Production of Leptoquarks and Zeros of Amplitude at e-γ Collider

ArXiv: 2003.11751 (accepted in EPJC)

Anirban Karan

Co-authors: Priyotosh Bandyopadhyay, Saunak Dutta

IIT Hyderabad

June 22, 2020

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 anomalies in B sector, muon $g-2$ and $h \to \mu^{\pm}\tau^{\mp}$.
- Lots of experimental searches. No success yet.

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:

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

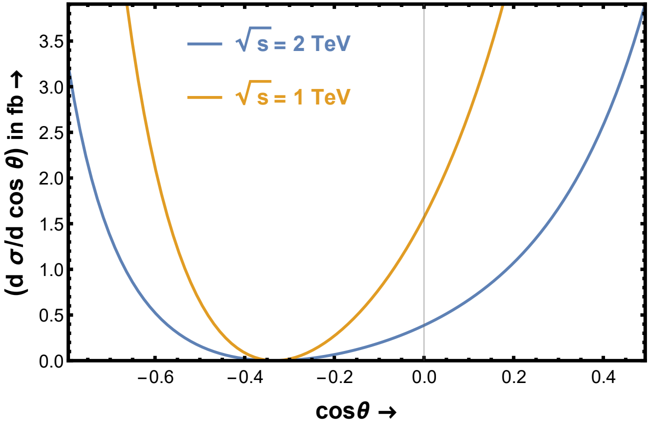
where, Q_{f_1} and Q_{f_2} are the charges for the incoming particles f_1 and f_2 and θ^* is the angle between photon and f_1 in the centre of momentum (CM) frame at which RAZ occurs provided that the masses of colliding particles are negligible w.r.t. $\sqrt{s}$.

- General Criterion: $\left(\frac{p_j \cdot k}{Q_j}\right)$ same for all the external particles (other than photon). ~ *S. J. Brodsky and R. W. Brown, [Phys. Rev. Lett. 49 (1982) 966]*

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

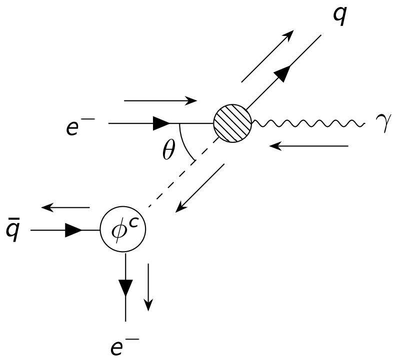
$$\frac{d\sigma}{d\cos\theta} \propto \frac{(1 + 2Q_d + \cos\theta)^2 \, [(s + m_W^2)^2 + (s - m_W^2)^2 \cos^2\theta]}{s^2 (s - m_W^2) \sin^2\theta},$$

θ is the angle between (d, W^-).

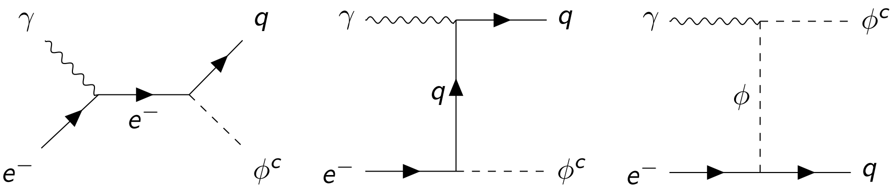


$e - \gamma$ *colliders:*

- 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.



Details of $e^-\gamma \to q\,\phi^c$:



- $\sum_{spin} |\mathcal{M}|^2 \propto \left[(s - M_\phi^2)(1-\cos\theta) + 2sQ_q\right]^2$
- Zero amplitude: $\cos\theta^* = 1 + \frac{2\,Q_q}{[1-(M_\phi^2/s)]} = f(Q_q, M_\phi^2/s)$
- It follows the general condition: $\frac{p_e.p_\gamma}{-1} = \frac{p_q.p_\gamma}{Q_q} = \frac{p_\phi.p_\gamma}{Q_\phi}$
- Condition for occurrence: $Q_q < 0$ and $\frac{M_\phi}{\sqrt{s}} \leq \sqrt{-Q_\phi}$

$$\implies -1 < Q_\phi < 0$$

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

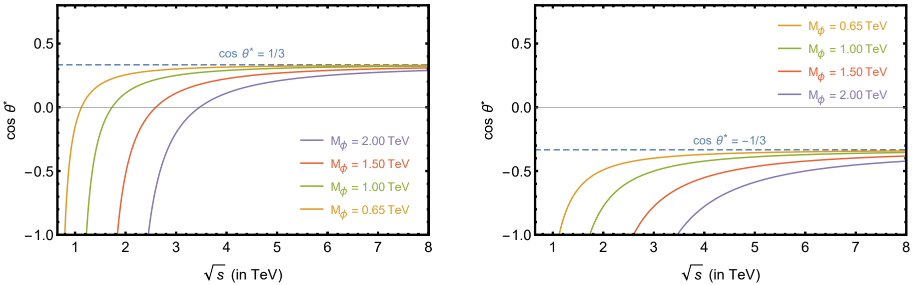


Figure: Variation of $\cos\theta^*$ with respect to $\sqrt{s}$ for $Q_q = -1/3$ and $Q_{\bar{q}} = -2/3$, respectively for different masses of leptoquark.

Scalar Leptoquarks:

LQ	Y	Q_{em}	Interaction	Process	$\cos\theta^*$
S_1	$2/3$	$1/3$	$\overline{\Psi}^c_q P_L\, i\sigma_2 \Psi_l\, S_1$, $\bar{q}^c_u P_R\, l_e\, S_1$	$\bar{u}\left(S_1^{+1/3}\right)^c$	$f(-2/3, M_\phi^2/s)$
$\widetilde{S}_1$	$8/3$	$4/3$	$\bar{q}^c_d P_R\, l_e\, \widetilde{S}_1$	$\bar{d}\left(\widetilde{S}_1^{+4/3}\right)^c$	——
$\vec{S}_3$	$2/3$	$4/3$ $1/3$ $-2/3$	$\overline{\Psi}^c_q P_L\,(i\sigma_2\, S_3^{ad})\,\Psi_l$	$\bar{d}\left(S_3^{+4/3}\right)^c$ $\bar{u}\left(S_3^{+1/3}\right)^c$ ——	—— $f(-2/3, M_\phi^2/s)$ ——
R_2	$7/3$	$5/3$ $2/3$	$\overline{\Psi}_q P_R\, R_2\, l_e$, $\bar{q}_u P_L\,(R_2^T\, i\sigma_2)\,\Psi_l$	$u\left(R_2^{+5/3}\right)^c$ $d\left(R_2^{+2/3}\right)^c$	—— $f(-1/3, M_\phi^2/s)$
$\widetilde{R}_2$	$1/3$	$2/3$ $-1/3$	$\bar{q}_d P_L\,(\widetilde{R}_2^T\, i\sigma_2)\,\Psi_l$	$d\left(\widetilde{R}_2^{+2/3}\right)^c$ —	$f(-1/3, M_\phi^2/s)$ —

Vector Leptoquarks:

LQ	Y	Q_{em}	Interaction	Process	$\cos\theta^*$
$V_{2\mu}$	$5/3$	$4/3$ $1/3$	$\overline{\Psi}^c_q\,\gamma^\mu P_R\,(i\sigma_2\,V_{2\mu})\,l_e,$ $\bar{q}^c_d\,\gamma^\mu P_L\,(V^T_{2\mu}\,i\sigma_2)\,\Psi_l$	$\bar{d}\,\left(V^{+4/3}_{2\mu}\right)^c$ $\bar{u}\,\left(V^{+1/3}_{2\mu}\right)^c$	—— $f(-2/3, M^2_\phi/s)$
$\widetilde{V}_{2\mu}$	$-1/3$	$1/3$ $-2/3$	$\bar{q}^c_u\,\gamma^\mu P_L\,(\widetilde{V}^T_{2\mu}\,i\sigma_2)\,\Psi_l$	$\bar{u}\,\left(\widetilde{V}^{+1/3}_{2\mu}\right)^c$ —	$f(-2/3, M^2_\phi/s)$ ——
$U_{1\mu}$	$4/3$	$2/3$	$\overline{\Psi}_q\,\gamma^\mu P_L\,\Psi_l\,U_{1\mu},$ $\bar{q}_d\,\gamma^\mu P_R\,l_e\,U_{1\mu}$	$d\,\left(U^{+2/3}_{1\mu}\right)^c$	$f(-1/3, M^2_\phi/s)$
$\widetilde{U}_{1\mu}$	$10/3$	$5/3$	$\bar{q}_u\,\gamma^\mu P_R\,l_e\,\widetilde{U}_{1\mu}$	$u\,\left(\widetilde{U}^{+5/3}_{1\mu}\right)^c$	——
$\vec{U}_{3\mu}$	$4/3$	$5/3$ $2/3$ $-1/3$	$\overline{\Psi}_q\,\gamma^\mu P_L\,U^{ad}_{3\mu}\,\Psi_l$	$u\,\left(U^{+5/3}_{3\mu}\right)^c$ $d\,\left(U^{+2/3}_{3\mu}\right)^c$ —	—— $f(-1/3, M^2_\phi/s)$ —

Background:

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

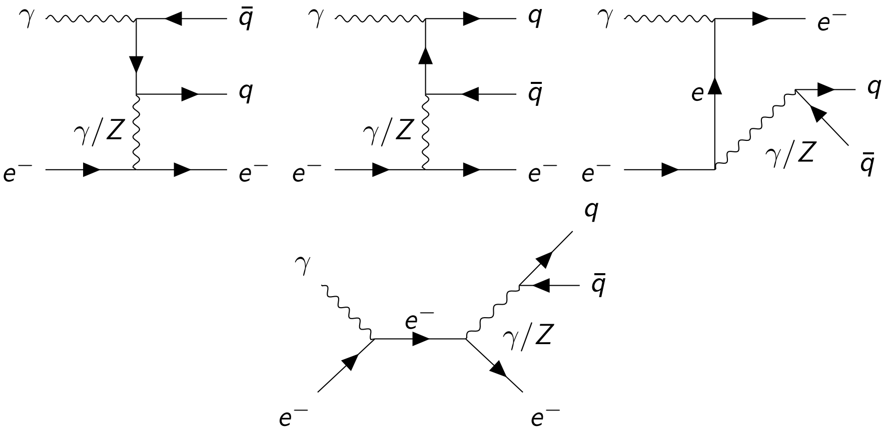


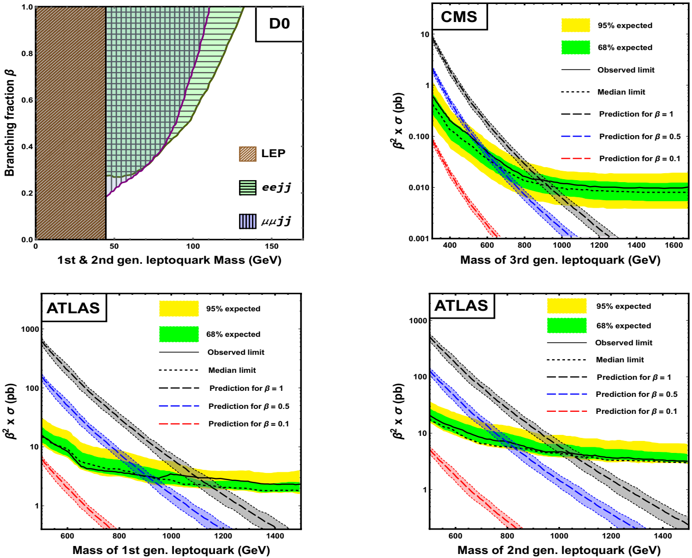
Figure: SM backgrounds

Simulation:

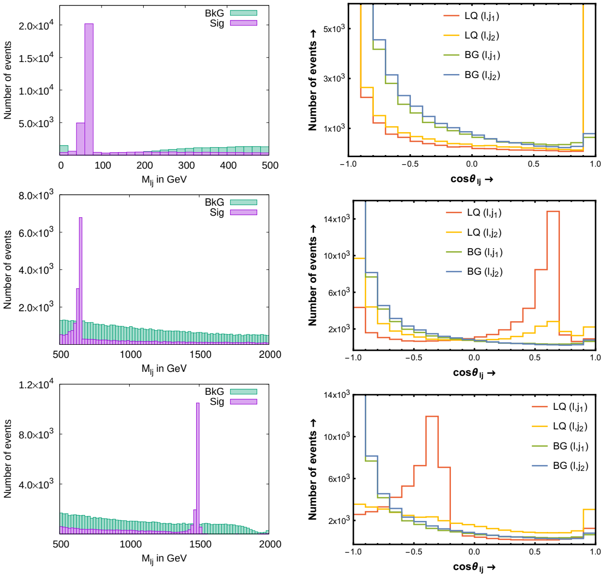
- $\sqrt{s} = \{200 \text{ GeV}, 2 \text{ TeV}, 3 \text{ TeV}\}$, Luminosity: 100 fb^{-1}.
- Model: SARAH; event generation: CalcHEP; simulation: PYTHIA.
- $p_{T,min}^{jet} = 20.0$ GeV; $p_{T,min}^{\ell} \geq 10$ GeV.
- Signal-background separation: Cut1 $\Rightarrow |M_{lj} - M_\phi| \leq 10$,
  Cut2 $\Rightarrow$ Angular cut
- We have simulated — Scalars: $(S_1^{+1/3})^c$, $(\widetilde{R}_2^{+1/3})^c$, $(R_2^{+5/3})^c$, $(S_3^{+4/3})^c$
  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	BP	M_ϕGeV	Y_L^{11}	Y_L^{22}	Y_L^{33}	Y_R^{11}	Y_R^{22}	Y_R^{33}
$(S_1^{+1/3})^c$	BP1	70	0.035	0.04	0.035	0.03	0.03	0.03
	BP2	650	0.1	0.1	0.1	0.1	0.1	0.1
	BP3	1500	0.1	0.1	0.1	0.1	0.1	0.1

Choice for BPs:



Signal-background separation for $(S_1^{+1/3})^c$ at $\sqrt{s} = 3$ TeV :



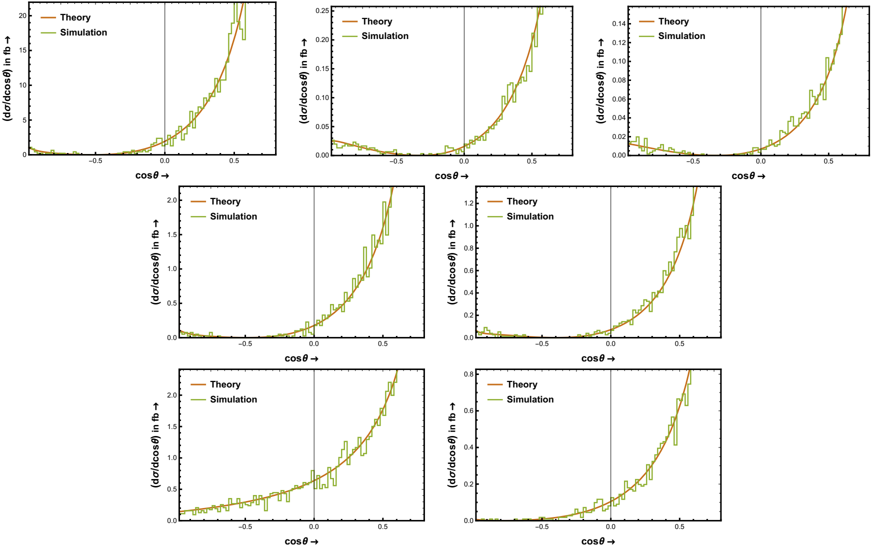
Signal-background analysis for $(S_1^{+1/3})^c$:

Benchmark points	$\sqrt{s}$ in TeV	Cut	Signal	Background	Significance
BP1	0.2	$\lvert M_{lj} - M_\phi \rvert \leq 10$ GeV	11133.6	43725.0	47.5
		cut1+$(-0.2) \leq \cos\theta_{\ell j} \leq 1$	10537.8	32989.8	50.5
	2	$\lvert M_{lj} - M_\phi \rvert \leq 10$ GeV	147.5	319.4	6.8
		cut1+$(0.9) \leq \cos\theta_{\ell j} \leq 1$	91.5	114.2	6.4
	3	$\lvert M_{lj} - M_\phi \rvert \leq 10$ GeV	61.2	219.8	3.7
		cut1+$(0.9) \leq \cos\theta_{\ell j} \leq 1$	34.5	44.2	3.9
BP2	2	$\lvert M_{lj} - M_\phi \rvert \leq 10$ GeV	394.4	2003.6	8.1
		cut1+$0 \leq \cos\theta_{\ell j} \leq 1$	299.5	129.1	14.5
	3	$\lvert M_{lj} - M_\phi \rvert \leq 10$ GeV	176.5	1660.7	4.1
		cut1+$0 \leq \cos\theta_{\ell j} \leq 1$	159.0	167.5	8.8
BP3	2	$\lvert M_{lj} - M_\phi \rvert \leq 10$ GeV	280.8	1061.6	7.7
		cut1+$(-0.9) \leq \cos\theta_{\ell j} \leq 1$	199.8	391.5	8.2
	3	$\lvert M_{lj} - M_\phi \rvert \leq 10$ GeV	106.2	815.0	3.5
		cut1+$(-0.8) \leq \cos\theta_{\ell j} \leq 1$	101.6	254.7	5.4

Position of the zeros of angular distribution:

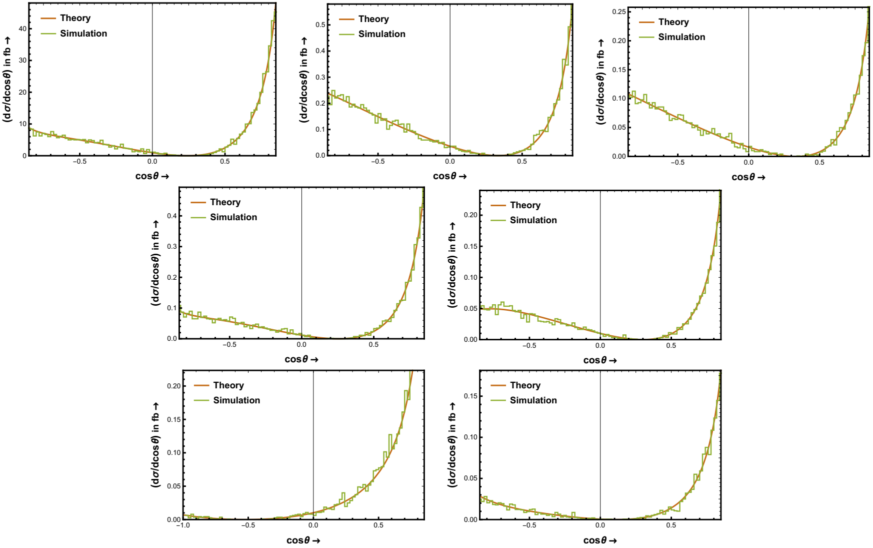
Benchmark points	Values of $\cos\theta^*$ for zeros of $(d\sigma/d\cos\theta)$ at different $\sqrt{s}$					
	For $Q_{\bar{q}} = {}^{-2}\!/_3$ or $Q_\phi = {}^{-1}\!/_3$			For $Q_q = {}^{-1}\!/_3$ or $Q_\phi = {}^{-2}\!/_3$		
	0.2 TeV	2 TeV	3 TeV	0.2 TeV	2 TeV	3 TeV
BP1	– 0.52	– 0.33	– 0.33	0.24	0.33	0.33
BP2	—	– 0.49	– 0.40	—	0.25	0.30
BP3	—	—	– 0.78	—	−0.52	0.11

Angular distribution for $(S_1^{+1/3})^c$:



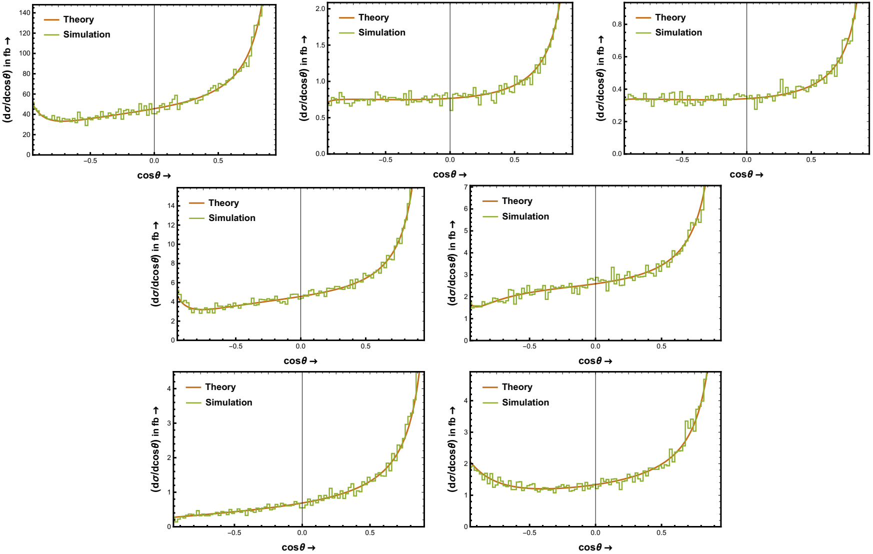
1st row: BP1, 2nd row: BP2, third row: BP3

Angular distribution for $(\widetilde{R}_2^{+2/3})^c$*:*



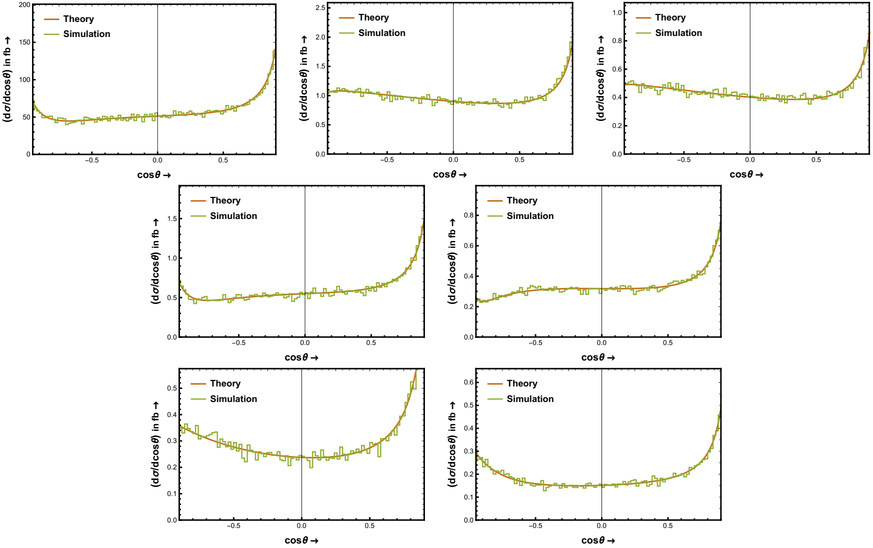
1st row: BP1, 2nd row: BP2, third row: BP3

Angular distribution for $(R_2^{+5/3})^c$:



1st row: BP1, 2nd row: BP2, third row: BP3

Angular distribution for $(S_3^{+4/3})^c$:



1st row: BP1, 2nd row: BP2, third row: BP3

Few Comments:

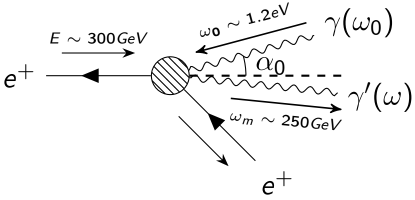
- Similar analysis are done for the following vectors: $(U_{1\mu}^{+2/3})^c$, $(\widetilde{V}_{2\mu}^{+1/3})^c$, $(U_{3\mu}^{+5/3})^c$, $(V_{2\mu}^{+4/3})^c$.
- There exist only left handed couplings for $(\widetilde{R}_2^{+2/3})^c$, $(S_3^{+4/3})^c$, $(\widetilde{V}_{2\mu}^{+1/3})^c$, $(U_{3\mu}^{+5/3})^c$.
- Significances for $(\widetilde{R}_2^{+2/3})^c$ and $(S_3^{+4/3})^c$ are very small, specially for BP2 and BP3. Higher luminosity is needed for them.
- Vector LQs have higher production cross-sections than the scalar ones.
- Systematic errors have not been considered. They will further reduce the significances in real experiments.

Non-monochromatic photon:

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

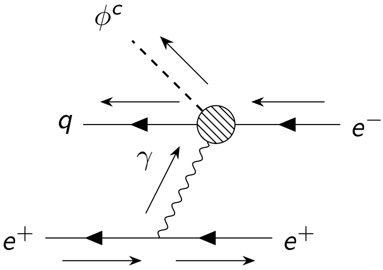
- Laser Backscattering (LB):

  ~ *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:

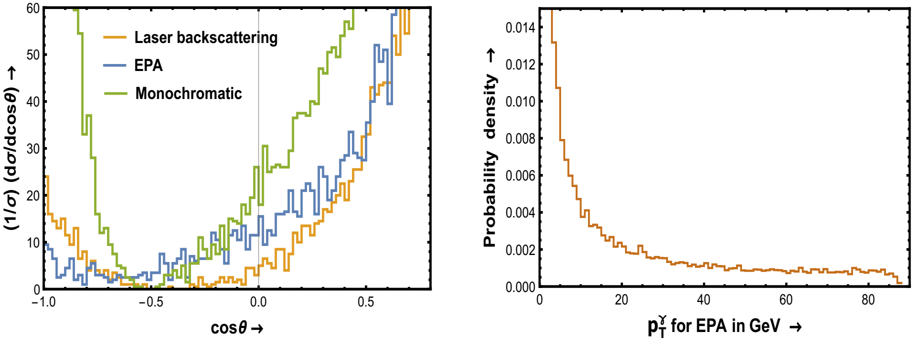


Figure: The comparison among LB, EPA and monochromatic photons (represented by orange, blue and green line respectively) in terms of weighted differential distribution $(\frac{1}{\sigma} \cdot \frac{d\sigma}{dcos\theta})$ for the production of $(\widetilde{V}_{2\mu}^{+1/3})^c$ in BP1 scenario at $\sqrt{s} = 0.2$ TeV is shown in the left panel. The distribution for transverse momentum of photon from 100 GeV positron under EPA scheme is shown in right panel.

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 $\frac{M_\phi}{\sqrt{s}} \leq \sqrt{-Q_\phi}$ and $Q_q < 0$.
- 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.

Thanks!

Back up :-

LQ	BP	M_ϕ	Y_L^{11}	Y_L^{22}	Y_L^{33}	Y_R^{11}	Y_R^{22}	Y_R^{33}
$(S_1^{+1/3})^c$, $(R_2^{+5/3})^c$, $(U_{1\mu}^{+2/3})^c$	BP1	70	0.035	0.04	0.035	0.03	0.03	0.03
	BP2	650	0.1	0.1	0.1	0.1	0.1	0.1
	BP3	1500	0.1	0.1	0.1	0.1	0.1	0.1
$(\widetilde{R}_2^{+2/3})^c$, $(S_3^{+4/3})^c$, $(\widetilde{V}_{2\mu}^{+1/3})^c$, $(U_{3\mu}^{+5/3})^c$	BP1	70	0.07	0.07	0.1	—	—	—
	BP2	650	0.07	0.07	0.1	—	—	—
	BP3	1500	0.07	0.07	0.1	—	—	—
$(V_{2\mu}^{+4/3})^c$	BP1	70	0.05	0.05	0.1	0.1	0.1	0.1
	BP2	650	0.05	0.05	0.1	0.1	0.1	0.1
	BP3	1500	0.05	0.05	0.1	0.1	0.1	0.1

$\sqrt{s}$ in TeV	Cross-section in fb			$\sqrt{s}$ in TeV	Cross-section in fb		
	BP1	BP2	BP3		BP1	BP2	BP3
Leptoquark $(S_1^{+1/3})^c$				Leptoquark $(U_{1\mu}^{+2/3})^c$			
0.2	430.24	—	—	0.2	482.41	—	—
2.0	6.61	50.65	31.95	2.0	803.82	58.95	14.84
3.0	3.30	26.03	17.98	3.0	812.59	68.04	10.55
Leptoquark $(R_2^{+5/3})^c$				Leptoquark $(V_{2\mu}^{+4/3})^c$			
0.2	517.5	—	—	0.2	12343.51	—	—
2.0	8.10	59.30	35.96	2.0	19110.75	152.70	15.38
3.0	3.70	30.79	20.70	3.0	19214.64	181.61	21.40
Leptoquark $(\widetilde{R}_2^{+2/3})^c$				Leptoquark $(\widetilde{V}_{2\mu}^{+1/3})^c$			
0.2	226.83	—	—	0.2	2127.02	—	—
2.0	3.61	2.89	1.78	2.0	485.34	26.58	16.38
3.0	1.66	1.49	1.02	3.0	477.98	15.46	9.18
Leptoquark $(S_3^{+4/3})^c$				Leptoquark $(U_{3\mu}^{+5/3})^c$			
0.2	327.44	—	—	0.2	9579.55	—	—
2.0	5.33	3.95	2.27	2.0	11769.27	117.41	21.17
3.0	2.43	2.08	1.36	3.0	11783.95	124.50	20.50

Table: Production cross-sections for the chosen leptoquarks at e-γ collider for the benchmark points at centre of momentum energies to be 200 GeV, 2 TeV and 3 TeV.

Modes	Branching fraction			Modes	Branching fraction		
	BP1	BP2	BP3		BP1	BP2	BP3
Leptoquark $(S_1^{+1/3})^c$				Leptoquark $(U_{1\mu}^{+2/3})^c$			
ue	0.245	0.229	0.223	$\bar{d}e$	0.222	0.225	0.223
$c\mu$	0.288	0.229	0.223	$\bar{s}\mu$	0.261	0.225	0.223
$t\tau$	—	0.199	0.218	$\bar{b}\tau$	0.222	0.225	0.223
$d\nu_e$	0.141	0.114	0.112	$\bar{u}\nu_e$	0.128	0.112	0.111
$s\nu_\mu$	0.185	0.114	0.112	$\bar{c}\nu_\mu$	0.167	0.112	0.111
$b\nu_\tau$	0.140	0.114	0.112	$\bar{t}\nu_\tau$	—	0.101	0.109
Leptoquark $(R_2^{+5/3})^c$				Leptoquark $(V_{2\mu}^{+4/3})^c$			
$\bar{u}e$	0.458	0.349	0.336	de	0.278	0.278	0.278
$\bar{c}\mu$	0.542	0.349	0.336	$s\mu$	0.278	0.278	0.278
$\bar{t}\tau$	—	0.302	0.327	$b\tau$	0.444	0.444	0.444
Leptoquark $(\widetilde{R}_2^{+2/3})^c$				Leptoquark $(\widetilde{V}_{2\mu}^{+1/3})^c$			
$\bar{d}e$	0.248	0.247	0.247	ue	0.500	0.261	0.250
$\bar{s}\mu$	0.248	0.247	0.247	$c\mu$	0.500	0.261	0.250
$\bar{b}\tau$	0.503	0.505	0.505	$t\tau$	—	0.478	0.500
Leptoquark $(S_3^{+4/3})^c$				Leptoquark $(U_{3\mu}^{+5/3})^c$			
$\bar{d}e^+$	0.248	0.247	0.247	ue^+	0.5	0.261	0.25
$\bar{s}\mu^+$	0.248	0.247	0.247	$c\mu^+$	0.5	0.261	0.25
$\bar{b}\tau^+$	0.503	0.505	0.505	$\bar{b}\tau^+$	0.503	0.505	0.505

Photon	Cross-section in fb			
	$(S_1^{+1/3})^c$, BP1 $\sqrt{s} = 0.2$ TeV	$(\widetilde{R}_2^{+2/3})^c$, BP2 $\sqrt{s} = 2$ TeV	$(U_{1\mu}^{+2/3})^c$, BP3 $\sqrt{s} = 2$ TeV	$(\widetilde{V}_{2\mu}^{+1/3})^c$, BP1 $\sqrt{s} = 0.2$ TeV
Laser back-scattering	688.20	4.87	11.11	3337.54
EPA	101.42	0.81	0.40	486.94
Monochromatic	430.24	2.89	14.84	2127.02

Table: Cross-section for production of leptoquarks in the chosen four scenarios with laser backscattering, equivalent photon approximation and monochromatic photon at e-γ collider.