

INTERPRETING NEW CLUES (?)
TO PHYSICS BEYOND THE
STANDARD MODEL

G. KANE
LA THULE, MARCH 2001

• THE SM IS ESTABLISHED -- IT WILL BE EXTENDED

• WHAT IS NOT DESCRIBED BY THE SM, AND CAN POINT THE WAY BEYOND?

-- GRAVITY

-- COSMOLOGICAL CONSTANT $\Lambda = 0 + \epsilon$

-- INFLATION, STRUCTURE FORMATION

-- HIERARCHY PROBLEM

-- STRONG CP PROBLEM

-- BROKEN ELECTROWEAK SYMMETRY

-- GAUGE COUPLING UNIFICATION

-- MATTER ASYMMETRY OF UNIVERSE

-- COLD DARK MATTER

-- ν MASSES

-- APPROXIMATE YUKAWA UNIFICATION FOR t, b, τ

-- α_μ (?)

-- PROPERTIES OF h^0 (?)

-- $\sin 2\beta$ (?)²

MAYBE

→ PHENOMENA NOT COSMOLOGICAL
OR VERY HIGH ENERGY

THE STANDARD MODEL CANNOT ACCOUNT
FOR ANY OF THESE (IGNORE $\sin 2\beta$ FOR THE MOMENT)

• (INDIRECT) EVIDENCE FOR WEAK SCALE SUPERSYMMETRY (WITH STRING BOUNDARY CONDITIONS)

MASSSES FOR BOSONS AND FERMIONS

HIGGS

- PROVIDES MECHANISM FOR EWSB
- STABILIZES HIERARCHY
- CAN EXPLAIN BARYON ASYMMETRY
- GAUGE COUPLING UNIFICATION
- PROVIDES CDM CANDIDATE
- HEAVY TOP
- LIGHT h
- PREDICTED EITHER SUPERPARTNERS AT LEP, OR NO SIGNIFICANT DEVIATIONS FROM SM IN PRECISION DATA

EXPLANATIONS

PREDICTIONS

• ALL SIMULTANEOUS

• THEORY NOT INVENTED TO DO ANY OF THESE

TODAY FOCUS ON:

(1) LEP h^0 PROPERTIES, IMPLICATIONS

(2) a_μ

(3) GENERAL τ_R , INCLUDING NON-SM SOURCES, AND $\sin 2\beta$

FOR h^0, a_μ ASSUME EFFECTS REAL,
EXAMINE IMPLICATIONS, CONSISTENCY
WITH EACH OTHER AND WITH OTHER
EXPLANATIONS OF BEYOND-THE-STANDARD-
MODEL PHENOMENA -- IN SUPERSYMMETRY
CONTEXT

• VERY GENERAL TREATMENT :

STRINGY THEORY, 10D, PLANCK SCALE

↓ 4D, ~~SUSY~~

YUKAWAS IN W, AND $\mathcal{L}_{\text{SOFT}}$



~125 PARAMETERS -- BUT ALL UNDERSTOOD,
USUALLY ONLY ≈ 10 RELEVANT, USUALLY
ONLY ~4 IMPORTANT

- NO UNCONTROLLED ASSUMPTIONS, APPROXIMATIONS
- NO MODELS
- (• NO LARGE EXTRA DIMENSIONS)

MSSM: SM PARTICLES + SUPERPARTNERS,
 $SU_3 \times SU_2 \times U_1$, 2 HIGGS DOUBLET, R-PARTY

$$-\mathcal{L}_{\text{SOFT}}^{\text{SUSY}} = \frac{1}{2} \left(M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B} + \text{h.c.} \right) \quad (6)$$

$M_i = |m_i| e^{i\varphi_i}$

$$(5) + m_{\tilde{Q}}^2 \tilde{Q} \tilde{Q}^* + m_{\tilde{U}}^2 \tilde{U}^c \tilde{U}^c + m_{\tilde{D}}^2 \tilde{D}^c \tilde{D}^c + m_{\tilde{L}}^2 \tilde{L} \tilde{L}^* + m_{\tilde{E}}^2 \tilde{E}^c \tilde{E}^c$$

3x3 HERMITEAN MATRICES

$$(54) + a_U \tilde{U}^c \tilde{Q} H_U + a_D \tilde{D}^c \tilde{Q} H_D + a_E \tilde{E}^c \tilde{L} H_D + \text{h.c.}$$

3x3 COMPLEX MATRICES

$$(4) + m_{H_U}^2 H_U^* H_U + m_{H_D}^2 H_D^* H_D + (B H_U H_D + \text{h.c.})$$

(2) + GRAVITINO

(2) + μ

-2 U_1 SYMMETRIES

\Rightarrow 33 MASS EIGENSTATES,
 43 PHASES, 5 CKM ANGLES

CAN HAVE LARGER THEORY, MORE PARAMETERS,
 E.G. EXTRA U_1 'S, ν -- CAN CHECK EXPERIMENTALLY

PHYSICS OF PARAMETERS UNDERSTOOD -- OBSERVABLE MANY WAYS

YUKAWA COUPLINGS, $\tan\beta$

- AT UNIFICATION SCALE g, l HAVE YUKAWA COUPLINGS, MASSES ZERO

$$W = Y_{lep} \bar{L} H_D l_R + \dots$$

└── 3x3 FLAVOR MATRIX

- AS UNIVERSE COOLS, AT EW PHASE TRANSITION

$$\langle H_U \rangle = v_U, \quad \langle H_D \rangle = v_D$$

$$\tan\beta = v_U / v_D$$

$$m_{q,l} = Y_{q,l} v_{U,D}$$

- TYPICALLY IN STRING THEORY YUKAWAS EITHER \sim GAUGE COUPLINGS OR \sim ZERO
-- INTERPRET LARGE YUKAWAS AS Y_t, Y_b, Y_τ
-- ALSO IN GUTS

- SO IF $Y_t \approx Y_b$, $m_t/v_U \approx m_b/v_D$

$$\Rightarrow \tan\beta \approx m_t/m_b \approx 35$$

SO "NATURAL" VALUES FOR $\tan\beta$ ARE $\sim 1, \sim 35$

- THEORY PERTURBATIVE $\rightarrow 1.5 \lesssim \tan\beta \lesssim 50$
(EVIDENCE: GAUGE COUPLING UNIFICATION, EWSB)

- NO GENERAL DATA ON $\tan\beta$ -- VERY HARD TO MEASURE AT HADRON COLLIDERS (UNLESS LUCKY)

- LEP: $\tan\beta \gtrsim 1.5$ (ANY STRONGER LIMIT MODEL-DEPENDENT)

HIGGS PHYSICS

EVIDENCE:

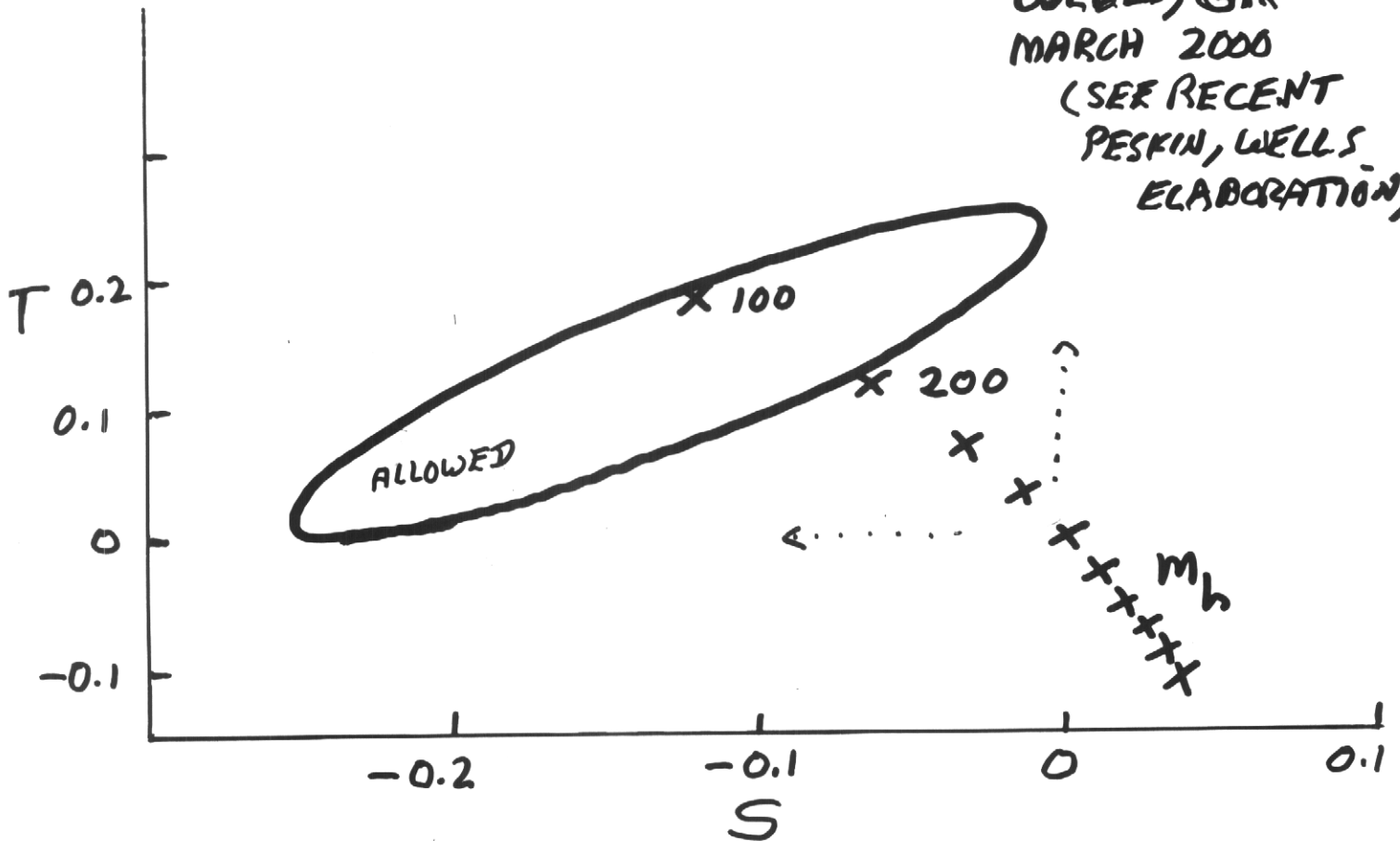
(1) GLOBAL LEP ANALYSIS $\Rightarrow m_h < "170 \text{ GeV}"$
-- CAN BE FAKED, HARD, REQUIRES
OTHER NEW PHYSICS

(2) LEP "LIKELY" SIGNAL,
 $m_h \approx 115 \text{ GeV}, \quad 2.9 \sigma$

ASSUME h INDEED DISCOVERED -- WHAT
DO WE LEARN?

GK, KING, WANG
hep-ph/0010312

hep-ph/0003249
WELLS, GK
MARCH 2000
(SEE RECENT
PESKIN, WELLS
ELABORATION)



$$\Rightarrow M_{h''} \lesssim 450 \text{ GeV}$$

AND

MUST HAVE NEW SOURCE OF
PHYSICS TO MOVE BACK

IF WANT TO AVOID $M_h \lesssim 200 \text{ GeV}$

- POINTLIKE, FUNDAMENTAL HIGGS BOSON EXISTS -- NEW KIND OF MATTER -- COMPLETES SM, POINTS TO HOW TO EXTEND SM
- h DECAYS DOMINANTLY TO $b\bar{b}$, LARGE g_{ZZh}
- h APPROXIMATELY SM-LIKE
- h CANNOT BE PURELY SM SINCE $m_h \lesssim 130$ DESTABILIZES VACUUM?

($m_t = 174$)

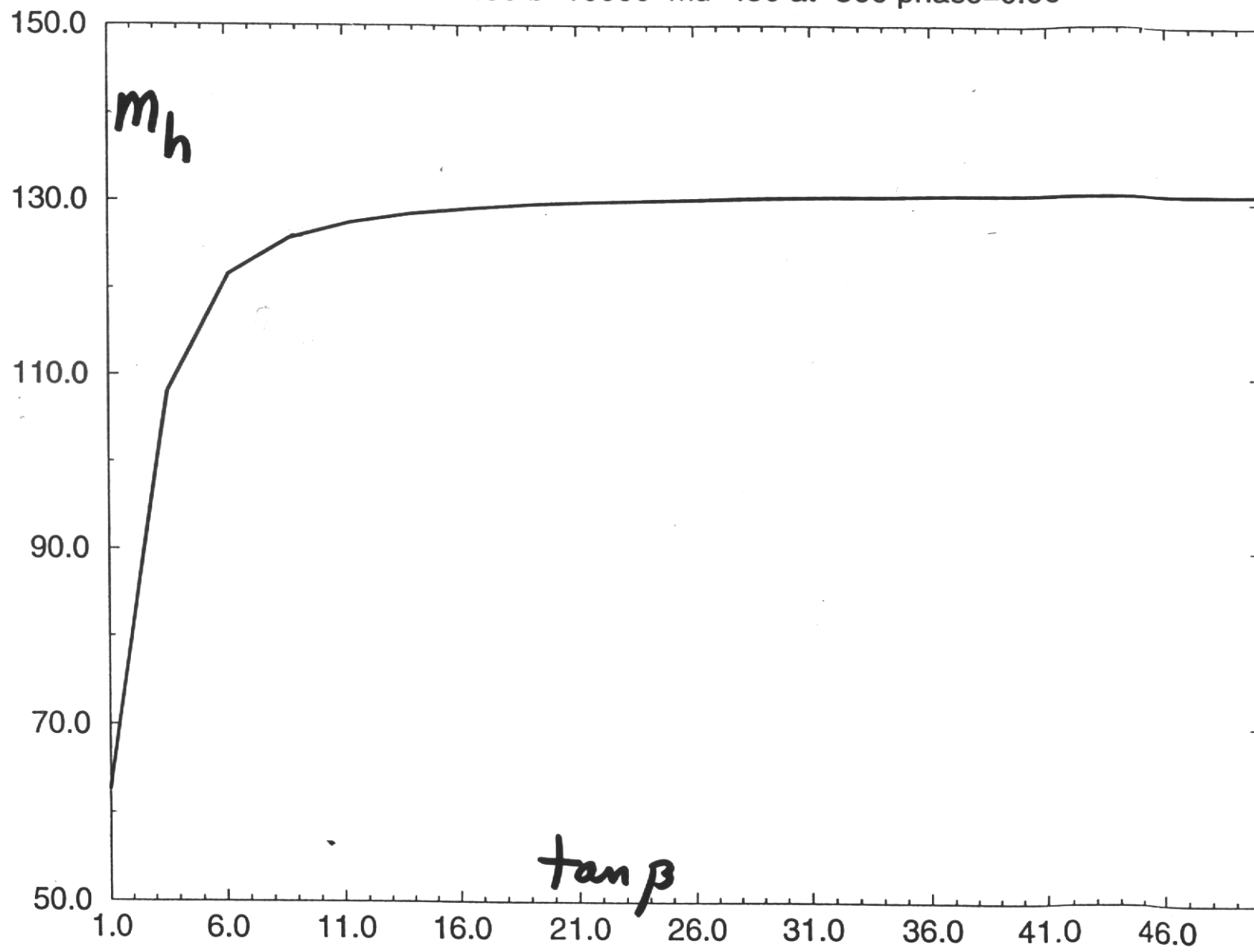


- $m_h \leq m_{top} \Rightarrow h$ UNLIKELY TO BE FROM STRONGLY INTERACTING SECTOR
- SUSY -- $m_h^{MSSM} \lesssim 130$ -- VACUUM STABLE -- ACTUAL VALUE $m_h \approx 115$ HARD TO GET IN MODELS UNLESS
 - (i) $\tan \beta \gtrsim 5$ $m_h^{tree} \approx m_Z |\cos 2\beta| \approx m_Z$
 - AND/OR (ii) LARGE PHASES ($\varphi_\mu + \varphi_{A_t}$)
 - AND/OR (iii) EXTRA SCALARS -- SINGLETs

mh1 vs tanb

WANG, KING, GK

ml=500 mr=450 b=10000 mu=450 at=500 phase=0.00



- BR($b\bar{b}$) MAXIMAL, MAYBE ENHANCED -- SUGGESTS LARGE LOOP CORRECTIONS, WHICH DO ARISE FOR LARGE $\tan\beta$

- ASSUMING LARGE $m_h^{\text{tree}} \approx m_z^2$, NEED ABOUT 25 GeV FROM ONE-LOOP RADIATIVE CORRECTIONS TO m_h -- SO NEED LARGE STOP SPLITTING OR LARGE SOFT STOP MASSES -- COMBINED WITH NATURALNESS SUGGESTS LIGHTER $\tilde{\chi}, \tilde{\eta}$ PRODUCED AT FNAL IN NEW RUN -- SUSY NATURALLY GIVES ~ 25 GeV

- IN GENERAL ≥ 7 PARAMETERS NEEDED TO SPECIFY SCALAR POTENTIAL, SO NO NEW RESULTS WITH 2 NEW PIECES OF DATA L. WANG, GK Ph/0003198



$$\tilde{m}_t^2 = \begin{pmatrix} \tilde{m}_{tL}^2 + Y_t^2 |H_U|^2 & Y_t (A_t H_U - \mu^* H_D^*) \\ Y_t (A_t H_U - \mu^* H_D^*) & \tilde{m}_{tR}^2 + Y_t^2 |H_U|^2 \end{pmatrix}$$

LARGE $\tan\beta$ SUGGESTS LOOPS IMPORTANT TOO

$$m_h, \sigma_h = F(\tilde{m}_{tL}^2, \tilde{m}_{tR}^2, |A_t|, |\mu|, B, \tan\beta, \varphi_\mu + \varphi_{A_t})$$

BRHLIK, GK; PILAFTSIS; DEMIR; CARENA et al; IBRAHIM, NATH; WANG, GK
 -- EFFECTS ON CDM ALSO DEPEND ON SLEPTON MASSES, ETC

- OPTIMAL FOR CONFIRMATION AT TEVATRON IF LEP EFFECT A SIGNAL -- $\sigma, BR(b\bar{b})$ MAXIMAL, MASS BIN PREDICTED -- CAN OPTIMIZE -- STATISTICAL CRITERIA CHANGE -- $\sigma_{\text{TEVATRON}}^h \approx 1.5 \text{ pb}$

IMPLICATIONS OF A NON-SM $g_{\mu-2}$

L. EVERETT, S. RIGOLIN, L. WANG, GK
hep-ph/0102145

- IF INDEED $\delta a_{\mu} = 425 \pm 165 \times 10^{-11}$ IS DIFFERENT FROM ZERO, IT IS THE FIRST DATA WHOSE EXPLANATION MUST BE NEW WEAK SCALE PHYSICS, ACCESSIBLE AT COLLIDERS
(OTHER EFFECTS SUCH AS BARYON ASYMMETRY, COLD DARK MATTER, ν MASSES, INFLATION COULD ALL BE EXPLAINED BY COSMOLOGICAL OR HIGH MASS SCALE PHENOMENA)
- CAN EXPLAIN $g_{\mu-2}$ WITH SUPERSYMMETRY IF SUPERPARTNER MASSES LIGHT ENOUGH, $\tan \beta \gtrsim \text{FEW}$ -- FULLY CONSISTENT WITH ALL EXPERIMENTS, DIRECT AND INDIRECT--LONG HISTORY
- EFFECTIVE LAGRANGIAN ANALYSIS: M. EINHORN, J. WUDKA
ph/0103034

a_μ

$$L_{\text{eff}} = \frac{e g_\mu}{2m_\mu} \bar{\mu} \sigma_{\alpha\beta} \mu F^{\alpha\beta}, \quad a_\mu = \frac{g_\mu - 2}{2}$$

└────────── ANY MASS

$$a_\mu^{\text{exp}} = 11\,659\,202(16) \cdot 10^{-10}$$

CURRENTLY 14 + 6

↓
6 MONTHS

↓
4 GOAL

$$a_\mu^{\text{th}} = a_\mu^{\text{EM}} + a_\mu^{\text{EW}} = 11\,659\,1596(67) \cdot 10^{-11}$$

HADRONIC

W, Z

$$a_\mu^{\text{EW}} = (19.5 - 43) \cdot 10^{-11}$$

ONE LOOP

TWO LOOP

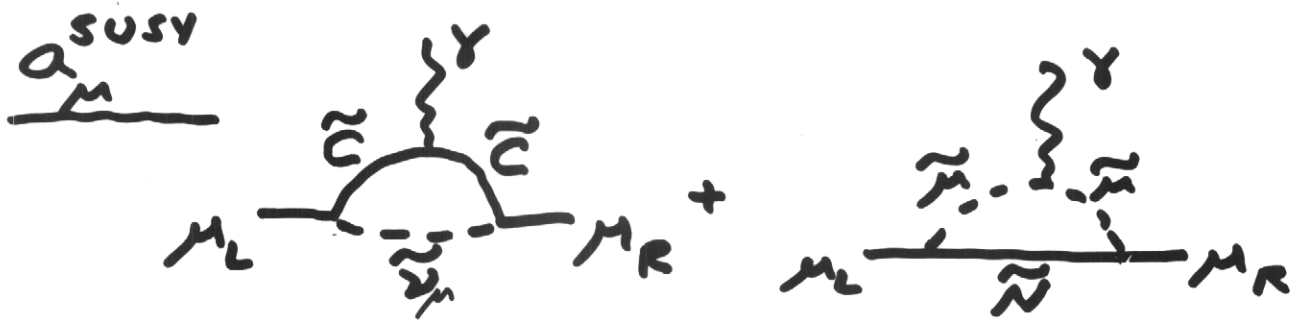
NOVOSIBIRSK, JAPANE, BEIJING

$$a_\mu^{\text{th}} = a_\mu^{\text{EM}} + a_\mu^{\text{EW}} + a_\mu^{\text{SUSY}}$$

$$a_\mu^{\text{th}} - a_\mu^{\text{expt}} = 425 \pm 165 \times 10^{-11}$$

≈ 3 × $a_\mu^{\text{W,Z}}$ BUT NOWHERE ELSE

ASSUME SIGNIFICANT, LOOK AT IMPLICATIONS



- FULL SET OF ≈ 1 PARAMETERS FROM $W, \mathcal{L}_{\text{SOFT}}$
 $|M_2|, |\mu|, \varphi_2 + \varphi_{\mu}, \tan\beta, \tilde{m}_{\nu}, \tilde{m}_{\mu_L}, \tilde{m}_{\mu_R}, |M_1|, \varphi_1 + \varphi_{\mu}, |A_{\mu}|, \varphi_A + \varphi_{\mu}$
- FOR SMALL MASSES BOTH DIAGRAMS IMPORTANT
- BUT WE WANT TO USE a_{μ} TO PUT UPPER LIMIT ON \tilde{m}_i , SO LOOK FOR LARGER MASSES

- FIND $\tilde{C}\tilde{\Sigma}$ DIAGRAM INCREASES $\sim \tan\beta$, DOMINATES FOR LARGE $\tan\beta$, AND

$$a_{\mu}^{\text{SUSY}} \approx a_{\mu}^{\text{EW}} \left(\frac{100 \text{ GeV}}{\tilde{m}} \right)^2 \tan\beta \overbrace{\cos(\varphi_2 + \varphi_{\mu})}^{\text{NEW}}$$

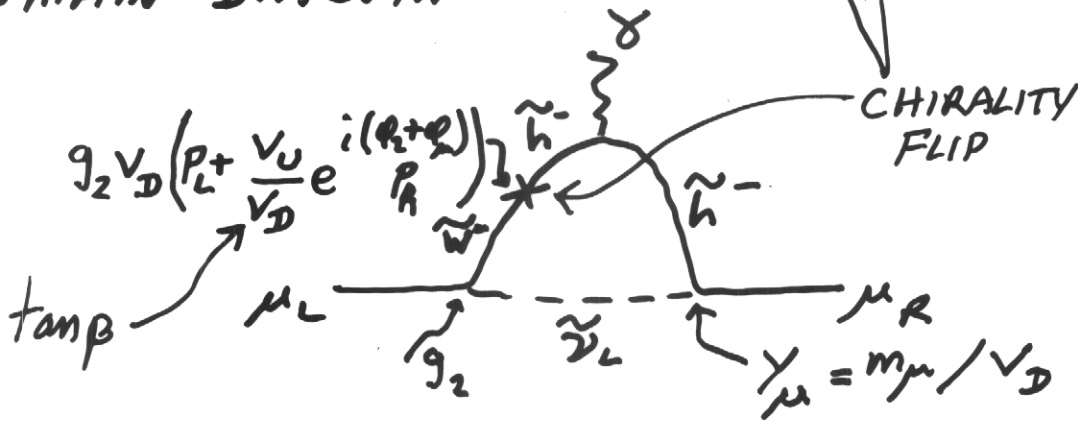
- ONLY $|M_2|, |\mu|, \varphi_2 + \varphi_{\mu}, \tan\beta, \tilde{m}_{\nu}$ ENTER
- GET LIMITS WHEN $\varphi_2 + \varphi_{\mu} = 0$! (NATH et al, GENERAL CASE CAN GO EITHER WAY)
- $|M_2|, |\mu|$ BASICALLY COMBINE TO GIVE \tilde{C}_{\pm}^{\pm} MASS
- SO FINALLY, 3 PARAMETERS, WITH NO UNCONTROLLED ASSUMPTIONS, APPROXIMATIONS
- LEP: $\tilde{m}_{\tilde{C}_{\pm}^{\pm}} \geq 100, \tilde{m}_{\mu} \geq 100 \text{ GeV}$
- $\tilde{m}_{\nu} \approx \tilde{m}_{\mu_L}$ ONCE $\tilde{m}_{\mu_L} \geq 150 \text{ GeV}$

- SIGN OF SUSY CONTRIBUTION NOT DETERMINED
 - EXPERIMENTAL SIGN OPPOSITE TO SIGN IN SUSY LIMIT IF $\tan\beta$ LARGE, $\tilde{E}\tilde{\nu}$ BIG
 - (-- $b \rightarrow s\gamma$ PHASE IS $\varphi_{A_t} + \varphi_\mu$ -- WITH USUAL CONVENTIONS $b \rightarrow s\gamma$ AND $g_{\mu-2}$ FAVOR $\mu > 0$)

• \tilde{C} MASS MATRIX

$$M_{\tilde{C}} = \begin{pmatrix} \tilde{w}^- & \tilde{h}^- \\ M_2 e^{i\varphi_2} & g_2 v_U / \sqrt{2} \\ g_2 v_D / \sqrt{2} & \mu e^{i\varphi_\mu} \end{pmatrix} \begin{pmatrix} \tilde{w}^- \\ \tilde{h}^- \end{pmatrix}$$

• MAIN DIAGRAM

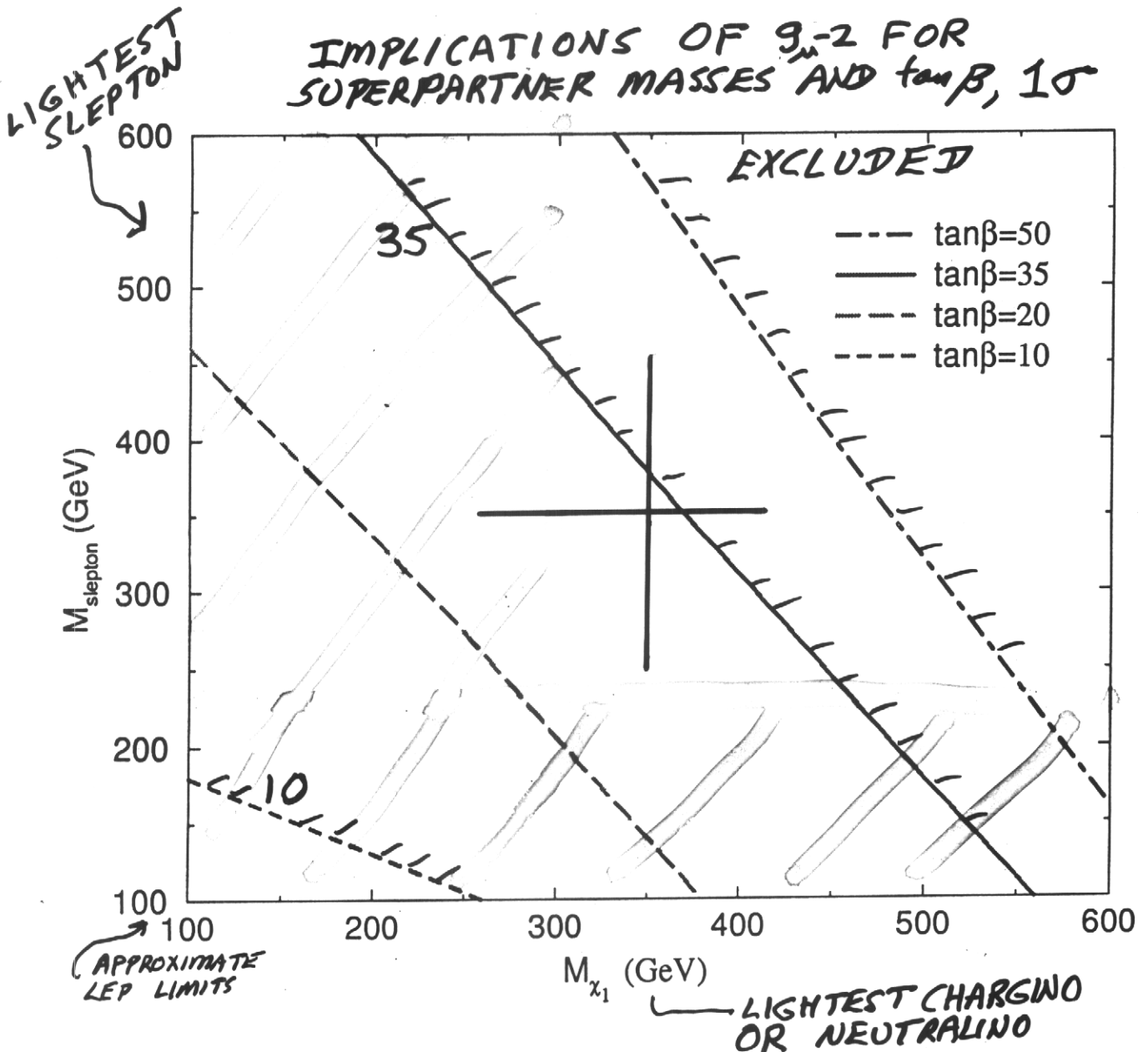


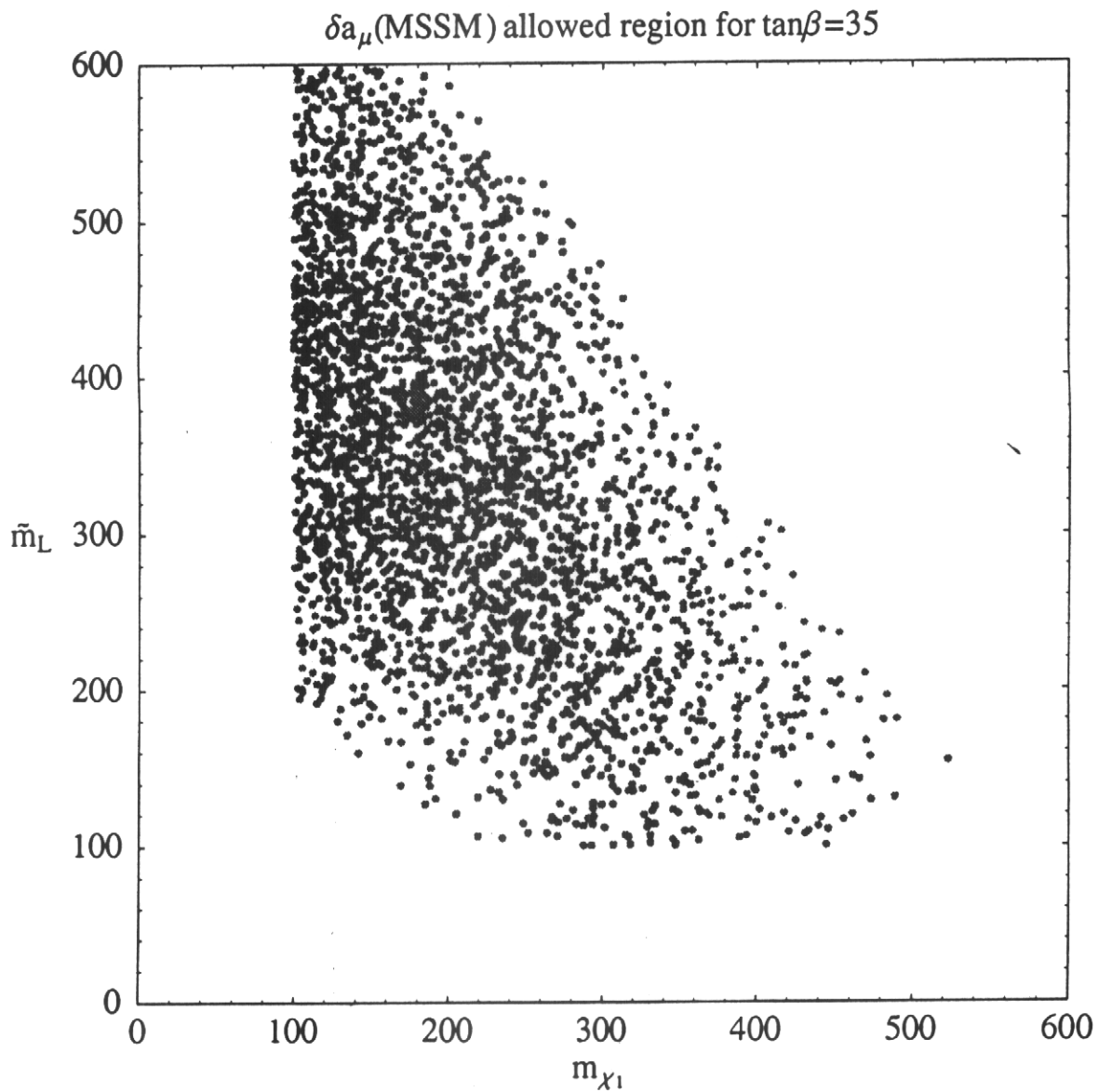
- NUMERICAL ANALYSIS -- IN ORDER TO LEARN WHAT UPPER LIMITS COULD ARISE WHEN THEORY AND EXPERIMENT IMPROVE (MONTHS), USE 1σ RESULTS -- THEN LIMITS ABOUT AS STRONG AS WILL BE IF EFFECT REAL

-- STATISTICS NOT LIKE SMALL-EVENT-BUMP BECAUSE TESTING A PRIORI STANDARD MODEL PREDICTION

WILL BE PRODUCED
AT TEVATRON

(NOTE -- IN ORIGINAL POSTED MANUSCRIPT WE PUT WRONG
FIGURE)





- FOR LARGER $\tan\beta$ SMALLEST MASSES EXCLUDED
- MASSES NOT NEAR LIMITS IN GENERAL

WHAT DO WE KNOW ABOUT THE ORIGIN OF ϵ_R

- STRING THEORY -- DEFINE CP TRANSFORMATION
 - STROMINGER, WITTEN 1985
 - CHOI, KAPLAN, NELSON 1993
 - DINE, LEIGH, MCINTYRE 1993
 - DENT 2000
- STRING-BASED MODELS
 - USUALLY PHASES ENTER VIA COMPLEX VEVs OF MODULI F-TERMS -- FEED THROUGH TO YUKAWAS, $\mathcal{L}_{\text{SOFT}}$ PHASES
- ONLY CONTACT WITH PHENOMENA IS VIA YUKAWAS, $\mathcal{L}_{\text{SOFT}}$ (EXCEPT POSSIBLY FOR MATTER ASYMMETRY)
- MEASURED PHASES MAY LEAD BACK TO PROVIDE INFORMATION ABOUT COMPACTIFICATION, SUSY, MODULI STABILIZATION
- CAN MEASURE PHASES MANY WAYS -- NOT ONLY ϵ_R ϵ , ϵ' , $\sin 2\beta$, EDMs, $A(b \rightarrow s\gamma)$ BUT ALSO Δm_K , Δm_{B_d} , Δm_{B_s} , LSP CDM, HIGGS SECTOR, SUPERPARTNER MASSES AND CROSS SECTIONS
- YUKAWA PHASES $\rightarrow \delta_{ij}^{\text{CKM}}$ FROM SUPERPOTENTIAL, SO COULD BE INDEPENDENT OF SUSY -- PHASES OF $\mathcal{L}_{\text{SOFT}}$ ONLY EXIST IF SUSY -- SO COULD HAVE EITHER OR BOTH

CALCULATE SUPERPOTENTIAL WHEN SUSY UNBROKEN

• δ_{ij}^{CKM} CAN DESCRIBE $\epsilon, \epsilon' (?)$

• δ_{ij}^{CKM} CANNOT PROVIDE MATTER ASYMMETRY
-- MAYBE $\delta_{ij}^{CKM} \approx 0!$

\Rightarrow INTERESTING TO EXAMINE WHETHER CAN DESCRIBE ALL τR WITHOUT δ_{ij}^{CKM}

FRERE + GAVELA; FRERE + ABEL; ... BRHLIK, EVERETT, KING, δ LEBEDEV, GK,
PRL, PH/9909480
EVERETT, KANE, KING, RIGOLIN, WANG IN PREPARATION

\Rightarrow YES, IF FLAVOR STRUCTURE IS DIFFERENT

$$\delta_{CKM} \approx 0 \Rightarrow$$

$$\bullet V_{td} \approx |V_{cb} \sin \theta_c| - |V_{ub}| \approx 0.005$$

- ALL SUSY EFFECTS FROM LOOPS SINCE THERE IS ALWAYS A TREE DIAGRAM FOR b DECAYS (EXCEPT $b \rightarrow s\gamma$)

$$\Rightarrow (\mathcal{CP})_b \sim \text{SUPERWEAK}$$

$$\bullet \sin 2\alpha = -\sin 2\beta$$

MEASURED CP ASYMMETRIES

[INDEPENDENT OF ANY PARAMETERS]

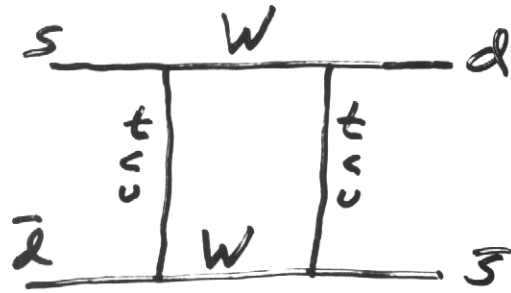
ALL CP PHENOMENA

THEN HAVE TO DESCRIBE $\epsilon, \epsilon', \dots$ WITH $\mathcal{L}_{\text{SOFT}}^{\text{SUSY}}$ PHASES -- CAN DO THAT (DETAILED STUDY IN PROGRESS) -- $\sin 2\beta$ NATURALLY $\lesssim 1/2$

BRHLIK, EVERETT, KANE, KING, LEBEDEV, PRL
 → EVERETT, KANE, RIGOLIN, WANG

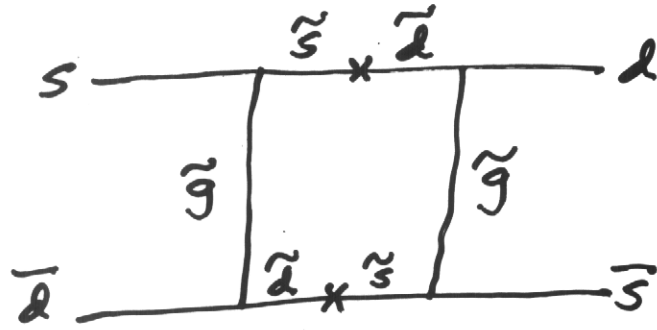
LOOP CONTRIBUTIONS TO MIXING (ANALOGOUS PENGUINS FOR DIRECT DECAYS)

STANDARD MODEL
(REAL IF $\delta_{CKM} \approx 0$)



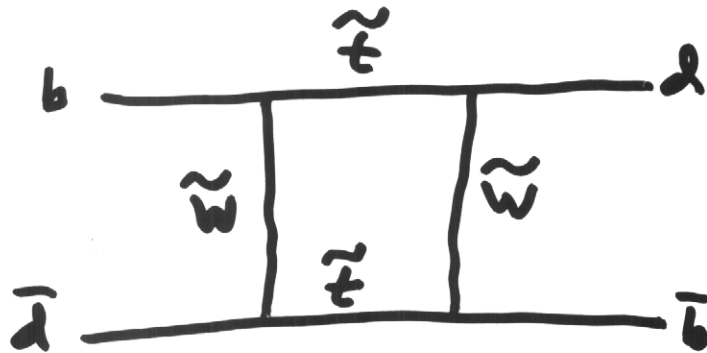
AND
 $s \rightarrow b$

$\tilde{g} \tilde{g}$



AND
 $s \rightarrow b$

$\tilde{W} \tilde{t}$



AND
 $b \rightarrow s$

REMEMBER :

- IF $g-2$ CONFIRMED AS DATA ADDED AND HADRONIC CONTRIBUTION CONTROLLED

→ STRONG EVIDENCE OF NEW WEAK SCALE PARTICLES

-- SUPERPARTNERS, LARGER $\tan\beta$

WORK -- CONSISTENT WITH $M_{\tilde{H}} \approx 115$ GeV

→ INCREASINGLY LIKELY SUPERPARTNERS WILL BE PRODUCED AT TEVATRON

- ER MAY TAKE SURPRISING FORMS -- MAY BE RATHER DIRECTLY CONNECTED TO STRING THEORY