Leptoquarks and Zeros of Amplitude at e-γ Collider

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Anirban Karan,

IIT Hyderabad, India.

Co-authors: Priyotosh Bandyopadhyay, Saunak Dutta

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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 $SU(2)_L$.
- Can explain flavour anomalies.
- Lots of experimental searches. No success yet.

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

Radiation Amplitude Zero (RAZ):

- First described for $\bar{u}\, d \to W^- \gamma$. ~ *K. Mikaelian, et al. [Phys. Rev. Lett. 43 (1979) 746]*
- In non-Abelian theories, single photon tree-level amplitude vanishes in certain kinematical zones depending on the charge and four momenta of external particles.
- For $2 \to 2$ process with photon in final state, this happens at:

$$\cos\theta^* = (Q_{f_2} - Q_{f_1})/(Q_{f_2} + Q_{f_1})$$

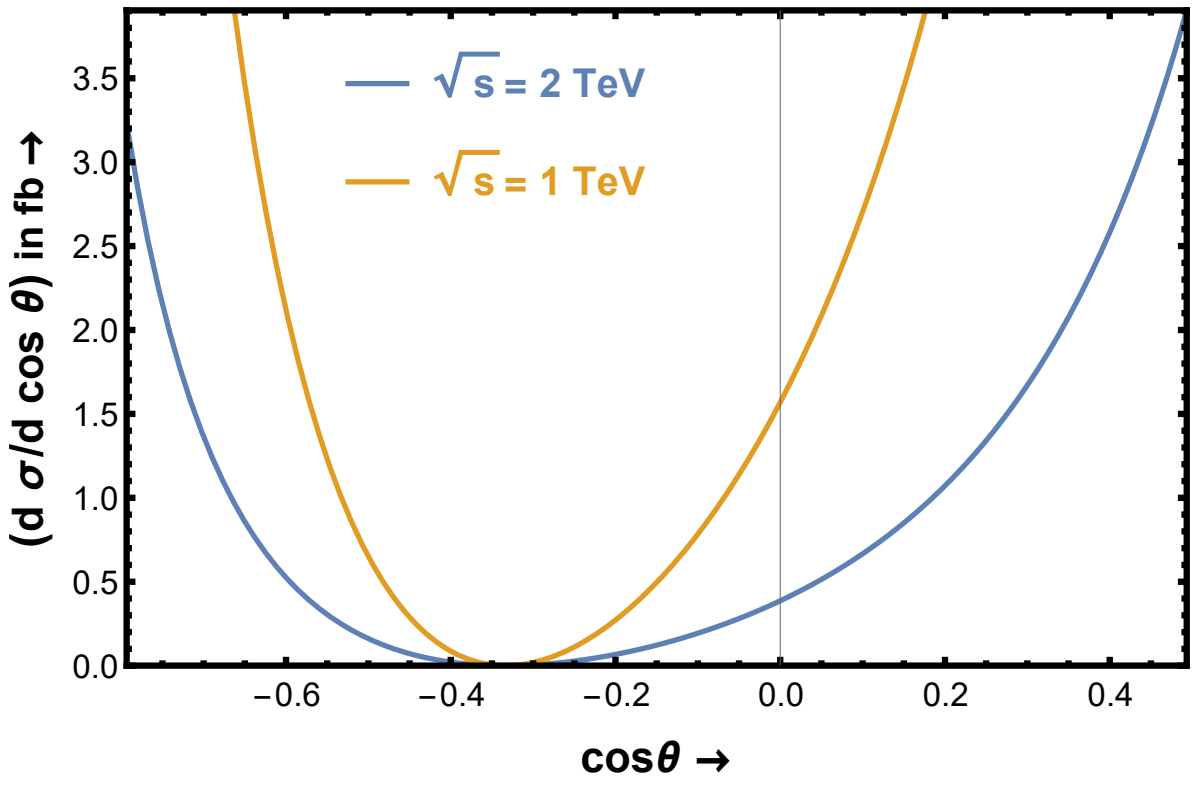
  where, Q_{f_1} and Q_{f_2} are the charges for the incoming particles f_1 and f_2 and θ^* is the angle between photon and f_1 in the centre of momentum (CM) frame at which RAZ occurs.
- General Criterion: $\left(\frac{p_j \cdot k}{Q_j}\right)$ same for all the external particles.

  ~ *S. J. Brodsky and R. W. Brown, [Phys. Rev. Lett. 49 (1982) 966]*

RAZ for $\bar{u}\,d \to W^-\gamma$:

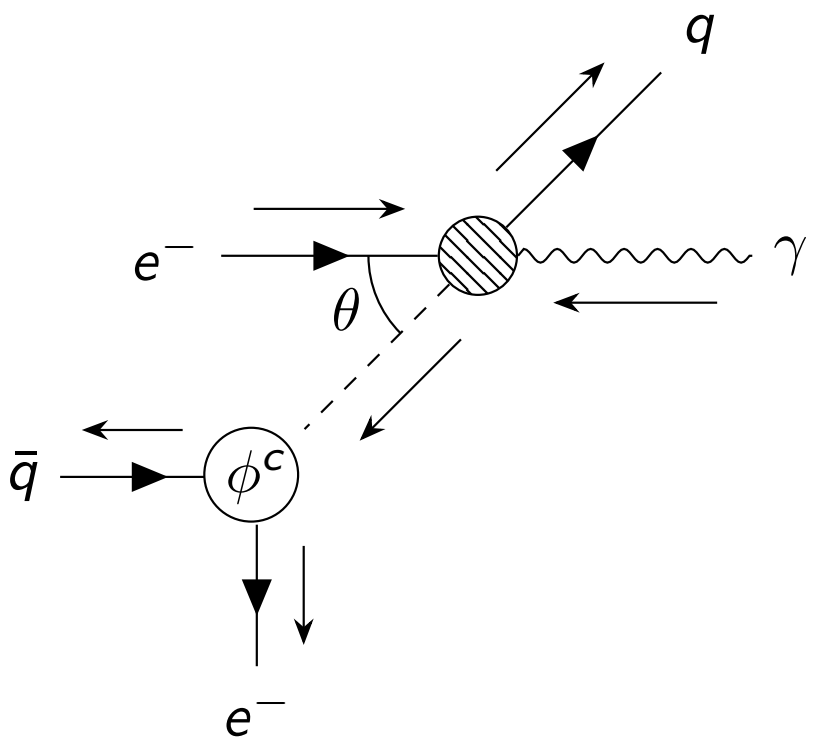
$$\frac{d\sigma}{d\cos\theta} \propto \frac{(1+2Q_d+\cos\theta)^2\,[(s+m_W^2)^2+(s-m_W^2)^2\cos^2\theta]}{s^2(s-m_W^2)\sin^2\theta},$$

θ is the angle between (d, W^-).



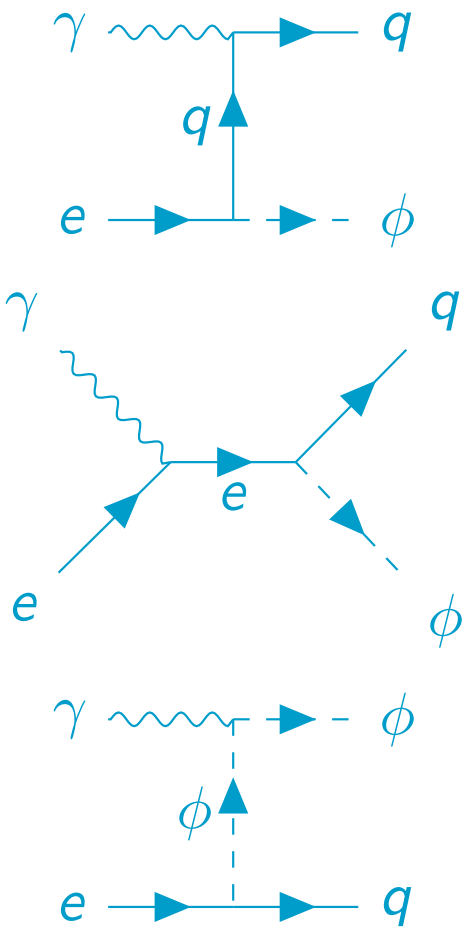
$e - \gamma$ colliders:

- Proposed collider.
- Linear $e^+ - e^-$ colliders (like ILC) can be used to study $e - \gamma$ interaction at high energy.
- Less background, $\sqrt{s}$ is exactly known (monochromatic).
- Our mode: $e^-\gamma \to q\,\phi^c$ (or $\bar{q}\,\phi$); ϕ is LQ.



Cross-section with Monochromatic Photon

$e\gamma \to q\phi$

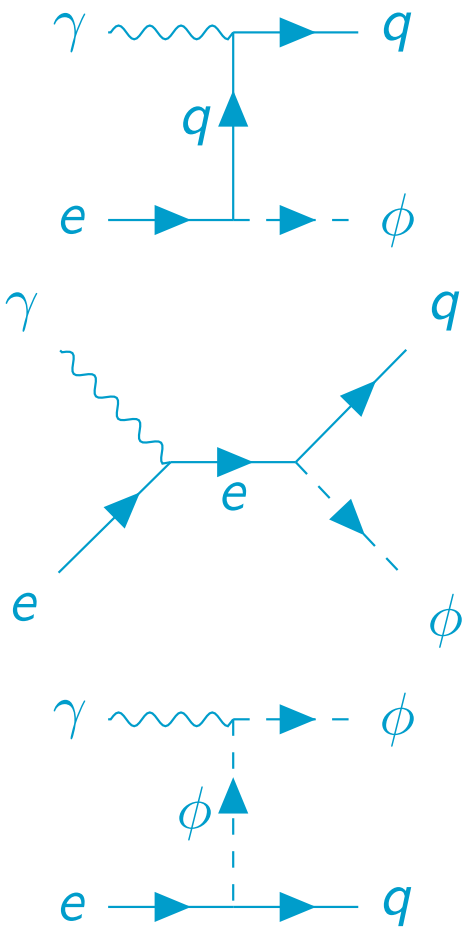


Cross-section with Monochromatic Photon

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

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

$e\gamma \to q\phi$

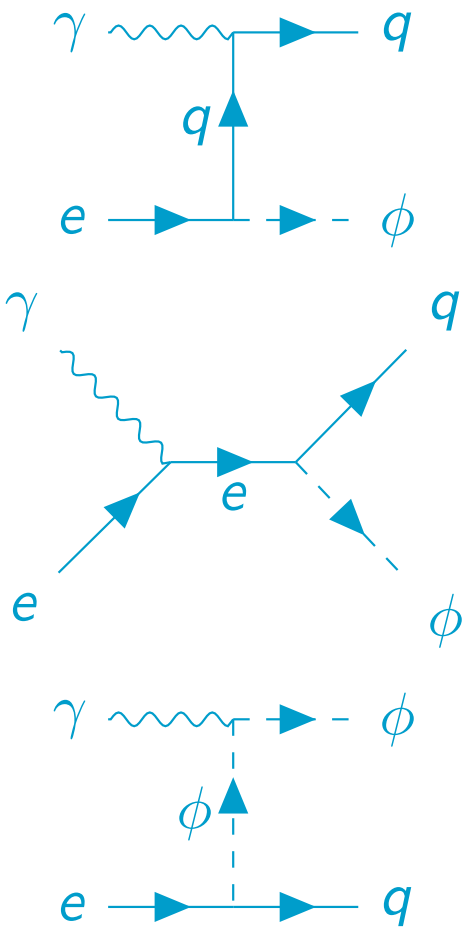


Cross-section with Monochromatic Photon

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

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

$e\gamma \to q\phi$



Cross-section with Monochromatic Photon

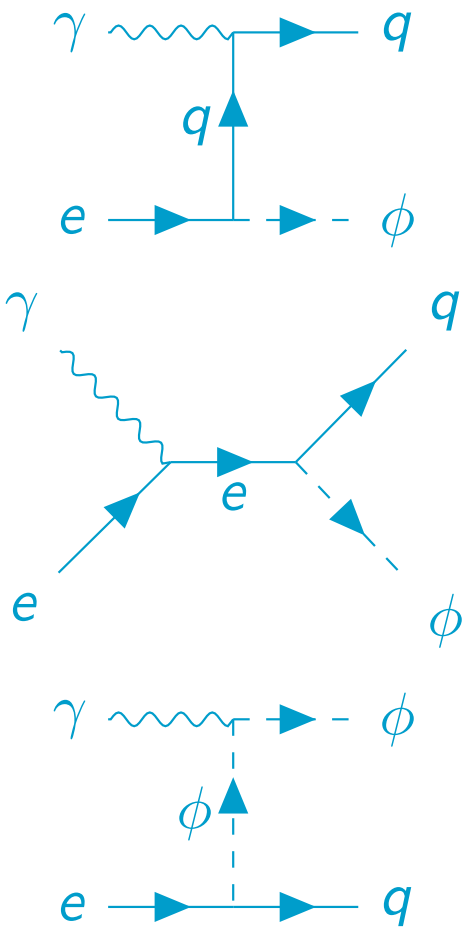
$$\sum_{spin} |\mathcal{M}^S|^2 = \frac{e^2\left[(Y_L^{eq})^2 + (Y_R^{eq})^2\right]\left[(s-M_\phi^2)^2(1+\cos\theta)^2 + 4M_\phi^4\right]}{s\,(s-M_\phi^2)\,(1-\cos\theta)\left[s(1+\cos\theta)+M_\phi^2(1-\cos\theta)\right]^2} \times \boxed{\left[(s-M_\phi^2)(1-\cos\theta)+2sQ_q\right]^2}$$

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

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

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

$e\gamma \to q\phi$



Cross-section with Monochromatic Photon

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

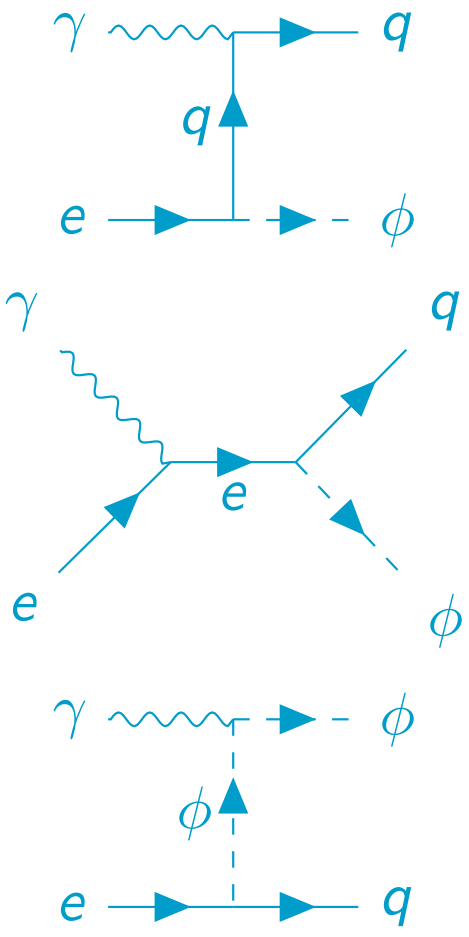
$$\sum_{spin} |\mathcal{M}^V|^2 = \frac{2e^2\left[(Y_L^{eq})^2 + (Y_R^{eq})^2\right]\boxed{\left[(s-M_\phi^2)(1-\cos\theta)+2sQ_q\right]^2}}{s\,(s-M_\phi^2)\,(1-\cos\theta)\left[s(1+\cos\theta)+M_\phi^2(1-\cos\theta)\right]^2} \times \left[\{s(1-\cos\theta)+M_\phi^2(1+\cos\theta)\}^2 + 4(s-M_\phi^2)^2\right]$$

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

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

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

$e\gamma \to q\phi$



$\cos\theta^*$ vs $\sqrt{s}$:

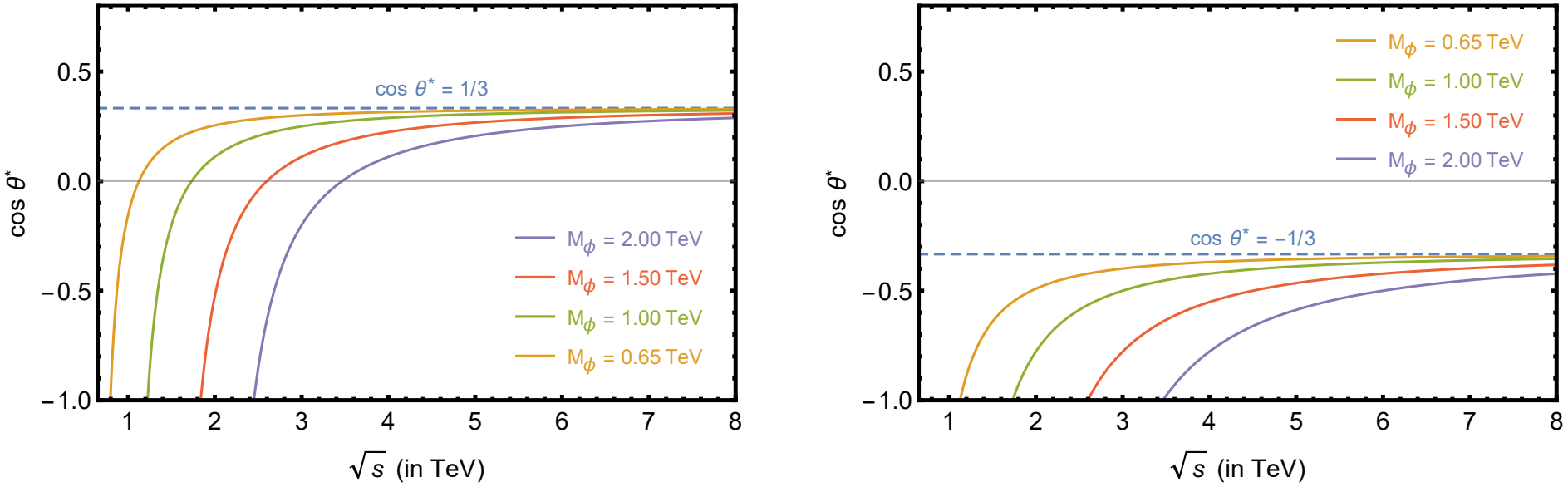


Figure: Variation of $\cos\theta^*$ with respect to $\sqrt{s}$ for $Q_\phi = -2/3$ and $Q_\phi = -1/3$, respectively for different masses of leptoquark.

Scalar Leptoquarks

ϕ	$\mathtt{Y}_\phi$	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	$\mathtt{Y}_\phi$	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	$1/3$	$\overline{\Psi}_q^c\, P_L\, i\sigma_2 \Psi_\ell\, S_1 \bigoplus \bar{q}_u^c\, P_R\, \ell_e\, S_1$	$\bar{u}\left(S_1^{+1/3}\right)^c$	$g(-1/3, M_\phi^2/s)$
$\widetilde{S}_1$	$8/3$	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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Vector Leptoquarks

ϕ	$\mathtt{Y}_\phi$	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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Vector Leptoquarks

ϕ	$\mathtt{Y}_\phi$	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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Vector Leptoquarks

ϕ	$\mathtt{Y}_\phi$	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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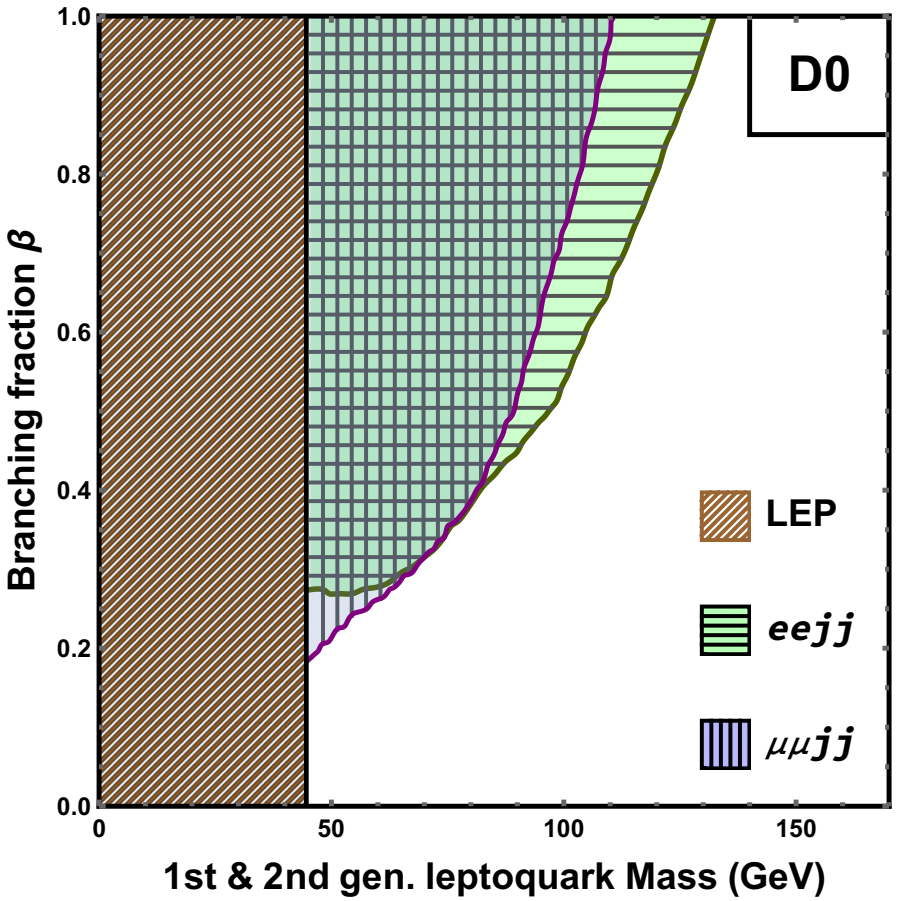
Vector Leptoquarks

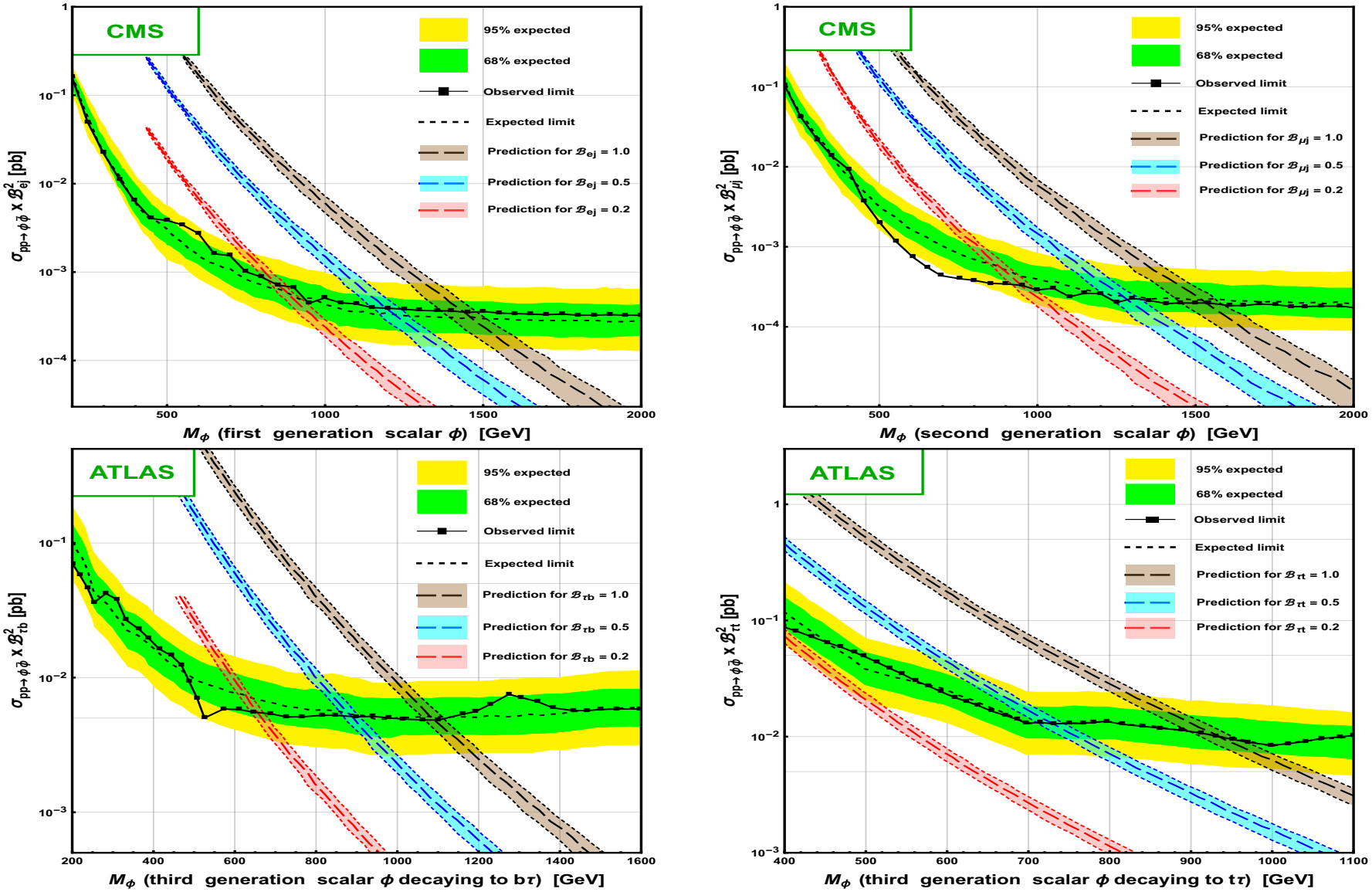
ϕ	Υ_ϕ	T_3	Q_ϕ	Interaction	Production	$\cos\theta^*$
$U_{1\mu}$	$4/3$	0	$2/3$	$\overline{\Psi}_q\,\gamma^\mu P_L\,\Psi_\ell\,U_{1\mu}$ $\bigoplus\,\bar{q}_d\,\gamma^\mu P_R\,\ell_e\,U_{1\mu}$	$d\left(U_{1\mu}^{+2/3}\right)^c$	$g(-2/3, M_\phi^2/s)$
$\widetilde{U}_{1\mu}$	$10/3$	0	$5/3$	$\bar{q}_u\,\gamma^\mu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

Back

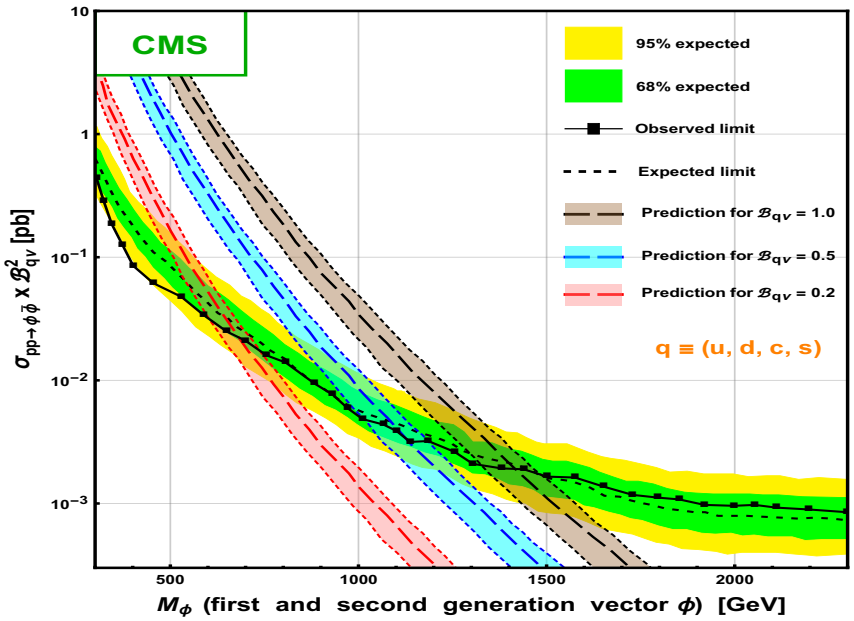
Light Leptoquark:

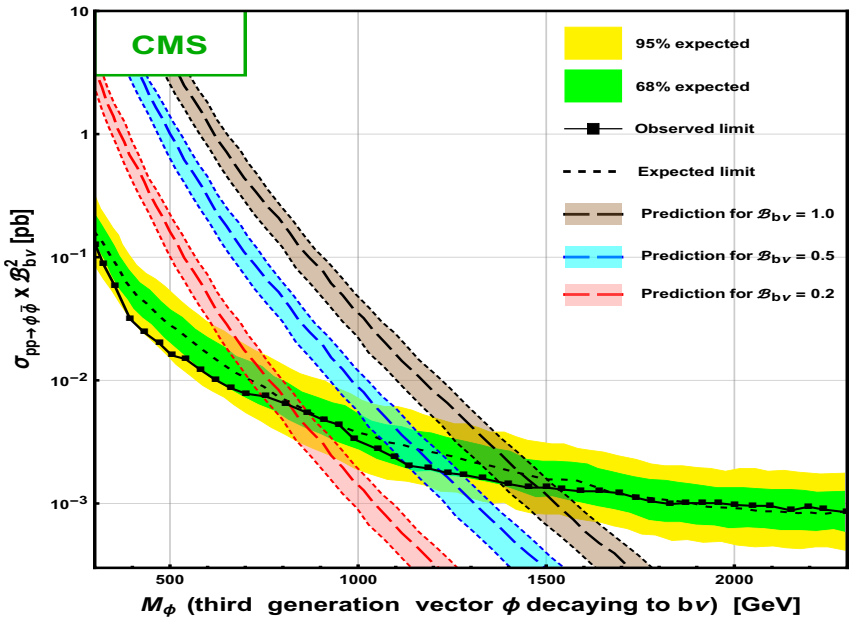


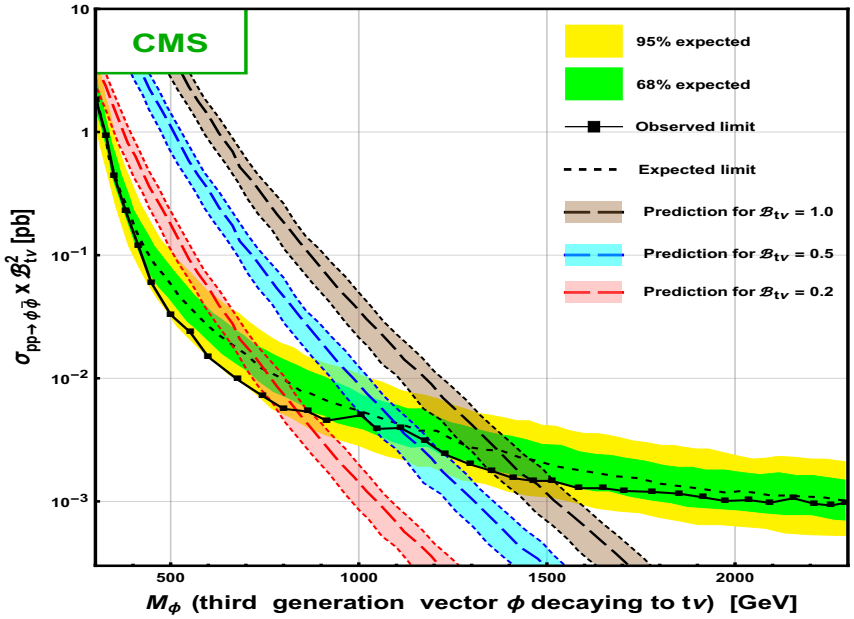
Bounds on Scalar Leptoquarks



Bounds on Vector Leptoquarks







Simulation:

- $\sqrt{s} = \{200 \text{ GeV}, 2 \text{ TeV}, 3 \text{ TeV}\}$, Luminosity: 100 fb^{-1}.
- $M_\phi = \{70 \text{ GeV}, 1.5 \text{ TeV}\}$
- Model: SARAH; event generation: CalcHEP; simulation: PYTHIA.
- $p^{jet}_{T,min} = 20.0$ GeV; $p^{\ell}_{T,min} \geq 10$ GeV.
- Signal-background separation: Cut1 $\Rightarrow |M_{lj} - M_\phi| \leq 10$,
  Cut2 $\Rightarrow$ Angular cut
- We have simulated — Scalars: $(S_1^{+1/3})^c$, $(\widetilde{R}_2^{+2/3})^c$, $(R_2^{+5/3})^c$, $(S_3^{+4/3})^c$
  Vectors: $(U_{1\mu}^{+2/3})^c$, $(\widetilde{V}_{2\mu}^{+1/3})^c$, $(U_{3\mu}^{+5/3})^c$, $(V_{2\mu}^{+4/3})^c$

LQ	M_ϕGeV	Y_L^{11}	Y_L^{22}	Y_L^{33}	Y_R^{11}	Y_R^{22}	Y_R^{33}
$S_1^{1/3}$	70	0.035	0.04	0.035	0.03	0.03	0.03
$U_{1\mu}^{2/3}$	1500	0.1	0.1	0.1	0.1	0.1	0.1

SM Backgrounds:

Decay of LQ: $\phi^c \to e^- q$ (or $\bar{q}$) $\implies$ $e^- + 2$ light-jets signal at detector.

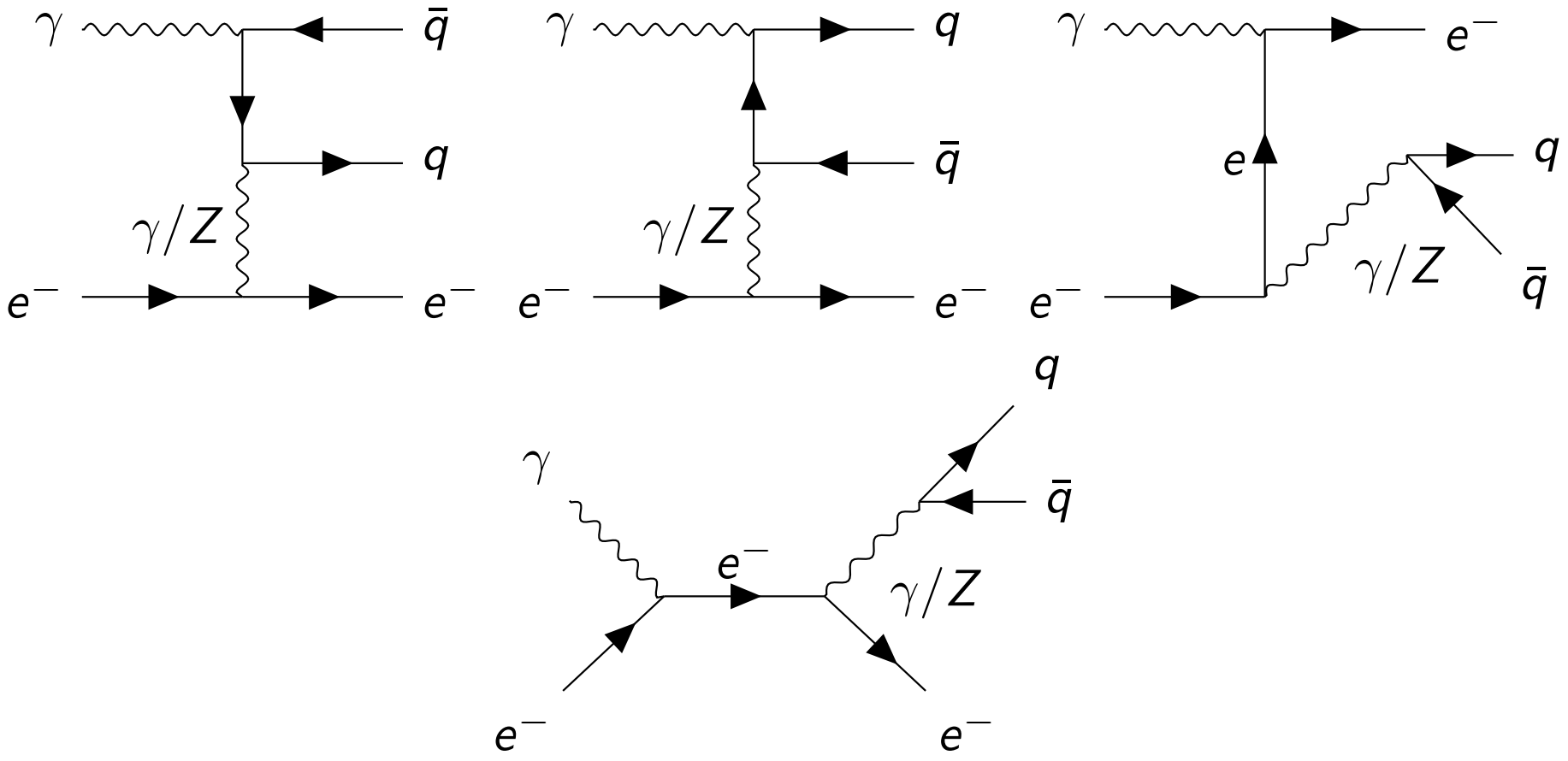
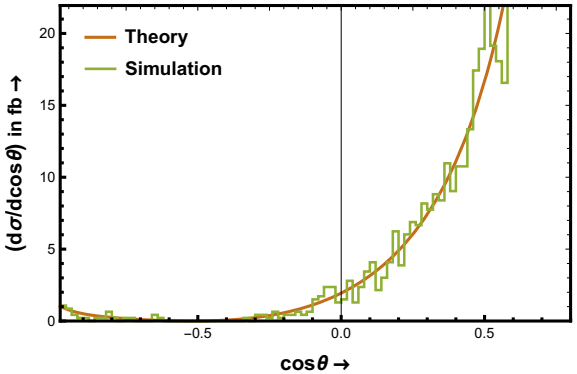
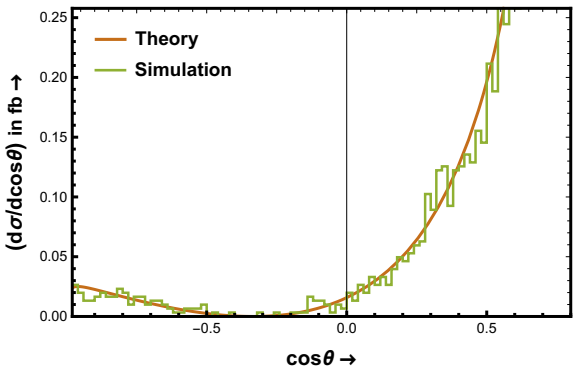


Figure: SM backgrounds

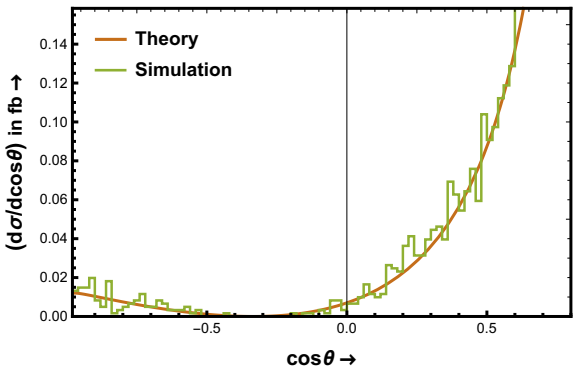
Angular distribution for $S_1^{1/3}$:



(a) $\sqrt{s} = 200$ GeV

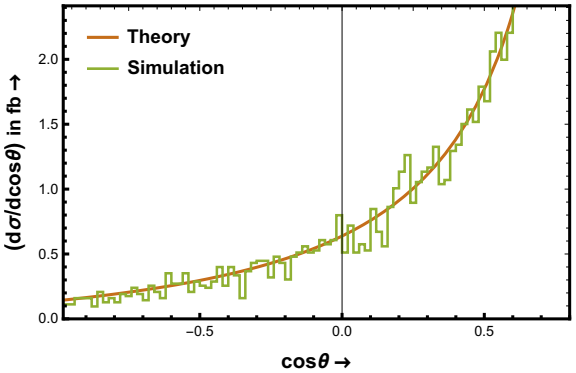


(b) $\sqrt{s} = 2000$ GeV

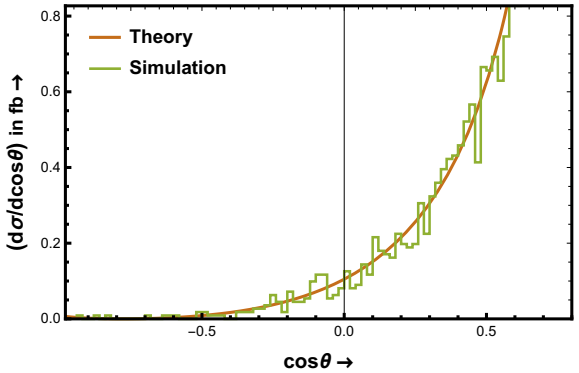


(c) $\sqrt{s} = 3000$ GeV

Figure: For 70 GeV LQ



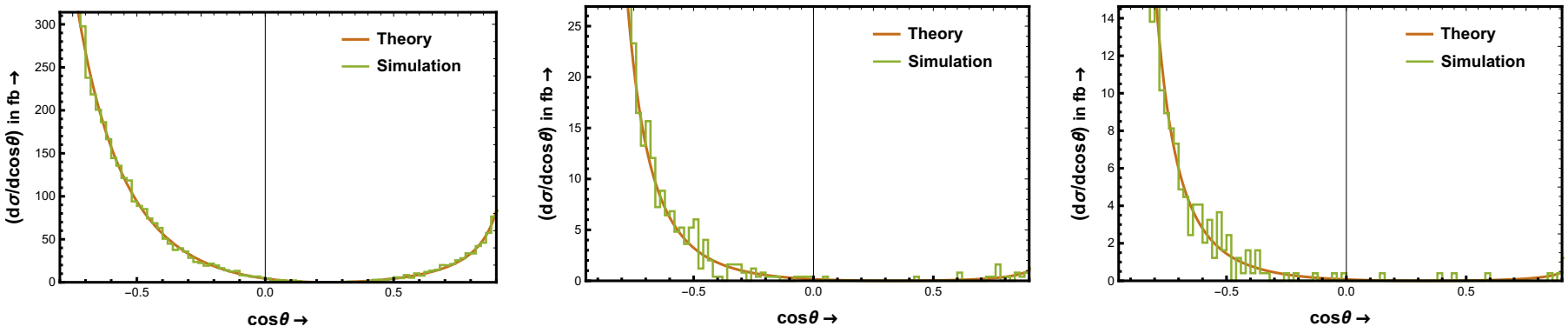
(a) $\sqrt{s} = 2000$ GeV



(b) $\sqrt{s} = 3000$ GeV

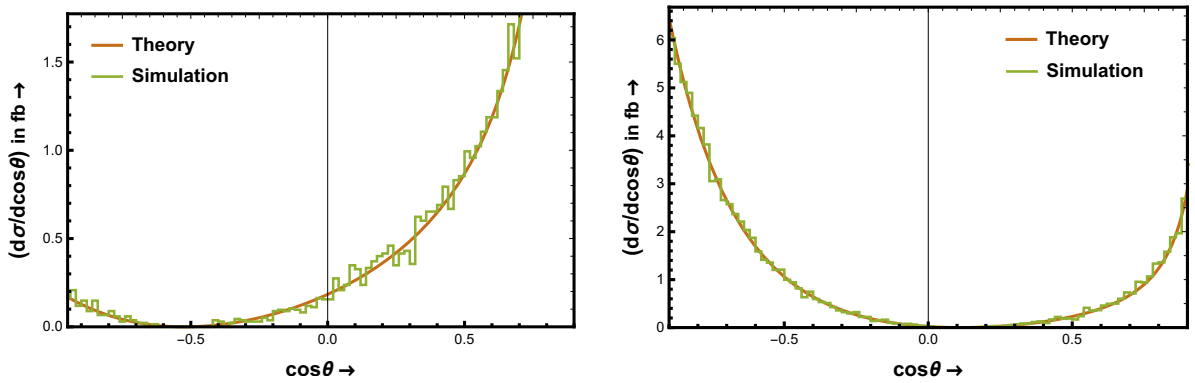
Figure: For 1500 GeV LQ

Angular distribution for $U_{1\mu}^{2/3}$:



(a) $\sqrt{s} = 200$ GeV (b) $\sqrt{s} = 2000$ GeV (c) $\sqrt{s} = 3000$ GeV

Figure: For 70 GeV LQ



(a) $\sqrt{s} = 2000$ GeV (b) $\sqrt{s} = 3000$ GeV

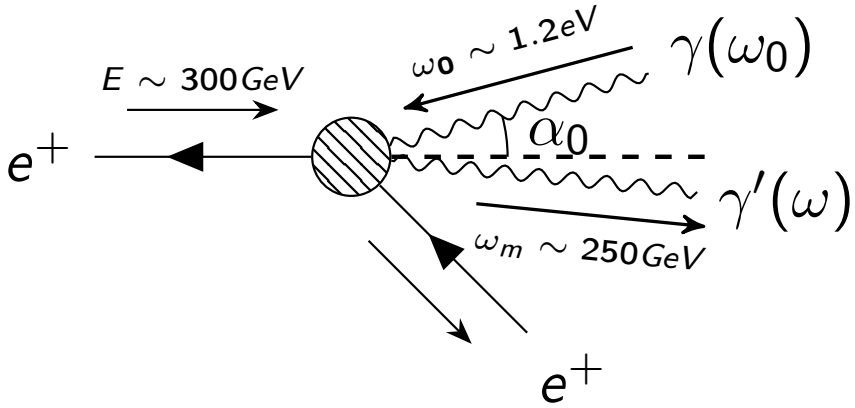
Figure: For 1500 GeV LQ

Non-monochromatic photon:

- Current technology cannot provide high-energetic monochromatic photon source.

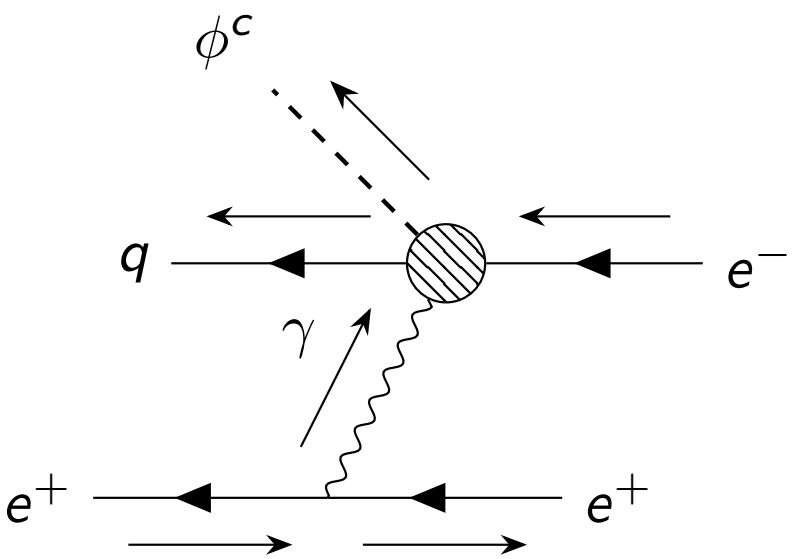
- Laser Backscattering (LB):

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



- Equivalent Photon Approximation (EPA): Any fast moving charged particle can be considered as an electromagnetic radiation field. This radiation can be interpreted as a flux of quasi-real photons with some energy distribution.

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



LB vs EPA:

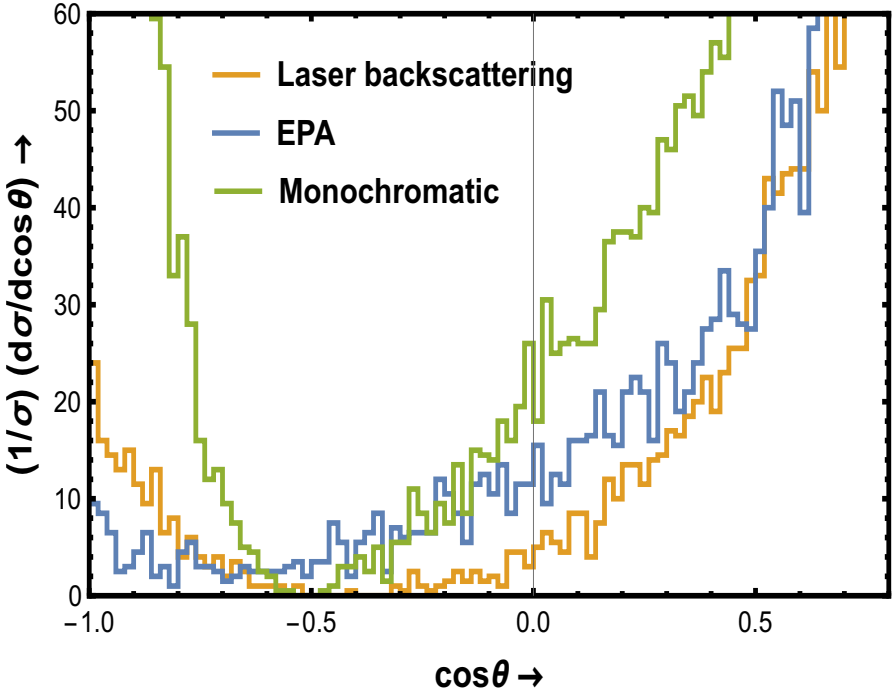
LB

- Real photons.
- Highly collimated.
- p_T distribution of photon goes to zero very fast while moving away from origin.
- Distributions w.r.t angles between (e^-, ϕ) and (γ, ϕ) are similar.
- Production cross section and significance get enhanced than monochromatic.
- Available in CalcHEP.

EPA

- Quasi-real photons.
- Not highly collimated.
- Though small, still photon has non-zero probability for gettimg very high p_T.
- Distributions w.r.t angles between (e^-, ϕ) and (γ, ϕ) are very different.
- Production cross section and significance get diminished than monochromatic.
- Available in CalcHEP & MadGraph.

Monochromatic vs non-monochromatic photons:



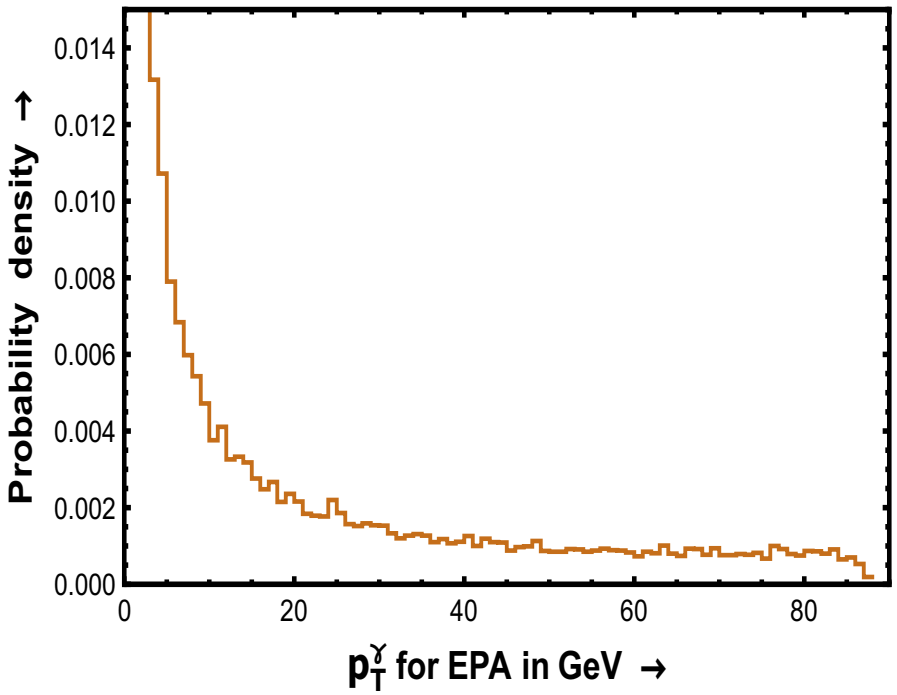


Figure: For $\widetilde{V}_{2\mu}^{+1/3}$ with 70 GeV mass at $\sqrt{s} = 200$ GeV

Summary:

- Unlike other colliders, the position of zeros of single photon tree-level amplitude in $e-\gamma$ collider does depend on $\sqrt{s}$ and M_ϕ along with Q_ϕ.
- Depending on sign of Q_ϕ, $\cos\theta^*$ approaches $\pm 1/3$ for $\sqrt{s} >> M_\phi$.
- Zero in amplitude can be found iff $Q_\phi < 0$ and $(M_\phi^2/s) < |Q_\phi| < 1$.
- In a PYTHIA based analysis we look for both light and heavy leptoquarks of various charges and spin at both low and high energy scales with monochromatic photons.
- About non-monochromatic photon source, LB enhances production cross-section and significance whereas EPA decreases them.
- EPA smears off the zeros of angular distributions completely whereas LB preserves them (though slightly deviated from the monochromatic case).
- Finding this kind of zero at $e-\gamma$ collider will indicate the presence of some leptoquarks.

Thank You!