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LEPTOQUARK PAIR PRODUCTION IN $\gamma\gamma$ SCATTERING

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DESY

1) INTRODUCTION
2) LQ's IN e^+e^-
3) $\gamma\gamma \rightarrow \Phi\bar{\Phi}$
4) QCD CORRECTIONS
5) CONCLUSION

1. Classification of Leptoquark States

B and L conserving

family–diagonal

$SU(3)_c \times SU(2)_L \times U(1)_Y$ invariant couplings

BUCHMÜLLER,
RÖCKL, WYLE
'8

leptoquark (Φ)	spin	F	colour	T_3	Q_{em}	$\lambda_L(lq)$	$\lambda_R(lq)$	$\lambda_L(\nu q)$
S_1	0	-2	$\bar{3}$	0	1/3	g_{1L}	g_{1R}	$-g_{1L}$
$\tilde{S}_1$	0	-2	$\bar{3}$	0	4/3	0	$\tilde{g}_{1R}$	0
$\vec{S}_3$	0	-2	$\bar{3}$	+1	4/3	$-\sqrt{2}g_{3L}$	0	0
				0	1/3	$-g_{3L}$	0	$-g_{3L}$
				-1	$-2/3$	0	0	$\sqrt{2}g_{3L}$
R_2	0	0	3	1/2	5/3	h_{2L}	h_{2R}	0
				$-1/2$	2/3	0	$-h_{2R}$	h_{2L}
$\tilde{R}_2$	0	0	3	1/2	2/3	$\tilde{h}_{2L}$	0	0
				$-1/2$	$-1/3$	0	0	$\tilde{h}_{2L}$
$V_{2\mu}$	1	-2	$\bar{3}$	1/2	4/3	g_{2L}	g_{2R}	0
				$-1/2$	1/3	0	g_{2R}	g_{2L}
$\tilde{V}_{2\mu}$	1	-2	$\bar{3}$	1/2	1/3	$\tilde{g}_{2L}$	0	0
				$-1/2$	$-2/3$	0	0	$\tilde{g}_{2L}$
$U_{1\mu}$	1	0	3	0	2/3	h_{1L}	h_{1R}	h_{1L}
$\tilde{U}_{1\mu}$	1	0	3	0	5/3	0	$\tilde{h}_{1R}$	0
$\vec{U}_{3\mu}$	1	0	3	+1	5/3	$\sqrt{2}h_{3L}$	0	0
				0	2/3	$-h_{3L}$	0	h_{3L}
				-1	$-1/3$	0	0	$\sqrt{2}h_{3L}$

$$\mathcal{L} = \mathcal{L}^f_{|F|=2} + \mathcal{L}^f_{F=0} + \mathcal{L}^{\gamma,Z,g}$$

$$\mathcal{L}^{\gamma,Z,g} = \sum_{scalars}\left[(D^\mu\Phi)^\dagger(D_\mu\Phi) - M^2\Phi^\dagger\Phi\right] + \sum_{vectors}\left[-\frac{1}{2}G^\dagger_{\mu\nu}G^{\mu\nu} + M^2\Phi^{\mu\dagger}\Phi_\mu\right]$$

$$D_\mu = \partial_\mu - ieQ^\gamma A_\mu - ieQ^Z Z_\mu - ig_s\frac{\lambda_a}{2}\mathcal{A}^a_\mu$$

$$\begin{aligned}\mathcal{L}^f_{F=0} &= (h_{2L}\bar{u}_R l_L + h_{2R}\bar{q}_L i\tau_2 e_R)R_2 + \tilde{h}_{2L}\bar{d}_R l_L\tilde{R}_2 \\ &+ (h_{1L}\bar{q}_L\gamma^\mu l_L + h_{1R}\bar{d}_R\gamma^\mu e_R)U_{1\mu} \\ &+ \tilde{h}_{1R}\bar{u}_R\gamma^\mu e_R\tilde{U}_{1\mu} + h_{3L}\bar{q}_L\vec{\tau}\gamma^\mu l_L\vec{U}_{3\mu} + h.c.\end{aligned}$$

$$\begin{aligned}\mathcal{L}^f_{|F|=2} &= (g_{1L}\bar{q}^c_L i\tau_2 l_L + g_{1R}\bar{u}^c_R e_R)S_1 \\ &+ \tilde{g}_{1R}\bar{d}^c_R e_R\tilde{S}_1 + g_{3L}\bar{q}^c_L i\tau_2\vec{\tau}l_L\vec{S}_3 \\ &+ (g_{2L}\bar{d}^c_R\gamma^\mu l_L + g_{2R}\bar{q}^c_L\gamma^\mu e_R)V_{2\mu} \\ &+ \tilde{g}_{2L}\bar{u}^c_R\gamma^\mu l_L\tilde{V}_{2\mu} + h.c.,\end{aligned}$$

Decay Pattern for Pair Production

states	$l^+l^- + 2jets$	$l\nu + 2jets$	$\nu\overline{\nu} + 2jets$
S_1 U_1	$\frac{4}{9}$ 1 $\frac{1}{4}$	$\frac{4}{9}$ 0 $\frac{1}{2}$	$\frac{1}{9}$ 0 $\frac{1}{4}$
$R_2^{2/3}$ $V_2^{1/3}$	$\frac{1}{4}$ 1 0	$\frac{1}{2}$ 0 0	$\frac{1}{4}$ 0 1
$S_3^{1/3}$ $U_3^{2/3}$	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{1}{4}$
$\tilde{S}_1$ $S_3^{4/3}$ $R_2^{5/3}$ $\tilde{R}_2^{2/3}$ $V_2^{4/3}$ $\tilde{V}_2^{1/3}$ $\tilde{U}_1$ $U_3^{5/3}$	1	0	0
$S_3^{-2/3}$ $\tilde{R}_2^{-1/3}$ $\tilde{V}_2^{-2/3}$ $U_3^{-1/3}$	0	0	1

Table 3: Branching ratios for final states arrising from the decays of leptoquarks associated with the first ($l = e$) and second ($l = \mu$) family. The sequence of branching fractions given in the second and third row refers to the assumptions $\lambda_L = \lambda_R, \lambda_L = 0,$ and $\lambda_R = 0$, respectively.

LINEAR COLLIDER:

$e^+e^- \longrightarrow \phi\bar{\phi}$

$\gamma\gamma \longrightarrow \phi\bar{\phi}$

σ WIDELY INDEPENDENT OF λ_{eq} !

$\longrightarrow$ GAUGE COUPLINGS

I) e^+e^- - ANNIHILATION:

- HEWETT / RIZZO, ZERWAS et al.
- JB, RÜCKL ; JB, BOOS, KRYUKOV.

MASS BOUNDS : $m_\phi \lesssim \sqrt{s}/2$

o LOSSES : BEAMSTRAHLUNG — JB '93

QED $O(\alpha)$, $-\Delta\sigma$: QED $O(\alpha^2)$.

o ENHANCEMENT OF σ:

QCD FS - CORR $\frac{1}{\beta}$ — JB '93

$\sqrt{s} = 500$ GeV ... 1 TeV nearly balanced,

i.e. losses + enhancement $\simeq 0$.

$\sigma_{eff} \simeq \sigma_{Born}$.

2. $\gamma\gamma$ Scattering

$U_{em}(1)$ invariant Lagrangian:

$$\mathcal{L} = \mathcal{L}_s + \mathcal{L}_v \tag{1}$$

with

$$\mathcal{L}_s = \sum_{scalars} \left[(D^\mu \Phi)^\dagger (D_\mu \Phi) - M_s^2 \Phi^\dagger \Phi \right] \tag{2}$$

and

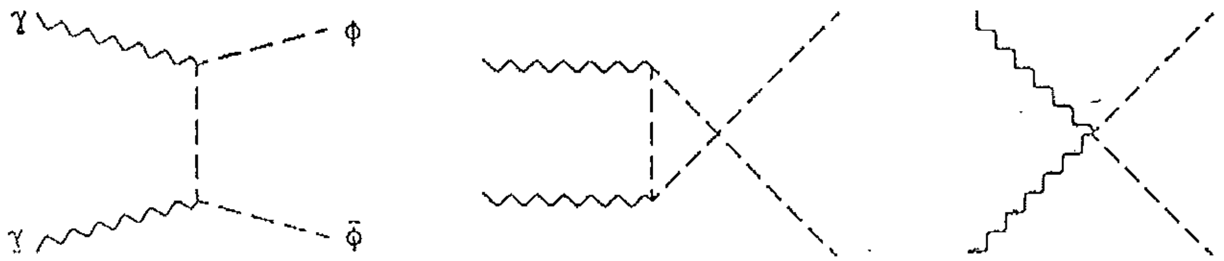
$$\mathcal{L}_v = \sum_{vectors} \left\{ -\frac{1}{2} G^\dagger_{\mu\nu} G^{\mu\nu} + M_v^2 \Phi^\dagger_\mu \Phi^\mu - ie \left[(1-\kappa_A) \Phi^\dagger_\mu \Phi_\nu F^{\mu\nu} + \frac{\lambda_A}{M_v^2} G^\dagger_{\sigma\mu} G^\mu_\nu F^{\nu\sigma} \right] \right. \tag{3}$$

Field strength tensors:

$$\begin{aligned} F_{\mu\nu} &= \partial_\mu A_\nu - \partial_\nu A_\mu, \\ G_{\mu\nu} &= D_\mu \Phi_\nu - D_\nu \Phi_\mu \end{aligned} \tag{4}$$

Covariant derivative:

$$D_\mu = \partial_\mu - ieQ^\gamma A_\mu \tag{5}$$



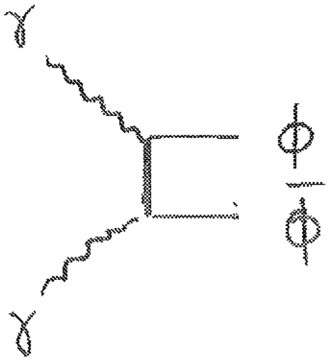
Anomalous couplings: κ_A and λ_A

$\Updownarrow$

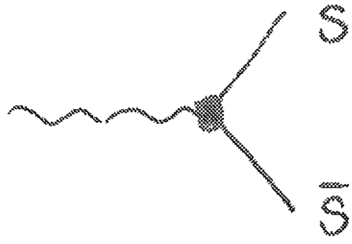
anomalous magnetic moment μ_Φ and electric quadrupole moment q_Φ of leptoquarks:

$$\begin{aligned} \mu_{\Phi,A} &= \frac{eQ_\gamma}{2M_\Phi} (2 - \kappa_A + \lambda_A) \\ q_{\Phi,A} &= -\frac{eQ_\gamma}{M_\Phi^2} (1 - \kappa_A - \lambda_A) \end{aligned} \tag{6}$$

WHY TO SEARCH FOR $\phi\bar{\phi}$ IN $\gamma\gamma$-SCATTERING?

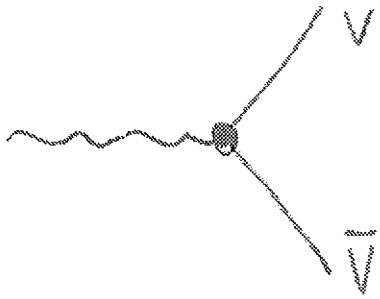


SCALARS & VECTORS



$\sigma \sim Q_\phi^4 \qquad |Q_\phi| = \frac{1}{3} \ldots \frac{5}{3}$!

$\sigma = O(1) \ldots O(625).$



$\sigma_V = \sigma_V(\kappa_\gamma, \lambda_\gamma)$

ANOMALOUS COUPLINGS.

Sensitivity to Quantum Numbers

Process	LQ	Quantum Numbers
e^+e^- Annihilation	S,V	$Q^\gamma_\Phi, Q^Z_\Phi\ , \lambda_{L,R}$
$\gamma\gamma$ Collider	S	Q^γ_Φ
	V	$Q^\gamma_\Phi, \kappa_A, \lambda_A$
$e\gamma$ Collider	S,V	$\lambda_{L,R}, Q^\gamma_\Phi$
ep Collider	single LQ	$\lambda_{L,R}$
	pairs : S	Q^γ_Φ
	pairs : V	$Q^\gamma_\Phi, \kappa_A, \kappa_G, \lambda_A, \lambda_G$
$p\overline{p}$ Collider	V	κ_G, λ_G

$\sigma \sim Q^4_{\Phi_{S,V}}$

2. CROSS SECTIONS

BORN:

J. BLÜMLEIN, E. BOOS, NUCL. PHYS (P.S.) 37B (1994) 181

J. BLÜMLEIN, E. BOOS, A. KRYUKOV, Z. PHYS. C76 (1997) 137;

CODE: LQPAIR 1.0 : J. BLÜMLEIN, E. BOOS, A. KRYUKOV '99.

⟶ CONVOLUT WITH COMPTON LASER SPECTRA

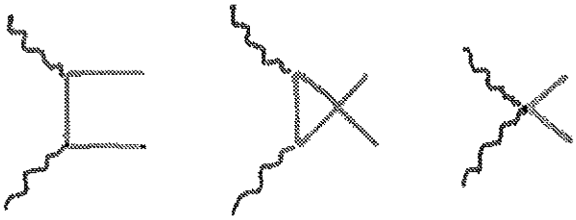
THREE CONTRIBUTIONS:

⟶ $\gamma_{DIR} \times \gamma_{DIR}$

MOST IMPORTANT TERM $\gamma_{DIR} \times \gamma_{RESOLVED}$ ⟵ HADRONIC

$\gamma_{RESOLVED} \times \gamma_{RESOLVED}$

DIRECT TERMS:

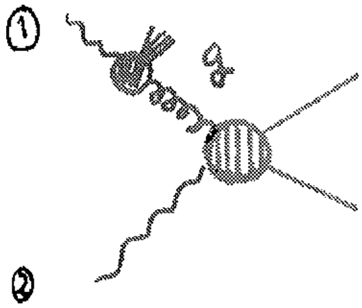


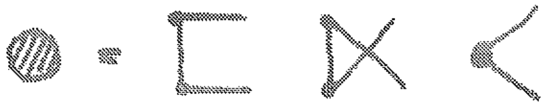
S V

$\bar{S}$ $\bar{V}$

V: κ_A, λ_A

DIRECT-RESOLVED CONTRIBUTIONS:





assume: $\lambda_{qe} \ll 1$.

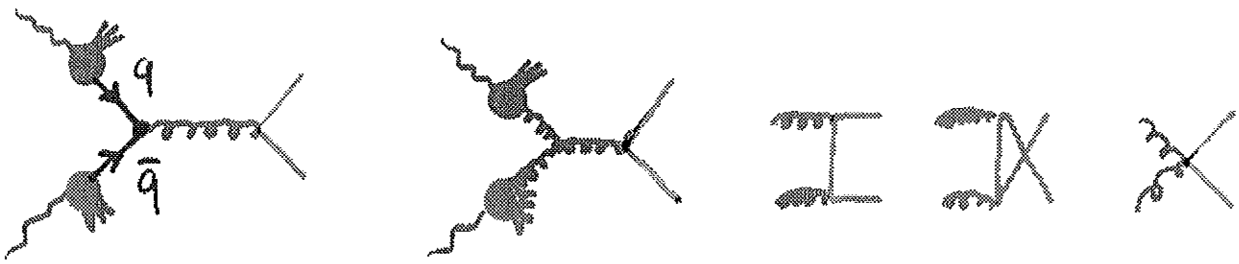
+ ① ↔ ②.

V: $\underline{\gamma}$ $\underline{g}$

κ_A, κ_G

λ_A, λ_G

RESOLVED-RESOLVED TERM:



V: κ_G, λ_G

V: direct.

$$
\begin{aligned}
\tilde{F}_0 &= \beta\left(\frac{11}{2}-\frac{9}{4}\beta^2+\frac{3}{4}\beta^4\right)-\frac{3}{8}\left(1-\beta^2-\beta^4+\beta^6\right)\ln\left|\frac{1+\beta}{1-\beta}\right| \\
\tilde{F}_1 &= -8\beta-\frac{3}{2}\left(1-\beta^2\right)\log\left|\frac{1+\beta}{1-\beta}\right| \\
\tilde{F}_2 &= 3\beta+\frac{1}{4}\beta\frac{\hat{s}}{M_\Phi^2}+\left(\frac{7}{2}-2\beta^2\right)\log\left|\frac{1+\beta}{1-\beta}\right| \\
\tilde{F}_3 &= -\frac{1}{4}\beta\frac{\hat{s}}{M_\Phi^2}+\left(-2+\frac{3}{4}\beta^2\right)\log\left|\frac{1+\beta}{1-\beta}\right| \\
\tilde{F}_4 &= -\frac{1}{96}\beta+\frac{5}{48}\beta\frac{\hat{s}}{M_\Phi^2}+\frac{4-\beta^2}{16}\log\left|\frac{1+\beta}{1-\beta}\right| \\
\tilde{F}_5 &= -\left(1-\beta^2\right)\log\left|\frac{1+\beta}{1-\beta}\right| \\
\tilde{F}_6 &= -\frac{1}{6}\beta+\frac{17}{12}\beta\frac{\hat{s}}{M_\Phi^2}+\left(-3-\frac{\beta^2}{2}+\frac{1}{2}\frac{\hat{s}}{M_\Phi^2}\right)\log\left|\frac{1+\beta}{1-\beta}\right| \\
\tilde{F}_7 &= -\beta+\frac{11}{6}\beta\frac{\hat{s}}{M_\Phi^2}-\frac{1}{3}\beta\frac{\hat{s}^2}{M_\Phi^4}-\frac{3+\beta^2}{4}\log\left|\frac{1+\beta}{1-\beta}\right| \\
\tilde{F}_8 &= -\frac{1}{96}\beta+\frac{59}{80}\beta\frac{\hat{s}}{M_\Phi^2}-\frac{113}{320}\beta\frac{\hat{s}^2}{M_\Phi^4}+\frac{43}{960}\beta\frac{\hat{s}^3}{M_\Phi^6}+\left(-\frac{1}{2}-\frac{1}{16}\beta^2+\frac{1}{8}\frac{\hat{s}}{M_\Phi^2}\right)\log\left|\frac{1+\beta}{1-\beta}\right| \\
\tilde{F}_9 &= 2\beta+(2+\beta^2)\log\left|\frac{1+\beta}{1-\beta}\right| \\
\tilde{F}_{10} &= 2\beta-\frac{7}{3}\beta\frac{\hat{s}}{M_\Phi^2}+\left(3+\frac{5}{4}\beta^2-\frac{1}{2}\frac{\hat{s}}{M_\Phi^2}\right)\log\left|\frac{1+\beta}{1-\beta}\right| \\
\tilde{F}_{11} &= \frac{1}{24}\beta-\frac{59}{48}\beta\frac{\hat{s}}{M_\Phi^2}+\frac{5}{32}\beta\frac{\hat{s}^2}{M_\Phi^4}+\frac{5+\beta^2}{4}\log\left|\frac{1+\beta}{1-\beta}\right| \\
\tilde{F}_{12} &= -\beta-\frac{1}{2}\beta\frac{\hat{s}}{M_\Phi^2}+\left(-\frac{1}{4}-\frac{7}{4}\beta^2\right)\log\left|\frac{1+\beta}{1-\beta}\right| \\
\tilde{F}_{13} &= \frac{1}{24}\beta+\frac{1}{3}\beta\frac{\hat{s}}{M_\Phi^2}-\frac{1}{4}\left(1-\beta^2\right)\log\left|\frac{1+\beta}{1-\beta}\right| \\
\tilde{F}_{14} &= -\frac{1}{16}\beta+\frac{11}{96}\beta\frac{\hat{s}}{M_\Phi^2}+\frac{17}{192}\beta\frac{\hat{s}^2}{M_\Phi^4}+\left(\frac{1}{8}\frac{\hat{s}}{M_\Phi^2}-\frac{3}{4}-\frac{3}{8}\beta^2\right)\log\left|\frac{1+\beta}{1-\beta}\right| \qquad (12)
\end{aligned}
$$

Tree–level unitarity:

$$\lambda_A = 0$$

$$\kappa_A^2\left[\left(\kappa_A-\frac{6}{5}\right)^2+\frac{24}{25}\right] = 0. \qquad (13)$$

Since κ_A, λ_A real $\rightarrow \kappa_A \equiv \lambda_A \equiv 0$.

V : RESOLVED - DiRECT.

$$
\begin{aligned}
F_{18} &= 2(5-\beta^2\cos^2\theta) - \frac{\hat{s}}{M_\Phi^2}\frac{11-15\beta^2\cos^2\theta+4\beta^4\cos^4\theta}{4} \\
&\quad - \frac{\hat{s}^2}{M_\Phi^4}\frac{(1-\beta^2\cos^2\theta)^2}{4}\,, \\[2ex]
F_{19} &= 3-\beta^2\cos^2\theta - \frac{\hat{s}}{M_\Phi^2}\frac{7-8\beta^2\cos^2\theta+\beta^4\cos^4\theta}{4} \\
&\quad + \frac{\hat{s}^2}{M_\Phi^4}\frac{11-13\beta^2\cos^2\theta+\beta^4\cos^4\theta+\beta^6\cos^6\theta}{32} \\
&\quad + \frac{\hat{s}^3}{M_\Phi^6}\frac{5-7\beta^2\cos^2\theta-\beta^4\cos^4\theta+3\beta^6\cos^6\theta}{128}\,, \\[2ex]
F_{20} &= -\frac{3-\beta^2\cos^2\theta}{2} + \frac{\hat{s}}{M_\Phi^2}\frac{(1-\beta^2\cos^2\theta)^2}{8} \\
&\quad + \frac{\hat{s}^2}{M_\Phi^4}\frac{11-23\beta^2\cos^2\theta+13\beta^4\cos^4\theta-\beta^6\cos^6\theta}{64}\,.
\end{aligned}
\tag{A.1}
$$

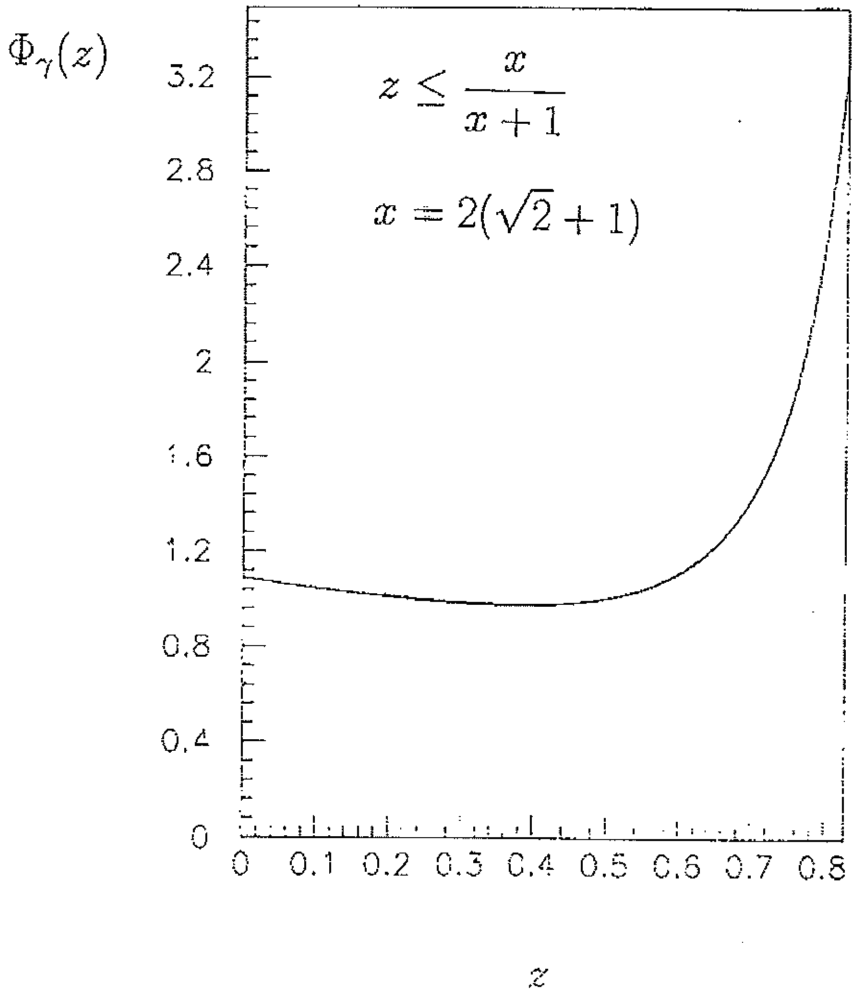
The functions $\tilde{F}_i(\hat{s},\beta)$, which describe the different contributions to the integrated cross-section (13), are:

$$
\begin{aligned}
\tilde{F}_0 &= \beta\left(\frac{11}{2}-\frac{9}{4}\beta^2+\frac{3}{4}\beta^4\right) - \frac{3}{8}\left(1-\beta^2-\beta^4+\beta^6\right)\ln\left|\frac{1+\beta}{1-\beta}\right|, \\
\tilde{F}_1 &= -4\beta - \frac{3}{4}(1-\beta^2)\log\left|\frac{1+\beta}{1-\beta}\right|, \\
\tilde{F}_2 &= \frac{1}{16}\beta\frac{\hat{s}}{M_\Phi^2} + \frac{3-\beta^2}{4}\log\left|\frac{1+\beta}{1-\beta}\right|, \\
\tilde{F}_3 &= 3\beta + \frac{1}{8}\beta\frac{\hat{s}}{M_\Phi^2} + \left(2-\frac{3}{2}\beta^2\right)\log\left|\frac{1+\beta}{1-\beta}\right|, \\
\tilde{F}_4 &= -\frac{1}{8}\beta\frac{\hat{s}}{M_\Phi^2} + \left(-1+\frac{3}{8}\beta^2\right)\log\left|\frac{1+\beta}{1-\beta}\right|, \\
\tilde{F}_5 &= -\frac{1}{96}\beta + \frac{5}{48}\beta\frac{\hat{s}}{M_\Phi^2} + \frac{4-\beta^2}{16}\log\left|\frac{1+\beta}{1-\beta}\right|, \\
\tilde{F}_6 &= -\frac{1}{2}(1-\beta^2)\log\left|\frac{1+\beta}{1-\beta}\right|.
\end{aligned}
$$

$$
\begin{aligned}
\tilde{F}_7 &= \frac{7}{12}\beta\frac{\hat{s}}{M_\Phi^2} + \frac{1}{24}\beta\frac{\hat{s}^2}{M_\Phi^4} - \frac{5+\beta^2}{4}\log\left|\frac{1+\beta}{1-\beta}\right|, \\
\tilde{F}_8 &= -\frac{1}{6}\beta + \frac{1}{4}\beta\frac{\hat{s}}{M_\Phi^2} - \frac{1}{12}\beta\frac{\hat{s}^2}{M_\Phi^4} + \left(-\frac{1}{2}+\frac{1}{2}\frac{\hat{s}}{M_\Phi^2}\right)\log\left|\frac{1+\beta}{1-\beta}\right|, \\
\tilde{F}_9 &= -\frac{1}{2}\beta + \frac{11}{12}\beta\frac{\hat{s}}{M_\Phi^2} - \frac{1}{6}\beta\frac{\hat{s}^2}{M_\Phi^4} - \frac{3+\beta^2}{8}\log\left|\frac{1+\beta}{1-\beta}\right|, \\
\tilde{F}_{10} &= -\frac{1}{96}\beta + \frac{59}{80}\beta\frac{\hat{s}}{M_\Phi^2} - \frac{113}{320}\beta\frac{\hat{s}^2}{M_\Phi^4} + \frac{43}{960}\beta\frac{\hat{s}^3}{M_\Phi^6} \\
&\quad + \left(-\frac{1}{2}-\frac{1}{16}\beta^2+\frac{1}{8}\frac{\hat{s}}{M_\Phi^2}\right)\log\left|\frac{1+\beta}{1-\beta}\right|, \\
\tilde{F}_{11} &= \frac{1}{2}(1+\beta^2)\log\left|\frac{1+\beta}{1-\beta}\right|, \\
\tilde{F}_{12} &= \beta + \frac{1}{2}\log\left|\frac{1+\beta}{1-\beta}\right|, \\
\tilde{F}_{13} &= \beta - \frac{5}{12}\beta\frac{\hat{s}}{M_\Phi^2} + \frac{1}{24}\beta\frac{\hat{s}^2}{M_\Phi^4} + \left[-\frac{1}{4}\frac{\hat{s}}{M_\Phi^2} + \left(\frac{3}{8}+\frac{1}{4}\beta^2\right)\right]\log\left|\frac{1+\beta}{1-\beta}\right|, \\
\tilde{F}_{14} &= -\frac{11}{24}\beta\frac{\hat{s}}{M_\Phi^2} - \frac{1}{24}\beta\frac{\hat{s}^2}{M_\Phi^4} + \frac{9+3\beta^2}{8}\log\left|\frac{1+\beta}{1-\beta}\right|, \\
\tilde{F}_{15} &= \frac{1}{48}\beta - \frac{59}{96}\beta\frac{\hat{s}}{M_\Phi^2} + \frac{5}{64}\beta\frac{\hat{s}^2}{M_\Phi^4} + \frac{5+\beta^2}{8}\log\left|\frac{1+\beta}{1-\beta}\right|, \\
\tilde{F}_{16} &= -\frac{1}{2}\beta - \frac{1}{8}\beta^2\log\left|\frac{1+\beta}{1-\beta}\right|, \\
\tilde{F}_{17} &= -\frac{1}{96}\beta + \frac{1}{48}\beta\frac{\hat{s}}{M_\Phi^2} + \frac{1}{48}\beta\frac{\hat{s}^2}{M_\Phi^4} - \frac{2+\beta^2}{16}\log\left|\frac{1+\beta}{1-\beta}\right|, \\
\tilde{F}_{18} &= -\frac{1}{4}\beta\frac{\hat{s}}{M_\Phi^2} - \frac{1-6\beta^2}{8}\log\left|\frac{1+\beta}{1-\beta}\right|, \\
\tilde{F}_{19} &= -\frac{1}{24}\beta + \frac{7}{96}\beta\frac{\hat{s}}{M_\Phi^2} + \frac{3}{64}\beta\frac{\hat{s}^2}{M_\Phi^4} + \left[\frac{1}{8}\frac{\hat{s}}{M_\Phi^2} - \frac{2+\beta^2}{4}\right]\log\left|\frac{1+\beta}{1-\beta}\right|,
\end{aligned}
\tag{A.2}
$$

$$\Phi_\gamma(z) = \frac{1}{N(x)}\left[1 - z + \frac{1}{1-z} - \frac{4z}{x(1-z)} + \frac{4z^2}{x^2(1-z)^2}\right]$$

$$N(x) = \frac{16 + 32x + 18x^2 + x^3}{2x(1+x)^2} + \frac{x^2 - 4x - 8}{x^2}\ln(1+x)$$



COMPTON - CONVERSION SPECTRUM

$$\sigma_{scalar}(s) \quad = \quad \frac{\pi\alpha^2}{s} Q_\Phi^4 \left\{ 2(2-\beta^2)\beta - (1-\beta^4)\ln\left|\frac{1+\beta}{1-\beta}\right| \right\}$$

$$\sigma = \int_0^{z_{max}} dz_1 \int_0^{z_{max}} dz_2 \Phi_\gamma(z_1)\Phi_\gamma(z_2)\hat{\sigma}(\hat{s})\theta\left(\hat{s} - 4M_\Phi^2\right)$$