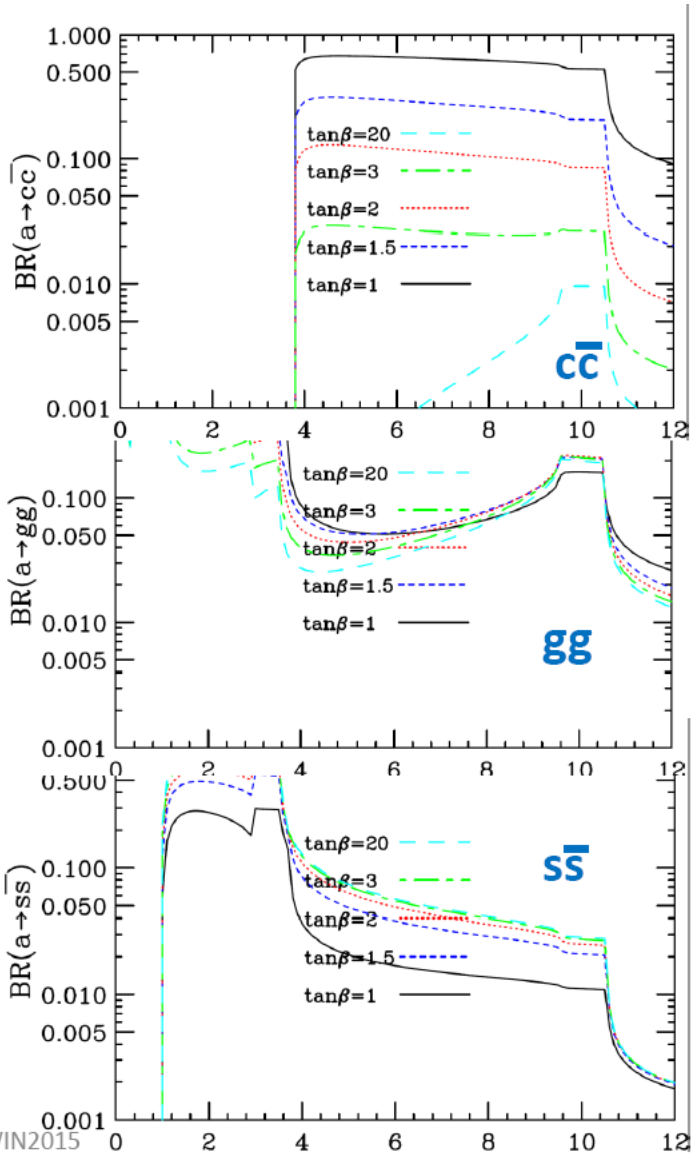




TABLE I: Summary of dark photon experiments.

Experiment	*Lab*	*Production*	*Detection*	*Vertex*	*Mass(MeV)*	*Mass Res. (MeV)*	*Beam*	*Ebeam (GeV)*	*Ibeam or Lumi*	*Machine*	*1st Run*	*Next Run*
APEX	JLab	e-brem	$\ell^+\ell^-$	no	$65-600$	0.5%	e^-	1.1–4.5	150 μA	CEBAF(A)	2010	2018
A1	Mainz	e-brem	e^+e^-	no	$40-300$	?	e^-	0.2–0.9	140 μA	MAMI	2011	–
HPS	JLab	e-brem	e^+e^-	yes	$20-200$	1–2	e^-	1–6	50–500 nA	CEBAF(B)	2015	2018
DarkLight	JLab	e-brem	e^+e^-	no	< 80	?	e^-	0.1	10 mA	LERF	2016	2018
MAGIX	Mainz	e-brem	e^+e^-	no	$10-60$	?	e^-	0.155	1 mA	MESA	2020	–
NA64	CERN	e-brem	e^+e^-	no	$1-50$	?	e^-	100	2×10^{11} EOT/yr	SPS	2017	2022
Super-HPS	SLAC	e-brem	vis	yes	< 500	?	e^-	$4-8$	1 μA	DASEL	?	?
(TBD)	Cornell	e-brem	e^+e^-	?	< 100	?	e^-	0.1-0.3	100 mA	CBETA	?	?
VEPP3	Budker	annih	invis	no	$5-22$	1	e^+	0.500	$10^{33}\,\mathrm{cm^{-2}s^{-1}}$	VEPP3	2019	?
PADME	Frascati	annih	invis	no	$1-24$	$2-5$	e^+	0.550	$\leq 10^{14}\,e^+\mathrm{OT/y}$	Linac	2018	?
MMAPS	Cornell	annih	invis	no	$20-78$	$1-6$	e^+	6.0	$10^{34}\,\mathrm{cm^{-2}s^{-1}}$	Synchr	?	?
KLOE 2	Frascati	several	vis/invis	no	$< 1.1\,\mathrm{GeV}$	1.5	e^+e^-	0.51	$2\times10^{32}\,\mathrm{cm^{-2}s^{-1}}$	DAϕNE	2014	-
Belle II	KEK	several	vis/invis	no	$\lesssim 10\,\mathrm{GeV}$	$1-5$	e^+e^-	4×7	$1\sim10\,\mathrm{ab^{-1}/y}$	Super-KEKB	2018	-
SeaQuest	FNAL	several	$\mu^+\mu^-$	yes	$\lesssim 10\,\mathrm{GeV}$	$3-6\%$	p	120	10^{18} POT/y	MI	2017	2020
SHIP	CERN	several	vis	yes	$\lesssim 10\,\mathrm{GeV}$	$1-2$	p	400	2×10^{20} POT/5y	SPS	2026	-
LHCb	CERN	several	$\ell^+\ell^-$	yes	$\lesssim 40\,\mathrm{GeV}$	~ 4	pp	6500	$\sim 10\,\mathrm{fb^{-1}/y}$	LHC	2010	2015

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