Radiation Amplitude Zero and Production of Leptoquark at *ep* and $e\gamma$ colliders

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భారతీయ సాంకేతిక విజ్ఞాన సంస్థ హైదరాబాద్
भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

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Leptoquarks

- Proposed particles.
- Couple to quarks and leptons simultaneously.
- Colour triplet, electromagnetically charged, bosons (spin 0 or 1).
- Singlet, doublet or triplet under $SU(2)_L$.
- Emerge naturally in several models with higher gauge representation.
- Can explain B-anomalies sector, muon $g-2$, neutrino mass, etc.
- Lots of experimental searches. No success yet.

$\sim$ *I. Doršner, et al. [Phys. Rept. 641 (2016) 1–68]*

Radiation Amplitude Zero

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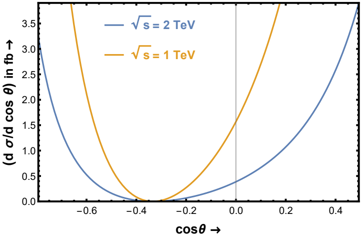

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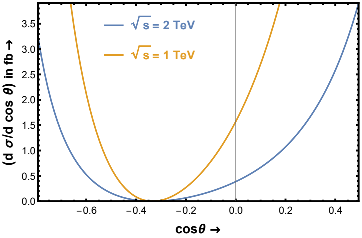

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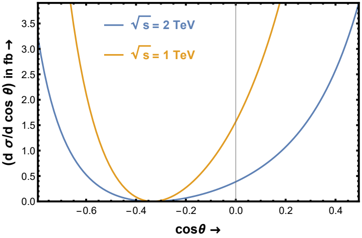

- For $2 \to 2$ process with photon in final state: $\cos\theta^* = \left(\frac{Q_{f_2} - Q_{f_1}}{Q_{f_2} + Q_{f_1}}\right)$

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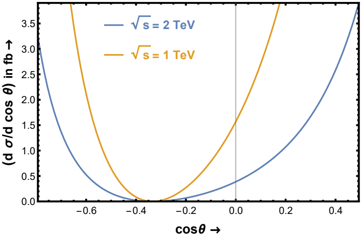

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- General Criterion: $\frac{\boldsymbol{p_1 \cdot k}}{\boldsymbol{Q_1}} = \frac{\boldsymbol{p_j \cdot k}}{\boldsymbol{Q_j}}$ ~ *Brodsky & Brown, [Phys. Rev. Lett. 49 (1982) 966]*

Production of Leptoquarks at *ep* collider

ep colliders

Collider	E_p	E_e	$\sqrt{s}$	$\mathcal{L}_{int}$
HERA	920 GeV	27.5 GeV	318.1 GeV	400 pb^{-1}
LHeC	7 TeV	50 GeV	1183.2 GeV	1 ab^{-1}
FCC-he I	20 TeV	60 GeV	2190.2 GeV	2 ab^{-1}
FCC-he II	50 TeV	60 GeV	3464.1 GeV	2 ab^{-1}

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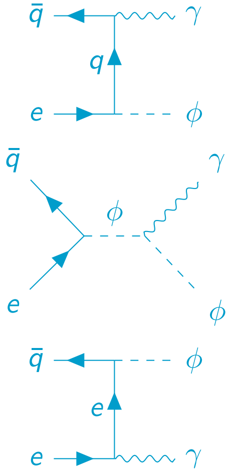
Partonic Cross-section

$e\bar{q} \to \phi\gamma$



Partonic Cross-section

$$\sum_{\text{spin}} \left|\mathcal{M}^S\right|^2 = e^2 \left[(Y_L^{eq})^2 + (Y_R^{eq})^2\right] \left[1 + \frac{(s+M_\phi^2)^2}{(s-M_\phi^2)^2}\right] \times \operatorname{cosec}^2\theta \left[Q_\phi \cos\theta - (2+Q_\phi)\right]^2$$

$$\sum_{\text{spin}} \left|\mathcal{M}^V\right|^2 = 2e^2 \left[(Y_L^{eq})^2 + (Y_R^{eq})^2\right] \left[\cos^2\theta + \frac{(s+M_\phi^2)^2}{(s-M_\phi^2)^2}\right] \times \operatorname{cosec}^2\theta \left[Q_\phi \cos\theta - (2+Q_\phi)\right]^2$$

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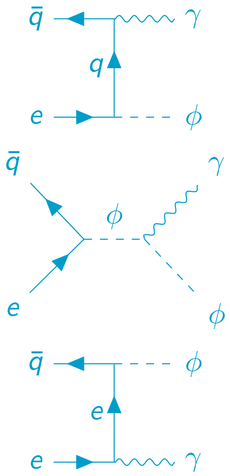

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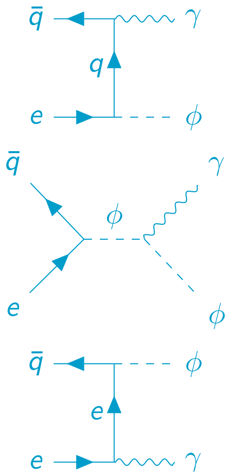

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$$\cos^* = \left(1 + \frac{2}{Q_\phi}\right) \implies \frac{p_e.k}{-1} = \frac{p_\phi.k}{Q_\phi} = \frac{p_{\bar{q}}.k}{Q_{\bar{q}}}$$

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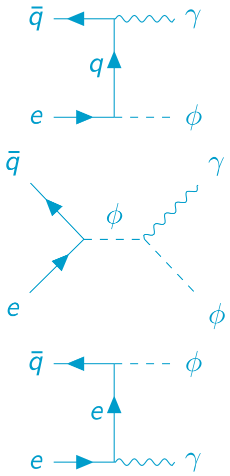

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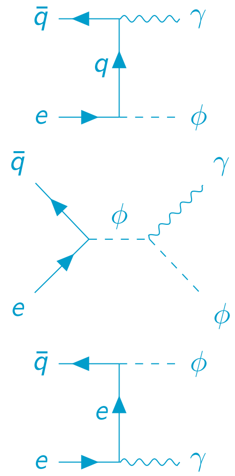
$Q_\phi < 0$ and $|Q_\phi| > 1$

$e\bar{q} \to \phi\gamma$



Scalar Leptoquarks

ϕ	Y_ϕ	T_3	Q_ϕ	Interaction	Production Channel	$\cos\theta^*$
S_1	$2/3$	0	$1/3$	$\overline{\Psi}^c_q\, P_L\, i\sigma_2 \Psi_\ell\, S_1 \bigoplus \bar{q}^c_u\, P_R\, \ell_e\, S_1$	$e^-\, u \to \gamma\left(S_1^{+1/3}\right)^c$	—
$\widetilde{S}_1$	$8/3$	0	$4/3$	$\bar{q}^c_d\, P_R\, \ell_e\, \widetilde{S}_1$	$e^-\, d \to \gamma\left(\widetilde{S}_1^{+4/3}\right)^c$	$-1/2$
R_2	$7/3$	$1/2$	$5/3$	$\bar{q}_u\, P_L\, (R_2^T\, i\sigma_2)\, \Psi_\ell$	$e^-\, \bar{u} \to \gamma\left(R_2^{+5/3}\right)^c$	$-1/5$
		$-1/2$	$2/3$	$\bigoplus\ \overline{\Psi}_q\, P_R\, R_2\, \ell_e$	$e^-\, \bar{d} \to \gamma\left(R_2^{+2/3}\right)^c$	—
$\widetilde{R}_2$	$1/3$	$1/2$	$2/3$	$\bar{q}_d\, P_L\, (\widetilde{R}_2^T\, i\sigma_2)\, \Psi_\ell$	$e^-\, \bar{d} \to \gamma\left(\widetilde{R}_2^{+2/3}\right)^c$	—
		$-1/2$	$-1/3$		—	—
$\vec{S}_3$	$2/3$	1	$4/3$	$\overline{\Psi}^c_q\, P_L\, (i\sigma_2\, S_3^{ad})\, \Psi_\ell$	$e^-\, d \to \gamma\left(S_3^{+4/3}\right)^c$	$-1/2$
		0	$1/3$		$e^-\, u \to \gamma\left(S_3^{+1/3}\right)^c$	—
		-1	$-2/3$		—	—

Go

Scalar Leptoquarks

ϕ	Y_ϕ	T_3	Q_ϕ	Interaction	Production Channel	$\cos\theta^*$
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$\widetilde{S}_1$	$8/3$	0	$4/3$	$\bar{q}_d^c\, P_R\, \ell_e\, \widetilde{S}_1$	$e^- d \to \gamma \left(\widetilde{S}_1^{+4/3}\right)^c$	$-1/2$
R_2	$7/3$	$1/2$	$5/3$	$\bar{q}_u\, P_L\, (R_2^T\, i\sigma_2)\, \Psi_\ell$	$e^- \bar{u} \to \gamma \left(R_2^{+5/3}\right)^c$	$-1/5$
		$-1/2$	$2/3$	$\bigoplus\ \overline{\Psi}_q\, P_R\, R_2\, \ell_e$	$e^- \bar{d} \to \gamma \left(R_2^{+2/3}\right)^c$	—
$\widetilde{R}_2$	$1/3$	$1/2$	$2/3$	$\bar{q}_d\, P_L\, (\widetilde{R}_2^T\, i\sigma_2)\, \Psi_\ell$	$e^- \bar{d} \to \gamma \left(\widetilde{R}_2^{+2/3}\right)^c$	—
		$-1/2$	$-1/3$		—	—
$\vec{S}_3$	$2/3$	1	$4/3$	$\overline{\Psi}_q^c\, P_L\, (i\sigma_2\, S_3^{ad})\, \Psi_\ell$	$e^- d \to \gamma \left(S_3^{+4/3}\right)^c$	$-1/2$
		0	$1/3$		$e^- u \to \gamma \left(S_3^{+1/3}\right)^c$	—
		-1	$-2/3$		—	—

Go

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$\widetilde{S}_1$	$8/3$	0	$4/3$	$\bar{q}^c_d\, P_R\, \ell_e\, \widetilde{S}_1$	$e^-\, d \to \gamma\, \left(\widetilde{S}_1^{+4/3}\right)^c$	$-1/2$
R_2	$7/3$	$1/2$	$5/3$	$\bar{q}_u\, P_L\, (R_2^T\, i\sigma_2)\, \Psi_\ell$	$e^-\, \bar{u} \to \gamma\, \left(R_2^{+5/3}\right)^c$	$-1/5$
		$\boxed{-1/2}$	$\boxed{2/3}$	$\bigoplus\, \overline{\Psi}_q\, P_R\, R_2\, \ell_e$	$e^-\, \bar{d} \to \gamma\, \left(R_2^{+2/3}\right)^c$	—
$\widetilde{R}_2$	$1/3$	$\boxed{1/2}$	$\boxed{2/3}$	$\bar{q}_d\, P_L\, (\widetilde{R}_2^T\, i\sigma_2)\, \Psi_\ell$	$e^-\, \bar{d} \to \gamma\, \left(\widetilde{R}_2^{+2/3}\right)^c$	—
		$\boxed{-1/2}$	$\boxed{-1/3}$		—	—
$\vec{S}_3$	$2/3$	1	$4/3$	$\overline{\Psi}^c_q\, P_L\, (i\sigma_2\, S_3^{ad})\, \Psi_\ell$	$e^-\, d \to \gamma\, \left(S_3^{+4/3}\right)^c$	$-1/2$
		$\boxed{0}$	$\boxed{1/3}$		$e^-\, u \to \gamma\, \left(S_3^{+1/3}\right)^c$	—
		$\boxed{-1}$	$\boxed{-2/3}$		—	—

Go

Scalar Leptoquarks

ϕ	Y_ϕ	T_3	Q_ϕ	Interaction	Production Channel	$\cos\theta^*$
S_1	$2/3$	0	$1/3$	$\overline{\Psi}^c_q\, P_L\, i\sigma_2 \Psi_\ell\, S_1 \bigoplus\, \bar{q}^c_u\, P_R\, \ell_e\, S_1$	$e^-\, u \to \gamma\, \left(S_1^{+1/3}\right)^c$	—
$\widetilde{S}_1$	$8/3$	0	$4/3$	$\bar{q}^c_d\, P_R\, \ell_e\, \widetilde{S}_1$	$e^-\, d \to \gamma\, \left(\widetilde{S}_1^{+4/3}\right)^c$	$-1/2$
R_2	$7/3$	$1/2$	$5/3$	$\bar{q}_u\, P_L\, (R_2^T\, i\sigma_2)\, \Psi_\ell$	$e^-\, \bar{u} \to \gamma\, \left(R_2^{+5/3}\right)^c$	$-1/5$
		$-1/2$	$2/3$	$\bigoplus\, \overline{\Psi}_q\, P_R\, R_2\, \ell_e$	$e^-\, \bar{d} \to \gamma\, \left(R_2^{+2/3}\right)^c$	—
$\widetilde{R}_2$	$1/3$	$1/2$	$2/3$	$\bar{q}_d\, P_L\, (\widetilde{R}_2^T\, i\sigma_2)\, \Psi_\ell$	$e^-\, \bar{d} \to \gamma\, \left(\widetilde{R}_2^{+2/3}\right)^c$	—
		$-1/2$	$-1/3$		—	—
$\vec{S}_3$	$2/3$	1	$4/3$	$\overline{\Psi}^c_q\, P_L\, (i\sigma_2\, S_3^{ad})\, \Psi_\ell$	$e^-\, d \to \gamma\, \left(S_3^{+4/3}\right)^c$	$-1/2$
		0	$1/3$		$e^-\, u \to \gamma\, \left(S_3^{+1/3}\right)^c$	—
		-1	$-2/3$		—	—

Go

Vector Leptoquarks

ϕ	Y_ϕ	T_3	Q_ϕ	Interaction	Production Channel	$\cos\theta^*$
$U_{1\mu}$	$4/3$	0	$2/3$	$\overline{\Psi}_q\,\gamma^\mu P_L\,\Psi_\ell\,U_{1\mu} \oplus \bar{q}_d\,\gamma^\mu P_R\,\ell_e\,U_{1\mu}$	$e^-\,\bar{d} \to \gamma\left(U_{1\mu}^{+2/3}\right)^c$	—
$\widetilde{U}_{1\mu}$	$10/3$	0	$5/3$	$\bar{q}_u\,\gamma^\mu P_R\,\ell_e\,\widetilde{U}_{1\mu}$	$e^-\,\bar{u} \to \gamma\left(\widetilde{U}_{1\mu}^{+5/3}\right)^c$	$-1/5$
$V_{2\mu}$	$5/3$	$1/2$	$4/3$	$\overline{\Psi}_q^c\,\gamma^\mu P_R\,(i\sigma_2\,V_{2\mu})\ell_e$	$e^-\,d \to \gamma\left(V_{2\mu}^{+4/3}\right)^c$	$-1/2$
		$-1/2$	$1/3$	$\oplus\,\bar{q}_d^c\,\gamma^\mu P_L\,(V_{2\mu}^T\,i\sigma_2)\,\Psi_\ell$	$e^-\,u \to \gamma\left(V_{2\mu}^{+1/3}\right)^c$	—
$\widetilde{V}_{2\mu}$	$-1/3$	$1/2$	$1/3$	$\bar{q}_u^c\,\gamma^\mu P_L\,(\widetilde{V}_{2\mu}^T\,i\sigma_2)\,\Psi_\ell$	$e^-\,u \to \gamma\left(\widetilde{V}_{2\mu}^{+1/3}\right)^c$	—
		$-1/2$	$-2/3$		—	—
$\vec{U}_{3\mu}$	$4/3$	1	$5/3$	$\overline{\Psi}_q\,\gamma^\mu P_L\,U_{3\mu}^{ad}\,\Psi_\ell$	$e^-\,\bar{u} \to \gamma\left(U_{3\mu}^{+5/3}\right)^c$	$-1/5$
		0	$2/3$		$e^-\,\bar{d} \to \gamma\left(U_{3\mu}^{+2/3}\right)^c$	—
		-1	$-1/3$		—	—

Go

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ϕ	Y_ϕ	T_3	Q_ϕ	Interaction	Production Channel	$\cos\theta^*$
$U_{1\mu}$	$4/3$	0	$2/3$	$\overline{\Psi}_q\,\gamma^\mu P_L\,\Psi_\ell\,U_{1\mu} \oplus \bar{q}_d\,\gamma^\mu P_R\,\ell_e\,U_{1\mu}$	$e^-\,\bar{d} \to \gamma\left(U_{1\mu}^{+2/3}\right)^c$	—
$\widetilde{U}_{1\mu}$	$10/3$	0	$5/3$	$\bar{q}_u\,\gamma^\mu P_R\,\ell_e\,\widetilde{U}_{1\mu}$	$e^-\,\bar{u} \to \gamma\left(\widetilde{U}_{1\mu}^{+5/3}\right)^c$	$-1/5$
$V_{2\mu}$	$5/3$	$1/2$	$4/3$	$\overline{\Psi}^c_q\,\gamma^\mu P_R\,(i\sigma_2\,V_{2\mu})\ell_e$	$e^-\,d \to \gamma\left(V_{2\mu}^{+4/3}\right)^c$	$-1/2$
		$-1/2$	$1/3$	$\oplus\,\bar{q}^c_d\,\gamma^\mu P_L\,(V^T_{2\mu}\,i\sigma_2)\,\Psi_\ell$	$e^-\,u \to \gamma\left(V_{2\mu}^{+1/3}\right)^c$	—
$\widetilde{V}_{2\mu}$	$-1/3$	$1/2$	$1/3$	$\bar{q}^c_u\,\gamma^\mu P_L\,(\widetilde{V}^T_{2\mu}\,i\sigma_2)\,\Psi_\ell$	$e^-\,u \to \gamma\left(\widetilde{V}_{2\mu}^{+1/3}\right)^c$	—
		$-1/2$	$-2/3$		—	—
$\vec{U}_{3\mu}$	$4/3$	1	$5/3$	$\overline{\Psi}_q\,\gamma^\mu P_L\,U^{ad}_{3\mu}\,\Psi_\ell$	$e^-\,\bar{u} \to \gamma\left(U_{3\mu}^{+5/3}\right)^c$	$-1/5$
		0	$2/3$		$e^-\,\bar{d} \to \gamma\left(U_{3\mu}^{+2/3}\right)^c$	—
		-1	$-1/3$		—	—

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$\widetilde{U}_{1\mu}$	$10/3$	0	$5/3$	$\bar{q}_u\,\gamma^\mu P_R\,\ell_e\,\widetilde{U}_{1\mu}$	$e^-\,\bar{u} \to \gamma\,\left(\widetilde{U}_{1\mu}^{+5/3}\right)^c$	$-1/5$
$V_{2\mu}$	$5/3$	$1/2$	$4/3$	$\overline{\Psi}_q^c\,\gamma^\mu P_R\,(i\sigma_2\,V_{2\mu})\ell_e$	$e^-\,d \to \gamma\,\left(V_{2\mu}^{+4/3}\right)^c$	$-1/2$
		$-1/2$	$1/3$	$\oplus\,\bar{q}_d^c\,\gamma^\mu P_L\,(V_{2\mu}^T\,i\sigma_2)\,\Psi_\ell$	$e^-\,u \to \gamma\,\left(V_{2\mu}^{+1/3}\right)^c$	—
$\widetilde{V}_{2\mu}$	$-1/3$	$1/2$	$1/3$	$\bar{q}_u^c\,\gamma^\mu P_L\,(\widetilde{V}_{2\mu}^T\,i\sigma_2)\,\Psi_\ell$	$e^-\,u \to \gamma\,\left(\widetilde{V}_{2\mu}^{+1/3}\right)^c$	—
		$-1/2$	$-2/3$		—	—
$\vec{U}_{3\mu}$	$4/3$	1	$5/3$	$\overline{\Psi}_q\,\gamma^\mu P_L\,U_{3\mu}^{ad}\,\Psi_\ell$	$e^-\,\bar{u} \to \gamma\,\left(U_{3\mu}^{+5/3}\right)^c$	$-1/5$
		0	$2/3$		$e^-\,\bar{d} \to \gamma\,\left(U_{3\mu}^{+2/3}\right)^c$	—
		-1	$-1/3$		—	—

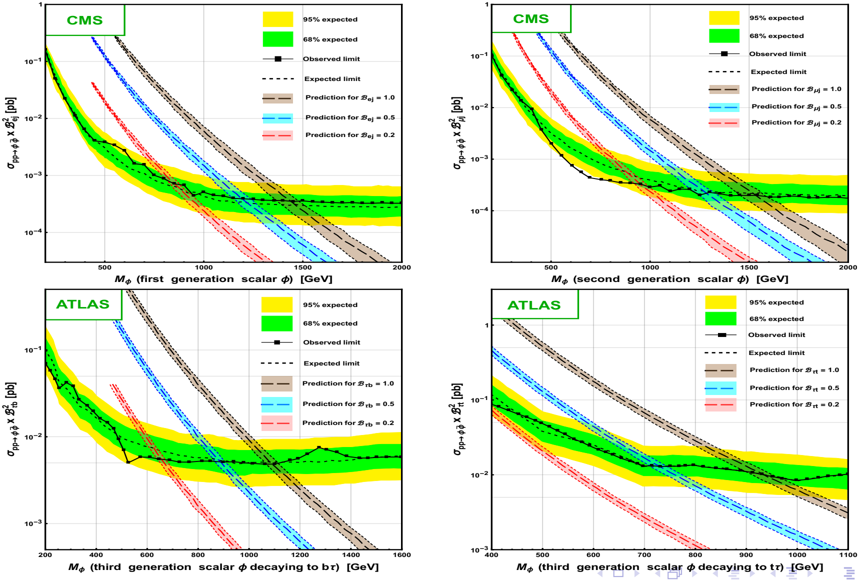
Go

Vector Leptoquarks

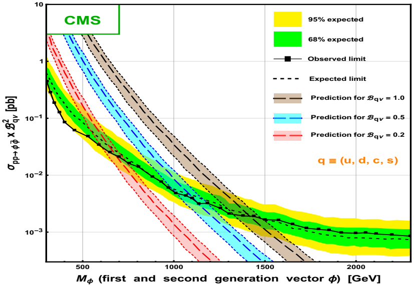
ϕ	Y_ϕ	T_3	Q_ϕ	Interaction	Production Channel	$\cos\theta^*$
$U_{1\mu}$	$4/3$	0	$2/3$	$\overline{\Psi}_q\,\gamma^\mu P_L\,\Psi_\ell\,U_{1\mu} \bigoplus \bar{q}_d\,\gamma^\mu P_R\,\ell_e\,U_{1\mu}$	$e^-\,\bar{d} \to \gamma\left(U_{1\mu}^{+2/3}\right)^c$	—
$\widetilde{U}_{1\mu}$	$10/3$	0	$5/3$	$\bar{q}_u\,\gamma^\mu P_R\,\ell_e\,\widetilde{U}_{1\mu}$	$e^-\,\bar{u} \to \gamma\left(\widetilde{U}_{1\mu}^{+5/3}\right)^c$	$-1/5$
$V_{2\mu}$	$5/3$	$1/2$	$4/3$	$\overline{\Psi}_q^c\,\gamma^\mu P_R\,(i\sigma_2\,V_{2\mu})\ell_e$	$e^-\,d \to \gamma\left(V_{2\mu}^{+4/3}\right)^c$	$-1/2$
		$-1/2$	$1/3$	$\bigoplus \bar{q}_d^c\,\gamma^\mu P_L\,(V_{2\mu}^T\,i\sigma_2)\,\Psi_\ell$	$e^-\,u \to \gamma\left(V_{2\mu}^{+1/3}\right)^c$	—
$\widetilde{V}_{2\mu}$	$-1/3$	$1/2$	$1/3$	$\bar{q}_u^c\,\gamma^\mu P_L\,(\widetilde{V}_{2\mu}^T\,i\sigma_2)\,\Psi_\ell$	$e^-\,u \to \gamma\left(\widetilde{V}_{2\mu}^{+1/3}\right)^c$	—
		$-1/2$	$-2/3$		—	—
$\vec{U}_{3\mu}$	$4/3$	1	$5/3$	$\overline{\Psi}_q\,\gamma^\mu P_L\,U_{3\mu}^{ad}\,\Psi_\ell$	$e^-\,\bar{u} \to \gamma\left(U_{3\mu}^{+5/3}\right)^c$	$-1/5$
		0	$2/3$		$e^-\,\bar{d} \to \gamma\left(U_{3\mu}^{+2/3}\right)^c$	—
		-1	$-1/3$		—	—

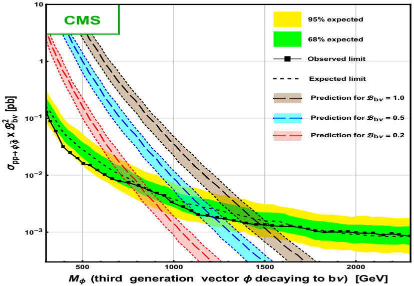
Go

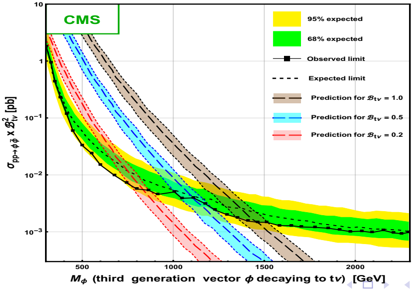
Bounds on Scalar Leptoquarks



Bounds on Vector Leptoquarks





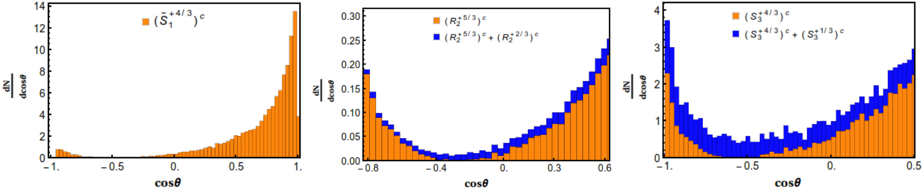


Set up

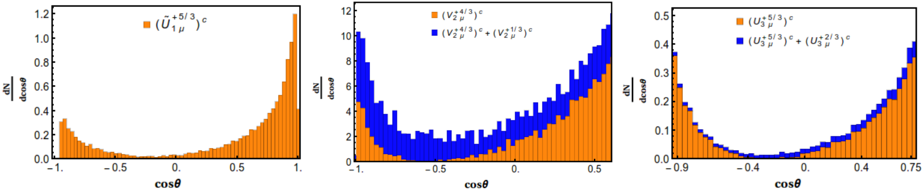
- $M_\phi = 1.5$ TeV, $Y^{ii}_{L,R} = 0.2$
- $e\ q \rightarrow \gamma\ \phi\ (\rightarrow \mu\ q')$
- No SM background. But there exists model background.
- Cuts on invariant mass, transverse momenta, etc., are implemented.

Results at FCC-I

Scalar Leptoquark



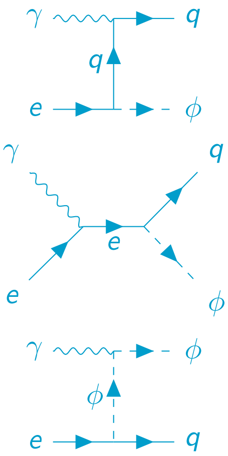
Vector Leptoquark



Production of Leptoquarks at $e\gamma$ collider

Cross-section with Monochromatic Photon

$e\gamma \to q\phi$

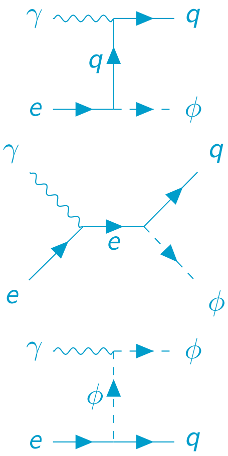


Cross-section with Monochromatic Photon

$$\sum_{spin} |\mathcal{M}^S|^2 = \frac{e^2\left[(Y_L^{eq})^2 + (Y_R^{eq})^2\right]\left[(s-M_\phi^2)^2(1+\cos\theta)^2 + 4M_\phi^4\right]}{s\,(s-M_\phi^2)\,(1-\cos\theta)\,\left[s(1+\cos\theta) + M_\phi^2(1-\cos\theta)\right]^2} \times \left[(s-M_\phi^2)(1-\cos\theta) + 2sQ_q\right]^2$$

$$\sum_{spin} |\mathcal{M}^V|^2 = \frac{2e^2\left[(Y_L^{eq})^2 + (Y_R^{eq})^2\right]\left[(s-M_\phi^2)(1-\cos\theta) + 2sQ_q\right]^2}{s\,(s-M_\phi^2)\,(1-\cos\theta)\,\left[s(1+\cos\theta) + M_\phi^2(1-\cos\theta)\right]^2} \times \left[\{s(1-\cos\theta) + M_\phi^2(1+\cos\theta)\}^2 + 4(s-M_\phi^2)^2\right]$$

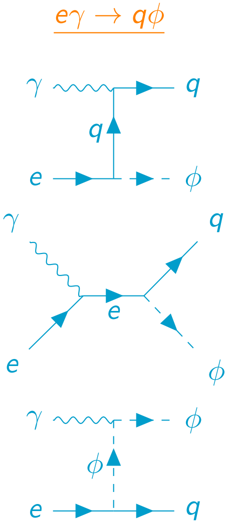
$e\gamma \to q\phi$



Cross-section with Monochromatic Photon

$$\sum_{spin} |\mathcal{M}^S|^2 = \frac{e^2\,[(Y_L^{eq})^2 + (Y_R^{eq})^2]\left[(s - M_\phi^2)^2(1+\cos\theta)^2 + 4M_\phi^4\right]}{s\,(s - M_\phi^2)\,(1-\cos\theta)\,\left[s(1+\cos\theta) + M_\phi^2(1-\cos\theta)\right]^2} \times \boxed{\left[(s - M_\phi^2)(1-\cos\theta) + 2sQ_q\right]^2}$$

$$\sum_{spin} |\mathcal{M}^V|^2 = \frac{2e^2\,[(Y_L^{eq})^2 + (Y_R^{eq})^2]\boxed{\left[(s - M_\phi^2)(1-\cos\theta) + 2sQ_q\right]^2}}{s\,(s - M_\phi^2)\,(1-\cos\theta)\,\left[s(1+\cos\theta) + M_\phi^2(1-\cos\theta)\right]^2} \times \left[\{s(1-\cos\theta) + M_\phi^2(1+\cos\theta)\}^2 + 4(s - M_\phi^2)^2\right]$$



Cross-section with Monochromatic Photon

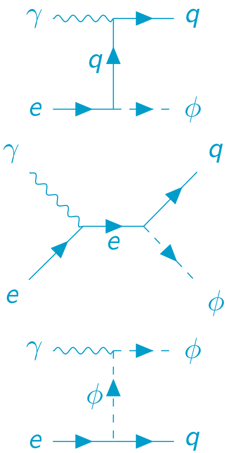
$$\sum_{spin} |\mathcal{M}^S|^2 = \frac{e^2\,[(Y_L^{eq})^2 + (Y_R^{eq})^2]\left[(s - M_\phi^2)^2(1+\cos\theta)^2 + 4M_\phi^4\right]}{s\,(s - M_\phi^2)\,(1-\cos\theta)\,\left[s(1+\cos\theta) + M_\phi^2(1-\cos\theta)\right]^2} \times \boxed{\left[(s - M_\phi^2)(1-\cos\theta) + 2sQ_q\right]^2}$$

$$\sum_{spin} |\mathcal{M}^V|^2 = \frac{2e^2\,[(Y_L^{eq})^2 + (Y_R^{eq})^2]\boxed{\left[(s - M_\phi^2)(1-\cos\theta) + 2sQ_q\right]^2}}{s\,(s - M_\phi^2)\,(1-\cos\theta)\,\left[s(1+\cos\theta) + M_\phi^2(1-\cos\theta)\right]^2} \times \left[\{s(1-\cos\theta) + M_\phi^2(1+\cos\theta)\}^2 + 4(s - M_\phi^2)^2\right]$$

$$\mathbf{\cos^* = 1 + 2\left[\frac{1+Q_\phi}{1-(M_\phi^2/s)}\right] = g\,(Q_\phi, M_\phi^2/s)}$$

$$\Longrightarrow \frac{p_e.p_\gamma}{-1} = \frac{p_q.p_\gamma}{Q_q} = \frac{p_\phi.p_\gamma}{Q_\phi}$$

$e\gamma \to q\phi$



Cross-section with Monochromatic Photon

$$\sum_{spin} |\mathcal{M}^S|^2 = \frac{e^2\left[(Y_L^{eq})^2 + (Y_R^{eq})^2\right]\left[(s-M_\phi^2)^2(1+\cos\theta)^2 + 4M_\phi^4\right]}{s\,(s-M_\phi^2)\,(1-\cos\theta)\,\left[s(1+\cos\theta)+M_\phi^2(1-\cos\theta)\right]^2} \times \boxed{\left[(s-M_\phi^2)(1-\cos\theta)+2sQ_q\right]^2}$$

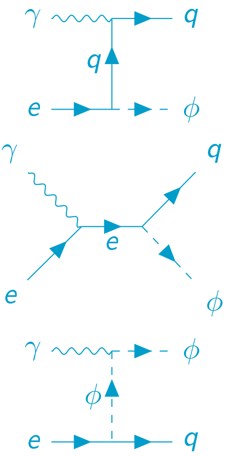
$$\sum_{spin} |\mathcal{M}^V|^2 = \frac{2e^2\left[(Y_L^{eq})^2 + (Y_R^{eq})^2\right]\boxed{\left[(s-M_\phi^2)(1-\cos\theta)+2sQ_q\right]^2}}{s\,(s-M_\phi^2)\,(1-\cos\theta)\,\left[s(1+\cos\theta)+M_\phi^2(1-\cos\theta)\right]^2} \times \left[\{s(1-\cos\theta)+M_\phi^2(1+\cos\theta)\}^2 + 4(s-M_\phi^2)^2\right]$$

$$\mathbf{\cos^* = 1 + 2\left[\frac{1+Q_\phi}{1-(M_\phi^2/s)}\right] = g\,(Q_\phi, M_\phi^2/s)}$$

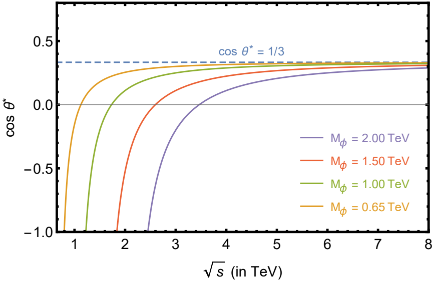
$$\implies \frac{p_e.p_\gamma}{-1} = \frac{p_q.p_\gamma}{Q_q} = \frac{p_\phi.p_\gamma}{Q_\phi}$$

$$Q_\phi < 0 \quad \text{and} \quad (M_\phi^2/s) < |Q_\phi| < 1$$

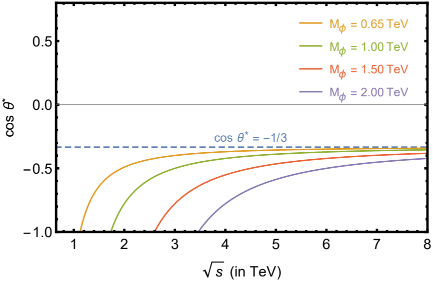
$e\gamma \to q\phi$



Variation of zero



$|Q_\phi| = 2/3$



$|Q_\phi| = 1/3$

Scalar Leptoquarks

ϕ	Y_ϕ	T_3	Q_ϕ	Interaction	Production	$\cos\theta^*$
S_1	$2/3$	0	$1/3$	$\overline{\Psi}^c_q\, P_L\, i\sigma_2 \Psi_\ell\, S_1 \bigoplus \bar{q}^c_u\, P_R\, \ell_e\, S_1$	$\bar{u}\left(S_1^{+1/3}\right)^c$	$g(-1/3, M_\phi^2/s)$
$\widetilde{S}_1$	$8/3$	0	$4/3$	$\bar{q}^c_d\, P_R\, \ell_e\, \widetilde{S}_1$	$\bar{d}\left(\widetilde{S}_1^{+4/3}\right)^c$	——
R_2	$7/3$	$1/2$	$5/3$	$\bar{q}_u\, P_L\, (R_2^T\, i\sigma_2)\, \Psi_\ell$	$u\left(R_2^{+5/3}\right)^c$	——
		$-1/2$	$2/3$	$\bigoplus\ \overline{\Psi}_q\, P_R\, R_2\, \ell_e$	$d\left(R_2^{+2/3}\right)^c$	$g(-2/3, M_\phi^2/s)$
$\widetilde{R}_2$	$1/3$	$1/2$	$2/3$	$\bar{q}_d\, P_L\, (\widetilde{R}_2^T\, i\sigma_2)\, \Psi_\ell$	$d\left(\widetilde{R}_2^{+2/3}\right)^c$	$g(-2/3, M_\phi^2/s)$
		$-1/2$	$-1/3$		——	——
$\vec{S}_3$	$2/3$	1	$4/3$	$\overline{\Psi}^c_q\, P_L\, (i\sigma_2\, S_3^{ad})\, \Psi_\ell$	$\bar{d}\left(S_3^{+4/3}\right)^c$	——
		0	$1/3$		$\bar{u}\left(S_3^{+1/3}\right)^c$	$g(-1/3, M_\phi^2/s)$
		-1	$-2/3$		——	——

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Scalar Leptoquarks

ϕ	Y_ϕ	T_3	Q_ϕ	Interaction	Production	$\cos\theta^*$
S_1	$2/3$	0	$1/3$	$\overline{\Psi}_q^c\, P_L\, i\sigma_2 \Psi_\ell\, S_1 \bigoplus \bar{q}_u^c\, P_R\, \ell_e\, S_1$	$\bar{u}\left(S_1^{+1/3}\right)^c$	$g(-1/3, M_\phi^2/s)$
$\widetilde{S}_1$	$8/3$	0	$4/3$	$\bar{q}_d^c\, P_R\, \ell_e\, \widetilde{S}_1$	$\bar{d}\left(\widetilde{S}_1^{+4/3}\right)^c$	——
R_2	$7/3$	$1/2$	$5/3$	$\bar{q}_u\, P_L\, (R_2^T\, i\sigma_2)\, \Psi_\ell$	$u\left(R_2^{+5/3}\right)^c$	——
		$-1/2$	$2/3$	$\bigoplus\ \overline{\Psi}_q\, P_R\, R_2\, \ell_e$	$d\left(R_2^{+2/3}\right)^c$	$g(-2/3, M_\phi^2/s)$
$\widetilde{R}_2$	$1/3$	$1/2$	$2/3$	$\bar{q}_d\, P_L\, (\widetilde{R}_2^T\, i\sigma_2)\, \Psi_\ell$	$d\left(\widetilde{R}_2^{+2/3}\right)^c$	$g(-2/3, M_\phi^2/s)$
		$-1/2$	$-1/3$		——	——
$\vec{S}_3$	$2/3$	1	$4/3$	$\overline{\Psi}_q^c\, P_L\, (i\sigma_2\, S_3^{ad})\, \Psi_\ell$	$\bar{d}\left(S_3^{+4/3}\right)^c$	——
		0	$1/3$		$\bar{u}\left(S_3^{+1/3}\right)^c$	$g(-1/3, M_\phi^2/s)$
		-1	$-2/3$		——	——

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Scalar Leptoquarks

ϕ	Y_ϕ	T_3	Q_ϕ	Interaction	Production	$\cos\theta^*$
S_1	$2/3$	0	$1/3$	$\overline{\Psi}_q^c\, P_L\, i\sigma_2 \Psi_\ell\, S_1 \bigoplus \bar{q}_u^c\, P_R\, \ell_e\, S_1$	$\bar{u}\left(S_1^{+1/3}\right)^c$	$g(-1/3, M_\phi^2/s)$
$\widetilde{S}_1$	$8/3$	0	$4/3$	$\bar{q}_d^c\, P_R\, \ell_e\, \widetilde{S}_1$	$\bar{d}\left(\widetilde{S}_1^{+4/3}\right)^c$	——
R_2	$7/3$	$1/2$	$5/3$	$\bar{q}_u\, P_L\, (R_2^T\, i\sigma_2)\, \Psi_\ell$	$u\left(R_2^{+5/3}\right)^c$	——
		$-1/2$	$2/3$	$\bigoplus\ \overline{\Psi}_q\, P_R\, R_2\, \ell_e$	$d\left(R_2^{+2/3}\right)^c$	$g(-2/3, M_\phi^2/s)$
$\widetilde{R}_2$	$1/3$	$1/2$	$2/3$	$\bar{q}_d\, P_L\, (\widetilde{R}_2^T\, i\sigma_2)\, \Psi_\ell$	$d\left(\widetilde{R}_2^{+2/3}\right)^c$	$g(-2/3, M_\phi^2/s)$
		$-1/2$	$-1/3$		——	——
$\vec{S}_3$	$2/3$	1	$4/3$	$\overline{\Psi}_q^c\, P_L\, (i\sigma_2\, S_3^{ad})\, \Psi_\ell$	$\bar{d}\left(S_3^{+4/3}\right)^c$	——
		0	$1/3$		$\bar{u}\left(S_3^{+1/3}\right)^c$	$g(-1/3, M_\phi^2/s)$
		-1	$-2/3$		——	——

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Scalar Leptoquarks

ϕ	Y_ϕ	T_3	Q_ϕ	Interaction	Production	$\cos\theta^*$
S_1	$2/3$	0	$1/3$	$\overline{\Psi}^c_q\, P_L\, i\sigma_2 \Psi_\ell\, S_1 \bigoplus \bar{q}^c_u\, P_R\, \ell_e\, S_1$	$\bar{u}\left(S_1^{+1/3}\right)^c$	$g(-1/3, M_\phi^2/s)$
$\widetilde{S}_1$	$8/3$	0	$4/3$	$\bar{q}^c_d\, P_R\, \ell_e\, \widetilde{S}_1$	$\bar{d}\left(\widetilde{S}_1^{+4/3}\right)^c$	——
R_2	$7/3$	$1/2$	$5/3$	$\bar{q}_u\, P_L\, (R_2^T\, i\sigma_2)\, \Psi_\ell$	$u\left(R_2^{+5/3}\right)^c$	——
		$-1/2$	$2/3$	$\bigoplus\ \overline{\Psi}_q\, P_R\, R_2\, \ell_e$	$d\left(R_2^{+2/3}\right)^c$	$g(-2/3, M_\phi^2/s)$
$\widetilde{R}_2$	$1/3$	$1/2$	$2/3$	$\bar{q}_d\, P_L\, (\widetilde{R}_2^T\, i\sigma_2)\, \Psi_\ell$	$d\left(\widetilde{R}_2^{+2/3}\right)^c$	$g(-2/3, M_\phi^2/s)$
		$-1/2$	$-1/3$		——	——
$\vec{S}_3$	$2/3$	1	$4/3$		$\bar{d}\left(S_3^{+4/3}\right)^c$	——
		0	$1/3$	$\overline{\Psi}^c_q\, P_L\, (i\sigma_2\, S_3^{ad})\, \Psi_\ell$	$\bar{u}\left(S_3^{+1/3}\right)^c$	$g(-1/3, M_\phi^2/s)$
		-1	$-2/3$		——	——

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Vector Leptoquarks

ϕ	Y_ϕ	T_3	Q_ϕ	Interaction	Production	$\cos\theta^*$
$U_{1\mu}$	$4/3$	0	$2/3$	$\overline{\Psi}_q\,\gamma^\mu P_L\,\Psi_\ell\,U_{1\mu}$ $\bigoplus\,\bar{q}_d\,\gamma^\mu P_R\,\ell_e\,U_{1\mu}$	$d\left(U_{1\mu}^{+2/3}\right)^c$	$g(-2/3, M_\phi^2/s)$
$\widetilde{U}_{1\mu}$	$10/3$	0	$5/3$	$\bar{q}_u\,\gamma^\mu P_R\,\ell_e\,\widetilde{U}_{1\mu}$	$u\left(\widetilde{U}_{1\mu}^{+5/3}\right)^c$	——
$V_{2\mu}$	$5/3$	$1/2$	$4/3$	$\overline{\Psi}_q^c\,\gamma^\mu P_R\,(i\sigma_2\,V_{2\mu})\ell_e$	$\bar{d}\left(V_{2\mu}^{+4/3}\right)^c$	——
		$-1/2$	$1/3$	$\bigoplus\,\bar{q}_d^c\,\gamma^\mu P_L\,(V_{2\mu}^T\,i\sigma_2)\,\Psi_\ell$	$\bar{u}\left(V_{2\mu}^{+1/3}\right)^c$	$g(-1/3, M_\phi^2/s)$
$\widetilde{V}_{2\mu}$	$-1/3$	$1/2$	$1/3$	$\bar{q}_u^c\,\gamma^\mu P_L\,(\widetilde{V}_{2\mu}^T\,i\sigma_2)\,\Psi_\ell$	$\bar{u}\left(\widetilde{V}_{2\mu}^{+1/3}\right)^c$	$g(-1/3, M_\phi^2/s)$
		$-1/2$	$-2/3$		——	——
$\vec{U}_{3\mu}$	$4/3$	1	$5/3$		$u\left(U_{3\mu}^{+5/3}\right)^c$	——
		0	$2/3$	$\overline{\Psi}_q\,\gamma^\mu P_L\,U_{3\mu}^{ad}\,\Psi_\ell$	$d\left(U_{3\mu}^{+2/3}\right)^c$	$g(-2/3, M_\phi^2/s)$
		-1	$-1/3$		——	——

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Vector Leptoquarks

ϕ	Y_ϕ	T_3	Q_ϕ	Interaction	Production	$\cos\theta^*$
$U_{1\mu}$	$4/3$	0	$2/3$	$\overline{\Psi}_q\,\gamma^\mu P_L\,\Psi_\ell\,U_{1\mu}$ $\bigoplus\,\bar{q}_d\,\gamma^\mu P_R\,\ell_e\,U_{1\mu}$	$d\left(U_{1\mu}^{+2/3}\right)^c$	$g(-2/3, M_\phi^2/s)$
$\widetilde{U}_{1\mu}$	$10/3$	0	$5/3$	$\bar{q}_u\,\gamma^\mu P_R\,\ell_e\,\widetilde{U}_{1\mu}$	$u\left(\widetilde{U}_{1\mu}^{+5/3}\right)^c$	——
$V_{2\mu}$	$5/3$	$1/2$	$4/3$	$\overline{\Psi}_q^c\,\gamma^\mu P_R\,(i\sigma_2\,V_{2\mu})\ell_e$	$\bar{d}\left(V_{2\mu}^{+4/3}\right)^c$	——
		$-1/2$	$1/3$	$\bigoplus\,\bar{q}_d^c\,\gamma^\mu P_L\,(V_{2\mu}^T\,i\sigma_2)\,\Psi_\ell$	$\bar{u}\left(V_{2\mu}^{+1/3}\right)^c$	$g(-1/3, M_\phi^2/s)$
$\widetilde{V}_{2\mu}$	$-1/3$	$1/2$	$1/3$	$\bar{q}_u^c\,\gamma^\mu P_L\,(\widetilde{V}_{2\mu}^T\,i\sigma_2)\,\Psi_\ell$	$\bar{u}\left(\widetilde{V}_{2\mu}^{+1/3}\right)^c$	$g(-1/3, M_\phi^2/s)$
		$-1/2$	$-2/3$		——	——
$\vec{U}_{3\mu}$	$4/3$	1	$5/3$		$u\left(U_{3\mu}^{+5/3}\right)^c$	——
		0	$2/3$	$\overline{\Psi}_q\,\gamma^\mu P_L\,U_{3\mu}^{ad}\,\Psi_\ell$	$d\left(U_{3\mu}^{+2/3}\right)^c$	$g(-2/3, M_\phi^2/s)$
		-1	$-1/3$		——	——

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Vector Leptoquarks

ϕ	Y_ϕ	T_3	Q_ϕ	Interaction	Production	$\cos\theta^*$
$U_{1\mu}$	$4/3$	0	$2/3$	$\overline{\Psi}_q\,\gamma^\mu P_L\,\Psi_\ell\,U_{1\mu} \oplus \bar{q}_d\,\gamma^\mu P_R\,\ell_e\,U_{1\mu}$	$d\left(U_{1\mu}^{+2/3}\right)^c$	$g(-2/3, M_\phi^2/s)$
$\widetilde{U}_{1\mu}$	$10/3$	0	$5/3$	$\bar{q}_u\,\gamma^\mu P_R\,\ell_e\,\widetilde{U}_{1\mu}$	$u\left(\widetilde{U}_{1\mu}^{+5/3}\right)^c$	——
$V_{2\mu}$	$5/3$	$1/2$	$4/3$	$\overline{\Psi}^c_q\,\gamma^\mu P_R\,(i\sigma_2\,V_{2\mu})\ell_e$	$\bar{d}\left(V_{2\mu}^{+4/3}\right)^c$	——
		$-1/2$	$1/3$	$\oplus\ \bar{q}^c_d\,\gamma^\mu P_L\,(V^T_{2\mu}\,i\sigma_2)\,\Psi_\ell$	$\bar{u}\left(V_{2\mu}^{+1/3}\right)^c$	$g(-1/3, M_\phi^2/s)$
$\widetilde{V}_{2\mu}$	$-1/3$	$1/2$	$1/3$	$\bar{q}^c_u\,\gamma^\mu P_L\,(\widetilde{V}^T_{2\mu}\,i\sigma_2)\,\Psi_\ell$	$\bar{u}\left(\widetilde{V}_{2\mu}^{+1/3}\right)^c$	$g(-1/3, M_\phi^2/s)$
		$-1/2$	$-2/3$		——	——
$\vec{U}_{3\mu}$	$4/3$	1	$5/3$		$u\left(U_{3\mu}^{+5/3}\right)^c$	——
		0	$2/3$	$\overline{\Psi}_q\,\gamma^\mu P_L\,U^{ad}_{3\mu}\,\Psi_\ell$	$d\left(U_{3\mu}^{+2/3}\right)^c$	$g(-2/3, M_\phi^2/s)$
		-1	$-1/3$		——	——

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Vector Leptoquarks

ϕ	Y_ϕ	T_3	Q_ϕ	Interaction	Production	$\cos\theta^*$
$U_{1\mu}$	$4/3$	0	$2/3$	$\overline{\Psi}_q\,\gamma^\mu P_L\,\Psi_\ell\,U_{1\mu}$ $\bigoplus \bar{q}_d\,\gamma^\mu P_R\,\ell_e\,U_{1\mu}$	$d\left(U_{1\mu}^{+2/3}\right)^c$	$g(-2/3, M_\phi^2/s)$
$\widetilde{U}_{1\mu}$	$10/3$	0	$5/3$	$\bar{q}_u\,\gamma^\mu P_R\,\ell_e\,\widetilde{U}_{1\mu}$	$u\left(\widetilde{U}_{1\mu}^{+5/3}\right)^c$	——
$V_{2\mu}$	$5/3$	$1/2$	$4/3$	$\overline{\Psi}_q^c\,\gamma^\mu P_R\,(i\sigma_2\,V_{2\mu})\ell_e$	$\bar{d}\left(V_{2\mu}^{+4/3}\right)^c$	——
		$-1/2$	$1/3$	$\bigoplus \bar{q}_d^c\,\gamma^\mu P_L\,(V_{2\mu}^T\,i\sigma_2)\,\Psi_\ell$	$\bar{u}\left(V_{2\mu}^{+1/3}\right)^c$	$g(-1/3, M_\phi^2/s)$
$\widetilde{V}_{2\mu}$	$-1/3$	$1/2$	$1/3$	$\bar{q}_u^c\,\gamma^\mu P_L\,(\widetilde{V}_{2\mu}^T\,i\sigma_2)\,\Psi_\ell$	$\bar{u}\left(\widetilde{V}_{2\mu}^{+1/3}\right)^c$	$g(-1/3, M_\phi^2/s)$
		$-1/2$	$-2/3$		——	——
$\vec{U}_{3\mu}$	$4/3$	1	$5/3$	$\overline{\Psi}_q\,\gamma^\mu P_L\,U_{3\mu}^{ad}\,\Psi_\ell$	$u\left(U_{3\mu}^{+5/3}\right)^c$	——
		0	$2/3$		$d\left(U_{3\mu}^{+2/3}\right)^c$	$g(-2/3, M_\phi^2/s)$
		-1	$-1/3$		——	——

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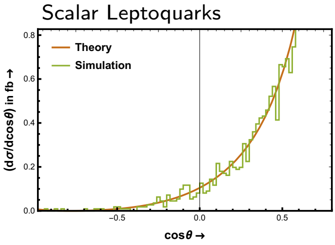
set up

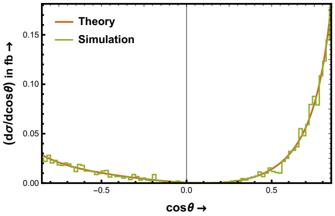
- $S_1^{1/3}$ & $U_{1\mu}^{2/3} \implies M_\phi = 1500$ GeV; $\sqrt{s} = 3$ TeV & $Y_L^{ii} = Y_R^{ii} = 0.1$
- $\widetilde{R_2}^{2/3}$ & $\widetilde{V}_{2\mu}^{1/3} \implies M_\phi = 1500$ GeV; $\sqrt{s} = 3$ TeV; $Y_L^{11} = Y_L^{22} = 0.07$ & $Y_L^{33} = 0.1$
- $e\gamma \to q\,\phi(\to e\,q)$. So, we look for $e + 2j$ signatures.
- There are SM backgrounds from γ, Z mediation.
- Cuts on invariant mass and $\cos\theta_{\ell j}$ have been used to reduce background.

Scalar Leptoquarks

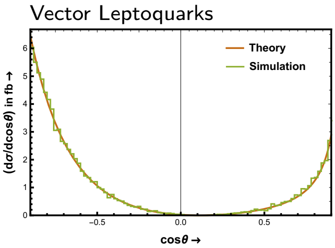
$(S_1^{1/3})^c$:



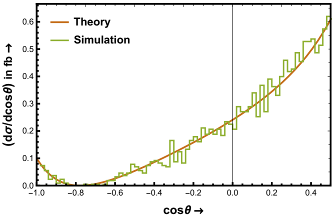
$(\widetilde{R}_2^{2/3})^c$:



$(U_{1\mu}^{2/3})^c$:

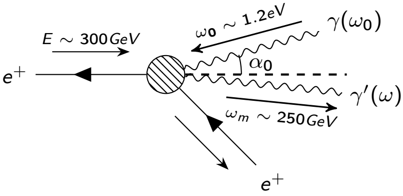


$(\widetilde{V}_{2\mu}^{1/3})^c$:



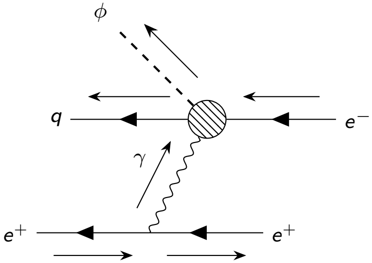
$e\gamma$ colliders

Laser Backscattering (LB):



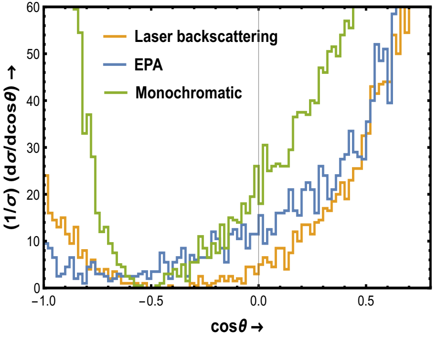
~ I.F. Ginzburg, et al., Nucl. Instrum. Methods Phys. Res. 205(1–2), 47–68 (1981)

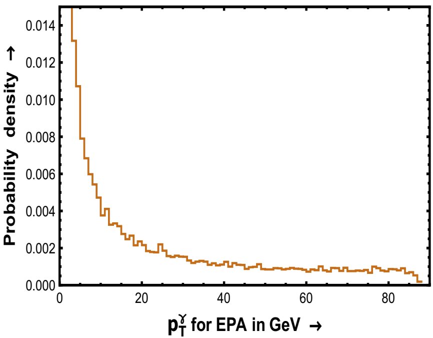
Equivalent Photon Approximation (EPA):



~ V. M. Budnev, et al., [Phys. Rept. 15 (1975) 181-281]

Non-monochromatic Photons





Conclusion

- For $e\,p$ collision, position of RAZ depends on Q_ϕ only.
- For $e\gamma$ collision, position of zero depends on M_ϕ^2/s as well as on Q_ϕ.
- $\widetilde{R}_2^{1/3}$, $S_3^{2/3}$, $\widetilde{V}_{2\mu}^{2/3}$ and $U_{3\mu}^{1/3}$ cannot be produced at both the colliders.
- To observe RAZ at ep collider : $|Q_\phi| > 1$; but at $e\gamma$ collider : $(M_\phi^2/s) < |Q_\phi| < 1$. Therefore, these two colliders are complementary.
- LB is better than EPA, even better than monochromatic photon at $e\gamma$ collider.
- LB shows the zero in angular distribution while EPA does not.


Thank You!