Studies of Dark Sector at Belle and Prospects with Belle II

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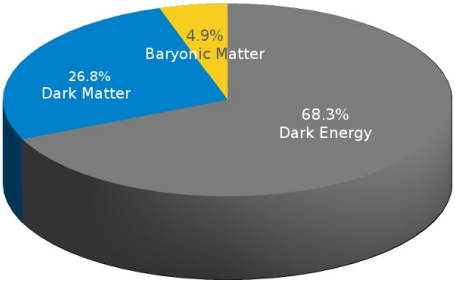
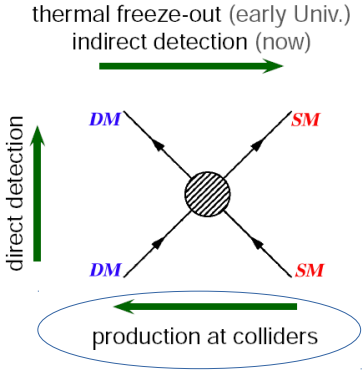
Outline

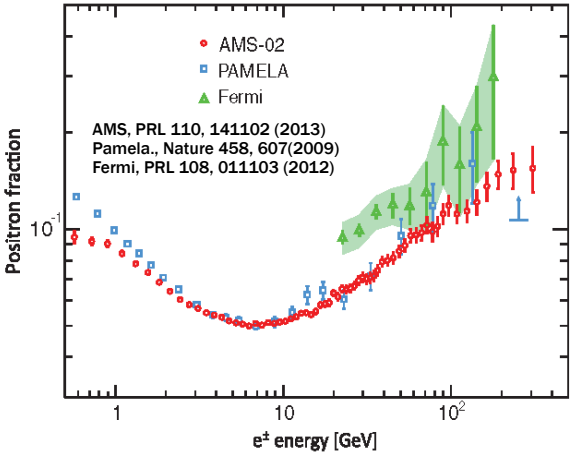
- Searches for dark-sector
  - ✓ motivations & opportunities at e^+e^- B-factories
- Recent results from Belle
  - ✓ Dark-photon search via Higgsstrahlung — PRL 114, 211801 (2015)
  - ✓ Search for dark-boson in η decays — PRD 94, 092006 (2016)
- Prospects with Belle II

*Age of en***Dark***enment?*





Motivations *for dark photon, etc.*



- Increasing e^+ fraction in excess of astrophysical expectations
- Theorists suggest dark-matter scenarios for explanations
- No such excess for anti-protons
- A dark-sector boson with $m \lesssim \mathcal{O}(\text{GeV})$?

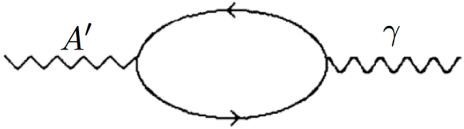
Linking SM and the Dark Sector

- Observations by PAMELA, AMS, etc. have triggered light-dark-matter scenarios.
- The dark sector can be connected to SM via the so-called "**portal**s".
- At low mass scale, vector portal is the most accessible, but other portals, e.g. (pseudo)scalar, can also be probed.

$H^\dagger H(AS + \lambda S^2)$	Higgs portal	(dim= 3, 4),
$\kappa F^Y_{\mu\nu} F'_{\mu\nu}$	Vector portal	(dim= 4),
$Y_N \bar{L} H N$	Neutrino portal	(dim= 4),
$f_a^{-1} \bar{\psi} \gamma_\mu \gamma_5 \psi \partial_\mu a$	Axion portal	(dim= 5).

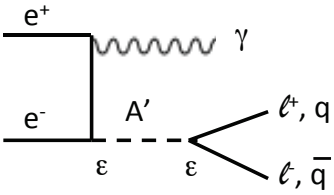
Dark photon & kinetic mixing – *as a portal*

- Dark photon, first proposed in P. Fayet, PL B**95**, 285 (1980)
- (Holdom, 1986) A boson A' belonging to an additional $U(1)'$ would mix kinetically with γ

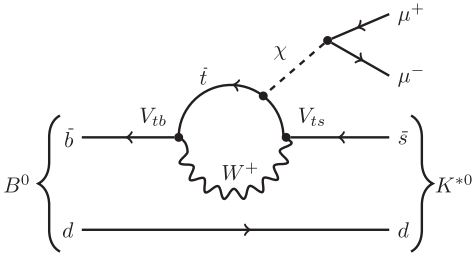


  - in general, one can express kinetic mixing as $(1/2)\epsilon\, F_{\mu\nu}F'^{\mu\nu}$
  - ϵ, the strength of the kinetic mixing, is supposed to be small, $(10^{-5} \sim 10^{-2})$.
- For A' to acquire mass, an extended Higgs sector is required to break this $U(1)'$

What to look for with B-factories



ISR



B decays

What to look for with B-factories

$e^+e^- \to \gamma\, A'(\to \chi\bar{\chi})$ $\qquad$ $e^+e^- \to \gamma\, A'(\to \ell^+\ell^-)$

$e^+e^- \to \Upsilon(nS) \to \gamma A^0$

$e^+e^- \to h'(\to A'A')A'$ with $A' \to \ell^+\ell^-$

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

$B \to K^{(*)}S \to K^{(*)}\ell^+\ell^-$

$B \to K^{(*)}A'(\to \ell^+\ell^-)$

$B \to K^{(*)}h'$ with $h' \to A'A' \to 2(\ell^+\ell^-)$

$B \to 2h' \to 4A' \to 4(\ell^+\ell^-)$

$B \to A'A' \to 2(\ell^+\ell^-)$ through off-shell $h - h'$ mixing

B decay modes from Batell, Pospelov, Ritz, PRD 83, 054005 (2011)

some predictions

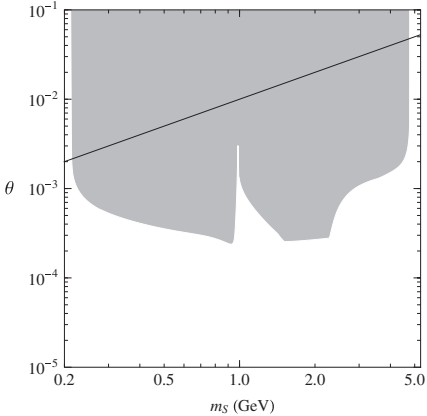


FIG. 1. Sensitivity of the *BABAR*/Belle data set to combined $B \to KS$ and $B \to K^* S$ decays in the dimuon channel. The region below the dashed line is technically natural as discussed in Eq. (5).

scalar portal case

$$\mathcal{L}_S = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \left(\frac{\theta S}{v} + \frac{\lambda S^2}{m_h^2}\right)\mathcal{L}_m - \frac{A'}{6}S^3 + \cdots.$$

for technical naturality

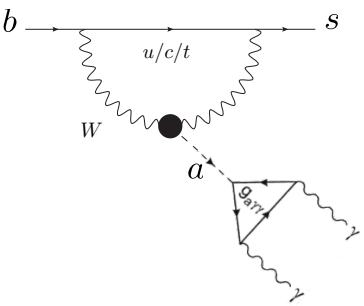
$$\theta \lesssim \frac{m_S}{m_h} \sim \mathcal{O}(10^{-2}) \times \left(\frac{m_S}{1\ \text{GeV}}\right),$$

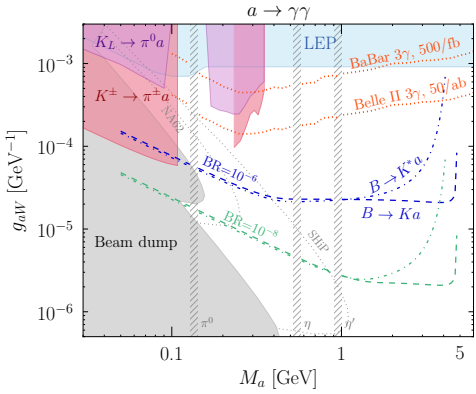
$$A' \lesssim (16\pi^2 m_S^2)^{1/2} \sim \mathcal{O}(10\ \text{GeV}) \times \left(\frac{m_S}{1\ \text{GeV}}\right).$$

Batell, Pospelov, Ritz
PRD 83, 054005 (2011)

some predictions

$$B \to K^{(*)} a(\to \gamma\gamma)$$

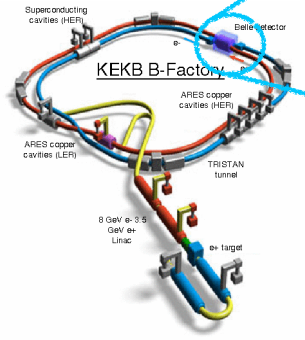


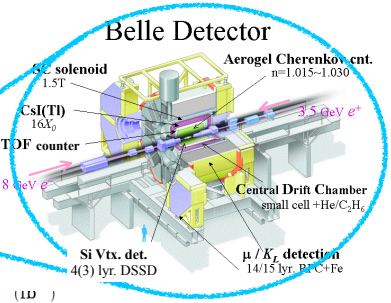


PRL 118, 111802 (2017) by Izaguirre, Lin, Shuve

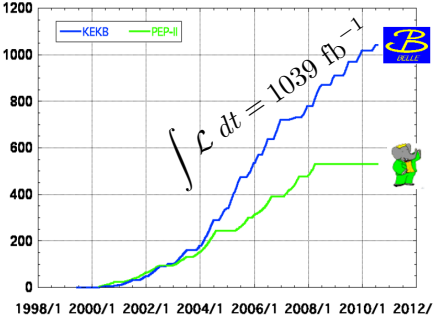
20 countries
90 institutions
~450 members

$\mathcal{L}_{\rm peak} = 21.1\ {\rm nb}^{-1}{\rm s}^{-1}$





$e^- \xrightarrow{8\ {\rm GeV}} (\star) \xleftarrow{3.5\ {\rm GeV}} e^+$

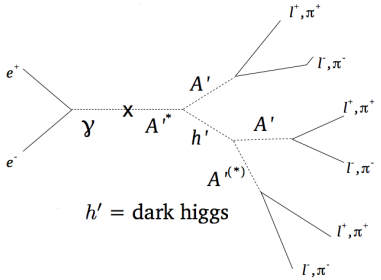


> 1 ab^{-1}
On resonance:
Υ(5S): 121 fb^{-1}
Υ(4S): 711 fb^{-1}
Υ(3S): 3 fb^{-1}
Υ(2S): 25 fb^{-1}
Υ(1S): 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 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}

Dark photon search via Higgsstrahlung

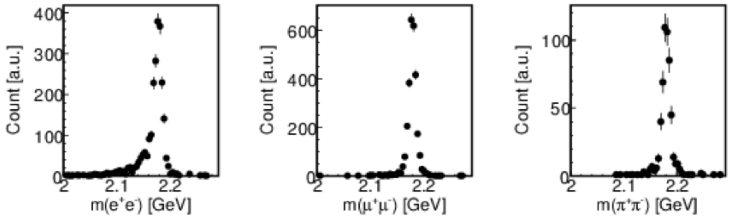
Belle, PRL 114, 211801 (2015)



- Search mode depends on $M_{h'}$ and $M_{A'}$
- In this talk, only $M_{h'} > 2M_{A'}$ is considered $\Rightarrow h' \to A'A'$ is used
  - ✓ 'exclusive': 3 charged-track pairs, each with the same invariant mass
  - ✓ 'inclusive': 2 charged-track pair, each with the same invariant mass, and missing $(E, \vec{p})$

Event selection

- 3 (at least 2) lepton/hadron pairs (e^+e^-, $\mu^+\mu^-$, or $\pi^+\pi^-$)
  - 10 exclusive channels: $3e^+3e^-$, $3\mu^+3\mu^-$, $2e^+2e^-\mu^+\mu^-$, $2\mu^+2\mu^-e^+e^-$, $3\pi^+3\pi^-$, $2\pi^+2\pi^-e^+e^-$, $2\pi^+2\pi^-\mu^+\mu^-$ $2e^+2e^-\pi^+\pi^-$, $2\mu^+2\mu^-\pi^+\pi^-$, $e^+e^-\mu^+\mu^-\pi^+\pi^-$
  - 3 inclusive channels for $m_A > 1.1$ GeV/c^2:$2e^+2e^-X$, $2\mu^+2\mu^-X$, $e^+e^-\mu^+\mu^-X$
- impact parameters and χ^2 of vertex fit requirements
- consistent with $(E, \vec{p})$ conservation
- mass of each $\ell^+\ell^-$, $\pi^+\pi^-$ pair be consistent with $M_{A'}$

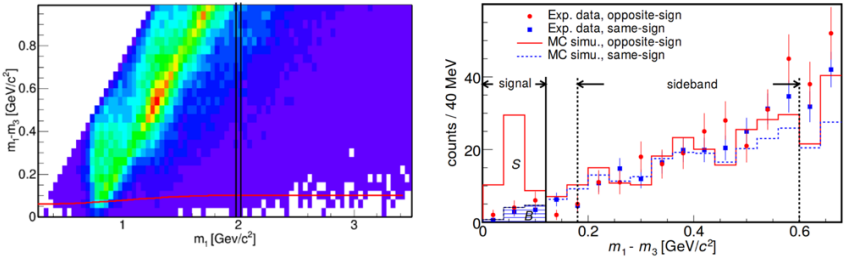


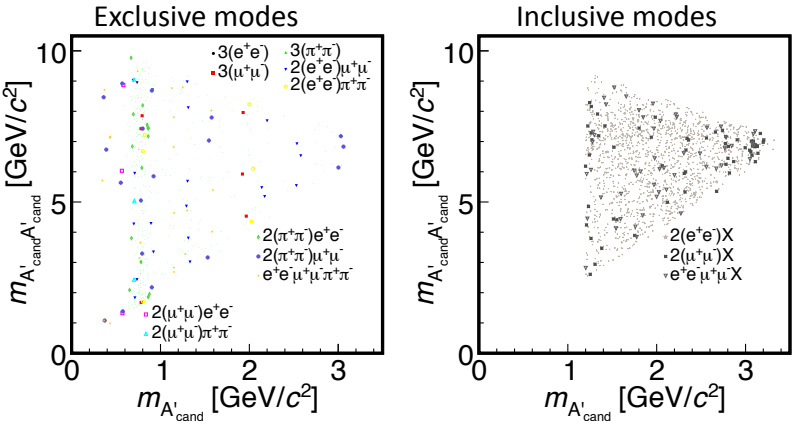
signal MC for $M_{h'} = 5$ GeV/c^2, $M_{A'} = 2.19$ GeV/c^2

Background

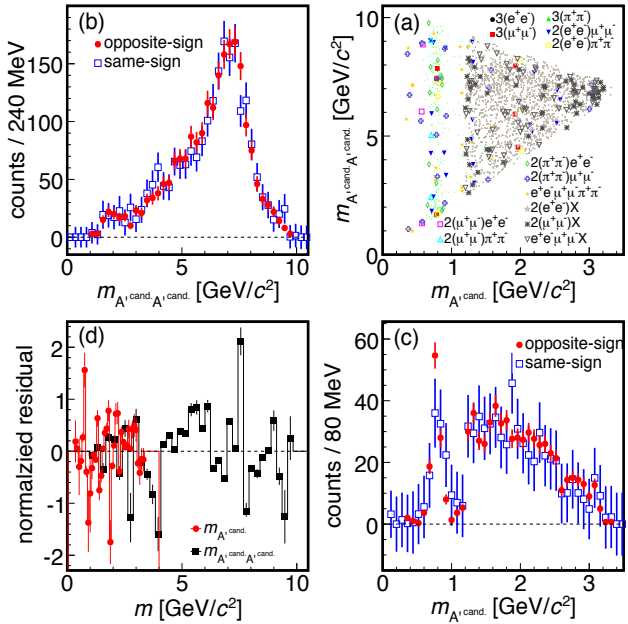
- estimated using "same-sign" pairs from $e^+e^- \to (\ell^+\ell^+)(\ell^+\ell^-)(\ell^-\ell^-)$
- Sort the pairs by invariant mass, $m_1 > m_2 > m_3$
  then plot $m_1 - m_3$ vs. m_1
- For each $M_{\ell^+\ell^-}$ region, scale same-sign yield to $\ell^+\ell^-$ in the side-band, then extrapolate into the $M_{\ell^+\ell^-}$ signal region.

for 6π mode, with $m_1 = 2$ GeV/c^2





- 19% of events due to $3(\pi^+\pi^-)$
- 74% of events due to $2(\pi^+\pi^-)\,X$


(b)
opposite-sign
same-sign
counts / 240 MeV
$m_{A'cand.A'cand.}$ [GeV/c^2]
(a)
3(e+e-)
3(μ+μ-)
3(π+π-)
2(e+e-)μ+μ-
2(e+e-)π+π-
2(π+π-)e+e-
2(π+π-)μ+μ-
e+e-μ+μ-π+π-
2(e+e-)X
2(μ+μ-)e+e-
2(μ+μ-)π+π-
2(μ+μ-)X
e+e-μ+μ-X
$m_{A'cand.}$ [GeV/c^2]
(d)
normalzied residual
$m_{A'cand.}$
$m_{A'cand.A'cand.}$
m [GeV/c^2]
(c)
opposite-sign
same-sign
counts / 80 MeV
$m_{A'cand.}$ [GeV/c^2]

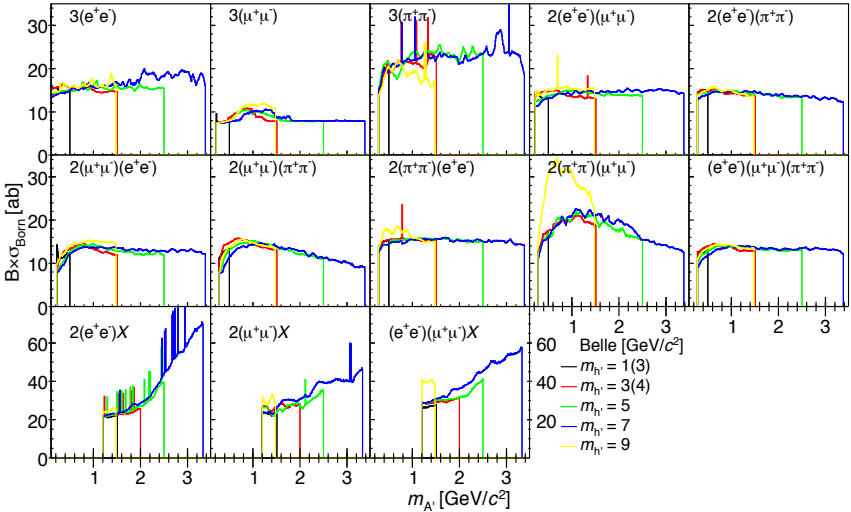
Results – Limits on $\mathcal{B} \times \sigma_{\rm Born}$

$$N_{\rm obs} = \sigma_{\rm Born}\ (1+\delta)|1-\Pi(s)|^2\ \mathcal{L}\ \mathcal{B}\ \epsilon + N_{\rm bkg}$$

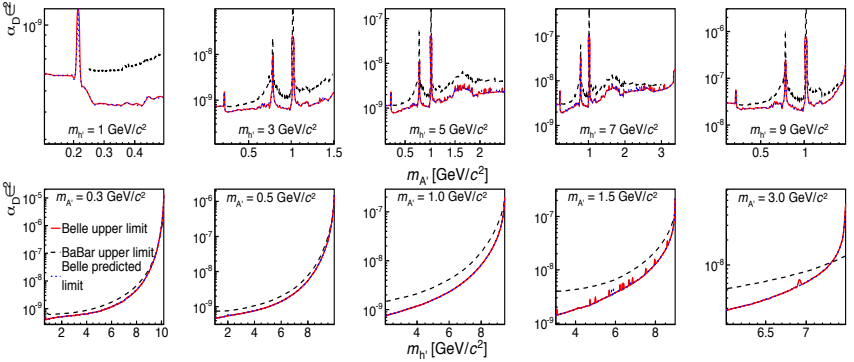
- $(1+\delta)$ from E.A. Kuraev and V.S. Fadin, Sov. J. Nucl. Phys. 41, 466 (1985)
- $|1-\Pi(s)|^2$ from S. Actis *et al.*, Eur. Phys. J. C 66, 585 (2010) and F. Ignatov, http://cmd.inp.nsk.su/∼ignatov/vpl/.
- Limits are obtined from Bayesian method, using Markov Chain Monte Carlo[1]
  - logarithmic prior for $\sigma_{\rm Born}$
  - gaussian prior for other parameters

[1] A. Caldwell, D. Kollar, K. Kröninger, BAT -The Bayesian Analysis Toolkit, Comp. Phys. Comm. 180, 2197 (2009).

Results – Limits on $\mathcal{B} \times \sigma_{\mathrm{Born}}$



Limits on kinetic mixing parameters



- $\epsilon \lesssim 8 \times 10^{-4}$ for $\alpha_D = 1/137$, $M_{h'} < 8$ GeV/c^2, $M_{A'} < 1$ GeV/c^2
  - ✓ Compare with BaBar limits with 516 fb^{-1} PRL 108, 211801 (2012)
- first limits (by any experiment) on $3(\pi^+\pi^-)$ and $2(e^+e^-)X$
- expect linear improvement with more data (almost background-free for many modes)

Search for $\eta \to U'(\to \pi^+\pi^-)\gamma$ at Belle

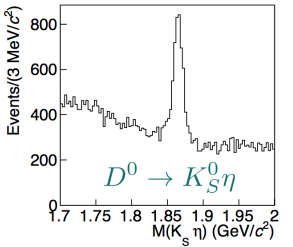
Belle, PRD 94, 092006 (2016)

- Search for a dark vector boson U' that couples to quarks ($U' \to \pi^+\pi^-$)
  - ✓ to constrain the baryonic fine structure constant $\alpha_{U'} \equiv g_{U'}^2/4\pi$, where the interaction is given by $\mathcal{L} = (1/3)g_{U'}\bar{q}\gamma^\mu q U'_\mu$

à la S. Tulin, PRD 89, 114008 (2014)

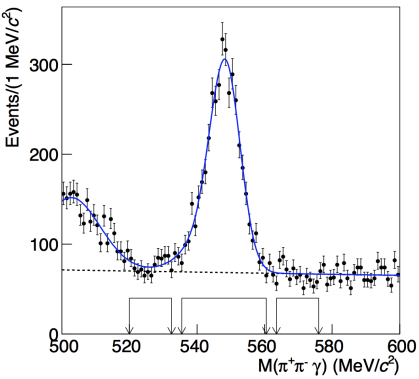
- Use Belle data sample of 976 fb^{-1}
- To suppress combinatorial background, demand:
  - ✓ η to come from $D^0 \to K^0_S\eta$
  - ✓ D^0 to come from $D^{*+} \to D^0\pi^+$

Search for $\eta \to U'(\to \pi^+\pi^-)\gamma$ at Belle



- γ selection
  - ✓ $E_\gamma > 60$ (100) MeV for barrel (endcap)
  - ✓ "E9/E25" > 0.85
- K^0_S selection by neural net
- vertex χ^2 cut for η and mass-constraint
- $p^{\rm cm}_{D^*} > 2.5,\ 2.6,\ 3.0$ GeV for $\sqrt{s}$ below, at, or above $\Upsilon(4S)$ resonance

Search for $\eta \to U'(\to \pi^+\pi^-)\gamma$ at Belle



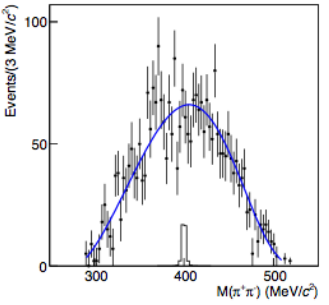
- $N_\eta = 2974 \pm 90$ events by binned max. likelihood fit to $M(\pi^+\pi^-\gamma)$
- Cross-check by measuring the ratio

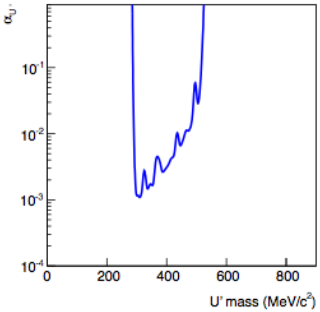
$$\frac{\mathcal{B}(\eta \to \pi^+\pi^-\gamma)}{\mathcal{B}(\eta \to \pi^+\pi^-\pi^0)} = 0.185 \pm 0.007$$

c.f. 0.184 ± 0.004 for W.A.

- Fit to $M(\pi^+\pi^-)$ after η sideband subtraction
  - ✓ global shape: QCD-based $d\Gamma/ds$
  - ✓ add U' part with $\sigma_M \sim (1 \sim 2)$ MeV

Results for $\eta \to U'(\to \pi^+\pi^-)\gamma$

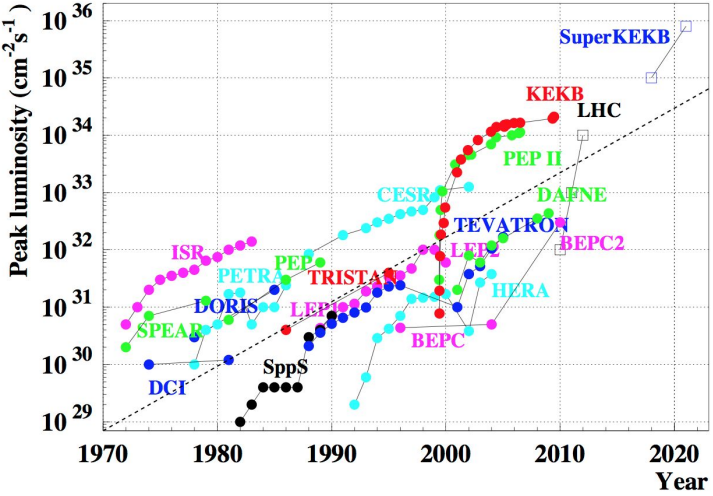




$$\alpha_{U'} = \left[\frac{\alpha}{2}\left(1-\frac{m_{U'}^2}{m_\eta^2}\right)^{-3}\left|\mathcal{F}(m_{U'}^2)\right|^{-2}\frac{1}{\mathcal{B}(U'\to\pi^+\pi^-)}\right] \times \left[\frac{\Gamma(\eta\to\pi^+\pi^-\gamma)}{\Gamma(\eta\to\gamma\gamma)}\right]\left[\frac{\Gamma(\eta\to U'\gamma\to\pi^+\pi^-\gamma)}{\Gamma(\eta\to\pi^+\pi^-\gamma)}\right],$$

Prospects with Belle II

for the next Luminosity Frontier

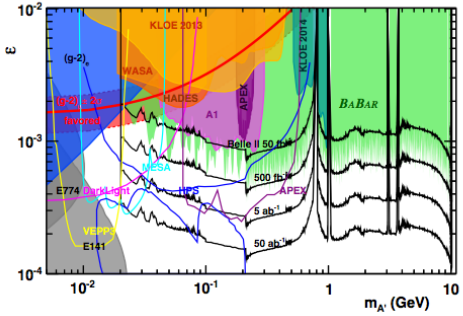


Belle II milestones

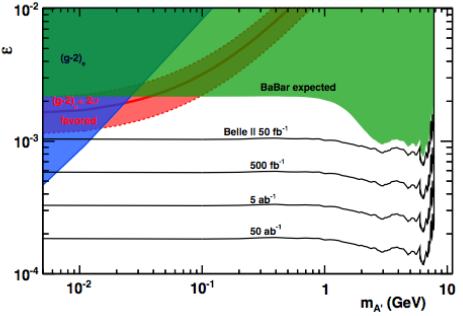
- Phase 1 (Feb. 2016): beam commissioning + beam background measurements
  - ✓ circulate beams; no collision
  - ✓ BEAST II (in place of Belle II) as a commissioning detector
- Recent highlights
  - ✓ Final Quads installed in Feb. 2017
  - ✓ Belle II roll-in on Apr. 11, 2017
- Phase 2 (Dec. 2017): Detector in place without SVD + PXD
  - ✓ *Dark-sector search can start!*
- Phase 3 (Nov. 2018): Start physics run with full Belle II detector

Dark-photon prospects with Belle II

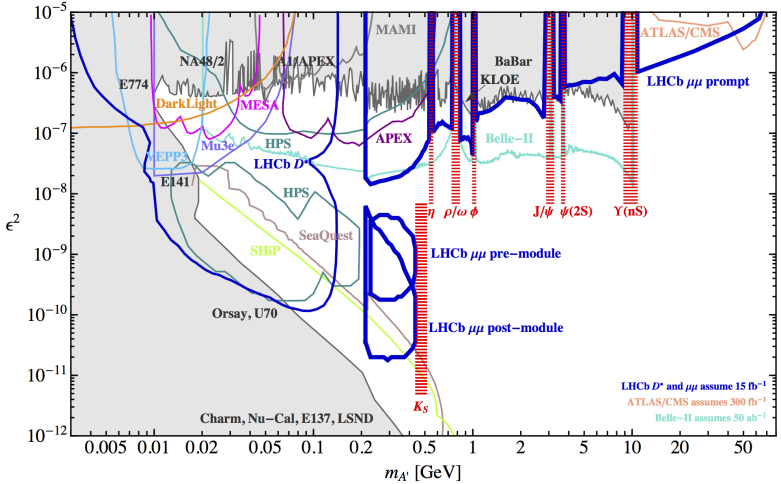
$e^+e^- \to \gamma\, A'(\to \ell^+\ell^-)$



$e^+e^- \to \gamma\, A'(\to \chi\bar{\chi})$



Dark-photon prospects (*wider view*)



Philip Ilten,[1,*] Yotam Soreq,[2,†] Jesse Thaler,[2,‡] Mike Williams,[1,§] and Wei Xue[2,¶]

PRL 116, 251803 (2016)

Closing words

- *B*-factory experiments are not merely good old CPV/CKM machines, but they probe much wider regions of physics.
  - e.g. exotic particles, heavy invisible particles, dark sector, etc.
- Dark photon searches at e^+e^- *B*-factories become available one by one.
  - Depending on the mass parameters of the dark sector, significant limists have been obtained in $\mathcal{O}(\text{GeV})$ region.
  - But there are many other modes which have yet to be explored.
  - *Please stay tuned for Belle II*