Title: Particle Phenomenology

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Abstract:

SUPERSYMMETRY AND THE REAL WORLD

GORDY KANE
PERIMETER, JUNE 2005

- LONG INTRODUCTION
  - -- BTSM, CLUES?
  - -- PERSPECTIVE, WORLDVIEW
  - -- NEW DATA?
- DERIVE LAGRANGIAN
- $\mathcal{L}_{SOFT}$
- DERIVE EWSB
- MSSM, SUPERPARTNERS
- HOW MIGHT SUPERPARTNERS SHOW UP?
  - -- VIRTUAL
  - -- COLLIDERS, SIGNATURES -- LHC
- FROM DATA TO THE UNDERLYING PHYSICS
  - -- LHC

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QUESTION	Standard Model(s)	Supersymmetric SM(s), light superpartners	String Theory
What is matter?	√		
What is light?	√√		√
What interactions give our world?	√		
Gravity			√
			√√
Stabilize weak scale hierarchy?		√√	
Explain weak scale hierarchy?			
Unify gauge couplings?			√
Higgs mechanism?		√√	
What is dark matter?		√	
Baryon asymmetry?		√	
Low scale superpartners?		√	√
How is supersymmetry broken?			√
			√
More than one family? 3?			
Values of quark, lepton masses?			√
Values of neutrino masses?			√
Origin of CP violation?			√
		√	√
Inflaton?		√	
Cosmological constant not large?			√
Dark energy?			√
			√
What is electric charge?			
Space-time?			√
Quantum theory?			√
Origin of universe?			√
			√

√ question addressed √√ good answer

String phenomenology attempts to **explain** at least:
(definition of string phenomenology)

No other subfield focuses on these

- No large cosmological constant
- Dark energy—what, how much
- What is the dark matter
- Baryon asymmetry – amount, origin
- Inflation, big bang
- Standard model (why quarks and leptons, their charges, gauge grou
- Electroweak symmetry breaking – calculate M_Z, tanβ
- Unification of forces
- Supersymmetry
- Supersymmetry breaking
- Superpartner masses – collider data
- Number of families – why not 1?
- Quark and lepton and neutrino masses
- Origin and pattern of CP violation
- Flavor changing interactions – size, chirality

- STRING THEOLOGY
  STRING THEORY
  STRING PHENOMENOLOGY
  -- STRING COSMOLOGY

ALL THESE COULD HAVE SHORT DISTANCE OR COSMOLOGICAL EXPLANATIONS

WHAT DATA COULD SOON GUARANTEE NEW PHYSICS AT WEAK SCALE?

** { • SUPERPARTNERS
• TEVATRON, LHC BTSM SIGNAL

→ • SIGNAL FROM DARK MATTER DETECTORS

→ • EDMs (e, n)

→ • $B_s \to \mu^+\mu^-$ (TEVATRON, LHC)

→ • $A_{CP}(B \to \phi K, \eta' K) \neq \sin 2\beta$

• LEPTON FLAVOR VIOLATION ($\mu \to e\gamma$, $\tau \to \mu\gamma$, LHC)

• HEAT POSITRON EXCESS, UNDERSTAND BACKGROUND

• $A_{CP}(b \to s\gamma) \neq 0$

WHAT (EXISTING OR NEW) DATA COULD HELP PROBE STRING THEORY?

- DARK ENERGY ($w=-1$? dw/dt?)
- INFLATION (INFLATON, SCALE)
- COSMIC STRINGS?

- PROTON DECAY?
- EDMs? -- STRONG CPV? -- PHASES?

→ • ν MASSES -- HIERARCHICAL OR DEGENERATE?

→ • FLAVOR CHANGING RARE DECAYS, FC CPV

(• MINIBOONE/LSND)

LHC
- SUPERSYMMETRY AT LOW SCALE?
- SUPERPARTNER MASSES?
- SOFT MASS PHASES?

- DARK MATTER

- HIGGS BOSONS
- HIGGS MECHANISM

(ILC - LHC > 10 YEARS)
→ ∞

FLAVOR AND STRING THEORY

* QUARKS, LEPTONS COME IN SEVERAL TYPES WITH SAME PROPERTIES EXCEPT FOR MASS

e, μ, τ
u, c, t
d, s, b

"FLAVORS"

* SM, SSM CAN ACCOMODATE FLAVOR BUT DON'T REQUIRE IT OR MOTIVATE IT OR EXPLAIN IT

* IF WE DIDN'T KNOW ABOUT FLAVOR, STRING THEORY WOULD MOTIVATE IT -- NOT KNOWN IF STRING THEORY IMPLIES FLAVOR -- NO OTHER APPROACH COULD REQUIRE IT

* SO FLAVOR MAY BE UNIQUE, POWERFUL PROBE OF STRING THEORY!

* NEW DATA COMING -- BETTER UNDERSTANDING OF THEORY

* RELATED TO ER, MATTER ASYMMETRY OF UNIVERSE

- RECENT INFORMATION:
  - Sin2β=0.726±0.037 from B→ ψ K **BUT FROM**

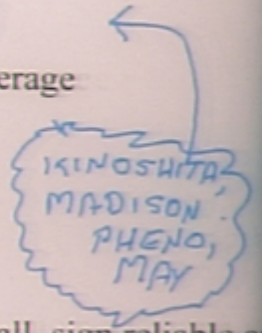
B→ φ K, η′ K GET

0.39±0.11	Belle
0.45±0.09	Babar
.43±0.07	World average

IN THE SM THEY WOULD BE THE SAME

DATA → 3.7 σ

- Could hadronic effects explain this?
- Recent analyses → NO



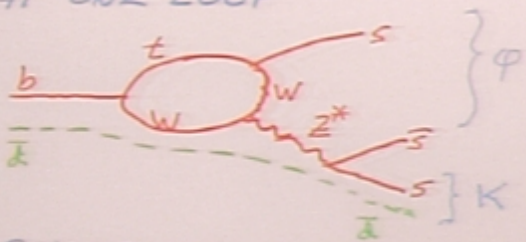
e.g. Martin Beneke, ph/0505075 --- effects small, sign reliable and goes opposite direction

IF EFFECT REMAINS AS DATA IMPROVES, IT IS MOST SIGNIFICANT DEVIATION FROM SM EVER THAT COULD NOT HAVE COSMOLOGICAL OR SHORT DISTANCE EXPLANATION

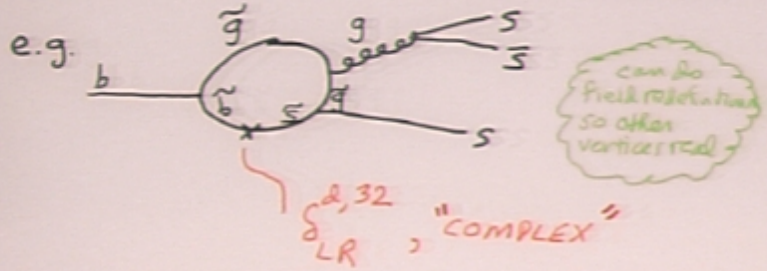
(DM, baryon asymmetry, neutrino masses)

CONSIDER $b \to s\bar{s}s$ $(s\bar{q}q)$

- NO SM TREE DIAGRAM
- SM AT ONE LOOP

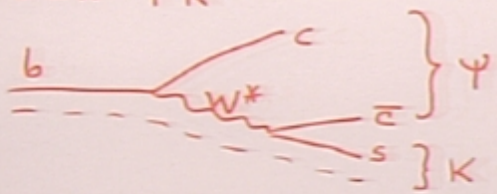


- CAN CHOOSE REAL SINCE NO 1st FAMILY
- SENSITIVE TO LIGHT SUPERPARTNER LOOPS



- FOCUS ON δ^{LR} -- HADRONIC EFFECTS SMALLER -- DISCOVERING EFFECT BTSM DOES NOT DEPEND ON UNDERSTANDING HADRONIC ISSUES, INTERPRETATION MIGHT

* CONSIDER ψK



-- CAN CHOOSE V_{bc}, V_{cs} REAL

→ $\not{CP}$ FROM INITIAL $B\bar{B}$ MIXING, FINAL $K\bar{K}$ MIXING

* DEFINE TIME DEPENDENT CP ASYMMETRY

$$a_f(t) = [\Gamma(\bar{B}_2 \to f) - \Gamma(B_2 \to f)] \,/\, \text{SUM}$$

$$= C_f \cos \Delta m\, t + S_f \sin \Delta m\, t$$

(C_f: $\psi K, \phi K$; Δm: Δm_{B_2})

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}, \quad C_f = \frac{1-|\lambda_f|^2}{+}, \quad S_f = \frac{2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2}$$

-- CAN CHOOSE $A^{SM}_{\psi K, \phi K}$ REAL

→ $\lambda^{SM}_{\psi K, \phi K} = e^{-2i\beta}$ → $S^{SM}_{\phi K} = \sin 2\beta$

DETAILS ON CP

* EW EIGENSTATES $|B_L^0\rangle = |\bar{b}L\rangle, |K^0\rangle = |s\bar{d}\rangle \cdots$

* MASS " $B_{H,L} = p_B|B^0\rangle \pm q_B|\bar{B}^0\rangle$

$K_{S,L} = p_K|K^0\rangle \pm q_K|\bar{K}^0\rangle$

* DECAY AMPLITUDE

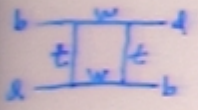
$$A(\psi K_S) = \langle \psi K_S | H_{EFF}^+ | B^0\rangle \approx p_K^* \langle \psi K_S^0 | H_{EFF}^+ | B^0\rangle$$
$$\bar{A}(\psi K_S) = \langle \psi K_S | H_{EFF} | \bar{B}^0\rangle \approx q_K^* \langle \psi \bar{K}^0 | H_{EFF} | \bar{B}^0\rangle$$
$$A(\psi K_S) \cdots$$
$$\bar{A}(\psi K_S) \cdots$$

* DEFINE

$$\lambda_f = \left(\frac{q}{p}\right)_B \frac{\bar{A}_f}{A_f}, \quad S_f = \frac{2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2}, \quad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

* THEN

$$\lambda_{\psi K_S} = \left(\frac{q}{p}\right)_B \left(\frac{\bar{A}}{A}\right)_{\psi K_S} = \left(\frac{q}{p}\right)_B \left(\frac{q}{p}\right)_K^* \left(-\,A^*_{\psi K^0}/A_{\psi K}\right)$$



SM BOX: $\dfrac{V_{tb}^* V_{td}}{V_{td} V_{tb}^*}$

SM / BOX: $\dfrac{V_{cs}^* V_{cd}}{V_{cs} V_{cd}^*}$

SM PENGUIN: $-\dfrac{V_{tb} V_{tc}^*}{V_{tb}^* V_{tc}}$

$$\Rightarrow \lambda_{\psi K_S}^{SM} = -e^{-2i\beta}$$

$$S_{\psi K_S} = \sin 2\beta$$

(1) * LOOK FOR HIGH SCALE MODELS THAT COULD DESCRIBE AN EFFECT

$\Rightarrow$ ONLY $\bar{\delta}^{d,LR}_{32} = \bar{\delta}^{d,RL*}_{23}$,

OTHERS TOO CONSTRAINED

CHIRALITY IMPORTANT

hep-ph/0407351
GK, L-T Wang, T. Wang, H. Wang

* MODELS

-- DOUBLE INSERTION

$$\bar{\delta}^{d,LR}_{23} \sim \delta^{d,LL}_{23} \times \underbrace{\frac{m_b}{m^2_{\tilde{q}}}}_{33,LR} (A_b - \mu \tan\beta)$$

ETC

$\Rightarrow$ NO

-- "MINIMAL FLAVOR VIOLATION" -- EFFECT PURELY FROM SCKM ROTATION - NO

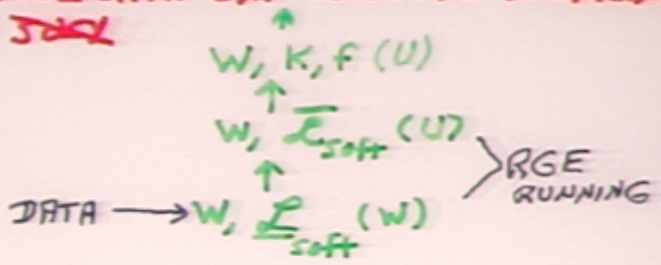
-- ABELIAN FLAVOR SYMMETRIES -- HARD

-- DIAGONAL, NON-UNIVERSAL KAHLER POTENTIAL CAN WORK

MAIN POINT -- LOW SCALE FLAVOR EFFECT CAN PROBE HIGH SCALE THEORY RATHER DIRECTLY

WORLD VIEW

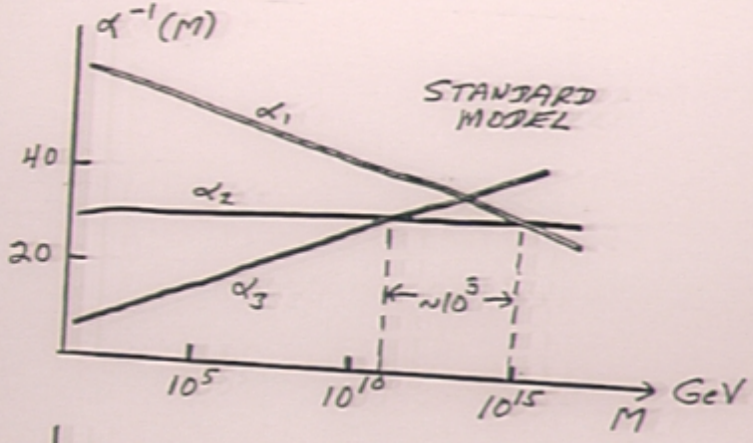
- PREFER TO RETAIN THE ATTRACTIVE PICTURE OF FUNDAMENTAL THEORY, PRESUMABLY STRING THEORY, IN 10 (11) D, SMALL, WITH 3D INFLATING
  → 4D EFFECTIVE THEORY, SCALE $\sim 10^{16}$ GeV
- CONSISTENT WITH ALL DATA, CONSTRAINTS -- CAN ADDRESS ALL BASIC QUESTIONS
- COULD BE CONSISTENT WITH ALL DIMENSIONS LARGE, OTHERS WARPED, OR DUAL THEORIES
- AT 10^{16} GeV, ALL FORCES COMPARABLE, SUPERSYMMETRIC, EW SYMMETRY UNBROKEN, PARTICLES MASSLESS
- ALL INFO ABOUT UNDERLYING THEORY ENCODED IN W, K, f
- ONCE ~~SUSY~~, ALL INFO IN W, $\mathcal{L}_{soft}$
- THEORY PERTURBATIVE BELOW $\sim 10^{16}$ GeV
- EWSB, HIGGS MECHANISM CRUCIAL TO EXPLAIN, TIED TO ~~SUSY~~

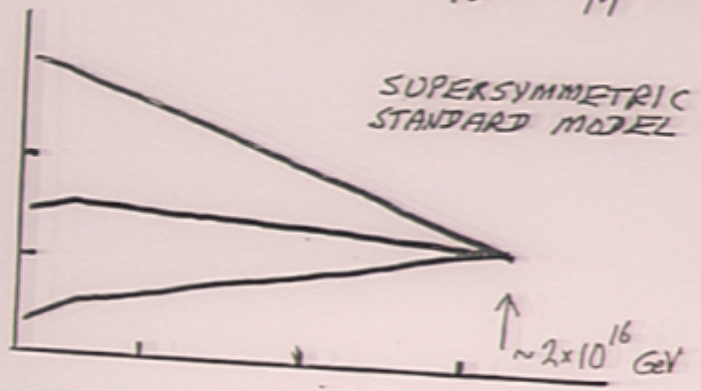


WHAT DOES SUPERSYMMETRY EXPLAIN?

- NO THEORY OF ~~SUSY~~ YET
- ASSUME SOFT MASSES ~ WEAK SCALE
- DERIVE STABLE HIERARCHY ~ m_W/m_{Pl}
- DERIVE BREAKING OF $SU(2)\times U(1)$ EW SYMMETRY OVER GOOD PART OF PARAMETER SPACE
- DERIVE GAUGE COUPLING UNIFICATION
- CAN EXPLAIN BARYON ASYMMETRY
- PROVIDES GOOD DARK MATTER CANDIDATE

GAUGE COUPLING UNIFICATION





SUGGESTS:

* THEORY PERTURBATIVE UP TO ~ UNIFICATION SCALE (NOT DESERT, JUST PERTURBATIVE)
* PHYSICS SIMPLER ~ UNIFICATION SCALE (NEED NOT HAVE HAPPENED)

PERTURBATIVE EW SYMMETRY BREAKING HAS SAME IMPLICATIONS

"DATA" -- SUBTLE

* MOON STAYS IN ORBIT

* FLAT, OLD UNIVERSE

* HIERARCHY PROBLEM

* NO DEVIATIONS FROM SM AT LEP

* GRAVITY

* FINE-TUNED EXPLANATIONS
(EWSB, $\bar{\Phi}$, ...

POSSIBLE "MSSM" PROBLEMS -- FINE TUNINGS

└ WHOLE WORLD VIEW

- Λ NOT $\sim m_{SUSY}^2 m_{Pl}^2$ $(H^2 m_{Pl}^2)$
- $\Omega_{DE} \sim \Omega_{DM} \sim \Omega_B$
- INFLATION
- $\bar{\Theta}$
- m_e/m_τ, m_τ/m_t
- SUPERPARTNER MASSES $\sim m_W \ll$ "m_{Pl}"
  - -- NOT SOLVED BY ANY APPROACH
  - -- PRESUMABLY ~~SUSY~~
- μ -- STRINGS + ~~SUSY~~ ? -- U_1' MSSM ?

  [ATTRACTIVE -- U_1' IMPLIES $\mu = 0$ UNTIL U_1' BROKEN -- THEN GIVES $\mu \sim \langle S \rangle$ -- ELIMINATES M_h FINE TUNING, $\tan\beta$ FT, MAYBE m_Z^2 FT -- SUCH U_1' NATURAL IN STRING THEORIES]

- $m_Z^2 \approx -2\bar{\mu}^2 + 6\bar{m}_3^2 + \cdots$ FROM EWSB

  [$\Rightarrow$ LIGHT $\tilde{g}$]
- $m_h^{SM} \gtrsim 115$ GeV
  - -- SHOULD HAVE $m_h < 100$
  - -- OK IN LOTS OF MSSM PARAMETER SPACE

- FLAVOR-CHANGING EFFECTS, EDMs ABSENT
  - -- CLUE, POINTS TO SPECIAL HIGH SCALE THEORY?
  - -- SOME WANT GENERAL SOLUTIONS
  - -- PHASES INTERESTING -- ZERO? WHY?

$B \to \phi K \ldots$?

NOTE -- FT IN LOW SCALE THEORY -- DON'T KNOW IF IN HIGH SCALE THEORY -- CAN TREAT ALL AS CLUES SINCE SUSY HAS A MEANINGFUL HIGH SCALE THEORY "ULTRAVIOLET COMPLETION" -- MANY APPROACHES DON'T ADDRESS SUCH QUESTIONS AT ALL

ALL STRING PHENOMENOLOGY

- $g_V \sim \sin^2\theta_W - \frac{1}{4}$ $\qquad g_A = 1/2$ } SM
- $(\epsilon'/\epsilon)_K$
- $\pi^2 - 9$

MOST PHYSICS IDEAS INVENTED IN ORDER TO EXPLAIN DATA OR PUZZLES

BUT SUPERSYMMETRY WAS

(A) NOTICED AS A PROPERTY OF SOME STRING THEORY MODELS ~ 1972

(B) INVENTED TO SEE IF A CONSISTENT QUANTUM FIELD THEORY WITH BOSON - FERMION SYMMETRY COULD BE CONSTRUCTED

ORIGINALLY NO ONE IMAGINED SUPERSYMMETRY WAS CRUCIAL, OR EVEN RELEVANT, TO EXPLAINING HOW NATURE WORKS

"SUSY IS AN ANSWER LOOKING FOR A PROBLEM"

SUPERSYMMETRY WAS NOT INVENTED TO DO ANY OF THE MANY THINGS IT DOES!!

INDIRECT EVIDENCE FOR SUPERSYMMETRY

(A) PREDICTED PHENOMENA

- ✓ UNIFICATION OF GAUGE COUPLINGS ($\sin^2\theta_W$) — ~1982
- ✓ HEAVY TOP QUARK — ~1982
- LSP IS COLD DARK MATTER — ~1983
- ✓? LIGHT HIGGS BOSON ($m_h < 200$ GeV 95% CL) — 1993
- ✓ ABSENCE OF LARGE DEVIATIONS IN PRECISION DATA IF NO EXPLICIT SUPERPARTNERS — ~1990

(B) EXPLANATIONS

- * ELECTROWEAK SYMMETRY BREAKING — ~1982
- STABILITY OF HIERARCHY — ~1980
- NATURALNESS PROBLEM ($m_W \ll M_{Pl}$) — ~1982
- BARYON ASYMMETRY — ~MID 1990's

(C) CONNECTION TO SUPERSTRINGS

- ALL BASED ON DATA (EXCEPT (C))
- ALL CONSISTENT, SIMULTANEOUS
- NOT INVENTED TO DO ANY OF THEM ! (UNIQUE IN HISTORY OF SCIENCE)

OUTCOMES SUPERSYMMETRY COULD NOT EXPLAIN:

* NO h^0 BELOW ~ 200 GeV
* $m_t \lesssim m_W$
* GAUGE COUPLINGS UNIFIED $\lesssim 10^{14}$ GeV, $\gtrsim 10^{18}$ GeV
* HERA LEPTOQUARKS
* ANY DEVIATION $\gtrsim 1\%$ AT LEP
* RAPID PROTON DECAY
* WIDE WW, ZZ RESONANCES $\lesssim$ TeV
* WHY 3 FAMILIES
* LARGE VIOLATIONS OF μ-e UNIVERSALITY

HISTORY OF SUPERSYMMETRY

1970-72, 1st SUSY REVOLUTION -- THE IDEA

1974, 2nd SUSY REVOLUTION -- SUPERSYMMETRIC RELATIVISTIC QUANTUM FIELD THEORY

1975, 3rd SUSY REVOLUTION -- LOCAL SUSY = SUPERGRAVITY

1979-83, 4th SUSY REVOLUTION -- CAN SOLVE A NUMBER OF PROBLEMS NOT DESIGNED TO SOLVE

2004-8? -- 5th SUSY REVOLUTION -- DIRECTLY DETECT SUPERPARTNERS, HIGGS BOSON

CURRENT LIMITS ON SUPERPARTNER MASSES

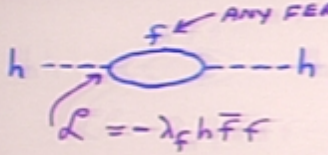
* SHOULD SUPERPARTNERS HAVE BEEN FOUND?
  -- WOULD HAVE BEEN LUCKY

* BUT h SHOULD HAVE BEEN FOUND!

- $\tilde{c}, \tilde{l}^{\pm} \lesssim 100$ GeV, LEP
- $\tilde{g} \lesssim 250$ GeV, TEVATRON
- $\tilde{t} \lesssim 100$ GeV "
- $\tilde{N}$ NO GENERAL LIMITS
  [$\gtrsim 40$ IF ASSUME GAUGINO DEGENERACY,
  $\gtrsim 10$ IF ASSUME DARK MATTER IN THERMAL EQUILBRIUM]

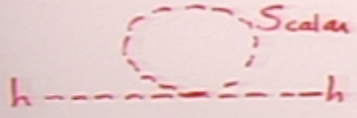
HIERARCHY PROBLEM — SERIOUS

FOR SM, SOME EXTENSIONS



$\mathcal{L} = -\lambda_f h \bar{f} f$

$$\delta m_h^2 = \frac{|\lambda_f|^2}{16\pi^2}\left[-2\Lambda^2 + 6m_f^2 \ln\frac{\Lambda}{m_f} + \cdots\right]$$

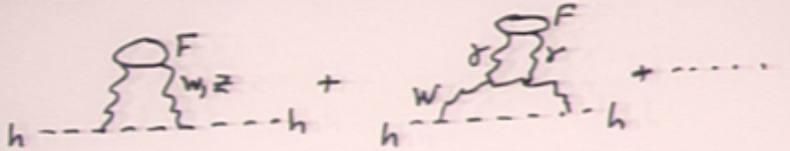


$\mathcal{L} = -\lambda_s h^2 S^2$

$$\delta m_h^2 = \frac{\lambda_s}{16\pi^2}\left[\Lambda^2 - 2m_S^2 \ln\frac{\Lambda}{m} + \cdots\right]$$

- QUADRATIC DIVERGENCE
- IF USE DIM REG INSTEAD OF MOMENTUM CUTOFF, NO Λ^2 PIECE -- BUT CAN'T ELIMINATE $m_{S,f}^2$ TERM -- COULD TUNE COUNTERTERM W ONE LOOP BUT WOULD STILL GET EFFECT IN HIGHER ORDER

- SO m_h^2 SENSITIVE TO MASS OF HEAVIEST PARTICLE THAT COUPLES TO h
- m_h AND ALL SM MASSES ARE SMALL, BUT ALL $\sim m_h$ SO WHY SMALL
- SUPPOSE HEAVY FERMION F DOESN'T COUPLE TO h, GETS MASS SOME OTHER WAY -- HAS SOME GAUGE INTERACTION (WITH γ, Z, W, g) -- THEN DIAGRAMS LIKE



$$\Rightarrow \delta m_h^2 \sim a\Lambda^2 + b m_F^2 \ln \Lambda/m_F + \cdots$$

- ALL SENSITIVITY TO HIGHER ORDERS, SCALES GONE IF EACH f ACCOMPANIED BY COMPLEX SCALAR, AND $\lambda_s = |\lambda_f|^2$
- SUSY NOT DESIGNED TO SOLVE THIS, BUT DID
- NOT JUST ABOUT HIGH SCALES

$$\delta m_h^2 \text{ (top loop)} \approx \frac{3}{\sqrt{2}\pi^2} G_F m_t^2 \Lambda^2 \approx \left(\frac{\Lambda}{4}\right)^2$$

(CUTOFF)

$$\gtrsim (100\ \text{GeV})^2 \quad \text{IF } \Lambda \gtrsim 400\ \text{GeV}$$

* - TO SOLVE HIERARCHY PROBLEM, MUST HAVE WAY TO CALCULATE m_h THAT IS NOT DIVERGENT, AND MUST BE ABLE TO SHOW RESULT IS NOT SENSITIVE TO HIGH SCALES OR HIGHER ORDERS

- NOTE – COSMOLOGICAL CONST ALSO A HIERARCHY PROBLEM -- BUT h CARRIES GAUGE SM Q.NOS., Λ DOES NOT

(COSM CONST)

- CAN THINK OF SUSY SOLUTION AS $h \to (h, \tilde{h})$ SUPERMULTIPLET, AND FERMION MASS NOT QUAD DIVERGENT, SO h MASS NOT QUAD DIV

$\gtrsim (100\,\text{GeV})^2$ IF $\Lambda \gtrsim 400\,\text{GeV}$

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CEKKLW

hep-ph/ 0312378

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DERIVE $\mathcal{L}_{SUSY}$

- CONSIDER SINGLE LH 2-COMPONENT FERMION ψ, SUPERPARTNER COMPLEX SCALAR φ

$$S = \int d^4x \, (\mathcal{L}_{SCALAR} + \mathcal{L}_{FERM})$$

$$\mathcal{L}_{SCALAR} = -\partial^\mu \varphi^* \partial_\mu \varphi \qquad \mathcal{L}_{FERM} = -i \psi^\dagger \bar{\sigma}^\mu \partial_\mu \psi$$

(φ, ψ) = CHIRAL SUPERMULTIPLET

NOTATION: $\xi\chi = \xi^\alpha \chi_\alpha = \xi^\alpha \epsilon_{\alpha\beta} \chi^\beta = -\chi^\beta \epsilon_{\alpha\beta} \xi^\alpha = \chi^\beta \epsilon_{\beta\alpha} \xi^\alpha = \chi^\beta \xi_\beta = \chi\xi$

(ANTICOMMUTING; ANTISYM OF ϵ)

- A SUSY TRANSFORMATION SHOULD TURN $\varphi \leftrightarrow \psi$
- ASSUME $\delta\varphi = \epsilon\psi$, $\delta\varphi^* = \epsilon^\dagger \psi^\dagger$
  - -- ϵ^α AN INFINITESIMAL, ANTICOMMUTING, 2 COMPONENT SPINOR
  - --GLOBAL SUSY $\partial^\mu \epsilon^\alpha = 0$
  - -- $[\epsilon] = m^{-1/2}$ SINCE $\psi \sim m^{3/2}$, $\varphi \sim m$
- THEN $\delta\mathcal{L}_{SCALAR} = -\epsilon \partial^\mu \psi \, \partial_\mu \varphi^* - \epsilon^\dagger \partial^\mu \psi^\dagger \partial_\mu \varphi$
- HOPE TO FIND $\delta\psi$ TO CANCEL THIS -- OBVIOUSLY $\delta\psi$ LINEAR IN $\epsilon^\dagger, \varphi$, NEED DERIVATIVE BY DIMENSIONS, TRY

$$\delta\psi_\alpha = i (\sigma^\mu \epsilon^\dagger)_\alpha \partial_\mu \varphi$$

(COEFFICIENT ARBITRARY)

$$\rightarrow \delta\mathcal{L}_{FERM} = -\epsilon \sigma^\mu \bar{\sigma}^\nu \partial_\nu \psi \, \partial_\mu \varphi^* + \psi^\dagger \bar{\sigma}^\nu \sigma^\mu \epsilon^\dagger \partial_\mu \partial_\nu \varphi$$

(AFTER ALGEBRA) $\rightarrow = \underbrace{\epsilon \partial^\mu \psi \, \partial_\mu \varphi^* + \epsilon^\dagger \partial^\mu \psi^\dagger \partial_\mu \varphi}_{\text{CANCEL}} - \underbrace{\partial_\mu [\cdots]}_{\text{INTEGRATES TO ZERO}}$

* FOR SUPERSYMMETRY MUST ALSO REQUIRE THAT THE ALGEBRA CLOSES, COMMUTATOR OF TWO SUSY TRANSFORMATIONS IS ANOTHER

(a) $(\delta_{\epsilon_1}\delta_{\epsilon_2} - \delta_{\epsilon_2}\delta_{\epsilon_1})\varphi = i(\epsilon_1\sigma^\mu\epsilon_2^\dagger - \epsilon_2\sigma^\mu\epsilon_1^\dagger)\partial_\mu\varphi$

-- OK, SINCE $\partial_\mu \sim P_\mu$ IS A GENERATOR

-- GET DERIVATIVE OF φ!

(b) (")$\psi_\alpha = i($ " $)\partial_\mu\psi_\alpha$

$+[\cdots]\bar{\sigma}^\mu\partial_\mu\psi_\alpha$

-- EXTRA TERM VANISHES ON-SHELL FOR MASSLESS FERMIONS, SO SUSY ALGEBRA CLOSES ON-SHELL (WHEN CLASSICAL EQUATIONS OF MOTION SATISFIED)

-- BUT NEED IT TO CLOSE FOR FULL QUANTUM FIELD THEORY

* TRICK -- INVENT NEW "AUXILIARY" COMPLEX SCALAR FIELD F, NO KINETIC TERM

$$\mathcal{L}_{AUX} = F^*F$$

- $[F] = m^2$
- EQNS OF MOTION $F = F^* = 0$ (WILL CHANGE FOR INTERACTIONS)
- GUESS $\delta F = i\epsilon^\dagger\bar{\sigma}^\mu\partial_\mu\psi$, $\delta\psi_\alpha = \text{OLD} + \epsilon_\alpha F$

* THEN THEORY WITH $\mathcal{L} = \mathcal{L}_{SCALAR} + \mathcal{L}_{FERM} + \mathcal{L}_{AUX}$ IS INVARIANT!

* FOR $X = \varphi, \psi, F$ EVEN OFF-SHELL GET

$$(\delta_2\delta_1 - \delta_1\delta_2)X = i(\epsilon_1\sigma^\mu\epsilon_2^\dagger - \epsilon_2\sigma^\mu\epsilon_1^\dagger)\partial_\mu X$$

* GET FIELD BACK AT SHIFTED SPACE-TIME POINT!

* CAN SEE WHY NEEDED F

- ON-SHELL φ HAS 2 d.o.f
  ψ " " "
- OFF-SHELL ψ A COMPLEX 2 COMPONENT SPINOR SO 4 d.o.f
- SO NEED 2 MORE SCALAR d.o.f THAT VANISH ON-SHELL

* (φ, ψ, F) = CHIRAL SUPERMULTIPLET

- EXPECT Q, L, U, d, e, H_U, H_d TO BE CHIRAL SUPERMULTIPLETS

(Q: LH QUARK DOUBLET IN SU(2); L: LH LEPTON DOUBLET IN SU(2); U, d, e: RH SINGLETS IN SU(2); H_U, H_d: HIGGS SU(2) DOUBLETS)

* INTERACTIONS OF CHIRAL SUPERMULTIPLETS

- INCLUDE FLAVOR INDICES BECAUSE MIGHT NOT BE DIAGONAL
- FOR EACH PARTICLE

$$\mathcal{L}_{FREE} = -\partial^\mu \varphi_i^* \partial_\mu \varphi_i - i\psi_i^\dagger \bar{\sigma}^\mu \partial_\mu \psi_i + F_i^* F_i$$

- MOST GENERAL SET OF SUPERSYMMETRIC RENORMALIZABLE INTERACTIONS (NON-GAUGE) IS

$$\mathcal{L}_{INT} = -\frac{1}{2} W^{ij} \psi_i \psi_j + W^i F_i + h.c.$$

(W^{ij}, W^i: ANY FUNCTIONS OF SCALAR FIELDS)

- W^{ij} SYMMETRIC SINCE $\psi_i \cdot \psi_j = \psi_j \psi_i$
- W^{ij}, W^i CANNOT BE FUNCTIONS OF ψ_i, F_i OR $\mathcal{L}$ WOULD HAVE MASS DIM > 4 AND NOT BE RENORM
- SINCE $\mathcal{L}_{FREE}$ WAS INVARIANT UNDER SUSY TRANSFORMATIONS ITSELF, SO MUST $\mathcal{L}_{INT}$ BE
- ANY TERM IN $\mathcal{L}_{INT}$ THAT WAS FUNCTION ONLY OF φ_i, φ_i^* WOULD GIVE TERMS NOT CANCELLED BY SUSY TRANS

* CONSIDER VARIATION OF $\mathcal{L}_{INT}$, PART WITH 4 SPINORS

$$0 \stackrel{?}{=} \delta\mathcal{L}_{INT,\,4\,SPINORS} = -\frac{1}{2}\frac{\delta W^{ij}}{\delta\varphi_k}(\epsilon\psi_k)(\psi_i\cdot\psi_j) - \frac{1}{2}\frac{\delta W^{ij}}{\delta\varphi_k^*}(\epsilon^+\psi_k^+)(\psi_i\cdot\psi_j) + H.C.$$

* NOTE FIERZ IDENTITY

$$(\epsilon\psi_i)(\psi_j\psi_k) + (\epsilon\psi_j)(\psi_k\psi_i) + (\epsilon\psi_k)(\psi_i\psi_j) = 0$$

SO FIRST TERM VANISHES IF, ONLY IF,
$\delta W^{ij}/\delta\varphi_k$ TOTALLY SYMMETRIC ijk

* NO SUCH IDENTITY FOR SECOND TERM!

$\Rightarrow$ REQUIRE $\delta W^{ij}/\delta\varphi_k^* = 0$,

W^{ij} DOES NOT DEPEND ON φ^*,

W^{ij} ANALYTIC, HOLOMORPHIC IN φ

* THUS MOST GENERAL $W^{ij} = m^{ij} + y^{ijk}\varphi_k$

* CAN DEFINE

$$W^{ij} = \partial^2 W/\partial\varphi_i\partial\varphi_j$$

"SUPERPOTENTIAL"

$$W \equiv \frac{1}{2}m^{ij}\varphi_i\varphi_j + \frac{1}{6}y_{ijk}\varphi_i\varphi_j\varphi_k$$

GAUGE INVARIANT, LORENTZ INVARIANT

WILL BE DIMENSIONLESS YUKAWA MATRIX

* SIMILARLY, $W^i = \partial W/\partial\varphi_i$

* SO MOST GENERAL NON-GAUGE INTERACTIONS FOR CHIRAL SUPERMULTIPLETS DETERMINED BY A SINGLE ANALYTIC FUNCTION OF COMPLEX SCALAR FIELDS

* RECALCULATE EQNS OF MOTION FOR F_i NOW,

$$F_i^* = -\partial W/\partial \varphi_i$$

SO F_i ARE FUNCTIONS OF SCALARS, NOT $\partial_\mu \varphi_i$

* REWRITE $\mathcal{L}$

$$\mathcal{L} = -\partial^\mu \varphi_i^* \partial_\mu \varphi_i - i\psi_i^\dagger \bar{\sigma}^\mu \partial_\mu \psi_i - \tfrac{1}{2} M_{ij} \psi_i \psi_j + H.C.$$
$$- \tfrac{1}{2} Y_{ijk} \varphi_i \psi_j \psi_k + H.C.$$
$$- V(\varphi)$$

$$V(\varphi) = \sum_i F_i F_i^*$$
$$= (M^* m)_{ij} \varphi_i^* \varphi_j + \left(\tfrac{1}{2} M^{in} Y^*_{ikn} \varphi_i \varphi_j^* \varphi_k^* + H.C.\right)$$
$$+ \tfrac{1}{4} Y_{ijn} Y^*_{kln} \varphi_i \varphi_j \varphi_k^* \varphi_l^*$$

POS DEF

φ_i INCLUDE HIGGS FIELDS SO HIGGS POTENTIAL HERE

* GET GAUGE THEORY BY $\partial_\mu \to D_\mu$

* CALCULATE EQUATIONS OF MOTION (LINEARIZE)

$$\partial_\mu \partial^\mu \varphi_i = (m^*_{ik} m_{kj}) \varphi_j$$

$$\partial_\mu \partial^\mu \psi_i = (\quad " \quad) \psi_j$$

SO SCALARS, FERMIONS HAVE SAME MASS !

GAUGE SUPERMULTIPLETS

* MASSLESS GAUGE BOSON A_μ^a, 2-COMPONENT FERMION GAUGINO λ^a

$a=1$ $U(1)_Y$

$a=1,2,3$ $SU(2)_L$

$a=1\cdots 8$ $SU(3)_C$

* 2 dof EACH ON-SHELL

* OFF-SHELL λ_α^a IS 2 COMPLEX, 4 REAL dof, A_μ HAS 3 dof

* SO ADD ONE REAL AUX FIELD D^a, $[D^a] \sim m^2$, FOR EACH OF $U(1)_Y$, $SU(2)_L$, $SU(3)_C$

* $\mathcal{L}_{GAUGE} = -\frac{1}{4} F_{\mu\nu}^a F_{\mu\nu}^a - i\lambda^{a\dagger} \bar{\sigma}^\mu D_\mu \lambda^a + \frac{1}{2} D^a D^a$

note unfortunate D^a, D_μ

$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - g f_{abc} A_\mu^b A_\nu^c$$

$$D_\mu \lambda^a = \partial_\mu \lambda^a - g f^{abc} A_\mu^b A_\mu^c$$

INTERACTIONS OF GAUGE, CHIRAL SUPERMULTIPLETS

$$D_\mu \varphi_i = \partial_\mu \varphi_i + i g_a A_\mu^a (T^a \varphi)_i$$

$$D_\mu \psi_i = \partial_\mu \psi_i + i g_a A_\mu^a (T^a \psi)_i$$

$$[T^a, T^b] = i f^{abc} T^c$$

e.g. $SU(2)$ $\quad \epsilon^{abc} = f^{abc}$, $T^a = \frac{1}{2}\tau^a$

* MIXED TERMS TOO! (BY INSPECTION)

$$A\left[(\varphi^* T^a \psi)\lambda^a + \text{H.c.}\right] + B\,(\varphi^* T^a \varphi) D^a$$

(INITIALLY ARBITRARY COEFF)

ONLY THESE

ONE EACH FOR 3-2-1

* REQUIRE INVARIANCE UNDER SUSY TRANSFORMATIONS, FIXES A, B!

$$\Rightarrow \mathcal{L} = \mathcal{L}_{\text{CHIRAL}} + \mathcal{L}_{\text{GAUGE}} + g_a (\varphi^* T^a \varphi) D^a - \sqrt{2} g_a \left[(\varphi^* T^a \psi)\lambda^a + \text{H.c.}\right]$$

* EQN OF MOTION $\rightarrow$ $D^a = -g_a (\varphi^* T^a \varphi)$ "D-TERMS"

* COMPLETE SCALAR POTENTIAL

$$V(\varphi) = \sum_i F^{*i} F^i + \sum_a \frac{1}{2} D^a D^a = W_i^* W_i + \frac{1}{2}\sum_a g_a^2 (\varphi^* T^a \varphi)^2 \geq 0$$

FULLY CALCULABLE IN UNBROKEN SUSY!

BUT NO HIGGS MECHANISM!

NOTE:

$$\delta\varphi = \epsilon\psi$$

$$\delta\psi = \partial_\mu \varphi + \epsilon F$$

$$\delta F = \partial_\mu \psi$$

- CAN'T GIVE $\partial_\mu\varphi$, $\partial_\mu\psi$, ψ VEV, OR BREAK LORENTZ INVARIANCE

- F, D CAN HAVE VEVS, BREAK SUSY

$$-\mathcal{L}^{CHIRAL} = \mathbb{D}^\mu \varphi_i^* \mathbb{D}_\mu \varphi_i + \bar{\psi}_i \gamma^\mu \mathbb{D}_\mu \psi_i + \left(\tfrac{1}{2} M_{ij} \psi_i \psi_j + \tfrac{1}{2} y^{ijk} \varphi_i \psi_j \psi_k + c.c. \right) + F_i^* F_i$$

$$-\mathcal{L}^{GAUGE} = +\tfrac{1}{4} F_a^{\mu\nu} F_{\mu\nu}^a + \bar{\lambda}^a \gamma^\mu \mathbb{D}_\mu \lambda_a + \tfrac{1}{2} D^a D^a$$

$$\mathcal{L} = \mathcal{L}^{CHIRAL} + \mathcal{L}^{GAUGE} - \sqrt{2}\, g \left[(\varphi_i^* T^a \psi_i) \lambda^a + c.c. \right] - \bullet\, g^2 (\varphi_i^* T^a \varphi_i)^2 + \mathcal{L}_{SOFT}$$

CENTRAL QUESTION:
HOW IS SUPERSYMMETRY BROKEN?

* MANY APPROACHES -- NONE COMPELLING -- NEED PHENOMENOLOGICAL INPUT

* CAN WRITE "MOST GENERAL", "SOFTLY-BROKEN" SUPERSYMMETRIC LAGRANGIAN -- ALL MODELS, MECHANISMS INCLUDED

* MOTIVATE BY CONSIDERING TOY MODEL, WESS-ZUMINO MODEL

$$W = \frac{m}{2}\varphi^*\varphi + g\varphi^3$$

$$\mathcal{L} = \partial_\mu \varphi^* \bar{\sigma}^\mu \partial_\mu \varphi + i\bar{\psi}\bar{\sigma}^\mu \partial_\mu \psi - F_\varphi^* F_\varphi + \left(\frac{1}{2} W_{\varphi\varphi} \bar{\psi}_R \psi_L + \text{H.C.}\right)$$

(2^{nd} DERIVATIVE)

- DEFINE $\varphi = (A+iB)/\sqrt{2}$, $F_\varphi = (F+iG)/\sqrt{2}$ (A, B, F, G REAL SCALARS)
- UNDER $\delta A = \bar{\epsilon}\gamma_5\psi$, $\delta B = -\bar{\epsilon}\psi$, $\delta\psi = F\epsilon - G\gamma_5\epsilon + \gamma^\mu\partial_\mu\gamma_5 A\epsilon + \gamma^\mu\partial_\mu B\epsilon$, $\delta F = -\bar{\epsilon}\gamma^\mu\partial_\mu\psi$, $\delta G = -\bar{\epsilon}\gamma_5\gamma^\mu\partial_\mu\psi$

  $\mathcal{L}$ CHANGES BY TOTAL DERIVATIVE, ACTION INVARIANT
- SUBSTITUTE

$$\mathcal{L} = \tfrac{1}{2}(\partial_\mu A)^2 + \tfrac{1}{2}(\partial_\mu B)^2 + \tfrac{i}{2}\bar{\psi}\gamma^\mu\partial_\mu\psi + \tfrac{1}{2}m\bar{\psi}\psi + \frac{g}{\sqrt{2}}A\bar{\psi}\psi - \frac{ig}{\sqrt{2}}B\bar{\psi}\gamma_5\psi$$

(m_ψ)

$$-\tfrac{1}{2}(F^2+G^2) - \frac{m}{2}(2AF - 2BG) - \frac{g}{2\sqrt{2}}\left[F(A^2-B^2) - 2GAB\right]$$

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  $\mathcal{L}$ CHANGES BY TOTAL DERIVATIVE, ACTION INVARIANT
- SUBSTITUTE

$$\mathcal{L} = \frac{1}{2}(\partial_\mu A)^2 + \frac{1}{2}(\partial_\mu B)^2 + \frac{i}{2}\bar{\psi}\gamma^\mu\partial_\mu\psi + \frac{1}{2}m\bar{\psi}\psi + \frac{g}{\sqrt{2}}A\bar{\psi}\psi - \frac{ig}{\sqrt{2}}B\bar{\psi}\gamma_5\psi$$

(m_ψ)

$$-\frac{1}{2}(F^2+G^2) - \frac{m}{2}(2AF - 2BG) - \frac{g}{2\sqrt{2}}\left[F(A^2-B^2) - 2GAB\right]$$

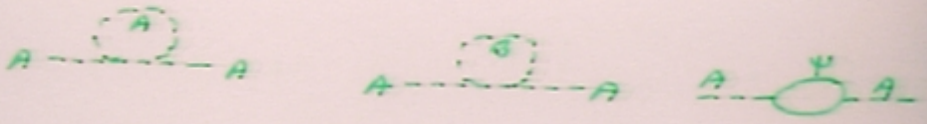
- EQNS OF MOTION FOR F, G

$$F = -mA - \frac{g}{2\sqrt{2}}(A^2 - B^2) \quad , \quad G = mB + \frac{g}{\sqrt{2}}AB$$

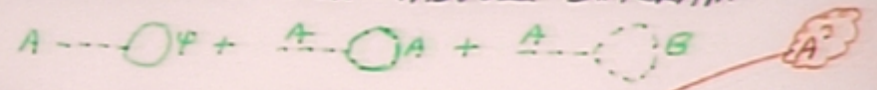
- SUBSTITUTE

$\rightarrow$ m^2A^2 (m_A), m^2B^2 (m_B), $\frac{mg}{2\sqrt{2}}A(A^2 - 3B^2)$ (m_g),

$$\frac{g^2}{4}(A^4 + 2A^2B^2 + B^4)$$



- ONE COUPLING g, ONE MASS m, FULL SUSY
- WITHOUT SUSY, COULD BE 4 MASSES (A, B, Ψ, m_g) AND 4 COUPLINGS, SO SUSY PREDICTS 6 RELATIONS ($A\bar{\Psi}\Psi$, $B\bar{\Psi}\Psi$, A^3, AB^2)
- WRITE EXPRESSION FOR TADPOLE DIAGRAM



$$\langle 0|\mathcal{L}|A\rangle = -\frac{g}{\sqrt{2}}\left\{-4m_\Psi \int \frac{d^4p}{p^2 - m_\Psi^2} + m_g \int \frac{d^4p}{p^2 - m_B^2} + 3m_g \int \frac{d^4p}{p^2 - m_A^2}\right\}$$

A^3

$\mathrm{Tr}(\gamma \cdot p + m_\Psi) = 4m_\Psi$

- HAVE QUADRATIC DIVERGENCE — CANCELS IN SUSY LIMIT
- QUAD DIV STILL CANCELS IF $m_A \neq m_B \neq m_g$!

$\rightarrow$ **SOFT BREAKING**

- DOES NOT CANCEL IF $m_\Psi \neq m_g$!

$\rightarrow$ **HARD BREAKING**

- TRUE TO ALL ORDERS OF PERTURBATION THEORY

* AFTER SOFT BREAKING 3 MASSES, 1 COUPLING
  $\longrightarrow$ 4 TESTS

- ONLY DIVERGENCES AFTER SOFT BREAKING ARE LOG ONES IN WAVE FUNCTION RENORMALIZATION
  -- NO MASS COUNTERTERMS

* PARAMETERS OF SUPERPOTENTIAL NOT RENORMALIZED!

$\Rightarrow$ IF LEAVE A TERM OUT OF SUPERPOTENTIAL IT IS NOT GENERATED BY RADIATIVE CORRECTIONS! (IN PERTURBATION THEORY)

NO F-TERMS OR M-TERM GENERATED

- COULD ALSO MODIFY $\mathcal{L}$ BY $\delta\mathcal{L} = a(\varphi^3 + \text{H.c.}) = \frac{a}{\sqrt{2}}(A^3 - 3AB^2)$
  $\longrightarrow$ SOFT TRILINEAR TERMS -- ONLY CUBIC SCALAR INTERACTIONS NOT INTRODUCING QUAD DIV -- CONTRIBUTIONS TO TADPOLE CANCEL -- TERMS $\sim A^3$ ALONE OR TO $\varphi^2\varphi^* + \text{H.c.}$ WOULD GIVE QUAD DIV

- $\delta\mathcal{L} \sim m_\lambda \bar{\lambda}\lambda$ FOR GAUGINO MASSES IS SOFT, BUT NOT MASS TERM FOR CHIRAL FERMIONS

- $\delta\mathcal{L} \sim m'(A^2 - B^2)$ SOFT, SPLITS A AND B

GENERAL STRUCTURE OF ~~SUSY~~

* CONSIDER SM, EWSB
  - CANNOT BREAK $SU(2) \times U(1)$ SYMMETRY FROM WITHIN SM
  - ADD NEW SECTOR, HIGGS SECTOR
  - ASSUME INTERACTIONS WITHIN AND WITH HIGGS SECTOR $\longrightarrow$ POTENTIAL WITH MINIMUM AWAY FROM ORIGIN
  - GENERATE MASS FOR W, Z, g, l BY WRITING INTERACTIONS THAT TRANSMIT THE BREAKING (vev) TO THE "VISIBLE" PARTICLES W, Z, g, l

    FERMIONS $g_f \bar{f}_L f_R h + H.C.$

    GAUGE BOSONS $(D^\mu h)(D_\mu h) \longrightarrow g^2 v^2 W^\mu W_\mu$

    NOTE: IN QUANTUM FIELD THEORY ONCE h FIELD IS PRESENT MUST INCLUDE ALL TERMS IN $\mathcal{L}$ THAT ARE GAUGE, LORENTZ INVARIANT
  - THE FUNDAMENTAL SYMMETRY BREAKING IS SPONTANEOUS (h GETS A vev), BUT THE EFFECTIVE LAGRANGIAN APPEARS TO HAVE EXPLICIT BREAKING

- SUSY A BROKEN SYMMETRY, OR WOULD HAVE SEEN $\tilde{e}$, ETC
- PHYSICS OF ~~SUSY~~ NOT YET UNDERSTOOD
  - -- LAST THING UNDERSTOOD IN SM TOO
  - -- WILL BE CENTRAL CHALLENGE OF FIELD ONCE SUPERPARTNERS DIRECTLY SEEN
- ~~SUSY~~ NOT IN "VISIBLE SECTOR" -- LIKE SM
- SO BREAKING IN "HIDDEN SECTOR"
  - -- MANY POSSIBILITIES
- THEN TRANSMITTED TO VISIBLE PARTICLES BY SOME COMMON INTERACTIONS -- GRAVITY + ...
- DON'T YET KNOW ORIGIN OF BREAKING OR TRANSMISSION
- NEVERTHELESS, CAN WRITE "MOST GENERAL" ~~SUSY~~ THEORY THAT PRESERVES HIERARCHY
  - -- NO DIMENSIONLESS ~~SUSY~~ COUPLINGS, ONLY DIMENSION 2,3 OPERATORS

$\Rightarrow \mathcal{L}_{SOFT}$

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- LEARN ABOUT BREAKING, TRANSMISSION FROM DATA -- DIFFERENT UNDERLYING MECHANISMS → DIFFERENT PATTERS OF SOFT PARAMETERS SO DIFFERENT SUPERPARTNER MASSES, DECAYS, PRODUCTION RATES, EFFECTS ON EDM, RARE DECAYS, DARK MATTER, BARYOGENESIS .....
- EFFECTS OF BREAKING, TRANSMISSION MIXED TOGETHER
- IN HIGGS CASE CAN COMMUNICATE BY GAUGE, YUKAWA COUPLINGS ALL AT SAME SCALE -- IN SUSY CASE NOT SO (BECAUSE OF SUPERTRACE THEOREM) -- MAYBE GOOD BECAUSE WANT UNDERLYING THEORY AT PLANCK/UNIFICATION SCALE SO CONNECTIONS GOOD

- RECALL HOW SOFT TERMS ARISE

  -- SOMEWHAT GENERAL -- FOCUS ON 4D ORIENTIFOLD MODELS

- KÄHLER POTENTIAL -- REAL -- DETERMINES KINETIC TERMS OF CHIRAL FIELDS -- DIMENSIONS $[\text{mass}]^2$

$$\mathcal{L}_{\text{KINETIC}} = \frac{\partial^2 K}{\partial\varphi_i \partial\varphi_i^*}\,\partial_\mu\varphi_i\,\partial^\mu\varphi_i^*$$

  -- FOR RENORMALIZABLE THEORY AT TREE LEVEL

$$K = \sum_i \varphi_i^*\varphi_i$$

  -- EXPECT NON-PERTURBATIVE CONTRIBUTIONS TOO

- SUPERPOTENTIAL W -- HOLOMORPHIC FUNCTION OF CHIRAL MULTIPLETS (NOT FUNCTION OF φ^*) -- DETERMINES YUKAWA COUPLINGS AND F-TERM PART OF SCALAR POTENTIAL V -- $[\text{mass}]^3$

$$V_F = e^{K/M_{pl}^2}\left\{\left[\overbrace{\frac{\partial W^*}{\partial\varphi_i^*}}^{\sim F_i^*} + W^*\frac{\partial K}{\partial\varphi_i^*}\right]\frac{\partial^2 K}{\partial\varphi_i\partial\varphi_j^*}\overbrace{\left[\frac{\partial W}{\partial\varphi_j} + W\frac{\partial K}{\partial\varphi_j}\right]}^{\sim F_j} - 3\frac{|W|^2}{M_{pl}^2}\right\}$$

- GAUGE KINETIC FUNCTION -- HOLOMORPHIC --

$$\mathcal{L}_{\text{GAUGE}} = \text{Re}\,f_{ab}\,F^a_{\mu\nu}F^{\mu\nu b} + \text{Im}\,f_{ab}\,F^a_{\mu\nu}\tilde{F}^{\mu\nu b}$$

AND CONTRIBUTES TO V_F -- DIMENSIONLESS, SYMMETRIC

- $\mathcal{L} = \mathcal{L}_{KE} + \mathcal{L}_W + \mathcal{L}_{SOFT}$

- NOW INTRODUCE COUPLING TO MATTER (MSSM) FIELDS

$$K_{OBS} = \tilde{K}_\alpha (T_i, T_i^*) |\phi_\alpha|^2$$

$$W_{OBS} = Y_{\alpha\beta\gamma}(T_i)\, \phi_\alpha \phi_\beta \phi_\gamma$$

- THEN

$$\tilde{A}_{\alpha\beta\gamma} = -\sum_{i=0}^{3} \left(\frac{\partial^2 K_0}{\partial T_i \partial T_i^*}\right)^{-1/2} \left[\sum_{\ell=\alpha,\beta,\gamma} \frac{\partial \ln \tilde{K}_\ell}{\partial T_i} - \frac{\partial}{\partial T_i} - \frac{\partial K_0}{\partial T_i}\right] \times$$

$$\times Y_{\alpha\beta\gamma} \sqrt{3}\, m_{3/2}\, X_i\, e^{-i\alpha_i}$$

$$m_\alpha^2 = m_{3/2}^2 \left[1 + (K_0^{ii})^{-1} \frac{1}{\tilde{K}_\alpha} \left(-\tilde{K}_\alpha^{ii} + \ldots\right) 3 X_i^2 + (K_0^{ii})^{-1/2} (K_0^{jj})^{-1/2} \ldots\ X_i X_j e^{i(\alpha_i - \alpha_j)} + \text{h.c.}\right]$$

SOFT SPARTICLE MASSES

$$M_\alpha = \frac{\sqrt{3}\, m_{3/2}}{2\, \mathrm{Re} f_\alpha} \left[\sum_{i=0}^{3} \frac{\partial f_\alpha}{\partial T_i} \left(\frac{\partial^2 K_0}{\partial T_i \partial T_i^*}\right)^{-\frac{1}{2}} X_i\, e^{-i\alpha_i}\right]$$

GAUGINO MASSES

- NOTE $\tilde{A}$ HAS TO BE RELABELED TO BE A MATRIX IN FLAVOR SPACE

- [redacted]

- KNOWLEDGE OF $\tilde{A}, m_\alpha^2, M_\alpha \Rightarrow K, W, f \Rightarrow$ STRUCTURE OF EFFECTIVE FIELD THEORY OF MASSLESS MODES $\Rightarrow$ CONSTRAINTS ON $\mathcal{U}$, SUSY

- NEED APPROPRIATELY FACTORIZED FLAVOR STRUCTURE FOR SOFT TRILINEAR COUPLINGS

$$W = Y_{\alpha\beta\gamma}\,\varphi_\alpha\varphi_\beta\varphi_\gamma$$

YUKAWAS

$$\rightarrow \mathcal{L}^{SUSY}_{SOFT} \sim A_{\alpha\beta\gamma}\,\varphi_\alpha\varphi_\beta\varphi_\gamma$$

$$A_{\alpha\beta\gamma} = \sum_{\substack{\text{DILATON,}\\ \text{MODULI}}} \Theta_i \left\{ \sum_{\alpha\beta\gamma} \frac{\partial \log K_{(-)}}{\partial T_i} - \frac{\partial K_0}{\partial T} - \frac{\partial}{\partial T_i} \right\} Y_{\alpha\beta\gamma}$$

CONSIDER FLAVOR TERMS, eg $Q_a U_b H_u$

$$\rightarrow \mathcal{L}^S_S \sim \tilde{Q}^a \tilde{A}_{ab} \tilde{U}^{*b} H_u$$

FLAVORS, 3×3 MATRIX

REARRANGEMENT OF $A_{\alpha\beta\gamma}$

PHENOMENOLOGICALLY, IT APPEARS NECESSARY TO HAVE

$$\tilde{A}_{ab} = a_{ac}\, Y_{cb}$$

$$\left[\text{Eg. } \tilde{A} = \begin{pmatrix} a_{11} m_R & a_{12} m_S & a_{13} m_b \\ \cdot\, m_R & \cdot\, m_S & \vdots \\ \cdot\, m_R & \cdot\, m_S & \cdot \end{pmatrix}\right]$$

WHICH IS NOT AUTOMATIC [ELEMENT OF a MUST BE ALL OF SAME ORDER, NOT SOME $\sim \tilde{m}/m_S$]

DEFINE MSSM

* SM PARTICLES + GAUGE GROUP $(SU(3) \times SU(2) \times U(1))$ + SUPERPARTNERS OF SM PARTICLES + 2 HIGGS DOUBLETS + CONSERVED R-PARITY

(+ RH- NEUTRINOS, SUPERPARTNERS ...)

** EXTENDED THEORIES WILL CONTAIN THE MSSM **