BEYOND THE STANDARD MODEL @COLLIDERS

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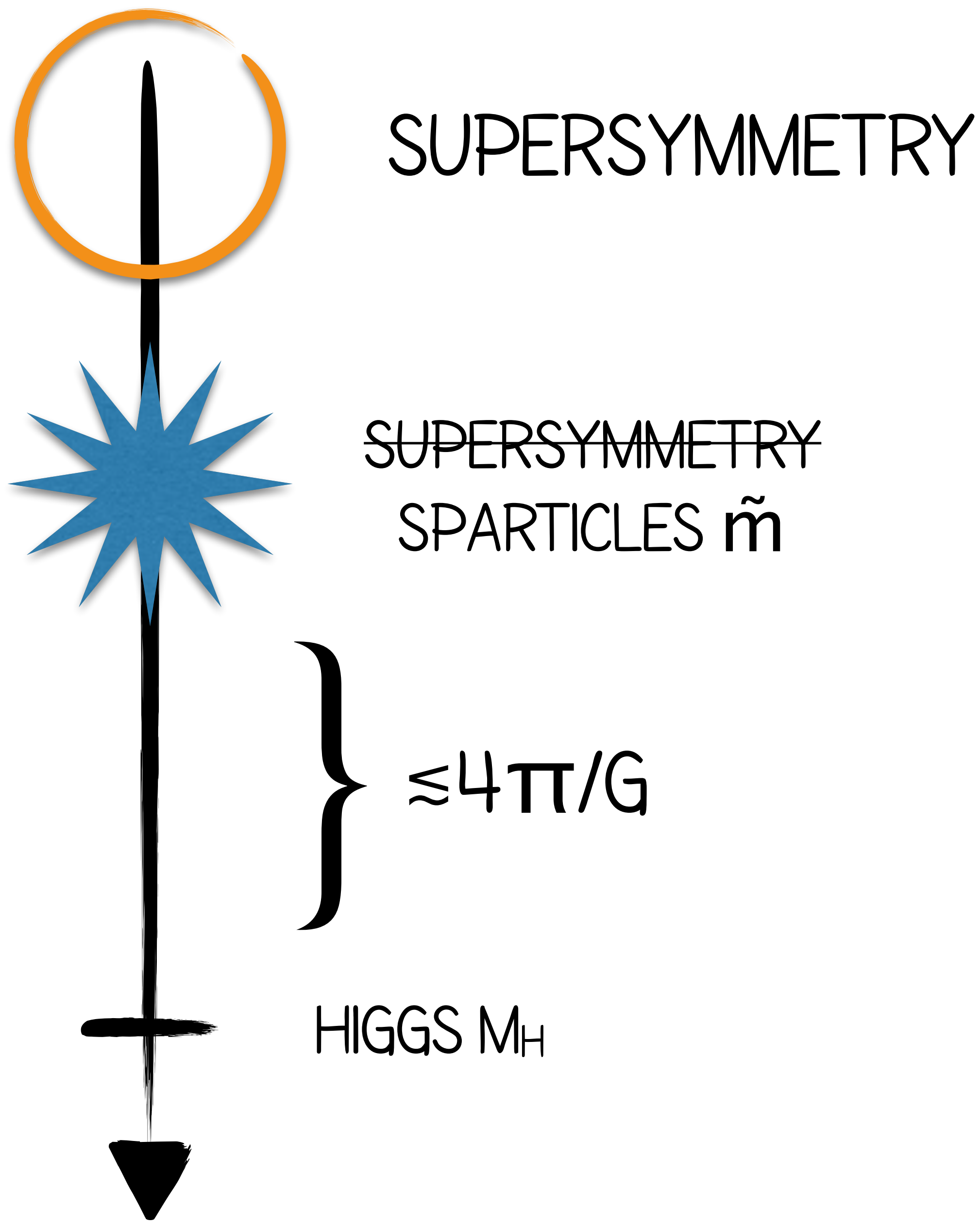
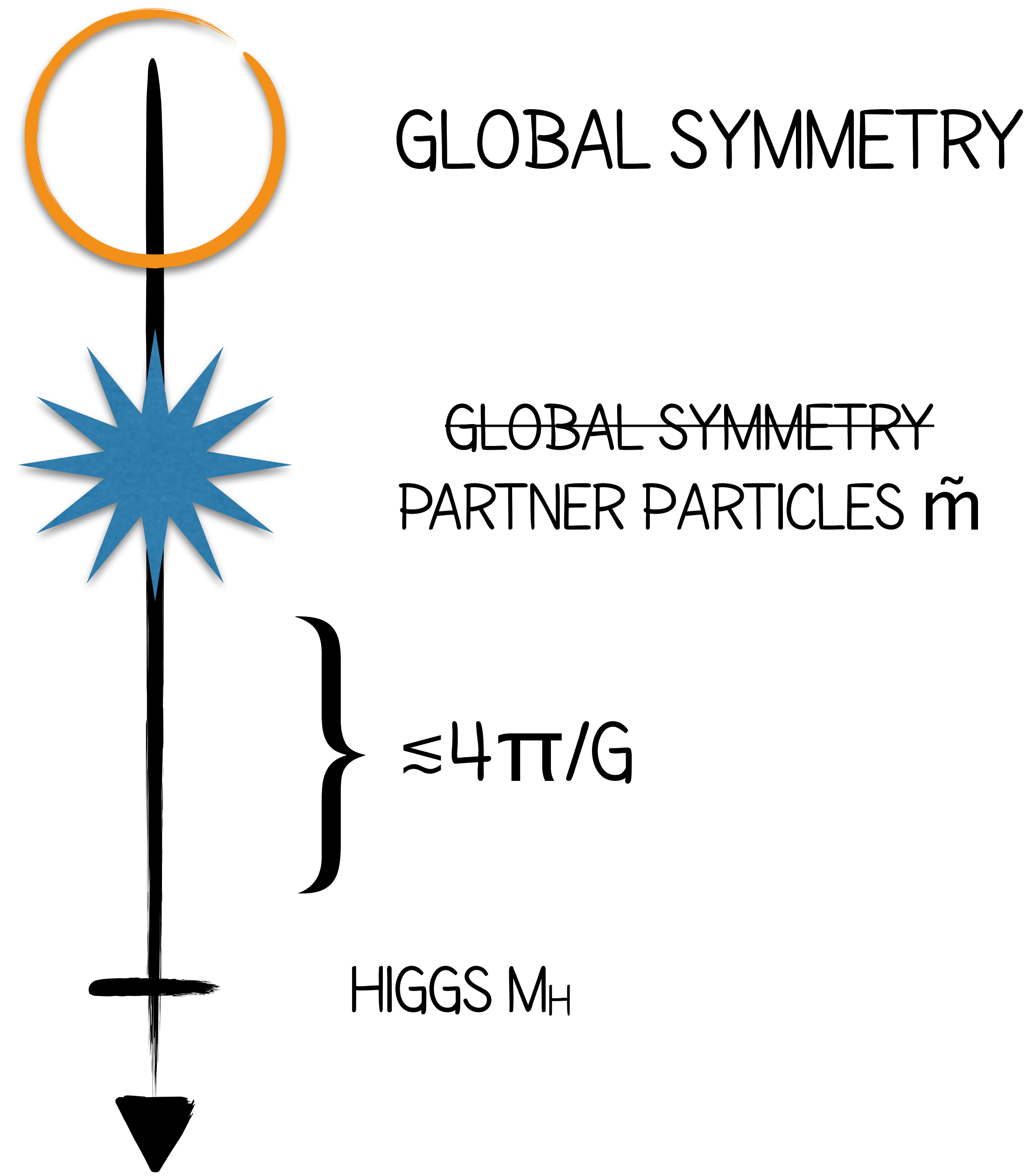
UC SANTA BARBARA

SSI 2016: NEW HORIZONS ON THE ENERGY FRONTIER

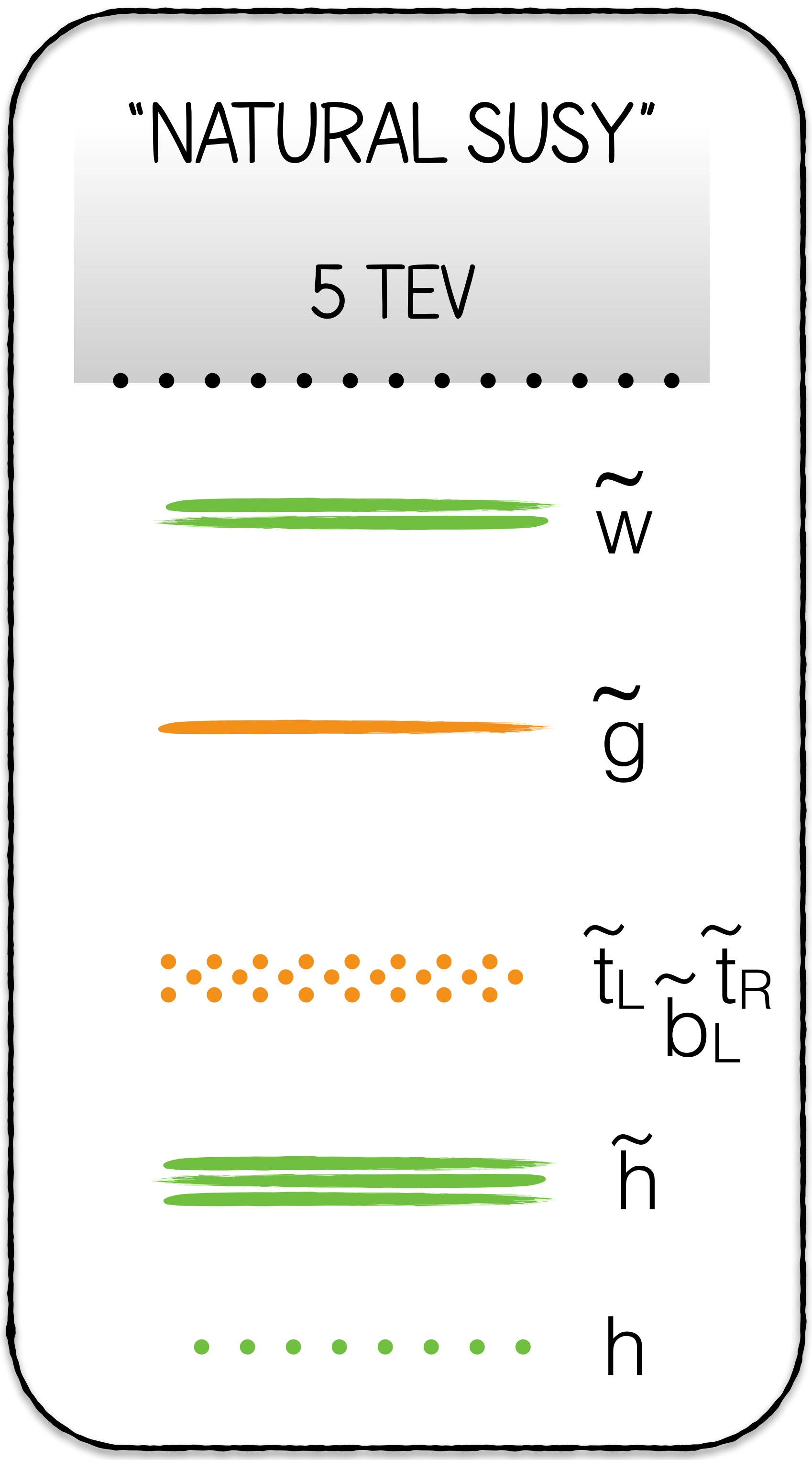
POSSIBLE SYMMETRIES

EXTEND THE SM WITH A SYMMETRY ACTING ON THE HIGGS





SUSY EXPECTATIONS



BEST CASE SCENARIO GIVEN NULL RESULTS: SUPERPARTNER MASS HIERARCHY INVERSELY PROPORTIONAL TO CONTRIBUTION TO HIGGS MASS

$$\delta m_h^2 \propto \mu^2$$ ("HIGGSINOS")

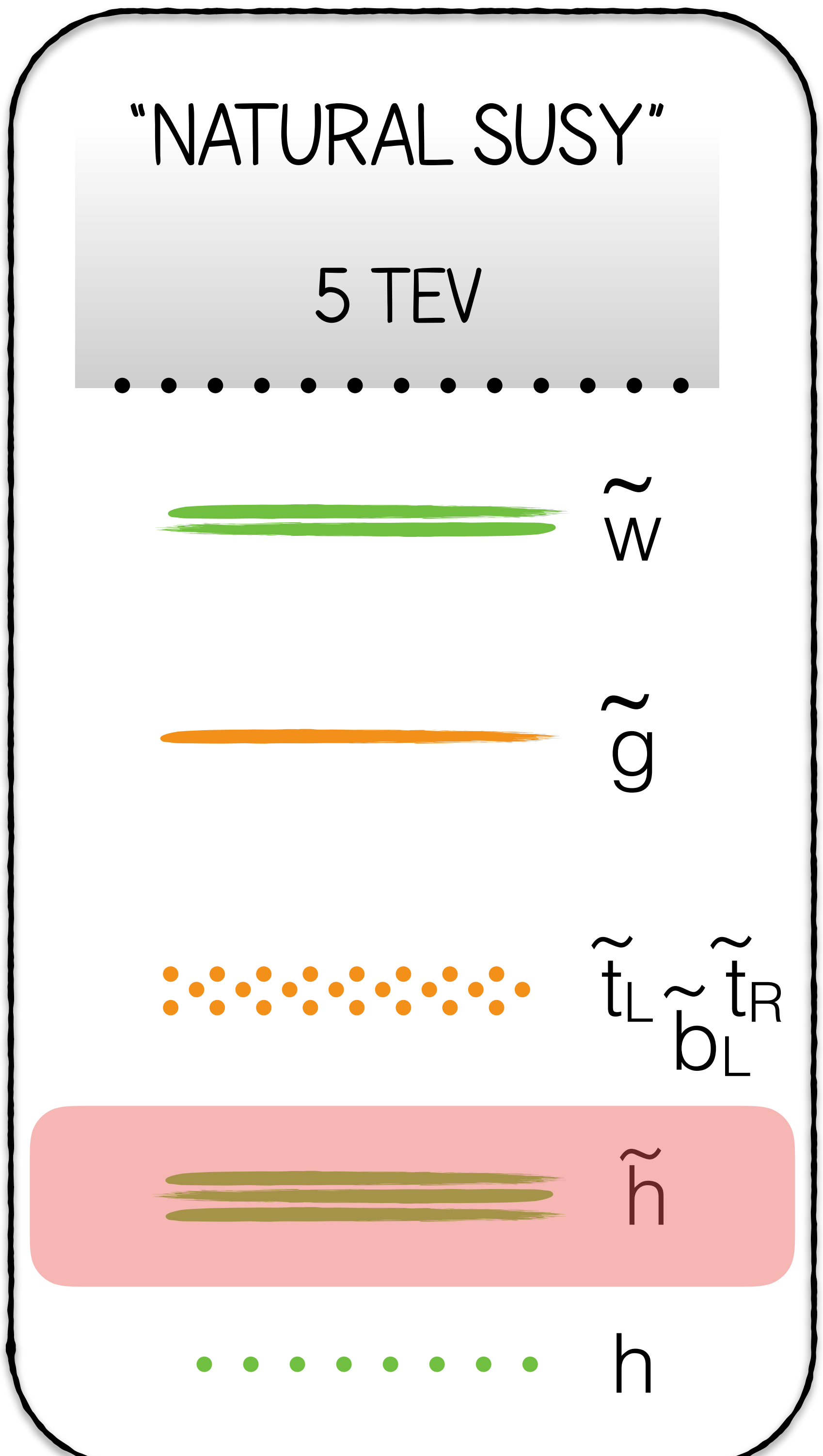
$$m_h^2 \sim \frac{3y_t^2}{4\pi^2}\tilde{m}^2 \log(\Lambda^2/\tilde{m}^2)$$ (STOPS)

ETC...

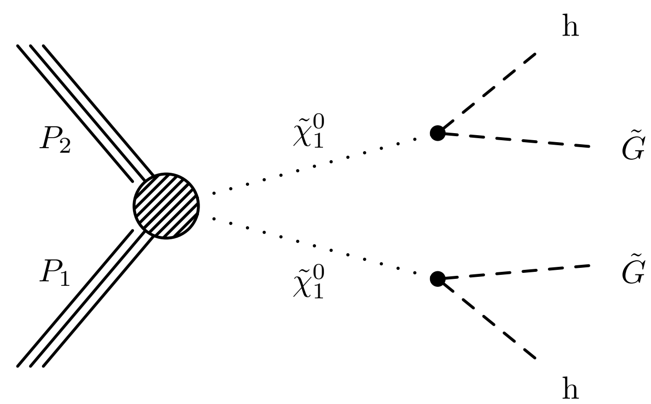
QCD PRODUCTION OF STOPS, GLUINOS LEADS TO STRONGEST CONSTRAINTS

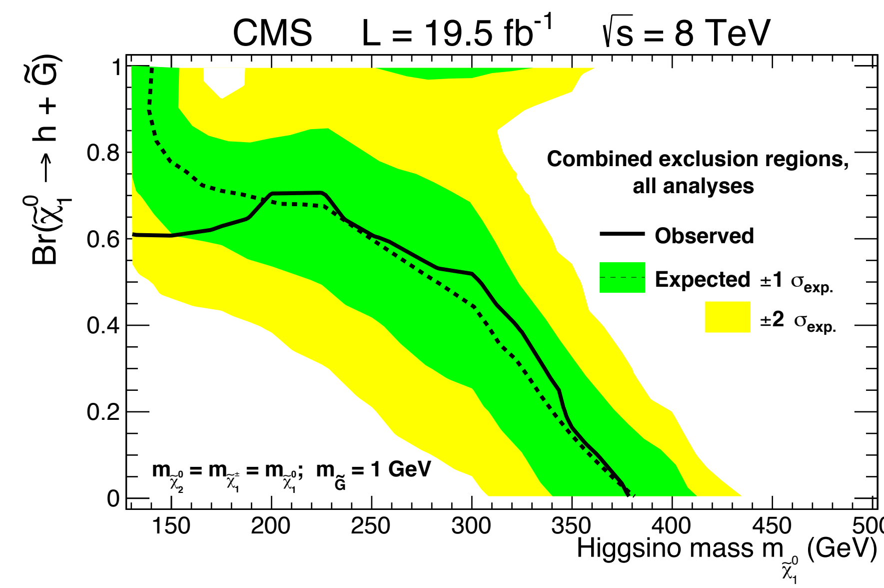
[DIMOPOULOS, GIUDICE '95; COHEN, KAPLAN, NELSON '96; PAPUCCI, RUDERMAN, WEILER '11; BRUST, KATZ, LAWRENCE, SUNDRUM '11]

HIGGSINO SIGNALS



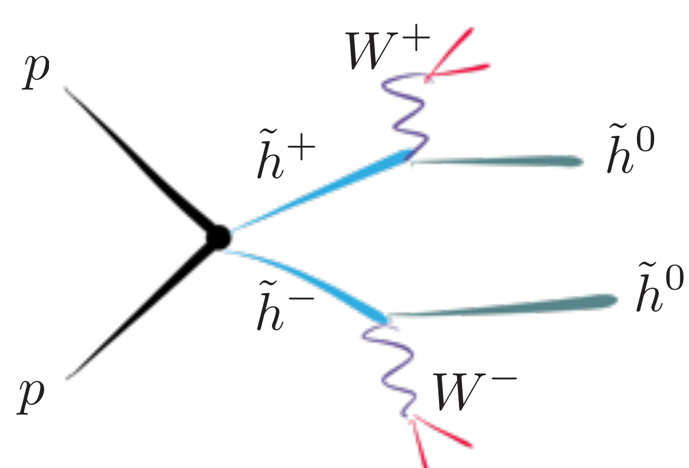
LOTS OF SEARCHES...

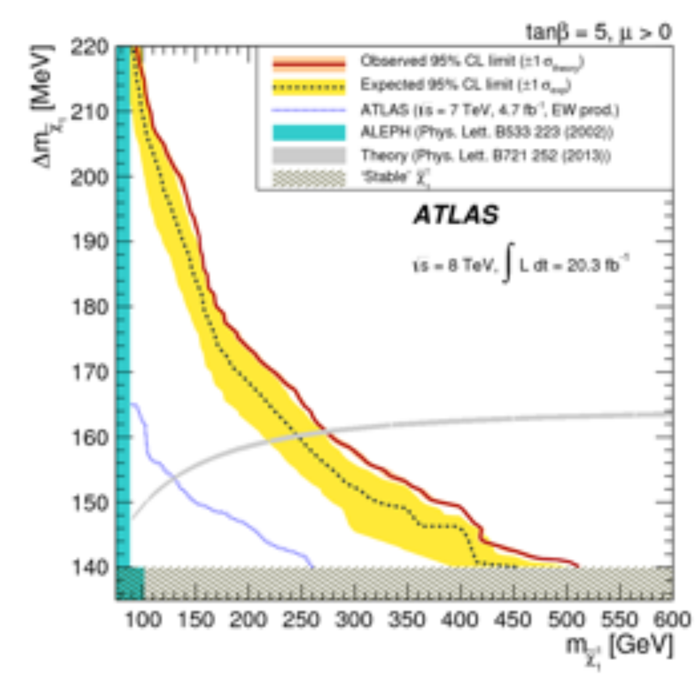




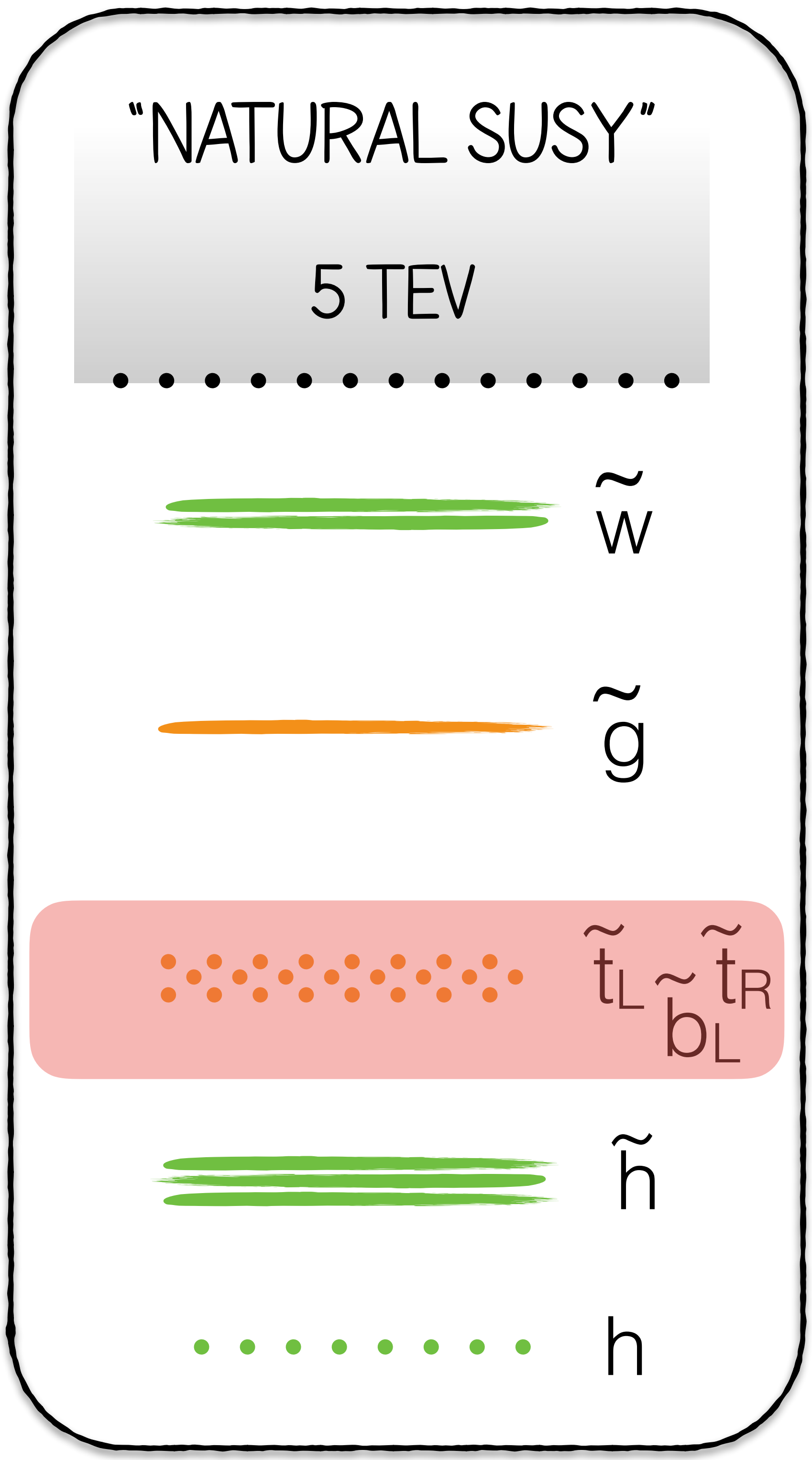
...BUT NO IRREDUCIBLE LIMITS

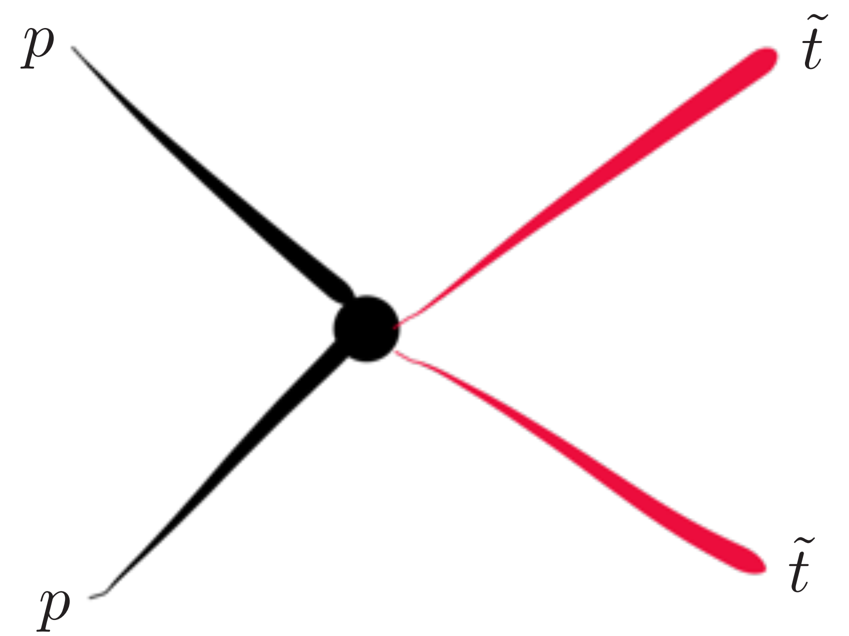
CHARGINO-NEUTRALINO SPLITTING IN PURE HIGGSINO MULTIPLET: 355 MEV
[THOMAS, WELLS '98]

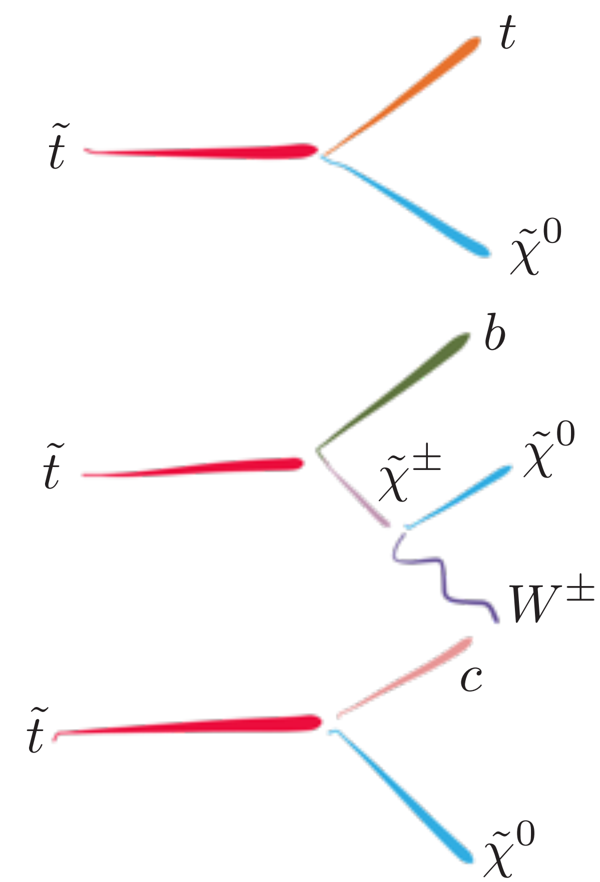


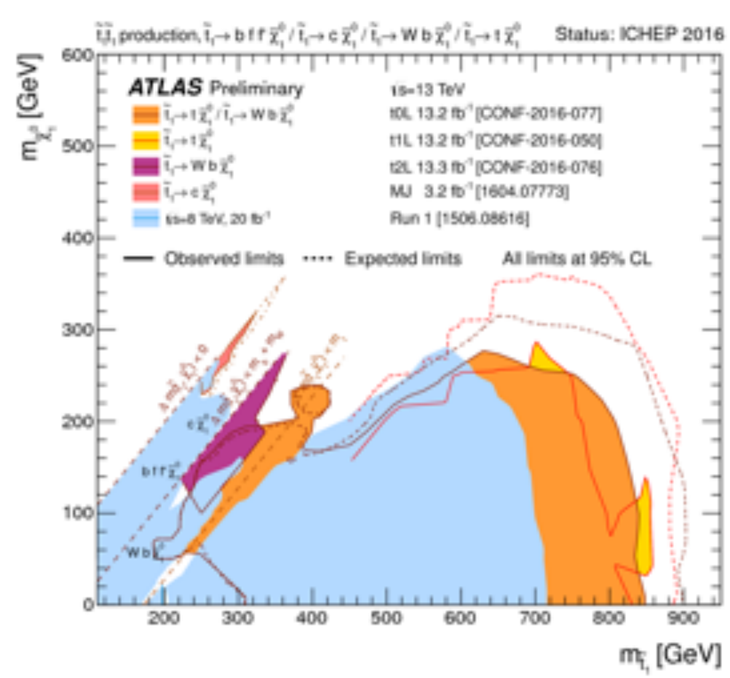


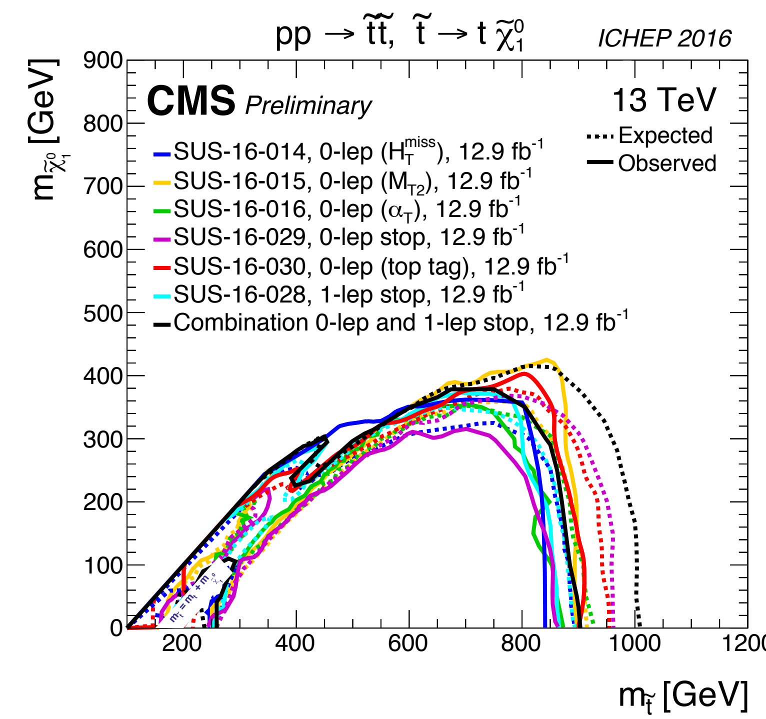
STOP SIGNALS



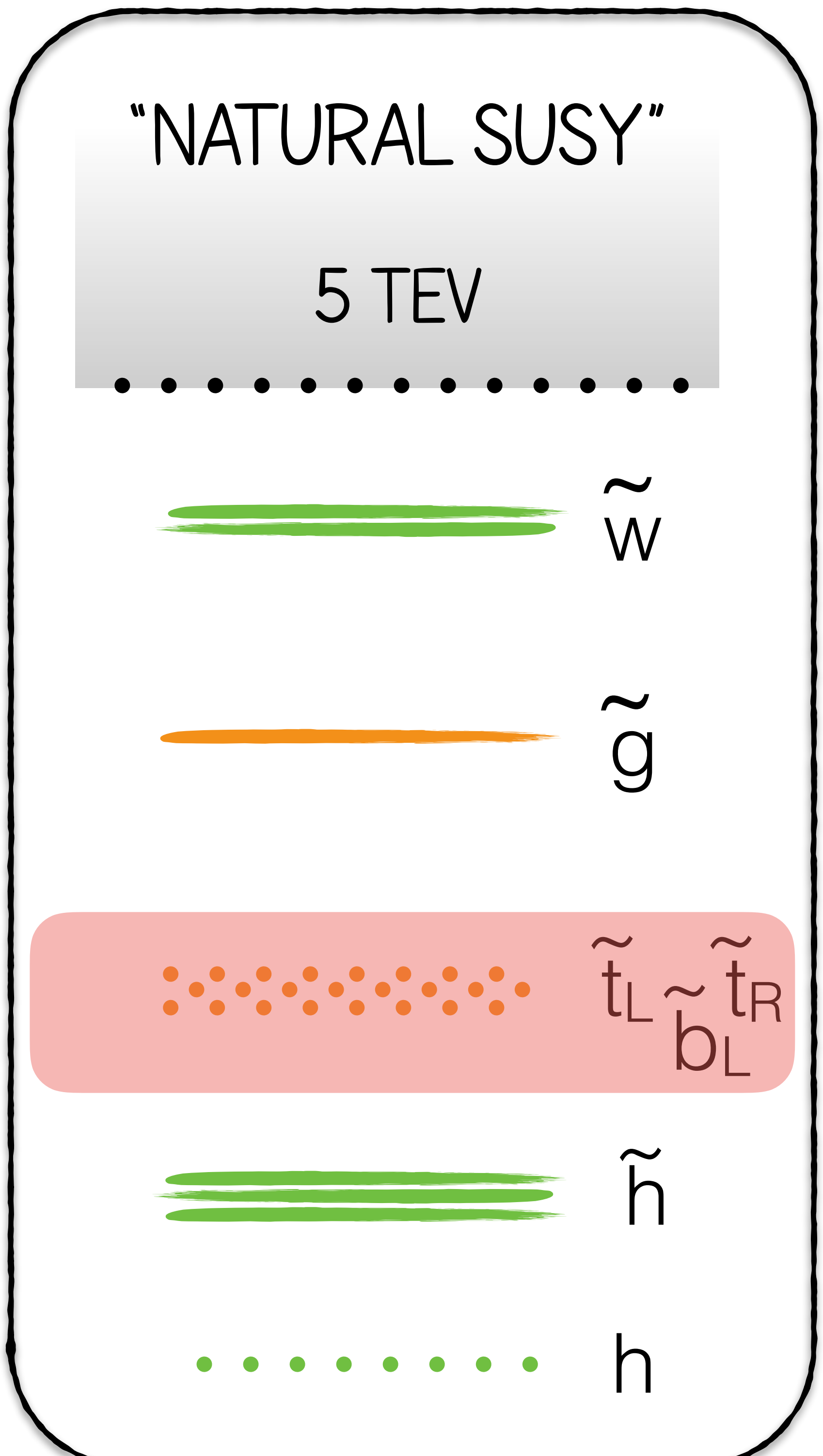




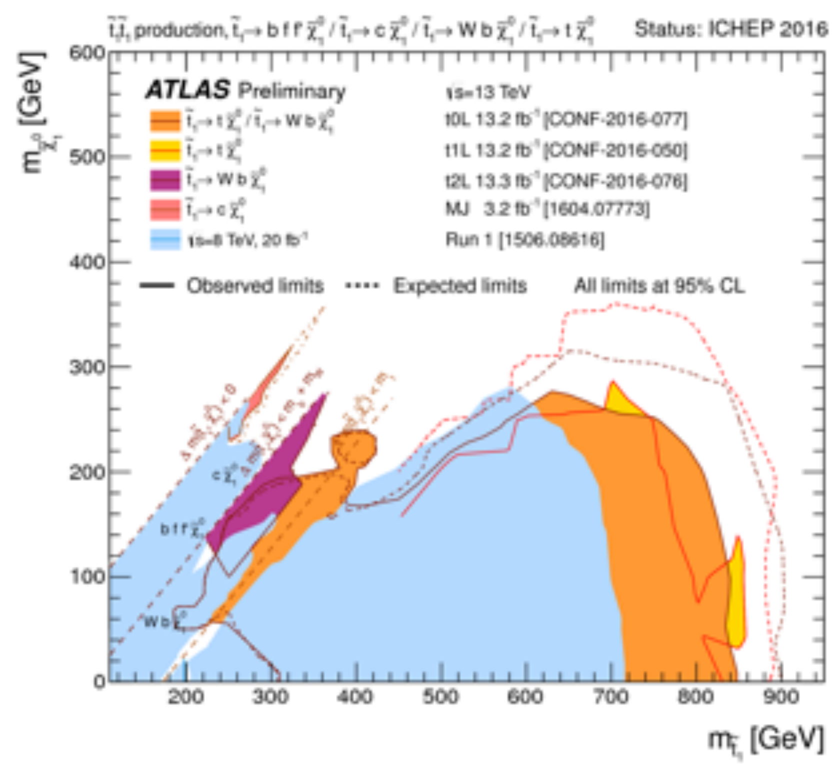




STOP SIGNALS



$$\delta m_H^2 \sim -\frac{3}{8\pi^2} y_t^2 (m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2) \log(\Lambda/\mathrm{TeV})$$



QUANTIFY TUNING (AS YOU LIKE)

$$\Delta \equiv \frac{2\delta m_H^2}{m_h^2}$$

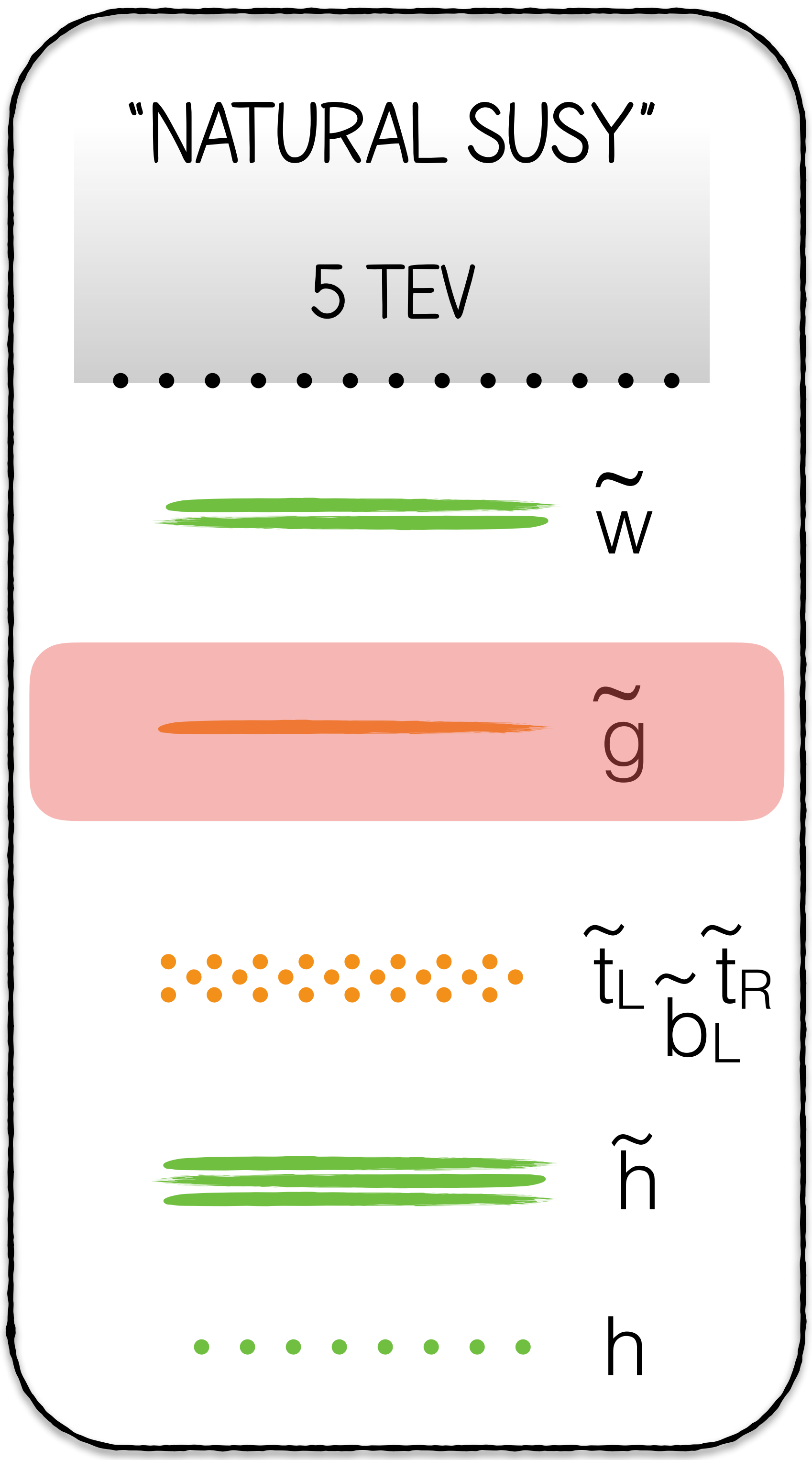
GENERIC LIMIT* > 800 GEV (BOTH STOPS)

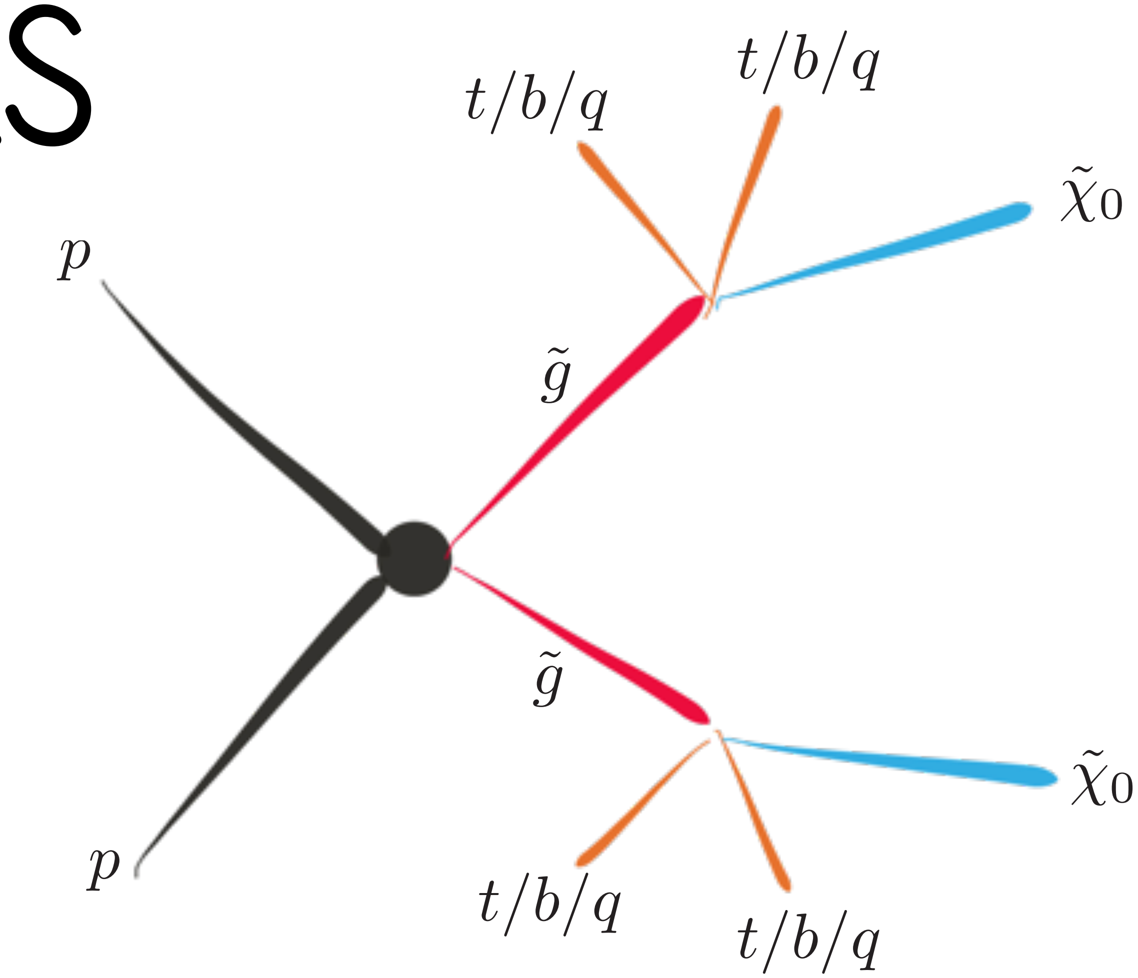
→ **Δ~90 (1% TUNING)**

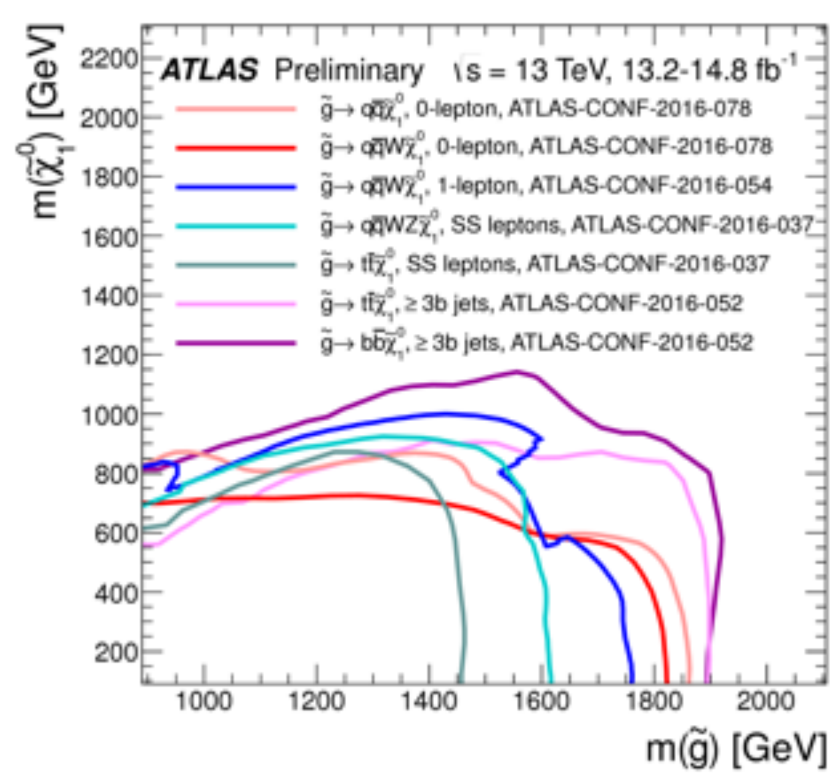
(Λ = 100 TEV)

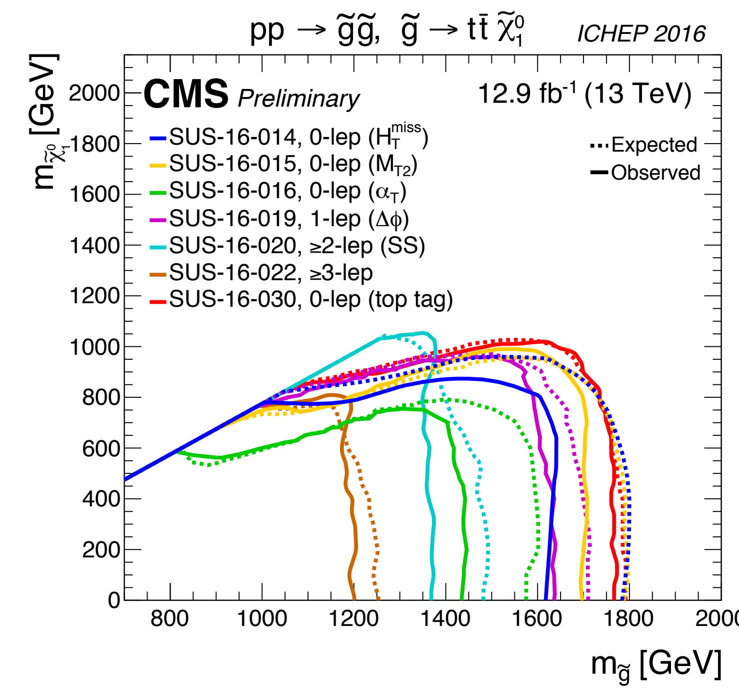
* I'LL COME BACK TO THIS

GLUINO SIGNALS

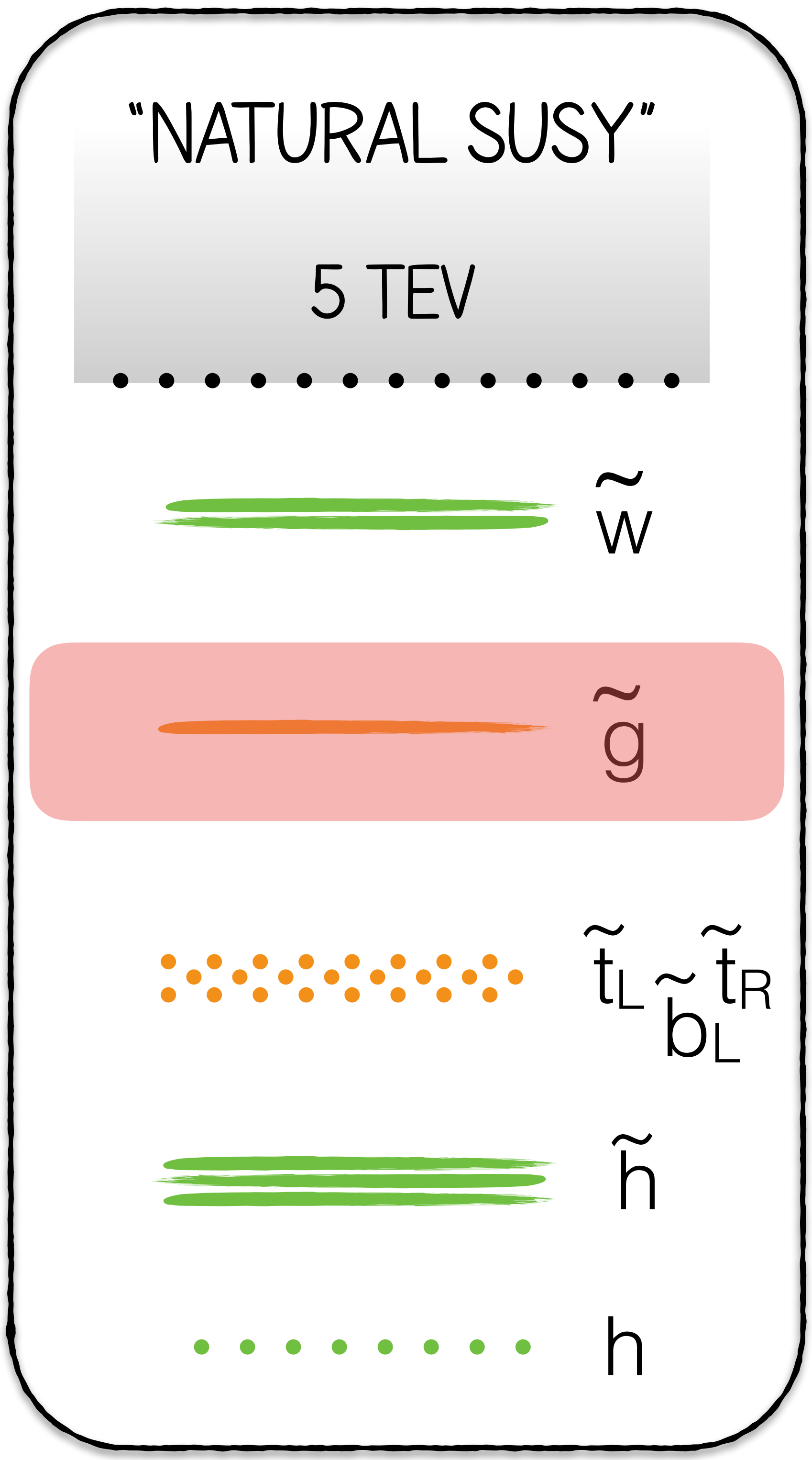






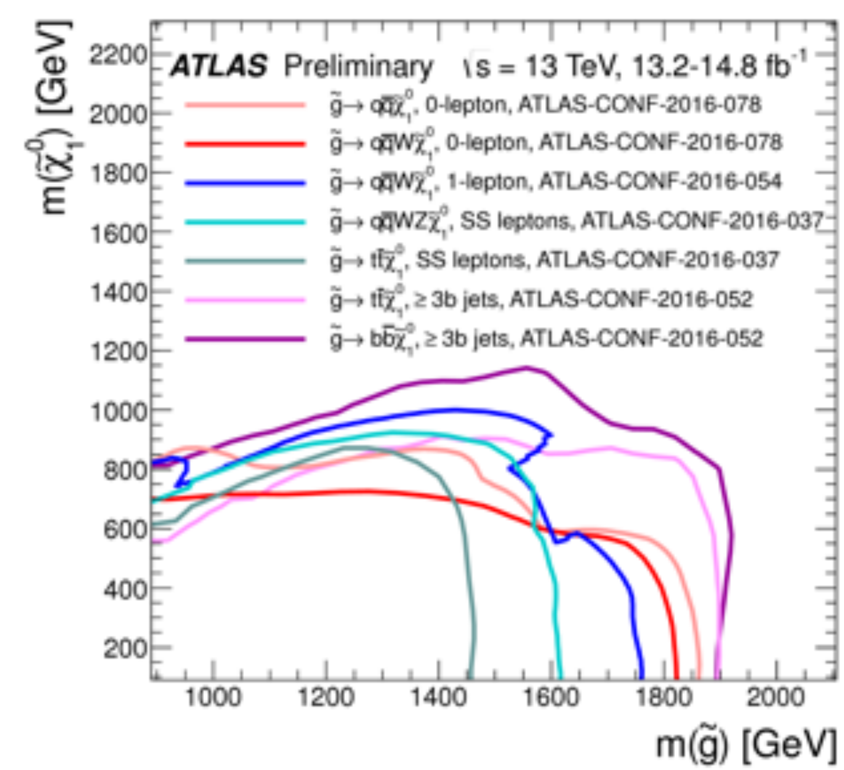


GLUINO SIGNALS



$$\delta m_H^2 \sim -\frac{2}{\pi^2} y_t^2 \left(\frac{\alpha_s}{\pi}\right) |M_3|^2 \log^2(\Lambda/\text{TeV})$$

LEADS TO "$m_{\tilde{t}} \gtrsim M_3/2$"



GENERIC LIMIT* > 1800 GEV

→ Δ~57 (2% TUNING)

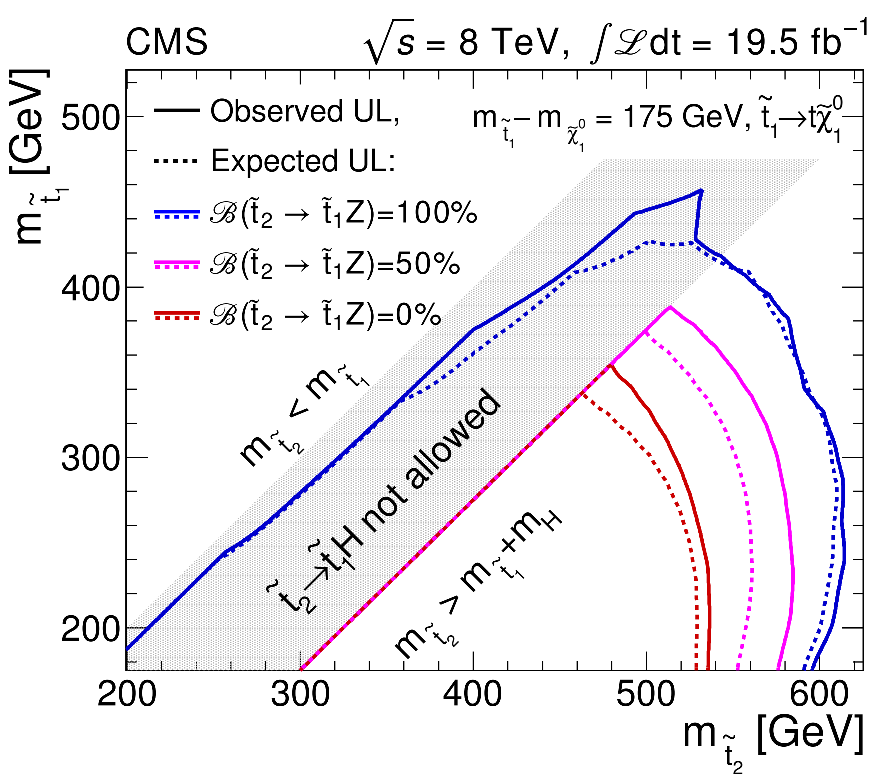
(Λ = 100 TEV)*

BREAK THE SIGNAL 1: COMPRESSION

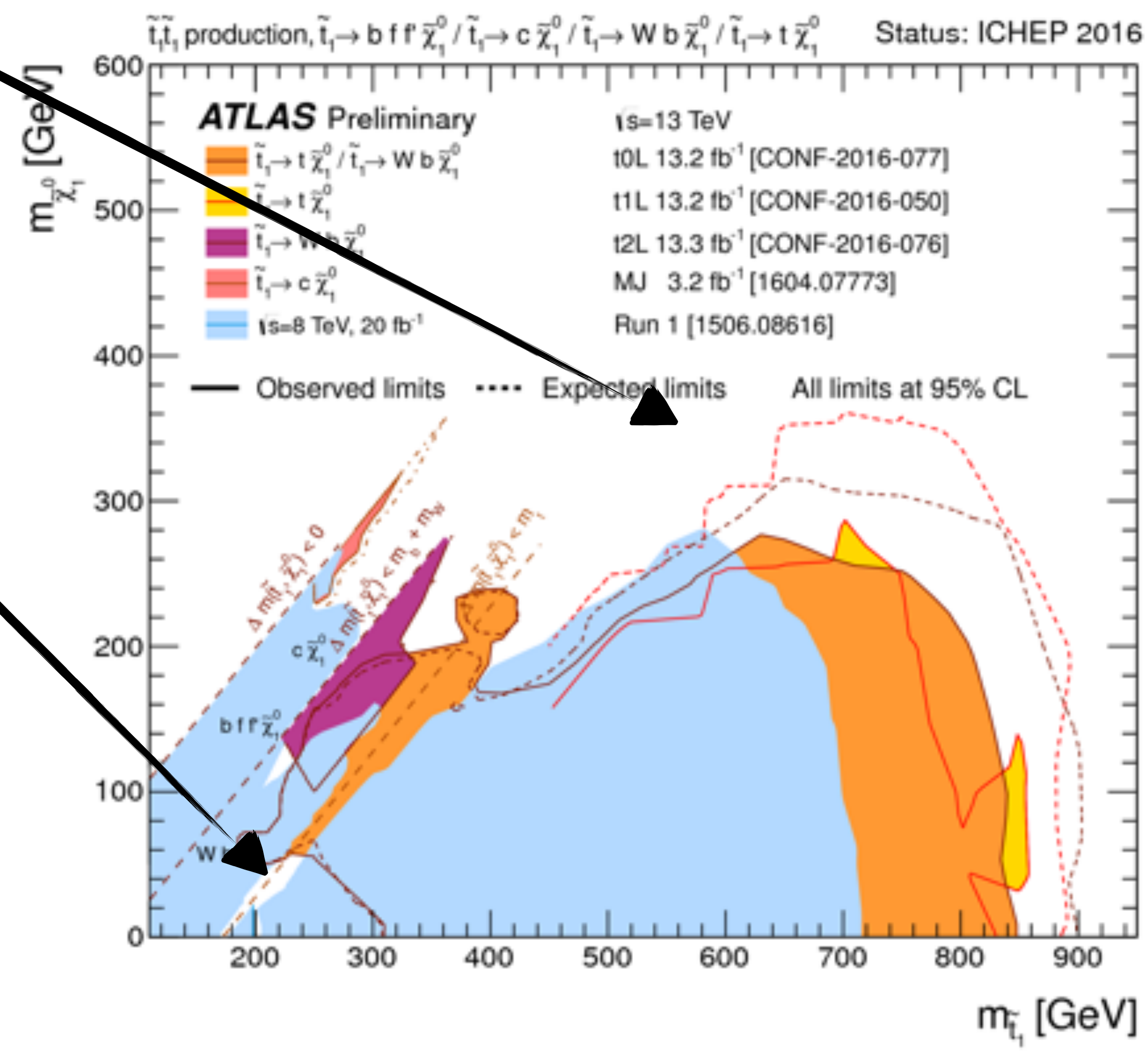
REDUCE MISSING ENERGY WITH MASS DEGENERACY

LIVING HERE? *LSP MASS IMPLIES HIGGSINO TUNING (~10%)*

LIVING HERE? *HAVE TO CONTEND WITH STOP1-STOP2 LIMITS*



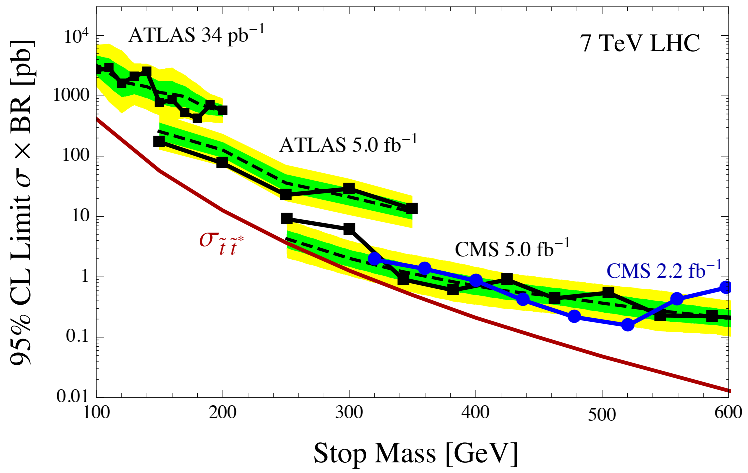
+STILL HAVE TO WORRY ABOUT GLUINOS.



RUNNING OUT OF ROOM FOR COMPRESSION @ LHC.

BREAK THE SIGNAL 2: RPV

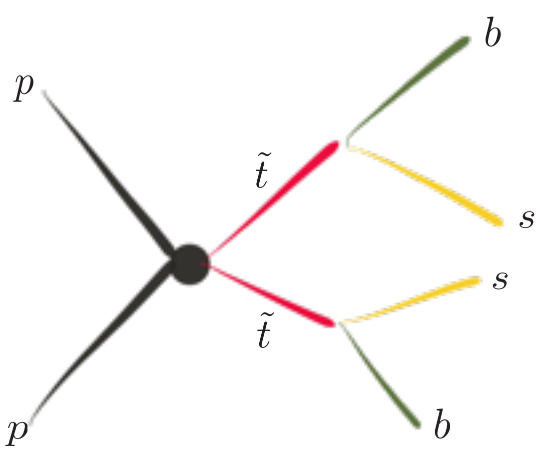
[Bai, Katz, Tweedie '13]

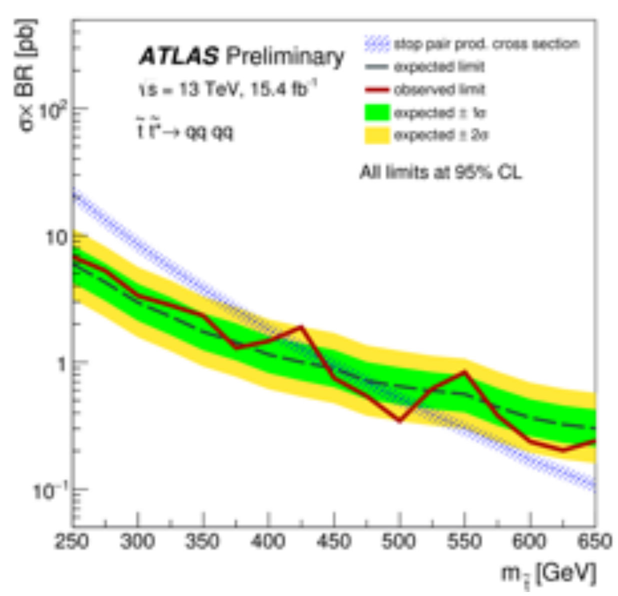


KILL MISSING ENERGY BY BREAKING R-PARITY. IN PRACTICE, LEPTONS ARE KILLERS. RPV CAN HELP PROVIDED NO LEPTONS → BARYONIC RPV.

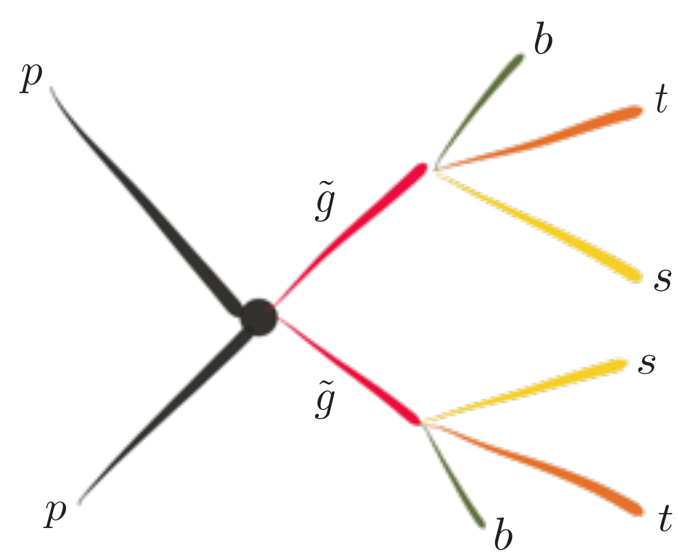
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$	1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$	1.45 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e,μ	-	Yes	13.3	$\tilde{\chi}_1^\pm$	1.14 TeV	m($\tilde{\chi}_1^0$)>400GeV, $\lambda_{12k}\neq0$ $(k=1,2)$
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$	450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^\pm$), $\lambda_{133}\neq0$
	$\tilde{g}\tilde{g}, \tilde{g}\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$	1.08 TeV	BR(t)=BR(b)=BR(c)=0%
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$	1.55 TeV	m($\tilde{\chi}_1^0$)=800 GeV
	$\tilde{g}\tilde{g}, \tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	13.2	$\tilde{g}$	1.3 TeV	m($\tilde{t}_1$)<750 GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	15.4	$\tilde{t}_1$	410 GeV / 450-510 GeV	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	$\tilde{t}_1$	0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%

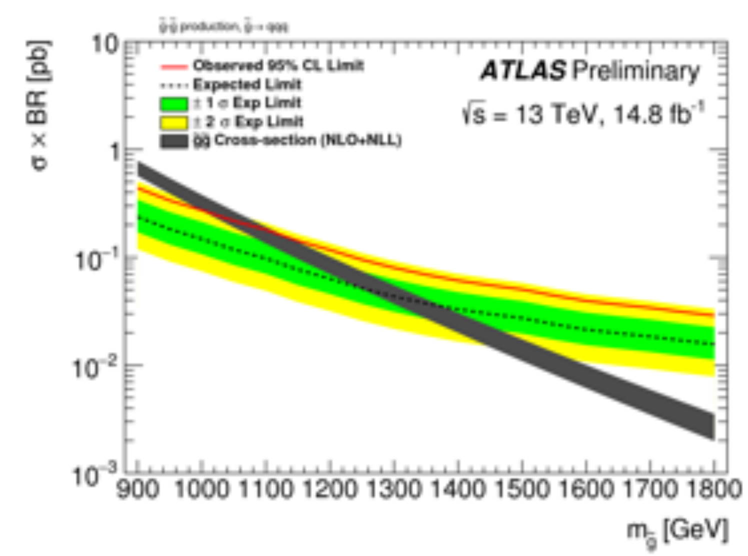
STOPS > 500 GEV (5%)





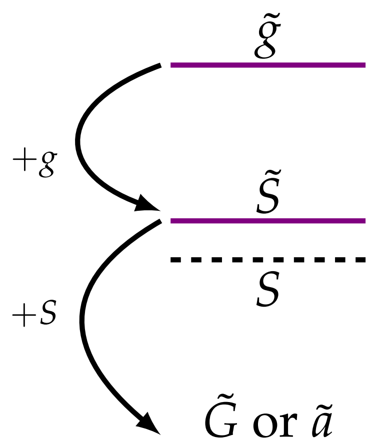
GLUINOS > 1 TEV (5%)

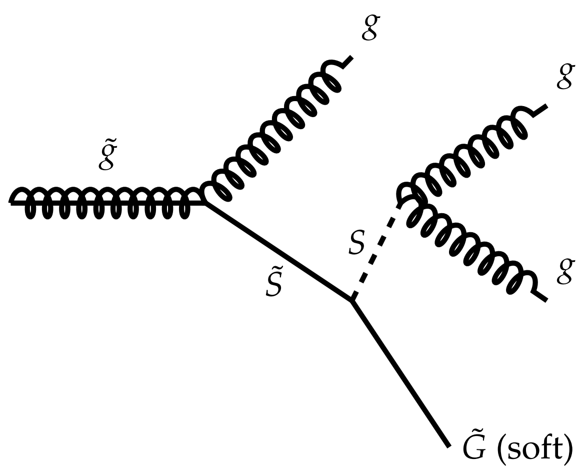


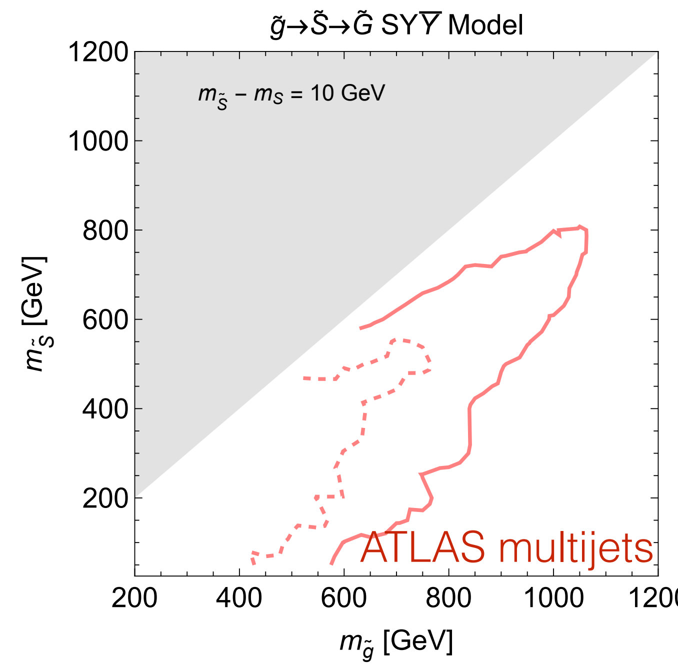


BREAK THE SIGNAL 3: STEALTH

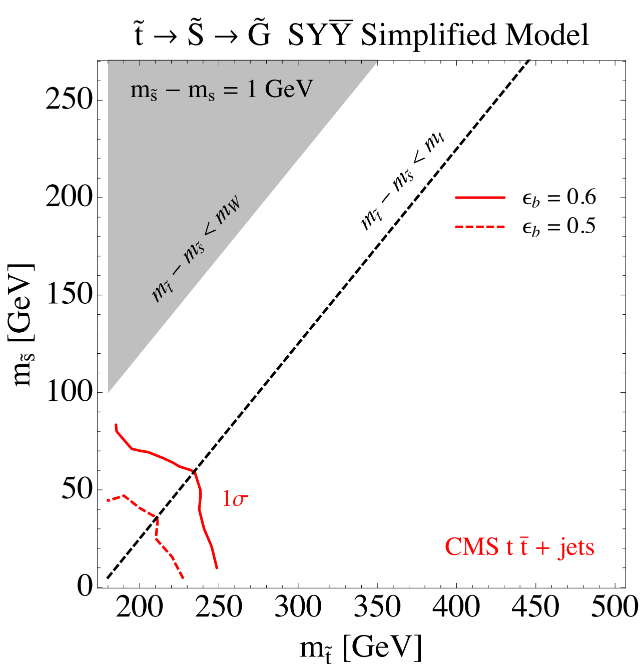
STEALTH SUSY: ERASE MET BY DECAYING INTO SECTOR WITH SMALL NON-SUSY SPLITTING
MOTIVATES ADDITION OF HIDDEN SECTORS TO THE MSSM.

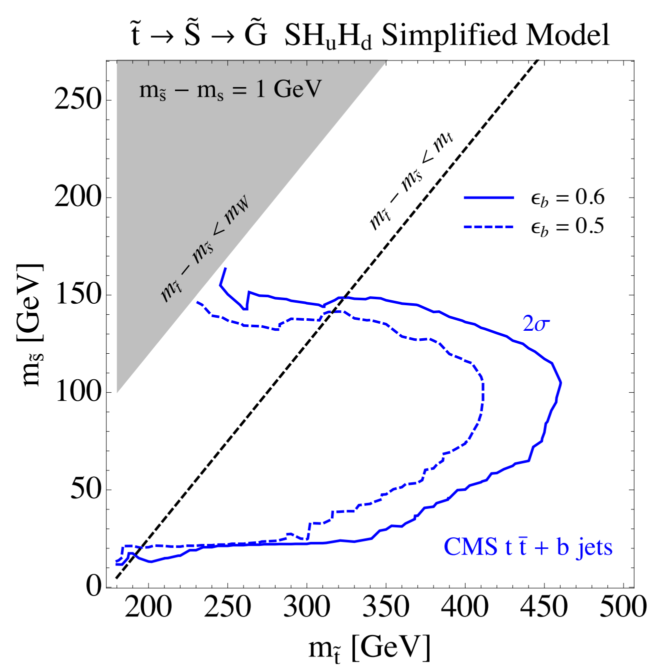


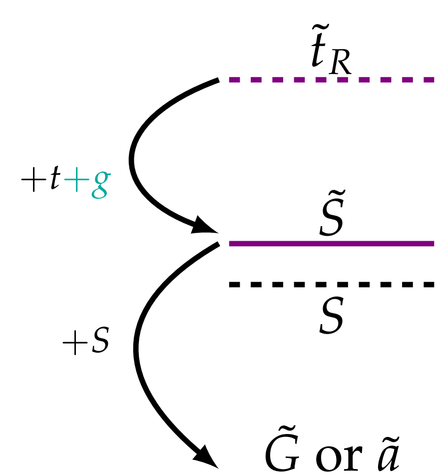


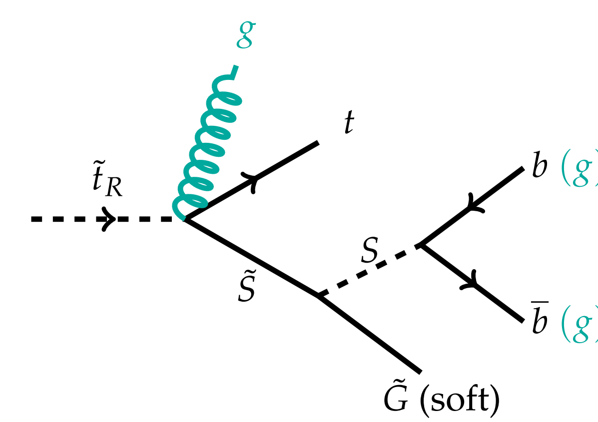


TRADE MET FOR ADDITIONAL EVENT ACTIVITY, MIGRATE SIGNALS TO EXOTICS; *SOMETIMES YOU WIN, SOMETIMES YOU LOSE.*









[Fan, Reece, Ruderman; Fan, Krall, Pinner, Reece, Ruderman]

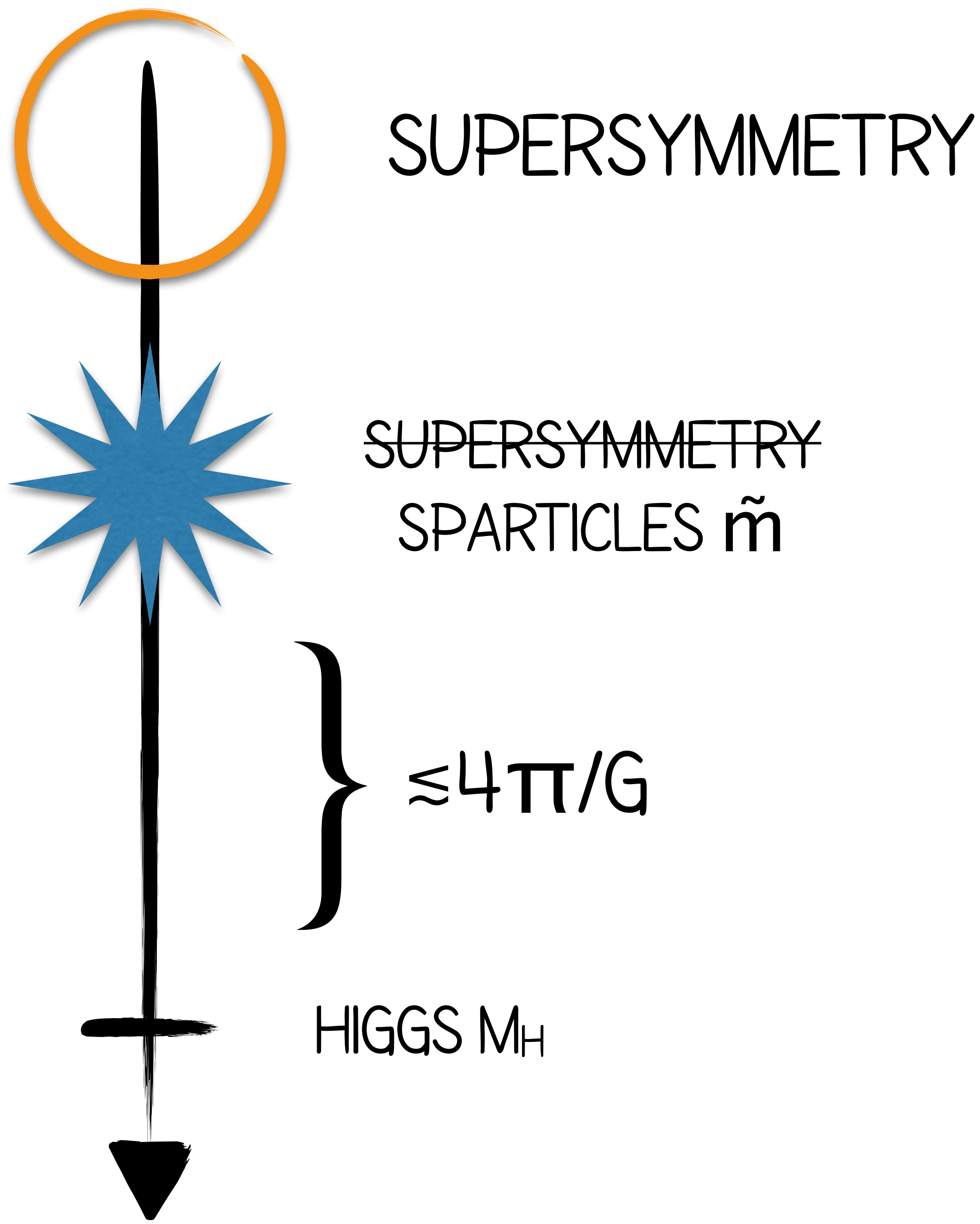
SUSY THE SIGNAL GENERATOR

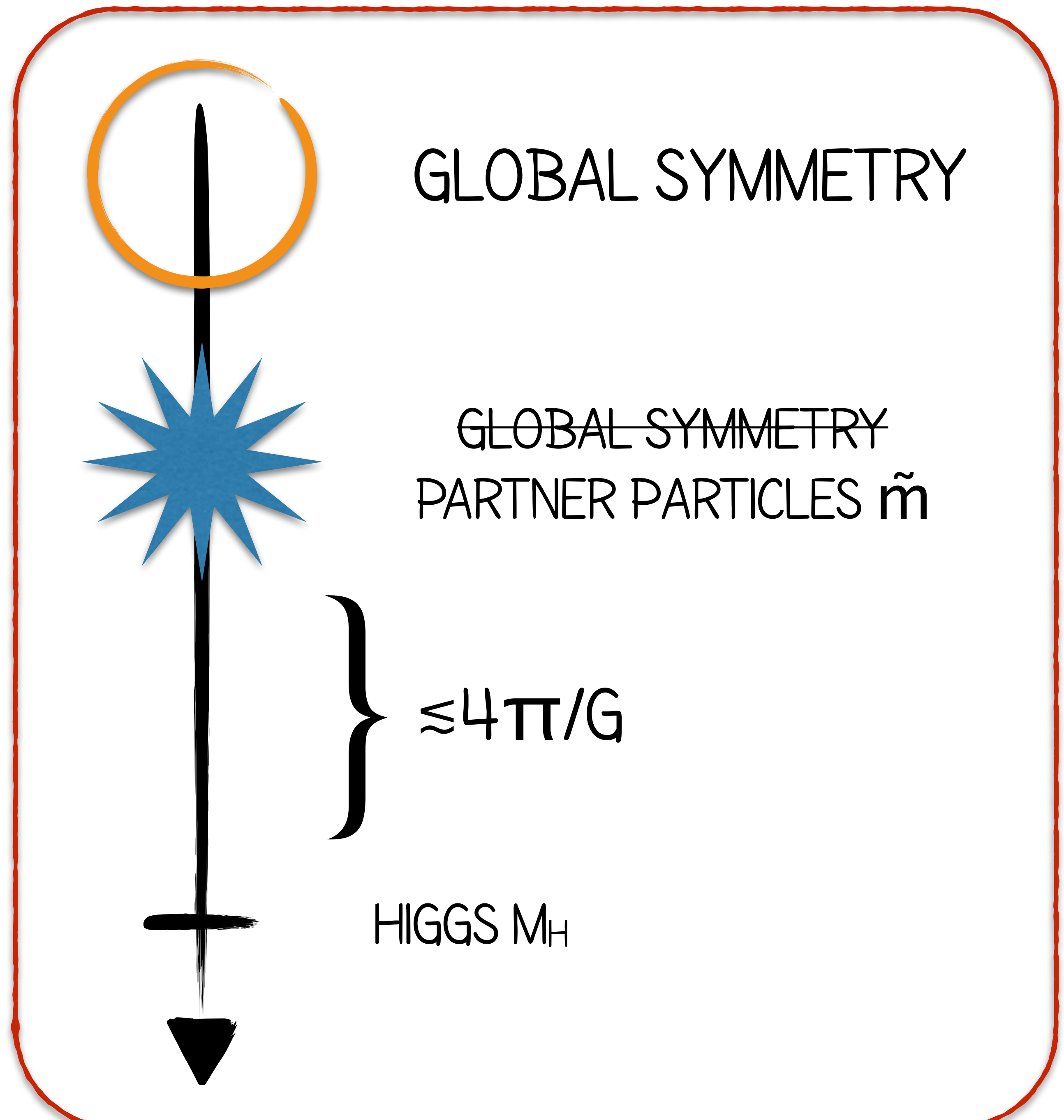
	γ	ℓ	τ	j	t	W	Z	h	MET
γ	H,A						H		$\chi^0{}_1$
ℓ		RPV	RPV	RPV	RPV				$\tilde{\ell}$
τ			H,A	RPV	RPV				$\tilde{\tau}$
j				H,A	RPV				$\tilde{q}$
t					H,A				$\tilde{t}$
W						H		$H^{\pm}$	$\chi^{\pm}$
Z							H	A	$\tilde{h}$
h								H	$\tilde{h}$
MET									h

HOWEVER YOU FEEL ABOUT THE HIERARCHY PROBLEM, SUPERSYMMETRY POPULATES A VAST ARRAY OF SIGNALS AT COLLIDERS.

POSSIBLE SYMMETRIES

EXTEND THE SM WITH A SYMMETRY ACTING ON THE HIGGS





GLOBAL SYMMETRY: AN EXAMPLE

CONSIDER A GLOBAL SU(3) WITH FUNDAMENTAL **S**.

*(**S** HAS ITS OWN HIERARCHY PROBLEM; BUT THIS SHOWS UP AT HIGHER ENERGIES).*

S GETS A VEV, $\langle S \rangle$ = F ~ TEV.

BREAKS SU(3)→SU(2), 5 GOLDSTONES.

GAUGE THE SU(2) (WEAK GROUP!) AND ASSEMBLE 4 GOLDSTONES INTO A COMPLEX DOUBLET **H**. PROTECTED BY SHIFT SYMMETRY! NOW WE HAVE A SCALAR DOUBLET OF SU(2) MUCH LIGHTER THAN F.

BUT! SM COUPLINGS BREAK THIS SYMMETRY. ADDING REALISTIC COUPLINGS (TOP YUKAWA!) WOULD *BADLY* EXPLICITLY BREAK SU(3); NO SENSE IN WHICH H IS PROTECTED. $M_H \sim Y_T \Lambda / 4\pi$, HIERARCHY PROBLEM ALL OVER AGAIN.

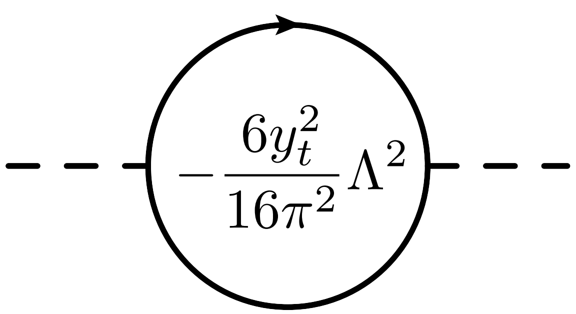
GLOBAL SYMMETRY: AN EXAMPLE

SOLUTION: EXTEND TOP MULTIPLET TO SU(3), AND WRITE DOWN SU(3) SYMMETRIC TOP YUKAWA.

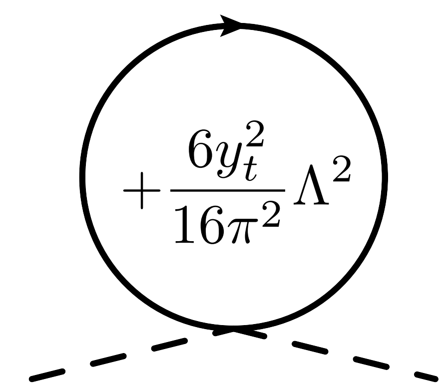
$$\begin{pmatrix} t_L \\ b_L \end{pmatrix} \rightarrow \begin{pmatrix} \begin{pmatrix} t_L \\ b_L \end{pmatrix} \\ T_L \end{pmatrix}$$

$$t_R \rightarrow t_R + T_R$$

INTEGRATE OUT THE RADIAL MODE OF **S** (I.E. HIGGS BOSON OF SU(3) BREAKING) AND ARRIVE AT THE LOW ENERGY THEORY:



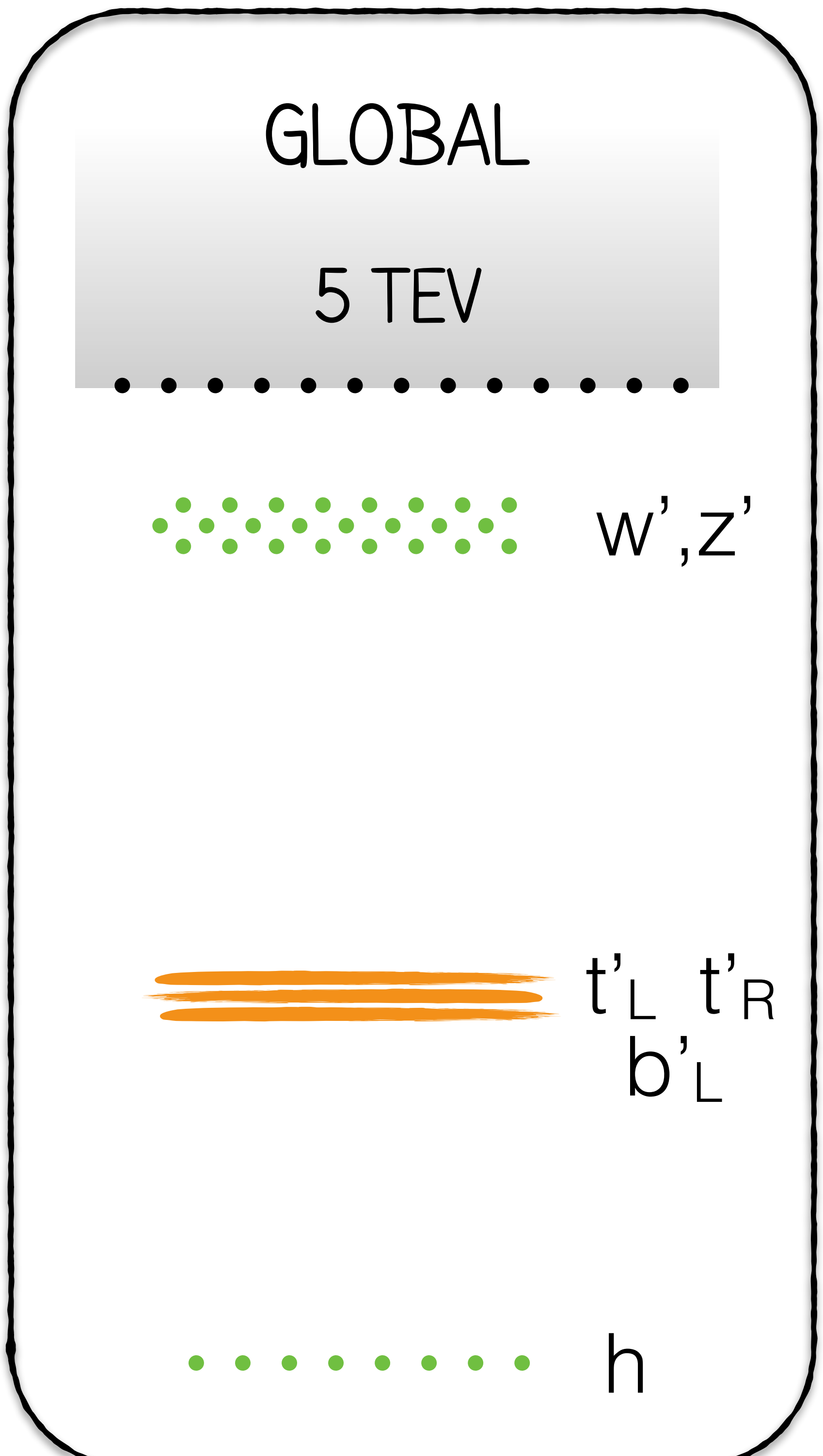
$$y_t H Q_3 t_R^\dagger - \frac{y_t^2}{2m_T}(H^\dagger H) T_L T_R^\dagger$$



COUPLINGS EXACTLY SO THAT TOP PARTNER CANCELS RADIATIVE CONTRIBUTIONS ("QUADRATIC DIVERGENCES") FROM HIGHER SCALES, AND $m_H^2 \sim -\frac{6y_t^2}{16\pi^2} m_T^2$

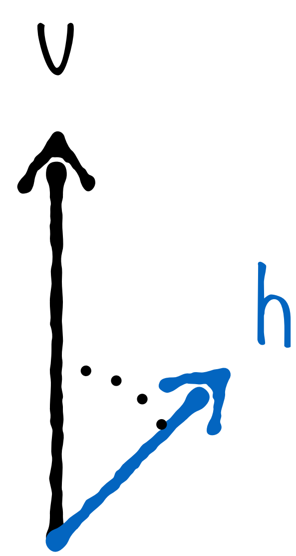
SIGN THAT THE GLOBAL SYMMETRY PROTECTS AGAINST PHYSICS @ HIGHER SCALES.

GLOBAL EXPECTATIONS



HIGGS A PNGB OF GLOBAL SYMMETRY BREAKING. COMPOSITENESS USUALLY PROTECTS SCALE OF GLOBAL SYMMETRY *F*

STORY BASICALLY THE SAME AS SUSY, BUT NOW W/ LIGHT FERMIONIC TOP PARTNERS & HIGGS MIXING



$$\Delta \sim f^2/v^2$$ (HIGGS MIXING)

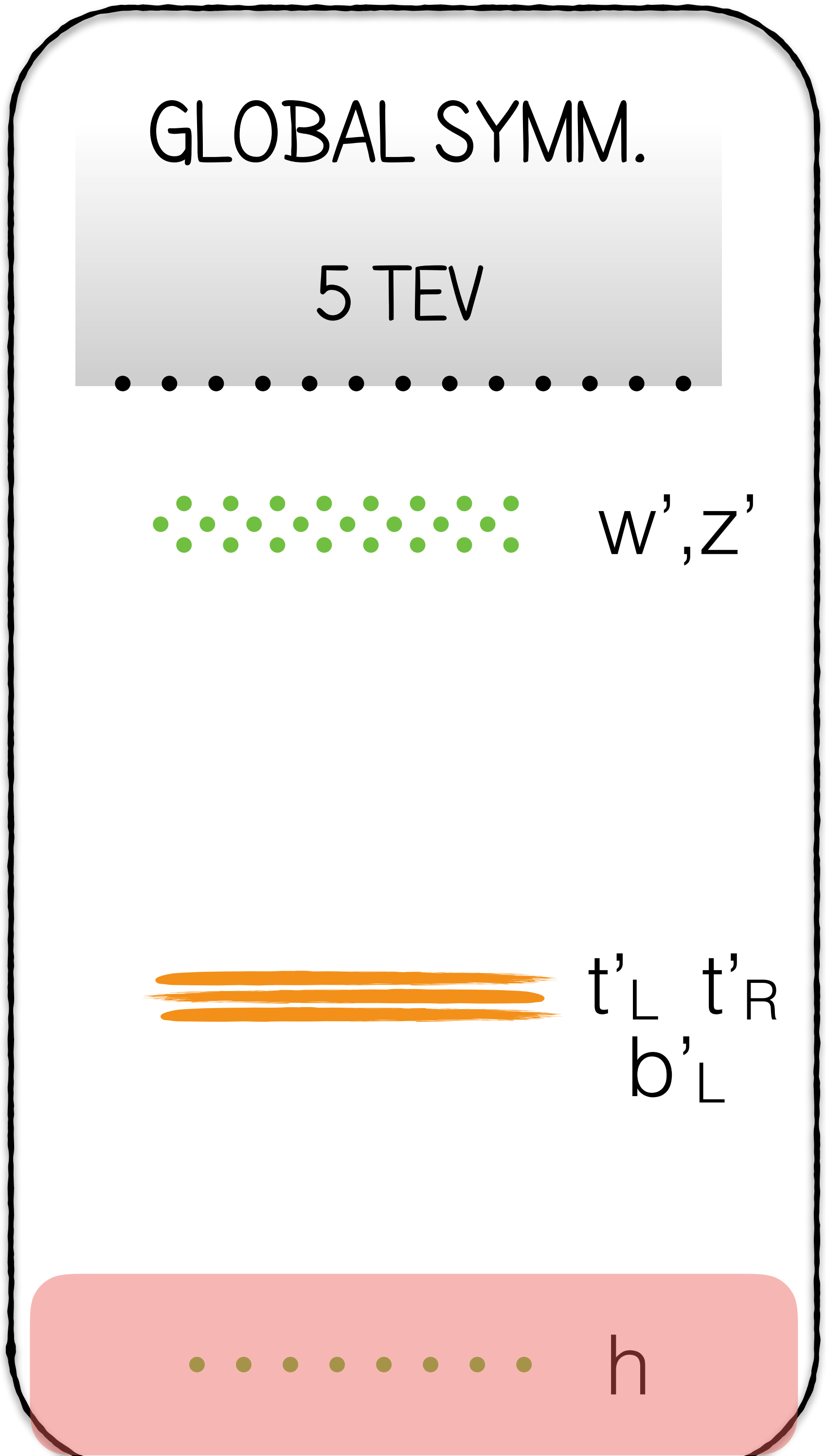
$$m_h^2 \sim \frac{3y_t^2}{4\pi^2}\tilde{m}^2 \log(\Lambda^2/\tilde{m}^2)$$

(TOP PARTNERS)

ETC...

LIMITS NOW FROM QCD-CHARGED STATES & HIGGS MIXING.

HIGGS SIGNALS



RADIATIVE HIGGS POTENTIAL FROM PARTNERS

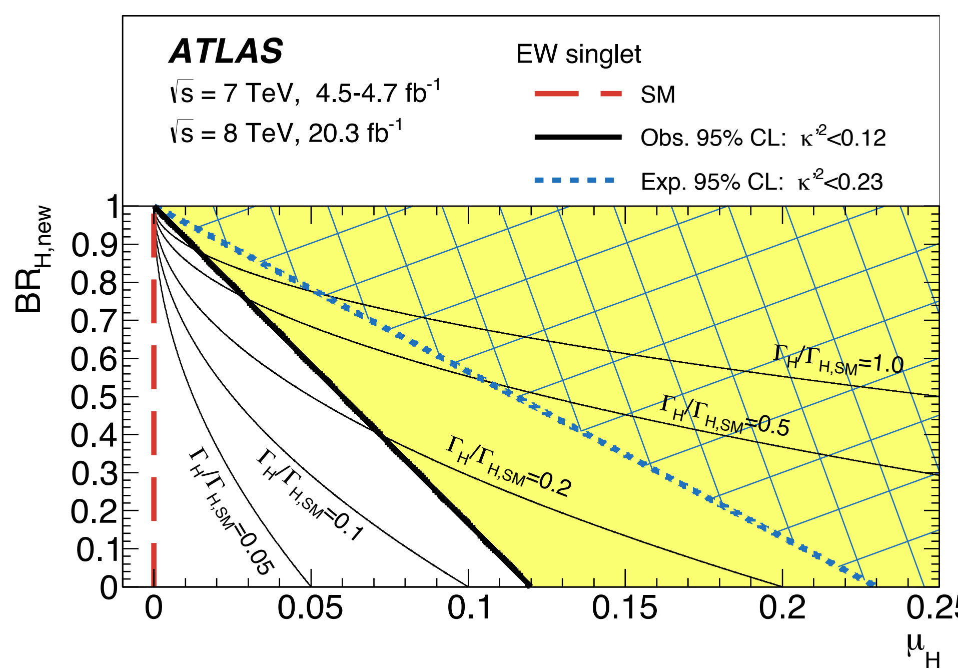
$$V(h) \sim \frac{N_c}{16\pi^2} m_\psi^4 \epsilon^2 \left[c_1 \frac{h^2}{f^2} + c_2 \frac{h^4}{f^4} \right]$$

QUARTIC & M^2 AT SAME LOOP ORDER, EXPECT **V~F**

I.E., NO SEPARATION BETWEEN WEAK SCALE & GLOBAL BREAKING

MAKING **V < F** REQUIRES TREE-LEVEL TUNING OF TERMS IN THE POTENTIAL

$$\Delta \sim f^2/v^2$$



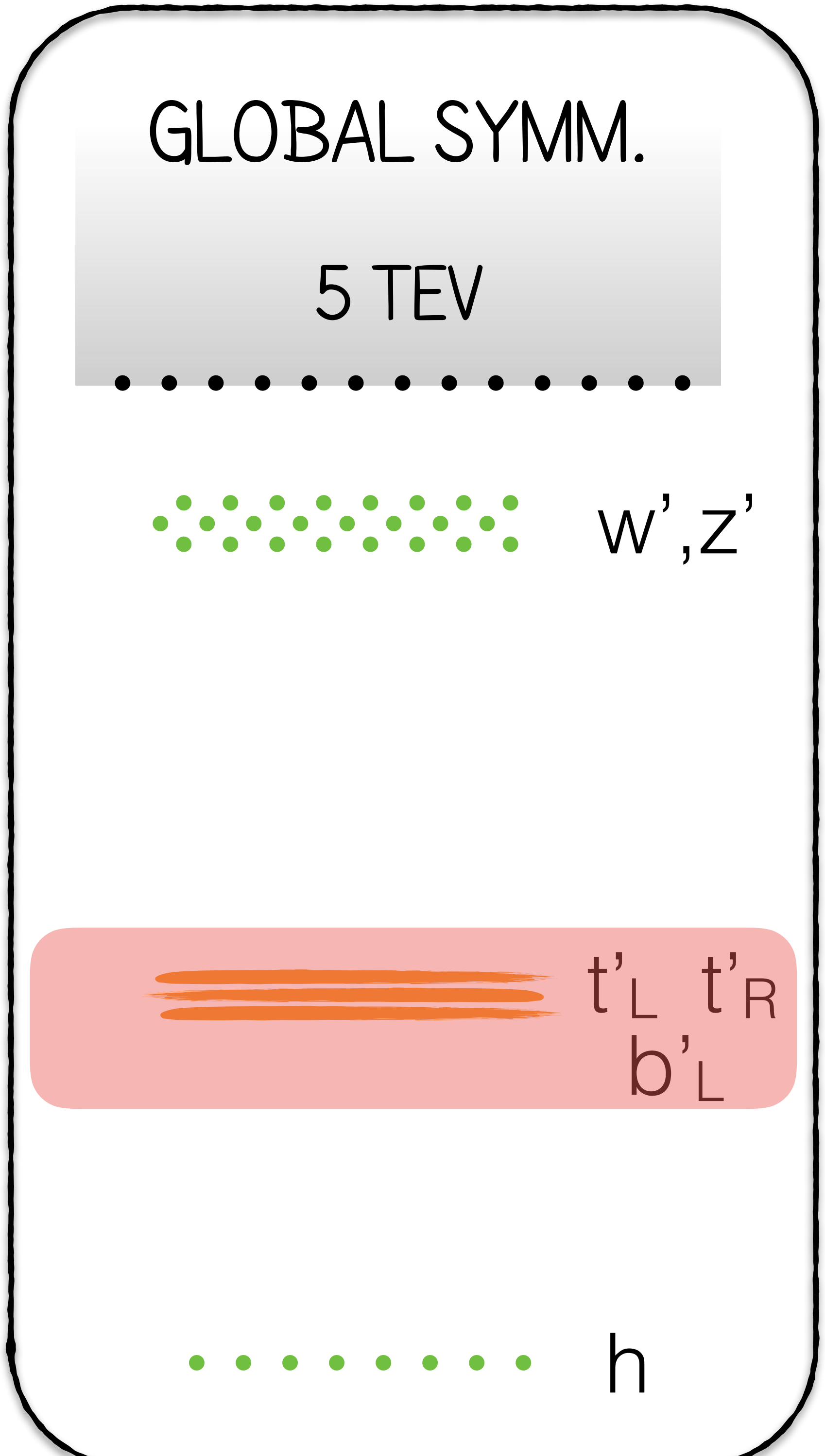
HIGGS IS A PNGB, MISALIGNED W/ SM VEV BY O(V/F)

LIMIT $V^2/F^2 < 0.1$

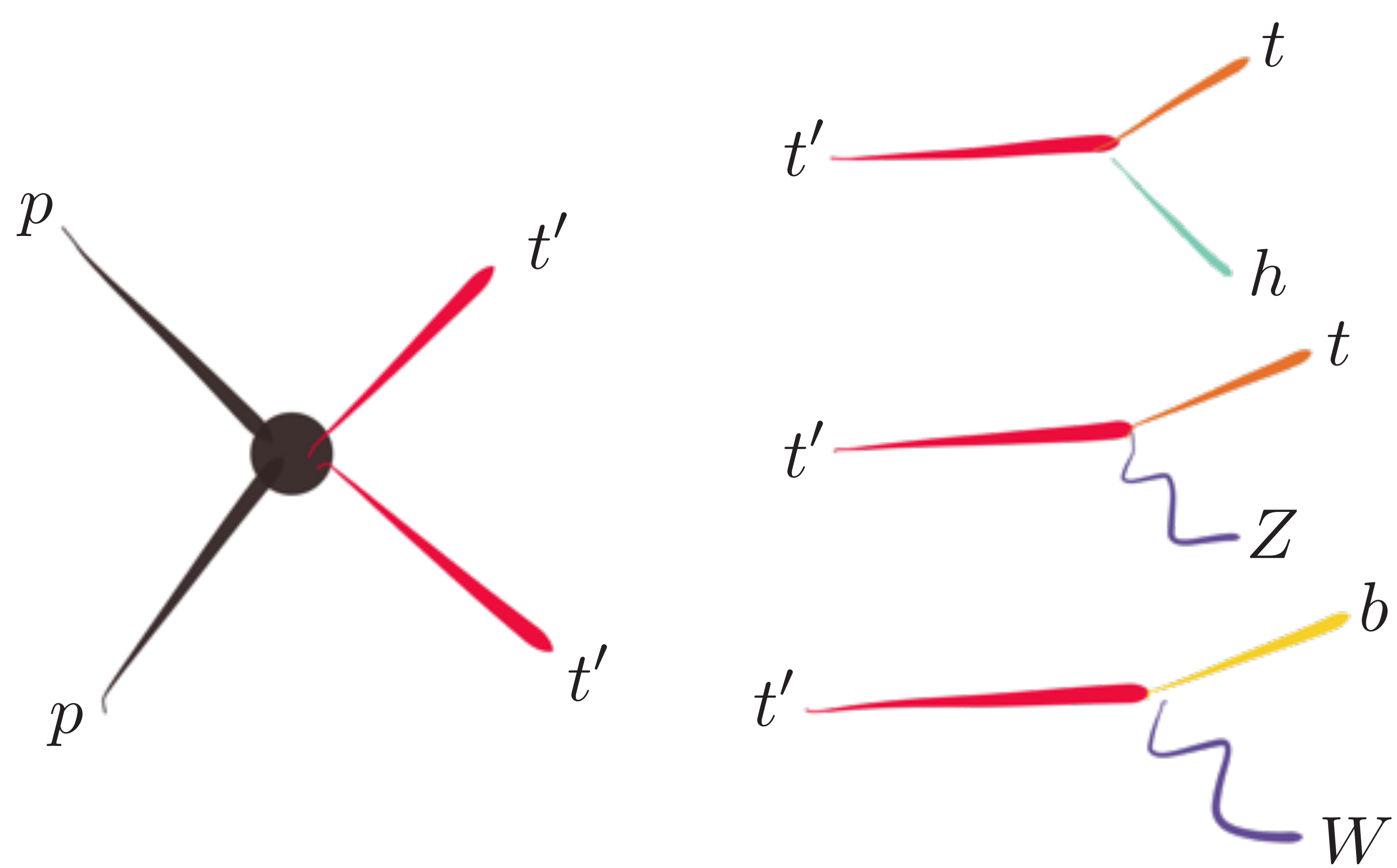
Δ~10 (10% TUNING)

UNLIKELY TO IMPROVE MUCH IN RUN 2

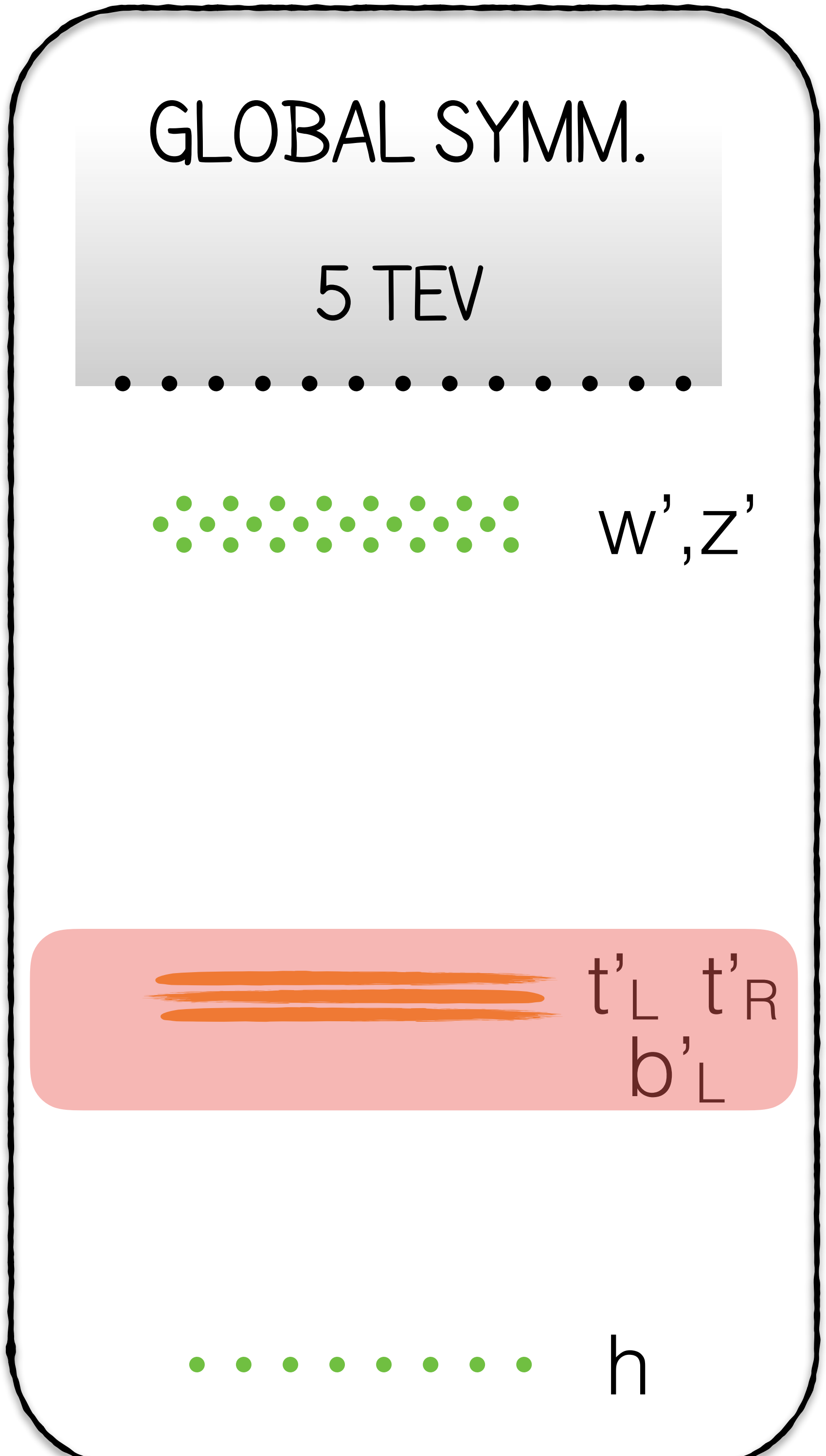
TOP PARTNER SIGNALS

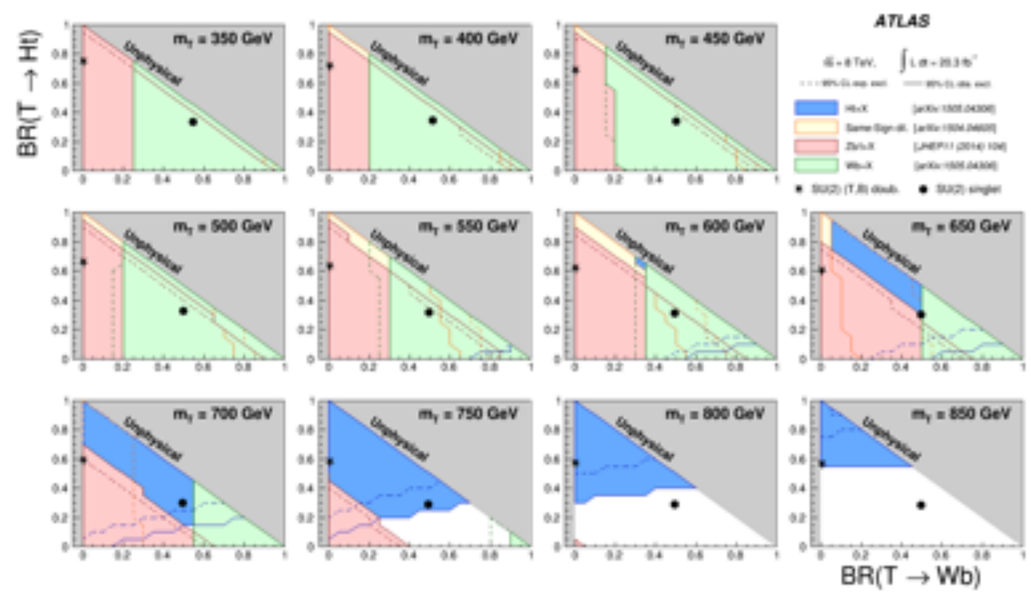


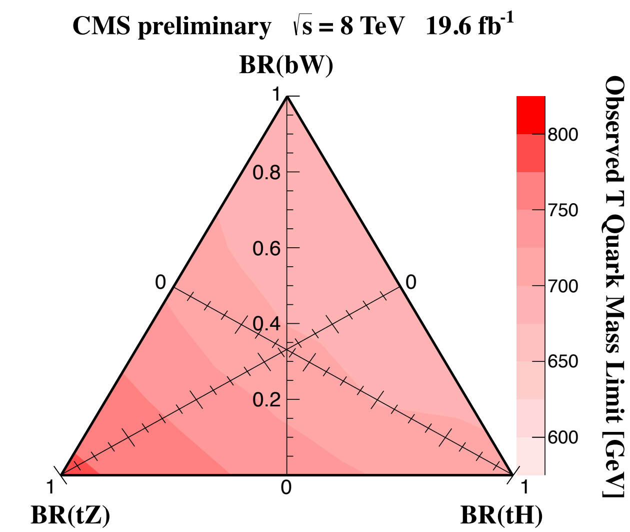
3RD-GENERATION VECTOR-LIKE QUARKS. EASIER GAME THAN SUSY: LARGER XSEC, NO MET NEEDED, SO FEWER HOLES. VARIOUS SM FINAL STATES.

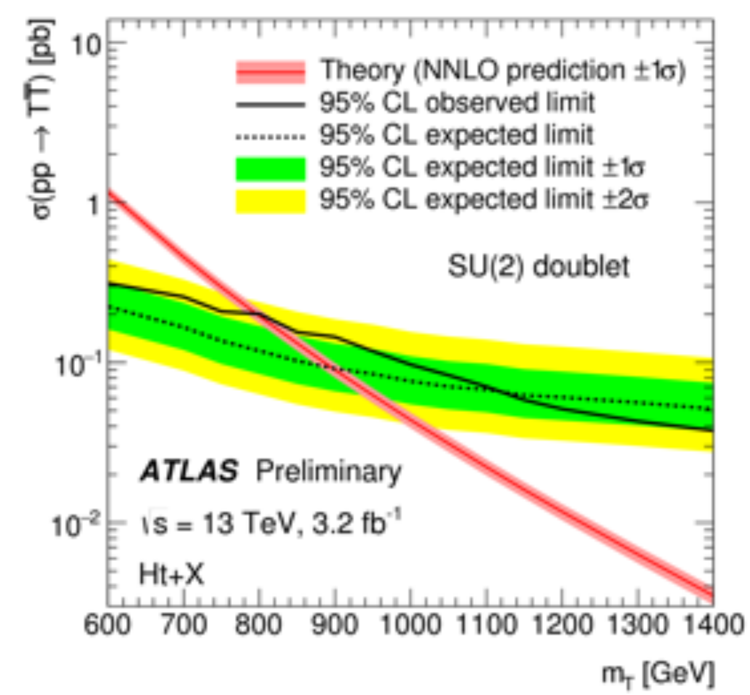


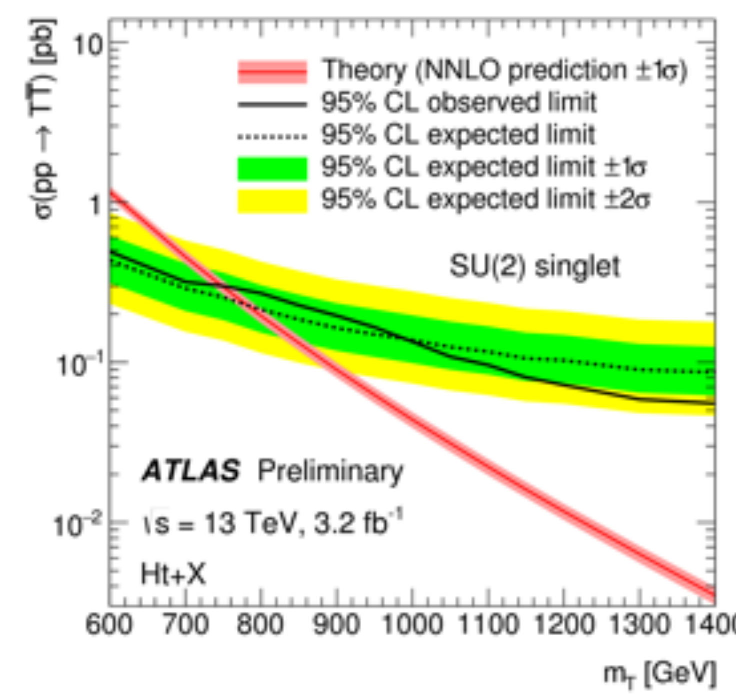
TOP PARTNER SIGNALS









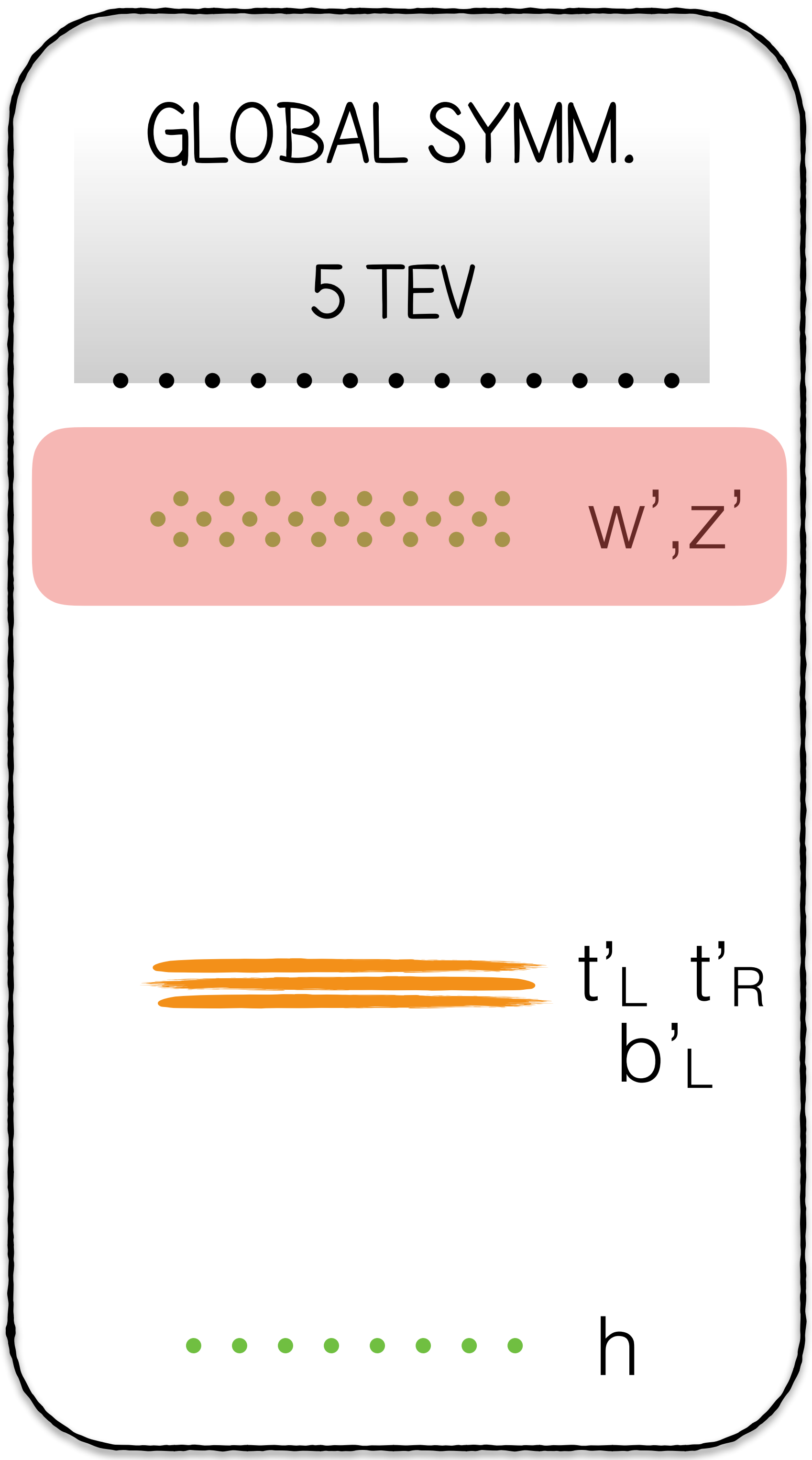


GENERIC LIMIT > 800 GEV (BOTH T')

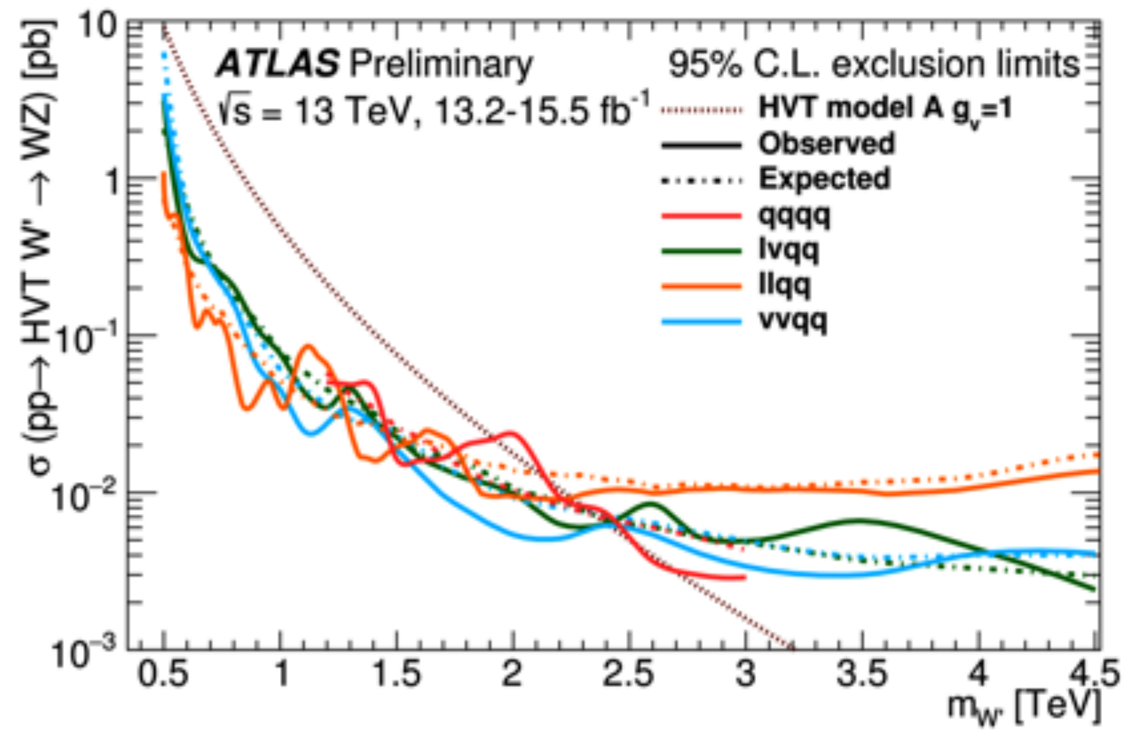
→ $\Delta \sim 30$ (3% TUNING)

(Λ = 5 TEV)

RESONANCE SIGNALS



WIDE VARIETY OF POSSIBLE RESONANCES & SIGNALS



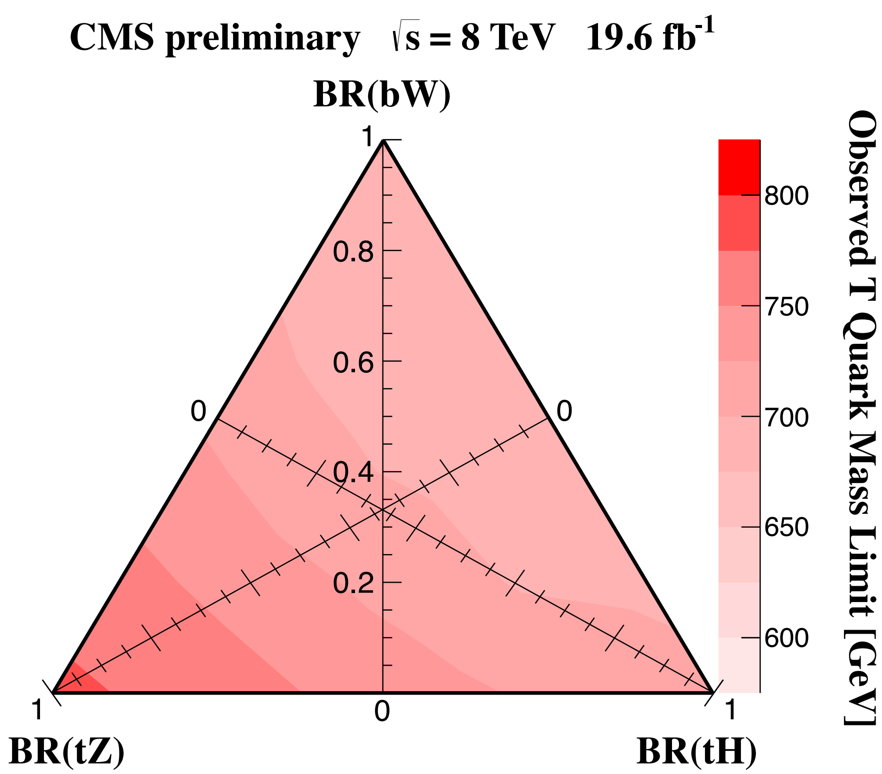
COMPARABLE TO PRECISION ELECTROWEAK LIMITS

$$S = 4\pi(1.36)\left(\frac{v}{m_\rho}\right)^2 \to m_\rho \gtrsim 3\ \mathrm{TeV}$$

GENERIC LIMIT > 3 TEV

→ **Δ~1 (NO TUNING)** (ON TOP OF V/F TUNING)

BREAKING THE GLOBAL SIGNAL

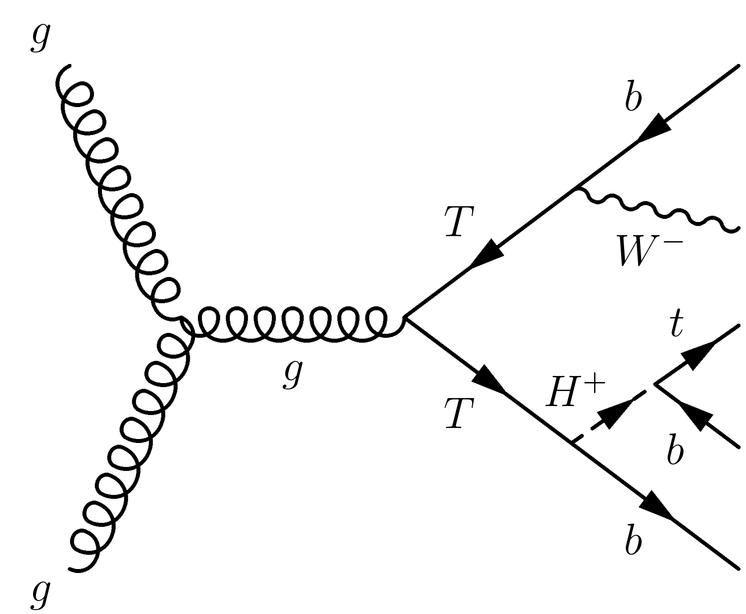


SEARCH FOR VECTOR-LIKE TOP PARTNERS ASSUMES DECAYS PROCEED INTO SM FINAL STATES (E.G. BW, TH, TZ)

CROSS SECTION LARGE ENOUGH THAT MISSING ENERGY UNNECESSARY, SO LESS KINEMATICALLY DELICATE THAN SUSY.

BUT: MANY COMPOSITE AND LITTLE HIGGS MODELS HAVE ADDITIONAL HIGGS SCALARS.

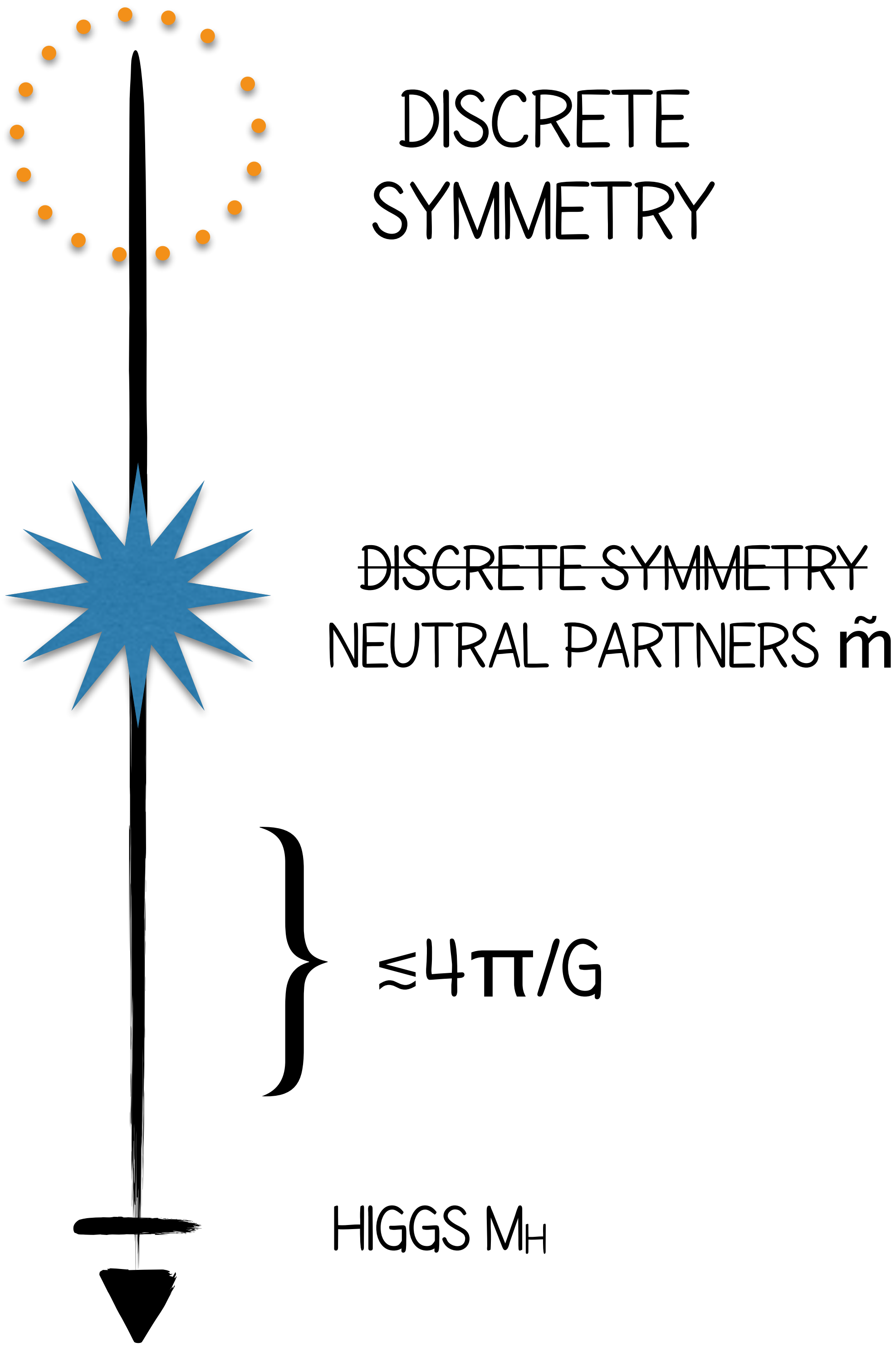
POSSIBLE/LIKELY FOR DECAYS TO PROCEED THROUGH ADDITIONAL HIGGSES, YIELDING NOVEL FINAL STATES.



[Kearney, Pierce, Thaler, '13]

BUT: IS THIS ALL THERE IS?

DISCRETE SYMMETRIES



SYMMETRY-BASED APPROACHES TO HIERARCHY PROBLEM EMPLOY *CONTINUOUS SYMMETRIES.*

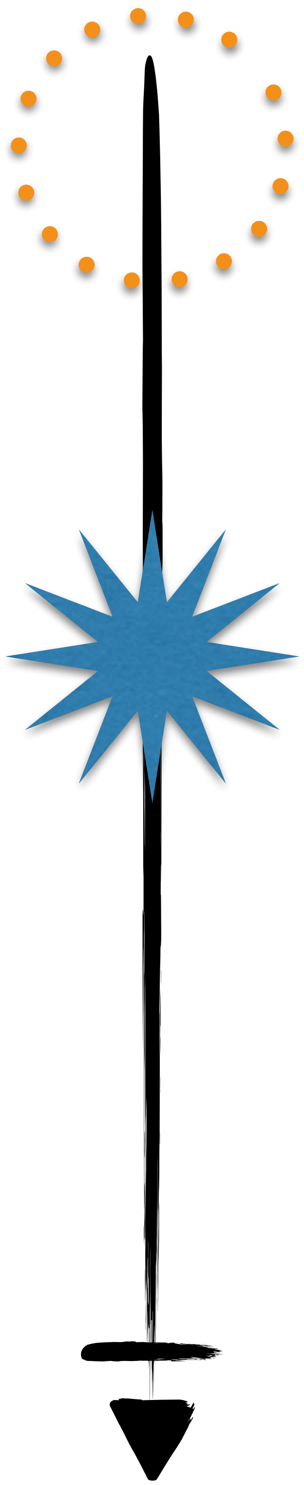
LEADS TO PARTNER STATES W/ SM QUANTUM NUMBERS.

DISCRETE SYMMETRIES CAN ALSO SERVE TO PROTECT THE HIGGS.

LEADS TO PARTNER STATES W/ NON-SM QUANTUM NUMBERS.

“NEUTRAL NATURALNESS”

AN EXAMPLE: TWIN HIGGS



STANDARD MODEL $\xleftrightarrow{Z_2}$ STANDARD MODEL

E.G., WEAK GAUGE SYMMETRY IS $SU(2)_{US} \times SU(2)_{TWIN}$

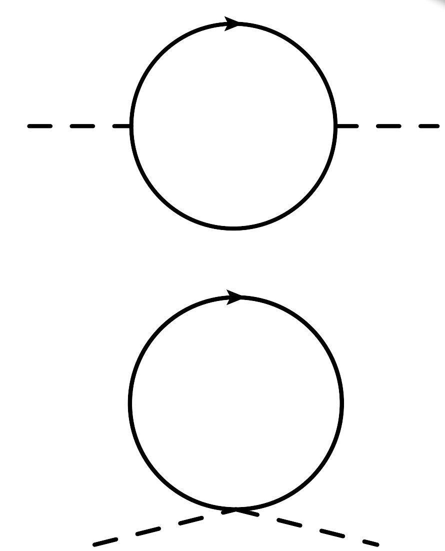
THANKS TO Z_2, RADIATIVE CORRECTIONS TO THE HIGGS MASS ARE SU(4) SYMMETRIC:

$$V(H) \supset \frac{9}{64\pi^2} g^2 \Lambda^2 \left(|H_A|^2 + |H_B|^2\right)$$

HIGGS IS A PNGB OF ~SU(4), BUT PARTNER STATES NEUTRAL UNDER SM.

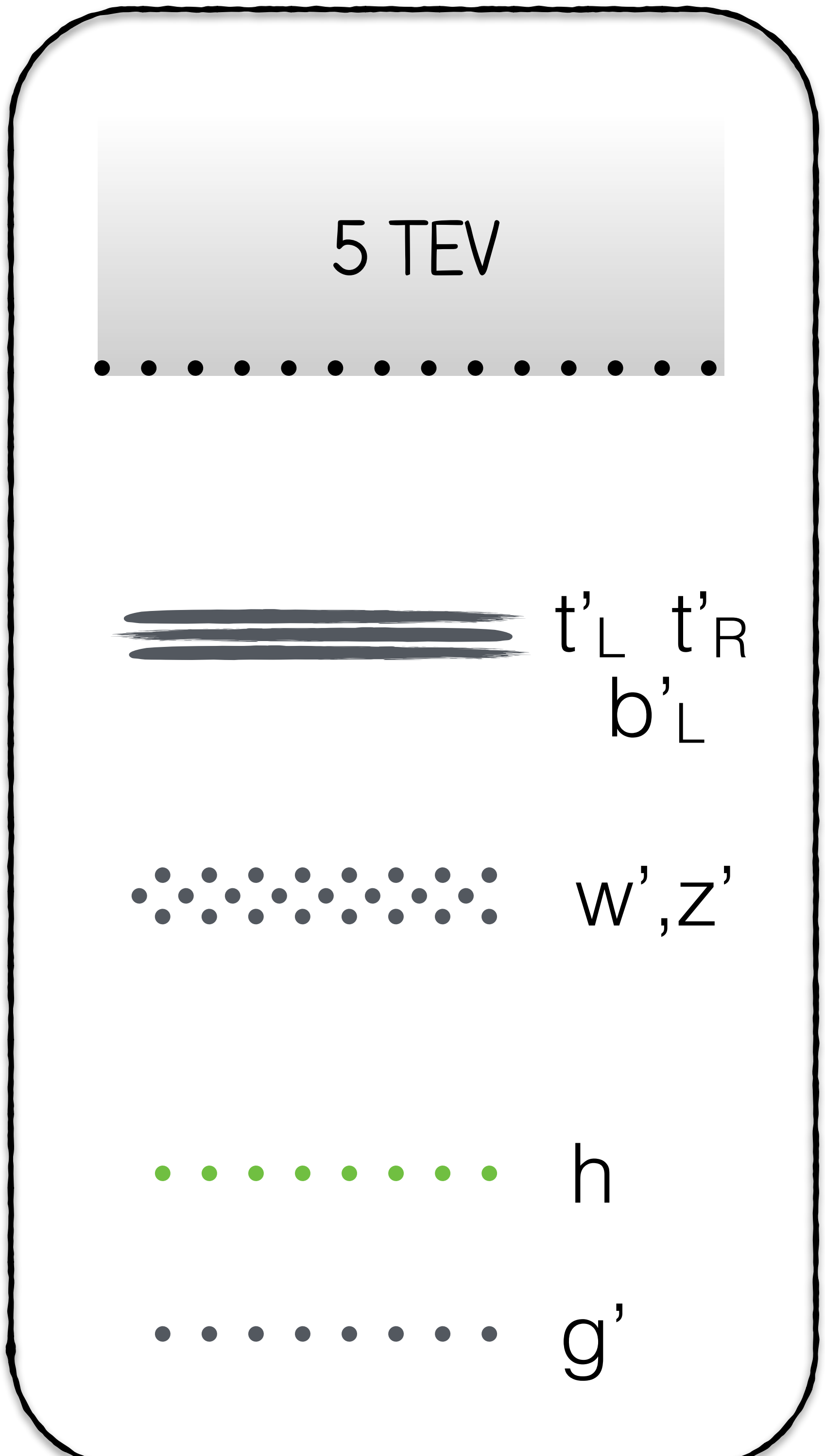
$$\mathcal{L} \supset -y_t H_A Q_3^A \bar{u}_3^A - y_t H_B Q_3^B \bar{u}_3^B$$

$H_A \to h + \ldots \qquad H_B \to f - \dfrac{h^2}{2f} + \ldots$



THERE ARE MANY MORE THEORIES OF THIS KIND...

"NEUTRAL" NATURALNESS



SIMPLEST THEORY: EXACT MIRROR COPY OF SM

[CHACKO, GOH, HARNIK '05]

BUT THIS IS MORE THAN YOU NEED, AND MIRROR 1ST, 2ND GENS LEAD TO COSMOLOGICAL PROBLEMS

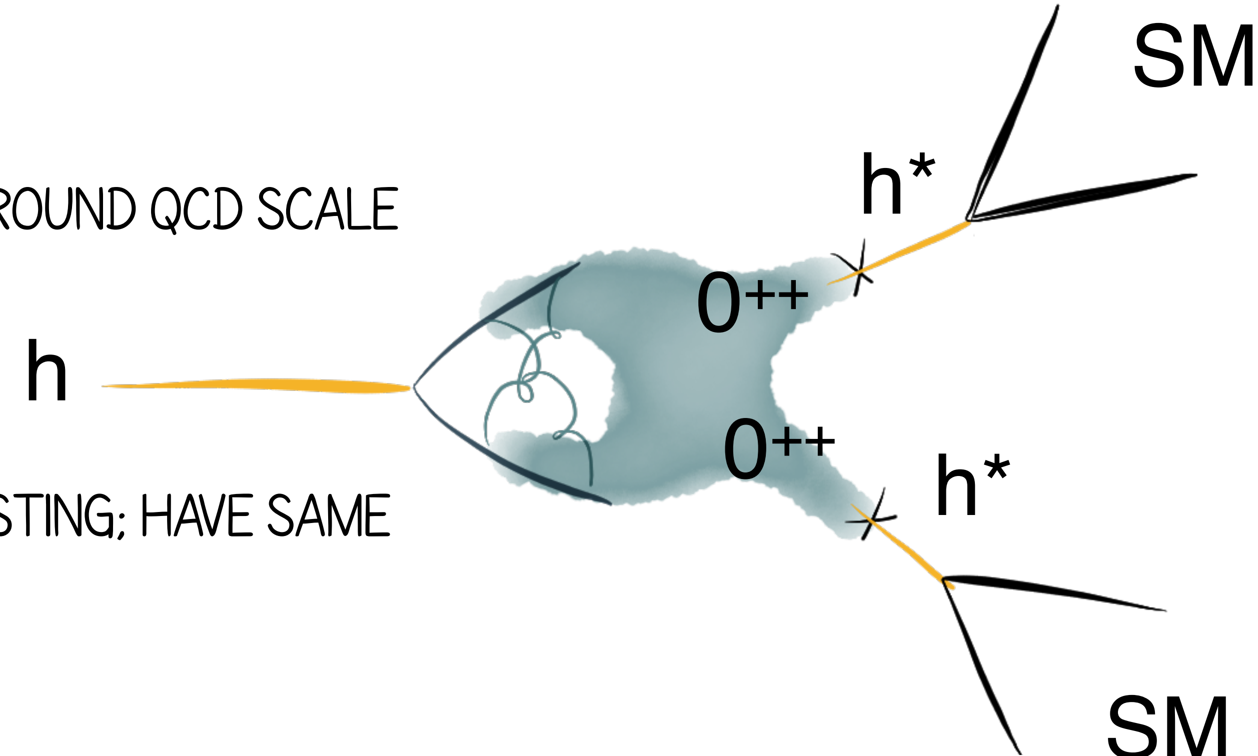
MANY MORE OPTIONS WHERE SYMMETRY IS APPROXIMATE, E.G. A GOOD SYMMETRY FOR HEAVIEST SM PARTICLES.

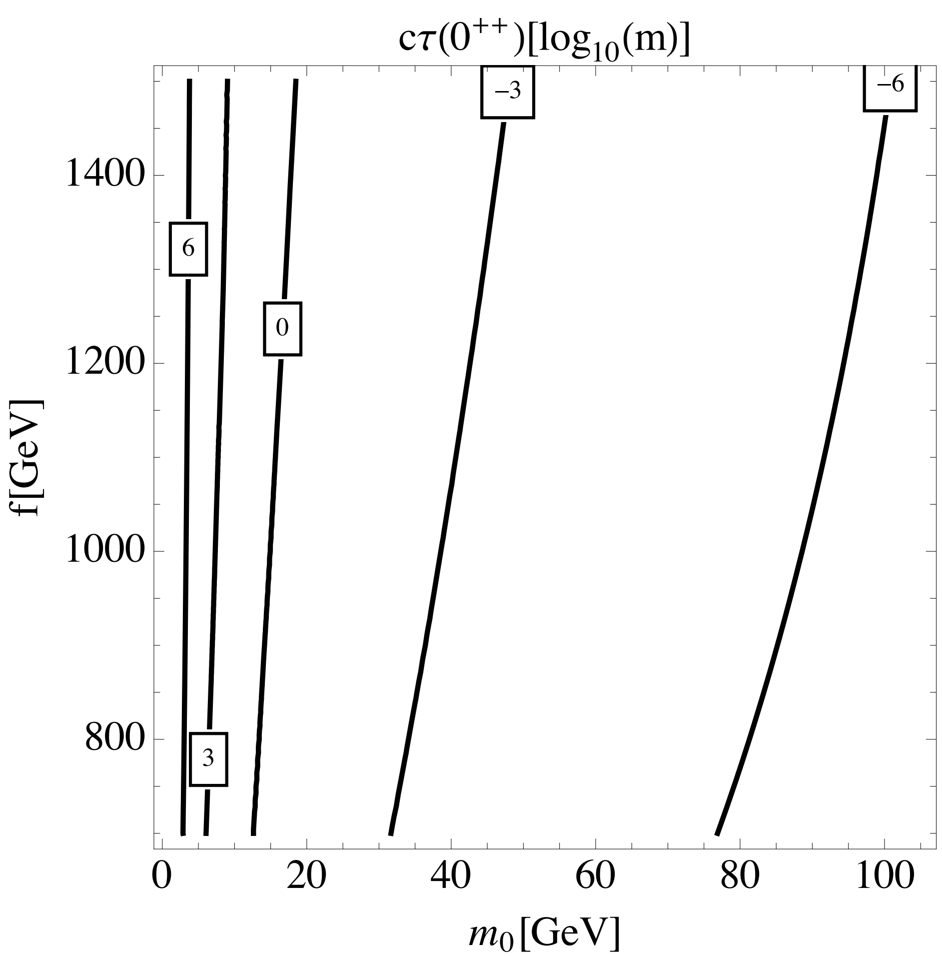
[NC, KNAPEN, LONGHI '14; GELLER, TELEM '14; NC, KATZ, STRASSLER, SUNDRUM '15; BARBIERI, GRECO, RATTAZZI, WULZER '15; LOW, TESI, WANG '15, NC, KNAPEN, LONGHI, STRASSLER '16]

[NC, Katz, Strassler, Sundrum '15; Curtin, Verhaaren '15; Chacko, Curtin, Verhaaren '16]

EXOTIC HIGGS DECAYS

- TWIN SECTOR MUST HAVE TWIN QCD, CONFINES AROUND QCD SCALE
- HIGGS BOSON COUPLES TO BOUND STATES OF TWIN QCD
- VARIOUS POSSIBILITIES. GLUEBALLS MOST INTERESTING; HAVE SAME QUANTUM # AS HIGGS





$$\mathcal{L} \supset -\frac{\alpha_3'}{6\pi}\frac{v}{f}\frac{h}{f}G'^{a}_{\mu\nu}G'^{\mu\nu}_{a}$$

PRODUCE IN RARE HIGGS DECAYS (BR~10^{-3}-10^{-4})

$$gg \to h \to 0^{++} + 0^{++} + \ldots$$

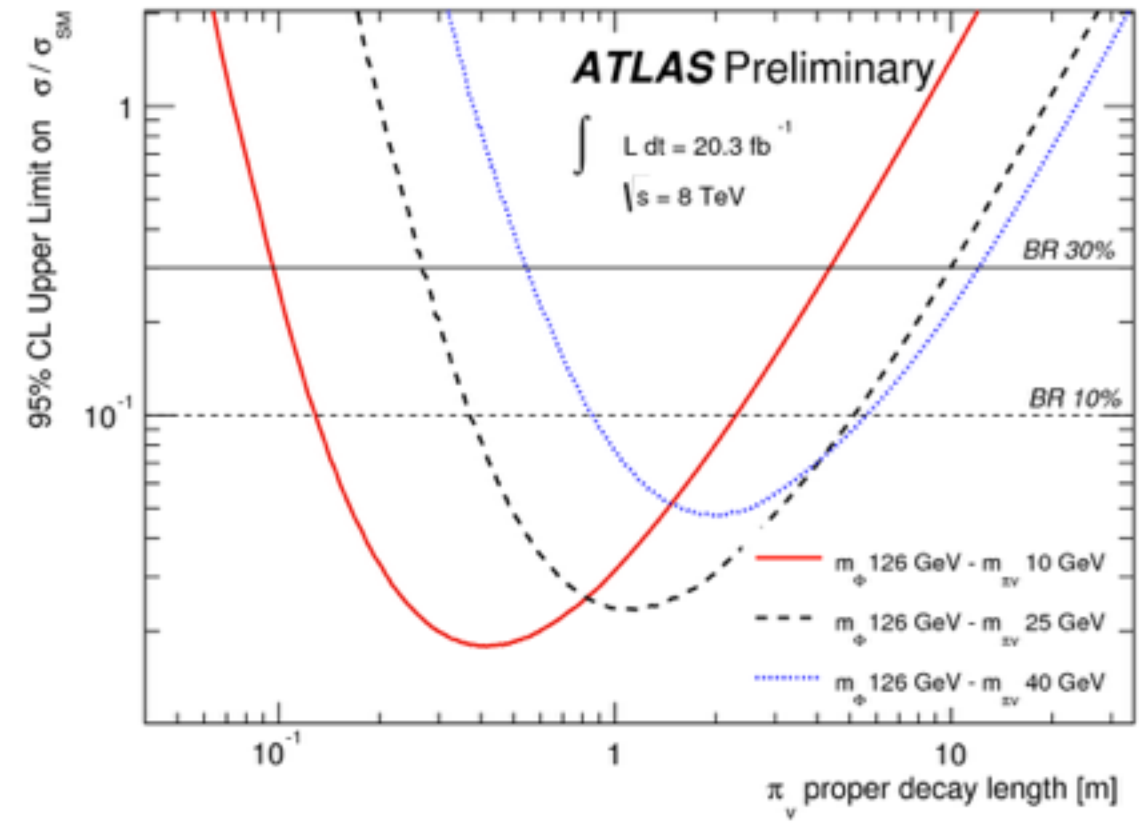
DECAY BACK TO SM VIA HIGGS

$$0^{++} \to h^* \to f\bar{f}$$

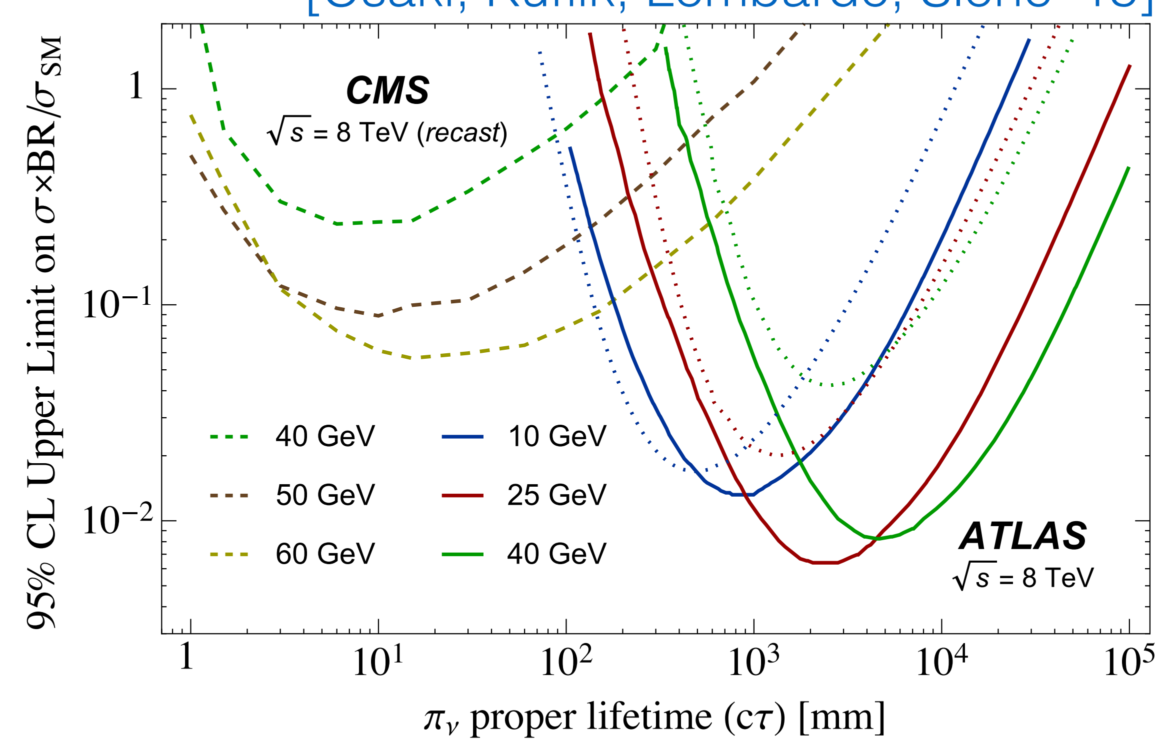
LONG-LIVED, DECAY LENGTH IS MACROSCOPIC; LENGTH SCALE ~ LHC DETECTORS

SEARCHING FOR MIRRORS

- ATLAS: HCAL/ECAL & MUON CHAMBER SEARCHES POWERFUL, SENSITIVE TO DISPLACED HIGGS DECAY.
- CMS: USE INNER TRACKER, SENSITIVITY TO SHORT DECAY LENGTHS. RELIANT ON VERTEXING, TRIGGER THRESHOLDS TOO HIGH FOR HIGGS DECAY.
- SIGNAL: DISPLACED DECAYS OF SM HIGGS WITH BR >10^{-3} (σ.BR~20FB @ RUN 1).
- MORE ROOM FOR INNOVATION IN THE DISPLACED DECAY SEARCH PROGRAM...



[Csaki, Kuflik, Lombardo, Slone '15]

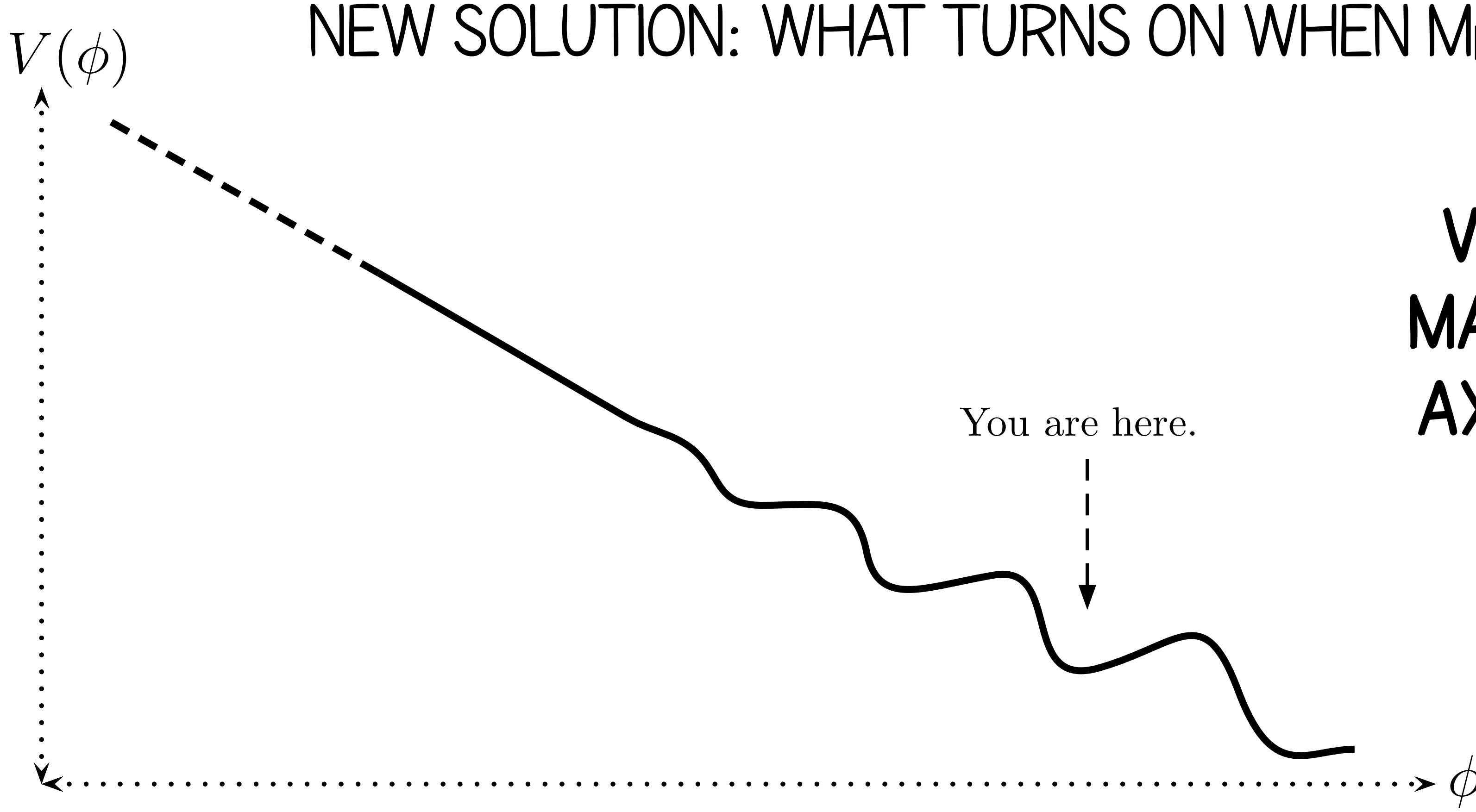


NOT SYMMETRIES?

WHAT IF THE WEAK SCALE IS SELECTED BY ***DYNAMICS****, NOT SYMMETRIES?*

OLD IDEA: COUPLE HIGGS TO FIELD WHOSE MINIMUM SETS $M_H = 0$
OLD PROBLEM: HOW TO MAKE $M_H = 0$ A SPECIAL POINT OF POTENTIAL?

NEW SOLUTION: WHAT TURNS ON WHEN M_H^2 GOES NEGATIVE?



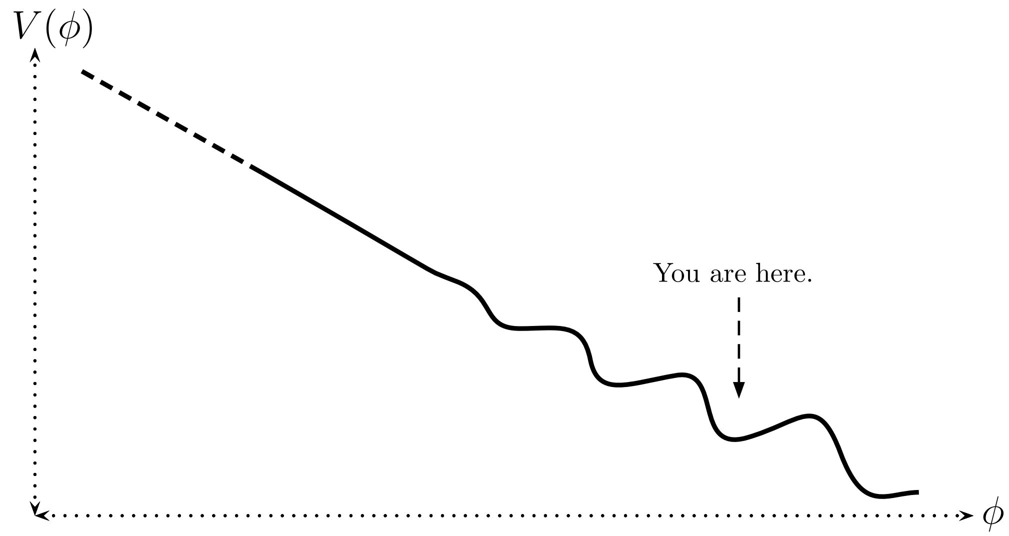
VEV GIVES **QUARK MASSES** WHICH GIVE **AXION POTENTIAL**!

"RELAXION"

[GRAHAM, KAPLAN, RAJENDRAN '15]

$$(-M^2 + g\phi)|H|^2 + V(g\phi) + \frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

$$\Rightarrow \quad (-M^2 + g\phi)|H|^2 + V(g\phi) + \Lambda^4 \cos(\phi/f)$$



BUT: IMMENSE ENERGY STORED IN ROLLING FIELD, STILL NEED TO STOP. **INFLATION** IS A GOOD SOURCE OF FRICTION.

JUST NEED HIGGS + NON-COMPACT AXION + INFLATION W/

- VERY LOW HUBBLE SCALE ($\ll \Lambda_{QCD}$)
- 10 GIGA-YEARS OF INFLATION

WARNING: LIKELY JUST TRANSFERRING FINE-TUNING TO INFLATIONARY SECTOR.

MINIMAL MODEL: CUTOFF IS $M < \left(\frac{\Lambda^4 M_P^3}{f}\right)^{1/6} \theta^{1/4} \sim 30 \text{ TeV} \times \left(\frac{10^9 \text{ GeV}}{f}\right)^{1/6} \left(\frac{\theta}{10^{-10}}\right)^{1/4}$

IN VACUUM, AXION GIVES O(1) CONTRIBUTION TO θ_{QCD}

NOT SYMMETRIES?

FIX: MAKE IT SOMEONE ELSE'S QCD + AXION

Field	$SU(3)_N$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
L	$\Box$	$-$	$\Box$	$-1/2$
L^c	$\overline{\Box}$	$-$	$\Box$	$+1/2$
N	$\Box$	$-$	$-$	0
N^c	$\overline{\Box}$	$-$	$-$	0

I.E. AXION OF A DIFFERENT SU(3); NEED TO TIE IN HIGGS VEV

1. NEW QUARKS MUST GET MOST OF MASS FROM HIGGS:

$$\mathcal{L} \supset m_L L L^c + m_N N N^c + y H L N^c + y' H^\dagger L^c N$$

2. MUST CONFINE, BUT WITH LIGHT FLAVOR $\Lambda^4 \simeq 4\pi f_{\pi'}^3 m_N$

...STILL NEW PHYSICS @ WEAK SCALE

NOW $$m_N \geq yy'v^2/m_L$$ (SMALLEST SEE-SAW MASS FROM EWSB IF L HEAVY)

BUT ALSO
$$\begin{cases} m_N \geq \frac{yy'}{16\pi^2} m_L \log(M/m_L) & \text{(RADIATIVE DIRAC MASS)} \\ m_N \geq yy' f_{\pi'}^2/m_L & \text{(HIGGS WIGGLES BIGGEST)} \end{cases}$$

THESE BOUNDS IMPLY $$f_{\pi'} < v \text{ and } m_L < \frac{4\pi v}{\sqrt{\log(M/m_L)}}$$

CAN'T DECOUPLE NEW DEGREES OF FREEDOM.
NEW CONFINING PHYSICS NEAR WEAK SCALE!

ELECTROWEAK PRODUCTION OF NEW FERMIONS (LOOK LIKE HIGGSINOS)
ALSO COUPLE TO HIGGS; CAN HAVE DECAY OF HIGGS INTO CONFINING SECTOR

ON ONE HAND, SPECULATIVE INDICATIONS OF BSM ARE ON, WELL, SPECULATIVE FOOTING!

ON THE OTHER HAND, THEY POINT TO DEEP & PROFOUND (RATHER THAN PIECEMEAL) CHANGES TO THE STRUCTURE OF THE SM, WHICH PERHAPS EXPLAINS THEIR APPEAL.

SUCCESSFUL ANSWERS TO THESE SPECULATIVE PROBLEMS OFTEN ALSO FULFILL OTHER INDICATIONS OF BSM PHYSICS (E.G. SUSY DARK MATTER, UNIFICATION, & BARYOGENESIS)

INVARIABLY PREDICT NEW STATES NEAR WEAK SCALE @ COLLIDERS.

CURRENT ERA IS A TIME OF OPPORTUNITY - POPULAR PARADIGMS UNDER STRESS, ROOM FOR INNOVATION.