Production of Scalar and Vector Leptoquarks in e^+e^- -annihilation

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1 Introduction

$SU_3^c \times SU_2^L \times U_1^Y$:

STRONG RELATIONS BETWEEN QUARK AND LEPTON FIELDS:

$\boxed{\text{CANCELLATION OF TRIANGLE ANOMALIES}}$

FUNDAMENTAL LEPTOQUARK FIELDS ?

SU_5, SO_4^{PS}, SO_{10}, E_6 ; SUBSTRUCTURE MODELS.

SU_{15} · P. Frampton (May 91 – indep. complete ! realiz.)

WHAT CAN BE PROBED AT e^+e^- COLLIDERS ?

- LQ - GAUGE BOSON (γ, Z) COUPLINGS
- LQ - FERMION (e, u, d) COUPLINGS, (1ST FAMILY.)

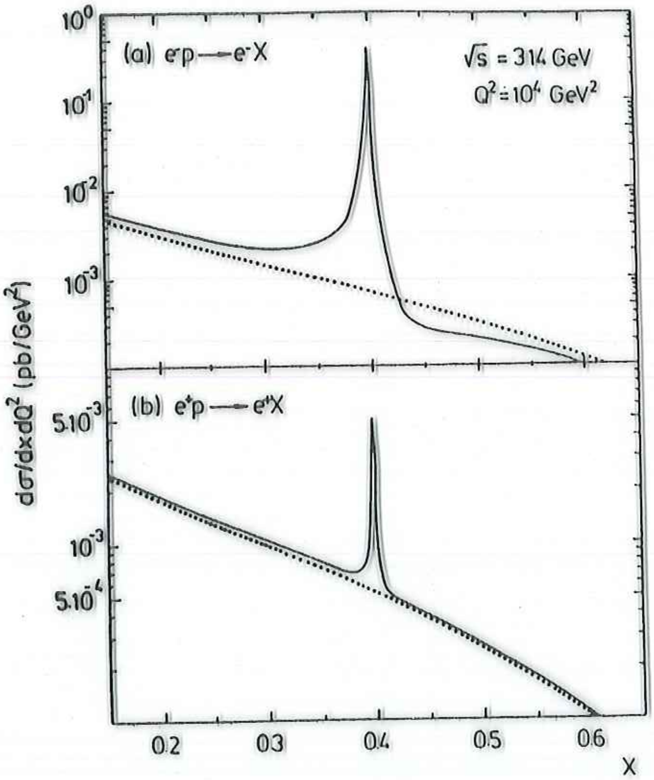

Figure 3: Differential cross section for unpolarized e^-p (a) and e^+p (b) scattering versus x at $Q^2 = 10^4$ GeV^2 at HERA. The full curves represent the theoretical distributions for an S (or an S^*) leptoquark with $m_S = 200$ GeV and $g_L = 0.3$, while the dashed curves are the standard model predictions. From [8]

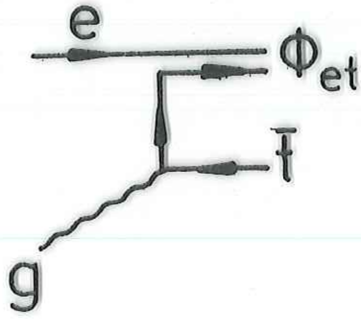

Figure 4: Associated leptoquark production in gluon - electron scattering

2 Basic Relations

$$\mathcal{L} = \mathcal{L}_{F=2} + \mathcal{L}_{F=0} + \mathcal{L}_{nc}^{gauge} \tag{1}$$

$$F = -(3B + L) \tag{2}$$

EFFECTIVE DIMENSIONLESS $SU_3 \times SU_{2L} \times U_1$
PRESERVING LAGRANGIAN : B & L CONSERVATION.

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

$$\begin{aligned}
\mathcal{L}_{F=0} &= (h_{2L}\bar{u}_R l_L + h_{2R}\bar{q}_L i\tau_2 e_R)\underline{R_2} + \tilde{h}_{2L}\bar{d}_R l_L \underline{\tilde{R}_2} \\
&+ (h_{1L}\bar{q}_L\gamma^\mu l_L + h_{1R}\bar{d}_R\gamma^\mu e_R)\underline{U_{1\mu}} \\
&+ \tilde{h}_{1R}\bar{u}_R\gamma^\mu e_R \underline{\tilde{U}_{1\mu}} + h_{3L}\bar{q}_L\vec{\tau}\gamma^\mu l_L \underline{\vec{U}_{3\mu}} + h.c.
\end{aligned} \tag{4}$$

$$q^c = C\bar{q}^T \tag{5}$$

$$\mathcal{L}_{nc}^{gauge} = \sum_{j=s}\left[(D_j^\mu\Phi^j)^\dagger(D_\mu^j\Phi_j) - m_j^2\right] + \sum_{j=v}\left[-\frac{1}{2}G_{\mu\nu}^{j\dagger}G_j^{\mu\nu} + m_j^2\right] \tag{6}$$

SCALARS VECTORS

NC : $$D_j^\mu = \partial^\mu - ieQ_j\underline{A^\mu} - \frac{ie}{\cos\theta_w\sin\theta_w}(T_j^3 - Q_j\sin^2\theta_w)\underline{Z^\mu} \tag{7}$$

$$G_{\mu\nu}^j = D_\mu^j\Phi_j^\nu - D_\nu^j\Phi_j^\mu \tag{8}$$

leptoquark	spin	F	color	T_3	Q_{em}	λ_L	λ_R
S_1	0	2	$\bar{3}$	0	1/3	g_{1L}	g_{1R}
$\tilde{S}_1$	0	2	$\bar{3}$	0	4/3	0	$\tilde{g}_{1R}$
S_3^+ S_3^3 S_3^-	0	2	$\bar{3}$	+1 0 −1	4/3 1/3 −2/3	$-\sqrt{2}g_{3L}$ $-g_{3L}$ 0	0 0 0
R_2^+ R_2^-	0	0	3	1/2 −1/2	5/3 2/3	h_{2L} 0	h_{2R} $-h_{2R}$
$\tilde{R}_2^+$ $\tilde{R}_2^-$	0	0	3	1/2 −1/2	2/3 −1/3	$\tilde{h}_{2L}$ 0	0 0
$V_{2\mu}^+$ $V_{2\mu}^-$	1	2	$\bar{3}$	1/2 −1/2	4/3 1/3	g_{2L} 0	g_{2R} g_{2R}
$\tilde{V}_{2\mu}^+$ $\tilde{V}_{2\mu}^-$	1	2	$\bar{3}$	1/2 −1/2	1/3 −2/3	$\tilde{g}_{2L}$ 0	0 0
$U_{1\mu}$	1	0	3	0	2/3	h_{1L}	h_{1R}
$\tilde{U}_{1\mu}$	1	0	3	0	5/3	0	$\tilde{h}_{2R}$
U_3^+ U_3^3 U_3^-	1	0	3	+1 0 −1	5/3 2/3 −1/3	$\sqrt{2}h_{3L}$ $-h_{3L}$ 0	0 0 0

Table 1: Couplings of leptoquarks to neutral current gauge bosons and electron- (anti)quark vertices. For $\Phi_3 = S_3, U_3$ the components $\Phi_3^\pm$ are given by $\Phi^\pm = (\Phi^1 \pm i\Phi^2)/\sqrt{2}$. The charge Q_{em} is defined for a particle flowing into the lepton-quark vertex. The coupling to the vector bosons is given by $Q^\gamma = Q_{em}$ and $Q^Z = (T_3 - Q_{em}\sin^2\theta_w)/\cos\theta_w \sin\theta_w$.

3.1 Scalar Leptoquarks

$$\frac{d\sigma}{d\cos\theta} = \frac{3\pi\alpha^2}{8s}\beta^3\sin^2\theta\sum_{j=L,R}\left\{|\kappa_j(s)|^2 + \left(\frac{\lambda_j}{e}\right)^2\frac{4\Re[\kappa_j(s)]}{t(\beta,\cos\theta)} + \left(\frac{\lambda_j}{e}\right)^4\frac{4}{t(\beta,\cos\theta)^2}\right\} \tag{9}$$

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$$\kappa_j(s) = \sum_{V=\gamma,Z} Q_j^V(e)\frac{s}{s-M_V^2+iM_V\Gamma_V}Q^V(\Phi) \tag{10}$$

$$t(\beta,\cos\theta) = 1+\beta^2-2\beta\cos\theta \tag{11}$$

$$\beta = \sqrt{1-4M_\Phi^2/s} \tag{12}$$

$$\sigma_{pt} = \frac{4\pi\alpha^2}{3s} \tag{13}$$

$$R_s = \frac{3\beta^3}{8}\sum_{j=L,R}\left\{|\kappa_j(s)|^2 + \left(\frac{\lambda_j}{e}\right)^2\Re[\kappa_j(s)]F_1^s(\beta) + \left(\frac{\lambda_j}{e}\right)^4F_2^s(\beta)\right\} \tag{14}$$

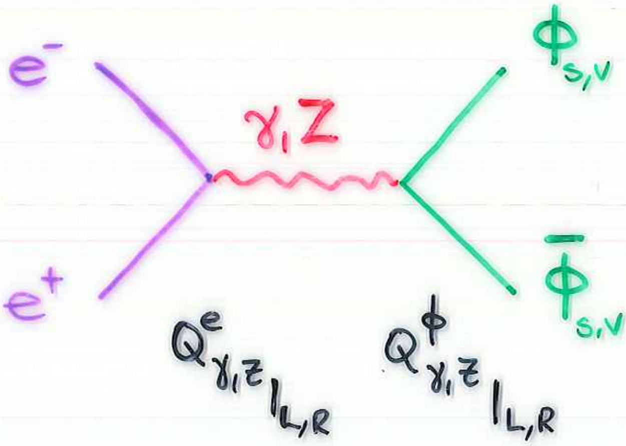
SCHAILE, ZERWAS '87
HEWETT, RIZZO '86

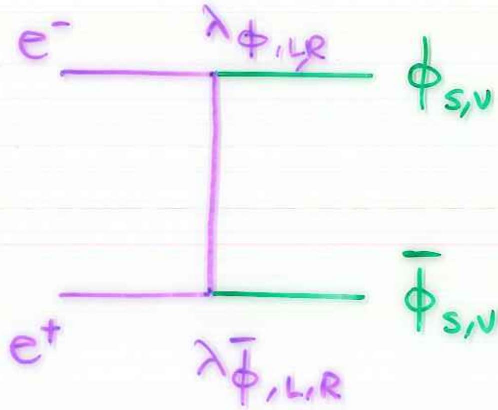
$$F_1^s(\beta) = \frac{3}{2}\left(\frac{1+\beta^2}{\beta^2} - \frac{(1-\beta^2)^2}{2\beta^3}\ln\frac{1+\beta}{1-\beta}\right) \tag{15}$$

$$F_2^s(\beta) = 3\left(-\frac{1}{\beta^2} + \frac{1+\beta^2}{2\beta^3}\ln\frac{1+\beta}{1-\beta}\right) \tag{16}$$

$$\sigma_s(s\to\infty) \propto \frac{4\pi\alpha^2}{8s}\sum_{j=L,R}\left\{|\kappa_j^\infty|^2 + 3\left(\frac{\lambda_j}{e}\right)^2\Re[\kappa_j^\infty] + 3\left(\frac{\lambda_j}{e}\right)^4\left[\ln\left(\frac{s}{M_\Phi^2}\right)-1\right]\right\} \tag{17}$$

3 Production cross sections





$$Q^{\phi}_{\gamma} = Q^{\phi}_{em} \quad ; \quad Q^{\phi}_{Z} = \frac{T_3 - Q_{em}\sin^2\theta_W}{\cos\theta_W \sin\theta_W}$$

THESE COUPLINGS ARE FULLY PREDICTED.

The production cross sections have the same analytical structure for $F = 0$ and $F = 2$ leptoquarks due to the masslessness of the exchanged fermions.

3.2 Vector Leptoquarks

$$\frac{d\sigma}{d\cos\theta} = \frac{3\pi\alpha^2}{8M_\Phi^2}\beta \sum_{j=L,R} \left\{ |\kappa_j(s)|^2 \tilde{F}_1(\theta,s) + \left(\frac{\lambda_j}{e}\right)^2 \Re[\kappa_j(s)]\tilde{F}_2(\theta,s) + \left(\frac{\lambda_j}{e}\right)^4 \tilde{F}_3(\theta,s) \right\} \tag{18}$$

$$\tilde{F}_1(\theta,s) = \beta^2 \left[1 + \frac{1}{4}(1-3\beta^2)\sin^2\theta \right] \tag{19}$$

$$\tilde{F}_2(\theta,s) = -2\left[1 - \frac{1-\beta^2}{t(\beta,\cos\theta)}\right](1-\beta^2) - 4\beta^2 + \beta^2\left[1 - 2\frac{1-\beta^2}{t(\beta,\cos\theta)}\right]\sin^2\theta \tag{20}$$

$$\tilde{F}_3(\theta,s) = 4 + \frac{\beta^2}{4}\left\{(1-\beta^2)\left[\frac{4}{t(\beta,\cos\theta)}\right]^2 + \frac{s}{M_\Phi^2}\right\}\sin^2\theta \tag{21}$$

$$R_v = \frac{3\beta}{8}\frac{s}{M_\Phi^2}\sum_{j=L,R}\left\{ |\kappa_j(s)|^2 F_1^v(\beta) + \left(\frac{\lambda_j}{e}\right)^2 \Re[\kappa_j(s)] F_2^v(\beta) + \left(\frac{\lambda_j}{e}\right)^4 F_3^v(\beta) \right\} \tag{22}$$

$$F_1^v(\beta) = \beta^2\left(\frac{7-3\beta^2}{4}\right) \tag{23}$$

$$F_2^v(\beta) = -\frac{15}{4} - 2\beta^2 + \frac{3}{4}\beta^4 + \frac{3}{8\beta}(1-\beta^2)^2(5-\beta^2)\ln\left|\frac{1+\beta}{1-\beta}\right| \tag{24}$$

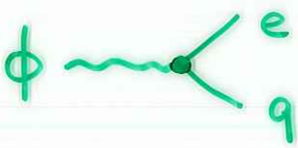
$$F_3^v(\beta) = 3(1+\beta^2) + \frac{\beta^2}{4}\frac{s}{M_\Phi^2} + \frac{3}{2\beta}(1-\beta^4)\ln\left|\frac{1+\beta}{1-\beta}\right| \tag{25}$$

$$\sigma_v(s \to \infty) \propto \sum_{j=L,R} \frac{\pi\alpha^2}{2M_\Phi^2} \left\{ |\kappa_j^\infty|^2 - 5\left(\frac{\lambda_j}{e}\right)^2 \Re(\kappa_j^\infty) + \left(\frac{\lambda_j}{e}\right)^4 \left[6 + \frac{s}{4M_\Phi^2}\right] \right\} \tag{26}$$

- CONTRARY TO THE CASE OF WW-PRODUCTION THE $|B|^2$- AND $|Bf|$- TERM BEHAVE NONSINGULAR !

- AS A CONSEQUENCE THE $|ff|^2$-SINGULARITY CAN NOT BE CANCELLED.
  (THERE IS ALSO NO RELATION BETWEEN λ_j & THE GAUGE COUPLINGS)

- THE EFFECTIVE LAGRANGIAN CAN NOT HOLD TO ARBITRARY HIGH ENERGIES, SINCE $\lambda \neq 0$



4a NUMERICAL RESULTS : LEP-1

SO FAR : ONLY SCALAR S_1 ANALYZED UNDER SIMPLIFYING ASSUMPTIONS

RESULTS FOR $s \simeq M_Z^2$:
- Re $K(s) \equiv 0$ NO $\gamma - Z$ INTERFERENCE
- $\lambda^4_{R,L}$ - TERMS $\ll 1$.

$$\sigma_S(\beta) = \frac{\pi\alpha^2}{2s}\beta^3 \sum_{j=L,R} |K_j(s)|^2$$

$$\sigma_V(\beta) = \frac{\pi\alpha^2}{8M_\Phi^2}\beta^3(7-3\beta^2)\sum_{j=L,R}|K_j(s)|^2$$

$\lim_{\beta\to 0}\sigma_V = 7 \lim_{\beta\to 0}\sigma_S$ modulo $|K_j|^2$

$\sigma(S_1) : \sigma(\vec{S}_3) : \sigma(\tilde{S}_1) : \sigma(R_2) : \sigma(\tilde{R}_2)$

$= 1 : 203.3 : 16 : 74.6 : 50.6$

$\sigma(U_1) : \sigma(\tilde{U}_1) : \sigma(V_2) : \sigma(\tilde{V}_2) : \sigma(\vec{U}_3)$

$= 1 : 6.25 : 15.65 : 12.64 : 53.1$

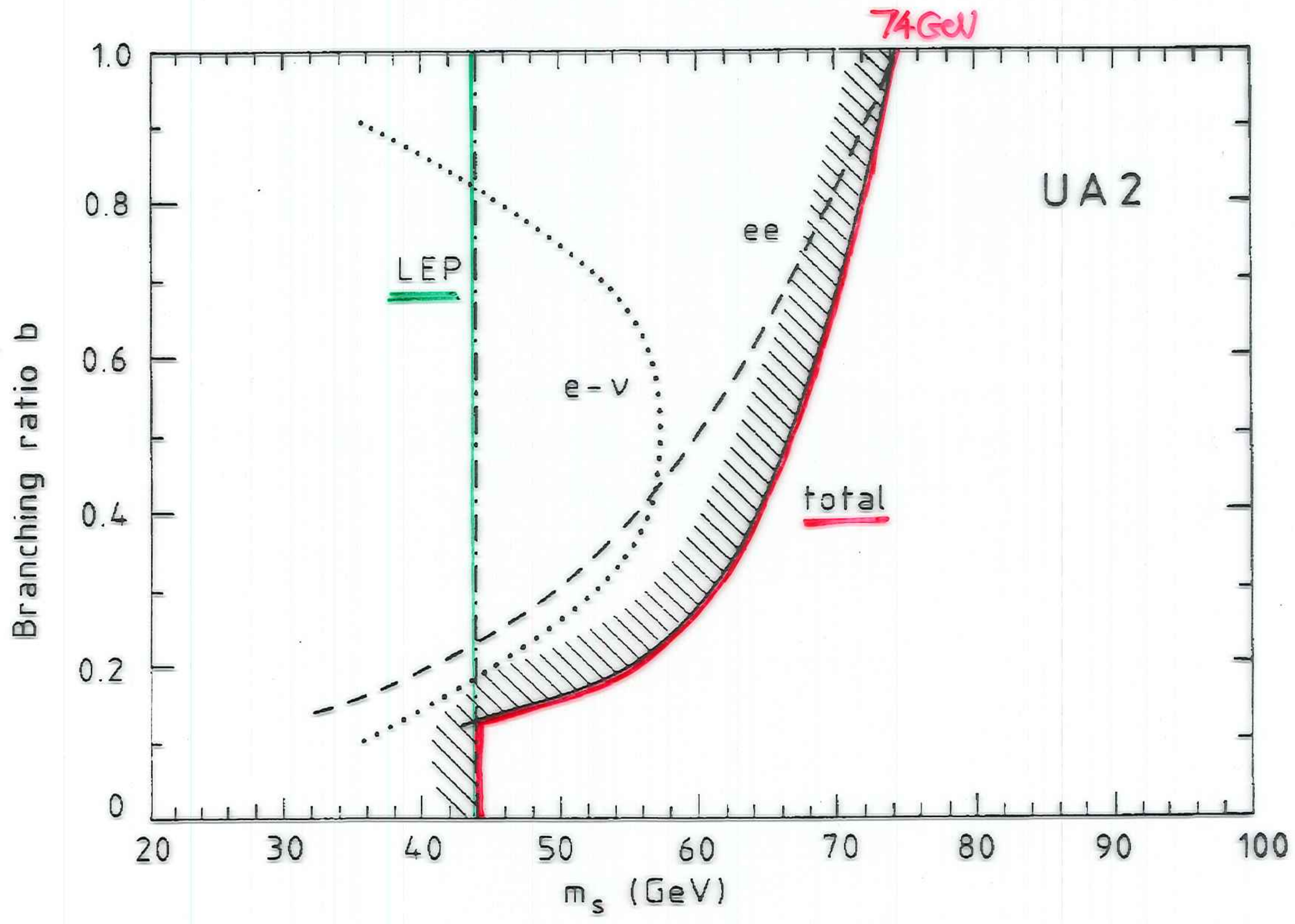
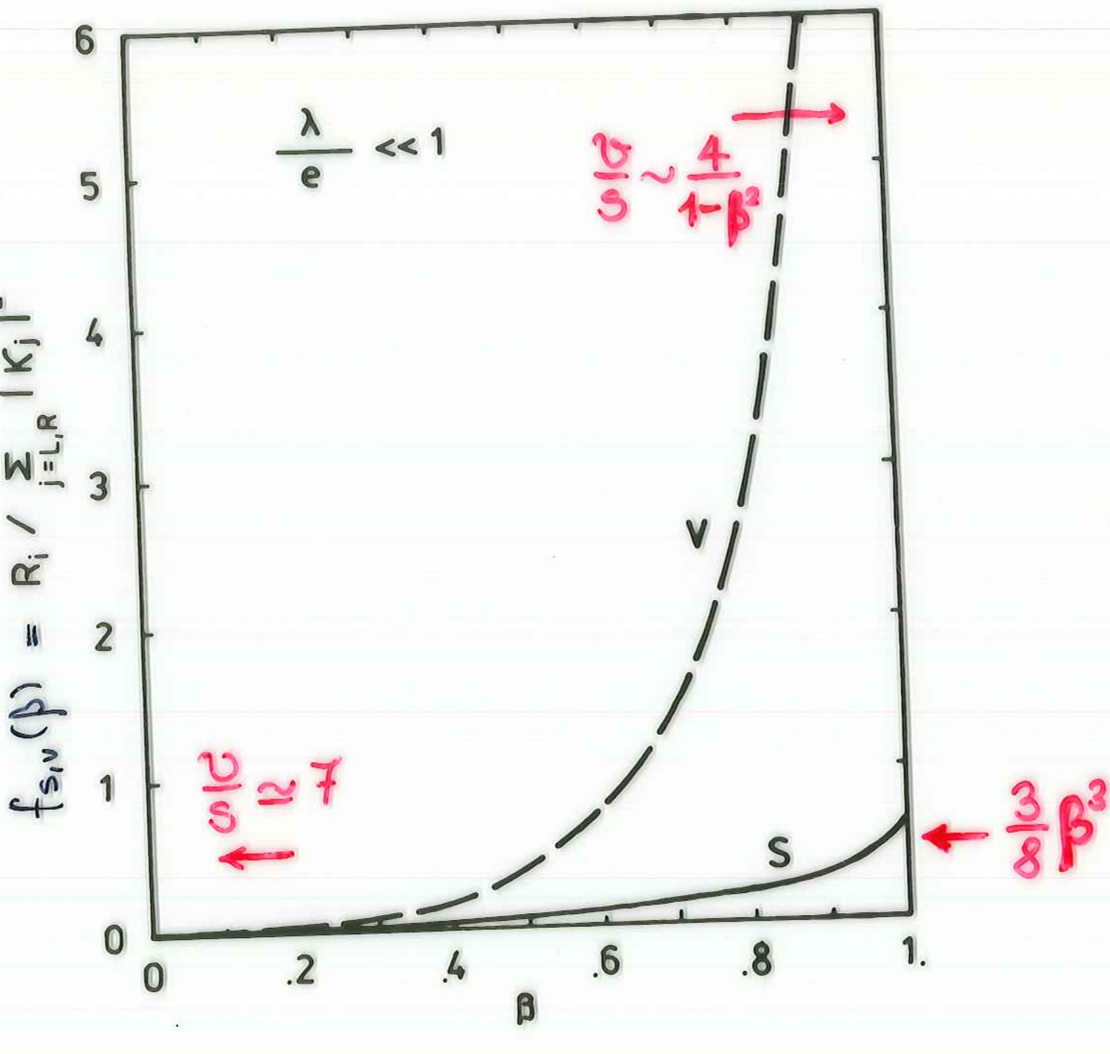

74GeV
1.0
0.8
0.6
0.4
0.2
0
UA2
ee
LEP
e-ν
total
Branching ratio b
20
30
40
50
60
70
80
90
100
m_s (GeV)

FIG. 2



6
5
4
3
2
1
0
0
.2
.4
.6
.8
1.
β
$f_{s,v}(\beta) \equiv R_i \,/\, \sum_{j=L,R} |K_j|^2$
$\frac{\lambda}{e} << 1$
$\frac{v}{s} \sim \frac{4}{1-\beta^2}$
V
S
$\frac{v}{s} \simeq 7$
$\frac{3}{8}\beta^3$

4b Numerical Results : LINACS $\sqrt{s} \gtrsim 200$ GeV

a) INTEGRATED CROSS SECTIONS

$\lambda/e \ll 1$:

$$R^{\phi}_{S,V} = f_{S,V}(\beta) \sum_{j=L,R} |K^{\phi}_{j}(s)|^2$$

$\boxed{\text{Fig.}}$

$$\sqrt{s} \gtrsim 200 \text{ GeV}: \sum_j |K^j_{S_1}|^2 \leq \sum_j |K^j_{u_1}|^2 \leq \sum_j |K^j_{\phi_i}|^2$$

$$\phi_i = \tilde{V}_2, \tilde{R}_2, V_2, \tilde{u}_1, R_2, \vec{S}_3, \vec{u}_3$$

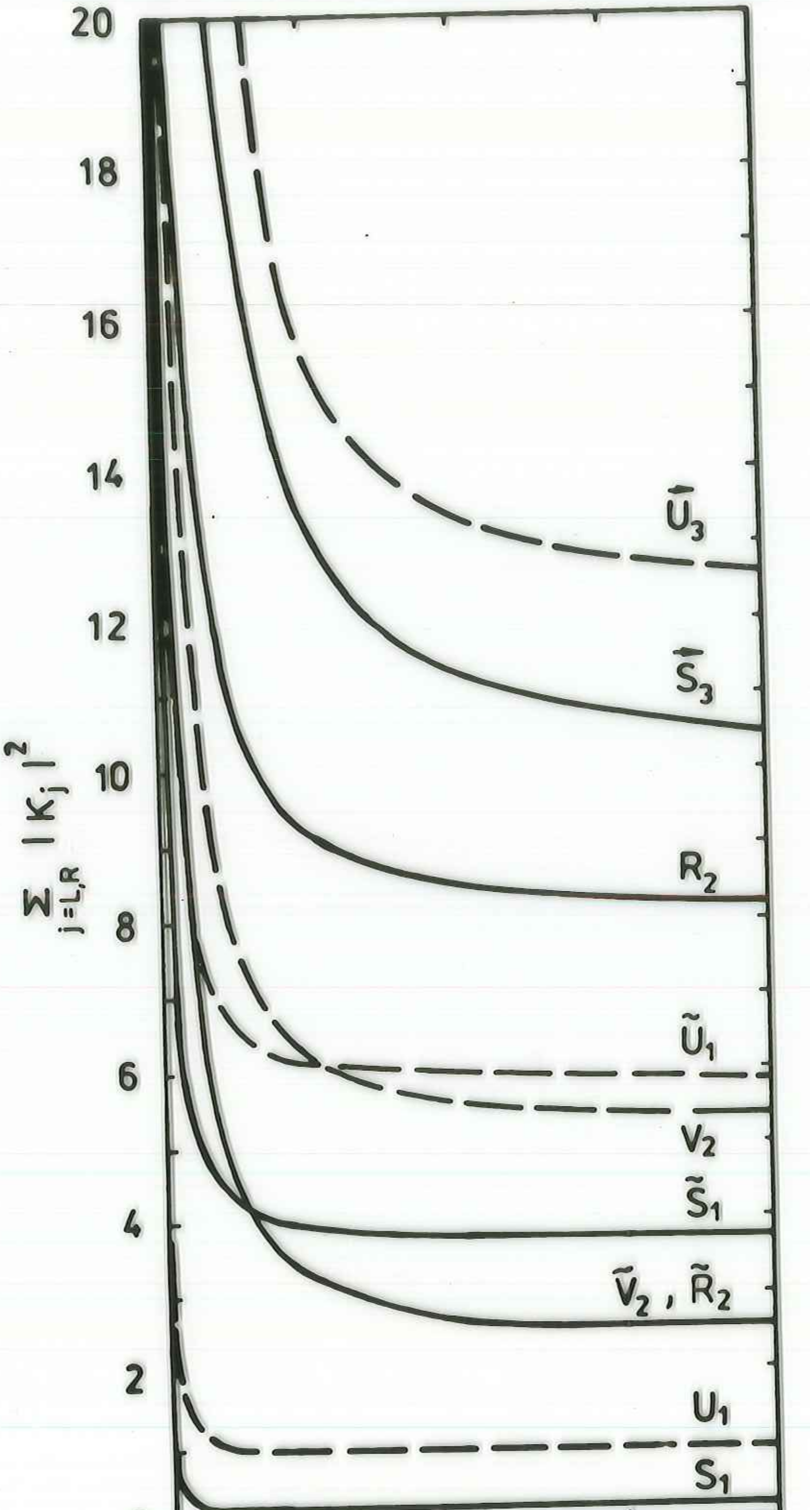
$\boxed{\text{Fig.}}$

INFLUENCE OF $(\lambda/e)^2$-TERMS:

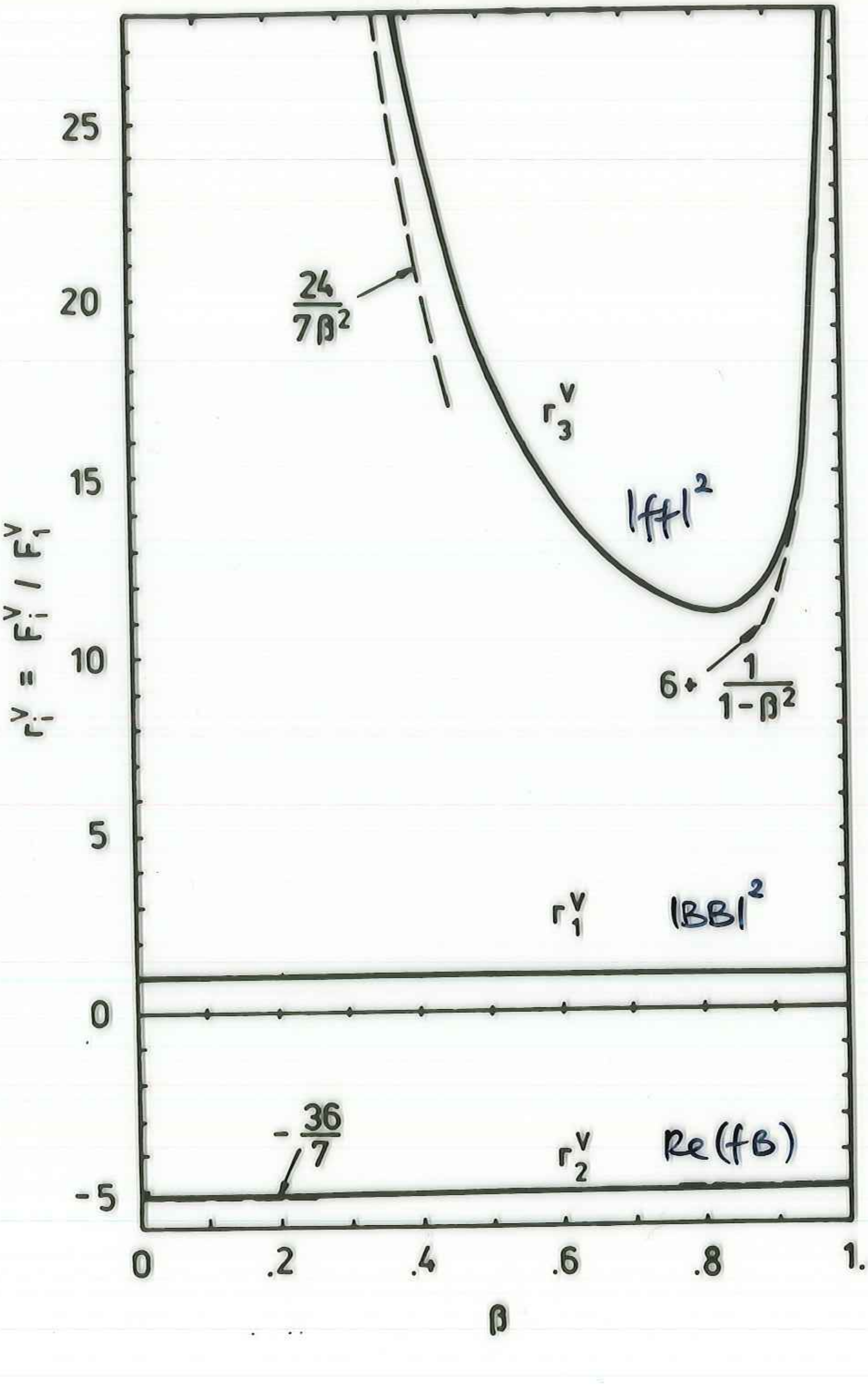
β-DEP. WEIGHT FACTORS:

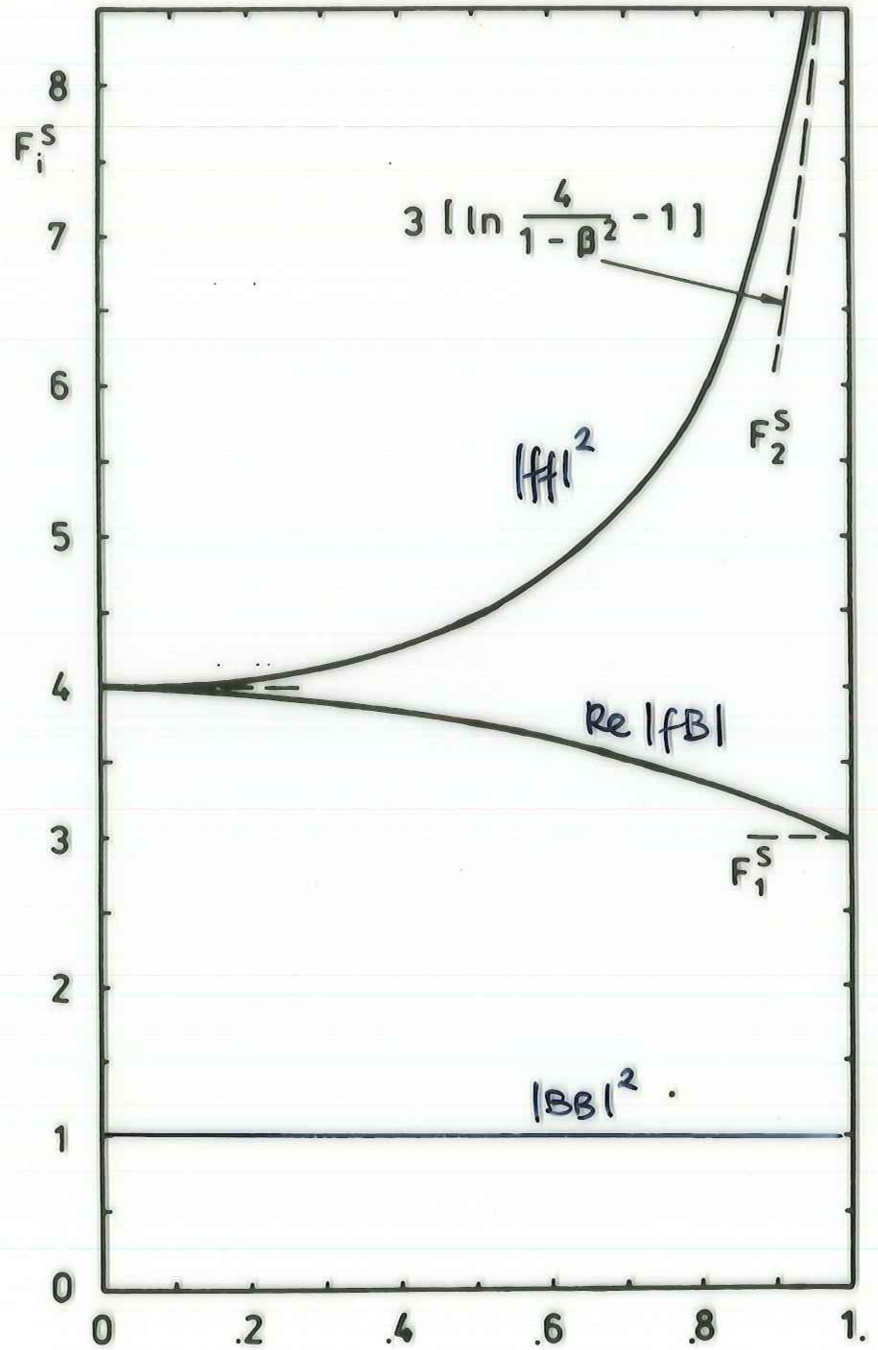
$$\sum_{L,R=j} |K_j(s)|^2 \quad : \quad \mathrm{Re} \sum_{L,R=j} K_j(s) \left(\frac{\lambda_j}{e}\right)^2 : \sum_{L,R} \left(\frac{\lambda}{e}j\right)^4$$

$\boxed{\text{Figs.}}$



20
18
16
14
12
10
8
6
4
2
0
$\sum_{j=L,R} |K_j|^2$
$\vec{U}_3$
$\vec{S}_3$
R_2
$\tilde{U}_1$
V_2
$\tilde{S}_1$
$\vec{V}_2$, $\tilde{R}_2$
U_1
S_1
100
200
300
400
500
$\sqrt{s}$ / GeV


25
20
15
10
5
0
-5
$r_i^V = F_i^V / F_1^V$
$\frac{24}{7\beta^2}$
r_3^V
$|ff|^2$
$6 + \frac{1}{1-\beta^2}$
r_1^V
$|BB|^2$
$-\frac{36}{7}$
r_2^V
$Re(fB)$
0
.2
.4
.6
.8
1.
β



F_i^S
8
7
6
5
4
3
2
1
0
0
.2
.4
.6
.8
1.
β
$3\,[\ln \frac{4}{1-\beta^2} - 1]$
F_2^S
$|ff|^2$
Re $|fB|$
F_1^S
$|BB|^2$

leptoquark	type	$\sigma[fb]$	
		$\lambda_{L,R}/e = 0$	$\lambda_L/e = 0.3$
S_1	scalar	7	5
$\tilde{S}_1$	"	106	99
$\vec{S}_3$	"	298	256
R_2	"	231	215
$\tilde{R}_2$	"	73	63
V_2	vector	1403	1562
$\tilde{V}_2$	"	666	670
U_1	"	243	378
$\tilde{U}_1$	"	1531	1531
$\vec{U}_3$	"	3287	3743

Table 1: Comparison of the integrated leptoquark cross sections for $M_\Phi = 200\,\mathrm{GeV}$ and $\sqrt{s} = 500\,\mathrm{GeV}$ taking $\lambda_{L,R} = 0$ and $\lambda_L/e = 0.3$, $\lambda_R \; = \; 0$.

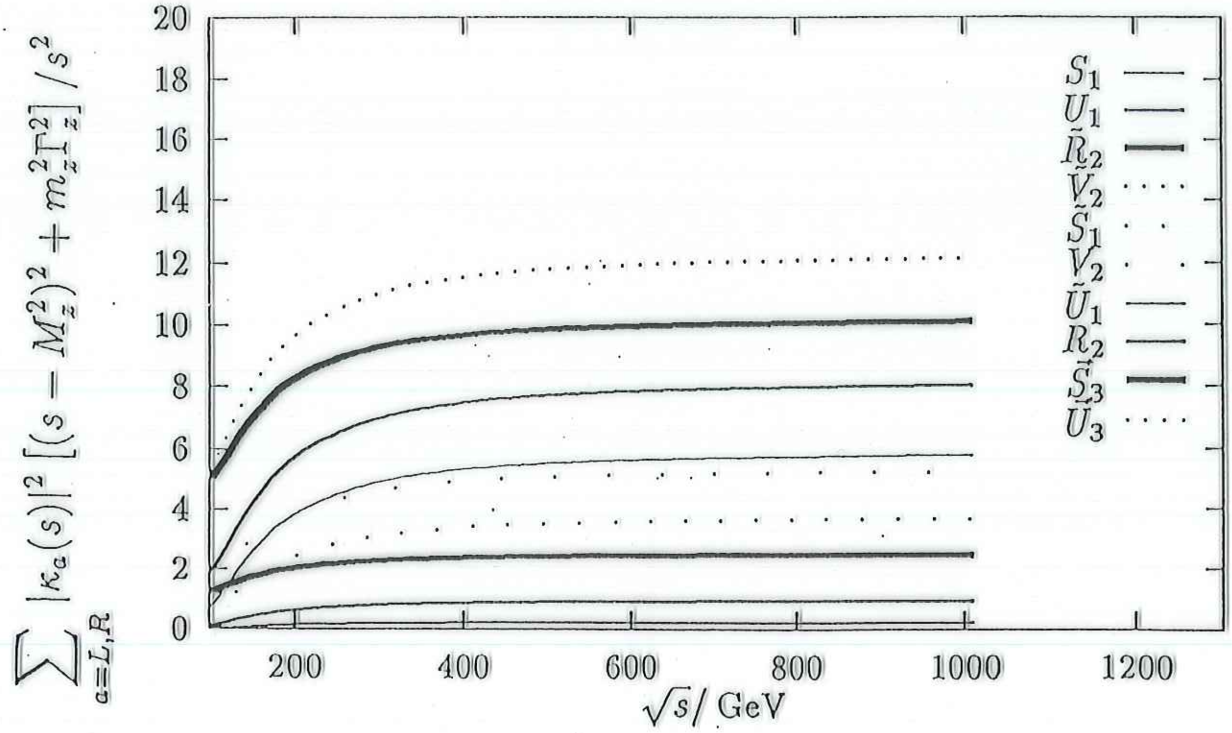


Figure 1: Energy dependence of the integrated production cross sections for scalar and vector leptoquarks. The cross sections are scaled by the factor $[(s \; - \; M_Z^2)^2 \; + \; M_Z^2\Gamma_Z^2]/s^2\sigma_{pt}F_i(\beta)$ with $F_s(\beta) = 3\beta^3/8$ and $F_v(\beta) = 3\beta^3(7-3\beta^2)/8(1-\beta^2)$, respectively.

ANGULAR DISTRIBUTIONS :

$dR_S / d\cos\theta$, $dR_V / d\cos\theta$

$\lambda/e \ll 1$: ALMOST SYMMETRIC (SIMILAR FOR ALL VECTORS AND ALL SCALARS)

$\lambda/e \sim 1$: PEAKING BEHAVIOR FOR $\cos\theta \to 1$
DIFFERENT FOR $\lambda_L = 1$, $\lambda_R = 0$
& $\lambda_L = 0$, $\lambda_R = 1$
$\longmapsto$ Z-BOSON EXCHANGE.

EXAMPLES: • SCALAR S_1 $\boxed{\text{Figs.}}$
• VECTOR U_1

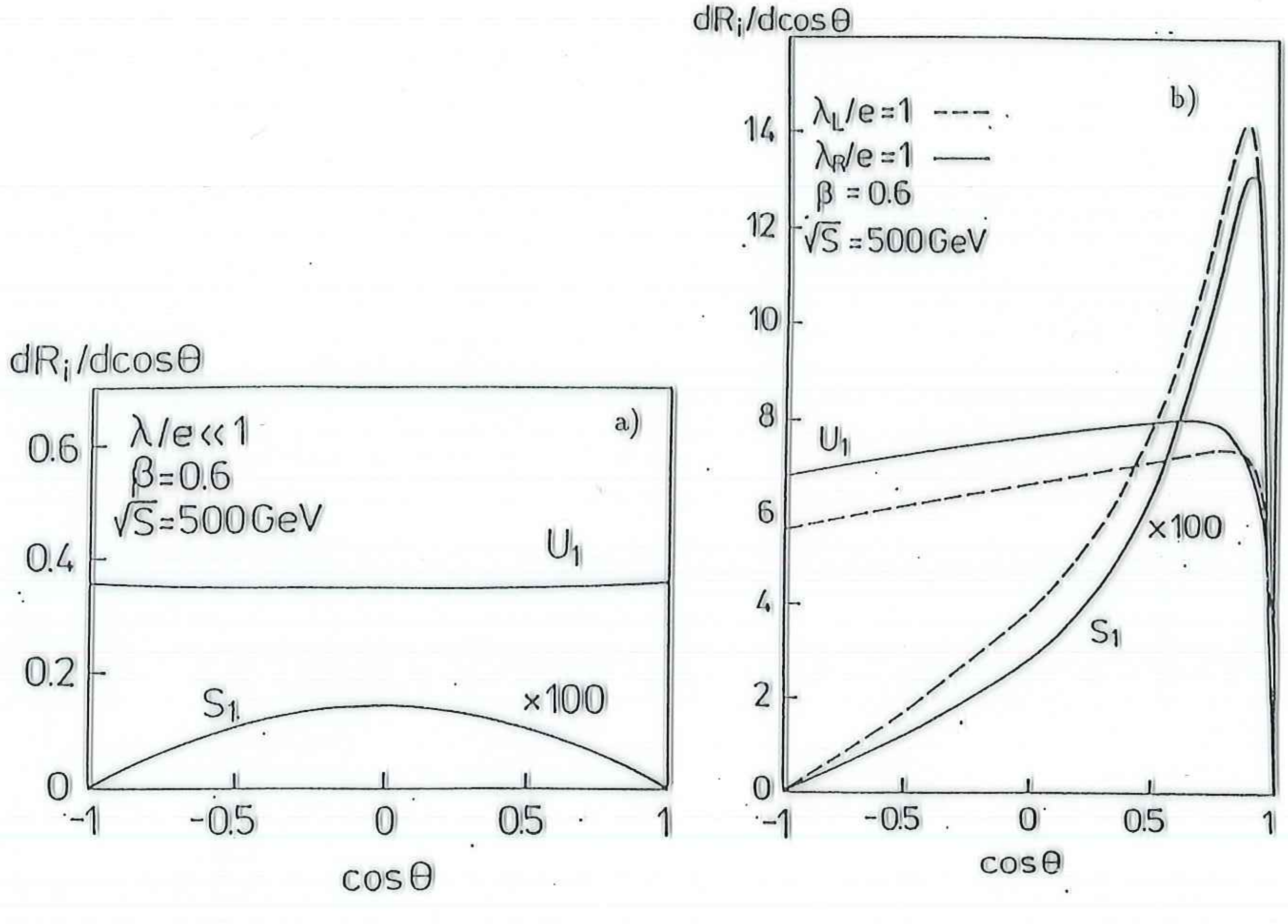


Figure 2: Differential cross sections $d\sigma/d\cos\theta$ for the scalar leptoquark S_1 and the vector leptoquark U_1 normalized by σ_{pt}. a) $\lambda_{L,R}/e = 0$; b) $\lambda_L/e = 1$, $(\lambda_R = 0)$ or $\lambda_R/e = 1$, $(\lambda_L = 0)$.

5 CONCLUSIONS

- LEPTOQUARKS MAY BE SEARCHED FOR AT HIGH ENERGY e^+e^- COLLIDERS.

- BECAUSE OF THEIR KNOWN GAUGE-BOSON COUPLINGS PRODUCTION CROSS SECTIONS OF

$$\sigma(S_1) \sim 7\,\text{fb}\;;\; \sigma(\vec{S}_3) \sim 300\,\text{fb}\;;\; \sigma(U_1) \sim 243\,\text{fb}$$

$$\sigma(\vec{U}_3) \sim 3300\,\text{fb}$$

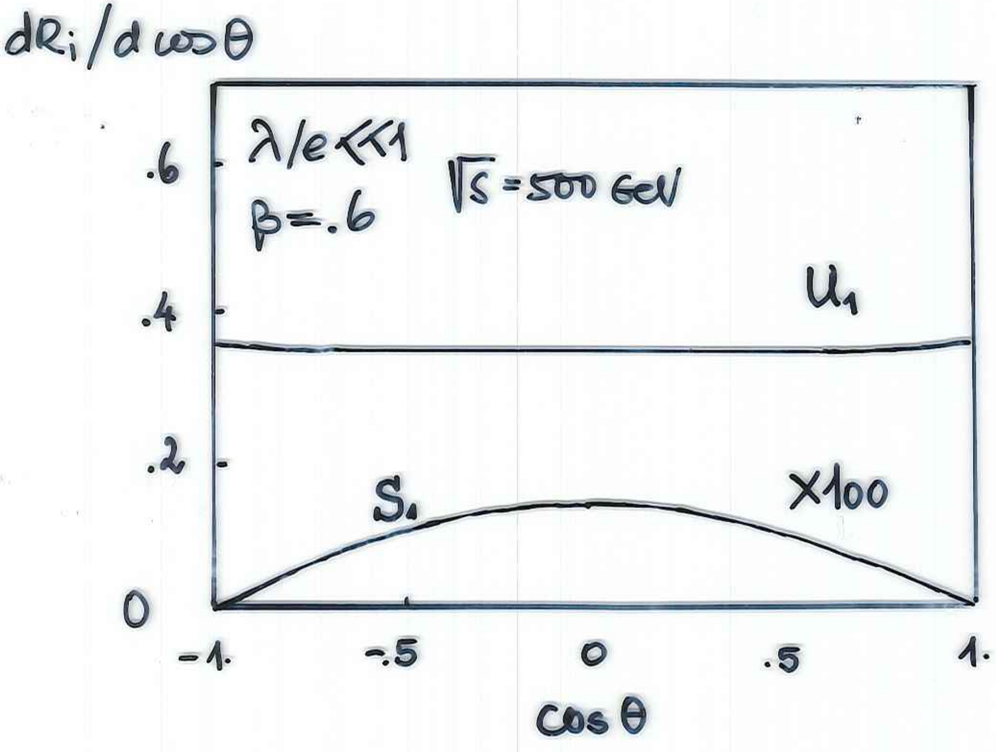
  ARE EXPECTED. $:\beta = .6,\ \sqrt{s} = 500\,\text{GeV}.$

- $(\lambda/e)^2 \sim O(1)$ TERMS CAUSE BOTH POSITIVE CORRECTIONS AND INTERFERENCE TERMS (DESTRUCTIVE IN SOME CASES).

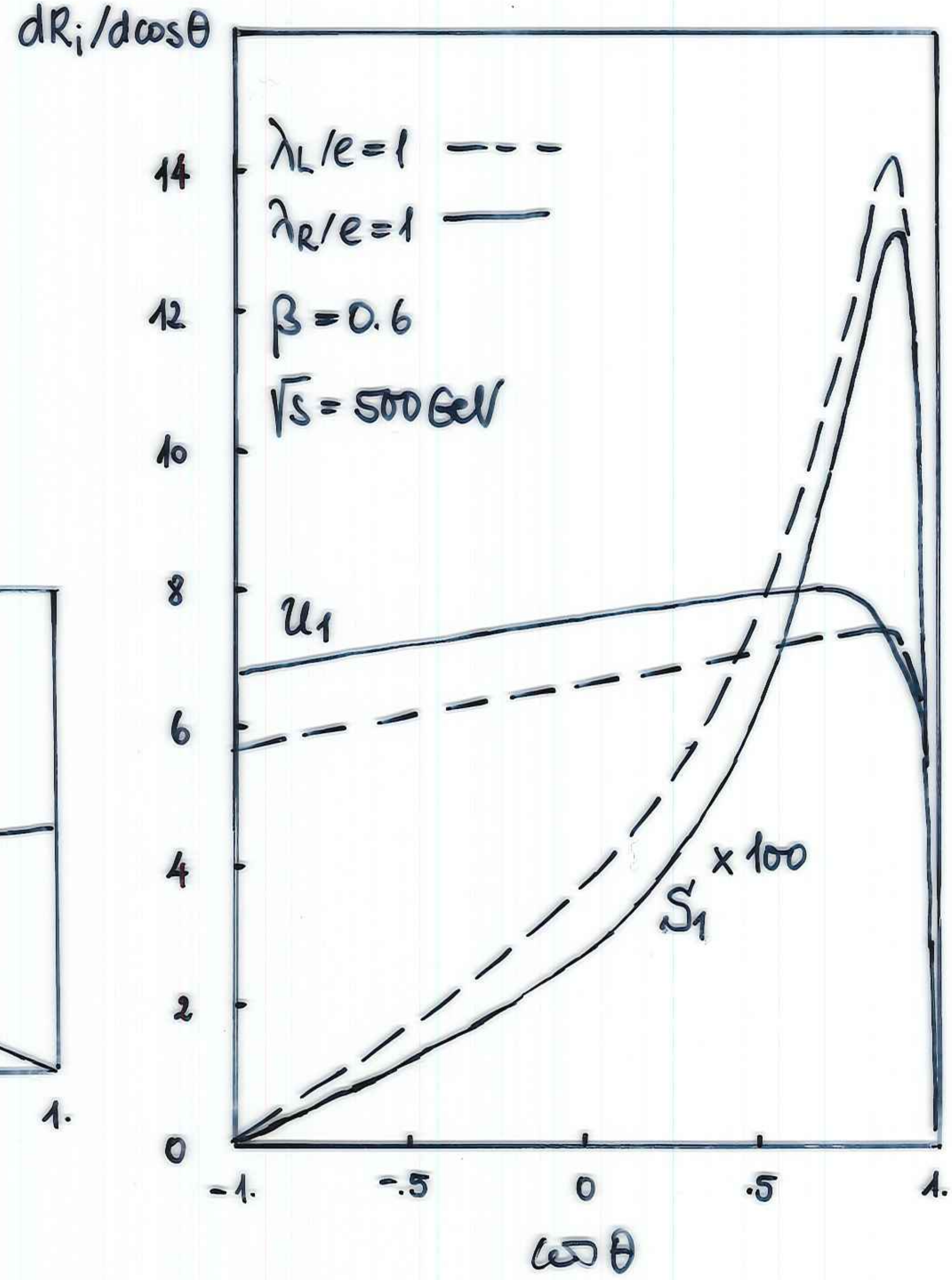
- FOR $\lambda/e \ll 1$ VECTORS & SCALARS CAN BE WELL SEPARATED VIA $dR_{s,v}/d\cos\theta$

- BOTH VECTORS & SCALARS SHOW THE β^3-BEHAVIOUR FOR THE $|BB|^2$-TERM

- THE EFFECTIVE LAGRANGIAN DOES NOT RESPECT UNITARITY FOR VECTORS → OTHER MECHANISMS REQU. AT HIGH ENERGIES, I.E. WHEN $\left(\frac{\lambda}{e}\right)^4 \frac{s}{M_\phi^2}$ GETS LARGE.



dR_i/dcosθ
λ/e<<1
β=.6
√s = 500 GeV
U_1
S_1
×100
0
.2
.4
.6
-1.
-.5
0
.5
1.
cos θ



dR_i/dcosθ
λ_L/e=1
λ_R/e=1
β = 0.6
√s = 500 GeV
U_1
S_1
×100
0
2
4
6
8
10
12
14
-1.
-.5
0
.5
1.
cos θ

INTEGRAL CROSS SECTIONS:

$\sqrt{s} = 500$ GeV , $m_\phi = 200$ GeV : $\beta = 0.6$

LEPTOQUARK	TYPE	σ [fb]	
		$\lambda_{L,R} = 0$	$\lambda_{L/R} = .3$
S_1	SCALAR	7	5.5
$\tilde{S}_1$	"	106	99
$\vec{S}_3$	"	298	256
R_2	"	231	215
$\tilde{R}_2$	"	73	63
V_2	VECTOR	1403	1562
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