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INTERNATIONAL ATOMIC ENERGY AGENCY
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

SMR.996 - 19

Lecture I & II

SUMMER SCHOOL IN HIGH ENERGY PHYSICS AND COSMOLOGY

2 June - 4 July 1997

SUSY PHENOMENOLOGY

G. KANE
Department of Physics
University of Michigan
Ann Arbor, MI 48109-1120
USA

LECTURE I

INCREASING EVIDENCE FOR SUPER PARTNERS?

(WHY I BELIEVE THAT)

IMPLICATIONS

GENERAL, RELEVANT SPHENOMENOLOGY

G. KANE

PLAN OF LECTURES

- INTRODUCTION -- LONG
- R_b, $BR(b \to s\gamma)$, α_s
- CDF $ee\gamma\gamma \not{E}_T$ EVENT
- LEP $\gamma\gamma \not{E}$ EVENTS
- EW BARYOGENESIS
- COLD DARK MATTER
- $\tilde{g}, \tilde{q}$ AT FNAL
- BEST VALUES FOR PARAMETERS -- PREDICTIONS, TESTS
- LIGHT HIGGS BOSON
- IMPLICATIONS OF PARAMETERS FOR THEORY

$\tilde{N}$LSP

- PHENOMENOLOGY OF GAUGE-MEDIATED SUSY BREAKING -- LIGHT GRAVITINO, GLSP
- TESTING STRING THEORIES
- OVERVIEW, PERSPECTIVES

TRADITIONAL ARGUMENTS FOR SUSY FINE

--SOLVE HIERARCHY PROBLEM

* --CAN UNIFY SM FORCES

--LOCAL SUSY RELATED TO GRAVITY

* --EXPLAIN HIGGS MECHANISM (IF M_{top} LARGE)

* -- COLD DARK MATTER CANDIDATE

--SUGGESTED BY STRING THEORY

(* = SOME PHENOMENOLOGICAL SUPPORT)

ALL BY MID-1980's

NOTE: SUSY NOT INVENTED TO DO ANY OF THESE -- ALL EMERGED

WHY PHENOMENOLOGY?

- FOR SUSY, NEVER A Z-LIKE ($Z \to e^+e^-$), OR EVEN W-LIKE ($W^\pm \to \ell^\pm \nu$) SIGNAL, WITH ONE MISSING PARTICLE -- HERE 2 LSP's ESCAPE
  → CONTINUUM, NO MASS PEAKS
  ⇒ CANNOT IDENTIFY SIGNALS WITHOUT THEORY
  ⇒ ALSO, MAIN SIGNATURES MAY BE SURPRISING

- CANNOT EXTRACT EVEN MASSES OF PRODUCED PARTICLES, AND PARTICULARLY ALL PARAMETERS OF WEAK SCALE EFFECTIVE LAGRANGIAN, WITHOUT VERY GOOD USE OF PHENOMENOLOGICAL THEORY
  -- e.g. NO PUBLISHED LIMITS GENERAL

- CAN DO MUCH BETTER JOB OF DETERMINING EFFECTIVE $\mathcal{L}$ AT WEAK SCALE BY COMBINING INFORMATION FROM DIFFERENT EXPERIMENTS -- THEORY ESSENTIAL

HOW MIGHT EVIDENCE FOR SUPERPARTNERS SHOW UP?

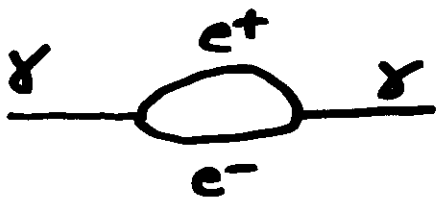
- CLEAR, EXPLICIT, UNAMBIGUOUS EFFECTS WOULD BE NICE
- SOME REFLECTION SHOWS THAT OBVIOUS EFFECTS UNLIKELY
- COULD PAIR-PRODUCE SUPERPARTNERS AS ENERGY OR LUMINOSITY INCREASES AT COLLIDERS
- BUT $\tilde{S} \longrightarrow$ SM + LSP, AND SO TWO LSP's PER EVENT, SO NEVER HAVE MASS PEAKS OR EVEN SIMPLE TRANSVERSE MASS PEAKS
- COULD SEE LOOP EFFECTS
  - --NO TREE LEVEL SM (e.g. $b \to s\gamma$) -- THEN 30% EFFECT NEEDS ERRORS $\lesssim 10\%$ FROM EXPT + TH
  - -- TREE LEVEL SM (e.g. $Z \to b\bar{b}$) -- THEN EFFECT $< 1\%$, SO NEED ERROSS $< \frac{1}{3}\%$

- AT FNAL HAVE DETECTED $\lesssim 100$ $t\bar{t}$, FEW W+Z -- IF SPARTICLES IN SAME MASS RANGE EXPECT FEW

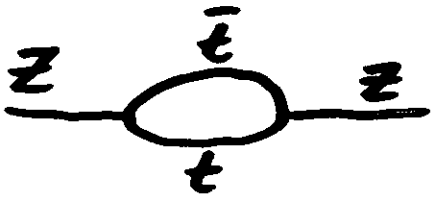
- OFTEN BACKGROUNDS -- MAY BE DIFFICULT TO EXTRACT SIGNAL -- OFTEN DIFFERENT CHANNELS GIVE SAME SIGNATURE

(B) EFFECTS OF "VIRTUAL" PARTICLES

PARTICLES IN LOOPS, NOT EXTERNAL PARTICLES THAT ENTER DETECTORS

- 

"LAMB SHIFT", 1947

- 

TOP QUARK FIRST "OBSERVED" THIS WAY, FROM LEP DATA --1991 -- ORIGINALLY MEASURED m_t TO ±30%, FINALLY AFTER LOTS OF DATA ±8% -- ABOUT SAME AS FNAL NOW

EFFECT OF LOOP $\lesssim \frac{1}{2}\%$ SO NEED VERY ACCURATE DATA

ALL PARTICLES SPEND PART OF TIME AS COMBINATIONS OF ALL OTHERS, SO PROPERTIES CONNECTED -- SOMETIMES CAN DEDUCE PROPERTIES OF VIRTUAL PARTICLES

→ SUSY NATURALLY AFFECTS FEW OBSERVABLES

- GENERAL AGREEMENT OF PRECISION DATA WITH SM WAS A SUCCESSFUL PREDICTION OF SUSY

- IN FACT
  - --SOME PHYSICS BEYOND SM IS REQUIRED, TO BREAK EW SYMMETRY, AND TO GENERATE BARYON ASYMMETRY
  - --ABSENCE OF LARGE EFFECTS IN PRECISION DATA → NEW PHYSICS IS A WEAKLY COUPLED EXTENSION OF THE SM

→ SUSY

WHY PUSH THE SEARCH FOR SUPERPARTNERS?

- SUSY MAY APPEAR IN SUBTLE, DIFFICULT-TO-RECOGNIZE WAYS -- $ee\gamma\gamma$ EVENT WAS AROUND FOR ~8 MONTHS UNNOTICED -- CONFIRMATION OF SUSY MAY COME FROM VERY DIFFERENT EVENTS --NEVER A MASS PEAK -- THEORY INVOLVEMENT PROBABLY ESSENTIAL-BACKGROUND FOR $\gamma\gamma\not{E}$ EVENTS!

- IF LIGHT SPARTICLES EXIST, THERE ARE MAJOR IMPLICATIONS FOR UTILIZATION OF LEP, FNAL, AND FOR FUTURE FACILITIES -- SO FAR ALL STUDIES, PANELS ASSUME NO DISCOVERIES FOR AT LEAST A DECADE -- IF SPARTICLES EXIST THE FRONTIER IS LUMINOSITY, NOT ENERGY--DETECTOR DEVELOPMENT WOULD BE HIGHER PRIORITY THAN ENERGY

- ONCE HAVE DATA ON SPARTICLES, CAN RELATE TO R_b, α_s, $b s \gamma$, CDM ..... --MANY OBSERVABLES AFFECTED (M_t, τ_t, RARE DECAYS, ...)

- LIKELY MAJOR IMPACT ON THEORY DEVELOPMENT -- SINCE EARLY 1980's GOOD THEORISTS WORKING IN MANY DIRECTIONS -- IF MANY FOCUSED ON ONE AREA, AND TOOK IT SERIOUSLY → FAST MAJOR PROGRESS

WE WOULD HAVE BEEN LUCKY IF ANY SPARTICLES OBSERVED SO FAR

- LEP
  - -- $M_{CHARGINO} \gtrsim 65$ GeV IF .....
    (but $M_W \approx 80$ GeV .....)
  - -- $M_{SLEPTON,\ SQUARK} \gtrsim 85$ GeV ($\sim \frac{1}{2} M_{top}$)
  - -- NO GENERAL NEUTRALINO LIMITS

- FNAL
  - -- CDF -- NO PUBLISHED GENERAL LIMITS
  - -- DØ -- ONE LIMIT ($\tilde{e}$)

NOTE -- ALL MSSM PARTICLES WHOSE MASS VANISHES IN LIMIT OF NO EWSB HAVE BEEN DETECTED EXCEPT h^0 -- SUPERPARTNERS CAN HAVE MASS TERMS THAT DO NOT BREAK GAUGE SYMMETRIES

ASSUMPTIONS :

LORENTZ INVARIANT, GAUGE INVARIANT

(1) WRITE MOST GENERAL SUPERSYMMETRIC THEORY THAT PRESERVES SEPARATION OF TWO SCALES WHEN SUSY BROKEN

AND

(2) CONNECTION BETWEEN TWO SCALES IS PERTURBATIVE (AS IT APPEARS TO BE)
"SOFTLY BROKEN"
DIMOPOULOS, GEORGI
GRISARU, CHIRIDELLI 1983

3) AT LOW ENERGIES, SPECTRUM IS SM PARTICLES + SUPERPARTNERS, GAUGE GROUP $SU(3)_C \times SU(2)_{EN} \times U(1)_Y$

(CAN CHANGE THIS SYSTEMATICALLY)

THEN — KNOWN HOW TO EXTEND TO INCLUDE SUSY BREAKING IN MOST GENERAL WAY — RESULTING LAGRANGIAN SIMPLE ENOUGH TO BE USEFUL FOR STUDY, PHENOMENOLOGY—NO ASSUMPTIONS

" MANY PARAMETERS, ONLY A FEW FOR ANY PARTICULAR PROCESS "

ABOUT 110 PARAMETERS -- BUT ABOUT 75 ARE CKM-LIKE FLAVOR ROTATION ANGLES + PHASES, 31 ARE SPARTICLE MASSES

IMPORTANT PARAMETERS

- μ — "Higgsino" mass ($-M_{Planck} \lesssim \mu \lesssim +M_{Planck}$)
- M_1, M_2 — U(1), SU(2) gaugino masses ($0 \lesssim M_1, M_2 \lesssim$ TeV)
- $\tan\beta$ — ratio of vevs ($1 \lesssim \tan\beta \lesssim 70$)
- $\tilde{t}_R$ — mass, coupling of light stop, mainly R ($m_t \tilde{t}_R b_L \tilde{C}^{\pm}$)

(PHYSICAL MASS EIGENSTATE)

THESE DETERMINE NEUTRALINO, CHARGINO MASSES, COUPLINGS

NOTATION:

$\tilde{N}_i$ = NEUTRALINOS, SUPERPARTNER MASS EIGENSTATES ($\tilde{\gamma}, \tilde{Z}, \tilde{H}_U, \tilde{H}_D \rightarrow \tilde{N}_1, \tilde{N}_2, \tilde{N}_3, \tilde{N}_4$)

$\tilde{C}_i$ = CHARGINOS ($\tilde{W}^{\pm}, \tilde{H}^{\pm} \rightarrow \tilde{C}_1, \tilde{C}_2$)

$\tilde{e}_{L,R}$; $\tilde{\nu}_{L,R}$; $\tilde{t}_{L,R}$ .....

LSP IS (MIXTURE OF)

$\tilde{\gamma}, \tilde{h}, \tilde{Z}, \tilde{\nu}, \tilde{G}$

AND NONE OF THESE INTERACT STRONGER THAN WEAKLY (LIKE NEUTRINOS OR WEAKER)

→ ALL LSP's CARRY ENERGY + MOMENTUM OUT OF DETECTOR, ESCAPE DETECTOR

→ SIGNATURE OF SUSY AT COLLIDERS IS MISSING ENERGY, MOMENTUM

ALL DECAYS OF SPARTICLES RAPID, $\lesssim 10^{-20}$ SEC, SO ONLY FINAL DECAY PRODUCTS EMERGE INTO DETECTOR

GOAL:

USE DATA FROM COLLIDERS, DECAYS, ETC TO GET $\mathcal{L}_{EFF}$ AT ELECTROWEAK SCALE -- CALCULATE $\mathcal{L}_{EFF}$ AT UNIFICATION SCALE -- WITHOUT DATA TO CONSTRAIN THEORY, WILL NOT FIND CORRECT THEORY -- WITHOUT PHENOMENOLOGY TO INTERPRET DATA, WILL NOT GET $\mathcal{L}_{EFF}^{UNIF}$ -- NEED TO MEASURE μ, tanβ, SOFT-BREAKING TERMS

GOOD PHENOMENOLOGY IS SUPERIMPORTANT IF NATURE IS SUPERSYMMETRIC

THESE LECTURES:

FOCUS ON $\tilde{H}$LSP WORLD (HIGGSINO)

--CLAIM MOTIVATED BY DATA

--VERY INTERESTING SPHENOMENOLOG

OTHER WORLDS

BINO → $\tilde{B}$LSP

--CONVENTIONAL $\tilde{N}$LSP -- IF ASSUME NO DATA IS RELEVANT, STUDY PARAMETER SPACE, MOST OF PARAMETER SPACE HERE

GRAVITINO → $\tilde{G}$LSP

— MOTIVATED BY A PARTICULAR FORM OF SUSY BREAKING, NOT BY DATA

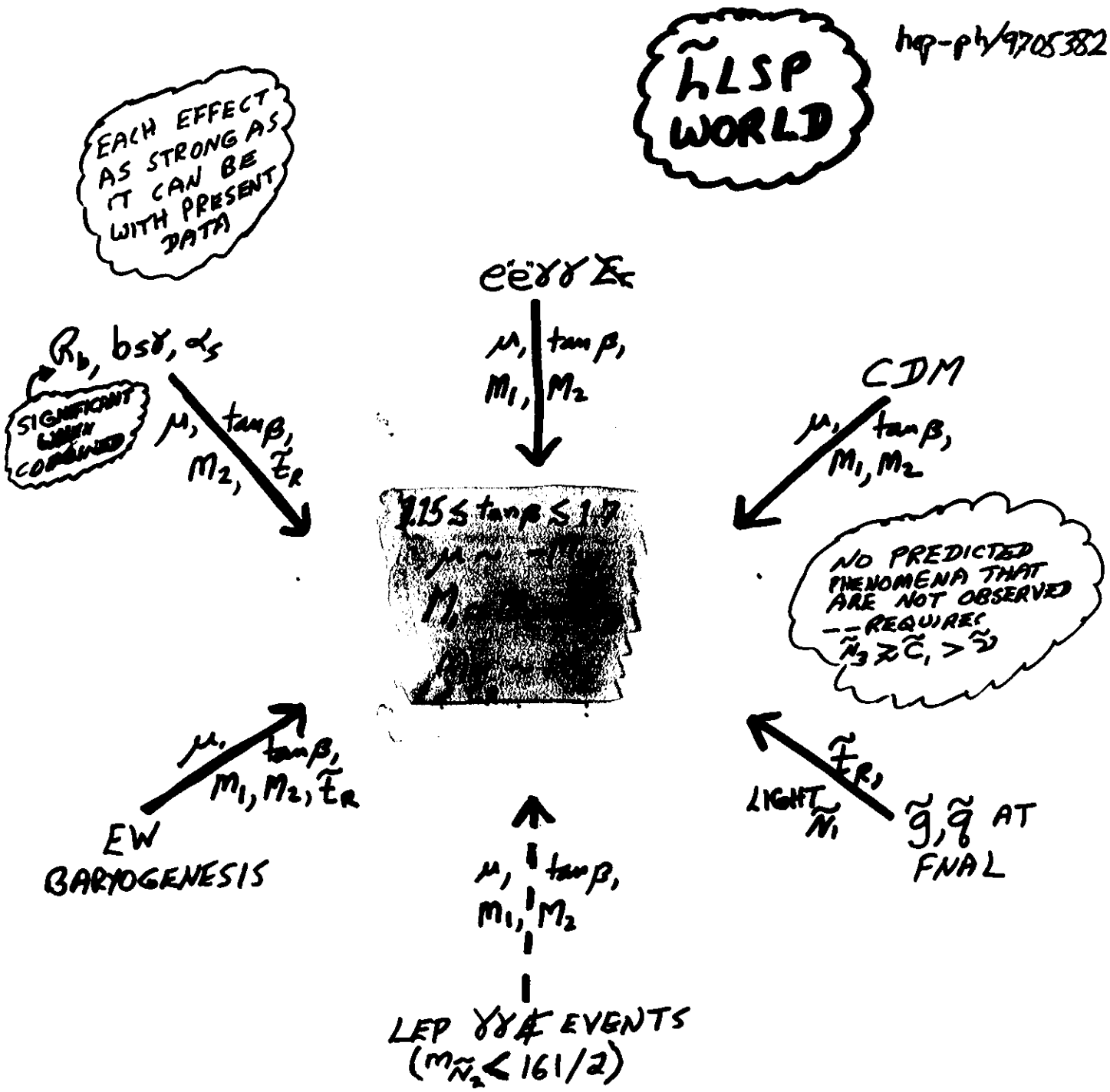
TWO PERSPECTIVES HERE

MAYBE "CORRECT"

CORRECT OR NOT, LEARN HOW TO DO THE PHENOMENOLOGICAL THEORY

Argue that get same $\sin^2\theta_W$ from many eqns in big text of SM, so same here

hep-ph/9705382



- NONE COMPELLING INDIVIDUALLY

- EACH ABOUT AS STRONG AS IT COULD BE GIVEN PRESENT EXPERIMENTAL ERRORS AND THEORETICAL UNCERTAINTIES

- EACH ONLY EVIDENCE IF PARAMETERS NEXT TO ARROW HAVE CERTAIN VALUES

- IF NOT EVIDENCE FOR SUSY, EACH MIGHT HAVE WORKED SEPARATELY, BUT EXTREMELY UNLIKELY ALL WOULD HAVE WORKED <u>AND</u> GIVE SAME $\tan\beta$, μ, m_1, m_2, $\tilde{t}_R$

$\tilde{h}$ LSP WORLD CANNOT EXPLAIN:

- CDF LARGE P_T JET EXCESS
- Aleph 4j EVENTS
- HERA EFFECT AS NEW PHYSICS
- $A_{LR} \neq A_{LR}^{SM}$
- $A_b \neq A_b^{SM}$
- $R_c \neq R_c^{SM}$

$$R_b = \Gamma(Z \to b\bar{b}) / \Gamma(Z \to had)$$

AND

$BR(b \to s\gamma)$

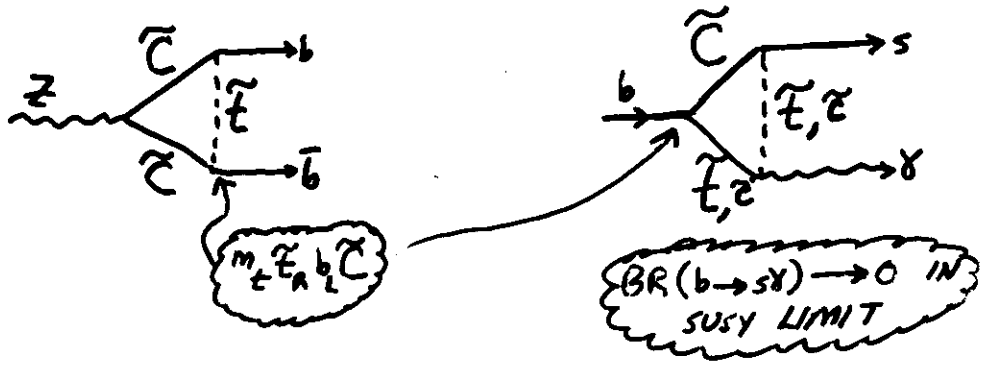
AND

$\alpha_s(M_Z)$

[redacted] [redacted]

SM

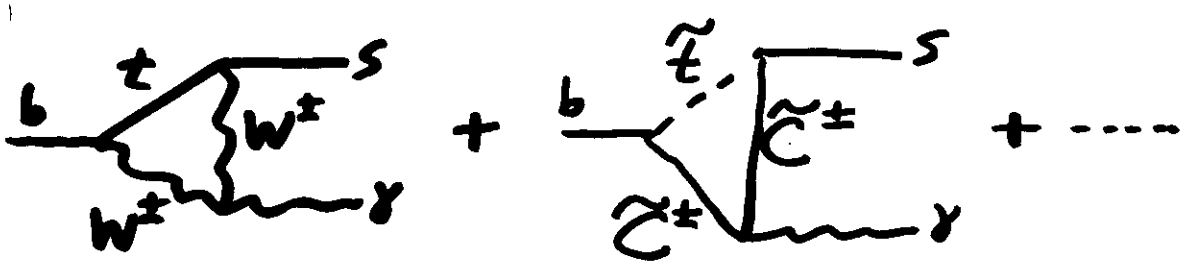
SUSY



SAME PARTICLES IN LOOPS!

AND α_s, $\delta\alpha_s \approx -4\,\delta R_b$

SUPERSYMMETRY $\widetilde{BR}(b \to s\gamma)$



THEOREM

- IN SUSY LIMIT CANNOT WRITE MAGNETIC DIPOLE OPERATOR THAT IS LORENTZ INVARIANT AND SUPERSYMMETRIC $\Rightarrow$

$$BR_{\substack{\text{SUSY} \\ \text{LIMIT}}}(b \to s\gamma) = 0$$

FERRARA, REMIDDI, 1974

- WHEN SUSY BROKEN, CANCELLATION INCOMPLETE

$\Rightarrow$ NATURAL SUSY PREDICTION IS

$$\widetilde{BR} < BR_{SM}$$

(BUT IF SUSY BADLY BROKEN CAN REVERSE)

BARBIERI, GIUDICE 1993
KANE, KOLDA, ROSZOWSKI, WELLS
LOPEZ, NANOPOULOS, PARK

⋮

BAER, BRHLIK

QCD CORRECTIONS

- AT TREE LEVEL, GIM CANCELLATION
- QCD CORRECTIONS PUT m_t, m_c, m_u IN LOGS, REDUCE CANCELLATION $\longrightarrow$ LARGE
- m_b, m_c NOT LARGE SO COULD HAVE EFFECTS $\sim 1/m_b^2, 1/m_c^2$ -- MAYBE NON-PERTURBATIVE
- SCALE DEPENDENCE IN LO NOT SMALL

RECENTLY CALCULATIONS COMPLETED SO NOW SM UNCERTAINTY $\lesssim 10\%$

- PERTURBATIVE
  CHETYRKIN, MISIAK, MÜNZ
  hep-ph/9612 313
  GREUB, HURTH / 9703349
- NON-PERTURBATIVE -- ALL EFFECTS STUDIED SO FAR $\lesssim 2.5\%$
  LIGETI, RANDALL, WISE
  hep-ph/97 02322

$$\longrightarrow BR(b\to s\gamma)_{SM} = 3.28 \pm 0.33 \times 10^{-4}$$

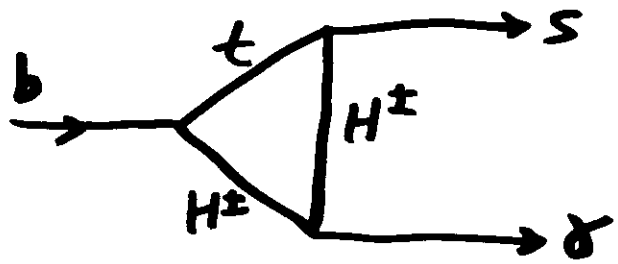
SUSY QCD

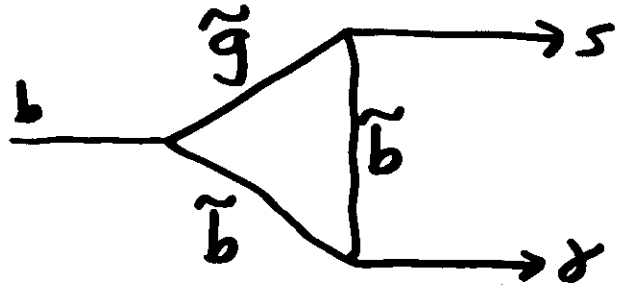
- IN PRINCIPLE NOT SAME AS SM SINCE ADDITIONAL OPERATORS

- SOME STUDY
  - ANLAUF, 1994
  - BAER + BRHLIK, 1996

- CAN PROBABLY USE SM PROCEDURES WITHOUT INTRODUCING MUCH ERROR

OTHER SUSY CONTRIBUTIONS

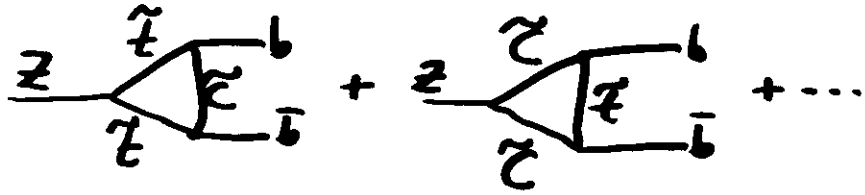


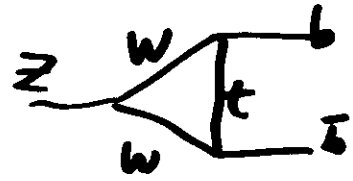


REQUIRES LARGE FCNC $\tilde{g}$ VERTEX, SUPPRESSED SINCE $\tilde{g}$, $\tilde{b}$ HEAVY

CONSIDER $R_b = BR(Z \to b\bar{b}) / BR(Z \to \text{had})$

-- COULD IT DEVIATE FROM SM?

- DIAGRAMS 

- BUT $\tilde{t} \approx \tilde{t}_R$, AND $\tilde{t}_R$ COUPLES TO Z WITH $T_{3\tilde{R}} Q s_W^2 \approx 0.14$
- SO $\tilde{C}$ DIAGRAMS DOMINATE
- SM top loop HAS FACTOR m_t^2 FROM W_{LONG} 

- SO NEED m_t^2 FROM SUSY DIAGRAM TO HAVE SIGNIFICANT EFFECT -- COMES FROM

$$Y_t \bar{Q}_L h_U t_R \longrightarrow \frac{2m_t}{v} \bar{b}_L \tilde{h}^+ \tilde{t}_R$$

SO $\tilde{t}_R$ INDEED WHAT IS NEEDED!

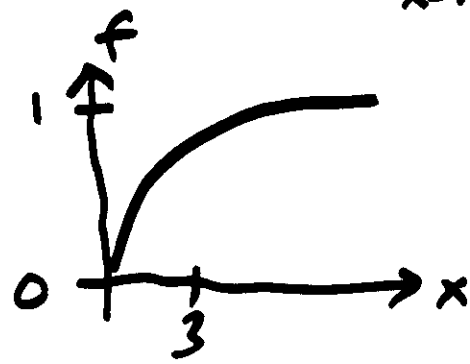
AND NEED $\tilde{h}^+$ IN CHARGINO

- COUPLING TO Z LARGE FOR $ZWW \to Z\tilde{C}^+\tilde{C}^-$
- SO NEED CHARGINO TO BE MAXIMAL MIXTURE OF $\tilde{h}^\pm, \tilde{W}^\pm$

- CAN DO THAT -- REQUIRES $M_2 \approx \mu$, $\mu < 0$, $\tan\beta \sim 1$

- IMPLIES $M_{\tilde{C}_2}$ NOT MUCH LARGER THAN $M_{\tilde{C}_1}$

- RESULT $\sim f(x) = \frac{x}{x-1} - \frac{x \ln x}{(x-1)^2}$, $x = \frac{m^2_{\tilde{C}_i}}{m^2_{\tilde{t}_R}}$



SO $f \to 0$ IF $M_{\tilde{t}} > M_{\tilde{C}}$ -- R_b SENSITIVE TO $M_{\tilde{t}_R}$

TURN IT AROUND -- IF WE KNOW $M_{\tilde{t}_R} \sim M_Z$, $M_2 \sim \mu$, $\mu < 0$, $\tan\beta \sim 1$ THEN WILL HAVE A δR_b SIGNIFICANTLY > 0

NEED LIGHT $\tilde{t}$ FOR NOTICEABLE EFFECT -- WHY MIGHT STOP BE LIGHT?

(a) RGE RUNNING -- SAME RADIATIVE EFFECTS THAT GIVE EWSB ALSO REDUCE $m_{\tilde{t}}$

$$m_{H_U}^2 = (m_{H_U}^2)_{UNIF} - 6\frac{y_t^2}{16\pi^2}\left(\ln\frac{m_{UNIF}^2}{m^2}\right) m_{\tilde{t}}^2$$

$$m_{\tilde{t}}^2 = (m_{\tilde{t}}^2)_{UNIF} - 4\frac{y_t^2}{16\pi^2}\left(\ln\frac{m_{UNIF}^2}{m^2}\right) m_{H_U}^2$$

→ ONLY $\tilde{t}$, NOT OTHER SQUARKS

(b) FORM OF MASS MATRIX AT EW SCALE

$$\begin{pmatrix} m_{\tilde{t}_L}^2 + m_t^2 + 0.35 m_Z^2 & -m_t(A_t + \mu\cot\beta) \\ & m_{\tilde{t}_R}^2 + m_t^2 + 0.15 m_Z^2 \end{pmatrix}$$

SO CAN HAVE DET ~ 0 → A SMALL EIGENVALUE -- ONLY FOR $\tilde{t}$

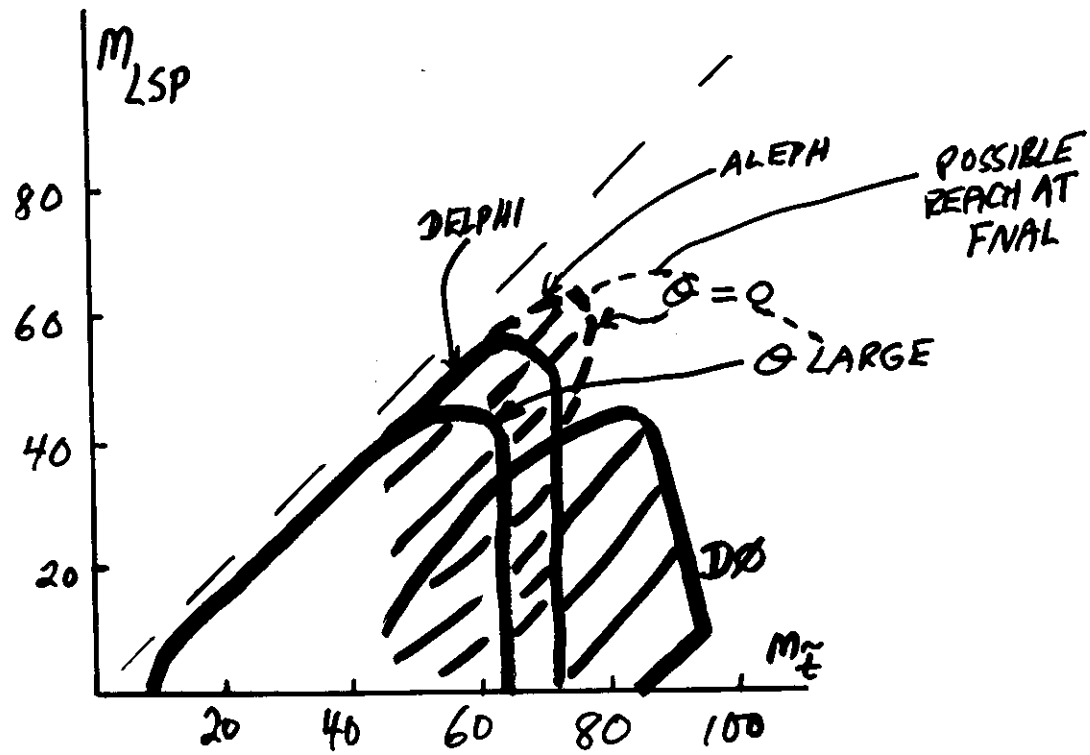
(c) EXPECT $\tilde{t}_1 \approx \tilde{t}_R$ FROM ρ-PARAMETER CONSTRAINT

$$\delta\rho = \frac{m_Z^2 c_W^2}{m_W^2} - 1 \sim \begin{cases} m_t^2 - m_b^2 \\ m_{\tilde{t}_L}^2 - m_{\tilde{b}_L}^2 \end{cases}$$

AND $\tilde{b}_L$ NOT AFFECTED BY ABOVE ARGUMENTS (UNLESS $\tan\beta$ VERY LARGE)

$$\tilde{t} \rightarrow \tilde{C}_1^+ + b$$

$$\tilde{t} \rightarrow c + LSP$$



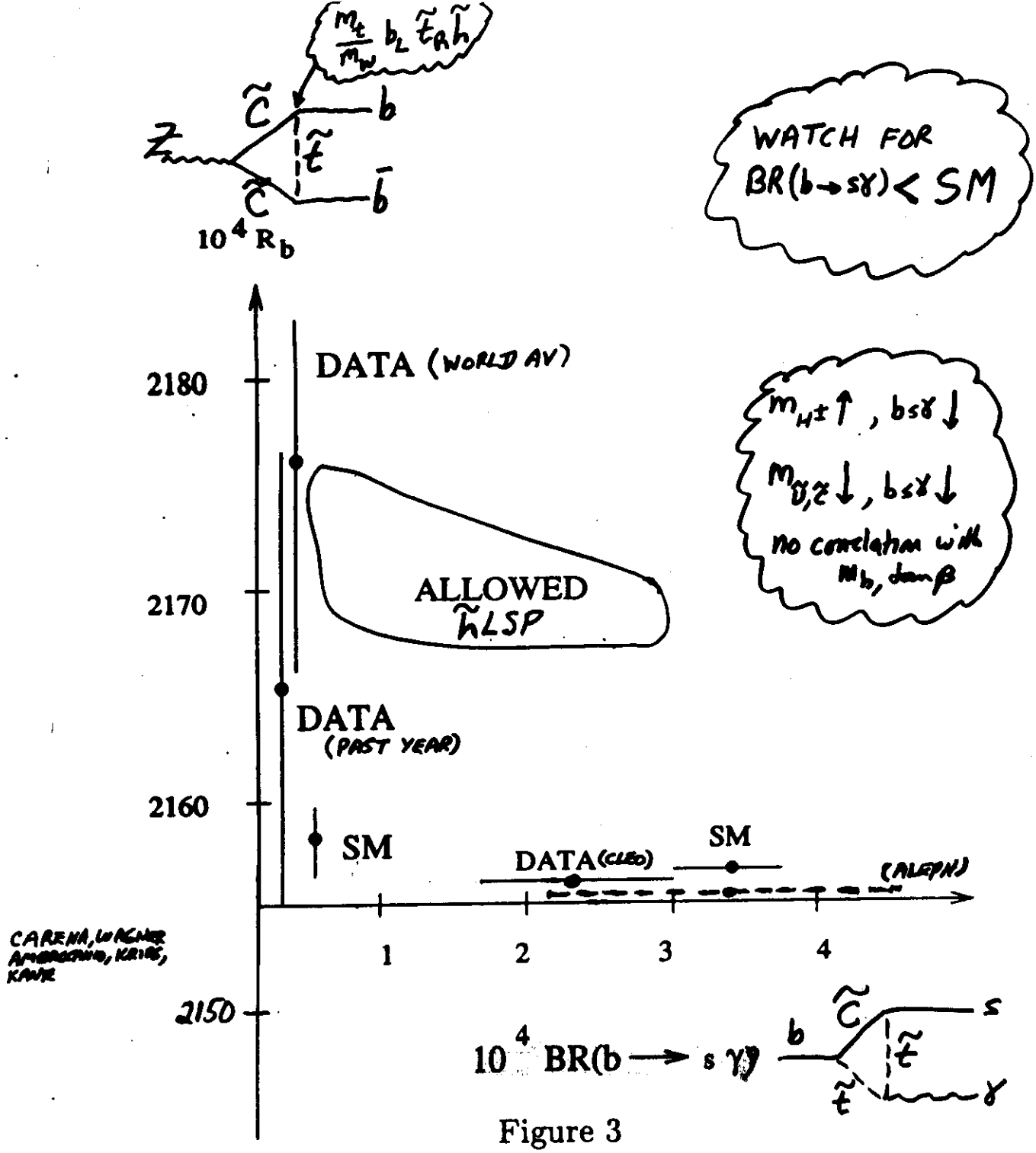


Figure 3

ALSO -- IN ALLOWED REGION, CONSISTENCY REQUIRES

$$\delta\alpha_s \equiv \alpha_s^{\overline{\text{MS}}}(Z) - \alpha_s^{\overline{\text{DR}}}(Z) \approx 4\delta R_b \approx 0.004 - 0.006$$

PRESENTLY

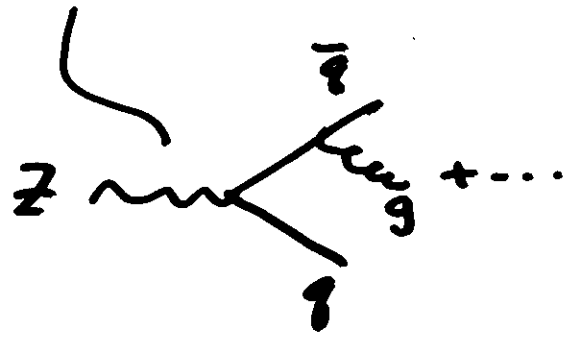
$$\alpha_s^{\overline{\text{MS}}} = 0.121 \pm 0.003 \quad , \quad \alpha_s^{\overline{\text{DR}}} = 0.117 \pm 0.003$$

OK

$\alpha_s(M_Z)$

VERY IMPORTANT CONSISTENCY REQUIREMENT

$$\Gamma_Z^{had} = \Gamma_{q\bar{q}}^{EW}\left(1 + \frac{\alpha_s}{\pi} + \cdots\right)$$



IF INCLUDE $\Gamma_{b\bar{b}}^{SUSY\ LOOP}$ IN $\Gamma_{q\bar{q}}^{EW}$,

THEN EXTRACT SMALLER $\alpha_s(M_Z)$

$$\delta\alpha_s \approx -4\,\delta R_b \approx -0.005$$

CURRENTLY $\alpha_s^{LEP,\Gamma_Z} = 0.121 \pm 0.003$

(CLEANEST WAY TO GET α_s FROM POINT OF VIEW OF QCD EFFECTS)

$\alpha_s^{ALL-\Gamma_Z} = 0.117 \pm 0.003$

MIGHT NOT HAVE WORKED

RECENT DATA SUGGESTS SMALLER α_s FROM EVENT SHAPES AT LEP

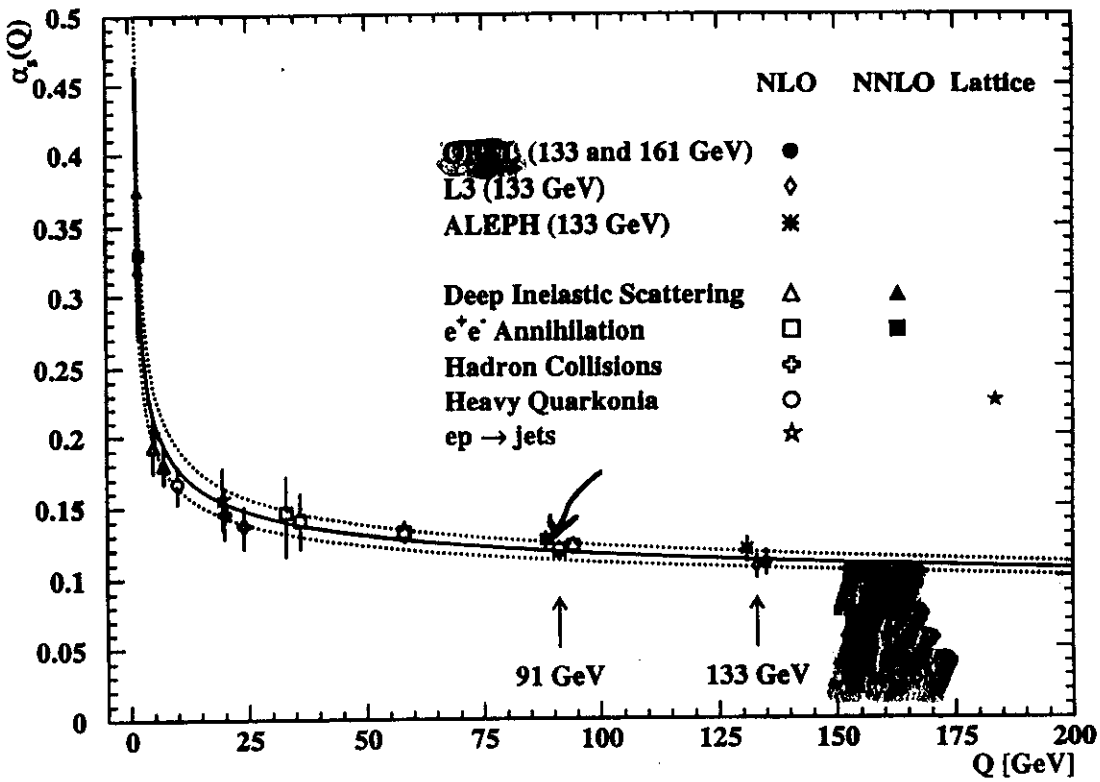
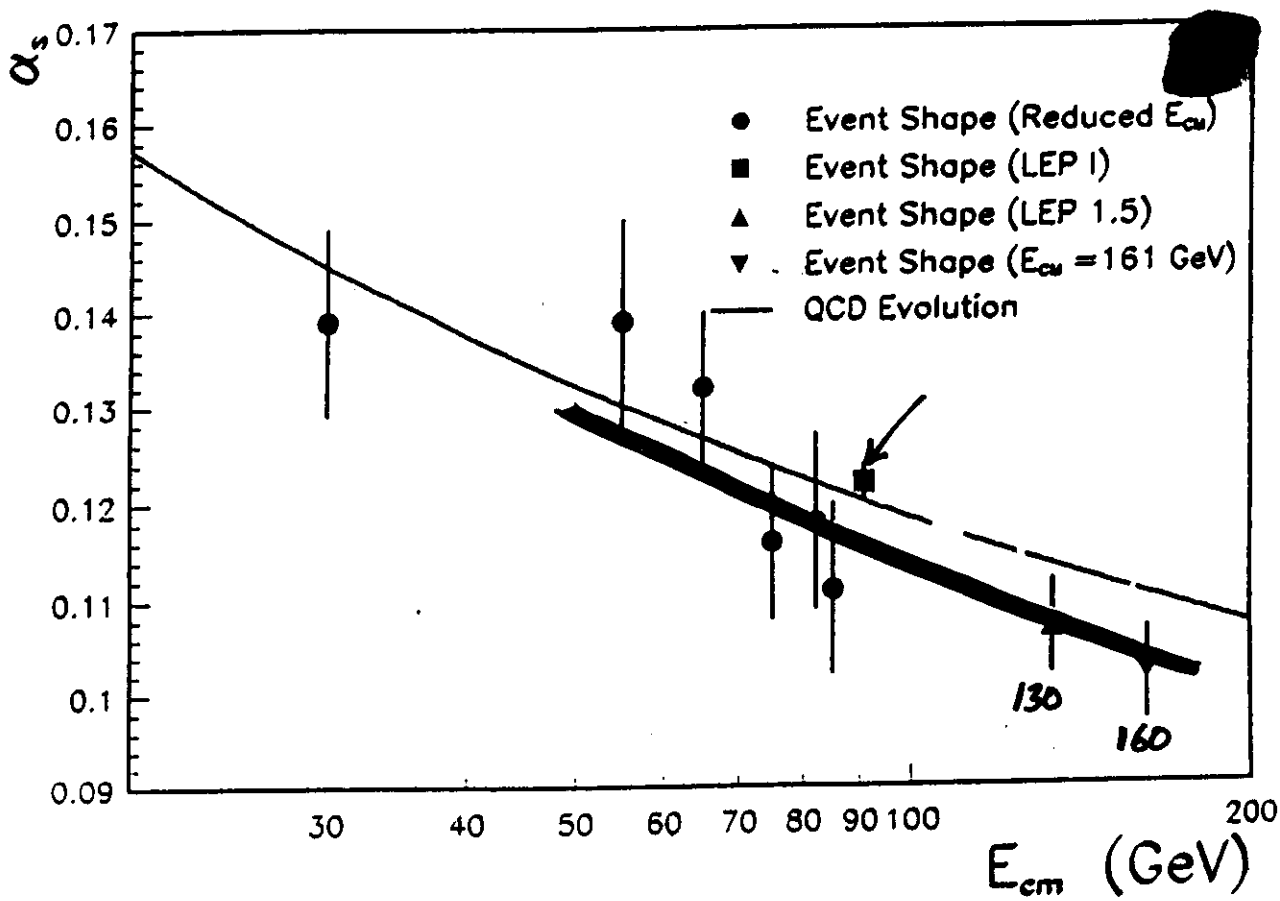


Figure 9: Values of α_s as function of energy [28]. The labels NLO and NNLO refer to the order of calculation used. NLO corresponds to $\mathcal{O}(\alpha_s^2)$ in e^+e^- annihilations, and NNLO to $\mathcal{O}(\alpha_s^3)$. The label Lattice refers to α_s values determined from lattice QCD calculations. The curves show the $\mathcal{O}(\alpha_s^3)$ QCD prediction for $\alpha_s(Q)$ using $\alpha_s(M_{Z^0}) = 0.118 \pm 0.006$; the full line shows the central value while the dotted lines indicate the variation given by the uncertainty.

α_s (161 GeV) = 0.101 ± 0.005 (stat.) ± 0.007 (syst.)

$\alpha_s(161\,\mathbf{GeV}) = 0.102 \pm 0.005\,(\mathbf{exp}) \pm 0.005\,(\mathrm{thec}$



⇒ $\alpha_s(Z)$ FROM SHAPE VARIABLES ≈ 0.114

Experimental errors only

L3 Preliminary, October 8, 1996

EVENT SHAPE

COMBINE LEP DATA FROM 161+172 GeV ➡ $\hat{\alpha_s}(Z) = 0.114 \pm .005$

UNFORTUNATELY -- R_b CANNOT PLAY MAJOR ROLE GIVEN EXPT ERRORS $\sim \pm 0.12$

(1) INCLUDING $b \to s\gamma$, α_s MEANS THAT THEORY ALONE (REGARDLESS OF EXPT) CANNOT GIVE $\delta R_b \gtrsim 0.0018$, i.e. NEVER ABOVE 1.5σ, OFTEN $\sim 1\sigma$

CHANKOWSKI, POKORSKI
CARENA, WAGNER
WELLS, KANE

(2) ALSO EXPT δR_b DECREASED, NOW $\sim 2\sigma$ ABOVE SM

BOTTOM LINE -- CURRENTLY $b \to s\gamma + R_b + \alpha_s$
$\longrightarrow$ $3+\sigma$ TEST OF SUSY -- SUSY INTERPRETATION OK ONLY IF $\mu < 0$,

$|\mu| \lesssim M_2$, $\tan\beta \sim 1$, $M_2 \sim M_Z$,
$\tilde{t}_1 \sim \tilde{t}_R \sim M_Z$

OR -- IF INPUT SUCH μ, $\tan\beta$ etc FROM OTHER DATA, THEN EXPECT $b \to s\gamma$, R_b, α_s TO HAVE DEVIATIONS AS SEEN

$$10^4(R_b - R_b^{SM}) = \begin{cases} 10 \pm 11 \\ (20 \pm 11) \end{cases} \text{ DATA}$$
$$8 \text{ ---- } 17 \text{ THEORY}$$

THEORY PREDICTS ONE QUADRANT OF 8, DATA THERE AT 1σ IN EACH DIRECTION

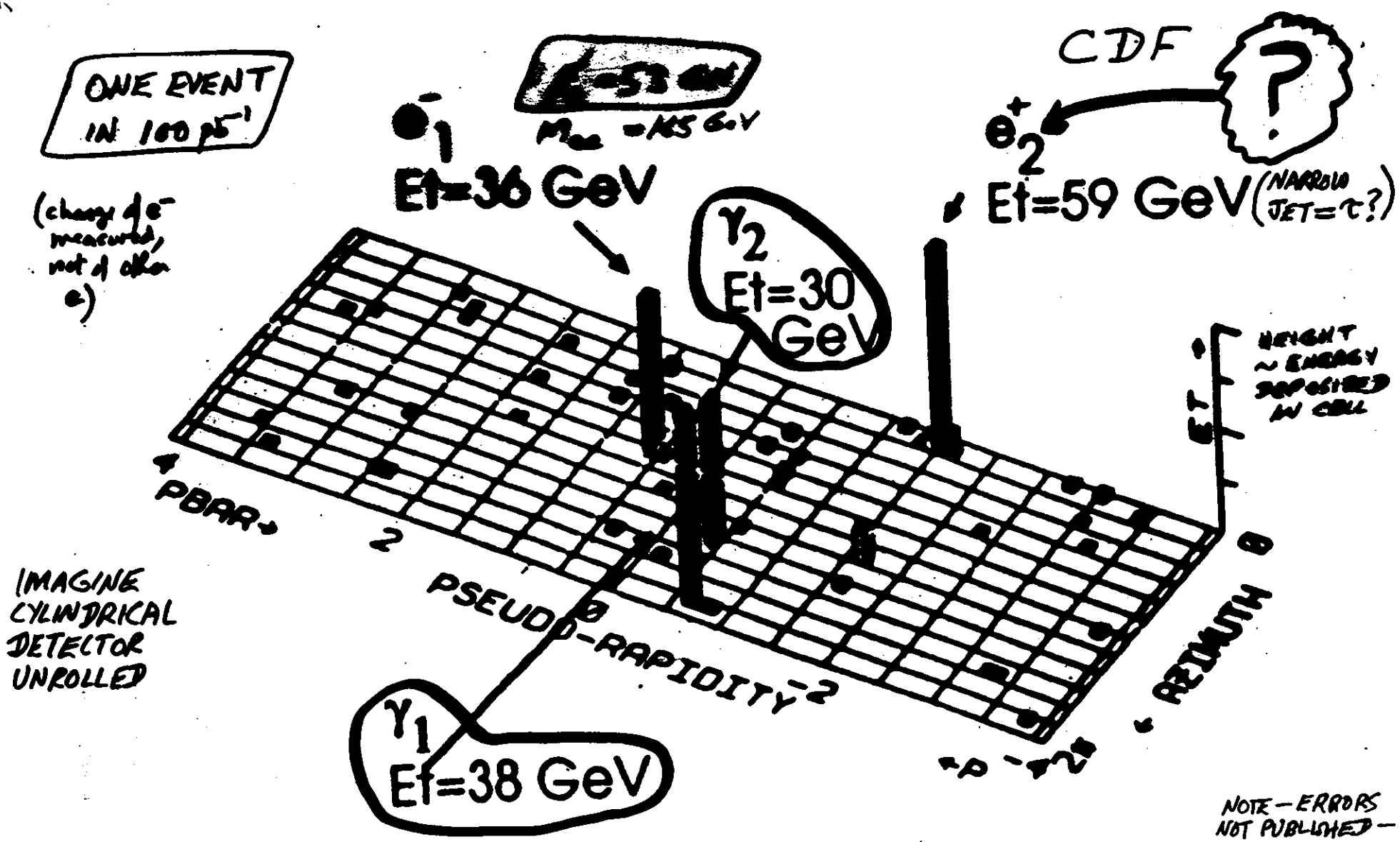
$$10^4(BR(b \to s\gamma)_{SM} - EXPT)$$
$$= \begin{cases} 1 \pm .67 & \text{DATA} \\ .3 \text{ ----- } 1.8 & \text{THEORY} \end{cases}$$

$$10^3(\alpha_s^{\Gamma_e} - \alpha_s^{WORLD})$$
$$= \begin{cases} (121 \pm 3) - (117 \pm 3) & \text{DATA} \\ 4 \ldots 5 & \text{THEORY} \end{cases}$$

CDF

$e^- e^+ (\tau?)\ \gamma\gamma\ \not{E}_T$

EVENT



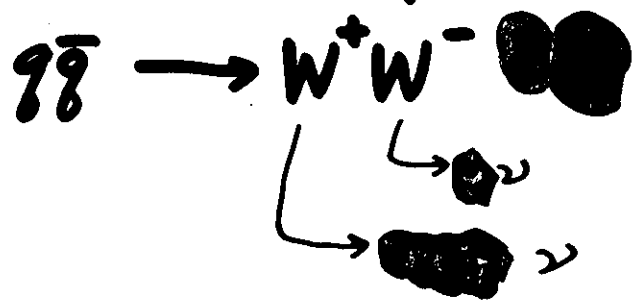
S. Park, in 10th $\bar{p}p$ Conf, May 95, ed. R. Raja and J. Yoh, AIP Conf. Proc. 357

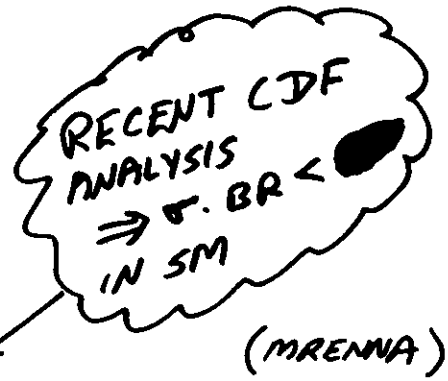
CDF EXPERTS: H. FRISCH + COLLABORATORS

NOTE — ERRORS NOT PUBLISHED — ALL NUMERICAL RESULTS HAVE ASSOCIATED UNCERTAINTY

CAN THE STANDARD MODEL EXPLAIN SUCH AN EVENT?

BEST POSSIBILITY:





(MRENNA)

$\longrightarrow \sigma \times BR \lesssim$ [redacted]

$\lesssim$ [redacted] 10^{-4} EVENTS IN PRESENT DATA

ALL OTHER SUGGESTED "BACKGROUNDS" SEEM TO BE SMALLER

R. Culbertson SUSY 97
FAKE EVENT? "VANISHINGLY SMALL"
SM WWYY? "MANY ORDERS OF MAGNITUDE TOO SMALL"
ANOMALOUS WWYY? "NO jjYY"

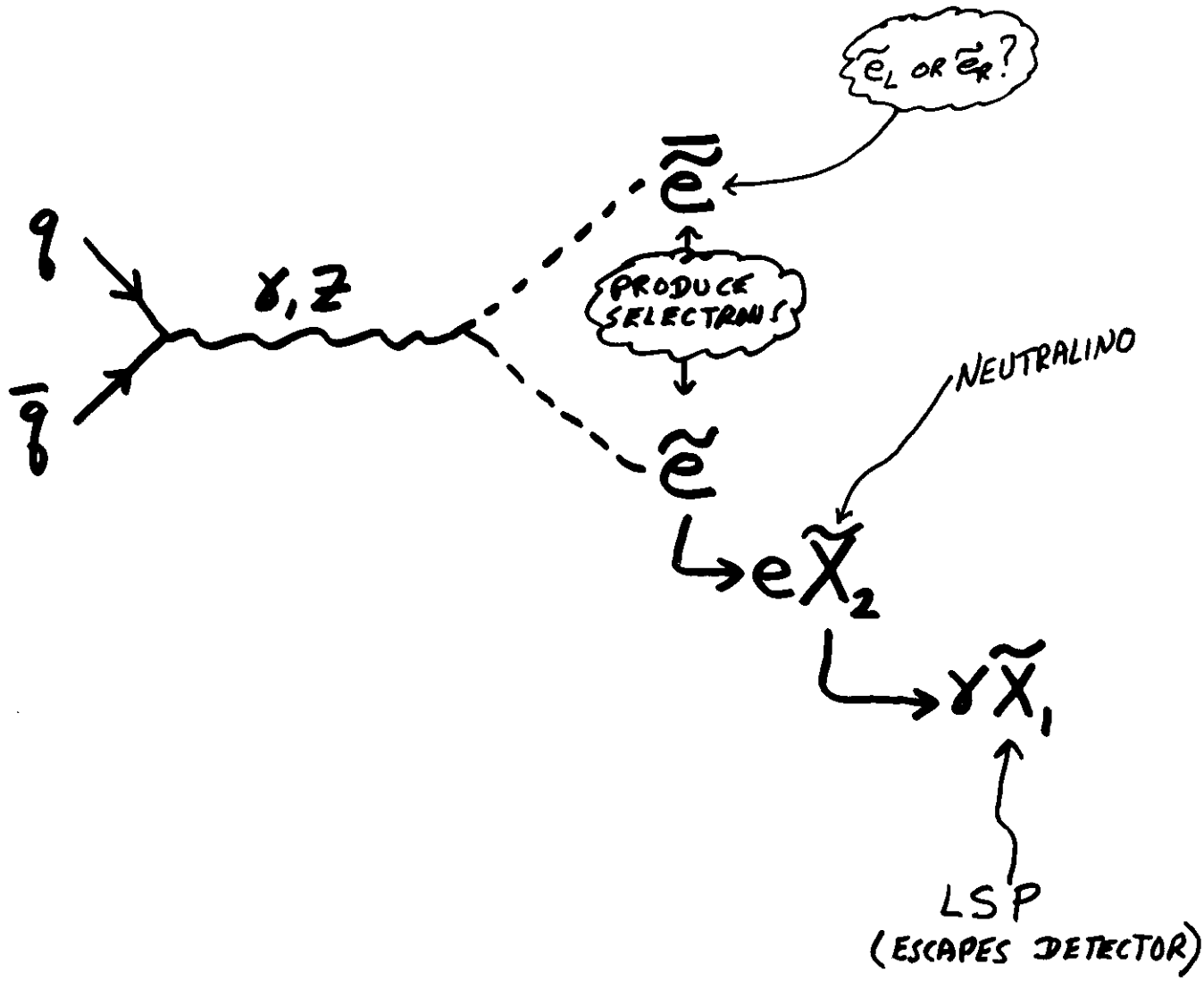
EFFICIENCY? DEPENDS ON HOW YOU DEFINE PROBLEM
-- TRIGGER -- ALL PARTICLES ABOVE WHAT CUTS?
-- ALL LEPTONS OR JUST OBSERVED FLAVORS?

HOWEVER DEFINE ANALYSIS,

$$\frac{\text{SUSY } \sigma \times BR}{\text{SM } \sigma \times BR} \sim 10^3 - 10^4$$

ONLY ONE EVENT -- BUT NO BACKGROUND
-- SO TAKE IT SERIOUSLY

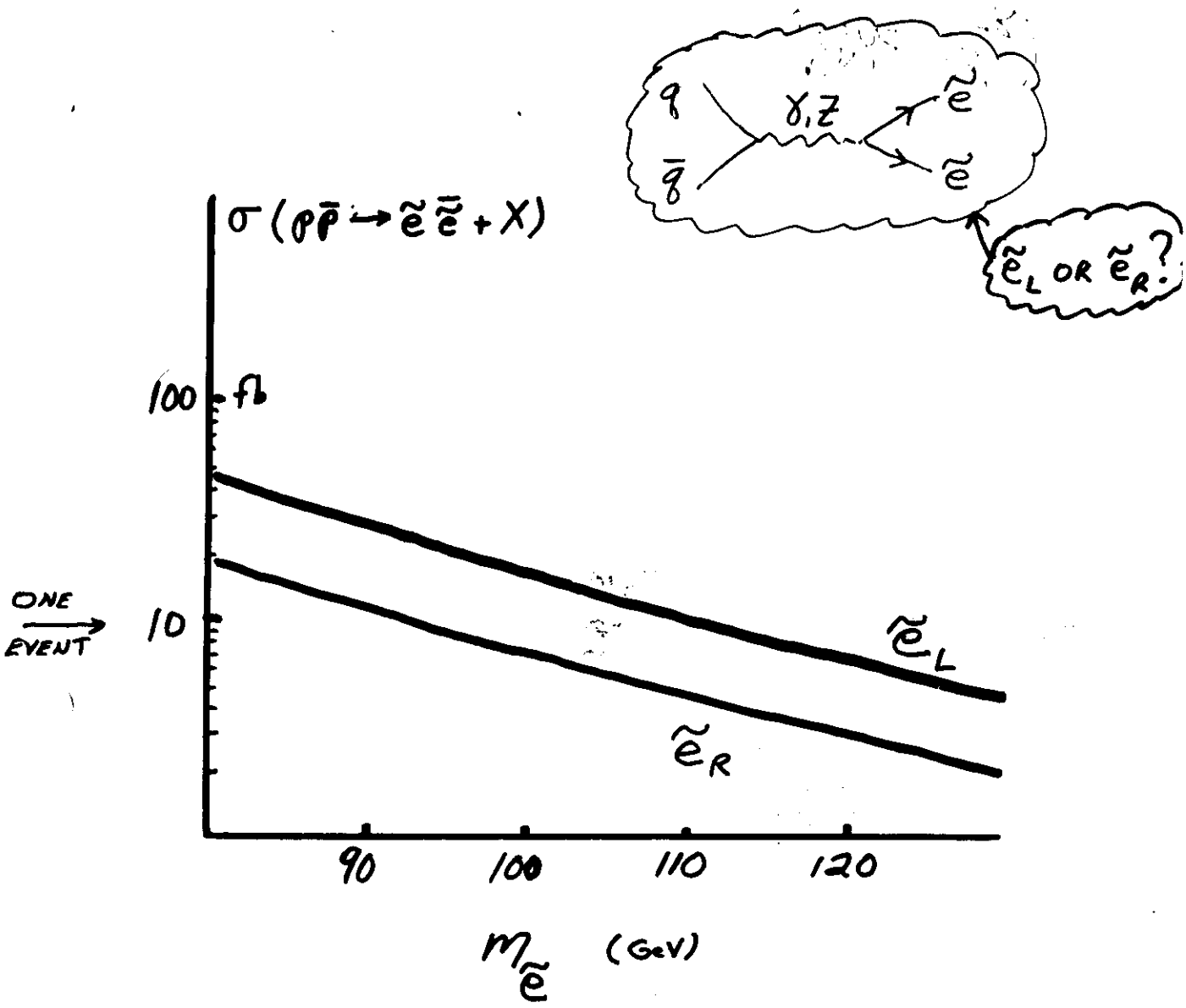
SUPERSYMMETRY INTERPRETATION(S)



HERE: $\tilde{\chi}_2 = \tilde{N}_2$; $\tilde{\chi}_1 = \tilde{N}_1 = LSP$

PRL
hep-ph/9602239
AMBROSANIO, KANE, KRIBS, MARTIN, MRENNA

$\Rightarrow \sigma \times BR \sim \frac{1}{2}$ EVENT IN PRESENT FNAL DATA



EFFICIENCY 0.05-0.25

- AT FIXED MASS, $\sigma_L \simeq 2.5\,\sigma_R$
- $\tilde{e}_R$ USUALLY LIGHTER IN MODELS

$\sigma(\tilde{\mu}\bar{\tilde{\mu}}) \simeq \sigma(\tilde{\tau}\bar{\tilde{\tau}}) \simeq \sigma(\tilde{e}\bar{\tilde{e}})$

NEED NOT HAVE WORKED

ALTERNATIVE SUSY INTERPRETATION POSSIBLE:

(a) $\tilde{\chi}_2 = \tilde{N}_1$ $\tilde{\chi}_1 = \tilde{G}$ = GRAVITINO = LSP

DIMOPOULOS, DINE, RABY, THOMAS
AMBROSANIO, KANE, KRIBS, MARTIN, MRENNA
DIMOPOULOS, THOMAS, WELLS
BABU, KOLDA, WILCZEK
LOPEZ, NANOPOULOS
⋮

(b) $\tilde{\chi}_2 = \tilde{N}_1$ $\tilde{\chi}_1$ = axino = LSP

Hisano, Tobe, Yanagida

BUT — LSP NOT COLD DARK MATTER
— NO EFFECT ON R_b, $b \to s\gamma$, α_s^Z
— NO $\tilde{g}, \tilde{t}$ AT FNAL ALREADY

MAINLY IGNORE THESE TODAY — FOCUS ON $\tilde{N}$LSP WORLD

CRUCIAL INFORMATION FROM "THE EVENT"

(1) ENERGETIC, ISOLATED γ's

PREDICTED AS SUSY SIGNATURE IN 1985

→ "$\tilde{\gamma}$" HEAVIER THAN LSP,

$\tilde{\gamma} \rightarrow \gamma + \text{LSP}$ (LSP = $\tilde{h}, \tilde{G}$)

→ BASICALLY DETERMINES PROPERTIES OF NEUTRALINOS, CHARGINOS (INCLUDING LSP), $\tan\beta$

(2) LARGE MISSING TRANSVERSE ENERGY

→ SUGGESTIVE OF SUPERSYMMETRY

(3) not background

DETERMINATION OF N_i, C_i MASSES, COUPLINGS, $\tan\beta$:

(1) LARGE BR($\tilde{e} \to N_2 e$) (COUPLES PROPORTIONAL TO FERMION MASS)

$\Rightarrow N_2 \sim a\tilde{\gamma} + b\tilde{Z}$, NOT HIGGSINO

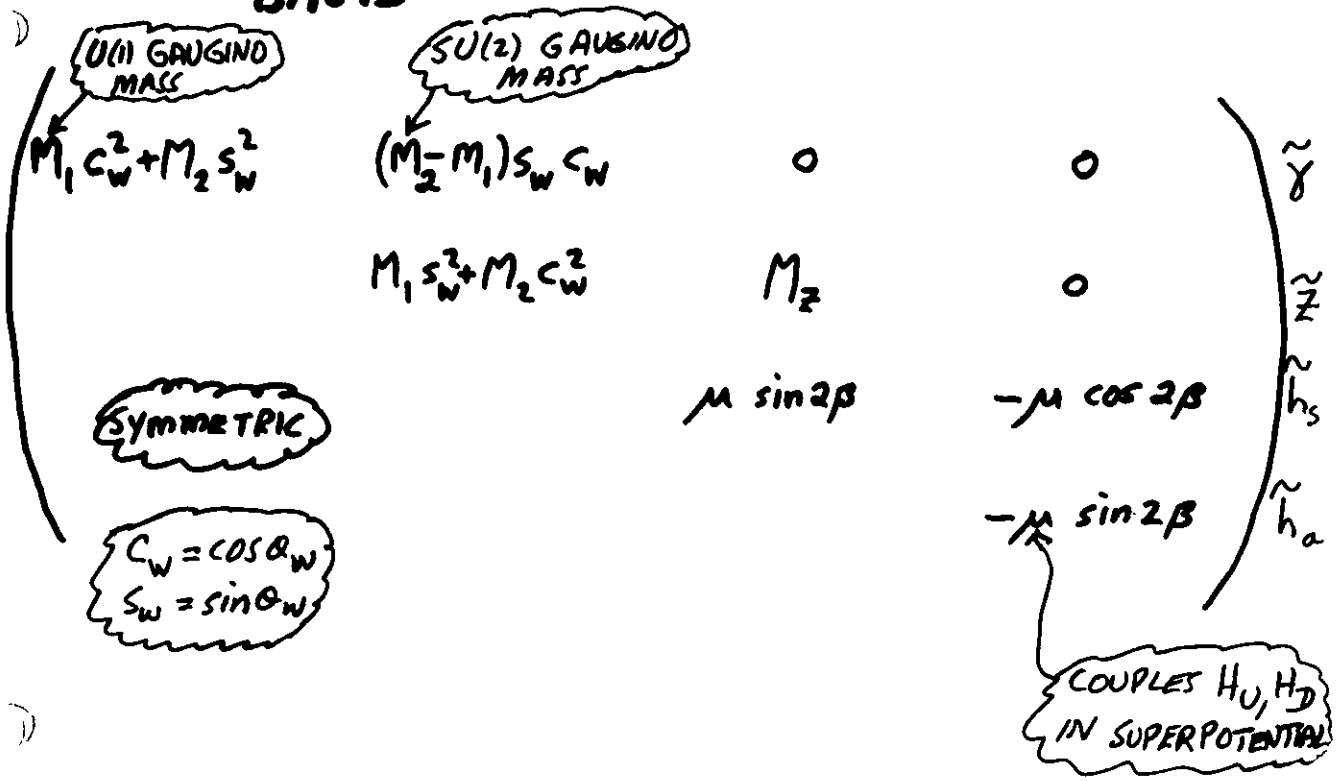
→ LARGE BR($N_2 \to N_1 \gamma$) — REQUIRES ONE OF N_1 OR N_2 IS $\tilde{\gamma}$, OTHER $\tilde{h}$ (PREDICTED, ROBUST)

TOGETHER

$$\Rightarrow N_2 \simeq \tilde{\gamma},\ N_1 \simeq \tilde{h}_{SYM}$$

(ANALYSIS OF $ee\gamma\gamma$ (AND R_b, α_s) BASED ON GENERAL LOW ENERGY SUSY — NO ASSUMPTIONS ABOUT GAUGINO OR SFERMION MASSES)

(2) NEUTRALINO MASS MATRIX IN $\tilde{\gamma}, \tilde{Z}, \tilde{h}_s, \tilde{h}_a$ BASIS



- $M_1 \simeq M_2$ MINIMIZES $\tilde{\gamma}, \tilde{Z}$ MIXING
- $\cos 2\beta \simeq 0$ MINIMIZES $\tilde{h}_{sym}, \tilde{h}_{anti}$ MIXING
  - $\tan\beta \simeq 1$
- MASS ORDERING $\Rightarrow \mu < 0$, $|\mu| < M_1 c_W^2 + M_2 s_W^2 \simeq M_1 \simeq M_2$

NUMERICAL STUDY $\Rightarrow$ NO OTHER SOLUTIONS

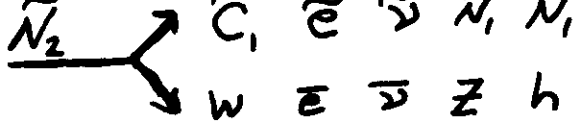
NON-TRIVIAL THAT IT WORKED AT ALL

NOTE: ISOLATED, HARD γ's AS SIGNATURE OF SUSY WAS PREDICTED ~ 1985

HABER, QUIROS, KANE
KOMATSU, KUBO

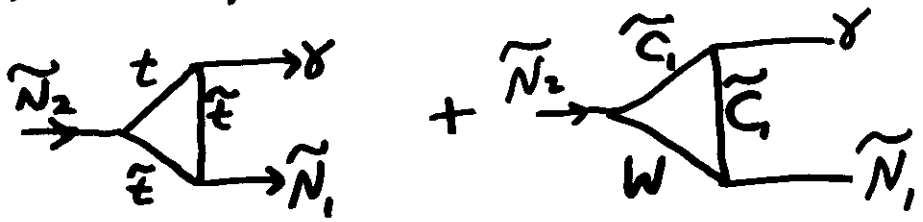
(HABER, KANE SCIENTIFIC AMERICAN 1986)

HOW SHOULD $\tilde{N}_2$ DECAY?



BUT -- ALL SUPPRESSED (PHASE SPACE, NO Zhh, γhh, γZh VERTICES)

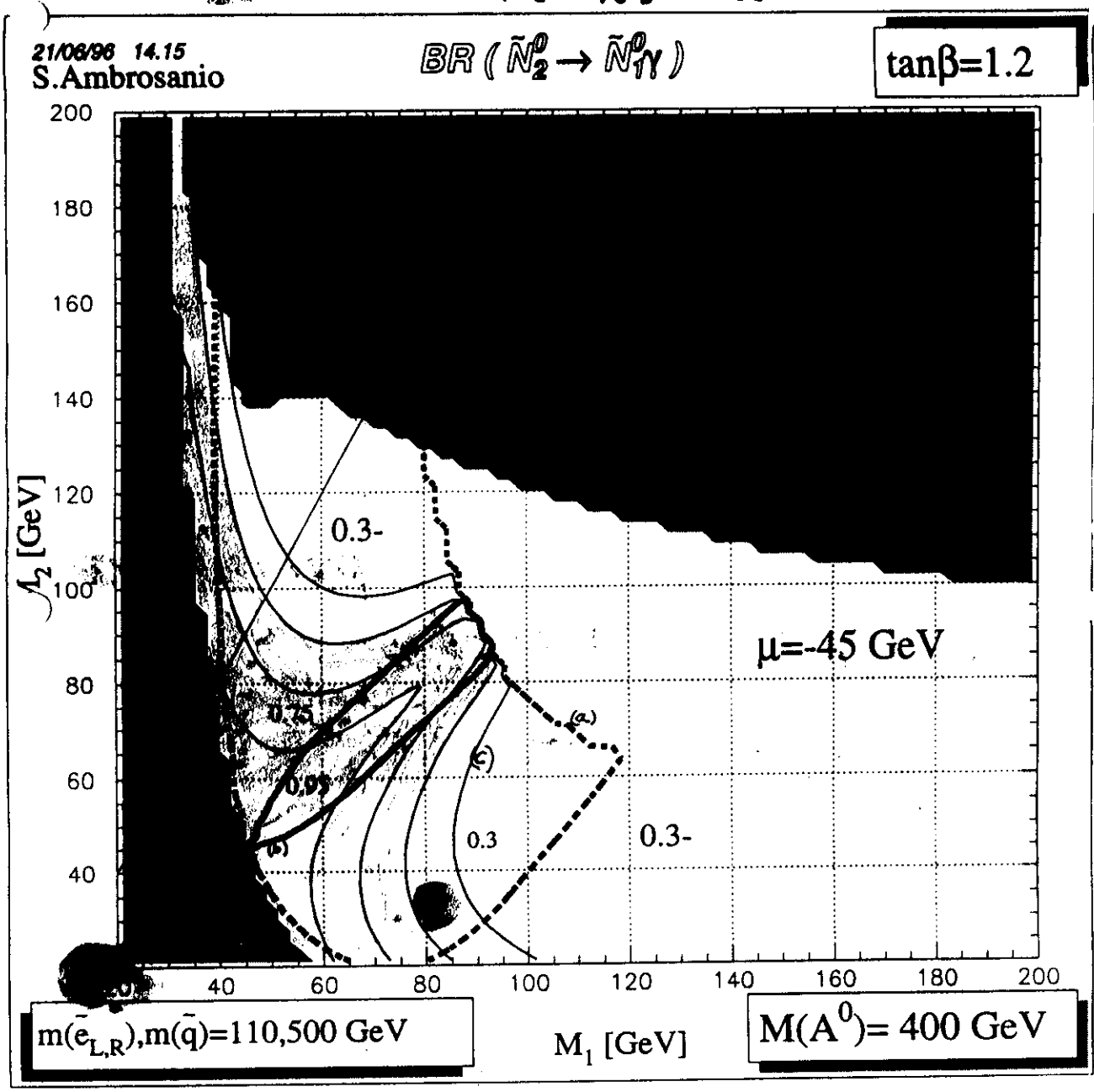
→ ONE LOOP DECAYS IMPORTANT



EXTENSIVE CALCULATIONS: HABER & WYLER 1989 AMBROSANIO & MELE 1995, 96

→ $\tilde{N}_2 \to \gamma \tilde{N}_1$ DOMINATES OVER SIGNIFICANT PART OF PARAMETER SPACE -- ESPECIALLY IF $M_1 \sim M_2$

$BR(N_2 \to N_1\gamma) > 1/2$

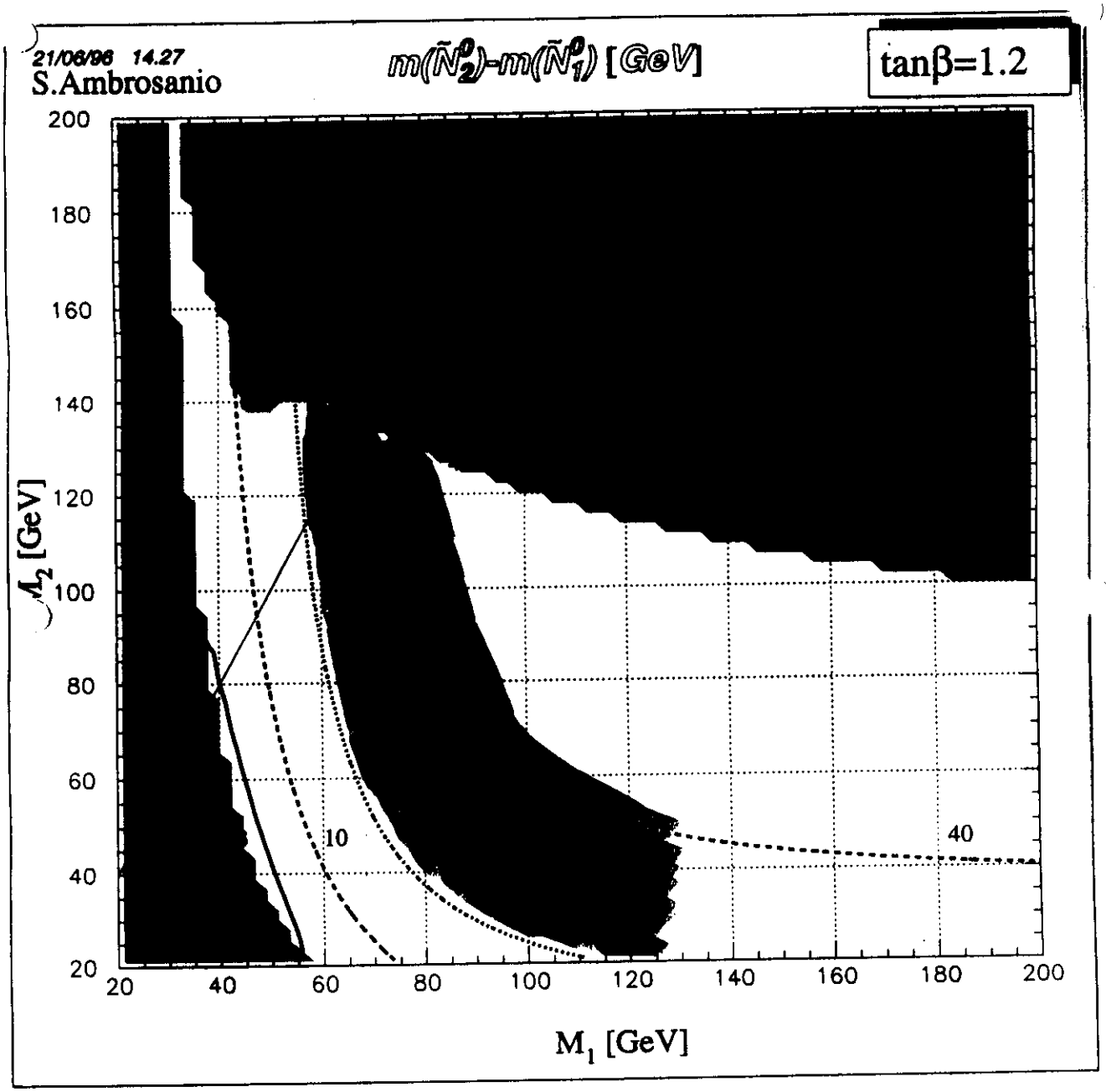


(a) $\langle N_1|\tilde{h}_b\rangle^2\langle N_1|\tilde{\gamma}\rangle^2 > 0.7$
(b) " > 0.99
(c) lines of const $BR(N_2 \to N_1\gamma)$

shaded — excluded by LEP

$BR(N_2 \to N_1\gamma)$ LARGE IF M_1 OR M_2 SMALL
OR IF $M_1 \approx M_2$

KINEMATICS OF eeγγ REQUIRES $m_{N_2} - m_{N_1} \gtrsim 20$ GeV



COMBINATION PICKS OUT
$M_1 \approx M_2$

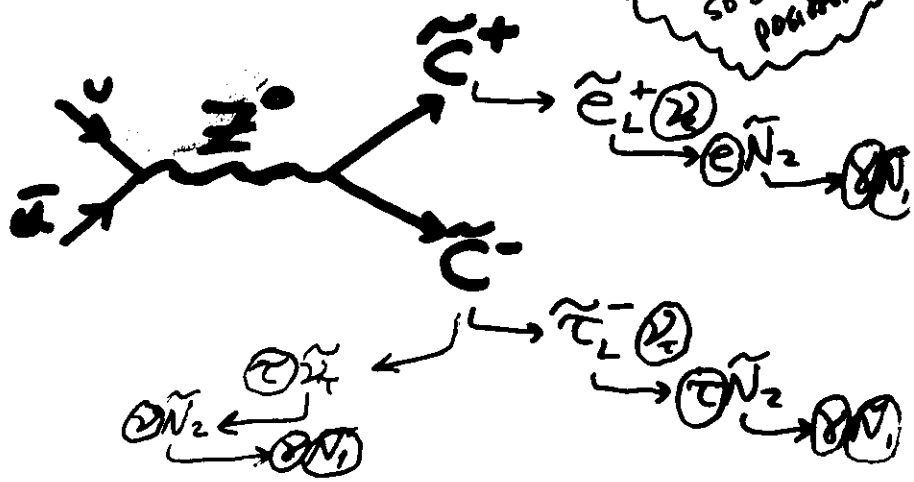
RECENTLY -- "e^+" MAYBE NOT e^+ ?

-- NARROW JET? (τ?)

OK
R. Culbertson, SUSY97
"Passes position cuts
so call it
position"

STILL "EVENT" -- NOT SM

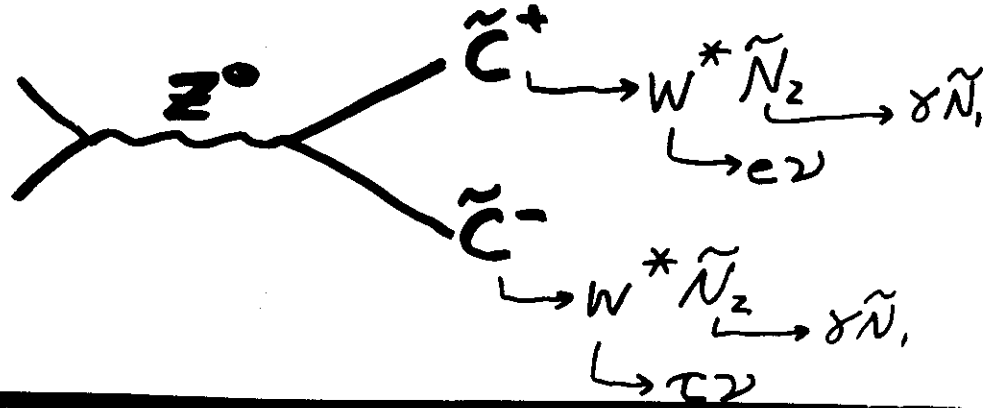
POSSIBLY:



hep-ph/9607414

→ PHYSICS RESULTS, LSP ESSENTIALLY UNCHANGED

OR:



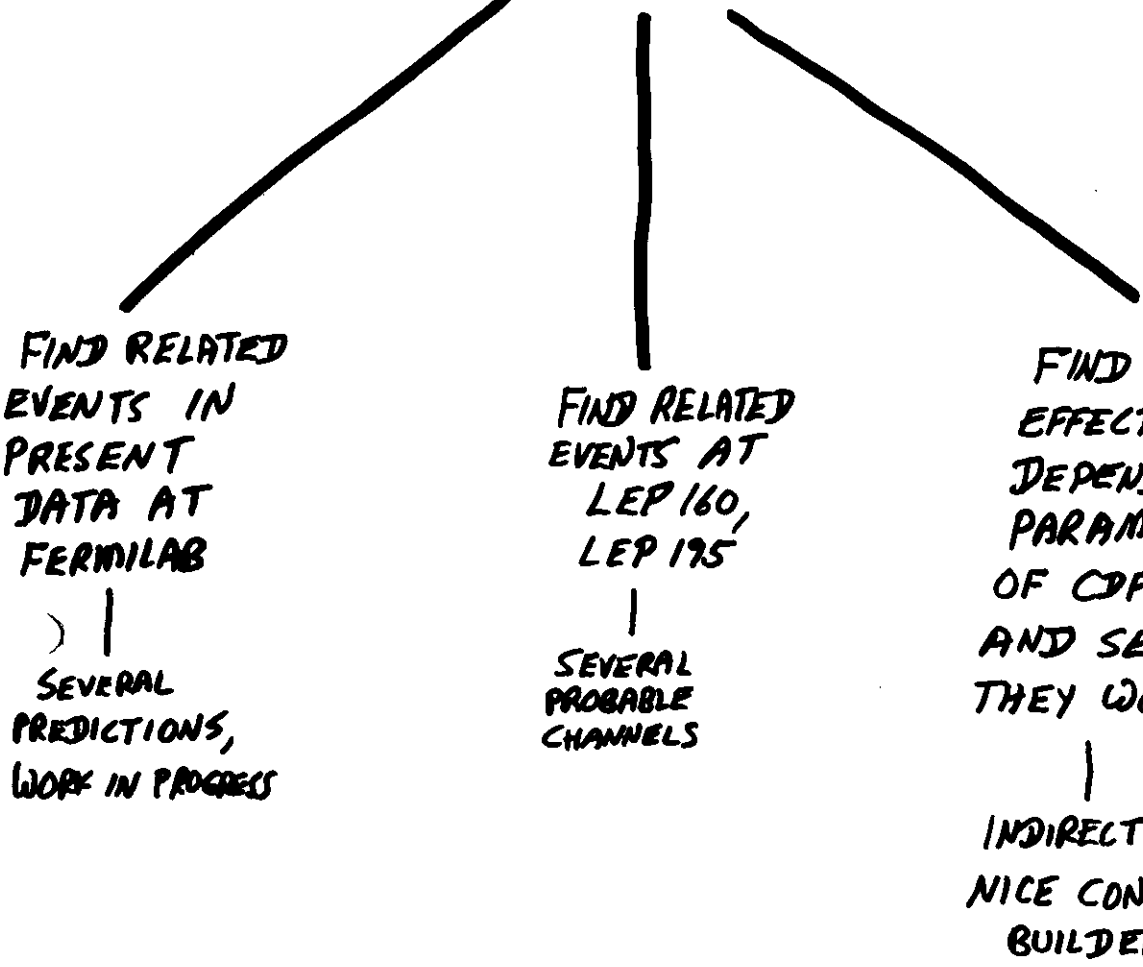
OR SLEPTON MIXING (HALL ET AL)

NOTE: NEUTRALINO SECTOR SAME

BOTTOM LINE:

CAN INTERPRET EVENT AS SUSY EVENT IF $\tan\beta \sim 1$, $\mu < 0$, $|\mu| \lesssim M_1 \approx M_2 \sim M_Z$

ONE EVENT — HOW DO WE FIGURE OUT IF IT'S A DISCOVERY?
AND PIN DOWN THE INTERPRETATION?

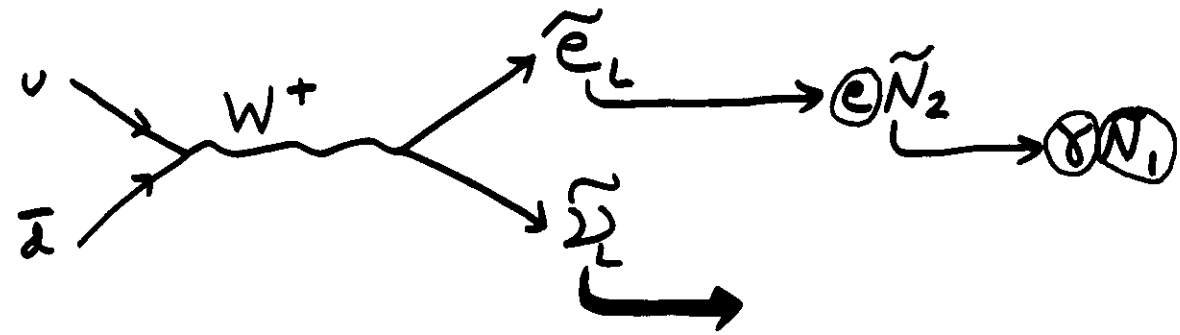


OR, WAIT UNTIL FNAL TAKES DATA AFTER UPGRADE

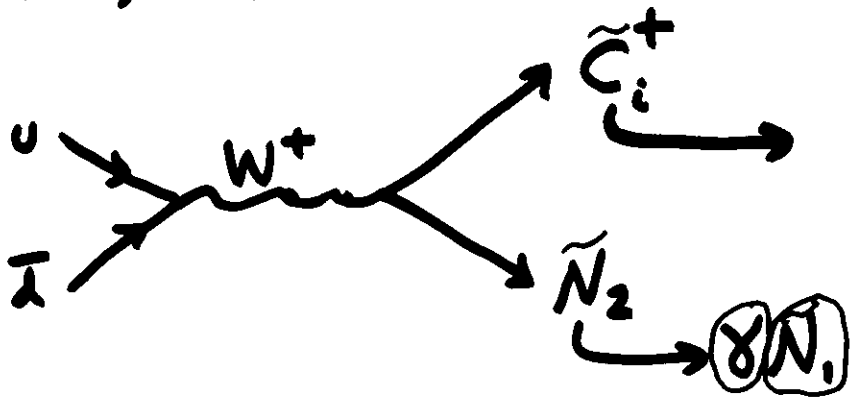
SEVERAL POSSIBLE ADDITIONAL CHANNELS AT FNAL

9607414

e.g.

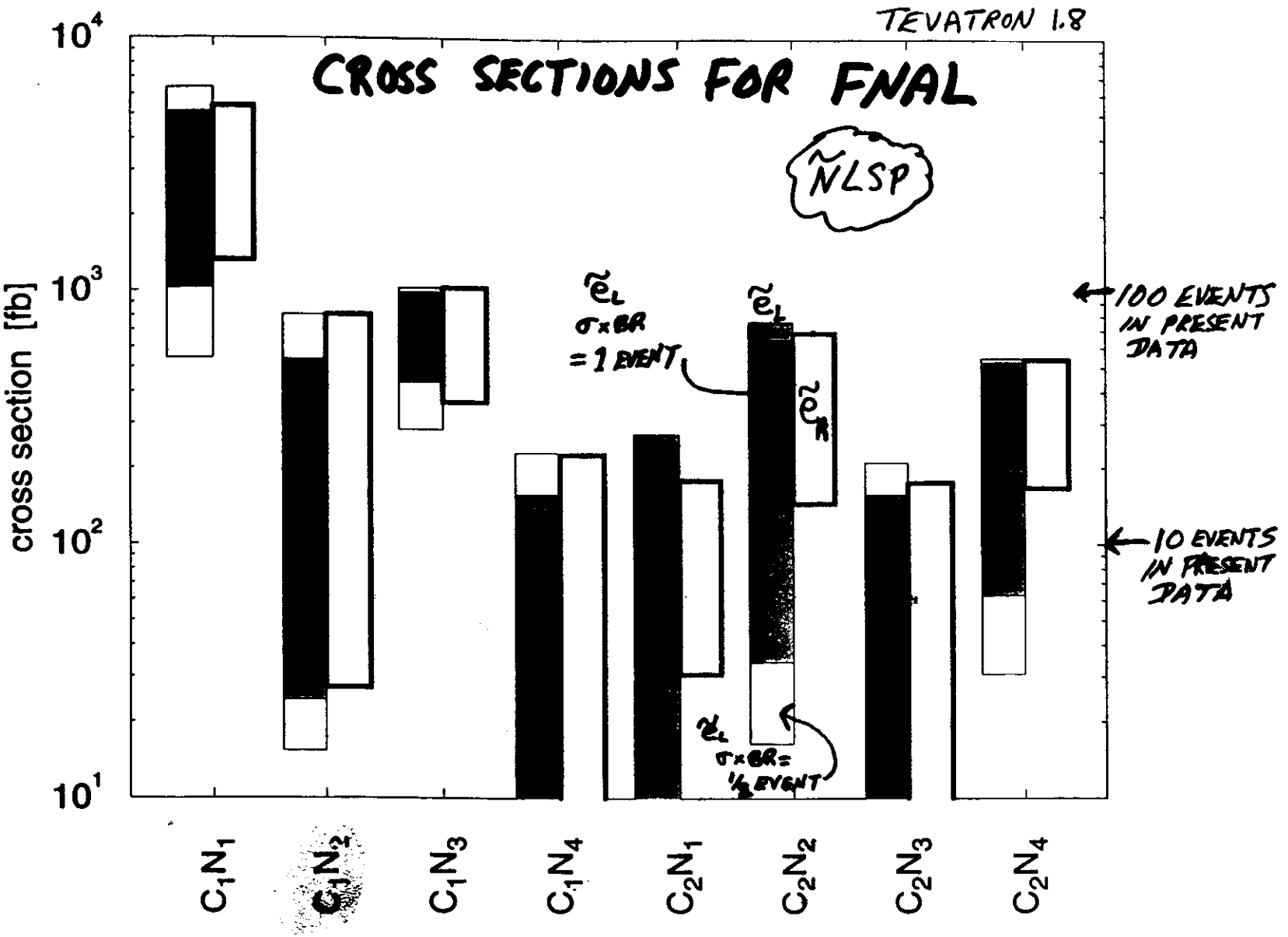


AND/OR



ETC.

Ambrosanio, Kane, Kribs, Martin, Mrenna hep-ph / 9607414



D0 limit: (hep-ex/9612011)

$$\sigma \cdot \mathcal{B}(p\bar{p} \to \gamma\gamma\not{E}_T + X) < 185 \text{ fb, } 95\% \text{ C.L.}$$

$$E_T^\gamma > 12 \text{ GeV}, \quad |\eta^\gamma| < 1.1, \quad \not{E}_T > 25 \text{ GeV}$$

2-photon sources in our models:

$$\tilde{C}_2^+\tilde{C}_2^-, \tilde{C}_2^\pm\tilde{N}_2, \tilde{N}_2\tilde{N}_2, \tilde{\ell}_L^+\tilde{\ell}_L^-, \tilde{\ell}_R^+\tilde{\ell}_R^-$$

[redacted]

If $\tilde{C}_2 \to \tilde{t}_1 b$ is allowed:

- 2-photon contribution is smaller.
- $\tilde{C}_2^+\tilde{C}_2^-$ can lead to $\gamma b\not{E}_T + X$ final states.
  (other SUSY sources of such events possible)

LEP

"hLSP LEP PREDICTIONS"

172 GeV	Oct 96	$\lesssim 10\ pb^{-1}$
194 GeV	~Oct 97	$\gg 100\ pb^{-1}$
186 GeV	June 97	$\sim 100\ pb^{-1}$

LARGEST CROSS SECTIONS:

$e^+e^- \longrightarrow \tilde{N}_1\tilde{N}_3$

Ambrosanio, Kane, Kribs, Martin, Mrenna hep-ph/9607414

$N_1, N_3 \rightarrow$ LARGE $\not{E}$ + jj, $\ell^\pm\ell'^\mp$, $\gamma\ell^+\ell^-$, γ, $\ell^\pm jj$

$\longrightarrow \tilde{C}_1^+\tilde{C}_1^-$

$\longrightarrow \tilde{N}_2\ \tilde{N}_3$

$\hookrightarrow \gamma\tilde{N}_1$

$\longrightarrow \tilde{e}^+\tilde{e}^- \longrightarrow e^+e^-\gamma\gamma\not{E}$ $\quad 80 \lesssim m_{\tilde{e}} \lesssim 130$

$\longrightarrow \tilde{\tau}\bar{\tilde{\tau}}$

$\hookrightarrow \bar{c}\tilde{N}_1$

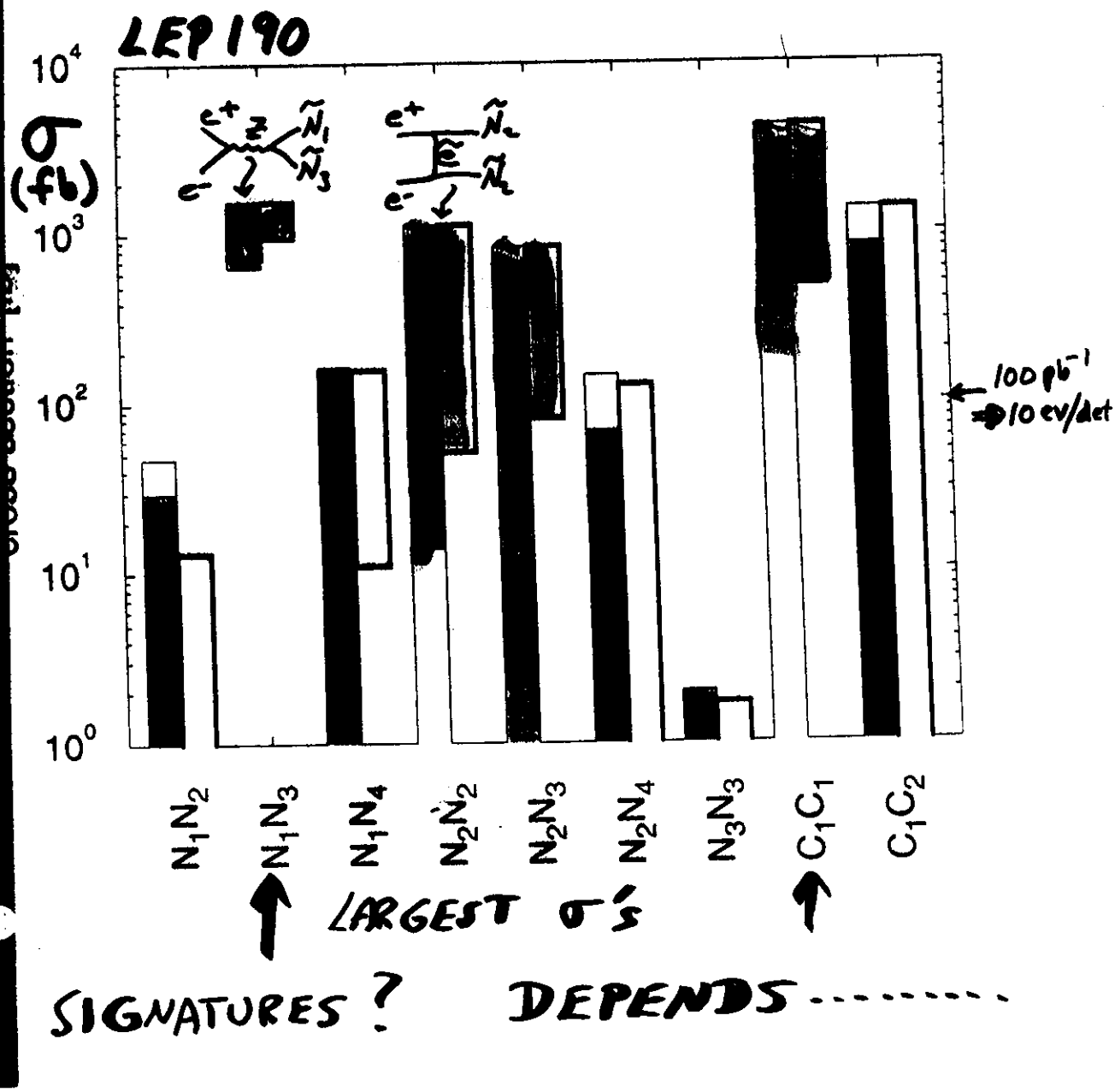
$\hookrightarrow c\tilde{N}_1$

$\tilde{C}_1 - \tilde{N}_1 > 20$ GeV

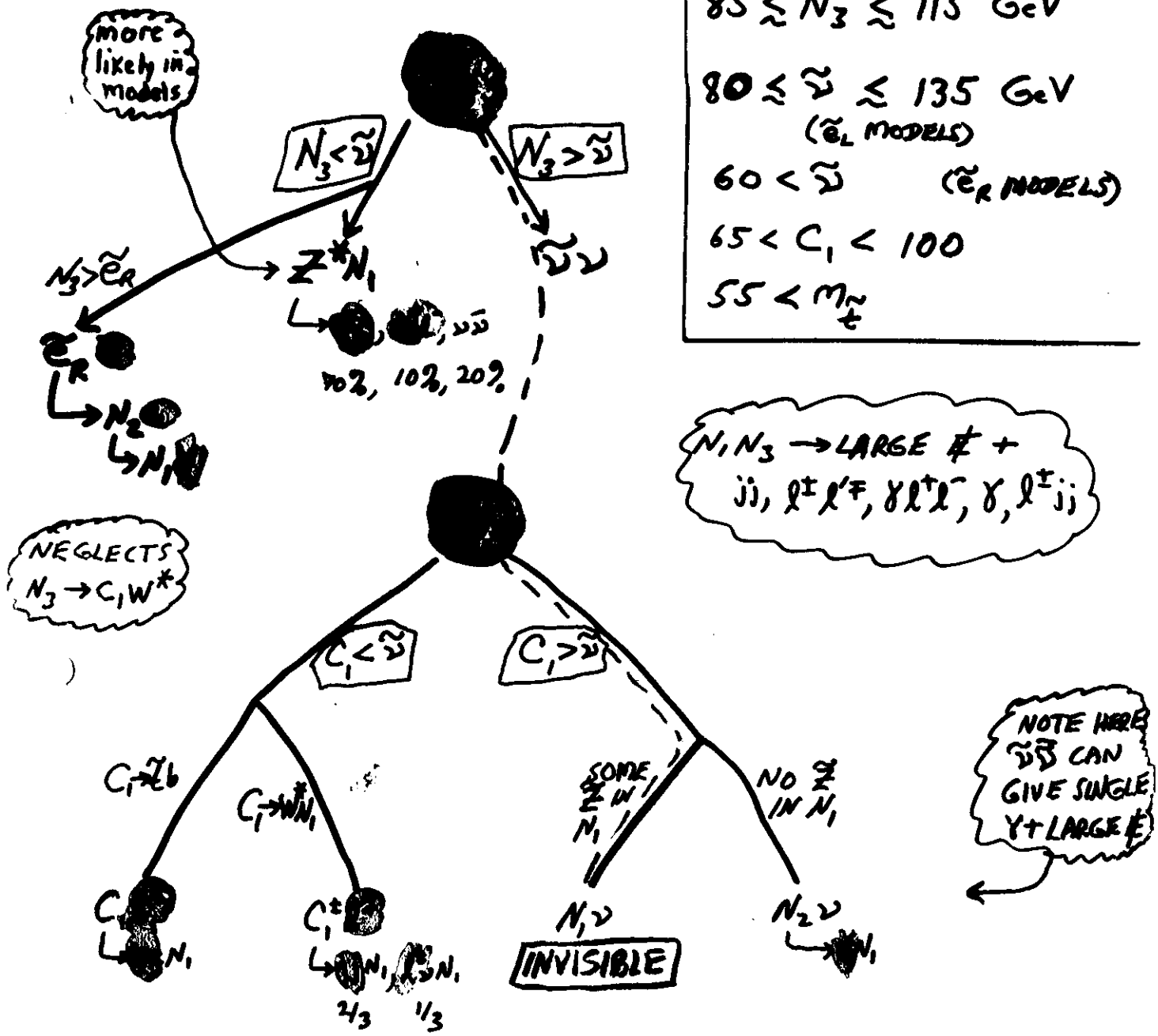
$\tilde{N}_2 - \tilde{N}_1 > 20$ GeV

$\tilde{\tau} - \tilde{N}_1 \gtrsim 10$ GeV

LEP IS SCHEDULED TO RUN ~ JUNE 97 AT 186 GeV, GET ~ $100\ pb^{-1}$



SIGNATURES ? DEPENDS .....



$85 \lesssim N_3 \lesssim 115$ GeV

$80 \lesssim \tilde{\nu} \lesssim 135$ GeV ($\tilde{e}_L$ MODELS)

$60 < \tilde{\nu}$ ($\tilde{e}_R$ MODELS)

$65 < C_1 < 100$

$55 < m_{\tilde{t}}$

$N_1 N_3 \rightarrow$
- $Z^* N_1 \rightarrow$ ~~$\not{E}$~~ $\not{E}$, $\ell^+\ell^- \not{E}$ [$\not{E} = N_1 + N_1$]
- INVISIBLE
- $\gamma \not{E}$
- $\ell^\pm jj \not{E}$, $\ell^\pm b\bar{c} \not{E}$
- $\ell^\mp \ell^\pm \not{E}$
- $\ell^+\ell^-\gamma \not{E}$

{ $\not{E} = N_1 + N_1 +$ AT LEAST ONE ν

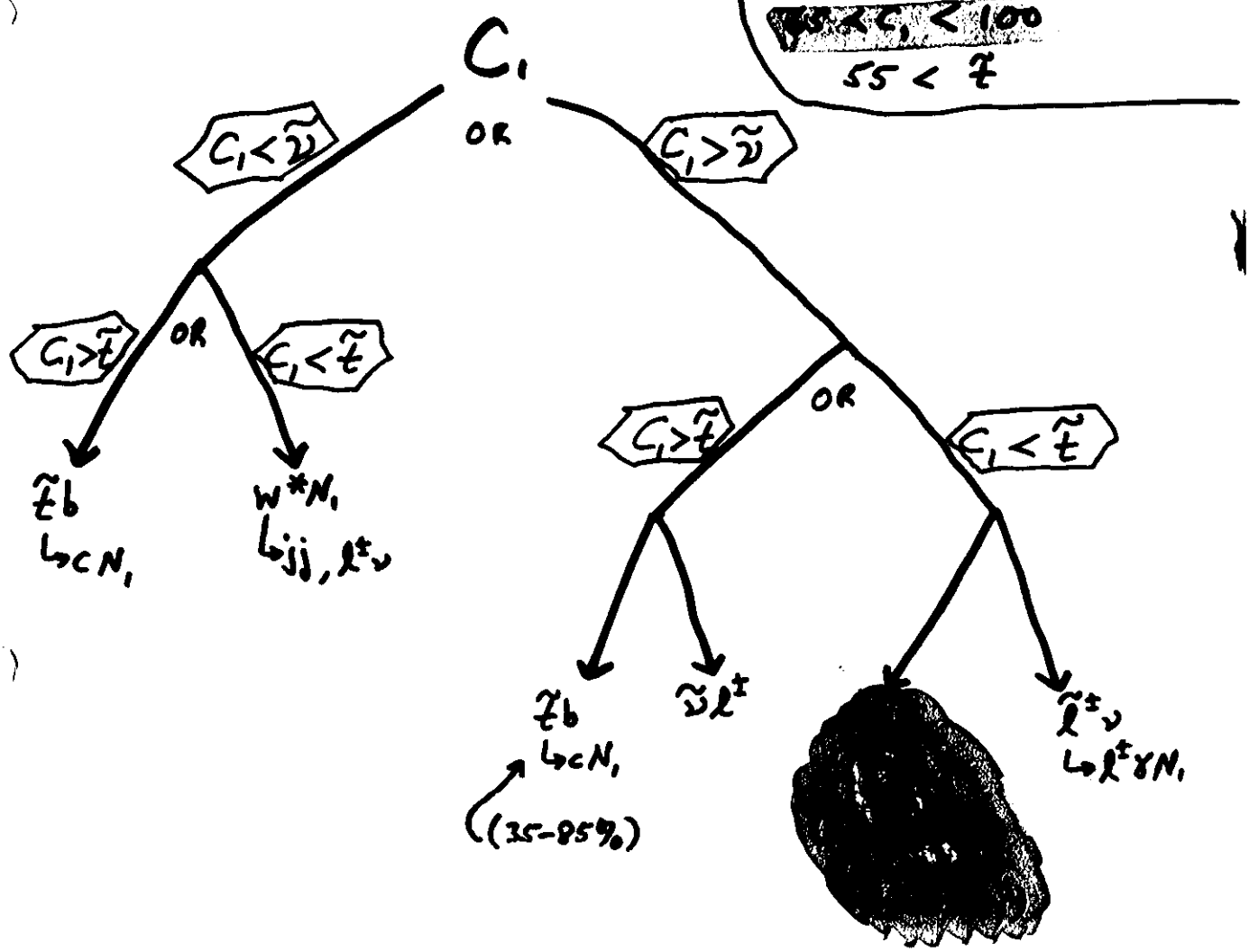
[illegible]

$80 \le \tilde{\nu} \le 135$ $(\tilde{e}_L)$

$60 < \tilde{\nu}$ $(\tilde{\chi}_R)$

$95 < C_1 < 100$

$55 < \tilde{t}$



$\tilde{\nu} \to l^\pm bc, l^\pm jj, l^\pm l^\mp, \gamma$, INVISIBLE $+ N_1$

$C_1 \to \{jj, l^\pm, l^\pm l^\mp jj, l^\pm l^\mp l^\pm, \gamma l^\pm\} + N_1 +$ possibly ν's

$(jj = \{c\bar{b}$ / $u\bar{d} + c\bar{s})$

$C_1^+ C_1^- \longrightarrow \{\} \times \{\} + N_1 + N_1 +$ possibly ν's

(not $bcjjN_1N_1$)

- CAN WE GET INFORMATION TO SHARPEN PREDICTIONS?

- IN 1996 -- LEP TOOK DATA AT $\sqrt{s} = 161, 172$ GeV
  -- ABOUT $10\,pb^{-1}$ INTEGRATED LUMINOSITY PER DETECTOR AT EACH ENERGY

- NO BTSM SIGNAL REPORTED -- HOWEVER, CAN ASK IF EVENTS WE MIGHT SEE ARE THERE

- RESULT -- ABOUT 6 $\gamma\gamma\not{E}$ EVENTS TOTAL -- NO EVENTS LIKE $\tilde{N}_1, \tilde{N}_3$

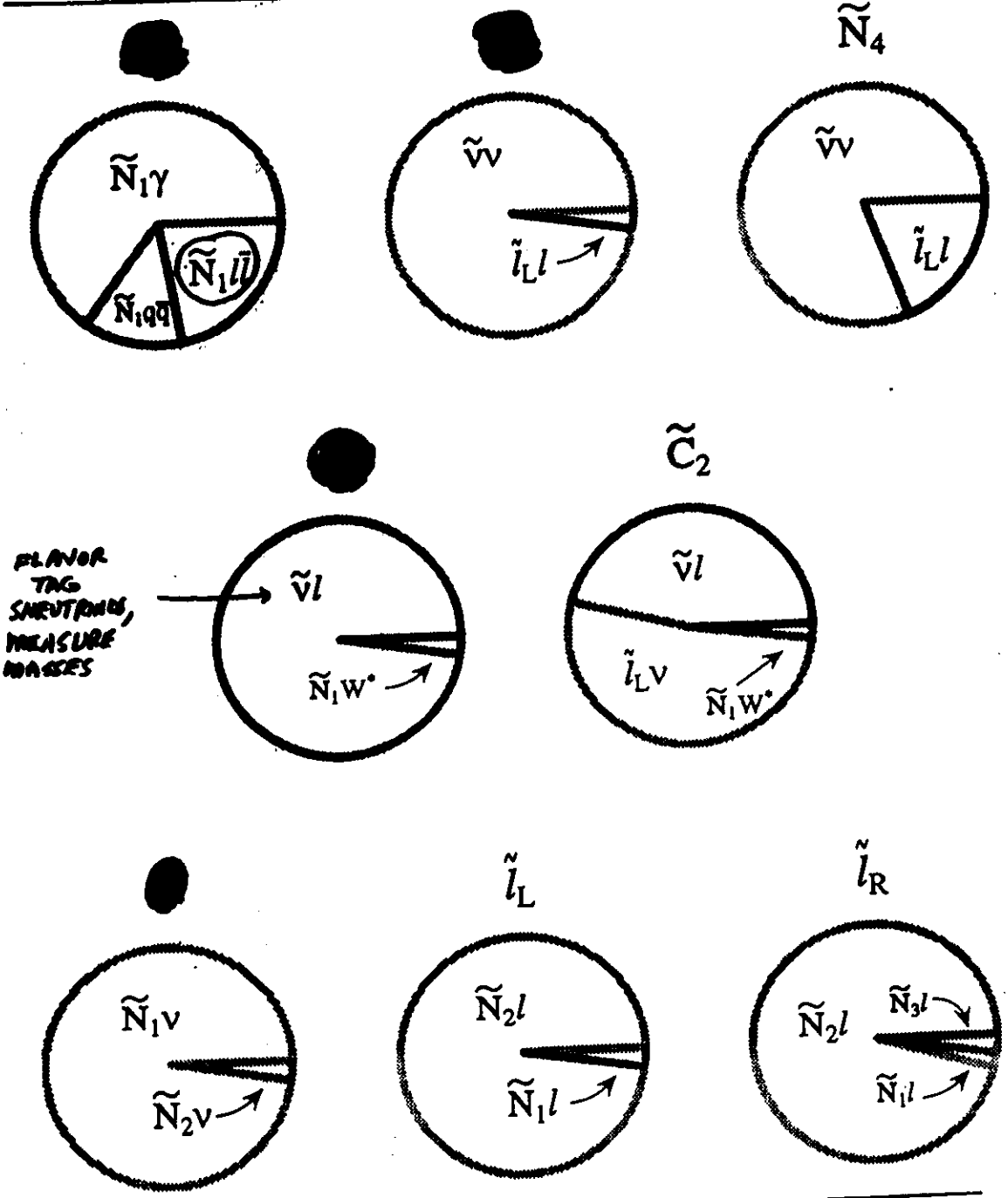
- SO STUDY $\gamma\gamma\not{E}$ EVENTS PREDICTION -- DETAILS OF SIGNAL -- EXPECTED BACKGROUND

- TENTATIVELY CHOOSE $\tilde{N}_3 > \tilde{\nu}$, $\tilde{C}_1 > \tilde{\nu}$
  SO NO $\tilde{N}_1, \tilde{N}_3$ SIGNAL EXPECTED

TYPICAL BR

SPARTICLE DECAYS

MAHLON, GK 9704450



$\tilde{N}_1$ INVISIBLE

$\tilde{N}_3$, $\tilde{\nu}$ ALMOST INVISIBLE

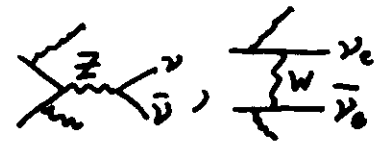
LEP $\gamma\gamma\not{E}$ EVENTS

$e^+e^- \to \gamma\gamma\not{E}$

INDEPENDENT BACKGROUND STUDIES BY AMBROSANIO, MAENNA

P. Bain and R. Pain DELPHI 97-98 PHYS-710 $e^+e^- \to \nu\bar{\nu}\gamma\gamma(\gamma)$

MAENNA, MORETTINI $\nu\bar{\nu}\gamma\gamma(\gamma)$ ~2x



BACKGROUND

$d\sigma/dM$ (fb/GeV)

10

1

TYPICAL PREDICTED SIGNAL FOR $\tilde{h}$ LSP

$e^+e^- \to \tilde{N}_2\tilde{N}_2$

$\hookrightarrow \gamma\tilde{N}_1$

PREDICTED SIGNAL FOR $\tilde{G}$ LSP

NO EVENTS REPORTED BELOW 80 GeV

1.3 EVENTS BACKGROUND FOR 1LH fb^{-1}

20 40 60 80 100 120 140 160

M

ENDPOINT DETERMINED BY LSP MASS

ABOUT $\frac{1}{2}$ EVENT FOR $|\cos\theta| < 0.7$

FOR LEP184

(PREDICTED SIGNAL $\lesssim$ 50 - 400 fb,

100 - 220 fb IF 3-10 EVENTS ALREADY OBSERVED)

- FOR SIGNAL $e^+e^- \to N_2(\to \gamma N_1)\, N_2(\to \gamma N_1)$

$$E^{\gamma}_{Max,Min} = \frac{\sqrt{s}}{4N_2^2}\left(N_2^2 - N_1^2\right)\left(1 \pm \sqrt{1 - 4N_2^2/s}\right)$$

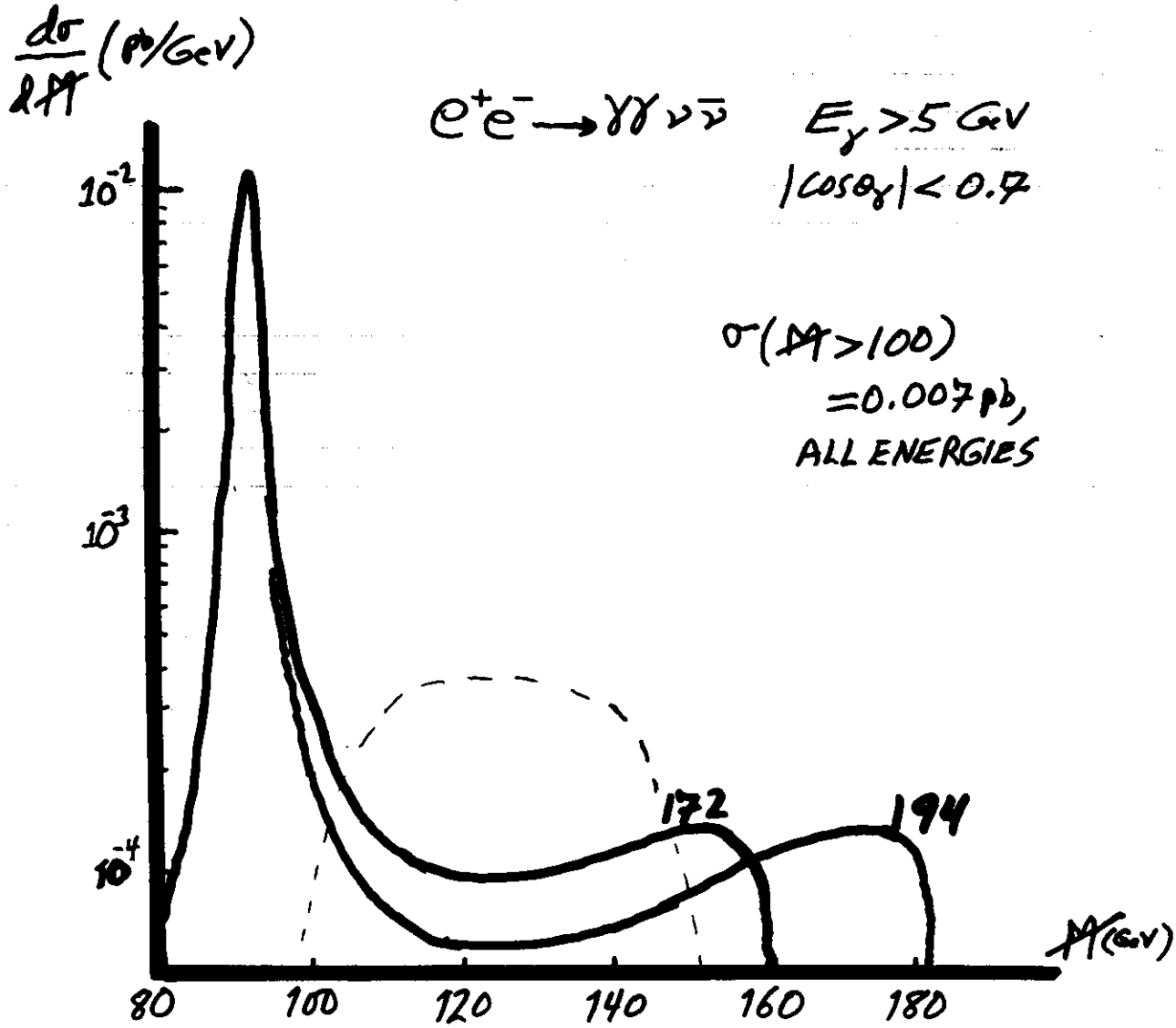
- TAKE μ, $\tan\beta$, M_1, M_2 CONSISTENT WITH R_b + $b \to s\gamma$ + α_s, CDF ~~AGM FOR (say) 3 TO XX EVENTS AT LEP~~

$$\longrightarrow E^{\gamma}_{Min} \approx 7\,GeV \qquad 5?\ 8?$$

- ALSO -- $M > 2M_{N_1} \approx 100$ GeV
  - -- DISTRIBUTION ~ FLAT SINCE N_2's ~ ISOTROPIC IN REST FRAME

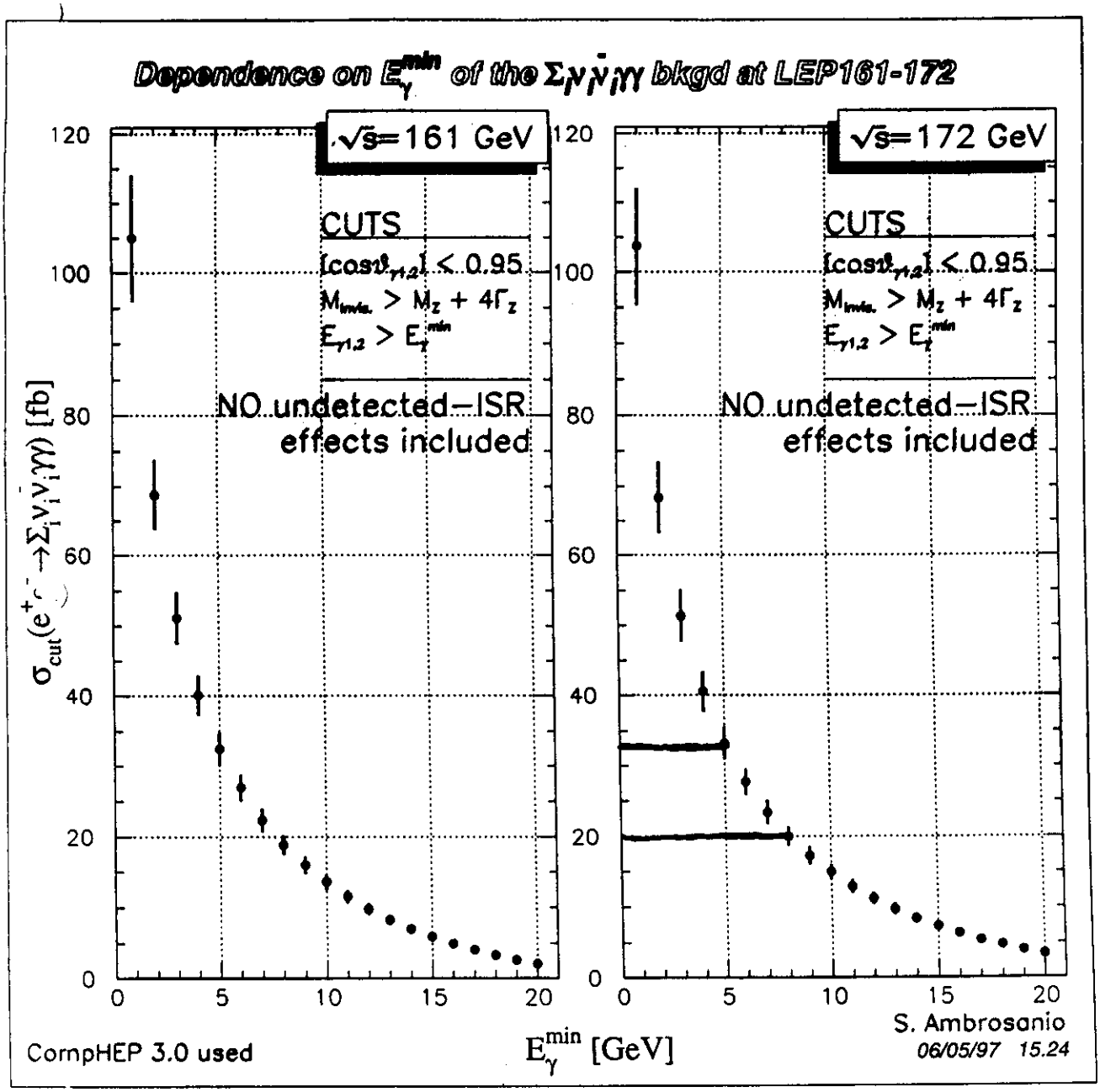
IF THE REPORTED EVENTS ARE A SIGNAL, THEY MUST LIE ABOVE $M \sim 100$ GeV, HAVE $E_{\gamma_i} \geq 7$ GeV, FLAT DISTRIBUTION IN M

MRENNA

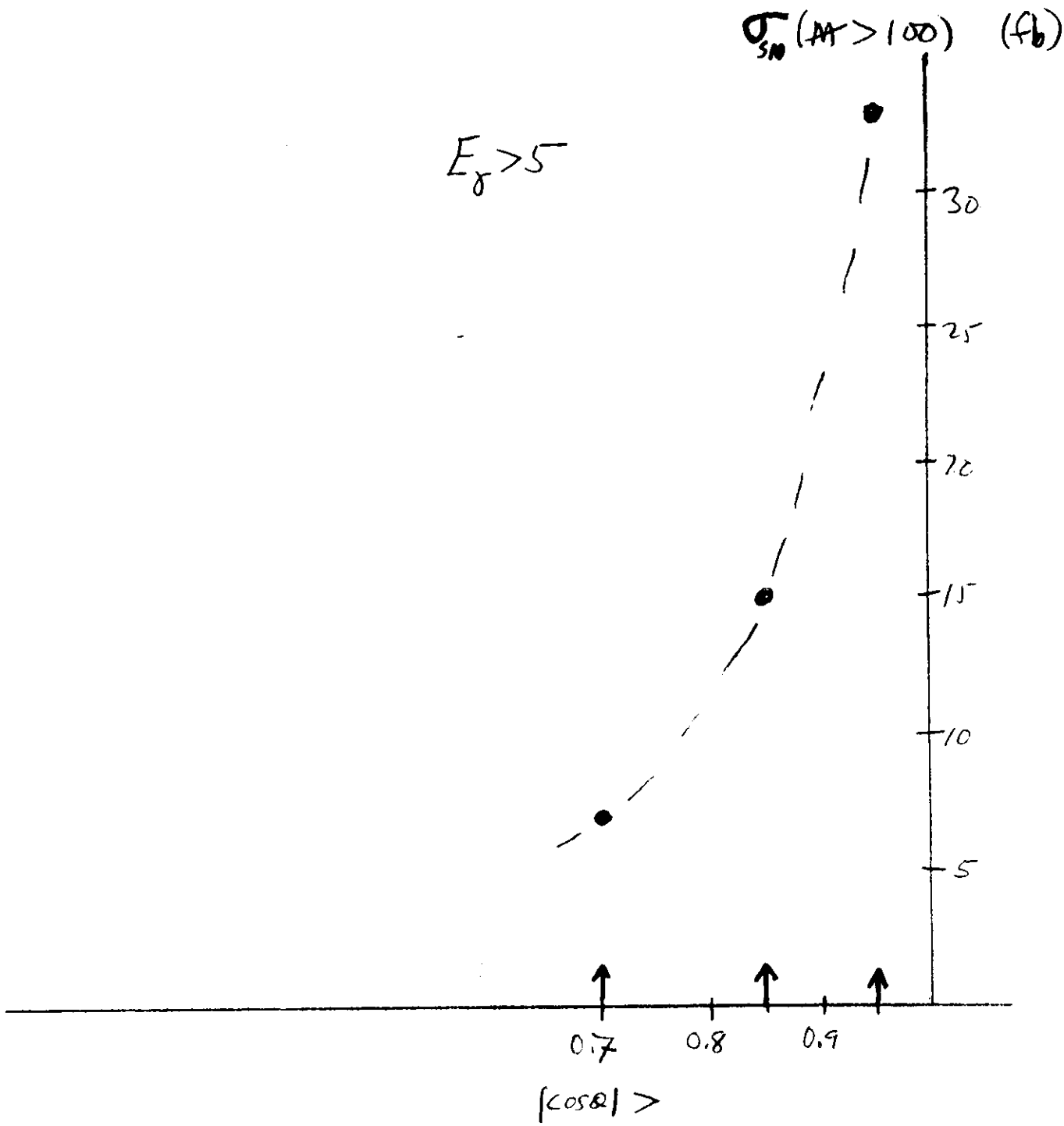


NOTE RATIO OF $(100 < M < 140)/\text{ALL}$
IS SMALL AT 172

$\sigma_{e^+e^- \to \Sigma \nu_i \bar{\nu}_i \gamma\gamma}$ (fb)



MRENNA



- SO --

NUMBER EVENTS = σ × INTEGRATED LUMINOSITY

$= 0.020\ pb \times 80\ pb^{-1}$

$= 1.6$

SUMMING 4 DETECTORS, 2 ENERGIES

PHOTON DETECTION EFF $\approx 3/4$

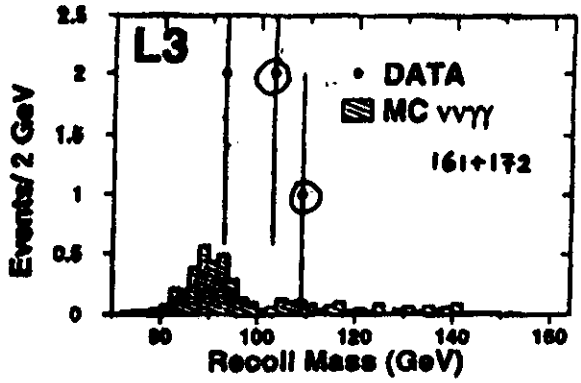
SO, FINALLY, EXPECT 1.2 EVENTS, SEE ABOUT 6 -- ENCOURAGING

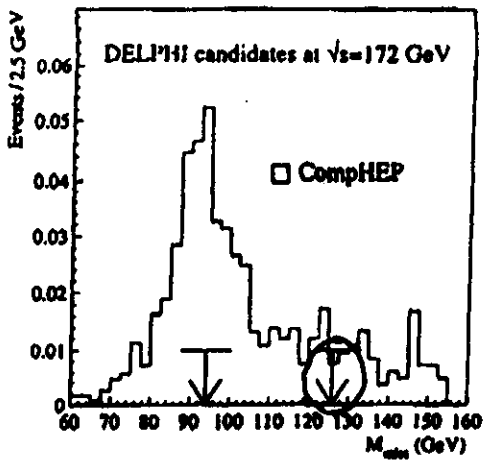
NEED TO BE MORE PRECISE ABOUT CUTS
-- MINIMUM E_γ
-- γ's NEAR BEAMPIPE

- ALSO "INITIAL STATE RADIATION"

γγE

Graham Wilson
Moriond





$|m_{recoil} - m_Z| > 7$ GeV

$\Rightarrow n_{obs} = 3$ (1.4) (1.0) GeV correction.

LEP1.5+161+172 $n_{obs} = 2$ (2.6)

ALEPH	n_{obs}	n_{exp}^{SM}	m_{recoil} (GeV)
$\sqrt{s} = 133$	0	2	
161	2	2.3	132, 95
172	1	2.1	(122)

OPAL	n_{obs}	n_{exp}^{SM}	
$\sqrt{s} = 133$	5	3.3	81, 91, 94, 92, 88
161	1	3.9	(107)
172	2	3.8	93, 93

$\Rightarrow$ ~~FAIR AGREEMENT~~ WITH SM EXPECTATION

LOW RECOIL MASS : BACKGROUND FROM $\nu\bar{\nu}\gamma\gamma$ IS LOW

$\Rightarrow$ NO EVENTS

HIGH RECOIL MASS : $\nu\bar{\nu}\gamma\gamma$ BKGD IS VERY POSSIBLE

$\Rightarrow$ SEVERAL EVENTS

(5)

• ANOTHER WAY TO LOOK AT SAME LEP DATA (OR FUTURE LEP)

$$S \equiv \frac{N(M > 100\ \text{GeV})}{N(\text{all } \not{q}\bar{q})}$$

ANY FIXED E_γ, $\cos\theta_\gamma$ CUTS

AMBROSANIO, MRENNA

$S < 5\%$ INCLUDING FACTOR ≥ 2 FOR ISR

DATA (SUSY 97)

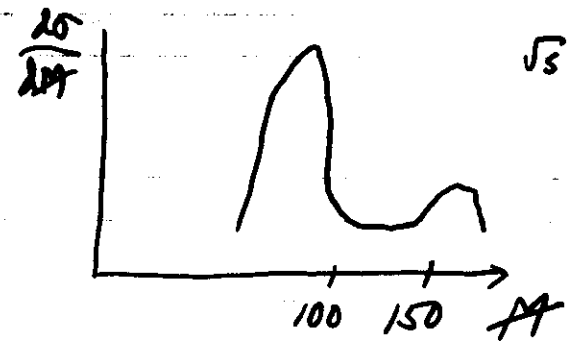
$S = 6/18$

ACTUALLY -- FOR FUTURE -- USE

$$S = \frac{N(100 < M < 150)}{\text{ALL}}$$

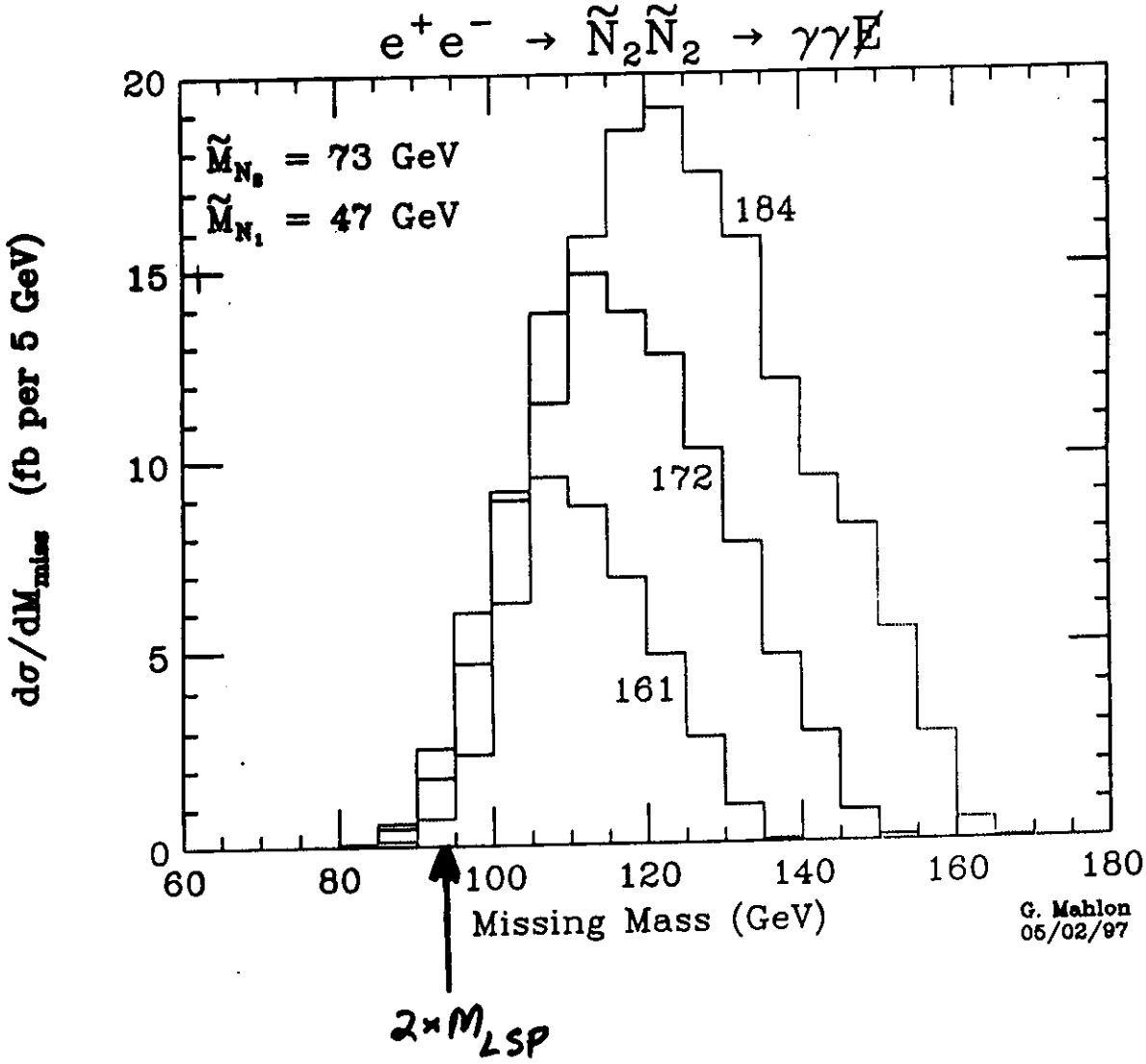
LEP NEXT RUN: GOOD CHOICES?

- $E_{\gamma_i} > 5$ (OR 8)
- $|\cos\theta_{\gamma_i}| < 0.85$
- $M_Z + 4\Gamma_Z < \not{M} \lesssim 150$ GeV



SIGNAL LARGEST HERE, BACKGROUND SMALLEST

Mahlon GK
hep-ph/9704450



$\sigma(161) = 52$ fb
$\sigma(172) = 98$ fb
$\sigma(184) = 146$ fb.

$E_T^\gamma > 4$ GeV
$|\eta^\gamma| < 2.5$