Phenomenology of light gauge bosons and dark matter

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Dark Side of the Universe
Corfu, Greece September 2024

Dirección General de Asuntos del Personal Académico

Intensity frontier with low-energy experiments

CEvNS

PV DIS

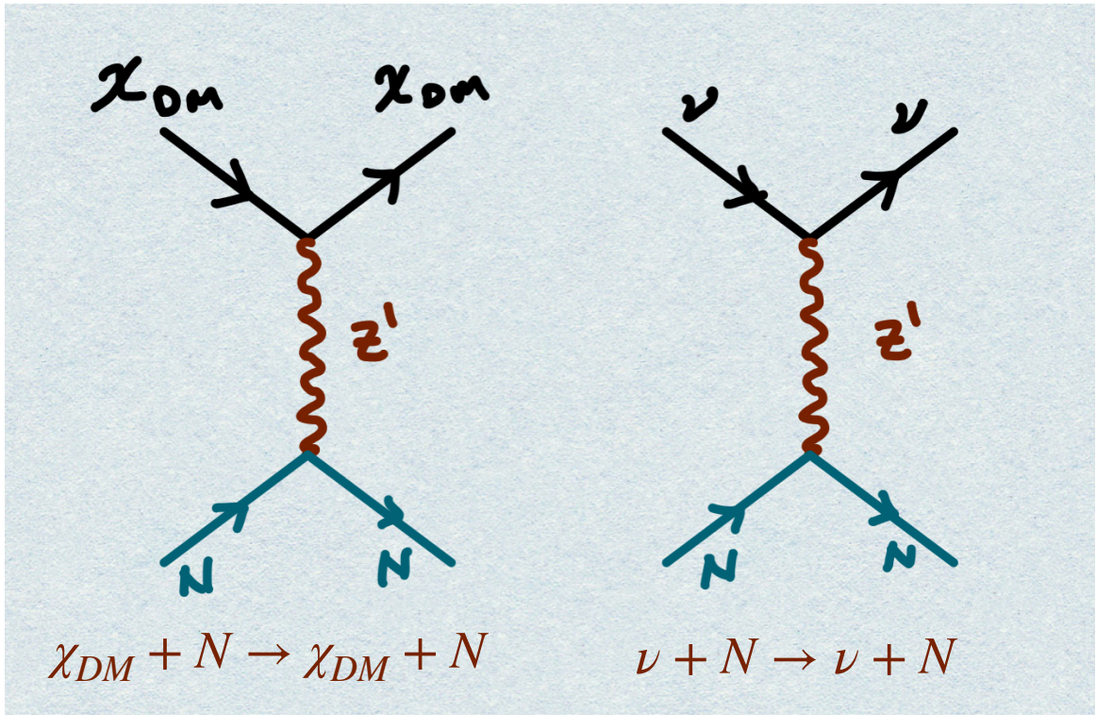
Dark Photon

Moller

Atomic PV

PV

Complementarity between Low energy experiments
and
DM direct searches is also possible



$U(1)$ Gauge extensions of the SM

$$E_6 \to SO(10) \times U(1) \qquad\qquad SO(10) \to SU(5) \times U(1)$$

Z'

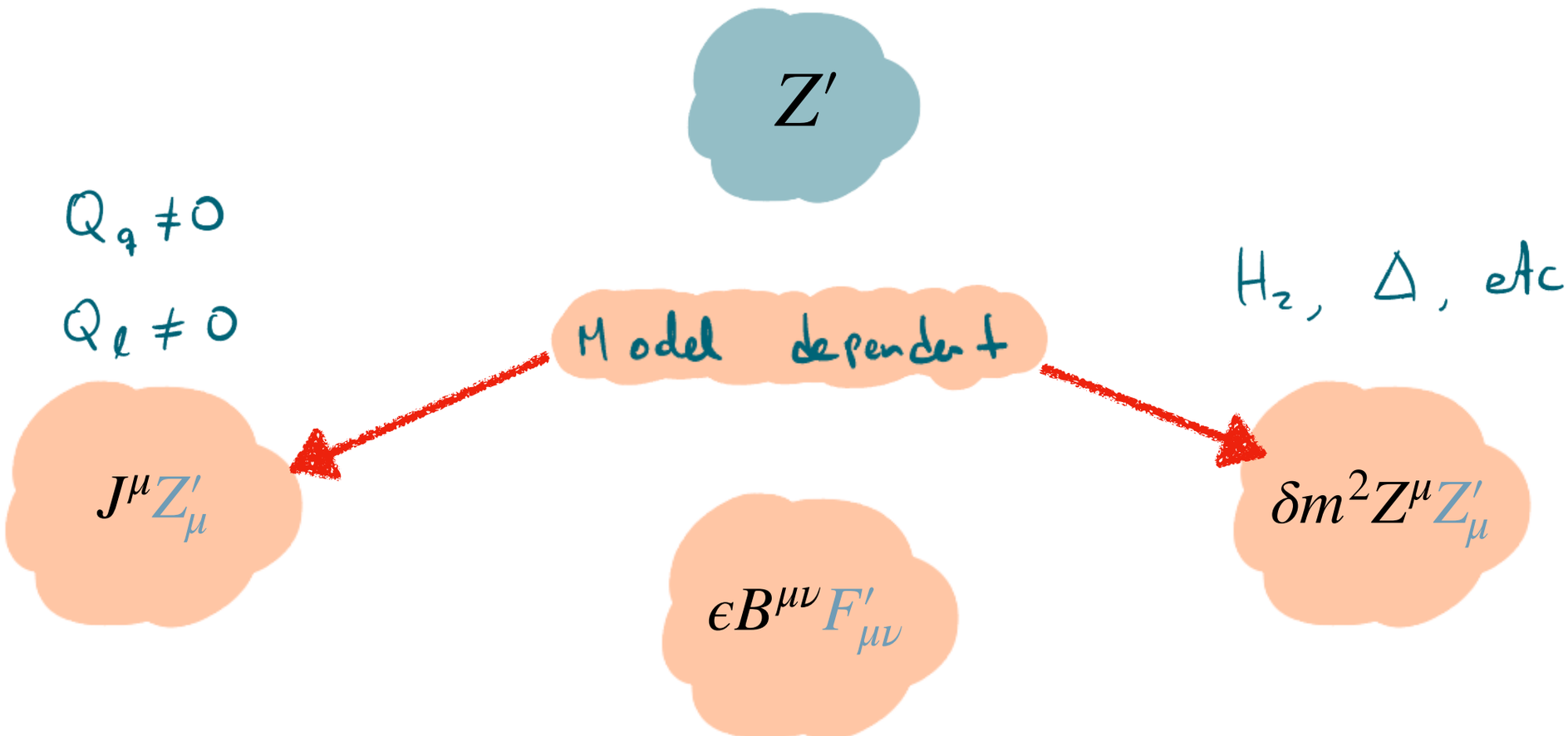
$J^\mu Z'_\mu$

$\epsilon B^{\mu\nu} F'_{\mu\nu}$

$\delta m^2 Z^\mu Z'_\mu$

$U(1)$ Gauge extensions of the SM

$$E_6 \to SO(10) \times U(1) \qquad SO(10) \to SU(5) \times U(1)$$



Light Z'

$$\mathscr{L} \supset \frac{m_{Z'}^2}{2} Z'^{\mu} Z'_{\mu} + i g' Z'_{\mu} (Q_f \bar{f} \gamma^{\mu} f)$$

SSB

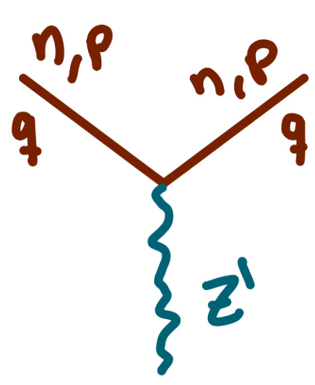
$$\langle \phi_i \rangle = \frac{v_i}{\sqrt{2}}$$

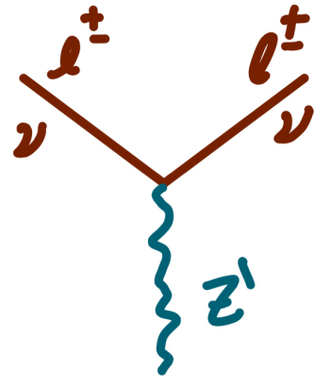
$$m_{Z'}^2 = \sum_i g'^2 Q_i^2 v_i^2$$

small g'

low scale v_i

$Q_q \neq 0$





$Q_\ell \neq 0$

Anomaly free solutions

Talks by
Ko
Erler
Allanach
Covi

$U(1)_{B-L}$

3 RH ν

$U(1)_{B-3L_\alpha}$

1 RH ν

$J^\mu Z'_\mu$

$U(1)_{B-2L_\alpha-L_\beta}$

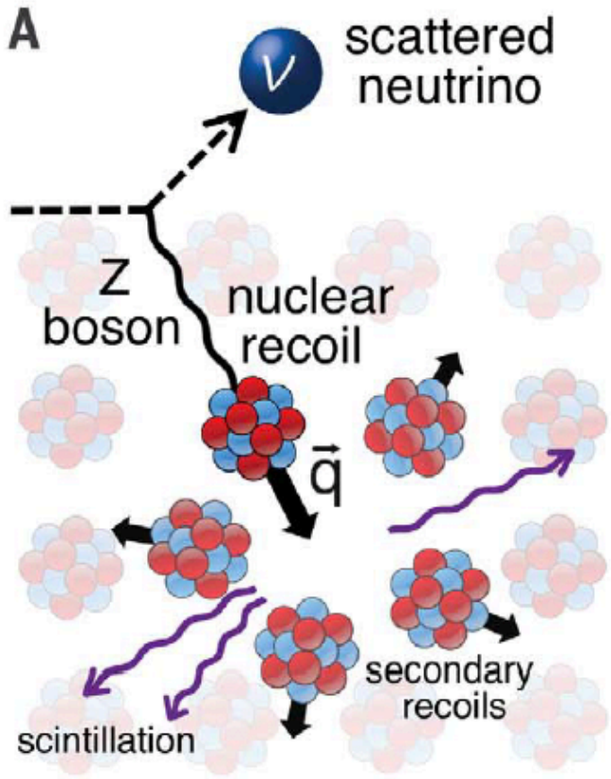
2 RH ν

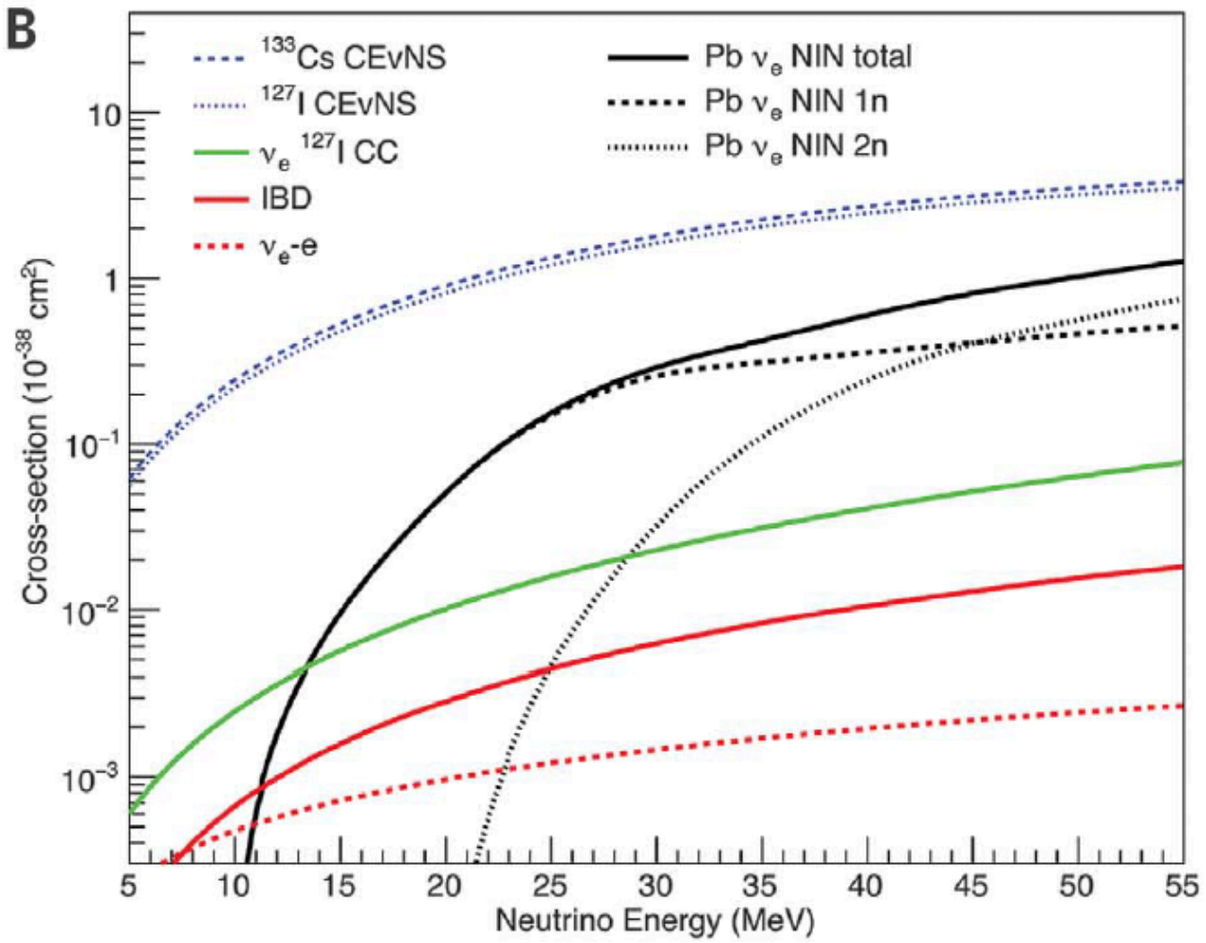
$U(1)_{L_\alpha-L_\beta}$

$U(1)'$

...

COHERENT Collaboration





$$\frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} M_N Q_w^2 \left(2 - \frac{M_N T}{E_\nu^2}\right)$$

$$Q_w^2 = \left[Z g_p^V F_Z(q^2) + N g_n^V F_N(q^2)\right]^2$$

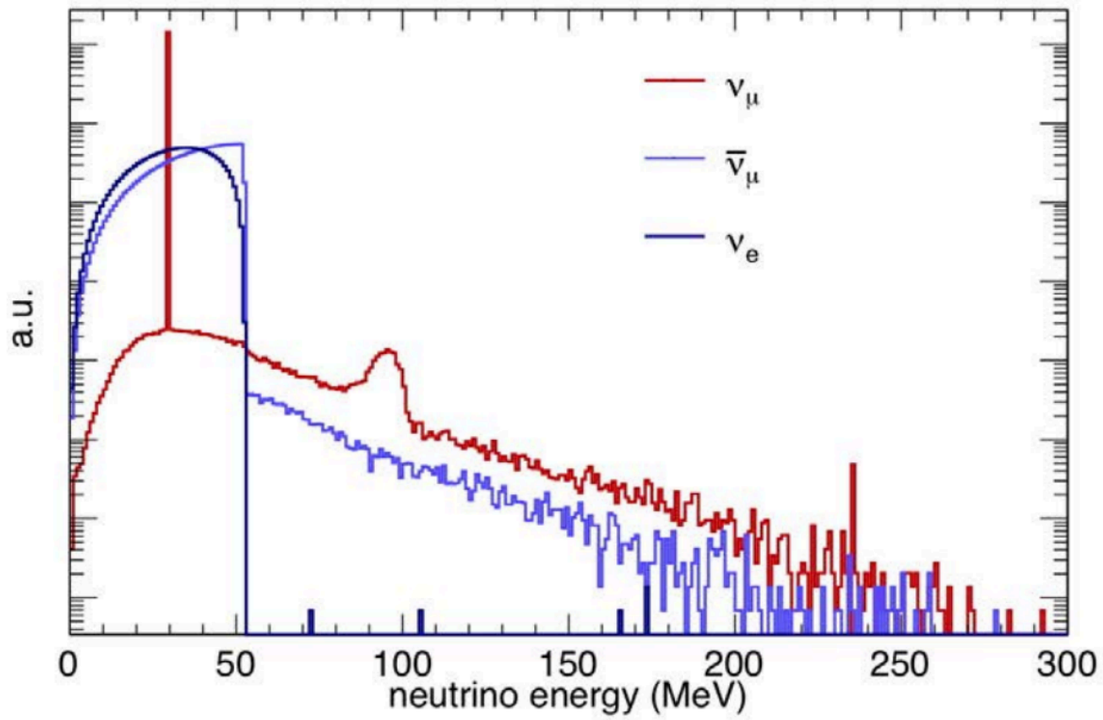
Akimov et al., Science 357, 1123–1126 (2017)

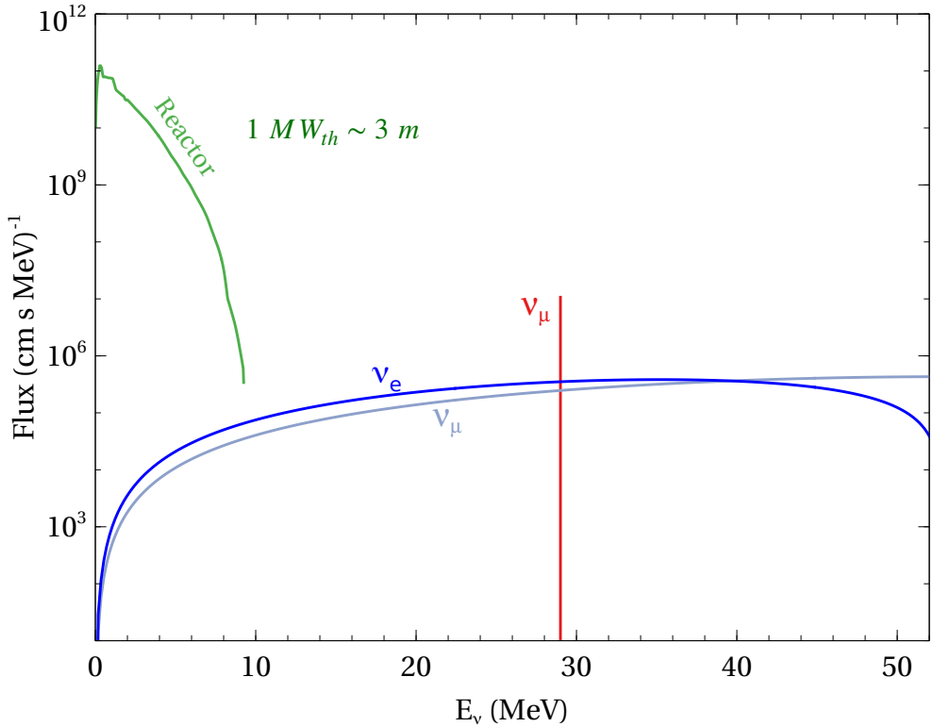
CEνNS

$$p \longrightarrow Hg \begin{cases} \nearrow \pi^- \quad (99.9\,\%\ captured\ by\ Hg) \\ \searrow \pi^+ \rightarrow \mu^+ + \nu_\mu (29.9\ MeV) \searrow e^+ + \bar{\nu}_\mu + \nu_e \end{cases}$$

14.6 Kg **CsI** 134 events (~300 day)

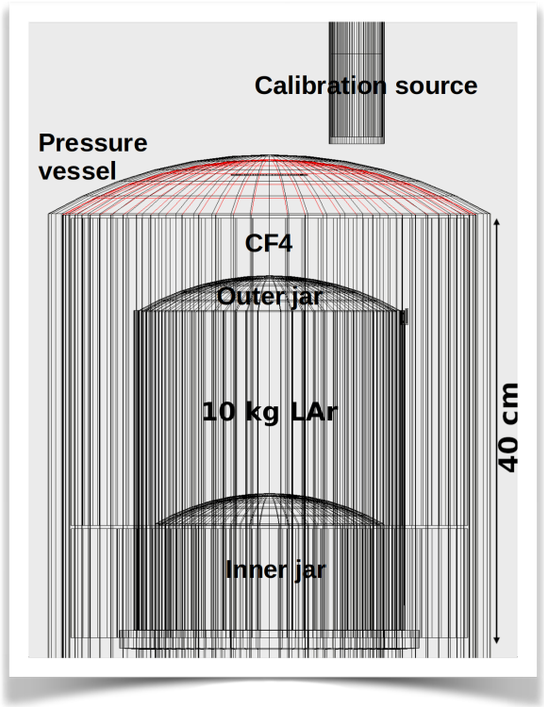
24 Kg **Ar** 159 events (~ 240 days)





SBC collaboration

L. Flores, et. al. SBC collaboration PRD (2021)

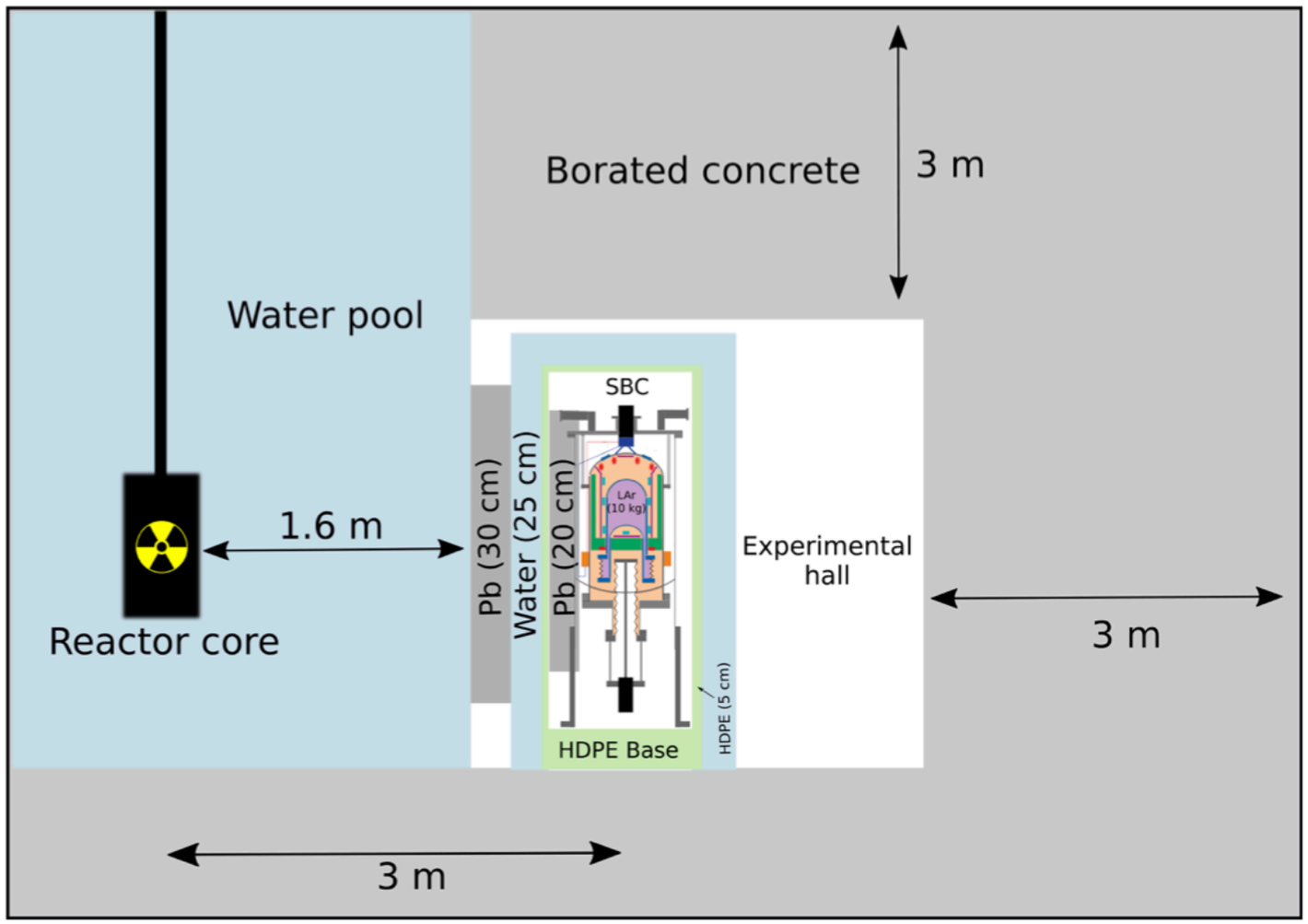


E. Alfonso-Pita

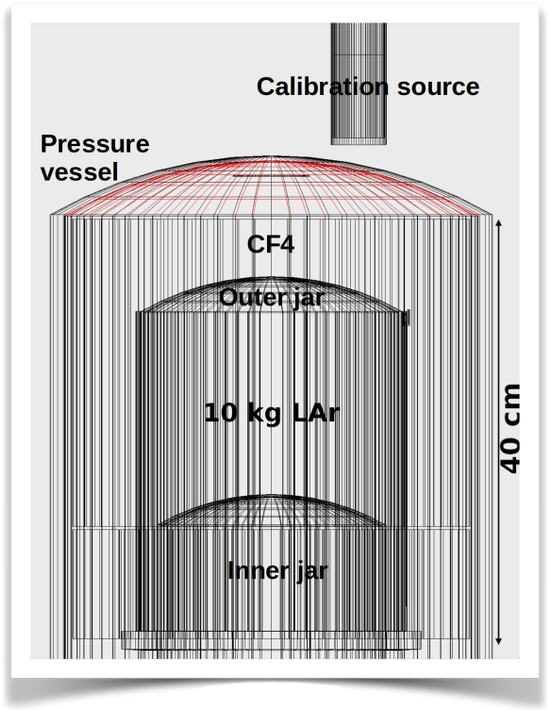
10 kg liguid Argon bubble chamber similar to PICO detector

T~90-130 ^oK
P~2 atm

100 eV threshold



SBC collaboration



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10 kg liguid Argon
bubble chamber
similar to PICO
detector

T~90-130 ^oK
P~2 atm

L. Flores, et. al. SBC collaboration PRD (2021)

100 eV threshold

Currently under construction

10 kg at 3 m a 1-MW_{th} reactor

A TRIGA Mark III research ININ

~8 neutrino events/day

~2,900 neutrino events in 1 year

~320 background events
cosmogenic

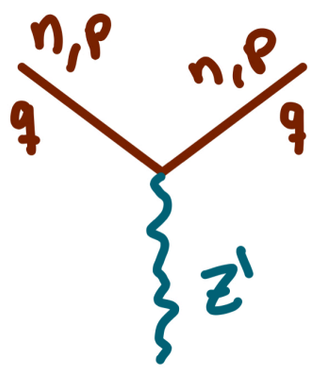
~140 background events
Neutrons from reactor

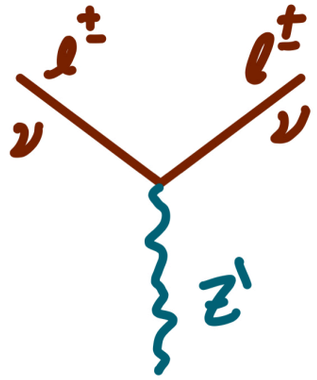
$U(1)_{B-L}$

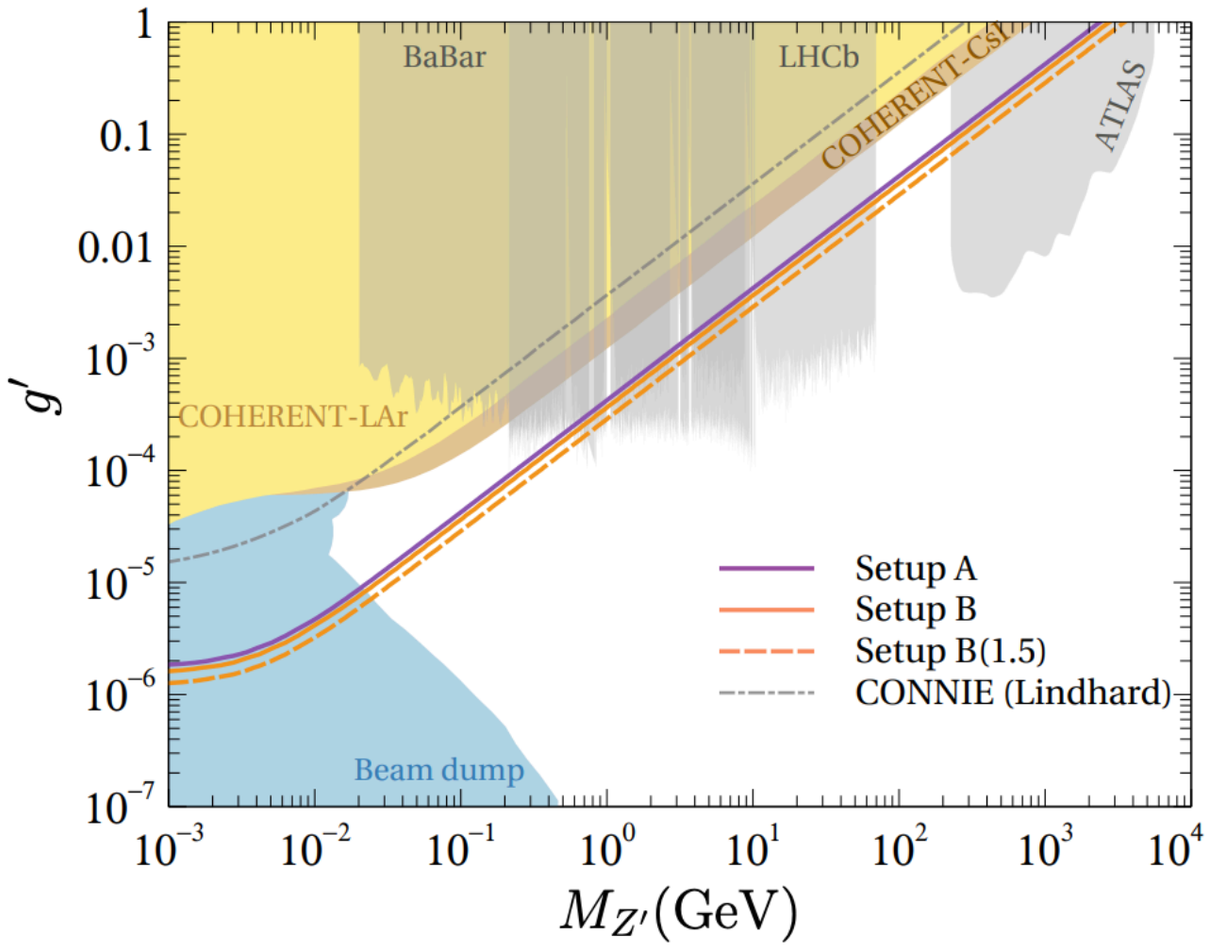
Anomaly free with 3 RH neutrinos (-1,-1,-1) or (-4,-4,5)

$Q_q \neq 0$

$Q_\ell \neq 0$

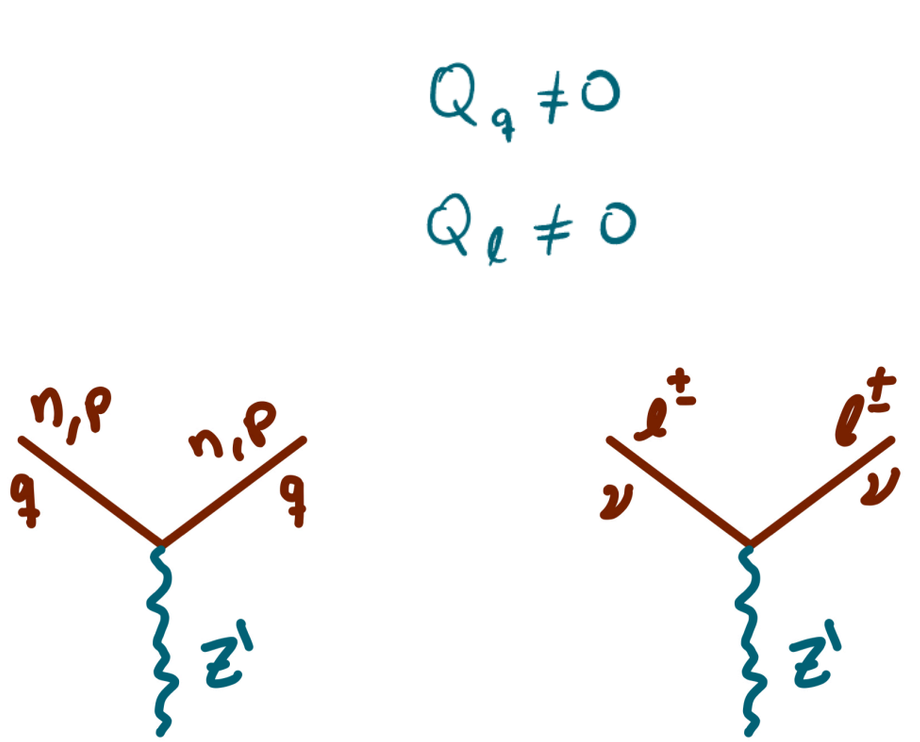


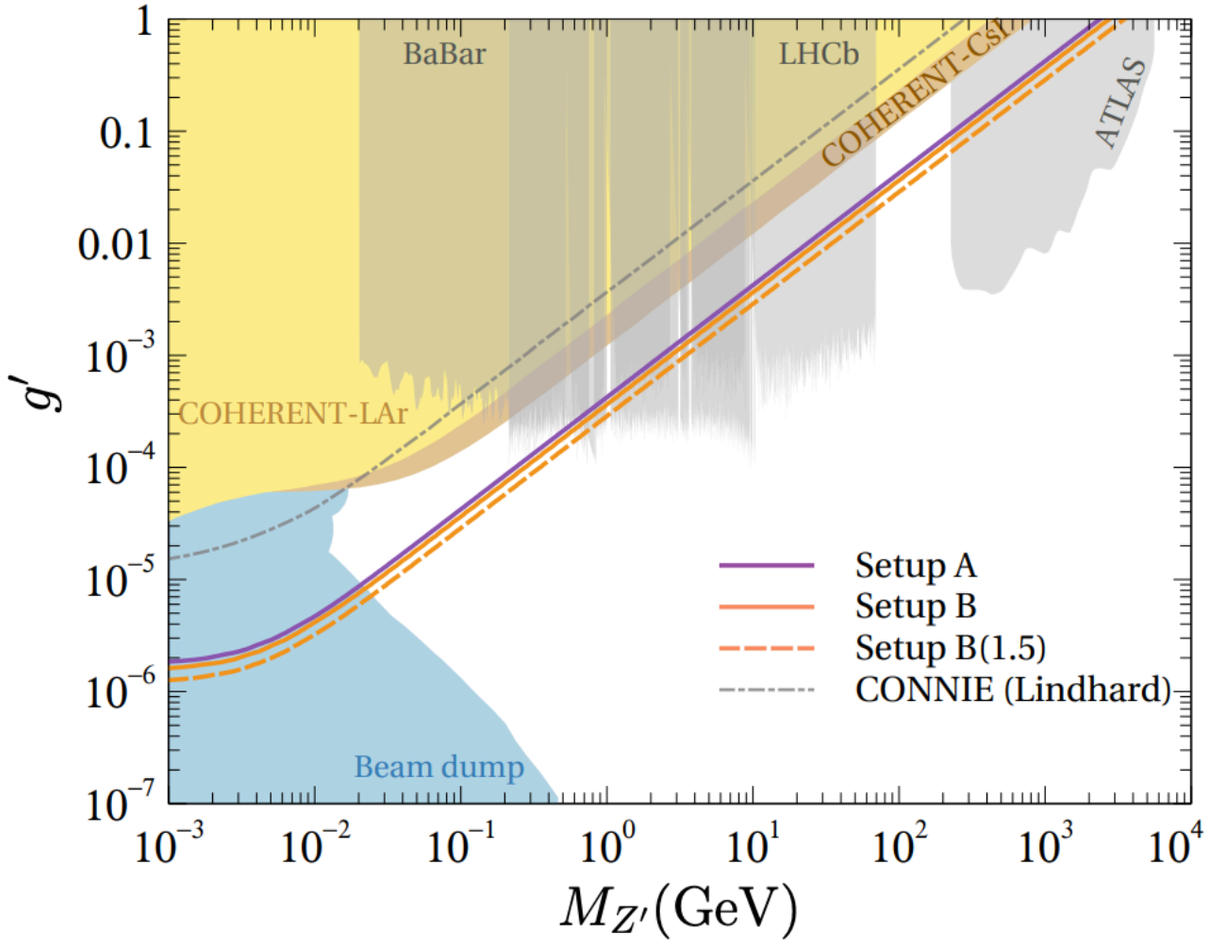




$U(1)_{B-L}$

Anomaly free with 3 RH neutrinos (-1,-1,-1) or (-4,-4,5)





Models for Dirac and Majorana neutrino masses at one-loop

Symmetry

Genuine

Accidental

Global

Residual from local

Cirelli, Fornengo, Strumia NPB (2006)

Mambrini et al PLB (2016)

$U(1) \to Z_N$

DM and ν nature

Bonilla, Centelles-Chulia, Cepedello, EP, Srivastava (2018)

Flavorful $U(1)'$

L. Flores, N. Nath, EP, JHEP (2020)

Gauge $U(1)_{B-2L_\alpha-L_\beta}$

Anomaly free

3 RH neutrinos

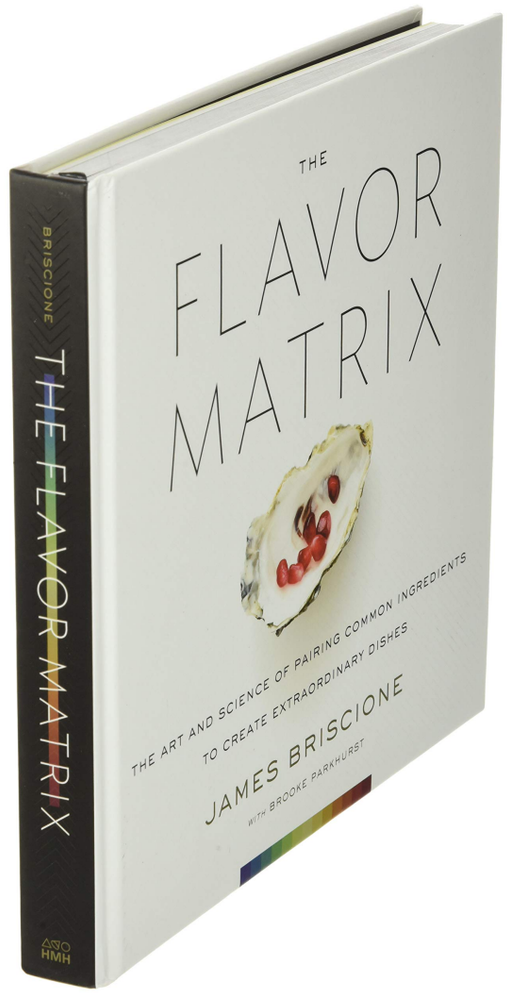
2 U(1) breaking scalar fields

$$\frac{1}{2}M_{Z'}^2 = g'^2\ \frac{1}{2}(v_1^2 + 4v_2^2)$$

$\langle\phi_1\rangle$ $\langle\phi_2\rangle$

	ϕ_1	ϕ_2
$U(1)$	1	2

Neutrino phenomenology



Allanach's talk

$U(1)_{B-L_\mu-2L_\tau}$

$$-\mathscr{L}_{Majorana} = \frac{1}{2} M_1 \overline{N_1^c} N_1 + \frac{1}{2} \overline{N_1^c} N_2 \phi_1 + \frac{1}{2} \overline{N_1^c} N_3 \phi_2 + \frac{1}{2} \overline{N_2^c} N_2 \phi_2$$

$$M_N = \begin{pmatrix} M_1 & y_1^N \langle \phi_1 \rangle & y_2^N \langle \phi_2 \rangle \\ y_1^N \langle \phi_1 \rangle & y_3^N \langle \phi_2 \rangle & 0 \\ y_2^N \langle \phi_2 \rangle & 0 & 0 \end{pmatrix}$$

L. Flores, N. Nath, EP, JHEP (2020)

x_e	x_μ	x_τ	Neutrino mass matrix	Type	NSI parameters
0	-1	-2	$\begin{pmatrix} 0 & 0 & \times \\ 0 & \times & \times \\ \times & \times & \times \end{pmatrix}$	A_1	$\varepsilon_{\mu\mu}$ & $\varepsilon_{\tau\tau}$
0	-2	-1	$\begin{pmatrix} 0 & \times & 0 \\ \times & \times & \times \\ 0 & \times & \times \end{pmatrix}$	A_2	$\varepsilon_{\mu\mu}$ & $\varepsilon_{\tau\tau}$
-1	0	-2	$\begin{pmatrix} \times & 0 & \times \\ 0 & 0 & \times \\ \times & \times & \times \end{pmatrix}$	B_3	ε_{ee} & $\varepsilon_{\tau\tau}$
-1	-2	0	$\begin{pmatrix} \times & \times & 0 \\ \times & \times & \times \\ 0 & \times & 0 \end{pmatrix}$	B_4	ε_{ee} & $\varepsilon_{\mu\mu}$
-2	-1	0	$\begin{pmatrix} \times & \times & \times \\ \times & \times & 0 \\ \times & 0 & 0 \end{pmatrix}$	$\times$	ε_{ee} & $\varepsilon_{\mu\mu}$
-2	0	-1	$\begin{pmatrix} \times & \times & \times \\ \times & 0 & 0 \\ \times & 0 & \times \end{pmatrix}$	$\times$	ε_{ee} & $\varepsilon_{\tau\tau}$

Frampton, Glashow, Marfatia, PLB (2002)

Benchmark point

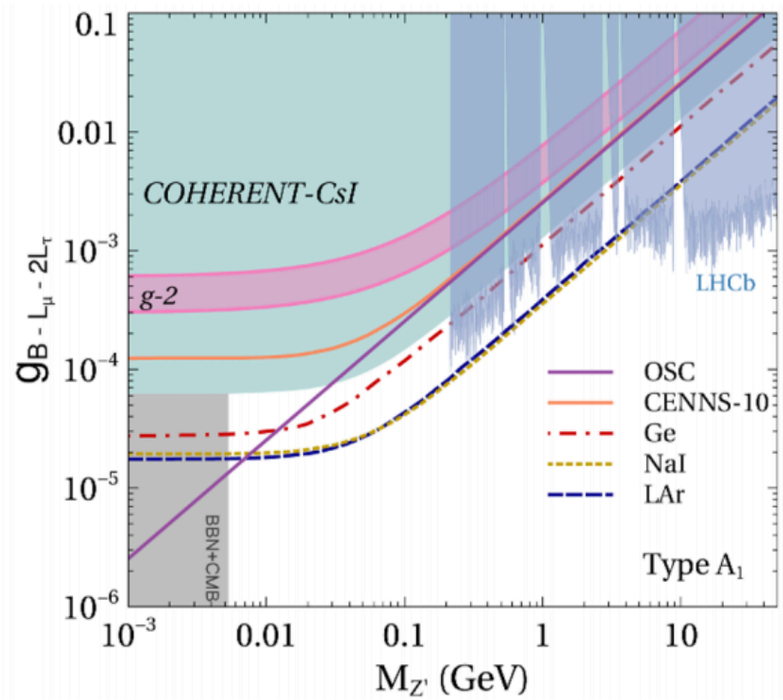
$$\frac{1}{2}M_{Z'}^2 = g'^2 \ \frac{1}{2}(v_1^2 + 4v_2^2)$$

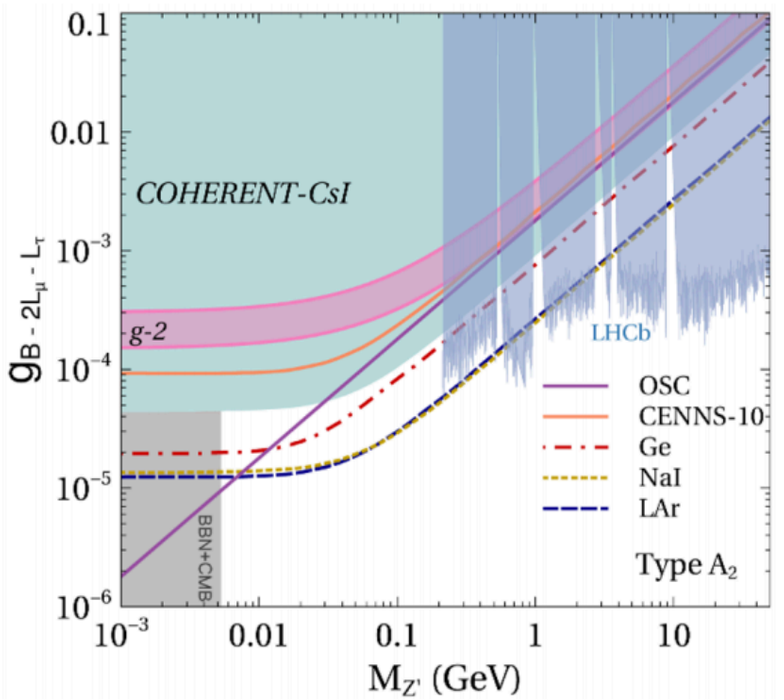
$$M_{Z'} = 0.1\,\mathrm{GeV}$$

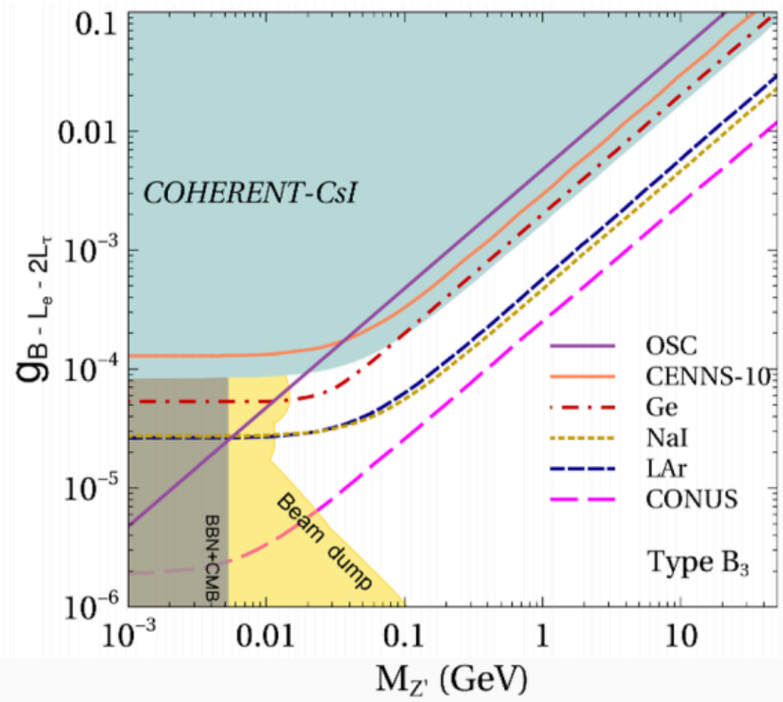
$$g' = 2.8 \times 10^{-5}$$

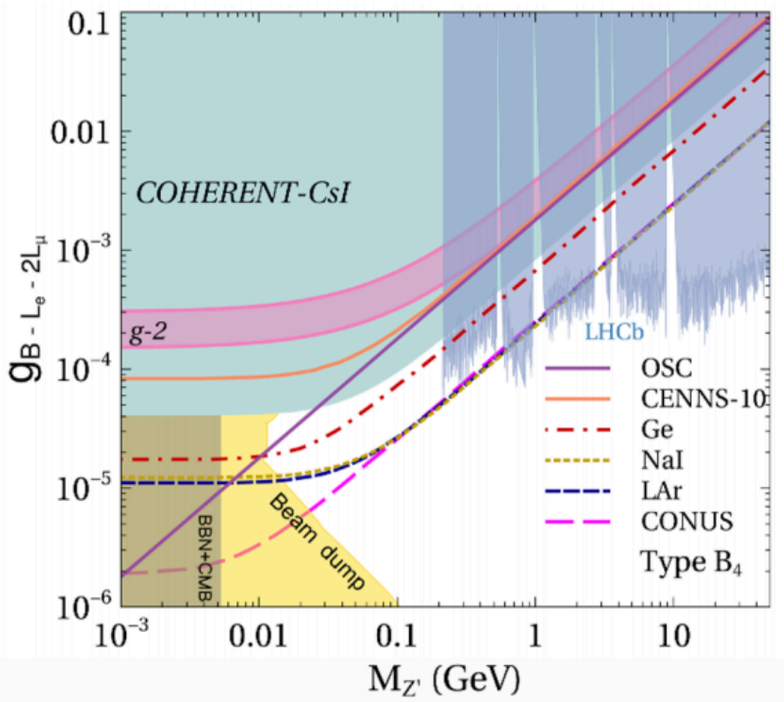
$$v_1 \approx 3\,\mathrm{TeV} \quad v_2 \approx 1\,\mathrm{TeV}$$

L. Flores, N. Nath, EP, JHEP (2020)







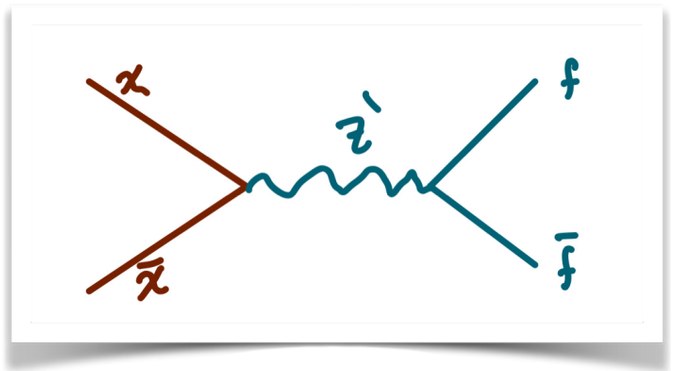


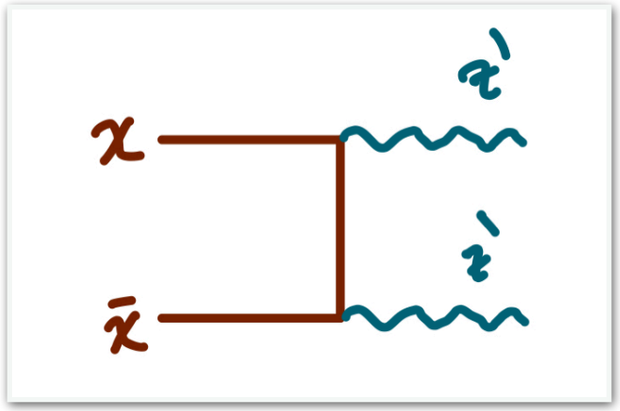
Fermionic DM

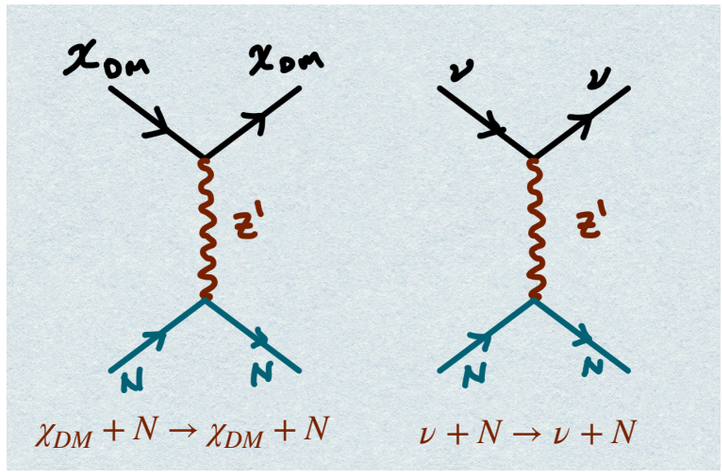
	$U(1)'$ models	Scalar Fields	Masses of Z' $(M^2_{Z'})$
MI	$U(1)_{B-L}$	ϕ_2	$g'^2(4v_2^2)$
MII	$U(1)_{B-2L_\alpha-L_\beta}$	$\phi_1,\ \phi_2$	$g'^2(v_1^2+4v_2^2)$
MIII	$U(1)'_{B-2L_\alpha-L_\beta}$	$\phi_1,\ \phi_2,\ \phi_4$	$g'^2(v_1^2+4v_2^2+16v_4^2)$
MIV	$U(1)_{B-3L_\alpha}$	$\phi_3,\ \phi_6$	$g'^2(9v_3^2+36v_6^2)$

Extend the SM with a Dirac fermion χ with $Q_\chi = 1/3$

$$\mathscr{L} \supset M_D\bar{\chi}\chi + \bar{\chi}\gamma^\mu(\partial_\mu + ig'Q_\chi Z'_\mu)\chi$$

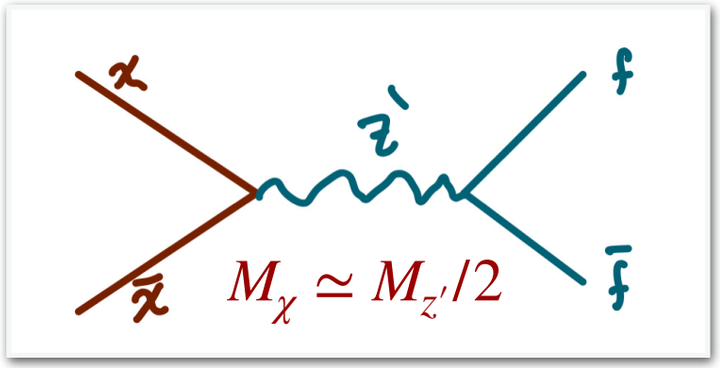




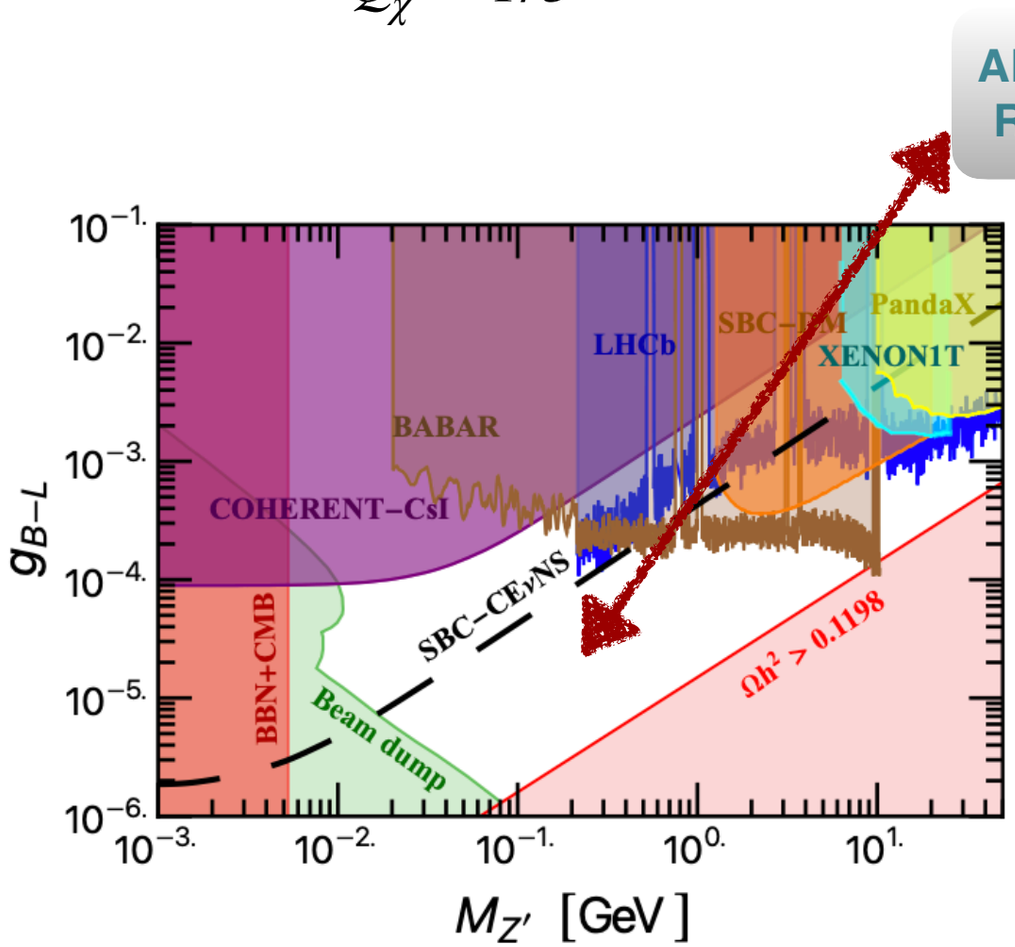


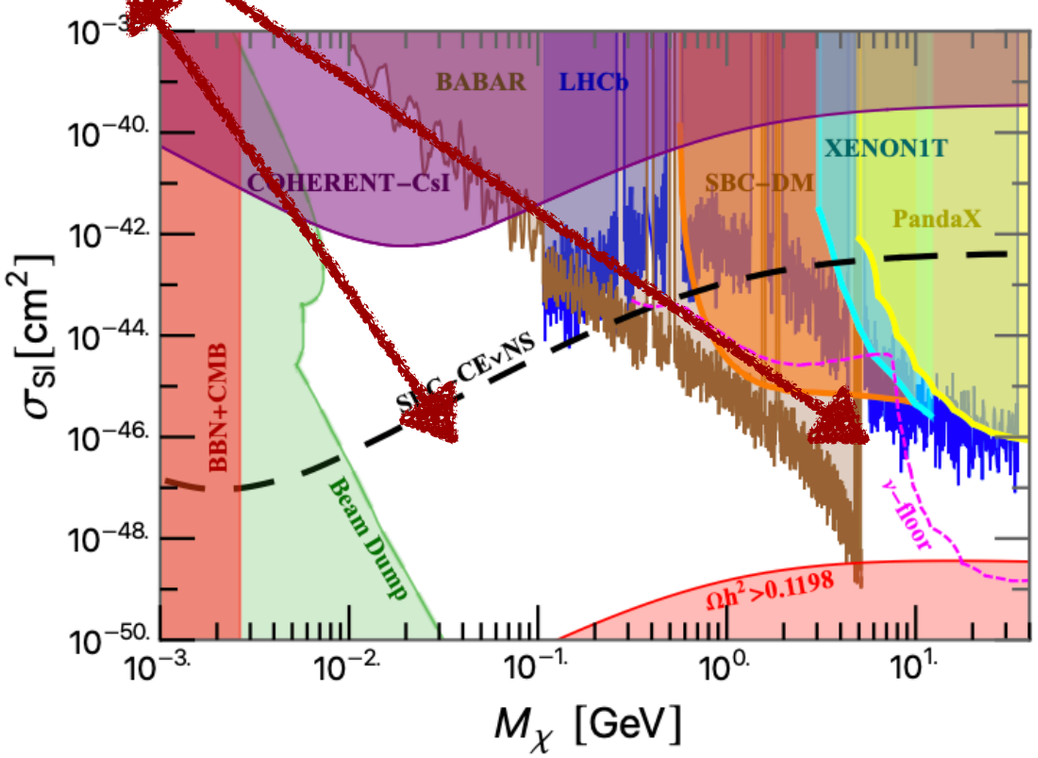
$U(1)_{B-L}$

Complementarity



$Q_\chi = 1/3$





De la Vega, L. Flores, N. Nath, EP, JHEP (2021)

Kinetic and mass mixing

$\epsilon B^{\mu\nu} F'_{\mu\nu}$

$\delta m^2 Z^\mu Z'_\mu$

Kinetic and mass mixing

Dark Photon

$\epsilon B^{\mu\nu} F'_{\mu\nu}$

Dark Z

$\delta m^2 Z^\mu Z'_\mu$

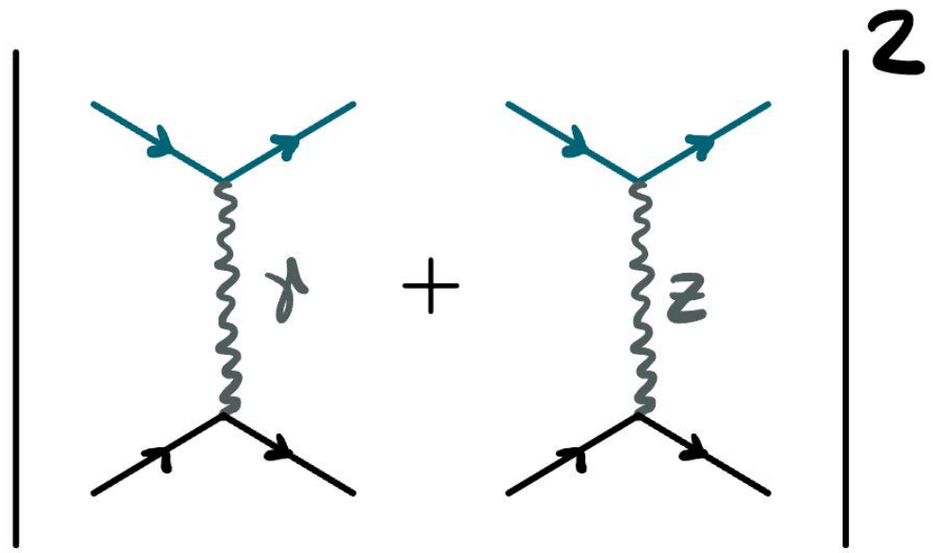
$SU(2)_L$ scalar charged under $U(1)'$

H_2, Δ, eAc

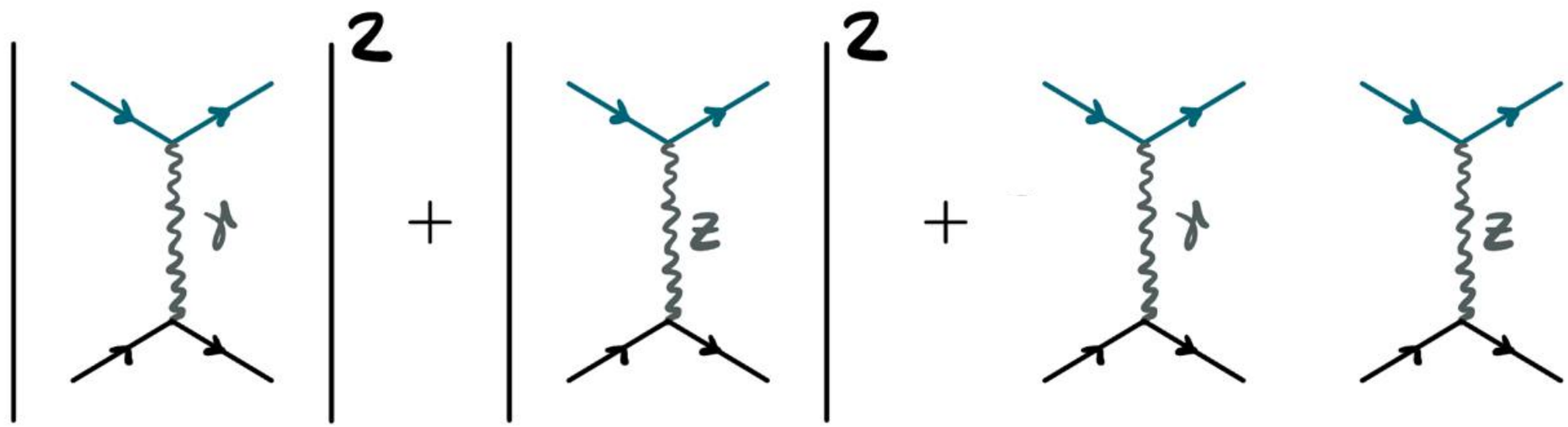
Parity Violation

$$e_R + P \to e_R + P \qquad e_L + P \to e_L + P$$

$$A_{PV} = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R} \sim$$



$\sim$



Parity Violation

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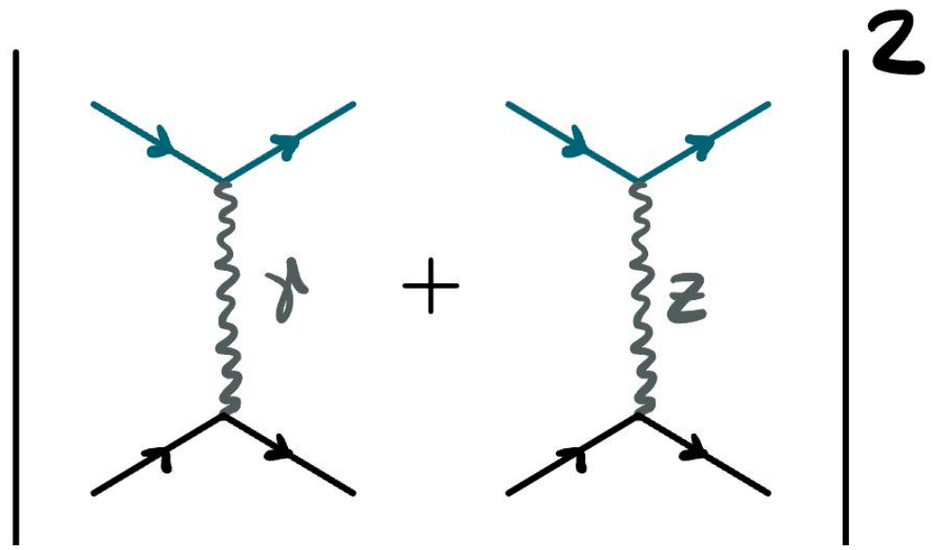
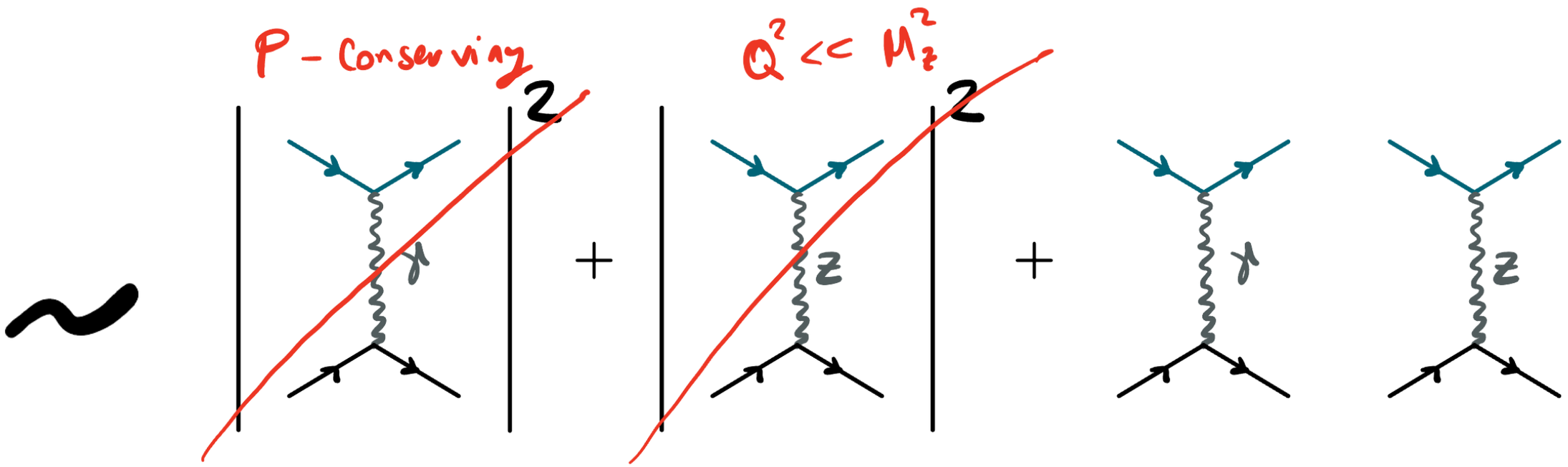




Pole Observables

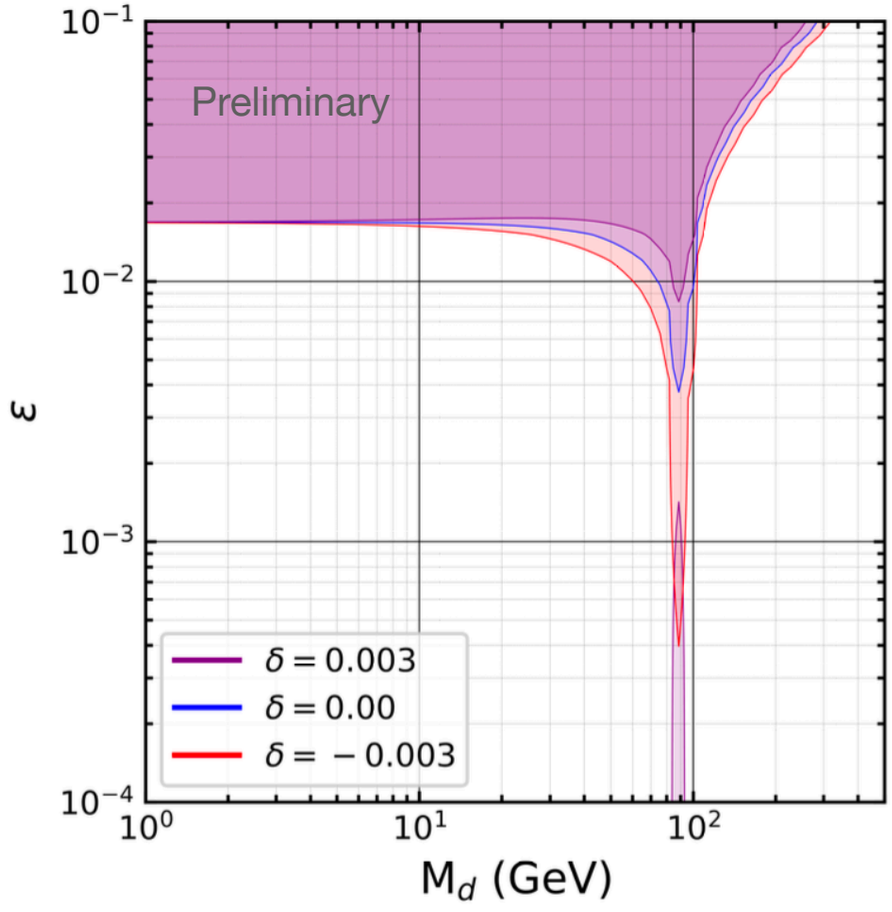
See for instance D. Curtin, R. Essig, S. Gori, and J. Shelton (2015)

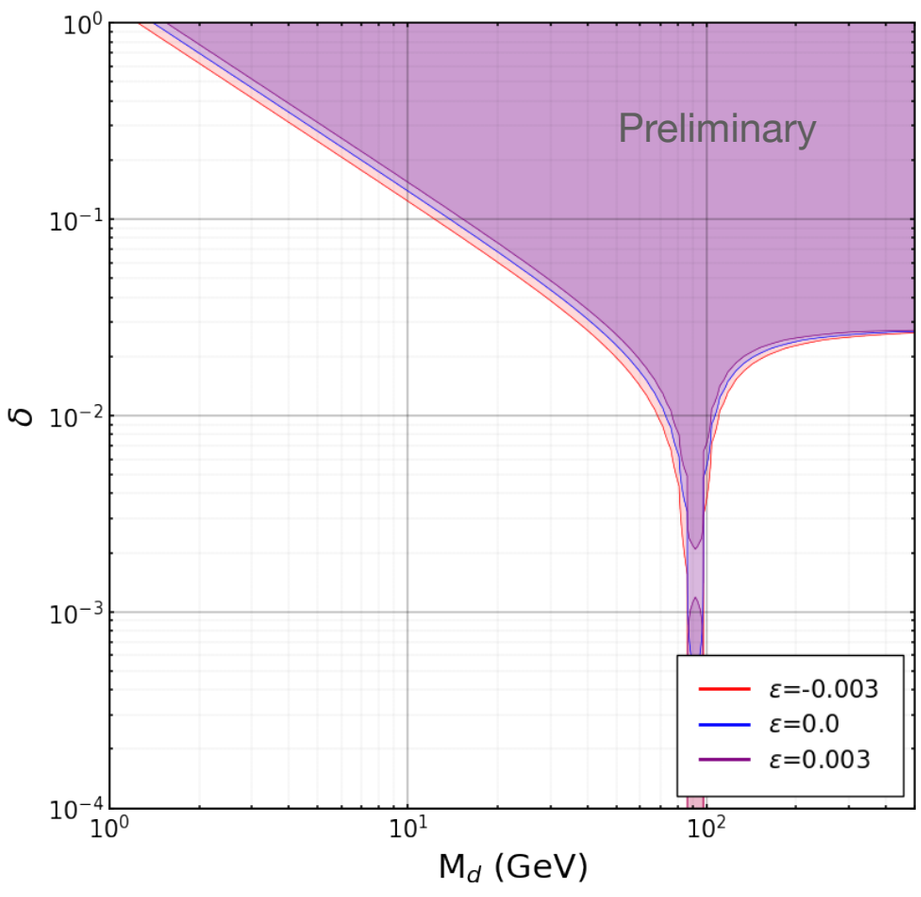
L.M. de la Vega, J Erler and R Ferro, EP In preparation

$$\Delta \sin^2\theta_W(p^2) = -\hat{s}\hat{c}\frac{\Pi^{\text{mixing}}_{\hat{A}\hat{Z}}(p^2)}{p^2} + \frac{\hat{s}^2\hat{c}^2}{\hat{c}^2-\hat{s}^2}\frac{\Pi^{\text{mixing}}_{\hat{Z}\hat{Z}}(M_Z^2)}{M_Z^2}.$$

$$\rho \to \rho_{SM} - \frac{\Pi^{\text{mixing}}_{\hat{Z}\hat{Z}}(-Q^2)}{Q^2+M_Z^2} = \rho_{SM} + \frac{\left(\delta M_d M_Z + \epsilon Q^2 \tan\hat{\theta}_W\right)^2}{(Q^2+M_d^2)(Q^2+M_Z^2)} = \rho_{SM} + \Delta\rho.$$

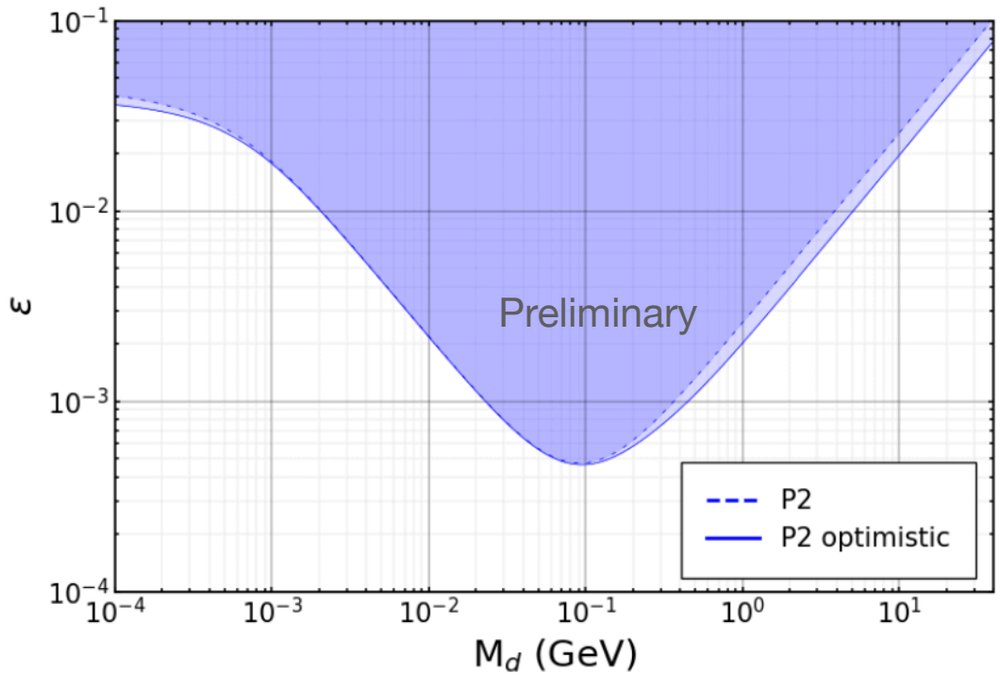
$\Delta\chi^2 > 2.7$

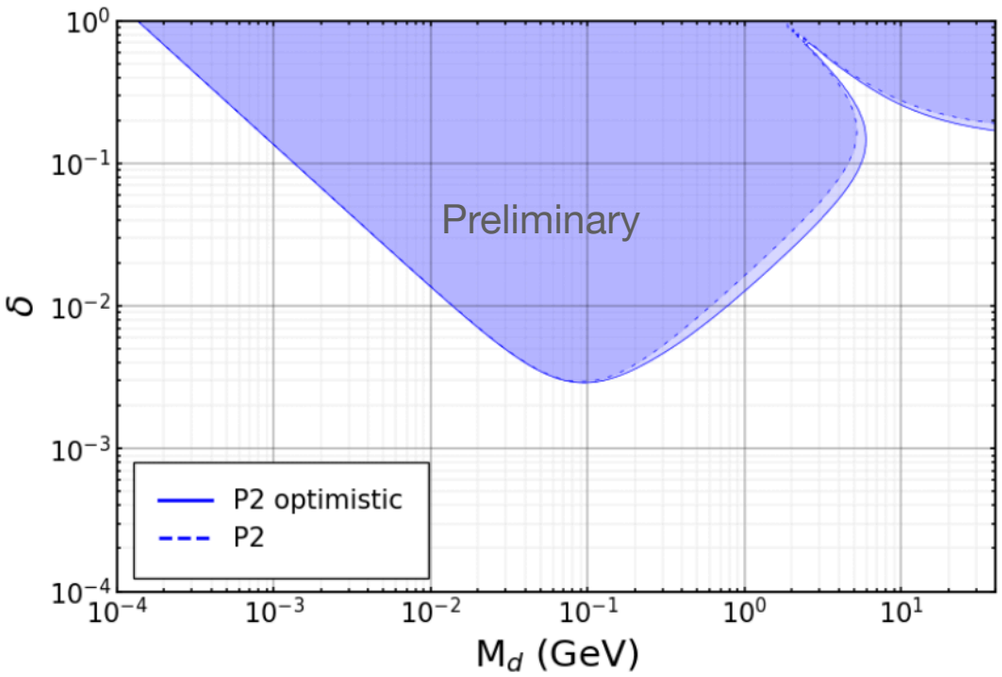


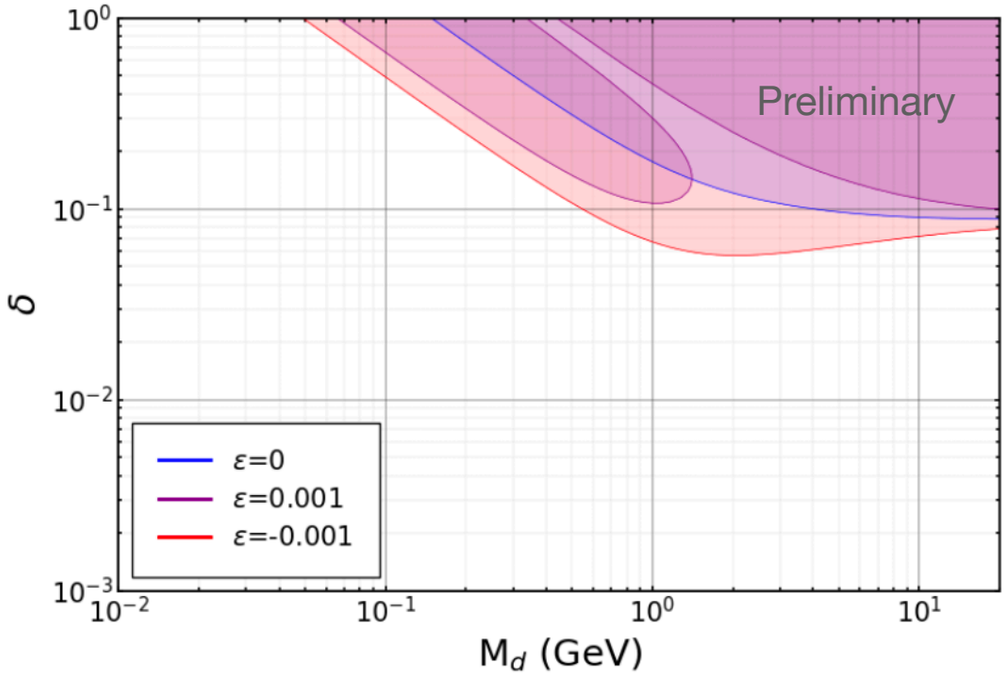


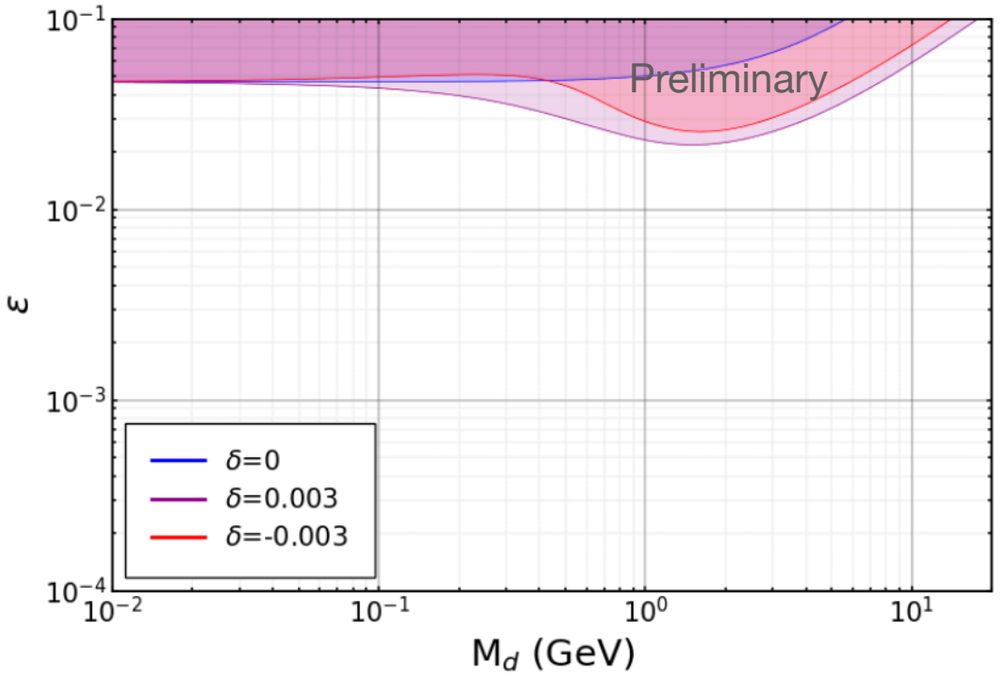
Future PV (P2 and Solid)

L.M. de la Vega, J Erler and R Ferro, EP In preparation









The SLAC E158 (PV Moller scattering)

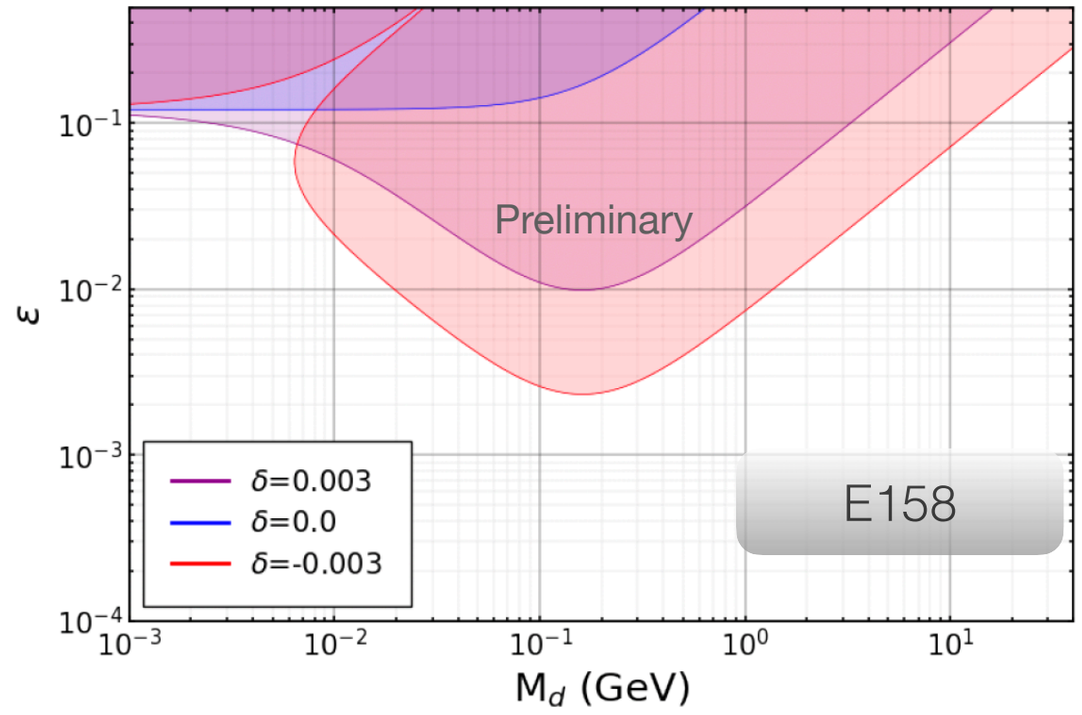
$50\ GeV$ Polarized e^- with an H target

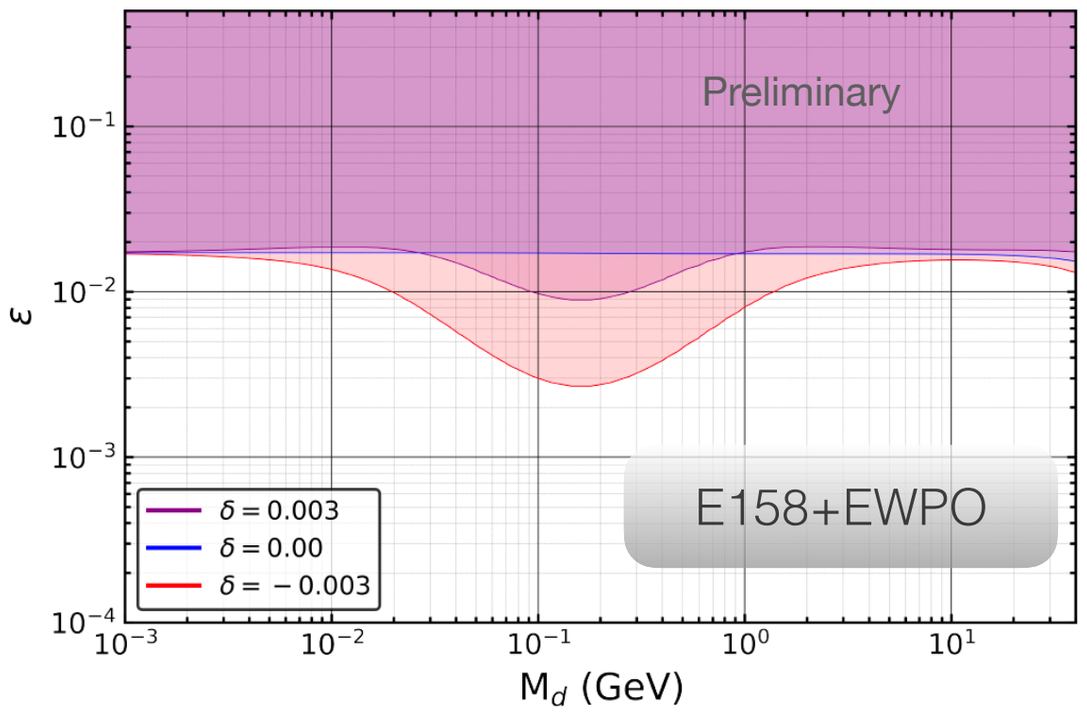
$$Q^2 = 0.026\ GeV^2$$

$$A_{PV} = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R} = -\,131 \pm 14\,(\mathrm{sys}) \pm 10\,(\mathrm{stat}) \times 10^{-9}$$

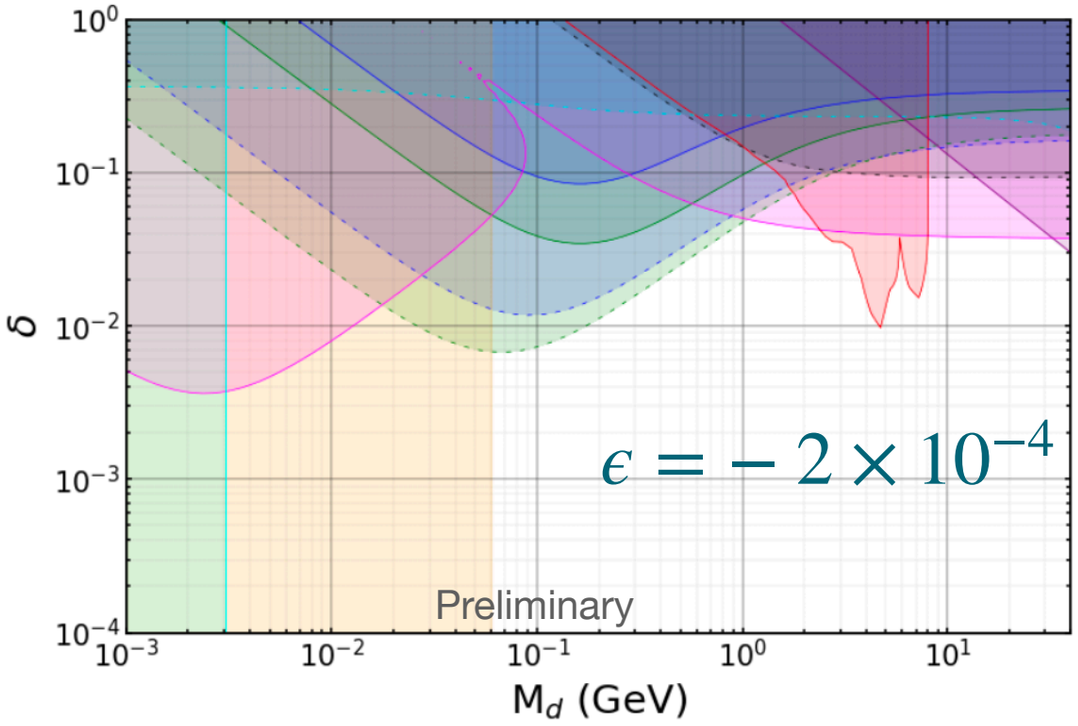
$$A_{\mathrm{PV}}^{tree} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha} \frac{1-y}{1+y^4+(1-y)^4} Q_W^e$$

$$Q_W^{e\,\mathrm{BSM}} = (1+\Delta\rho-\Delta\alpha)Q_W^{e\,(\mathrm{SM})} - 4\Delta\sin^2\theta_W$$

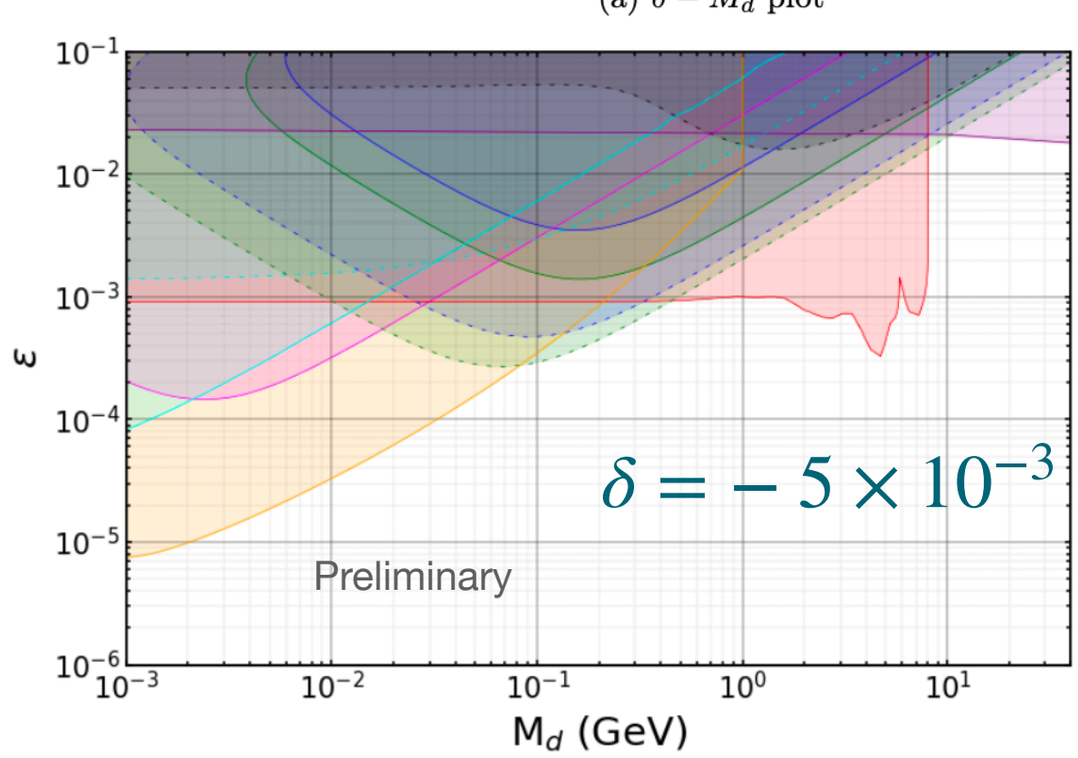




Summary



(a) $\delta - M_d$ plot



(b) $\epsilon - M_d$ plot.

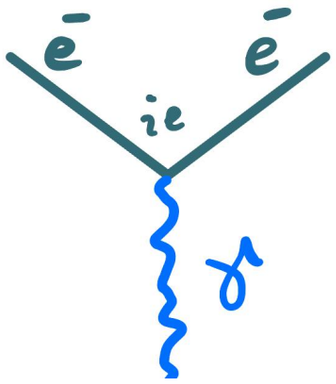
In preparation, in collaboration with L.M. de la Vega, J Erler and R Ferro

Dark QED

$$\mathscr{L}_e = \bar{\psi}_e(i\gamma^\mu \partial_\mu + e\gamma^\mu A_\mu - m_e)\psi_e - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

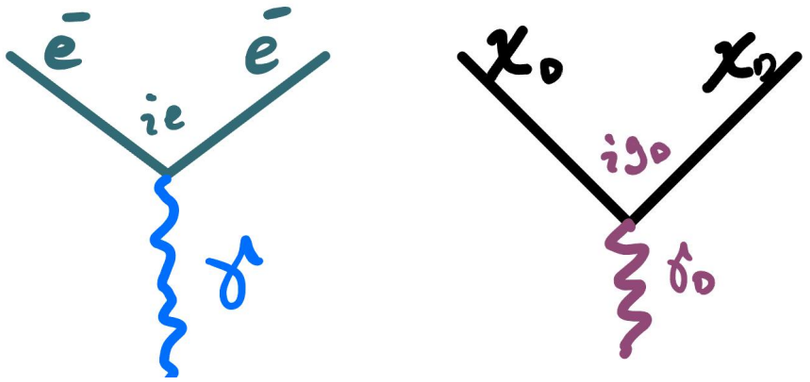
Dark QED

$$\mathscr{L}_e = \bar{\psi}_e(i\gamma^\mu \partial_\mu + e\gamma^\mu A_\mu - m_e)\psi_e - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$



Dark QED

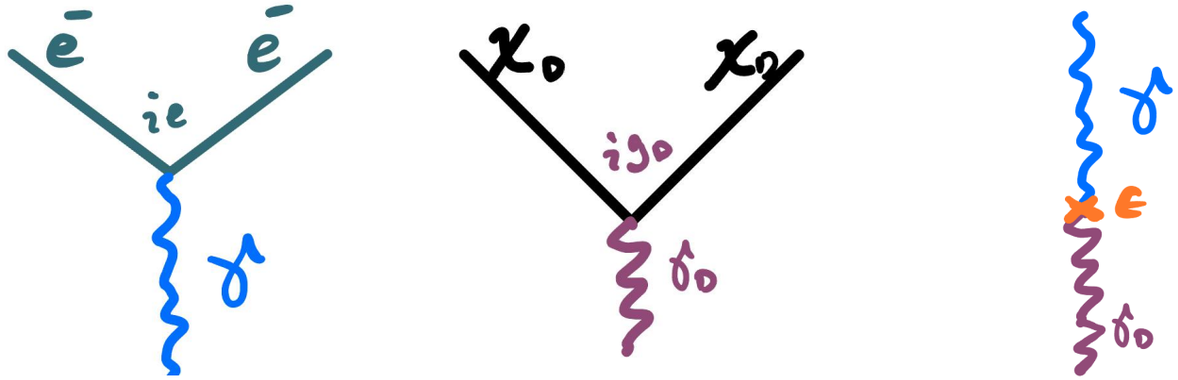
$$\mathscr{L}_e = \bar{\psi}_e(i\gamma^\mu \partial_\mu + e\gamma^\mu A_\mu - m_e)\psi_e - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$



$$\mathscr{L}_{DM} = \bar{\chi}(i\gamma^\mu \partial_\mu + e\gamma^\mu A'_\mu - m_e)\chi - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu}$$

Dark QED

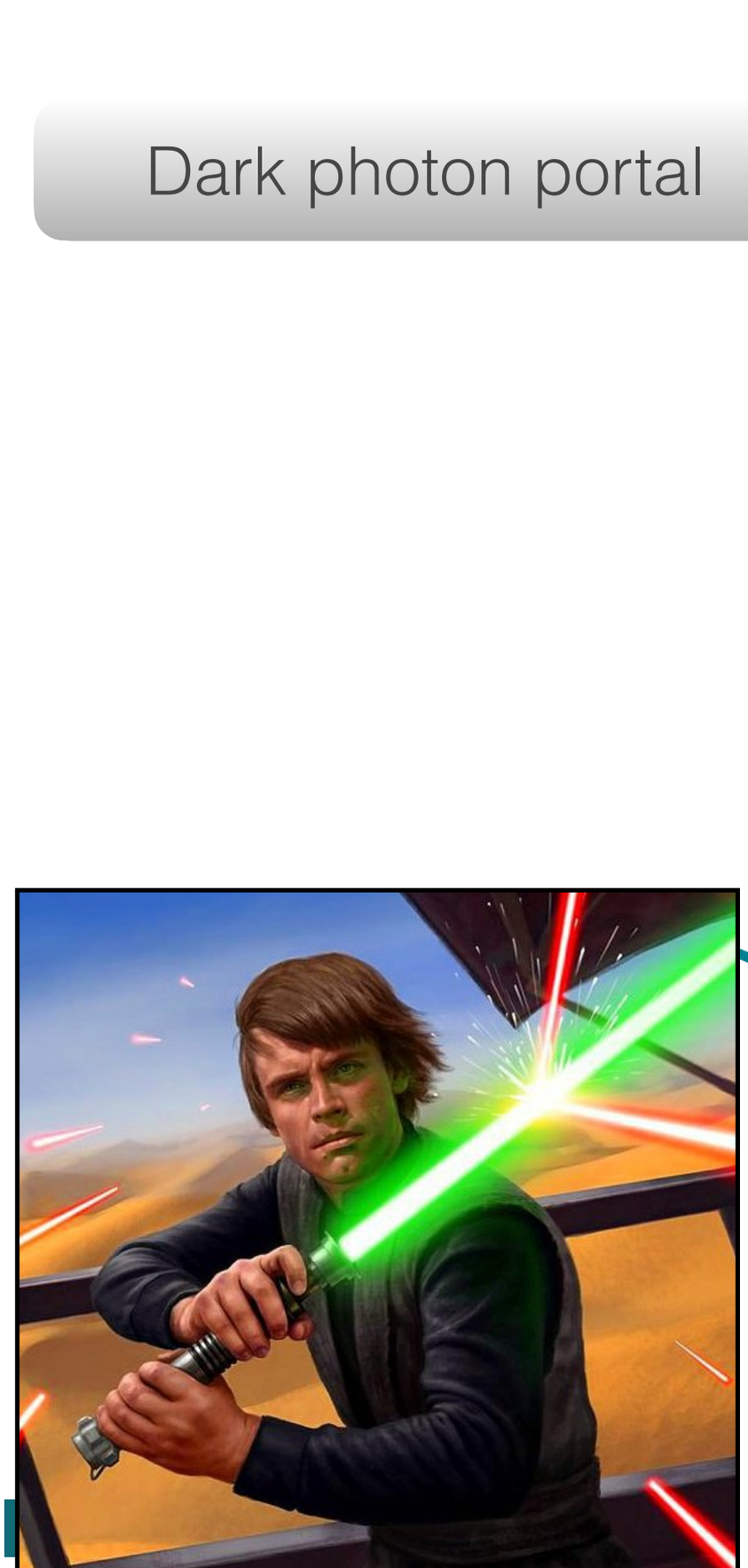
$$\mathscr{L}_e = \bar{\psi}_e(i\gamma^\mu\partial_\mu + e\gamma^\mu A_\mu - m_e)\psi_e - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

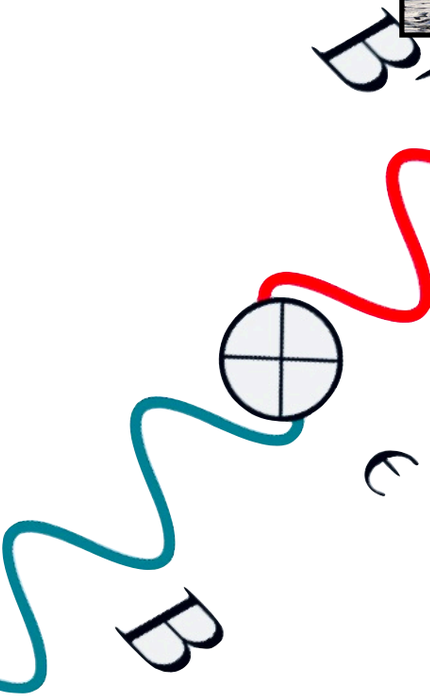


$$\mathscr{L}_{mix} = -\frac{\epsilon}{4}F^{\mu\nu}F'_{\mu\nu}$$

$$\mathscr{L}_{DM} = \bar{\chi}(i\gamma^\mu\partial_\mu + e\gamma^\mu A'_\mu - m_e)\chi - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu}$$

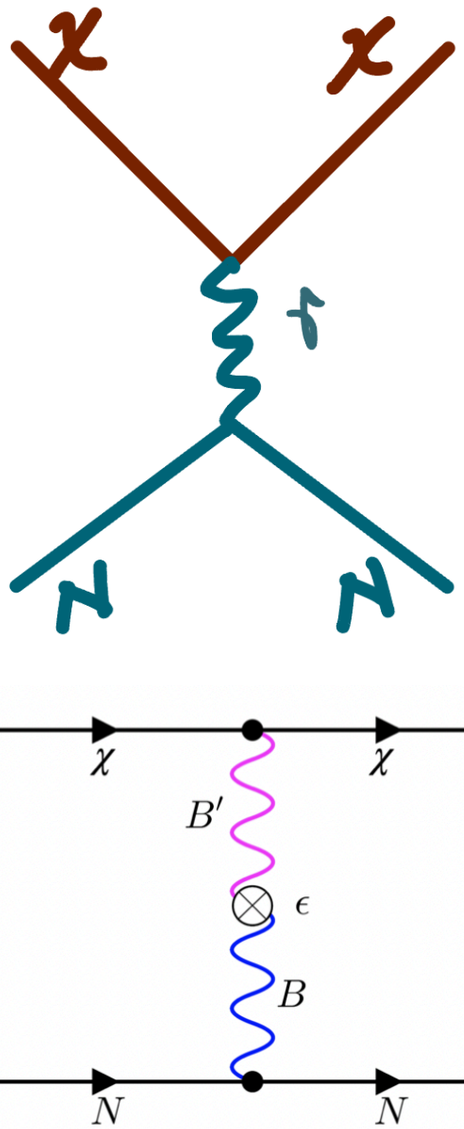
Dark photon portal





Millicharge DM constraints

$$\mathcal{L}_{\mathcal{M}} = e\epsilon_\chi A_\mu \bar{\chi}\gamma^\mu \chi$$



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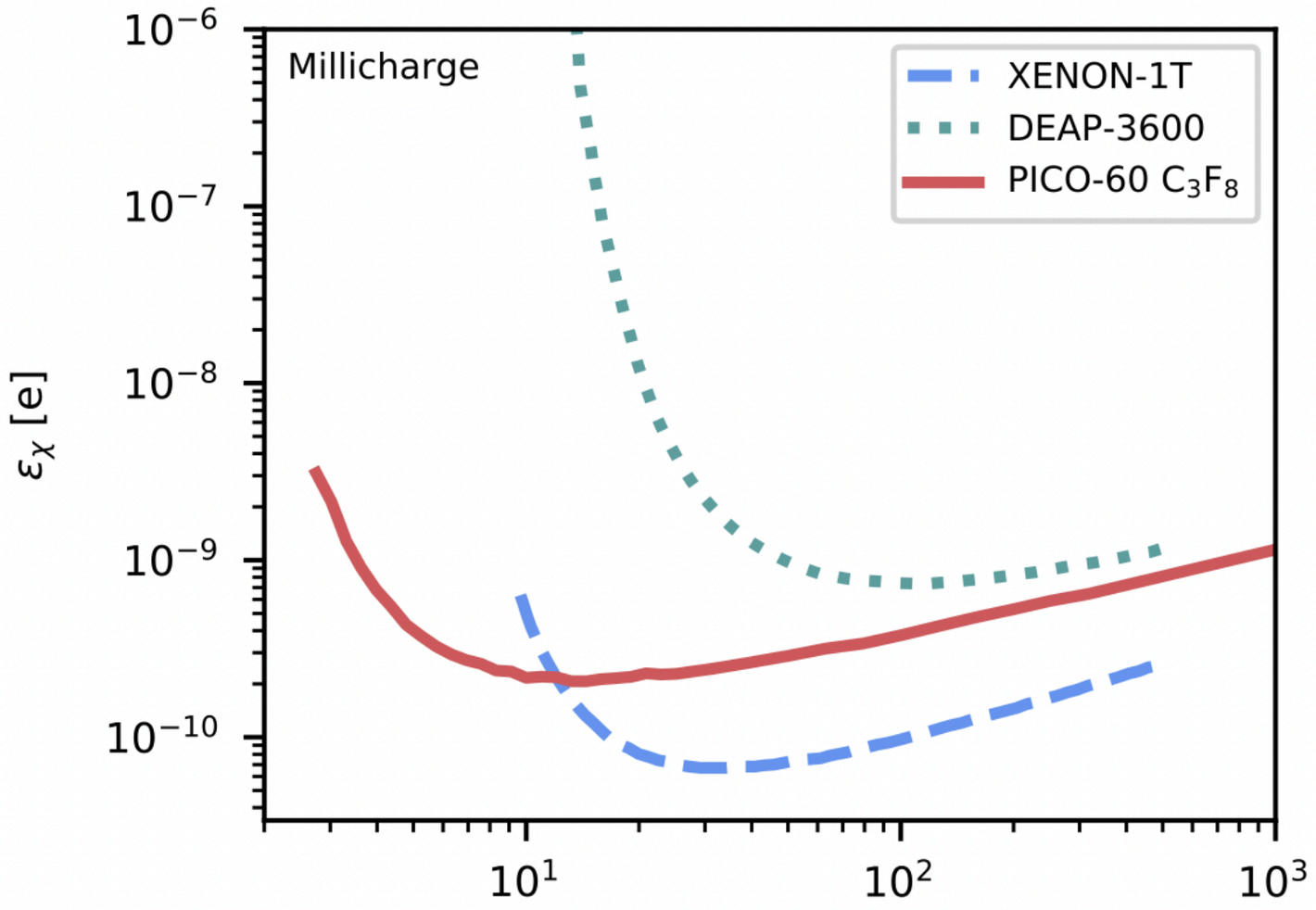
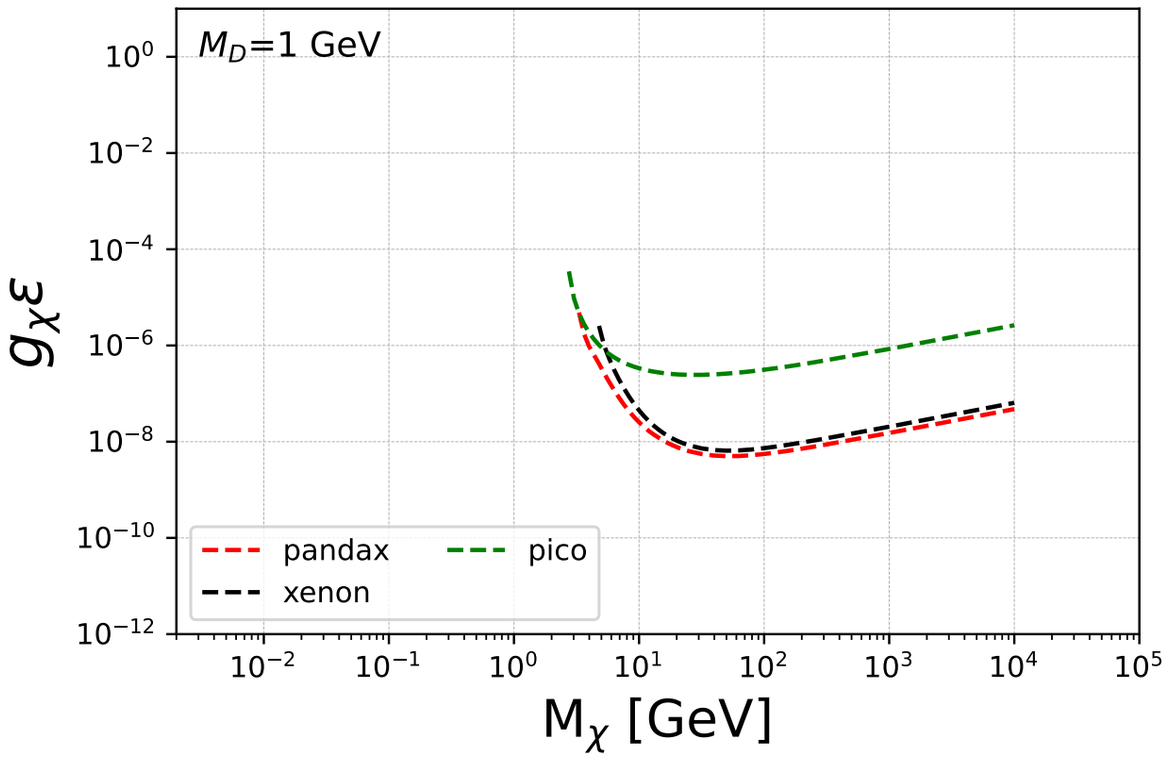
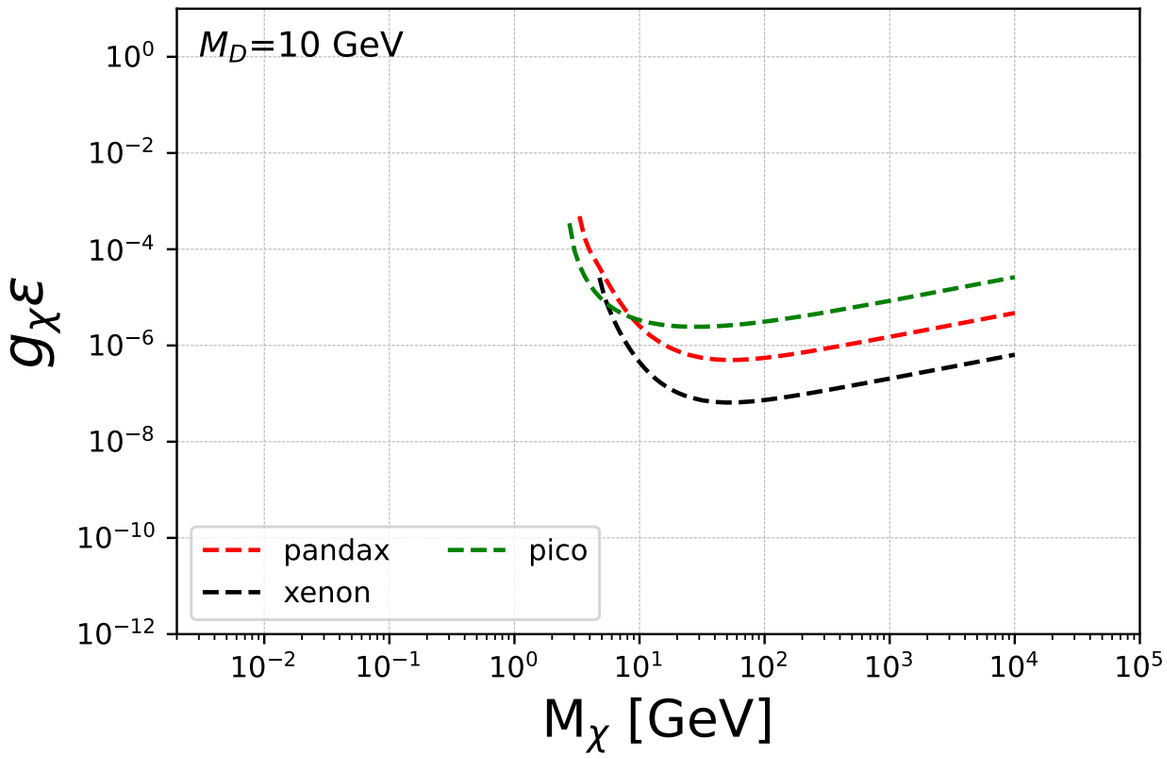
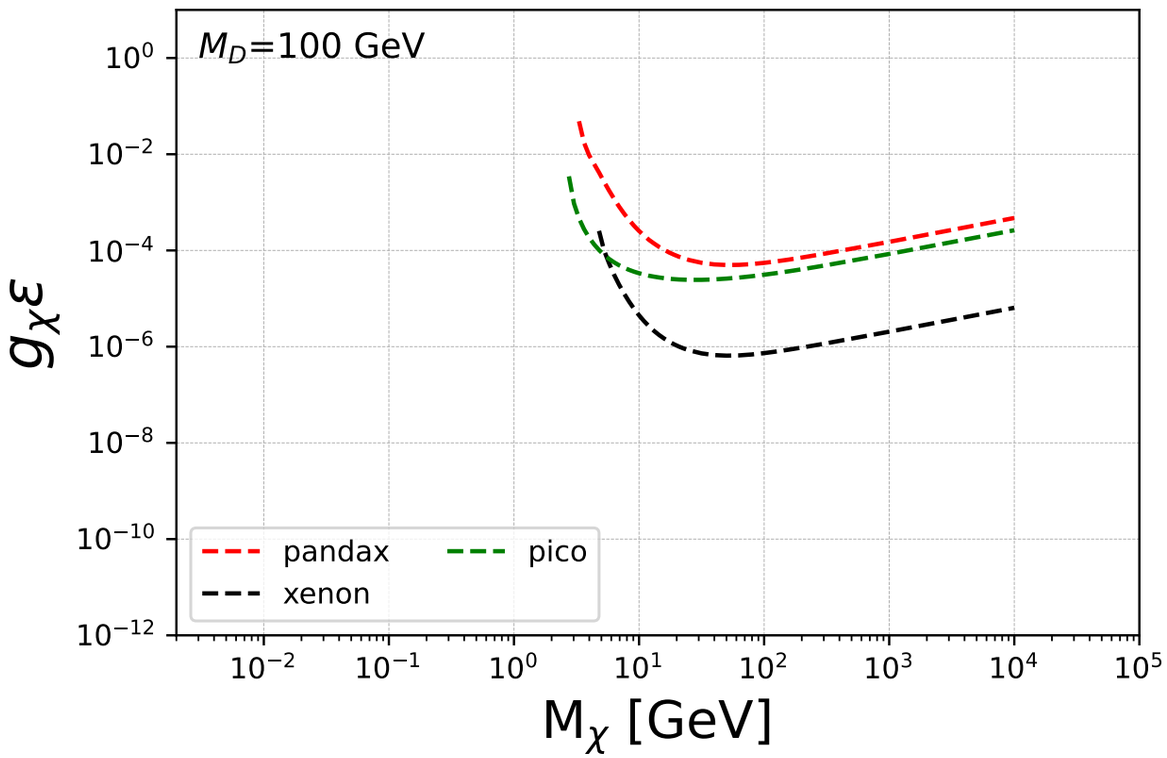
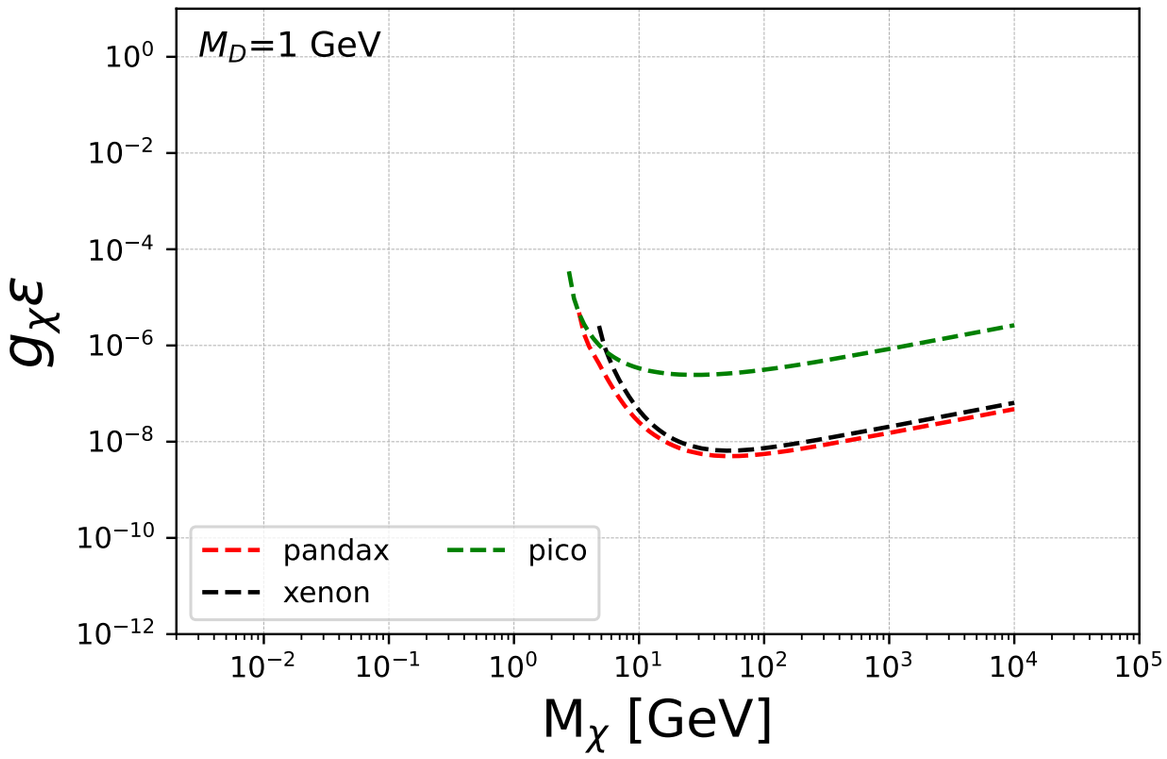


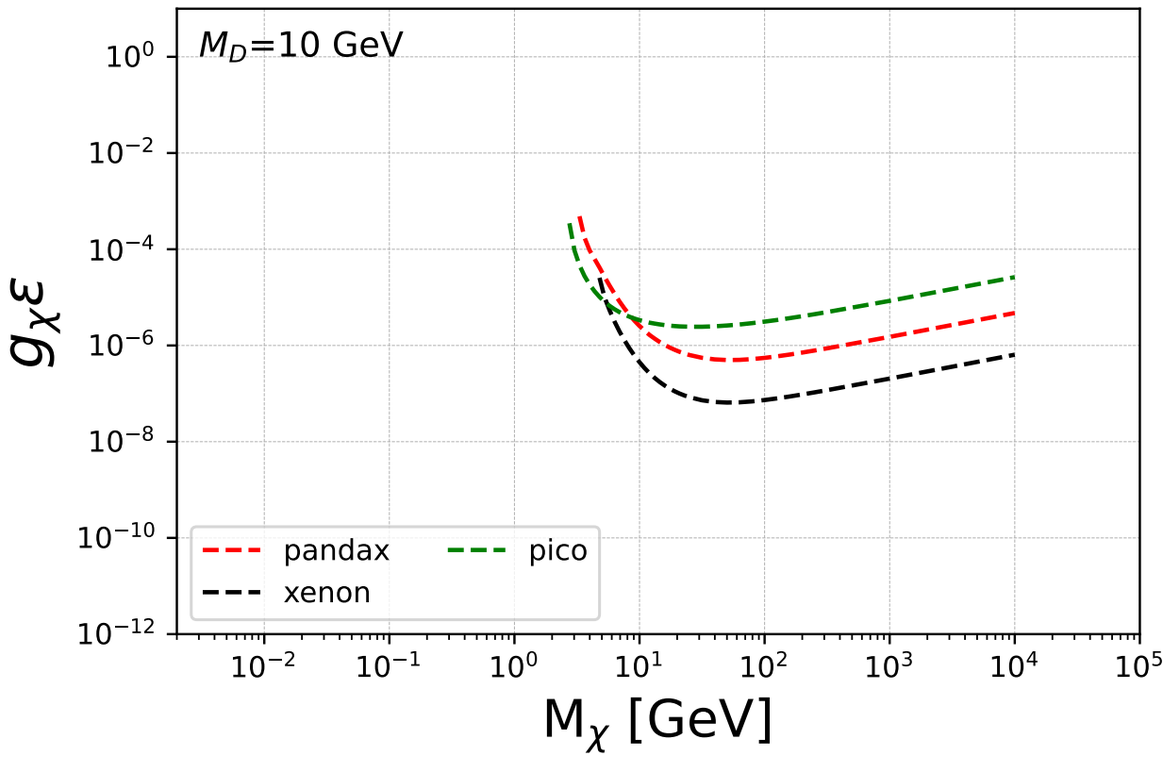


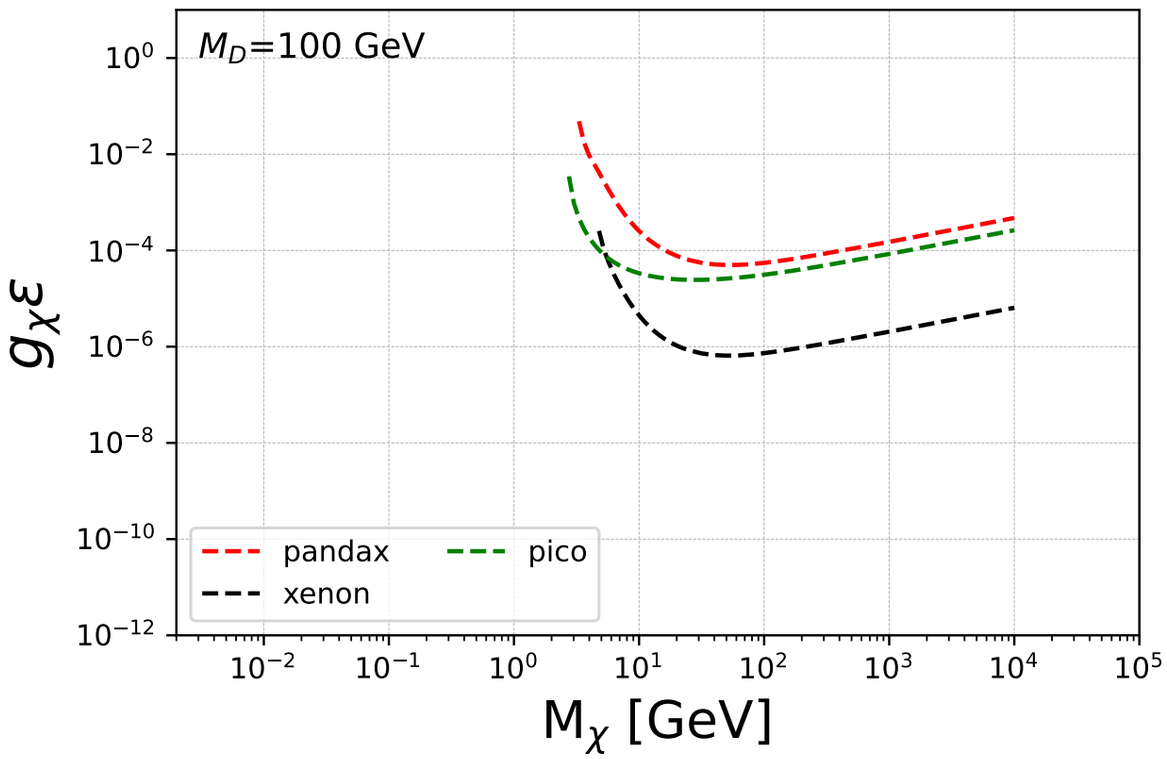


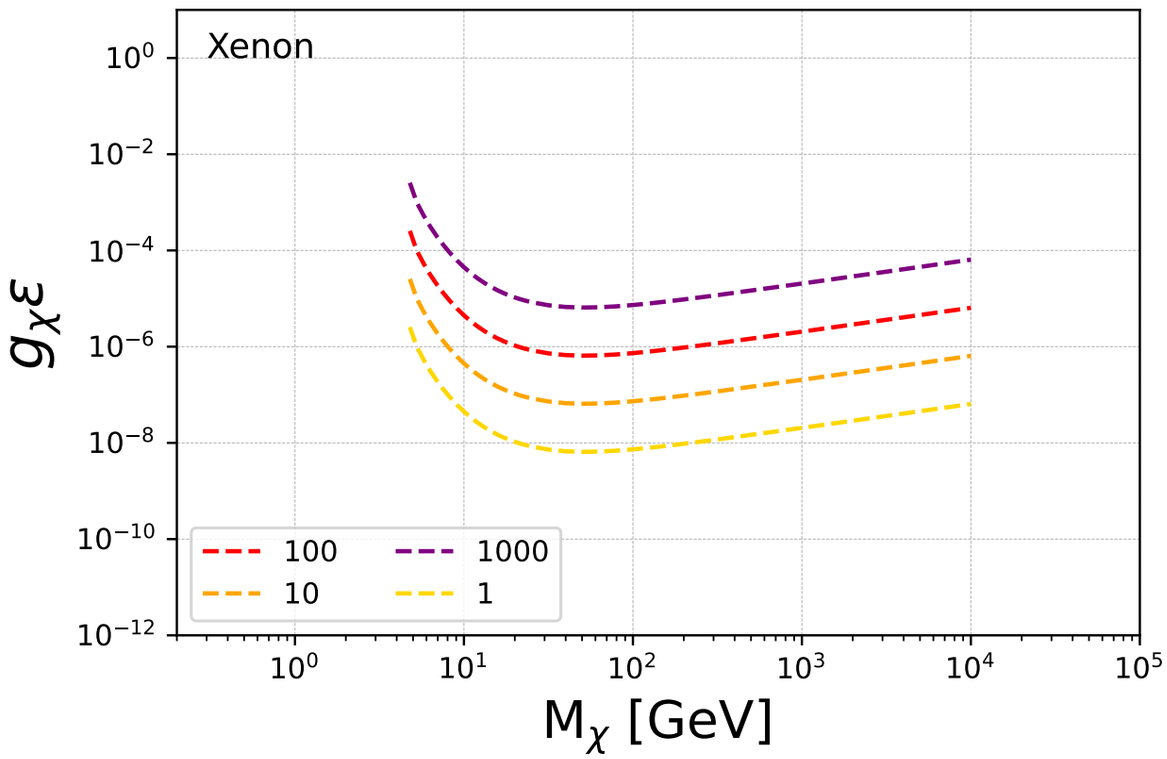


L.M. de la Vega, Garcia-Viltres, R. Ferro, Fitzpatrick, EP, E. Vazquez-Jauregui, arXiv:2311.17987









L.M. de la Vega, Garcia-Viltres, R. Ferro, Fitzpatrick, EP, E. Vazquez-Jauregui, arXiv:2311.17987

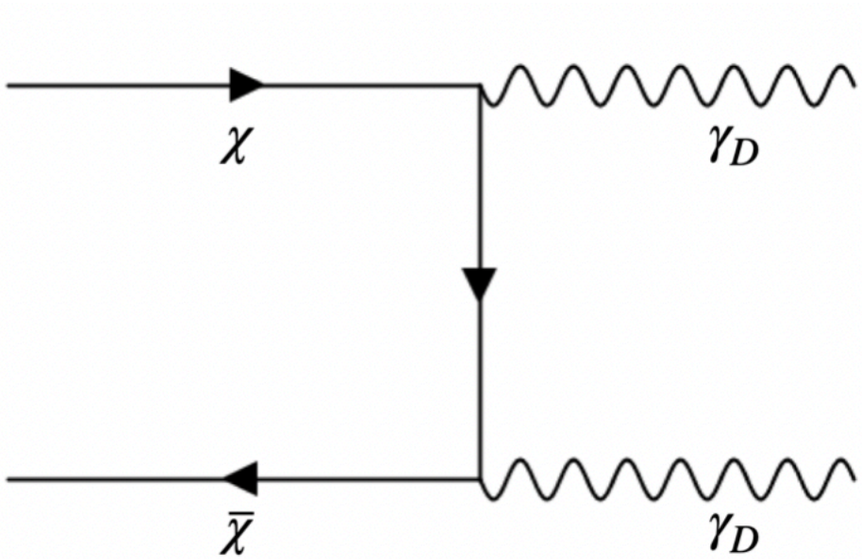
Dark photon portal DM

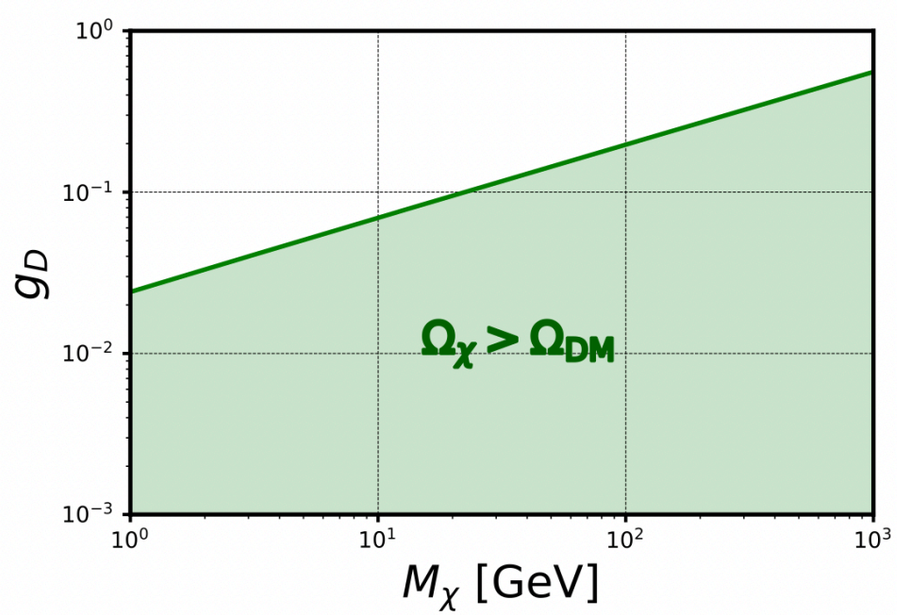
$\epsilon B^{\mu\nu} F'_{\mu\nu}$

DM

$$\mathcal{L} = -\frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} - \frac{\epsilon}{2\cos\theta_W} B'_{\mu\nu} B^{\mu\nu} + \bar{\chi}(\gamma^\mu D_\mu + M_\chi)\chi + \text{h.c.}$$

$$m_D < m_\chi$$

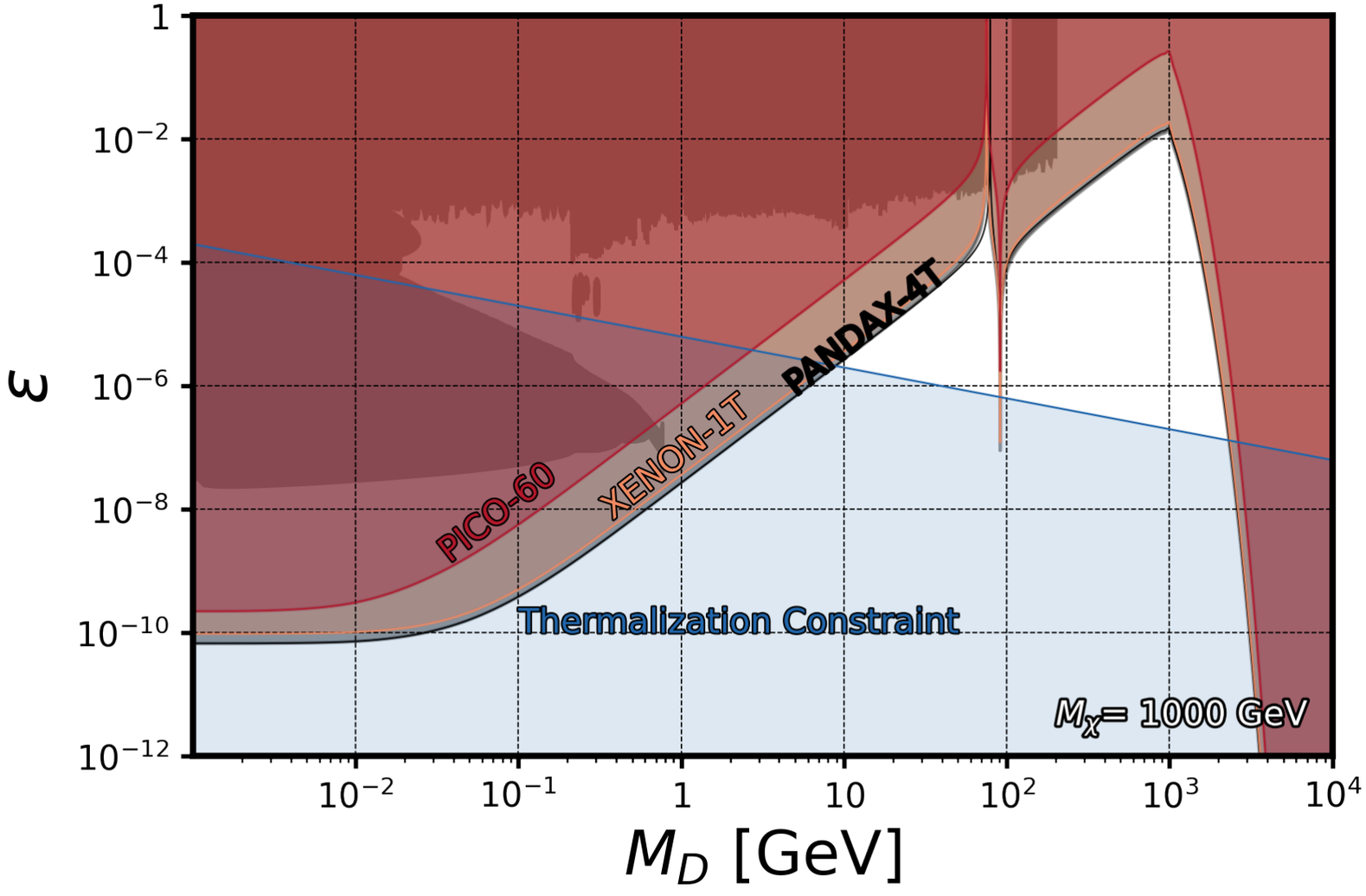


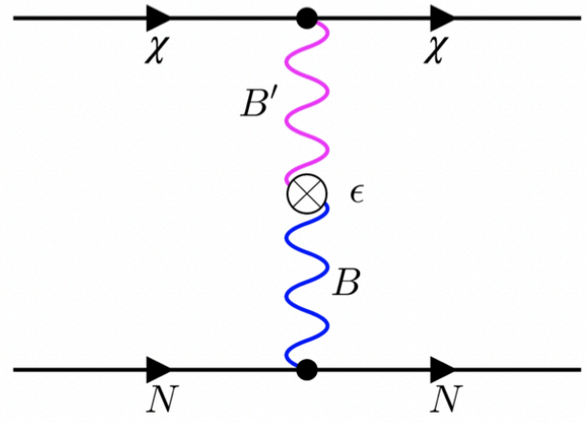


L.M. de la Vega, Garcia-Viltres, R. Ferro, Fitzpatrick, EP, E. Vazquez-Jauregui, arXiv:2311.17987

Direct detection

J. Evans, S. Gori, and J. Shelton (2017)



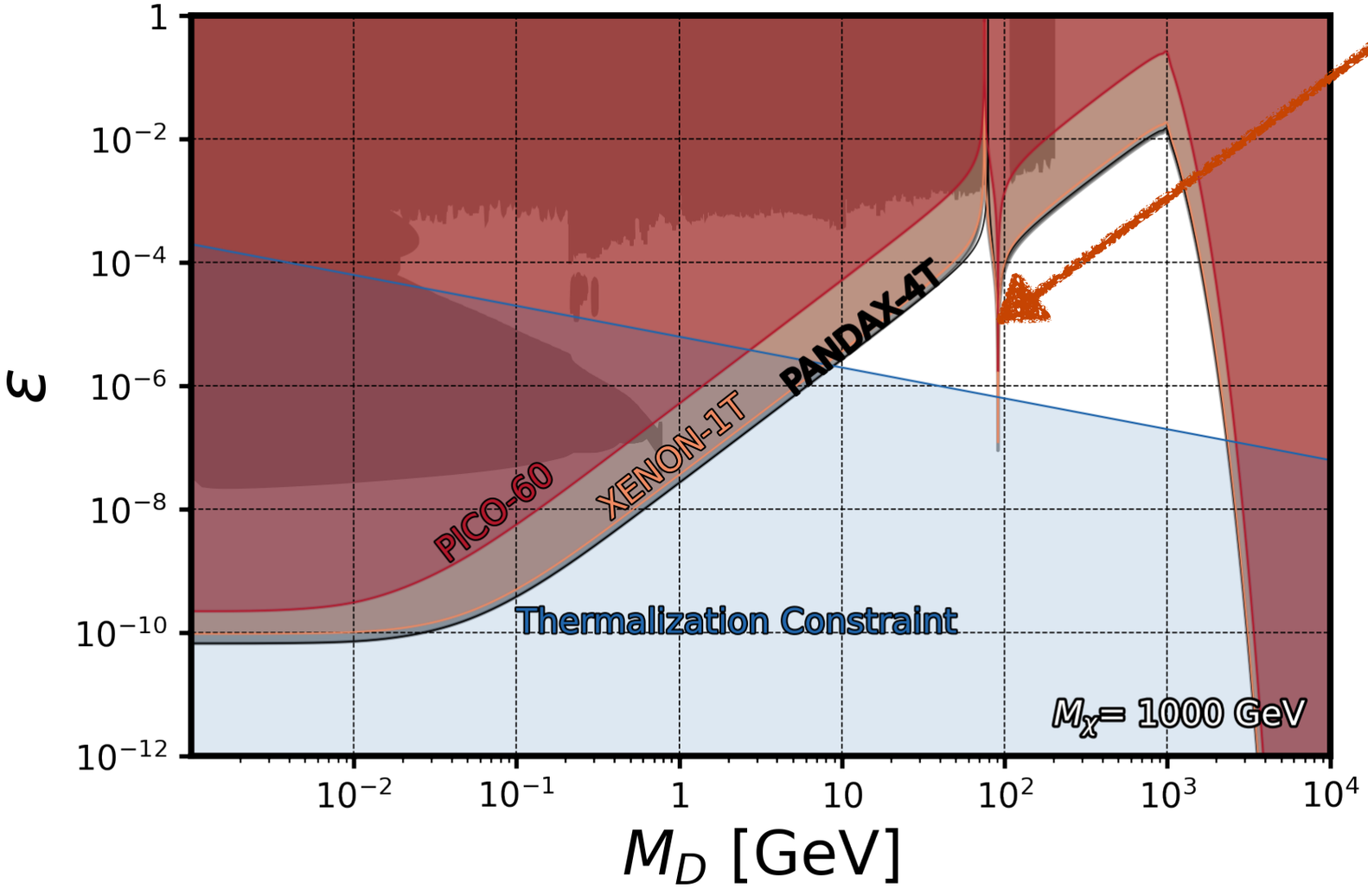


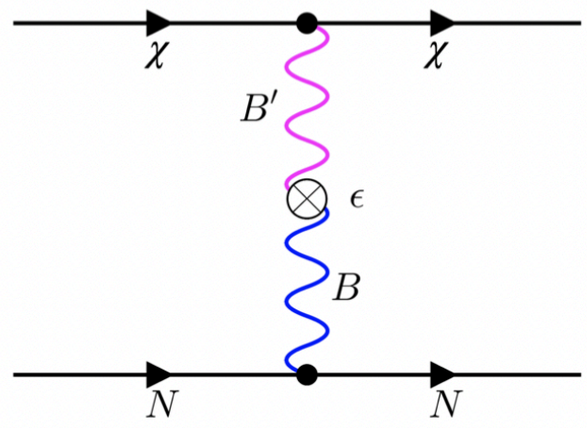
L.M. de la Vega, Garcia-Viltres, R. Ferro, Fitzpatrick, EP, E. Vazquez-Jauregui, arXiv:2311.17987

Direct detection

$$g_V^f = e\epsilon \left[Q_f + \frac{1}{2c^2} \frac{M_D^2}{M_Z^2 - M_D^2} \left(t_3^f - 2s^2 Q_f \right) \right]$$

J. Evans, S. Gori, and J. Shelton (2017)





L.M. de la Vega, Garcia-Viltres, R. Ferro, Fitzpatrick, EP, E. Vazquez-Jauregui, arXiv:2311.17987

Direct detection

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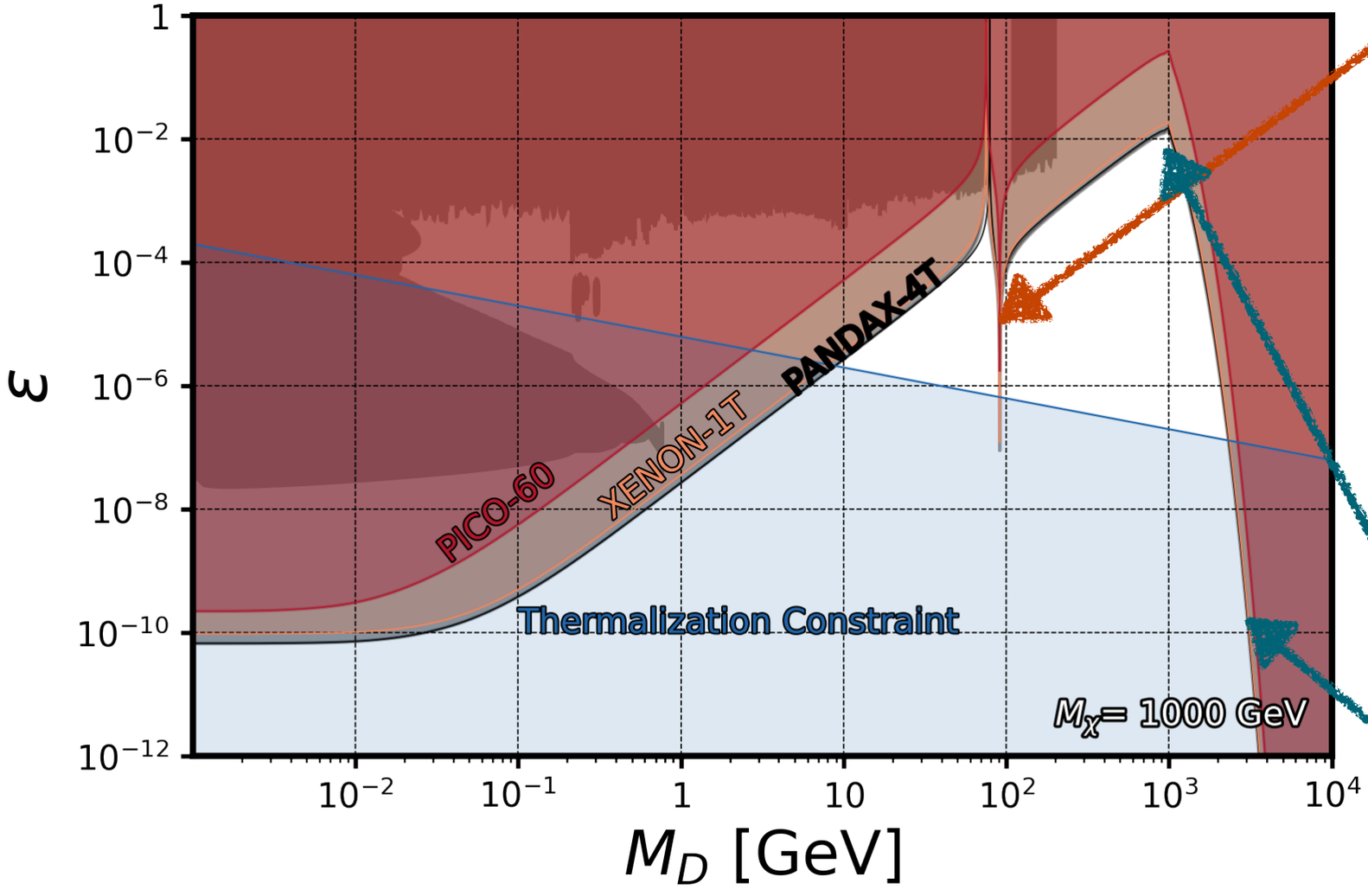
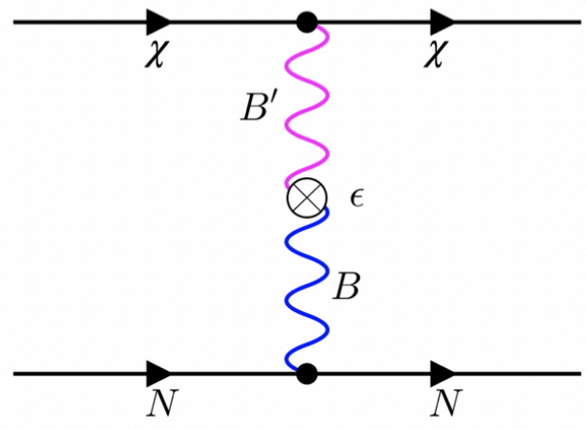
J. Evans, S. Gori, and J. Shelton (2017)



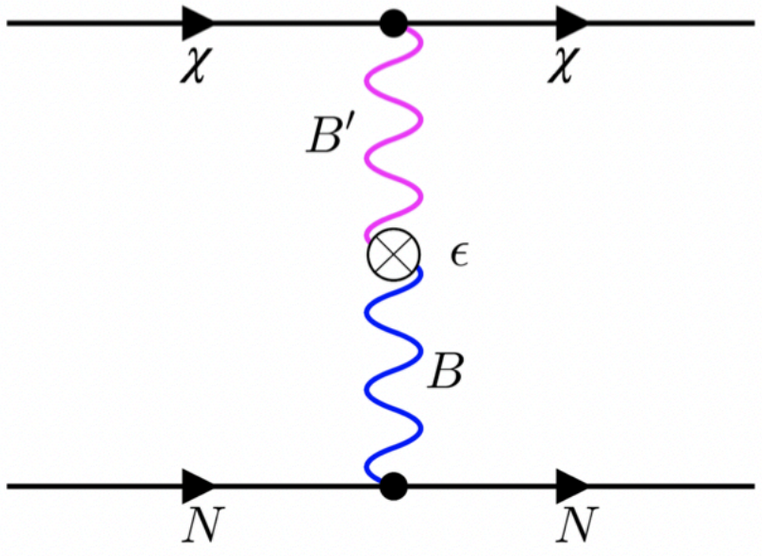


Non-perturvative

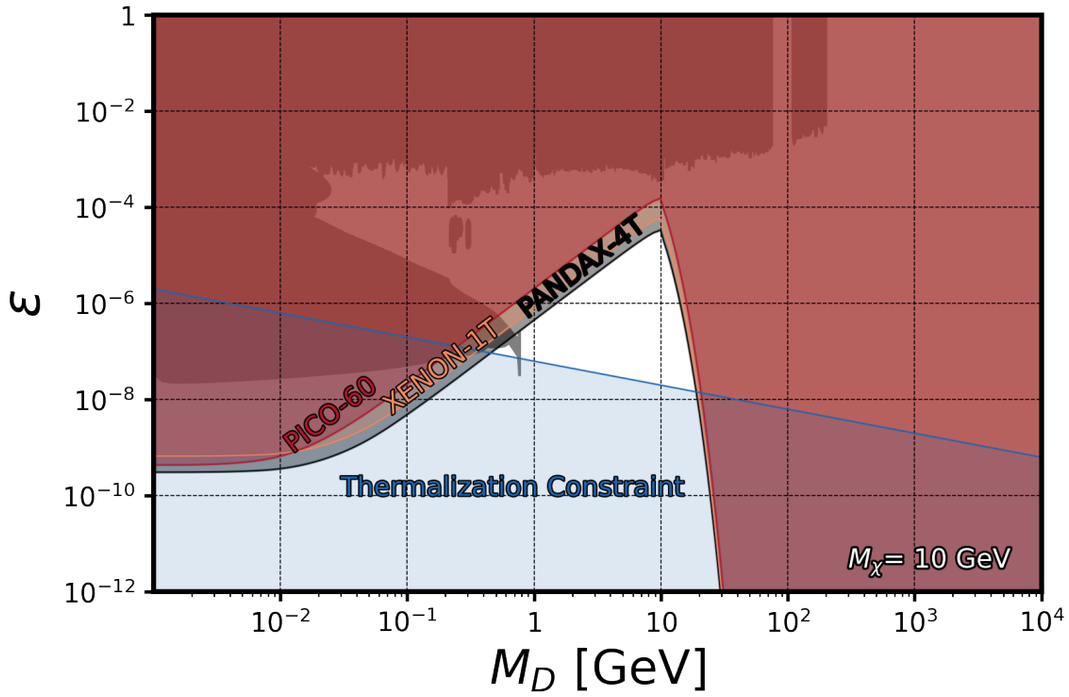
$M_D > m_\chi$

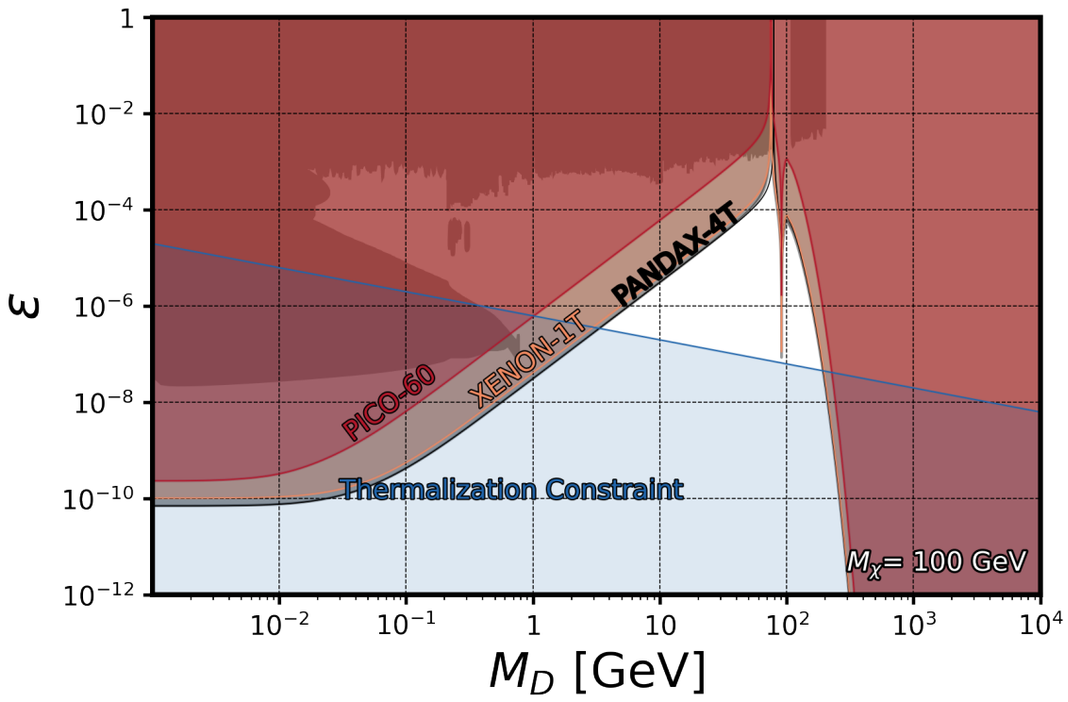
L.M. de la Vega, Garcia-Viltres, R. Ferro, Fitzpatrick, EP, E. Vazquez-Jauregui, arXiv:2311.17987

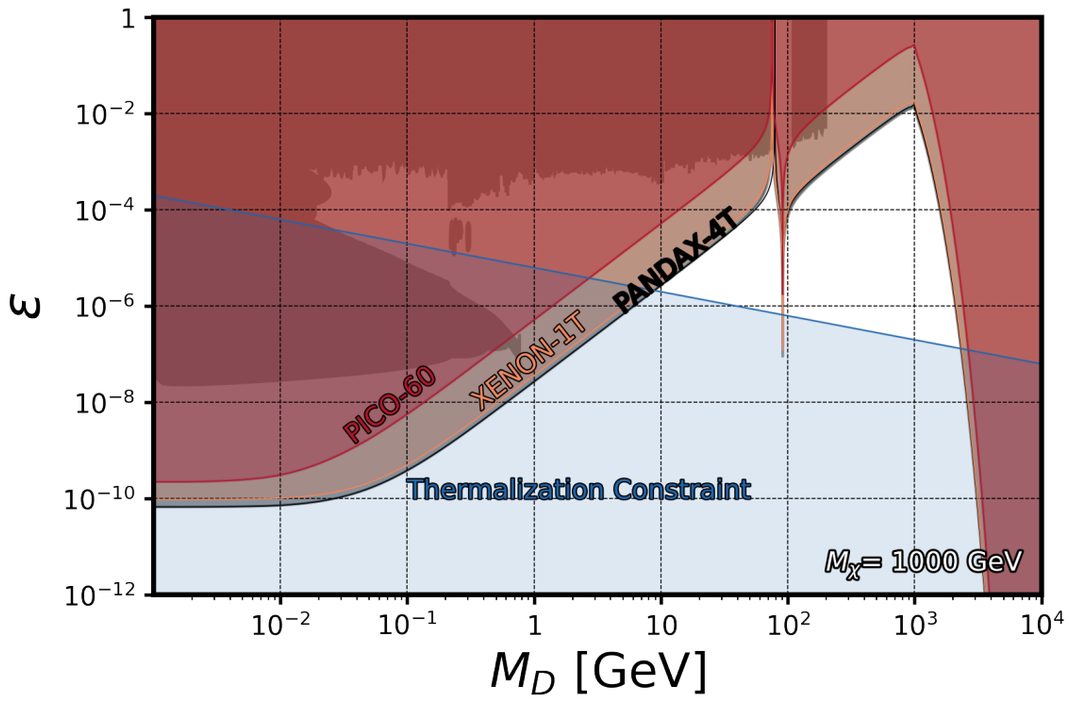
Direct detection



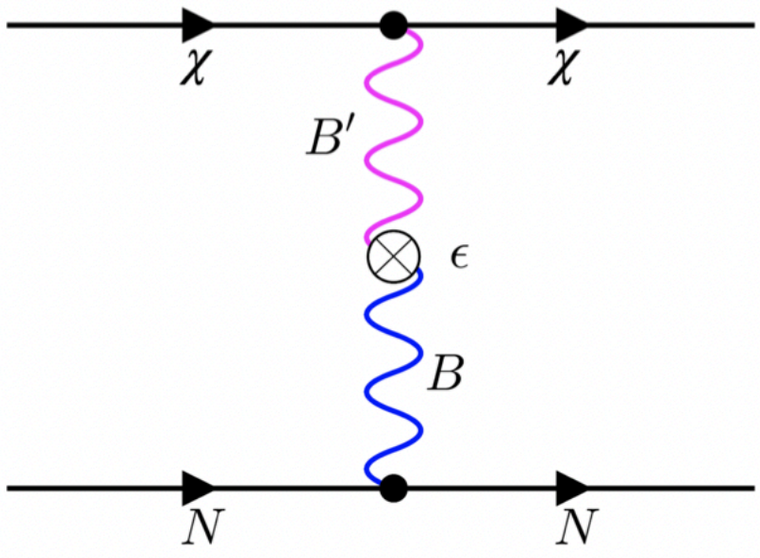
100% DM



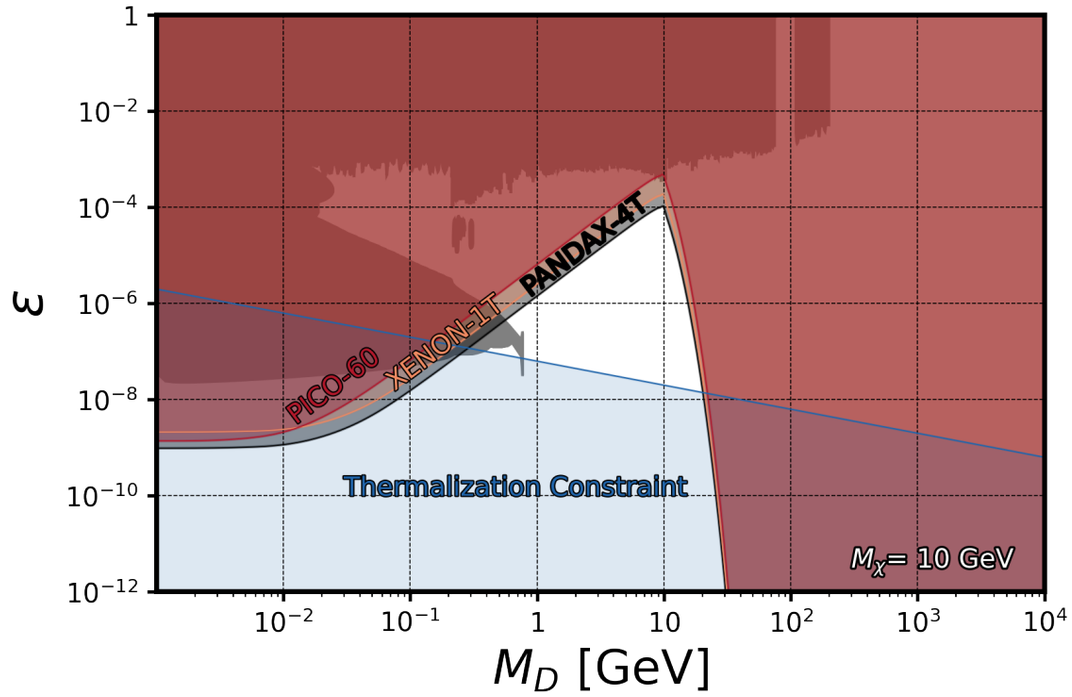


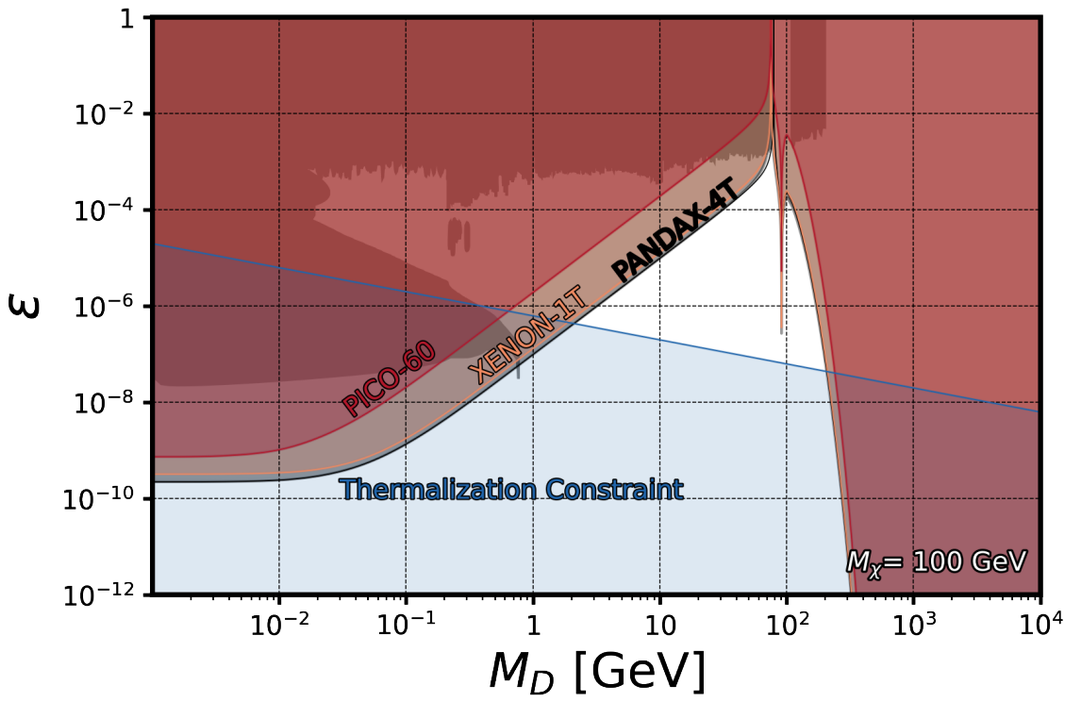


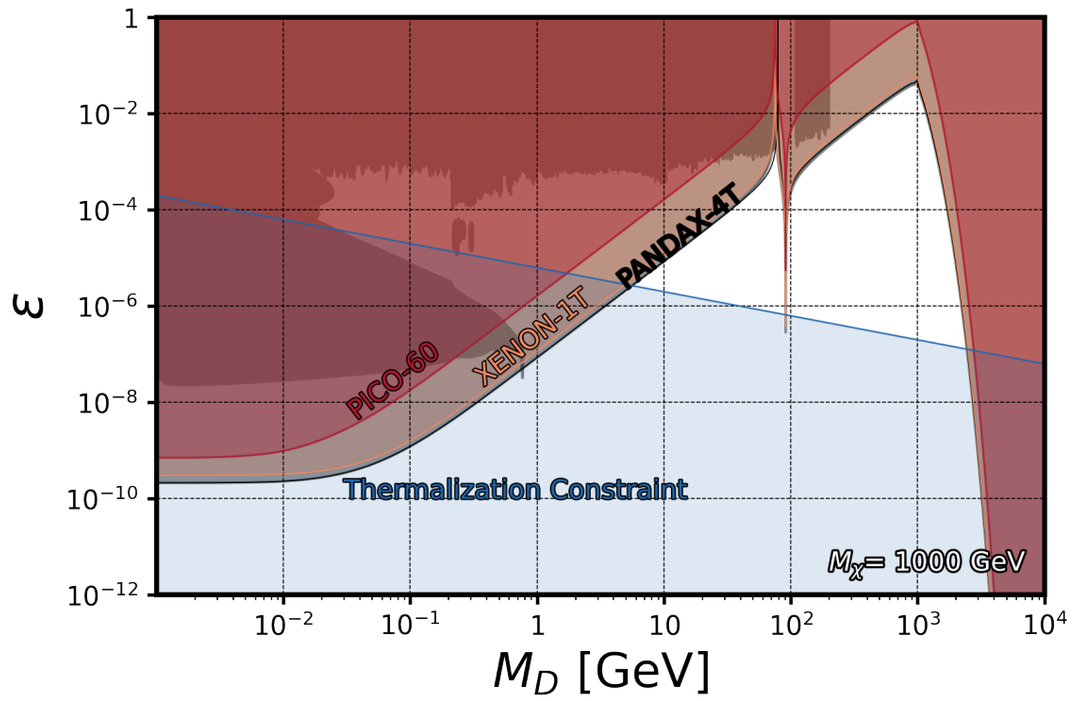
Direct detection



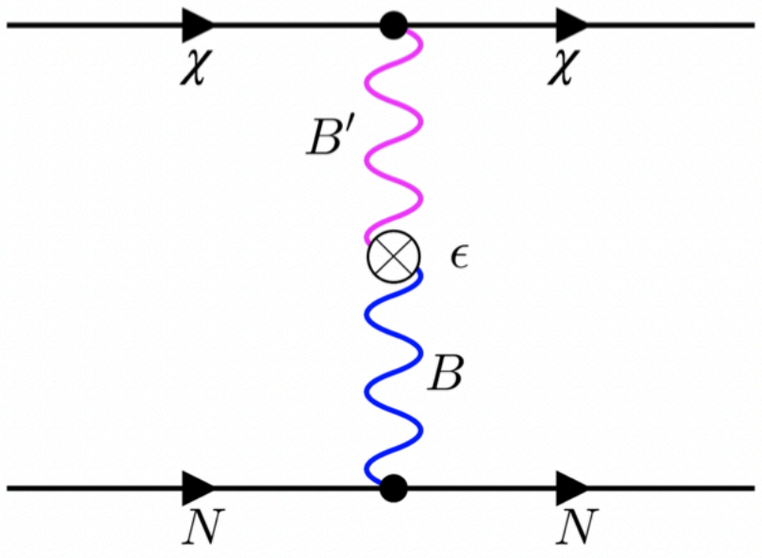
1% DM

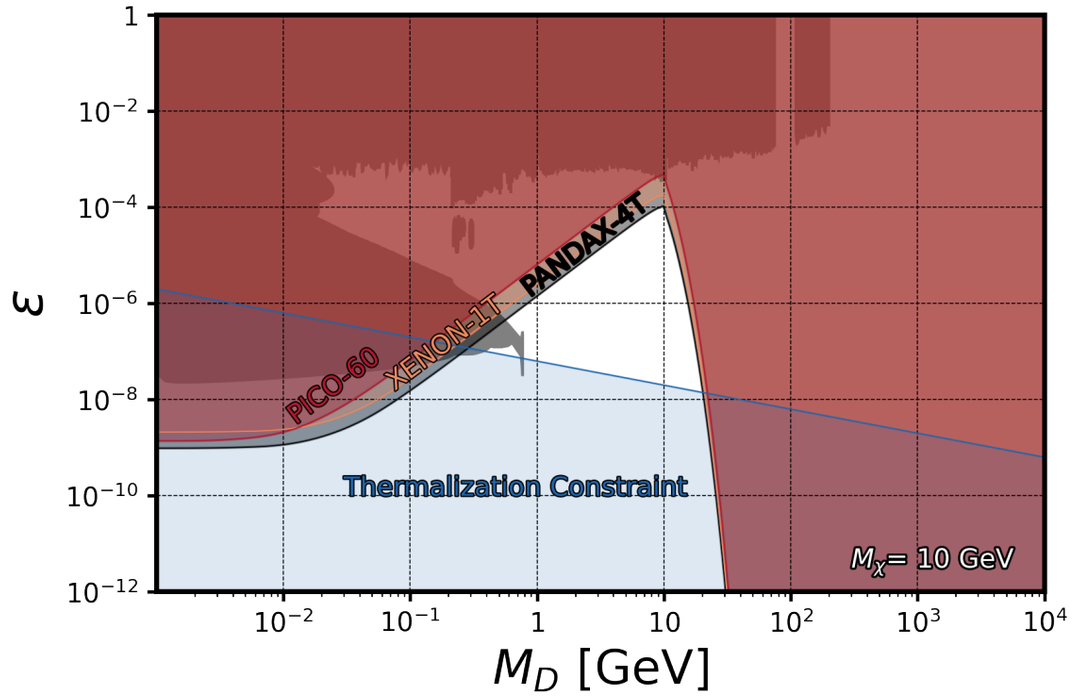


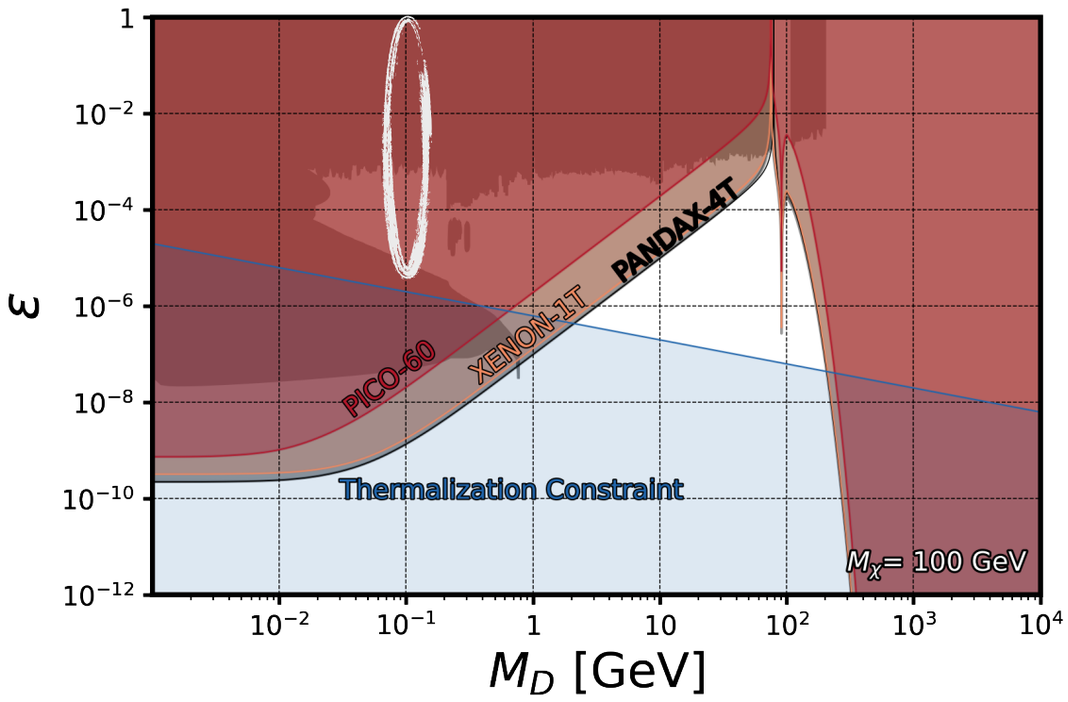


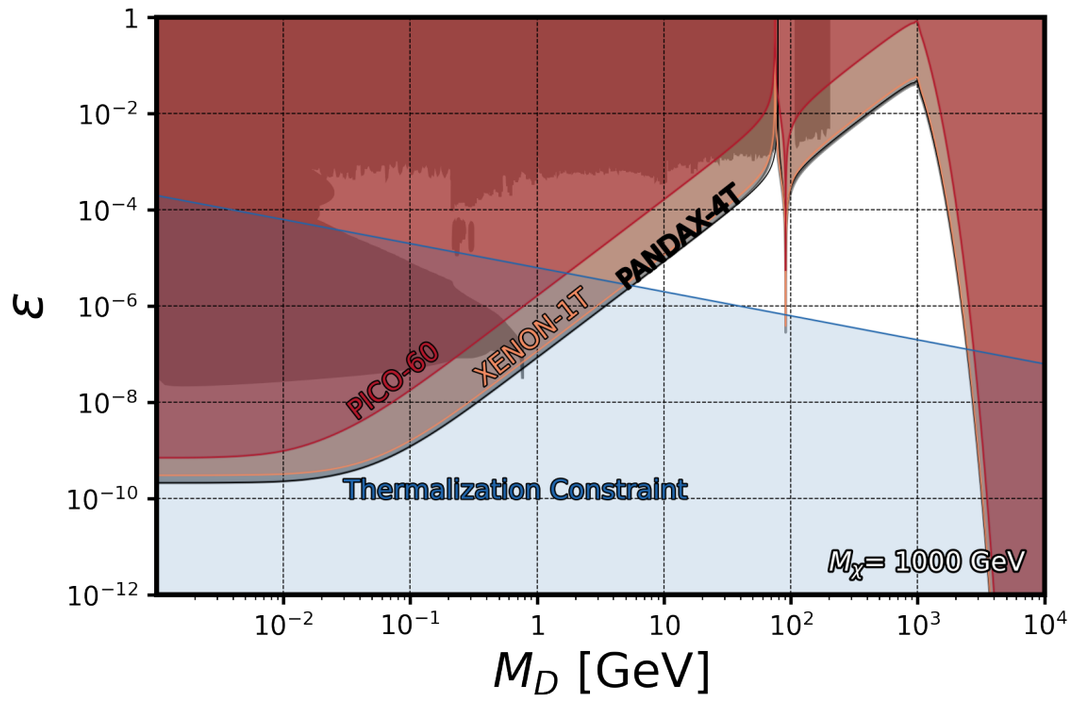


Direct detection









Conclusions

- Light gauge bosons can play a role in low-energy experiments
- Complementarity between DM direct searches and low-energy experiments
- If dark photon or dark Z is a portal to DM, the dark sector further constrains the parameter space

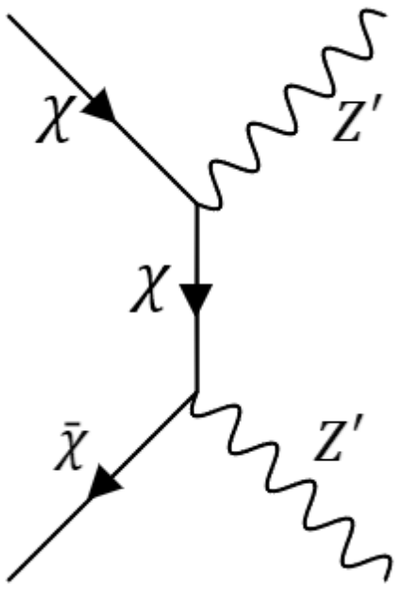
!Gracias¡

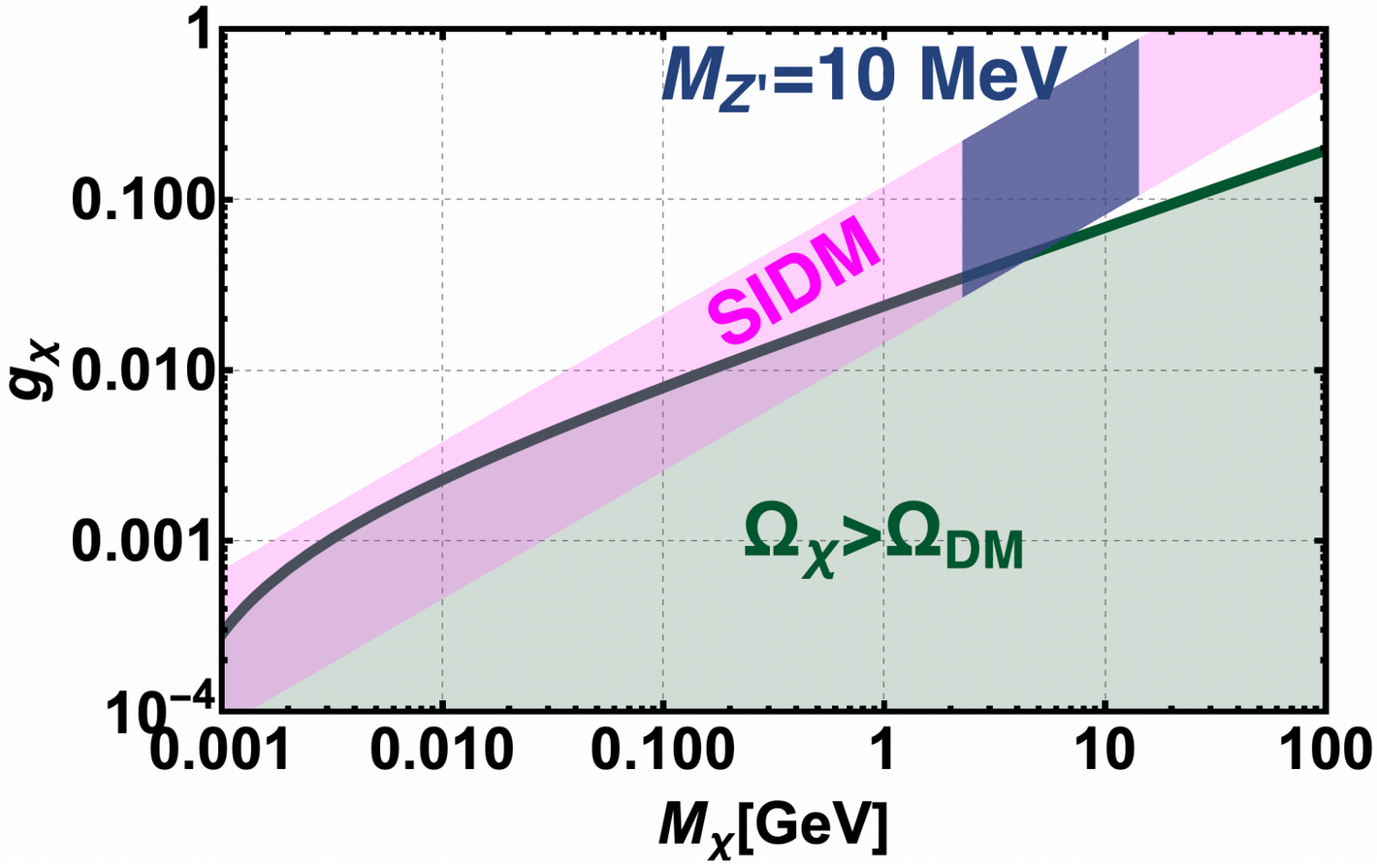
χάρης

Dark Z portal DM

	L	N	N'	F	H_1	H_2	ϕ	χ_L	χ_R^c
$SU(2)_L$	2	1	1	1	2	2	1	1	1
$U(1)_Y$	$-1/2$	0	0	0	$1/2$	$1/2$	0	0	0
$U(1)_D$	0	1	-1	0	0	1	-1	Q_D	$-Q_D$

$$\mathcal{L}_\nu = Y_1^\nu \overline{L}\tilde{H}_1 F + Y_2^\nu \overline{L}\tilde{H}_2 N + M_1 \overline{N^c} N' + Y^N \overline{N^c} F\phi + Y^{N'} \overline{N'^C} F\phi^* + M_F \overline{F^C} F + h.c.$$





L.M. de la Vega, EP and Wudka, PRD (2022)

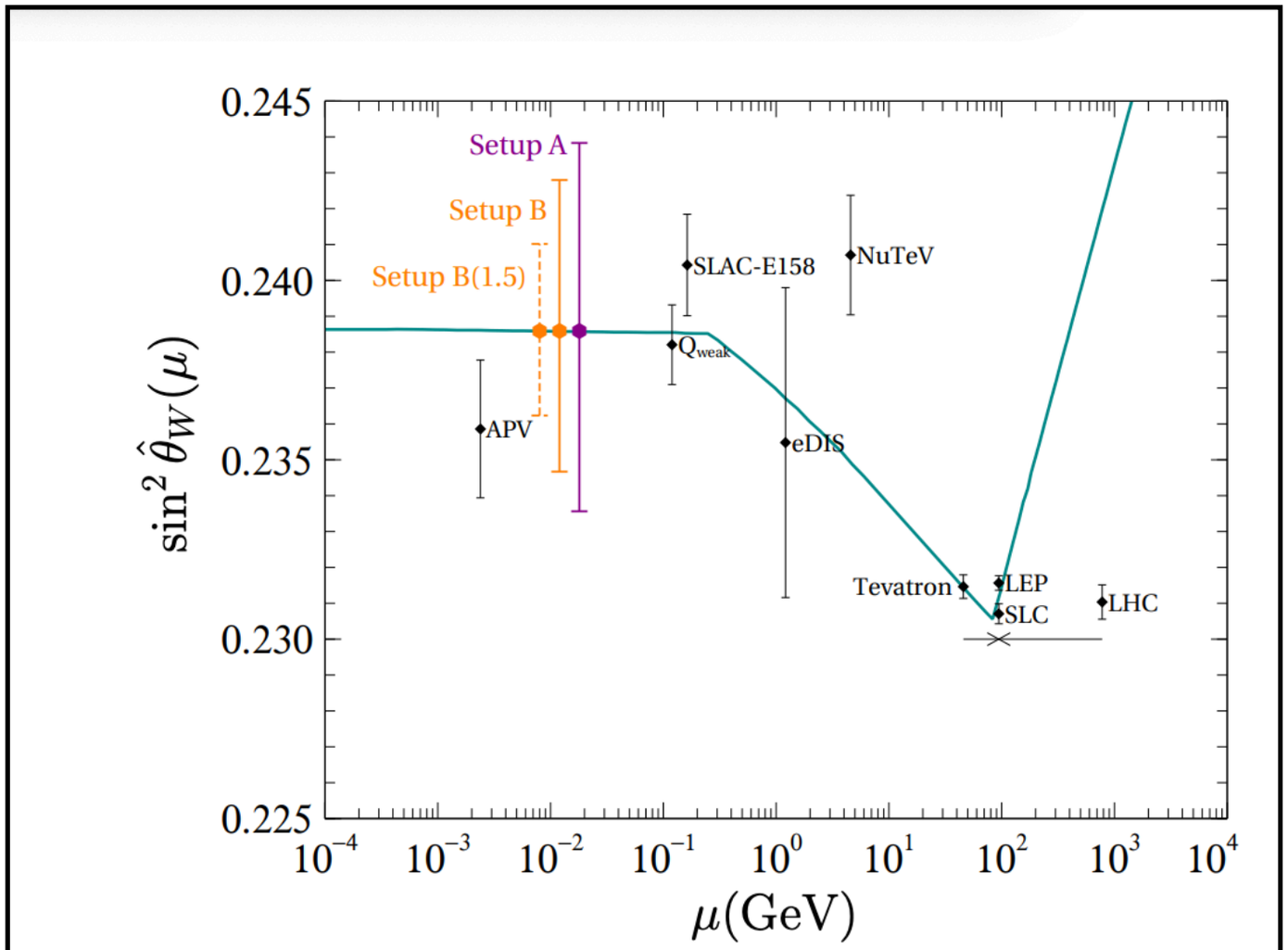
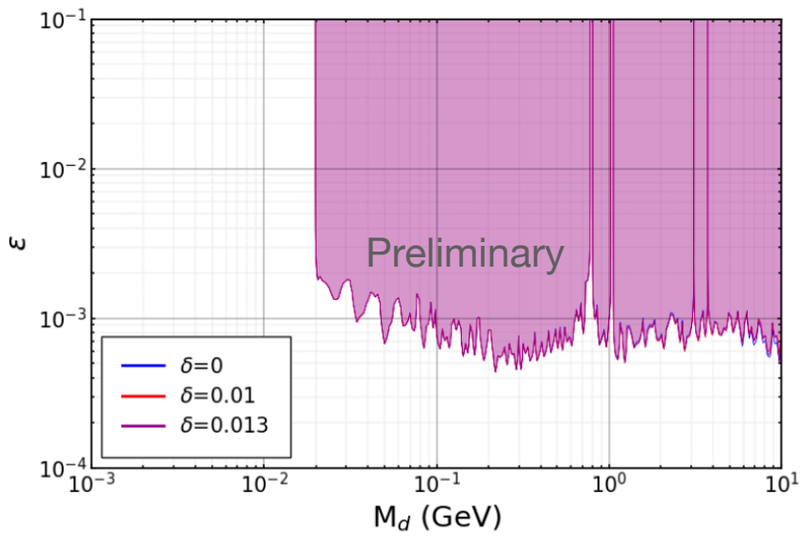


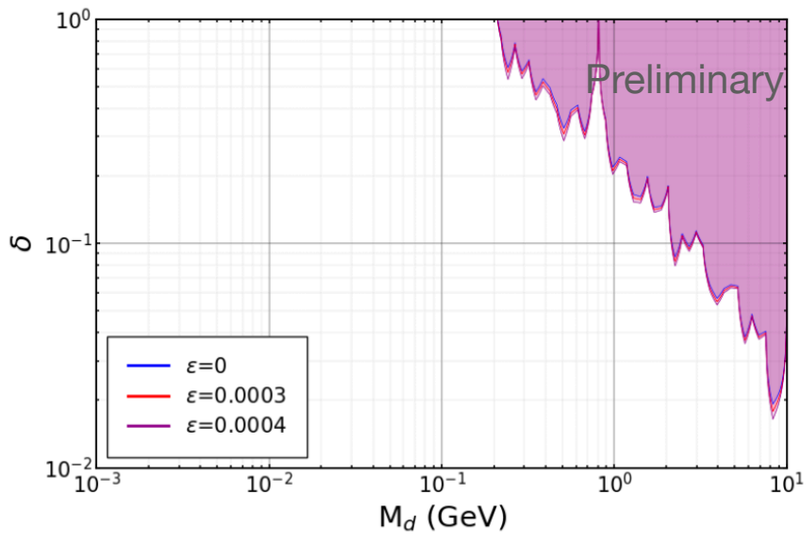
FIG. 1: RGE running of the weak mixing angle in the $\overline{\text{MS}}$ renormalization scheme [39, 40], as a function of the energy scale μ. The expected measurements and 1σ uncertainties for setups A, B and B(1.5) are shown in solid purple, solid orange, and dashed orange, respectively. Measurements from other experiments are also presented. Figure adapted from [39].

BABAR $e^+e^- \to \gamma(Z' \to e^+e^-)$

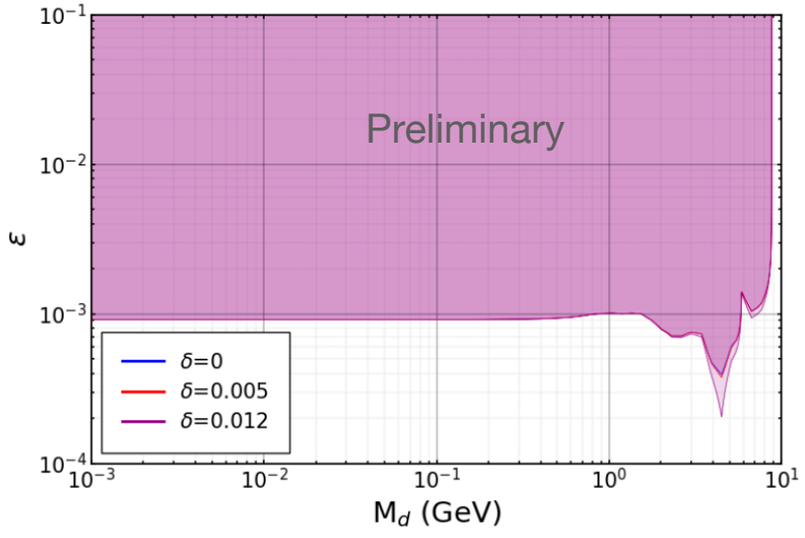
In preparation, in collaboration with L.M. de la Vega, J Erler and R Ferro



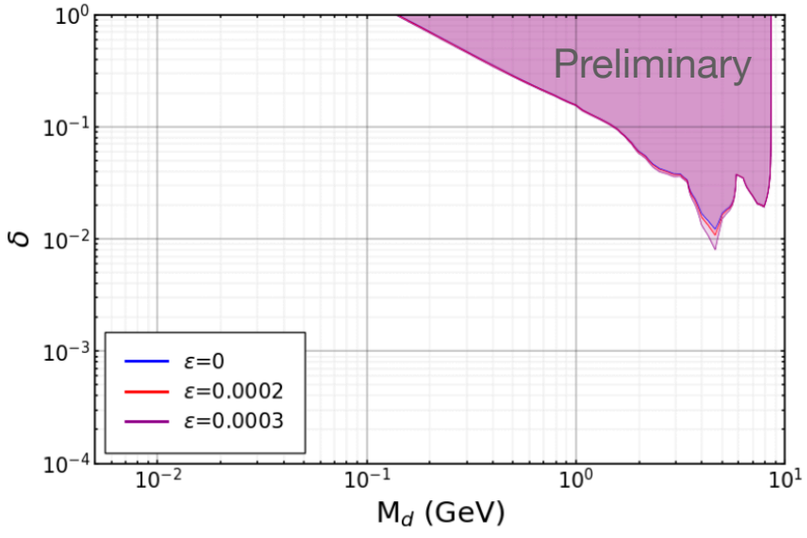
(a) $\epsilon - M_d$ plot for BaBar to lepton pairs, assuming the $B_d = 0$.



(b) $\delta - M_d$ plot for BaBar to lepton pairs, assuming the $B_d = 0$.



(c) $\epsilon - M_d$ plot for BaBar to invisible, assuming the $B_d = 1$.



(d) $\delta - M_d$ plot for BaBar to invisble, assuming the $B_d = 1$.