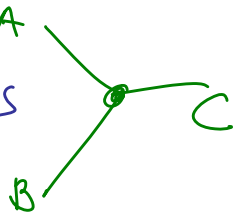
(Split) SUSY

+

The Higgs

Whatever the Ultimate Theory

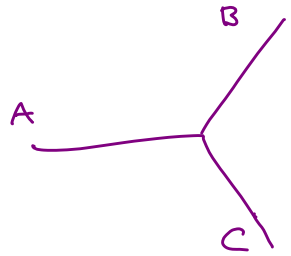
Relativity ↓ Quantum Mechanics

At "Long" distances, particles interacting as 

with spins $0, \frac{1}{2}, 1, \frac{3}{2}, 2$. ← unique, "gravity"

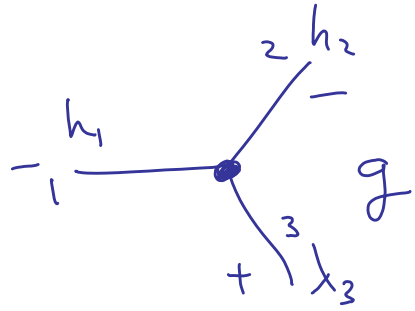
Massless Particles

$$p_{\alpha\dot\alpha} = \begin{pmatrix} p_0+p_3 & p_1-ip_2 \\ p_1+ip_2 & p_0-p_3 \end{pmatrix} = \lambda_\alpha \tilde\lambda_{\dot\alpha}$$



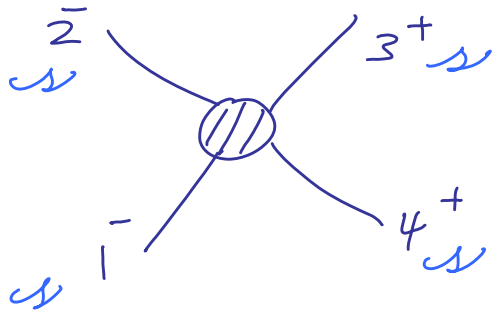
Either $\lambda_A \propto \lambda_B \propto \lambda_C$

$\tilde\lambda_A \propto \tilde\lambda_B \propto \tilde\lambda_C$

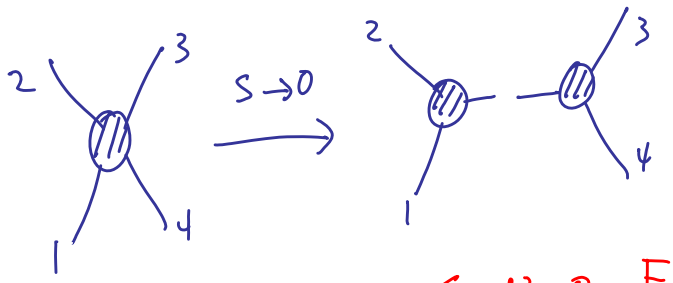


$$g\,\langle 12\rangle^{h_1+h_2-h_3}\langle 23\rangle^{h_2+h_3-h_1}\langle 31\rangle^{h_3+h_1-h_2}$$

COMPLETELY DETERMINED BY POINCARÉ



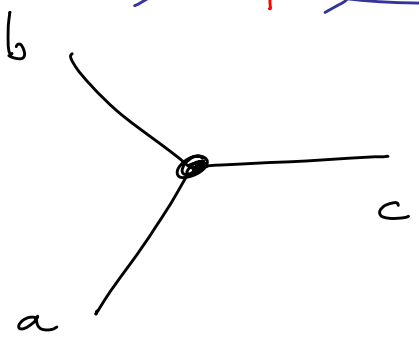
$$\left(\langle 12\rangle [34]\right)^{2s} F(s,t,u)$$



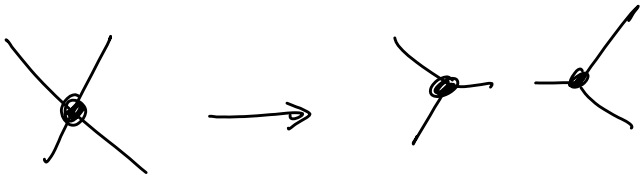
$$\Rightarrow F(s,t,u) \to \begin{cases} \frac{1}{s} \cdot \frac{g^2}{t^s u^s} \\ \frac{1}{t} \quad \frac{g^2}{u^s s^s} \\ \frac{1}{u} \quad \frac{g^2}{s^s t^s} \end{cases}$$

$$\Rightarrow \text{Only} \begin{cases} s=0, \; F = g^2\left(\frac{1}{s}+\frac{1}{t}+\frac{1}{u}\right) \\ s=2 \quad F = \frac{g^2}{stu} \end{cases} !$$

Spin 1



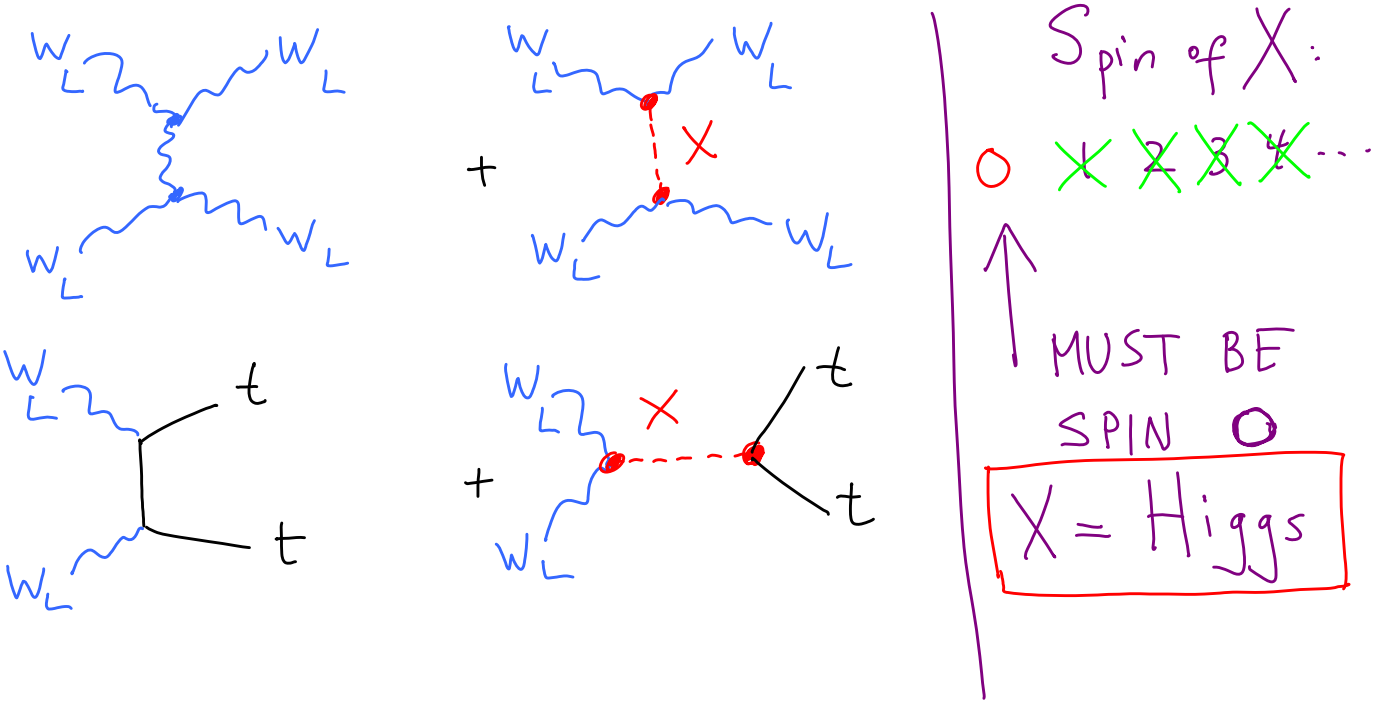
$(g\ f^{abc})$



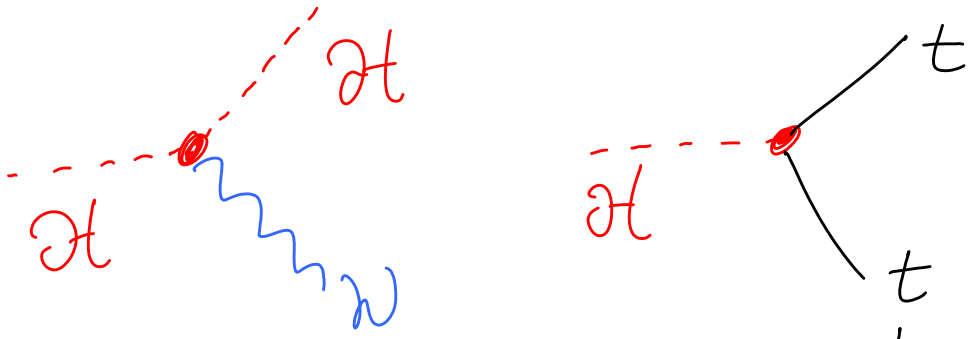
$\Rightarrow f^{abc}$ satisfies Jacobi

Gauge "Symmetry" Does Not Exist

(Sometimes) convenient redundancy to describe physics in manifestly local way.


W_L
W_L
W_L
W_L
+
X
W_L
W_L
W_L
W_L
t
t
W_L
+
X
W_L
t
t
Spin of X:
0
1
2
3
4
...
MUST BE
SPIN 0
X = Higgs

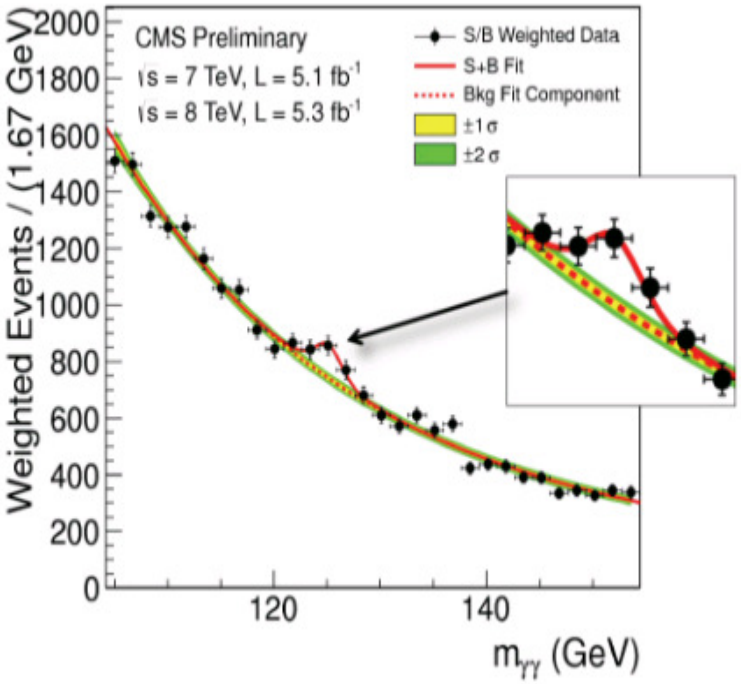
At very high energies, H and W_L, Z_L are all united into $\mathcal{H}$.



Usual Allowed Interactions

This was a Bold Proposal:

No Fundamental Spin 0 had ever been seen.


CMS Preliminary
√s = 7 TeV, L = 5.1 fb-1
√s = 8 TeV, L = 5.3 fb-1
S/B Weighted Data
S+B Fit
Bkg Fit Component
±1σ
±2σ
Weighted Events / (1.67 GeV)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
120
140
mγγ (GeV)

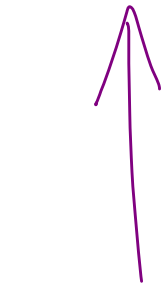
TRIUMPH FOR EXPERIMENT

TRIUMPH FOR THEORY

PHYSICS WORKS

Belief in Principles Paid Off

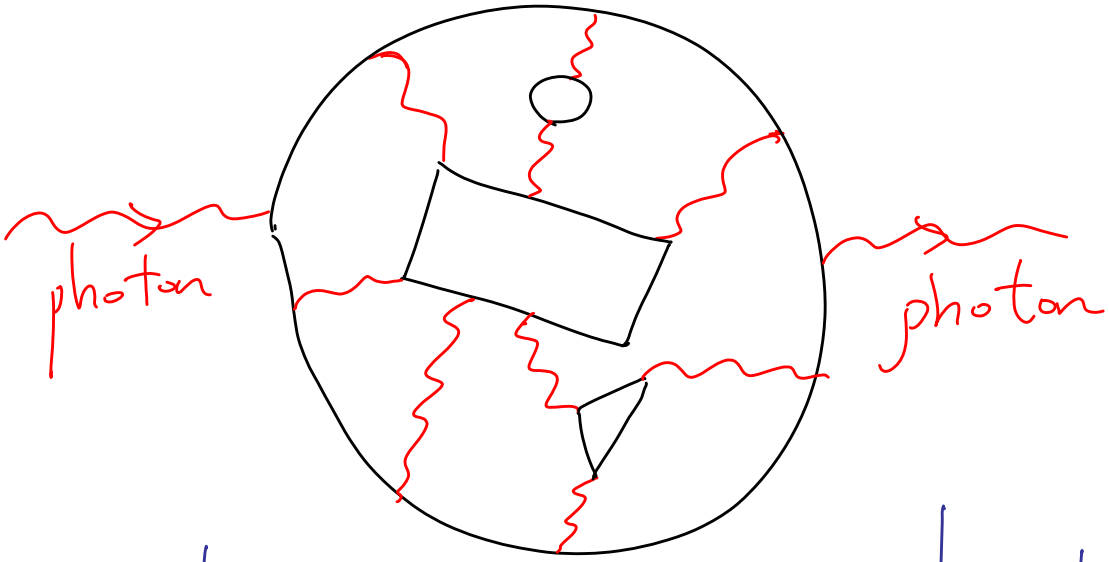
$$0, \frac{1}{2}, 1, \frac{3}{2}, 2$$



Higgs is first "really new" particle we've seen

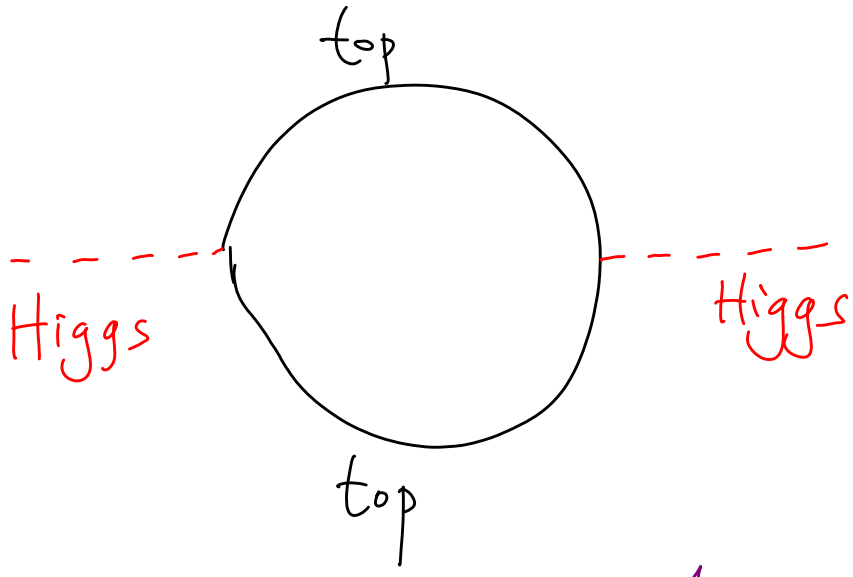
Why is there a Macroscopic Universe?

* Why are particles (nearly) massless relative to Planckian Scales?



But photon MUST stay massless, because

massless helicities → $2 \neq 3$ ← # massive spins

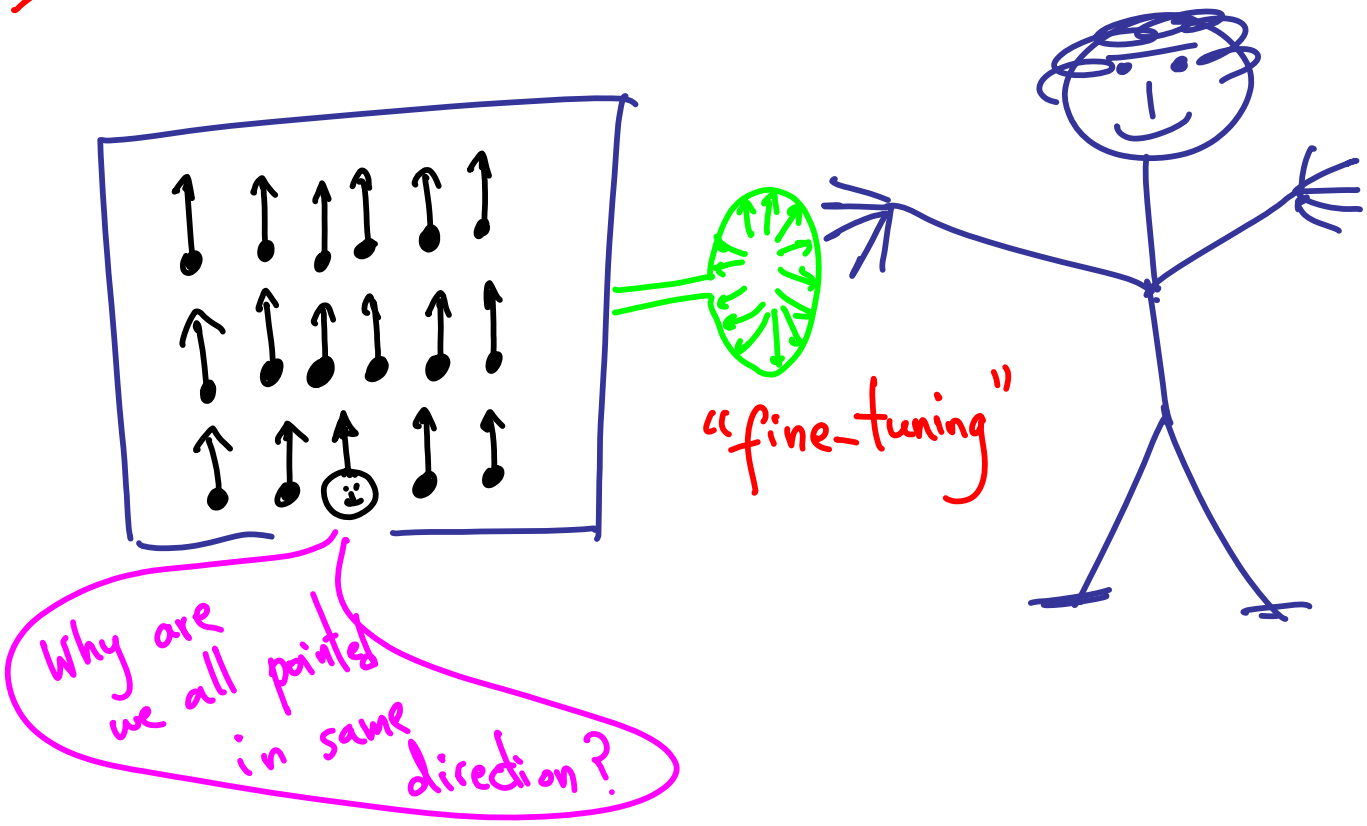


massless spin 0 $\frac{1}{\quad} = \frac{1}{\quad}$ massive spin 0

NO DIFFERENCE

WHY ISN'T HIGGS ENORMOUSLY MASSIVE? PLANCKIAN?

Never seen before in "state of nature"

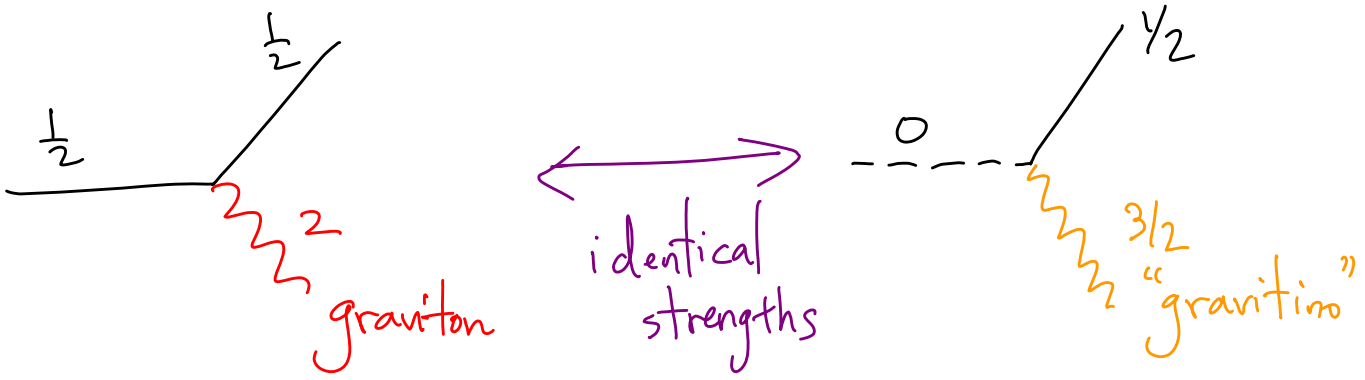


An Obious Gap!

$$\left\{0, \frac{1}{2}, 1, \frac{3}{2}, 2\right\}$$

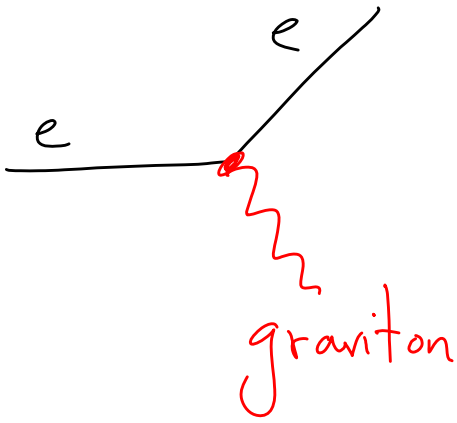
↑ POSSIBLE, VERY SPECIAL!

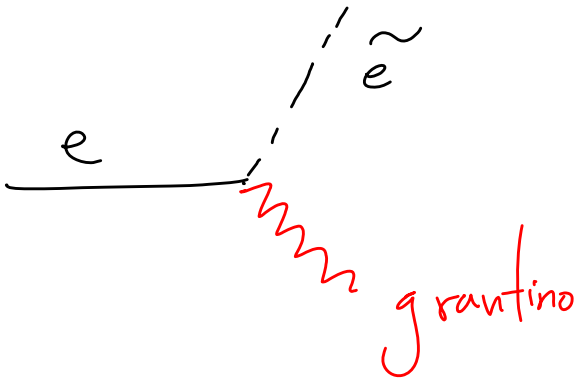
SUPERSYMMETRY



All spin $\frac{1}{2}$ particles have spin 0 partners

All spin 1 particles have spin 1/2 partners





Conserved Quantity

Energy + Momentum

Conserved Quantity

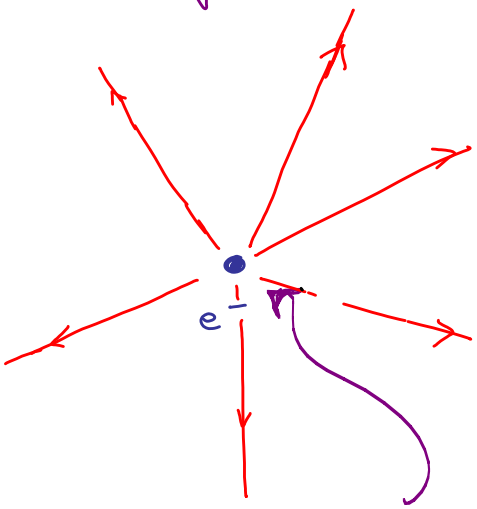
$Q_{1,2,3,4}$

$Q_1 Q_2 = -Q_2 Q_1$

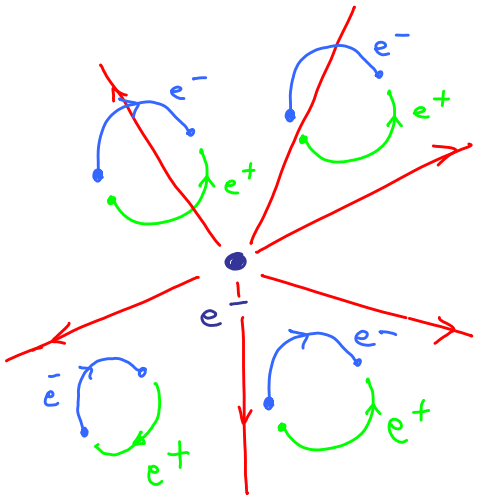
Supersymmetry

- ★ Last Consistent Possibility
- ★ Dramatic extension of Spacetime

Infinite Energy In Electric Field



Q.M.
Rel.

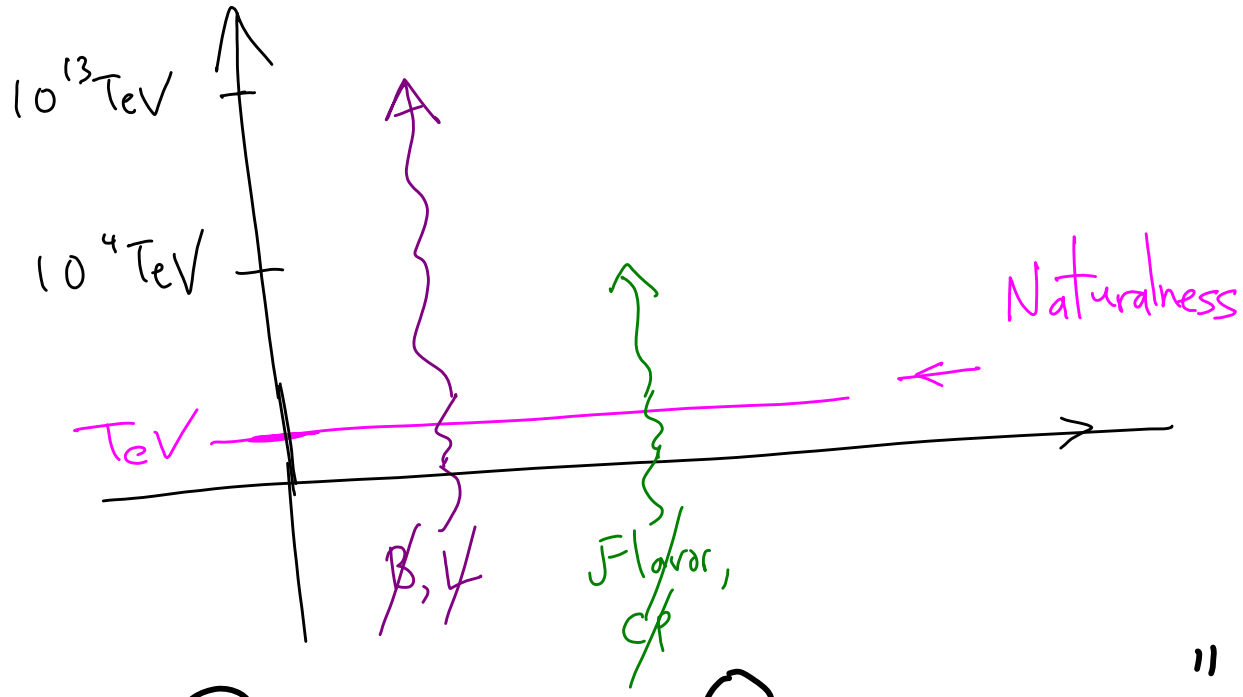


$$\frac{e^2}{4\pi a_{cl}} \sim m_e c^2 \Rightarrow a_{cl} \sim \frac{e^2}{4\pi m_e c^2}$$

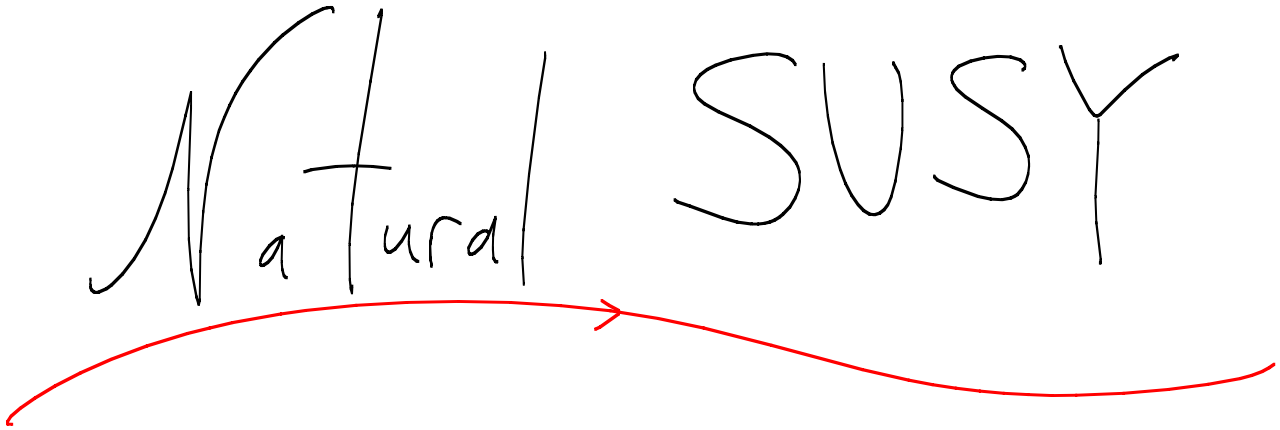
$$a_{compton} \sim \frac{\hbar}{m_e c}$$

$$\sim \left[\frac{e^2}{4\pi\hbar c}\right]^{-1} \times a_{cl} \; !$$

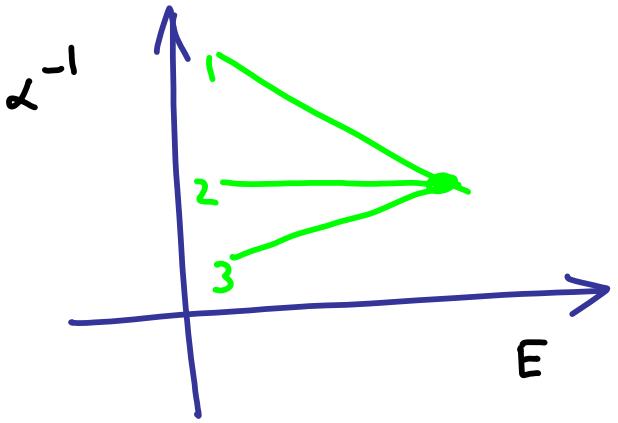
Tension Driving BSM Physics For 30 yrs



"Not Problems – Opportunities"


Natural SUSY

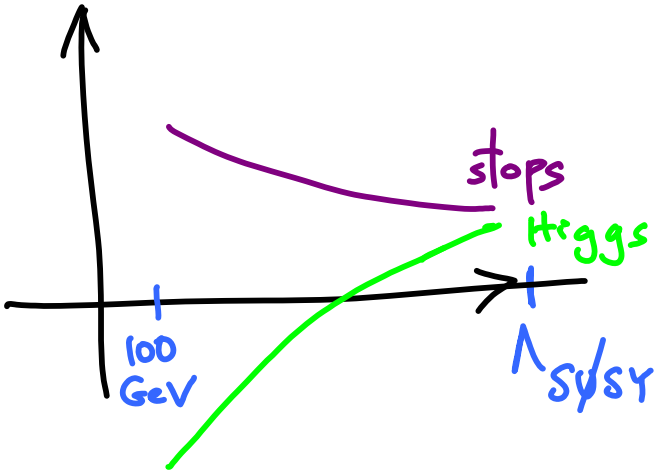
SUSY circa 1990

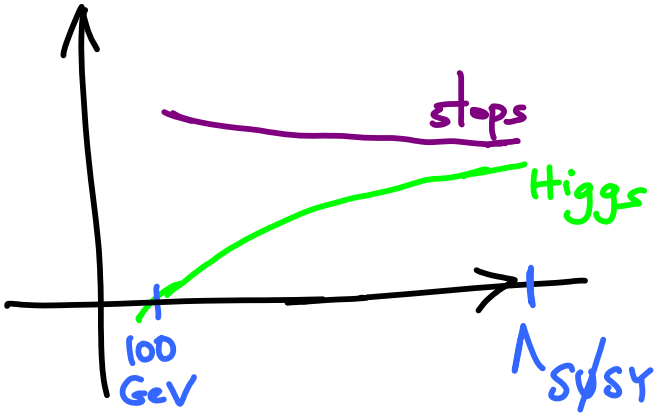


+ D.M.

SPECTACULAR

Why No SUSY @ LEP?





—— $Z, h, \tilde{t}, \tilde{g}$...

—— $\tilde{\ell}$, EWKinos

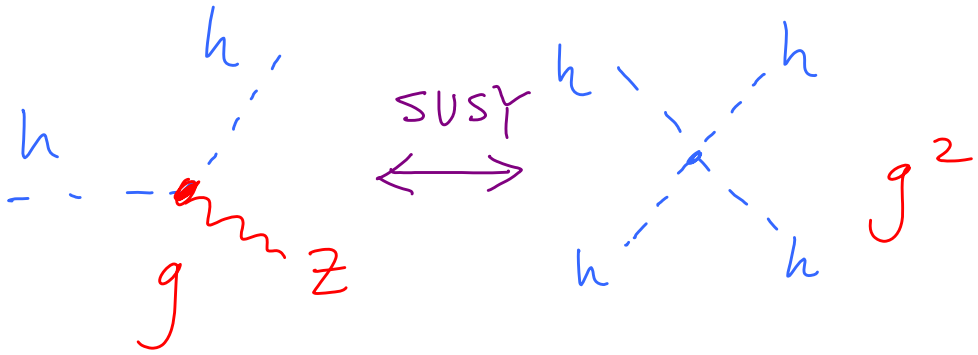
"Natural" Spectrum

?

↑

—— Z, h

"Nature-al" spectrum


h
h
g
Z
SUSY
h
h
h
h
g²

• In the MSSM, a milder cousin of this problem is

$$m_h \lesssim m_Z + m_h^{\text{syst, stops}}$$

threshold + log-enhanced

With $m_h \sim 125$, this alone is a few % tuning.

Non-dec F terms

$\delta\lambda\,|h|^4$

Non-dec. D terms

$W \supset \lambda S H_u H_d \to |\lambda|^2 |H_u H_d|^2$

$M_h^2 \sim (M_h^2)_{MSSM} + \frac{4|\lambda|^2 v^2}{t_\beta^2}$

$\downarrow$

$(115\ \text{GeV})^2$

$\downarrow$

Boost limited by UV

$\downarrow$

$(125\ \text{GeV})^2$

MSSM + $U(1)_X$

$M_h^2 \sim (M_h^2)_{MSSM} + \left(\frac{g_X^2}{g^2}\right) M_Z^2$

$\downarrow$

$(115\ \text{GeV})^2$

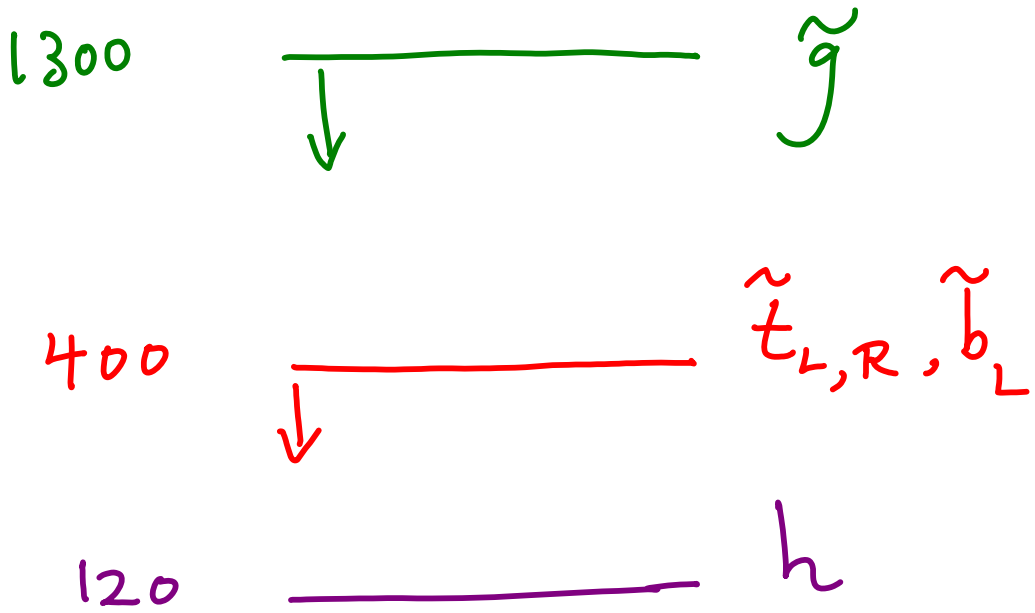
$\downarrow$

Boost limited by UV

$\downarrow$

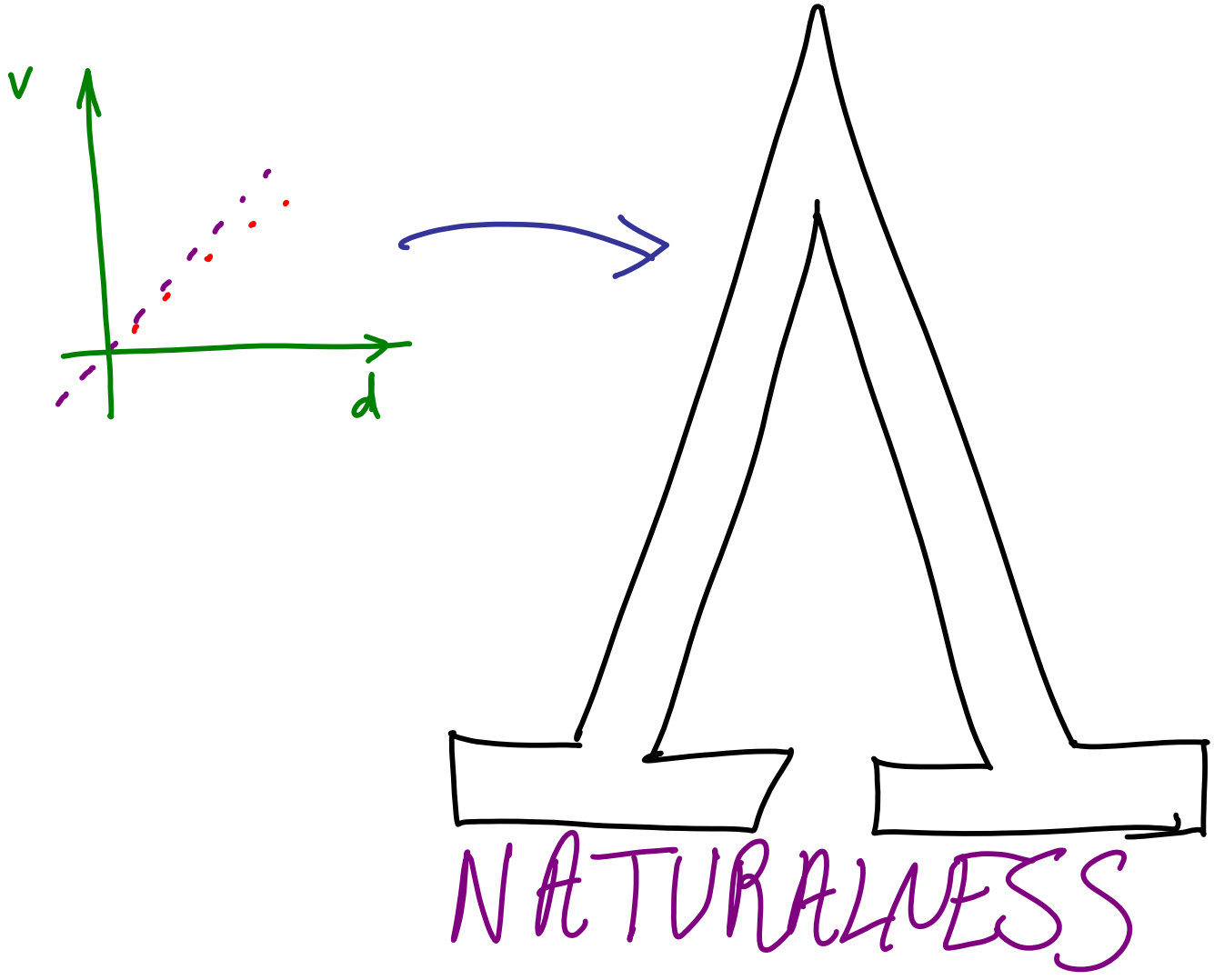
$(125\ \text{GeV})^2$

Compulsory Natural SUSY



Unavoidable tunings: $\left(\frac{400}{m_{\tilde{t}}}\right)^2, \left(\frac{4 m_{\tilde{t}}}{M_{\tilde{g}}}\right)^2$

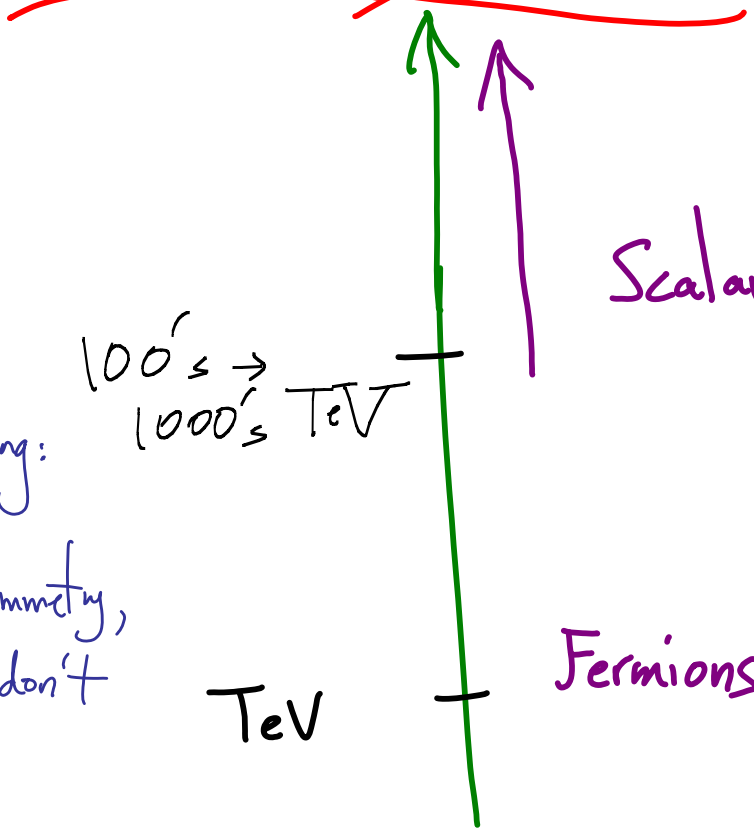
Letting Go of Naturalness


v
d
NATURALNESS

Plausible anthropic tuning for weak scale: existence of atoms other than hydrogen

$(m_n - m_p) \gtrsim$ nuclear binding energies

Split Susy



Scalars

100's → 1000's TeV

Reason for splitting: fermions carry R symmetry, scalars don't

TeV

Fermions

Unification ✓

Dark Matter ✓

NO Flavor, CP, moduli, ... problems

Indeed, a 1-loop splitting between gauginos + scalars was ubiquitous in simplest models of SUSY.

Modern guise: H.S. SUSY: Anomaly med.

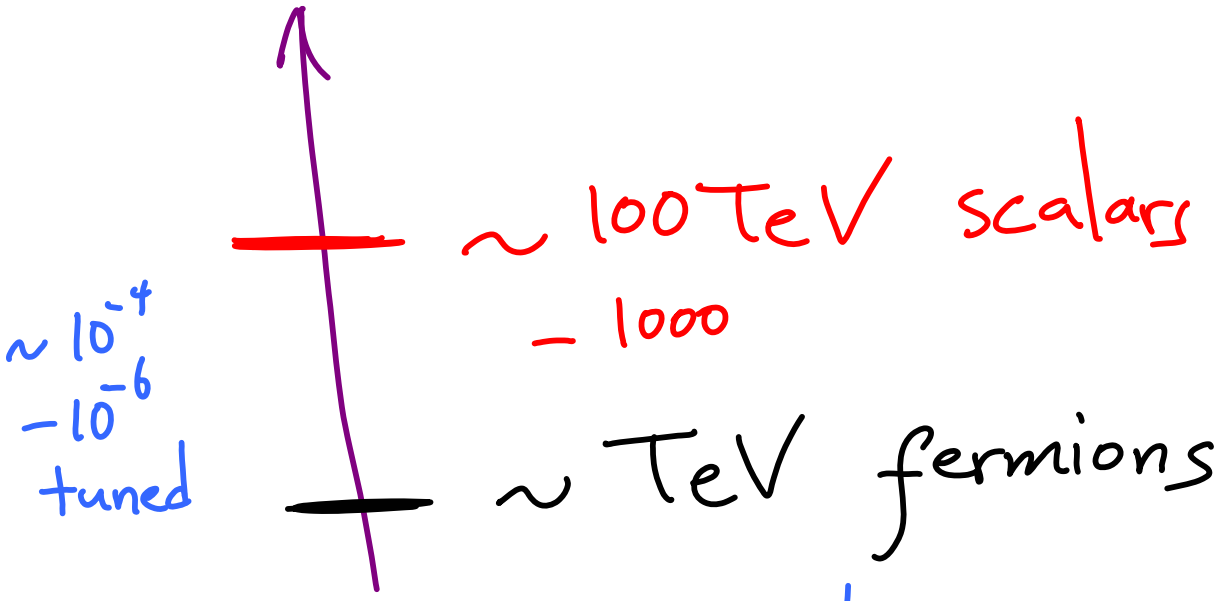
$m_\lambda \sim \frac{\alpha}{4\pi} m_{3/2}$

$m_S \sim m_{3/2}$

Unless you work!

["Not problem-opportunity"]

THIS SPECTRUM



IS WHAT SUSY MODELS "WANT TO DO". LET THEM!

Simplest Split SUSY

Also $\mu \sim m_S \sim m_{3/2}$

So only gluino, wino, bino light

An Idea With a Long History

Early 80's: 1-loop split spectrum common in SUSY models

1999 : Giudice-Luty-Murayama-Rattazzi anom-med

Split Spectrum thought of as embarrasment

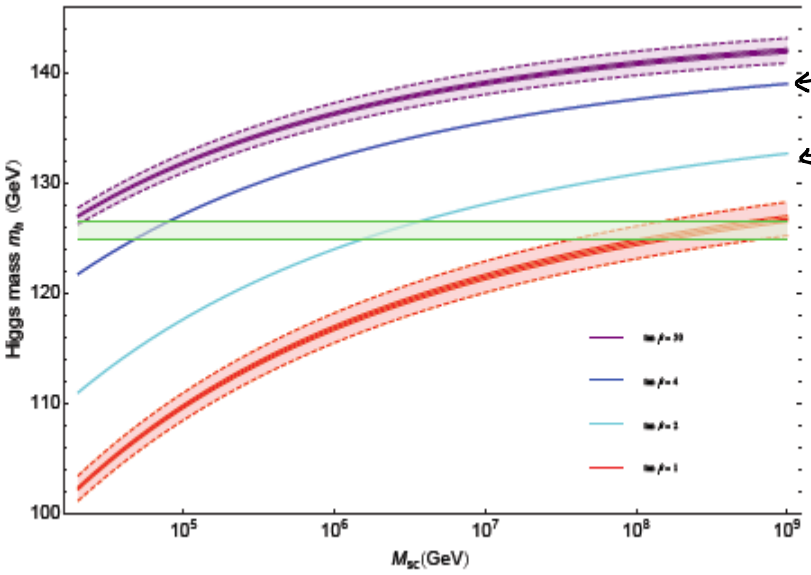
2003 : J. Wells "PeV-scale SUSY"

2004 : NAH + Savas, Giudice+Romanino "Split SUSY"

2006 : NAH, Delgado, Giudice "Simplest Split SUSY"

⋮ Many Others

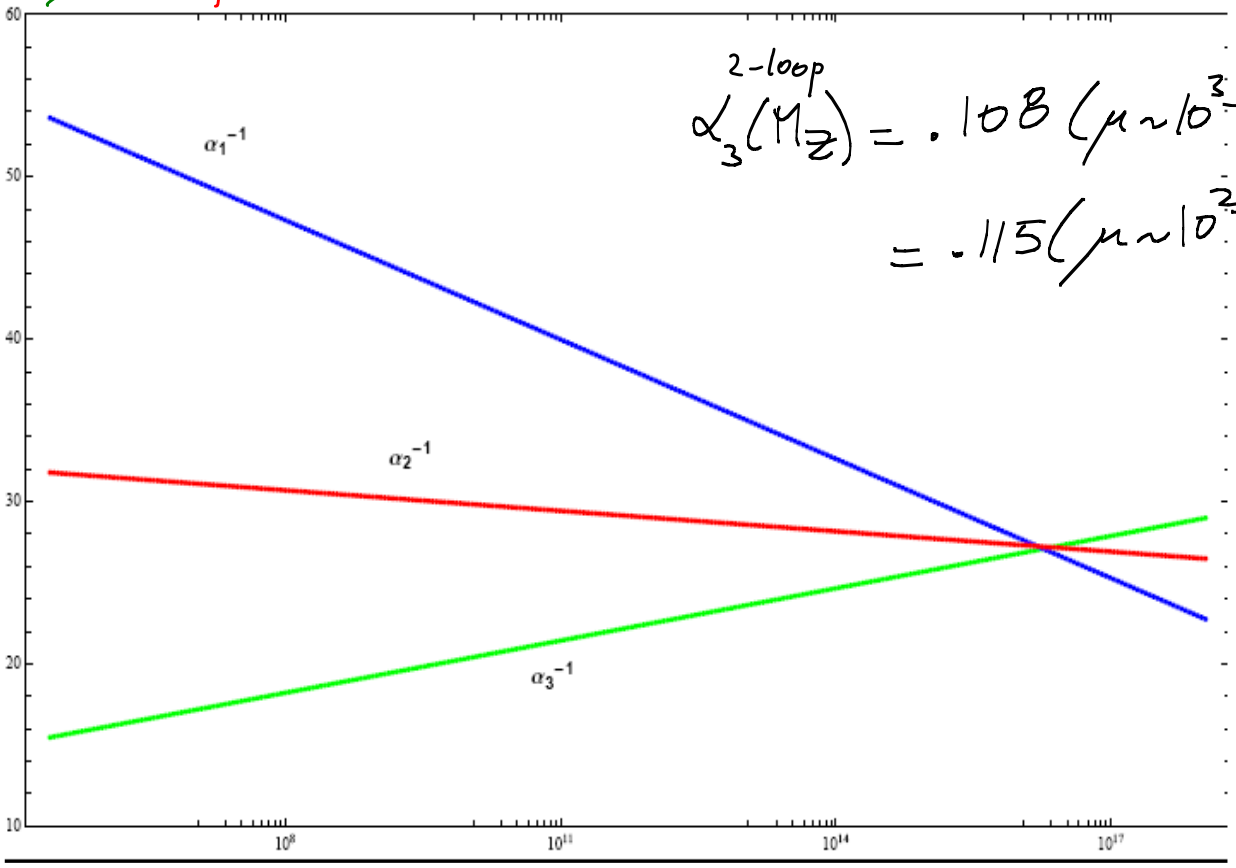
Higgs Mass



$\leftarrow t_\beta = 4$

$\leftarrow t_\beta = 2$

Unification a Bit Better than Natural SUSY



2-loop

$\alpha_3(M_Z) = .108 \; (\mu \sim 10^3 \text{ TeV})$

$= .115 \; (\mu \sim 10^2 \text{ TeV})$

The Obvious Worry

"WIMP miracle" relic could mean

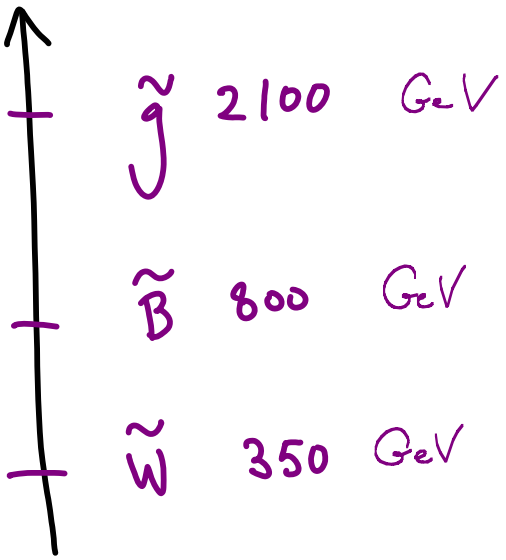
$m_{\text{Higgsino}} \sim 1\,\text{TeV}$ or $m_{\text{Wino}} \sim 3\,\text{TeV}$.

Won't ever see even fermionic superpartners.

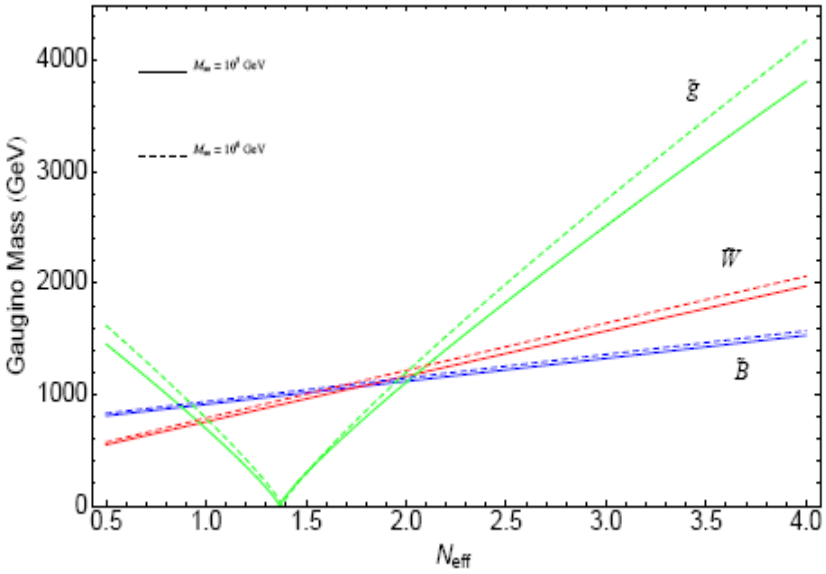
(A) Could still be "well-tempered" relic, lighter OK.

(B) Relic could constitute part of DM [rest, say, axions] → lower bottom of spectrum.

(C) Moduli near ~ 100 TeV decay late, dilute initial abundance [+ largely solve axion overclosure problem!], repopulate DM still favors light $\lesssim$ TeV LSP.


$\tilde{g}$ 2100 GeV
$\tilde{B}$ 800 GeV
$\tilde{W}$ 350 GeV

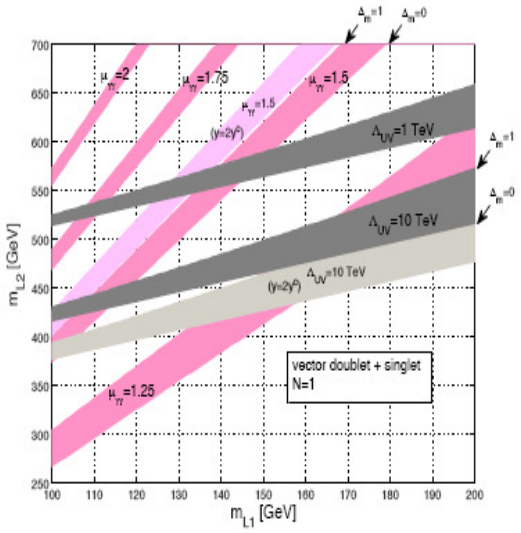
WITH EXTRA VECTOR-LIKE STATES

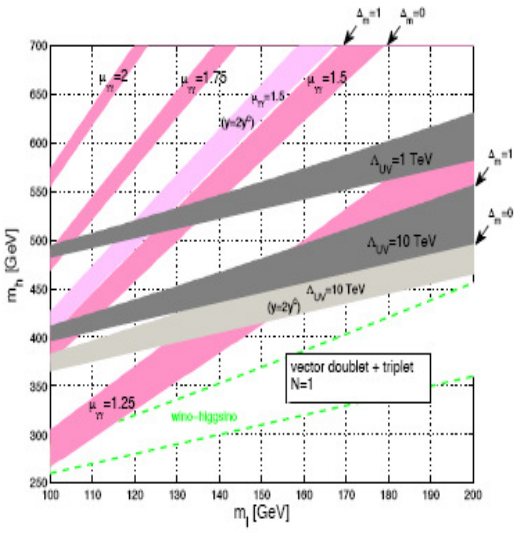


L·H·C Signals, Smoking Guns

Any observed deviation in higgs properties KILLS ALL SUCH THEORIES

Vacuum Stability Disaster





Probing Higher Scale

With $\tilde{g}, \tilde{W}, \tilde{b}$ as only new particles - their decays can only proceed through higher-dimension operators!

Inside detector $\longrightarrow$ scale $\gtrsim 10^3$ TeV

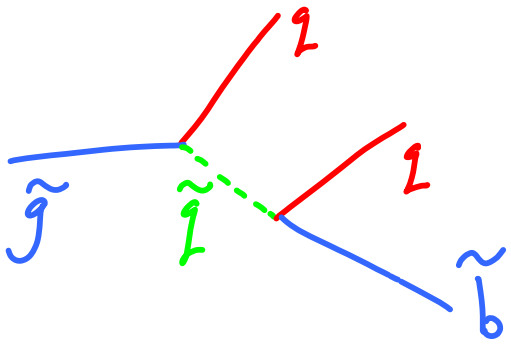
If seen: experimental future for HEP on ~50 yr timescale

[WE CAN BUILD 100 TeV COLLIDERS]

Gluino Decays

$$\frac{\bar{q}\,\tilde{g}\,q\,\tilde{b}}{M^2}$$

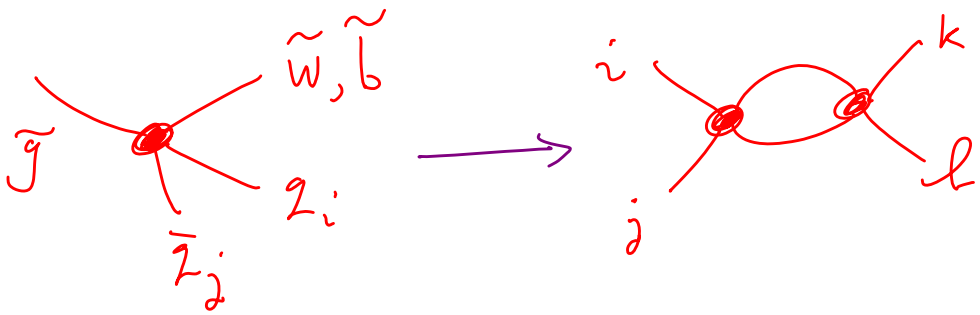
$$\frac{\bar{q}\,\tilde{g}\,q\,\tilde{W}}{M^2}$$



$\sim$ mm displ. for

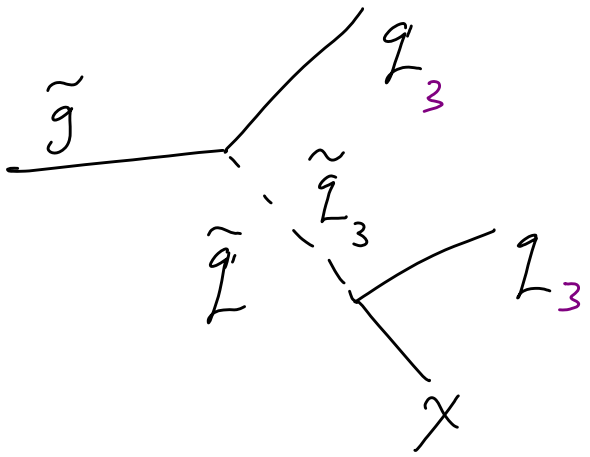
$m_{\tilde{q}} \gtrsim (300\,\text{TeV}) \left(\frac{\Delta m}{\text{TeV}}\right)^{5/4}$

Flavor-violation in gluino decays



Unless Operator is suppressed by

$\sim 100 - 1000$ TeV



Here, EW breaking contributions to squark masses are tiny, $\equiv$ 3 param $m^2_{Q_3, U_3, D_3}$

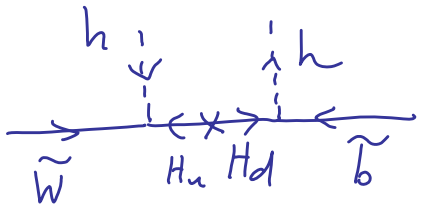
$\tilde{g} \to t\bar{t}\ \tilde{b}$
$b\bar{b}\ W$
$\to t b \tilde{W}^-$

} 5 final states
4 ratios ←

1 relation ↑

Wino + Bino Decays

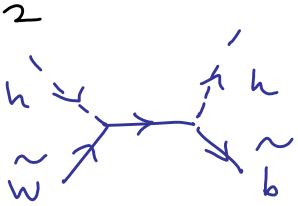
$$\frac{h^\dagger \tilde{W} h \tilde{b}}{M}$$



$\tilde{b} \to \tilde{W}^0 h$ only

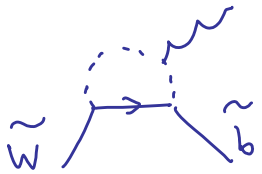
$\tilde{b} \to \tilde{W}^0 Z$ ✗

$$\frac{h^\dagger D^\mu h \, \tilde{W} \bar{\sigma}_\mu \tilde{b}}{M^2}$$



$\tilde{b} \to \tilde{W}^0 Z$

$$\frac{\alpha}{4\pi} \frac{\tilde{W} \sigma^{\mu\nu} \tilde{b} F_{\mu\nu}}{M}$$



$\tilde{b} \to \tilde{W}^0 Z$

$\to \tilde{W}^0 \gamma$

$$Br\left[\tilde{W}^0 \longrightarrow \tilde{b}Z\right] \sim \left(\frac{m_Z}{M}\right)^2 \text{ or } \left(\frac{\alpha}{4\pi}\right)^2$$

↓

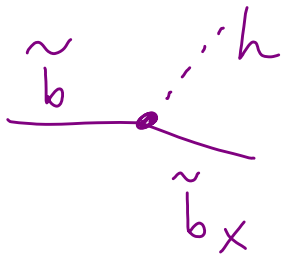
Probes heavy Higgsino, directly tuning

$\gtrsim 10$ TeV

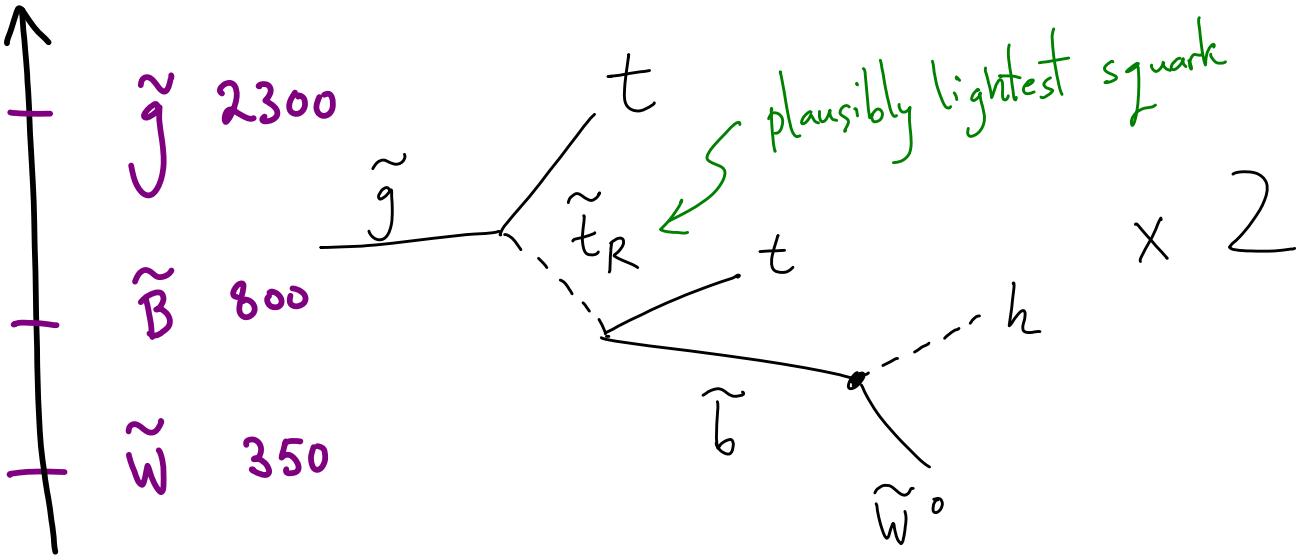
Decaying To Other Sectors

$$SM \times U(1)_X, \quad \epsilon F_X F_Y$$

$$\epsilon \frac{\tilde{b}\,\tilde{b}_X\, h^\dagger h}{M}, \quad \epsilon \frac{h^\dagger \tilde{W} h\, \tilde{b}_X}{M}$$

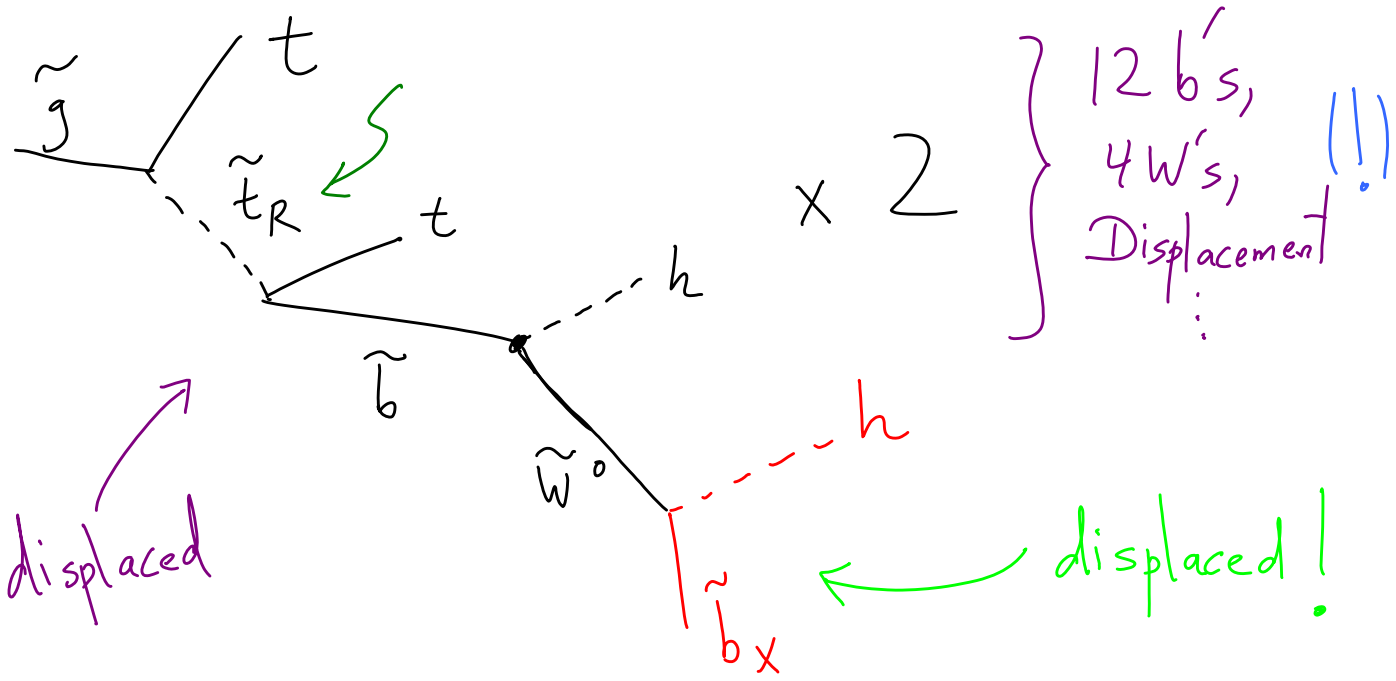


Displaced!



$\Rightarrow$ 8 b's, 4 W's [+ perhaps displacement]

in every event!


$\tilde{g}$
t
$\tilde{t}_R$
t
h
$\tilde{b}$
$\tilde{w}^0$
h
$\tilde{b}_X$
displaced
displaced!
x 2
12 b's,
4 W's,
Displacement
(!!)

The Stakes Are Very High

$M_H \sim 125$ GeV