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GOAL: UNDERSTAND THE TYPES OF DM CANDIDATES IN THE MSSM

1. REVIEW OF SM
2. MSSM SPECTRUM + INTERACTIONS
   - DM CANDIDATES

} "need to know" only! LOTS OF HOLES, BUT ASTRO PEOPLE WON'T NOTICE

3. THE WELL TEMPERED NEUTRALINO
4. SINGLINO
5. GRAVITINO
6. ~~DARK DM IN THE MSSM~~ AXINO

} R PARITY, NATURAL SUSY, ...

Standard Model: refresher

MATTER (FERMIONS): $Q\ \bar{u}\ \bar{d}\ L\ \bar{e}$ × 3 FLAVORS EACH

$Q = \begin{pmatrix} u \\ d \end{pmatrix}$ $L = \begin{pmatrix} \nu \\ e \end{pmatrix}$

CONVENTION: DO EVERYTHING W/ 2 COMPONENT WEYL SPINORS SO WRITE ALL FERMIONS AS LH FERMIONS

u = LH UP QUARK
$\bar{u}$ = LH ANTI-UP QUARK

} combines into mass eigenstate

HIGGS: scalar boson

~~THE HIGGS~~

$$H = \begin{pmatrix} h + i\phi^0 \\ \phi_1 + i\phi_2 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \frac{v + h + i\phi^0}{\sqrt{2}} \end{pmatrix}$$

also: $i\sigma^2 H^* = \begin{pmatrix} h - i\phi^0 \\ \phi_1 - i\phi_2 \end{pmatrix} = \begin{pmatrix} \frac{v + h - i\phi^0}{\sqrt{2}} \\ \phi^- \end{pmatrix}$

the Higgs

couples to $\bar{d}, \bar{e}$

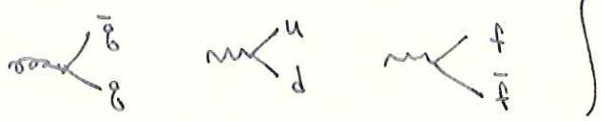
couples to $\bar{u}$ (essentially the same coupling)

arrows depend on convention.

GAUGE BOSONS : $SU(3)_c \times SU(2)_L \times U(1)_Y$

vector bosons

g W B



} also non Abelian vertices.

ELECTROWEAK SYMMETRY BREAKING: from [scalar] HIGGS VEV

$(W^1 \pm i W^2)$ $\phi^\pm$ $\Rightarrow$ MASSIVE $W^\pm$

$(gW^3 - g'B)$ ϕ^0 $\Rightarrow$ MASSIVE Z

$(g'W^3 + gB)$ $\Rightarrow$ γ

WE USUALLY TALK ABOUT THESE STATES.

BUT THESE ARE THE BASIC BUILDING BLOCKS & HAVE SUPERPARTNERS W/ WELL DEFINED EW QUANTUM #s.

WILL HAVE A DIFFERENT MIXING PATTERN!

~~QUICK & DIRTY GUIDE TO INTERACTIONS~~

[SUSY] many good reasons to like it, few reasons to believe it exists

@ its HEART: EXTENSION OF SPACETIME SYMMETRY } theorist's SUSY ☺
severely constrains QFT

PRACTICALLY: ① DOUBLES PARTICLE SPECTRUM (DM ??) } experimentalist SUSY ☹
② BROKEN SUSY → MANY NEW PARAMETERS

IDEA:

FERMIONS → SUCKS! CHARGED except $\tilde{\nu}$ ... too big couplings.

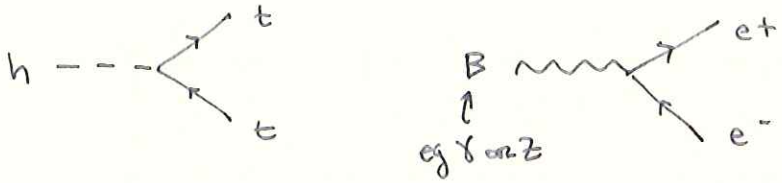
HIGGSINO

GAUGINO

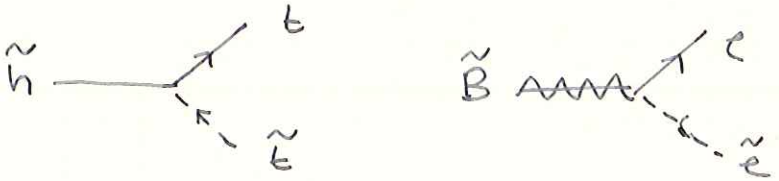
} DM CANDIDATES (except charged guys.)

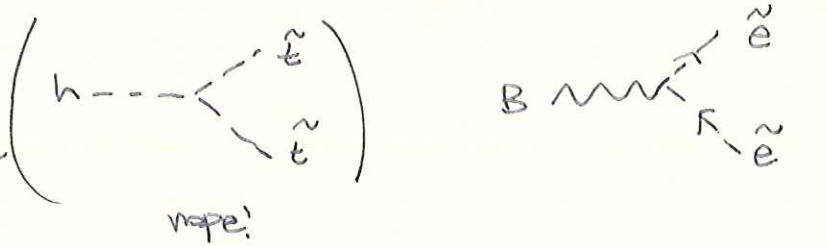
Bastard SUSY Recipe for interactions

1. TAKE SM INTERACTION



2. CONVERT <u>TWO</u> LEGS TO SUPERPARTNERS (required to conserve ang. momentum)





[THIS MISSES A FEW INTERACTIONS
eg. NON-ABELIAN VERTICES (D terms)
↳ usually don't care about these]

3. INCLUDE NEW ~~susy~~'ing INTERACTIONS

→ trilinear scalar couplings "SOFT MASSES"

the parts of the MSSM [that you care about]

SM FERMIONS $q\bar{u}d\bar{L}\bar{e}$ → "SFERMIONS" SCALAR PARTNERS ↓ QCD/QED

except $\tilde{\nu}$, but that typically has problems w/ $\not{z}$ interactions to SM

{ THESE TEND TO BE CHARGED PARTICLES THAT ARE EXCLUDED BY THE LHC TO $\mathcal{O}(700\ \text{GeV})$

also: they don't do much for us theoretically (... 'cept NATURALNESS...)

⇒ IGNORE THESE.

SM HIGGS: H_d

$i\sigma^2 H^*$ ⇓ H_u — SUSY REQUIRES 2HDM! ⇒ $\tilde{H}_u$, $\tilde{H}_d$ FERMIONS

separate DOF

$h, \phi^0, \phi^\pm$; $H, A, H^\pm$

ϕ: EATEN

H: HEAVY HIGGS; A: PSEUDO SCALAR; $H^\pm$: CHARGED SCALAR

not our problem.

$\tilde{h}$ $\tilde{H}$ ↓

ELECTRIC. 2 NEUTRAL HIGGSINO ↑ $(h+i\phi^0)$ $(H+iA)$

2 CHARGED HIGGSINOS ↑ $\phi^\pm, H^\pm$ ↑ $\tilde{H}_1^\pm$ $\tilde{H}_2^\pm$

FERMIONS

SM GAUGE: $g' \approx .35$ B; $g \approx .65$ W; g g

$\tilde{B}$	BINO	→ $\tilde{W}^\pm, \tilde{W}^3$
$\tilde{W}$	WINO	
$\tilde{g}$	GLUINO	(COLORED)

NEUTRAL-inos (DM CANDIDATES): $\tilde{h}, \tilde{H}, \tilde{B}, \tilde{W}^3$

MIX INTO $\tilde{N}_{1,2,3,4}$ = LIGHTEST CAN BE DM

(charginos also mix: $\tilde{W}^+, \tilde{W}^-, \tilde{H}_u^+, \tilde{H}_d^-$) = $\tilde{C}_{1,2}^\pm$

MSSM NEUTRALINOS — study pure gauge states

stability of LIGHTEST NEUTRALINO IS ASSUMED (R-parity)

~~BINO $\tilde{B}$ has small-ish coupling~~

MASSES come from (mostly) soft susy'ing terms
↑ DON'T REINTRODUCE HIERARCHY

↑ you don't care about this
PRACTICALLY: FREE-ISH PARAMETERS
(eg GUT CONSTRAINS MASS RATIOS, ...)

IF DM =

BINO $\tilde{B}$: smallish coupling $g' \approx .35$

INTERACTION W/ SM IS SMALL → $\langle \sigma v \rangle$ SMALL
↑ annihilation

SO: DOESN'T ANNIHILATE FAST ENOUGH
LEFT WITH TOO MUCH DM.

WINO $\tilde{W}$ & HIGGSINO $\tilde{H}$

$g \sim .65$ ↑ large-ish couplings ↑ via W, Yukawas

↳ PURE $\tilde{W}$ or $\tilde{H}$ DM HAS ANNIHILATION RATE TOO BIG

ANNIHILATES TOO FAST, LEFT W/ TOO LITTLE DM

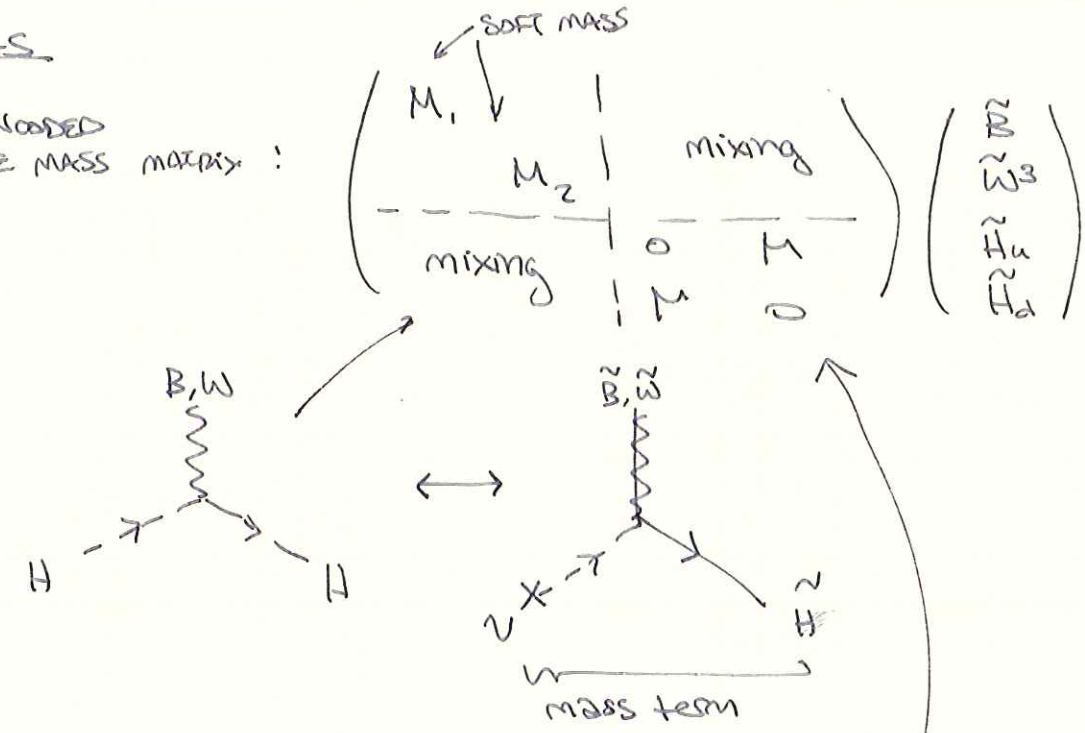
Well tempered Neutralino (Goldilocks)

to get correct relic abundance, need a careful admixture of $\tilde{B}$ & $\tilde{W}/\tilde{H}$

↑ ASSUMING THERMAL FREEZE OUT

Remarks

- MIXING ENCODED IN THE MASS MATRIX :



(μ) is a funny term in the MSSM

1. it is the only dimensionful SUSY'IC parameter in MSSM
   (~~SUSY~~ terms are ~~mass~~ dimensionful, w/ characteristic scale given by ~~SUSY~~ing scale)
   → what is the natural value? M_P?

2. $\mu \tilde{H}_u \tilde{H}_d$ is the only allowed HIGGSINO MASS TERM BY GAUGE INVARIANCE
   ↳ no ~~SUSY~~ CONTRIBUTION (due to ~~SUSY~~)
   (cf $M_{1,2}$ which can be anything)

3. μ PLAYS CRITICAL ROLE IN EWSB, REALLY SHOULD BE @ WEAK SCALE (tuning preference)

ASSUMING UNIFICATION

$$M_1 = \frac{5}{3}\tan^2\theta_W M_2 \approx \frac{1}{2} M_2 \qquad @\ M_Z$$

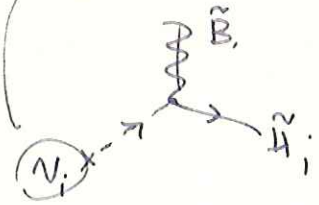
LIMITING CASES

- $\mu \gg M_{1,2} \gg M_Z$: $\tilde{N}_1$ is MOSTLY GAUGINO in fact, mostly BINO w/ $\tilde{W}$ nearby.
- $\mu \ll M_{1,2}$: $\tilde{N}_1$ is MOSTLY HIGGSINO
- $\mu \approx M_1 \sim M_2$: LOTS of GAUGINO/HIGGSINO MIXING
- $\mu, M_2 \gg M_Z$: $\tilde{N}_2$ & $\tilde{C}_s$ HAVE SIMILAR MASS.

"TYPICAL Neutralino" PARAMETER SPACE

M_1, M_2, μ → $\tilde{B}$, $\tilde{W}$, $\tilde{H}$ MASSES

$\tan\beta = \frac{v_u}{v_d}$ → ratio of vevs ; we know $v^2 = v_u^2 + v_d^2$



OF COURSE, ALL SORTS OF CAVEATS.

↳ but this is what you should know "caveats" are the responsibility of the perverse model builder to explain

Theory Aside (opinion)

- I personally don't put much stock in taking MSSM parameters too seriously
  ↑ $O(100)$ in total!
- constrained (CMSSM, mSUGRA, PMSSM) models don't mean anything to me
- what is useful to appreciate is the gauge bits & how things fit together.

  eg. ingredients for charging & neutralino come from same places

  ↳ doing something to M_2 affects $\tilde{W}^\pm$ as well as $\tilde{W}^3$.

- "susy blobs" → mean nothing to me.

No susy @ colliders

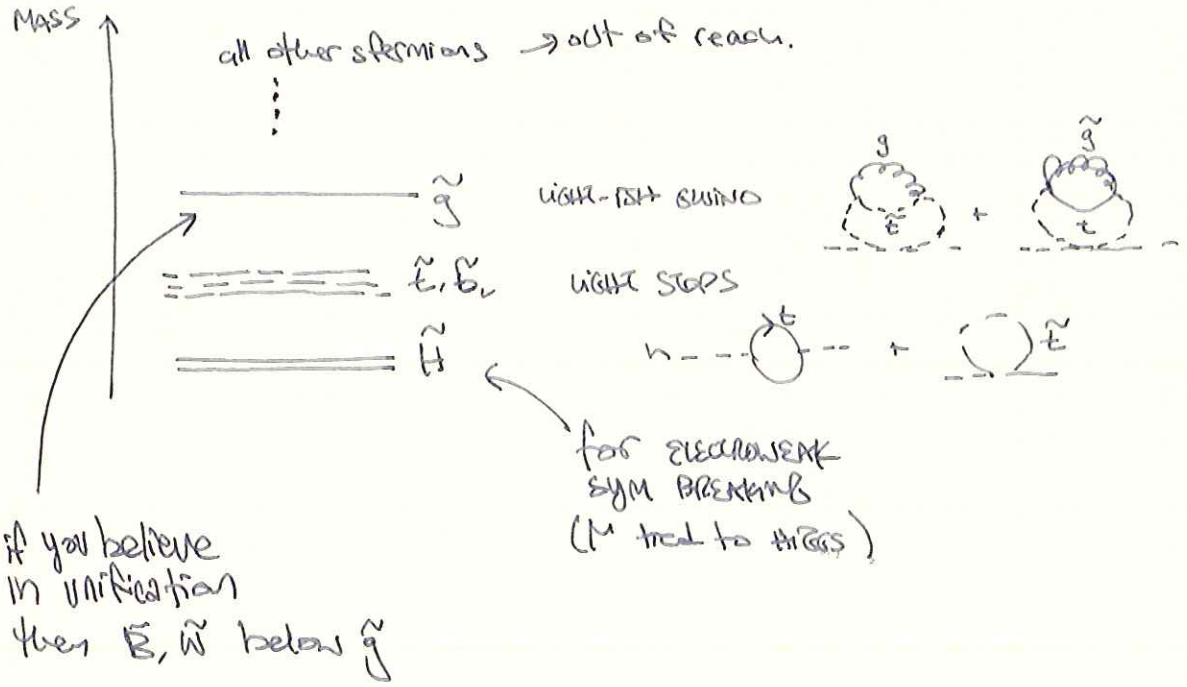
implications on DM?
two roads come to mind (or could be other)

(I) Natural susy → ☺

(II) RPV susy → ☹

I. Natural SUSY

no "easy to find" superpartners @ LHC.
WHAT IS THE MINIMUM ~~cost~~ SUPER SPECTRUM THAT WE NEED FOR NATURALNESS?



then: DM candidates are all nearby.

II. RPV SUSY: SUSY doesn't give MET signal b/c no R-parity.

IMMEDIATE SACRIFICE: AUTOMATIC DM STABILITY
↳ would have to try to cook something up.

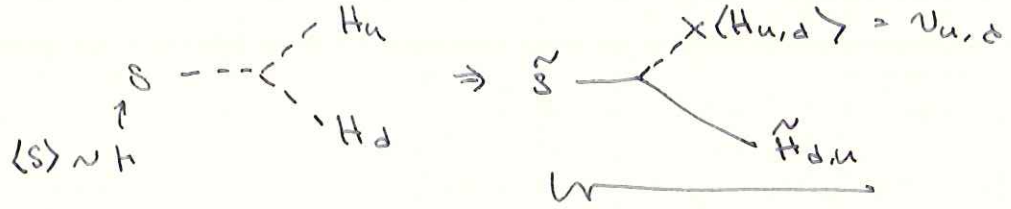
No DM. ∴

other-inos

- singlino : NMSSM
  (next-to-minimal)

  WHY: ↳ PARAMETER IS WEIRD (↳ actually often problematic) INSTEAD OF DIMENSIONFUL PARAMETER, MAKES IT IS THE VEV OF A NEW FIELD, SINGLET.

  the fermionic PARTNER IS A SINGLINO



  mixing given by H_u vs H_d vev!

  can give extra knob to turn, but not much.

- GRAVITINO

  RECALL: $W^\pm$ eats $\phi^\pm$ (↳ Goldstone) → massive $W^\pm$

  $\tilde{G}$ eats ψ (↳ goldstino of susy) → massive gravitino

  GOLDSTONE EQUIV. THM: $Q \; E \gg m_{Goldstone}$, THE 'MASSIVE' ~~GOLDSTONE~~ FIELD IS WELL DESCRIBED BY JUST GOLDSTONE COMP.

  $\tilde{G}$ IS SPIN 3/2, BUT GOLDSTINO IS 1/2

  MASS DEPENDS ON SUSY SCALE.
  LOW SCALE → LOW $\tilde{G}$ MASS → PLAUSIBLE LSP

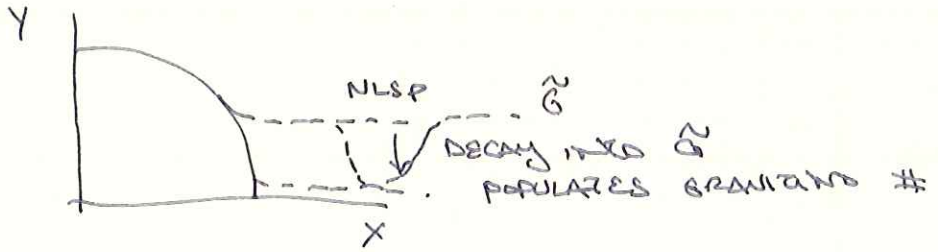
  can be eV — TeV DEPENDING ON HOW SUSY IS BROKEN

Gravitino

beyond the MSSM
BUT REALLY SHOULD BE THERE

LIGHT GRAVITINO
eg GAUGE MEDIATION

- can be true LSP
- MSSM LSP is NLSP
  - ↳ can be charged!
  - → can still set relic abundance via SUPERWIMP / ~~FREEZE~~ FIMP mechanism
- typically small couplings $\sim 1/M_{Pl}$



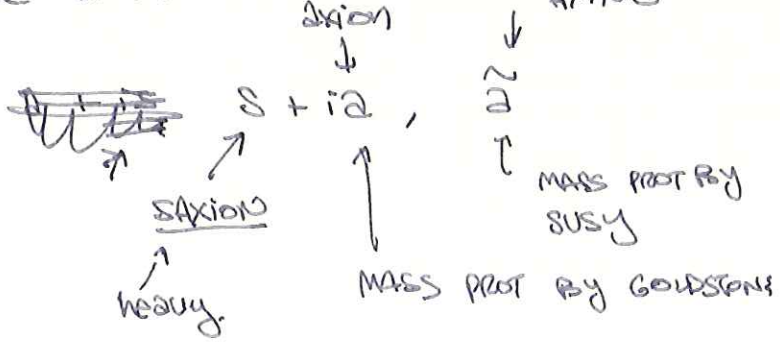
AXINO

axion → motivated by strong CP
GOLDSTONE BOSON OF SPONTANEOUSLY BROKEN (but anomalous) U(1) sym.

OR: ANY OTHER SIMILAR FIELD
(string thy is lousy w/ them

axion itself can be DM.

SUPERSYMMETRIZE:



↳ automatically a SUSY sector that is ~~weakly~~ barely coupled to MSSM!

CASE STUDY: LIGHT (Higgsino) DM in the MSSM

MAIN COLLIDER BOUNDS:

LEP: $M_{\tilde{e}} > 100$ GeV, $M_{\tilde{\chi}} > 85$ GeV
↑ e^+e^- MACHINE

+ other "intensity" machines

SUPPOSE WE WANT $M_{\tilde{N}_1} \lesssim 30$ GeV (Higgsino) } recall: main params are $M_1, M_2, \mu, \tan\beta$

- HAVE TO GIVE UP ON GAUGINO MASS UNIFICATION
  ↳ would req ~~MM~~ $M_{\tilde{N}} > 46$ GeV

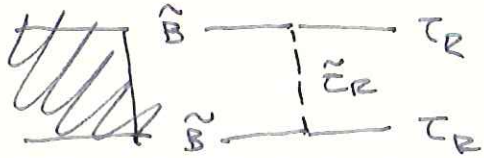
- LEP BOUND ON $M_{\tilde{e}} \Rightarrow M_2, \mu \gtrsim 90$ GeV
  ↳ puts bounds on $M_{\tilde{N}}$ BECAUSE THIS IS CONNECTED TO HIGGSINO, $\tilde{W}^3$ CONTENT

$\Rightarrow \tilde{N}_1$ MUST BE MOSTLY $\tilde{B}$ → M_1 small (~30 GeV)

→ needs a way to annihilate more efficiently

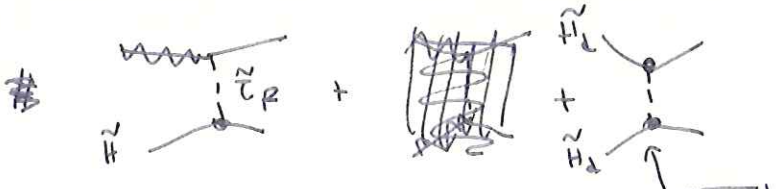
↓ TRICKS: coannihilation, resonance, ...

turns out: look @ t CHANNEL SFERM. MED.



why R? Hypercat. why $\tilde{\tau}$? other sfermions constr. by LEP, LHC

IS THIS ENOUGH TO MAKE ANNIHILATION SUFFICIENTLY EFFICIENT? TYPICALLY STILL NEED A BOOST FROM HIGGSINOS.



recall

μ can't be too big

sneg version of Yukawa

coupling depends on how much τ talks to H_d → ~~gives~~ constraint on $\tan\beta = \frac{v_u}{v_d}$