Constraints on the Dark Sector from Electroweak Precision Observables

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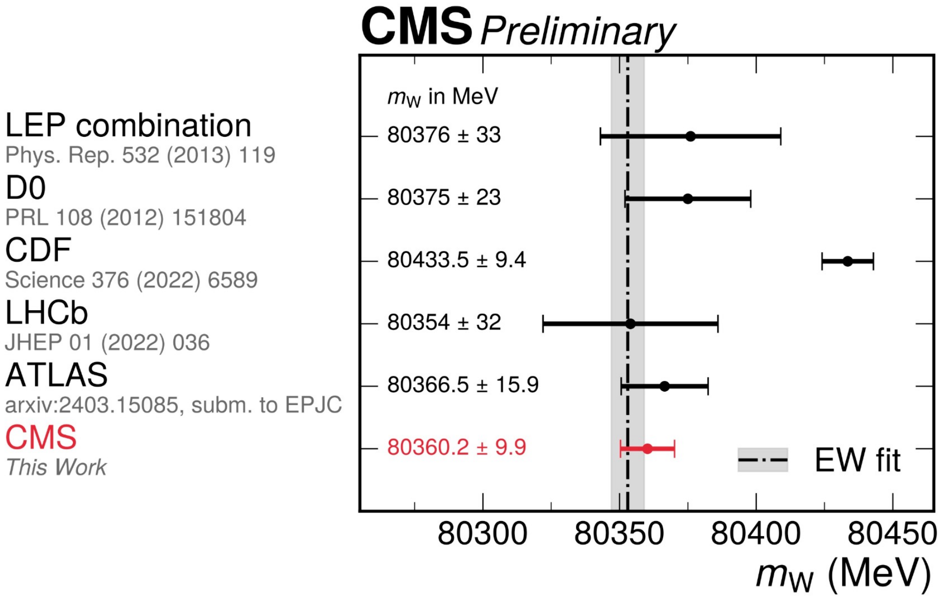
Talk Structure

- Motivation for a dark photon
- Dark photon model formalism
- SM-only baseline fit
- Dark photon mixing parameter constraints
- Dark fermion coupling constraints
- Summary

Why care about dark photons?

- Hidden U(1)'s are the **minimal** dark portals: one extra gauge boson and a mixing term.
- They appear in UV completions and are testable across *many* frontiers[1].
- CDF's m_w anomaly $(80.4335 \pm 0.0094\ GeV)$[2] may hint at BSM EW structure.
- Disagreement with global average value $(80.377 \pm 0.012\ GeV)$[3], but CDF motivates new physics. Could a heavy A_D help?
- Can be used EWPO global fits to constrain couplings to dark matter.



[1] Pospelov M 2009 Phys. Rev. D 80 095002 (Preprint 0811.1030)
[2] Aaltonen T et al. 2022 Science 376 170–176
[3] Workman R L et al. (Particle Data Group) 2022 PTEP 2022 083C01

Dark Photon Formalism[4]

Kinetic Mixing parameter

Dark Fermion coupling

$$\mathcal{L} \supset -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m^2_{A'} A'_\mu A'^\mu + \frac{\epsilon}{2\cos\theta_w} F'_{\mu\nu} B^{\mu\nu} + g'_\chi \bar{\chi} \gamma^\mu \chi A'_\mu$$

Dark field strength tensor

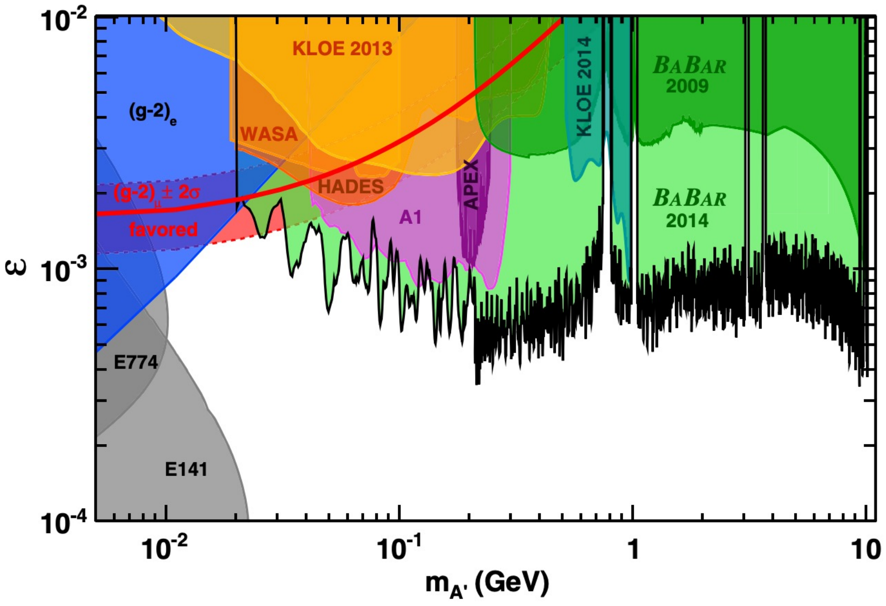
Dark photon field

SM hypercharge

- $A'_\mu = Z_\mu \sin\alpha + A_{D\mu} \cos\alpha$

[1] Okun L B 1982 Sov. Phys. JETP 56 502

Current limits



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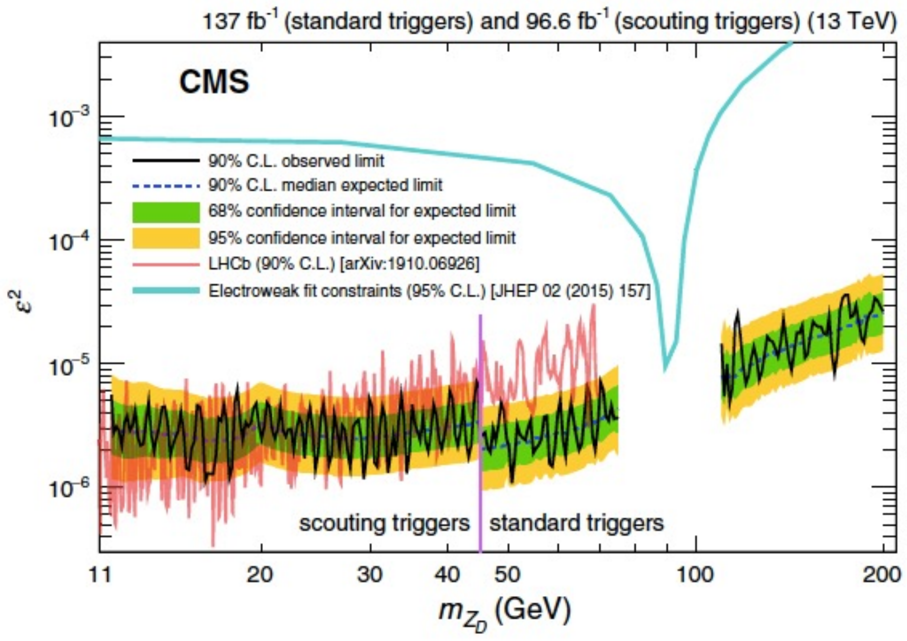
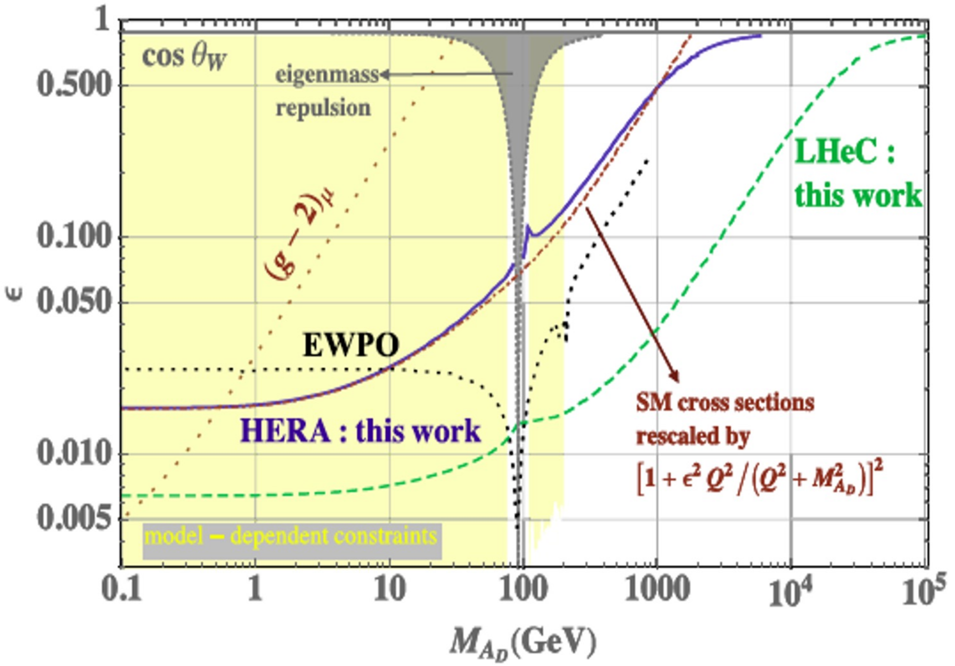


CMS Collaboration, Phys. Rev. Lett. 124 (2020) 131802

Current limits



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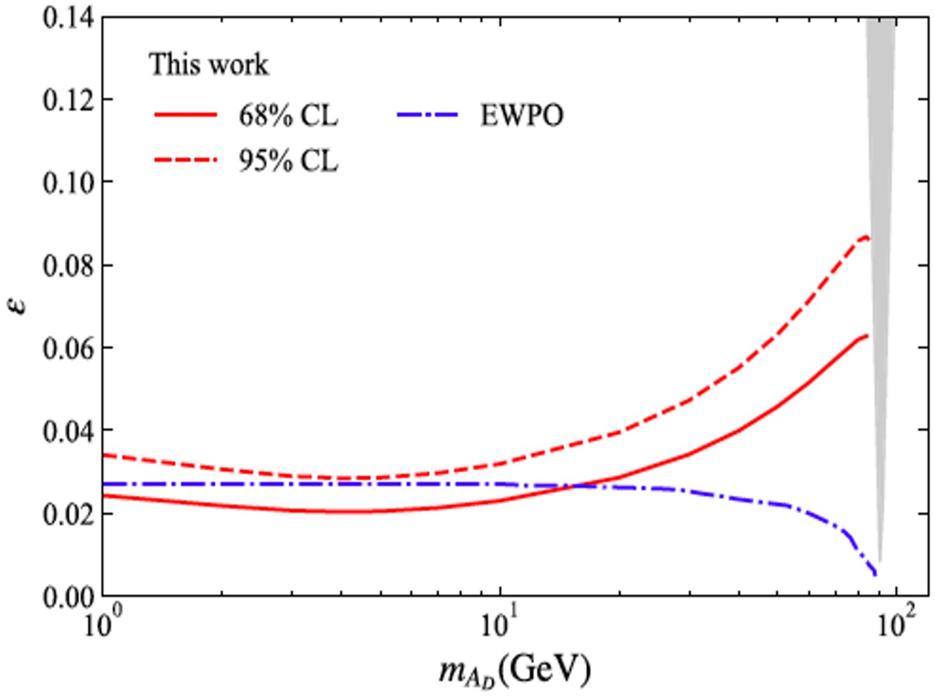

G.D. Kribs, D. McKeen, N. Raj, Phys. Rev. Lett. 126 (2021) 011801
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SM global fit

- Use the free parameters: $\left\{m_h, m_Z, m_t, \alpha_s, \Delta\alpha_{had}^{(5)}\right\}$.
- These are used to derive the remaining 12 EWPO data points:

$$\left\{\Gamma_Z, \sigma_{hadron}^0, A_{\{\ell,b,c\}}, R_{\{\ell,b,c\}}^0, A_{FB}^{\{\ell,b,c\},0}, m_W, \Gamma_W\right\}.$$

- Fit to experimental values.
- The SM fit χ_{SM}^2 provides a reference point for constraining our dark photon parameters.
- Perform two fits: first with CDF reported m_W, second with PDG global average m_W (excluding CDF measurement).
- Extract $\chi_{SM}^{2\,\{CDF\}}$ and $\chi_{SM}^{2\,\{PDG\}}$.

SM Baseline Fits

Observable	Measurement	Fit result (m_W^{PDG})	Fit result (m_W^{CDF})
m_Z (GeV)	91.1875 ± 0.0021	91.1880 ± 0.0020	91.1910 ± 0.0020
m_h (GeV)	125.25 ± 0.17	125.25 ± 0.17	125.24 ± 0.17
m_t (GeV)	172.69 ± 0.30	172.75 ± 0.30	173.09 ± 0.29
$\alpha_s(m_Z^2)$	0.1179 ± 0.0009	0.1203 ± 0.0026	0.1176 ± 0.0026
$\Delta\alpha_{\mathrm{had}}^{(5)}$	0.02757 ± 0.00010	0.02755 ± 0.00010	0.02745 ± 0.00010
Γ_Z (GeV)	2.4955 ± 0.0023	2.4963	2.4953
σ_{had}^0 (nb)	41.4802 ± 0.0325	41.4704	41.4814
A_ℓ	0.1499 ± 0.0018	0.1471	0.1476
A_b	0.923 ± 0.020	0.935	0.935
A_c	0.670 ± 0.027	0.668	0.668
R_ℓ^0	20.7666 ± 0.0247	20.7529	20.7358
R_b^0	0.21629 ± 0.00066	0.21581	0.21581
R_c^0	0.1721 ± 0.0030	0.1723	0.1722
$A_{FB}^{\ell,0}$	0.0171 ± 0.0010	0.0162	0.0164
$A_{FB}^{b,0}$	0.0992 ± 0.0016	0.1031	0.1034
$A_{FB}^{c,0}$	0.0707 ± 0.0035	0.0737	0.0739
m_W^{PDG} (GeV)	80.377 ± 0.012	80.359	
m_W^{CDF} (GeV)	80.4335 ± 0.0094		80.3686
Γ_W (GeV)	2.085 ± 0.042	2.091	2.091
$\chi^2_{d.o.f}$		$12.92/(17-5)$	$68.23/(17-5)$

Softening CDF Tension with Heavy Dark Photon

- Heavy dark photon (200GeV) can soften CDF tension.
- Predicted $m_w = 80.406\ GeV$ → only 2.9σ off CDF.
- Still not a perfect fix, but interesting!

Observable	Measurement	$(m_{A_D}, \epsilon) = (200\ \text{GeV}, 0.1001)$
m_Z (GeV)	91.1875 ± 0.0021	$m_Z = 91.1894$
m_h (GeV)	125.25 ± 0.17	125.25 ± 0.17
m_t (GeV)	172.69 ± 0.30	172.81 ± 0.30
$\alpha_s(m_Z^2)$	0.1179 ± 0.0009	0.1205 ± 0.0026
$\Delta\alpha_{\text{had}}^{(5)}$	0.02757 ± 0.00010	0.02759 ± 0.00010
Γ_Z (GeV)	2.4955 ± 0.0023	2.4936
σ_{had}^0 (nb)	41.4802 ± 0.0325	41.4660
A_ℓ	0.1499 ± 0.0018	0.1518
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.670
R_ℓ^0	20.7666 ± 0.0247	20.7640
R_b^0	0.21629 ± 0.00066	0.21579
R_c^0	0.1721 ± 0.0030	0.1723
$A_{FB}^{\ell,0}$	0.0171 ± 0.0010	0.0173
$A_{FB}^{b,0}$	0.0992 ± 0.0016	0.1064
$A_{FB}^{c,0}$	0.0707 ± 0.0035	0.0763
m_W^{CDF} (GeV)	80.4335 ± 0.0094	80.4060
Γ_W (GeV)	2.085 ± 0.042	2.095
$\chi^2_{d.o.f}$		33.69/(17-5)

Constraints on the dark photon

Constraints on the dark photon

$$\frac{\epsilon}{2\cos\theta_w} F'_{\mu\nu} B^{\mu\nu}$$

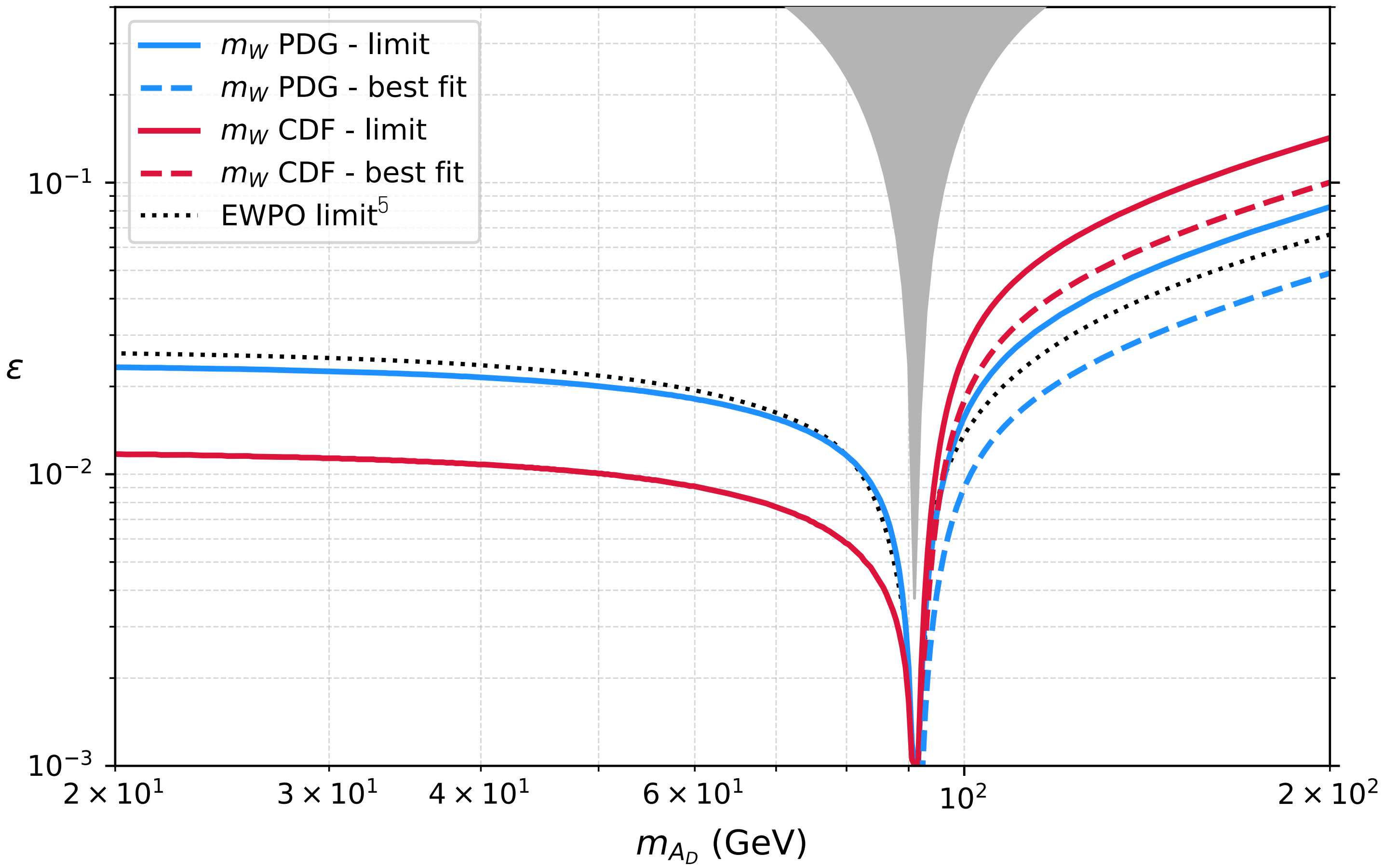
- Set limits on kinetic mixing parameter ϵ, given its mass m_{A_D}.
- For each mass m_{A_D}, we scan over ϵ from 0 to 1.
- For each ϵ we vary $\left\{m_h, m_Z, m_t, \alpha_s, \Delta\alpha_{had}^{(5)}\right\}$ until a χ^2 minimum is found.
- The minimum χ^2 obtainable is dependent upon ϵ, and the 95% excluded region on ϵ is defined such that:

$$\chi^2_{A_D}(\epsilon) - \chi^2_{SM} \geq 3.8,$$

- $\chi^{2\,\{CDF\}}_{SM} = 68.23$, $\chi^{2\,\{PDG\}}_{SM} = 12.92$

Dark Photon Exclusion Limits

$$\chi^2_{A_D}(\epsilon) - \chi^2_{SM} \geq 3.8$$



B. M. Loizos, X. G. Wang, A. W. Thomas, M. J. White, and A. G. Williams, J. Phys. G 51, 075002 (2024), arXiv:2306.13408 [hep-ph].

[5] Curtin D, Essig R, Gori S and Shelton J 2015 JHEP 02 157 (Preprint 1412.0018)

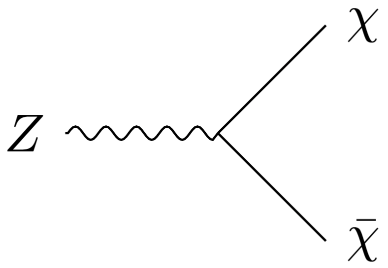
Constraints on dark fermions

Constraints on dark fermions χ

$$g'_\chi \bar{\chi}\gamma^\mu \chi A'_\mu$$

- Constraints have been placed on the parameter $y = \frac{\epsilon^2 g_\chi^2}{4\pi}\left(\frac{m_\chi}{m_{A'}}\right)^4$ through relic density and direct detection.
- But we can place constraints on g_χ directly using EWPOs.
- Z boson decay width receives extra contribution from $\chi\bar{\chi}$ final states for $m_\chi < \frac{m_Z}{2}$:

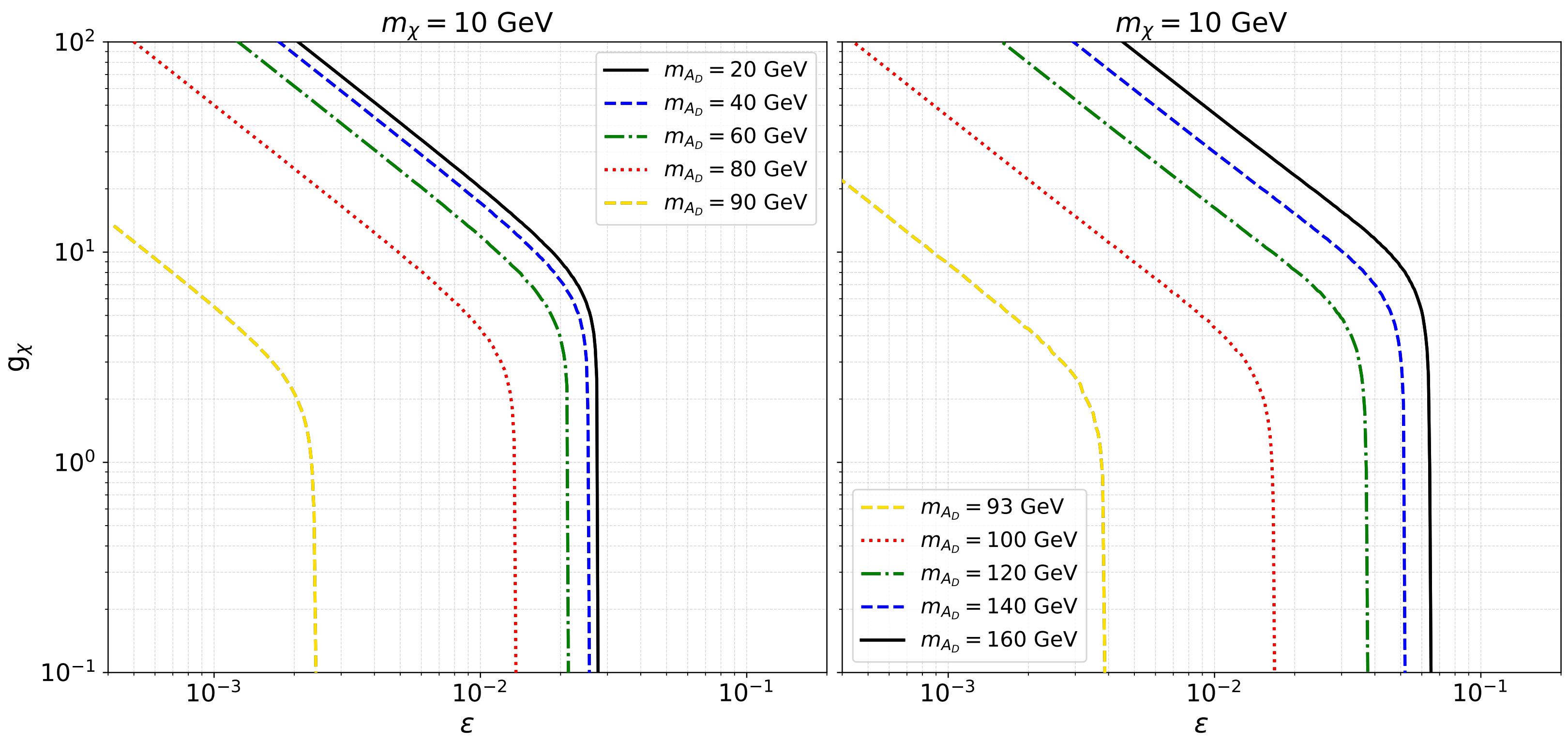
$$\Gamma_Z = \Gamma_{had} + \Gamma_e + \Gamma_\mu + \Gamma_\tau + 3\Gamma_\nu + \Gamma_\chi,$$



$$\Gamma_\chi = \frac{m_Z C_{Z,\chi\bar{\chi}}^2}{12\pi}\left(1 + \frac{2m_\chi^2}{m_Z^2}\right)\sqrt{1 - \frac{4m_\chi^2}{m_Z^2}}$$

Dark Fermion Exclusion Limits

$$\chi^2_{A_D}(\epsilon, g_\chi) - \chi^2_{SM} \geq 5.99$$



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Summary

- Revisited constraints on the dark photon from electroweak precision observables, including the latest CDF m_W measurement and it's impacts on the mixing parameter ϵ.
- Upper bounds for ϵ tighten for $m_{A_d} < m_Z$ and weakened for $m_{A_D} > m_Z$.
- Introduced couplings between the dark photon and fermionic dark matter, g_χ.
- Using EWPO, set exclusion limits on g_χ for massive dark fermions.
- Upper bounds for g_χ tighten as $m_{A_d} \to m_Z$, and weakens as m_χ increases.