

BEYOND THE STANDARD MODEL

Lecture II

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THE HIERARCHY PROBLEM

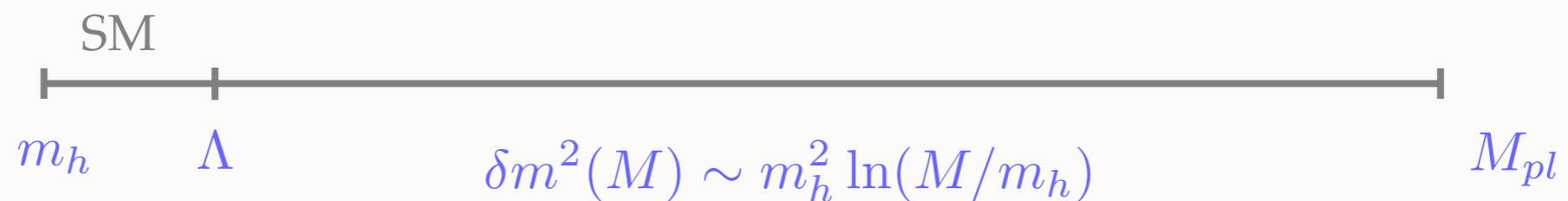
- Natural expectation for scalar fields: $m_s \sim \Lambda$
- natural EWSB needs new physics near TeV



- but this new physics must be special: theory above Λ must be free of quadratic divergences

THE HIERARCHY PROBLEM

- Idea 1: cancellation of quadratic divergences



- new physics closely related to SM:



THE HIERARCHY PROBLEM

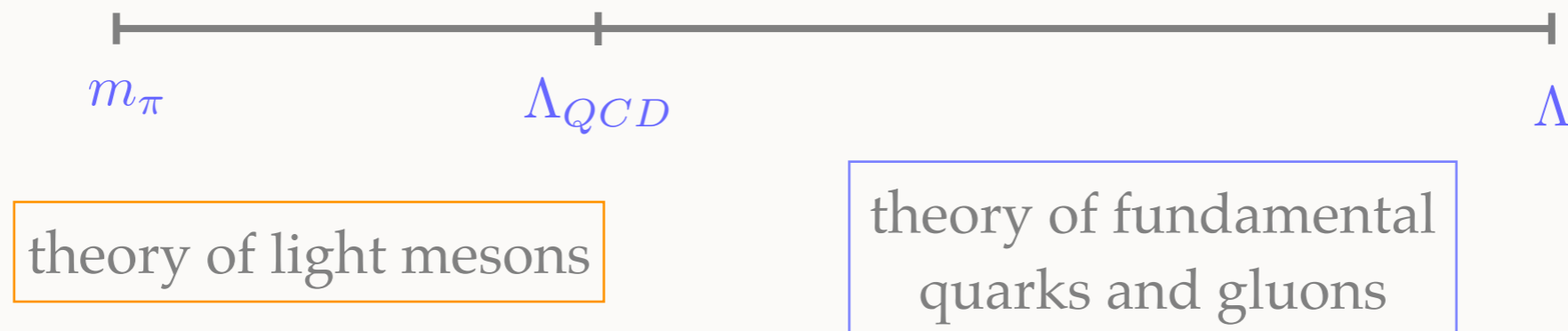
- Complete solution: cancellation must be **exact**
 - This requires a **lot** of new states!
 - **symmetry** to relate couplings of NP to those of the SM
 - e.g.: **SUSY**
- If there is no symmetry, then cancellation is **accidental** and will break down at higher scales: **defers** hierarchy problem

THE HIERARCHY PROBLEM

- Idea 2: get rid of the problematic operator



- Analogy: QCD

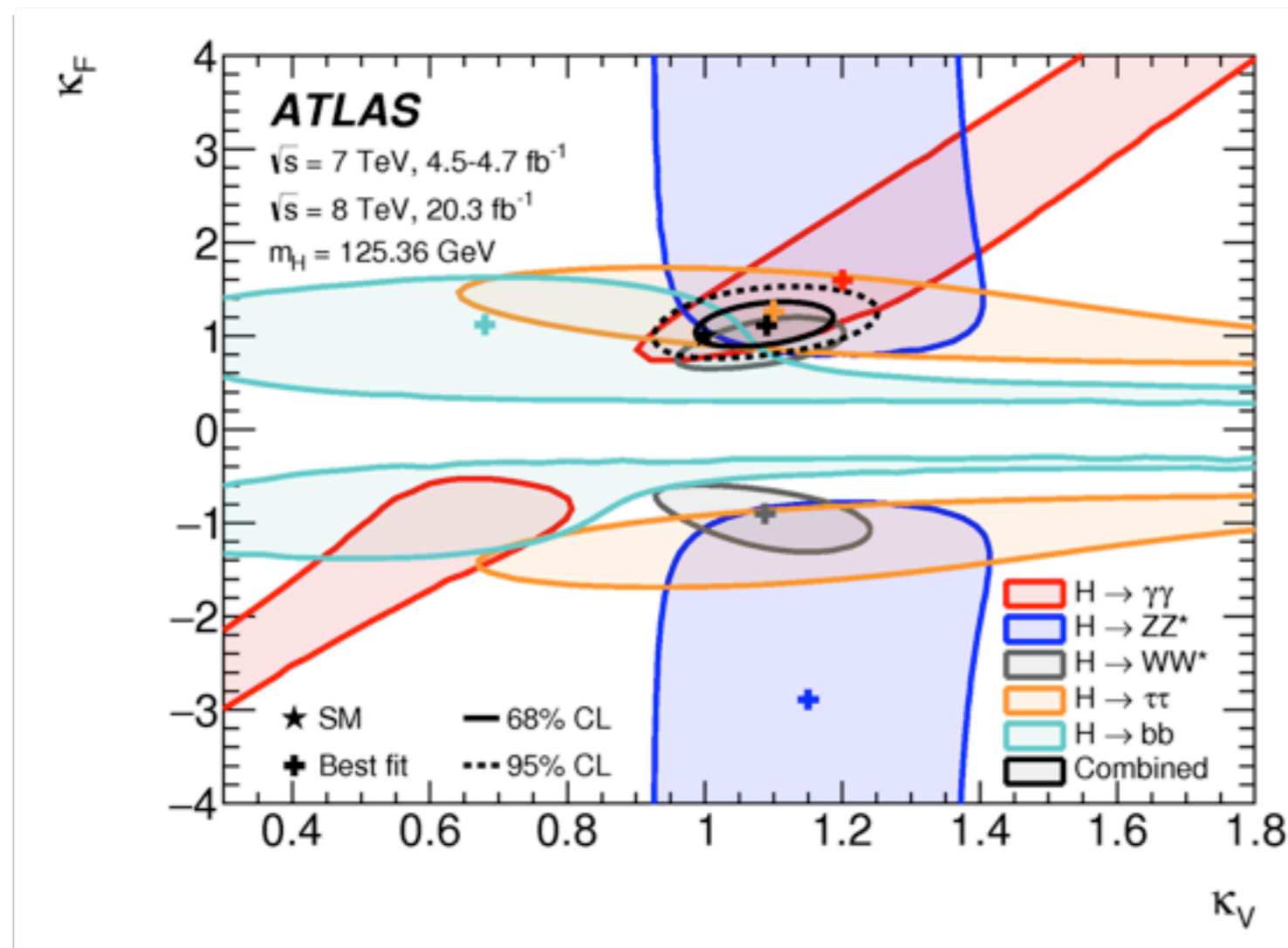


THE HIERARCHY PROBLEM

- In these models the Higgs is a **composite state**
- Generically we would expect $m_h \sim \Lambda_G$, but then:
 - we should generically have many new degrees of freedom at the same scale as the Higgs (again, compare QCD).
 - expect sizeable deviations in Higgs couplings from (very successful) SM predictions
- \Rightarrow experimentally, require **little hierarchy**: $m_h \ll \Lambda_G$
- How to get an anomalously light scalar? **pseudo-Goldstone bosons**

THE HIERARCHY PROBLEM

- Higgs coupling measurements are a robust and model-independent way to search for signs of compositeness:



parametrization of
couplings relative
to SM: expect

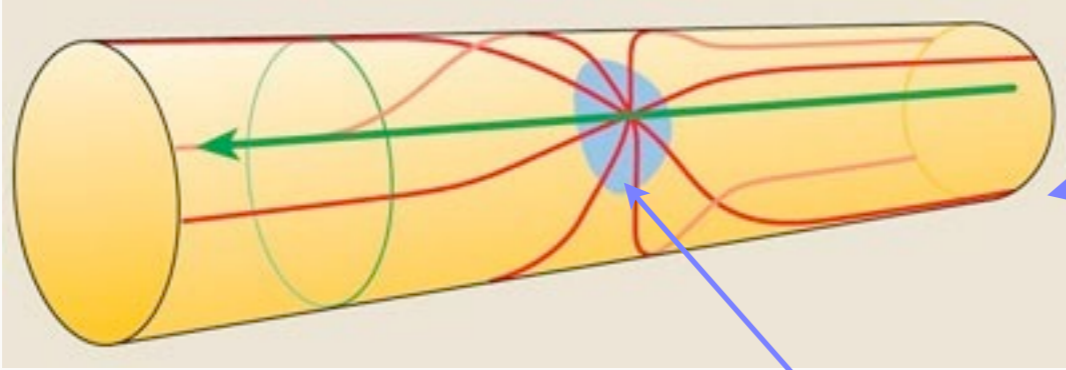
$$\kappa_i \sim \left(\frac{v}{f} \right)^2$$

THE HIERARCHY PROBLEM

- Idea 3: **no running**

$$\begin{array}{c} \text{---} \\ m_h \quad M_{pl} \end{array}$$

- apparent weakness of gravity compared to SM forces is an **illusion** due to **geometry of spacetime**
- SM particles are inherently 4D (string theory makes this plausible)



short distance behavior
is $4+n$ -dimensional

$$V(r) = \frac{m}{M_{Pl(4+n)}^{n-2}} \frac{1}{r^{n+1}}$$

$$V(r) = \frac{m}{M_{Pl(4+n)}^{n-2}} \frac{1}{R^n} \frac{1}{r}$$

but for $r > R$, field
propagation is 4-dimensional

THE HIERARCHY PROBLEM

- Other ideas aim to **explain**, not solve, hierarchy problem
 - **anthropics**: fine-tuning is real! We see the value of m_h that we do because something about the observed value favors the development of galaxies, planets, etc.
 - **relaxion**: fine-tuning is real, but dynamics in the early universe actively select a vacuum with weak-scale m_h

THE HIERARCHY PROBLEM

- Today I am going to focus on SUSY
 - Many consequences of SUSY as applied to the hierarchy problem are **qualitatively similar** to those of other models
 - **partner particles** for SM
 - **parity** symmetry leading to **dark matter** candidates (**MET**)
 - collider searches for **heavy states with SM charges**
 - SUSY is an excellent **signature generator**, especially when including variants on standard MSSM (*R*-parity violation, extended matter content, ...)

SUPERSYMMETRY

- Theory of 1 complex scalar + 1 Weyl fermion:

$$\mathcal{L} = \partial_\mu \phi \partial^\mu \phi^* + i\bar{\psi} \gamma^\mu \partial_\mu \psi$$

- invariant under **supersymmetry** transformation:

$$\delta\phi = \bar{\epsilon}\psi \qquad \delta\psi = -i\epsilon\gamma^\mu \partial_\mu \phi$$

- two SUSY variations yield a **translation**:

$$[\delta_1, \delta_2] \phi = -i\bar{\epsilon}_2 \gamma^\mu \epsilon_1 \partial_\mu \phi$$

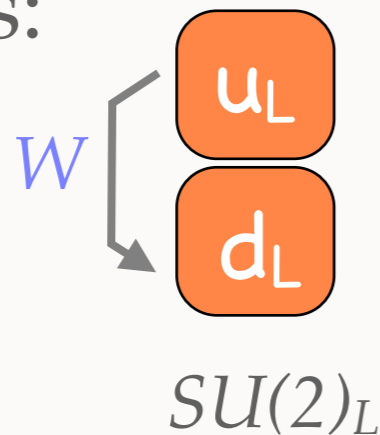
- recall $\delta\phi = a^\mu \partial_\mu \phi$: generated by **momentum**

SUPERSYMMETRY

- SUSY is thus inherently intertwined with spacetime (Poincare) symmetry
 - SUSY: a statement about background spacetime
 - we can't pick and choose a subsector of the universe to supersymmetrize
 - the kinds of representations of SUSY that we can have depend on particle's Lorentz quantum numbers, in particular, on their spin.

SUPERSYMMETRY

- Multiplets:

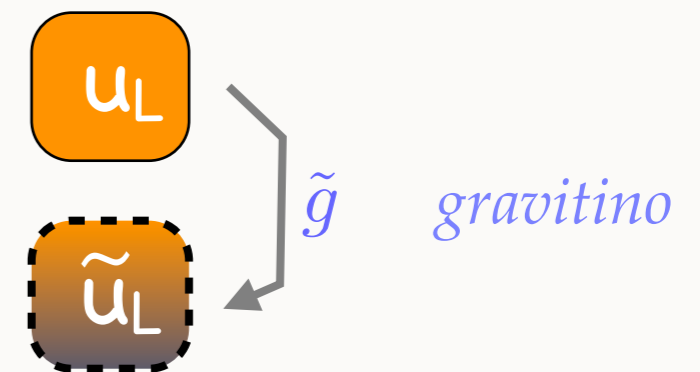


- supermultiplets: particle and superpartner

- fermion - sfermion (\tilde{u}_L, u_L)

- gauge boson - gaugino (\tilde{B}, B_μ)

- Higgs boson - higgsino (H_u, \tilde{H}_u)



chiral multiplets

vector multiplets

SUPERSYMMETRIC THEORIES

- Supersymmetry restricts possible interactions
 - Analogy: EWSB
 - Below scale of EWSB, u_R, u_L seem to have quantum numbers allowing Dirac mass term: $m_u u_R u_L$
 - But forbidden under underlying $SU(2)_L \times U(1)_Y$ - need $\frac{y_u v}{\sqrt{2}} u_R u_L$
 - from the parent interaction $y_u H u_R Q_L$
 - which also yields the interaction $\frac{y_u}{\sqrt{2}} h u_R u_L$

SUPERSYMMETRIC THEORIES

- SUSY relates Yukawa interactions $H Q_L u_R$ to quartic scalar couplings $|H|^2 |\tilde{Q}_L|^2, \dots$
- useful compact formalism: **superpotential**

superfields \nearrow $W = y_u Q_L H u_R + \dots$ renormalizable interactions are cubic

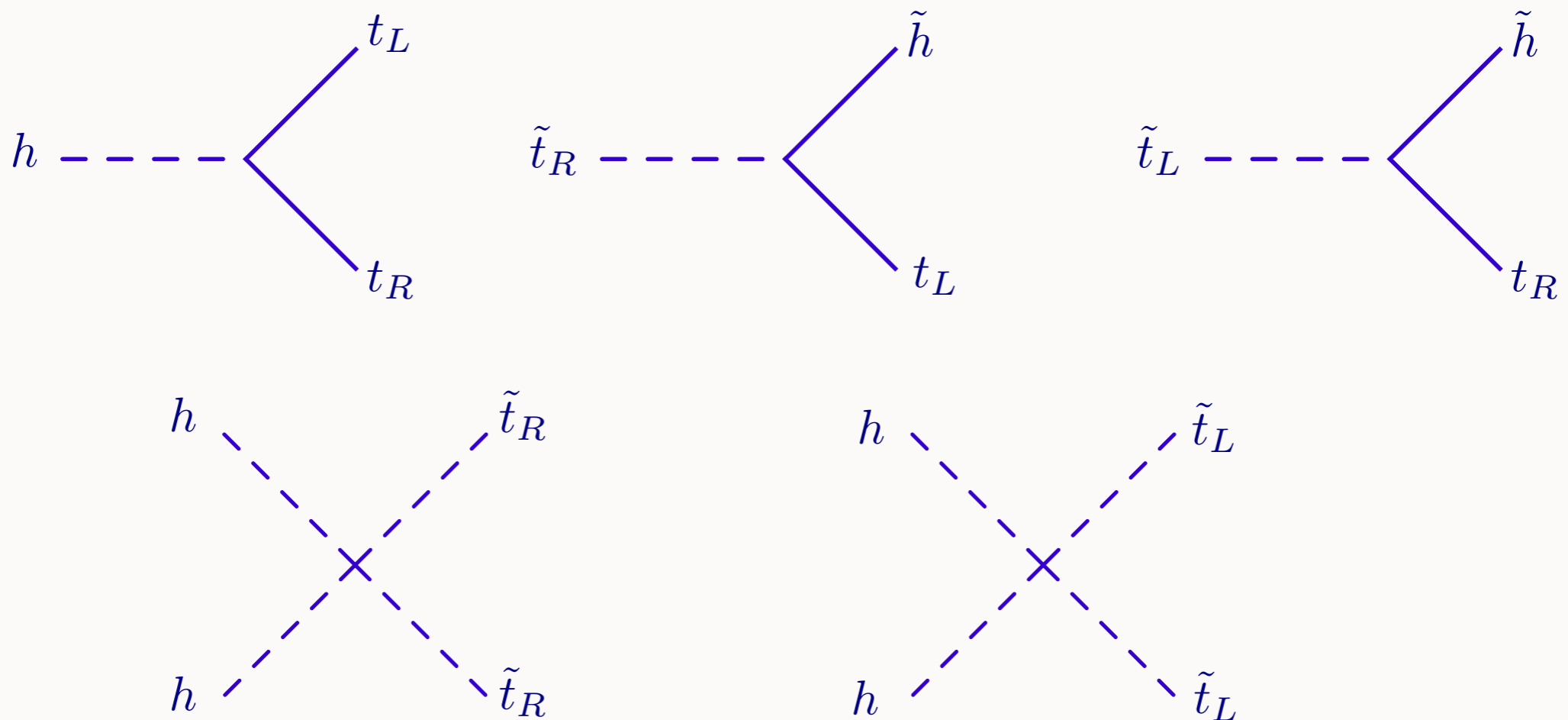
- determines all supersymmetric interactions between chiral multiplets:

$$\mathcal{L}_{Yuk} = -W_{ij} \psi_i \psi_j$$

$$V(\phi) = |W_i|^2$$

SUPERSYMMETRIC THEORIES

- Thus one cubic superpotential term $y Q_L H u_R$ encodes



SUPERSYMMETRIC THEORIES

- SM Yukawas:

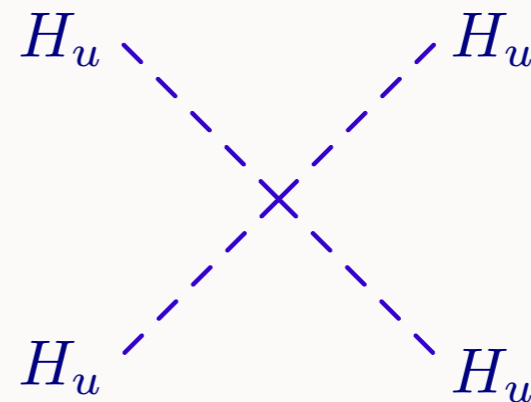
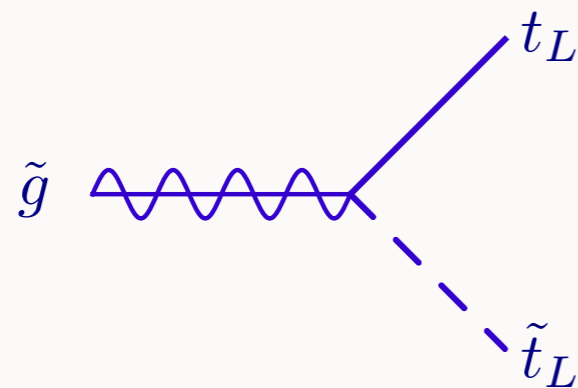
$$\mathcal{L}_{SM} = y_d Q_L H d_R + y_\ell L_L H e_R + y_u Q_L H^c u_R$$

- But only superfields, not their complex conjugates, can appear in W : cannot be supersymmetrized
- Must introduce two Higgs doublets H_u, H_d
 - also fixes up quantum consistency of MSSM: anomaly cancellation
- SUSY quadratic Higgs potential terms from $W = \mu H_u H_d$

SUPERSYMMETRIC THEORIES

- What about gauge interactions?
- Gauge invariance uniquely dictates interactions of gauge bosons with charged particles
- SUSY relates these to **gaugino interactions** and new **scalar quartics**,

$$\mathcal{L}_{new} = -\sqrt{2}g(\phi^* t^a \psi) \lambda^a + H.c. - \frac{g^2}{2} (\phi^* t^a \phi)^2$$



SUPERSYMMETRIC MSSM

- This gives us the SUSY-preserving part of the MSSM:

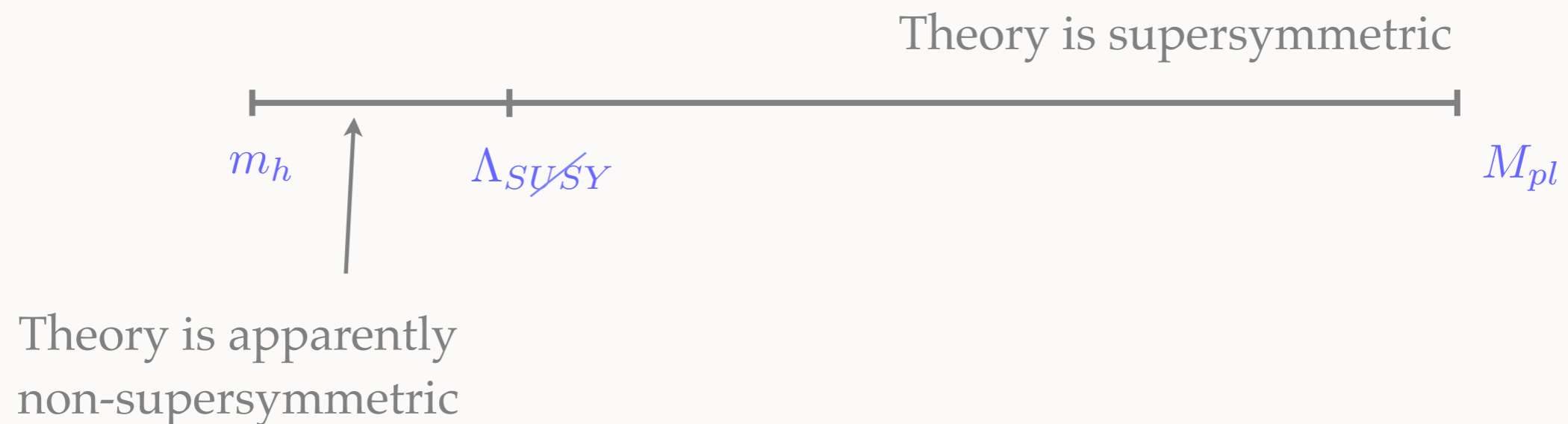
particles	sparticles
$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad u_R \quad d_R$	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix} \quad \tilde{u}_R \quad \tilde{d}_R$
$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad e_R \quad \nu_R$	$\begin{pmatrix} \tilde{\nu}_L \\ \tilde{e}_L \end{pmatrix} \quad \tilde{e}_R \quad \tilde{\nu}_R$
$H_u \quad H_d$	$\tilde{H}_u \quad \tilde{H}_d$
$g_\mu^a \quad W_\mu^a \quad B_\mu$	$\tilde{g}^a \quad \tilde{W}^a \quad \tilde{B}$

- Extremely predictive!
 - More than double the particles of the SM
 - Fewer parameters

- Of course, SUSY is broken in nature...

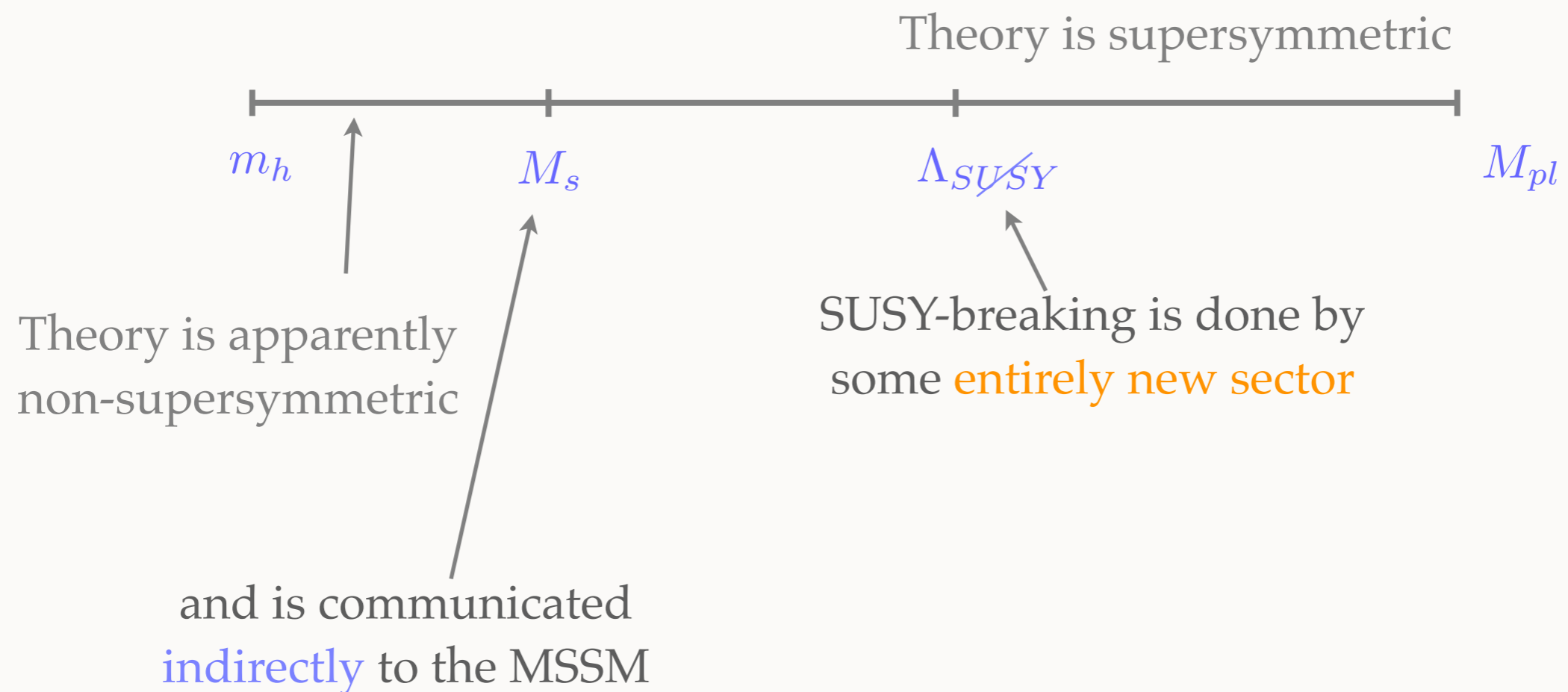
SUSY BREAKING

- How can we break SUSY without spoiling the solution to the hierarchy problem?
- Must break SUSY *spontaneously*



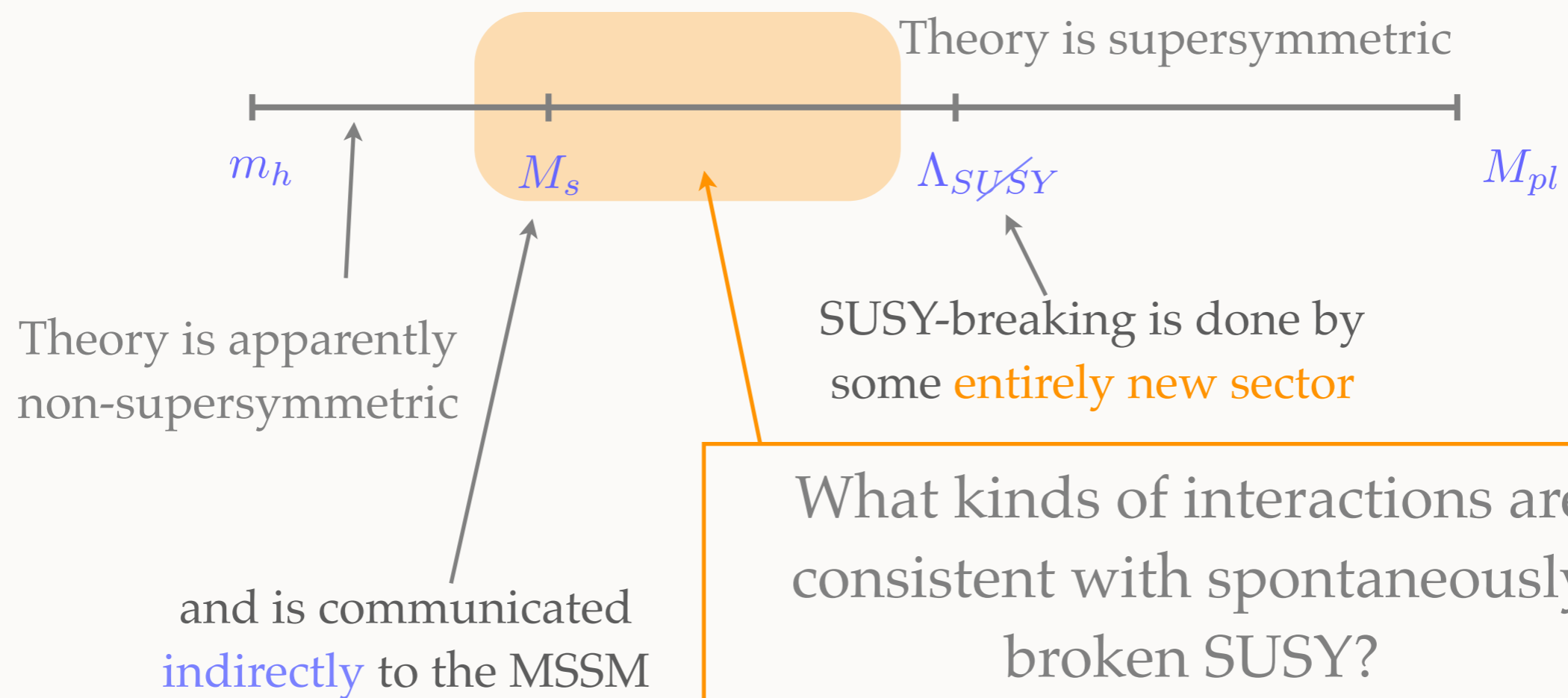
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SUSY BREAKING

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- Must break SUSY **spontaneously**



SUSY BREAKING

- This induces the “soft SUSY-breaking” Lagrangian:

$$\mathcal{L}_{soft} = -\frac{1}{2} \left(M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B} + H.c. \right)$$

masses for superpartners only

$$-\tilde{Q}_L^* M_Q^2 \tilde{Q}_L - \tilde{u}_R^* M_u^2 \tilde{u}_R - \tilde{d}_R^* M_d^2 \tilde{d}_R - \tilde{L}_L^* M_L^2 \tilde{L}_L - \tilde{e}_R^* M_e^2 \tilde{e}_R$$

trilinear couplings: one for each super-potential term

$$-\left(A_u \tilde{u}_R \tilde{Q}_L H_u + A_d \tilde{d}_R \tilde{Q}_L H_d + A_e \tilde{e}_R \tilde{L}_L H_d + H.c. \right)$$

and same in the Higgs sector

$$-m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + H.c.)$$

- over 100 free parameters!

R-PARITY

- Unlike in the SM, we cannot write down all interactions allowed by gauge symmetries:

$$W = \mu H_u H_d + Y_u Q_L H_u u_R + Y_d Q_L H_d d_R + Y_e L_L H_d e_R \\ + \hat{\mu} H_u L_L + \lambda'' u_R d_R d_R + \lambda' Q_L L_L d_R + \lambda L_L L_L e_R$$

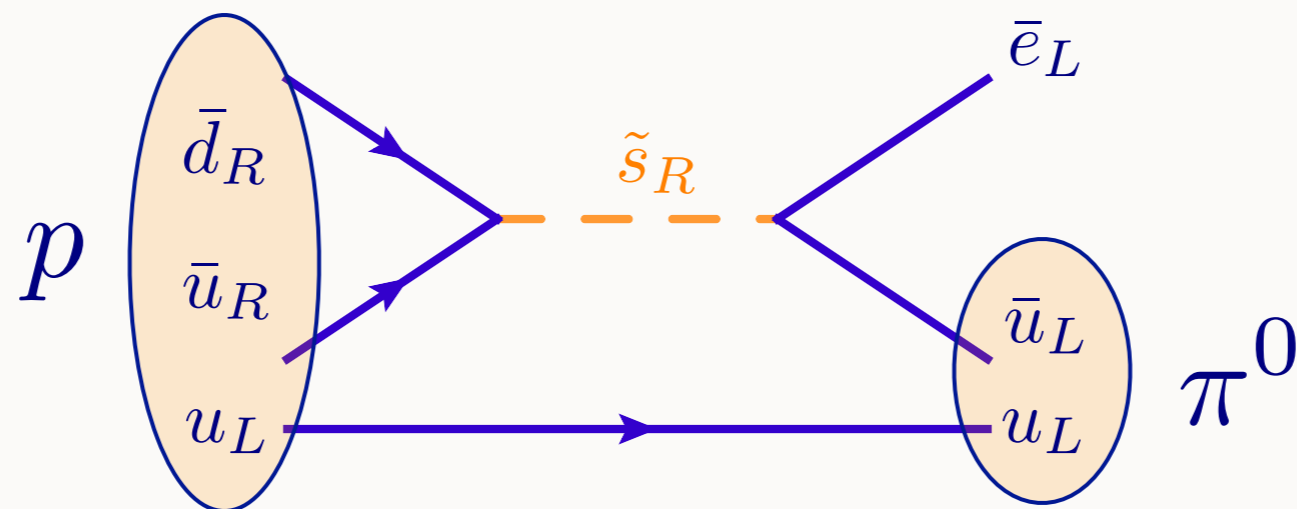
violates B

violates L

- Leads to whole tensors of new B and L -violating couplings:
 - e.g. Yukawas, $\lambda''_{112}(u_R d_R) \tilde{s}_R$, $\lambda'_{112} \tilde{s}_R (e_L u_L)$

R-PARITY

- Catastrophic proton decay:



- product of B, L violating Yukawa couplings must be **extremely** small:

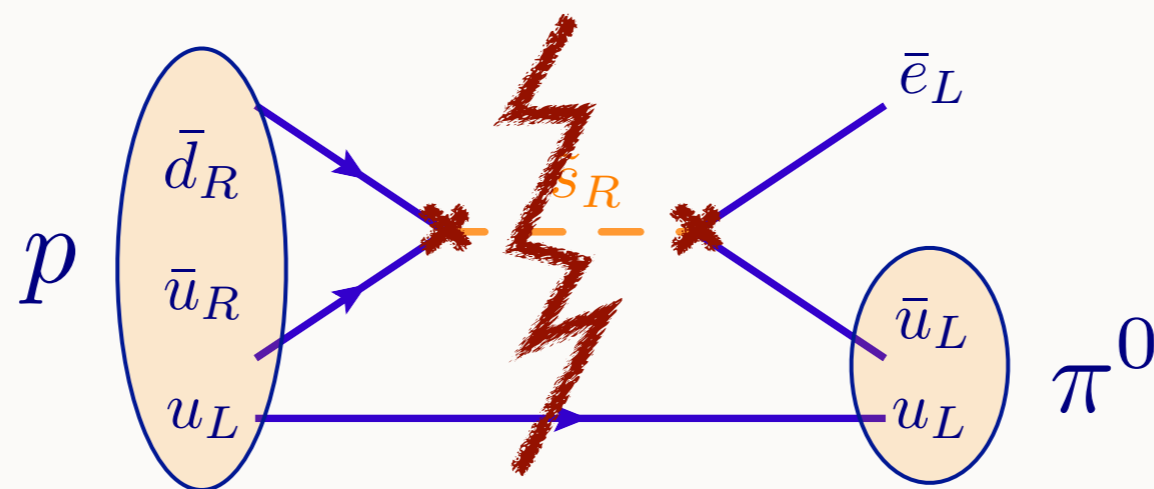
$$\Gamma \sim \frac{|\lambda''_{112}\lambda'_{112}|^2 m_p^5}{m_{\tilde{s}}^4} < 10^{34} \text{ years}$$

R-PARITY

- Easy solution: impose a new **global** symmetry:

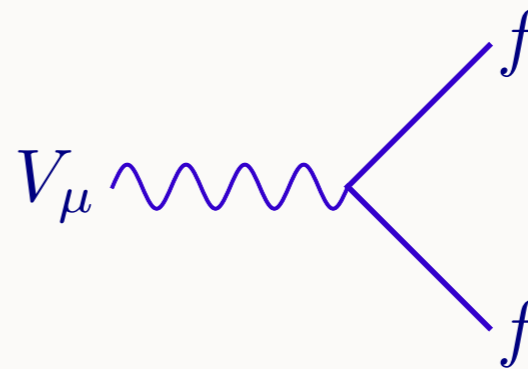
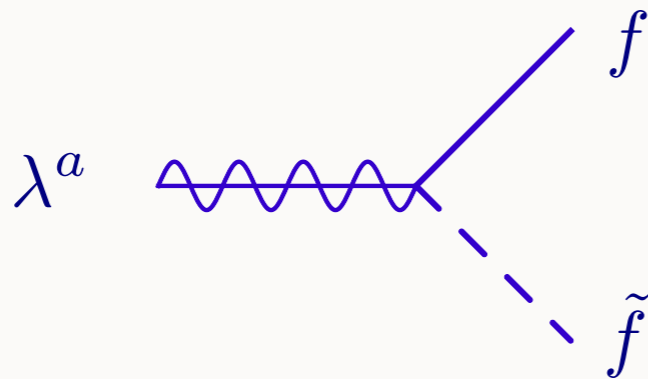
$$W = \mu H_u H_d + Y_u Q_L H_u u_R + Y_d Q_L H_d d_R + Y_e L_L H_d e_R \\ + \hat{\mu} H_u L_L + \lambda'' u_R d_R d_R + \lambda' Q_L L_L d_R + \lambda L_L L_L e_R$$

- impose **matter parity**: $P_M = (-1)^{3(B-L)}$



R-PARITY

- Gauge interactions:



- define **R-parity**:

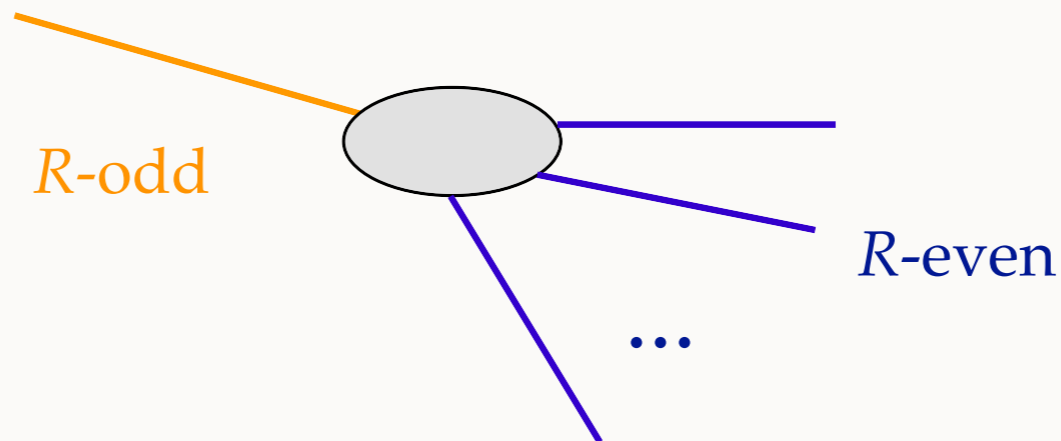
$$P_R = (-1)^{3(B-L)+2s}$$

- exactly the same! but easier to see consequences

even	odd
f (spin 1/2)	\tilde{f} (spin 0)
V (spin 1)	\tilde{V} (spin 1/2)
H (spin 0)	\tilde{H} (spin 1/2)

R-PARITY

- Immediate consequence: lightest superpartner is **stable**



- This significantly restricts the spectrum:
 - lightest superpartner must be **neutral**
 - and must not **over-close the universe**

R-PARITY: DARK MATTER

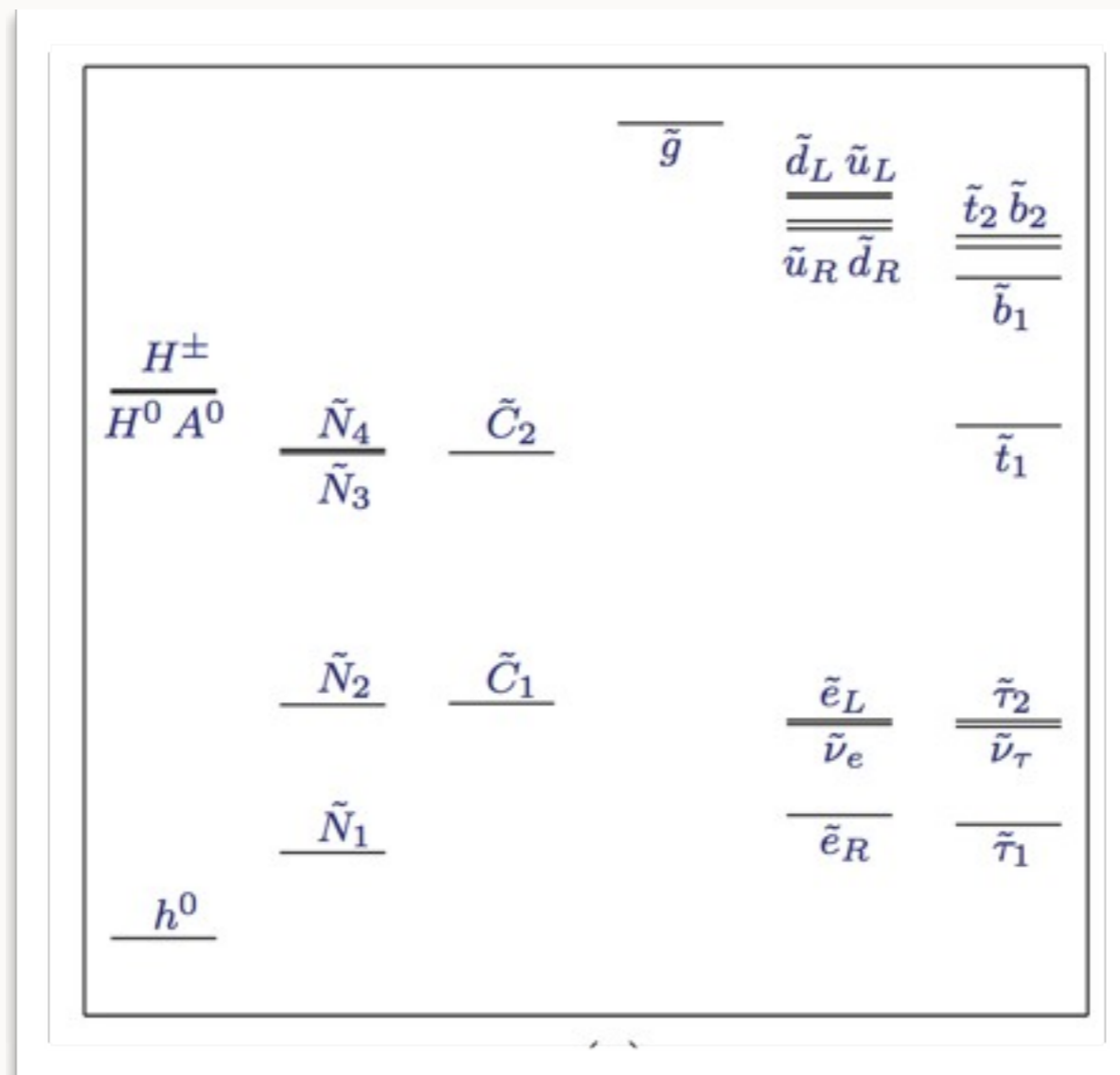
- Lightest Supersymmetric Particle is an attractive DM candidate:
 - electroweak interactions, electroweak scale mass
 - Possible candidates:
 - neutralinos $\tilde{B}, \tilde{W}^3, \tilde{h}_u, \tilde{h}_d$
 - sneutrinos $\tilde{\nu}_L, \tilde{\nu}_R$
 - the devil is in the details

SUSY BREAKING

- So about those >100 free parameters...
 - Tremendous constraints from flavor, CP
 - flavor structure can't be arbitrary: SUSY flavor problem
 - Top-down: specific models of SUSY-breaking impose characteristic relationships between soft parameters
 - gauge mediation, gravity mediation, anomaly mediation, ...
 - Bottom-up: CP-preserving, nearly flavor-symmetric sector
 - “pMSSM”: a mere 20 parameters

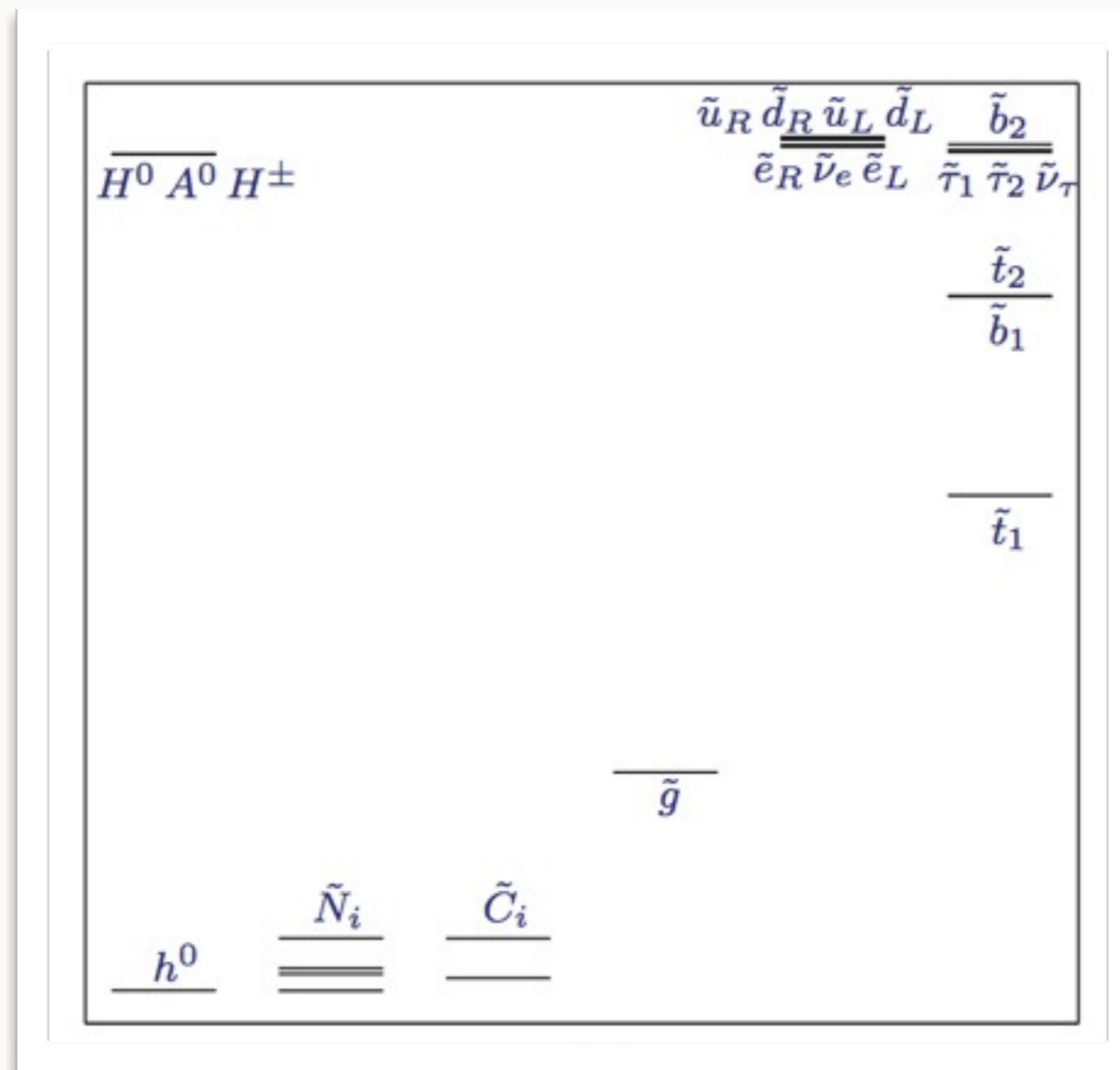
MSSM SPECTRA

- Example gravity-mediated spectrum



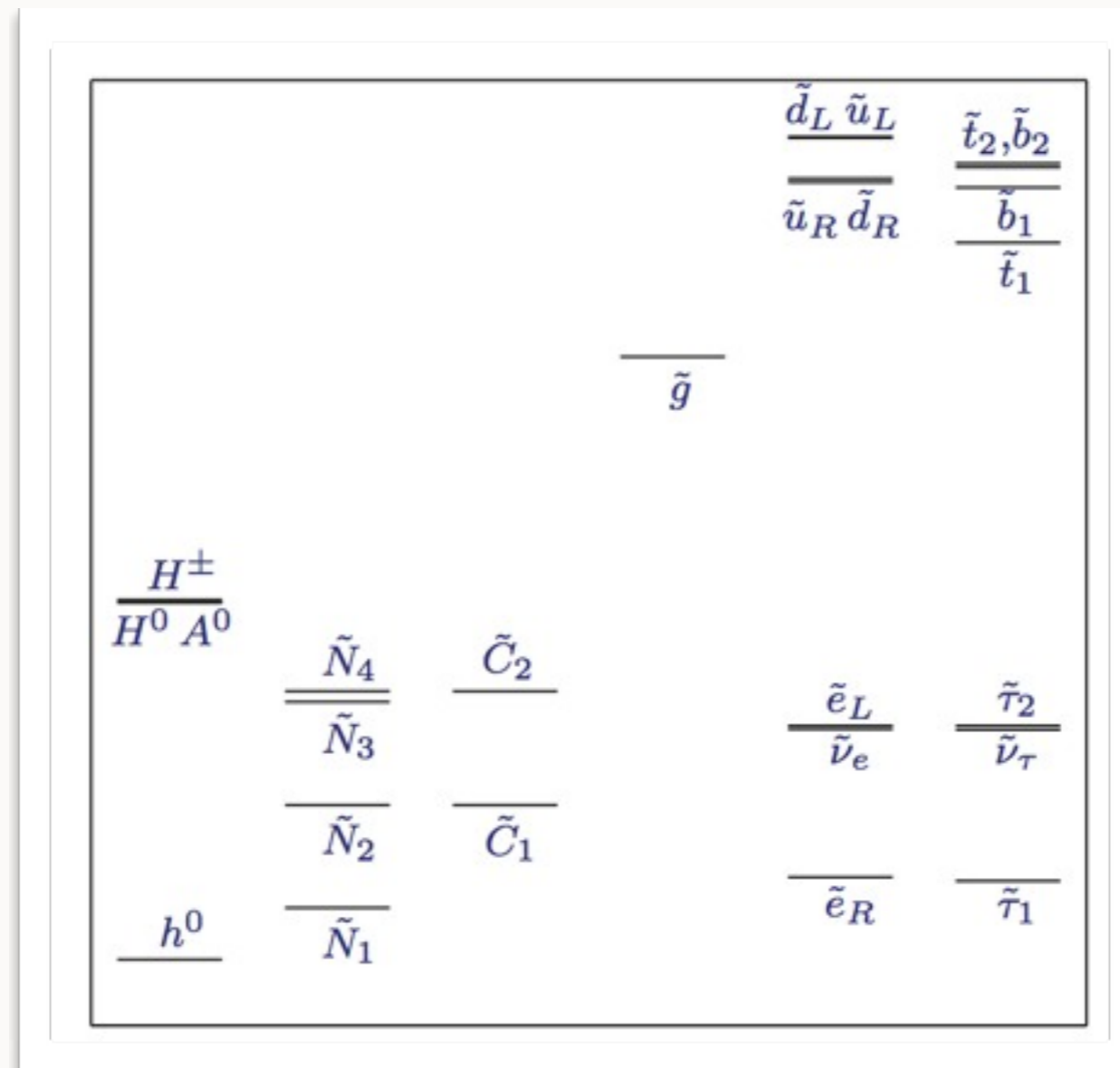
MSSM SPECTRA

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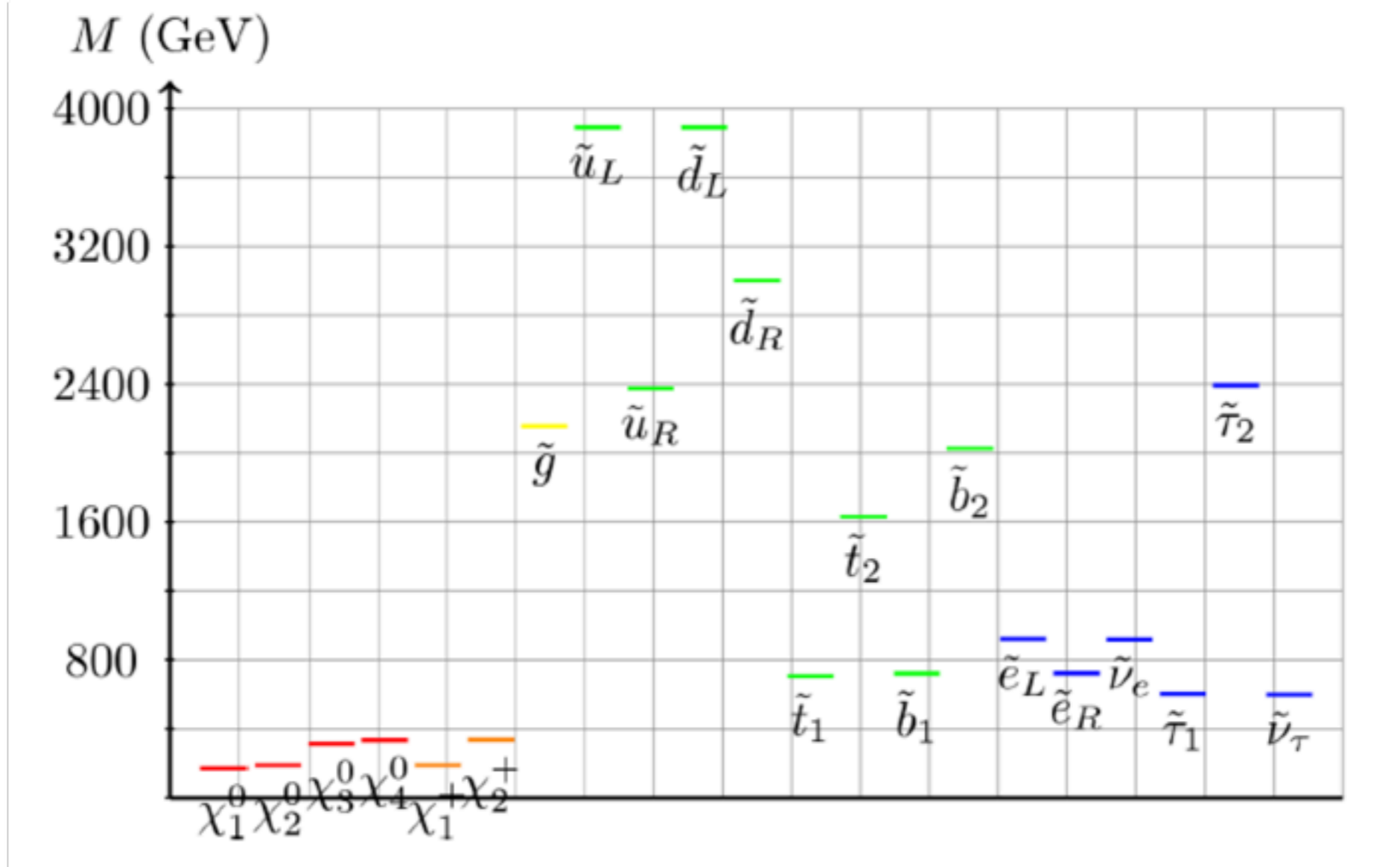
MSSM SPECTRA

- Example gauge-mediated spectrum



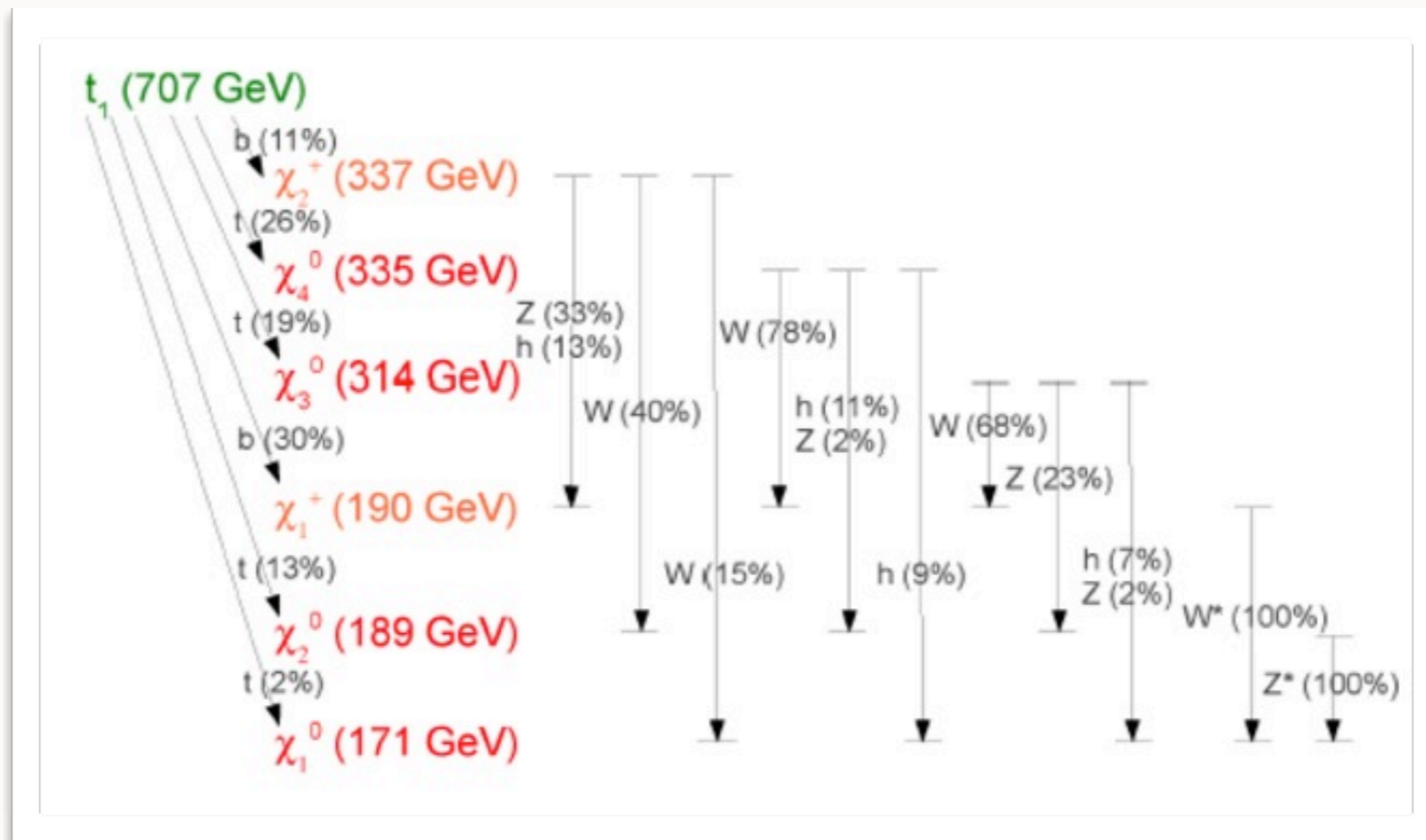
MSSM SPECTRA

- Example bottom-up spectrum



MSSM SPECTRA

- Rich spectrum means complicated decays:



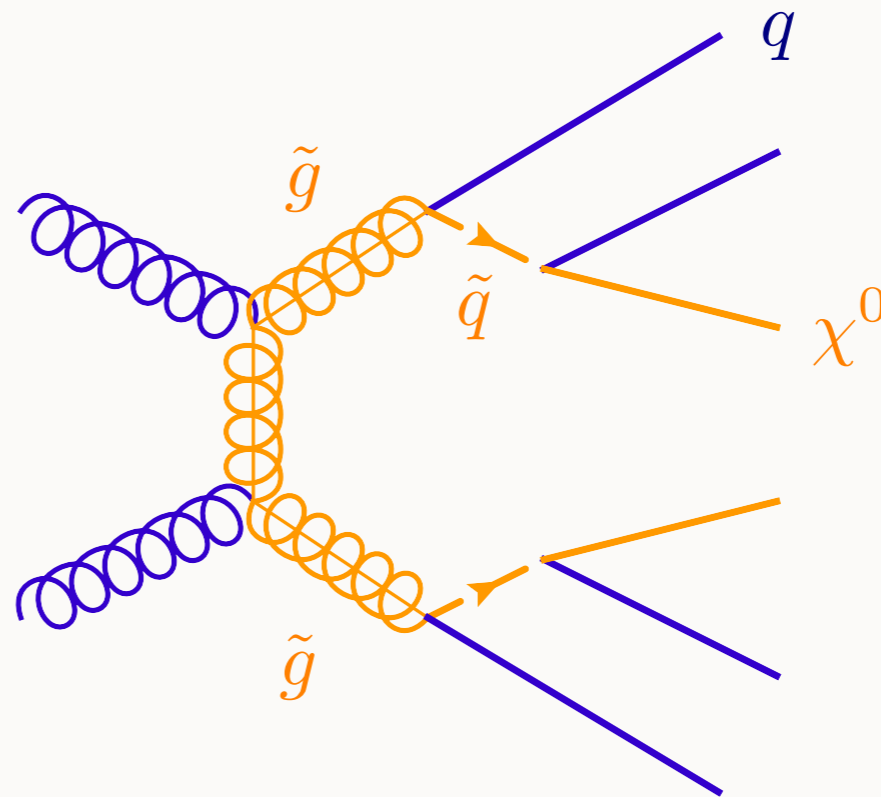
SUSY SEARCHES

- Given enormous complexity and variability of signals, **how should we approach SUSY searches at colliders?**
 - in some ways easier to approach now than at the beginning of the LHC program, as we have learned that copious production of multiple BSM species is not in the cards
 - On the other hand, we have also learned that, if weak-scale SUSY exists, it is likely to take a substantially different form than the models intensively developed by the pre-LHC community (non-minimal, fine-tuned ($< 0.1\%$), etc.)

SUSY AT COLLIDERS

- *R*-parity: produce superparticles in pairs

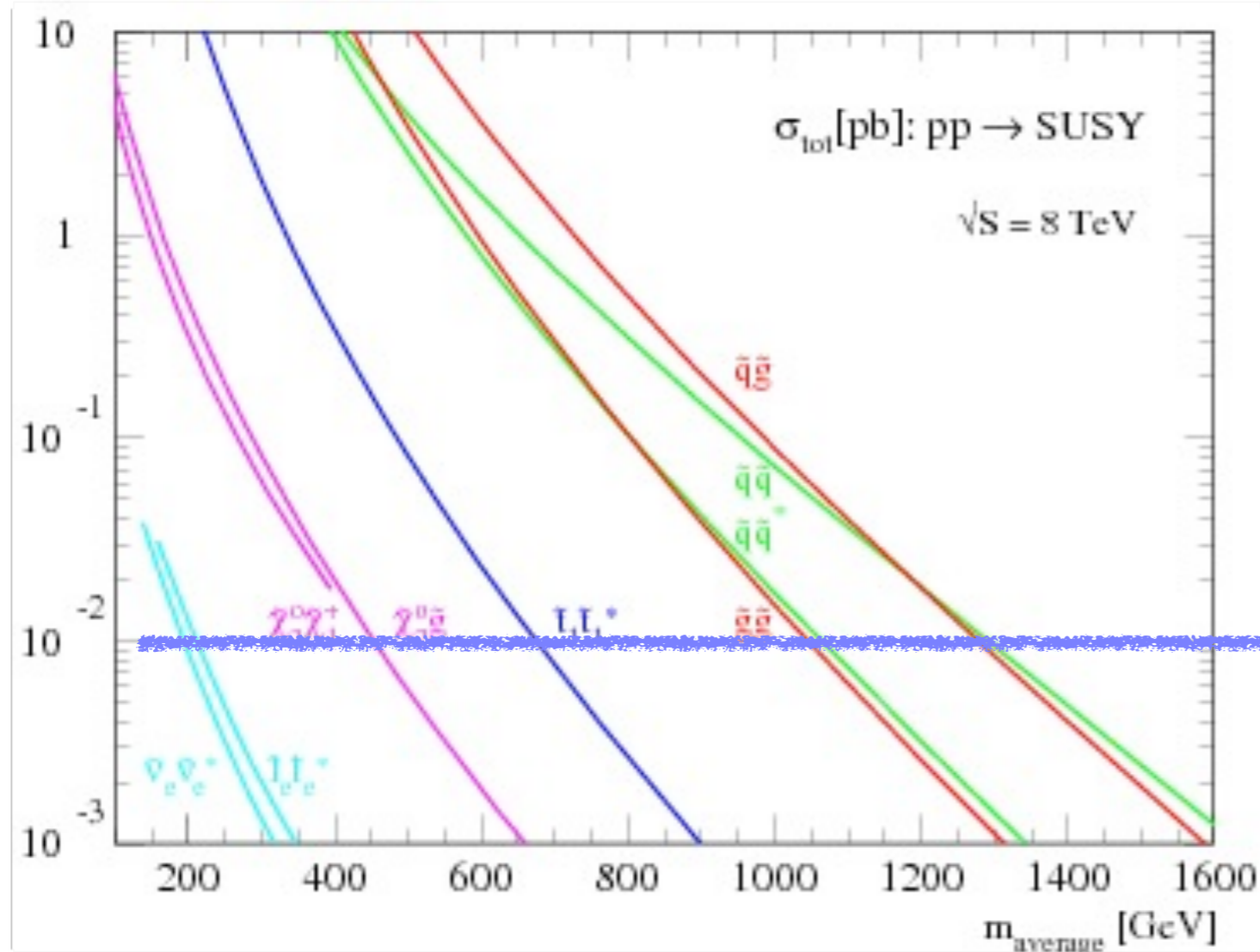
gluino pair production



- superparticles cascade down to pairs of (N)LSPs: generic missing energy

SUSY AT COLLIDERS

- Superpartner production cross-sections

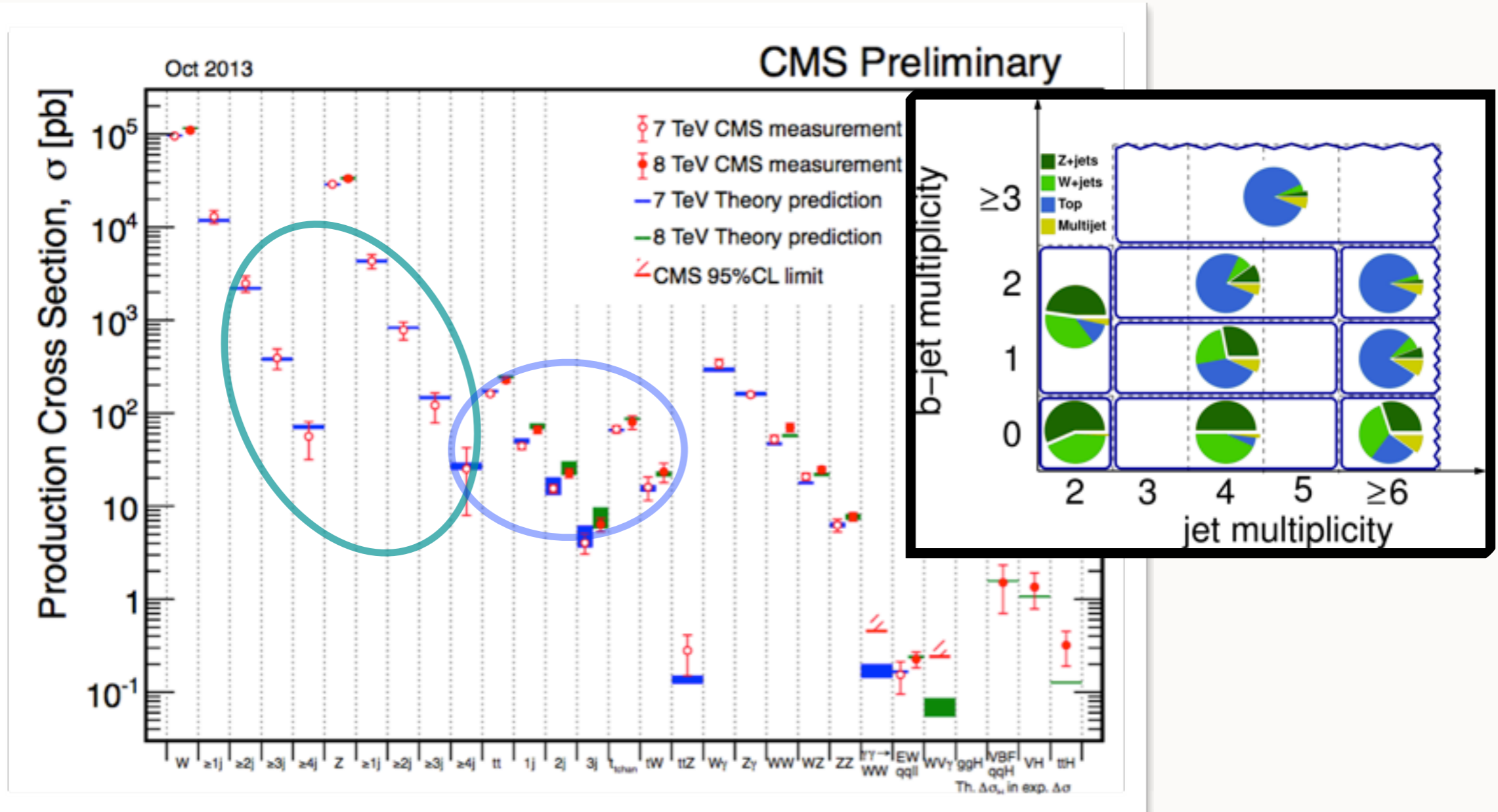


colored states dominate
production

~10 events in 1 fb⁻¹

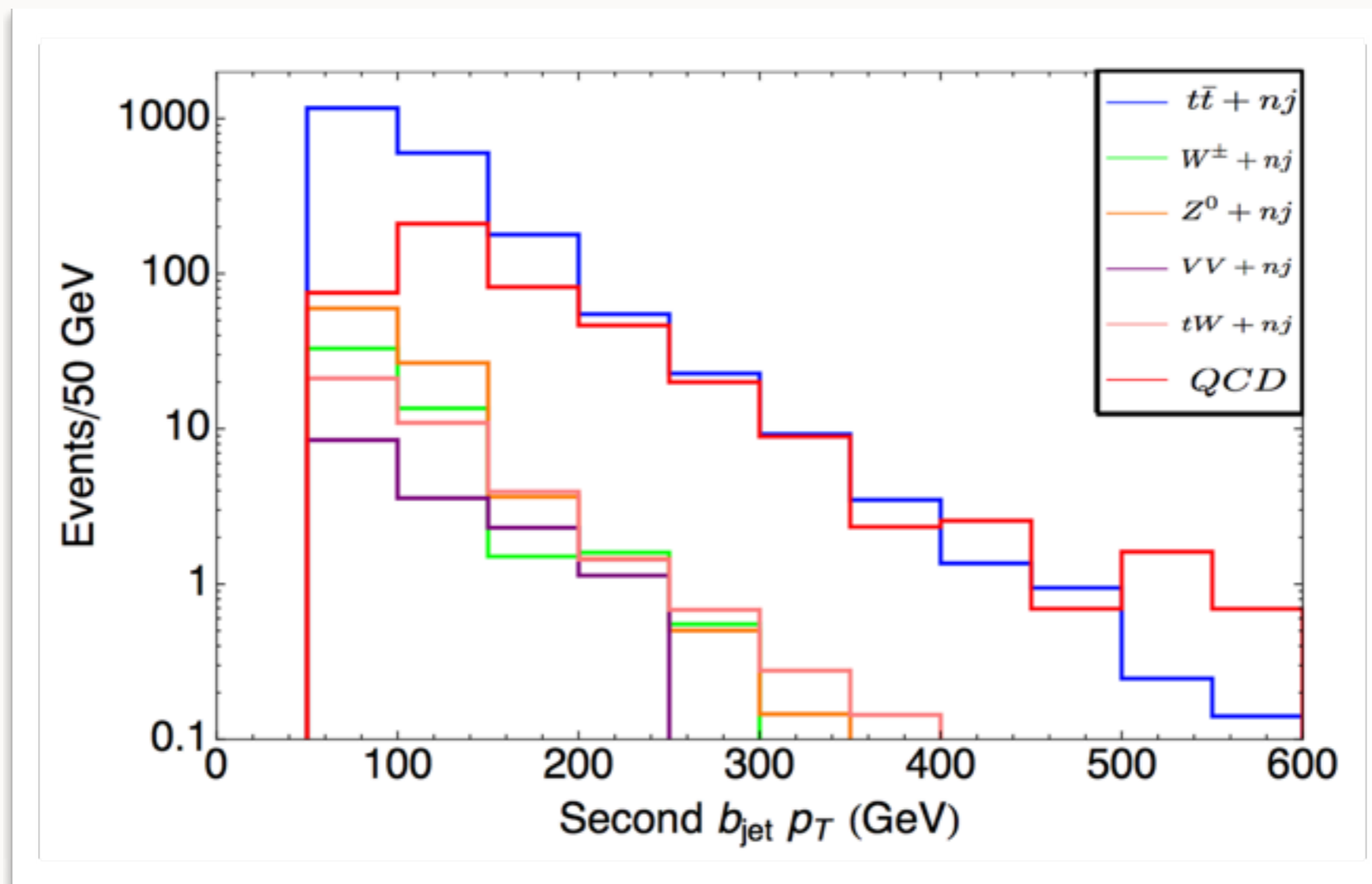
SUSY AT COLLIDERS

- SM background cross-sections are much larger overall



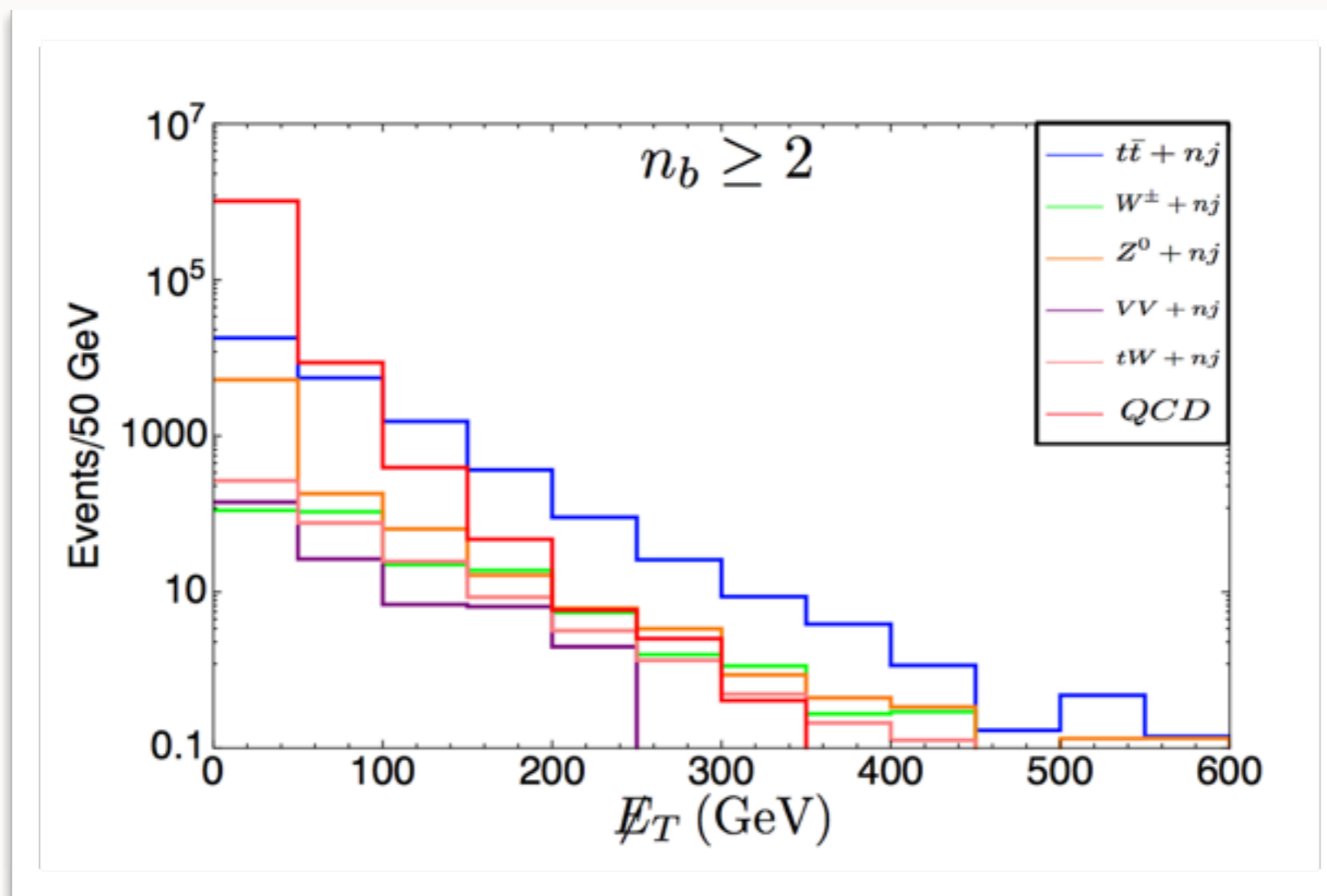
SUSY AT COLLIDERS

- ...but **fall off rapidly** with just about any kinematic variable that has dimensions of **mass**:



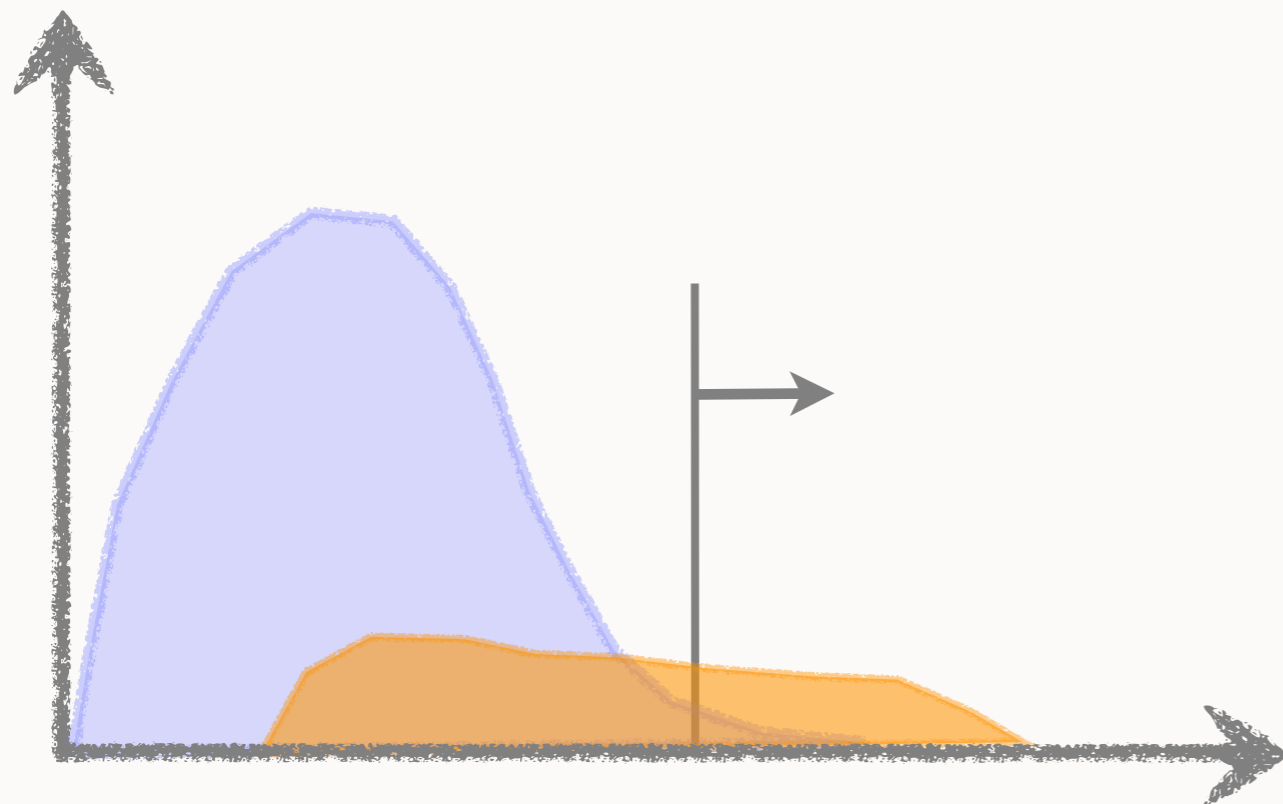
SUSY AT COLLIDERS

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SUSY SEARCHES

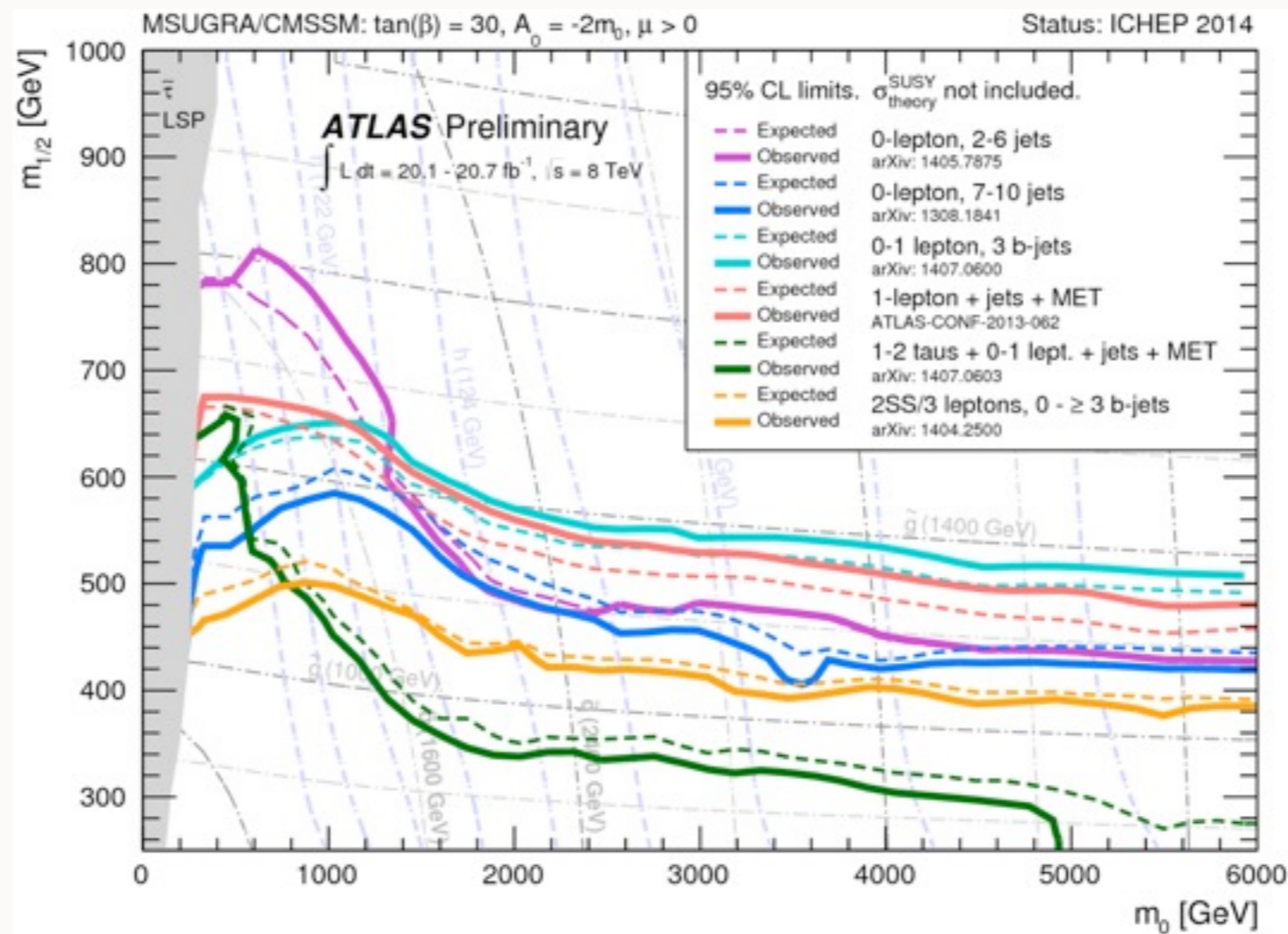
- Essential discovery strategy:



- demand certain numbers of objects (jets, b -jets, MET, leptons...)
- determine a suitable kinematic variable or two
- count events in the energetic tail

SUSY SEARCHES

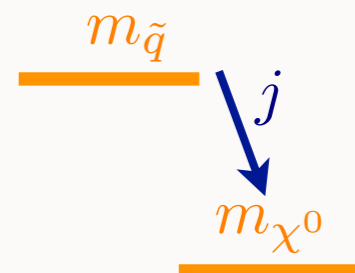
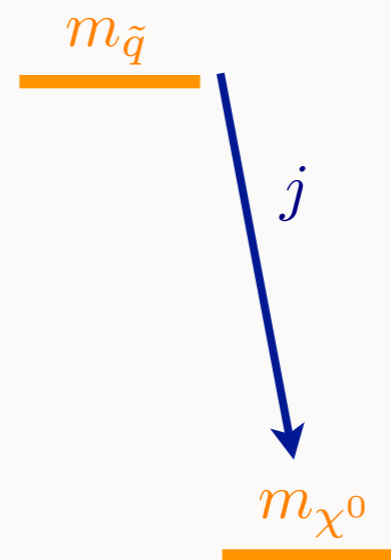
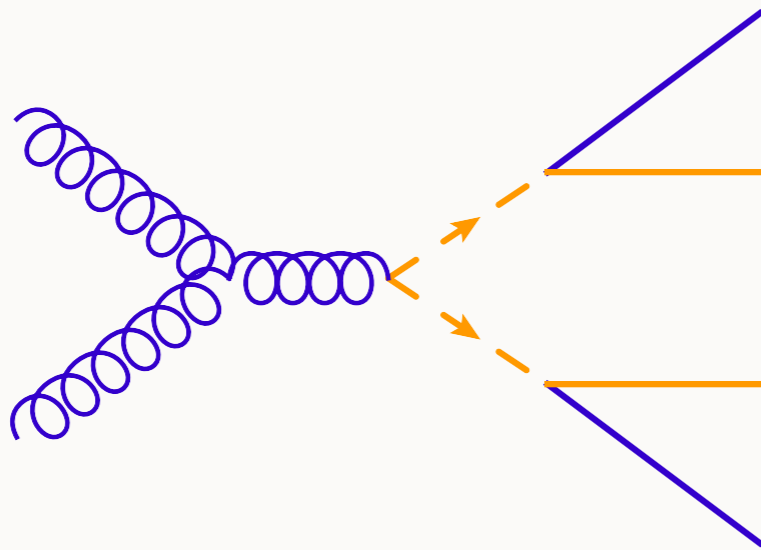
- Efficiently parameterize search for whole model at once?



- not transparent; not flexible

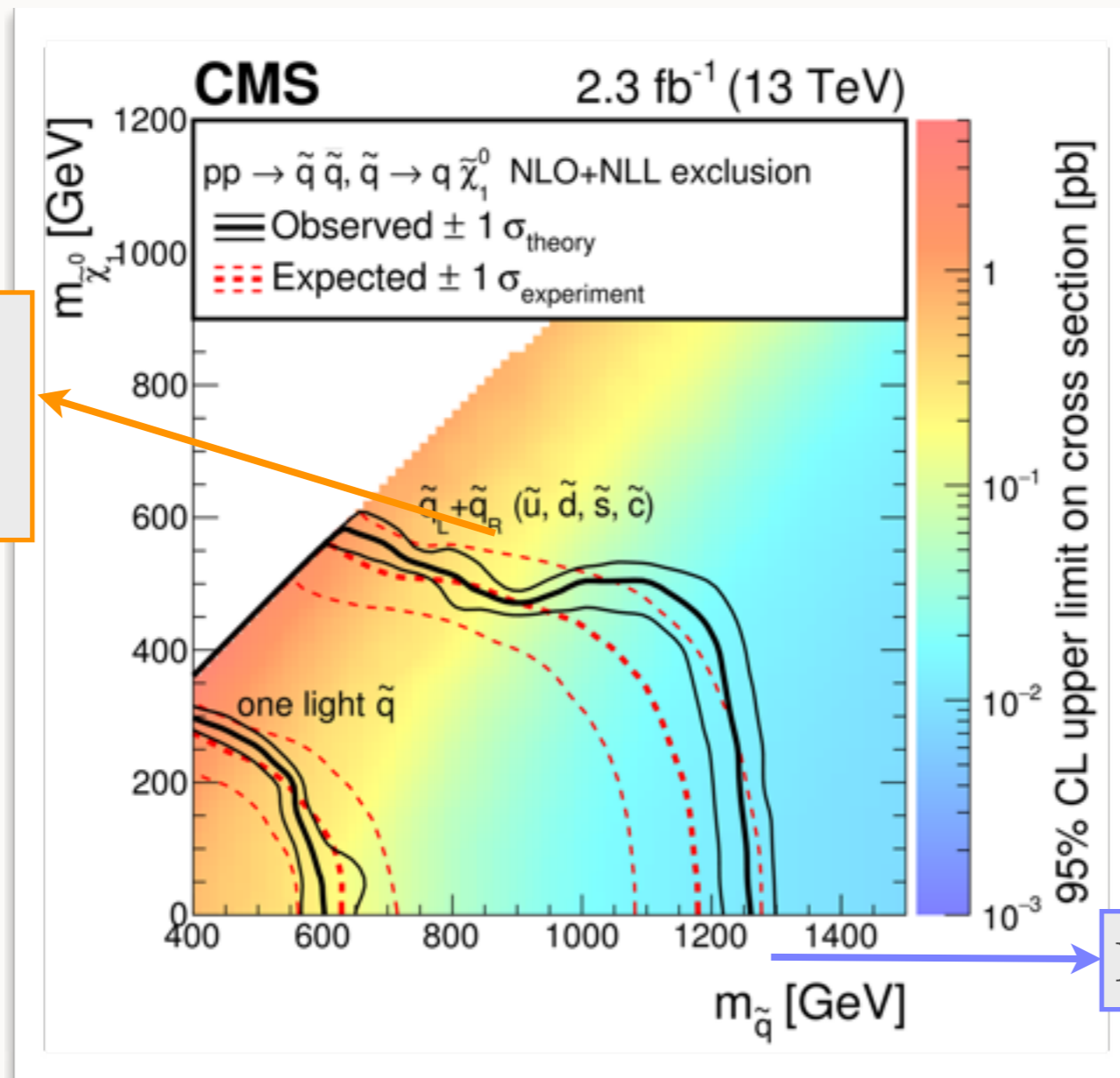
SUSY SEARCHES

- Design search regions that balance:
 - **high signal efficiency**, i.e., are well-targeted to the model
 - **flexibility**, i.e., also have reach for the model next door
- Useful to focus on **a few particles at a time**:



SUSY SEARCHES

- Results for specific simplified event topology:



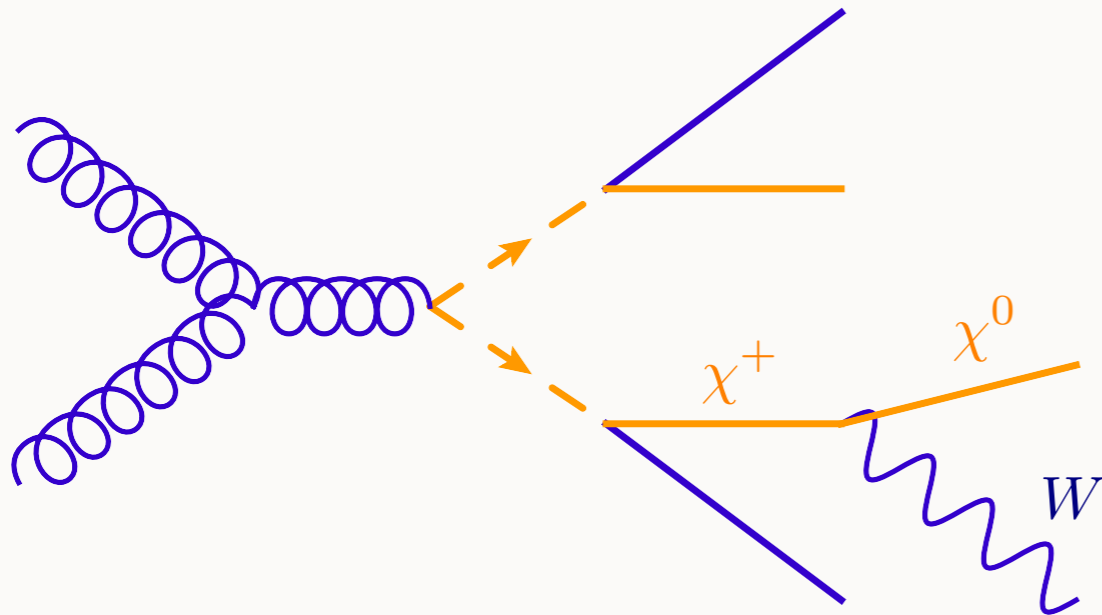
Not enough
visible
momentum

Big difference:
8 squarks
vs
1 squark

Not enough signal events

SUSY SEARCHES

- Often a model will predict additional processes:



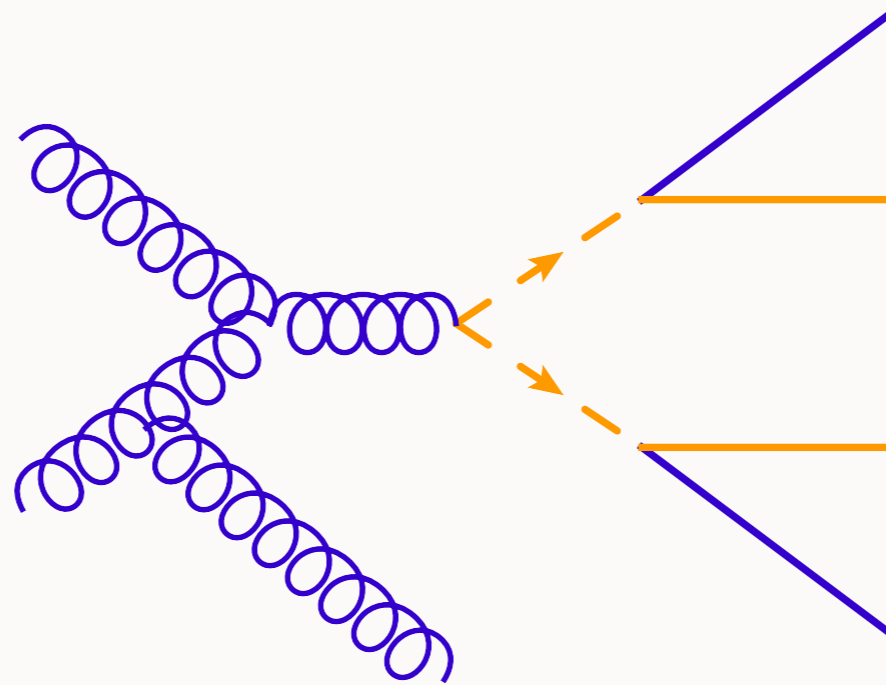
- Different search: jets + MET + lepton
- define enough search regions to cover all common production, decay modes; kinematics
- and remember that a typical MSSM signal will have finite branching ratios for any specific search topology

SUSY SEARCHES

- Search reach is maximized for:
 - **high**, but not too high, **mass**
 - **large cross-section**: many **colored** degrees of freedom
 - **lots of MET**
- Remaining spaces for SUSY signals (and BSM signals in general) where these conditions break down

SQUEEZED SUSY

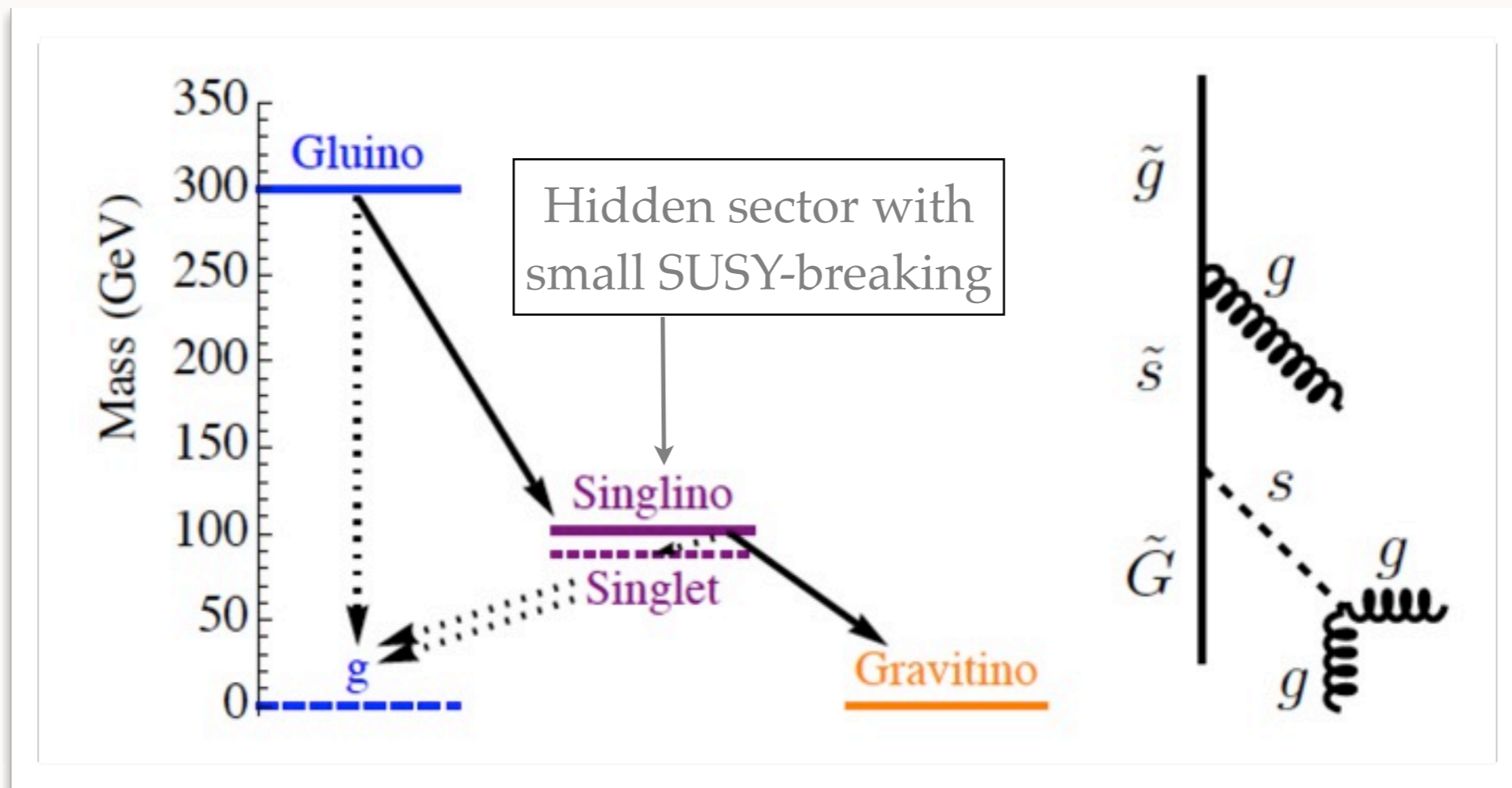
- Maybe SUSY spectrum is **compressed**?



- Need hard ISR jet: reduces rate by $\mathcal{O}(\alpha_s) \sim 0.1$
- Increased signal rates at 13 TeV make it harder and harder to accomodate really light superpartners

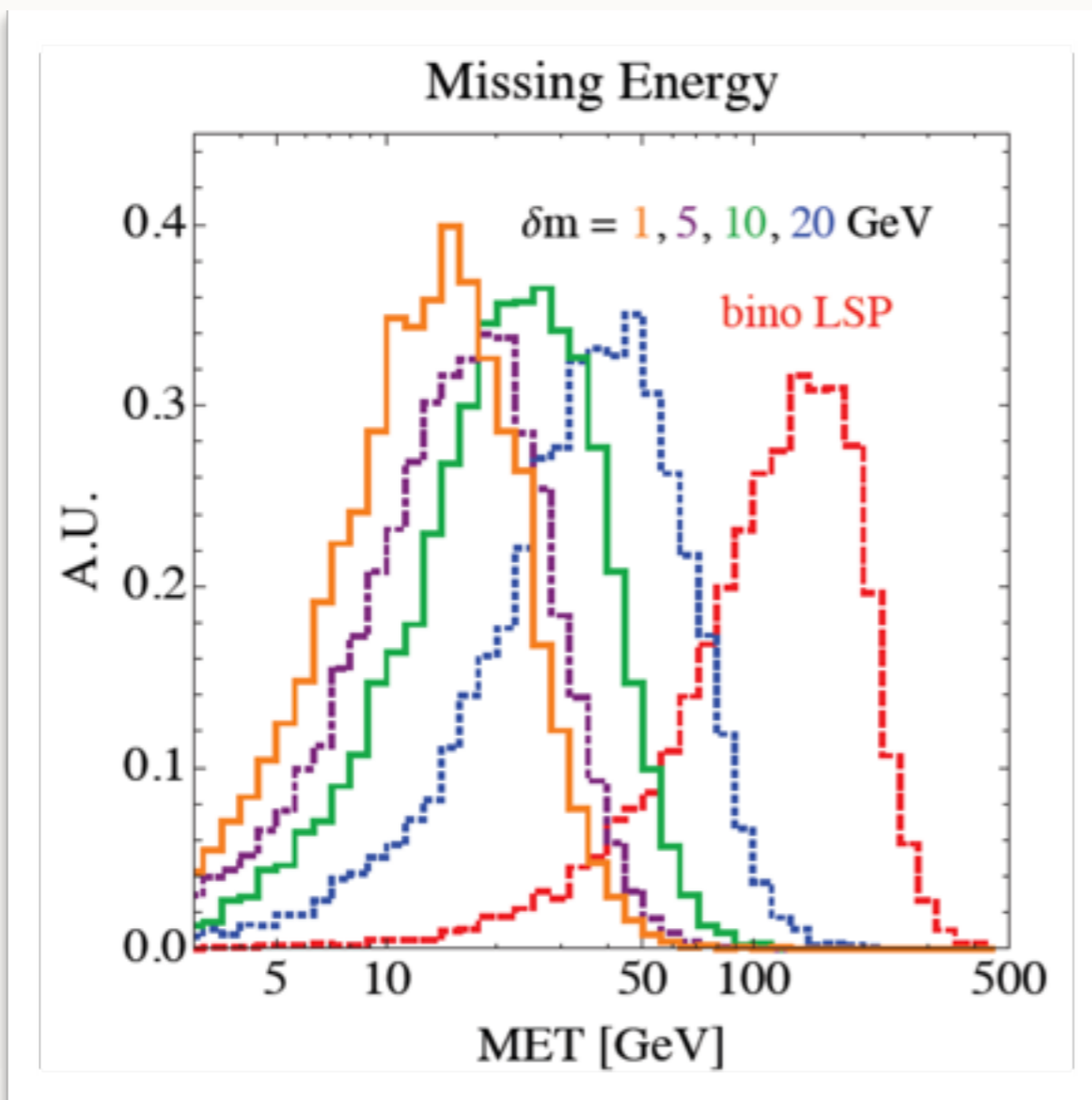
STEALTH SUSY

- Hide SUSY by sticking a small mass splitting on the **end** of the cascade decay:



STEALTH SUSY

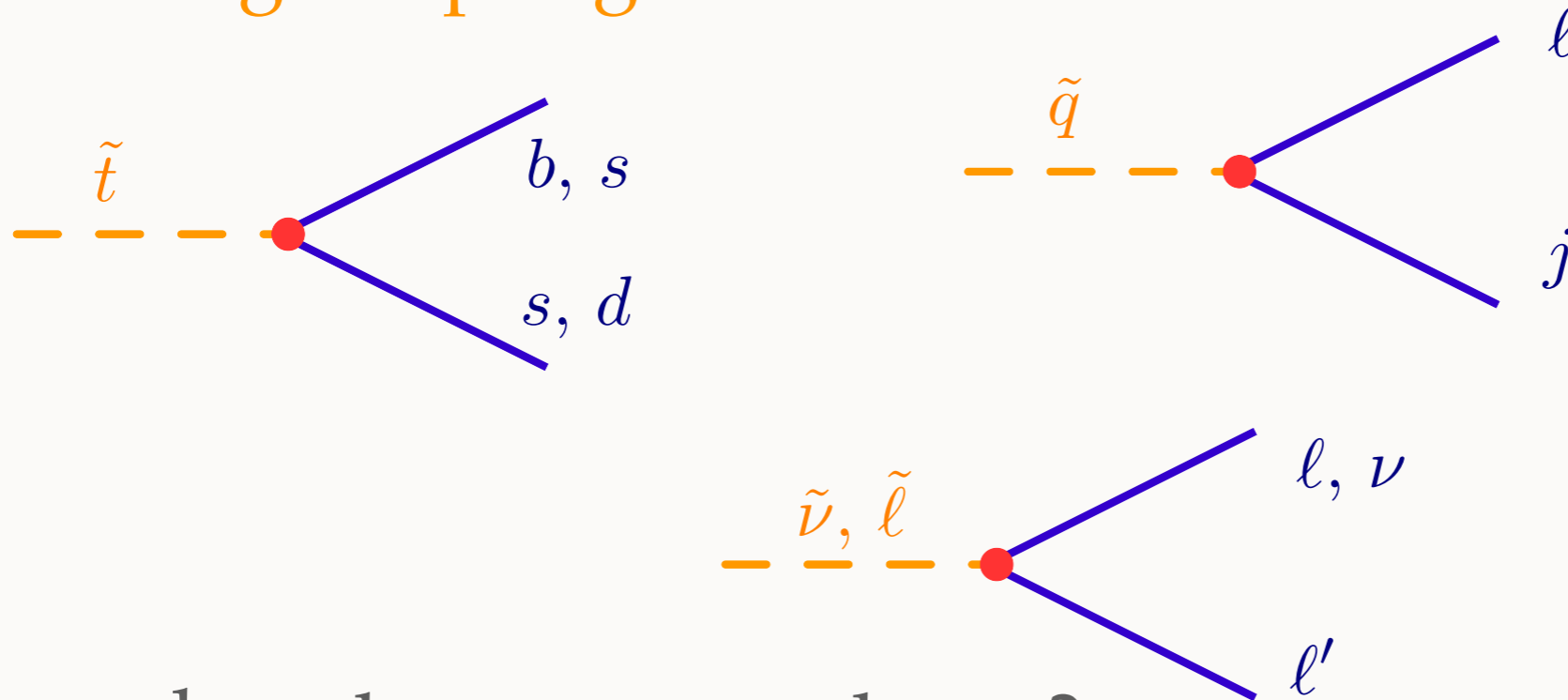
- Trading MET for high jet multiplicities



- Experimental handles:
 - resonances
 - jet substructure
 - possibly: high-multiplicity *b*-jets
 - possibly: displaced vertices
- Hidden sectors signatures: more tomorrow

RPV SUSY

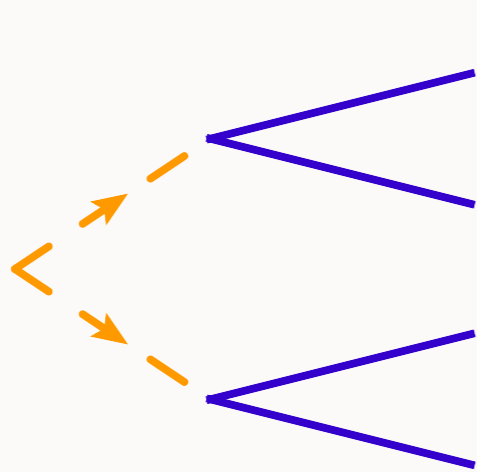
- Can also eliminate MET signal by allowing *R*-parity violating couplings



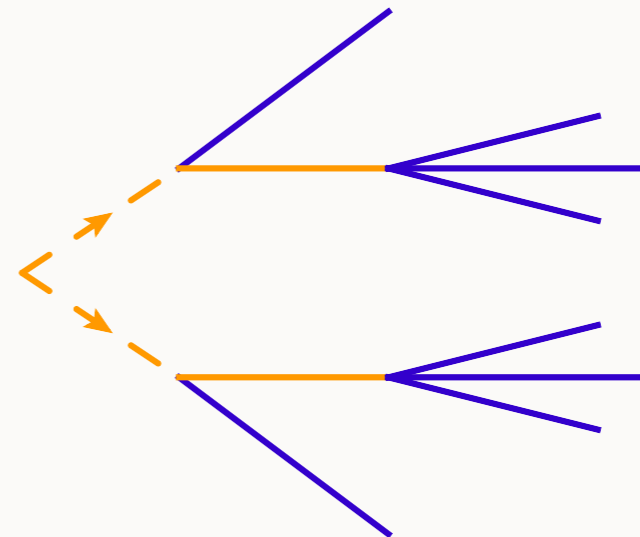
- But what about proton decay?
 - switch on only *B*-violating or only *L*-violating couplings

RPV SUSY

- Still expect pair production to dominate: $\lambda_{RPV} \ll g, g_s$



squark is lightest



neutralino / chargino is lightest

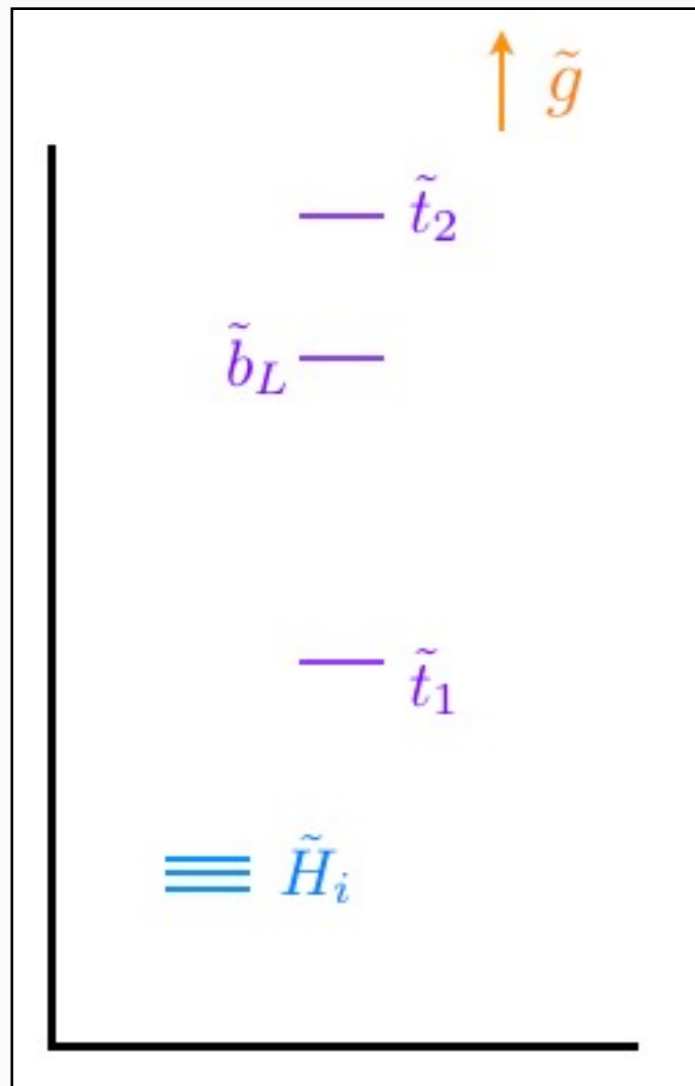
- Signatures have **variable number of jets** (and / or leptons, tops), **2 or 3 object resonances**, possibly **displaced vertices**

RPV SUSY

- Search reach highly dependent on **spectrum, type, flavor structure** of **RPV** coupling
 - **leptonic** RPV: excellent (e.g.: gluinos excluded up to kinematic limit)
 - **all-hadronic**: **much harder**, requires careful modelling of QCD, but high scales and large multiplicities do offer handles (e.g. $\tilde{g} \rightarrow jjj$ excluded up to ~ 900 GeV)
 - challenging at **low mass** (e.g. squarks): high backgrounds
 - Resonances don't help as much as you might think, for multijet decays (can get $\tilde{g} \rightarrow 5j$): combinatorics, smearing

NATURAL SUSY

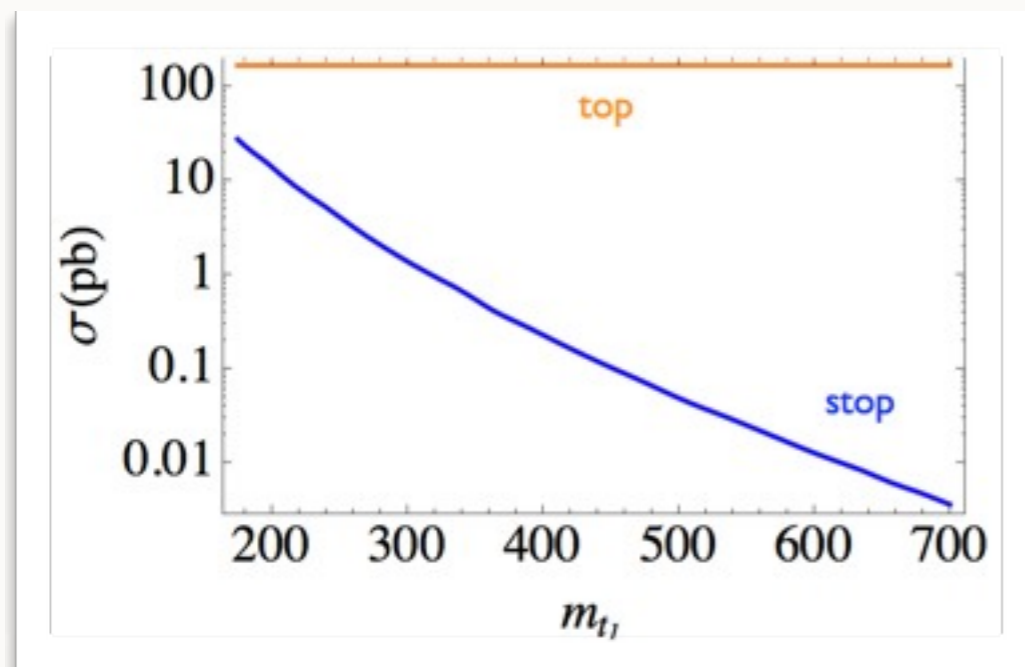
- Maybe we don't have the whole zoo of MSSM states near the weak scale



- Maybe just the states **most immediately important** for addressing the hierarchy problem:
 - **higgsinos** - mass related to m_h at tree level
 - **stops** - most important quantum correction
 - **gluinos** - stops have their own hierarchy problem!

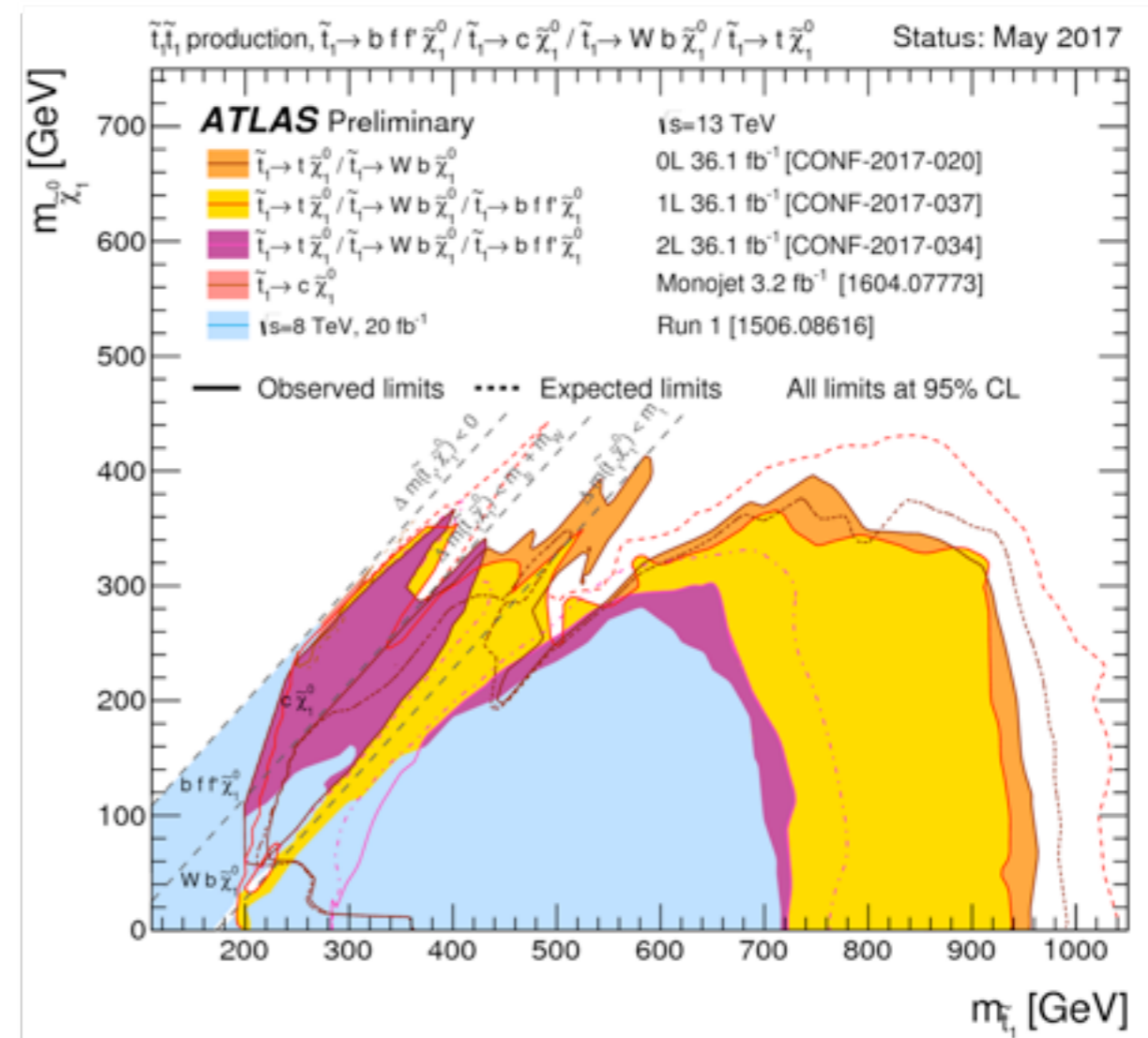
NATURAL SUSY

- Direct stop production is a tougher target than gluinos



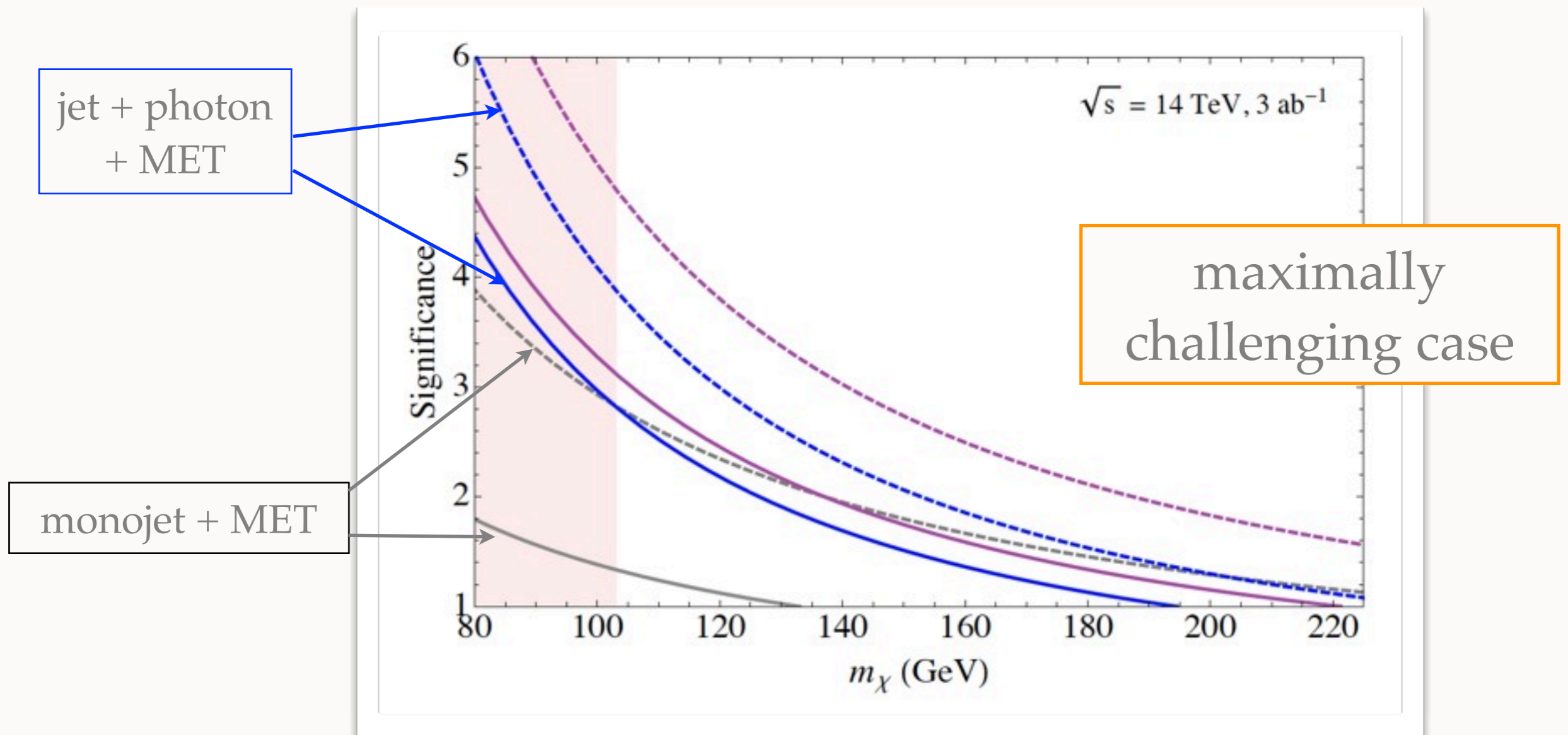
Compressed spectra are hard!

but 13 TeV results fill in many gaps at low mass



ELECTROWEAK SUSY

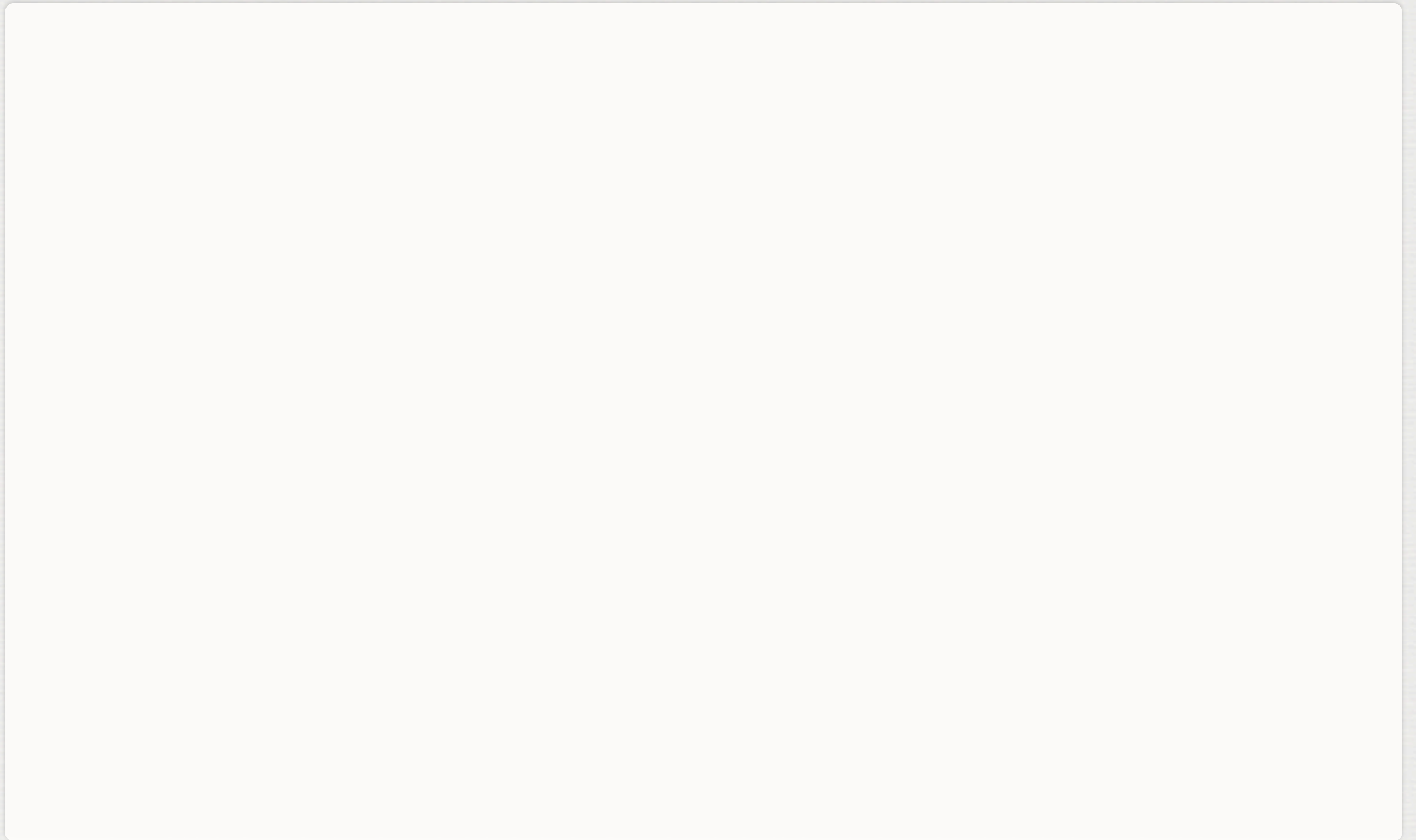
- Direct higgsino production is **very** hard:



MINI-SPLIT SUSY

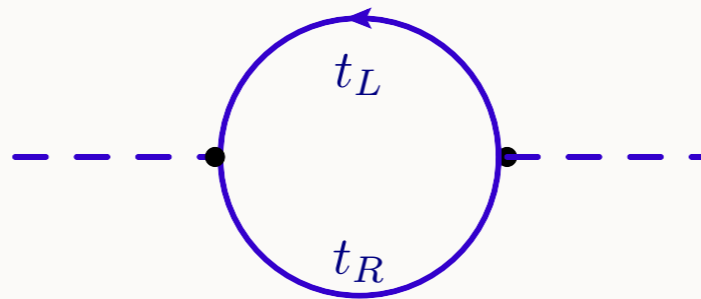
- Maybe much of the spectrum is simply **out of reach**
 - tuned! Put sfermions up at ~ 100 TeV, keep inos near(ish) weak scale
 - keeps **unification**, **DM candidate**
 - solves SUSY flavor issue
 - jibes well with $m_h=125$ GeV
 - can predict **displaced decays** (more tomorrow)

BACKUP



SUSY BREAKING

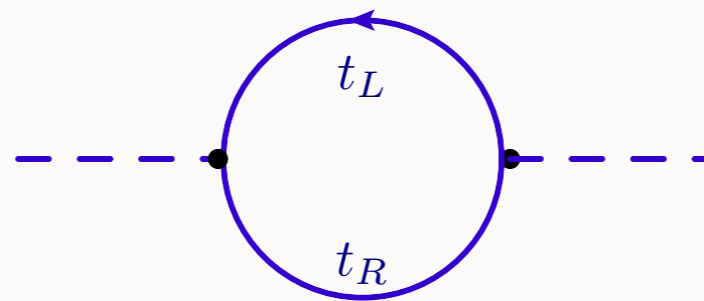
- Let's do an explicit example: top and stop loops



$$-i \delta m_h^2|_{top} = -2N_c y_t^2 \int \frac{d^4 k}{(2\pi)^4} \frac{k^2 + m_t^2}{(k^2 - m_t^2)^2}$$

SUSY BREAKING

- Let's do an explicit example: top and stop loops



overall minus sign
from fermion loop

logarithmic
divergence

$$-i \delta m_h^2|_{top} = -2N_c y_t^2 \int \frac{d^4 k}{(2\pi)^4} \frac{k^2 + m_t^2}{(k^2 - m_t^2)^2}$$

color degrees
of freedom

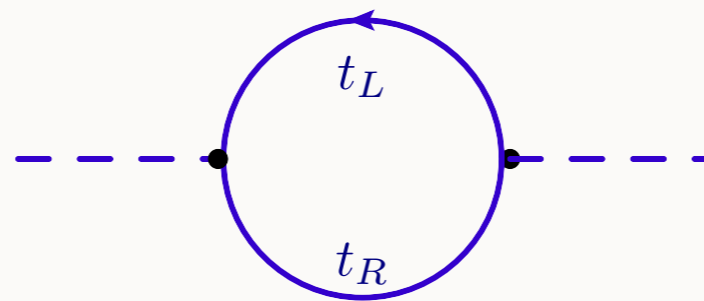
vertices

two propagators

quadratic
divergence

SUSY BREAKING

- Let's do an explicit example: top and stop loops

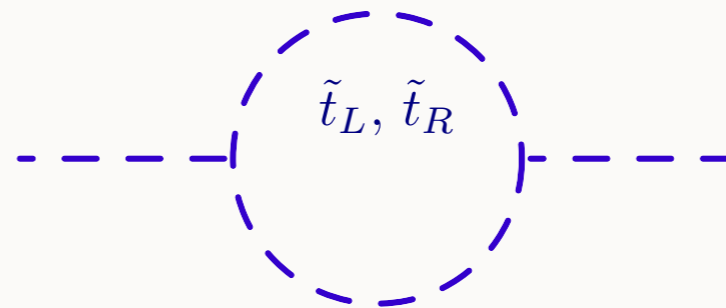
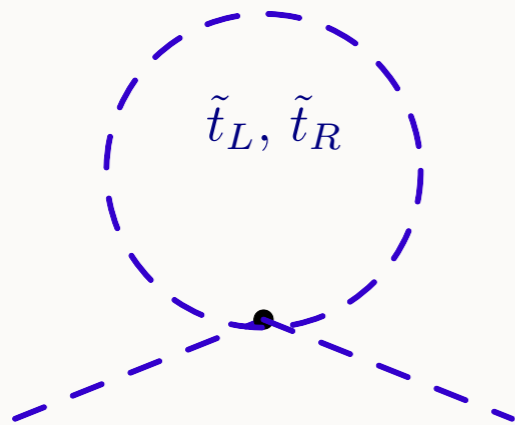


$$-i \delta m_h^2|_{top} = -2N_c y_t^2 \int \frac{d^4 k}{(2\pi)^4} \frac{k^2 + m_t^2}{(k^2 - m_t^2)^2}$$

$$\delta m_h^2|_{top} = -\frac{3y_t^2}{8\pi^2} \left(\Lambda^2 - 3m_t^2 \ln \left(\frac{\Lambda^2 + m_t^2}{m_t^2} \right) + \dots \right)$$

SUSY BREAKING

- Let's do an explicit example: top and stop loops



$$\mathcal{L}_{stop} = -\frac{1}{2}(v+h)^2 (|\tilde{t}_L|^2 + |\tilde{t}_R|^2)$$

SUSY-preserving

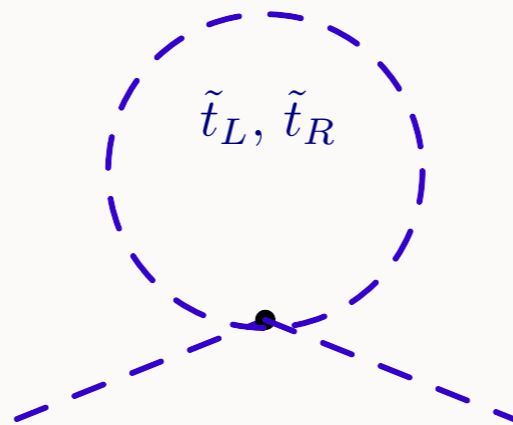
$$+m_R^2|\tilde{t}_R|^2 + m_L^2|\tilde{t}_L|^2$$

SUSY-breaking

- In general also SUSY-breaking contribution to trilinears

SUSY BREAKING

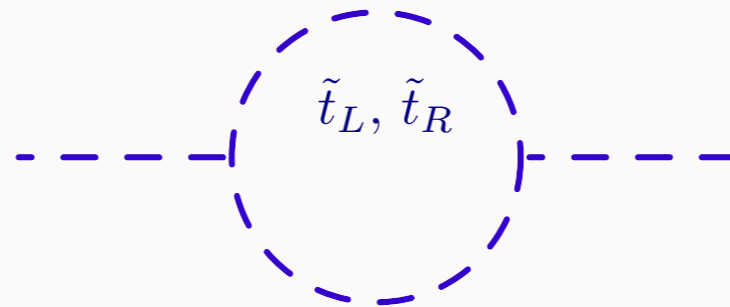
- Let's do an explicit example: top and stop loops



$$\delta m_h^2|_{stop\ 1} = \frac{3y_t^2}{16\pi^2} \left(2\Lambda^2 - m_L^2 \ln \left(\frac{\Lambda^2 + m_L^2}{m_L^2} \right) - m_R^2 \ln \left(\frac{\Lambda^2 + m_R^2}{m_R^2} \right) + \dots \right)$$

SUSY BREAKING

- Let's do an explicit example: top and stop loops



$$\delta m_h^2|_{stop 2} = -\frac{3y_t^2}{8\pi^2} \left(m_t^2 \ln \left(\frac{\Lambda^2 + m_L^2}{m_L^2} \right) - m_t^2 \ln \left(\frac{\Lambda^2 + m_R^2}{m_R^2} \right) + \dots \right)$$

No quadratic divergences:
dimensionally impossible

SUSY-breaking trilinears:
mt \rightarrow more general function

SUSY BREAKING

- Let's do an explicit example: top and stop loops
 - Add everything up:

$$\delta m_h^2|_{top} = -\frac{3y_t^2}{8\pi^2} \left(\Lambda^2 - 3m_t^2 \ln \left(\frac{\Lambda^2 + m_t^2}{m_t^2} \right) + \dots \right)$$

$$\delta m_h^2|_{stop\ 1} = \frac{3y_t^2}{16\pi^2} \left(2\Lambda^2 - m_L^2 \ln \left(\frac{\Lambda^2 + m_L^2}{m_L^2} \right) - m_R^2 \ln \left(\frac{\Lambda^2 + m_R^2}{m_R^2} \right) + \dots \right)$$

$$\delta m_h^2|_{stop\ 2} = -\frac{3y_t^2}{8\pi^2} \left(m_t^2 \ln \left(\frac{\Lambda^2 + m_L^2}{m_L^2} \right) - m_t^2 \ln \left(\frac{\Lambda^2 + m_R^2}{m_R^2} \right) + \dots \right)$$

Quadratic divergence cancels
independently of soft breaking terms

Exact SUSY: log
divergence cancels too