Dark Sector Motivation
What is the Dark Sector?
Flavor Experiments capable of probing the Dark Sector
e^+e^- Colliders

Dark sector searches on flavor experiments @ FPCP 2017

Thomas Czank for the BELLE and Belle II collaborations

Tohoku University

June 8th, 2017

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Outline

Dark Sector Motivation
What is the Dark Sector?
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Galaxy Rotation Problem

Stacy S. McGaugh, Federico Lelli, and James M. Schombert Phys. Rev. Lett. 117, 201101 – Published 9 November 2016
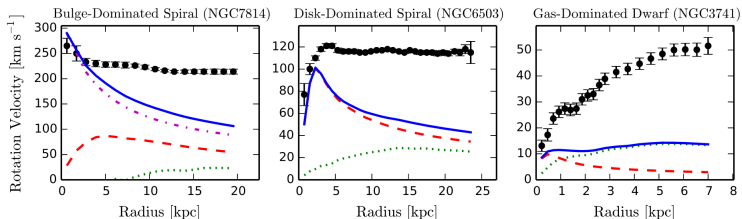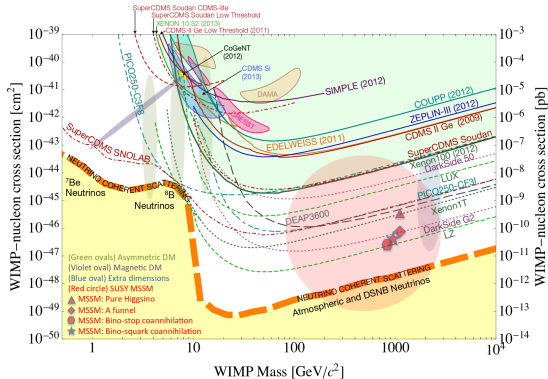

Black dots are the observed rotation curves, dotted lines are gas components, dashed lines are stellar disk, dot and dashed lines are the Bulge and the continuous line is the visible components together

- **There is extra invisible Matter!**

- Could be elegantly explained by Supersymmetry with Weakly Interacting Massive Particle (WIMP), Cold Dark Matter
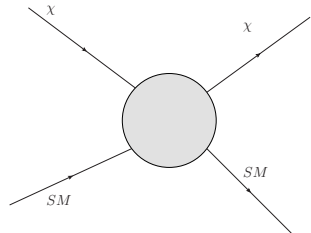
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Searched Region Map

The Snowmass 2013 Proceedings Organized by APS (FERMILAB-CONF-13-648)

- Sensitive for 10 GeV∼1 TeV

- **No Signal Found! Yet**

- <10 GeV region could be investigated by flavor experiments

- WIMP Search via Nuclear Recoil Direct Detection

Dark Sector Motivation
What is the Dark Sector?
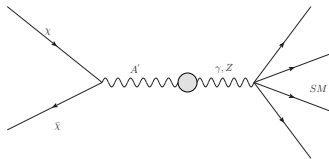Flavor Experiments capable of probing the Dark Sector
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Positron fraction in Cosmic rays detection experiments

M.Aguilar et al.(AMS Collaboration) Phys.Rev.Lett.110,141102– 2013

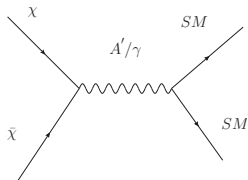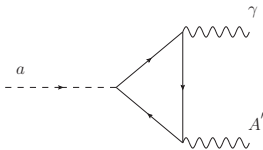- Positron fraction excess not expected from SM

- Antiproton fraction excess **not** observed

- Secluded $U(1)_D$ boson as a possible model
  < 2 GeV
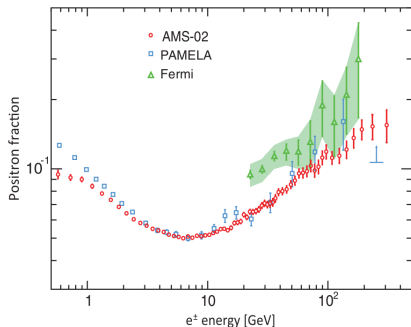
- aka <u>Dark Photon</u> A'

- High intensity low energy experiments can search
  1MeV$\sim$10GeV region

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Solution to SM gaps?


Vector Portal Diagram

Axion Portal Diagram

Dark Sectors 2016 Workshop:Community Report (1608.08632)

- **Neutrino Portal**
- **Vector Portal**
- **Higgs Portal**
- **Axion portal**

- Portals are the window to the Dark Sector by SM particles
- Every portal has a Dark Sector SM interaction

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Dark Sector Models
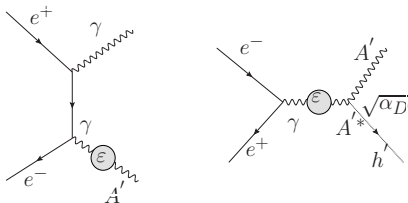
Dark Photon Flavor experiments typical channel

Dark Sectors 2016 Workshop:Community Report (1608.08632)

- **minimal kinetically mixed dark photon**

$$\mathcal{L}_{\text{int}_{A'}} \propto \frac{1}{2} \frac{\epsilon}{\cos\theta_{\text{W}}} F^{\mu\nu} F'_{\mu\nu}, \epsilon = \frac{\alpha'}{\alpha}$$

- SM gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$
- Dark vector boson group $U(1)_D$

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Flavor Experiments Types

Dark Sectors 2016 Workshop:Community Report (1608.08632)
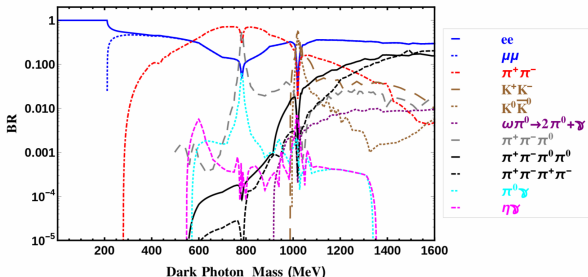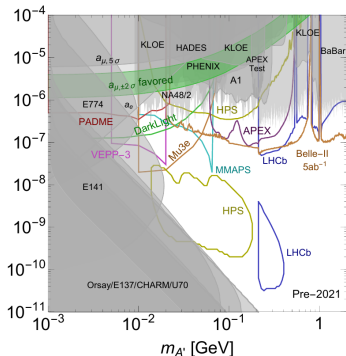
| Experiment Class	Typical Production Modes	Detection
e^+e^- collider	$e^+e^- \rightarrow \gamma A'$	bump hunt
Electron fixed-target	$e^- Z \rightarrow e^- Z A'$	DM scatter or bump hunt
Hadron collider	$pp \rightarrow (\text{jet}/\gamma) A'$	bump hunt or Drell-Yan
Positron fixed-target	$e^+ e^- \rightarrow \gamma A'$	bump hunt
Proton fixed-target	$\pi^0/\eta/\eta' \rightarrow \gamma A', q\bar{q} \rightarrow A', pZ \rightarrow pZA'$	DM scatter or Drell-Yan

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Summary of dark photon experiments

Dark Sectors 2016 Workshop:Community Report (1608.08632)

Exp	Lab	Product	Detect	M(MeV)	Res (MeV)	Beam	EBeam (GeV)	Ibeam/Lim	Run
APEX	JLab	e-brem	$\ell^+\ell^-$	65–600	0.5%	e^-	1.1–4.5	150μA	2010(18)
A1	Mainz	e-brem	e^+e^-	40–300	?	e^-	0.2–0.9	140μA	2011
HPS	JLab	e-brem	e^+e^-	20–200	1–2 %	e^-	1–6	50–500nA	2015(18)
DarkLight	JLab	e-brem	e^+e^-	< 80	?	e^-	0.1	10 mA	2020
MAGIX	Mainz	e-brem	e^+e^-	10–60	?	e^-	0.155	1mA	2020
NA64	CERN	e-brem	e^+e^-	1–50	?	e^-	100	2×10^{11} EOT/yr	2017(22)
Super-HPS	SLAC	e-brem	visible	< 500	?	e^-	4–8	1μA	?
VEPP3	Budker	annih	invis	5–22	1	e^+	0.500	$10^{33} cm^{-2}/s$	2019
PADME	Frascati	annih	invis	1–24	2–5	e^+	0.550	$\leq 10^{14} e^+$OT/y	2018
MMAPS	Cornell	annih	invis	20–78	1–6	e^+	6.0	$10^{34} cm^{-2}/s$	?
BES-III	BEPC II	several	vis/in	$\lesssim$ 5GeV	1	e^+e^-	$\leq$4.63	$10^{33} cm^{-2}/s$	2008
BaBar	PEP II	several	vis/in	$\lesssim$ 12GeV	1–5	e^+e^-	9 × 3.1	$3 \times 10^{33} cm^{-2}/s$	2008
KLOE 2	Frascati	several	vis/in	< 1.1GeV	1.5	e^+e^-	0.51	$2 \times 10^{32} cm^{-2}/s$	2014
BELLE	KEKB	several	vis/in	$\lesssim$ 10GeV	1–5	e^+e^-	8 × 3.5	$2 \times 10^{34} cm^{-2}/s$	2008
Belle II	SuperKEK	several	vis/in	$\lesssim$ 10GeV	1–5	e^+e^-	7 × 4	$1 \sim 10ab^{-1}/y$	2018
SeaQuest	FNAL	several	$\mu^+\mu^-$	$\lesssim$ 10 GeV	3–6%	p	120	10^{18} POT/y	2017(20)
SHIP	CERN	several	visible	$\lesssim$ 10 GeV	1–2	p	400	2×10^{20} POT/5y	2026
LHCb	CERN	several	$\ell^+\ell^-$	$\lesssim$ 40 GeV	$\sim$ 4	pp	6500	$\sim 10fb^{-1}/y$	2010(15)

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BES III (BEPC II)

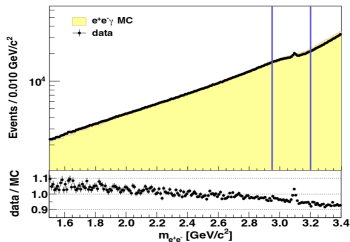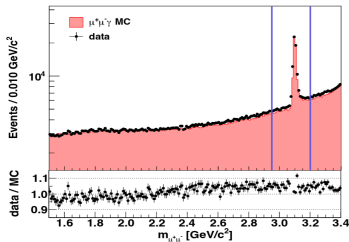Design and construction of the BESIII detector Nucl.Instr.and Meth.A, 614(2010), p.345
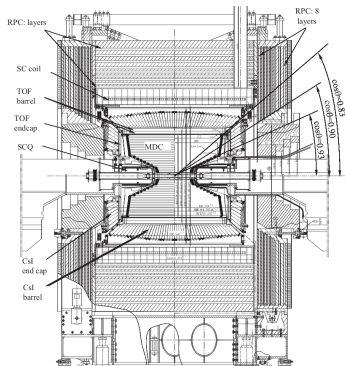
- Symmetric Collider
- $2 < \sqrt{s} < 4.63$ GeV collision energy
- $\tau-$Charm factory
- integrated luminosity 10.3fb^{-1}
- $\varepsilon < 10^{-2}$

- $e^+e^- \rightarrow A^{'}\gamma_{\mathrm{ISR}} \rightarrow \ell^+\ell^-\gamma_{\mathrm{ISR}}$

Dark Sector Motivation
What is the Dark Sector?
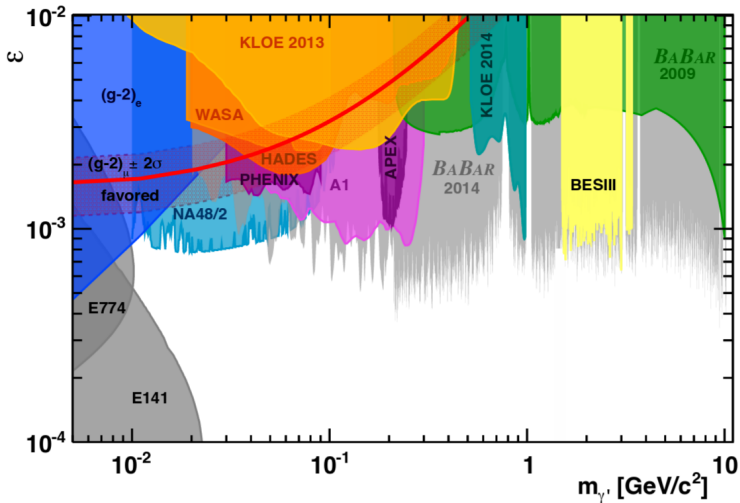Flavor Experiments capable of probing the Dark Sector
e^+e^- Colliders

BES III Dark Photon Search

- 2.93 fb^{-1} data taken at $\sqrt{s} = 3.773$ GeV
- $e^+e^- \to e^+e^-(\mu^+\mu^-)\gamma_{\mathrm{ISR}}$
- lepton invariant mass **no** <u>obvious increase</u> in $1.5 \sim 3.4$ GeV/c^2

Dark Photon Search in the Mass Range Between 1.5 and 3.4 GeV/c^2 (1705.04265) - 2017

lines for the J/ψ resonance exclusion region

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BES III Dark Photon EL

Dark Photon Search in the Mass Range Between 1.5 and 3.4 GeV/c^2 (1705.04265) - 2017

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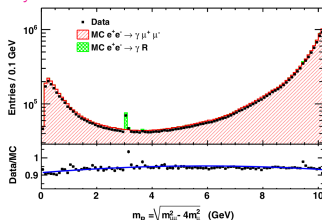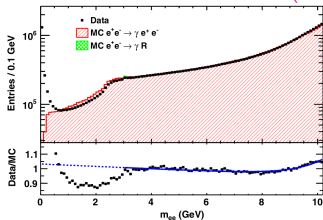
BABAR (PEP II)

The BaBar detector: Upgrades, operation and performance Nucl.Instr.and Meth.A,729(2013) p.615
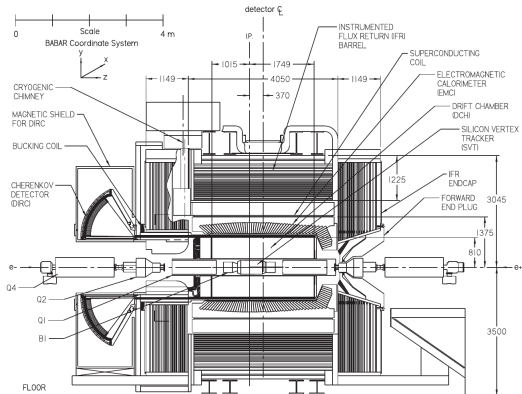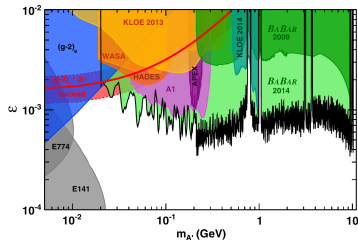

- Asymmetric collider

- B-factory

- 9.0×3.1 GeV

- integrated luminosity 557 fb^{-1}

- $10^{-4} < \varepsilon < 10^{-3}$

- $e^+e^- \rightarrow \gamma A'/A' 2\ell$ as well as displaced Vertex

- Single energetic photon trigger

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BABAR Dark Photon Search

J.P.Lees et al.(BaBar Collaboration) Phys.Rev.Lett. 113 201801

- $e^+e^- \rightarrow A'\gamma, A' \rightarrow \ell^+\ell^-$
- 514fb^{-1}
- **no** signal found

Dark Sector Motivation
What is the Dark Sector?
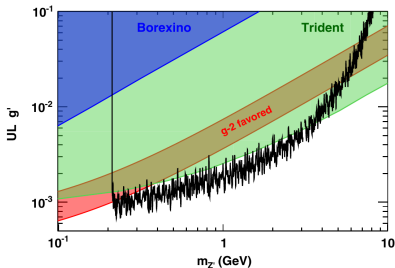Flavor Experiments capable of probing the Dark Sector
e^+e^- Colliders

BABAR Leptophilic Dark Gauge Search

Search for a muonic dark force at BABAR Phys.Rev.D.94.011102 - 2016
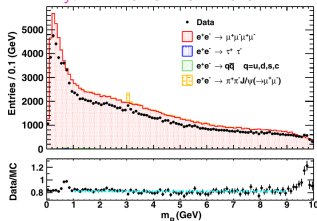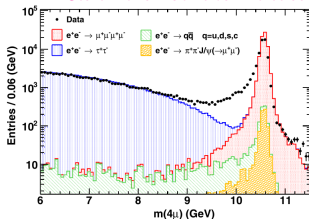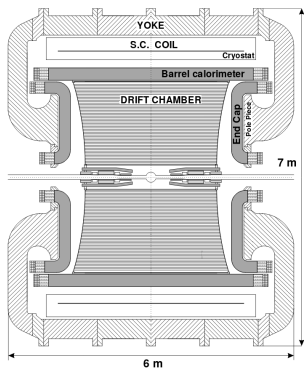
- $e^+e^- \rightarrow \mu^+\mu^-Z' \rightarrow \mu^+\mu^-\mu^+\mu^-$ search
- Z', μ coupled dark gauge
- **no** signal found
- $M_{Z'} \propto g' < S >$

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KLOE 2 (DAΦNE)

The tracking detector of the KLOE experiment Nucl.Instr.and Meth.A,488(2002),p.51

- Symmetric collider
- ϕ-factory
- $m_\phi \simeq 1.019$ GeV
- integrated luminosity 1.8 fb^{-1}
- Apart from usual channel, $\phi \to \eta A'$
- Kinetic mixing range $10^{-4} < \varepsilon < 10^{-3}$

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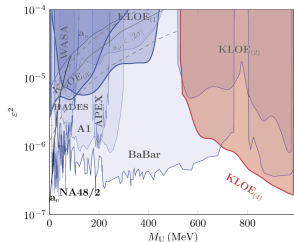
KLOE 2 Dark Photon Search

Limit on the production of a new vector boson in $e^+e^- \to U\gamma$, $U \to \pi^+\pi^-$ Phys.Lett.B 757(2016) p.356
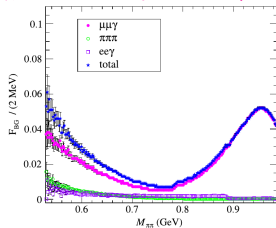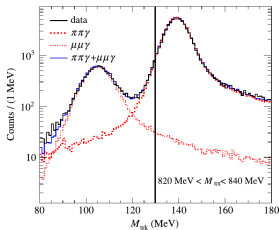
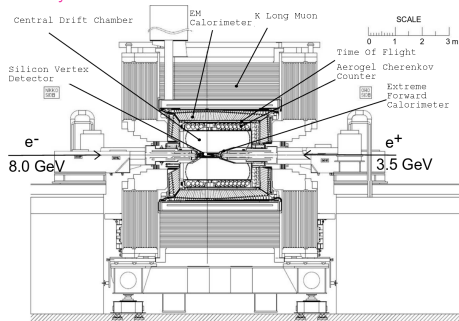- $e^+e^- \to A'\gamma \to \pi^+\pi^-\gamma$

- no invisible decay assumed due to $m_{A'} < m_\chi$

- **no** signal found

- new constraints on ε

Dark Sector Motivation
What is the Dark Sector?
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Belle (KEKB)

The Physics of B factories - 2014

Central Drift Chamber

EM Calorimeter

K Long Muon

SCALE

0 1 2 3 m

Time Of Flight

Silicon Vertex Detector

Aerogel Cherenkov Counter

Extreme Forward Calorimeter

e^-
8.0 GeV

e^+
3.5 GeV

- Asymmetric collider

- B-factory

- integrated luminosity 1040fb^{-1}

- $e^+e^- \to \gamma A^{'}/A^{'}h^{'}/A^{'}2\ell$, as well as displaced Vertex

- Better resolution for charged final states compared to BaBar, but no single energy photon trigger

Dark Sector Motivation
What is the Dark Sector?
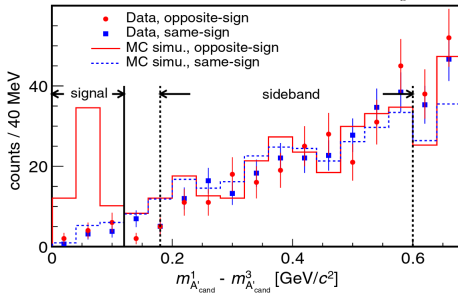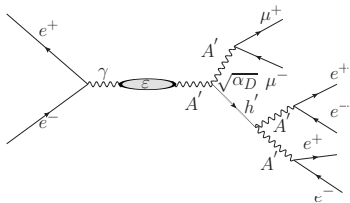Flavor Experiments capable of probing the Dark Sector
e^+e^- Colliders

Belle Dark Photon, Dark Higgs Search

Search for the Dark Photon and the Dark Higgs Boson at Belle Phys.Rev.Lett.114.211801 - 2015

- $e^-e^+ \to A'h', h' \to A'A', A' \to \ell^-\ell^+$ or $\pi^+\pi^-$

- $1.1 < m_{A'} < 3.5$ GeV/c^2

- $2.2 < m_{h'} < 10.5$ GeV/c^2

$P_X = P_{e^+e^-} - P^1_{A'_{\to \ell^+\ell^-}} - P^2_{A'_{\to \ell^+\ell^-}}$

- $A'h' \to 3A' \to 6\pi$
  $m^1_{A'}$ highest mass, $m^3_A{}'$
  lowest mass

- **no** signal found

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Search for the Dark Photon and the Dark Higgs Boson at Belle Phys.Rev.Lett.114.211801 - 2015

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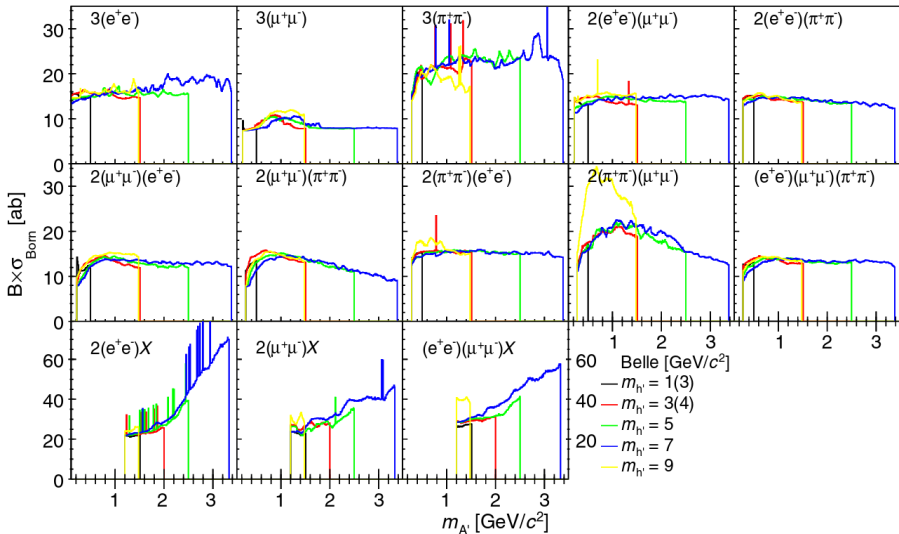
BELLE quark coupled dark sector search

Search for a dark vector gauge boson decaying to $\pi^+\pi^-$ using $\eta \to \pi^+\pi^-\gamma$ decays Phys.Rev.D.94.092006

- dark sector gauge boson U'
- $D^{*+} \to D^0\pi^+$, $D^0 \to K_S^0\eta$, $\eta \to U'\gamma$, $U' \to \pi^+\pi^-$
- $\alpha_{U'} = \frac{g_{U'}^2}{4\pi}$
- baryonic fine structure $10^{-3} < \alpha_{U'} < 10^{-2}$
- $290 < m_{U'} < 520 \text{MeV}/c^2$
- **no** signal found
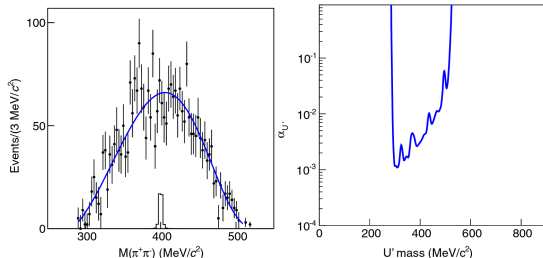
Blue curve is the PDF fitted over the pion pair invariant mass distribution

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Belle II (SuperKEKB)

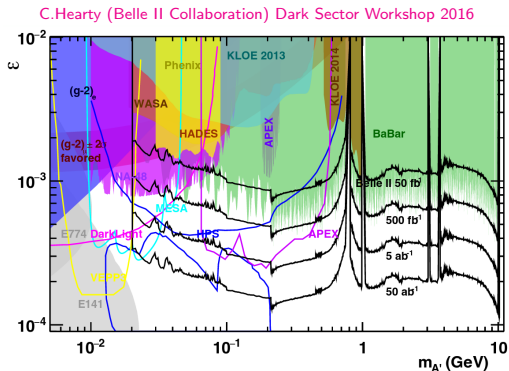The Belle II Experiment and SuperKEKB Upgrade, Boqun Wang for Belle II (1511.09434v2) - 2016
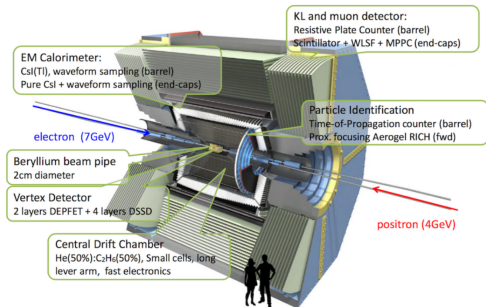
- e^+e^- annihilation at $\sqrt{s} \sim 10$ GeV
- Single Photon trigger planned
- Watch **Elisa** and **Riccardo** Talks tomorrow for whole Belle II Physics prospects and current status

- A' mass range 20MeV – 10 GeV, for $\gamma \ell^+ \ell^-$
- $e^+e^- \to \gamma A' / A' h' / A' 2\ell$, as well as displaced Vertex, (BELLE channels)

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Belle II Dark Photon Search prospects

C.Hearty (Belle II Collaboration) Dark Sector Workshop 2016

- extrapolation based on BABAR dark photon search
- bigger luminosity and momentum resolution will improve dark photon search

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Flavor experiments prospects

- BES III

  - $J/\psi \to A^{'} \ell^+ \ell^-$
  - dark higgstrahlung

- KLOE 2

  - $\phi \to \eta A^{'}$
  - dark higgstrahlung
    $e^+ e^- \to A^{'} h^{'}$
  - invisible $A^{'}$ decays to
    light dark matter

- BABAR

  - invisible decays and
    displaced vertex decays

- BELLE

  - $e^+ e^- \to A^{'} \gamma_{\mathrm{ISR}}$
    channel
  - $Z^{'}$ prompt decays
    $\mu^+ \mu-$
  - invisible decays and
    displaced vertex decays

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Summary

- **no** evidence for WIMPs, other dark sector models to be searched
- **no** signal found for different coupling models of the Dark Photon
- Still many signal searches have not been performed
- Many experiments are currently concluding upgrades
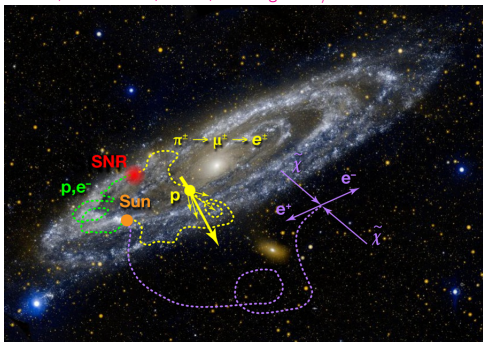
Dark Sector Motivation
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Backup

Dark Sector Motivation
What is the Dark Sector?
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e^+e^- Colliders

Positron fraction explanations

GALEX, JPL-Caltech, NASA; Drawing: APS/Alan Stonebraker

- Standard Model predicted decreasing e^+ fraction with increasing energy

- Pulsar accelerated $e^{\pm}$

- Dark matter decays

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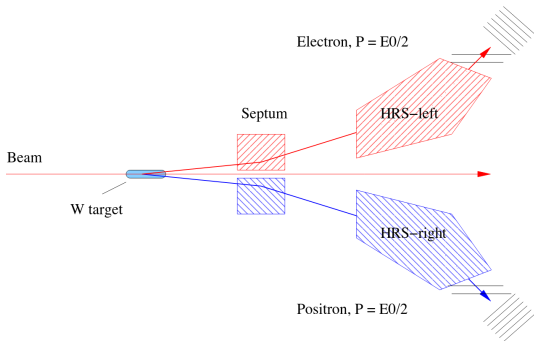e^+e^- Colliders

Visible Dark Photons

Dark Sectors 2016 Workshop: Community Report (1608.08632)

$$\mathcal{L}_{\text{kin.mix}} = \frac{1}{2}\epsilon F^{\mu\nu}F'_{\mu\nu} \ \text{ with } \ F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$$

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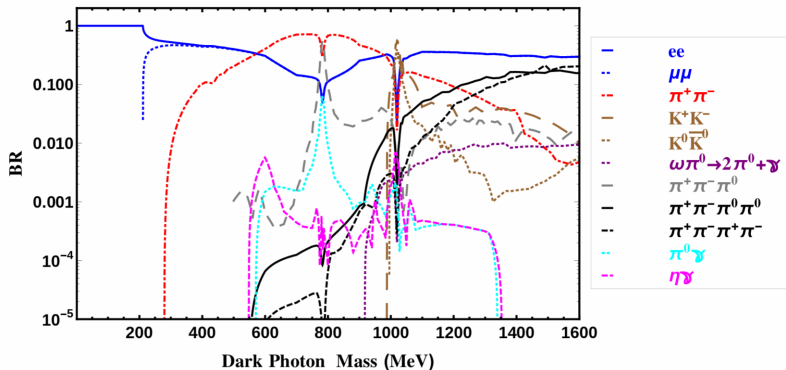
APEX (JLab)

APEX Proposal 2013

- e^- beam bremsstrahlung after collision with W target
- A' bump hunt in $65 < m_{A'} < 600$ MeV

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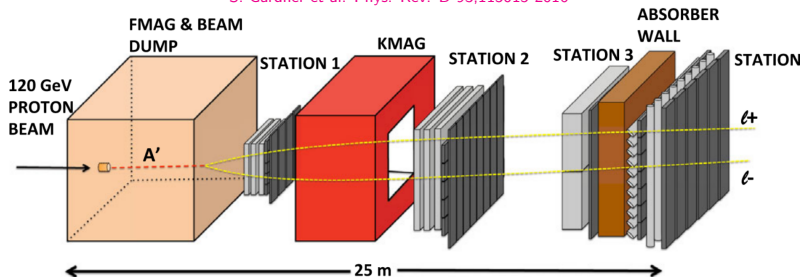e^+e^- Colliders

PADME (Frascati)

The PADME experiment at LNF M. Raggi on behalf of the PADME Collaboration 2017
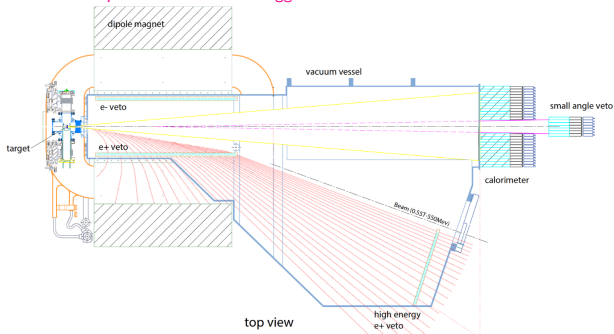
- 550MeV e^+ beam incident on diamond target
- looking for the $e^+e^- \to A^{'}\gamma$, missing mass , γ prompts shower in the calorimeter

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e^+e^- Colliders

Sea Quest (FNAL)

S. Gardner et al. Phys. Rev. D 93,115015-2016

- 120GeV p beam incident on diamond target
- looking for the $q\bar{q} \to A' \to \ell^+\ell^-$, proton-bremsstrahlung, others