Z' and Leptoquark Searches at the P2 Experiment

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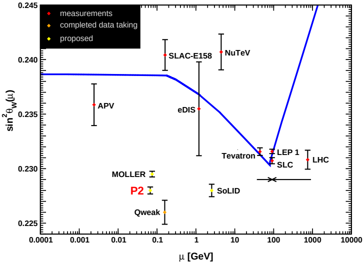
based on

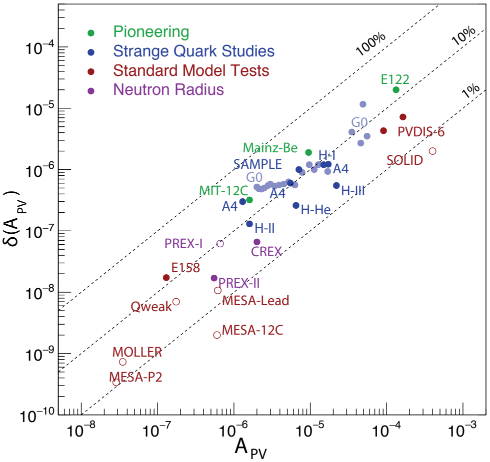
P. S. B. Dev, W. Rodejohann, X.-J. Xu & YCZ, JHEP **06**(2021)039 [2103.09067]

I. Bischer, P. S. B. Dev, W. Rodejohann, X.-J. Xu & YCZ, PRD **105**(2022)095016 [2112.12051]

Parity-violating electron scattering (PVES) experiments

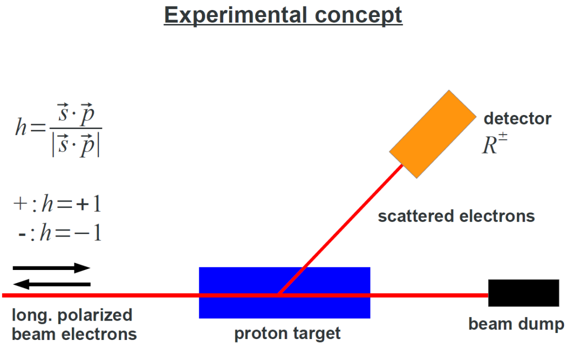
P2, EPJA 54 (2018) 208





P2 experiment

P2, EPJA 54 (2018) 208; `https://www.blogs.uni-mainz.de/fb08p2/`



New physics contributions

New Feynman diagrams for $e + p$ and $e+^{12}\mathrm{C}$ scatterings

- Chiral & non-chiral (light) Z' models:
  [Dev, Rodejohann, Xu & YCZ '21; Crivellin, Hoferichter, Kirk, Manzari & Schnell '21]
- Heavy leptoquarks:
  [Bischer, Dev, Rodejohann, Xu & YCZ '22; Crivellin, Hoferichter, Kirk, Manzari & Schnell '21]
- Heavy vector-like quarks:
  [Crivellin, Hoferichter, Kirk, Manzari & Schnell '21]
- Heavy vector-like leptons:
  (not as constraining as EWPO limits)
  [Crivellin, Hoferichter, Kirk, Manzari & Schnell '21]
- SM Effective Field Theory operators:
  [Boughezal, Petriello & Wiegand '21]

Extra light particles emitted in $e + p$ and $e+^{12}\mathrm{C}$ scatterings

- Bremsstrahlung processes:

$$\text{e.g.}\;\; e + p\,(^{12}\mathrm{C}) \to e + p\,(^{12}\mathrm{C}) + Z'$$

Z' contributions

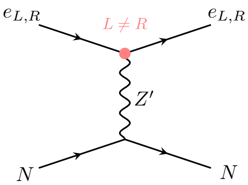
- chiral models:

diagrams with $g'_{f_L} \neq g'_{f_R}$ → $A^{\rm PV}_{\rm NP}$

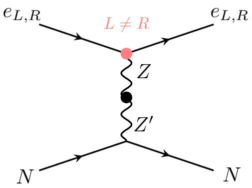
- non-chiral models:

$Z - Z'$ mixing → $g'_{f_L} \neq g'_{f_R}$ → $A^{\rm PV}_{\rm NP}$

$A^{\rm PV}$ from chiral $U(1)'$



$A^{\rm PV}$ from non-chiral $U(1)'$



Interactions

- Gauge couplings:

$$\mathcal{L} = Z_\mu (g_{e_L} \overline{e_L} \gamma^\mu e_L + g_{e_R} \overline{e_R} \gamma^\mu e_R) + Z_\mu (g_V \overline{N} \gamma^\mu N + g_A \overline{N} \gamma^\mu \gamma^5 N)$$
$$+ Z'_\mu (g'_{e_L} \overline{e_L} \gamma^\mu e_L + g'_{e_R} \overline{e_R} \gamma^\mu e_R) + Z'_\mu (g'_V \overline{N} \gamma^\mu N + g'_A \overline{N} \gamma^\mu \gamma^5 N).$$

- Vector couplings of $Z^{(\prime)}$ to nucleus with $\mathcal{Z}$ protons and $\mathcal{N}$ neutrons:

$$g_V = \mathcal{Z} \left(g_{u_L} + g_{u_R} + \frac{1}{2} g_{d_L} + \frac{1}{2} g_{d_R} \right) + \mathcal{N} \left(g_{d_L} + g_{d_R} + \frac{1}{2} g_{u_L} + \frac{1}{2} g_{u_R} \right),$$
$$g'_V = \mathcal{Z} \left(g'_{u_L} + g'_{u_R} + \frac{1}{2} g'_{d_L} + \frac{1}{2} g'_{d_R} \right) + \mathcal{N} \left(g'_{d_L} + g'_{d_R} + \frac{1}{2} g'_{u_L} + \frac{1}{2} g'_{u_R} \right).$$

- Axial-vector couplings of $Z^{(\prime)}$ to nucleus: not calculable from first principle,

$$\text{suppressed by } \frac{E_e}{m_N} \frac{q^2}{4E_e^2} \lesssim 0.014$$

Parity-violating asymmetry $A^{\rm PV}$

For the process $$e^-_{L,\,R} + N \to e^-_{L,\,R} + N$$

- Amplitudes

$$\mathcal{M}_{L,\,R} \propto G_{L,\,R}\,, \quad G_{L,R} = -\frac{e^2}{q^2} + \frac{g_{e_L,e_R} g_V}{q^2 - m_Z^2} + \frac{g'_{e_L,e_R} g'_V}{q^2 - m_{Z'}^2}$$

- Parity-violating asymmetry

$$\begin{aligned} A^{\rm PV} &= \frac{G_R^2 - G_L^2}{G_R^2 + G_L^2} \\ &\simeq \frac{\left(g_{e_L} - g_{e_R}\right) g_V}{4\pi\alpha} \frac{Q^2}{m_Z^2} + \frac{\left(g'_{e_L} - g'_{e_R}\right) g'_V}{4\pi\alpha} \frac{1}{1 + m_{Z'}^2/Q^2} \end{aligned}$$

- Neglecting the new physics contributions

$$\begin{aligned} A^{\rm PV}_{\rm SM}(e+p) &\simeq -\frac{G_F Q^2 \left(1 - 4 s_W^2\right)}{4\sqrt{2}\pi\alpha} \\ A^{\rm PV}_{\rm SM}(e + {}^{12}{\rm C}) &\simeq \frac{3\sqrt{2} G_F Q^2 s_W^2}{\pi\alpha} \end{aligned}$$

Chiral $U(1)'$ models

Oda, Okada & Takahashi '15 [PRD]; Campos, Cogollo, Lindner, Melo, Queiroz & Rodejohann '17 [JHEP]

Table: Quantum numbers of fermions in the three chiral $U(1)'$ models

model	(x,y)	$U(1)'$ charge assignment			
		(ν_L, e_L)	(ν_R, e_R)	(u_L, d_L)	(u_R, d_R)
		$-\frac{3}{2}(x+y)$	$-(x+2y,\ 2x+y)$	$\frac{1}{2}(x+y)$	$(x,\ y)$
$U(1)'_L$	$(-\frac{2}{3}, \frac{4}{3})$	-1	$(-2, 0)$	$\frac{1}{3}$	$(-\frac{2}{3}, \frac{4}{3})$
$U(1)'_R$	$(1, -1)$	0	$(1, -1)$	0	$(1, -1)$
$U(1)'_X$	$(0, 1)$	$-\frac{3}{2}$	$(-2, -1)$	$\frac{1}{2}$	$(0, 1)$

New physics contribution

$$\Delta A^{\rm PV} \equiv A^{\rm PV} - A^{\rm PV}_{\rm SM} \approx \frac{g'^2 Q'_N Q'_{LR}}{4\pi\alpha} \frac{1}{1 + m^2_{Z'}/Q^2}$$

$$Q'_{LR} \equiv Q'_{e_L} - Q'_{e_R}$$

$$Q'_p \equiv Q'_{u_L} + Q'_{u_R} + \frac{1}{2}\left(Q'_{d_L} + Q'_{d_R}\right)$$

$$Q'_{^{12}\mathrm{C}} \equiv 9\left(Q'_{u_L} + Q'_{u_R} + Q'_{d_L} + Q'_{d_R}\right)$$

Non-chiral models

Lindner, Queiroz, Rodejohann & Xu '18 [JHEP]

- Kinetic and mass mixing of Z and Z' bosons:

$$\mathcal{L} \supset -\frac{\epsilon}{2} B^{\mu\nu} F'_{\mu\nu} + \delta m^2 \hat{Z}^{\mu} \hat{Z}'_{\mu}$$

$$\tan\theta \equiv \frac{\delta m^2}{m^2_{Z'} - m^2_{Z}}$$

- Couplings of the physical gauge bosons:

$$\mathcal{L} \supset Z_{\mu} \left[J^{\mu}_{\rm NC} \cos\beta - J^{\mu}_{X} \sin\beta\right] + Z'_{\mu} \left[J^{\mu}_{\rm NC} \sin\beta + J^{\mu}_{X} \cos\beta\right]$$

$$\tan\beta \approx \frac{\epsilon s_W}{r_m - 1} + \tan\theta + \mathcal{O}(\theta^2,\ \epsilon^2)\,, \quad r_m \equiv \frac{m^2_{Z'}}{m^2_Z}$$

$$J^{\mu}_{\rm NC} = \sum_f g_f^{\rm SM} \overline{f} \gamma^{\mu} f\,,$$

$$J^{\mu}_{X} = \sum_f \frac{\overline{f}\gamma^{\mu} f}{\sqrt{1-\epsilon^2}} \left[g' Q'_f - g_Z \epsilon s_W Y_f\right]\,,$$

Mixing induced $A^{\rm PV}$

$A^{\rm PV}$ for the non-chiral $U(1)'$ models:

only mass mixing ($g' = 0$)

$$\frac{\Delta A^{\rm PV}}{A^{\rm PV}_{\rm SM}} = \sin^2\theta\left(\frac{m_Z^2}{m_{Z'}^2 + Q^2} - 1\right).$$

only kinetic mixing ($g' = 0$)

$$\frac{\Delta A^{\rm PV}}{A^{\rm PV}_{\rm SM}}(e+p) = \frac{m_{Z'}^2(1-r_m)\left(1-4s_W^2\right) + Q^2\left(4r_m s_W^2 + 2r_m - 3\right)}{(1-r_m)^2\left(1-4s_W^2\right)\left(m_{Z'}^2 + Q^2\right)} s_W^2\epsilon^2$$

$$\frac{\Delta A^{\rm PV}}{A^{\rm PV}_{\rm SM}}(e + {}^{12}{\rm C}) = \frac{m_{Z'}^2 s_W^2(1-r_m) + Q^2\left(1 - r_m - r_m s_W^2\right)}{(1-r_m)^2\left(m_{Z'}^2 + Q^2\right)}\epsilon^2$$

Mixing induced A^{PV}

A^{PV} for the non-chiral $U(1)'$ models:

only mass mixing ($g' \neq 0$)

$$\frac{\Delta A^{\mathrm{PV}}}{A^{\mathrm{PV}}_{\mathrm{SM}}} = \sin^2\theta \left[\frac{m_Z^2(1+R)}{m_{Z'}^2 + Q^2} - 1 \right]$$

$$\begin{aligned} R_{e+p}[U(1)_B] &= \frac{12g'}{g_Z \sin\theta(1-4s_W^2)} \\ R_{e+{}^{12}\mathrm{C}}[U(1)_B] &= -\frac{6g'}{g_Z \sin\theta s_W^2} \\ R[U(1)_{B-L}] &= -\frac{1}{3}R[U(1)_B]\,. \end{aligned}$$

Calculation procedure

- Momentum transferred:

$$Q^2 \approx 4E_i E_f \sin(\theta_f/2)\,, \quad \overline{\theta} = 35^\circ \quad [\delta\theta = 20^\circ].$$

- Calculating prospects at the 90% C.L.

$$\frac{\Delta A^{\rm PV}}{A^{\rm PV}} = \begin{cases} \sqrt{2.71} \times 1.4\% & = & 2.30\% & (e + p \text{ scattering})\,, \\ \sqrt{2.71} \times 0.3\% & = & 0.49\% & (e{+}^{12}\text{C scattering})\,, \end{cases}$$

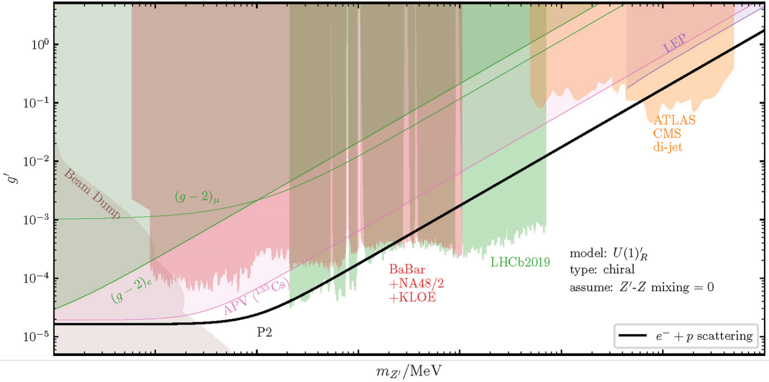
- Weak mixing angle at the low-Q^2 scale:

  [Erler & Ramsey-Musolf '05 [PRD]; Erler & Ferro-Hernandez '18 [JHEP]]

$$\sin^2\theta_W = 0.230 \pm 0.00003$$

neglecting the effects of $\Delta\sin^2\theta_W$ on new physics contributions in the non-chiral models.

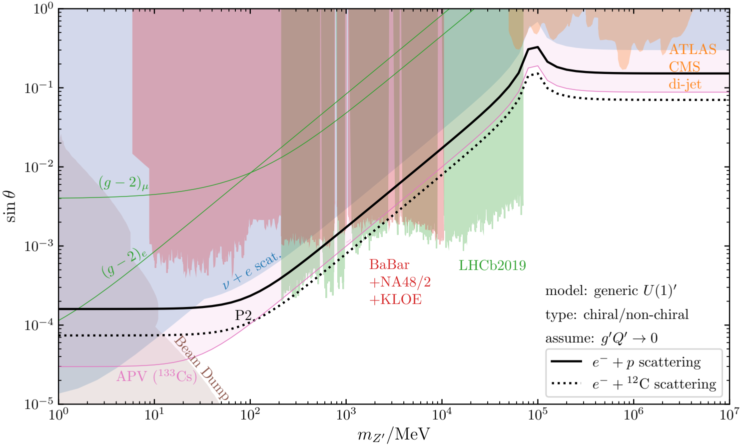
P2 prospects: $U(1)'_R$ model



- Absence of prospects in ^{12}C mode:

$$Q'_{^{12}\mathrm{C}} \propto Q'_{u_L} + Q'_{u_R} + Q'_{d_L} + Q'_{d_R} = 0$$

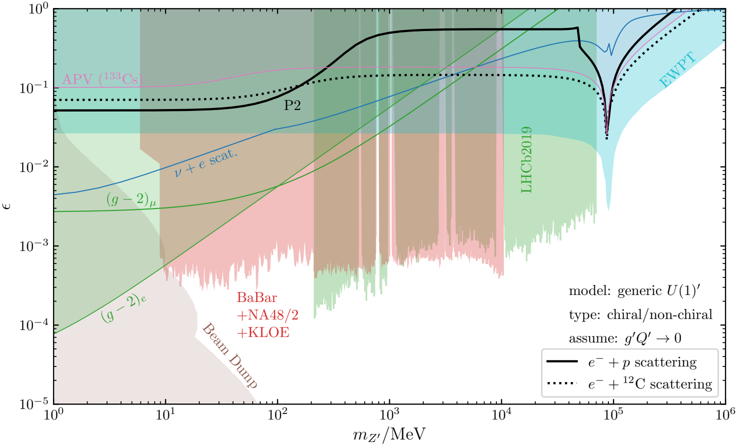
P2 prospects: non-chiral $U(1)'$ model: mass mixing



- When $m_{Z'} > m_Z$:

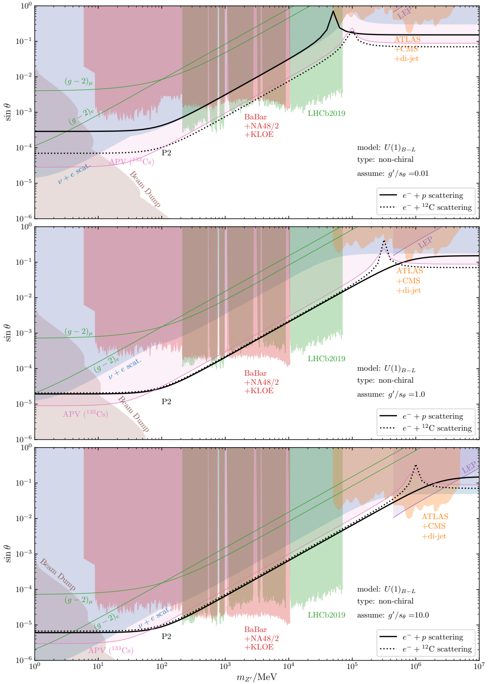
$$\frac{\Delta A^{\rm PV}}{A^{\rm PV}_{\rm SM}} \propto \left(\frac{m_Z^2}{m_{Z'}^2 + Q^2} - 1\right) \to -1$$

P2 prospects: non-chiral $U(1)'$ model: kinetic mixing



- Z' couplings are much photon-like when Z' is light:

$$\left(g'_{e_L} - g'_{e_R}\right) \propto \frac{m_{Z'}^2}{m_Z^2} \to 0$$



non-chiral $U(1)_{B-L}$ model: mass mixing ($g' \neq 0$)

- Absence of P2 sensitivities:

$$m_{Z'} = \sqrt{1+R}m_Z$$

$$e + p: \quad 51 \text{ GeV},$$
$$e + {}^{12}\text{C}: \quad 96 \text{ GeV}, \quad 325 \text{ GeV}, \quad 990 \text{ GeV}$$

For $g'/\sin\theta = 1$ and 10 with p, $R < -1$, no cancellation.

Leptoquarks & D-6 EFT operators

Table: Leptoquarks with $F = 3B + L$ the fermion number.

	$F = 3B + L$	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
S_1	2	0	3	1	-1/3
$\widetilde{S}_1$	2	0	3	1	-4/3
S_3	2	0	3	3	-1/3
V_2	2	1	3	2	-5/6
$\widetilde{V}_2$	2	1	3	2	1/6
R_2	0	0	3	2	7/6
$\widetilde{R}_2$	0	0	3	2	1/6
U_1	0	1	3	1	2/3
$\widetilde{U}_1$	0	1	3	1	5/3
U_3	0	1	3	3	2/3

Parity-violating EFT operators:

$$
\begin{aligned}
\mathcal{O}_{lq(1)} &= \left(\bar{l}\gamma^{\mu} l\right)\left(\bar{q}\gamma_{\mu} q\right) \\
\mathcal{O}_{lq(3)} &= \left(\bar{l}\gamma^{\mu}\tau^{i} l\right)\left(\bar{q}\gamma_{\mu}\tau^{i} q\right) \\
\mathcal{O}_{eu} &= \left(\bar{e}\gamma^{\mu} e\right)\left(\bar{u}\gamma_{\mu} u\right) \\
\mathcal{O}_{ed} &= \left(\bar{e}\gamma^{\mu} e\right)\left(\bar{d}\gamma_{\mu} d\right) \\
\mathcal{O}_{lu} &= \left(\bar{l}\gamma^{\mu} l\right)\left(\bar{u}\gamma_{\mu} u\right) \\
\mathcal{O}_{ld} &= \left(\bar{l}\gamma^{\mu} l\right)\left(\bar{d}\gamma_{\mu} d\right) \\
\mathcal{O}_{qe} &= \left(\bar{q}\gamma^{\mu} q\right)\left(\bar{e}\gamma_{\mu} e\right)
\end{aligned}
$$

Couplings of leptoquarks

$$\begin{aligned}
\mathcal{L}_{F=2} \;=\;& \left(s_{1L}\,\overline{q}^a\epsilon^{ab}(l^c)^b + s_{1R}\,\overline{u_R}e^c_R\right) S_1 + \widetilde{s}_1\,\overline{d_R}e^c\,\widetilde{S}_1 + s_3\overline{q}^a(\vec{\tau})^{ab}\epsilon^{bd}(l^c)^d\,\vec{S}_3 \\
&+ \left(v_{2R}\,\overline{q}^a\gamma_\mu e^c_R + v_{2L}\,\overline{d_R}\gamma_\mu(l^c)^a\right) V_2^{\mu,a} + \widetilde{v}_2\,\overline{u_R}\gamma_\mu(l^c)^a\widetilde{V}_2^{\mu,a} \;+\; \text{H.c.}, \\
\mathcal{L}_{F=0} \;=\;& \left(r_{2R}\,\overline{q}^b e_R + r_{2L}\,\overline{u_R}\,l^a\epsilon^{ab}\right) R_2^b + \left(\widetilde{r}_2\,\overline{d_R}\,l^a\epsilon^{ab}\right) R_2^{b\prime} \\
&+ \left(u_{1L}\,\overline{q}\gamma_\mu l + u_{1R}\,\overline{d_R}\gamma_\mu e_R\right) U_1^\mu + \widetilde{u}_1\,\overline{u_R}\gamma_\mu e_R\,U_1^{\mu\prime} + u_3\,\overline{q}\,\vec{\tau}\gamma_\mu\,l\,\vec{U}_3^\mu \;+\; \text{H.c.},
\end{aligned}$$

Integrating out heavy leptoquarks and mapping into SMEFT operators

$$\begin{aligned}
C_{lq(1)} &= -\frac{1}{4}|s_{1L}|^2 - \frac{3}{4}|s_3|^2 + \frac{1}{2}|u_{1L}|^2 + \frac{3}{2}|u_3|^2 \qquad & C_{qe} &= \frac{1}{2}|r_{2R}|^2 - |v_{2R}|^2 \\
C_{lq(3)} &= +\frac{1}{4}|s_{1L}|^2 - \frac{1}{4}|s_3|^2 + \frac{1}{2}|u_{1L}|^2 - \frac{1}{2}|u_3|^2 \qquad & C_{lu} &= \frac{1}{2}|r_{2L}|^2 - |\widetilde{v}_2|^2 \\
C_{eu} &= -\frac{1}{2}|s_{1R}|^2 + |\widetilde{u}_1|^2 & C_{ld} &= \frac{1}{2}|\widetilde{r}_2|^2 - |v_{2L}|^2 \\
C_{ed} &= -\frac{1}{2}|\widetilde{s}_1|^2 + |u_{1R}|^2 & &
\end{aligned}$$

Effective Lagrangian

Effective parity-violating Lagrangian for P2 experiment:

$$\mathcal{L}_{\rm PV} = \frac{1}{\Lambda^2}\sum_{f=u,d}\sum_{X=L,R}(\bar{e}\gamma_\mu P_X e)\left[C_{XVf}(\bar{f}\gamma^\mu f) + C_{XAf}(\bar{f}\gamma^\mu\gamma^5 f)\right]$$

with the coefficients

$$C_{LVu} = \frac{1}{2}(C_{lq(1)} - C_{lq(3)} + C_{lu}) \qquad C_{RVu} = \frac{1}{2}(C_{qe} + C_{eu})$$

$$C_{LVd} = \frac{1}{2}(C_{lq(1)} + C_{lq(3)} + C_{ld}) \qquad C_{RVd} = \frac{1}{2}(C_{qe} + C_{ed})$$

$$C_{LAu} = \frac{1}{2}(-C_{lq(1)} + C_{lq(3)} + C_{lu}) \qquad C_{RAu} = \frac{1}{2}(-C_{qe} + C_{eu})$$

$$C_{LAd} = \frac{1}{2}(-C_{lq(1)} - C_{lq(3)} + C_{ld}) \qquad C_{RAd} = \frac{1}{2}(-C_{qe} + C_{ed})$$

Quark couplings → nucleus couplings

- Nuclear form factors:
  [Del Nobile '22]

$$\langle N(p')|\bar{f}\gamma^\mu f|N(p)\rangle = \bar{u}(p')\left[F_1^{f,N}(q^2)\gamma^\mu + F_2^{f,N}(q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2m_N}\right]u(p)$$

$$\langle N(p')|\bar{f}\gamma^\mu\gamma^5 f|N(p)\rangle = \bar{u}(p')\left[G_A^{f,N}(q^2)\gamma^\mu\gamma^5 + G_P^{f,N}(q^2)\frac{\gamma^5 q^\mu}{2m_N}\right]u(p)$$

- The form factors for nuclei $\mathcal{N}$ are very similar.
- Effect of axial couplings is strongly suppressed in the parity asymmetry parameter and nuclear weak charge.

Parity asymmetry

$$A_{\rm PV} = \frac{\frac{{\rm d}\sigma_R}{{\rm d}t} - \frac{{\rm d}\sigma_L}{{\rm d}t}}{\frac{{\rm d}\sigma_R}{{\rm d}t} + \frac{{\rm d}\sigma_L}{{\rm d}t}} = \frac{|\mathcal{M}_R|^2 - |\mathcal{M}_L|^2}{|\mathcal{M}_R|^2 + |\mathcal{M}_L|^2},$$

$$i\mathcal{M}_{L,R}^{\pm s' r r'} = \sum_{j=1}^{8} \frac{K_j}{\Lambda^2} \left(\overline{u}_{s'}(k_e)\mathcal{O}_j u_\pm(p_e)\right)\left(\overline{u}_{r'}(k_\mathcal{N})\mathcal{O}'_j u_r(p_\mathcal{N})\right) .$$

j	K_j	$\mathcal{O}_j$	$\mathcal{O}'_j$
1	$C_{LVu}F_1^{u,\mathcal{N}} + C_{LVd}F_1^{d,\mathcal{N}}$	$\gamma_\mu P_L$	γ^μ
2	$C_{LVu}F_2^{u,\mathcal{N}} + C_{LVd}F_2^{d,\mathcal{N}}$	$\gamma_\mu P_L$	$i\sigma^{\mu\nu}q_\nu/2m_\mathcal{N}$
3	$C_{RVu}F_1^{u,\mathcal{N}} + C_{RVd}F_1^{d,\mathcal{N}}$	$\gamma_\mu P_R$	γ^μ
4	$C_{RVu}F_2^{u,\mathcal{N}} + C_{RVd}F_2^{d,\mathcal{N}}$	$\gamma_\mu P_R$	$i\sigma^{\mu\nu}q_\nu/2m_\mathcal{N}$
5	$C_{LAu}G_A^{u,\mathcal{N}} + C_{LAd}G_A^{d,\mathcal{N}}$	$\gamma_\mu P_L$	$\gamma^\mu\gamma^5$
6	$C_{LAu}G_P^{u,\mathcal{N}} + C_{LAd}G_P^{d,\mathcal{N}}$	$\gamma_\mu P_L$	$\gamma^5 q^\mu/2m_\mathcal{N}$
7	$C_{RAu}G_A^{u,\mathcal{N}} + C_{RAd}G_A^{d,\mathcal{N}}$	$\gamma_\mu P_R$	$\gamma^\mu\gamma^5$
8	$C_{RAu}G_P^{u,\mathcal{N}} + C_{RAd}G_P^{d,\mathcal{N}}$	$\gamma_\mu P_R$	$\gamma^5 q^\mu/2m_\mathcal{N}$

New physics contribution

- We make a double expansion in powers m_Z^{-2n} & Λ^{-2n}.
- Leading-order New Physics contribution:

$$\Delta A_{\rm PV}^{LVf}(\mathcal{N}) \approx \frac{C_{LVf}}{\Lambda^2}\frac{q^2}{4\pi\alpha}\frac{F_1^{f,\mathcal{N}}}{q_u F_1^{u,\mathcal{N}} + q_d F_1^{d,\mathcal{N}}}$$

$$\Delta A_{\rm PV}^{RVf}(\mathcal{N}) \approx -\frac{C_{RVf}}{\Lambda^2}\frac{q^2}{4\pi\alpha}\frac{F_1^{f,\mathcal{N}}}{q_u F_1^{u,\mathcal{N}} + q_d F_1^{d,\mathcal{N}}}$$

$$\Delta A_{\rm PV}^{LAf}(\mathcal{N}) \approx \frac{C_{LAf}}{\Lambda^2}G_A^{f,\mathcal{N}}\frac{E_e q^4}{4\pi\alpha(2E_e^2 - m_e^2)m_{\mathcal{N}}}\frac{q_u(F_1^{u,\mathcal{N}} + F_2^{u,\mathcal{N}}) + q_d(F_1^{d,\mathcal{N}} + F_2^{d,\mathcal{N}})}{(q_u F_1^{u,\mathcal{N}} + q_d F_1^{d,\mathcal{N}})^2}$$

$$\Delta A_{\rm PV}^{RAf}(\mathcal{N}) \approx \frac{C_{RAf}}{\Lambda^2}G_A^{f,\mathcal{N}}\frac{E_e q^4}{4\pi\alpha(2E_e^2 - m_e^2)m_{\mathcal{N}}}\frac{q_u(F_1^{u,\mathcal{N}} + F_2^{u,\mathcal{N}}) + q_d(F_1^{d,\mathcal{N}} + F_2^{d,\mathcal{N}})}{(q_u F_1^{u,\mathcal{N}} + q_d F_1^{d,\mathcal{N}})^2}$$

P2 sensitivities to effective operator coefficients

Target	C	$\Lambda/\sqrt{C}$ [TeV]	C	$\Lambda/\sqrt{C}$ [TeV]
p	C_{LVu}	13.1	C_{LVd}	9.3
	C_{RVu}	13.1	C_{LVd}	9.3
	C_{LAu}	2.6	C_{LAd}	1.8
	C_{RAu}	2.6	C_{LAd}	1.8
^{12}C	C_{LVu}	8.4	C_{LVd}	8.4
	C_{RVu}	8.4	C_{RVd}	8.4

Coupling	$\Lambda/\sqrt{C}$ [TeV]			
	P2 (p)	P2 (^{12}C)	APV (^{133}Cs)	ATLAS dilepton
$C_{lq(1)}$	11.4	8.4	11.1	7.7
$C_{lq(3)}$	6.9	–	2.6	9.2
C_{eu}	9.4	5.9	3.2	7.5
C_{ed}	6.4	5.9	3.4	4.8
C_{qe}	11.3	8.4	4.6	7.2
C_{lu}	9.0	5.9	7.6	6.2
C_{ld}	6.7	5.9	8.1	5.0

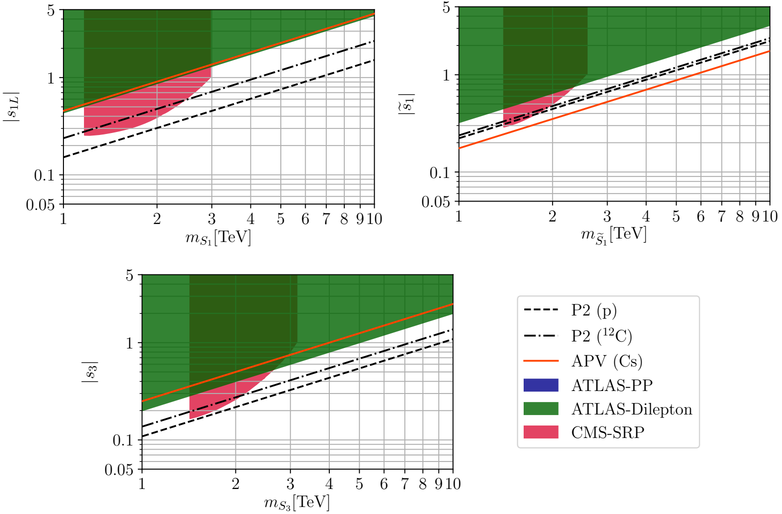
- APV limits: Sahoo, Das & Spiesberger '21
- ATLAS dilepton limits: ATLAS, 2006.12946

P2 sensitivities to leptoquark masses

Leptoquark	Coupling	$m_{\rm LQ}$[TeV]			
		P2 (p)	P2 (^{12}C)	APV (^{133}Cs)	ATLAS dilepton
S_1	s_{1L}	6.6	4.2	2.2	2.3
S_1	s_{1R}	6.6	4.2	5.4	2.6
$\widetilde{S}_1$	$\widetilde{s}_1$	4.5	4.2	5.7	3.1
S_3	s_3	9.2	7.3	4.0	5.0
V_2	v_{2R}	11.3	8.4	4.6	8.7
V_2	v_{2L}	6.7	5.9	8.1	6.5
$\widetilde{V}_2$	$\widetilde{v}_2$	9.0	5.9	7.6	7.8
R_2	r_{2R}	7.9	5.9	3.3	4.5
R_2	r_{2L}	6.4	4.2	5.4	4.1
$\widetilde{R}_2$	$\widetilde{r}_2$	4.7	4.2	5.7	2.3
U_1	u_{1L}	6.4	5.9	3.4	4.1
U_1	u_{1R}	6.4	5.9	8.1	4.6
$\widetilde{U}_1$	$\widetilde{u}_1$	9.4	5.9	7.6	7.3
U_3	u_3	14.8	10.3	5.6	10.8

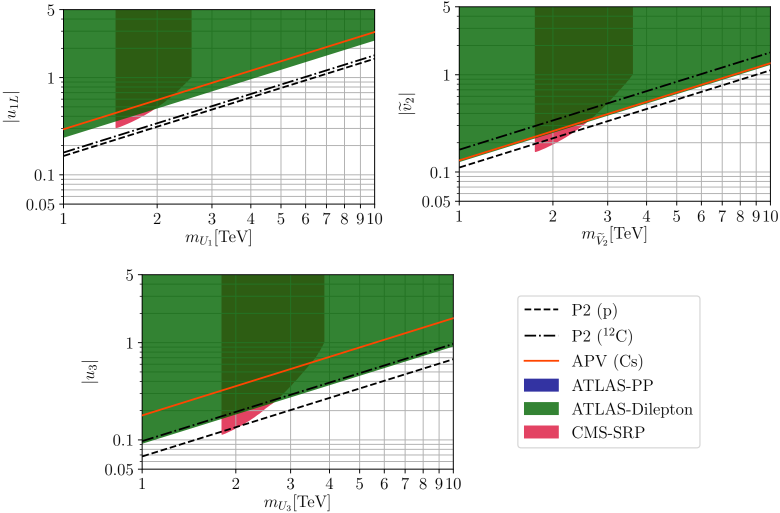
- APV limits: Sahoo, Das & Spiesberger '21
- ATLAS dilepton limits: ATLAS, 2006.12946

P2 prospects: scalar leptoquarks



- APV limits: Sahoo, Das & Spiesberger '21
- Collider limits: 2006.05872, 1706.05033; 2006.12946; Crivellin, Müller & Schnell '21

P2 prospects: vector leptoquarks



- APV limits: Sahoo, Das & Spiesberger '21
- Collider limits: 2006.05872, 1706.05033; 2006.12946; Crivellin, Müller & Schnell '21

P2 prospects: distinguishing different contributions

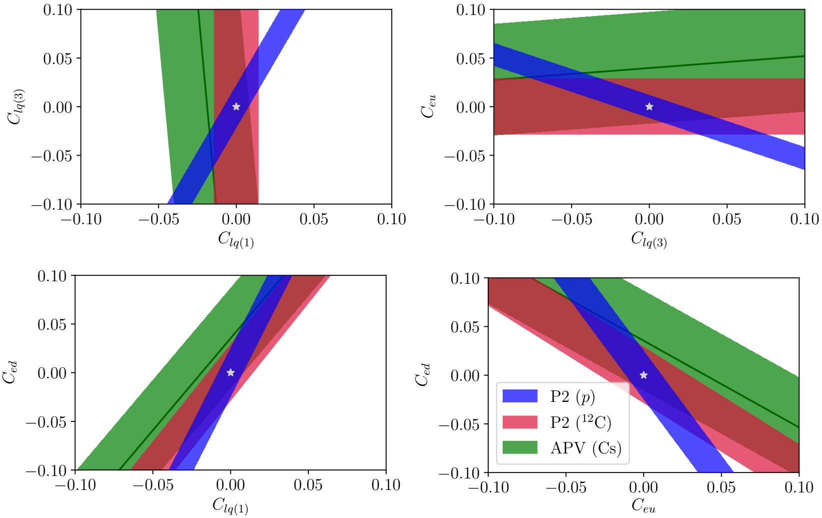


Figure: EFT scale $\Lambda = 1$ TeV.

Conclusion

- The low-energy high precision PVES experiment P2 is sensitive to a large variety of new physics scenarios, including Z' bosons and leptoquarks.
- For chiral $U(1)'$ models, the P2 experiment is sensitivities to a Z' mass up to 79 TeV in the proton mode and up to 90 TeV in ^{12}C mode.
- For non-chiral $U(1)'$ models, the P2 sensitivities are independent of $m_{Z'}$ for sufficiently heavy Z'.
- For leptoquarks, the P2 experiment can probe mass up to roughly 15 GeV, well above the high-energy collider and APV limits.

Thank you very much!

Coupling of Z and Z' bosons

models	SM	chiral models	non-chiral models	
$A^{\rm PV}$ caused by	NC	$Q'_{e_L} \neq Q'_{e_R}$	$\epsilon B^{\mu\nu} F'_{\mu\nu}$	$\delta m^2 Z^\mu Z'_\mu$
g_{e_L}	$g_Z\left(-\frac{1}{2}+s_W^2\right)$	$g_{e_L}^{\rm SM}$	$g_{e_L}^{\rm SM}+\frac{3-2r_m-2s_W^2}{4(1-r_m)^2}g_Z s_W^2\epsilon^2$	$g_{e_L}^{\rm SM}\cos\theta$
g_{e_R}	$g_Z s_W^2$	$g_{e_R}^{\rm SM}$	$g_{e_R}^{\rm SM}+\frac{2-2r_m-s_W^2}{2(1-r_m)^2}g_Z s_W^2\epsilon^2$	$g_{e_R}^{\rm SM}\cos\theta$
g_{u_L}	$g_Z\left(\frac{1}{2}-\frac{2}{3}s_W^2\right)$	$g_{u_L}^{\rm SM}$	$g_{u_L}^{\rm SM}-\frac{5-2r_m-4s_W^2}{12(1-r_m)^2}g_Z s_W^2\epsilon^2$	$g_{u_L}^{\rm SM}\cos\theta$
g_{u_R}	$g_Z\left(-\frac{2}{3}s_W^2\right)$	$g_{u_R}^{\rm SM}$	$g_{u_R}^{\rm SM}-\frac{2-2r_m-s_W^2}{3(1-r_m)^2}g_Z s_W^2\epsilon^2$	$g_{u_R}^{\rm SM}\cos\theta$
g_{d_L}	$g_Z\left(-\frac{1}{2}+\frac{1}{3}s_W^2\right)$	$g_{d_L}^{\rm SM}$	$g_{d_L}^{\rm SM}+\frac{1+2r_m-2s_W^2}{12(1-r_m)^2}g_Z s_W^2\epsilon^2$	$g_{d_L}^{\rm SM}\cos\theta$
g_{d_R}	$g_Z\left(\frac{1}{3}s_W^2\right)$	$g_{d_R}^{\rm SM}$	$g_{d_R}^{\rm SM}+\frac{2-2r_m-s_W^2}{6(1-r_m)^2}g_Z s_W^2\epsilon^2$	$g_{d_R}^{\rm SM}\cos\theta$
g'_{e_L}	0	$Q'_{e_L}g'$	$\frac{c_W^2-r_m/2}{1-r_m}\epsilon g_Z s_W$	$g_{e_L}^{\rm SM}\sin\theta$
g'_{e_R}	0	$Q'_{e_R}g'$	$\frac{c_W^2-r_m}{1-r_m}\epsilon g_Z s_W$	$g_{e_R}^{\rm SM}\sin\theta$
g'_{u_L}	0	$Q'_{u_L}g'$	$\frac{r_m-4c_W^2}{6(1-r_m)}\epsilon g_Z s_W$	$g_{u_L}^{\rm SM}\sin\theta$
g'_{u_R}	0	$Q'_{u_R}g'$	$\frac{2(r_m-c_W^2)}{3(1-r_m)}\epsilon g_Z s_W$	$g_{u_R}^{\rm SM}\sin\theta$
g'_{d_L}	0	$Q'_{d_L}g'$	$\frac{r_m+2c_W^2}{6(1-r_m)}\epsilon g_Z s_W$	$g_{d_L}^{\rm SM}\sin\theta$
g'_{d_R}	0	$Q'_{d_R}g'$	$\frac{c_W^2-r_m}{3(1-r_m)}\epsilon g_Z s_W$	$g_{d_R}^{\rm SM}\sin\theta$

P2 sensitivities in the limits of $m_{Z'} \to 0$ & $m_{Z'} \to \infty$

models	$m_{Z'} \to 0$		$m_{Z'} \to \infty$	
	$e+p$	$e+{}^{12}\mathrm{C}$	$e+p$	$e+{}^{12}\mathrm{C}$
$U(1)'_L$	$g' < 1.7 \times 10^{-5}$	$g' < 1.2 \times 10^{-5}$	$\frac{m_{Z'}}{g'} > 5.9$ TeV	$\frac{m_{Z'}}{g'} > 8.3$ TeV
$U(1)'_R$	$g' < 1.7 \times 10^{-5}$	–	$\frac{m_{Z'}}{g'} > 5.6$ TeV	–
$U(1)'_X$	$g' < 1.5 \times 10^{-5}$	$g' < 1.5 \times 10^{-5}$	$\frac{m_{Z'}}{g'} > 7.7$ TeV	$\frac{m_{Z'}}{g'} > 7.7$ TeV
$U(1)'$ $(\sin\theta)$	$\sin\theta < 1.7 \times 10^{-4}$	$\sin\theta < 7.3 \times 10^{-5}$	$\sin\theta < 0.13$	$\sin\theta < 0.07$
$U(1)'$ (ϵ)	$\epsilon < 0.05$	$\epsilon < 0.07$	$\frac{m_{Z'}}{\epsilon} > 350$ GeV	$\frac{m_{Z'}}{\epsilon} > 600$ GeV
$U(1)_B$ (0.01)	$\sin\theta < 9 \times 10^{-5}$	$\sin\theta < 9 \times 10^{-5}$	$\sin\theta < 0.13$	$\sin\theta < 0.07$
$U(1)_B$ (1)	$\sin\theta < 1.1 \times 10^{-5}$	$\sin\theta < 1.2 \times 10^{-5}$	$\sin\theta < 0.13$	$\sin\theta < 0.07$
$U(1)_B$ (10)	$\sin\theta < 3.7 \times 10^{-6}$	$\sin\theta < 4.1 \times 10^{-6}$	$\sin\theta < 0.13$	$\sin\theta < 0.07$
$U(1)_{B-L}$ (0.01)	$\sin\theta < 2.9 \times 10^{-4}$	$\sin\theta < 6.9 \times 10^{-5}$	$\sin\theta < 0.13$	$\sin\theta < 0.07$
$U(1)_{B-L}$ (1)	$\sin\theta < 2 \times 10^{-5}$	$\sin\theta < 2 \times 10^{-5}$	$\sin\theta < 0.13$	$\sin\theta < 0.07$
$U(1)_{B-L}$ (10)	$\sin\theta < 6 \times 10^{-6}$	$\sin\theta < 6.5 \times 10^{-6}$	$\sin\theta < 0.13$	$\sin\theta < 0.07$

P2 improvements of $m_{Z'}$ and g': chiral $U(1)'$ models

models	mode	$m_{Z'}$ ranges	g' ranges
$U(1)'_L$	$e+p$	$-$	$-$
	$e+^{12}$C	[100 MeV, 200 MeV] [70 GeV, 600 GeV] [5 TeV, 90 TeV]	$[2.0\times10^{-5}, 3.3\times10^{-5}]$ [0.01, 0.09] $[0.70, 4\pi]$
$U(1)'_R$	$e+p$	[20 MeV, 200 MeV] [70 GeV, 600 GeV] [5 TeV, 70 TeV]	$[1.7\times10^{-5}, 4.0\times10^{-5}]$ [0.012, 0.1] $[0.9, 4\pi]$
$U(1)'_X$	$e+p$	[93 MeV, 430 MeV] [70 GeV, 700 GeV] [5 TeV, 79 TeV]	$[2.0\times10^{-5}, 7.5\times10^{-5}]$ [0.01, 0.11] $[0.8, 4\pi]$
	$e+^{12}$C	[93 MeV, 430 MeV] [70 GeV, 700 GeV] [5 TeV, 79 TeV]	$[2.0\times10^{-5}, 7.5\times10^{-5}]$ [0.01, 0.11] $[0.8, 4\pi]$

models	mode	$m_{Z'}$ ranges	$\sin\theta$ or ϵ ranges
$U(1)'$ ($\sin\theta$)	$e+p$	–	–
	$e+{}^{12}$C	[110 MeV, 200 MeV] (> 70 GeV)	$[1.1\times10^{-4}, 1.9\times10^{-4}]$ [0.07, 0.15]
$U(1)'$ (ϵ)	$e+p$	–	–
	$e+{}^{12}$C	–	–
$U(1)_B$ (0.01)	$e+p$	[120 MeV, 200 MeV] [70 GeV, 100 GeV]	$[1.4\times10^{-4}, 2.3\times10^{-4}]$ [0.08, 0.20]
	$e+{}^{12}$C	[120 MeV, 200 MeV] (> 70 GeV)	$[1.4\times10^{-4}, 2.3\times10^{-4}]$ [0.07, 0.13]
$U(1)_B$ (1)	$e+p$	[70 MeV, 10 GeV] [70 GeV, 500 GeV]	$[1.2\times10^{-5}, 1.2\times10^{-3}]$ $[8\times10^{-3}, 0.06]$
	$e+{}^{12}$C	[83 MeV, 10 GeV] [70 GeV, 650 GeV] (> 2.3 TeV)	$[1.4\times10^{-5}, 1.3\times10^{-3}]$ $[9\times10^{-3}, 0.055]$ [0.067, 0.07]
$U(1)_B$ (10)	$e+p$	[70 MeV, 305 GeV]	$[4.0\times10^{-6}, 0.012]$
	$e+{}^{12}$C	[83 MeV, 305 GeV] (> 5 TeV)	$[4.2\times10^{-6}, 0.012]$ [0.067, 0.07]
$U(1)_{B-L}$ (0.01)	$e+p$	[90 GeV, 110 GeV]	[0.17, 0.19]
	$e+{}^{12}$C	[110 MeV, 560 MeV] (> 70 GeV)	$[1\times10^{-4}, 5.0\times10^{-4}]$ [0.07, 0.2]
$U(1)_{B-L}$ (1)	$e+p$	[80 MeV, 600 MeV] [70 GeV, 620 GeV]	$[2.4\times10^{-5}, 1.2\times10^{-4}]$ [0.013, 0.1]
	$e+{}^{12}$C	[80 MeV, 600 MeV] [70 GeV, 260 GeV] (> 400 GeV)	$[2.4\times10^{-5}, 1.2\times10^{-4}]$ [0.013, 0.18]
$U(1)_{B-L}$ (10)	$e+p$	[70 MeV, 200 MeV] [70 GeV, 420 GeV]	$[7.0\times10^{-6}, 1.4\times10^{-5}]$ $[4.3\times10^{-3}, 0.028]$
	$e+{}^{12}$C	[83 MeV, 600 MeV] [70 GeV, 420 GeV]	$[9.0\times10^{-6}, 1.5\times10^{-5}]$ $[4.5\times10^{-3}, 0.032]$