DOUBLY CHARGED SCALARS AND FERMIONS AT LC.

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OUTLINE:

I. INTRODUCTION

IS THERE A DESERT BETWEEN M_W AND UNIFICATION SCALE 10^{16} GeV?

IN SUSY GUT-s NO!!!

II. SUSY SO(10) MOTIVATED LOW ENERGY MODEL.

III. $e^+e^- \to \Delta_L^{++}\Delta_L^{--}$

IV. $e^+e^- \to \tilde{\Delta}^{++}\tilde{\Delta}^{--}$

V. CONCLUSIONS

WORK DONE WITH P. ZERWAS.

I. INTRODUCTION

SUSY HAS BECOME ONE OF THE CENTRAL QUESTIONS IN PARTICE PHYSICS. OFTEN REPEATED MOTIVATIONS FOR MSSM:

1) SOLVES THE HIERARCHY PROBLEM;

2) PREDICTS SUCCESSFULLY THE UNIFICATION OF GAUGE COUPLINGS.

POINT 2) IMPLIES DESERT BETWEEN 1 TeV AND 10^{16} GeV.

ON THE OTHER HAND:

1) INCREASING EVIDENCE FOR $m_\nu \neq 0$;

2) BARYOGENESIS IMPOSSIBE WITH SM PARTICLE CONTENT.

THE SIMPLEST SOLUTION: INTERMEDIATE SCALE AROUND

$$\boxed{10^{10} - 10^{15}\ \text{GeV}}$$

FOR EXAMPLE N WITH M_R

$$\left.\begin{array}{l} \text{1) SEE-SAW FOR } m_\nu \sim \frac{m_D^2}{M_R} \\ \text{2) LEPTOGENESIS} \end{array}\right\} (B-L) \text{ BROKEN AT } M_R$$

SURVIVAL PRINCIPLE ASSUMED:

IN GUTS, THE SINGLETS UNDER A GAUGE GROUP G HAVE MASSES CORRESPONDING TO THE SCALE $G' \supset G$ UNDER WHICH THEY ARE NOT SINGETS.

IN SUSY GUTS IT IS NOT SO!!

A GENERAL EXAMPLE WITH FIELD Φ

$$V = -m^2 \Phi^\dagger \Phi + \lambda^2 (\Phi^\dagger \Phi)^2 + \dots$$

$$m_\phi \sim \lambda \langle \Phi \rangle$$

IF $\lambda \sim 1 \Rightarrow m_\phi \sim \langle \Phi \rangle$

HOWEVER, IN SUSY $\lambda^2(\Phi^\dagger\Phi)^2$ TERM COMES FROM SUPERPOTENTIAL

$$\boxed{W \sim \frac{\lambda}{3} \Phi^3}$$

WHICH IS OFTEN PROHIBITED BY SYMMETRIES.

E.G., IF Φ HAS $U(1)_{B-L}$ NON-ZERO QUANTUM NUMBER.

TO BREAK SYMMETRY ONE INTRODUCES

$$W_{NR} \sim \frac{\Phi^{3+N}}{M_{PL}^N} \Rightarrow \lambda^{\#} \sim \frac{\langle \Phi \rangle^N}{M_{PL}^N} \Rightarrow m_\phi \ll \langle \Phi \rangle$$

THIS RESULT IS GENERAL.

II. SUSY SO(10) MOTIVATED LOW ENERGY MODEL.

SO(10) IS WELL MOTIVATED CANDIDATE FOR UNIFICATION GROUP.

$$SO(10) \xrightarrow{M_X} SU(2)_L \times SU(2)_R \times SU(4)_c$$
$$\xrightarrow{M_{PS}} SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_c$$
$$\xrightarrow{M_R} SU(2)_L \times U(1)_Y \times SU(3)_c$$

THE INTERMEDIATE PATI-SALAM OR LR THEORIES STUDIED EXTENSIVELY.

SUSY LR MODEL: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

MINIMAL HIGGS CONTENT:

$$\Phi = (2,2,0)$$

$$\Delta = (3,1,2) \qquad \bar{\Delta} = (3,1,-2)$$
$$\Delta_c = (1,3,-2) \qquad \bar{\Delta}_c = (1,3,2)$$

NOTE: NO CUBIC TERMS OF Δ ALLOWED IN W.

DETAILED STUDIES SHOW:

1) $W_{NR} \sim \frac{\Delta^4}{M_{PL}}$ NEEDED TO BREAK $SU(2)_R$

2) LOW ENERGY THEORY IS

$$MSSM + \Delta, \bar{\Delta}, \Delta_c^{--}, \bar{\Delta}_c^{++} \quad \text{WITH } m \sim \frac{M_R^2}{M_{PL}}$$

3) R-PARITY <u>CONSERVED</u> DUE TO SPONTANEOUS BREAKING OF B-L

POSSIBLE WAYS TO APPROACH GENERAL SUSY SO(10) GUTs:

1) <u>TOP DOWN APPROACH</u>

* NO UNIQUE SYMMETRY BREAKING CHAIN
* NO UNIQUE HIGGS SECTOR

SERVES AS A SOURCE OF MOTIVATIONS FOR COLLIDER STUDIES.

2) <u>BOTTOM UP APPROACH</u>

THE ONLY MEANINGFUL APPROACH FOR COLLIDER PHYSICS. (E.G., NMSSM = = MSSM + EXTRA SINGLET)

OUR LOW ENERGY EFFECTIVE MODEL BASED ON

$$SU(2)_L \times U(1)_Y$$

CONTAINS MSSM SPECTRUM +

$$\Delta = (3,2) \qquad \bar{\Delta} = (3,-2)$$
$$\delta^{--} = (1,-4) \qquad \bar{\delta}^{++} = (1,4)$$

SUPERPOTENTIAL

$$W = W_{MSSM} + W_T + W_S$$
$$W_T = M_\Delta \, Tr(\Delta \bar{\Delta}) + i f_\Delta L^T \tau_2 \Delta L$$
$$W_S = M_\delta \, \delta^{--} \bar{\delta}^{++} + f_\delta \, l^c l^c \delta^{--}$$

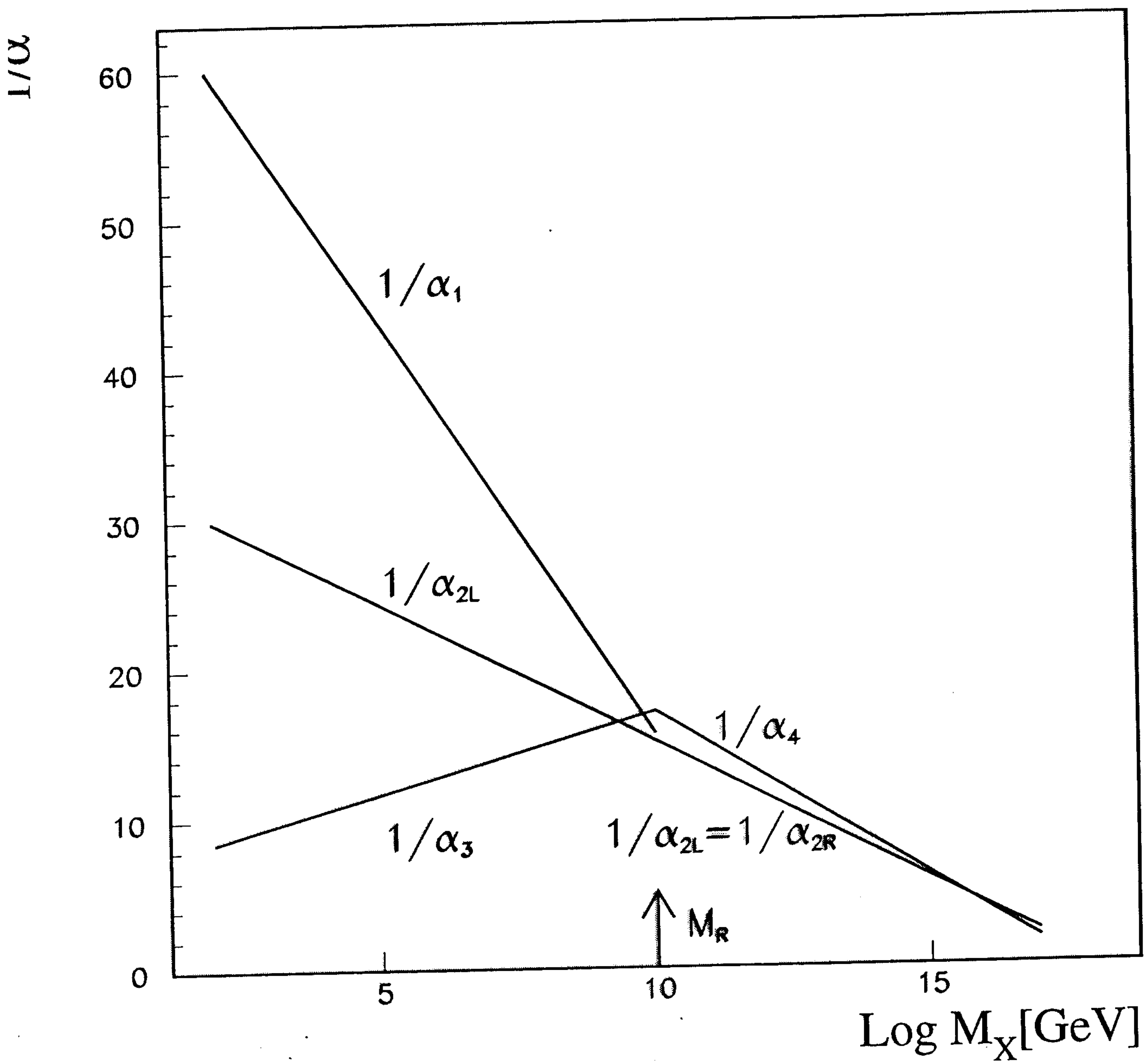
$$M_\Delta \sim M_\delta \sim \frac{M_R^2}{M_{Pl}} \Rightarrow \underline{M_R \gtrsim 10^{10}\,GeV}$$

BOUNDARY CONDITION:

$$\alpha_1^{-1}(M_R) = \frac{3}{5}\alpha_2^{-1}(M_R) + \frac{2}{5}\alpha_3^{-1}(M_R)$$

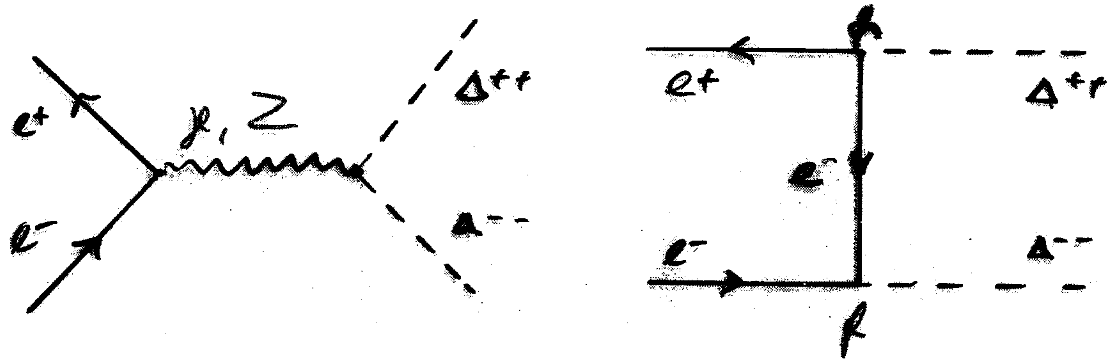
ABOVE M_R: 2 $SU(2)_L$ AND 2 $SU(2)_R$ TRIPLETS
4 $SU(4)$ 10-PLETS

$SO(10) \rightarrow SU(4) \times SU(2)_L \times SU(2)_R \rightarrow SU(2)_L \times U(1)_Y$



III. $e^+e^- \to \Delta_L^{++}\Delta_L^{--}$

RECEIVES CONTRIBUTION FROM 3 DIAGRAMS



ADVANTAGES:

1) DEPENDS ON ALL 3 PARAMETERS WE WANT TO DETERMIN:

$$M_\Delta \; ; \; I_3 \; ; \; \Gamma_\Delta$$

2) PRODUCTION POSSIBLE EVEN IF $f = 0$ DUE TO PHOTON AND Z COUPLINGS TO Δ_L^{--}.
SINGE PRODUCTION PROCESSES ARE PROPORTIONAL TO f ($e^-e^- \to l^-l^-$, $e^-\gamma \to \Delta^{--}l^+$ ETC.)

COUPLINGS: $\mathcal{L} = (D_\mu \Delta_L)^\dagger (D^\mu \Delta_L)$

$$i D_\mu = i\partial_\mu + e Q_\gamma A_\mu + \frac{e}{C_W S_W} Q_Z Z_\mu$$

$$Q_\gamma = I_3 + \frac{1}{2} Y$$

$$Q_Z = I_3 - S_W^2 Q_\gamma$$

YUKAWA'S: $\mathcal{L} = i f_{ij} L_{iL}^T C \tau^2 \Delta_L L_{jL} + h.c.$

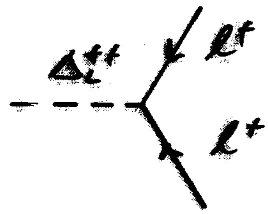
$$\mathcal{L}_{\Delta^{++}} = - f_{ij} \overline{l_{iL}^c} l_{jL} \Delta^{++} + h.c.$$

$\left.\begin{array}{l} \mu \to e\gamma \\ \tau \to \mu\gamma \end{array}\right\} \Rightarrow f_{ij} (i \neq j) \ll f_{ii}$; $M - \bar{M} \Rightarrow \frac{f_{ee} f_{\mu\mu}}{(1\,TeV)^2} \lesssim 0.$

DECAYS OF Δ_L^{++}

I ASSUME THE DOMINANT DECAY TO BE

$$\Delta_L^{++} \to \ell^+ \ell^+$$



COLLIDER SIGNAL:

$$\boxed{\begin{array}{l} e^+ e^- \longrightarrow \Delta_L^{++} \; \Delta_L^{--} \\ \qquad\qquad\quad \Delta_L^{--} \longrightarrow \ell^- \ell^- \\ \qquad\qquad\quad \Delta_L^{++} \longrightarrow \ell^+ \ell^+ \end{array}}$$

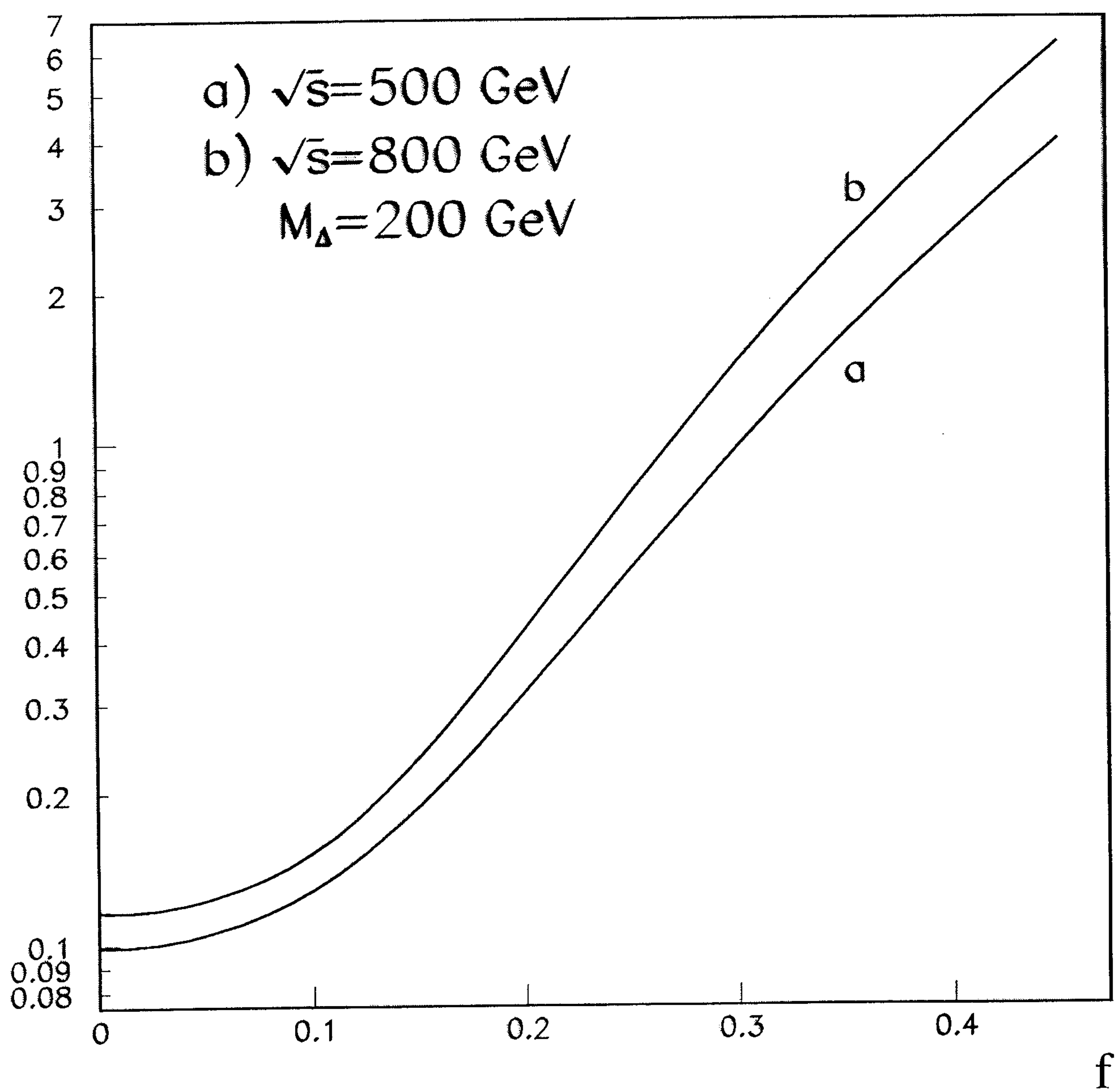
4 LEPTON FINAL STATES, SAME CHARGE DILEPTON ASSOCIATED WITH ONE DECAYING PARTICLE. NO MISSING ENERGY.

* NO SM BACKGROUND
* EVENTS FULLY RECONSTRUCTABLE

CROSS SECTION IS LARGE $\xrightarrow{\text{PLOT}}$

IT IS A SMOOTH FUNCTION OF f_Δ.

$e^+ e^- \rightarrow \Delta_L^{++} \Delta_L^{--}$



HOW TO DETERMIN UNKNOWN PARAMETERS?

M_Δ: $\sigma(e^+e^- \to \Delta_L^{++}\Delta_L^{--}) \sim \beta$

MASS CAN BE MEASURED VERY PRECISELY AT THRESHOLD.

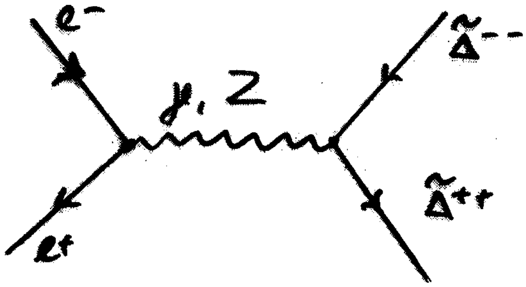
I_3 AND f_Δ: BECAUSE σ IS A MONOTONICALLY DEPENDENT FUNCTION OF f_Δ IT IS SUFFICIENT TO MEASURE σ AT TWO $\sqrt{s}$ TO DETERMIN I_3; f_Δ.

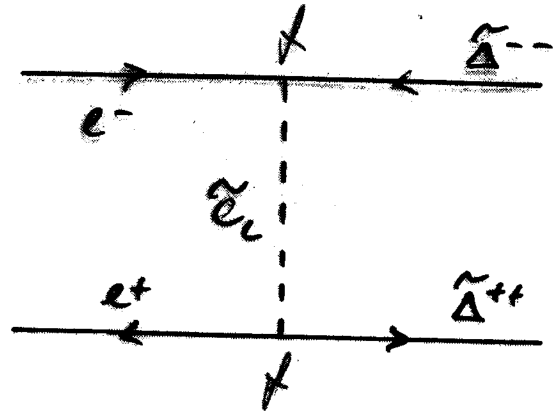
IF POLARIZATION AVAILABLE THEN CHOOSING APPROPRIATE BEAM POLARIZATION ONE CAN TURN OFF THE T-CHANNEL GRAPH AND I_3 DIRECTLY MEASURABLE.

$M_\Delta \sim \frac{\sqrt{s}}{2}$ CAN BE PROBED.

IV. $e^+ e^- \to \tilde{\Delta}^{++} \tilde{\Delta}^{--}$

PROCESS MORE COMPLICATED THAN $\Delta^{++} \Delta^{--}$ PRODUCTION.





GAUGE INTERACTIONS:

$$\mathcal{L} = \overline{\tilde{\Delta}_L^{++}}\, i \not{D}\, \tilde{\Delta}_L^{++} + \overline{\tilde{\Delta}_R^{++}}\, i \not{D}\, \Delta_R^{++}$$

$$i D_\mu = i\partial_\mu + e Q_\gamma A_\mu + \frac{e}{c_w s_w} Q_Z Z_\mu$$

$\tilde{\Delta}$ HAS VECTORLIKE COUPLING TO Z.

YUKAWA INTERACTIONS:

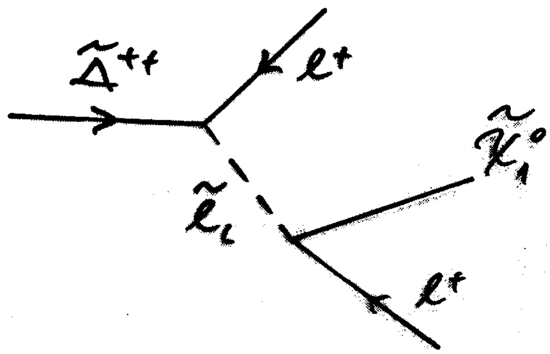
$$\mathcal{L} = -2 f\, \overline{\ell_L^c}\, \tilde{\Delta}_L^{++}\, \tilde{\ell}_L + h.c.$$

$$\sigma(e^+e^- \to \tilde{\Delta}^{++}\tilde{\Delta}^{--}) \sim \sigma(f, I_3, M_\Delta, M_{\tilde{\ell}_L})$$

I ASSUME $M_{\tilde{\ell}_L}$ TO BE KNOWN.

DOMINANT $\tilde{\Delta}^{++}$ DECAY MODE

$$\underline{\tilde{\Delta}^{++} \longrightarrow \ell^+ \ell^+ \tilde{\chi}_1^0}$$



COLLIDER SIGNATURE: $e^+e^- \to \ell^-\ell^-\ell^+\ell^+ + \not{E}$

$e^+e^- \longrightarrow \tilde{\Delta}^{++}\ \tilde{\Delta}^{--}$

$\tilde{\Delta}^{--} \to \tilde{\chi}^0 + (\ell^-\ell^-)$

$\tilde{\Delta}^{++} \longrightarrow \tilde{\chi}^0 + (\ell^+\ell^+)$

SM BACKGROUND: $e^+e^- \to W^+W^-Z \longrightarrow \ell^+\ell^+\ell^-\ell^- + \not{E}$
$W^+W^-\gamma^*$

MSSM BACKGROUND: $e^+e^- \longrightarrow \tilde{\chi}_2^0\,\tilde{\chi}_2^0 \longrightarrow \ell^+\ell^+\ell^-\ell^- + \not{E}$

HOWEVER, IN THE SM AND MSSM $(\ell^+\ell^+)$ ALWAYS COME FROM <u>DIFFERENT</u> PARTICLES, IN $e^+e^- \to \tilde{\Delta}^{++}\tilde{\Delta}^{--}$ THEY ORIGINATE FROM <u>THE SAME</u> PARTICLE.

BACKGROUND CAN BE SUPPRESSED EFFECTIVELY.

BECAUSE $\tilde{\Delta}^{++}$ IS A FERMION $\ell^+\ell^- \to \tilde{\Delta}^{++}\tilde{\Delta}^{--}$ HAS THE FOLLOWING COMPLICATIONS:

1) TWO FOLD DEPENDENCE OF σ ON f_Δ $\xrightarrow{\text{PLOT}}$

2) $\tilde{\Delta}^{++}$ DISTRIBUTIONS IN $\ell^+\ell^- \to \tilde{\Delta}^{++}\tilde{\Delta}^{--}$ CAN BE RECONSTRUCTED WITH TWO FOLD AMBIGUITY (BECAUSE OF $\not{E}$). $\xrightarrow{\text{PLOT}}$

3) $\tilde{\Delta}^{++}$ IS A FERMION: PRODUCTION AND DECAY CANNOT BE FACTORIZED. ONE HAS TO STUDY THE FULL PROCESS

$$\ell^+\ell^- \to \tilde{\Delta}^{++}\tilde{\Delta}^{--} \to \tilde{\chi}_1^0\tilde{\chi}_1^0 (\ell^+\ell^+)(\ell^-\ell^-)$$

TAKING INTO ACCOUNT SPIN-SPIN CORRELATIONS.

THE MEASURABLE ANGLES ARE:

$(\ell^+\ell^+)$ — $\cos\theta^*$, φ^*

$(\ell^-\ell^-)$ — $\cos\bar{\theta}^*$, $\bar{\varphi}^*$

IN TERMS OF THESE ANGES

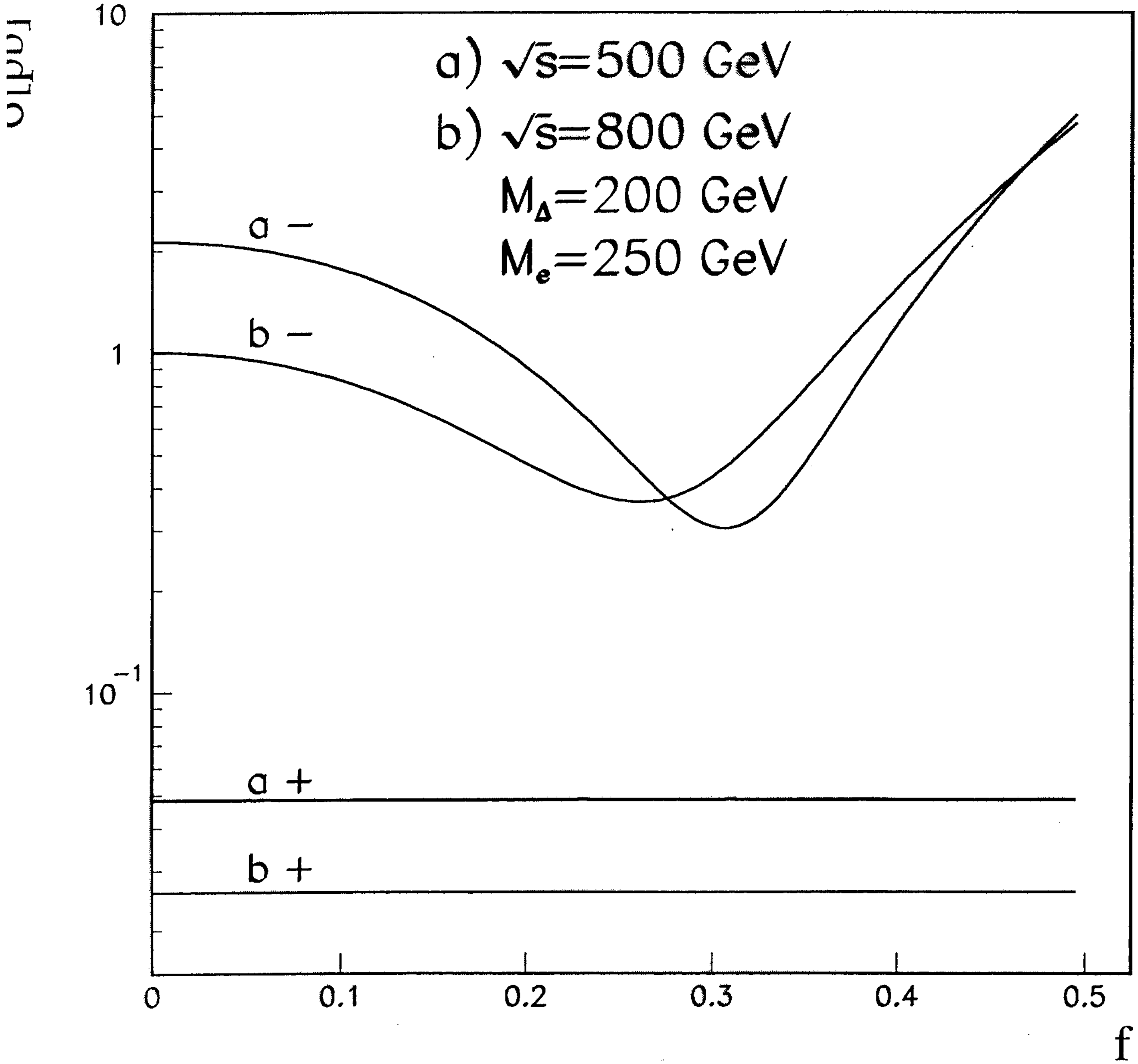
$$\frac{d^4\sigma}{d\cos\theta^* d\varphi^* d\cos\bar{\theta}^* d\bar{\varphi}^*} = \frac{\alpha^2\beta}{128\pi s} B_r(\tilde{\Delta}^{++} \to \tilde{\chi}^0\ell^+\ell^+) B_r(\tilde{\Delta}^{--} \to \tilde{\chi}^0\ell^-\ell^-) \Sigma(\theta,\bar{\theta},\varphi,\bar{\varphi})$$

$$\Sigma = \Sigma_{UNPOL} + \cos\theta^* \kappa P + \cos\theta^* \cos\bar{\theta}^* \kappa\bar{\kappa} Q +$$
$$+ \sin\theta^* \sin\bar{\theta}^* \cos(\varphi^* + \bar{\varphi}^*) \kappa\bar{\kappa} Y + \ldots$$

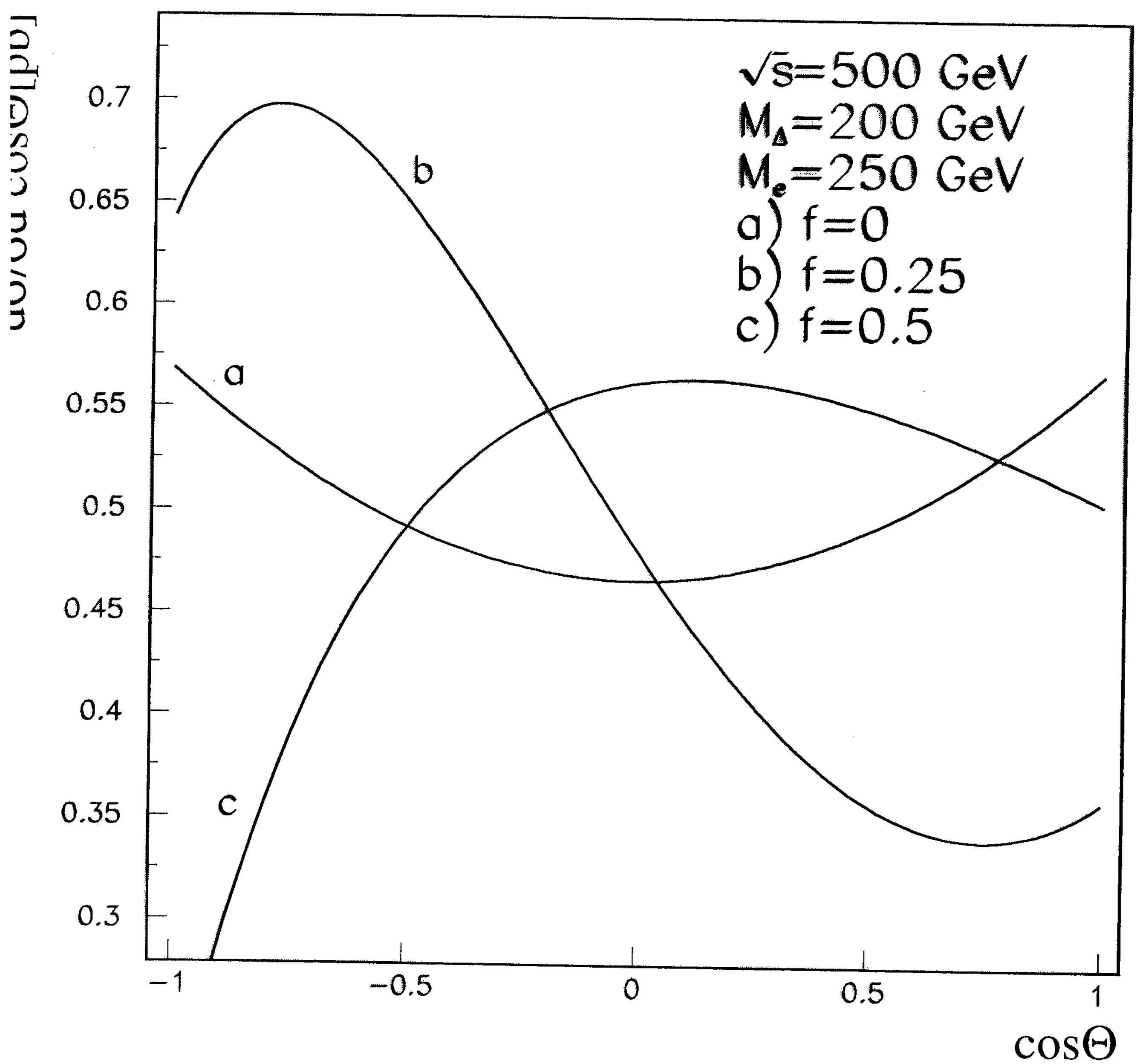
P, Q, Y – FUNCTIONS OF PRODUCTION HELICITY AMPLITUDES

$\kappa, \bar{\kappa}$ – CHARACTERIZE THE DECAYS

$e^+ e^- \to \tilde{\Delta}^{++} \tilde{\Delta}^{--}$



$e^+ e^- \rightarrow \tilde{\Delta}^{++} \tilde{\Delta}^{--}$



THE EXPERIMENTAL MEASURABLES WHICH DESCRIBE THE PRODUCTION $\ell^+\ell^- \to \tilde{\Delta}^{++}\tilde{\Delta}^{--}$ AND ARE INDEPENDENT OF DECAYS ARE

$$\sigma \ ; \ \frac{P^2}{Q} \ ; \ \frac{Y}{Q}$$

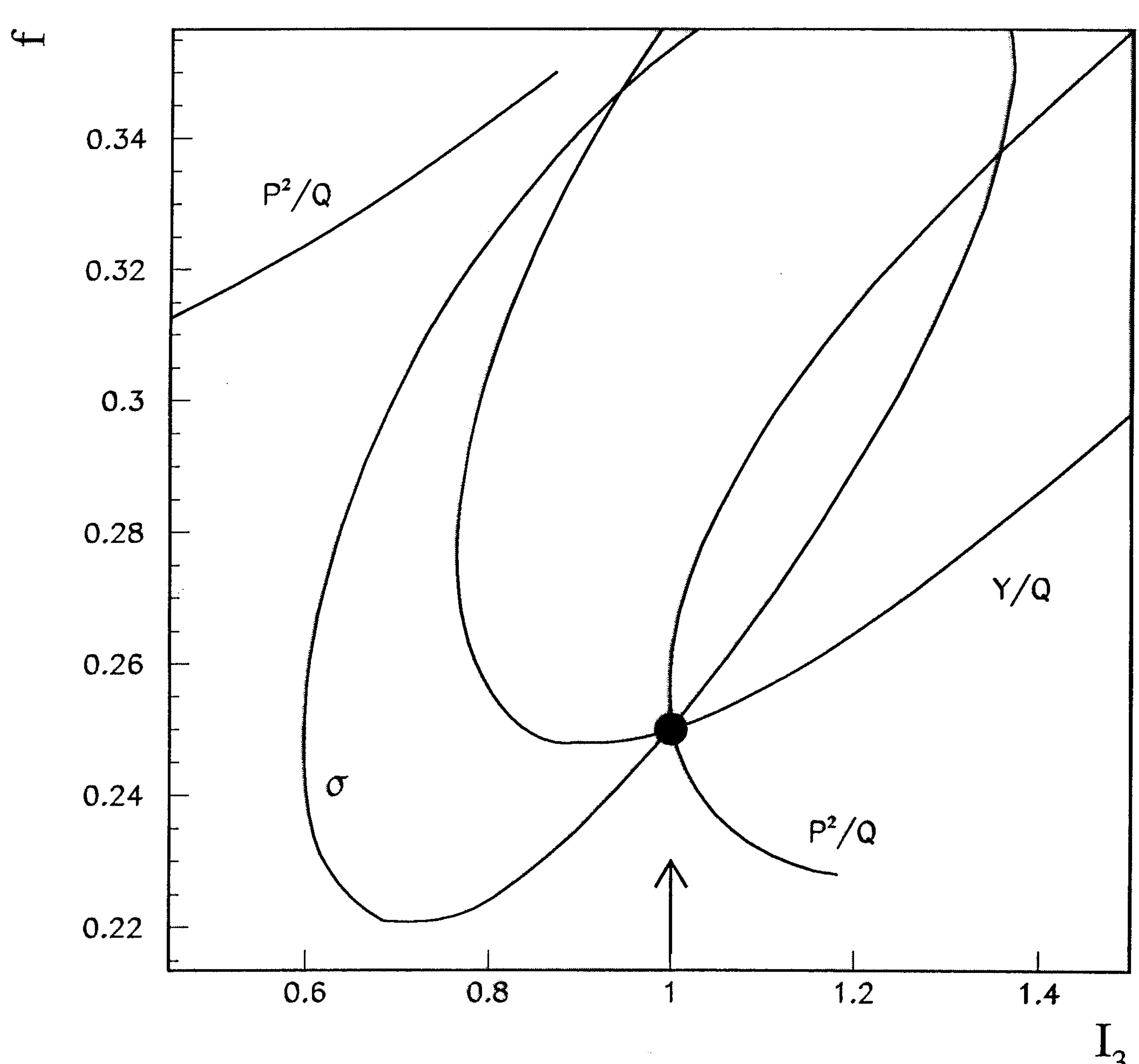
ASSUMING THE MEASUREMENT GIVES

$$\sigma = 0.14\ pb \ ; \ \frac{P^2}{Q} = -2.8 \ ; \ \frac{Y}{Q} = 0.27$$

ONE GETS SEVERAL CURVES ON (I_3, f_Δ) PLANE. $\xrightarrow{\text{PLOT}}$

COMMON CROSSING POINT DETERMINES $I_3 = 1$; $f_\Delta = 0.25$.

$e^+ e^- \to \tilde{\Delta}^{++} \tilde{\Delta}^{--}$



V. CONCLUSIONS

* SUSY SO(10) GUTs WITH INTERMEDIATE SCALES AROUND $10^{10}-10^{15}$ GEV PREDICT LIGHT DOUBLY CHARGED SCALARS Δ^{++} AND FERMIONS $\tilde{\Delta}^{++}$.

* PAIR PRODUCTION PROCESSES $\ell^+\ell^- \to \Delta^{++}\Delta^{--}$ AND $\ell^+\ell^- \to \tilde{\Delta}^{++}\tilde{\Delta}^{--}$ ALLOW UNAMBIGOUS DETERMINATION OF MASSES, QUANTUM NUMBERS AND YUKAWA COUPLINGS OF THESE PARTICLES.