Constraints on the dark photon from deep inelastic scattering

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Outline

- Dark photon hypothesis
- $e^{\pm}p$ deep inelastic scattering (DIS) with dark photon
- Our work of constraints on the dark photon
- Summary

Part I: Dark photon hypothesis

Dark Matter Candidates

- WIMPs are still attracting much efforts:
  - XENON: Aprile *et al.*, Eur. Phys. J. C 77, 881 (2017)
  - ANAIS: Amare *et al.*, Phys. Rev. D 103, 02005 (2021)
  - SABRE: Antonello *et al.*, Astropart. Phys. 106, 1 (2019)
  - COSINE-100: Adhikarj *et al.*, arXiv: 2104.0537
- Stringent limits from null experiments have motivated alternative DM hypothesis
- Dark photon: a portal between DM and ordinary particles
  Fabbrichesi, Gabrielli, Lanfranchi, arXiv: 2005.01515

Dark Photon

The dark photon was proposed as an extra $U(1)$ gauge boson, interacting with SM particles through kinetic mixing with hypercharge Okun, Sov. Phys. JETP 56, 502 (1982)

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\bar{m}^2_{A'}}{2}A'_\mu A'^\mu + \frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu} \,. \qquad (1)$$

where θ_W is the Weinberg angle, $F'_{\mu\nu}$ is the dark photon strength tensor and ϵ is the mixing parameter

Experimental searches

$A' \to \mu^+\mu^-$:

- LHCb Collaboration
  Aaij *et al.*, Phys. Rev. Lett. 124, 041801 (2020)
- CMS Collabortaion
  Sirunyan *et al.*, Phys. Rev. Lett. 124, 131802 (2020)

$A' \to \chi\bar{\chi}$:

- NA64 Experiment: $1\ \mathrm{MeV} \leq \bar{m}_{A'} \leq 250\ \mathrm{MeV}$
  Banerjee *et al.*, Phys. Rev. Lett. 123, 121801 (2019)
- BaBar Collaboration: $250\ \mathrm{MeV} \leq \bar{m}_{A'} \leq 8\ \mathrm{GeV}$
  Lees *et al.*, Phys. Rev. Lett. 119, 131804 (2017)

$$\Rightarrow \epsilon \leq \mathcal{O}(10^{-3})$$

It could be weakened by taking into account the detailed structure of the dark sector Essig, Schuster, Toro, Phys. Rev. D 80, 015003 (2009)

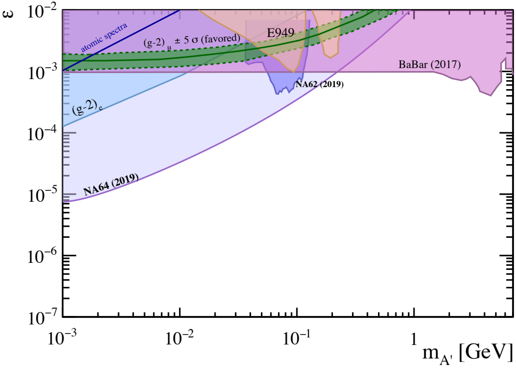


Figure: The strongest limits on ϵ from energy missing events. This figure is taken from Fabbrichesi, Gabrielli, Lanfranchi, arXiv: 2005.01515 [hep-ph]

Decay-agnostic processes

Independent on its production mechanism and decay modes:

- muon $g-2$
  → dark photon mediated loop contribution
  negligible for $m_{A_D} \geq 10\ \mathrm{GeV}$
  Pospelov, Phys. Rev. D 80, 095002(2009)
- Electroweak precision observables (EWPO)
  → Z boson mass shift relative to $m_W/\cos\theta_W$
  Curtin, Essig, Gori, Shelton, JHEP 02, 157 (2015)
- $e^{\pm}p$ deep inelastic scattering (DIS)
  Kribs, McKeen, Raj, Phys. Rev. Lett. 126, 011801 (2021)

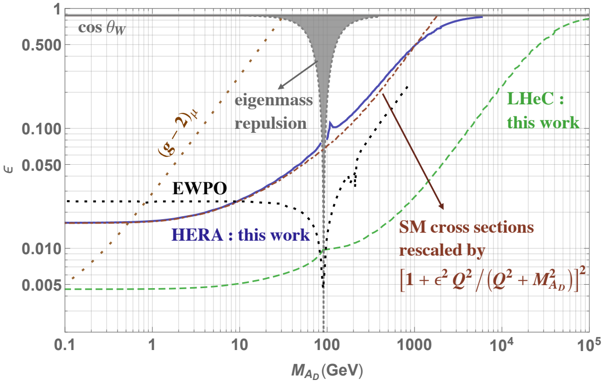


Figure: Existing limits on ϵ from decay-agnostic processes. This figure is taken from Kribs, McKeen, Raj, Phys. Rev. Lett. 126, 011801 (2021)

Part II: $e^{\pm}p$ deep inelastic scattering with dark photon

$e^{\pm}p$ DIS

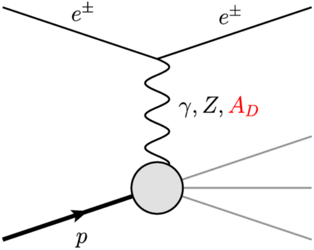
Kribs, McKeen, Raj, Phys. Rev. Lett. 126, 011801 (2021)

- Broad kinematic coverage:

  $0.15 \leq Q^2/\mathrm{GeV}^2 \leq 10^6$ (even higher)
  $5 \times 10^{-6} \leq x \leq 0.8$

  $\Rightarrow 100\ \mathrm{MeV} \leq m_{A_D} \leq 100\ \mathrm{TeV}$

- The dark photon contribution to the proton structure function has non-DGLAP feature → smoking gun



The proton structure function

By including the dark photon contributions, the transverse structure function of the proton is

$$\tilde{F}_2 = \sum_{i,j=\gamma,Z,A_D} \kappa_i \kappa_j F_2^{ij} \,, \tag{2}$$

where $\kappa_i = Q^2/(Q^2 + M_{V_i}^2)$. At leading order (LO) in α_s

$$F_2^{ij} = \sum_q x \, \underbrace{f_q}_{\text{PDFs}} \, \underbrace{(C_{i,e}^v C_{j,e}^v + C_{i,e}^a C_{j,e}^a)}_{\text{couplings to electron}} \, \underbrace{(C_{i,q}^v C_{j,q}^v + C_{i,q}^a C_{j,q}^a)}_{\text{couplings to quarks}} \,,$$

After diagonalizing the mixing term through field redefinitions, the couplings of the physical Z and A_D to SM particles are given by

$$\begin{aligned} C_Z^v &= (\cos\alpha - \epsilon_W \sin\alpha)\bar{C}_Z^v + \epsilon_W \sin\alpha \cot\theta_W C_\gamma^v , \\ C_Z^a &= (\cos\alpha - \epsilon_W \sin\alpha)\bar{C}_Z^a \end{aligned} \tag{3}$$

and

$$\begin{aligned} C_{A_D}^v &= -(\sin\alpha + \epsilon_W \cos\alpha)\bar{C}_Z^v + \epsilon_W \cos\alpha \cot\theta_W C_\gamma^v , \\ C_{A_D}^a &= -(\sin\alpha + \epsilon_W \cos\alpha)\bar{C}_Z^a . \end{aligned} \tag{4}$$

where $\bar{C}_Z^v$, $\bar{C}_Z^a$, C_γ^v are the SM coulings

α is the $\bar{Z} - A'$ mixing angle

$$\tan\alpha = \frac{1}{2\epsilon_W}\left[1 - \epsilon_W^2 - \rho^2 - \mathrm{sign}(1-\rho^2)\sqrt{4\epsilon_W^2 + (1 - \epsilon_W^2 - \rho^2)^2}\right],$$

with

$$\begin{aligned} \epsilon_W &= \frac{\epsilon \tan\theta_W}{\sqrt{1 - \epsilon^2/\cos^2\theta_W}}, \\ \rho &= \frac{\bar{m}_{A'}/\bar{m}_{\bar{Z}}}{\sqrt{1 - \epsilon^2/\cos^2\theta_W}}. \end{aligned} \tag{5}$$

Kribs, McKeen, Raj, Phys. Rev. Lett. 126, 011801 (2021):

- only perturbative contributions, $\tilde{F}_2$
- fix PDFs from the best fit results of HERA analysis without dark photon

Our work:

- two-component model: Vector Meson Dominance
  $$\gamma \rightarrow (q\bar{q})$$
  photo-production limit
  $$F_2 \propto Q^2 \text{ as } Q \rightarrow 0$$
- simultaneous determination of PDFs and dark photon parameters

Part III: Our work

Thomas, Wang, Williams, arXiv: 2111.05664 [hep-ph]

Two-component model

We embed the perturbative contributions to a two-component model, Martin, Ryskin, Stasto, Eur. Phys. J. C 7, 643 (1999)

$$F_2(x,Q^2) = F_2^{\mathrm{VMD}}(x,Q^2) + \frac{Q^2}{Q^2+M_0^2}\tilde{F}_2(\bar{x}, Q^2+M_0^2)\,, \qquad (6)$$

where

$$\bar{x} = x\frac{Q^2+M_0^2}{Q^2+xM_0^2}\,, \qquad (7)$$

with M_0^2 being in the range $1.0 - 1.5\ \mathrm{GeV}^2$.

The VMD term has the form Szczurek, Uleshchenko, Eur. Phys. J. C 12, 633 (2000)

$$F_2^{\mathrm{VMD}} = \frac{Q^2}{\pi} \sum_{V=\rho,\omega,\phi} \frac{M_V^4 \sigma_{VN}}{f_V^2 (Q^2 + M_V^2)^2} \Omega(x, Q^2)\,, \tag{8}$$

In phenomenological analysis, a Gaussian form factor is often introduced

$$\Omega(x, Q^2) = \exp(-(\Delta E/\lambda_G)^2)\,, \tag{9}$$

where

$$\Delta E = \frac{M_V^2 + Q^2}{Q^2} M_N x\,. \tag{10}$$

with $1/\Delta E$ characterizing the lifetime of the hadronic fluctuations of the photon.

Initial PDFs

We adopt the leading order (LO) HERA parametrization of the PDFs at an initial scale, $Q_0^2 = 1.9\ \mathrm{GeV}^2$, Abramowicz *et al.*, Eur. Phys. J. C 75, 580 (2015)

$$\begin{aligned}
xg(x,Q_0^2) &= A_g x^{B_g}(1-x)^{C_g}, \\
xu_v(x,Q_0^2) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}[1+E_{u_v}x^2], \\
xd_v(x,Q_0^2) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\bar{u}(x,Q_0^2) &= A_{\bar{u}} x^{B_{\bar{u}}}(1-x)^{C_{\bar{u}}}[1+D_{\bar{u}}x], \\
x\bar{d}(x,Q_0^2) &= (1-0.4)A_{\bar{d}} x^{B_{\bar{d}}}(1-x)^{C_{\bar{d}}}, \\
x\bar{s}(x,Q_0^2) &= 0.4A_{\bar{d}} x^{B_{\bar{d}}}(1-x)^{C_{\bar{d}}}\,. \qquad (11)
\end{aligned}$$

The PDFs at DIS scale Q^2 are obtained by DGLAP evolution.

- DIS only fit
  F_2 is insensitive to the d-quark distributions
  → We fix xd_v and $x\bar{d}$ from HERA analysis
  → 7 free parameters in PDFs
- Limited data set
  HERA: $Q^2 \in [3.5, 30000]\ \mathrm{GeV}^2$,
  BCDMS: $Q^2 \in [7.5, 230]\ \mathrm{GeV}^2$
- Our work should be view as exploratory, aiming at investigating whether a full scale search based on this approach would be justified

Without dark photon

	without VMD			with VMD ($\lambda_G = 0.897$ GeV)		
	xg	xu_v	$x\bar{u}$	xg	xu_v	$x\bar{u}$
A	5.3368	4.4790	0.0894	4.9008	4.4531	0.0904
B	0.0745	0.7441	-0.3020	0.0659	0.7419	-0.3255
C	9.4590	3.9314		8.9941	4.1885	
D						
E		4.8071			6.6852	
χ^2	195.59+151.34=346.93			180.10+111.69=291.79		
$\langle xq^+ \rangle$	0.4320	0.3575		0.4277	0.3620	

Table: Refit to HERA and BCDMS data with $Q^2 \in [3.5, 30000]\ \mathrm{GeV}^2$, $N_{\mathrm{data}} = 158 + 101 = 259$. The individual contributions to the total χ^2 correspond to HERA and BCDMS sets, respectively. The parameters A for xu_v and xg are fixed by number and momentum sum rules, respectively.

With dark photon

	$\Delta\chi^2 = 1$ (68% CL)			$\Delta\chi^2 = 2$ (95% CL)		
(M_{AD}, ϵ)	$(5.0, 0.0205)$			$(5.0, 0.0286)$		
	xg	xu_v	$x\bar{u}$	xg	xu_v	$x\bar{u}$
A	4.8556	4.4424	0.0901	4.8121	4.4322	0.0898
B	0.0638	0.7411	-0.3258	0.0617	0.7403	-0.3261
C	8.9561	4.1894		8.9198	4.1903	
D						
E		6.7063			6.7263	
χ^2	180.97 +111.82=292.79			181.83+111.96=293.79		
$\langle xq^+ \rangle$	0.4280	0.3617		0.4282	0.3614	

Table: Fit results by including the dark photon with $\Delta\chi^2 = 1$ and $\Delta\chi^2 = 2$ in respect to the best fit results without dark photon. We take the dark photon mass $m_{A_D} = 5$ GeV as an example.

Exclusion constraints

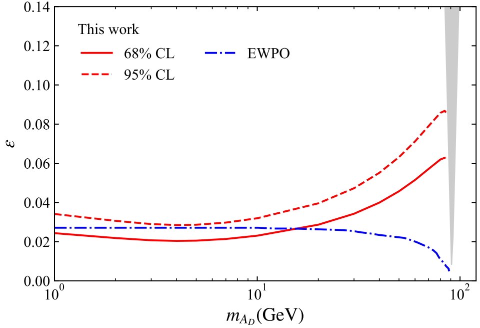


Figure: The exclusion limits on the mixing parameter ϵ. The region in grey is not accessible due to the "eigenmass repulsion" associated with the Z mass.

- weaker than the result in Kribs, McKeen, Raj, Phys. Rev. Lett. 126, 011801 (2021)
- compatible with the EWPO limits for $m_{A_D} \leq 20\ \mathrm{GeV}$
- the upper bounds on ϵ increase slightly when m_{A_D} moves down to 1 GeV

Summary

- We investigate the dark photon properties in analysis of DIS data
- VMD and correct photo-production limit are incorporated in a two-component model of the proton structure function
- By allowing variations in PDFs, we extract the exclusion limits on ϵ with 68% and 95% CL, which are competitive with the EPWO determination for $m_{A_D} \leq 20\ \mathrm{GeV}$.
- More accurate constraints could be obtained from global fit analysis beyond leading order.

Thanks!

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