BEYOND THE STANDARD MODEL @COLLIDERS

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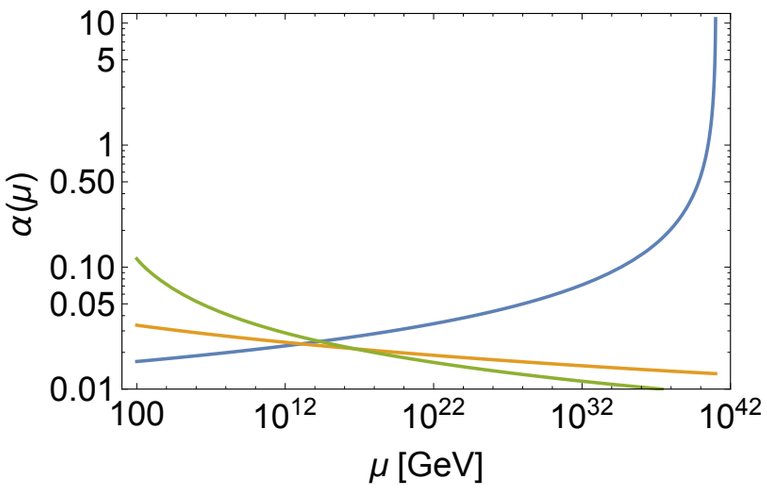
UC SANTA BARBARA

SSI 2016: NEW HORIZONS ON THE ENERGY FRONTIER

THE STANDARD MODEL IS INCOMPLETE

(1) "QUANTUM" GRAVITY CONSISTENT BUT NON-RENORMALIZABLE, DEMANDS UV COMPLETION AT THE PLANCK SCALE; PRESUMABLY ALSO INVOLVES SM*.

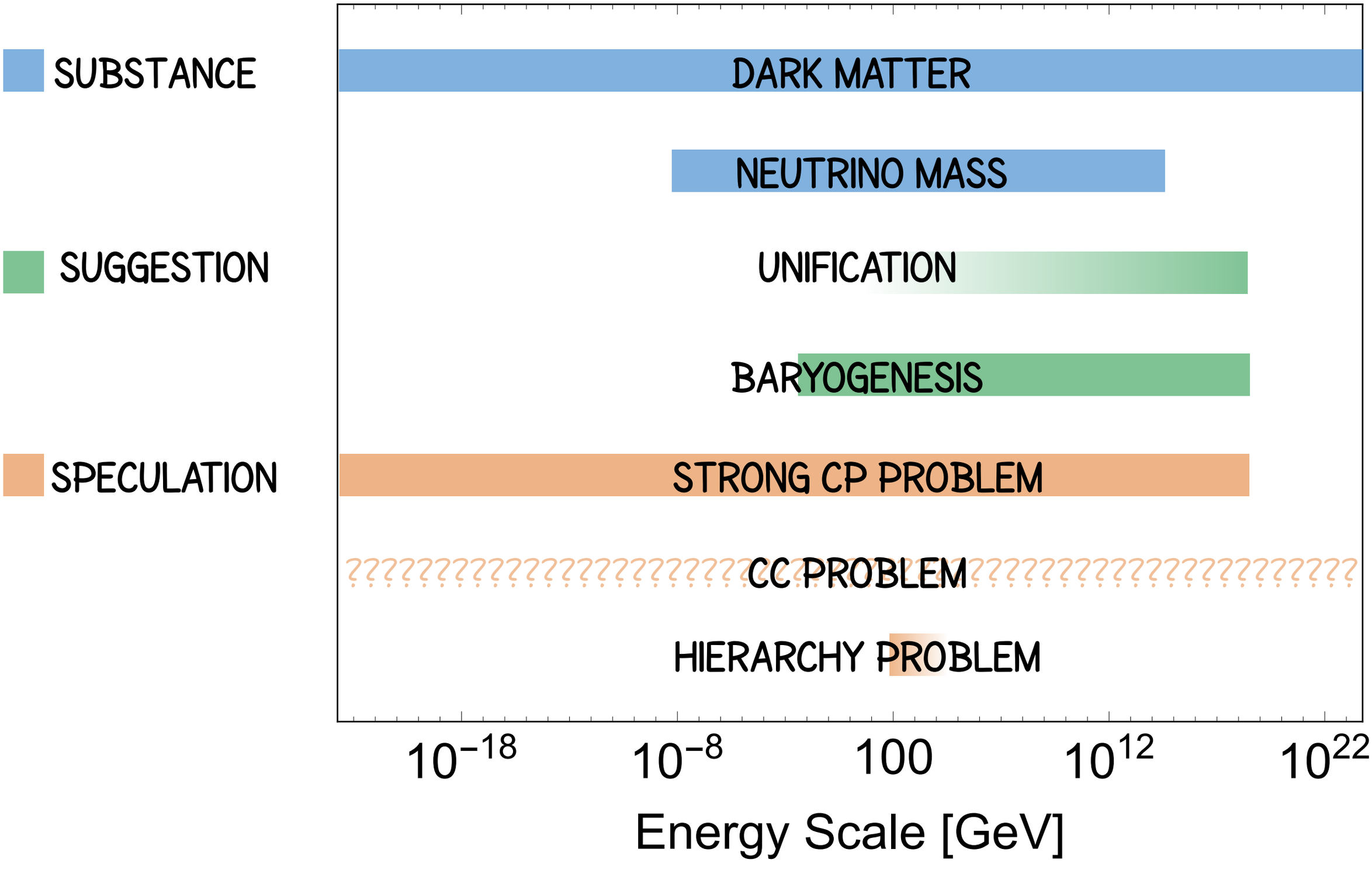
(2) WE HAVE INCONTROVERTIBLE EVIDENCE FOR ADDITIONAL FIELDS AND/OR OPERATORS BEYOND SM.



***WHAT IF GRAVITY DECOUPLES FROM SM IN THE UV?**

RUNNING SM GAUGE COUPLINGS INTO FAR UV EVENTUALLY GIVES LANDAU POLE IN $U(1)_Y$. WOULD CAUSE FERMIONS TO CONDENSE IN UV. SO UV COMPLETION OF SM IS UNAVOIDABLE!

BEYOND THE STANDARD MODEL



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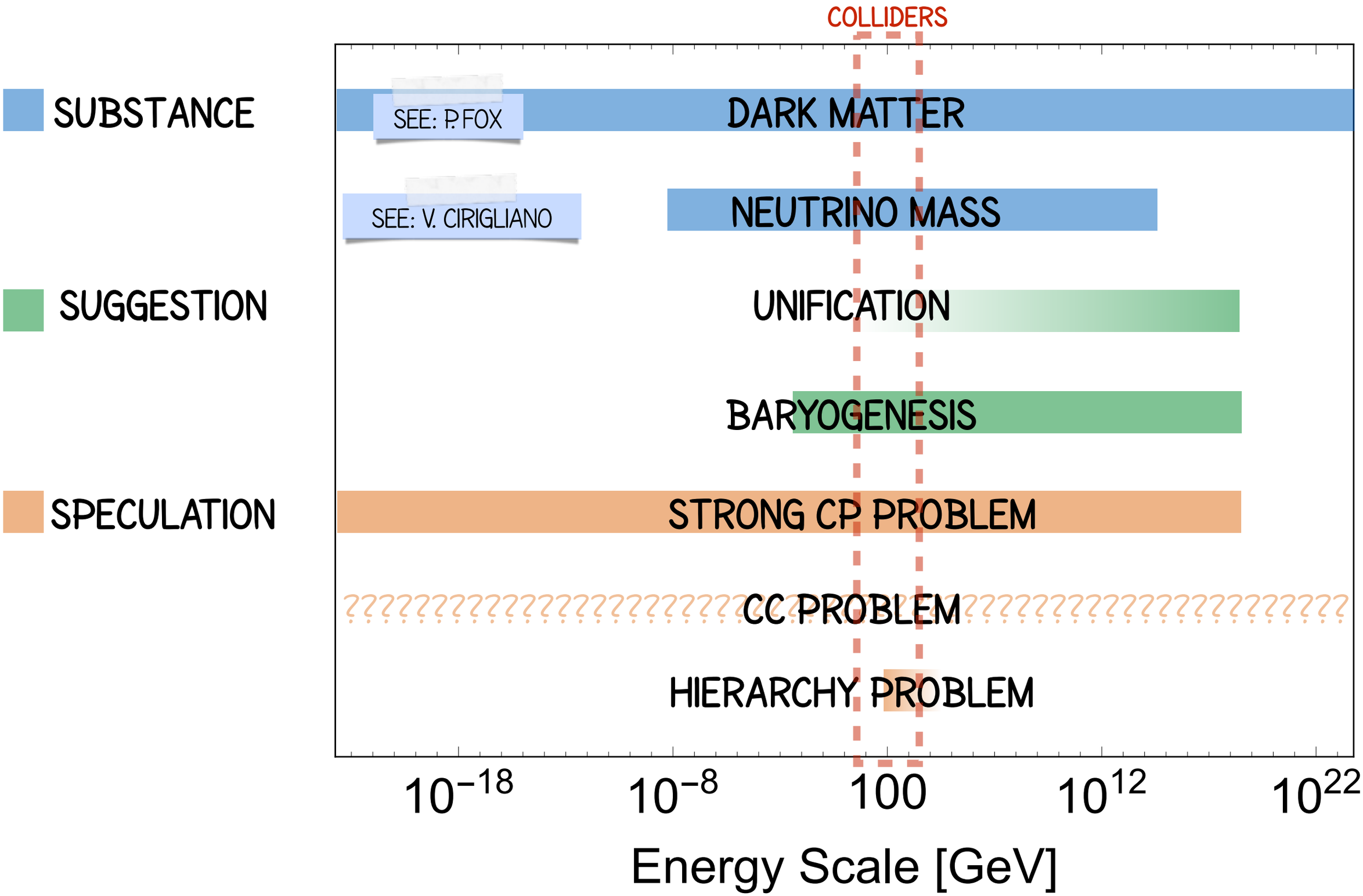

PART 1: SPECULATIVE BSM

SPECULATIVE BSM: THERE ARE PLACES WHERE THEORY PREFERENCES FOR PARAMETERS TO BE GENERIC BUMP UP AGAINST MEASURED QUANTITIES.

NATURALNESS CRITERIA

"**DIRAC NATURAL**:" IN THEORY WITH FUNDAMENTAL SCALE Λ,
NATURAL SIZE OF OPERATOR COEFFICIENTS IS

$$c_O = \mathcal{O}(1) \times \Lambda^{4-\Delta_O}$$

BORNE OUT COUNTLESS TIMES IN NATURE & SIMULATION.

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BORNE OUT COUNTLESS TIMES IN NATURE & SIMULATION.

"**TECHNICALLY NATURAL** ('T HOOFT):" COEFFICIENTS CAN BE MUCH SMALLER IF THERE IS AN ENHANCED SYMMETRY WHEN THE COEFFICIENT IS ZERO.

$$c_O = \mathcal{S} \times \mathcal{O}(1) \times \Lambda^{4-\Delta_O}$$

WHERE $\mathcal{S}$ IS A PARAMETER THAT VIOLATES SYMMETRY.

PHILOSOPHICAL UNDERPINNING: QUANTUM CORRECTIONS RESPECT SYMMETRY; IF SYMMETRY IS BROKEN, QUANTUM CORRECTIONS PROPORTIONAL TO SYMMETRY BREAKING.

NATURALNESS IN NATURE

DIRAC'S QUESTION: WHY IS $M_P \ll M_{PL}$?

18 ORDERS OF MAGNITUDE!

ANSWER: QCD SCALE IS DYNAMICALLY GENERATED BY LOGARITHMIC EVOLUTION OF QCD COUPLING: "DIMENSIONAL TRANSMUTATION"

$$m_p \sim \Lambda_{QCD} = M_{Pl} e^{\frac{2\pi}{b_3} \frac{1}{\alpha_s(M_{Pl})}}$$

THE DIMENSIONLESS COUPLING IS O(1), TOTALLY NATURAL

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FLAVOR HIERARCHIES

LARGE RANGE OF YUKAWAS, $y_e/y_t \sim 10^{-5} \quad y_\nu/y_t \sim 10^{-11}$

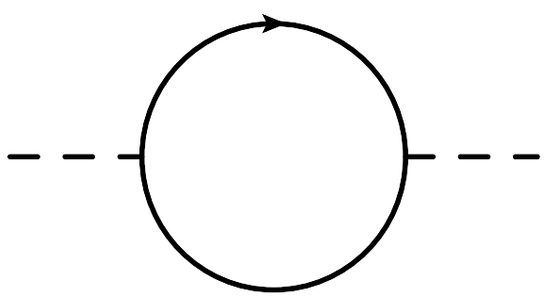
ANSWER: NOT DIRAC NATURAL, BUT TECHNICALLY NATURAL!

IN LIMIT $Y \to 0$, NEW SYMMETRY OF SM: $U(3)^5$ FLAVOR SYMMETRY

RADIATIVE CORRECTIONS TO YUKAWAS ARE PROPORTIONAL TO YUKAWAS
(IN SUCH A WAY THAT MAKES FLAVOR HIERARCHIES NUMERICALLY OK)

$\Delta_O = 2$
natural $\sim \mathcal{O}(1)\Lambda^2$

HIERARCHY PROBLEM



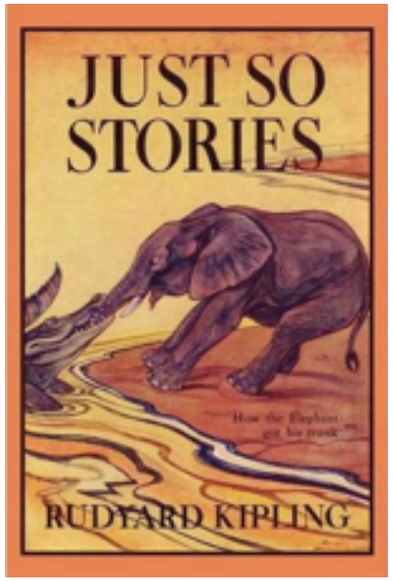
OFTEN HEARD:
"HIGGS MASS IS QUADRATICALLY DIVERGENT, STANDARD MODEL LOOPS UP TO CUTOFF Λ GIVE CONTRIBUTION:"

$$\delta m_H^2(\mu) = \frac{\Lambda^2}{16\pi^2}\left[6\lambda(\mu) + \frac{9}{4}g_2^2(\mu) + \frac{3}{4}g_Y^2(\mu) - 6\lambda_t^2(\mu)\right]$$

BUT THEN YOU REMEMBER: DIVERGENCES ARE NOT PHYSICAL, WE INTRODUCE COUNTERTERMS TO ABSORB THEM AND USE DATA TO FIX THE COUPLINGS!

WHY NOT CANCEL DIVERGENCE WITH COUNTERTERM? OR BETTER YET, USE A REGULARIZATION & RENORMALIZATION SCHEME WITHOUT DIVERGENCES, E.G. DIMENSIONAL REGULARIZATION WITH MINIMAL SUBTRACTION?

THIS IS NOT WHAT'S AT STAKE HERE. THE "QUADRATIC DIVERGENCE" ABOVE IS AN INDICATION OF THE PROBLEM, BUT NOT THE PROBLEM ITSELF. FIRST, SOME PHYSICS...



SCALARS ARE SPECIAL

MASS NOT TECHNICALLY NATURAL IN SM,

HIERARCHY PROBLEM IS NOT A "JUST-SO STORY"

FIELD	SYMMETRY AS $m \to 0$	IMPLICATION
SPIN-1/2 $m\Psi\bar{\Psi}$	$\Psi \to e^{i\alpha\gamma_5}\Psi$ (CHIRAL SYMMETRY)	$\delta m \propto m$ NATURAL!
SPIN-1 $m^2 A_\mu A^\mu$	$A_\mu \to A_\mu + \partial_\mu \alpha$ (GAUGE INVARIANCE)	$\delta m \propto m$ NATURAL!
SPIN-0 $m^2\lvert H\rvert^2$	NONE	$\delta m \propto \Lambda$ UNNATURAL!

TWO DEGREES OF DANGER

$$\delta m_H^2(\mu) = \frac{\Lambda^2}{16\pi^2}\left[6\lambda(\mu) + \frac{9}{4}g_2^2(\mu) + \frac{3}{4}g_Y^2(\mu) - 6\lambda_t^2(\mu)\right]$$

1. **THE STRONG FORM OF THE HIERARCHY PROBLEM**: THE FUNDAMENTAL THEORY IS *FINITE*. DIVERGENCES ENCOUNTERED IN AN EFFECTIVE THEORY ARE PHYSICAL (E.G. CUTOFF = LATTICE SPACING), COUNTERTERMS JUST IMPLEMENT TUNING. THE "QUADRATIC DIVERGENCE" IN THE SMEFT IS A DIRECT MEASURE OF FINE TUNING.

2. **THE WEAK FORM OF THE HIERARCHY PROBLEM:** LET US ONLY SPEAK OF OBSERVABLE QUANTITIES LIKE POLE MASSES. DIVERGENCES ARE UNPHYSICAL. THE "QUADRATIC DIVERGENCE" IN THE SMEFT IS A STAND-IN FOR FINITE THRESHOLD CORRECTIONS FROM *POSSIBLE* NEW PHYSICS.

THE STRONG FORM HOLDS TRUE IN ALL KNOWN EXTENSIONS OF THE STANDARD MODEL THAT ARE FINITE (E.G. SUPERSYMMETRY, STRING THEORY), I.E., WHEREVER THE HIGGS MASS CAN BE *PREDICTED*.

BUT EVEN THE WEAK FORM POSES AN IMMENSE DANGER.

(WEAK) HIERARCHY PROBLEM

CONSIDER A TOY MODEL WITH A SCALAR AND DIRAC FERMION:

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4!}\phi^4 + \bar{\Psi} i \not{\partial} \Psi - M\bar{\Psi}\Psi + y\phi\bar{\Psi}\Psi$$

IMAGINE WE ARRANGE FOR THE SCALAR TO BE MUCH LIGHTER, M << M.
WE CAN STUDY THE EFFECTIVE THEORY AT ENERGIES E << M.

THIS ENTAILS INTEGRATING OUT THE FERMIONS AT THE SCALE M AND MATCHING BETWEEN THE EFFECTIVE THEORY AND THE FULL THEORY.

THE HIERARCHY PROBLEM

IMAGINE COMPUTING THE SCALAR MASS IN THE EFFECTIVE THEORY WITH A HARD MOMENTUM CUTOFF Λ:

$$m_{eff}^2 = m^2 + \frac{y^2}{16\pi^2}\left[c_1\Lambda^2 + c_2 m^2 \ln\frac{\Lambda}{\mu} + c_3 M^2 + \mathcal{O}(M^4/\Lambda^2)\right]$$

OR WE CAN COMPUTE IT USING DIMENSIONAL REGULARIZATION IN $4-\epsilon$ DIMENSIONS WITH MINIMAL SUBTRACTION:

$$m_{eff}^2 = m^2 + \frac{y^2}{16\pi^2}\left[\frac{c_2}{\epsilon}m^2 + c_3 M^2 + \mathcal{O}(\epsilon)\right]$$

IN BOTH CASES, WE CAN WRITE THE ANSWER IN TERMS OF THE RENORMALIZED MASS $M^2(\mu=M)$:

$$m_{eff}^2(\mu = M) = m^2(\mu = M) + \frac{c_3 y^2}{16\pi^2} M^2$$

NO DEPENDENCE ON CUTOFF, BUT PHYSICAL DEPENDENCE ON M.

THE HIERARCHY PROBLEM

$$m^2_{eff}(\mu = M) = m^2(\mu = M) + \frac{c_3 y^2}{16\pi^2} M^2$$

SCALAR WANTS TO BE WITHIN A LOOP FACTOR OF THE DIRAC FERMION. TO KEEP SCALAR LIGHTER, NEED TO TUNE RENORMALIZED PARAMETERS OF THE FULL THEORY SO THERE IS A CANCELLATION ON THE RHS.

THIS REQUIRES A TUNING OF ORDER $\frac{y^2}{16\pi^2}\frac{m^2}{M^2}$

SEE FINE-TUNING IN TERMS OF RENORMALIZED PARAMETERS, INDEPENDENT OF REGULATOR; IT'S APPARENT EVEN IN DIM. REG. WHERE THERE ARE NO QUADRATIC DIVERGENCES.

THE INTUITION ABOUT QUADRATIC DIVERGENCES IS CORRECT IF WE ASSOCIATE $\Lambda \sim M$, *I.E., CUTOFF* $\sim$ *THRESHOLD.*

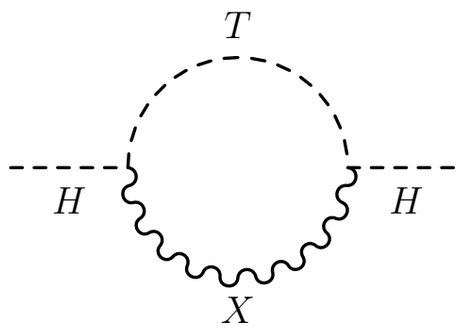
$$\delta m_H^2 \propto \frac{y^2}{16\pi^2}\Lambda^2$$

BSM STRIKES BACK

PROBLEM IS, ALL OF OUR OTHER MOTIVATED BSM THEORY INTRODUCES SUCH CORRECTIONS.

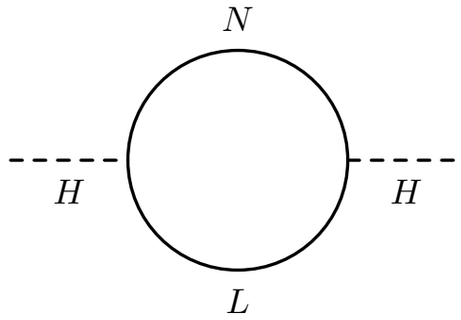
UNIFICATION

FINITE CORRECTIONS FROM LOOPS OF HEAVY GAUGE BOSONS/HIGGS TRIPLETS.



$$\delta m_H^2 \sim \frac{\alpha_{GUT}}{4\pi} M_{GUT}^2$$

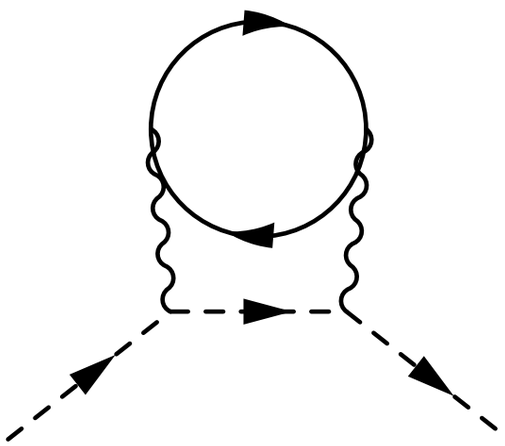
NEUTRINOS



FINITE CORRECTIONS FROM LEPTON + RHN

$$\delta m_H^2 = -\frac{1}{4\pi^2} \sum_{ij} |y_{ij}|^2 M_j^2$$

DARK MATTER



FINITE CORRECTIONS AT TWO LOOPS FROM WIMP DARK MATTER (I.E. LIVES IN SU(2) MULTIPLET)

$$\delta m_H^2 \sim \left(\frac{\alpha}{4\pi}\right)^2 \times g\left(\frac{m_W^2}{m_\Psi^2}\right) \times m_\Psi^2$$

Quantum numbers $\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	Spin	DM could decay into	DM mass in TeV	$m_{\mathrm{DM}^\pm} - m_{\mathrm{DM}}$ in MeV	Finite naturalness bound in TeV	σ_{SI} in $10^{-46}\,\mathrm{cm}^2$
2	1/2	0	EL	0.54	350	$0.4 \times \sqrt{\Delta}$	$(0.4 \pm 0.6)\,10^{-3}$
2	1/2	1/2	EH	1.1	341	$1.9 \times \sqrt{\Delta}$	$(0.3 \pm 0.6)\,10^{-3}$
3	0	0	HH^*	$2.0 \to 2.5$	166	$0.22 \times \sqrt{\Delta}$	0.12 ± 0.03
3	0	1/2	LH	$2.4 \to 2.7$	166	$1.0 \times \sqrt{\Delta}$	0.12 ± 0.03
3	1	0	HH, LL	$1.6 \to ?$	540	$0.22 \times \sqrt{\Delta}$	0.001 ± 0.001
3	1	1/2	LH	$1.9 \to ?$	526	$1.0 \times \sqrt{\Delta}$	0.001 ± 0.001
4	1/2	0	HHH^*	$2.4 \to ?$	353	$0.14 \times \sqrt{\Delta}$	0.27 ± 0.08
4	1/2	1/2	(LHH^*)	$2.4 \to ?$	347	$0.6 \times \sqrt{\Delta}$	0.27 ± 0.08
4	3/2	0	HHH	$2.9 \to ?$	729	$0.14 \times \sqrt{\Delta}$	0.15 ± 0.07
4	3/2	1/2	(LHH)	$2.6 \to ?$	712	$0.6 \times \sqrt{\Delta}$	0.15 ± 0.07
5	0	0	(HHH^*H^*)	$5.0 \to 9.4$	166	$0.10 \times \sqrt{\Delta}$	1.0 ± 0.2
5	0	1/2	stable	$4.4 \to 10$	166	$0.4 \times \sqrt{\Delta}$	1.0 ± 0.2
7	0	0	stable	$8 \to 25$	166	$0.06 \times \sqrt{\Delta}$	4 ± 1

GRAVITY STRIKES BACK

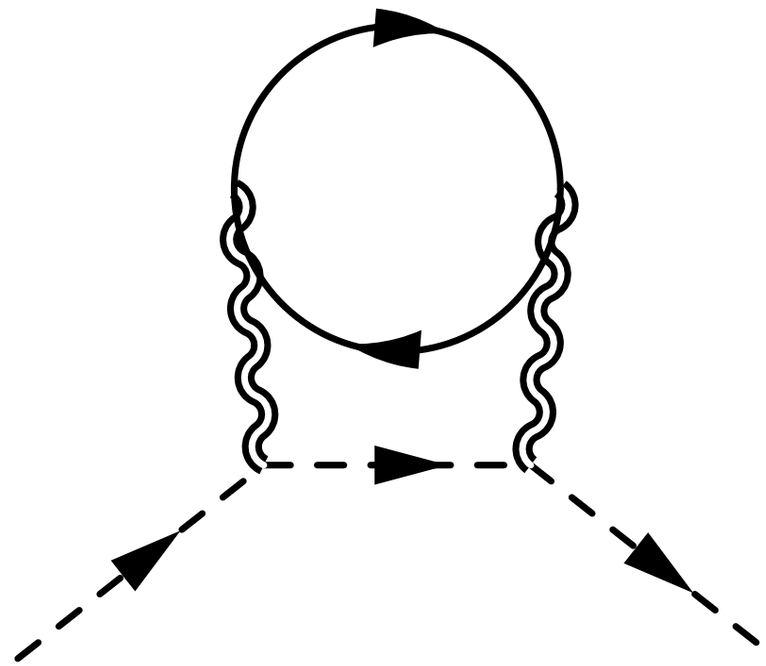
GRAVITY IS WORSE.

DON'T KNOW THE THEORY OF QUANTUM GRAVITY, BUT REASONABLE TO SUPPOSE IT CONTAINS NEW STATES WHOSE MASS IS OF ORDER M_{PL}

CONSIDER E.G. A HEAVY FERMION THAT ONLY COUPLES TO THE HIGGS THROUGH LOOPS OF GRAVITONS.

(CAN COMPUTE THIS USING QUANTUM GRAVITY EFT)

$$\delta m_H^2 \sim \frac{m_H^2}{(16\pi^2)^2} \frac{m_\Psi^4}{M_{Pl}^4}$$



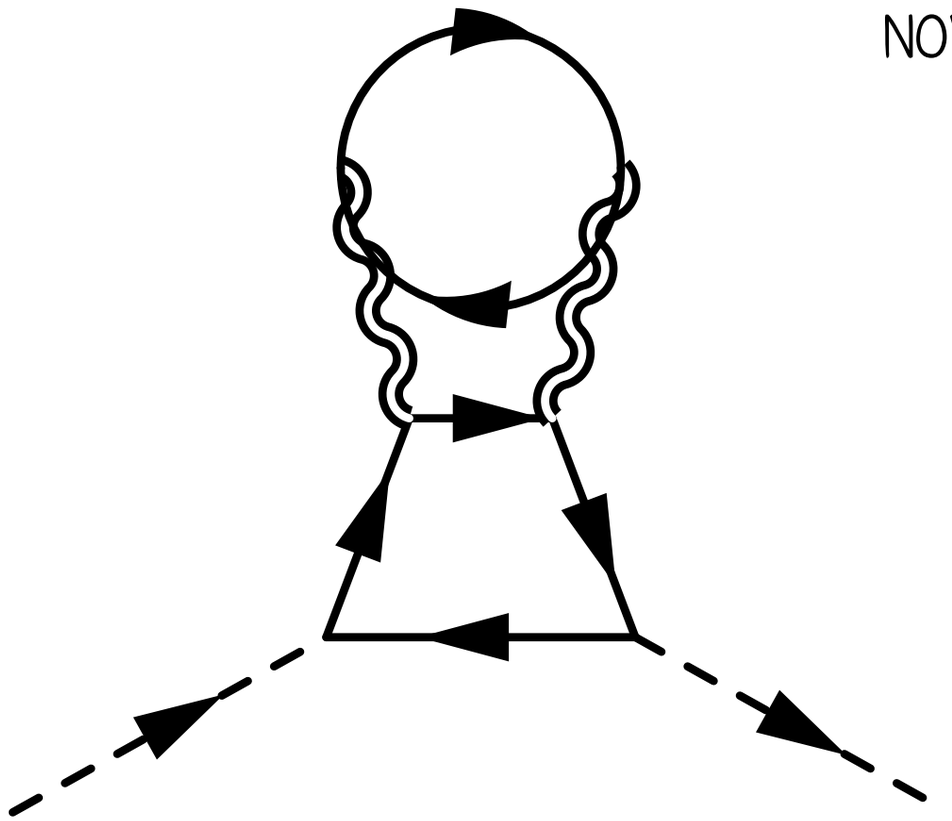
HEY WAIT, THAT'S NOT SO BAD!

(SMALL BECAUSE THE GRAVITON COUPLING TO A MASSLESS, ON-SHELL PARTICLE AT ZERO MOMENTUM VANISHES, SO RESULT IS PROPORTIONAL TO M_H)

GRAVITY STRIKES BACK HARDER

GRAVITY IS WORSE.

MEH, LET'S GO TO THREE LOOPS, SO THE GRAVITON COUPLES VIA A LOOP OF TOP QUARKS. TOP QUARKS ARE OFF SHELL, SO COUPLING NOT SUPPRESSED



NOW WE FIND A CORRECTION PROPORTIONAL TO MASS OF THE HEAVY FERMION,

$$\delta m_H^2 \sim \frac{6y_t^2}{(16\pi^2)^3}\frac{m_\Psi^6}{M_{Pl}^4}$$

SUMMING OVER ALL SM PARTICLES IN THE LOOP, THIS LOOKS LIKE OUR NAIVE ONE-LOOP QUADRATIC DIVERGENCE CALCULATION WITH

$$\Lambda \sim M_{Pl}/16\pi^2$$

SO EVEN HEAVY STUFF WITH PURELY GRAVITATIONAL COUPLINGS TO SM GIVES LARGE FINITE CORRECTIONS.

THE THREE-FOLD PATH

THREE POSSIBILITIES:

1. THE HIERARCHY PROBLEM IS NOT SOLVED DYNAMICALLY; THE HIGGS IS FINELY TUNED. PERHAPS THERE IS STILL AN EXPLANATION, E.G. ANTHROPICS.

NO FIRM ANTHROPIC BOUND EXISTS.

2. THE HIERARCHY PROBLEM IS SOLVED BECAUSE THERE IS NO HIERARCHY; THE FUNDAMENTAL CUTOFF OF THE HIGGS (OR THE WHOLE SM) IS NEAR THE WEAK SCALE.

NO EVIDENCE NEAR M_H.

3. THE HIERARCHY PROBLEM IS SOLVED BY NEW SYMMETRIES ENTERING NEAR THE WEAK SCALE THAT MAKES THE THEORY FINITE AND INSENSITIVE TO UV PHYSICS.

3. NEW SYMMETRIES

- AT A SCALE NOT FAR ABOVE THE HIGGS MASS, **NEW PHYSICS ASSOCIATED WITH SOME EXTENDED SYMMETRY** ENTERS.

- THE HIGGS MASS IS TECHNICALLY NATURAL IN THIS MORE SYMMETRIC THEORY.

- THE FUNDAMENTAL CUTOFF (E.G. QUANTUM GRAVITY) IS AT MUCH HIGHER SCALES; THE EXTENDED SYMMETRY PROTECTS THE HIGGS FROM THIS CUTOFF AND ANY OTHER PHYSICS AT HIGHER ENERGIES.

- NOW HIGGS MASS IS SENSITIVE TO FINITE CORRECTIONS FROM NEW PHYSICS SCALE; HIERARCHY PROBLEM IS RECAPITULATED UNLESS THIS SCALE IS CLOSE TO THE WEAK SCALE.

WHAT'S THE SCALE?

THE HIERARCHY PROBLEM IS SENSITIVITY TO HIGHER SCALES; QUANTIFY SENSITIVITY OF HIGGS MASS TO NEW PHYSICS VIA RATIO

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

A *GUIDEPOST* TO WHERE NEW PHYSICS SHOULD ENTER; IN THE SM WITH A UNIFORM CUTOFF Λ, SM LOOPS UP TO Λ GIVE

$$\delta m_H^2(\mu) = \frac{\Lambda^2}{16\pi^2}\left[6\lambda(\mu) + \frac{9}{4}g_2^2(\mu) + \frac{3}{4}g_Y^2(\mu) - 6\lambda_t^2(\mu)\right]$$

EXPECT NEW PHYSICS TO ENTER AND ALTER SM AT SOME SCALE*

$\Delta \lesssim 1$ (NO TUNING) REQUIRES $\Lambda \lesssim 500$ GEV;

$\Delta \lesssim 10$ (10%-LEVEL TUNING) REQUIRES $\Lambda \lesssim 1.6$ TEV;

$\Delta \lesssim 100$ (1%-LEVEL TUNING) REQUIRES $\Lambda \lesssim 5$ TEV.

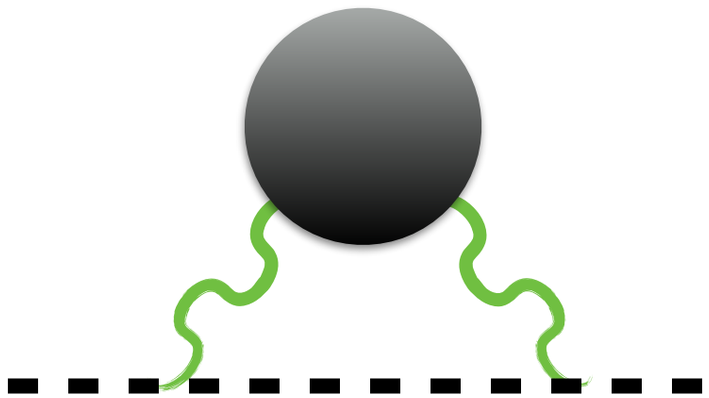
*BEST-CASE SCENARIO, NO LARGE LOGS

THE NATURALNESS STRATEGY

THIS IS A *STRATEGY* FOR NEW PHYSICS NEAR M_H, NOT A *NO-LOSE THEOREM*,
BECAUSE THE THEORY DOES NOT BREAK DOWN IF IT IS UNNATURAL.

BUT NATURALNESS HAS OFTEN BEEN A VERY *SUCCESSFUL* STRATEGY.
WE HAVE OTHER SCALARS IN NATURE, THANKS TO QCD.

E.G. CHARGED PIONS



PIONS ARE GOLDSTONES, BUT ELECTROMAGNETISM EXPLICITLY BREAKS GLOBAL SYMMETRY.

ELECTROMAGNETIC CONTRIBUTION TO THE CHARGED PION MASS
SENSITIVE TO THE CUTOFF OF THE PION EFT.

$$m^2_{\pi^\pm} - m^2_{\pi^0} = \frac{3\alpha}{4\pi}\Lambda^2$$

$$m^2_{\pi^\pm} - m^2_{\pi^0} = (35.5\,\mathrm{MeV})^2 \Rightarrow \Lambda < 850\,\mathrm{MeV}$$

RHO MESON (NEW PHYSICS!) ENTERS AT 770 MEV: $\Delta \sim 1$

POSSIBLE SYMMETRIES

WHAT SYMMETRIES MIGHT WE EMPLOY?

The Coleman-Mandula theorem (1967): *in a theory with non-trivial interactions (scattering) in more than 1+1 dimensions, the only possible conserved quantities that transform as tensors under the Lorentz group are the energy-momentum vector P_μ, the generators of Lorentz transformations $M_{\mu\nu}$, and possible scalar symmetry charges Z_i corresponding to internal symmetries, which commute with both P_μ and $M_{\mu\nu}$.*

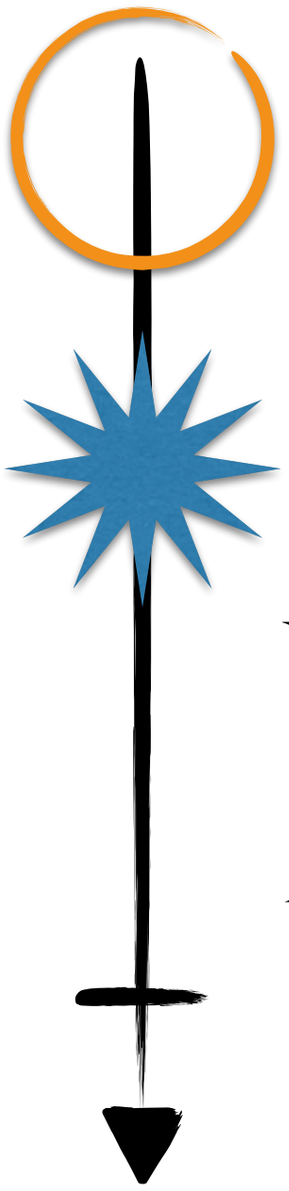
EXTENSION TO SPINOR SYMMETRY CHARGES BY HAAG, LOPUSZANSKI, SOHNIUS

SO THE OPTIONS ARE: **GLOBAL SYMMETRY** OR **SUPERSYMMETRY**

(CAN FANCY THE THEORY UP IN EXTRA DIMENSIONS, ETC., BUT 4D EFFECTIVE THEORY STILL USES ONE OF THESE SYMMETRIES)

POSSIBLE SYMMETRIES

EXTEND THE SM WITH A SYMMETRY ACTING ON THE HIGGS



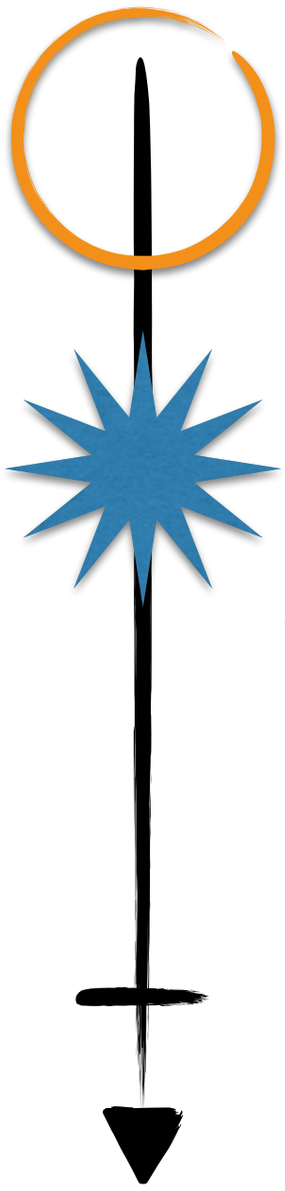
SUPERSYMMETRY

~~SUPERSYMMETRY~~

SPARTICLES $\tilde{m}$

$\lesssim 4\pi/G$

HIGGS M_H



GLOBAL SYMMETRY

~~GLOBAL SYMMETRY~~

PARTNER PARTICLES $\tilde{m}$

$\lesssim 4\pi/G$

HIGGS M_H

NEW PARTICLES

CONTINUOUS SYMMETRIES COMMUTING W/ SM →
PARTNER STATES W/ SM QUANTUM NUMBERS

SUPERSYMMETRY

$$\phi \to \phi + \epsilon\psi$$
$$\psi \to \psi + c^\mu \partial_\mu \phi$$

OPPOSITE-STATISTICS PARTNER
FOR EVERY SM PARTICLE

GLOBAL SYMMETRY

$$\Phi \to (1 + i\alpha T)\Phi$$

SAME-STATISTICS PARTNER
FOR EVERY SM PARTICLE

CONTRIBUTE TO THE HIGGS MASS:

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

SUPERSYMMETRY

SPIN	0	1/2	1
	$\tilde{Q}_I$	Q_I	
	$\tilde{\bar{u}}_I$	$\bar{u}_I$	
	$\tilde{\bar{d}}_I$	$\bar{d}_I$	
	$\tilde{L}_I$	L_I	
	$\tilde{\bar{e}}_I$	$\bar{e}_I$	
		$\tilde{g}$	g
		$\tilde{W}^{\pm,0}$	$W^{\pm,0}$
		$\tilde{B}$	B
	H_u	$\tilde{H}_u$	
	H_d	$\tilde{H}_d$	

BOSE-FERMI SYMMETRY, PREDICTS OPPOSITE-STATISTICS PARTNER FOR EVERY STATE IN THE SM. E.G. SCALAR PARTNERS FOR FERMIONS, FERMIONIC PARTNERS FOR SCALARS & GAUGE BOSONS. COUPLINGS DICTATED BY SYMMETRY

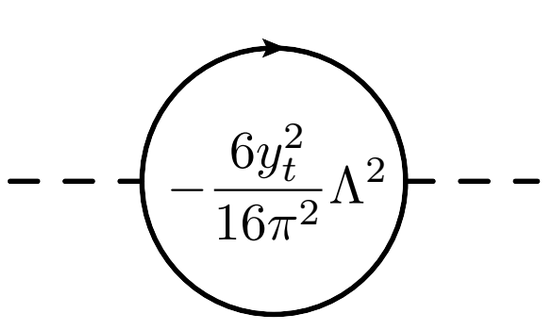
NEED EXTENDED HIGGS SECTOR IN ORDER TO WRITE DOWN ALL SM YUKAWA COUPLINGS

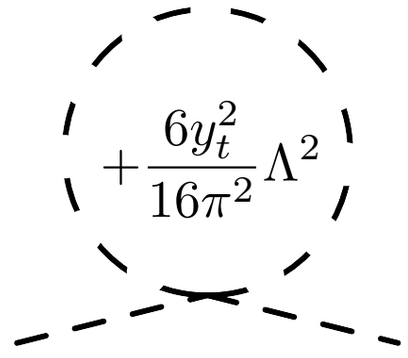
SUPERSYMMETRY

NEW INTERACTIONS RELATED BY SUPERSYMMETRY TO SM INTERACTIONS. E.G. IN TOP-STOP SECTOR,

$$\mathcal{L} \supset y_t H Q_3 t_R^\dagger + |y_t|^2 |H \cdot \tilde{Q}_3|^2 + |y_t|^2 |H|^2 |\tilde{t}_R|^2$$

TO SEE THAT SYMMETRY ELIMINATES UV SENSITIVITY, COMPUTE "QUADRATIC DIVERGENCE", WHICH CANCELS BETWEEN TOP & STOP LOOPS

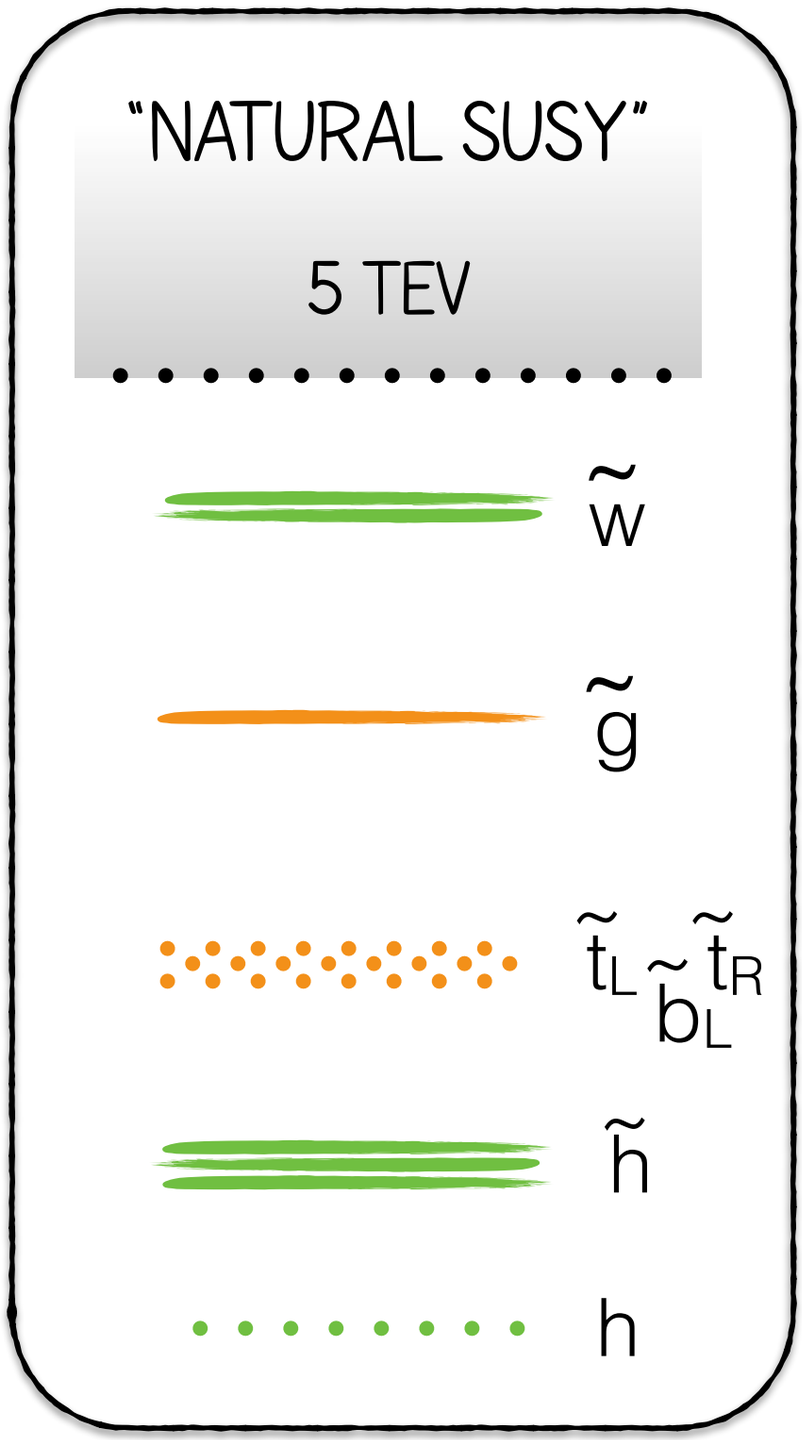




LEAVES ONLY FINITE THRESHOLD CORRECTION $m_H^2 \sim -\frac{6y_t^2}{16\pi^2}\tilde{m}_t^2$

SUPERSYMMETRY PROTECTS AGAINST ARBITRARY PHYSICS AT HIGH SCALES, BUT SUPERPARTNERS MUST ENTER NEAR WEAK SCALE.

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

"NATURAL SUSY"

5 TEV

$\tilde{W}$

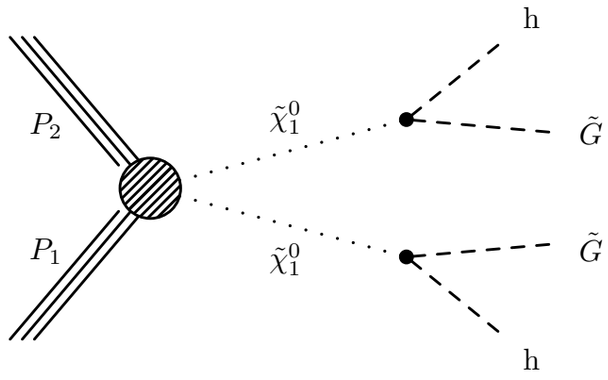
$\tilde{g}$

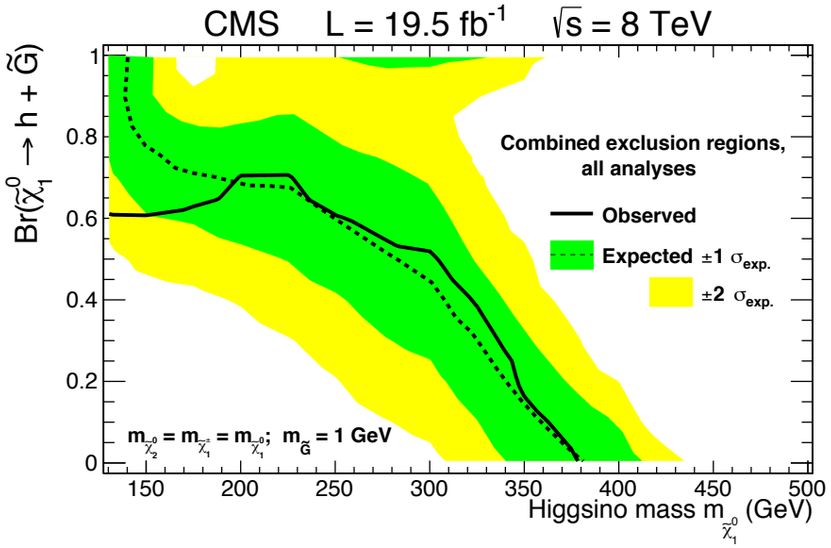
$\tilde{t}_L$ $\tilde{b}_L$ $\tilde{t}_R$

$\tilde{h}$

h

LOTS OF SEARCHES...

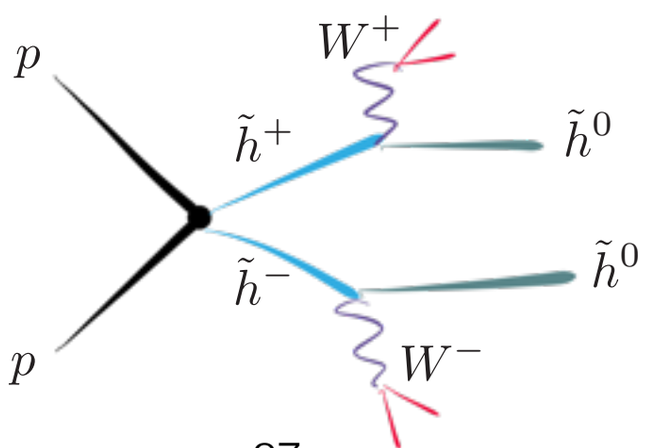


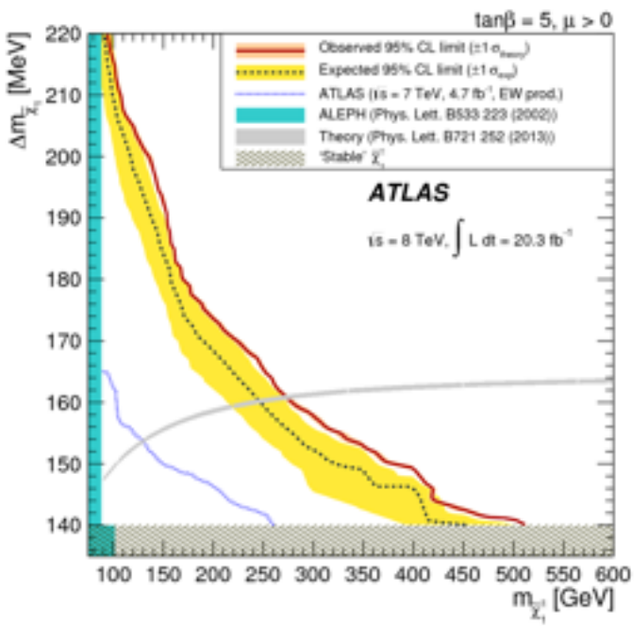


...BUT NO IRREDUCIBLE LIMITS

CHARGINO-NEUTRALINO SPLITTING IN PURE HIGGSINO MULTIPLET: 355 MEV

[THOMAS, WELLS '98]





STOP SIGNALS

"NATURAL SUSY"

5 TEV

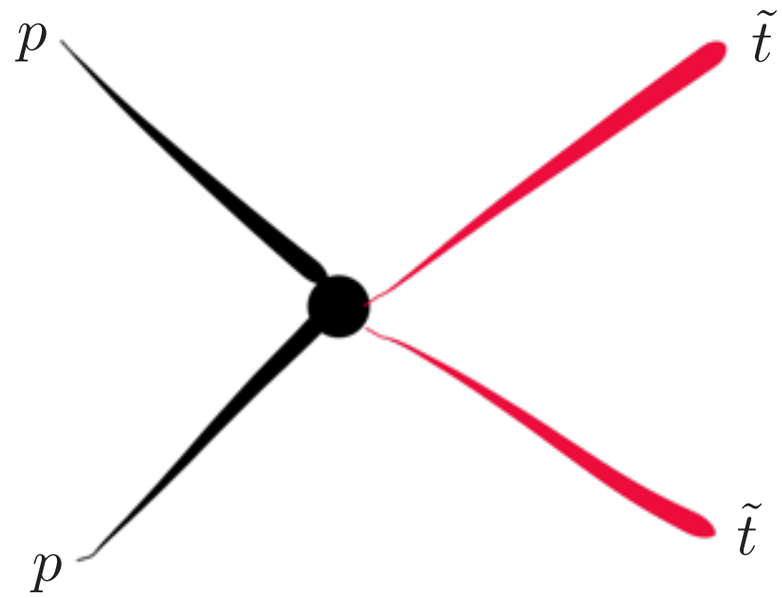
$\tilde{W}$

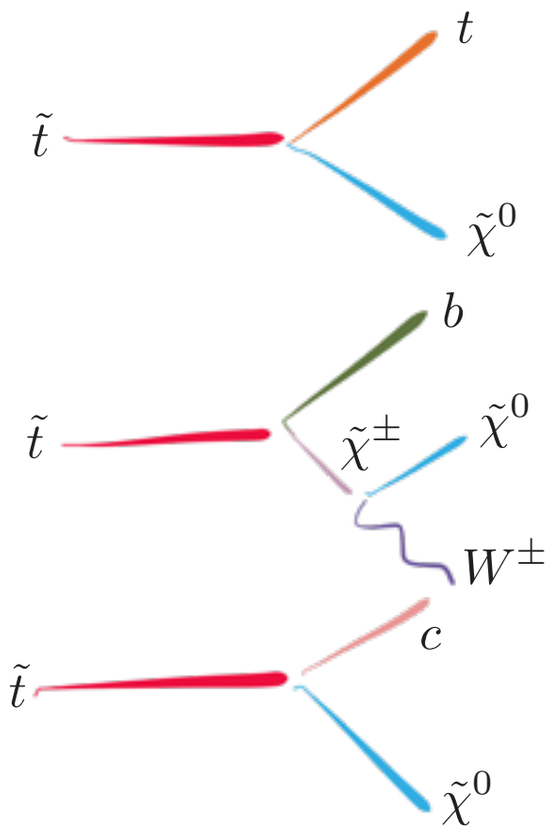
$\tilde{g}$

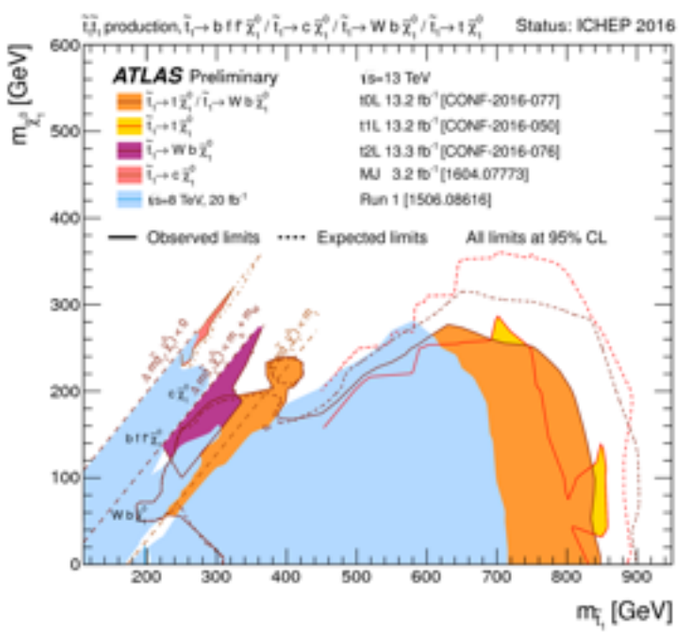
$\tilde{t}_L$ $\tilde{b}_L$ $\tilde{t}_R$

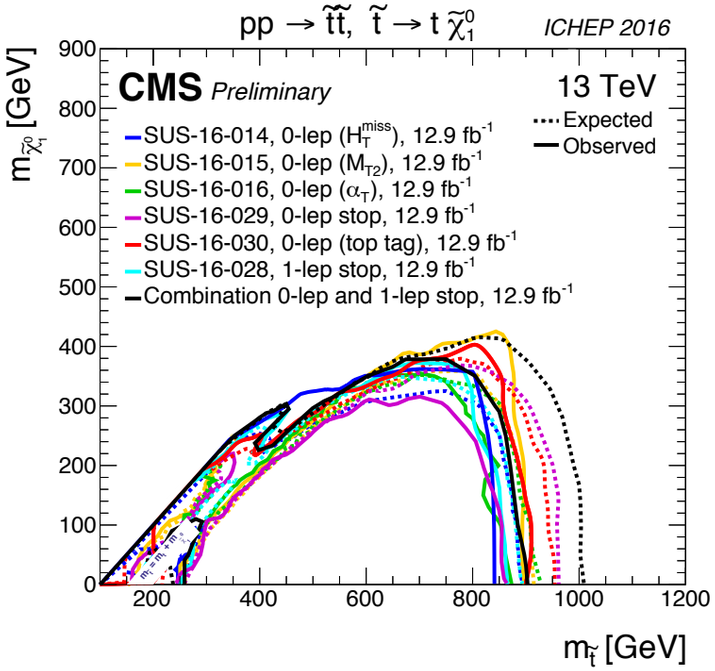
$\tilde{h}$

h









STOP SIGNALS

"NATURAL SUSY"

5 TEV

$\tilde{W}$

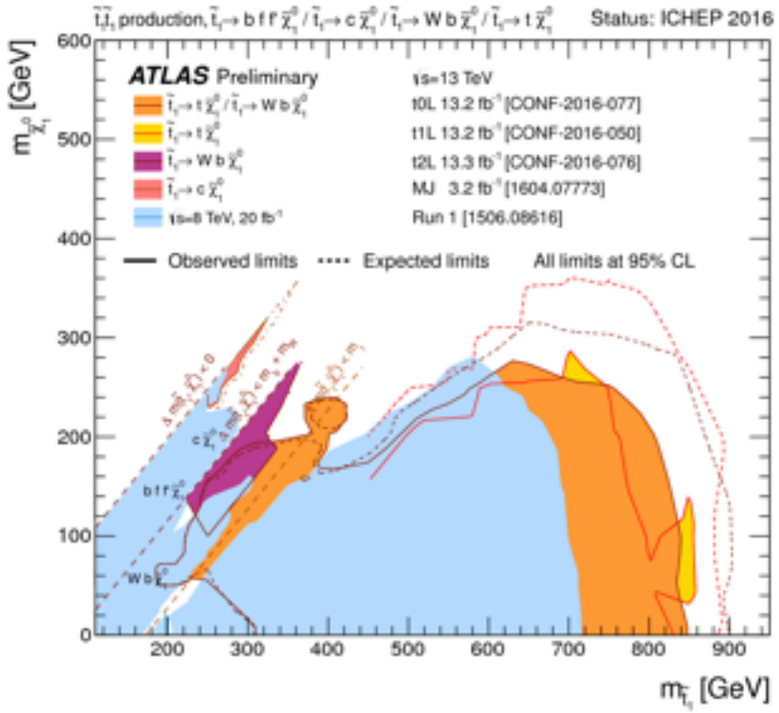
$\tilde{g}$

$\tilde{t}_L \; \tilde{b}_L \; \tilde{t}_R$

$\tilde{h}$

h

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



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

"NATURAL SUSY"

5 TEV

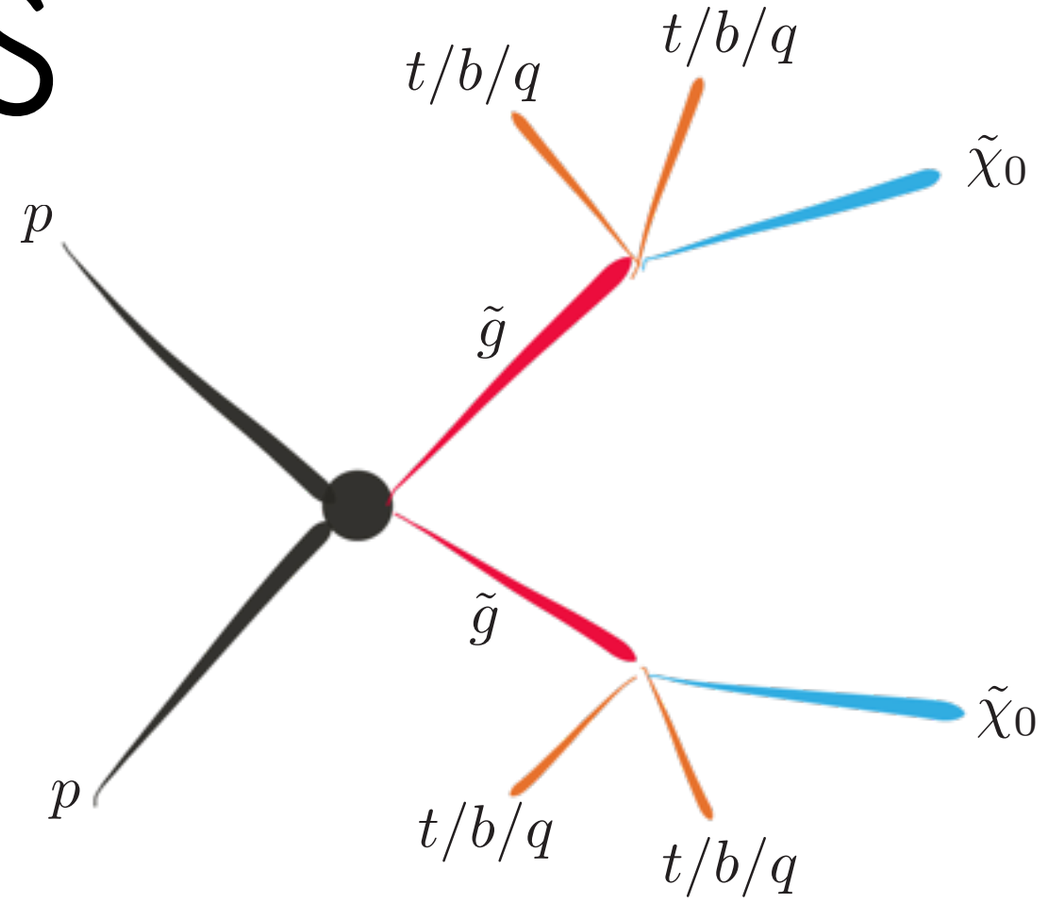
$\tilde{W}$

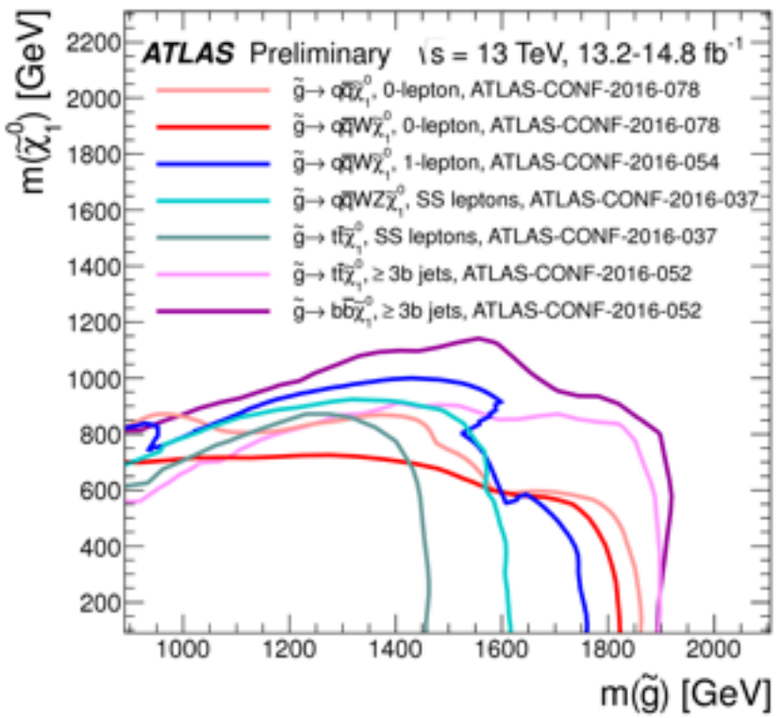
$\tilde{g}$

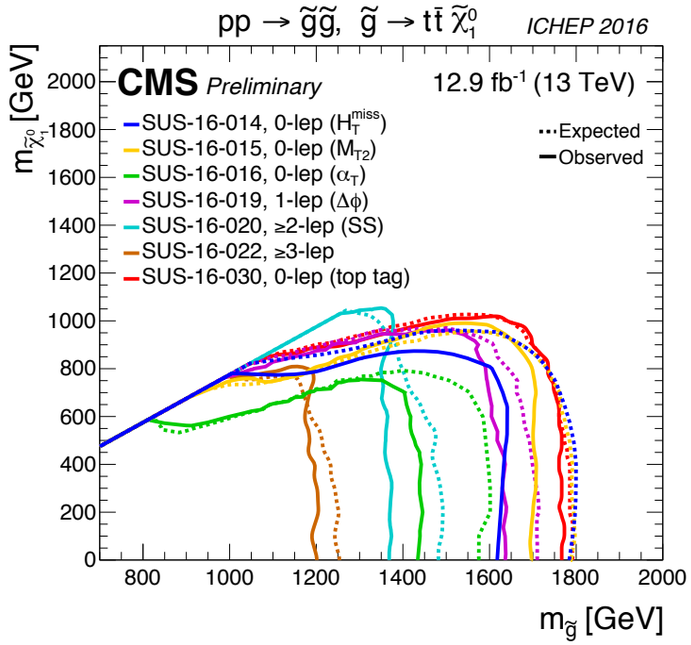
$\tilde{t}_L$ $\tilde{b}_L$ $\tilde{t}_R$

$\tilde{h}$

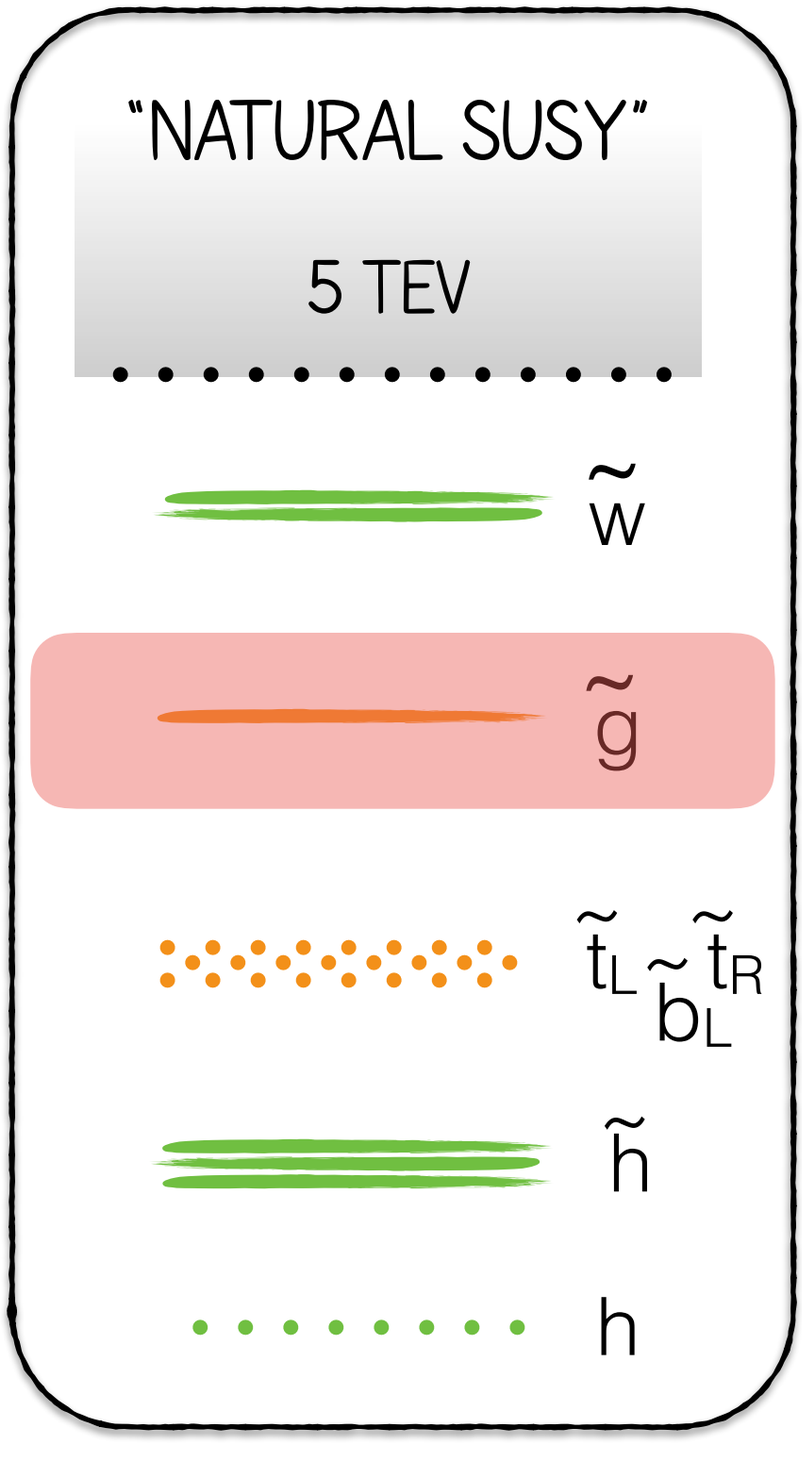
h





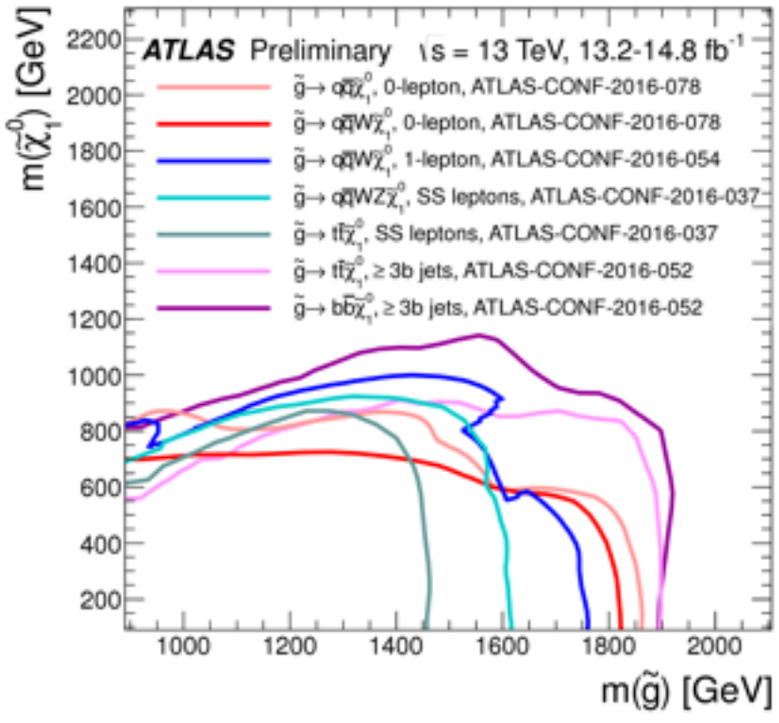


GLUINO SIGNALS



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

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



GENERIC LIMIT* > 1800 GEV

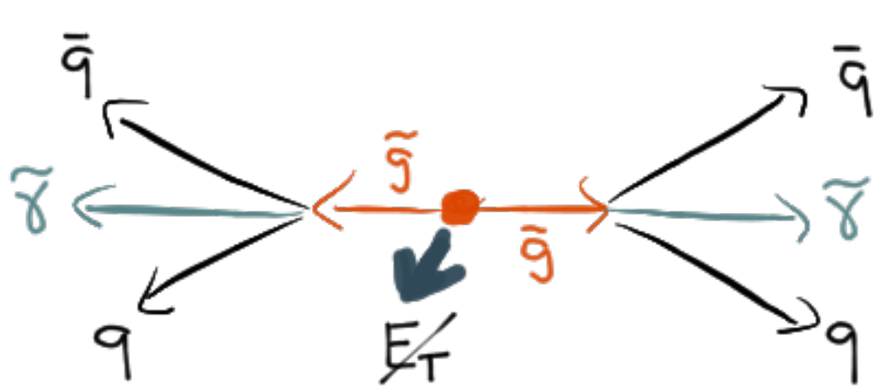
→ **Δ~57 (2% TUNING)**

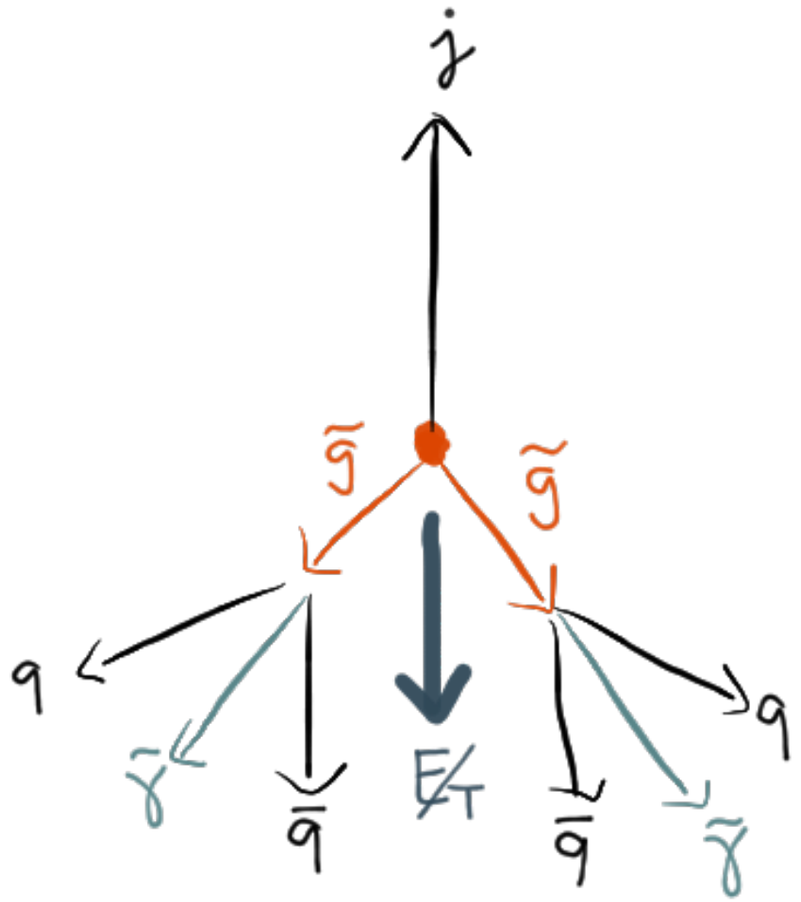
(Λ = 100 TEV)*

BREAK THE SIGNAL 1: COMPRESSION

ROBUST REDUCTION IN EVENT ACTIVITY. SMALL SPLITTING BETWEEN MASS OF PARTICLE AND LSP LEAVES LITTLE ROOM FOR MISSING ENERGY.

EFFECTIVE AGAINST SEARCHES USING HIGH ACTIVITY.





BUT: MET REDUCTION IS NOT ROBUST.

LSP CARRIES SUBSTANTIAL MOMENTUM; MET SIGNAL ONLY REDUCED BECAUSE LSP DECAYS ARE TYPICALLY BACK-TO-BACK. ANY ISR CAN INCREASE THE MET SIGNAL.

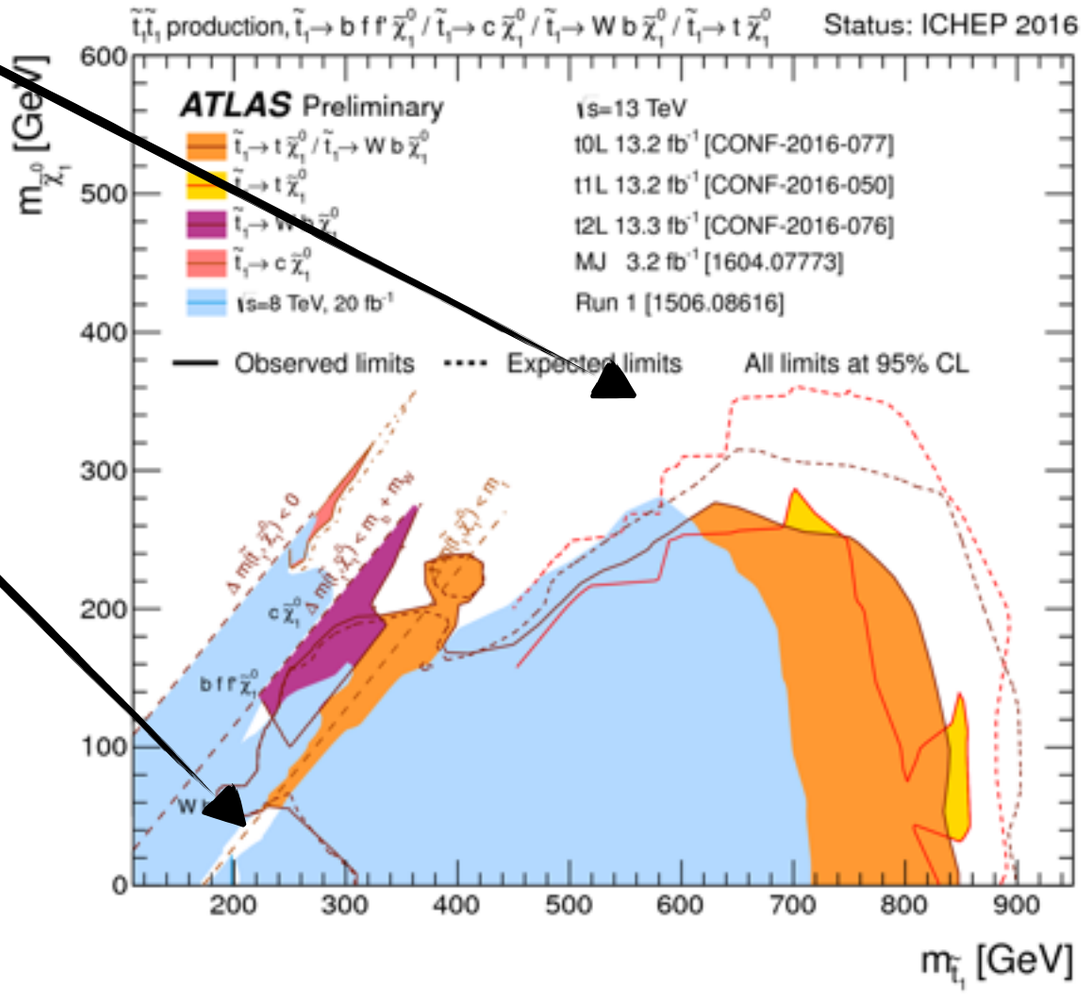
COMPRESSION

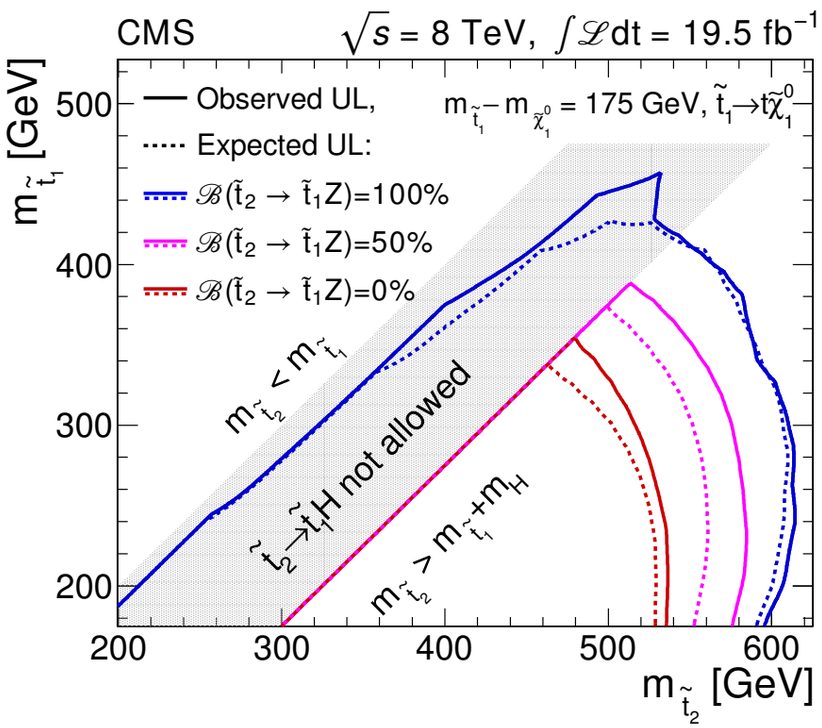
HOW WELL DOES IT WORK IN PRACTICE?

+STILL HAVE TO WORRY ABOUT GLUINOS.

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

LIVING HERE? *HAVE TO CONTEND WITH STOP$_1$-STOP$_2$ LIMITS*





RUNNING OUT OF ROOM FOR COMPRESSION @ LHC.

BREAK THE SIGNAL 2: RPV

- MET SIGNATURES AROSE BECAUSE WE ASSUMED R-PARITY, WHICH RENDERS LSP STABLE. NO R-PARITY, NO STABLE LSP, NO MET.

- IF WE VIOLATE R-PARITY, WE CAN NOW WRITE DOWN NEW MARGINAL AND RELEVANT OPERATORS:

$$W_{RPV} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k$$

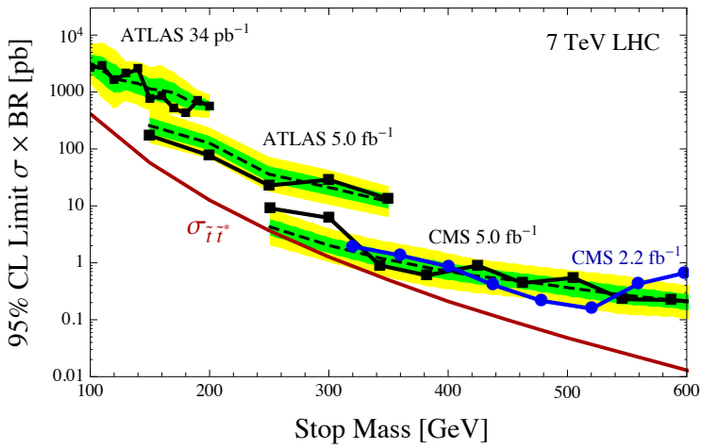
- 48 NEW COMPLEX PARAMETERS (3+9+27+9).

- THESE OPERATORS INDIVIDUALLY VIOLATE BARYON OR LEPTON NUMBER. DISASTROUS IF BOTH B AND L VIOLATION ARE PRESENT.

- EVEN IF ONLY B OR L IS VIOLATED, CONSTRAINTS ON LIGHT-GENERATION RPV COUPLINGS FROM E.G., N-$\bar{\text{N}}$ OSCILLATION OR $\mu \to e\gamma$. HELPFUL TO HAVE A THEORY FOR ORIGIN OF RPV OPERATORS!

- ONE IDEA: MFV SUSY, RPV COEFFICIENTS GOVERNED BY MINIMAL FLAVOR VIOLATION. ONLY UDD IS NONZERO, WITH COEFFICIENTS PROPORTIONAL TO $Y_U Y_D Y_D$.

[Bai, Katz, Tweedie '13]



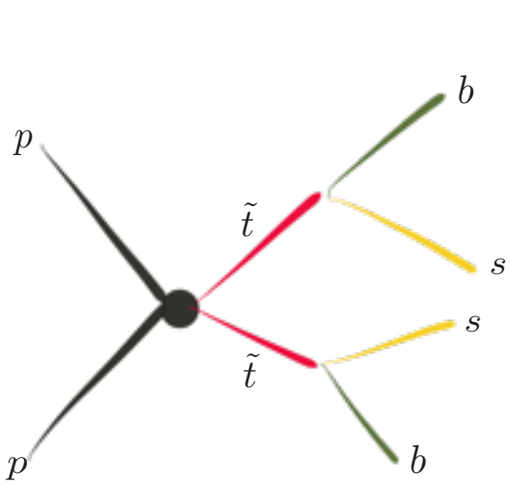
R-PARITY VIOLATION

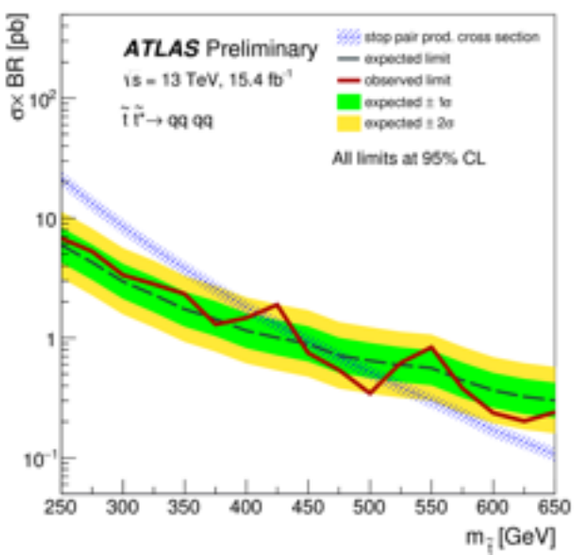
IN PRACTICE, LEPTONS ARE KILLERS. RPV CAN HELP PROVIDED NO LEPTONS → BARYONIC RPV.

PROMPT, BECAUSE DISPLACED SEARCHES POWERFUL.

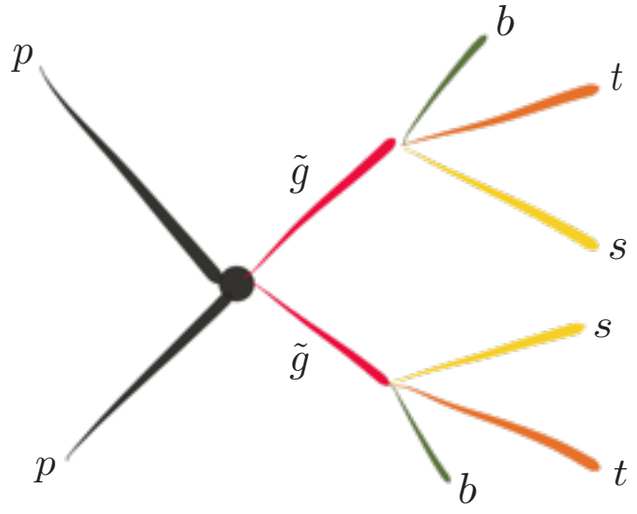
RPV	LFV $pp \to \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$	1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q}$, $\tilde{g}$	1.45 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<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, $\lambda_{12k}\neq 0$ ($k = 1, 2$)
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \to W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to \tau\tau\nu_e, e\tau\nu_\tau$	3 $e,\mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$	450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^\pm$), $\lambda_{133}\neq 0$
	$\tilde{g}\tilde{g}, \tilde{g} \to qqq$	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%

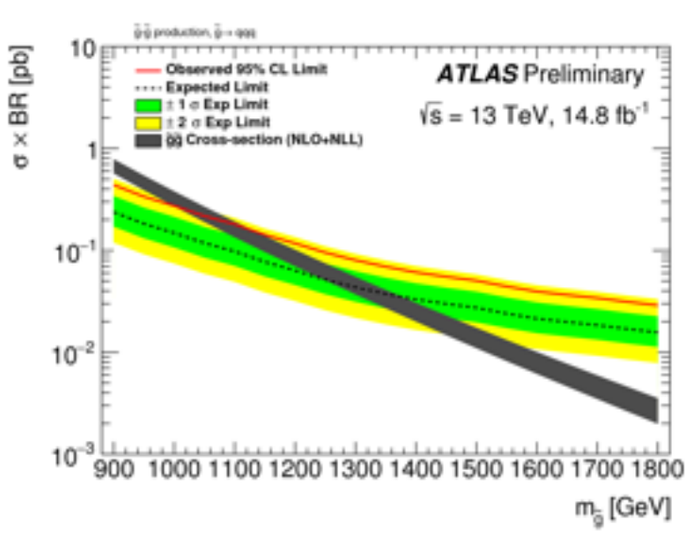
STOPS > 500 GEV (5%)





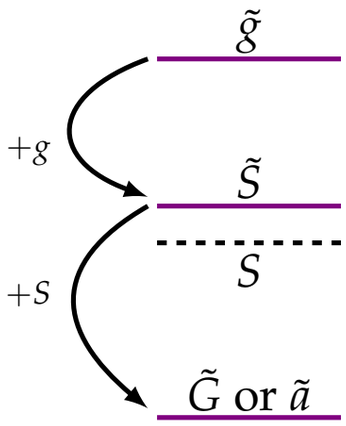
GLUINOS > 1 TEV (5%)

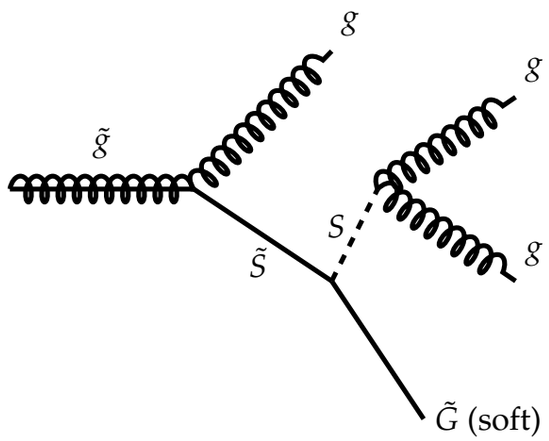


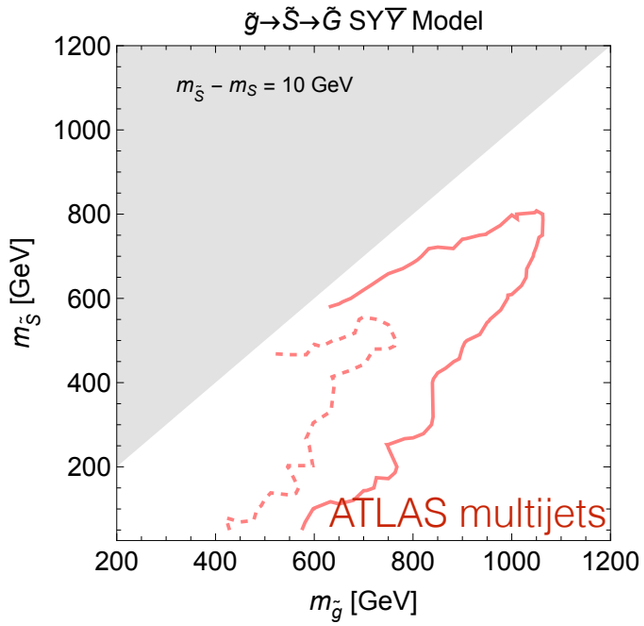


BREAK THE SIGNAL 3: STEALTH

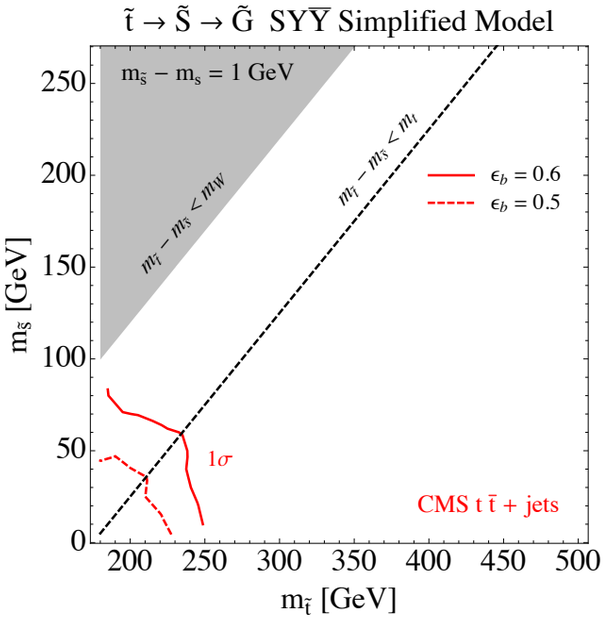
STEALTH SUSY: ERASE MET BY DECAYING INTO SECTOR WITH SMALL NON-SUSY SPLITTING
MOTIVATES ADDITION OF HIDDEN SECTORS TO THE MSSM.

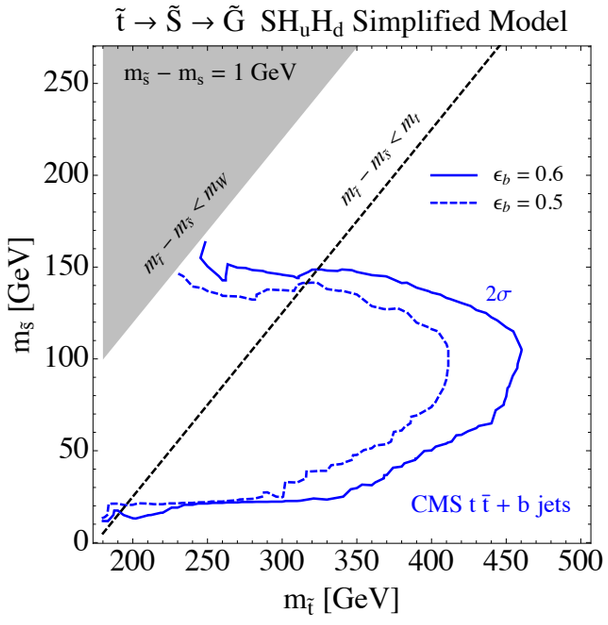


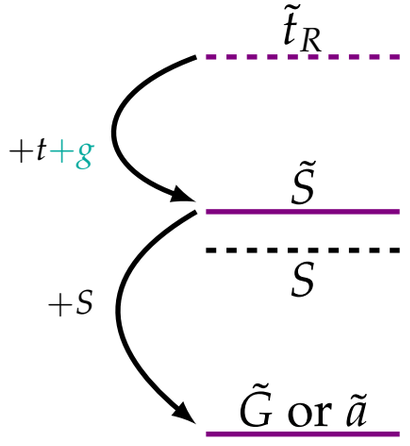


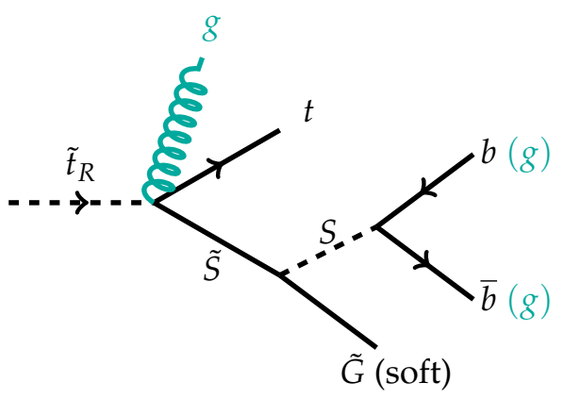


TRADE MET FOR ADDITIONAL EVENT ACTIVITY, MIGRATE SIGNALS TO EXOTICS; *SOMETIMES YOU WIN, SOMETIMES YOU LOSE.*









[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		χ^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.