Dark photons: bridging the gap between resonant and beam dump searches with LHCb

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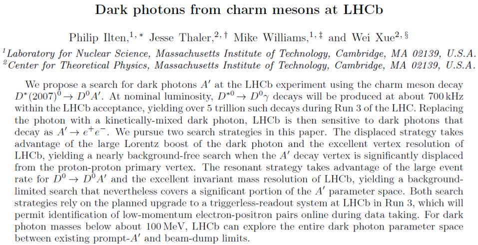
UNIVERSITY OF LIVERPOOL Seminar

Introduction

- search for dark photons via $D^{*0} \to D^0 A'$
- still preliminary, so limits will probably change slightly!
- to be released soon (about a month)

- dark matter and dark photons
- dark photon motivation
- current limits
- LHCb detector
- signal rate
- detector response
- search



Dark photons from charm mesons at LHCb

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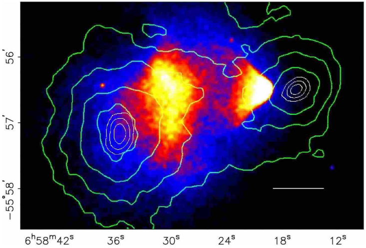
We propose a search for dark photons A' at the LHCb experiment using the charm meson decay $D^*(2007)^0 \to D^0 A'$. At nominal luminosity, $D^{*0} \to D^0\gamma$ decays will be produced at about 700 kHz within the LHCb acceptance, yielding over 5 trillion such decays during Run 3 of the LHC. Replacing the photon with a kinetically-mixed dark photon, LHCb is then sensitive to dark photons that decay as $A' \to e^+e^-$. We pursue two search strategies in this paper. The displaced strategy takes advantage of the large Lorentz boost of the dark photon and the excellent vertex resolution of LHCb, yielding a nearly background-free search when the A' decay vertex is significantly displaced from the proton-proton primary vertex. The resonant strategy takes advantage of the large event rate for $D^0 \to D^0 A'$ and the excellent invariant mass resolution of LHCb, yielding a background-limited search that nevertheless covers a significant portion of the A' parameter space. Both search strategies rely on the planned upgrade to a triggerless-readout system at LHCb in Run 3, which will permit identification of low-momentum electron-positron pairs online during data taking. For dark photon masses below about 100 MeV, LHCb can explore the entire dark photon parameter space between existing prompt-A' and beam-dump limits.

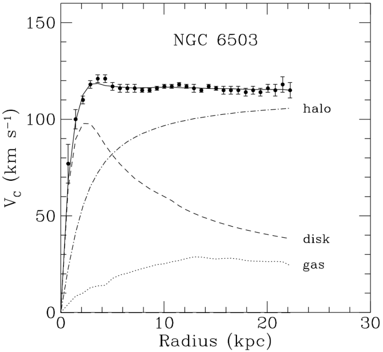
Dark Matter

Indirect Observation

- $\approx 85\%$ of matter estimated to be dark matter
- large body of experimental evidence, see Phys. Rept. **405** (2005) 279 for a full review
  - spiral galaxy rotation curves
  - strong and weak lensing
  - cosmic microwave background
  - merging clusters and galaxies
  - and many more ...



Astrophys. J. **648** (2006) L109



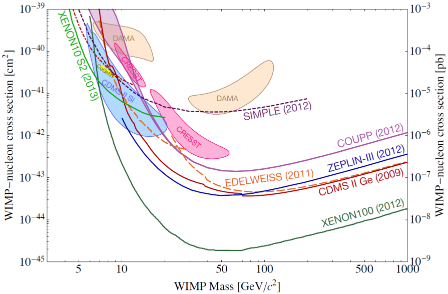
MNRAS **249** (1991) 523

Dark Matter Types

- hot dark matter
  - light ultra-relativistic particles, *e.g.* neutrinos
  - not consistent with structure formation
- cold dark matter
  - weakly interacting massive particles, WIMPS
  - possible candidates from SUSY and hidden valley models

$$\Omega_\chi h^2 \propto \frac{1}{\langle\sigma_a v\rangle} \implies \langle\sigma_a v\rangle \approx 0.9 \text{ pb}$$

$$\langle\sigma_a v\rangle \approx \frac{\pi\alpha^2}{8m_\chi^2} \implies m_\chi \approx 100 \text{ GeV}$$



arXiv:1310.8327 [hep-ex]

Dark Sector Portals

- limited number of SM symmetries allow dark matter interactions

type	particles	operator
vector	dark photons	$B_{\mu\nu}F'^{\mu\nu}$
pseudo-scalar	axions	$F_{\mu\nu}\widetilde{F}^{\mu\nu}$, $G_{i\mu\nu}\widetilde{G}_i^{\mu\nu}$, $\psi^\dagger\gamma^\mu\gamma^5\psi$
scalar	dark Higgs	$H^\dagger H$
fermion	sterile neutrinos	LHN

- scalar (Higgs) portal explored via high-energy colliders
- fermion (neutrino) portal via neutrino experiments
- vector and pseudo-scalar (dark photon and axion) portals via high luminosity experiments

Dark Photons

- minimal model, assume broken $U(1)$ gauge symmetry in dark sector
- allow mixing between dark and SM hypercharge fields via $B_{\mu\nu}F'^{\mu\nu}$

$$\mathcal{L} \supset -\frac{1}{4}\widetilde{F}_{\mu\nu}\widetilde{F}^{\mu\nu} - \frac{1}{4}\widetilde{F}'_{\mu\nu}\widetilde{F}'^{\mu\nu} + \frac{\epsilon}{2}\widetilde{F}_{\mu\nu}\widetilde{F}'^{\mu\nu} + \frac{m_{A'}^2}{2}\widetilde{A}'_{\mu}\widetilde{A}'^{\mu} + eJ_{\mathrm{EM}}^{\mu}\widetilde{A}_{\mu}$$

- transform to eliminate the non-diagonal mixing terms

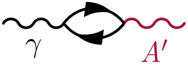
$$\widetilde{A}'_{\mu} = \frac{1}{1-\epsilon^2}A'_{\mu}, \quad \widetilde{A}_{\mu} = A_{\mu} + \frac{\epsilon}{1-\epsilon^2}A'_{\mu}$$

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{m_{A'}^2}{2}A'_{\mu}A'^{\mu} + eJ_{\mathrm{EM}}^{\mu}A_{\mu} + e\epsilon J_{\mathrm{EM}}^{\mu}A'_{\mu}$$

- mass of the dark photon, $m_{A'}$ and mixing ϵ are free parameters

Phenomenology

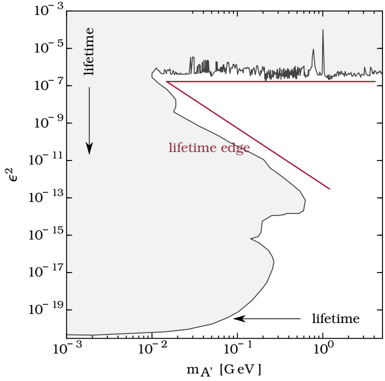
$\Longrightarrow$



$\Longrightarrow$

$$\epsilon \approx \frac{ee'}{16\pi^2} \ln \frac{m_1^2}{m_2^2}$$

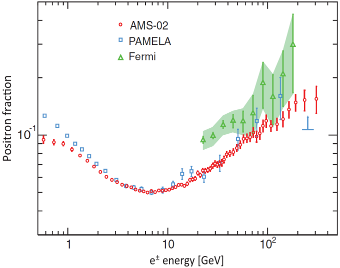
- $\epsilon \approx 10^{-3}$ if heavy lepton with SM and DM charge
- $\epsilon \approx 10^{-5}$ if SM embedded in GUT symmetry
- assume only visible SM decays (invisible also possible)
- search via prompt decays (resonance searches) or displaced decays (usually beam dumps)



Motivation

Cosmic Ray Positrons

- PAMELA, Fermi Large Area Telescope, and AMS-02 observe unexpected rise in positron to electron ratio
    - also consistent with complementary measurement from Fermi Gamma-Ray Telescope

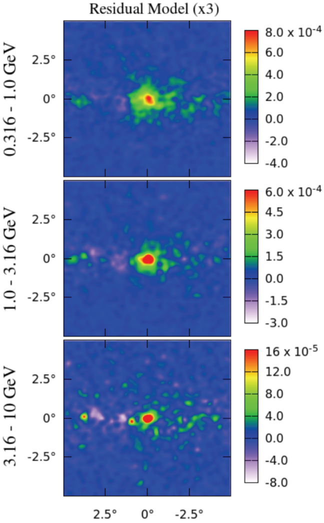


Phys. Rev. Lett. **110** (2013) 141102

- possible via modification of cosmic ray propagation model
    - significantly less radiation loss of positrons required
- viable with change in positron production model
    - positrons from proton scattering primarily from cosmic ray origin
- dark photon annihilation also consistent with data

Lighter Dark Matter

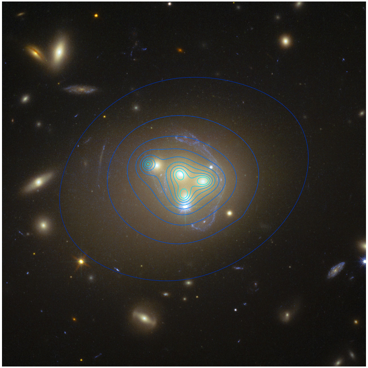
- CDMS observed three events consistent with a WIMP mass between 7 – 20 GeV
  - compatible with CoGeNT results
  - both CDMS and CoGeNT in tension with XENON100 results
  - SuperCDMS in tension with CoGeNT
  - CoGeNT excess possibly explained via surface background
- possible dark matter annihilation from the galactic center with mass of 10 – 50 GeV
- results not compatible with Z or H scattering
  - compatible with dark photons



arXiv:1402.6703 [astro-ph.HE]

Self-Interacting Dark Matter

- galaxy structure not perfectly modeled by collisionless dark matter
    - cusps are flatter then expected in data
    - observed sub-halos are not as concentrated as expected
- lag between halo and dark matter halo observed in some merging galaxies
    - non-observation in some sets limits on interactions

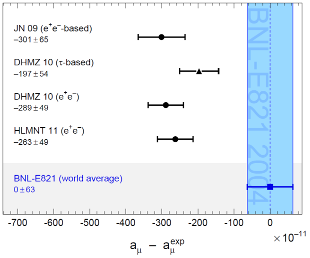


ESO/R. Massey

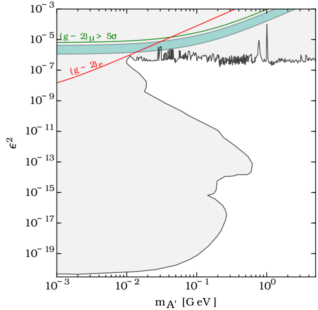
- self-interaction via long range forces can resolve both modeling and lag issues

Muon Anomalous Magnetic Moment

- the electron and muon anomalous magnetic moments, a_e and a_μ, constrain the $\epsilon^2 - m_{A'}$ parameter space
- tension between a_μ theory and experiment favors a specific parameter space
- further work needed on both experiment and theory, but well in hand here at Liverpool!



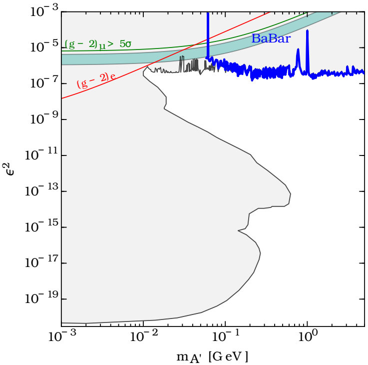
Phys. Rev. D **86** (2012) 010001

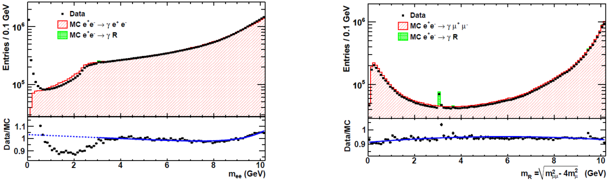


Prompt Limits

BaBar

- BaBar detector at SLAC
  - Phys. Rev. Lett. **113** (2014) 20, 201801
  - 514 fb^{-1} of data from 1999 – 2008
  - e^+ beam (3.1 GeV), e^- beam (9 GeV)
  - $e^+e^- \to \gamma A'$ production
  - search for $A' \to e^+e^-$ and $A' \to \mu^+\mu^-$

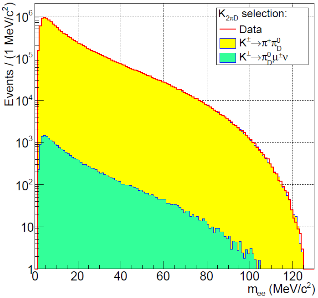




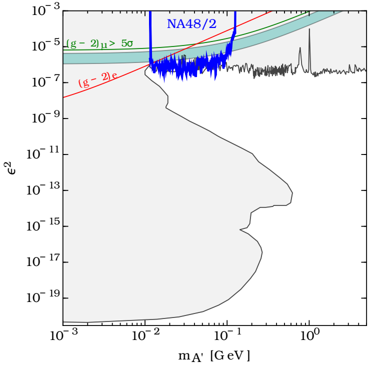
Phys. Rev. Lett. **113** (2014) 20, 201801

NA48/2

- NA48/2 experiment at CERN
  - Phys. Lett. B **746** (2015) 178
  - 2003 - 2004 run
  - $K^{\pm}$ beam (60 GeV from 400 GeV proton beam)
  - use $K^{\pm} \to \pi^{\pm}\pi^{0}$ and $K^{\pm} \to \pi^{0}\mu^{\pm}\nu$ decays
  - search for $A' \to e^{+}e^{-}$ from $\pi^{0} \to \gamma A'$
  - irreducible $\pi^{0} \to \gamma e^{+}e^{-}$

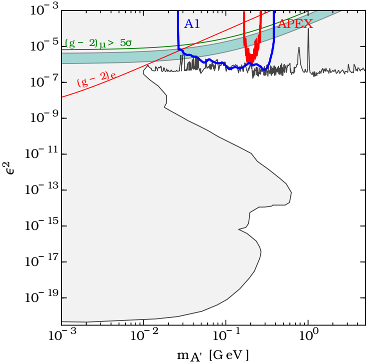


Phys. Lett. B **746** (2015) 178



APEX and MAMI

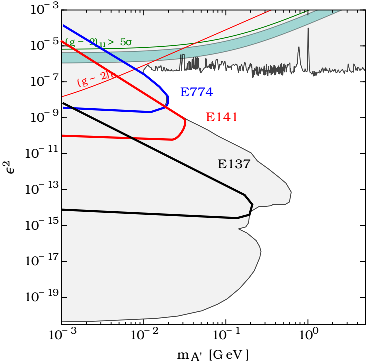
- A1 detector at the Mainz Microtron (MAMI)
    - Phys. Rev. Lett. **106** (2011) 251802, Phys. Rev. Lett. **112** (2014) 22, 221802
    - 2011 and 2014 runs
    - electron beam (180 – 855 MeV), heavy nuclei target
    - search for $\gamma/A' \to e^+e^-$
- APEX (A' experiment) at Jefferson Lab
    - Phys. Rev. Lett. **107** (2011) 191804
    - 2011 test run
    - electron beam (2.3 GeV), heavy nuclei target
    - search for $\gamma \to e^+e^-$
- future runs expected for both experiments



Displaced Limits

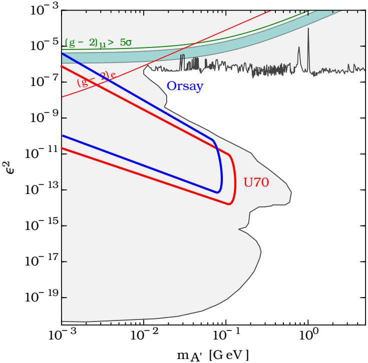
E137, E141, and E774

- Phys. Rev. D **80** (2009) 075018, A' interpretation of beam-dump data
- E137 experiment at SLAC
  - Phys. Rev. D **38** (1988) 3375
  - electron beam (20 GeV), aluminum target
  - 200 m through earth, 200 m through air
  - 3 m detector
- E141 experiment at SLAC
  - Phys. Rev. Lett. **59** (1987) 755
  - electron beam (9 GeV), tungsten target (10 cm)
  - 35 m through vacuum
- E774 experiment at FermiLab
  - Phys. Rev. Lett. **67** (1991) 2942
  - electron beam (275 GeV), tungsten target (30 cm, 28 radiation lengths)
  - 7.25 m through vacuum



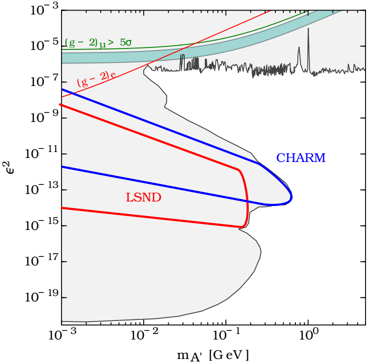
Orsay and U70

- Orsay
  - Phys. Lett. B **229** (1989) 150
  - electron beam (1.7 GeV), lead target
- U70 experiment at IHEP Serpukhov
  - interpretation in Phys. Lett. B **701** (2011) 155
  - Z. Phys. C **51** (1991) 341
  - proton beam (70 GeV), iron target (140 cm)
  - 64 m through vacuum
  - A' from $\pi^0 \to \gamma A'$
  - $A' \to e^+e^-$



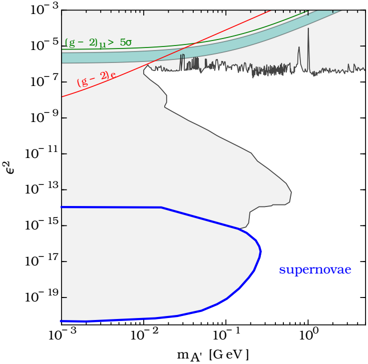
Charm and LSND

- can use results from neutrino experiments to place limits
- CHARM experiment at CERN
    - interpretation in Phys. Lett. B **713** (2012) 244
    - Phys. Lett. B **166** (1986) 473
    - proton beam (400 GeV), copper target
    - use $\eta \to \gamma A'$ and $\eta' \to \gamma A'$
    - $A' \to e^+ e^-$
- LSND experiment at Los Alamos
    - Phys. Rev. C **58** (1998) 2489
    - proton beam (800 MeV), water target (30 cm)
    - A' from $\pi^0 \to \gamma A'$
    - $A' \to e^+ e^-$



Supernovae

- can also use results from supernovae to place limits
  - supernovae cooling mechanism well modeled
  - any cooling faster than expected indicative of dark matter
- Phys. Rev. D **89** (2014) 10, 105015
- dark fermions ψ' and scalars ϕ can be produced from electrons, positrons, and nucleons



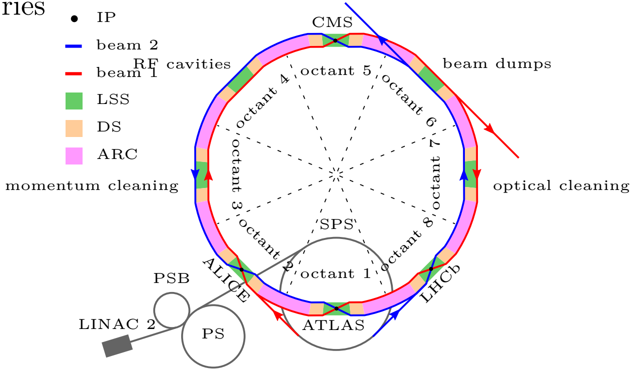
$$e^+e^- \to \bar{\psi}'\psi', \qquad NN \to NN\bar{\psi}'\psi'$$

$$e^+e^- \to \phi'^\dagger\phi', \qquad NN \to NN\phi'^\dagger\phi'$$

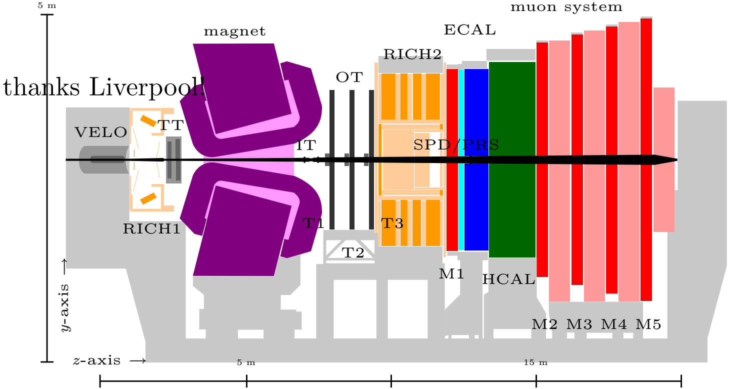
LHCb

Collaboration

- Large Hadron Collider beauty experiment on the LHC
- letter of intent 1995, CERN-LHCC-95-5
- *a forward collider detector dedicated to the study of CP violation and other are phenomena in the decays of Beauty particles*
- 1111 members, 69 institutes (including Liverpool and MIT), 17 countries



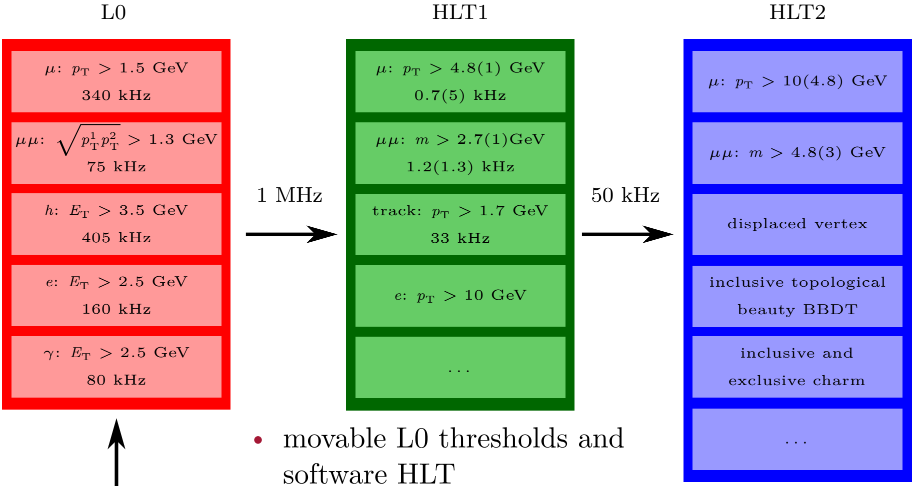
Detector



- fully instrumented between $2 < \eta < 5$
- momentum resolution between 0.4% at 5 GeV to 0.6% at 100 GeV
- impact parameter resolution of $13 - 20\ \mu$m for tracks
- secondary vertex precision of $0.01 - 0.05(0.1 - 0.3)$ mm in $xy(z)$

Trigger

JINST 8 (2013) P04022



L0

μ: $p_{\mathrm{T}} > 1.5$ GeV
340 kHz

$\mu\mu$: $\sqrt{p_{\mathrm{T}}^{1} p_{\mathrm{T}}^{2}} > 1.3$ GeV
75 kHz

h: $E_{\mathrm{T}} > 3.5$ GeV
405 kHz

e: $E_{\mathrm{T}} > 2.5$ GeV
160 kHz

γ: $E_{\mathrm{T}} > 2.5$ GeV
80 kHz

1 MHz

HLT1

μ: $p_{\mathrm{T}} > 4.8(1)$ GeV
0.7(5) kHz

$\mu\mu$: $m > 2.7(1)$GeV
1.2(1.3) kHz

track: $p_{\mathrm{T}} > 1.7$ GeV
33 kHz

e: $p_{\mathrm{T}} > 10$ GeV

...

50 kHz

HLT2

μ: $p_{\mathrm{T}} > 10(4.8)$ GeV

$\mu\mu$: $m > 4.8(3)$ GeV

displaced vertex

inclusive topological beauty BBDT

inclusive and exclusive charm

...

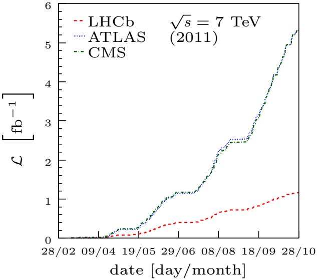
15 MHz

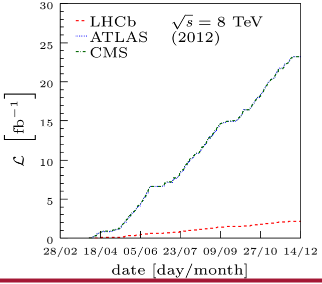
5 kHz

- movable L0 thresholds and software HLT
- low p_{T} leptons/photons and tracks (IP > 0.1 mm)

Current Datasets

- current data testament to incredible LHCb performance
- 1 fb^{-1} pp collisions at $\sqrt{s} = 7$ TeV (2011)
- 2 fb^{-1} pp collisions at $\sqrt{s} = 8$ TeV (2012)
- 1.1 nb^{-1} pPb collisions at $\sqrt{s} = 5$ TeV (2013)
- 0.5 nb^{-1} Pbp collisions at $\sqrt{s} = 5$ TeV (2013)
- excellent luminosity uncertainty, JINST **9** (2014) 12, P12005
  - 1.71% for 7 TeV dataset
  - 1.16% for 8 TeV dataset





Future Datasets

- projected luminosity (see V. Vagnoni (2015) HL-LHC)

LHC era				HL-LHC era	
Run 1(a) 2011	Run 1(b) 2012	Run 2 2015 - 2018	Run 3 2020 - 2022	Run 4 2025 - 2028	Run 5 2030 - ?
1 fb^{-1}	2 fb^{-1}	5 fb^{-1}	15 fb^{-1}	23 fb^{-1}	54 fb^{-1}

- LHCb upgrade during LS 2
  - LHCb-PUB-2014-040
  - replacement of ring imaging Cherenkov detectors
  - replacement of tracking detectors
  - huge effort here at Liverpool on VELO upgrade
  - full software trigger, see LHCB-TDR-016
    - currently limited by hardware readout at 1 MHz
    - upgrade will read out entire detector at 40 MHz
- side-note, interesting EWK opportunities outlined in LHCb-TALK-2015-113

Signal Rate

Production

- generate soft QCD generates with PYTHIA 8.2
    - non-diffractive, elastic, single-diffractive, double-diffractive, central-diffractive
    - `SoftQCD:all = on`
    - Monash tune
    - check against LHCb tune (minimal difference)
- perform hadron decays with EVTGEN
- final state radiation in decays with PHOTOS
- require $D^{*0} \to D^0 X$ decay with $X \in \gamma, \pi^0$
    - fiducial requirement of $p_{\mathrm{T}}(D^0) > 1$ GeV, $2 < \eta(D^0) < 5$

$$\sigma(pp \to D^{*0} \to D^0 X) = 0.95 \text{ mb}$$

$$N_{\text{run 3}}(D^{*0} \to D^0 \gamma) = 5.4 \times 10^{12}$$

- cross-sections validated against LHCb measurements

D^{*0} Decays

- D^{*0} ideal candidate for search
    - copious production within LHCb
    - $I(J^P) = \frac{1}{2}(1^-)$ allows needed decays
    - mass of 2006.96 ± 0.1 MeV provides large range of $m_{A'}$, $\Delta m_D = 142$ MeV
    - width of 2.1 MeV provides prompt decays

$$\mathcal{B}(D^{*0} \to D^0\pi^0) = (61.9 \pm 2.9),\ \mathcal{B}(D^{*0} \to D^0\gamma) = (38.1 \pm 2.9)$$

- use operator analysis to calculate $\mathcal{B}(D^{*0} \to D^0 e^+ e^-)$ and $\mathcal{B}(D^{*0} \to D^0 A')$

$$\frac{\Gamma(D^{*0} \to D^0 e^+ e^-)}{\Gamma(D^{*0} \to D^0\gamma)} = 6.4 \times 10^{-3}$$

$$\frac{\Gamma(D^{*0} \to D^0 A')}{\Gamma(D^{*0} \to D^0\gamma))} = \epsilon^2 \left(1 - \frac{m_{A'}^2}{\Delta m_D^2}\right)^{3/2}$$

Rare π^0 Decays

- the rare decay $\pi^0 \to \gamma A'$ (used by NA48/2, U70, and LSND) also contributes
- use effective $\mathcal{L}$ to calculate the amplitude

$$|\mathcal{M}_{\pi^0 \to \gamma e^+ e^-}|^2 = \frac{4\alpha_{\rm EM}^3}{\pi f_\pi^2 m_{\gamma e^-}^2} \Big(m_{\pi^0}^4 + 2m_{\gamma e^-}^4 + m_{e^+ e^-}^4 + 2m_{\gamma e^-}^2 m_{e^+ e^-}^2 - 2m_{\pi^0}^2 (m_{\gamma e^-}^2 + m_{e^+ e^-}^2) \Big)$$

- $\Gamma(\pi^0 \to \gamma e^+ e^-)$ verified against experimental value

$$\frac{\Gamma(\pi^0 \to \gamma e^+ e^-)}{\Gamma(\pi^0 \to \gamma\gamma)} = 0.012$$

$$\frac{\Gamma(\pi^0 \to \gamma A')}{\Gamma(\pi^0 \to \gamma\gamma)} = 2\epsilon^2 \left(\frac{m_\pi^2 - m_{A'}^2}{m_\pi^2} \right)^3$$

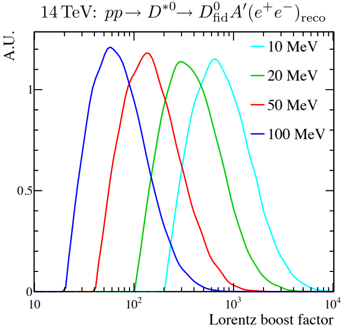
Dark Photon Decays

- assume only e^+e^- final state
    - invisible decays to dark sector modify limits
    - $\mu^+\mu^-$ and heavier decays suppressed by Δm_D

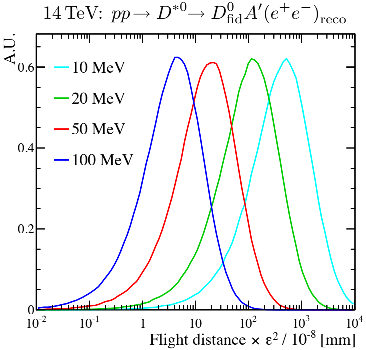
$$\Gamma_{A'} = \frac{\epsilon^2 \alpha_{\mathrm{EM}}}{3} m_{A'} \left(1 + 2\frac{m_e^2}{m_{A'}^2}\right) \sqrt{1 - 4\frac{m_e^2}{m_{A'}^2}}$$

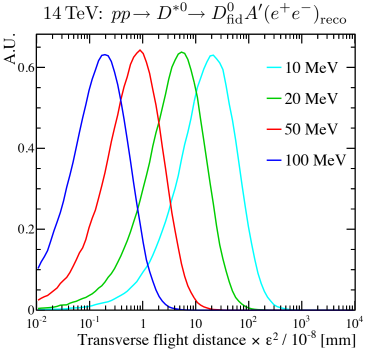
- mean flight distance can be written in terms of boost

$$\ell_{A'} \simeq 16\,\mathrm{mm} \left(\frac{\gamma_{\mathrm{boost}}}{10^2}\right) \left(\frac{10^{-8}}{\epsilon^2}\right) \times \left(\frac{50\ \mathrm{MeV}}{m_{A'}}\right)$$



Dark Photon Flight



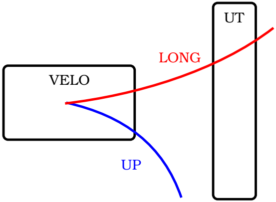


Detector Response

Track Types

- use simplified model to estimate detector response
- consider simplified LONG tracks and UP tracks
  - $2 < \eta < 5$ and $p > 3$ is LONG
  - $2 < \eta < 5$ and $p > 1$ and not LONG is UP

	LONG	UP
σ_p/p	0.5%	12%
σ_θ	$(0.2 + (1.7\text{GeV})/p)$ mrad	
σ_ϕ	$\sigma_\theta \cot\theta$	



- momentum resolution from IJMPA **30** (2015) 1530022
- angular resolution determined from $m_{J/\psi}$ resolution and multiple scattering

$$\left(\frac{\sigma_p}{p}\right)^2 \approx 2\left(\frac{\sigma_{m_{J/\psi}}}{m_{J/\psi}}\right)^2 - 2\left(\frac{p\sigma_\alpha}{m_{J/\psi}}\right)^2$$

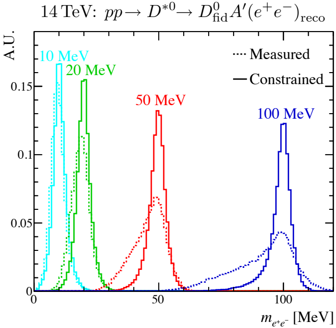
D^0 Reconstruction

- consider two types of D^0 reconstruction
  - F-type: fully reconstructed, all children are charged and reconstructed with least two LONG tracks
  - P-type: pseudo-fully reconstruct, at least two LONG tracks (provides flight direction), mass constraint

decay	$\mathcal{B}$	$\mathcal{B} \times \mathrm{eff}_D^{\mathrm{F}}$	$\mathcal{B} \times \mathrm{eff}_D^{\mathrm{P}}$
$D^0 \to \{K^-\pi^+, KK, \pi\pi\}$	4.4%	2.5%	–
$D^0 \to \{K^-3\pi, 2K2\pi, 4\pi\}$	9.1%	4.5%	1.0%
$D^0 \to K\ell(\nu)$	6.8%	–	2.0%
$D^0 \to K\pi(\pi^0)_{[0,m_{K^0}]}$	22.0%	–	6.6%
$D^0 \to KK(K^0)_{[\mathrm{all}]}$	1.5%	–	0.5%
$D^0 \to K3\pi(\pi^0)_{[0,m_{K^0}]}$	8.5%	–	1.4%
total		7.0%	11.5%

Dark Photon Reconstruction

- tracks from $A' \rightarrow e^+e^-$ are $\approx$ 60% UP and 40% LONG
- electrons should be well identified by RICH
- bremsstrahlung and multiple scattering models implemented in fast simulation
    - uses LHCb upgrade material budget
    - low mass tail from bremsstrahlung



- can apply simple mass correction

$$m_{e^+e^-}^{\text{corr}} = m_{e^+e^-}^{\text{reco}} \left(2 - \frac{\Delta m_D^{\text{reco}}}{\Delta m_D}\right)$$

- alternatively, require full energy-momentum conservation

D^{*0} Reconstruction

- F-type or P-type D^0
- reconstructed A' candidate
- require mass difference consistent with D^{*0}

$$\Delta m_D^{\mathrm{reco}} = m_{\mathrm{reco}}(D^0 e^+ e^-) - m_{\mathrm{reco}}(D^0)$$

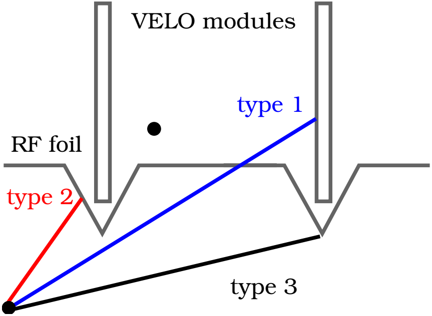
$$-50\mathrm{MeV} < \Delta m_D^{\mathrm{reco}} - \Delta m_D < 20\mathrm{MeV}$$

- mass requirement efficiency ≈ 85%
- highly suppresses production from $D^{*0} \to D^0\pi^0$
    - $\pi^0 \to \gamma e^+ e^-$ or $\pi^0 \to A' e^+ e^-$

Search

Conversion Veto

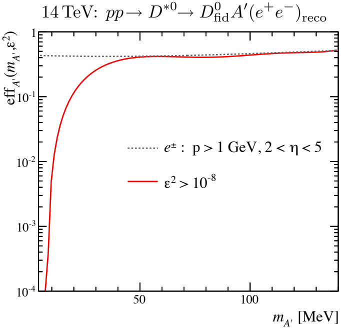
- large background from conversions in the VELO
- effectively three types of conversions
  - type 1: conversion in the VELO module
  - type 2: conversion in the RF foil
  - type 3: conversion in the RF foil tip



- type 1, require e^+ and e^- have hit in the first module encountered with separation of one pixel
- type 2, require at least one pixel separation between e^+ and e^- hits
- type 3, require hits in same module as tip, if intersected

Prompt Selection

- F-type D^0
- effective conversion veto
    - $2.6 < \eta_{A'} < 5.0$
    - $\alpha_{e^+e^-} > 8$ mrad if $\ell_\mathrm{T} < 5.1$ mm
    - $\alpha_{e^+e^-} > 25$ mrad if $5.1 < \ell_\mathrm{T} < 16.6$ mm



Prompt Reach

- primary background from $D^{*0} \to D^0 e^+ e^-$
- set 95% confidence limits for $S/\sqrt{B} > 2$

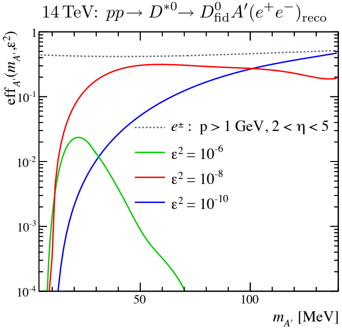
$$\frac{S}{\sqrt{B}} = \frac{\Gamma(D^{*0} \to D^0 A')}{\sqrt{\Gamma(D^{*0} \to D^0 \gamma) \Delta\Gamma}} \times \sqrt{N\,(D^{*0} \to D^0 \gamma)\,\mathrm{eff}_{\Delta m_D} \mathrm{eff}_D^{\mathrm{F}} \mathrm{eff}_{A'}(m_{A'}, \epsilon^2)}$$

$$\Delta\Gamma \equiv \int_{m_{A'} - \Delta m_{A'}}^{m_{A'} + \Delta m_{A'}} \mathrm{d}m_{e^+ e^-} \frac{\mathrm{d}\Gamma(D^{*0} \to D^0 e^+ e^-)}{\mathrm{d}m_{e^+ e^-}}$$

$$\Delta m_{A'} = 2\sigma(m_{e^+ e^-})$$

Displaced Selection

- final selection still under consideration
- F or P-type D^0
- A' decay vertex greater than 7σ from pp collision
    - roughly equivalent to $\ell_{\mathrm{T}} > 0.1$ mm
- effective conversion veto
    - $2.6 < \eta_{A'} < 5.0$
    - $\alpha_{e^+e^-} > 8$ mrad if $\ell_{\mathrm{T}} < 5.1$ mm
    - $\alpha_{e^+e^-} > 25$ mrad if $5.1 < \ell_{\mathrm{T}} < 16.6$ mm



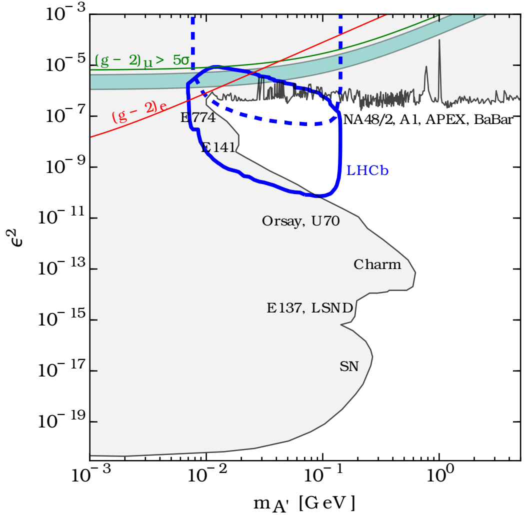
Displaced Reach

- assume $\mathcal{O}(100)$ background events over entire region
  - various backgrounds assessed with large Pythia sample to obtain estimates
  - set 95% confidence level for $S \geq 5$

$$\begin{aligned} S(m_{A'}, \epsilon^2) &= N(\Gamma(D^{*0} \to D^0\gamma)\, \frac{\Gamma(D^{*0} \to D^0 A')}{\Gamma(D^{*0} \to D^0\gamma)}\, \mathrm{eff}_{\Delta m_D} \\ &\quad \times \left(\mathrm{eff}_D^{\mathrm{F}} + \mathrm{eff}_D^{\mathrm{P}}\right) \mathrm{eff}_{A'}(m_{A'}, \epsilon^2) \\ &\simeq 85 \left(\frac{\epsilon^2}{10^{-10}}\right) \left(1 - \frac{m_{A'}^2}{\Delta m_D^2}\right)^{3/2} \mathrm{eff}_{A'}(m_{A'}, \epsilon^2) \end{aligned}$$

Conclusions

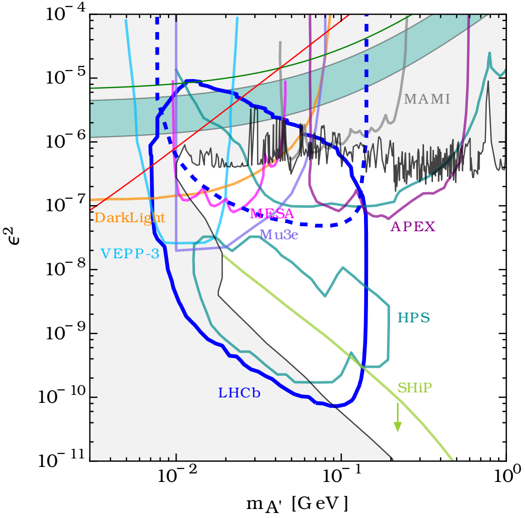
LHCb Limits


$(g-2)_\mu > 5\sigma$
$(g-2)_e$
E774
E141
NA48/2, A1, APEX, BaBar
LHCb
Orsay, U70
Charm
E137, LSND
SN
ϵ^2
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
10^{-3}
10^{-2}
10^{-1}
10^{0}
$m_{A'}$ [GeV]

Future Experiments

- MESA
  - 2017+, Mainz Energy-Recovering Superconducting Accelerator
  - Phys. Rev. D **88** (2013) 015032
- APEX
  - 2018, Jefferson Lab
  - JHEP **1102** (2011) 009
- DarkLight
  - 2016, Jefferson Lab
  - arXiv:1307.4432
- VEPP-3
  - Budker, Russia
  - arXiv:1207.5089 [hep-ex]
- Mu3e
  - 2018+, Paul Scherrer Institute, Switzerland
  - JHEP **1501** (2015) 113
- HPS
  - 2016, Jefferson Lab
  - arXiv:1310.2060 [physics.ins-det]
- SHiP
  - 2023, CERN
  - arXiv:1504.04855 [hep-ph]

Future Limits



Summary

- dark photons are well motivated within the dark matter sector
- a significant effort is being invested through a variety of experiments
- LHCb should be able to unify the coverage gap between $10 - 100$ MeV, something not possible even with current planned experiments
- further reach can be obtained via additional channels, *e.g.* $D^0 \to K^{*0} A'$
- additional experimental techniques, *e.g.* bremsstrahlung recovery, improved mass constraint, *etc.* can improve reach
- can begin to validate methods on actual data during Run 2

Thank you!